Progress of plasma confinement studies in the Gas Dynamic Trap

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Abstract. The paper includes a brief overview of previous researches on the stabilization of MHD instabilities, study of micro-instabilities, and demonstration a tangible increase of the electron temperature with application of auxiliary ECR heating. A review of the results of recent researches related to application of microwave radiation for plasma generation, and plasma heating in the GDT device is presented. The paper summarizes also recent results of researches that oriented on study of expander physics.

1. Introduction

Worldwide activity of studies of plasma confinement in magnetic mirror traps decreased dramatically in the late 80's of the last century. The reason is that the mirror concept is thought to have three unattractive characteristics. The magnets are complex, the plasma is plagued with micro-instabilities and the electron temperature would never approach required keV levels. Researches on the Gas Dynamic Trap (GDT) device at the Budker Institute of Nuclear Physics demonstrated the possibility to overcome these three deficiencies. Stable high energy density plasma can be confined with simple circular magnets [1,2], micro-instabilities can be tamed [3], and electron temperatures reaching a keV have been measured [4,5]. These three accomplishments provide a basis to reconsider the mirror concept as a neutron source for materials development, nuclear fuel production, and fusion energy production. Furthermore, these three achievements allowed to go to the next level of tasks, aimed at support of the next generation of research facilities, as well as fusion reactors based on mirror traps. List of the most important next-level problems includes the following: optimization of heating modes using neutral beam injection and auxiliary ECR heating and a detailed study of physical processes in the expanders (regions with an expanding magnetic field behind the magnetic mirrors), limiting longitudinal energy losses.

The paper includes a brief overview of researches on the stabilization of MHD instabilities, study of micro-instabilities, and demonstration a tangible increase of the electron temperature with application of auxiliary ECR heating. According to Thomson scattering data, the electron temperature exceeds 0.9 keV thus demonstrating more than threefold increase as compared with modes, where only neutral beams were applied [4,5].

The paper focuses mainly on recent results obtained in studies related to application of microwave radiation for plasma generation and plasma heating in the GDT. An overview of the recent studies of the physical processes in the expanders, which determine the longitudinal energy transport, is also presented in this paper.

2. A Brief Description of the GDT Device

The GDT device is an experimental facility for studies on the main issues of development of fusion systems based on axisymmetric mirror traps. It is an axially symmetric linear open system with a long central solenoid and high mirror ratio [6]. The schematic layout of the GDT is shown in FIG.1.

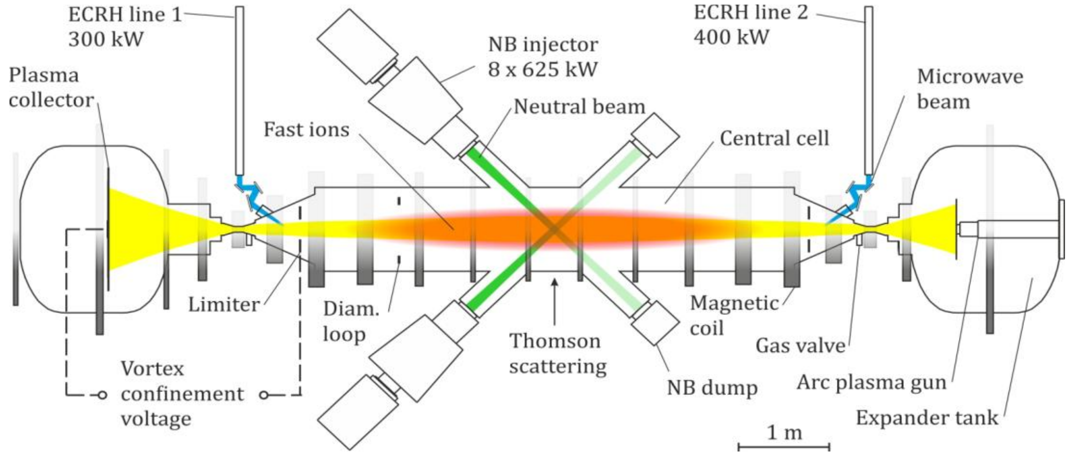

FIG. 1. Schematic layout of the GDT device.

