Siberian Branch of Russian Academy of Science

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Budker INP 99-9

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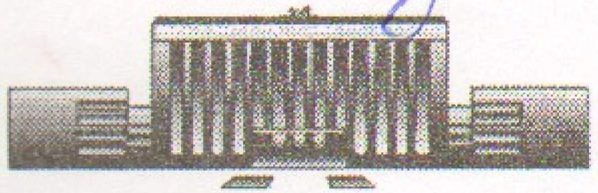

Novosibirsk
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Abstract

Studies of confinement of the hot anisotropic ions is one of the basic objectives of the GDT experimental program. The method of confinement study consists essentially in comparison of the measured ion parameters with parameters predicted by computer simulations based on theory of ion-ion Coulomb collisions. Self-sufficient set of diagnostics for measurements of fast ion parameters has been developed. In particular this set includes special diagnostic to measure the local energy ion distribution function. In parallel Monte-Carlo transport code was developed for numerical study of the fast ions. Comparison of the measured and simulated parameters clearly demonstrates, that energy confinement time of the fast ions is governed by Coulomb collisions, significant anomalous ion losses were not yet observed in GDT experiments. Computer simulations assuming that fast ion scattering was also governed by Coulomb collisions, provide density of the fast ions up to $\approx 10^{13}$cm^{-3} near by magnetic mirrors in reasonable agreement with the experimental results. From measurement of the energy spectra one can determine the mean energy of ions, that was estimated to be 5-8 keV. In this experiment plasma β was evaluated up to $\approx$20%.

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1. Introduction

The Gas-Dynamic Trap (GDT) [1], is a long axisymmetric mirror confinement system with the high mirror ratio. To provide MHD stability of plasma axisymmetric min-B cell is attached to one end of the device. The plasma confined in the trap consists of two components. One of those is the collisional warm plasma with the temperature of about 100 eV and the density of (2-6) 10^{13} cm^{-3}. For this component the ion mean free path of scattering into loss cone is less then mirror to mirror distance that suggests the gas-dynamic regime of confinement (as a gas inside the container with small opening) for this component. Following to [1] one can estimate the confinement time of this plasma as:

$$\tau \approx \mathbf{L} \cdot \mathbf{R} / \mathbf{V}_i,$$

where **L** is length of the magnetic mirror, **V**$_i$ is thermal velocity of the ions, **R** is the mirror ratio.

The high power Neutral Beam (NB) injection creates the second plasma component - hot ions with energies of 2-15 keV and density up to $\approx 10^{13}$cm^{-3}. For this component the ion mean free path of scattering into loss cone exceeds mirror to mirror distance many times. Consequently the mirror regime of confinement is realized for this component. Fokker-Planck simulations show, that in these circumstances the energy confinement time of fast ions is basically governed by drag in the warm plasma, the role of angular scattering is not significant. That means, that fast ions have a small spread over of pitch-angle executing the bounce-oscillations between the mirrors. This angular spread is close to that in initial NBs. Near the magnetic mirrors where the longitudinal ion velocities are small, the ion density increases by a factor of $\sim[\sin(\theta_0)\Delta\theta]^{-1/2}$, where θ_0 is the angle at which the neutral beam is injected, and $\Delta\theta$ is the angular spread of the ions. Confinement of the hot sloshing ions with «beam-like» character of the ion angular distribution functions is the distinguishing feature of the neutron source based on the Gas Dynamic Trap [2]. Such a source can be applied for fusion materials irradiation testing. Calculations show that, when deuterium and tritium beams with an energy of ~100 keV are injected into the device, the flux of thermonuclear neutrons with a power density of ~2 MW/m^2 can be obtained near the mirror regions where the densities of trapped tritons and deuterons are maximumal. It is essential for engineering applications that the total power consumed by this source is relatively small (~50 MW) [2].

The role of collisional warm plasma is twofold. On the one hand the warm plasma feeds the min-B cell providing the MHD stability of the entire plasma and of fast anisotropic ions [3], on the other hand it serves to trap the NBs and stabilizes microinstabilities. In the case of microinstabilities stabilizing effect of warm plasma consists in filling the loss-cone ion distribution at low energies [4].

Behavior of the fast ions is the key problem of the physical feasibility of the projecting neutron source. Therefore confinement of hot ions is the basic problems of the GDT experimental program.

The physical phenomena that could reduce confinement time of fast ions are as follows:

- curvature-driven flute mode of MHD instability;
- ballooning mode of MHD instability;
- microinstabilities driven by non-Maxwellian distribution of fast ions;
- nonadiabatic effects in fast ion motion.

In [3] theoretical predictions concerning MHD stability of two component plasma have been tested experimentally in low β (5-10%) regimes of plasma confinement. It was shown, that the plasma is MHD stable, i.e. MHD stability criterion for two component plasmas is satisfied. In the last experiments plasma β was relatively higher (up to 20%) being close to the theoretical predicted limit for MHD ballooning modes [5]. Note that perturbations of magnetic field caused by confined plasma with high β are able to cause non adiabatic motion of fast ions and anomalous scattering into the loss cone. Based on the results of previous studies of microinstabilities in the open traps (see for example [6]) one can conclude, that in the conditions of GDT experiment, microinstabilities driven by the anisotropical distribution function of the hot ions in the velocity space is to be stabilized by warm plasma. However it was important to corroborate this conclusion directly in the GDT experiment, as far as anomalous scattering, which can be caused by microinstabilities, can be essentially reduce the parameters of projecting GDT-based neutron source.

