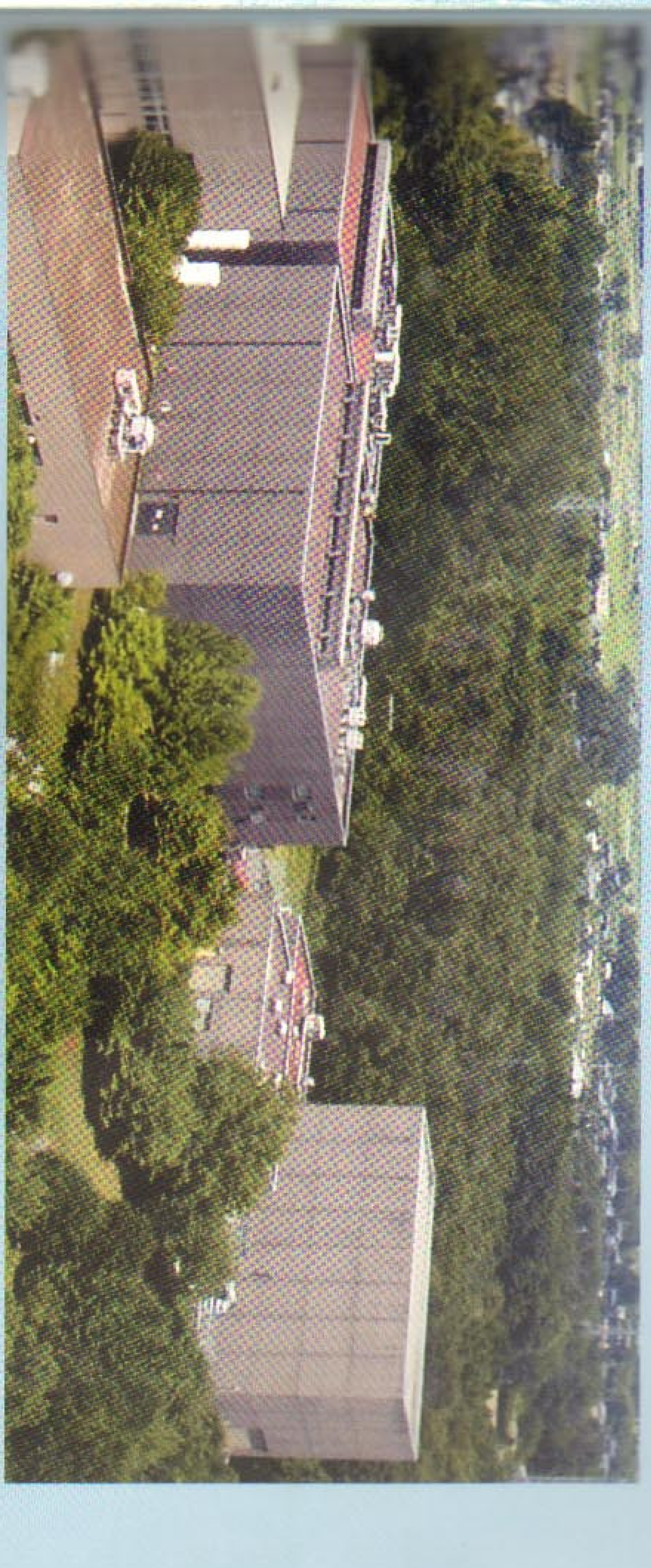
Program of Open Systems 2006

July 17 (Mon.)	July 18 (Tue.)	July 19 (Wes.)	July 20 (Thu.)	July 21 (Fri.)
8:30 *Registration*				
chair: Dolan, Kruglyakov 9:00 **Opening** (Cho, Iwasaki) 9:20 Alpha Channeling (Fisch) 9:55 IAEA fusion (Clark)	chair: Sasao, Yasaka 9:00 Microwave (Mase) 9:35 Thomson Scattering (Hatae) 10:00 Thomson Scattering (Kondoh)	chair: Pastukhov, Yoshikawa 9:00 GOL-3 (Burdakov) 9:35 Kinetic Stabilizer (Horton) 9:55 HANBIT (England) 10:20 GAMMA10 (Katanuma)	chair: Ivanov, Mase 9:00 Plasma Flow (Inutake) 9:35 LHD (Watanabe) 9:55 Wave Excitation (Ichimura)	chair: Fisch, Horton 9:00 Drift Wave Turbulence (Kishimoto) 9:35 Straight Field Line Mirror (Agren) 10:00 Distribution Functions (Kohagura)
10:30 ***Coffee Break***	10:20 ***Coffee Break***	10:40 ***Coffee Break***	10:15 ***Coffee Break***	10:25 ***Coffee Break***
chair: Kwon, Horton 10:45 GAMMA10 (Cho) 11:20 Axi- Mirror (Kruglyakov)	chair: Inutake, Agren 10:35 GDT (Noack) 11:00 MAP-II (Chung) 11:20 Space Thruster (Ando) 11:40 GAMMA10 (Yoshikawa)	chair: Clark, Sasao 10:55 EUV Spectra (Kato) 11:30 Impurity Molecules (Kimura) 11:55 Cross Sections (Kusakabe) 12:15 Atomic and Molecular (Sataka) 12:35 NIFS Database (Murakami)	chair: Agren, Burdakov 10:30 High Power ECRH (Hatakeyama) 11:05 Cyclotron Heating (Moiseenko) 11:30 Full-Wave Simulations (Hojo) 11:50 TST-2 (Ejiri)	chair: Kruglyakov, Dolan 10:40 ECRH System (Imai) 11:15 170GHz Gyrotron (Kasugai) 11:40 **Concluding** (Cho, Kwon)
11:55 ***Lunch Break***	12:00 ***Lunch Break***	12:55 ***Group Photo*** 13:10 ***Lunch Break***	12:10 ***Lunch Break***	11:55 Close
chair: Kishimoto, Ivanov 13:10 Confinement (Horton) 13:45 HANBIT (Kwon) 14:20 RT-1 (Yoshida)	chair: Noack, Pastukhov 13:10 GDT (Ivanov) 13:45 GAMMA10 (Nakashima) 14:10 HANBIT (Park) 14:30 AMBAL-M (Akhmetov)	14:00-16:50 Poster Session chair: Katanuma, Kohagura (15:15- 15:30 ***Coffee Break***) chair: Ichimura, Hirata	chair: England, Nakashima 13:30 Energy Conversion (Yasaka) 14:05 Cusp DEC (Tomita) 14:25 Bounce Instability(Beklemishev) 14:45 Confining Potentials (Hirata)	13:00 ***Tour to GAMMA10***
14:55 ***Coffee Break***	14:50 ***Coffee Break***		15:05 ***Coffee Break***	
chair: Clark, Kato 15:10 Transport (Pastukhov) 15:45 Diagnostics (Sasao) 16:20 Tokamak (Takase)	chair: Kato, Imai 15:05 Turbulence (Ryu) 15:30 Diocotron Modes (Kabantsev) 15:55 Transport (Sokolov) 16:15 Drift-Wave (Kaneko) 16:35 Drift-Wave (Yoon)	16:50 Close	chair: Hatakeyama, Ichimura 15:20 Multiple Mirror (Kotelnikov) 15:45 D - ^{3}He (Ryzhkov) 16:10 FRC (Okada) 16:35 RFP (Masamune)	
16:55 Close	16:55 Close	18:30 ***Banquet***	16:55 Close	

6th International Conference on Open
Magnetic Systems for Plasma Confinement

July 17-21, 2006 in Tsukuba, Japan

PROGRAM AND BOOK OF ABSTRACTS



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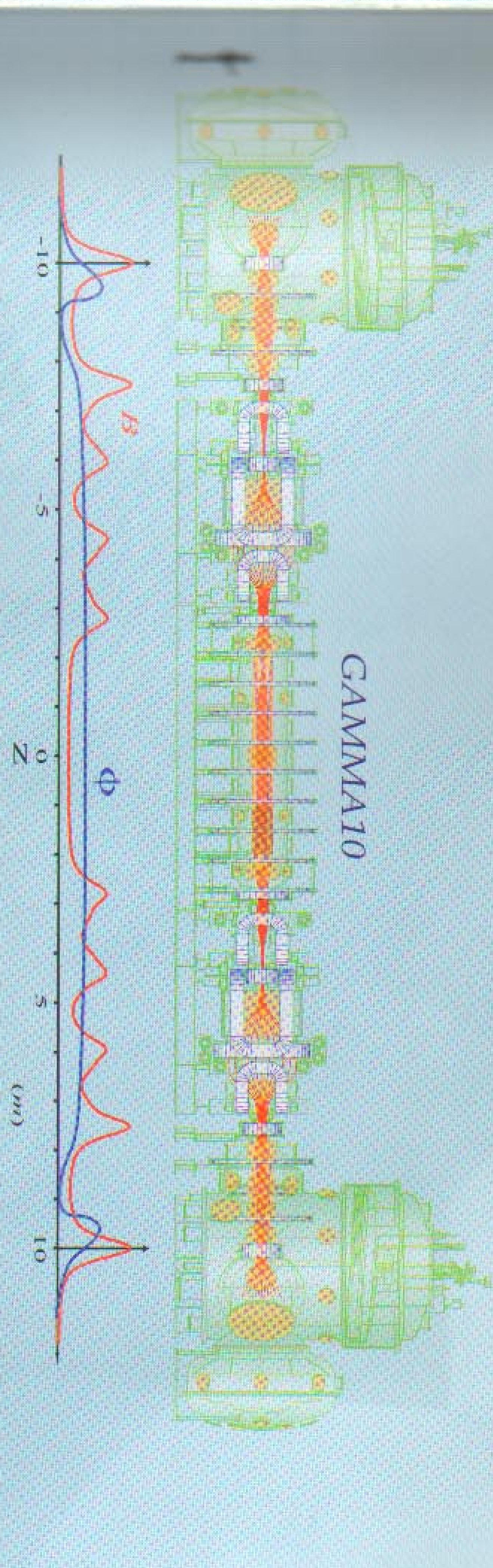

Open Systems 2006

Organized by the Plasma Research Center
University of Tsukuba

Program of Open Systems 2006

July 17 (Monday) **R:** Invited and Review Paper

Chair: T.J.Dolan, E.P.Kruglyakov

09:00-09:10 **Opening Remarks1** (T.Cho : Plasma Research Center, University of Tsukuba)

09:10-09:20 **Opening Remarks2** (Y.Iwasaki : President of University of Tsukuba)

09:20-09:55 17**R01** Alpha Channeling in Mirror Machines and in Tokamaks,
N.J. Fisch, (Department of Astrophysical Sciences, Princeton University, USA)

09:55-10:30 17**R02** IAEA Fusion Activities and Nuclear Data Support for Innovative Concepts,
R.E.H.Clark, (International Atomic Energy Agency, Austria)

10:30-10:45 **Coffee Break**

Chair: W.Horton, M.Kwon

10:45-11:20 17**R03** Overview of Recent Progress in the GAMMA10 Tandem Mirror,
T. Cho, (Plasma Research Center, University of Tsukuba, Japan)

11:20-11:55 17**R04** Axially Symmetric Magnetic Mirror Traps. Status and Perspectives,
E.P.Kruglyakov, (Budker Institute of Nuclear Physics, Russia)

11:55-13:10 **Lunch**

Chair: Y.Kishimoto, A.Ivanov

13:10-13:45 17**R05** Energy Confinement Scaling Predictions for the Kinetically Stabilized Tandem Mirror,
W. Horton, (Institute for Fusion Studies, The University of Texas at Austin, USA)

13:45-14:20 17**R06** Progress of the HANBIT Device,
M.Kwon, (National Fusion Research Center, Korea)

14:20-14:55 17**R07** RT-1 Project - Magnetosphere-like Plasma Experiment,
Z.Yoshida, (Graduate School of Frontier Sciences, The University of Tokyo, Japan)

14:55-15:10 **Coffee Break**

Chair: R.E.H.Clark, T.Kato

15:10-15:45 17**R08** Low-frequency Turbulence and Non-diffusive Cross-field Plasma Transport in Mirror Systems, V.P.Pastukhov, (Russian Research Centre "Kurchatov Institute", Russia)

15:45-16:20 17**R09** Advanced Diagnostics for Burning Plasma Experiments,
M.Sasao, (Department of Quantum Science and Energy Engineering, Tohoku University, Japan)

16:20-16:55 17**R10** Tokamak and Spherical Tokamak Research in Japan,
Y. Takase, (Graduate School of Frontier Sciences, The University of Tokyo, Japan)

<u>July 18 (Tuesday)</u> **R:** Invited and Review Paper

Chair: M.Sasao, Y.Yasaka

09:00-09:35 18**R01** Progress in Microwave Diagnostics and Physics Issues in Magnetically Confined Plasmas,
A. Mase, (Art, Science and Technology Center for Cooperative Research, Kyushu University, Japan)

09:35-10:00 18**R02** Progress in Development of Edge Thomson Scattering System for ITER,
T. Hatae, (Japan Atomic Energy Agency, Japan)

10:00-10:20 18**R03** CO_2 Laser Collective Thomson Scattering Diagnostic of α-particles in Burning Plasmas,
T.Kondoh, (Japan Atomic Energy Agency, Japan)

10:20-10:35 **Coffee Break**

Chair: M.Inutake, O.Agren

10:35-11:00 18**R04** The GDT as Neutron Source in a Sub-critical System for Transmutation?
K. Noack, (Forschungszentrum Rossendorf, Germany)

11:00-11:20 18**R05** Measurement Density Profiles with Pressure in MAP-II Linear Device,
K.-S.Chung, (The University of Tokyo / Hanyang University, Korea)

11:20-11:40 18**R06** ICRF Heating and Plasma Acceleration with an Open Magnetic Field for the Advanced Space Thruster,
A.Ando, (Graduate School of Engineering, Tohoku University, Japan)

11:40-12:00 18**R07** Plasma Spectroscopy in the Tandem Mirror GAMMA10,
M.Yoshikawa, (Plasma Research Center, University of Tsukuba, Japan)

12:00-13:10 **Lunch**

Chair: K.Noack, V.P.Pastukhov

13:10-13:45 18**R08** The Synthesized Hot Ion Plasmoid Experiment at GDT,
A.Ivanov, (Budker Institute of Nuclear Physics, Russia)

13:45-14:10 18**R09** Investigation of Neutral Particles Using High Speed Camera and Monte-Carlo Simulation in the GAMMA10 Central-cell,
Y.Nakashima, (Plasma Research Center, University of Tsukuba, Japan)

14:10-14:30 18**R10** Simulation Study of Stepwise-Density Variation with RF Power in a HANBIT Device,
B.H.Park, (National Fusion Research Center, Korea)

14:30-14:50 18**R11** Behavior of the Initial Plasma in AMBAL-M,
T.Akhmetov, (Budker Institute of Nuclear Physics, Russia)

14:50-15:05 **Coffee Break**

Chair: T.Kato, T.Imai

15:05-15:30 18**R12** Indication of a Low Frequency Coherent Structure Driven by Turbulence in a Hanbit Mirror Plasma, C.M. Ryu, (Pohang University of Science and Technology, Korea)

15:30-15:55 18**R13** Ion-induced Instability of Diocotron Modes in Electron Plasmas Modelling Curvature-driven Flute Modes, A.Kabantsev, (University of California at San Diego, USA)

15:55-16:15 18**R14** A New Paradigm for Radial Ion Plasma Transport in Axisymmetric Magnetic Field,
V.Sokolov, (Plasma Research Laboratory, Columbia University, USA)

16:15-16:35 18**R15** Drift-Wave Instability Modified by Superimposed Parallel and Perpendicular Plasma Flow Velocity Shears,
T.Kaneko, (Department of Electronic Engineering, Tohoku University, Japan)

16:35-16:55 18**R16** Characterization of Electron Drift Wave and Interchange Mode in HANBIT Mirror Device,
S.W.Yoon, (National Fusion Research Center, Korea)

<u>July 19 (Wednesday)</u> **R:** Invited and Review Paper

Chair: V.P.Pastukhov, M.Yoshikawa

09:00-09:35 19**R01** Plasma heating and confinement in GOL-3 Multiple Mirror Trap,
A.Burdakov, (Budker Institute of Nuclear Physics, Russia)

09:35-09:55 19**R02** The Kinetic Stabilizer Axisymmetric Tandem Mirror: A Review of Approaches to its Implementation,
R.F.Post, (Lawrence Livermore National Laboratory, USA) (presented by W. Horton)

09:55-10:20 19**R03** Divertor Stabilization Experiments in the Hanbit Mirror Device,
A.C.England, (National Fusion Research Center, Korea)

10:20-10:40 19**R04** Concept of the Magnetic Divertor in GAMMA10,
I. Katanuma, (Plasma Research Center, University of Tsukuba, Japan)

10:40-10:55 **Coffee Break**

Chair: R.E.H.Clark, M.Sasao

10:55-11:30 19**R05** EUV Spectra Measaured from Large Helical Device and Atomic Data,
T.Kato, (National Institute for Fusion Science, Japan)
11:30-11:55 19**R06** Fragmentation of Hydrocarbon Impurity Molecules as a Result of Electron Capture,
M.Kimura, (Graduate School of Sciences, Kyushu University, Japan)
11:55-12:15 19**R07** Charge Transfer Cross Sections of H^+ Ions in Collisions with some Hydrocarbon Molecules in the Energy Range of 0.2 to 4 keV, T.Kusakabe, (Department of Science School of Science and Engineering, Kinki University, Japan)
12:15-12:35 19**R08** Atomic and Molecular Data Base and Data Activities for Fusion Research in Japan Atomic Energy Agency, M.Sataka, (Japan Atomic Energy Agency, Japan)
12:35-12:55 19**R09** NIFS Atomic and Molecular Database for Collision Processes in Plasma,
I.Murakami, (National Institute for Fusion Science, Japan)

12:55-13:10 **Group Photo**

13:10-14:00 **Lunch**

Chair: I.Katanuma, J.Kohagura (14:00-15:25)
Chair: M.Ichimura, M.Hirata (15:25-16:50)
14:00-16:50 **Poster Session**

Coffee Break (15:15 - 15:30)

18:30-21:00 **Conference Bancket**

July 20 (Thursday) **R:** Invited and Review Paper

Chair: A.Ivanov, A.Mase
09:00-09:35 20**R01** Transonic Plasma Flow Passing through a Magnetic Mirror,
M.Inutake, (Graduate School of Engineering, Tohoku University, Japan)
09:35-09:55 20**R02** Role and Contribution of the Open Field Line Region in the Large Helical Device,
T.Watanabe, (National Institute for Fusion Science, Japan)
09:55-10:15 20**R03** Wave Excitation in Magnetically Confined Plasmas with an Anisotropic Velocity Distribution, M.Ichimura, (Plasma Research Center, University of Tsukuba, Japan)

10:15-10:30 **Coffee Break**

Chair: O.Agren, A.Burdakov

10:30-11:05 20**R04** Nonlinear Effects of High Power Plug/Barrier ECRH on Propagation and Radiation of Cyclotron Waves,
R.Hatakeyama, (Department of Electronic Engineering, Tohoku University, Japan)
11:05-11:30 20**R05** Second Harmonic Cyclotron Heating of Sloshing Ions in a Straight Field Line Mirror,
V.Moissenko, (Angstrom Laboratory, Uppsala University, Sweden)
11:30-11:50 20**R06** Full-Wave Maxwell Simulations for Electron Cyclotron Resonance Heating,
H.Hojo, (Plasma Research Center, University of Tsukuba, Japan)
11:50-12:10 20**R07** ECH and HHFW Start-up Experiments on the TST-2 Spherical Tokamak,
A.Ejiri, (Graduate School of Frontier Sciences, The University of Tokyo, Japan)

12:10-13:30 **Lunch**

Chair: A.C.England, Y.Nakashima
13:30-14:05 20**R08** Direct Energy Conversion Experiment on the GAMMA10 Tandem Mirror,
Y.Yasaka, (Department of Electrical and Electronics Engineering, Kobe University, Japan)
14:05-14:25 20**R09** Effects of Non-axisymmetric Magnetic Field on Characteristics of Axisymmetric Cusp DEC,
Y.Tomita, (National Institute for Fusion Science, Japan)
14:25-14:45 20**R10** Bounce Instability in a Multi-mirror Trap,
A.Beklemishev, (Budker Institute of Nuclear Physics, Russia)
14:45-15:05 20**R11** Study of the Effects of Plasma-Confining Potentials Using End-Loss Analysing Systems,
M. Hirata, (Plasma Research Center, University of Tsukuba, Japan)

15:05-15:20 **Coffee Break**

Chair: R.Hatakeyama, M.Ichimura
15:20-15:45 20**R12** New Results in the Theory of Multiple Mirror Plasma Confinement,
I.Kotelnikov, (Budker Institute of Nuclear Physics, Russia)
15:45-16:10 20**R13** Comparison of a Deuterium - Helium-3 FRC and Mirror Trap for Plasma Confinement,
S.V.Ryzhkov, (Bauman Moscow State Technical University, Russia)
16:10-16:35 20**R14** Recent FRC Plasma Studies,
S.Okada, (Graduate School of Engineering, Osaka University, Japan)
16:35-16:55 20**R15** Research Plans for Low-Aspect Ratio Reversed Field Pinch (RFP),
S.Masamune, (Kyoto Institute of Technology, Japan)

July 21 (Friday) **R:** Invited and Review Paper

Chair: N.J.Fisch, W.Horton

09:00-09:35 21**R01** Role of Large Scale Structures in Multiple-scale Drift Wave Turbulence,
Y.Kishimoto, (Graduate School of Energy Science, Kyoto University, Japan)

09:35-10:00 21**R02** On MHD Stability, Ellipticity, Omnigenuity, Constants of Motions and a Modified Thermal Barrier of a Straight Field Line Mirror,
O.Agren, (Angstrom laboratory, Uppsala University, Sweden)

10:00-10:25 21**R03** Investigation of Electron Distribution Functions in the Plug Region of the GAMMA10 Tandem Mirror, J.Kohagura, (Plasma Research Center, University of Tsukuba, Japan)

10:25-10:40 **Coffee Break**

Chair: E.P.Kruglyakov, T.J.Dolan

10:40-11:15 21**R04** Upgrade program of ECRH system for GAMMA10,
T.Imai, (Plasma Research Center, University of Tsukuba, Japan)

11:15-11:40 21**R05** High Power and High Efficiency Operation of 170GHz Gyrotron,
A.Kasugai, (Japan Atomic Energy Agency, Japan)

11:40-11:55 **Concluding Remarks** (T.Cho, M.Kwon)

July 19 (Wednesday) Poster Session

19P01. Plasma flow measurement by Mach probes in GAMMA10,
A.Ando

19P02. Influences of the Hall Effect on the Plasma Flows in a Magnetoplasmadynamic Thruster,
K.Kubota

19P03. Measurement of flow velocity of MPD Arcjet in GAMMA10,
K.Nemoto

19P04. Interaction between Plasma Flow and Magnetic Field in scale model experiment of Magnetic Sail,
K.Ueno

19P05. Numerical Simulation of Fusion Plasma Behaviors in a Magnetic Nozzle for Laser Fusion Rocket,
Y.Kajimura

19P06. Development of Two Space Propulsion Systems with Helicon Plasmas,
G.-S.Choi

19P07. Measurement and Analysis of Magnetic Fluctuations in the HANBIT Mirror Device,
J.H.Yeom

19P08. Equilibrium of charged plasmas with weak axisymmetric magnetic perturbations,
I.Kotelnikov

19P09. Enhancement and suppression of velocity-shear-driven drift instability due to negative ions,
R.Ichiki

19P10. Fast neutral particle ionization in magnetic field by ECR for collector mirror protection in EUV light source,
H.Komori

19P11. Plasma Polarization Spectroscopy on Cusp Plasma and GAMMA10 Tandem Mirror Plasma,
A.Iwamae

19P12. Two-dimensional Spectroscopic Measurement of Hydrogen Emission in JT-60U Divertor Plasmas,
K.Fujimoto

19P13. Development of a Thermal Probe Method for Heat Flux and Ion Temperature Measurement in Divertor Simulator MAP-II,
K.Kurihara

19P14. Spectroscopic measurement using wide range UV/Visible spectroscopic system in GAMMA10,
K.Matama

19P15. Study of oxygen ions behavior by using collisional-radiative model in GAMMA10,
T.Kobayashi

19P16. Behavior of fueled particles and its effects on plasma parameters in the GAMMA10 Tandem Mirror,
Y.Kubota

19P17. Measurement of the Degree of Dissociation of Molecular Hydrogen in Divertor Simulator MAP-II Using Fulcher-Balmer Ratio,
Y.Kuwahara

19P18. Gamma-ray Spectroscopy Method for High Energetic Particle in Burning Plasma,
K.Ochiai

19P19. Potential and Density Fluctuation Characteristics of the Hot-Cathode-Biased Supersonic Plasma in TU-Heliac,
Y.Tanaka

19P20. Ion Temperature Measurements in the Biased Plasma with a Hot Cathode in Tohoku University Heliac,
M.Ogawa

19P21. Dynamics of One-dimensional SOL-divertor Plasmas after an ELM Crash in Tokamak H-mode Plasma,
T.Takizuka

19P22. Observation of Radial Particle Transport Induced by the Fluctuation Measured with a Gold Neutral Beam Probe,
A.Kojima

19P23. Measurements of 2-dimensional plasma density distributions by the phase-imaging method in GAMMA10,
A.Nakahara

19P24. Density Measurement Using a Lithium Beam Probe at the Inner Mirror Throat of the Tandem Mirror GAMMA10,
H.Kakiuchi

19P25. Beam emission diagnostic for estimating neutral beam attenuation,
K.Ikeda

19P26. Measurement of relative flux of fractional-energy emissions using beam emission diagnostic,
K.Ikeda

19P27. Behavior of high energy ions during drift type instability in the GAMMA10 tandem mirror,
M.Katano

19P28. Observation of Fluctuations Appeared in End-Loss Ion Current and Ion Transport in Velocity Space Induced by AIC Waves in the Tandem Mirror,
N.Kaidou

19P29. Plasma density profile measurement in the Hanbit,
Seong-Heon Seo

19P30. Ion temperature measurement in the RF heated Hanbit plasma,
Won Ha KO

19P31. Detection of bounce ions by use of a charge exchange bounce ion analyzer,
Y.Miyata

19P32. Fast Measurement of Ion Temperature in JT-60U by Using New Fast Charge Exchange Recombination Spectroscopy,
M.Yoshida

19P33. Electron Density Measurements of a Thin Plasma Layer by Surface Plasmon Interferometry,
H.Hojo

19P34. Stability Study of Kelvin-Helmholtz Modes due to Radial Electric Field Shear,
H.Hojo

19P35. Electron Bernstein Wave Heating on Internal Coil Device Mini-RT,
E.Yatsuka

19P36. 1-Dimmensional Analysis of Polarization Reversal Relating to Electron Cyclotron Resonance,
K.Takahashi

19P37. On the experiment of electron cyclotron resonance heating in the central cell of the GAMMA10 tandem mirror,
M.K.Islam

19P38. Numerical Analysis of the Second Harmonic Resonance Ion Heating in the HIEI Tandem Mirror,
N.Sugimoto

19P39. Numerical Study of Microwave Generation by Electromagnetic Surface Wave on Deeply Corrugated Metal Plate,
O.Watanabe

19P40. Improved Performance of Oversized Backward Wave Oscillator driven by Weakly Relativistic Electron Beam,
S.Aoyama

19P41. Development of the ICRH system at AMBAL-M,
T.D.Akhmetov

19P42. Effective Excitation of ICRF Waves by Use of Phased Antennas in GAMMA10,
Y.Yamaguchi

19P43. Slow Cyclotron and Cherenkov Instabilities in Weakly Relativistic Oversized Backward Wave Oscillator,
Y.Kiuchi

19P44. A Steady State Cusp Plasma Device for Plasma Studies and Technological Applications,
G.Gervasini

19P45. Radial electric fields and radial currents in the gas dynamic trap,
A.D.Beklemishev

19P46. Influence of radial electric field on high-beta plasma confinement in the gas dynamic trap,
A.D.Beklemishev

19P47. Effects of Plasma Confining Potentials and the Associated Radially Sheared Electric Fields on the Plasma Energy Confinement,
T.Numakura

19P48. First experiments with upgraded neutral beam injectors on the GDT device,
A.A.Ivanov

19P49. High-power 5 ms neutral beam injector for plasma heating,
A.A.Ivanov

19P50. Experiments in the Hanbit Mirror Device with the Kinetic Stabilizer,
A.C.England

19P51. Stability analysis of flute interchange mode in GAMMA10 divertor configuration,
Y.Mizoguchi

19P52. Anomalous fast heating of ions in GOL-3 facility,
A.V.Burdakov

19P53. Use of pellet injection technology at GOL-3 for plasma fueling and plasma-surface interaction research,
A.V.Burdakov

19P54. Transverse loses and Z_{eff} measurements at GOL-3 facility,
A.Burdakov

19P55. Visible Light and H_α Imaging of Mirror Confined Plasmas in the Central Cell of GAMMA10,
H.Higaki

19P56. Effect of magnetic configuration on the neutral particle recycling in Compact Helical System,
H.Matsuura

19P57. Analysis of Neutral Transport in fully 3-Dimensional Geometry in the GAMMA10 Tandem Mirror,
Y.Higashizono

19P58. On the ion radial diffusion in the end-mirror cell of GAMMA10 analyzed by mapping equation,
H.Saimaru

19P59. Rotation of a field-reversed configuration plasma due to resistive flux decay,
H.Yamaura

19P60. Investigation of translation process of FRC plasma using computer tomography of two different cross-sections on FIX,
S.Yoshimura

19P61. Heating and particle build-up of field-reversed configuration due to neutral particle injection in a translation process,
T.Asai

19P62. A self-consistent beam-plasma equilibrium of a Field-Reversed Configuration,
T.Takahashi

19P63. Axisymmetric tandem mirror magnetic fusion energy power plant with thick liquid-walls*,
Thomas J.Dolan

19P64. Numerical Study of Charge Separation of Cusp DEC Installed at GAMMA10,
R.Kawana

19P65. Performance Analyses of Newly Designed Helmholtz DEC with Commercial Scale,
T.Nemoto

19P66. Optimization of Decelerator Structure of Traveling Wave Direct Energy Converter Simulator for D-^{3}He Fusion,
T.Yamamoto

19P67. Research on Characteristics of Particle Discrimination and Direct Energy Conversion for Cusp Direct Energy Converter,
Y.Kurumatani

19P68. Fast and Efficient Data Acquisition System for Ubiquitous Participation in DEC Experiment on GAMMA10,
H.Yonemori

19P69. Optimization of 28GHz gyrotron output performance for ECRH experiment of the GAMMA10,
T.Kariya

19P70. Recent development of transmission systems for ECRH in the GAMMA10 tandem mirror,
Y.Tatematsu

19P71. Study of Efficient Electron Cyclotron Wave Coupling with Grooved Mirror Polarizer in the GAMMA10 Tandem Mirror,
R.Minami

19P72. Performance test of power transmission system newly designed for ECRH in GAMMA10,
N.Machida

19P73. A newly installed 84GHz electron cyclotron heating system in LHD,
T.Notake

19P74. Characteristics of 28GHz gyrotron for ECRH on GAMMA10,
Y.Kamata

19P75. Study of spatial distribution of microwave power deposition for plug ECRH in GAMMA10,
T.Kaitsuka

Invited and Review Papers

17R01. Alpha Channeling in Mirror Machines and in Tokamaks,
Nathaniel J.Fisch

17R02. IAEA Fusion Activities and Nuclear Data Support for Innovative Concepts,
R.E.H.Clark, A.Malaquias, G.Mank, and A.L.Nichols

17R03. Overview of Recent Progress in the GAMMA10 Tandem Mirror,
T.Cho, H.Higaki, M.Hirata, H.Hojo, M.Ichimura, K.Ishii, K.Md.Islam, A.Itakura, I.Katanuma, J.Kohagura, R.Minami, Y.Nakashima, T.Numakura, T.Saito, Y.Tatematsu, M.Yoshikawa, O.Watanabe, A.Kojima, Y.Kubota, A.Mase, Y.Yasaka, K.Ogura, K.Sakamoto, M.Yoshida, Y.Nagayama, T.Kariya, Y.Mitsunaka, V.P.Pastukhov, T.Imai, and S.Miyoshi

17R04. Axially Symmetric Magnetic Mirror Traps. Status and Perspectives,
A.V.Burdakov, A.A.Ivanov, and E.P.Kruglyakov

17R05. Energy Confinement Scaling Predictions for the Kinetically Stabilized Tandem Mirror,
W.Horton and J.Pratt

17R06. Progress of the HANBIT Device,
M.Kwon, B.J.Lee, A.C.England, and HANBIT Team

17R07. RT-1 Project - Magnetosphere-like Plasma Experiment,
Z.Yoshida

17R08. Low-frequency Turbulence and Non-diffusive Cross-field Plasma Transport in Mirror Systems,
V.P.Pastukhov and N.V.Chudin

17R09. Advanced Diagnostics for Burning Plasma Experiments,
M.Sasao

17R10. Tokamak and Spherical Tokamak Research in Japan,
Y.Takase

18R01. Progress in Microwave Diagnostics and Physics Issues in Magnetically Confined Plasmas,
A.Mase

18R02. Progress in Development of Edge Thomson Scattering System for ITER,
T.Hatae, M.Nakatsuka, H.Yoshida, K.Ebisawa, Y.Kusama, K.Satoh, Y.Neyatani, A.Katsunuma, H.Kubomura, and K.Shinobu

18R03. CO_2 Laser Collective Thomson Scattering Diagnostic of α-particles in Burning Plasmas,
T.Kondoh, T.Hayashi, Y.Kawano, Y.Kusama, T.Sugie, and Y.Miura

18R04. The GDT as Neutron Source in a Sub-critical System for Transmutation?
K.Noack, A.Rogov, A.A.Ivanov, and E.P.Kruglyakov

18R05. Measurement Density Profiles with Pressure in MAP-II Linear Device,
K.-S.Chung, H.-J.Woo, Y.-J.Seo, S.Kado, T.Shikama, S.Filippo, and S.Tanaka

18R06. ICRF Heating and Plasma Acceleration with an Open Magnetic Field for the Advanced Space Thruster,
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17R01

Alpha Channeling in Mirror Machines and in Tokamaks

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Significant advances in the confinement of hot plasma might be enabled by the use of radio frequency waves, through which the phase space of resonant ions or electrons can be affected in detail. Recent technological and conceptual advances in applying radio freqency waves to hot plasma suggest that this very precise control might be exerted to large advantage. One such recent advance that might significantly enhance fusion prospects for tokamak fusion reactors is the so-called *alpha-channeling effect.*

The alpha-channeling effect in tokamaks exploits the higher population of high-energy alpha particles in the tokamak interior compared to that of low-energy alpha particles at the periphery.[1] Because of the population inversion, upon injecting waves that diffuse resonant particles along diffusion paths connecting these regions, hot alpha particles diffuse to the periphery and cool at the same time. However, the population inversion for fuel deuterium ions is opposite to that of the alpha particles. There are no MeV fuel ions in the center, but there are many relatively cold fuel ions near the periphery. Thus, in a tokamak, the same wave that taps alpha particle energy, while rejecting the alpha particles to the periphery, also can fuel the plasma by sucking in fresh fuel ions and heating them.

Similar possibilities might be expected in mirror machines. Both mirrors and tokamaks are devices with a symmetry direction, so that the diffusion paths can be written similarly. Using effects similar to the alpha channeling effect in tokamaks, important improvements in open traps might be had through the use of rf fields interacting with mirror-confined ions, such that the ions diffuse in the rf fields along highly constrained orbits, losing energy as they are forced out of the trap.

While the alpha-channeling effects in either tokamaks or mirrors will employ diffusion paths, the most successful alpha-channeling effects in a mirror machine will exploit the fact that the periphery of the mirror machine is defined very differently. Particles exit a tokamak by diffusing across magnetic field lines past the last closed magnetic surface. In mirror geometry, the open geometry defines a very different periphery in the phase space that includes both configuration space and velocity space. Particles leave a mirror machine not only through radially through diffusion across field lines, but also axially, along open field lines, through velocity-space diffusion.

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IAEA fusion activities and nuclear data support for innovative concepts

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The International Atomic Energy Agency (IAEA) has long been involved in the technical support of fusion energy research. Most of the technical activities take place under the guidance of the International Fusion Research Council (IFRC). Programmes in nuclear fusion energy are being pursued in nearly 50 countries and involve about 300 research institutes, laboratories, and university departments. The IAEA plays an important role in co-ordinating various aspects of their work [1]. Priority activities in plasma physics and fusion are summarized, including efforts to ensure the exchange of ideas on topics that would benefit from further understanding to achieve future utilization of fusion as an energy resource.

The IAEA supports studies of a variety of confinement concepts. Worldwide fusion studies are undertaken in support of ITER and other fusion efforts, and the administrative infrastructure is provided for ITER activities and the organisation of many relevant high-level meetings. Furthermore, the IAEA sponsors the exchange of scientific and technical information through their biennial Fusion Energy Conference. The first conference was held at Salzburg in 1961, and the proceedings have been made available on the Internet since 1998 [2].