Plasma with two fractions is confined. The first fraction is rather dense collisional plasma called background or target plasma. This plasma is produced at the beginning of experiment with help of an arc discharge plasma gun. The target plasma can also be produced by microwave breakdown of neutral gas, using one of the gyrotrons of the ECRH system. The target plasma is confined in the gas-dynamic regime. During the filling stage, that lasts 4.5 ms, temperature of the target plasma is about 3÷5 eV. After filling the trap with initial plasma, heating neutral beams are turned on. Deuterium beams are injected at the centre of the GDT confinement vessel. Fast neutrals of the beams are ionized in the target plasma and form the second plasma fraction – a population of fast ions. These ions are confined in the adiabatic regime and being gradually dragged by the background plasma. In 0.5 ms after the heating beams are turned on, the plasma gun is switched off. During 5 ms of operation of the heating neutral beams, the target plasma is heated up to about 200÷250 eV. At the same time, ions of the fast component reach the mean energy of about 10 keV and the density at the mirror points of 5×10^{13} cm^{-3}. Particle balance of the target plasma is sustained by fuelling with a cold gas. The ECRH system is built upon two 54.5 GHz gyrotrons with total incident power of up to 0.7 MW, in addition to the main 5 MW heating power from the neutral beams [7]. Key parameters of the GDT device and the confined plasma are given in Table I.

3. Conclusions from the Previous Studies

In the previous decade, following important problems have been solved in studies on the GDT device.

- The methods, to suppress anomalous transverse transport, caused by MHD instabilities in axisymmetric magnetic field configuration, were developed.
- Detailed studies of micro-instabilities were carried out. As result only one type micro-instability is discovered - Alfven Ion Cyclotron. It is shown, that under conditions of

oblique injection of neutral beams this instability does not lead to substantial losses of hot ions.

- The possibility of increasing the electron temperature of 1 keV range of values has been shown.

TABLE I: KEY PARAMETERS OF THE GDT DEVICE AND CONFINED PLASMA.

Parameter	**Value**	**Parameter**	**Value**
Mirror-to-mirror distance	7 m	Mirror ratio	33
Magnetic field at midplane	0.36 T	Duration of NB injection	up to 5 ms
Mirror magnetic field	up to 14 T	NB particles energy	25 keV
Bulk plasma density	up to $2{\cdot}10^{19}$ m^{-3}	Injected NB power	5 MW
Peak density of fast ions	up to $5{\cdot}10^{19}$ m^{-3}	Trapped NB power	2 MW
Mean energy of fast ions	9 keV	Electron temperature (NBI only)	0.25 keV
Maximum plasma beta	60%	Electron temperature (with ECRH)	up to 0.9 keV

3.1. Suppression of Transverse Transport Caused by MHD Instabilities

It is well known, that configuration of axisymmetric magnetic mirror trap is not favourable for MHD stability. In previous experiments, we studied efficiency of two types of axisymmetric MHD anchors attached to the main part of the GDT device. In one a series of research, expanders with favourable curvature of magnetic field lines and gas-dynamic pressure of the outflowing plasma enough for suppression of flute-like instability were studied [8]. Expanders located on both sides of the GDT. Maximum value of the relative pressure $\beta_{max\_exp} \approx 0.1$ obtained in this regime of operation. Note, that $\beta=8\pi{\cdot}P_{\perp plasma}/B^2_{vac}$ introduced as ratio between perpendicular plasma pressure and effective pressure of vacuum magnetic field. The pressure of hot ions in GDT experiment mainly determines value of β.

Axisymmetric cusp-like cell (anti mirror cell) was used also as MHD anchor in a special series of experiment [9]. Cusp cell was attached to the one of GDT ends and was filled with warm plasma, which was created by flux from the central cell and confined inside the cusp in the gas dynamic regime. The plasma confinement time in the anti-mirror cell is significantly greater than the corresponding time in the expander, so the effectiveness of this method of stabilization was significantly higher. Maximum value of the relative pressure in this mode of operation was $\beta_{max\_cusp} \approx 0.15$.

However, it turned out, that the most effective way to suppress the transverse losses caused by MHD instabilities is the vortex confinement method. This method was originally proposed and successfully implemented in experiment on GDT [1]. The vortex confinement is based on initiation of sheared rotation of plasma in a relatively thin peripheral layer of plasma column. Application of this method allowed obtaining the maximum relative pressure up to $\beta_{max\_vortex}= 0.6$ [2].

3.2. Study of Micro-instabilities

High frequency fluctuations of electromagnetic field inside the plasma column were studied in detail in the operation mode of GDT with high-energy content of plasma [3]. It was shown that fluctuations detected are driven by Alfven Ion Cyclotron (AIC) instability. It was shown also, that only small part of hot ions from narrow region of phase space exciting the instability. More precisely, the instability is excited by the ions with longitudinal rates close to the initial longitudinal speed of injected ions. This group of fast ions come out of resonance with the wave due to small scattering or braking, without reaching the loss cone. This fact explains the saturation of the oscillation amplitude at a low level and insignificant increase power of the losses of hot ions under the development of the instability. Micro-instabilities of other types (such as DCLC et al.) have not been registered in the experiments on the GDT until now.

3.3. Demonstration of the Electron Temperature of keV Range

Application of auxiliary 0.7 MW = 54.5 GHz electron cyclotron resonance heating system in addition to standard 5 MW heating by neutral beams, and application of a radial electric field to mitigate the flute instability allowed to obtain electron temperature exceeds 900 eV. This corresponds to at least a threefold increase with respect to previous experiments both at GDT and at other comparable machines, thus, demonstrating the highest quasistationary (about 1 ms) electron temperature achieved in open traps [4,5].

The measured increase of electron temperature to nearly 1 keV along with results of previous GDT experiments, which demonstrated high-density plasma confinement with $\beta \approx 0.6$, provide a firm basis for extrapolating the gas dynamic trap concept to fusion relevant applications. These electron temperatures are adequate for a neutron source that needs T_e ~700 eV to test and develop fusion materials, or to initiate work on subcritical fission reactors and nuclear waste processing based on a fusion driven burning of minor actinides [10]. In addition, these results encourage expectations, that the higher temperatures, needed for fusion power production, are possible.

4. ECR Discharge Start-up

A new discharge start-up scenario has been developed for the GDT experiment. The initial plasma is generated from neutral gas with a help of a high-power microwave beam available from the ECR plasma heating system. The approach was extensively tested in the conditions of a large-scale axisymmetric magnetic mirror machine with neutral beam injection. In the experiments we scanned the ECR layer with the microwave beam, studied the dependence on the incident microwave power, polarization and initial neutral gas pressure. It was found that the seed plasma density saturates at a certain level depending on the amount of neutral gas initially admitted to the vessel, in case the power is sufficiently high. Below a certain value, the incident microwave power becomes a limitation to plasma density. Positioning of the microwave beam relative to the ECR layer does not affect the plasma build-up, as long as the beam intersects the first harmonic ECR surface.

The transition from ECR-generated plasma to purely NBI-supported discharge was shown to be sufficiently short and even more energy saving than the conventional start-up with arc plasma generator. After the transition, the discharge becomes essentially similar to a one initiated by the plasma gun. It can be concluded that a sufficiently dense plasma target in GDT may be generated using a 50 kW microwave beam directed at the fundamental EC resonance with the minimum duration of ECRH pulse of ~ 3 ms.

Finally, our experience with ECR-initiated discharges leads us to conclusion that such start-up scenario will be easily achieved in a next-generation magnetic mirror machine based on similar physics. It should be stressed that despite the lack of external stabilization against the interchange modes during the ECRH pulse, the transverse energy transport does not seem to be extraordinary high, leaving a significant power budget to spare and allowing a reliable plasma start-up in each discharge. In the frame of this part of activity, theoretical description of the physical processes responsible for ECR discharge start-up in the GDT device was developed.