A dedicated set of evaluated nuclear data for fusion applications has recently been updated in response to the recommendations of a Consultants' Meeting in 2003. These files contain evaluated neutron cross-section data for seventy-one target nuclides. This improved library is known as FENDL-2.1, and is available on request and can be downloaded from the Internet [3].

Significant quantities of atomic and molecular (A+M) data are compiled and assembled to assist in plasma modelling and diagnostics. Large amounts of cross-section data and rate coefficients are contained within an electronic database, and an extensive bibliographic database can also be readily interrogated. Results from research projects in A+M physics are also published in the refereed IAEA journal, *Atomic and Plasma-Material Interaction Data for Fusion*. Access to all of these electronic databases is available through the Internet [4].

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Overview of Recent Progress in the GAMMA 10 Tandem Mirror

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(1) *Four-time progress in ion-confining potential height* (ϕ_c) through these three years is achieved in the hot-ion mode with T_i=several keV having the favorably increasing scaling of ϕ_c with plug electron-cyclotron heating (ECH) powers.

(2) The advance in the potential formation leads to a finding of *remarkable effects of radially sheared electric fields* dE_r/dr *on turbulence suppression* and *transverse-loss reduction.*

(3) A preferable dependence of a *weak decrease in* ϕ_c *with increasing* n_c ranging to ~10^{19} m^{-3} along with the *recovery of* ϕ_c *with increasing plug ECH powers* (P_{ECH}) is obtained.

(4) A *transverse energy-transport barrier is produced* by *off-axis ECH* in a barrier mirror for the first time, with the formation of a cylindrical layer having energetic electrons flowing through the whole device. This leads to *suppress intermittent turbulent vortex-like structures near the layer* in the central cell, and results in T_e and T_i rises surrounded by the layer having a localized bumped ambipolar potential Φ_C. The radial transport barrier is explained by the formation of a strong E_r shear or peaked vorticity W with the direction reversal of $E_r \times B$ sheared flow near the Φ_C peak for the turbulence suppression.

(5) *Preliminary* central ECH (170 kW, 20 ms) in a standard tandem-mirror operation raises T_{e0} from 70 to 300 eV together with $T_{i\perp 0}$ from 4.5 to 6.1 keV, and $T_{i//0}$ from 0.5 to 1.2 keV with τ_{p0}=95 ms for ϕ_c (=1.4 kV) trapped ions. The on-axis particle to energy confining ratio of τ_{p0}/τ_{E0} is observed to be 1.7 for ϕ_c trapped ions (consistent with Pastukhov's theory) and 2.4 for central mirror-trapped ions with 240-kW plug ECH and 90-kW ICH (η_{ICH}~0.3; nl_c=$4.5\times10^{17}m^{-2}$).

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17R04

AXIALLY SYMMETRIC MAGNETIC MIRROR TRAPS. STATUS AND PERSPECTIVES.

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At present, two modern types of magnetic mirror devices are running in Novosibirsk. These are multi-mirror device GOL-3 and the Gas Dynamic Trap (GDT). From the engineering point of view, these systems are very attractive due to their simple axially symmetric geometry. In the paper, the status of the experiments on the GOL-3 and GDT devices is presented. The most crucial experiments for the mirror concept are described, which demonstrate different mechanisms of suppression of longitudinal electron heat conduction in GDT and GOL-3 devices, establishing of MHD-stable regimes of high-β (more than 0.4) plasma confinement in the axisymmetric magnetic field in both machines, an effective heating of a dense plasma with density of the order of 10^{21} m^{-3} by high-current relativistic electron beam in GOL-3 device, etc. In the case of multi-mirror geometry of GOL-3, significant increase, up to several tenfold in comparison with a single mirror geometry, of hot plasma confinement time was obtained. Besides, electron heating up to 2 keV as a result of high current electron beam – plasma interaction, and fast heating of ions up to 2 keV following the REB switch off were discovered in the multi-mirror geometry with 55 mirror cells with total length of the trap of 12 meters. Note that no effect of the ion heating is observed in the single mirror geometry. The reasons why the ion heating appeared in the multi-mirror geometry of the magnetic field are discussed.

It should be mentioned that the GOL-3 and GDT devices are capable of providing an important information for ITER and for future fusion program. In the case of GOL-3, the plasma energy exhaust after heating by REB can be as high as 50 MJ/m^2. A lot of experiments can be made on plasma-wall interaction including a study of evaporation, erosion and ionization of the wall material, transport of the ionized material deeply into hot plasma, etc. Some of these experiments are described in the paper.

An oblique injection of fast D and T neutrals with energy of several tens of keVs into “warm” collisional plasma confined in a solenoid with highly increased magnetic field at the ends, provides fast ions oscillating between the turning points near the end mirrors. Typical magnetic field in the solenoid is about 1T. It increases towards the ends of the solenoid up to ~15T providing the mirror ratio more than 10. The fast ion density is strongly peaked in the vicinity of the turning points where ion longitudinal velocity is small. Collisions between fast deuterons and tritons produce a powerful 14 MeV neutron flux in these regions. This is the main idea underlying the concept of the neutron source based on the GDT. According to the simulations, 2 MW/m^2, or approximaly 10^{18} of 14 MeV neutrons per square meter per second, can be produced in such a source within of the order of 1 m^2 area testing zone. This neutron flux is adequate for testing construction materials of future fusion reactors. It should be noted that there is no other candidate on the role of a plasma-based neutron source with such a low tritium consumption amounting to only 150 gram/year and with moderate power consumption of about 60 MW.

At present, the main physical properties of plasma confined in the GDT device have already been studied. The longitudinal profile of D-D fusion reaction yield obtained for the case of 4 MW deuterium beam injection during 1 ms was measured and was found to be in reasonable agreement with the results of numerical simulations. The major experimental results obtained on the GDT device are described in the paper. The initial experiments planned to be done at the GDT-Upgrade with 10 MW, 5ms injection are also discussed.

17R05

Energy Confinement Scaling Predictions for the Kinetically Stabilized Tandem Mirror

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We report on transport studies for the kinetically stabilized tandem mirror (KSTM), an attractive magnetic confinement device for achieving a steady-state burning plasma. For a MHD stable system, we investigate three different radial transport models with Bohm, gyro-Bohm, and electron temperature gradient (ETG) scaling. As a conservative estimate, numerical coefficients in the models are taken to be consistent with tokamak and stellarator databases. The plug mirrors create an ambipolar potential that controls end losses, whereas radial losses are driven by drift wave turbulence, which lowers the electron temperature through radial trapped particle modes and ETG transport losses. We analyze the radial transport equations, taking into account the Pastukhov energy and particle end losses with time dependent heating pulses.

Profiles and total energy confinement times are calculated for the GAMMA-10 experiment and for a test reactor facility (L = 30m, a=1 to 2 m, B=3T). The test reactor device is similar in size to an unrolled ITER machine. The confining magnetic field in the toroidal configuration is the poloidal of field of $B_p \leq 1T$ for 15MA of plasma current. Some details of the study are given in Pratt and Horton, Physics of Plasmas, April, 2006.

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17R06

Progress of the HANBIT Device

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HANBIT device has been operated for last five years aiming at investigating characteristics of the ICRF-produced plasmas in asymmetric mirror geometry. The 250 kW rf power was regularly and reliably applied to produce target plasmas and extensive studies have been done in various physical topics such as wave-plasma interaction, effect of neutral particles and mechanisms of MHD stabilities.

For the next five years, new ideas are solicited to increase the usability and applicability of the device toward wider fields; wave physics in linear, quiescent plasmas, space simulation and plasma application as well as a mirror physics. Ideas and direction of the renovated device and the future experimental program will be presented.

Oral Presentation

17R07

RT-1 Project – magnetosphere-like plasma experiment

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1. Flowing Plasma

The study of "flowing plasmas" is entering a new era of advanced physics that may reveal the mechanism of creation and sustainment of diverse structures in the universe. In a magnetized plasma, the flow is closely related to the electric field. The self-electric field has a similarity to the self-gravity (while the direction of the force is opposite), and the (canonical) angular momentum is the essential causal of any structures such as a galactic disc. The physics of the flowing plasmas, thus, may have a wide horizon where we explore collective phenomena induced by general electromagnetic and gravitational interactions.

While "flow" is one of the determining characteristics of plasmas, the modeling and analysis of flowing plasmas often encounter fundamental difficulties. In this paper, we discuss the origin of these problems and describe recent movements.

2. RT-1 Project

The Ring Trap 1 (RT-1) of the University of Tokyo is a novel plasma device constructed to study various flow-induced phenomena in a simple magnetosphere-like configuration. A super-conducting ring, levitated in the vacuum chamber, produces a magnetic field that traps high-temperature plasma. Giving a radial electric field yields a strong flow whose hydrodynamic pressure can balance the thermal pressure.

The RT-1's mechanism of plasma confinement is based on the theory of self-organized states in flowing plasmas, which predicts that the hydrodynamic pressure in a fast plasma flow can balance the thermal pressure (Bernoulli's law) creating a relaxed state with very high-beta value [1,2]. The equilibrium state produced by this device simulates Jupiter's magnetosphere.

The RT-1 project encompasses the subjects including the self-organization of flow-field coupling, boundary layer (plasma edge) formation, waves and instabilities in shear flow, and creation of singularities. All these problems pose theoretical challenges that require novel analytical methods.

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17R08

Low-frequency turbulence and non-diffusive cross-field plasma transport in mirror systems

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Low-frequency (LF) turbulence and the resultant cross-field plasma transport in mirror-based systems are studied on the basis of direct computer simulations of nonlinear plasma dynamics. Under the low-beta assumption the nonlinear dynamics can be described in a frame of adiabatically reduced one-fluid MHD model [1, 2]. Simulations of self-consistent plasma evolution have shown formation of large-scale flute-like stochastic vortex structures, which have broad-bend frequency and wave-number spectra and are similar to the intermittent vortex-like structures observed in GAMMA 10 experiments [3, 4]. The simulations were performed both for the conventional tandem mirror configurations and for axisymmetric non-paraxial configurations with divertor-like separatrix as well.

Various regimes of plasma confinement with sheared plasma rotation have been modeled and analyzed. The results obtained show a rather complex influence of sheared flows on the nonlinear plasma dynamics and the resultant cross-field plasma transport in mirror systems. It is shown that ability to control profiles of plasma rotation and sufficiently high dynamic vorticity of sheared flows can lead to turbulence reduction, modification of dominant vortex vorticity structures and transport barrier formation.

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17R09

Advanced Diagnostics for Burning Plasma Experiments

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Abstract

Several unexplored physics issues will be studied in burning plasma experiments, planned in near future on ITER. Self-heating of a DT plasma by fusion-produced alpha particles is the key to realise self-sustainable ignition of a thermonuclear plasma in a fusion reactor. Recent progress in improved confinement modes has revealed the correlation between the potential or electric field gradient and the fluctuation suppression. Furthermore, it is important to control profiles of pressure gradient, $\nabla\beta(\rho)$ and plasma current, $I_p(\rho)$ in tokomaks. Self-heating by alpha particles will complicate the control of these profiles.

In order to carry out burning plasma experiments which involve these issues, it is essential to develop diagnostic systems, such as innovated fusion product measurement systems and high-resolution, high-reliability profile measurement of various plasma parameters. A scientific research of priority areas on “Advanced Diagnostics for Burning Plasma Experiment” was established under the support of MEXT in 2004. In this priority area, more than twenty sub-projects are going. Their activities are grouped into three: the group A is developing confined and escaping alpha particle diagnostics, and neutron diagnostics as its counter part, the group B is developing innovative profile measurement systems, and the group C researches the underlying physics in self-heating plasma and the diagnostic requirement. In this talk, recent progress in these subprojects are presented, and discussed from viewpoints of burning and profile control.

17R10

Tokamak and Spherical Tokamak Research in Japan

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Tokamak research is entering a new era of burning plasma research with the formal agreement to construct the International Thermonuclear Experimental Reactor (ITER). The Working Group on Fusion Research (WGFR) reviewed Japanese fusion research and recommended concentration of research in several areas, particularly stressing the importance of tokamak research focused on achieving high beta in steady state to establish the scientific basis for a fusion demonstration reactor (DEMO). In recent years, research using a low aspect ratio variation of the tokamak called the spherical tokamak (ST) is making a rapid progress, taking advantage of the superior stability characteristics at high beta. WGFR further recommends pursuit of innovative high beta plasma research using ST at universities, utilizing both domestic and international collaborations.

After several years of nation-wide discussion based on the WGFR recommendation, an upgrade of the JT-60U tokamak to a superconducting tokamak capable of producing highly shaped plasmas for 100 seconds was chosen as the most appropriate facility to perform central functions of the prioritized tokamak program. This device will also perform functions of the Satellite Tokamak in the JA-EU Broader Approach program, and has been named JT-60SA. Its main mission for the domestic program is to achieeve a high beta ($\beta_N = 3.5$–5.5) plasma maintained noninductively for 100 seconds. It will explore regimes of high shaping factor (low aspect ratio, high elongation and triangularity) favorable for achieving high beta, and is equipped with active feedback control methods to suppress instabilities. It was agreed to upgrade the heating and current drive power to 41 MW for 100 seconds to extend accessible operating regimes of interest for ITER and DEMO, as a result of JA-EU negotiation.

Japanese universities have contributed to the development of ST using small but unique devices. ST research in Japan has been reorganized as All-Japan ST Research Program under NIFS Bi-Directional Collaboration. It is a coordinated program consisting of existing and new university-scale experiments as well as theory and simulation established to realize the recommendations of WGFR, with the purpose of contributing to the establishment of scientific and technical bases for a practical and economically competitive fusion reactor. To ensure international competitiveness, the strategy of All-Japan ST Research Program is to carry out creative and innovative research focused on ultra-high beta and ultra-long pulse regimes. This strategy supports and complements the mainline tokamak research, and contributes to broadening the possibilities for future fusion reactors. In order to accomplish these goals, innovative research in plasma start-up, noninductive current drive, heat and particle control, and plasma-wall interaction is important. New devices such as UTST to explore ultra-high beta plasma formation by plasma merging, and QUEST to study plasma-wall interaction and heat and particle control in steady state, are being constructed.

Tokamak and ST research programs are complementary and are necessary to train a new generation of scientists who can take leadership in the ITER Project, development of DEMO, and early realization of a commercial reactor. In addition, a study of the highly autonomous high beta plasmas can contribute to other branches of science such as complex systems and astrophysics. An example is understanding of physical processes involved in reconnection, which plays an important role in self-organization.

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18R01

Progress in Microwave Diagnostics and Physics Issues in Magnetically Confined Plasmas

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Microwave techniques such as interferometry, reflectometry, scattering, and radiometry have been powerful tools for diagnosing magnetically-confined high-temperature plasmas. Important plasma parameters, specifically plasma fluctuations were measured to clarify the physics issues such as stability, wave phenomena, and fluctuation induced transport. Recent advances in microwave and millimeter-wave technology together with computer technology have enabled the development of new generation of diagnostics for visualization of 2D and 3D structures of plasmas. Millimeter-wave imaging and reflectometry are expected to be one of the most promising diagnostic methods for this purpose. We report here on the recent progress of microwave diagnostics and the results obtained in magnetically confined plasmas.

Progress in Development of Edge Thomson Scattering System for ITER

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The incoherent Thomson scattering method is one of the standard diagnostic techniques for the measurement of local electron temperature and density, and is broadly used from the measurement of high temperature fusion plasmas to very low temperature laboratory plasmas. The H-mode (high confinement mode), in which the electron temperature and density profiles have steep gradients near the separatrix due to the formation of edge transport barrier, is considered a standard operation scenario for ITER (International Thermonuclear Experimental Reactor). The structure of the peripheral profile including the edge transport barrier is called the "edge pedestal". Since the characteristics of the edge pedestal correlate with those of the core and peripheral plasma transport, an understanding of the edge pedestal structure becomes crucial. Therefore, the edge Thomson scattering system in ITER is required to measure the edge plasma (r/a > 0.9) with good spatial (5 mm) and temporal (10 ms) resolution. In order to realize this requirements, the edge Thomson scattering does not use the LIDAR technique but use the conventional technique.

1. Laser system: A Nd:YAG laser (wavelength=1064nm) planned to be used as a diagnostic laser system for the edge Thomson scattering system requires a high output energy (5 J), high repetition rate (100 Hz). To develop the high power laser, stimulated-Brillouin-scattering-based phase conjugate mirrors (SBS-PCMs) are to be used to compensate the wavefront distortion induced in the high-power amplifying laser rods. A high power MOPA (Master oscillator and power amplifier) laser employing the SBS-PCM which delivers 7.46 J × 50 Hz has been developed in JT-60U. This laser design using the SBS-PCM is directly applicable to the new laser system for ITER. A stable single-longitudinal-mode (SLM) laser oscillator is necessary to draw out its performance of the phase conjugate mirror. We have developed a laser-diode pumped SLM laser oscillator for ITER which has a ring-type cavity configuration with injection seeder. A high power laser amplifier with 6 flash lamps having pumping energy of 100 J has been also developed.
2. In-vessel optics: In vessel optics (collection optics, laser guide optics) has been designed during the ITER Engineering Design Activity (EDA) phase. These optics are mounted on a port plug to be installed at upper port #11 of ITER. The vacuum boundary is located at the center of the port plug in the original design. However, maintenance is difficult in this design, because the access to the center of the port plug is difficult. The simple radiation analysis has shown that lens and optical fibers are easy to be influenced by the radiation. Considering the influence by the radiation, the lens and optical fibers are arranged more backward where they can be shielded sufficiently. The in-vessel optics design has been optimized in order to arrange the vacuum boundary at the end of the port plug.
3. Spectrometers: We are considering the conventional filter polychromator which has 4-6 channels. A new spectrometer based on a Fourier transform spectroscopy is also considered. The Fourier transform spectrometer using birefringent filters has the following advantages: high throughput, compact, no relative calibration needed.

This work is supported in part by Grant-in-Aid for Scientific Researches on Priority Areas from Ministry of Education, Culture, Sports, Science and Technology (No. 17044009, No. 18035016), and has been performed under the JT-60 Collaborative Research Program.

CO_2 laser Collective Thomson scattering diagnostic of α-particles in burning plasmas

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A diagnostic of fusion-generated α-particles is important for the understanding of their contribution to plasma heating and plasma instabilities in burning plasmas. However, an effective measurement method has not yet been established. In International Thermonuclear Experimental Reactor (ITER), measurement of velocity and spatial distributions of confined α-particles requires temporal resolution of 0.1 s and spatial resolution of $a/10$, where a is the plasma minor radius of ITER. A collective Thomson scattering (CTS) diagnostic for the measurement of alpha particles is being developed using carbon dioxide (CO_2) lasers. The CTS based on the CO_2 laser (wavelength 10.6 μm) has an advantage of small plasma refraction, simplifying the tracking of the scattered radiation.

To realize the CTS diagnostic, a high-repetition Transversely Excited Atmospheric (TEA) CO_2 laser is being developed. Figure 1 shows schematic drawing of newly developed TEA laser. The laser was designed based on a commercially available laser, TEA CO_2 marking laser SEL4000 made by SHIBUYA KOGYO Co., Ltd. Maximum output energy of 36 J has been obtained with a cavity configuration of stable resonator. In order to obtain single-mode output, which is needed for CTS diagnostic, seed laser is injected to the cavity with unstable resonator. Using this technique, output energy of 10 J in frequency of 10 Hz has been achieved with single-mode output. Proof-of-principle test will be performed with the improved laser system on the JT-60U tokamak.

In this paper, we will describe development of the new TEA laser system, measurement results of the CTS on the JT-60U tokamak. Application of the CTS diagnostic to the mirror systems will be also described. This work was supported by Grant-in-Aid for Scientific Research on Priority Areas "Advanced Diagnostics for Burning Plasmas" from Ministry of Education, Culture, Sports, Science and Technology, No. 16082210.

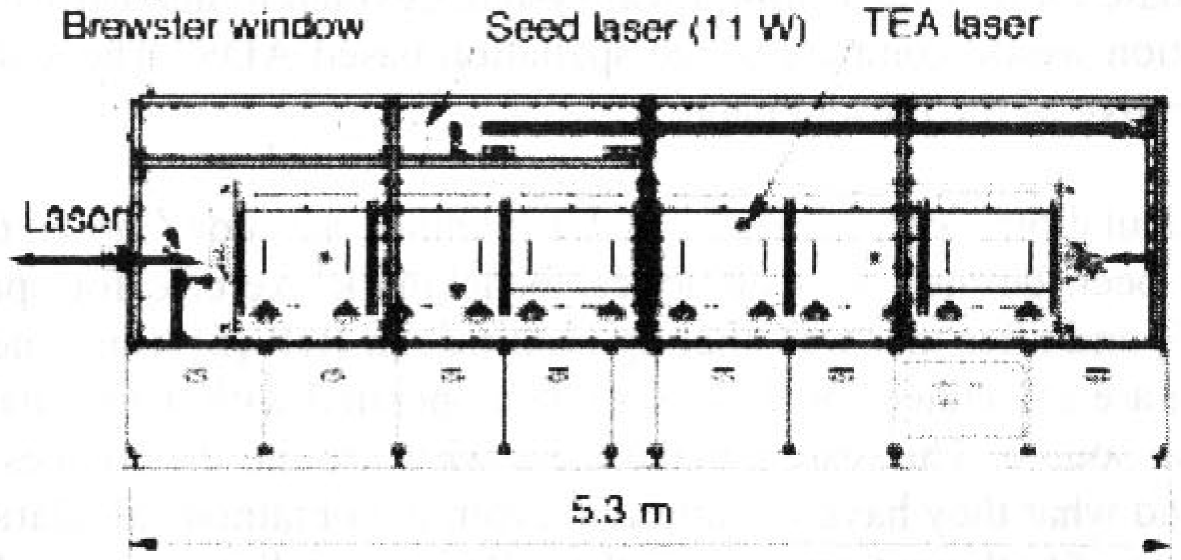

Fig. 1 High-repetition TEA CO_2 laser developed for the collective Thomson scattering diagnostics. Maximum output energy of 36 J has been obtained. Energy of 10 J in frequency of 10 Hz has been achieved with single-mode output.

The GDT as neutron source in a sub-critical system for transmutation?

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Abstract

To become a long-term sustainable option for the world's energy supply fission reactor technology has to solve the high-level waste repository (HLWR) problem. To solve the problem, worldwide great R&D effort is made to develop new closed fuel cycle options and their technical solutions for minimizing the high-level waste that finally must be stored. Long-lived fission products and, in particular, minor actinides are the components of the spent nuclear fuel which cause the most concern. Regarding the incineration of minor actinides, systems producing and confining the high-energetic (fast) neutrons have the highest efficiency. These systems can be built as fast reactors and as sub-critical nuclear fuel systems, the so-called driven systems, which are fed with neutrons from an outer neutron source. Because of the high achievable neutron emission intensity, currently the accelerator driven spallation neutron source is favored for this purpose. The combined accelerator driven system (ADS) has several advantages as compared with fast reactors. Most important are the higher possible burning of actinides and the enhanced inherent safety characteristics. Therefore this development line is intensively pursued by several research projects, e.g. by the project EUROTRANS of the European Union [1].

The Budker Institute of Nuclear Physics Novosibirsk has made the proposal of a powerful 14 MeV neutron source on the base of the gas dynamic trap (GDT) plasma device [2,3]. This neutron source is primarily thought for an irradiation test facility of materials that must be developed for the fusion DEMO reactor. A research project of the Budker Institute aims at completing the database of the GDT in the high plasma parameter range, which is essential for the neutron source and at demonstrating its feasibility and suitability by a H-prototype [4].

The situation outlined before raises the questions whether the GDT based neutron source could also be a candidate for driving a sub-critical system devoted to nuclear waste transmutation and how this option would compare to the spallation based ADS? The answers on these questions are the objective of the present paper.

Neutron transport calculations were carried out for a minor actinide burner the scheme of which originally has been defined as a numerical benchmark exercise for spallation based ADS by the IAEA [5] and after that was slightly modified in Ref. [6]. Basic neutron characteristics of the system are calculated for the cases when operated with the spallation source or with the GDT neutron source. The results make clear what are the differences in neutronics between both cases and what they have in common. From the obtained calculation results and from known parameters of both neutron sources the following preliminary conclusions can be drawn:

- The GDT based neutron source has parameters, which are necessary for an actinide burner in an industrial scale.
- Compared to a spallation based ADS the GDT neutron source should be further developed to increase the neutron emission intensity and to improve its energetic efficiency.

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18R05

Measurement Density Profiles with Pressure in MAP-II Linear Device

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Radial profiles of plasma density and electron temperature have been measured by a fast-scanning probe (FSP) system with various neutral pressures in the MAP-II linear device for the divertor simulation. The probe system is made of three probe tips, two of which is for a Mach probe consiting of two opposite-directional probes, and one is for an emissive probe installed on the pneumatically driven fast-scanning system with stroke of 30 cm. Mach probe is used for the measurement of the flow velocity and density profiles, while the emissive probe is for the measurement of plasma potential with hot-emission mode and for the measurement of plasma density and electron temperature with single probe mode. Densities at the center have been varied from $2\times10^{13}\ cm^{-3}$ to $0.5\times10^{13}\ cm^{-3}$ with pressures of 55 to 150 mtorr. Relation of density profile with the working pressure/magnetic field is analyzed by using a simple fluid model.

Electron temperatures at the center are also measured by the Thomson scattering method and compared with those of FSP, which are varied from 0.6 to 6.5 eV. Characteristics of MAP-II, fast-scanning probe system, Mach and emissive probes, Thomson scattering system will be addressed.

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18R06

ICRF heating and plasma acceleration with an open magnetic field for the advanced space thruster

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Recently, it is expected that many plasma technologies developed in the long-running fusion researches should be utilized in other research fields. Near-future space exploration missions need further investigation of advanced electric propulsion systems which use high density plasma production and acceleration technique. A magnetic nozzle acceleration and ion heating in a fast flowing plasma attracts much attention in such an advanced electric propulsion system. In the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) project, proceeded in NASA as a main engine in manned Mars missions, it is proposed to control a ratio of specific impulse to thrust at constant power [1]. This engine utilizes a combined system of an ion cyclotron heating and a magnetic nozzle, where a flowing plasma is heated by ICRF (ion cyclotron range of frequency) power and the plasma thermal energy is converted to flow energy via a diverging magnetic nozzle.

ICRF heating of a fast-flowing plasma has been clearly demonstrated with an input RF power up to 15kW in the HITOP device, and Doppler effect due to the plasma flow was observed [2,3]. A fast flowing plasma produced by a magneto-plasma-dynamic arcjet (MPDA) was exhausted into an axial magnetic channel and RF power was injected through a right-handed, helically wound antenna to excite $m = -1$ ion cyclotron waves. It is found that plasma thermal energy $W_\perp$ measured by a diamagnetic loop coil increases drastically when RF waves are launched as shown in Fig.1. These strong ion cyclotron heating occurred when a plasma density was lower than 10^{18} m^{-3}, where an ion-ion collision frequency ν_{ii} becomes much less than an ion cyclotron frequency f_{ci}. Ion temperature increased linearly to the input power and attains to nearly 100eV with a plasma density around 10^{17}m^{-3}.

Plasma acceleration due to the energy conversion from the thermal energy to a flow energy in a diverging magnetic nozzle was also observed as shown in Fig.2. After passing through the diverging magnetic nozzle, increase of $T_{i//}$ and decrease of $T_{i\perp}$ were clearly observed in the electrostatic energy analyzer signals as shown in the figure. It is confirmed that the magnetic moment $\mu = W_\perp / B$ was kept to be constant in the diverging magnetic nozzle.

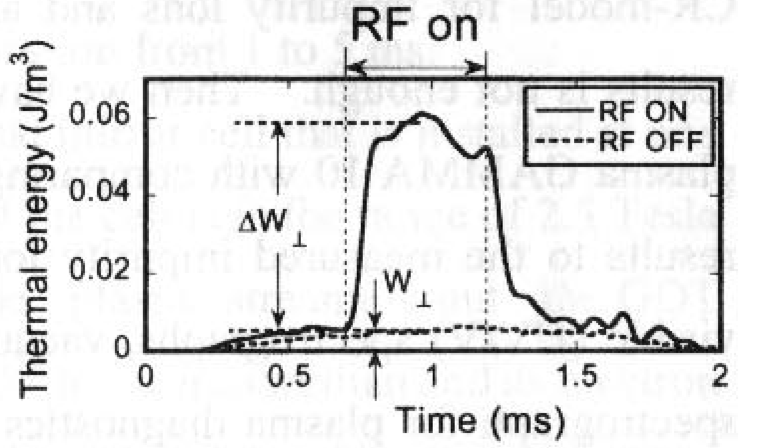

Fig1. **Time evolutions of $W_\perp$. He plasma. f_{RF}=236kHz. P_{RF}=15kW.**

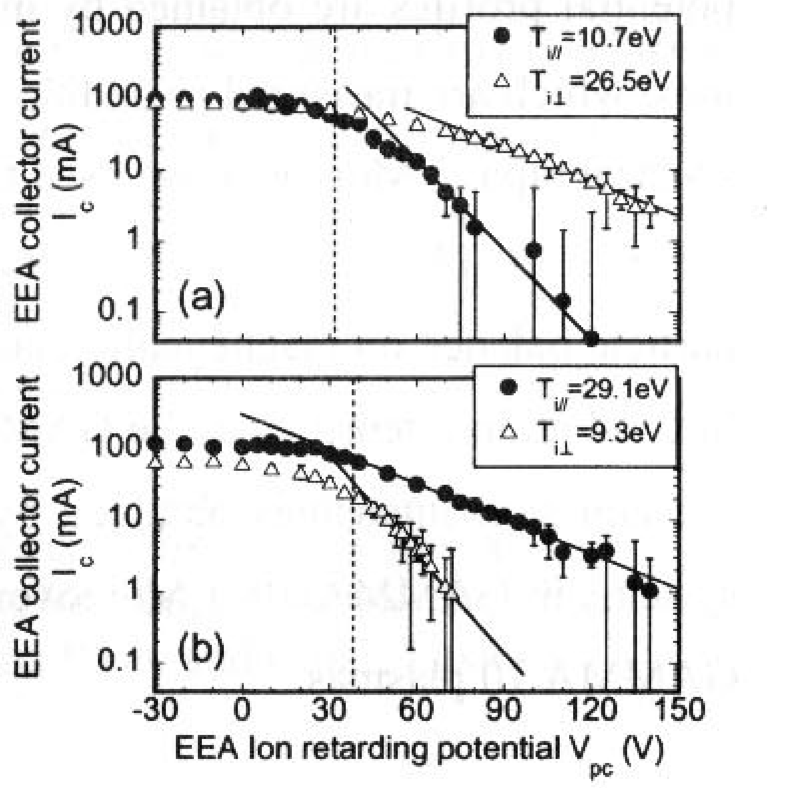

Fig.2 Electrostatic energy analyzer (EEA) signals measured at (a) Z=2.23m (B_z=575G) and (b) Z=3.03m (B_z=192G). He plasma. f_{RF} =236kHz.

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18R07

Plasma Spectroscopy in the Tandem Mirror GAMMA 10

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Spectroscopic measurements are important study for fusion plasmas. They have a lot of important information of the fusion plasmas, such as plasma particle confinements, impurity transport, plasma density, and plasma temperature, etc. We have studied impurity ion and neutral hydrogen radiation intensities in the fusion plasma GAMMA 10 for plasma diagnostics. In these days, a collisional-radiative model (CR-model) is an important model for the plasma spectroscopy. However the comparison between the calculation results of CR-model for impurity ions and atoms and the experimental spectroscopic measurement results is not enough. Then we have studied impurity ion radiation intensities in the fusion plasma GAMMA 10 with comparing the collisional-radiative model (CR-model) calculation results to the measured impurity ion spectra using spectrograph systems of ultraviolet and visible (UV/V) spectrographs, vacuum ultraviolet (VUV) spectrograph, and soft X-ray (SX) spectrograph for plasma diagnostics. These spectrograph systems are absolutely calibrated by using suitable light sources for their wavelength range. The CR-models for carbon ions has been developed to use impurity ion densities and their transport. Radial electrostatic potential profiles are obtained by measuring plasma rotations of variously charged impurity ions, which are measured as addition of diamagnetic drift and E×B drift, by using the UV/V spectrograph. Moreover, we used the Hα measurement systems for studying neutral particle behavior in GAMMA 10. A neutral hydrogen behavior is an important subject to clarify the particle balance on magnetically confined plasmas. In this paper, we show the impurity ions line radiation intensities in the GAMMA 10 plasma and the results of comparing the impurity ion emission intensities obtained by CR-model calculation to those obtained spectroscopic systems in GAMMA 10. Moreover, we show the neutral particle behavior in some types of GAMMA 10 plasmas.

18R08

The synthesized hot ion plasmoid experiment at GDT

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An idea of the Synthesised **H**ot **I**on **P**lasmoid (SHIP) experiment at the GDT device in the Budker Institute has been presented in [1]. In the next two years the required experimental equipment were constructed and plasma parameters in SHIP were calculated using the Integrated Transport Code System (ITCS). In December 2004 the experiments at the GDT-SHIP device has been started. The first results of study of SHIP plasmas with moderate parameters of injected neutral beams were presented in [2]. Later on, the new power supply of the SHIP-NB injection system was installed and the parameters of neutral beams were sufficiently increased with extension of the beam pulse duration from 1 to 5 ms.

The experiments are carried out in a small additional mirror cell that is installed at one side of the GDT central cell. The magnetic field on axis of the cell is in the range of 2.5 Tesla and the mirror ratio is set to ~ 2. The cell is filled with the plasma streaming out the GDT central cell. This plasma component with density of $1\text{-}3\times10^{19}$ m^{-3} is maxwellian and its electron temperature is about 100 eV. The two upgraded hydrogen/deuterium neutral beam injectors are used to provide a total equivalent current of about 60 amperes incident on a plasma in the mirror cell. Beam energy is set to 22 keV, pulse duration is 5 ms. The beam injection gives rise to high-energetic strongly anisotropic ion component build up, which maximum density exceeds that of the background warm plasma. The mean energy of the energetic beam-injected ions is about 10 keV. A set of special diagnostics was developed for this experiment.

This paper presents the recent results obtained in the experiments with SHIP. The results of numerical simulations are compared with the experimental results.

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18R09

Investigation of Neutral Particles Using High Speed Camera and Monte-Carlo Simulation in the GAMMA 10 Central-cell

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Recent development of the performance in high-speed camera enables us to understand dynamic and detailed behavior of high temperature plasmas in magnetic confinement devices. [1-3] It is also important for the investigation of the plasma fluctuation and plasma-wall interactions to observe detailed motion of plasmas in periphery region. Two-dimensional imaging diagnostic is one of the most effective methods for these purposes.

GAMMA 10 is a minimum-B anchored tandem mirror device with thermal barrier at both end-mirrors [4]. The device consists of an axisymmetric central-mirror cell, anchor-cells with quadrupole magnetic configuration, and plug/barrier regions with axisymmetric mirrors. In GAMMA 10 visible imaging measurement by using two fast cameras (Ultima-SE, Photron Inc. and K4, NAC Inc.) was recently performed for the first time in the GAMMA 10 central-cell. In standard ion cyclotron range of frequency (ICRF) heated plasmas, a short gas puffing of hydrogen (3-5 ms) close to the central-cell midplane was carried out to illuminate the plasma periphery and the time evolution of visible light emission from the gas cloud was captured precisely.

During the operation of gas puffing, the time evolution of the shape in the plasma boundary as well as the light emission is determined from the analysis of two-dimensional images. The localization of neutrals is also studied in terms of neutral particle transport by using the Monte-Carlo simulation code DEGAS. [5, 6]

By using this camera system, strong light emission and its significant behavior accompanied by a plasma heating pulse are also observed on a disk limiter installed near the central-cell midplane for the first time. In the early state of wall conditioning of GAMMA 10, localized light emission on the limiter was recognized during a central electron cyclotron heating (C-ECH) pulse. It is also confirmed that the light spot rotates in the direction of electron diamagnetic drift. This strong light emission coincides with an abrupt decrease of the central diamagnetism, which strongly indicates the enhancement of hydrogen recycling near the central-cell limiter during C-ECH. In this paper, we describe the detailed behavior of 2-d visible image of the plasma near the midplane of the GAMMA 10 central-cell and the results are examined in terms of neutral particle transport and edge plasma diagnostics.

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18R10

Simulation Study of Stepwise-Density Variation with RF Power in HANBIT Device

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One of the peculiar characteristics of the HANBIT discharge is that plasma density varies as stepwise manner when we vary the applied RF power. We believe that the plasma density is determined as the balance of loss power caused by transport and absorbed power coupled with radio frequency antenna. According to previous simulation concerning RF wave coupling with the plasma, the antenna loading impedance or the plasma resistance is very peaky on the plasma density variation. It implies that the plasma impedance at the density at which the power is balanced is not continuous on applied RF power. Even though the plasma resistance is very sensitive to the plasma conditions of density and external magnetic field and have peaky dependence on plasma conditions, up to now we have used fixed RF matching condition and successfully implemented discharge experiments. To investigate the characteristics of density variation with the applied RF power and to see how does the impedance well adjust to separated discharge conditions, we performed a self-consistent discharge simulation. The results well explain the dependence of the plasma density on applied RF power and the reason why we can use fixed matching condition for various plasma conditions.