5. Optimization of Heating Mode Using Auxiliary ECRH

Two heating modes were realized in previous experiment with auxiliary ECRH [5]. One of them is “core heating” mode. In this mode, microwave power deposited and the electron temperature increases only in paraxial region of plasma column, characteristic radius of temperature peak is ~5 cm. In this mode, the electron temperature reaches the highest values.

Another mode of operation characterized by the broad power deposition area and, respectively, broader radial profile of electron temperature. In this mode (“broad mode”), on axis electron temperature does not exceed 350 eV, but there is a substantial increase in the confinement time of hot ions and therefore nearly doubled the intensity of D-D fusion reactions [5]. Realization of one or the other mode of heating depends on the position of the EC resonance surface relative to the microwave radiation beam.

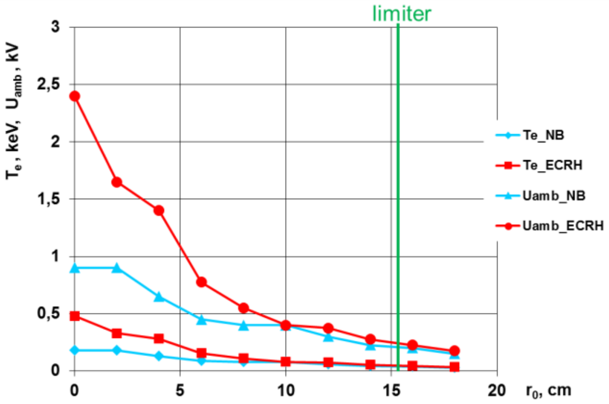

FIG. 2. Measured radial profiles of electron temperature and simulated profiles of ambipolar potential at the midplane of the trap in regimes without and with auxiliary ECRH (rhombi, squares – temperature profiles; triangles, circles – potential profiles).

Peaked profile of electron temperature in “core heating” mode causes peaked profile of ambipolar potential (see FIG.2.) and, respectively, causes azimuthal $E \times B$ drift of plasma core, which is effective driver of MHD instability. Perhaps, because of this, heating of paraxial region occurs within 0.4 ÷ 0.6 ms after start of ECRH [4]. At the same time ECRH system operates 4 ms. During this time electron temperature rises approximately linearly and rises amplitude of low frequency electromagnetic fluctuations monitored by set of magnetic probes. Based on these data, it is reasonable to assume, that MHD instability is developing in “core heating” mode and limits the maximum electron temperature.

One possible way to overcome this problem is usage of sectioned target plates installed in expanders and biased with electric potential, which is distributed in sections to minimize the peak ambipolar potential in the axial region of the plasma column. In July 2016, a system of 12 concentric electrodes was installed from both sides of the machine behind the magnetic mirrors to realize this idea. The discharge start-up scenario by EC waves is necessary to this experiment which scheduled on the middle of October 2016.

6. Expander Physics Studies

Axial electron heat loss is the essential challenge for open magnetic systems for plasma confinement [11]. In an idealized mirror trap, where plasma jet flows through the magnetic mirror into open space, electron heat losses show favourable behaviour: convective law $Q_e \sim T_e^{3/2}$ and $5.3{\cdot}T_e$ per lost electron [12]. In real machines, however, interaction of plasma outflow with surfaces and with background neutral gas argued to cause substantial increase of electron heat losses [11].

Diminution of negative effects of plasma interaction with surfaces and background neutrals is attributed to geometry of expanders: end divertors, where magnetic field strongly decreases between the mirror and some target plates [13]. Such an arrangement was originally intended to improve plasma stability by adding sections with favourable field curvature and to reduce the heat load on the target plates to manageable values. Positive effect of expanders on the electron confinement inspired theoretical and experimental studies of the divertor physics and extrapolation of applicability of this approach for fusion reactor devices. Previous experimental studies dedicated to the role of expanders in the overall plasma confinement had been carried out on the GDT machine about 20 years ago at much lower plasma parameters than presently achieved [14]. It is necessary to extend the available set of experimental data to the recently achieved regimes with higher plasma temperature.

Current theoretical understanding of expander/divertor physics is summarized in [15]. Below is a list of the main conclusions of theoretical studies on the subject.

Balance of electron and ion currents on the target plate and quasi-neutrality law require formation of positive ambipolar potential drop between plasma inside the trap and surface of the target plate. The value of this drop depends on plasma parameters in the trap and confinement physics of particles. In the most cases value of this potential drop is about few T_e ($\Delta\varphi_{amb}= a{\cdot}T_e$, where $a \approx 3 \div 5$). In idealized situation without taking into account electron collisions and generation of cold electrons due to ionization of residual gas in expander region as well as secondary electron emission from the target plates the most part of this potential should be concentrated in a thin Debye layer in front of the target plate surface ($\Delta\varphi_{Debye}\approx \Delta\varphi_{amb}= a{\cdot}T_e$). For T_e values of keV range, relevant for fusion devices, this high voltage drop can trigger arc discharges on the target plate surfaces and destroy plasma equilibrium in the trap.

In more realistic situation, main feature of the expander is existence of a fraction of electrons trapped in a well of effective potential between the magnetic mirrors and the negatively biased target plate. This fraction is populated by collisions as well as ionization and second emission processes. In this situation, the theory predicts monotonic decay of potential in the whole expander region from mirror throat to the Debye layer at the vicinity of the target plate. In the case of expansion ratio: $K = B_{mirror}/B_{target} > (m_i/m_e)^{1/2}$, (where B_{mirror}, B_{target} are magnetic field values in the mirror throat and on the target plate, m_e, m_e – ion and electron mass respectively) theory predicts also that the value of potential drops in Debye layer in front of the target plate becomes much less than T_e inside the trap ($\Delta\varphi_{Debye}<<T_e$). At the same time characteristic energy of electrons at the vicinity of target plate becomes also much less T_e ($\varepsilon_e<<T_e$). Moreover for the case $K\geq (m_i/m_e)^{1/2}$ theory predicts negligible influence of electron emission from target plates on energy confinement in mirror trap.

Experimentally confirmed answers to the following two questions are very important for the development of new facilities based on the magnetic mirror trap.

1. What is the minimum expansion ratio K_{min} in which influence of electron emission from target plate is insignificant on longitudinal heat losses in the mirror trap?
2. What is the value of ambipolar potential drop in Debye layer at the vicinity of target plate surface installed in position with $K \geq K_{min}$?

Answer to the last question is important for development of protection method against arc discharges on the target plates.

The recent researches on the GDT device were partially oriented on answers to above questions. Plasma potential and mean electron energy at the vicinity of the plasma target plates in the expander was measured at various values of the magnetic field expansion. First insight on influence of the magnetic field expansion on parameters of the confined plasma is also obtained. Below please find the main conclusions from the results of the first stage of researches of expander physics.

Observed values of the plasma potential and the mean electron energy indicate presence of low temperature plasma at the vicinity of the plasma collector. Most probably, this plasma is formed due to ionization of the background neutral gas in the expander tank. Electron temperature of this plasma is about 15÷20 eV, which is much lower than the electron temperature of hundreds of electron volts at the corresponding magnetic field lines in the centre of the magnetic trap.

In case of magnetic field expansion $K > 40$, the plasma potential near the plasma collector is only several tens of volts, and has a trend to drop with the increase of K. This means, that potential drop in the Debye layer at the plasma collector is much lower than T_e in the centre of the magnetic trap.

These conclusions are in a good agreement with theoretical predictions made by Ryutov et al. [15] According to these predictions; there is a population of cold electrons confined in the expander by the effective Yushmanov's potential. Drop of the plasma potential from $\sim 5 \cdot T_e$ at the centre of the magnetic trap to the ground at the plasma collector does not occur at the Debye sheath at the collector but closer to the magnetic mirror, and apparently not as abrupt as it could be in the sheath. Earlier experimental works confirmed this prediction at substantially lower T_e. The present results prove the theoretical predictions in the range of much higher electron temperatures.