Behavior of the initial plasma in AMBAL-M

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Recent experimental results on the initial plasma behavior in the AMBAL-M solenoid are reported in this paper. A turbulent plasma stream generated by an external plasma gun and propagating into the solenoid was studied in some detail. Observations of unstable MHD plasma behavior after cut-off of the essentially stabilizing plasma gun are presented. Attempts of forced destabilization and stabilization of the solenoid plasma by varying magnetic field structure in the solenoid to create a local mirror trap and divertor are described. A circular limiter was installed to cut off a low-density peripheral plasma which otherwise could hamper the ICRH antenna efficiency. This limiter is also convenient for studies of the initial plasma population in the solenoid, for diagnostics of MHD activity, and probably for creating radial electric field gradient. A Rutherford scattering diagnostic for ion temperature measurement was installed at the solenoid. A plasma gun with a cylindrical discharge channel, contrary to the previously used one with an annular channel, was prepared for experiments and is expected to provide less turbulent initial plasma that is more adequate for MHD stability studies.

Indication of a low frequency coherent structure driven by turbulence in a Hanbit mirror plasma

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Low frequency fluctuations of plasmas in a mirror machine have been analyzed in search of a coherent structure generated by turbulence. Ion saturation currents of a Hanbit mirror plasma measured by a Langmuir probe, which is located at the edge of the plasma, have been analyzed by using a bispectral method. An interesting structure indicating a coherent mode is found around 500Hz, which is much lower than the frequency of the geodesic acoustic mode observed in a conventional toroidal device. The energy transfer to this mode is shown to follow the nonlocal resonant three-wave coupling with exact frequency match. Analysis of the nonlinear time series has also been carried out for further characterization of the Hanbit mirror plasma turbulence.

Oral Presentation

Ion-induced instability of diocotron modes in electron plasmas modelling curvature-driven flute modes

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Curvature-driven flute modes have been a problem for magnetic confinement from the beginning of fusion research. Magnetically confined pure electron plasmas are naturally free from this problem, until a small fraction ([illegible] 1%) of positive ions is added. Then, the ions destabilize the electron plasma diocotron modes, analogous to the curvature-driven destabilization of neutral plasma flute modes.

We study ion-induced instability of flute-like ($k_z \approx 0$) diocotron modes in pure electron plasmas confined in a cylindrical Penning-Malmberg trap. In the absence of positive ion contamination, the diocotron modes are either neutrally stable (for $m_\theta = 1$) or weakly damped (for $m_\theta = 2,3,...$) by Landau resonance on electrons co-rotating with the diocotron waves. By adding some positive ions (H_2^+) into the system, we observe exponential instability of diocotron modes with growth rates γ_m directly proportional to the overall ion fraction, N_i/N_e, and proportional to an effective (bounce-averaged) drift separation of oppositely charged particles in the wave perturbation.

In our experiments we use a Penning-Malmberg trap in a double-well (nested trap) configuration, where the inner end cylinders are negatively biased with respect to the plasma potential to confine electrons, while the outer end cylinders are biased positively to confine ions. A strong axial magnetic field ensures radial confinement both for the electrons and ions. The positive ion population is maintained either by controlled external injection of ions or by ionization of the background gas within rf-heated ($T_e \approx$ 7-9 eV) electron plasmas.

The double-well confinement configuration results in a significant difference between the bounce-averaged azimuthal E×B drift rotation velocities of electrons and ions. This difference mainly comes from the two species sampling different radial electric fields at the plasma ends; in neutral plasmas, the magnetic curvature causes this separation of electrons and ions which destabilizes the flute modes. This is a major factor that distinguishes charged and neutral plasmas behavior in our experiments. However, it allows us an easy control over the effective drift separation of oppositely charged particles in the wave perturbation, by simply varying the ratio of the ion end bounce time τ_{end} to the electron bounce time τ_{bnc}. This ratio gives an average phase shift accumulated between electrons and ions during one diocotron orbit as $\phi_d = 2\pi\tau_{end}/\tau_{bnc}$.

As a result, the measured ion-induced growth rates show rather simple dependence $\gamma_m \approx (N_i/N_e)\, f_m\, (1 - \cos\phi_d)$ verified in a broad range of relevant plasma and trap parameters. Here N_i/N_e is the reduction factor taking into account the smallness of ion fraction, and the rest of the expression represents the contribution of an effective „curvature acceleration".

This strong instability may have important implications for a variety of experiments that continuously propel a bunch of ions through an electron or positron cloud, as in recently used anti-hydrogen creation technique [1, 2].

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A New Paradigm for Radial Ion Plasma Transport in Axisymmetric Magnetic Field

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Abstract

A series of basic transport physics experiments on the anomalous ion thermal conduction due to ion temperature gradient instabilities are performed in Columbia Linear Machine [Fusion Science and Technology, **47,** 1T p.270 (2005)]. The CLM results like most tokamak experimental data results indicate dependence of the ion thermal conductivity on the isotopic mass close to $\chi_\perp \sim A_i^{-0.5}$, i.e., inverse gyro-Bohm [Phys.Plasmas, **10,** p.3174 (2003)]. This is in stark contradiction to most present theoretical models predicting Bohm (A_i^0) or gyro-Bohm ($A_i^{0.5}$) scaling.

We now report another series of experiments designed to explore the physics basis of this scaling which appears to lead to a new model for this scaling based on 3-wave coupling of two ion temperature gradient radial harmonics and an ion acoustic wave. [Nucl. Fusion, **45,** p.439 (2005)] The resulting isotopic scaling of transport is ~ $A_i^{-0.5}$ dictated primarily by the ion acoustic damping. This basic physics is deemed to be extrapolatable to other experiments resolving the paradox and is tantamount to new paradigm for plasma turbulent transport.

18R15

Drift-Wave Instability Modified by Superimposed Parallel and Perpendicular Plasma Flow Velocity Shears

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In recent studies, the ion flow velocity shear parallel to magnetic field lines has been reported to enhance the drift-wave instability in open-ended magnetic configurations [1,2], while the perpendicular flow velocity shear has been confirmed to suppress not only the drift-wave but also ion-cyclotron instabilities independent of the sign of the shear [3]. In order to clarify the mechanisms of excitation and suppression of these instabilities in the real situation of space and fusion plasmas, it is necessary to realize the controlled superposition of the parallel and perpendicular flow shears in magnetized plasmas. Therefore, the aim of the present work is to independently control and superimpose the parallel and perpendicular flow shears in a basic plasma device with concentrically three-segmented electron and ion emitters [4], and to carry out laboratory experiments on the drift-wave instability excited and suppressed by the superimposed flow shears in collisionless open-ended magnetized plasmas.

Experiments are performed in the Q_T-Upgrade machine of Tohoku University. We attempt to modify a plasma-synthesis method with opposed electron and potassium ion emitters, where the both emitters are concentrically segmented into three sections. When each of the electron emitter is individually biased, the radially different plasma potential, i.e., radial electric field is generated. This electric field causes the E × B flows and flow shears perpendicular to the magnetic-field lines. On the other hand, the parallel ion flow with radially different energy, i.e., the parallel ion flow shear, is generated when each section of the segmented ion emitter is individually biased at a positive value above the plasma potential that is determined by the bias voltage of the electron emitter. Therefore, these parallel and perpendicular flow shears can be superimposed by controlling the bias voltage of the ion and electron emitters independently. Under our conditions, the plasma density is 10^8 cm^{-3}, the electron temperature is 0.2 eV, and the ion temperature is almost the same as the electron temperature. A background gas pressure is less than 10^{-6} Torr.

The fluctuation amplitude of the drift-wave instability is observed to increase with increasing the parallel shear strength, but the instability is found to be gradually stabilized when the shear strength exceeds the critical value. The experimental results are in good agreement with the dependence of the theoretical growth rate on the shear strength, which is calculated in the kinetic treatment including the effect of the radial density gradient.

When the positive perpendicular flow shear, which is caused by the outward radial electric field, is superimposed on the parallel flow shear, the drift-wave instability is found to be suppressed by the slight shear of the perpendicular flow velocity even in the presence of the parallel shear. In the case that the negative perpendicular shear caused by the inward radial electric field is superimposed, on the other hand, the shear strength required for the suppression of the drift-wave instability becomes large in proportion to the parallel shear strength even in the same range of the parallel shear as the case that the positive perpendicular shear is superimposed. Based on these results, the sign of the perpendicular shear is found to be important in modifying the parallel shear enhanced instability.

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18R16

Characterization of electron drift wave and interchange mode in HANBIT mirror device

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Based on the previous study on the characteristics of interchange mode in HANBIT, the effect of the plasma parameters on the onset of the electron drift wave in HANBIT is also investigated experimentally varying the input power of radio frequency(RF) heating, the external magnetic field(B_{ext}) and the neutral pressure. Similar to the interchange mode, as the RF power and B_{ext} are increased, the drift wave is stabilized due to the its non-linear interaction with the external RF wave. Interestingly, the drift wave is stabilized and on the other hand, the interchange mode is unstable as the neutral pressure increases. The measured onset criteria for the interchange mode and the drift wave are compared with the local two-fluid dispersion relation taking into account of nonlinear interactions with the RF wave and the effect of ion-neutral collisionality. According to the preliminary calculations, the effect of the finite Larmor radius may be responsible for the distinct dependence on the neutral pressure of the interchange mode and the drift wave.

19R01

Plasma heating and confinement in GOL-3 Multiple Mirror Trap

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Resent results of the experiments on GOL-3 facility are presented. In present configuration of the device, plasma with a density of $10^{19}\div10^{22}$ m^{-3} is confined in a 12-meter-long solenoid, which comprises 55 corrugation cells with mirror ratio $B_{\max}/B_{\min}$=4.8/3.2 T. The plasma in the solenoid is heated up to 2-4 keV temperature by a high power relativistic electron beam (~1 MeV, ~30 kA, ~8 µs, ~120 kJ) injected through one of the ends. Mechanism of experimentally observed fast ion heating, issues of plasma stability and confinement are discussed.

19R02

The Kinetic Stabilizer Axisymmetric Tandem Mirror: A Review of Approaches to its Implementation

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Plasma confinement experiments, some dating back to the early days of fusion research, point to axisymmetric open systems as being capable of confining plasmas in near-quiescent states, with radial transport rates approaching "classical" values. In recent experiments MHD-stabilization of mirror-confined plasma, predicted theoretically by Ryutov [1], was verified in the axisymmetric Gas Dynamic Trap at Novosibirsk. The Kinetic Stabilizer Tandem Mirror concept [2,], under study theoretically at the Livermore Laboratory, represents an attempt to apply Ryutov's stabilizing technique to tandem-mirror systems. This objective, if accomplished, would markedly improve the tandem-mirror, making it a major contender in the search for practical fusion power. The concept involved is that the presence of a low-pressure, low density, plasma on outward-curving field lines can, under the proper circumstances, stabilize a high-density fusion plasma confined in an otherwise MHD-unstable axisymmetric tandem-mirror system. This counter-intuitive result comes about from the strongly stabilizing effect of the positive curvature and the radial expansion of the "expander" magnetic field beyond the outer mirror. In optimized designs of the expander the effluent stabilizer plasma can be effective at pressures and densities that are many orders of magnitude smaller than those of the confined plasma. Because of its low density it is possible to employ techniques for the creation and maintenance of the stabilizer plasma, e.g. the injection of directed ion beams into the expander, that would be infeasible or would require unacceptably high power losses if attempted at high plasma density. In the outermost parts of the stabilizer Debye lengths can be of order centimeters, allowing the use of grid-based techniques, or of ponderomotive forces, to create and/or maintain the stabilizer plasma. The paper will review results from studies of ion-beam-created stabilizer plasmas, and of the optimization of the expander field configuration to be used with them. It will then describe some as-yet-uninvestigated approaches to the problem of creating the stabilizer plasma that might be simpler to execute than those that have been studied. It should be noted that the wide variety of possible approaches by which to implement these ideas stems directly from the open-ended nature of the magnetic fields involved. Only in open-field systems, such as the tandem mirror, with direct access to the field lines that connect to the confined plasma, can manipulations, such as control of the radial potential, physical separation from the radial bounding surface of the confinement chamber, or, as here, MHD-stabilization by plasma exterior to the fusion plasma, be contemplated.

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19R03

Divertor Stabilization Experiments in the Hanbit Mirror Device

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The Hanbit device is a magnetic mirror machine which has a central cell, one anchor cell and one plug cell plus associated vacuum chambers. It is about half of the original TARA mirror device from MIT. The Hanbit device has been involved in a series of experiments on stabilization of the MHD flute type mode. Earlier work [1] showed that it was possible to stabilize the m=-1 flute type MHD instability with RF power near the cyclotron resonance by the sideband coupling process. We have undertaken investigations to see if a divertor can stabilize the m=-1 MHD instability. Divertors were used previously in experiments on the TARA mirror device [2-4] and the HIEI mirror device [5, 6]. A divertor stabilizes the plasma by providing a region of low poloidal field at a separatrix in which the electrons can drift azimuthally. The high plasma conductivity causes the potential of perturbations with azimuthal numbers |m| > 0 to vanish and thus shorts out the electric field due to the interchange instability. For the flute modes, the separatrix serves as a perfectly conducting end wall that shorts out the electric field. In contrast to this, Pastukhov [7] has argued that the main stabilizing effect is compressibility.

In Hanbit, we could not place any coils inside the vacuum system nor could we modify the vacuum chamber or coils, so the divertor had to be composed of existing field coils energized with separate power supplies. The present configuration uses just one divertor coil in one end of Hanbit and produces an left-right asymmetry in the magnetic field. One of the central cell coils with reversed current is used as the divertor coil and two adjacent coils with increased current are used to compensate for the field droop and to prevent the field lines from intercepting the bare ICRH antenna. The anchor is turned off for the experiments so that it will not influence the stability. The divertor strongly reduces the m=-1 instability when the null point (x-point) is sufficiently inside the vacuum tank. However, the diverted plasma is directed into a wall and the divertor cannot be used to eliminate impurities. Details of this experiment will be given.

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19R04

Concept of the magnetic divertor in GAMMA10

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The GAMMA10 tandem mirror consists of non-axisymmetric min.B mirror cells as well as axisymmetric central solenoid and axisymmetric end-mirror cells. The non-axisymmetric min.B mirror enhances the transverse plasma transport[1-3] although they play a roll of MHD stabilizer. We are planning to make a tandem mirror axisymmetric by introducing a magnetic divertor. MHD modes in an axisymmetric mirror can be stabilized by a finite-ion Larmor radius effect and non-paraxial magnetic effect. The non-paraxial effect on the MHD stability was studied by Ryutov and Stupakov.[4] They showed that the m=1 flute mode was stabilized by an axisymmetric mirror with non-paraxial magnetic fields. The m=1 flute mode can also be stabilized by a magnetic divertor[5,6], where the uniform electrostatic potential is realized along a circular magnetic null line by electrons' nonadiabatic response. The higher m flute modes, however, are not stabilized by the above boundary condition. Pastukhov and Sokolov showed that the higher m flute modes were stabilized by the non-paraxial magnetic filed but not ion finite Larmor radius effects.[6] We made a design of magnetic divertor in the GAMMA10 central cell under the condition that the present GAMMA10 coils were used to the divertor coils,[7] where the equilibrium existed until beta = 1.

In the presentation we will give the concept of the divertor design in the GAMMA10 anchor region, where the non-axisymmetric min.B anchor mirror cell is replaced by an axisymmetric mirror cell with a magnetic divertor. We will present the equilibrium calculation there and consider the interchange flute mode stability.

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EUV Spectra measaured from Large Helical Device and Atomic Data

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EUV spectra from plasma are important because most of the radiation energiy is emitted in EUV wavelength regions in the peripheral plasma in fusion plasmas. Visible spectra are easy to measure. However visible emission does not directly reflect the plasma state because visible specra are often emitted in transitions between highly excited states and their emission energy is low. Visible spectra are often difficult to analyze. On the other hand EUV emission is generally emitted in lines excited directly from the ground states, and reflect the density of the ions. Many electron ions such as L shell ions emit radiation more efficiently than one or two electron ions (K shell ions). We have measured EUV spectra of C L-shell ions, Fe L-sehll and M-shell ions and Xe N-shell ions from LHD (Large Helical Device) in the National Institute for Fusion Science.

For C ions we have made a collisional radaitive model and studied the intensity ratios during radiation collapse in LHD. For Fe ions we identified the lines and studied the time evolution of the line intensity ratios. For Xe ions we identified the complicated spectra. We compared the spectra with radiation collapse and without radiation collapse.

For the analysis of EUV emission, it is necessary to have reliable atomic data for wavelengths, transition probabilities and collision data. We have evaluated the atomic data for carbon atom and ions for collisional cross sections and rate coefficients of ionization, excitation and charge transfer processes [1]. We also evaluated the atomic data for excitation rate coefficients of Fe L shell ions [2]. These data are published in the NIFS-DATA series. These evaluated data as well as the original data before evaluation are stored in AMDIS (electron impact exciatiaon, ionization and recombination) and in CHART (ion impact charge transfer and ionization). These data can be retrieved on the Web (http://dbshino.nifs.ac.jp) in NIFS atomic databases [3].

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Fragmentation of hydrocarbon impurity molecules as a result of electron capture

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Various kinds of impurity hydrocarbon molecules are known to be produced abundantly at near divertor region. The knowledge of their species, amounts, energy distributions of these impurity molecules as well as their dynamics with plasma are critical for plasma diagnostics and reactor design. Fragmented species of hydrocarbon molecules such as CH, CH_2 and CH_3 produced from CH_4 and C_2H_2 molecules have been in fact utilized in plasma-spectroscopy as marker molecules for diagnostics. Therefore, it is essential and important to establish concrete knowledge of production dynamics and their amount of these fragmented species.

We have carried out joint theoretical and experimental investigations on (i) electron capture dynamics in collisions of proton with hydrocarbon molecules [1-5], and (ii) fragmentation dynamics and fragmented species thus produced. A majority of molecular ions produced as a result of electron capture and electronic excited molecules is known to be unstable and hence undergo fragmentation processes. By fragmentation, they produce various and a large amount of fragmented species (neutrals and ions), and kinds of species produced depend sensitively on parent molecular-ionic species and excited states. Specifically, we have investigated collision dynamics of CH_4 molecule by proton impact, electron capture and electronically excitation, and fragmentation in the energy region from 25 keV down to a few tens of eV. The dominant electron capture forms the ground-state CH_4^+ ions which are stable, while the next largest contributions to dynamics are from excited CH_4^+ and excited CH_4^*, both of which are unstable and break up producing many fragmented species particularly CH_2 radicals. These latter two processes are found to increase rather drastically as the energy increases and the quantity produced is sufficient for spectroscopic purpose.

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19R07

Charge transfer cross sections of H^+ ions in collisions with some hydrocarbon molecules in the energy range of 0.2 to 4 keV

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In the edge plasmas of recent large tokamak devices with plasma facing walls using carbon materials, the production of many kinds of ions and carbon containing molecules has been reported. Among many collision processes relevant to low temperature fusion edge plasmas, charge transfer by ions from these molecules play a key role in determining properties of high temperature plasmas at the core region. We therefore systematically measured the charge transfer cross sections of H^+, C^+, O^+, and He^{2+} ions in collisions with various molecules [1-5].

In 2000, we measured the charge transfer cross sections of H^+ ions in collisions with CH_4, C_2H_2, C_2H_6, and C_3H_8 in the energy range from 0.2 to 4 keV [3]. Janev *et al.* compiled and assessed our data and the other existing experimental cross section data for the charge transfer process in $H^+ + C_xH_y$ collision systems with $x = 1 - 3$ and $1 \leq y \leq 2x + 2$ in 2002 [6]. They also presented the recommended values with the analytic fits, and predicted the cross section values for the collision systems, such as $H^+ + C_3H_4$, for which no data are available.

In this work, therefore, we have measured the charge transfer cross sections of H^+ions in collisions with C_3H_4 [Allene and Propyne], C_3H_6, $(CH_2)_3$, normal-C_4H_{10} and iso-C_4H_{10} in the energy range of 0.2 to 4 keV. In the present experiments, the H^+ ions were extracted from an electron impact ion source and introduced into a 4 cm long collision cell filled with high pure hydrocarbon molecules. The cross sections of charge transfer were determined by an initial growth rate method with a position sensitive micro channel detector.

The present observed cross sections for C_3H_6 molecules gradually decrease as the collision energy increases. This behavior indicates that the charge transfer process in this energy region takes place in a near-resonant manner. The predicted and recommended values by Janev *et al.* [6] are just in accordance with the present cross sections. The present observed cross sections for $(CH_2)_3$ molecules are in good agreement with those for C_3H_6 molecules. The energy dependence of the present measured cross sections for both n-C_4H_{10} and i-C_4H_{10} molecules behaves also in a near-resonant manner. The recommended values of Janev *et al.* [6] are close to the present cross sections. For two C_3H_4 molecules [Allen and Propyne], the present cross sections have the maximum point at about 1.5 keV. The predictions of Janev *et al.* [6] are close to the present cross sections, but slightly smaller than the present measurements.

This work was performed as a collaborative research programme of the National Institute for Fusion Science, in Japan.

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19R08

Atomic and molecular data base and data activities for fusion research in Japan Atomic Energy Agency

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In fusion reactors, heat and particle control is essential for obtaining high fusion performance and preventing damage of the plasma-facing materials. Plasma modeling considering atomic and molecular processes is necessary for establishment of such control. Atomic and molecular processes are also applied to various plasma diagnostics. Therefore, the atomic and molecular data base is essential for fusion research. The data base is also useful for other plasma research.

We have been compiling and evaluating the cross section data for atomic and molecular collisions and spectral data relevant to fusion research[1]. We have also been producing atomic and molecular data required for fusion research. The collision data have been compiled in the database JEAMDL (Japanese Evaluated Atomic and Molecular Data Library). JEAMDL is available for about 1000 collision processes through the Web at the URL www-jt60.naka.jaea.go.jp/JEAMDL/index.html. Through the web, in addition to figures of the cross sections as a function of collision energy, analytical functions written in FORTRAN programs have been available for about 360 processes. Cross sections for the following fusion-relevant processes were evaluated: charge transfer of H atoms and ions colliding with gaseous atoms and molecules, and with metal vapor, state-selective electron capture of C^{+6} and O^{+8} ions colliding with H atoms, collisions of H, H_2, He and Li atoms and ions with atoms and molecules, electron collisions with CO, CO_2 and H_2O molecules, and with hydrocarbon molecules. The databases include other many processes for the species and they cover wide collision energy ranges.

Production of atomic and molecular data is also significant subjects of our present and future activities. We are producing cross section data that play important roles in cold diverter plasmas and are producing spectroscopic data for heavy atoms. As to the production, cross sections for various processes including hydrocarbon molecules have been measured. Charge transfer cross sections of Be, B, C, Cr, Fe and Ni ions with gaseous atoms and molecules have also been measured. Cross sections of state-selective electron capture in collisions of C^{+4} ions with H* (n=2) atoms have been calculated using a molecular-bases close-coupling method. Band emission rates for CH/CD and C_2 produced from hydrocarbon molecules have been investigated in JT-60U divertor plasmas. Measurement of spectral lines from highly ionized Xe and W is also in progress using the Tokyo-EBIT and JT-60U.

We published a monograph on spectral data for highly ionized atoms, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Kr and Mo, in collaboration with National Institute of Standards and Technology. In the monograph, critically evaluated data for wavelengths, energy levels, oscillator strengths, transition probabilities and ionization energies are tabulated. Both observed and calculated data are compiled. The data tables include data for all stages ionization from Ca-like through H-like spectra, except for Kr and Mo that start at Ge-like and Rb-like, respectively. Recently, we have been compiling spectral data for Ga and W ions.

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19R09

NIFS Atomic and Molecular Database for Collision Processes in Plasma

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We are making and providing the Atomic and Molecular Numerical Database on collision processes in plasma. Atomic data are important for plasma modeling or plasma diagnostics. We are working on various atomic data activities, such as atomic data production, compilation, evaluation and application to plasmas, as well as making the atomic database.

The atomic data compilation has started in 1975 as the results of the collaboration works by working groups organized with atomic physicists and plasma physicists in Japanese universities [1]. The atomic database and data retrieval and display system were constructed in 1980s in a main frame computer in the former institute, the Institute of Plasma Physics, Nagoya University [2,3]. The database has been continuously provided for researchers. Since 1997 the database system has been changed. The retrieval system was reconstructed in a unix workstation with relational database managing system, oracle, in order to access the database through internet [4]. Since then, researchers can access the database from the web page, http://dbshino.nifs.ac.jp/ and the database system is maintained and updated and new databases have been added. Atomic data updates are carried out with a help of the working group by Japanese atomic physicists [5].

Currently 6 atomic and molecular databases are opened as follows: AMDIS (cross sections and rate coefficients for ionization, excitation, recombination, and dissociation of atoms, ions, and molecules by electron impact), CHART (cross sections for charge transfer and ionization of atoms, ions, and molecules by ion collision), AMOL (cross sections and rate coefficients of various collision processes for molecules by electron impact), CMOL (cross sections and rate coefficients of various collision processes for molecules by heavy particle collision), SPUTY (sputtering yields by ions), and BACKS (particle- and energy-back scattering coefficients from solids). All databases are accessible via internet and data can be retrieved by querying an element name, an ionic stage, or other conditions. Atomic data set consists of numerical data, information on data such as experimental or theoretical method (AMDIS), and bibliographic information. Numerical data are displayed in a tabular form or in a graph which can be downloaded as a PDF file. Users are required to register before using the database. The registration form can be submitted from the web page.

A part of our database, AMDIS, can be accessed freely from the GENIE by IAEA Atomic and Molecular Data Unit [6], where only numerical data tables are shown.

We provide other small atomic and molecular databases, such as data for autoionizing states, differential cross sections for molecules by electron impact, and differential cross sections of ionization for atomic hydrogen by proton impact. All such databases are linked to our main database homepage at dbshino.nifs.ac.jp for free access.

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20R01

Transonic plasma flow passing through a magnetic mirror

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Dynamics of a fast flowing plasma through a magnetic mirror field is very important to clarify a variety of MHD phenomena in space plasmas, electric propulsion plasmas and also fusion plasmas in such as GDT, multiple mirror and tokamak divertor. A magneto-plasma-dynamic arcjet (MPDA) is one of promising candidates for a space plasma thruster.

A highly-ionized, high-density, fast-flowing plasma was produced by use of a quasi-steady MPDA in an externally-applied axial magnetic field. The fast flowing He plasma was injected into a magnetic mirror in the HITOP device.[1]

Ion acoustic Mach number M_i is defined as follows: $M_i = U / ((\gamma_i T_i + \gamma_e T_e)/ m_i)^{1/2}$, where, γ_i and γ_e are specific heat ratios of ion and electron, respectively. The ion Mach number was estimated by use of a Mach probe. The conversion formula from the ion saturation current ratio of the Mach probe to M_i was calibrated by using spectroscopic measurements of U and T_i.[2] T_e was measured by a Langmuir probe.

In the uniform field region near downstream of the MPDA muzzle, M_i was around unity under various discharge conditions. When the plasma expands in the diverging field, M_i increases from unity to about 2. When the supersonic plasma flows into the converging mirror field, a shock-like structure with a thickness of ion-ion mean free path appeared. The subsonic flow downstream of the shock was re-accelerated up to M_i of 2 by passing through a Laval-type magnetic nozzle.[3]

It is reasonable to assume that $\gamma_e = 1$ (isothermal), because T_e is nearly constant along the field line. In order to estimate the value of γ_i, the experimental axial profile of M_i was compared with that predicted by 1D isentropic flow model. The best fitting was obtained when γ_i is1.2. This value is smaller than 5/3 for an ideal He ion gas. The observed shock jumps agree reasonably with those predicted by the Rankine-Hugoniot relation with γ_i of 1.2. it is concluded that the sonic condition (M_i=1) is satisfied at the magnetic mirror throat as in a conventional Laval nozzle.

In order to clarify mechanism of the Mach number saturation at unity (i.e. choking) near downstream of the MPDA muzzle, magnetic field components were measured. It was found that a large diamagnetic effect due to the high density plasma deforms the uniform field applied near the MPDA to an effectively converging nozzle.[4] Then, in analogy of the flow structure observed in the far downstream mirror region, it is expected that a subsonic flow ejected from the MPDA will be accelerated isentropically to a sonic flow, while a supersonic flow will be decelerated isentropically to sonic or suddenly to subsonic through a shock and then re-accelerated to sonic. This could be the reason why the flow was mostly choked (M_i =1) when the external field is uniform near the MPDA.

These findings indicate that an axial profile of the externally-applied field at the MPDA can be optimized so that the plasma flow ejected from the MPDA is kept to be hypersonic. This results in developing a plasma thruster with a higher propulsion efficiency.

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20R02

Role and contribution of the open field line region in the Large Helical Device

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Open field line region plays the key role for steady state operation of the Large Helical Device (LHD) and greatly contributes to the high-performance plasma confinement in the LHD. Theoretical and experimental results are shown.

The characteristics of the LHD magnetic field are the high magnetic shear configuration in the peripheral region and the existence of the chaotic field line layer which surrounds the last closed flux surface (LCFS). Lines of force outsides the LCFS show a fractal structure and create a chaotic field line layer[1],[2]. This chaotic field line layer is the open field line layer in the LHD. The typical thickness of this layer is the order of 3 ~ 15 cm. Various sizes of magnetic islands are imbedded in the layer. divertor field lines have extended from this layer to the vacuum vessel wall. The connection length L_c (length of lines of force until reaching vacuum vessel wall) is extremely long ($L_c \gtrsim 10\,\mathrm{km}$) when the lines of force come close to the LCFS. On the other hand, lines of force that leave the chaotic field line layer reach the vacuum vessel wall very soon ($L_c \simeq$ a few m).

The chaotic field line layer can sustain low temperature ambient plasma due to the long connection length of lines of force, presence of the imbedded magnetic islands and mirror confinement effect of helical ripple nature of magnetic field [3]. This low temperature ambient plasma is clearly observed always by the CCD camera in the LHD experiment. This ambient plasma plays a role of an impregnable barrier for the core plasma, which suppresses both the MHD instabilities and the cooling of the core plasma due to charge exchange processes.

1) The chaotic field line layer plasma stabilizes the interchange mode due to the neutralization of the charge separation that causes the instability.

2) The pinning effects of divertor field lines at vacuum vessel wall can stabilize the ballooning mode and the vertical displacement events of plasma column.

3) The chaotic field line layer plasma can prevent the penetration of neutrals outside the plasma (role of the plasma blanket).

It is necessary to control the concentration and the decentralization of the divertor heat flux to achieve the long pulse plasma sustainment. In the LHD, it is demonstrated that the slow and small periodic change of magnetic axis position (swing divertor mechanism) can control the concentration and the decentralization of the divertor heat flux.

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20R03

Wave excitation in magnetically confined plasmas with an anisotropic velocity distribution

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In magnetically confined plasmas, fluctuations in the ion cyclotron range of frequency (ICRF) will be driven by the presence of non-thermal ion energy distribution. In strong ICRF heating experiments on the GAMMA 10 tandem mirror, plasmas with a strong temperature anisotropy have been formed when the fundamental resonance layer exists near the mid-plane of the central mirror configuration. In a typical discharge, Alfvén-ion-cyclotron (AIC) modes are spontaneously excited due to such strong temperature anisotropy [1]. On the while, in fusion-oriented devices with a toroidal configuration, the neutral beam (NB) injection is commonly used to create high performance plasmas. Resultant high-energy ions are trapped in the local mirror configuration and will form the velocity distribution with the strong anisotropy. Especially in burning plasma experiments on JET and TFTR, fusion-product (FP) ions will form the non-thermal ion energy distribution on the bulk plasma and the ion cyclotron emissions (ICEs) have been observed [2,3] in the ion cyclotron frequency and its higher harmonics. To study the relation among the AIC modes, ICEs and beam-driven electrostatic instabilities in the magnetically confined plasmas with non-thermal energy distribution is the main purpose of this work. In GAMMA 10, the effects of the AIC modes to plasma parameters have been clearly observed. In the toroidal configuration, these spontaneously excited waves will have the different influence on the particle transport and confinement.

Recently, the fluctuation measurement by using ICRF antennas as pickup loops on JT-60U has been started. When the deuterium-NBs are injected into the deuterium bulk plasma, the magnetic fluctuations due to injected beams and FP ions are detected. In GAMMA 10, the magnetic fluctuations with higher harmonic frequencies have been also observed. The wave excitation near ion cyclotron and its higer harmonic frequencies are studied experimentally and theoretically in plasmas with non-thermal ion energy distribution.

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20R04

Nonlinear Effects of High Power Plug/Barrier ECRH on Propagation and Radiation of Cyclotron Waves

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An electron cyclotron wave (ECW) has been recognized as an important plasma wave in the fields of basic plasma physics, thermonuclear fusion, and some applications. Especially, high power electron cyclotron resonance (ECR) heating (ECRH) is hoped to be the most effective method for the formation of transport barrier in tandem-mirror devices [1], where localized strong electron heating is demanded. Although the localized wave absorption is necessary for efficient and strong electron heating, the Doppler shift effect by high energy electrons expands the ECR region, namely, broadens the wave absorption region. In Tohoku University, on the other hand, it was reported that a left-hand polarized wave (LHPW), which has been believed not to be related to ECR, is also unexpectedly and sharply absorbed near the ECR point [2,3]. In addition, the experimental results demonstrated that the damping region of the LHPW is more localized than that of the right-hand polarized wave (RHPW). When this new damping mechanism of the ECW is applied to the efficient electron heating in large fusion devices such as a tandem-mirror device using the high power ECRH, it is necessary to clarify the nonlinear effects of the strong wave field on the propagation and radiation of the ECW. Based on these backgrounds, the purpose of the present work is to clarify the propagation and radiation characteristics of the ECW, including the nonlinear effects such as parametric decay which can cause the degradation of the heating efficiency.

Experiments are carried out with a plasma in the west plug/barrier cell of the GAMMA10 tandem mirror. The plasma is produced in the central solenoid by radio-frequency (RF) wave heating, and a potential barrier is created by ECRH in the plug/barrier cells at the machine ends. The ECRH power, variable up to 500 kW, is generated in a newly developed gyrotron, transmitted through a cylindrical corrugated wave-guide system in HE_{11} mode and radiated to the resonance layer with newly designed mirrors. We have set up a measurement system for receiving and analyzing electromagnetic radiation in the electron cyclotron range of frequencies, which consists of a movable receiver antenna, a heterodyne mixer with a Gunn oscillator (28 GHz, 13 dBm), and a spectrum analyzer.

When we observe frequency spectra of radiated electromagnetic waves from the plug region, a continuum radiation is observed extending over several hundred MHz above the fundamental electron cyclotron frequency, where the launched plug ($\omega_1/2\pi$ =28.00 GHz) and barrier ($\omega_2/2\pi$ =28.06 GHz) ECRH powers are 240 kW and 100 kW, respectively. Moreover, several sharp peaks are observed around $\omega_1/2\pi$ and $\omega_2/2\pi$ at intervals of 20MHz. Since this interval frequency is near the ion cyclotron frequency in the plug region, the sharp peaks are considered to be caused by nonlinear effects between the strong electromagnetic wave for plug/barrier ECRH and the ion cyclotron wave excited in the plasma.

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20R05

Second Harmonic Cyclotron Heating of Sloshing Ions in a Straight Field Line Mirror

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Sloshing ions trapped in magnetic mirror are energetic ions that have a certain ratio of perpendicular and parallel velocity. Their concentration increases near mirror point. They play a substantial role for plasma confinement in mirror traps. The sloshing ions sustain in a mirror trap could be maintained either by neutral beam injection or radio-frequency (RF) heating. A scenario of light minority sloshing ion heating on the fundamental cyclotron harmonic is theoretically studied in [1]. That study relates to the recently proposed straight field line mirror [2] and sloshing-ions based fusion reactor [3]. In [3], both deuterium and tritium sloshing ions are considered. The problem how to sustain the heavy sloshing ion component with RF heating have not been treated in [1], and that problem remains open. In the present report, a possibility of heating the heavy sloshing ion component on the second ion cyclotron harmonic is examined.

The second harmonic heating in mirrors is explained and reviewed. A new coordinate-independent form of the second harmonic term in the plasma dielectric response is derived. The second harmonic heating in the WKB limit is addressed and compared with minority heating. A newly developed three-dimensional model for the time-harmonic boundary problem for Maxwell's equations is developed. For the radio-frequency heating, a sectioned strap antenna is used. Computations show that it has low antenna Q and operates in the regime of global resonance overlapping. Only a small portion of the wave energy transits through the cyclotron layer and penetrates to the central part of the trap. The power deposition is peaked at the plasma core. Calculations show that this scenario is prospective for a practical implementation in reactor-scale mirror devices.

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20R06

Full-Wave Maxwell Simulations for Electron Cyclotron Resonance Heating

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The standard method studying electron cyclotron resonance heating (ECRH) in magnetically confined plasmas is ray-tracing method based on the geometrical optics. This method describes wave absorption due to wave-particle resonances, however, cannot take into account wave diffraction, wave tunneling across the wave-evanescent region between cutoff and resonance, and also mode conversion (or, cross polarization scattering process).

In this article, we study full-wave Maxwell simulations for the fundamental ECRH of magnetically confined plasmas. We here solve numerically Maxwell equations for electromagnetic wave fields ($\boldsymbol{E}$, $\boldsymbol{B}$) and the equation of motion for an induced electron current $\boldsymbol{J}$ with the use of a finite difference and time domain (FDTD) method. These basic equations can describe O and X (or, R and L) modes under the approximations of infinite ion mass and cold plasma. We note that our numerical scheme can take into account wave diffraction, wave tunneling across the wave-evanescent region between cutoff and resonance, and also mode conversion, since it solves full Maxwell equations directly. The wave absorption mechanism in our scheme can be taken into account as follows: The collisional damping of electromagnetic waves can be introduced by adding $-\nu\boldsymbol{J}$ term to the equation of motion for the induced electron current $\boldsymbol{J}$, on the other hand, the wave dissipations due to wave-particle resonances such as cyclotron and Landau resonances can be introduced by adding $-\vec{\sigma}_R \cdot \boldsymbol{E}$ term to the Ampere's equation. The conductivity tensor $\vec{\sigma}_R$ being introduced artificially is determined so that our basic equations can reproduce the local dispersion relation of electromagnetic waves with wave-particle resonances in the limit of $k_\perp \to 0$, where $k_\perp$ is the wavenumber perpendicular to a magnetic field.

We perform the full-wave Maxwell simulations for fundamental ECRH in a simple magnetic beach configuration, and show the numerical results on the power absorption in ECRH and also the wave tunneling across a wave-evanescent region between cutoff and resonance. We find that the power absorption estimation in ECRH by our full-wave Maxwell simulation is consistent with the ray-tracing method, and also that our simulation code can be applied to a wider range of plasma than the ray-tracing method.

20R07

ECH and HHFW start-up experiments on the TST-2 spherical tokamak

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One of the key issues for a spherical tokamak (ST) research is to develop a method to start-up plasma current and to form an ST configuration without using central Ohmic coils. Various scenarios have been studied on STs. RF start-up is a method to inject high power RF wave to a configuration with a toroidal field and a weak vertical field. It is believed that RF plasma production and resultant pressure driven current in open field line region play key roles to produce a closed flux surface. In this case, RF power deposition, pressure driven current and magnetic configuration are coupled each other, and the situation is quite complicated.

Experiments on TST-2@K (TST-2 at Kyushu University) demonstrated steady state discharges with a plasma current of 4 kA using high power RF (i.e. ECH) sources (8.2 GHz/~100 kW) [1]. TST-2 has been moved to the new Kashiwa Campus, and plasma start-up experiments using a low power ECH source (2.45GHz/4kW) and a high power high harmonic fast wave (HHFW) source (21MHz/~50kW) have started recently. ECH is strongly absorbed at the EC harmonics, thus the deposition profile depends strongly on the toroidal field. HHFW, on the other hand, is expected to show strong beta dependence and to have broader deposition profile. Therefore, the effects on plasma, such as current production efficiency, resultant magnetic configuration are probably different.

TST-2 is a spherical tokamak device with the following typical parameters [2]: major radius $R < 0.38$ m, minor radius $a < 0.25$ m, aspect ratio $A=R/a > 1.5$, toroidal magnetic field $B_t < 0.3$ T, plasma current $I_p < 140$ kA.

ECH wave (with a net power of 3 kW) was injected from an outboard lower port (z=-0.25 m) to the vacuum field which has steady toroidal and vertical fields. Wave polarization is that of ordinary mode. Plasma currents up to about 0.3 kA were obtained. The current increases with the decrease in the toroidal field as long as the fundamental resonance layer exists inside the vacuum vessel. The vertical field with positive index is necessary to produce the plasma current. The obtained density is around the cutoff density for 2.45 GHz, and it tends to stay at the value even if the toroidal field, ECH power, vertical field strength and resultant plasma current change. It can be interpreted as that the EC wave cannot access the higher density region due to the cutoff.

HHFW is injected to the ECH plasma, and the plasma current increased by up to 0.5 kA. At the same time, the electron density increased slightly and radiation increased largely. At the injection power of 50 kW, abrupt increase in radiation and decrease in plasma current were found and the reflected power measured at the RF transmission line decreases below the detection level. These results suggest strong RF wave absorption in front of the antenna, impurity contamination and cooling of the plasma. When we turn off ECH power during HHFW injection, plasma current disappears and we cannot sustain the plasma current. Without ECH, HHFW cannot produce the plasma.

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Direct Energy Conversion Experiment on the GAMMA 10 Tandem Mirror

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It has long been recognized that direct energy conversion combined with magnetic fusion is one of the most attractive power plants because of its high efficiency of power production. Several types of plasma direct energy converters were proposed or actually tested in connection to linear fusion devices such as a simple mirror, a field reversed configuration (FRC), and so on. Momota et al. [1] considered a direct energy converter (DEC) using a cusp magnetic field, in which electrons and thermal ions from the FRC reactor are deflected and separated consecutively in the two-stage cusp magnetic field, and ions are led to Venetian-blind type electrodes at the line cusp of the second cusp to produce DC power. This type of DEC, called a cusp DEC, has been studied using simulations and small-scale experiments. The Kobe cusp DEC device, with improvements over the original configuration such as employment of a slanted cusp field for better capability of charge separation, has demonstrated the basic characteristics of discrimination of electrons and ions of low energies in the cusp magnetic field and deceleration and collection of ions separated from electrons.

We now apply the Kobe cusp DEC device to GAMMA 10 tandem mirror, one of the major fusion experimental devices, in order to investigate the capability of discrimination of charged particles as well as to demonstrate energy conversion from ions in much more reactor-relevant environment. The cusp DEC device consists of a guide field section, a cusp field section, electron collectors at the line cusp side, and ion collectors at the point cusp end. The device is capable of changing the curvature of the magnetic fields from normal to slanted cusp fields.

The end loss flux from GAMMA 10 is introduced into the cusp field through the guide field and V-I characteristics of each collector are measured. The energy ranges of the end loss flux are up to 1 keV for electrons and a few keV for ions. We define the transmission ratio of the particles as the ratio of the flux at the point cusp end with the cusp field to that without the cusp field. As the magnetic field is changed from diverging type to normal cusp type, and then to the slant cusp type, the transmission ratio of electrons decreases down to 0.1. The electron flux that does not reach to the point cusp end appears at the line cusp side. The transmission ratio of ions does not depend much on the slant of the cusp field. The separation of electrons and ions with energies of the order of keV is thus achieved by using the slanted cusp field for the first time. The separated ions are decelerated by the electric field in front of the ion collectors and flow into an external load resistor at a high potential. The V-I characteristics are measured and the energy conversion efficiency is obtained for cases with different values of ion energies.

This work is partly carried out under the bilateral collaboration research of Plasma Research Center, Univ. Tsukuba, National Institute for Fusion Science, and Kobe University.

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Effects of non-axisymmetric magnetic field on characteristics of axisymmetric cusp DEC*

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We studied the effects of non-axisymmetric magnetic field on characteristics of a direct energy converter (DEC) with an axisymmetric cusp configuration. The main tasks of the double cusp DEC are separation of electrons from ions and energy discrimination between thermal ions and high-energy ions such as fusion protons with 15 MeV in D-^{3}He fusion. Electrons are separated from ions to a first line cusp and a second cusp takes a role of energy discrimination between thermal ions and high-energy fusion products. To investigate the performance of separation of electrons and ions, the Kobe-Cusp DEC, which has a single cusp configuration, is installed at the end of the GAMMA10 mirror device. At the conversion region the magnetic field of the GAMMA10 is weak compared to that of the Kobe-Cusp DEC, but it breaks the axisymmetry of the DEC.

One of the indices for the separation of ions from electrons is Störmer potential, which indicates an accessible region of the charged particles. In this study oblique and uniform magnetic field is applied to the axisymmetric slanted single cusp configuration. The first order perturbed Hamiltonian H_1 at the position (r, θ, z) is

$$H_1 = q_j B_1 [P_{q0} - q_j Y(r,z)](r^2 \cos a \cos^2 q - r z \sin a \cos q) / m_j r^2 ,$$

here m_j and q_j are the mass and charge of the j-th species, respectively. The perturbation field is expressed by B_1 and α, which are magnitude and oblique angle of the uniform magnetic field, respectively. The unperturbed canonical angular momentum is indicated by $P_{\theta 0}$, which is one of the constants of motion in the axisymmetric system and Y is the flux function of the slanted cusp magnetic field. In Fig.1 the perturbed Hamiltonian of ions at the stagnation point of the Störmer potential is shown for the case of $\alpha = \theta = 0$ and $B_1 / (m_0 I_{c1} / p R_{c1}) = 0.01$: I_{c1} and R_{c1} are the coil current and the radius of the inlet cusp coil. The stagnation point of the Störmer potential gives classification between trapped charged particles in a line cusp region and those which are passed through a single cusp field to a point cusp region. The perturbed Hamiltonian changes its sign around 0.5 of the normalized canonical angular momentum. The ions with larger momentum than this momentum are separated to the point cusp due to the perturbation field. The detail characteristics of the charge separation in the cusp DEC are discussed.

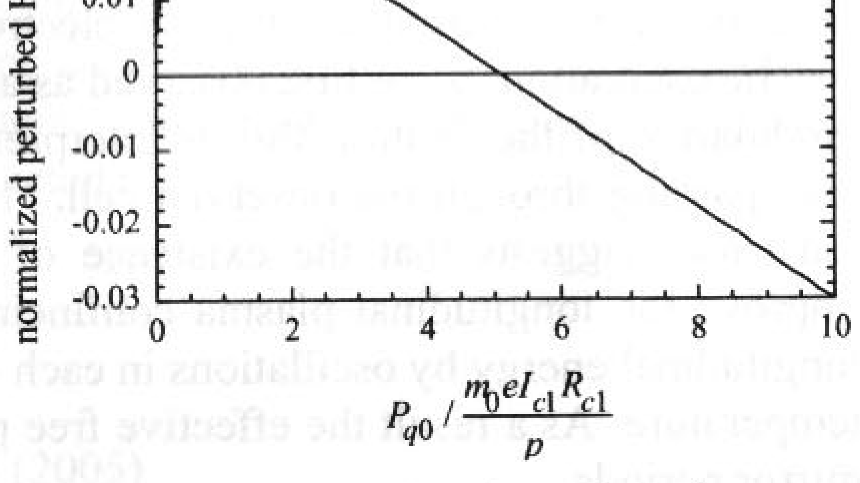

Fig.1 Perturbed Hamiltonian at the point of the stagnation of the Störmer potential.

* This study is carried out under the bilateral collaboration research between Plasma Research Center, Univ. Tsukuba, National Institute for Fusion Science, and Kobe University.

20R10

Bounce instability in a multi-mirror trap

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It is well known that there are no electrostatic plasma oscillations with phase velocities of the order of the ion thermal velocity if the electrons are colder than the ions. This is true at least in a uniform plasma and if the distribution function is close to the equilibrium. However, such oscillations are observed and possibly are crucially important for confinement in the multi-mirror trap GOL-3. Its plasma is neither uniform nor close to the equilibrium, but still it is necessary to find why and how such oscillations exist. They persist for a long time during the quasi-stationary stage of plasma decay [1]. Modes are localized to individual sub-traps, so that oscillations in the neighboring cells differ in phase, frequency and amplitude. The value and scaling of the frequency corresponds to the typical (thermal) bounce frequency of ions, while the electron component is 3-10 times colder than ions. Excitation of oscillations with phase velocity in the range of the ion thermal velocity suggests that they can effectively scatter outflowing ions, thus increasing the longitudinal lifetime. In other words, this turbulence is very favorable for longitudinal confinement and without significant influence on the radial transport.

In this report we present theoretical analysis of possible electrostatic oscillations near the ion bounce frequency in an axisymmetric multi-mirror trap. Collisionless kinetic equation is solved for ions. The quasi-neutrality condition along with the Boltzmann distribution for electrons leads to the integral equation for the distribution of the electrostatic potential along the field line. Trapped and passing ions are treated separately. Landau damping on electrons is estimated to be relatively small due to specific distribution of the equilibrium electrostatic potential: if the density of passing ions is small, the ion density in the bottlenecks decreases and they are thus charged negatively. As a result, the lowest-energy electrons are electrostatically trapped with a significant bounce frequency. If it exceeds the wave frequency the resonant electrons are few and exist only close to the separatrix.

Analysis shows that unstable oscillations confined to a single sub-trap are possible if the distribution function for ions is significantly overpopulated in the region of weakly trapped particles or if the flow of passing ions across the sub-trap is locally supersonic. Both cases are consistent with experimental data. Indeed, the current interpretation of the ion-heating mechanism (as a result of shock-waves collisions) suggests that the hot ions are born with high longitudinal velocities. Also, the oscillations are observed in cells with high flows and are abcent in cells with highest pressures (without flows). The natural limit of nonlinear saturation for such oscillations is the electron temperature.

The oscillations were first observed as a feature of the neutron flux signal. In our model the modulation of the neutron flux is interpreted as a result of the modulation of density of hot ions passing through the observed cell. Modulation of the longitudinal velocity of passing ions also suggests that the existence of non-correlated oscillations in different cells can improve the longitudinal plasma confinement. Indeed, the passing ions will be scattered in longitudinal energy by oscillations in each cell. The change will be of the order of the electron temperature. As a result the effective free path of ions along the trap will be reduced to a few mirror periods.

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20R11

Study of the Effects of Plasma-Confining Potentials Using End-Loss Analysing Systems

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Recently, the remarkable effects of radially produced shear of electric fields E_r on the suppression of turbulence-like fluctuations are found in the end-loss currents flowing from the central cell along with the central soft x-ray brightness.[1-3] The effects are observed in the form of remarkably different fluctuation levels and Fourier spectrum shapes in relation to the formation and disappearance of the vortex-like structures in the cases without and with E_r shears, respectively. To understand the common physics bases for such E_r shear confinement improvements, a remarkable characteristic advantage of open-ended mirror devices is employed by the use of the ease of control of a radial potential profile due to locally heated electron axial flow from a plug ECH applied region[4,5] into an end region along lines of magnetic force.

Furthermore, a transverse energy-transport barrier is produced by off-axis ECH in a barrier mirror for the first time, with the formation of a cylindrical layer having energetic electrons flowing through the whole device. This experiment denotes a formation of a strong shear of radial electric fields E_r, and suppression of intermittent turbulent vortex-like structures near the layer in the central cell with a transverse energy-transport improvement.

From this point of view, observations of the end-loss-ions and -electrons play various important roles in the studies of plasma parameters including ion and electron currents, ion temperatures, plasma potentials, effects of radially sheared electric-field formation, and plasma-confinement improvements. For the purpose of observations of these important parameters in tandem mirror plasma, we have been developing several types of multigridded electrostatic ion-energy spectrometers[6-8] because of their compact-sized simple structures and convenient handling without providing their effects on the plasma-confining magnetic fields of the GAMMA 10 device. In addition, the fabrication of various wide-ion-energy-sensitive semiconductor detectors is made under the extension of our recently proposed semiconductor-response theory for x-ray diagnostics. In this presentation, we give the structures of end-loss analysing system, and experimental results with and without the energetic-electron layer using our constructed systems.

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New results in the theory of multiple mirror plasma confinement

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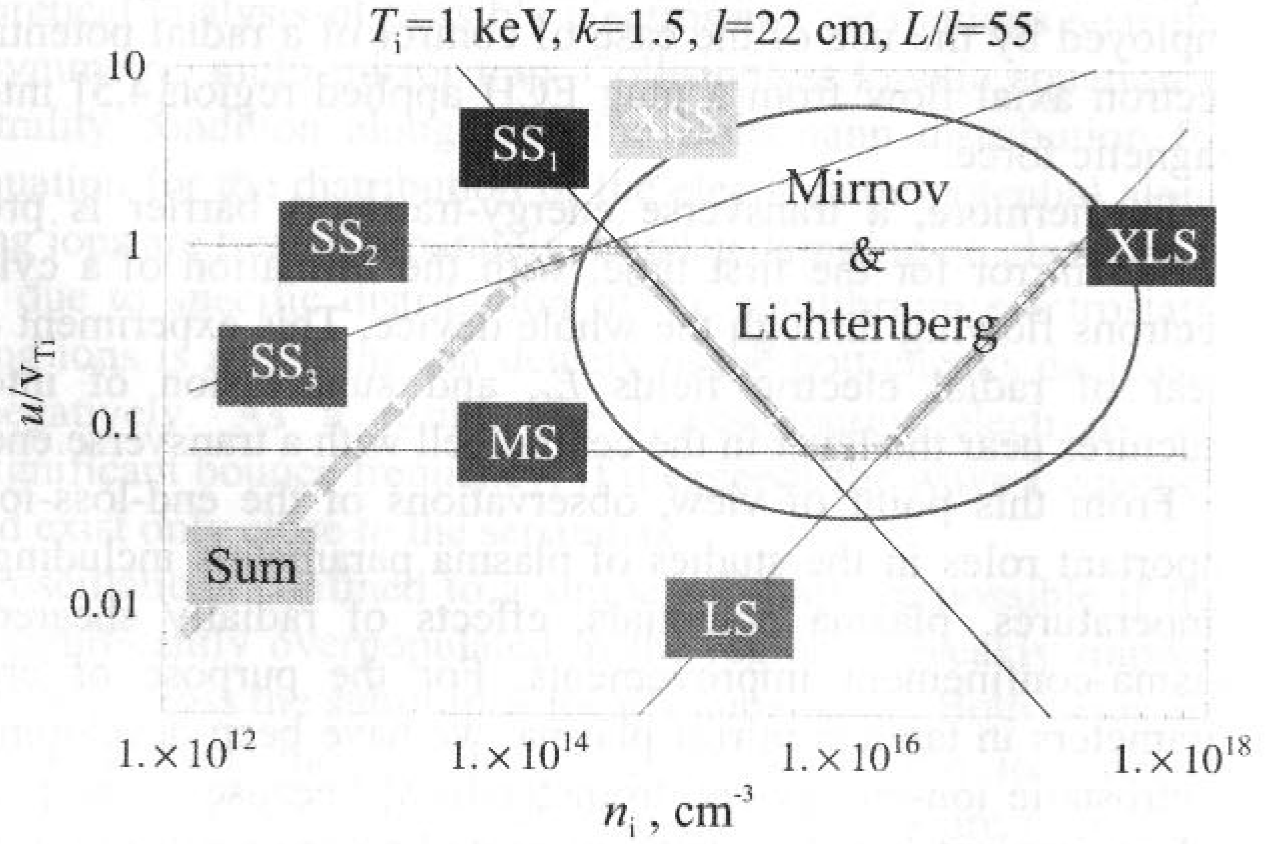
As it is long known, a dramatic improvement of longitudinal confinement in open systems can be obtained with a corrugated magnetic field. Following Mirnov and Lichtenberg [1], traditional theory distinguishes feasible regimes of multiple mirror confinement giving estimations of the plasma expansion velocity u (or confinement time $\tau=L/u$) as a function of mean free path λ, individual mirror cell length l, total device length L and the mirror ratio k. Main regimes are classified first by the ratio λ/l, designating $\lambda>l$ as the regime of Small Scale (SS) corrugation and $\lambda<l$ as the regime of Large Scale (LS) corrugation. Secondarily, $k-1>1$ is designated as the regime of Strong Corrugation (SC) and $k-1<1$ as the regime of Weak Corrugation (WC). Thus, the condition $l>\lambda$ together with $k-1>1$ characterizes the regime of Small Scale Weak Corrugation (SSWC); other main regimes are LSWC, SSSC and LSSC.

In exploring these regimes Mirnov and Lichtenberg have found some sub-regimes for which explicit calculations can be made. However existing theory misses some regimes of interest, as shown in the figure, where the range of plasma density covered by Ref. [1] for GOL-3 multitple mirror at Budker institute is encircled. In this report, it is shown that for a given mirror ratio k there can exist up to 7 distinct scalings $\tau(\lambda)$, every of which corresponds to a distinct dependency of τ on n provided that classical law $\lambda=1/\sigma n$ holds, with σ being independent on plasma density n. Few of these regimes were not theoretically studied earlier though they are observed experimentally. This report fills up white spots in the theory at a level of simple estimations. More accurate theory would actually represent purely academic exercise since even rough estimations by an order of magnitude reveal that longitudinal losses from GOL-3 device are suppressed by almost two orders of magnitude as compared with the predictions of the theory, if the cross section σ of ion scattering is evaluated from classical theory of Coulomb collisions. This conclision suggests that plasma turbulence of unspecified nature survives after termination of a relativistic electron beam injection, which is known to excite Langmuir turbulence at the stage of beam injection [2, 3].



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Comparison of a deuterium - helium-3 FRC and Mirror Trap for Plasma Confinement

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Power balance of deuterium - helium-3 (D-^3He) plasma in a FRC power plant is shown. Results were compared with the power balance for a central cell of D-^3He tandem mirror reactor. Calculations are made with taking into account selective ion (protons and α-particles) pumping. Obviously, that FRC with ash pumping system will provide more best power and economic parameters.

Direct energy conversion systems for different types of fusion and fission reactors are compared. Societal and technical problems of thermonuclear energy including proliferation and raidoactive hazard are considered. Energy in the helium-3 on the Moon and isotop-geochemical investigation of deep rock of the hydrocarbon in the Niigata basin are discussed. Near and long terms of D-^{3}He applications such as small electrical power plants, hydrogen production are presented.

To show the advantage of low radioactive fuel the comparison of D-^3He and D-T systems (tokamaks and their main opponents) is summarized.

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Recent FRC Plasma Studies

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The field reversed configuration (FRC) plasma [1] has a toroidal geometry even if it is sustained in a simple linear solenoidal field. In addition, it has extremely high beta value of 1 at its magnetic axis. These features are desirable for a reactor because higher pressure plasma can be contained in a simple geometry with smaller confining field than in low beta systems. There are two different strategies to approach FRC based reactor; one is a high density pulsed system[2] and the other is a continuous system. For the latter case, neutral beam injection (NBI) experiment[3] and wave excitation experiment[4] are conducted to study preliminary aspects of these methods to sustain the FRC. The experiments to drive and sustain toroidal current by azimuthally rotating transversal magnetic field (RMF)[5] belongs to this latter category. As for the RMF current drive, there are proposals to sustain the plasmas continuously with the help of the NBI[6] or the counter rotating RMF[7]. Possibility of sustaining the FRC by high energy ions is discussed anticipating that they have good confinement property[8]. As for the wave heating of the FRC plasma, because of the fact that the electron plasma frequency ω_{pe} is by far larger than the electron gyro frequency ω_{ce} even in the peripheral region, for the wave with $\omega_{ci} < \omega < \omega_{ce}$, there is a cut off zone and therefore, low frequency wave is chosen to introduce the wave deep in the plasma. Actually, it is already reported in basic plasma experiments[9] that a compressional magnetic oscillation excited by an external antenna is mode converted to the shear Alfven wave, which propagates along magnetic lines of force. In the experiments, the plasma has a spatial (radial) profile and the behavior of the wave is influenced through the change of the Alfven velocity. In the FRC plasma, not only the density but also the magnetic field strength has strong spatial variation, it decreases from outside toward the magnetic axis. For the low frequency wave, ω_{ci} is larger than ω outside the plasma. But inside the plasma, ω_{ci} decreases gradually and eventually, it becomes smaller than ω. Shear Alfven wave is not accessible to such region. However in our experiment on the FRC Injection Experiment (FIX) apparatus, finite-amplitude shear wave is observed. Kinetically modified shear Alfven wave[10] may be responsible for this observation, which is desirable for the heating of the FRC plasma.

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Abstract for os2006

Research Plans for Low-Aspect Ratio Reversed Field Pinch (RFP)

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In recent years, reversed field pinch (RFP) research has shown great progress that has changed conventional concepts and introduced new advanced regimes of RFP.

In the RFP, the high plasma current in weak toroidal magnetic field (with safety factor $q \ll 1$) and the peaked current profile easily drive tearing instabilities. The instabilities result in magnetic fluctuations, stochastic magnetic field and enhanced energy transport. The conventional RFP has been characterized by the stochastic transport.

Recently, two concepts have emerged as possible solutions to the confinement problem. The first one is to control the current density profile to realize the tearing-mode-stable profile. Using the technique of pulsed poloidal current drive (PPCD), the confinement comparable to that of a tokamak of similar size. The second one to the confinement problem is to attain to a (quasi-) single helicity ((Q)SH) RFP state, in which a large magnetic island (single mode) dominates in an otherwise stochastic field. A spontaneous transition to QSH state has been observed with improved confinement due to chaos healing within the island. MHD mode dynamics at the transition, however, is yet to be studied.

A low-aspect ratio RFP may have an advantage of simpler magnetic mode dynamics because of larger separation of mode rational surfaces in the core region, which may allow us to expect easier access to the QSH RFP state. Furthermore, it has also been pointed out that the QSH configuration may be self-sustained by the laminar dynamo mechanism, which does not accompany magnetic chaos. Those are the major motivations of studies for this configuration. Others include equilibrium and stability with and without plasma flow (including development of a means of drive of plasma flow). With the aim to explore the possibility of active control of transition to QSH state, a low aspect ratio RFP research has started at Kyoto Institute of Technology (KIT), following the STE-2 RFP with medium aspect ratio of 4.. We have used a 4-mm thick SS vacuum vessel with aspect ratio of 2 ($R/a = 0.51\ \mathrm{m}/0.25\ \mathrm{m}$) for the purpose of control of MHD mode dynamics by means of external helical field.

After reviewing the active MHD control experiments in STE-2, advantages of the low aspect ratio RFP configuration are discussed based on some recent theoretical studies. Research plans for low-aspect ratio RFP experiments will be discussed with a brief description of the new machine. Present status of the experiment will then follow.

21R01

Role of large scale structures in multiple-scale drift wave turbulence

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Fluctuations in magnetically confined plasma, like drift wave turbulence in tokamak, reveals multiple spatio-temporal scale and spectral anisotropy due to the richness of linear and nonlinear instabilities. Typically, large scale structures such as zonal flows, geodesic-acoustic modes (GAMs), streamers, low frequency long wavelength fluctuations produced by beat wave and secondary/tertiary instabilities etc. can coexists with their maternal turbulence, leading to a complex behavior in turbulent transport [1,2]. Therefore, it is necessary to know the *selection rule* of such large scale structures and/or their *energy partition law* in order to control turbulent transport. Magnetic structure such as magnetic shear and safety factor is found to be one of important key parameters in controlling the energy partition between turbulent fluctuation and that of zonal flow. It is demonstrated that the spectral anisotropy of large scale structure, e.g. whether the system prefers zonal flow or streamer, depends on the strength of magnetic shear [3], whereas the temporal characteristics of large scale structure, e.g. whether the zonal flow becomes stationary or oscillatory coupling with GAM, depends on safety factor [4]. The effect of zonal flows and GAMs on the transport near critical gradient is investigated. We found a new type of intermittent behavior influenced by GAMs in nonlinear Dimits shift regime which leads the transport to gradual quenching.

Furthermore, in a multiple-scale spatio-temporal turbulence, complicated cross-scale interactions are exhibited. While short wavelength ETG-driven zonal flow can interplay with ITG fluctuation through non-local mode coupling, leading to an intermittent critical dynamics [5], meso-scale ITG-driven zonal flow acts on ETG turbulence as a low frequency mean shear flow through different channels. Through a complex analysis of modulational process, it is demonstrated that the mean shear flow may reduce the generation of ETG-driven zonal flow [6]

We also investigated various statistical quantities from the data of our gyro-fluid simulation such as fractal dimension, probability distribution function (PDF), cross coherence etc. It is found that a significant reduction of dimensionality is observed in plasmas dominated by zonal flows, suggesting that the transport is regulated rather by coherent process in contest to the idea of random scattering of turbulent vortices into micro-scale structures.

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21R02

On MHD stability, ellipticity, omnigenuity, constants of motions and a modified thermal barrier of a Straight Field Line Mirror

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The straight field line mirror field [1] is the unique field which gives the lowest ellipticity of the flux tube of an MHD stable minimum B mirror field. In this particular vacuum field, each gyro center bounces back and forth on a single magnetic field line, and a pair of two new constants of motion is associated with this property [2]. Using these invariants in the Vlasov equation, it can be shown that the radial drift of the particles is absent to first order in the plasma beta, and the equilibrium is omnigenous. The neoclassical increase of the radial transport can thus be avoided without an axisymmetrization of this single cell mirror.

A scheme to improve end confinement of ions, and simultaneously creating an electric potential barrier for the electrons, has briefly been analyzed in [3]. The scheme involves plugging of the end loss by a production of sloshing ions by ICRH (ion cyclotron resonance heating). A more detailed numerical study on production of sloshing ion by an RF technique has been carried out in [4], showing a strong absorption of the RF field near the fundamental gyro frequency resonance of the minority deuterium ions. Similar results for the second harmonic heating of tritium ions are also obtained more recently. The scenario in [3] indicates a theoretical possibility to achieve a high Q factor (energy gain factor) in this single cell mirror field with the proposed modified thermal barrier.

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21R03

Investigation of Electron Distribution Functions in the Plug Region of the GAMMA 10 Tandem Mirror

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In GAMMA 10 [1-3] electron cyclotron heating (ECH) is utilized for the formation of a thermal-barrier potential ϕ_b, as well as of an ion-confining potential ϕ_c in the plug region. The enhancement of ϕ_c is theoretically predicted with increasing ϕ_b because of the efficient heating of localized plug electrons. The theoretical scaling of ϕ_c vs ϕ_b has been described in terms of Cohen's weak ECH and strong ECH theory. [4,5] The scaling law of the potentials is one of the most important and critical issues for the future development and the design of tandem mirrors. [1-3]

One of the most essential and direct methods to study the bases of these scaling theories is to observe the plug electron distribution function f_{ep}, since an essential difference of the strong ECH theory from the weak one is whether the characteristic time of plug electron heating by ECH for a plateau distribution formation dominates over the collisions for a Maxwellian formation.

The main tandem mirror operations in GAMMA 10 have been characterized in terms of (i) a high potential mode having kV order plasma confining potentials, and (ii) a hot ion mode having bulk-ion temperatures of several keV. Energy spectra, from x-ray pulse height analyses (PHA) are investigated in these representative operational modes so as to interpret the electron-velocity-distribution functions as well as the formation mechanism of plasma-confining potentials.

X-ray diagnostic systems are as follows. In the plug region, energy spectra using x-ray PHA systems are measured with a Si(Li) detector and Ge detectors. In particular, an ultra-low-energy-sensitive pure-Ge (ULE Ge) detector is employed for the observation of x-ray spectra down to a few hundred eV in the hot ion mode. The detection efficiency of the ULE Ge detector is studied by using synchrotron radiation. An x-ray tomography system using micro-channel plates (MCP) is utilized in order to obtain total x-ray emissivity from the plug electrons bounded by electron-confining potential as a function of the x-ray absorber thickness. [6-8]

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21R04

Upgrade program of ECRH system for GAMMA10

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An ECRH is a key tool to get high ion confining potential and high electron temperature in tandem-mirror devices. Power upgrade of the ECRH systems for the plug and central sections in GAMMA 10 tandem- mirror has been successfully conducted. Power per one plug/central section has increased from 200 kW to 400 ~ 500kW with a new high power gyrotron at 28 GHz frequency. Injection mirror antennas have also been improved to get efficient transmission to the resonance surface. New record of the ion confining potential more than 3kV has been achieved by use of the new upgraded ECRH system.

The GAMMA 10 is a tandem-mirror device and axisymmetric mirror cells in both ends play important role to improve axial confinement of both ions and electrons through the formation of thermal barrier for electrons and plug potential for ions. The ECRH power is a key tool to produce these confining potential in these plug/barrier in mirror cells. In last 20 years, ECRH power source of the GAMMA 10 was 200 kW gyrotrons at 28 GHz and the ECRH power produced 0.7 kV ion confining, in maximum. The combined theory of the Pastukhov and Cohen which was proposed by T. Cho, et al. [1] was verified in the power region of 200kW. It predicts power scaling of the ion confining potential and further higher potential formation would be expected corresponding to the plug ECRH power upgrade. New high power gyrotron of 500kW at 28GHz has been developed to verify this scaling. $TE_{4,2}$ mode is selected to reduce wall ohmic loss and beam current density for the new gyrotron. The design details and performance of the new gyrotron are presented in another paper[2]. The output mode is Gaussian like mode using quasi-optical mode converter, which couples efficiently to $HE_{1,1}$ mode transmission line. Parabolic mirror was designed to make transmission efficiency high and power profile at resonance surface axisymmetric in both plug and central antennas using newly developed code[3]. Using these new high power gyrotron and efficient antenna, high power ECRH experiment is going on. Gyrotrons of 500kW level are installed into the GAMMA10 ECRH system, two for plug and one for central. More than 400 kW power was injected into the one plug region and the maximum ion confining potential of 3kV was obtained, which is four times higher than the previous value before the upgrade. As for the central ECRH, the new antenna was tested before installing the new gyrotron and remarkable electron heating from tens eV to hundreds eV was obtained. An upgrade of the central ECRH system is being made, with the DC power supply of JFT-2M ECRH system. The output power test of this upgraded central system with the 500kW level gyrotron was conducted and more than 400 kW power at MOU (Mirror Optics Unit) was successfully obtained. The combination of this gyrotron, new antenna, and transmission line system will be experimented in the next campaign aiming to high central electron temperature which reduces electron cooling of high energy ions and hence improves the ion confinement of the tandem mirror.

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21R05

High Power and High Efficiency Operation of 170GHz Gyrotron

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Plasma heating by high power millimeter waves are very attractive for magnetic fusion devices such as Tokamak, helical and open system. The ITER requires a 170 GHz high-power gyrotron system with a total power of 24 MW, for electron cyclotron heating (ECH), current drive (ECCD) and suppression of plasma instabilities. Intensive development of a 170 GHz gyrotron (1 MW, CW operation and 50% efficiency) is under way in JAEA (Japan Atomic Energy Agency). A gyrotron is a microwave tube that utilizes electron-cyclotron resonance maser effect and weakly relativistic electron beam (<100kV) with gyro-motion in magnetic field. The rotating electron beam is generated at a magnetron injection gun (MIG) and 170GHz millimeter waves with $TE_{31,8}$ mode oscillate in a cylindrical cavity with the magnetic field of ~6.7T. The power is delivered as the Gaussian beam through an artificial diamond window. Up to now, the gyrotron has demonstrated 1MW-10s level operation and quasi-steady state operation of 1000 s with the output power of 0.2 MW by beam current control and high power cavity technology.

Recently, further improvement for high power and high efficiency operation has been carried out. For efficiency enhancement, a mode converter and internal mirrors for Gaussian beam output were modified and energy recovery system with depressed collector was optimized. In the preliminary experiment, the mode conversion efficiency of ~98%, which agrees well with the design value, was obtained, and 1MW-50%-0.1s operation was demonstrated. In this gyrotron, the experiment of long pulse operation with high power of 0.6~0.7 MW level and high efficiency of~50% level is under way for ITER application.

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Poster Presentations

19P01. Plasma flow measurement by Mach probes in GAMMA10,
A.Ando, H.Tobari, M.Shibata, H.Isobe, K.Hattori, M.Inutake, K.Nemoto, H.Higaki, and M.Ichimura

19P02. Influences of the Hall Effect on the Plasma Flows in a Magnetoplasmadynamic Thruster,
K.Kubota, I.Funaki, and Y.Okuno

19P03. Measurement of flow velocity of MPD Arcjet in GAMMA10,
K.Nemoto, M.Ichimura, H.Higaki, A.Ando, H.Tobari, H.Isobe, Y.Yamaguchi K.Hattori, M.Inutake, M.Katano, H.Muro, I.Kozawa, and T.Cho

19P04. Interaction between Plasma Flow and Magnetic Field in scale model experiment of Magnetic Sail,
K.Ueno, I.Funaki, Y.Shimizu, H.Yamakawa, T.Kimura, and H.Horisawa

19P05. Numerical Simulation of Fusion Plasma Behaviors in a Magnetic Nozzle for Laser Fusion Rocket,
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19P01

Plasma flow measurement by Mach probes in GAMMA10

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Recently, plasma flow has been regognized to play an important role in magnetically confined plasma, especially in open magnetic systems. A Mach probe is a simple and costless tool for measurement of plasma flow field. Though it should not be inserted in a hot and dense plasma core region, we can obtain ion Mach number M_i , which is represented as a ratio of ion flow velocity U to ion acoustic velocity C_s, in a peripheral region and an end-cell region.

A Mach probe consists of two current-collection tips facing in different directions against plasma flow. We used an up-down type Mach probe and M_i is derived as $M_i = M_c \ln(J_{up} / J_{down})$, where J_{up} and J_{down} are ion saturation current densities measured by the tips facing upward and downward to the plasma flow, respectively. M_c is a constant depending on the plasma conditions. We have evaluated M_c by comparing the PIC results by Hutchinson [1] with experimental data using subsonic and supersonic plasma flow in HITOP device [2].

First attempts to measure plasma flow field using a Mach probe have been performed at the open-end section in GAMMA10. There observed an increase of ion temperature in the open-end section under the high ion temperature mode operated with central ion beach heating. An ion Mach number was measured by an up-down type Mach probe located at 30cm downstream of the central cell in order to investigate a relationship between central ion heating and an ion flow toward the end cell. Though the magnetic field at the measurement position is 1 T, the Mach probe is still under the unmagnetized condition because of the high ion temperature more than 100eV.