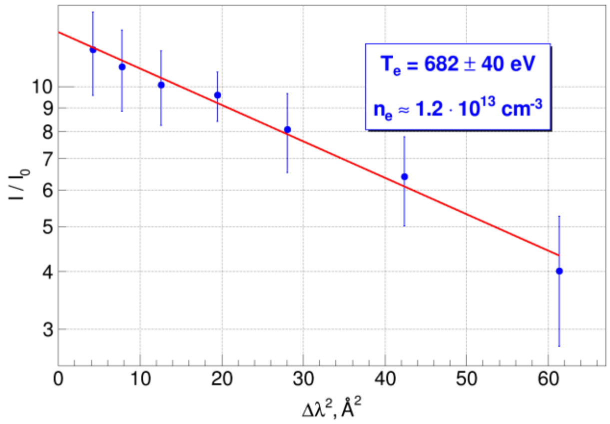

FIG. 3. Spectral data from Thomson scattering diagnostics, where I — energy spectral density (arb. unit), $\Delta\lambda^2 = (\lambda - \lambda_0)^2$, λ — wavelength, λ_0 — laser wavelength. Line-least square approximation. Electron temperature was measured on the axis at the midplane of the GDT

Another important conclusion comes from the fact that variation of the magnetic field expansion ratio in the range of $40 < K < 200$ does not influence much the major parameters of plasma at the centre of the magnetic trap. Possibility of effective plasma heating at low the magnetic field expansion ratio has very important practical implication for open magnetic systems. The present set of experiments proves the possibility heat the confined plasma to hundreds of eV at $K \sim 30$. FIG.3. shows spectral data from Thomson scattering diagnostics. Electron temperature extracted from these data is $T_e \sim 0.6$ keV at $K = 30$. This result is close to the record values for this method of plasma confinement and heating [4,5].

7. Acknowledgments

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8. References

[1] BEKLEMISHEV, Alexei, et al., “Vortex Confinement of Plasmas in Symmetric Mirror Traps”, Fusion Sci. Technol. **57**, (2010) 351.

[2] SIMONEN, Tom, et al., “High Beta Experiments in the GDT Axisymmetric Magnetic Mirror”, J. Fusion Energ. **29**, (2010) 558.

[3] ZAYTSEV, Konstantin, et al., “Kinetic instability observations in the Gas Dynamic Trap“,Physica Scripta **2014**, (2014) 014004.

[4] BAGRYANSKY, Peter, et al., “Threefold Increase of the Bulk Electron Temperature of Plasma Discharges in a Magnetic Mirror Device”, Physical Review Letters **114**, (2015) 205001.

[5] BAGRYANSKY, Peter, et al., “Overview of ECR plasma heating experiment in the GDT magnetic mirror”, Nuclear Fusion **55**, (2015) 053009.

[6] IVANOV, Alexander, and PRIKHODKO, Vadim, “Gas-dynamic trap: an overview of the concept and experimental results“, Plasma Phys. Control. Fusion **55**, (2013) 063001.

[7] SHALASHOV, Alexander, et al., “Auxiliary ECR heating system for the gas dynamic trap”, Physics of Plasmas **19**, (2012) 052503-1.

[8] IVANOV, Alexander, et al., “Experimental study of curvature-driven flute instability in the gas-dynamic trap”, Physics of Plasmas **1**, (1994) 1529.

[9] ANIKEEV, Andrey, et al., “Measurements of MHD stability limit in GDT with a cusp end cell and comparison with theory based on energy principle”, Physics of Plasmas **4**, (1997) 347.

[10] BAGRYANSKY, Peter, et al., “”, Fusion Eng. Des. **70**, (2004) 13.

[11] BALDWIN, D., “End-loss processes from mirror machines”, Rev. Mod. Phys., **49**, (1977) 317.

[12] PASTUKHOV, Vladimir, “Collisional losses of electrons from an adiabatic trap in a plasma with a positive potential”, Nucl. Fusion **14**, (1974) 3.

[13] KONKASHBAEV, I., et al., “Possibility of decreasing the electron heat flux from open traps”, Sov. Phys. JETP, **47**, (1978) 501.

[14] ANIKEEV, Andrey, et al., “Longitudinal confinement of particles and energy in a gas-dynamic trap”, Plasma Physics reports **25**, (1999) 775.

[15] RYUTOV, Dmitri, “”, Fusion Science and Technology **47,** (2005) 148.