Figure 1 shows a radial profile of M_i at 30cm downstream of the central cell. The abscissa is an equivalent central cell radius. It is found that M_i at r=0 is more than 2, namely a supersonic plasma flow is formed in the end-cell region.

Experimental researches of high-power RF heating effect on the plasma flow are important not only for the confinement study but for the researches of advanced space thrusters [3], where the heating energy is converted to flow energy in a diverging magnetic nozzle. A well-organized large-scale linear magnetic device, GAMMA10, with a number of useful diagnostics and high-power RF systems is one of the most promising devices suitable for these researches. Investigation of the high-power ICRF heating effect on the plasma flow toward the end cell should be pursured further.

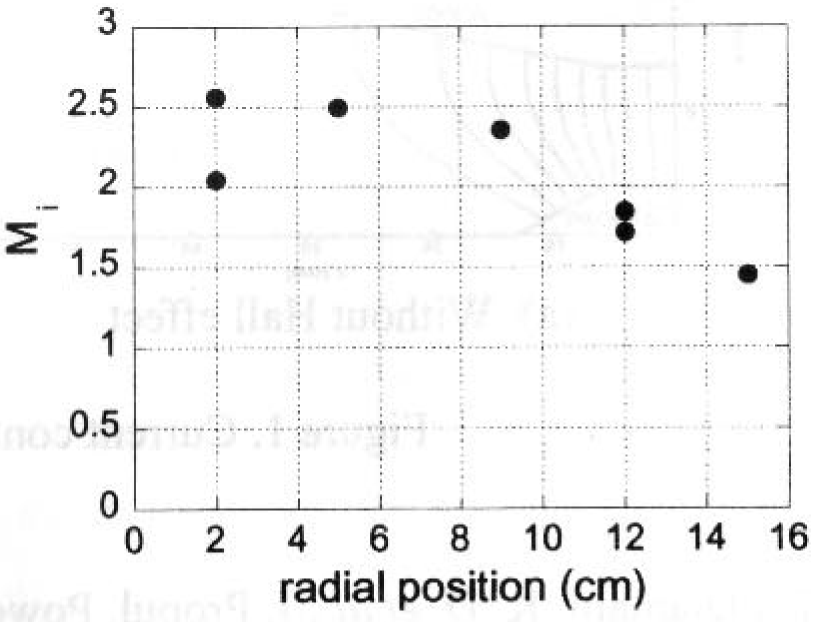

Fig.1 Radial profile of an ion Mach number M_i at end-mirror cell in Gamma 10. (an equivalent center cell radius)

[1] I. H. Hutchinson, Plasma Phys. Control. Fusion **44**, (2002) 1953.
[2] A.Ando, et.al., J. Plasma Fusion Res. **81** (2005) 451 ; Contributions to Plasma Physics, **46** (2006) 335.
[3] F.R.ChangDíaz, Scientific American,. **283** (2000) 90.

19P02

Influences of the Hall Effect on the Plasma Flows in a Magnetoplasmadynamic Thruster

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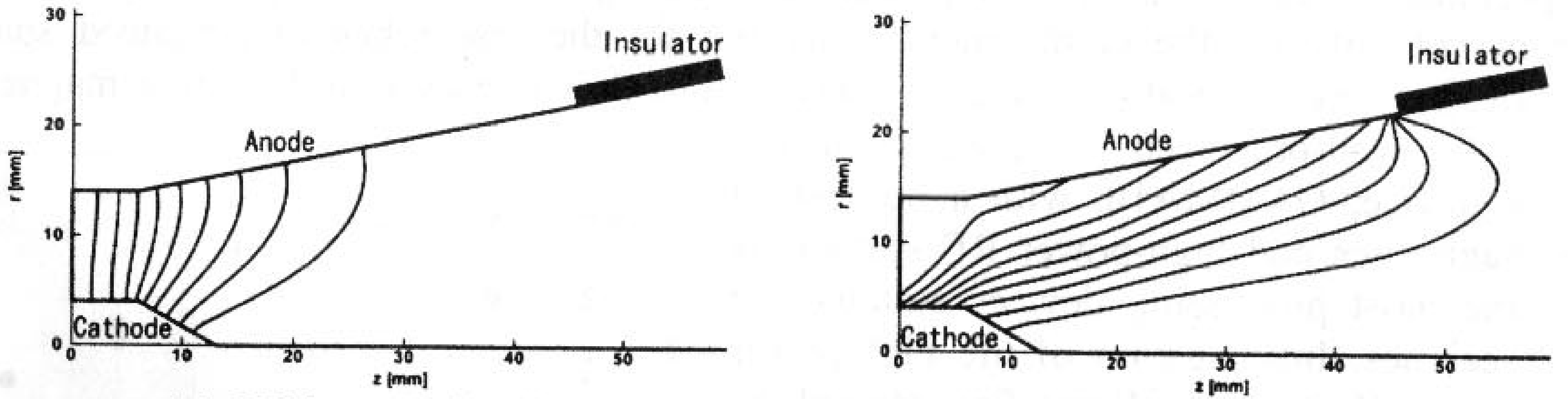
The Magnetoplasmadynamic(MPD) thruster is a candidate for the electric propulsion device available for the missions calling for high-power thruster. It is considered that the Hall effect closely relates with the anode power deposition, which corresponds to the main energy loss[1,2]. In this study, the influence of the Hall effect on the plasma flows is examined with numerical simulations in a self-field MPD thruster with a short cathode and a flared anode. We compared the results taking account of the Hall effect with those ignoring the effect. Argon is used as the propellant, and the mass flow rate and the total discharge current are set to 0.8 g/s and 5 kA respectively in both cases.

The results without and with the Hall effect are described in Figs. 1(a) and 1(b). In the case without the Hall effect, almost all the currents flow in the upstream area ($z \lesssim 30$ mm), and the contour lines are almost perpendicular to the electrodes. On the other hand, in the case with the Hall effect, the distribution of the currents extends over the thruster. The currents on the anode surface approach the edge of the anode, and then flow into the cathode obliquely. On the cathode surface, the currents concentrate on the side of the cathode ($z \leqq 6$ mm).

These difference of the current distribution lead to the change of the axial velocity and the ionization fraction distributions. The maximum axial velocity obtained around the symmetric axis near the outlet decreases when the Hall effect is taken into account. This is due to the increase in the density of heavy particles around the symmetric axis caused by the growth in the radial Lorentz force. This leads to the increase in the thrust in the case with the Hall effect, although the maximum axial velocity decreases. In addition, the intensive ionization occurs on the side of the cathode owing to the concentration of the currents around the region.

In addition, the correspondence between the Hall effect and the potential drop is specified. The voltage drop betwwn the anode and cathode is about 20.0 V, while that of the result in the case without Hall effect is about 10.0 V. According to the radial distribution of the potential at z=1.77mm, the region with the high Hall paramter corresponds to the region with the steep potential drop.



(a) Without Hall effect (b) With Hall effect

Figure 1. Current contour lines (Ar, $\dot{m}$ =0.8 g/s, J=5 kA)

[1] Diamant, K. D. *et al.*, J. Propul. Power, **14**, No. 6 (1998) 1036-1042.

[2] Gallimore, A. D. *et al.*, J. Propul. Power, **9**, No. 3 (1993) 361-368.

19P03

Measurement of flow velocity of MPD Arcjet in GAMMA10

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In the GAMMA 10 tandem mirror, the research aiming for high-density and high-temperatаure plasma production is proceeding. For the generation of initial plasma, two of MPD Arcjet (Magneto Plasma Dynamic : MPDA) are installed on both ends. MPDA can produce quasi-stationary plasma of which duration is 1 msec. The arcjet method for particle accereration is well known to be a ejectional method of the charged particle with high efficiency. So this is applied for space propultion of artificial stellite. Discharge region of the MPDAs installed in GAMMA 10 consists of two electrodes. One is the stick of molybdic cathode of which diameter is 10mm. Another is the tungsten anode which is coaxial-cylinder shape, and the cavity radius of which diameter is 15mm. The arc-starting voltage of MPDAs around 370V and there is a proportional relationship between the arc voltage and the discharge current. On the while, the discharge current has no relation with the input gas pressure. In GAMMA 10, the main plasma is produced by ion cyclotron range of frequency (ICRF) waves in combination with the hydrogen gas injection and MPDA as the seed plasma.

In this research, the flow velocity of the initial plasma near the end mirror throat is measured by using a Mach Probe which is developed by the group of Tohoku University[1]. For the measurement of the strongly magnetized plasma flow, the Mach Probe is well known as one of the simplest and easiest diagnostic methods. The Mach Probe used in this research has two of symmetrical tungsten tips on both up and down sides. The diameter of tips is 3.0mm, and the whole size is almost 1.0cm. The Mach Probe is installed just at 0.1m from the end mirror throat and 3.1m from MPDA. The magnetic field strengths at MPDA and at the location of the Mach Probe are 0.02T and 1T, respectively.

The average flow velocity which is estimated by the time-of-flight from MPDA to the Mach Probe is around 10 km/s on the axis of GAMMA 10. The Mach number is estimated to be 0.5~1.0. The radial profile of the average flow velocity and Mach number is measured and both the flow velocity and Mach number become larger on the outer region. The interpretation of such a radial profile is discussed including the magnetic field configuration in the end region.

[1] A. Ando, Journal of Plasma Research , Vol. **81**(2005), p.451

19P04

Interaction between Plasma Flow and Magnetic Field in scale model experiment of Magnetic Sail

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Now, a lot of new propulsion systems are designed for the deep space exploration. A Magnetic sail is one of those propulsion systems utilizing natural energy "the solar wind". Previously, there are some reports about the study of the magnetic sail by numerical analyses, so we conducted an experimental simulation of a plasma flow around the magnetic sail. Until now we developed a Solar Wind Simulator using MPD arcjet consisting of $\phi 40mm$ discharge chamber (number density: $\sim 2.0\times10^{18}\,m^{-3}$, velocity: $\sim 50km/s$)and a Magnetic Sail Simulator using a solenoidal coil of 20mm in diameter (magnetic flux density at coil center: $\sim 1.8T$). In this study, we simulated the interaction between the plasma flow as the solar wind and the magnetic filed by the coil as the magnetic sail using above simulators.

Fig.1 shows an operational view of the simulator inside a vacuum chamber. High speed plasma jet, generated by the Solar Wind Simulator (SWS) attached to the wall of the vacuum, streamed from the left to the right in the photo. In the close-up view around the coil shown in Fig.2, The plasma interacted with an artificial magnetic field produced by a coil, showing a plasma flow structure like the large-scale interaction between the Geomagnetic field and the solar wind. In Fig.2 we can find two boundaries. We considered a bundary near the coil as a magnetopause and the other as a bow shock or other phenomena, which will block and decelerate the plasma flow, hence drag-force on the coil may appear.

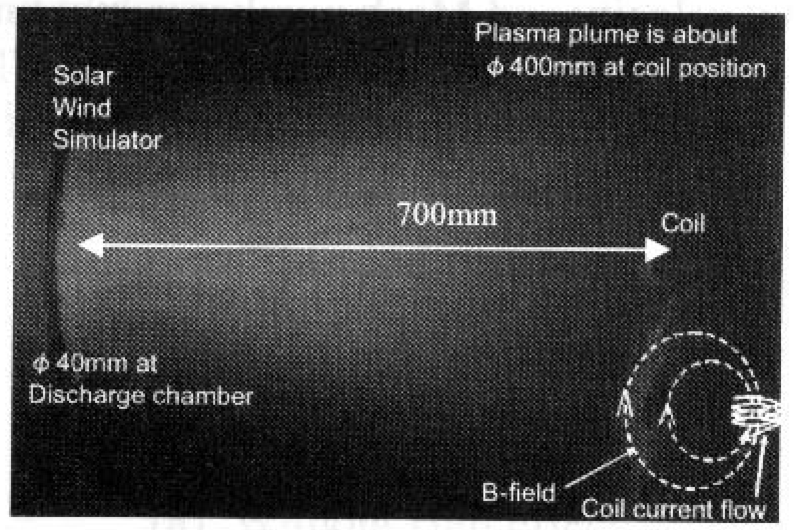

Fig.1 SWS/Magsail are in operation in vacuum chamber.

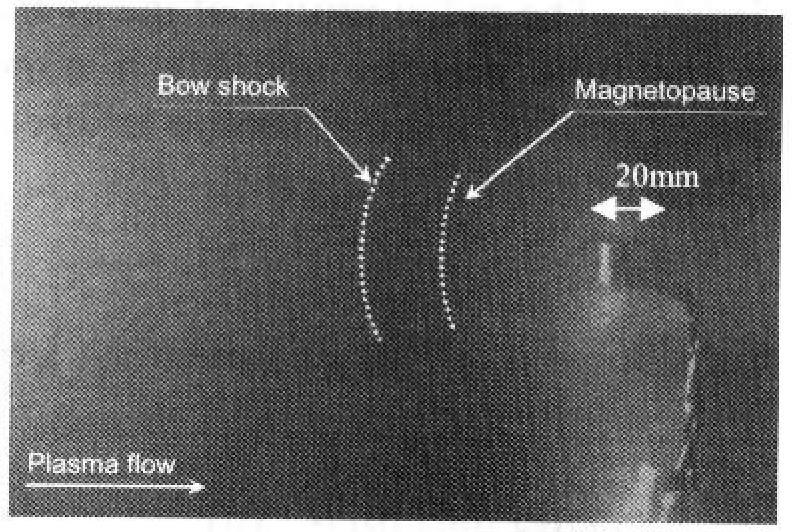

Fig.2 The interaction the plasma and the magnetic field around the coil.

(u, n and B represent plasma velocity, plasma density, and magnetic flux density at the coil center. The plasma parameters are measured by the Langmuir probes and the time of flight method.)

19P05

Numerical Simulation of Fusion Plasma Behaviors in a Magnetic Nozzle for Laser Fusion Rocket

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A Laser Fusion Rocket (LFR) has a magnetic nozzle that controls the plasma flow resulting from laser fusion by using a superconducting magnetic (SCM) coil, obtaining thrust by exhausting the plasma flow from the back of the rocket. An analysis of plasma behavior in a magnetic nozzle would be very useful for designing plasma propulsion systems using a laser fusion. We examine by using a 3-dimensional (3D) hybrid code how a thrust vector varies in several coil configuration.

In our recent simulations, Nagamine and Nakashima simulated plasma behaviors and calculated thrust efficiency for a magnetic nozzle using 3D hybrid code for one coil system, and examined how the thrust efficiency varies with certain parameters [1]. Sakaguchi et al., using the same simulation code, have investigated the behavior of fusion plasma for the two-coil system by changing the current and position of a rear coil and they have concluded that the maximum thrust efficiency is 75[%] [2]. Furthermore, we examined how a thrust vector varies with changing positions of the fusion explosion (off-axis explosion) for the one-coil system and we also examined how the thrust vector varies by tilting the rear coil in two-coil system [3].

In this paper, we assume the magnetic nozzle for one-coil system, generated by a lot of small square coils located on the ring shape, and simulate the fusion plasma in this magnetic nozzle, and examine how the thrust vector varies by changing the current of each square coil.
For two-coil system, we examine how the thrust vector varies by not tilting the rear coil but moving the rear coil to the normal direction against the axis of two coils.

Moreover, we will propose the technique that we can control the steering angle of Laser Fusion Rocket by using the locally concentrated momentum of expellant obtained from the fusion plasma.

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Y. Kajimura, R. Kawabuchi, H. Nakashima, submitted Fusion & Advanced Technology.

19P06

Development of Two Space Propulsion Systems with Helicon Plasmas*

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Two space propulsion systems, which are called DiPS (Diversified Plasma Simulator) and K2H (KBSI-KAIST-Hanyang University) device, have been developed with the concept of VASIMR (Variable Specific Impulse Magnetoplasma Rocket: JSC, NASA). K2H has three regions such as helicon source region, ion cyclotron resonance heating (ICRH) region, magnetic nozzle and expansion region. The shape of the magnetic field is open-ended mirror field, which is made of 6 magnetic coils. The magnetic field strength is 800 G at helicon plasma source and 1700 G at ICRH region. Part of the DiPS is for the space plasma simulation and it has three regions: helicon plasma source, extraction region and space simulation region. Helicon plasmas of both devices are generated by 13.56MHz rf power up to 1kW using M=+1 right-helical type antenna at pressure of several mTorr. Plasma parameters were meseared by a laser induced fluorescense (LIF) system and a fast scanning electric probe system with an rf-compensated Langmuir probe and a Mach probe at ICRH and magnetic nozzle regions, which are typically given as the following: plasma density = 10^{11} - 10^{13} cm^{-3} (K2H) and 10^{11} - 10^{13} cm^{-3} (DiPS); electron temperature = 6 - 8 eV(K2H) and 3 - 5 eV (DiPS) ; ion temperature = 0.14 - 0.17 eV(K2H) and 0.05 - 0.2 eV (DiPS); and drift velocity = 1 km/s (K2H) and 0.2 – 0.5 km/s (DiPS). A simple analysis is to be given for the profiles of plasma parameters.

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19P07

Measurement and Analysis of Magnetic Fluctuations in the HANBIT Mirror Device

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Structures of magnetic field fluctuations in the HANBIT mirror device have been measured using movable magnetic probe. The effects of the magnetic field and the RF power on the magnetic fluctuations have been studied. Electromagnetic plasma waves in low-pressure plasmas and high-pressure plasmas have been analyzed and the result indicates that sideband mode coupling is smaller in low-pressure plasmas. It is also found that the lower sideband coupling is enhanced at the resonance point, where the frequency of applied RF wave is similar to that of local ion cyclotron frequency, and a local stabilization of mantic fluctuations is observed to occur there.

Poster Presentation

19P08

Equilibrium of charged plasmas with weak axisymmetric magnetic perturbations

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The effect of weak axisymmetric distortions of the external magnetic and electric fields on the equilibrium of pure electron plasmas in a Malmberg-Penning trap is analyzed. Analytical and semi-analytical solutions for the electric potential variations induced inside the plasma column by external long-thin (paraxial) distortions are found for various radial density profiles of the plasma, including the case of global thermal equilibrium.

It is shown that a weak magnetic squeeze, $\delta B > 0$, produces an electric potential well in the bulk of the plasma column with $e\delta\varphi / T \approx -\delta B / B_0$, and that the magnetically induced potential perturbation $\delta\varphi$ changes its sign near the column edge. The fractions of magnetically and electrically trapped particles thus created are calculated explicitly for the case of a Maxwellian particle distribution function; surprisingly, these fractions do not depend on the sign of the magnetic field distortion δB.

Two-dimensional thermal equilibrium simulations for parameters relevant to the CamV device at UCSD confirm the predictions of the analytical theory for smooth and weak perturbations of the magnetic field. More generally, the simulations are used to check the limits of validity of the one-dimensional approximations used in the analytical estimates of the potential perturbations.

It is shown that the magnetically induced perturbation of the electric potential becomes independent from the plasma temperature if the plasma radius a exceeds a threshold value, $a / \lambda_D \geq \omega_c / \omega_p$. This regime is out of the feasibility range for pure electron plasmas but might be accessible for pure ion plasmas; it has not been observed yet experimentally and therefore deserves further investigation.

Finally, the analysis of the potential perturbations is extended to the case of an anisotropic distribution function, with an arbitrary ratio between the parallel temperature $T_\parallel$ and the perpendicular temperature $T_\perp$ of the plasma. Several phenomena that lead to deviations from the paraxial equilibrium are also discussed, including non-paraxial effects per se and a plasma density range close to the Brillouin limit.

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19P09

Enhancement and suppression of velocity-shear-driven drift instability due to negative ions

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Sheared plasma flows, flows of charged particles with a velocity gradient perpendicular to the flow direction, are closely related to various instabilities. Particularly in the field of space/circumterrestrial plasma physics *the sheared magnetic-field-aligned flow* has been studied to interpret fluctuations observed by radars, rockets, and satellites. For example, the ion acoustic instability predominantly observed in Earth's ionosphere is explained by the hypothesis that the field-aligned sheared flow degrades the ion Landau damping of the ion acoustic mode to render this mode more prominent than the ion cyclotron mode, which was supposed to be dominant in the previous theory [1]. This hypothesis was benchmarked by several experiments [2,3]. The shear-modified instability, however, has recently been extended to a more general case, namely, *the drift instability* comming about when a plasma has density gradient [4]. More generally, we can take into account effects of *negative ions* or dust grains on the shear-driven instability because space plasmas often contain such negatively charged, heavy particles. This fact is motivating us to perform experiments on the shear-driven drift instability in negative ion plasmas.

The experiments are carried out using the Q_T-Upgrade Machine in Tohoku University. In a plasma composed of K^+, SF_6^-, and electrons ($n \sim 10^9$ cm^{-3}, $T_e \sim T_i \sim 0.2$ eV, $\phi_s \sim -6$ V), sheared magnetic-field-aligned positive-ion (K^+) flows are generated with the combination of a concentrically segmented tungsten (W) hot plate (positive-ion source) at one end and a W disk cathode (electron source) at the opposite end of a magnetized plasma column [5].

A spontaneously excited fluctuation is observed, the amplitude of which peaks when the shear strength is small but finite. The propagation direction and speed are consistent with those of the electron diamagnetic drift and the amplitude is large around the maximum radial density gradient, which comply drift wave features. Several characteristics of the shear-modified drift instability are found to change when negative ions are introduced into the plasma. With increasing the negative ion exchange fraction, $\varepsilon = n_-/n_+$, first the amplitude increases [6], but at ε around 0.2 it peaks and then starts to decrease. For ε over 0.5 the spectral signal of the drift wave becomes invisible. This tendency is observed all over the shear strength. No shift of the shear strength that gives the maximum amplitude is seen, contradicting the linear-theoretical prediction. In addition to these results we will present other properties such as frequency spectra and wave number vectors with a theoretical description of the relevant instability.

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19P10

Fast neutral particle ionization in magnetic field by ECR for collector mirror protection in EUV light source

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Hiratsuka Research & Development Center
EUVA - Extreme Ultraviolet Lithography System Development Association

Extreme ultraviolet lithography (EUVL) at 13.5 nm is a major candidate of next generation lithography (NGL) planned to manufacture IC devices at the 32 nm node and below. The required EUV output power of 115 W for a high volume manufacturing EUV lithography tool is very high to meet industry's required throughput of more than 100 wafer/hour. In addition, the lifetime of expensive collector mirror placed close to the plasma light source has to be sufficiently long in order to minimize the operation costs of the EUV lithography system. Fast ions from laser-produced EUV plasma are significantly damage the collector mirror by sputtering the multilayer structure. We are developing ion mitigation technology based on a magnetic mirror confinement in order to extend the collector mirror lifetime. A significant decrease of the Faraday cup signal and of the QCM (quartz crystal microbalance) erosion rate were monitored with Nd:YAG laser produced Xe plasma by applying a magnetic field of 0.6 T produced by a coil pair [1].

Fast neutrals are also expected from plasma. We are examining the feasibility of fast neutrals ionization by electron cyclotron resonance (ECR) to increase the effectiveness of the magnetic field mitigation. Microwave of 14-GHz frequency was irradiated to the resonance reason with 0.5-T magnetic flux density. A Xe gas puff was used as a neutral Xe source instead of laser produced Xe plasma to simplify the analysis of the experimental result. The effectiveness of the ECR ionization was examined by monitoring the ion charge with Faraday cups and by monitoring the Xe emission spectra at visible range. The ion to excited neutral ratio was estimated from the intensity ratio between the ion emission line and the excited neutral line. About 80% of the excited Xe was ionized by the ECR ionization from this estimation.

This work was supported by the New Energy and Industrial Technology Development Organization (NEDO), Japan.

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19P11

Plasma Polarization Spectroscopy on Cusp Plasma and GAMMA10 Tandem Mirror Plasma

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Polarization of emission lines from atoms or ions in a plasma contains information on the anisotropy of the electron velocity distribution function (EVDF) [1, 2]. Plasmas produced by means of electron-cyclotron resonance (ECR) microwaves are investigated in a cusp plasma at Kyoto University and in the GAMMA10 Tandem Mirror at University of Tsukuba.

A helium plasma is produced in a cusp-configuration magnetic field. Several neutral helium lines are found polarized in the direction perpendicular to the magnetic field. The polarization degree exceeds 10% at the edge of the cusp magnetic field. The intensity and the longitudinal alignment of the emission lines yield, respectively, the population and the alignment of the upper levels. The observed population and alignment distribution at the edge of the cusp is least-square fitted by the population-alignment collisional-radiative (PACR) model with an anisotropic EVDF. The oblate EVDF is observed [3].

In the GAMMA10 Tandem Mirror device emission lines of neutral helium are observed in the plug-barrier region during the ECR discharge cleaning. Figure 1 shows an example of the polarization separated spectra. For the emission line at λ501.6 nm ($2^1S - 3^1P$), the intensity of the π component is higher than that of the σ component. Thus this line is polarized in the direction parallel to the magnetic field. The polarization degree is 15%.

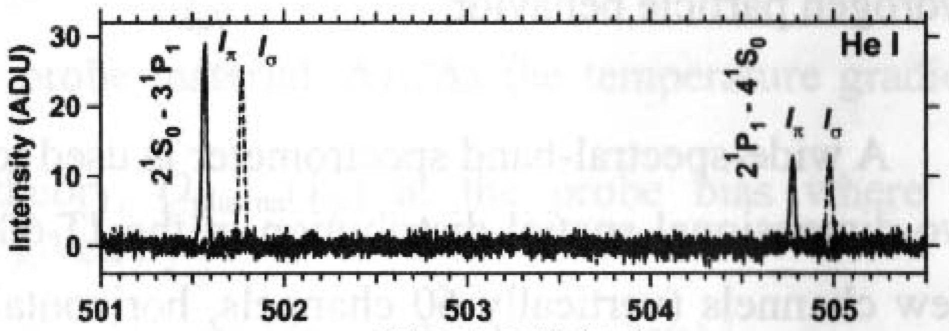

Fig. 1. Polarization separated spectra of He I lines at λ504.8 nm and λ501.6 nm observed at the plug-barrier region in GAMMA10 Tandem Mirror at ECR discharge cleaning. The σ component is displaced by 0.2 nm for easier comparison.

Figure 2 shows an example of the emission lines from C III and O II ions at the central region in the ordinary discharge. The emission lines C III λ465.15 nm ($2s3s\ {}^3S_1 - 2s3p\ {}^3P_0$) and O II λ465.08 nm ($2p^23s\ {}^4P_{1/2} - 3p\ {}^4D_{1/2}$) are unpolarized and can be used as the reference. The total angular momentum of the upper level is $J = 0$ and 1/2, respectively. Polarization degree of other lines, however, has not been determined owing to the large shot noise.

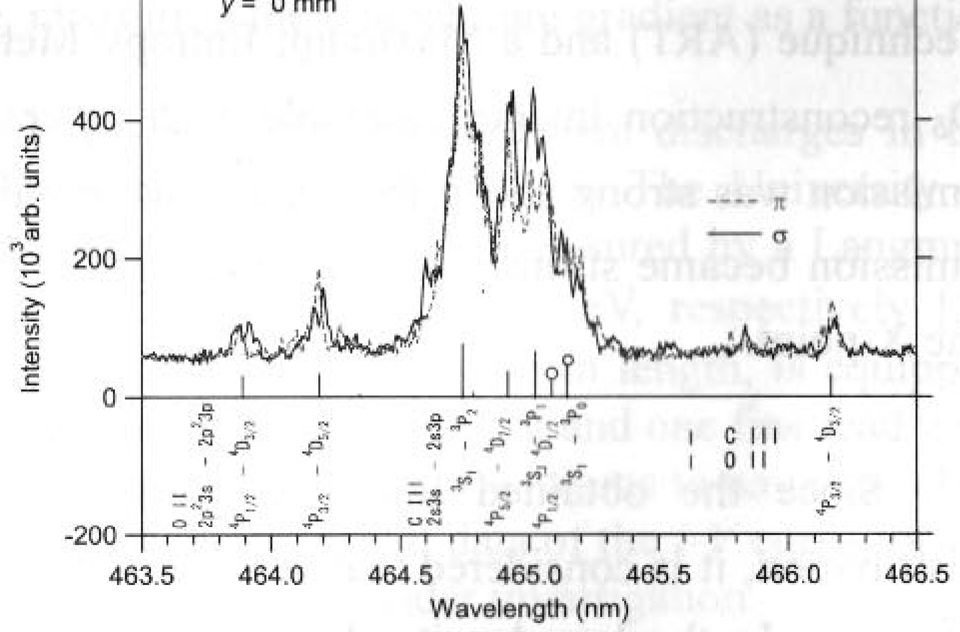

Fig. 2. Polarization separation spectra of C III and O II lines

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19P12

Two-dimensional Spectroscopic Measurement of Hydrogen Emission in JT-60U Divertor Plasmas

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In tokamak fusion reactors, heat and particle control is one of the issues mitigating the damage of plasma-facing materials. One of the most promising methods for the heat and particle control is a poloidal divertor. For a divertor plasma, the recombination process has an important role to mitigate the damage of the divertor wall. Understanding hydrogen particle (H_2, H, H^+) behavior in the divertor plasma is necessary to study the recombination plasma. Two-dimensional spectroscopic measurement of hydrogen emission is useful for study of the hydrogen particle behavior.

A wide-spectral-band spectrometer is used to observe deuterium Balmer-series lines with two-dimensional spatial distribution in the JT-60U divertor region. The spectrometer has 92 view channels (vertically 60 channels, horizontally 32 channels) with a spatial resolution of ~1cm. It covers a spectral range of 350-800nm, and it can simultaneously observe Balmer-series lines. From the measurement, we can obtain a two-dimensional distribution using a computer tomography technique.

A D_δ (n=2-5, 410.2nm) emission is reconstructed. An Algebraic Reconstruction Technique (ART) and a Maximum Entropy Method (MEM) were used for comparison. The D_δ reconstruction images resemble each other. In the low-density divertor plasma, the D_δ emission was strong above the inner strike point. In the high-density divertor plasma, the D_δ emission became strong above the inner strike point, around the outer strike point, and near the X-point.

Since the obtained line intensities from n=2-5 to n=2-10 follow the Boltzmann distribution, it is considered that the recombination plasma component is dominant on the D_δ emission. In the low-density divertor plasma, the recombination process occurs above the inner strike point. It means it is an inner-detached and outer-attached divertor plasma. On contrast, in the high-density divertor plasma, the recombination process is prominent around the inner strike point, the outer strike point, and the X-point. It means it is an inner- and an outer-detached divertor plasma.

19P13

Development of a Thermal Probe Method for Heat Flux and Ion Temperature Measurement in Divertor Simulator MAP-II

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Thermal probe method was developed by Stamate [1] and its capability of the ion temperature measurement based on the heat flow from plasma (Q_{plasma}) versus probe bias voltage (V_p) characteristic was proposed by Matsuura [2]. In order to apply this method to fusion divertor/edge plasmas, where the heat flux is considerably higher than that in laboratory plasmas, we have modified the design of the probe so that we can measure the temperature gradient along the probe tip mounted on the water-cooled heat sink. Since thermal conduction governs the heat flux in the probe under our present condition, the heat balance equation can be written as

$$Q_{\mathrm{plasma}}(V_\mathrm{p}) = -\kappa \frac{\Delta T_\mathrm{p}}{\Delta x} \mathrm{S}, \qquad (1)$$

where κ is the thermal conductivity of the probe material, $\Delta T_\mathrm{p}/\Delta x$ the temperature gradient, and S the cross section of the probe tip.

On the other hand from the sheath theory, $Q_{\mathrm{plasma}}(V_\mathrm{p})$ at the probe bias where the contribution of the electrons is negligible is given by

$$Q_{\mathrm{plasma}}(V_\mathrm{p}) = \frac{I_\mathrm{i}(V_\mathrm{p})}{\mathrm{e}}\left[2kT_\mathrm{i}(1-R_\mathrm{E}) + e(V_\mathrm{s}-V_p)(1-R_\mathrm{E}) + e(E_{\mathrm{ion}}-W)\right], \qquad (2)$$

where R_E is the ion energy reflection coefficient of the surface material, V_s the space potential, E_{ion} the ionization energy and W the work function of the surface material. The ion current $I_\mathrm{i}(V_\mathrm{p})$ can be measured by picking up the probe current, like an electrostatic single probe. The first, second, and third terms on the RHS in eq. (2) represent the contributions of the ion thermal motion in bulk plasma, of the ion acceleration by the sheath, and of the recombination at the probe surface, respectively. Therefore, measuring the temperature gradient as a function of V_p, T_i and R_E can be deduced.

The experiments were conducted with the low-pressure helium dc-arc discharges in the linear steady-state divertor simulator MAP(Material and Plasma)-II in The University of Tokyo. Typical electron density and temperature in helium plasmas measured by a Langmuir probe in the down stream chamber are 10^{11}-2×10^{12} cm^{-3} and 3-15 eV, respectively [3]. Thermal probe made of molybdenum, 5 mm in diameter and 36 mm in length, is equipped with a pair of thermocouples for the temperature gradient measurement and one fine lead wire for applying the probe. The preliminary result of the Q_{plasma}- V_p curve seems to have an offset compared to that deduced from the theory using the experimental data of the *I-V* curve for the thermal probe itself. The reason for this deviation is currently under investigation.

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19P14

Spectroscopic measurement using wide range UV/Visible spectroscopic system in GAMMA 10

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Measurements of impurity spectra in magnetically confined plasmas are very important to investigate impurity behavior and radiation loss. Impurity spectral intensity data has the information of electron density, temperature, velocity and population density. Then the measurement of impurity spectra are effective for plasma diagnostics[1-2]. In GAMMA 10, the spectroscopic measurements have been performed at wavelength ranges of ultraviolet and visible (UV/Visible), vacuum ultra violet and soft X-ray[3-5]. We newly constructed the UV/Visible spectroscopic system for impurity line identification and investigation of behavior of emission intensity in the tandem mirror GAMMA 10 at each cell. It is constructed with a collective lens, optical fiber and two spectrometers. The spectrometers are able to measure absolute intensity of spectra in the wavelength range of UV/Visible, 200-700 nm. It has an advantage to measure whole wavelength range of UV/Visible impurity spectra within the high wavelength resolution in one plasma shot. We have applied this system to GAMMA 10 plasma, and successfully obtained behavior of emission intensity in detail and information of time varying population density of impurity. The measurements of impurity spectra are carried out in GAMMA 10 at each region. We have revealed impurity behavior and identify useful spectra to apply spectroscopic model, collisional-radiative model (CRM), for plasma diagnostics. Further more, we evaluate radiation loss from the GAMMA 10 plasma in UV/Visible range and estimate the electron density and temperature after applying the measured spectral intensity data to CRM. We show the newly constructed UV/Visible spectroscopic system and its application to the GAMMA 10 plasma spectroscopy and the impurity behavior in GAMMA 10 plasma for some plasma condition.

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19P15

Study of oxygen ions behavior by using collisional-radiative model in GAMMA 10

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In the fusion plasmas, impurity behavior is one of the important issue because of radiation loss and plasma-wall interactions. In order to study impurity behavior, spectroscopic measurements have been carried out in a lot of fusion devices. In the GAMMA 10 tandem mirror, a soft x-ray spectrograph, a vacuum ultra-violet spectrograph and two ultra-violet/visible spectrographs have been used for measurement of impurity spectra[1-4]. All of them are time and space resoled systems. Then we can evaluate the temporary behavior of the profiles of impurity spectra. They have been also absolutely calibrated. Therefore we can obtain impurity density profile by using collisional-radiative model (CR-model). The CR-model is used for determining the population density of excited state of atom/ions in the plasma with given electron temperature and electron density. The CR-model for carbon ions have been developed. Then we evaluated the carbon density profiles in the central cell of GAMMA 10[5]. However, measurable carbon ion spectra in GAMMA 10 were only CII and CIII. The higher charged carbon ion spectra were not measured owning to lack of the measurement system in the wavelength range of 100 – 200 nm and weekly radiation intensity in the other wavelength region. Then it was difficult to evaluate the impurity transport by carbon spectra. Recently, the CR-model of oxygen ions included lower charged ion states also have been developed. In the GAMMA 10 central cell, OII, OIII, OIV and OV spectra are strongly emitted. All of them are measured in the ultra-violet/visible wavelength region. Therefore it is easy to measure the radial profiles of oxygen ion spectra for obtaining the density profiles of each charge state of oxygen ions. As a result, we can discuss the impurity transport in the mirror plasma.

In this paper, we show the measurement results of oxygen ions spectra by using ultra-violet/visible spectroscopic system in the central cell of GAMMA 10 and the results of CR-model calculations. Furthermore, we discuss the impurity behavior in the mirror plasma.

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[5] T. Kobayashi et al., J. Plasma Fusion Res. SERIES, 7(2005) to be printed

19P16

Behavior of fueled particles and its effects on plasma parameters in the GAMMA 10 Tandem Mirror

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The sustenance of the steady state plasma with higher densities and temperatures is an important subject to realize the fusion reactor. For steady state plasma operation, particle fueling is an indispensable technique. The development and optimization of the fueling method enable us to increase and sustain the plasma density.

In the present plasma experiments, there are three major ways for particle supply to keep or increase the plasma density. One is the pellet injection, which has mainly been used to obtain high dense plasma, is used as a particle source in the core region of the plasma. The neutral gas puffing is a standard method used as a particle source from the edge region of the plasma column. Almost all experimental devices are equipped with gas puffing systems. Neutral beam injection (NBI) is used as heating and fueling system in most of the large devices because neutral hydrogen is injected as high-energy beam.

In the GAMMA 10 tandem mirror, the study of particle fueling has been carried out in term of high performance plasma production. In the central cell of GAMMA 10, a pellet injector, a neutral beam injector and some gas puffers have been installed. The gas puffers are usually used to build up and sustain the plasma discharge, and the gas puffer is also used as re-fueling system during the plasma discharge. The objective of neutral beam injector at the central cell (C-NBI) is to supply the energetic particle to the main plasma and plasma heating. The pellet injector, which is a pipe-gun type pneumatic pellet injector, is installed to improve the plasma parameters and to study the pellet-plasma interaction in an open system.

To clarify the feature of particle fueling method and compare with each other, the effects of these fueling methods from the point of view of the behavior of particles are calculated with simple model. As the calculation results, it is found that the change of the spatial profile caused by pellet injection and neutral beam injection has the peak near the center of the plasma. On the other hand, the spatial profile of plasma parameters during particle fueling buy gas puff has the peak in peripheral region of injection side where the contribution of molecular hydrogen is large. These calculation results are applied to the experimental results, and the effects of the particle fueling, for example, electron density, neutral hydrogen density and intensity of H_α line emission etc, are compared experimentally.

In this paper, we show the detail of the calculation and experimental results and discussion of the comparison of the feature of particle fueling methods.

19P17

Measurement of the Degree of Dissociation of Molecular Hydrogen in Divertor Simulator MAP-II Using Fulcher-Balmer Ratio

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In the analysis of atomic and molecular processes of hydrogen in the partially ionized fusion divertor plasmas, behavior of molecules has a great effect on the measurement of various parameters, such as the negative ion density [1] or the intensity ratio of atomic spectra [2]. Determination of the atomic/molecular ratio from the atomic line spectra, however, tends to loose its sensitivity in high density plasmas ($>10^{12}\mathrm{cm}^{-3}$), where dissociative excitation is relatively small. Therefore, we have proposed to use the ratio of the high-n (=5 or 6) Balmer series to the ro-vibrational structure of the Fulcher-α band emission of molecular hydrogen, and applied it to the plasma of low degree of dissociation (~1%)[1]. In this study, we apply this method to the regime of higher degree of dissociation to verify its reliability.

Ro-vibrational structures of the electronic system of the Fulcher-α band in a coronal model, $X^1\Sigma_g$, $d^3\Pi_u$ and $a^3\Sigma_g$, can be labeled by the vibrational (v) and rotational (J) quanta with the primes as (X, v, J), (d, v', J') and (a, v'', J''), respectively. The radiative decay, from d to a states is balanced by the electron impact excitation from X to d states. Therefore, the emissivity of the Fulcher-α band can be described as

$$\varepsilon_{\mathrm{Fulcher}}^{dv'J'\to a} = n_e \sum_{v,J} \left[N_{XvJ} R_{XvJ}^{dv'J'}(T_e) \right] , \qquad (1)$$

where n_e is the electron density, $R_{XvJ}^{av'J'}$ is the electron impact excitation rate as a function of the electron temperature, T_e, N_{XvJ} is the ro-vibrational distribution of the ground electronic state, for which Boltzmann distribution having vibrational ($T^X{}_{\mathrm{vib}}$) and rotational temperatures ($T^X{}_{\mathrm{rot}}$) are assumed. The population of the molecular hydrogen of the ground electronic state, N_X, is the sum of N_{XvJ} with respect to v and J. On the other hand, a collisional radiative (CR) model is applied to the emissivity of the Balmer series (n=2←p), namely,

$$\varepsilon_{\mathrm{H}_p} = n_e N_1 R_1(p, n_e, T_e) A_{2\leftarrow p} , \qquad (2)$$

where N_1 is the population of the ground state of atomic hydrogen, R_1 is the population coefficient for the ionizing component relating to the ground state, that can be calculated based on a CR model for given T_e and n_e, $A_{2\leftarrow p}$ is the spontaneous emission coefficient. Thus, from the ratio of $\varepsilon_{\mathrm{H}_p}$ to $\varepsilon_{\mathrm{Fulcher}}^{dv'J'\to a}$ measured in the same viewing chord using the same optical system, the atomic/molecular ratio, then the degree of dissociation, can be obtained.

The experiments were conducted for pure hydrogen discharges in the divertor simulator MAP-II [3]. The MAP-II consists of dual chambers, a higher density ($\sim10^{13}\mathrm{cm}^{-3}$) source chamber (upstream) and a lower density ($\sim10^{12}\mathrm{cm}^{-3}$) target chamber (downstream), which are connected to each other with a drift tube. T_e, and n_e in the source chamber, where electrical probe method is difficult to apply, were measured using a Laser Thomson scattering.

In our preliminary results, the obtained degree of dissociation in the source chamber is at least several times higher than that in the target chamber.

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Gamma-ray Spectroscopy Method for High Energetic α Particle in Burning Plasma

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It is necessary to investigate methodologies of fast ion measurements in burning plasma. Especially, in D-T burning plasma, the measurements of the density of α particle and the rate of leakage α particle are important to success the self-ignition plasma. Gamma-ray spectroscopy method is used for the diagnosis of fast ions in D-D and D-T burning plasmas.

For the density of 3.5-MeV α particle and the leakage α particle in D-T plasmas, we propose the observation of 2.186-MeV gamma-ray produced by $D(\alpha,\gamma)^6Li$ reaction and the use of the activation method by $^{19}F(\alpha,n)^{22}Na$ reaction, respectively. And we experimentaly examined the methodologies due to D-T burning plasma diagnostics using by tandem accerelator. In case of the observation of 2.186-MeV gamma-ray, as there is few data of the $D(\alpha,\gamma)^6Li$ reaction rate near the range of E_α=3.5 MeV, we carried out the experimental verification of the gamma-ray diagnostics technique by using an accelerator. He^{++} ions in the energy range of 2-4 MeV were bombarded into a thick deuterated polyethylene, where the gamma-ray spectrum was measured with a Ge-detector. The bombardment of He^{++} ions into a usual carbon disk was also done to obtain the background gamma spectrum. Photo peak of 2.186-MeV gamma-ray was clearly observed. From our experiment, $D(\alpha,\gamma)^6Li$ reaction rate is estimated to be 10^{11} m^{-3} s^{-1} in the ITER typical plasma condition. So we obtained good prospect of the gamma-ray measurement as the confined α diagnostics by using high efficiency detector.Also, the activation method with $^{19}F(\alpha,n)^{22}Na$ reaction was examined exprimentaly. 3.5-4.0 MeV He^{++} ion beam was implanted into calcium floride crystal sample. After irradiation, 1.26-MeV and 0.511-MeV gamma ray from Na-22 induced by $^{19}F(\alpha,n)$ reaction were obviously detected with a Ge-detector. Concernign the activation method, it is seemed that the activation method with CaF_2 sample

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Potential and Density Fluctuation Characteristics of the Hot-Cathode-Biased Supersonic Plasma in TU-Heliac

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The suppression and the control of the particle transport are important for the fusion reactor. The understanding of the anomalous transport is required since the substantial part of the particle transport is anomalous. The suppression of the anomalous transport and the formation of the radial electric field have been measured in many experiments such as the H-mode in tokamaks [1, 2]. Therefore it has been considered that plasma flow and/or flow shear, which are formed by the radial electric field, has the key role. It is important to understand the mechanism of the anomalous transport and the mechanism of the suppression by the radial electric field. The electrode biasing is useful tool to form the radial electric field actively and to drive the supersonic poloidal flow. Therefore in Tohoku University Heliac (TU-Heliac) negative biasing experiments using a LaB_6 hot cathode have been carried out. The formation of the radial electric field was confirmed, the 3-fold increase of the electron line density, and the decrease of the electron density outside the last closed flux surface were measured [3]. The poloidal Mach number M_p, which was estimated from the radial electric field, exceeded unity and reached ~5 and the poloidal flow was supersonic regime.

The ion saturation fluctuation has been measured in TU-Heliac since the ion saturation fluctuation can be used as the density fluctuation [4]. The wave number vector had the large perpendicular component compared to the parallel component and depended on the magnetic field. By biasing, the direction of the wave number vector changed from the ion to the electron diamagnetic direction and the phase velocity of the fluctuation was nearly the same as the ***ExB*** drift velocity [5]. The fluctuation had the large power in the high frequency 100 ~ 300 kHz. These results suggested that the fluctuation was affected by the ***ExB*** poloidal flow and that the fluctuation had the Doppler shifted frequency during biasing.

The account of the anomalous particle flux is important to evaluate the degree of the improvement in the biasing experiment. It is necessary to measure the space potential fluctuation and the density fluctuation simultaneously for the estimation of the particle flux. In the Langmuir probe method, the floating potential fluctuation can be used as the space potential fluctuation and the ion saturation current fluctuation can be used as the density fluctuation. In the biased plasma, Doppler shifted fluctuation had higher frequency spectra over 100 kHz. Thus it is important to suppress the high frequency noise through the insulation ceramic tube in the floating potential measurement. So the shielded triple probe, which consists of a Mo probe tip, a Cu shield and alumina ceramic tubes, is installed in TU-Heliac and the high frequency anomalous particle flux in the hot-cathode-biasing experiment is estimated.

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Ion Temperature Measurements in the Biased Plasma with a Hot Cathode in Tohoku University Heliac

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We observed the transition to the improved confinement mode in the biased plasma with a hot cathode inserted into plasma in Tohoku University Heliac (TU-Heliac), which is a 4-period small size Heliac. The hot cathode was made of LaB_6. From these biasing experiments, we concluded that this transition appeared when the $\boldsymbol{J} \times \boldsymbol{B}$ driving force reached local maximum in ion viscosity [1-3]. To clarify this mechanism experimentally, we have to know the relationship between the ion viscosity and the poloidal Mach number. The ion viscosity can be evaluated from the $\boldsymbol{J} \times \boldsymbol{B}$ driving force and the information of ion temperature. The Mach number can be evaluated from the radial electric field and the ion temperature. Therefore it is important to measure the ion temperature precisely.

We have been trying to measure the ion temperature by Doppler Broadening using a high-resolution spectroscope, and become able to estimate the ion temperature with sufficient accuracy. In these experiments the working gas was Helium, and the spectrum of HeII (468.57nm) was observed. In the plasma without biasing, the ion temperature measured by Doppler broadening was about 3eV at most frequent operational conditions in TU-Heliac. When the plasma was biased with the hot cathode, radial electric current flowed, and radial electric field was formed. Then the plasma started rotating in poloidal direction by the $\boldsymbol{J} \times \boldsymbol{B}$ driving force. This poloidal flow velocity was high speed, up to 20 km/s. In the plasma with biasing, as the effect of Doppler shift on the line shape was large, we could not neglect the effect of Doppler shift broadening by plasma rotation. To decrease the influence of Doppler shift, the view port for a new sight line perpendicular to magnetic surfaces was installed. In addition, as described above, the ion temperature in TU-Heliac was a few eV, we have to analyze line shape with the effect of fine structure ignored in the case of high temperature plasma. So it is important evaluating the influence of Zeeman effect on a line shape and of a special integral effect along the line of sight. In this presentation, we report the dependence of gas pressure on ion temperature, and the effect of Doppler shift caused by the plasma rotation on the broadening of spectrum.

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Dynamics of One-dimensional SOL-divertor Plasmas after an ELM Crash in Tokamak H-mode Plasma

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The tokamak plasma is confined in the closed toroidal magnetic field, and is surrounded by the scrape-off-layer (SOL) plasma with open-field configuration. Particle and energy outfluxes from the closed-field region to the SOL region are lost to the divertor plate along the magnetic field line. In a tokamak reactor such as ITER, it is considered that the divertor plate is hardly harmed by the stationary particle and energy fluxes. On the contrary, enhanced particle and energy fluxes to the divertor plate after an ELM crash in H-mode plasmas can give the serious load to the plate. Evaluation of those values for ITER has been carried out with the numerical simulations based on the fluid model. The applicability of the present fluid model to the transient behavior of SOL-divertor plasmas after an ELM crash, however, is not verified. Kinetic effects, such as the fast-electron-tail effect on the sheath potential and on the energy transmission coefficient etc., are not yet well understood. The particle simulation is one of powerful tools to study such kinetic effects [1-3]. We have developed a PARASOL (PARticle Advanced simulation for SOL-divertor plasmas) code for this research [1]. In the present work, we focus the dynamic characteristics of SOL-divertor plasmas related with the transport parallel to the magnetic field, and treat a one-dimensional system bounded by two divertor plates with oblique incidence of a uniform magnetic field. An electrostatic PIC method combined with a Monte-Carlo binary collision model is adopted. Hot particles are supplied around the central region and cold particles are generated in front of the plates as recycled particles. An ELM crash suddenly releases a large amount of hotter particles into a stationary SOL plasma. The electron heat pulse propagates fast to the plate. Next the ion heat pulse and the plasma particle pulse reach the plate slowly with the sound-speed time scale. Dependences of propagation characteristics on the collisionality and on the recycling were studied [3]. The fast-time-scale electron heat transport is reduced with the increase of collisionality. On the other hand, the slow-time-scale heat transport is more slowed down by the higher recycling [3]. In the present paper, we study the effects of the ELM-induced-source asymmetry and of the recycling asymmetry. The SOL current plays an important role in the dynamics with the asymmetry. When two divertor regions have different recycling rates and the system is originally asymmetric, the direction of the SOL current is sometimes changed by the ELM-induced heat and particle pulses.

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Observation of Radial Particle Transport Induced by the Fluctuation Measured with a Gold Neutral Beam Probe

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The transport induced by fluctuations is a universal phenomenon for the magnetic confined plasma. Then the fluctuations have been measured at lots of deveices regardless of configurations. Many results show that the radial electric field shear is effective to reduce the fluctuaitons. In this study, the radial particle flux induced by the fluctuation is measured by a Gold Neutral Beam Probe (GNBP). Then the transient transport phenomenon induced by the fluctuation is investigated.

In the tandem mirror GAMMA 10, ion confinement potentials are generated by carrying out electron cyclotron resonance heating at both plug regions of the plasma. The generated potentials are measured with GNBPs using the gold neutral particle as the primary beam. We measured the radial and two-dimensional profiles of the plasma potential by the GNBPs installed in the central cell and the barrier cell[1,2], and also measured the low and high frequencies fluctuations[3]. Beam probes are powerful tools for the measurement of density and potential fluctuations, and for the measurement of radial particle flux even in the core plasma[4]. The phase difference between the density and potential fluctuations is one of the key parameters for the anomalous transport due to the electrostatic fluctuations because the phase difference decides the direction and amount of the flux and the growth of the fluctuations.

As a result, when the drift wave is excited at the central cell, the density near the center is reduced and the divergence of the flux becomes similar to the time derivative of the electron density. It shows that the density reduction is caused by the flux induced by the drift wave. Then the drift wave is saturated and comes to the steady state because the density reduction accompany the reduction of density gradient. Therefore, the transport phenomenon accompanying the growth and saturation of the drift wave is observed experimentally.

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Measurements of 2-dimensional plasma density distributions by the phase-imaging method in GAMMA 10

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Plasma density measurements are one of the important studies, such as plasma temperatures, plasma particle confinement and plasma confining potentials for achievement of nuclear fusion. We have studied plasma electron density distributions and its fluctuation frequencies by using microwave interferometers, an ultra-short pulse reflectometer, and a Fraunhofer diffraction method in GAMMA 10. We have constructed a 2-dimensional density measurement system by phase-imaging method for studying the 2-dimensional density distributions and 2-dimensional density fluctuation in the GAMMA 10 plasma. GAMMA10 is the tandem mirror type nuclear fusion experiment device. It consists of five mirrors roughly separately. Especially, The mirror at both ends is called plug/barrier mirror region. The confinement potential of thermal barrier is formed there with electron cyclotron resonance heating and Neutral Beam Injection. 2-dimensional plasma electron density distributions have been studied in plug region of GAMMA10 by using newly installed a phase imaging measurement system. In this system, as shown Fig.1, it is a heterodyne-type interferometer. It consist the 4 × 4 multi-channel detector array, and 69.75 and 70 GHz Impatt microwave oscillators. A probe microwave penetrated in the plasma is connected on the detector array with the lens system and the 2-dimensional image is observed. In this paper, we show the first results of the 2-dimensional density distribution in the plug region of GAMMA 10.

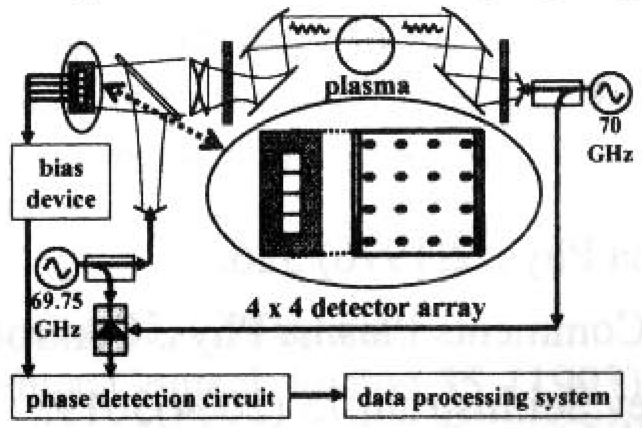

Fig. 1 phase-imaging method

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Density Measurement Using a Lithium Beam Probe at the Inner Mirror Throat of the Tandem Mirror GAMMA10

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Existence of the bounced ion by the plug potential is essential to improve the axial confinement in the tandem mirror [1,2]. The inner mirror throat (IMT) of the plug/barrier cell is the most suitable locations to measure the bounced ion by the plug potential in the tandem mirror GAMMA10, because the IMT is located near the plug region and the bounce ion has relatively high pitch angle in the neighborhood of the IMT so as to be detectable easily [3]. We adopted the method to measure the charge exchange neutral particle changed from the plug potential (PP) bounce ion instead of detection of the PP bounce ion, and also designed the diagnostic system to measure simultaneously both electron and neutral particle density profiles near the IMT, which contains Hα measurement. A lithium beam probe (LiBP) system is used in order to measure the radial profile of the electron density. The neutral lithium beam is injected into the plasma and the emitted light from the beam is detected. We estimated the upper limit with respect to the plasma density by reconstruction of the radial profile of the density and the validity of the reconstruction for various radial profiles. We adopted a Gaussian type of radial profile of the density with the radius of 3 cm for the estimation of the upper limit of the plasma density. It was found that the profile reconstruction was carried out well up to the central density of 5×10^{13} cm^{-3}, and also well even the non-symmetric radial profiles. The LiBP method is quite appropriate for the measurement of the density profile at the IMT in the tandem mirror from the view point of the space and time resolution.

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19P25

Beam emission diagnostic for estimating neutral beam attenuation

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Neutral beam injector is widely used for ion heating on many magnetically confined plasma devices. A high-power NBI heating is needed for fusion device that products high temperature and high-density plasma. Three neutral beam injectors based on the negative-ion source have been operated in the Large Helical Device (LHD). [1] Hydrogen neutral beams with the energy of 180keV are injected tangentially. So the beam penetration length of the tangential injection is longer than that of the perpendicular injection. It is important obtaining the beam absorption to improve the heating in plasma center. It is well known that hydrogen neutral beam particles emit visible spectra by the interaction with plasma particles. [2] So we applied the beam emission diagnostic in order to estimate the beam attenuation inside of the plasma.

Beam emission diagnostic system consists of two quartz optical fiber arrays, a 25cm spectrometer and an intensified charge coupled device (ICCD) detector. One optical fiber array views the upstream side of the injected neutral beam and the other array views the downstream beam. The angle between the beam injection axis and the sight line of the upstream side and the downstream side is 62.4 degrees and 134.7 degrees, respectively. So, each beam emission shifted by the Doppler effect to the red shift side or blue shift side due to the direction of relative motion of beam particles. The spectrometer is equipped with the 1800 grooves/mm high-resolution grating. The hydrogen Balmar-α emission (Hα) spectrum is detected using the ICCD detector located on the focal plane in the spectrometer. The wavelength resolution of the spectrometer system is 0.21nm totally, and the interval of the acquisition is 40ms when the 20ms exposure time.

We have clearly observed the spectrum of beam emission that is located on the expected wavelength corresponding with the beam energy. The beam emission spectrum consists of a single energy beam component because the fractional energy beam dose not exists in the hydrogen negative ion source. The intensity of the beam emission from the downstream sight is less than that from the upstream sight due to the beam attenuation. The intensity of the beam emission changes when the electron density changes. This behavior includes both the process of the neutral beam attenuation and the Hα emission. So we have estimated the effective cross-section of beam attenuation by the database of the effective emission coefficient [3] used the Atomic Data and Analysis Structure (ADAS) code. We have also observed the difference of the beam intensity in the various target plasmas such as a helium discharge and an argon discharge with the same density. This result indicates that the cross-section of the beam attenuation increases when the atomic mass of the target plasma increases.

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Measurement of relative flux of fractional-energy emissions using beam emission diagnostic

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Supply of fast ions is a key issue to produce high temperature plasmas for fusion development. Neutral beam injection (NBI) heating is effective to heat fusion particles. We have installed the low-energy (40keV-3MW) NBI system in order to improve the ion temperature in the Large Helical Device. A hydrogen neutral beam produced on a positive ion source is injected perpendicularly. It is well known that different energy particles such as the energy of E, E/2 and E/3, are mixed into the beam because the hydrogen molecular ions are exist on the positive ion source. [1] Increasing of the first energy component of the neutral beam is necessary in order to improve the heating efficiency. The information of relative flux of the fractional-energy is also important for the calculation of heating efficiency using a Monte Carlo simulation code. In this article we will show the beam emission diagnostic to obtain the relative flux of the fractional-energy inside of the plasma.

The optical system is consisted of quartz lenses and quartz optical fibers. The measurement sight line is arranged along the beam injection axis with the angle of 14.3 degree on the LHD 5-O port. We use the hydrogen Balmer-α (Hα) beam emission spectrum that is separated from a plasma emission spectrum by the Doppler effect. Optical fibers are set on the 100µm entrance slit of a spectrometer which focal length is 25cm long. The intensified charge couple device (ICCD) detector (Andor DH720-18) is coupled on the focal plane of the spectrometer. Pixels of the detector are 1024 pixels horizontal and 256 pixels vertical. The spectral resolution and the reciprocal dispersion are 0.21nm and 1.4nm/mm, respectively. We typically use the 40ms sampling times with the 20ms exposure times. The record of the spectrum and operation of the ICCD are controlled by the personal computer with the 16bit A/D converter for data acquisition.

We have clearly observed the beam emission Hα spectra of first, second and third energy components. It is expected that the Doppler shift of the beam energy of 40keV, 20keV and 13.3keV are the 5.9nm, 4.2nm and 3.4nm, respectively, of the Hα emission (656.3nm). The Doppler shift of the each line is consistent of the calculation values. Intensity of the line spectrum is estimated by the summation of the spectrum, where we use the background spectrum to reduce the weak impurity lines. Beam intensity ratio is almost proportional to the beam density ratio, so we have obtained the fraction of the beam energy into the plasma. Flux ratio varied by the time evolution. It is indicated that the effective heating power changes into the discharge due to the changing of the fractional-energy beam.

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Behavior of high energy ions during drift type instability in the GAMMA 10 tandem mirror

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In the GAMMA 10 tandem mirror, an ion cyclotron range of frequency (ICRF) waves have been used for the plasma production and heating. When high power ICRFs for the plasma production is applied, some fluctuations which are typified by the drift type instability are observed. It seems to be possible that these instabilities transport high energy ions in the radial direction and degrade the plasma confinement. In this research, the correlation between behavior of high energy ions and fluctuations is analyzed.

To measure the behavior of high energy ions, a semiconductor detector with the silicon surface barrier is installed at the mid-plane of the central cell (named central cell High Energy ion Detector: ccHED). This detector is inserted perpendicularly to the magnetic field line. The position in the radial direction is arbitrary determined. The ccHED can measure high energy ions which energy are above 10keV and can measure a pitch angle distribution of ions by rotating the detector. On the other hand, fluctuations are measured by using electrostatic probes (ESP) which are installed near the mid-plane of central cell. ESP can measure the ion saturation current. The conventional Fast Fourier Transform (FFT) method is using for the analysis.

When ccHED is located at the radius of R=25cm, the burst like signal on ccHED is observed. The frequency component of the burst has the same peak as one of the frequency components of the fluctuations and has the pitch angle dependence. The intensity of the signal has also the pitch angle dependence and becomes strongest at the pitch angle corresponding to the cyclotron resonance layer. The observation suggests the existence of the radial transport of high energy ions due to the drift type fluctuations.

Observation of Fluctuations Appeared in End-Loss Ion Current and Ion Transport in Velocity Space Induced by AIC Waves in the Tandem Mirror

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In open systems, loss regions exist necessarily in the velocity space of the plasma particles. The plasma scattered from the trapped region to the loss region flows into the loss region and goes to the end walls along the magnetic field line. An end-loss energy component analyzer (ELECA) has been used to measure the velocity and energy distribution functions of the end-loss ion in the tandem mirror GAMMA10. The velocity distribution function provides information about the noticeable structure which appears on the ion distribution in the loss region.

We prepared three kinds of analog-to-digital converters (ADC) in order to analyze simultaneously many fluctuations, and observed Alfvén ion-cyclotron (AIC) waves and the beat phenomenon appeared in the end-loss ion current [1]. The AIC waves are excited spontaneously due to the isotropic ion heating in the central cell of the tandem mirror [2]. It was found that the excitation of the AIC waves caused the hump structure on the energy distribution function of the end-loss ion in the rf-driven tandem mirror plasma [3]. The velocity distribution function of the end-loss ion was measured and the hump structure was analyzed in the velocity space. In the hump structure region, we observed that large pitch angle scattering due to the AIC waves was enhanced as compared with the same scattering due to the Coulomb interaction. We found that the relation between the ion distribution in the loss region and the pitch angle dependence of the amplitude of the AIC beat waves appeared in each end-loss ion signal of the multi-channel detectors.

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Plasma density profile measurement in the Hanbit

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A heterodyne reflectometer (8-12 GHz) is constructed to measure the density profile of the Hanbit plasma. A new phase measurement algorithm[1] and a new frequency calibration technique[2] are developed. Using this reflectometer, the plasma density profiles are measured as varing the discharge conditions in the Hanbit. Especially, the initial phase of the ECR assisted breakdown and the diverted plasma are experimentally investigated. The experimental results are shown.

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19P30

Ion temperature measurement in the RF heated Hanbit plasma*

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The ion temperature, rotation velocity, and impurity density can be obtained from Charge exchange recombination spectroscopy (CES) diagnostics, one of active beam diagnostics, using NBI or DNB.

We measure the charge exchange emission line of the helium using CES and DNB system and analyze the ion temperature and rotation velocity from the emission line in the RF heated Hanbit plasma. DNB system which has 25 kW beam power and 20 msec pulse width must be controlled critically to measure the exact ion temperature in the experiments.

End loss ion temperature measured using energy analyzer is compared with the ion temperature obtained from the charge exchange emission line. The CES diagnostics has been widely used to measure ion temperature and poloidal rotaion velocity in tokamak

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Detection of bounce ions by use of a charge exchange bounce ion analyzer

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In the tandem mirror GAMMA 10, electrostatic potential hills are created on both sides of the plasma for the purpose of decrease of the loss regions. Existence of the plug potential (PP) bounce ion is quite essential for the effective improvement of the axial confinement time, which are bounced in the neighborhood of the plug potential hill. We tried to detect the PP bounce ion by use of a charge exchange bounce analyzer (CX-BIA) located near the inner mirror throat (IMT) of the plug barrier cell. We paid attention to the neutral particles changed from the bounced ions through the charge exchange process and detected simultaneously both neutral particle energy and angle of emergence with respect to the direction of the magnetic field instead of the energy and pitch angle of the bounce ions. We call the ions, which are bounced near the inner mirror throat (IMT) and the outer mirror throat (OMT) of the plug/barrier cell, and the plug potential (PP), as the IMT, OMT and PP bounce ion, respectively. These bounce ions are assigned to the PP, IMT and OMT bounce ion by selection of both energy and pitch angle of the bounce ions.

The CX-BIA is composed of a pitch angle selector, a stripping gas cell, a mass flow controller and a cylindrical type of electrostatic energy analyzer with a deflection angle of $\pi/2\sqrt{2}$ radian. The characteristic of the analyzer is that the incident parallel beams are strongly focused at the exit slit of the analyzer, therefore high counts are obtained using a wide entrance aperture and a multi-channel detector is available.

We detected successfully the bounce ions and assigned to the PP and OMT bounce ion during plugging in addition to the IMT bounce ion without plugging by use of the CX-BIA device. The main purpose of this measurement is study of radial diffusion of the PP and OMT bounce ions related to the radial potential profile created in the plasma during plugging, and these data give us a useful research base with respect to the experiment of higher potential confinement.

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Fast Measurement of Ion Temperature in JT-60U by Using New Fast Charge Exchange Recombination Spectroscopy

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A new fast charge exchange recombination spectroscopy (CXRS) system (minimum time resolution: 0.16 ms) is developed, and applied for fast measurements of ion temperature and plasma rotation in JT-60U. This fast CXRS system is based on the CXRS diagnostics with interference filter assembly [1]. The three-filters system has an ability to determine the temperature and rotation velocity without non-linear least square fitting. Thus, we present an analytical scheme for rapidly calculating the temperature and rotation velocity, assuming that the spectral profile forms a Maxwellian distribution. In the three-filters CXRS system, although a small degree of ambiguity of the intensity ratio creates a relatively large error in calculating the temperature and rotation because of the minimum measurement points in spectrum.

In this report, in order to improve signal-to-noise (S/N) ratio of the intensity of the CXR emission in the fast CXRS system and a measurement range, the transmission rate of each filter is improved in ~64% from ~47% with optimising the passband of each filer and the number of channel is increased (maximum mesurement points: 12), respectively. By the use of the new fast CXRS system, the rapid changes of the ion temperature and rotation velocity are measured with ~1 ms time resolution. Moreover, as basic application toward the operation of future fusion reactors, the real-time measurement and feedback control of the central ion temperature has been demonstrated.

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19P33

Electron Density Measurements of a Thin Plasma Layer by Surface Plasmon Interferometry

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In this article, we present a new simple method for measuring the electron density of a thin plasma layer. As in this method we assume a overdense plasma for electromagnetic wave propagation and then utilize evnescent waves being exponentially damped, we call this method as surface plasmon interferometry.

In this surface plasmon interferometry, we examine the transmittance of transverse-magnetic (TM) electromagnetic waves incident obliquely to a thin plasma layer. In this case, we find that the wave transmittance across the thin plasma layer has a maximum at a certain angle of wave incidence. Since the angle of wave incidence corresponding to the maximum transmittance just depends on the dielectric constant of plasma related with the electron density, thus we can determine the electron density of a thin-plasma layer from the measurement of the optimal angle corresponding to the maximum transmittance. On the other hand, in the case of transverse-electric (TE) electromagnetic waves, we see that the transmittance has a maximum for the normal incidence regardless of the angle of wave incidence. Therefore, this method cannot be applied to TE electromagnetic waves. We think that this method is useful in measuring the electron density of industrial microplasmas such as plasma-display-panel (PDP) plasmas.

19P34

Stability Study of Kelvin-Helmholtz Modes due to Radial Electric Field Shear

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The Kelvin-Helmholtz instability is of importance of importance for the low-frequency stability of magnetically confined plasmas in the presence of an equilibrium radial electric field. Strong shear in the $\boldsymbol{E}\times\boldsymbol{B}$ drift velocity will make the Kelvin-Helmholtz modes unstable. However, it is known that since a smooth radial gradient of the $\boldsymbol{E}\times\boldsymbol{B}$ drift frequency leads to the stabilization of the Kelvin-Helmholtz modes, there exists a threshold in the radial gradient of the $\boldsymbol{E}\times\boldsymbol{B}$ drift frequency for instability[1].

In this article, we numerically study the Kelvin-Helmholtz mode in a cylindrical cold plasma in the presence of an equilibrium radial electric field with a finite gradient. In the present cylindrical plasma model, the eigenmode equation describing the Kelvin-Helmholtz modes is given by the Rosenbluth-Simon equation, and it is solved numerically by a shooting method. We see that the growth rate of the Kelvin-Helmholtz mode decreases with the increase of the gradient scale length of radial electric field and is completely stabilized for the further increase of the gradient scale length, when the magnitude of the $\boldsymbol{E}\times\boldsymbol{B}$ drift frequency is fixed. We also find that the mode is stabilized for the smaller magnitude of the $\boldsymbol{E}\times\boldsymbol{B}$ drift frequency, when the gradient scale length of radial electric field is fixed.

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19P35

Electron Bernstein Wave Heating on Internal Coil Device Mini-RT

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Mahajan-Yoshida developed a new relaxation theory, and suggested confining of ultra high beta ($\beta>1$) plasma [1]. To investigate this possibility, the internal coil device Mini-RT was constructed [2]. Figure 1 shows the cross section of Mini-RT. The internal coil (floating coil) was made of high temperature superconductor (Bi-2223) and levitated by applying current to the levitation coil. So-called overdense plasma were generated at the experiments with internal coil levitated [3]. Internal coil devices have steep magnetic field gradient ($B \propto R^{-3}$). It means that many harmonic electron cyclotron resonance (ECR) layers appear in the plasma confinement region, as shown in Fig. 1.

Electron cyclotron heating experiments with internal coil supported were carried out to investigate the possibility of EBW heating. The frequency and power of ECH are 2.45GHz and 2.8kW, respectively. Incident electromagnetic waves were launched from low field side with the X-mode. As shown in Fig. 1, plasma is confined inside the separatrix, and has a steep density gradient at the separatrix region. By applying the levitation coil current $I_{\text{L-coil}}$, we can change the separatrix position. Here we have compared three cases ($I_{\text{L-coil}}$ =0 kA, 6.8 kA and 13.6 kA), and profiles of electron density and temperatures are shown in Fig. 2 for each case. Measurements were carried out by using triple probe, which was confirmed by line-integrated density measurement with microwave interferometer. The increase of the electron temperature near the steep density gradient has been observed, as shown in Fig. 2(b). One possibility to explain this electron heating might be an EBW heating mode-converted from the X-mode wave.. It seems that the peaks of the electron temperature in the cases of $I_{\text{L-coil}}$ = 6.8 kA and 13.6 kA are located at the 4th and 3rd harmonics of ECR layer, respectively. The location of the mode conversion to the EBW is sensitive to the Upper Hybrid Resonance (UHR) layer, which is almost determined by electron density. We can explain the relationship between T_e peak and the locations of UHR, harmonic ECR layers, if the electron density measured by triple probe has an ambiguity of ±20%.

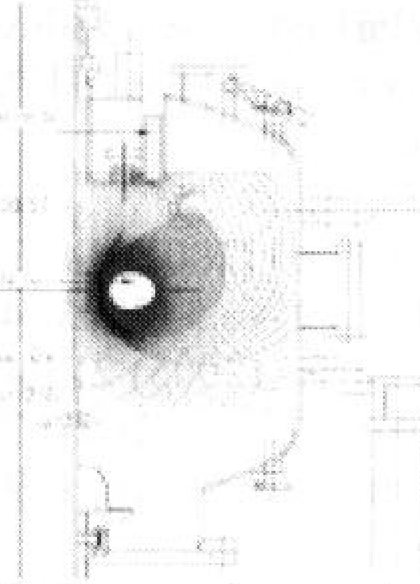

Fig .1 Cross section and plasma confinement region of Mini-RT

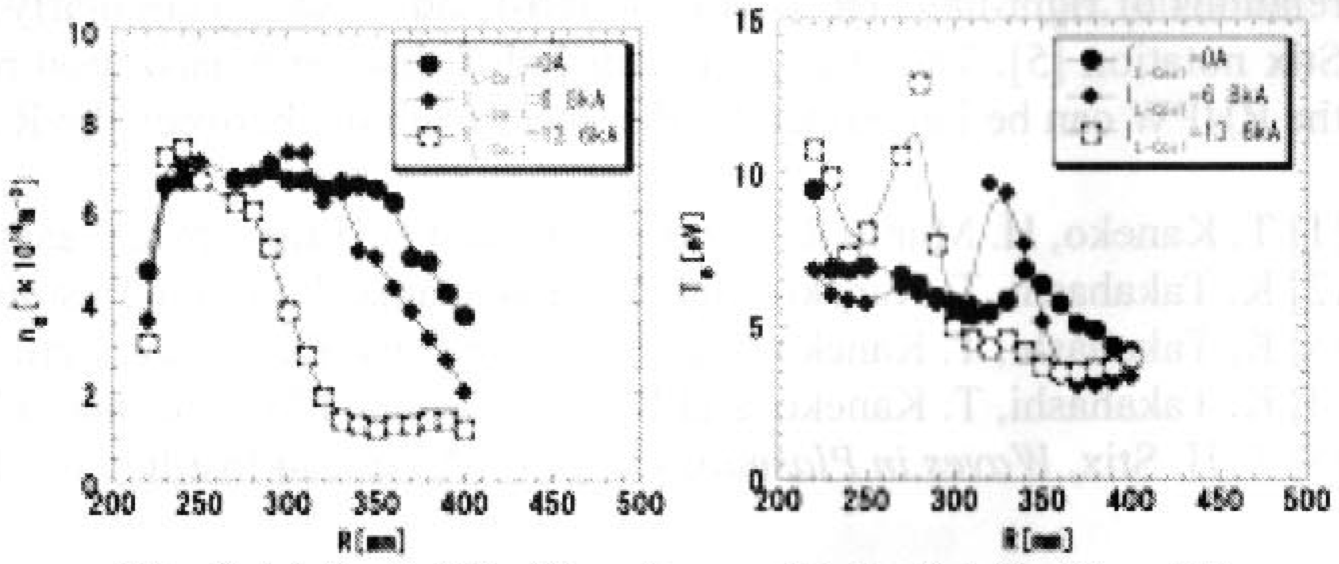

Fig. 2 (a) Radial Profile of n_e (b) Radial Profile of T_e

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19P36

1-Dimmensional Analysis of Polarization Reversal Relating to Electron Cyclotron Resonance

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Electron cyclotron waves are important plasma waves relating to an efficient electron heating and a formation of local confining-potential structure in tandem-mirror devices. A polarization of the wave plays a key role in the efficient absorption near the electron cyclotron resonance (ECR) point due to its interaction with the electron gyro motion. We have experimentally demonstrated a polarization reversal from a left-hand (LHPW) to a right-hand (RHPW) polarized wave in an inhomogeneously magnetized plasma and a resultant absorption of the launched LHPW at the ECR point [1-4]. Although we explained the polarization reversal by a theory of plasma-filled waveguide, effects of the inhomogeneous magnetic field are not strictly included in our previous analysis [4]. Therefore, we introduce a one-dimensional code of full wave analysis with cold plasma approximation. In this paper, a comparison is made between the numerical results by the code and the experimental results.

An axial profile of a polarization index S ($\equiv |E_x + iE_y| / |E_x - iE_y|$) is derived from the numerical results of E_x and E_y, where, $0 < S < 1$, $S = 1$, and $1 < S < \infty$ represent right-handed, linear, and left-handed polarizations, respectively. The numerically obtained polarizations are left-handed ($S > 1$) and right-handed ($S < 1$) in the high magnetic-field area and near the ECR point, respectively. This result signifies that the wave polarization varies from left-handed to right-handed along the magnetic field; the polarization reversal from the LHPW to the RHPW near the ECR point can be demonstrated by using the one-dimensional code. Moreover, the axial positions of the polarization reversal are investigated with the magnetic-field configuration and the wavenumber perpendicular to the magnetic-field lines as parameters. It is found that the polarization reversal occurs at a certain value of ω/ω_{ce}, which is in good agreement with the experimentally observed results.

In order to identify the condition of the polarization reversal, we analytically derive the electromagnetic fields in a plasma-filled waveguide from Maxwell equations. It gives us the polarization-reversal condition of $n^2 = (R + L)/2$, where $n^2 = R$ and $n^2 = L$ are the dispersion relations of right-hand (R wave) and left-hand (L wave) circularly polarized waves following Stix notation [5]. Therefore, it is concluded that the polarization reversal from the LHPW to the RHPW can be interpreted by the linear coupling between the R and L waves.

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On the experiment of electron cyclotron resonance heating in the central cell of the GAMMA 10 tandem mirror

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Target plasma in the GAMMA 10 tandem mirror is produced using ion cyclotron range of frequency (ICRF) heating with the combination of gas fueling [1]. Relatively low density ($\sim 10^{18}$ m^{-3}), but high-β (ion temperature $\geq$10 keV) plasma in the central cell is obtained in this plasma production mode and this mode of operation is referred as hot ion mode [2]. Electron cyclotron resonance heating (ECRH) is then applied on the target plasma at the plug/barrier cell for the production of plug/barrier potentials [3]. On the other hand, in the hot ion mode of operation electron temperature (T_e) of the central cell plasma is usually low (few hundred eV). It is, thus, important to increase T_e of the plasma in the central cell to overcome the related problem of efficient ion heating, etc.

To increase the electron temperature of the central cell plasma, electron cyclotron resonance heating in this cell (c-ECRH) is applied. It is observed that both the density and temperature of the plasma decrease during c-ECRH, especially in the time of insufficient wall conditioning. To understand the obtained results, plasma parameters including the H_α measurements at the central and anchor cells are studied. Computational study on MHD stability of GAMMA 10 is also done. It is suggested that sufficient β value of the plasma in the anchor cell is necessary for MHD stability of the GAMMA 10 plasma during c-ECRH. Related problem to increase the β value of the plasma in the anchor cell is pointed out.

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19P38

Numerical Analysis of the Second Harmonic Resonance Ion Heating in the HIEI Tandem Mirror

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For efficient ICRF ion heating of high density mirror plasma, use of a fast wave is more desirable than a slow wave. In the central cell of HIEI tandem mirror, ion heating via fast wave-slow wave mode conversion process in the two ion species plasma was achieved[1] where non-linear effect of the propagating RF wave field provided MHD stability of the plasma.

Recently, a magnetic divertor was introduced in the HIEI as an effective stabilization method[2]. In this operation, the external field of the central cell becomes quite weak, thus ICRF waves with large wave number could be excited which could directly couple with ions. By using a suitable frequency, higher harmonic resonance regions can be formed in the central cell. In the HIEI tandem mirror, this scenario was confirmed experimentally. By introducing a low frequency RF at the midplane, and the second harmonic resonance ion heating was examined. As a result, significant ion heating was observed, and the increment of energy density was estimated to overcome that by mode conversion heating[2]. Although good experimental results were obtained, the mechanism of ion heating has not been clarified yet.

In this paper, numerical analysis of the second harmonic resonance ion heating in the divertor configuration of HIEI was presented. The purpose of the paper is to clarify the physical mechanism of ion heating by comparing the result with the experimental result in HIEI.

In this analysis, wave propagation in two dimensions is solved by using finite difference method. Non-uniformities in the radial and axial directions are taken into account, and azimuthal variation is expressed by mode number (m). Because heating of plasma by a fast wave is caused by the finite Larmor radius effect, evaluating of wavenumbers, $k_{\parallel}$ (axial) and $k_{\perp}$ (perpendicular), is necessary. $k_{\parallel}$ is evaluated by employing the dispersion relation of cylindrical plasma surrounded by a vacuum region and a perfectly conducting cylindrical shell. $k_{\perp}^2$ is given by $k_r^2 + k_\theta^2$, where $k_r = (\partial E_+ / \partial r)/E_+$, $k_\theta = m/r$, and E_+ means left-hand polarized electric field. Using these values, power absorptions by the second harmonic resonance at each position of the $r-z$ plane are calculated.

As a result of calculation, RF field with large wavenumber was confirmed in the divertor configuration which could not be found out in the non-divertor configuration. Power absorption in the vicinity of higher harmonic resonance regions was also confirmed, and qualitative variation of absorbed power to the external field configuration was consistent with experimental results. The approximation in the expression of power absorption by the second harmonic resonance is under improvement, so a refined result and detailed discussion will be presented in the full paper.

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19P39

Numerical Study of Microwave Generation by Electromagnetic Surface Wave on Deeply Corrugated Metal Plate

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Cherenkov instability of a surface wave mode on a corrugated metal surface is analyzed numerically. Surface wave is always slow wave, because surface wave is evanescent wave to the direction away from the corrugated metal surface.[1] And the surface wave is possible to be backward wave, due to the periodic nature of the corrugation of metal surface. Thus, the surface wave mode can be excited absolute instability by the Cherenkov interaction.

A model of the numerical analysis is formed by a deeply corrugated metal plate and a sheet electron beam passing above this plate. It is assumed that there is strong guiding magnetic field in the direction of the electron beam propagation and the electron cyclotron motion is approximated to 0. The corrugation of the metal surface has sinusoidal waveform to the direction of the guiding magnetic field. The sheet electron beam is flat and has no thickness. On the each plane, the metal plate and the sheet electron beam are extended uniformly and infinitely.

To examine the characteristic features of the surface wave on the deeply corrugated metal surface, a dispersion equation was derived. Because the Rayleigh hypothesis has failed for the analysis of electromagnetic field upon deeply corrugated surface, dispersion relations are solved by direct numerical computation of wave equations. Results of this computation, it is confirmed that the surface wave mode is excite the Cherenkov instability by the slow space charge wave.

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19P40

Improved Performance of Oversized Backward Wave Oscillator driven by Weakly Relativistic Electron Beam

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We investigate a K-band backward wave oscillator (BWO) as a high-power microwave source. In BWO, a slow wave structure (SWS) is used to reduce the phase velocity of electromagnetic wave to the beam velocity. Axially streaming electron beams interact with the electromagnetic field to generate high-power microwaves. In order to increase the output power and the operation frequency, oversized SWSs are used [1-3]. The term of "oversized" means that the diameter of SWS is larger than free-space wavelength of output electromagnetic wave by several times or more. For the oversized SWS, the electromagnetic wave is localized near the wall. Hence, the electron beam should be propagated close to the SWS wall, in order to ensure the sufficient beam coupling. The output radiation also depends on the location of the interacting point in the dispersion diagrams. If the interacting point is shifted toward the upper cutoff point with $k_z z_0=\pi$ (π point), the group velocity of the electromagnetic wave decreases and the beam interaction may be improved [1,2]. Here, k_z is longitudinal wave number and z_0 is period of SWS.

In ref. [3], about 100 kW output power was obtained from a K-band BWO. We improve the performance of the K-band oversized BWO. The beam is annular and weakly relativistic. The voltage is less than 100 kV and the current is less than 500 A. The operation frequencies are in the range of 23-26GHz. The electromagnetic field of the K-band BWO concentrates in the vicinity of the SWS wall and the electron beam should be propagated within a few mm from the wall. The uniformity of beam is also very important for the efficient beam coupling. First, we modify the oversized SWS so that the beam interaction point is shifted closer to the π point than ref. [3]. The output power increases above 300 kW with this modification. By shifting the operation point to the π point, the group velocity of electromagnetic wave approaches to zero and the beam interaction may be enhanced. Secondly, we improve uniformity of the annular electron beam and the output power increases up to about 500 kW level.

In conclusion, the maximum output power of the K-band BWO driven by the weakly relativistic electron beam increases up to about 500 kW level by modifying the SWS and improving the beam uniformity. The factor Pf^2 is often used as a measure of quality of microwave sources. The best experimental data is close to $Pf^2=3.5*10^5$ [kW*GHz^2].

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19P41

Development of the ICRH system at AMBAL-M

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Ion cyclotron resonance heating is the nearest perspective for creating quasistationary hot-ion plasma in the AMBAL-M solenoid. Large diameter of the initial plasma obtained in the solenoid and the plasma density up to $6\cdot10^{13}$ cm^{-3} enabled design of an antenna capable of fast-wave heating with good wave penetration to the axis. This approach is realized using tokamak-like half-turn antennas generating $m=\pm1$ modes with a relatively narrow k_z-spectrum. Two antennas with side graphite limiters and Faraday shields have been manufactured and now the 10 MW, 2-8 MHz RF power-supply and RF diagnostics are under preparation.

19P42

Effective Excitation of ICRF Waves by Use of Phased Antennas in GAMMA 10

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Strong excitation of eigenmodes by use of phased antennas is investigated in the central cell of the GAMMA 10 tandem mirror.

Higher density plasma production is one of the most important tasks for the tandem mirror experiments. In the GAMMA10 central cell, which has the axisymmetric plasmas, the fast Alfvén waves with the ion-cyclotron range of frequency (ICRF) has been used for the plasma production. Althougth the high ion temperature above 10 keV has been realized, the density is relatively low on such a high performance discharge [1]. In the present experimental conditions, the inhomogeneity scale length of the plasma and the magnetic field configuration are in the same order of the wave length. It is indicated that the wave excitation is strongly affected by the boundary conditions such as the configuration of the antennas and the magnetic field, and the density profile. The wave is strongly excited with large amplitude when the the eigenmodes are formed [2]. It is essencial for the higher density plasma production that the eigenmodes are formed continuously in the plasma when the density is changed.

In this study, phased antennas are introduced for the effective excitation of eigenmodes. The optimum locations and the phase difference between the antennas are investigated for the several applied frequencies in the central cell. In order to evaluate the eigenmode formations of the excited waves in the axisymmetric mirror configurations, two-dimensional full wave code is used [3]. In the calculations, the setting of a pair of antennas and the phase difference are modified for the various values of the density. It is found that the optimum phase difference exists for a pair of antennas at each density. The experimental test is also performed in the central cell, and compared with the results of the numerical computations. For the higher density plasma production, it is suggested that the feedback control of the phase difference is needed during the discharge.

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19P43

Slow Cyclotron and Cherenkov Instabilities in Weakly Relativistic Oversized Backward Wave Oscillator

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The backward wave oscillator (BWO) is a high-power microwave source and can be driven by an axially injected electron beam. In order to increase the operation frequency and/or the power handling capability, periodically corrugated oversized slow wave structures (SWSs) are used. The diameter of oversized SWS is larger than free-space wavelength of output electromagnetic wave by several times or more.

In this work, we analyze slow cyclotron and Cherenkov instabilities of oversized BWO designed for K-band operations. Slow cyclotron instability as well as Cherenkov instability can be driven by axial electron beam without any initial perpendicular velocity. A self-consistent field theory to analyze these instabilities was presented in ref. [1], in which three-dimensional beam perturbation are considered properly. By applying this new version of self-consistent theory, instabilities of axisymmetric and nonaxisymmetric modes were studied for non-oversized X-band BWO case [2, 3]. For oversized SWS, the electromagnetic field is a surface wave that is localized near the SWS wall [4]. It becomes hard to analyze electromagnetic fields and instabilities.

We improve the new version of field theory to analyze slow cyclotron and Cherenkov instabilities in oversized BWO. The growth rate of slow cyclotron instability is smaller than that of Cherenkov instability. It should be noted that these instabilities are also excited for nonaxisymmetric modes by completely axisymmetric beams and that the growth rates of both modes are in the same order. Hence, nonaxisymmetric as well as axisymmetric operation of oversized BWO may occur. We examine the dependence of growth rate on the beam radius. The growth rates are the maximum in the vicinity of SWS for both slow cyclotron and Cherenkov instabilities. If the beam is apart from SWS, the growth rates decrease exponentially. The beam radius should be controlled carefully to drive oversized BWOs.

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A Steady State Cusp Plasma Device for Plasma Studies and Technological Applications

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We describe a steady state plasma machine for the production of a quiescent plasma. This facility is located at the Institute of Plasma Physics of CNR in Milano (Italy). The magnetic field confinement has a cusp configuration, which is obtained by two bundles of four water-cooled solenoids carrying electric current in opposite directions. The line cusp radius is 19 cm with a peak magnetic field intensity of 0.25 T. The length between the two point cusps is 78 cm with a magnetic field intensity of 0.4 T.

The plasma is generated by microwaves at a frequency of 2.45 GHz with power up to 1000 W, the waves are launched through a quartz window situated near one point cusp and absorbed at the resonance regions (where the magnetic field strength is 87.5 mT) located close to the center of the cusp device. Gas is fed continuously by a mass flow controller and pumped out by turbo molecular pumps, keeping a constant gas pressure between 10^{-3} and 10^{-2} Pa. Additional radiofrequency power (frequencies 1-16 MHz, 10 kW maximum power) can be coupled to the plasma by means of two ring shaped electrodes, which enclose the thin plasma at the line cusp.

Langmuir probes, provided with linear motion drives, determine plasma density and temperature profiles at the line cusp. Depending on the gas pressure and applied microwave power, the electron density for argon gas is between 10^{10} and 10^{11} cm^{-3}, with electron temperature up to 10 eV. Emission spectroscopy and gas mass analyzers provide additional plasma and gas diagnostics.

The main experimental activities that have been carried out with this facility, concern basic plasma physics studies (characterization of cusp plasmas, low frequency plasma fluctuations in presence of dust particles) and technological applications (hydrogen formation by methane cracking, production of hydrocarbon (a-H:C) film).

In future activities rf power will be applied to the ring plates with frequencies close to the ion cyclotron frequency with the purpose to study ponderomotive force effects, and ion species separation. These investigations are of prominent interest in fusion technology for the impurity processing of the exhaust mixture pumped out from the vacuum vessel of a tokamak like ITER.

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Radial electric fields and radial currents in the gas dynamic trap

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Application of electrostatic potential to limiters and/or end-plate sections in an open mirror like the GDT can be used for plasma stabilisation. However, it is not yet clear why it affects plasma so drastically and how external fields can influence the plasma interior. Obviously, it is necessary to understand what mechanisms are responsible for formation of an internal profile of potential as a result of a change in the potential of the limiter. Such processes should include radial currents and transport of the angular momentum.

A related problem exists for the multi-mirror trap GOL-3, where application of the limiter potential is used for formation of an initial plasma current, which, again, has a radial component. In some phases of a discharge in GOL-3 at least a part of the longitudinal current is closed radially.

In this report we present experimental measurements of radial fields in the GDT and theoretical interpretation of the data. What is the profile of the ambipolar potential along any field line in an open trap is well understood. If there are no radial currents, and the end plate is conductive and grounded the plasma potential results completely defined. In this case the limiter potential should have no effect on the potential distribution. Experimentally this is not the case. In other words there is a radial correlation between potentials on different field lines that is not due to currents in the end plate. Thus there are radial currents in the plasma itself. For the effect on potential to be observable the current has to be large: the total radial current should be comparable to longitudinal currents to the end plate. If the radial currents depend on radial electric fields, we find the mechanism of transfer of potential from the limiter into the plasma column.

It should be noted that radial currents in axisymmetric configurations result in uncompensated azimuthal Lorenz forces. In a quasi-stationary case, such as in the GDT, this is possible only in presence of the radial flow of angular momentum (due to an effective turbulent viscosity) or in presence of the outflow of the momentum along the magnetic field (due to plasma flow through the mirrors). Estimate of a possible longitudinal loss of momentum limits the maximum radial current to a small fraction of the longitudinal current of ions to the end plate, so that the ambipolar balance on each field line is shifted insignificantly. Thus the only realistic explanation of experimental observations in the GDT is the turbulent transfer of angular momentum. Estimates of the required level of turbulence and comparison with experimental data on turbulence are presented.

Radial fields in the GOL-3 device are highly variable, while the radial currents, which can be deduced from charge conservation, are much higher than any momentum transfer can explain. Thus the plasma angular momentum probably varies in time resulting in excitation of alfven waves.

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Influence of radial electric field on high-beta plasma confinement in the gas dynamic trap

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One of the most important aspects of the GDT research program is achievement of the MHD-stability of its high-pressure two-component plasma. In recent experiments good radial plasma confinement was realized by using biased limiters and without any other special MHD-stabilizers. The report presents experimental and theoretical analysis of possible mechanisms responsible for this apparent stabilisation. One possibility is stabilisation due to line tying to limiters, the second one is plasma differential rotation caused by the limiter biasing. Resistance of the Debye layer near the radial limiter is experimentally measured. It was shown that the observed MHD-stable mode of operation couldn't be completely provided by the plasma line tying to limiters.

Experimental studies of influence of the radial electric field in the plasma scrape-off layer on MHD-stability were carried out. By appropriate biasing of the radial sections of the limiters ~40 V jumps of potential near the plasma surface were produced, i.e., resulted in differential rotation. Then it was observed that the plasma lifetime is considerably (1.5 times) increased. This experimental observation indicates that the differential rotation either considerably reduces the increment of MHD-instability (as is predicted by linear theory), or else it just increases radial decorrelation in turbulent states (as is probably the case in transport barriers in tokamaks).

Identification of the stabilisation mechanism depends on detailed measurement of the radial profile of the electrostatic potential, as well as fluctuation spectra. Discussion of how the biased external limiters may influence plasma potential in inner regions, what its radial profile should be like in quiet and turbulent plasmas, and what is actually measured is set in our separate report. In short, profiles of the potential are consistent with the "turbulent" plasma model, even in regimes with "good" radial confinement. Fluctuation measurements show an order of magnitude decrease in their level with transition from "bad" to "good" confinement. Thus it seems likely that the observed improvement of radial confinement is similar to formation of "transport barriers" in tokamaks rather than indicates a true plasma stabilisation.

At the moment, initial experiments to measure spatial and temporal variation of plasma parameters in this regime of confinement are carried out. A probe, which allows one to measure a transverse particle flux and plasma diffusion coefficient, is deployed. Additionally, an array of plasma dumps, to which the ion current can be independently measured, is installed at the end wall in the end tank. The purposes of these experiments are to estimate the influence of radial electric field on transversal transport and to find the radial potential, which is optimal for confinement. Relationship between plasma confinement time and radial potential profile is studied experimentally.

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Effects of Plasma Confining Potentials and the Associated Radially Sheared Electric Fields on the Plasma Energy Confinement

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The effects of the plasma-confining potentials and the associated radially sheared electric fields on the central-cell plasma energy confinement are theoretically and experimentally investigated in the GAMMA 10 tandem mirror [1]. In particular, the scaling of the central-cell plasma temperatures with plasma-confining potentials is studied on the basis of the local energy-balance equation. The obtained theoretical scaling of plasma temperatures with plasma-confining potentials [2] is then compared with the experimentally observed relation between these two parameters.

Recently, by the use of new 0.5-kW level gyrotrons [2] in the plug region, four-time progress in the formation of the ion-confining potential ϕ_c including a new record of 3 kV has been achieved in a hot-ion mode having bulk-ion temperature T_i= several keV [1]. In the hot-ion mode, intermittent vortex-like turbulent structures are observed in the case without the plug gyrotron injections; in this case, radially produced *weak* shear of electric fields dE_r/dr and appreciable transverse losses are observed [1]. However, during the application of electron-cyclotron heatings in the plug region, the associated potential rise produces a stronger shear in the central cell (dE_r/dr = several 10 kV/m^2) resulting in the disappearance of such intermittent turbulent vortices with plasma confinement improvement [1,3].

In order to investigate the effect of the radially sheared electric fields on the plasma energy confinement, the radial profiles of the thermal diffusivity [4] are derived from the local power-balance analysis by the use of the data from the following various diagnostics in the above-described hot-ion mode (that is, diagnostics including the "matrix-type" semiconductor detector array [5], the end-loss ion-energy spectrometer arrays [6], the gold neutral beam probes (HIBP) [7], the standard microwave interferometer arrays, as well as the standard H_a detector arrays). The obtained radial profiles of radial electric field and thermal diffusivity imply that the reduction of the thermal diffusivity is associated with the radially produced *strong* shear of electric fields.

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First experiments with upgraded neutral beam injectors on the GDT device.

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Abstract

The Gas Dynamic Trap (GDT) approach to a fusion reactor suggests the possibility of collisional plasma confinement in a long axisymmetric mirror device with a high mirror ratio. The GDT neutral beam system consists of six "START-3" injectors that are azimuthally arranged in two groups on opposite sides of the central cell. The current of each neutral beam injector is about 40-45 eq.A, the energy of neutrals lies in the range 16-17 keV, the duration of the neutral beam pulse is 0.8-1 ms and the total power exceeds 4 MW. The angular divergence of the neutral beams is about 1° in direction perpendicular to the machine axis and 2.5° along the axis. Typical parameters of the GDT experiment: temperature of the target plasma up to 100 eV; peak density fast ions up to $2x10^{13}$ cm^{-3} with mean energy 10 keV.

To increase the GDT plasma parameters, the upgrade of the neutral beam heating system was proposed. To realize this approach, a modern high power neutral beam injector with the atom's energy 20-25 keV and beam current 50 eq.A at four-millisecond pulse was developed. This paper presents the results of first test of the new neutral beam heating system for the Synthesized Hot Ions Plasmoid (SHIP) experiment on the GDT.

High-power 5 ms neutral beam injector for plasma heating

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Abstract

The paper describes an ion source developed for upgrade of the neutral beam system of the GDT device. The ion source provides 25keV, 60A proton beam with pulse duration of 5ms. The source design is similar to that of the 1.2 ms neutral beam injector [1] previously developed for plasma heating in the MST device. In the ion source, four electrodes, multi-hole ion–optical system (IOS) with diameter of 200 mm is used for proton beam extraction and acceleration. The grids are made of 0,5 mm thick molybdenum plates, which have spherical shape for geometrical beam focusing. Minimal beam diameter was measured to be 5 cm at the 1/e level at the distance of 170 cm from the grids. It corresponds to angular divergence of about 15 mrad. Plasma emitter in the source is produced by a plasma jet diverging from anode orifice of an arc-discharge plasma generator with discharge current up to 1000 A. The plasma jet diverges into a chamber with peripheral multipole magnetic field. Some fraction of the plasma is reflected by the peripheral magnetic field, so that uniformity of plasma flow at the plane of the 1st grid is better than ±10 %. Measurements indicate that the beam contains more than 90 % protons.

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Experiments in the Hanbit Mirror Device with the Kinetic Stabilizer

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The Hanbit device is a magnetic mirror machine which has a central cell, one anchor cell and one plug cell plus associated vacuum chambers. It is about half of the original TARA mirror device from MIT. The Hanbit device has been involved in a series of experiments on stabilization of the MHD flute type mode. Earlier work [1] showed that it was possible to stabilize the m=-1 flute type MHD instability with RF power near the cyclotron resonance and this was attributed to the sideband coupling process. We have now undertaken investigations to see if the Kinetic Stabilizer (KS) of R. F. Post [2-5] can stabilize this MHD instability. The concept is an outgrowth of work by Ryuthov [6] and is also based on the original idea of Rosenbluth and Longmire [7]. According to the theory, by locating a stabilizing plasma pressure on the field lines at a region with a strong second derivative and large radius in the expanding field region outside the mirrors, the main plasma in the mirror central cell in regions with unfavorable field line curvature can be stabilized. Consider the stability integral:

$$I = \int_{L}^{L} a^3 \frac{d^2 a}{dz^2}\left[p_{\perp} + p_{\|} + \rho v^2\right] dz > 0$$

Here a is the outer radius of the plasma, z is the axial distance, $p_{\|}$ is the perpendicular plasma pressure, $p_{\|}$ is the parallel plasma pressure, ρ is the plasma mass density and v is the plasma flow velocity. The integral is from one end of the device [-L] to the other [+L]. If the integral is positive, the plasma will be stable.

The original idea of Post was to inject low energy ion beams along field lines in the expanding field section at the end of the device. The ions would stagnate in the increasing field and provide the stabilizing plasma pressure. The Hanbit KS uses microwave produced plasmas on field lines in the cusp tank region. Two coils on the cusp tank are configured to produce expanding field lines with a large positive radius of curvature. A 5-kW 2.45 GHz magnetron is used to produce the stabilizing ECRH plasma pressure in this region. Details of the experimental arrangement and stabilizing plasma parameters were previously reported [8]. The anchor coils are turned off for the experiments. A reduction in the instability duration has been observed. The range of density where the instability occurs has also decreased. More microwave power is expected this year. Experimental details will be presented.

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Stability analysis of flute interchange mode in GAMMA10 divertor configuration

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At the Plasma Research Center, the plan which installs the divertor magnetic configuration on the GAMMA10 tandem mirror is progressing. In order to design the magnetic divertor the calculation of plasma equilibrium (in order to estimate beta-limit in equilibrium) and flute interchange stability (which is necessary to estimate beta-limit of stability) and radial transport (which is very important to understand the axisymmetrical benefit). In this paper, we derived the fundamental equation for stability solution of flute mode. Furthermore, we applied that equation to divertor magnetic fields of GAMMA10 and determine the stability boundary. In particular, this stability analysis is new equation that takes into account ion finite-Larmor-radius effect, the correct curvature of nonparaxial magnetic fields, and an anisotropic ion distribution function ($T_{i\|} \neq T_{i\perp}$).

Anomalous fast heating of ions in GOL-3 facility

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An investigation of plasma heating and confinement in a long open trap is carried out at the GOL-3 facility in the Institute of Nuclear Physics. The facility consists of multimirror trap with corrugated magnetic field and generator of high-current relativistic electron beam being used for heating of dense deuterium plasma placed in the magnetic field.

High effective plasma heating is observed in multimirror magnetic field. The electron temperature reaches 2-4 keV for plasma density ~$3\cdot10^{20}$ m^{-3} and electron beam with energy of 0.8 MeV, current of 20 kA and duration of 8 μs. The electron temperature of plasma decreases to ~100 eV during ~30 μs after the beam pulse. Ion energy increases up to some keV during the beam pulse. This fast transfer of energy from electrons to ions can not be explained by classical Coulomb *e-i* collisions for used plasma density, because the classical energy exchange time ($\tau_{class} \geq 1$ ms) is much greater than observed in the experiment ($\tau_{exp} \leq 10$ μs).

The paper consists of review and analysis of experimental facts that prove an anomalous character of ion heating in multimirror trap GOL-3. It considers some estimates and model of the phenomenon that explain its nature.

The work is partially supported by RFBR Grant 04-01-00244.

Use of pellet injection technology at GOL-3 for plasma fueling and plasma-surface interaction research

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A pellet injection technique is used at GOL-3 multimirror trap for the solution of several physical problems. Earlier use of small impurity pellets (CH_2, LiD) for the purposes of plasma diagnostics and for formation of dense plasma bunch inside the main plasma column was already discussed (see, e.g. [1]). In the report other two topics of the pellet injection activity will be presented.

The first topic is connected with continuing reactor-relevant studies of influence of a high-power pulsed stream of electron-hot plasma on solids (see, e.g., [2]). The new problem of expansion of dense target plasma along the magnetic field through a several-meters distance was investigated. A carbon pellet of 2-mm diameter was exposed to ~50 MJ/m^2 energy flow of a beam-plasma system. The purpose of the experiments was to simulate behaviour of surface plasma in reactor-class tokamaks during ELM events.

Other physical problem for pellet injection is the increase in plasma density near the axis of GOL-3. Now achievable density is limited by decrease of conductivity of a preliminary (start) plasma and respective deterioration of compensation of a current of heating relativistic electron beam with a plasma return current that leads to disruption. In the report the status of works on cryogenic pellet injector which is developed jointly by BINP and SPbSPU will be presented.

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Transverse loses and Z_{eff} measurements at GOL-3 facility

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Plasma heating and confinement in the multimirror magnetic field is investigated at GOL-3 facility in Budker Institute of Nuclear Physics, Novosibirsk. Plasma with density ~10^{15}cm^{-3} is heated by relativistic electron beam (1 MeV, 8 μs, up to 200 kJ). After heating stage plasma temperature exceed 1 keV.

Key challenge of these experiments is determination of energy confinement time and channels of energy loses from the trap. In the paper analysis of transverse loses was presented. Spectroscopic study of plasma radiation in visible and VUV spectral ranges allow to find concentration of impurities in plasma and flux of neutrals from hot plasma core. Value of neutral transport and full radiation loses calculated using STRAHL code were compared with bolometric measurements of heat flux to the wall. Transverse diffusion coefficient has estimated by spatially resolved measurements of spectral lines intensities.

In GOL-3 the effective charge is determined by light impurities. Calculation gives estimation for Z_{eff} of 1.2-1.6. The value Z_{eff} influences to collision frequency and hence plasma confinement time. Comparison of measured and predicted confinement time [1] points to non-classical mechanism of longitudinal transport in multimirror trap.

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Visible Light and H_α Imaging of Mirror Confined Plasmas in the Central Cell of GAMMA 10

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Recent technical development of imaging systems, especially charge coupled device (CCD) cameras, facilitated their use for the field of plasma science [1,2]. Here, an imaging system with a progressive scan CCD camera and a mirror polished stainless steel was employed to observe low frequency fluctuations in a mirror confined plasma in the central cell of GAMMA 10. The SUS mirror was used to improve the line of sight of the CCD camera. It was found that strong plasma-limiter interaction resulted in the undesirable stored energy loss and emission of light. With the aid of a pair of electrostatic probes (ESP's) installed on the limiter [3], the properties of excited fluctuations have been investigated.

Further investigation with an improved imaging system associated with ESP's and a visible light detector is necessary, because the higher stored energy with the higher electron temperature may lead to the stronger plasma-limiter interaction.

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Effect of magnetic configuration on the neutral particle recycling in Compact Helical System

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Neutral particle transport is an important issue not only to study plasma particle/energy balance but also to improve core plasma confinement. Dominant neutral particle source is due to the recycling at the first wall, limiter, and divertor plates. In devices such as Stellarator/Heliotron, nested magnetic surfaces are sourrounded by the so-called separatrix layer, which consists of open field lines with various connection length to the vacuum chamber wall and/or divertor plates.[1] The complicated ergodic properties of the separatrix layer and the divertor whisker structure are thought to change with the magnetic axis shift or the plasma beta effect.

Recently, the DEGAS neutral transport simulation code(ver.63)[2] has been applied to evaluate neutral density profile in Compact Helical System (CHS) in NIFS.[3] By shifting the magnetic axis position along torus outward direction in CHS, magnetic configuration for the plasma confinement changes from the material limiter to the magnetic divertor. The distribution of neutral recycling on the vacuum vessel is also expected to change with the magnetic axis shift.

In the so-called standard configuration, the configuration is the limiter like, and the recycling occures the inner wall of vertically elongated polodal cross sections, where core plasma has direct contact with the vacuum chamber. According to DEGAS simulations, neutral atomic/molecular density has a peak there.

In outward shifted configuration, however, the distribution of recycling source is not so clear. If their toroidal/poloidal distribution is changed, neutral particle transport will also be affected. We use the simulation results of magnetic field line tracing and are developing the model on the distribution of the neutral particle recycling.

Details will be presented and discussed on the confference.

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Analysis of Neutral Transport in fully 3-Dimensional Geometry in the GAMMA 10 Tandem Mirror

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Analysis of neutral transport is essential to study a global particle balance or appropriate plasma fueling for fusion devices. In the GAMMA 10 tandem mirror, hydrogen Balmer-α (Hα) line detectors and high-speed cameras have been installed for the measurement of neutral particles. Monte-Carlo simulation code (DEGAS) [1, 2] has been applied coupling with the experimental results, which is useful method for us to analyze the detailed neutral transport.

In the central cell of GAMMA 10, antennas for wave heating (ECRH or ICRH), gas puffers, limiters configured with nonaxisymmetric shapes exist within the vacuum vessel. These objects affect the behavior of neutral particles. In addition, neutral flux accompanied by NBI or pellet injection must have a characteristic distribution which is different from that of gas puffing [3, 4]. Therefore, fully 3-dimensional geometry for DEGAS code was newly applied in order to achieve the detailed neutral transport. Fig.1 shows the DEGAS mesh model. In this model, almost all objects of the central cell are completely implemented in realistic configuration. Moreover, the test particles simulated as NBI are given with the high energy and one-directional velocity.

Based on the above measurement and DEGAS simulation, neutral transport during the gas puffing and NBI in the central cell is investigated. The predicted Hα profile using DEGAS well explained the experiment. The behavior of Atomic and molecular hydrogen behaviors are quantitatively analyzed in the plasma core and edge. It is clarified that the localized source has much influence with the behavior of neutral particles in the plasma. In the paper, detailed discussion has been shown from the view point of both the experiment and the simulation.

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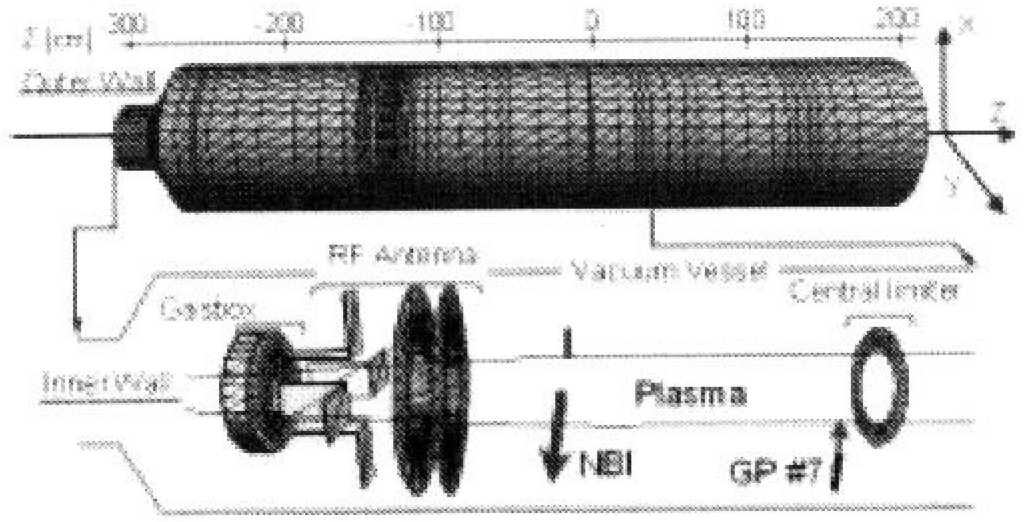

Fig.1 DEGAS mesh model

19P58

On the ion radial diffusion in the end-mirror cell of GAMMA10 analyzed by mapping equation

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For the magnetic field of GAMMA10, the existance of the nonaxisymmetric electrostatic potential in the plug region can yield the ions radial loss in the thermal barrier cell theoretically [1,2] . Numerical calculation using the differential equation for ion drift motion reveals that the ion orbits show the transition from the regular to the chaotic as the nonaxisymmetric electrostatic potential increases [3]. The detailed ion behavior in the nonaxisymmetric potential and its contribution to the transport is not known in GAMMA10.

In this study, by modeling the plug potential and the actual magnetic field in the end-mirror cell and estimating the amount of radial shifts of ions by following ion drift motion per bounce, the resultant mapping equations is used to analyze the transport. Because the mapping equation makes an understanding of the ion radial behavior easier in comparison with the differential equation, the local structure of ion orbits or the behavior in the neighborhood of a fixed point can be studied at length, and the relation between the initial conditions and the unstable behavior can be also investigated [4]. Furthermore, the mean-square displacement of the trapped ions are calculated, then the global diffusion is estimated numerically.

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19P59

Rotation of a field-reversed configuration plasma due to resistive flux decay

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Rotation of a Field-Reversed Configuration (FRC) plasma due to resistive flux decay is numerically studied. End-shorting [1] and particle loss have been considered so far as two most promising mechanisms to rotate the FRC. Recent hybrid simulation shows that weakly-confined plasma ions are gradually lost as the poloidal flux decays [2]. Since the lost ions have a preferred sign of their angular momentum, the remaining plasma acquir a rotational motion by low of action and reaction.

The present study will, however, show that rotation can take place without particle loss. A toroidal electric field induced by resistive flux decay can accelerate betatron particles moving near the field-null. Moreover, in an axisymmetric case the canonical angular momentum is conserved, and a decrement of the poloidal flux changes to an increment of the kinetic angular momentum. Therefore, a FRC plasma can start to rotate due to resistive flux decay alone without particle loss.

Single-particle motions in a quasi-steady resistively decaying FRC equilibrium are calculated numerically. A local flow velocity is estimated by a particle-in-cell method. Comparison with information of particles lost out of the mirror end can explain contribution of a rotational motion without particle loss. Relationship between a rotational motion and a plasma temperature, a current profile, and a resistivity will be reported.

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19P60

Investigation of translation process of FRC plasma using computer tomography of two different cross-sections on FIX

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The field reversed configuration (FRC) is considered to be a promising candidate for the D-^{3}He fusion reactor because of its high β value. Mostly, FRC plasmas are produced in theta pinch devices which are made of a quartz discharge tube and massive high voltage pinch coils. The accessibility of the plasma to heating facilities is so bad that heating experiments of FRC plasmas have been scarcely carried out so far. On the FIX device, the FRC plasma produced in a quartz tube is translated to a metal confinement chamber. As a result of the translation, the accessibility to heating facilities is greatly improved.

Investigation of the translation process is the subject of intense study, related to many interesting phenomena, such as the spontaneous toroidal field [1], the shock wave formation at the reflection by the magnetic mirror, and the rethermalization [2]. In those previous papers [1,2], the translation process was investigated by measuring the time evolution of the separatrix radius profile in the axial (z) direction. Although the behavior of the FRC plasma during the translation in the x-y plane perpendicular to the device axis is also important because of the frequent appearance of instabilities such as the n=2 rotational instability. For this purpose, computer tomography (CT) seems to be one of the most powerful techniques. Previously, we have reported the measurement result of the translation of the FRC plasma using a CT apparatus [3,4]. In order to understand the translation process of FRC plasmas, CT measurement at only one cross-section seems to be insufficient and measurement in the z-direction is desirable. Therefore, we have installed two sets of CT systems on the FIX device. One is installed at the entrance section and the other is located at the end section of the confinement region. Each system is composed of three detector arrays. Each array consists of an optical filter and two pieces of 16-channel photodiode array. The spectral sensitivity range of the system is λ = 720-1100 nm. To avoid light reflection at the vacuum wall, a black anodized aluminum panel is installed just inside of the metal chamber. The Fourier-Bessel expansion technique is employed to reconstruct the two dimensional distribution of the light emissivity. The reflection of the plasma by the magnetic mirror field is clearly shown by the temporal evolution of reconstructed images. Furthermore, it is shown that the translated FRC plasma displaces from the center of the FIX device in some cases. The experimental results show that the location of the peak of the reconstructed profile of the light emissivity at the upstream side is similar to that at the downstream side, namely, the FRC plasma is displaced in the radial direction as one body without tilt.

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19P61

Heating and particle build-up of field-reversed configuration due to neutral particle injection in a translation process

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A field-reversed configuration (FRC) has an attractive attention as a future reactor core for D-D and D-^{3}He fusion reaction because of its extremely high beta nature[1]. The magnetic configuration of FRC has a center closed region and surround open field region. Because of this geometrical property, a FRC can be translated from formation theta-pinch region into confinement region while it keeps the closed magnetic field. Field-reversed theta-pinch (FRTP) is most appropriate formation technique for high-beta FRC. However, the plasma parameter formed by FRTP method, *i.e.* very high density of ~10^{21}m^{-3}, is not suitable for application of additional heating method of neutral beam injection. Because of high beta nature of FRC (*i.e.* very low magnetic field), NBI is the only candidate for sustainment of steady-state operation.

For the effective application of NBI, the plasma parameters have to be changed into lower density ~ 10^{20}m^{-3}, higher trapped flux and larger plasma volume. In this work, the "equivalent" NBI in the translation process has been proposed as a heating and particle injection method for FRC. Translating a FRC plasma through a neutral gas background is equivalent an end-on NBI into the FRC. The estimation has been performed for the FRC plasma produced on NUCTE (Nihon University Compact Torus Experiment) device[2]. The typical plasma parameters in a formation region are electron density $n_e \sim 3 \times 10^{21}$m^{-3}, total temperature T_t ~ 300eV and poloidal magnetic field at separatrix $B_z(r_s)$ ~ 0.4T. For these parameters of plasma and translation velocity of ~100km/s (equivalent kinetic energy ~ 100eV), most likely atomic and molecular process are an electron impact ionization on deuterium molecule and atom, an electron impact dissociation on D_2^+ and charge exchange process. A characteristic length of the ionization of the injected D_2 molecule is about ~10mm under the assumption of uniform density distribution of 3×10^{21}m^{-3}and electron temperature of 100eV. The gyro-radius of the ionized ion is ~ 3mm and it is much less than plasma radius of ~ 50mm. Therefore, at least particle injection effect can be expected by this "equivalent" NBI. Other effects depend on the conditions of background neutral particle density and translation velocity of FRC. For the neutral particle density of 1×10^{20}m^{-3}, translation velocity of 100km/s and translation length of 1m, the particle number of ~ 3×10^{18} and the kinetic energy of ~ 40J are supplied due to the equivalent NBI.

Detailed estimation considering magnetic configuration, distribution of background neutral particles, electron density and rate equation have been performed and will be presented together with the preliminary experimental results performed on NUCTE device.

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19P62

A self-consistent beam-plasma equilibrium of a Field-Reversed Configuration

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An equilibrium state of a Field-Reversed Configuration (FRC) is obtained numerically, where three-fluid equations of motion are used; those are for ions, electrons, and beam particles.

In FRC researches, an equilibrium state of a beam-plasma system is discussed by a generalized Grad-Shafranov equation derived by Finn and Sudan [1]. A recent simulation study [2, 3] for neutral beam injection into an FRC plasma also used the Finn's Grad-Shafranov equation including a beam current term. According to a paper written by Yoshida [4], however, the pressure function can never be written by the flux function alone, since the centrifugal force of a beam-fluid modifies the conventional and Finn's Grad-Shafranov equation.

The equilibrium equation used in this study is basically the same as the Yoshida's model. With the aid of the three-fluid equations, however, more detailed results such as an electric field profile and a pressure ratio (ion/electron) can be obtained. Moreover, a balance condition of toroidal forces (i.e., the friction forces) is considered here. Otherwise, ions can acquire the toroidal angular momentum; this is inconsistent with an assumption of the non-flowing plasma.

The beam fluid density and flow velocity are given from the calculation of single particle orbit and the particle-in-cell method. A solution to the Grad-Shafranov equation is used as an initial guess. An iterative calculation is done until the total force balance equation is satisfied.

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19P63

Axisymmetric tandem mirror magnetic fusion energy power plant with thick liquid-walls*

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A fusion power plant is described that utilizes a new version of the tandem mirror device including spinning liquid walls. The magnetic configuration is evaluated with an axisymmetric equilibrium code predicting an average beta of 60%. The geometry allows a flowing molten salt, (flibe–Li_2BeF_4), which protects the walls and structures from damage arising from neutrons and plasma particles. The free surface between the liquid and the burning plasma is heated by bremsstrahlung radiation, line radiation, and by neutrons. The temperature of the free surface of the liquid is calculated, and then the evaporation rate is estimated from vapor-pressure data. The allowed impurity concentration in the burning plasma is taken as 1% fluorine, which gives a 17% reduction in the fusion power owing to D/T fuel dilution, with F line-radiation causing minor power degradation. The end leakage power density of 0.6 MW/m^2 is readily handled by liquid jets. The tritium breeding is adequate with natural lithium. A number of problem areas are identified that need further study to make the design more self-consistent and workable; however, the simple geometry and the use of liquid walls promise the cost of power competitive with that from fission and coal.

Numerical Study of Charge Separation of Cusp DEC Installed at GAMMA 10

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1. Direct Energy Converter

A small-scale cusp type direct energy experimental converter has been designed and fabricated to examine separation characteristics of charged particles by a cusp magnetic field. Recently, the experiment that uses the end loss electrons and protons from the GAMMA 10 has started. The objective of the present study is to analyze separation capability of charged particles of the small-scale cusp type direct energy experimental converter under the experimental condition of GAMMA 10 by means of numerical simulation with two-dimensional approximation.

2. Numerical Modeling[1]

The basic equations used in the two-dimensional (r-z-plane) analysis, which are formulated with the cylindrical coordinates, are Poisson's equation for the electric field, and the momentum conservation equations for protons and electrons. Poisson's equation is solved using Galerkin Finite Element Method. The momentum conservation equations for protons and electrons are analytically solved within an FEM element used for the electric potential. The guiding-center approximation is used for electrons.

3. Numerical Results

Figure 1 shows characteristics of proton's input power and the separation rate, which is defined as a ratio of the number of protons that reach probe 3 and probe 4 per unit time to the number of protons that are injected into Cusp DEC per unit time. When proton's input power is less than or equal to 1W, the separation rate is 100%. On the other hand, the separation rate becomes about 5% when proton's input power is 5W.

Figure 2 depicts trajectories of the protons and the electrons, which are injected when the Cusp DEC becomes in the steady state. The electrons of which radius of incidence is small become trapped in the vicinity of separation point. These results depend on magnitude of self-induced electric field, which is formed in the vicinity of separation point.

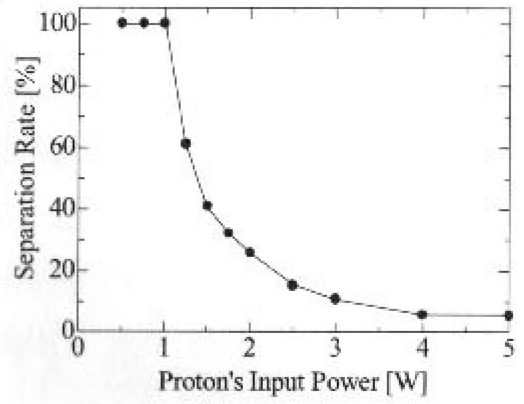
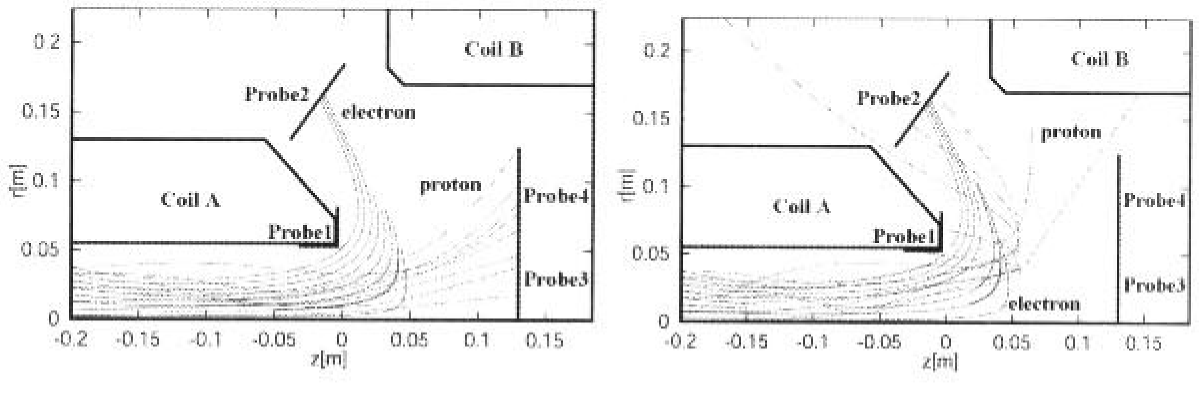


Fig.1. Characteristics of proton's input power and separation rate



(a) proton's input power: 1W

(b) proton's input power: 5W

Fig.2. Trajectories of protons and electrons

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Performance Analyses of Newly Designed Helmholtz DEC with Commercial Scale

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1. Large-Scale Direct Energy Converter

If the D-^{3}He fusion is realized, the direct energy converters (DECs) become very attractive, and possibility of large-scale DECs must, therefore, be studied. Then the fusion protons (14.7MeV), thermal ions (160keV) and electrons must be separated each other and their kinetic energy must be also converted into electricity. The present study intends to analyze separation capability of charged particles of a newly proposed large-scale Helmholtz type DEC with input energy of 250 MW.

2. Mathematical Model and Numerical Schemes

The basic equations used in the present analyses are formulated with the cylindrical coordinates with two-dimensional approximation on the r-z-plane, because the whole facilities including DECs are axi-symmetric. Poisson's equation is the basic equation for the electric field, which is solved by using Galerkin Finite Element Method with the first order triangular elements, whereas the momentum conservation equations for protons and electrons are analytically solved within one FEM element used for the electric potential. The guiding-center approximation is used for the electrons [1].

3. Calculation Results and Discussion

Figure 1 shows trajectories of the thermal ions and the slow electrons, where the plasma diameter is 1.2 m, and the anode and cathode are grounded. Even when the electrodes are grounded, the thermal ions are pulled to the cathode due to the induced electric potential, resulting in the separation rate of about 59%. It is found that the energy conversion efficiency becomes about 16.5 % when the anode voltage is 100 kV.

Figure 2 depicts trajectories of the fusion protons and the fast electrons. The fusion protons can pass through the Helmholtz DEC and go into the TWDEC which can convert the kinetic energy of protons into electricity. This is because the kinetic energy of the fusion protons is 14.7 MeV, being much higher than the induced electric potential of about 160 kV. The separation rate is 100%.

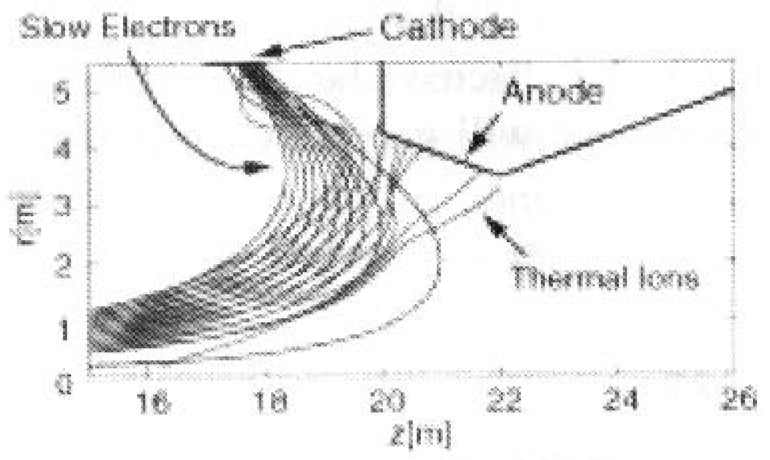

Fig1.Trajectories of thermal ions and slow electrons.

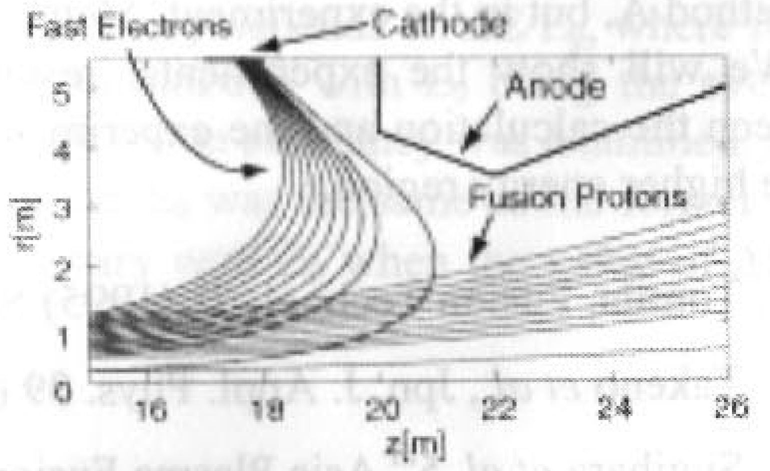

Fig.2. Trajectories of fusion protons and fast electrons.

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19P66

Optimization of Decelerator Structure of Traveling Wave Direct Energy Converter Simulator for D-^{3}He Fusion

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In D-^{3}He fusion, most of fusion energy is carried by created protons, so the direct energy conversion is an important subject for fusion reactor. Energy of the proton is 14.7 MeV, which exceeds an engineering limit for a conventional electrostatic converter. Concept of traveling wave direct energy converter (TWDEC) is applied for the purpose to construct an energy converter with less handing voltage and higher efficiency.

A TWDEC consists of a modulator and a decelerator. In the modulator, a radio frequency electric field provides the high-energy proton beam with velocity modulation. The velocity-modulated proton beam bunches in the downstream, and is guided into the decelerator. The decelerator is an array of electrodes connected to a transmission circuit. The introduced velocity-modulated beam excites a radio frequency potential on the electrodes by electrostatic induction, and a traveling wave is created. The field of traveling wave decelerates the beam, thus the energy of proton is converted into electric energy. Several numerical simulation studies of TWDEC have been performed and conversion efficiencies of around 70% have been reported [1]. Experimental verification is also necessary for detailed design of TWDEC. The authors are continuing experimental studies and this paper treats a subject of structure of decelerator.

We produce an experimental device in which fast protons were simulated by accelerated helium ions. In the original TWDEC, deceleration field is induced by proton beam. In our simulator, however, the beam is so weak that the induced field is insufficient to examine the structure of decelerator [2]. Therefore, the deceleration experiment was performed by the externally excited traveling wave. To improve the conversion efficiency, we optimized the structure of decelerator which provided matching between beam velocity and velocity of traveling wave in the decelerator. Two methods are given to realize it. One was optimization by adjusting the phase difference between electrodes (Method A) [3]. The other was optimization by adjusting the axial position of the decelerator electrodes with a fixed phase difference (Method B). In this paper, we compare two methods.

As a result, when the length of decelerator designed by methods of optimization was changed, the higher decreasing rate of averaged beam energy was measured with the longer decelerator length. In the numerical calculation, Method B was superior in the decreasing rate to Method A, but in the experiment, Method B was inferior to Method A.

We will show the experimental results in detail and discuss the cause of difference between the calculation and the experiment. In addition, we will give an experimental result in the higher energy region.

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[3] K. Sugihara *et al.* 5th Asia Plasma Fusion Association (2005) TP22.

19P67

Research on Characteristics of Particle Discrimination and Direct Energy Conversion for Cusp Direct Energy Converter

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In a D-^{3}He fusion reactor, most of produced energy is carried by charged particles, so direct energy conversion is expected. It is necessary to discriminate electrons from other ions to produce electric power. On this account, the authors suggest a means to separate electrons and ions in cusp magnetic field. The electrons are deflected and guided along the magnetic field line to the line cusp, while the ions pass through the point cusp, because both mass is quite different from each other. This device is called as CUSPDEC.

The authors are continuing experimental studies on CUSPDEC. We use an experimental device, which consists of a low-energy plasma source, a guide field section, and a cusp magnetic field section. The device is capable of changing the curvature of the cusp magnetic field from normal one to slanted ones. We inject a plasma beam with ions accelerated up to a few keV into the slanted cusp field to simulate the separation of electrons and ions. It also can examine direct energy conversion process of separated ions.

In previous works[1], we have presented that ions which have high velocity and heavy mass are not influenced by the magnetic field and that electrons in strong magnetic field cannot pass the point cusp region as predicted by the numerical analysis based on the Störmer potential[2]. As for direct energy conversion, we also examined the relationship between energy distribution function and conversion efficiency. In this paper, we present a kind of scaling of particle separation and results of direct energy conversion in higher energy region.

According to the theory of the Störmer potential, the orbit of charged particles are characterized by a value of $|qA_0/mv_0|$, where q and m are charge and mass of particle, and A_0 and v_0 are azimuthal component of vector potential and velocity at injected point, respectively. We examined the relation ship between this value and transmission ratio, which was defined as ratio of particle flux at an injection point and that in the downstream of cusp point. A clear relationship was found and the transmission ratio decreased as $|qA_0/mv_0|$ increased for wide range of parameters. When we apply this scaling to fusion parameters, the transmitted electrons and ions are estimated to 10-20% or less and 60-70% or more, respectively.

As for the direct energy conversion, conversion efficiency depends on $\Delta E/E_0$, where ΔE is the full width half maximum of the energy distribution function with E_0 being the average energy. Using a higher energy ion beam of 1-5keV, conversion efficiency was examined. As a result, the dependence of the conversion efficiency on $\Delta E/E_0$ was the same as the former one. In addition, we confirmed that the efficiency did not vary with E_0 when the value of $\Delta E/E_0$ was 0.08-0.12.

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Fast and Efficient Data Acquisition System for Ubiquitous Participation in DEC Experiment on GAMMA 10

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Remote participation to an experiment performed in national project facilities or large devices in core universities is one of the most efficient ways for intensive investigation of collaborating research topics as well as for time-saving and cost-effective operation. A direct energy conversion (DEC) experiment in GAMMA 10 is underway as a bilateral collaboration research by combining the GAMMA10 facility and the Cusp DEC device developed in Kobe University[1]. Under limitted experimental time, man power, and equipment resources, remote participation in the DEC experiment from the Kobe University greatly enhances efficiency and flexibility of the experiment. In general, it is conceivable that the construction of the remote experiment system that used the data acquisition system of the high speed and efficient network correspondence is possible by using the IT (Infomation Technology) such as VPN (Virtual Private Network) connection environment.

This paper deals with the experimental result that is obtained from the GAMMA 10 and Kobe Cusp DEC experiment system in the Tsukuba-Kobe university internet connected VPN remote participation system. The DEC was installed in the GAMMA 10 and particle which injected from GAMMA 10 was used for the discrimination experiment in slanted cusp fields. To perform the internet connected remote DAQ (Data Acquisition) experimentation in secure, the gateway device which has capability of VPN connection is employed. The DSO (Digital Sampling Oscilloscope) and PC (Personal Computer) server as the controller and the data storage server are used as a simulation experiment of DAQ system. The PC server, which is installed as the HTTP (HyperText Transfer Protocol) and FTP (File Transfer Protocol) server system, operates for the experiment data delivering under the request from the VPN connected client system based on the HTTP by using browser. This is adopted as a simple method that monitors the experimental facility from the remote site, and acquisition time and the sufficient data transmission speed was confirmed. The communication between the Kobe University and the University of Tsukuba did the information transmission between the monitor site of Kobe University and the experimental system operator site of the University of Tsukuba, by using the communication of the browser base. Because the data format that is transmitted from the data storage server is CSV (Comma Separated Values)the graphical processing is possible and the data of present shot can be reflected to the confirmation and parameter change of the experiment of next shot. In addition to this, VNC (Virtual Network Computing) server was installed in the PC server as the DSO controller. Thus the setting and control of DSO etc. becomes possible, without controlling through the operator of the University of Tsukuba. Finally, we will show the experimental results in detail at the final paper, including the concept designing of the fast and efficient data acquisition system by using the HTTP based information terminal such as portable telephone etc, not only a PC based information system.

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Optimization of 28GHz gyrotron output performance for ECRH experiment of the GAMMA 10

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[c]K. Sakamoto, [b]R. Minami, [b]O. Watanabe, [b]T. Numakura· [b]Y. Endo,

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Gyrotron is a key tool for the electron cyclotron wave heating and current drive for magnetic confinement systems. Recent progress of the gyrotron has widened the use of gyrotrons for fusion devices. High power operation of the gyrotron and its efficient transmission are quite important to make a better heating experiments. In GAMMA10, the gyrotron output power was increased to 500kW from 200kW for the higher potential formation. This report describes the design of gyrotron which can work with existing facilities of GAMMA10, and the experimental optimization of gyrotron performance from the practical operation point of view.

The new 500kW gyrotron adopts diode gun to be able to put it on the existing electromagnet. It has a built-in mode converter to output the high power. To control electron beam orbit, each design of collector coil, supporting coil near the radiator and magnetic shield of main magnet is optimized.

There are several knobs to get high injection power from gyrotron output. The first is the adjustment of the main magnetic field. The second point is the gun coil field. The third point is to maximize the coupling power to the HE11 mode corrugate waveguide at Matching Optics Unit (MOU), in case of the gaussian output mode gyrotron.

The magnetic field must be optimized corresponding to the each beam current value. Fine adjustment of both main and gun field enabled maximum power output of 570 kW. Transmission efficiency is the other important point to get high injection power to the plasma. The key to get high transmission efficiency is to get high HE11 mode purity of gyrotron output. This is usually realized with the design optimization of mirror systems inside and outside of gyrotron. From the experimental point of view, this is done by the adjustment of mirrors of MOU. The coupling loss of the gyrotron output power to the HE11 waveguide could be minimized by this procedure. About 90% of the gyrotron output could be coupled to the waveguide in the case of GAMMA 10 ECRH system.

In case of actual operation, the leakage field of the magnet system of the fusion device affects the magnetic field distribution of the gyrotron. This leakage sometimes causes the beam over current and restricts the operation. The compensation of the leakage field is inevitable in this case. The magnetic shield from the leakage field is effective way to reduce this effect.

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Recent development of transmission systems for ECRH in the GAMMA 10 tandem mirror

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Electron cyclotron resonance heating (ECRH) is applied for creating confining potentials and for increasing the electron temperature in the GAMMA 10 tandem mirror. Fundamental ECRH generates the axial ion-confining-potential at the plug regions, where high power launching is essential to increase the confining-potential. A new type of high power gyrotron (28GHz, 500kW, 100ms) has recently been equipped. The new gyrotron oscillates in TE_{42} mode and the output power is extracted in a quasi-Gaussian mode. It couples to the HE_{11} currugated wave guide mode through an MOU and is transmitted to the antenna section. It was found from previous experimental results that the power density profile of the radiated microwave should be axisymmetrical on the resonance layer in order to reduce the radial transport of plasma. Thus, power launching mirrors were carefully designed with our electromagnetic code.[1] Power density profile of the radiated microwave beam is controlled to be axi-symmetrical on the resonance layer with the mirrors. The combination of the new gyrotron and the well designed transmission system provided a record value of the confining potential, 3 kV, at the incident microwave power of 470 kW.

In the central cell of GAMMA 10, the ion temperature, T_i, is much higher than electron temperature, T_e, due to effective ICRF heating. Heated ions are cooled down through collisions with cold electrons. To increase the electron temperature fundamental ECRH has started. Improvement of the antenna system with the newly designed reflection mirrors and a mode converter has achieved efficient power transmission to the resonance layer. As a result, a finite increment of the soft-X ray signal and a clear increase in the plasma diamagnetism are observed during the pulse of central-cell-ECRH.[2] A record value of the bulk- T_e has reached 290 eV.

[1] Y.Tatematsu *et al.*, Jpn. J. Appl. Phys. **44** (2005) 6791.
[2] Y.Tatematsu *et al.*, Trans. Fusion Sci. Tech **47**(2005) 257.

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Study of Efficient Electron Cyclotron Wave Coupling with Grooved Mirror Polarizer in the GAMMA 10 Tandem Mirror

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An improvement of electron cyclotron heating (ECH) system for the central-cell in GAMMA 10 is carried out by the use of two grooved mirrors. Two grooved mirrors consist of a twister and a circular polarizer. The grooved mirror is constructed by cutting a series of parallel grooves on the surface of a metal plate. The groove depth of a twister and a circular polarizer are 2.9 mm and 1.7 mm. In the central-cell region of GAMMA 10, hot ion with the temperature up to several keV is produced by ion cyclotron heating. However, because of low electron temperature less than 100 eV, heated ion is cooled down by electron drag. It is necessary to heat the bulk electron efficiently for reduction of electron drag. In the present ECH system in the central-cell region, the resonance surface locates far from the antenna and the microwave beam is launched obliquely. In case of the ECH system in central-cell region, launched microwave beam from the antenna propagates through the two parabolic mirrors and an angle between the reflected beam toward the resonance surface and magnetic field line is 35.1 degrees. Also, the polarization of incident wave is linear polarization at the antenna. Oblique launch of the electromagnetic wave to magnetized plasma demands specified elliptical polarization for high mode purity of ordinary or extraordinary waves. Two grooved mirrors can generate suitable elliptical polarizations for both of ordinary mode and extraordinary mode in oblique launch with a slanted magnetic field line. In this paper, the characteristics properties of ECH system with two grooved mirrors are reported.

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Performance test of power transmission system newly designed for ECRH in GAMMA10

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Since the electron temperature is much lower than the ion temperature in the central cell of GAMMA10, rise in the ion temperature is suppressed by electron drag. To increase the electron temperature and to reduce the electron drag, fundamental electron cyclotron resonance heating (ECRH) has been applied for bulk electron heating in the central cell. However, efficient transmission of the heating microwave power to the ECR layer was very difficult because of the small radius of the available port to insert the ECRH antenna into the vacuum vessel and the limited room in the vacuum vessel. Therefore, to improve the power transmission rate and the heating efficiency, a new transmission system composed of a taper, a vacuum window, a waveguide and reflection mirrors has been designed.

To examine the performance of the designed transmission system, low power test was carried out. Microwave power of 1 W is generated in the rectangular TE_{10} mode by a Gunn-oscillator. The same configuration of the transmission system as that to be used in the GAMMA10 experiment is mocked up in the atmosphere. A plane microwave absorber is set at the place where the radiation profile is to be measured. The temperature increment on the absorber due to power absorption was measured with an infrared thermographic camera (TVS8100, Nippon Avionics). The temperature increment is assumed to be proportional to the incident microwave power density. By comparing the integrated values of the profile of the temperature increase on two different planes, the power transmission rate between the two planes can be evaluated. Then, the power transmission rates through the taper and the vacuum window were determined and the total efficiency of the newly designed launching system was evaluated. The evaluated transmission rates well agree with the designed values.

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A newly installed 84GHz electron cyclotron heating system in LHD

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Electron cyclotron resonance heating (ECH) have been established as an well useful tool for nuclear fusion researches. ECH have been used in controlling profiles of electron temperature, plasma current and potential, in suppressing the MHD activities, and in the investigation of the energy transport. Technologically, prosperity of ECH has been supported by development of high power electromagnetic engineering in the frequency range of giga-hertz.

Large Helical Device (LHD) experiments have been carried out since 1998 and 9th experimental campaign was finished in February, 2006. ECH system in LHD have been upgraded steadily and have got some accomplishments such as achievement of 10keV central electron temperature, formation of electron internal transport barrier and long pulse discharge of 65 minutes and so on [1-3]. For 9th experimental campaign of LHD, an 84GHz gyrotron which has depressed collector was newly installed to achieve higher power injection. Output electrical power of the gyrotron is 800kW with 3 seconds operation in the specification. In order to transmit the electrical power from the gyrotron to magnetic confinement fusion device with low dissipation, the corrugated waveguide is popularly used and the one with inner diameter of 88.9mm was employed for the new 84GHz gyrotron system. To avoid arc-event, which sometimes restricts high power transmission, the corrugated waveguide system was evacuated. The high power millimeter-waves transmitted by the corrugated waveguide are injected to LHD using some quasi-optical mirrors made of SUS or aluminum. The shapes and sizes of the quasi-optical mirrors are essential for effective ECH but they must be designed under the consideration of some factors such as distance from antenna to plasma, property of radiated beam from aperture of the corrugated waveguide and spatial size of the port. Because the corrugated waveguide of the new 84GHz gyrotron system is connected to an outside port of LHD where relatively larger space exist than other ports, beam steerings to toroidal/poloidal directions are enabled widely. Therefore, this system is useful for not only ECH but electron cyclotron current drive or Bernstein mode heating. For these purpose, control of ellipticity of the wave polarization is required for the best coupling to desired electromagnetic mode in plasma. To control polarization, non-rectangular grooved mirrors were installed in the corrugated waveguide line by replacing normal miter bends with them. After the installation of the new system, actual focused beam sizes and controllability of beam steering by quasi-optical mirrors were checked using kapton target plate in the inside of vacuum vessel of LHD.

The new 84GHz system was applied to LHD experiments and the electron heating and current drive effects with generation of non-thermal electron population were observed. Eventually, the injected power of the new 84GHz system to LHD had reached to 500kW with 3 seconds without arc-event in the evacuated corrugated waveguide line. As a result, high power ECH experiments exceeded 2MW in total had became possible at the 9th experimental campaign.

[1] S.Kubo *et al.*, Plasma Physics and Controlled Fusion **47**(2005) A81-A90

[2] T.Shimozuma *et al.*, Plasma Physics and Controlled Fusion **45**(2003) 1183-1192

[3] Y.Yoshimura *et al.*, Journal of Physics: Conference Series **25**(2005) 189-197

19P74

Characteristics of 28GHz gyrotron for ECRH on GAMMA10

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The formation of ion confining potential in plug cell and strong electron heating in central cell are essential for tandem mirror devices to get good plasma performance. University of Tsukuba pushes physics studies of plasma confinement improvement by plasma potential and electric field in GAMMA10, using ECRH. A gyrotron is a high power mm wave power source for the ECRH. In the previous experiments, power of the gyrotron was 200 kW and which limited the experiments in GAMMA 10. Along the upgrade program of ECRH system in GAMMA10, gyrotron of 500kW level at 28GHz has been developed. The new gyrotron has $TE_{4,2}$ mode cavity to reduce its wall loss and beam current density in it. It has an internal mode converter for Gaussian output. The first 500kW gyrotron delivered 500kW at the windows and contributed to produce high ion confining potential. During the operation, it is found that there were some points to be improved: 1) Saturation level of output is a bit large. 2) Body current is large. 3) Beam over current occurs frequently. we change these 3 points in the next gyrotron for stable operation.

The next gyrotron has been changed in the design of internal mode converter, the shape of structure in collector and the slope of internal bottom on collector for stable operation to cope with above-mentioned points. Concerning the first point, parasitic oscillation or diffraction loss is considered to be a cause of saturation of output in high power. So we changed in the design of internal mode converter with optimized inner surface of the radiator for suppression of parasitic oscillation and diffraction loss. As for the second point, we considered a part of electron beam touched to the body-part, which is near the collector, and this caused large body current. Extended shield from collector was added on collector-body insulation ceramic for preventing it. As for the final point, we considered reflection electron or secondary electron caused flash over, so we changed the slope of internal bottom on collector for suppression of effects of the reflection electron and secondary electron. As a result of 3 improved points, the maximum output power increased from 516kW to 565kW, body current decreased from 5mA to 2mA, and the number of flash over decreased significantly.

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Study of spatial distribution of microwave power deposition for plug ECRH in GAMMA 10

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Fundamental electron cyclotron resonance heating (ECRH) is applied for creation of an axial confining potential in the GAMMA 10 plug region with high power microwave of 28 GHz up to 500 kW. From the experimental knowledge so far obtained spatial potential distribution is closely related to the spatial distribution of the microwave power deposition. When the potential distribution is non-axisymmetrical or off-axis, radial transport of plasma takes place owing to an ECRH-induced non-axisymmetrical radial electric field and plasma confinement will be deteriorated. Thus, to control the radial distribution of the power deposition is very important for the GAMMA 10 plug ECRH. To do so, reflection mirrors, which transmit heating microwave to the resonance layer with an axi-symmetric radiation profile on it, have been designed. However, the power deposition profile is not necessarily axisymmetrical since the microwave beam is injected upward obliquely to the machine axis. Moreover, the distribution of power deposition may be shifted downward even if the microwave beam is directed to the on-axis point on the resonance layer.

Then, wave propagation is analyzed by directly calculating the hot plasma dielectric tensor for obliquely propagating electron cyclotron wave around the ECR layer with a magnetic beach geometry. The power deposition profile is determined from the imaginary part N_i of the complex refractive index and the absorption coefficient are evaluated by integrating N_i along the ray of the microwave beam. To obtain the axi-symmetrical power absorption profile, both of the injection beam shape and the injection angle are optimized with the calculation.

An array of waveguide antennas has been installed on the wall inside the vacuum vessel where the heating microwave power reaches after transmitting the ECR layer. Power deposition profile is estimated from measurement of the radial distribution of the transmitted power through the ECR layer. The power absorption coefficient was obtained as a function of the electron density and agreed with the theoretically expected value.

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