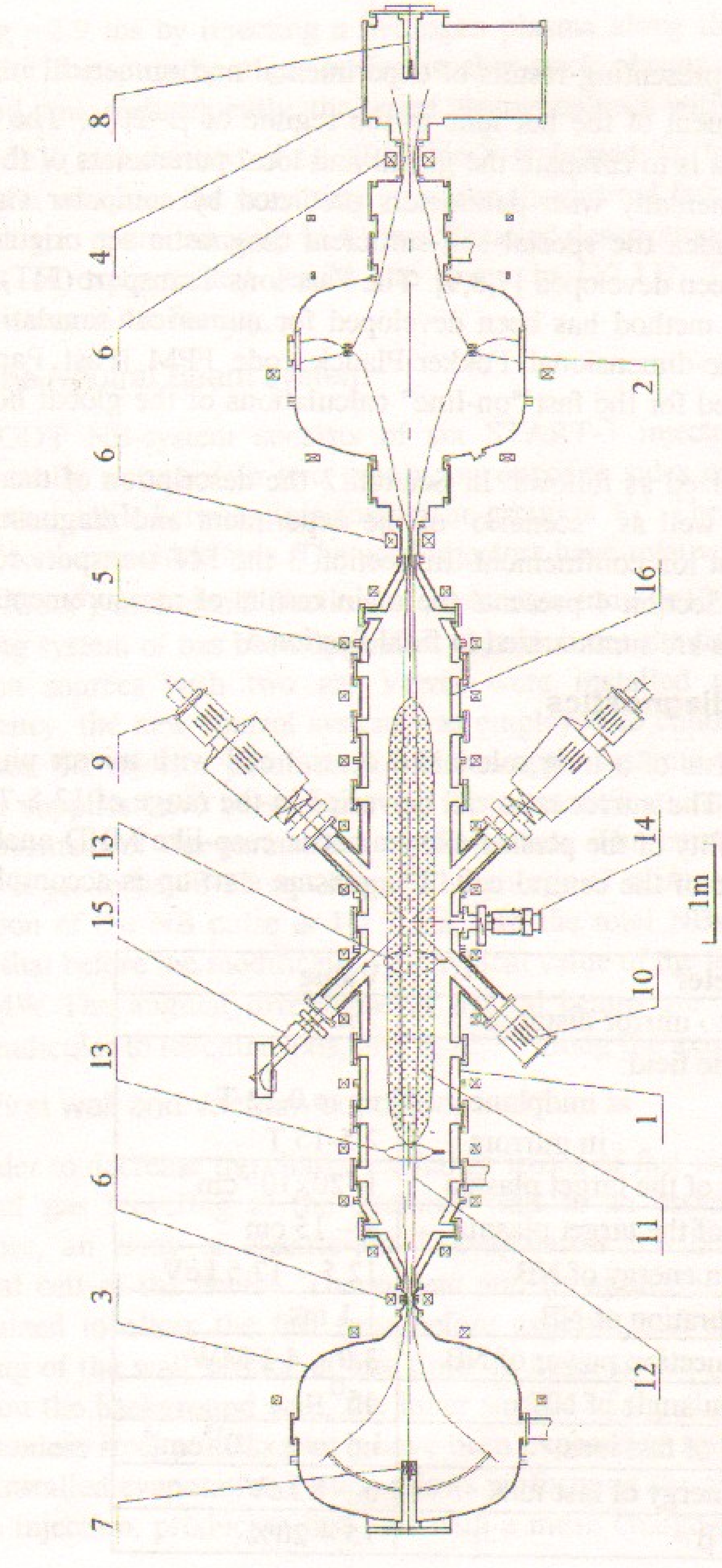

Figure 1. The GDT layout
1 — central cell, 2 — cusp end cell, 3 — expander end cell, 4 — end tank, 5 — solenoid coils, 6 — mirror plugs, 7 — plasma gun, 8 — additional plasma gun, 9 — NB-injectors, 10 — NB-dumps, 11 — hot ions, 12 — warm plasma, 13 — diamagnetic loops, 14 — diagnostic NB-injector, 15 — electrostatic analyzer of charge-exchange neutrals (azimuthally separated from NB-injector), 16 — Ti-coated first wall.

This paper aims at presenting results of experimental and numerical investigations of the confinement of the hot ions in the regime of β=20%. The basic idea analysis of the data is to compare the global and local parameters of the fast ions measured experimentally with parameters predicted by computer simulations. To realize this idea the special self-sufficient diagnostic set oriented to study of fast ions has been developed [7,8,9]. The Fast Ions Transport (FIT) code based on Monte-Carlo method has been developed for numerical simulation of fast ions [10]. The one-dimensional Fokker-Planck code FPM (Fast Particles Model) has been applied for the fast "on-line" calculations of the global hot ion parameters [11].

The paper is organized as follows. In Section 2 the description of the GDT device is presented as well as, 'scenario' of the experiment and diagnostic set oriented to study of fast ion confinement. In Section 3 the FIT transport code is briefly described. The Section 4 presents the main results of measurements and simulations. The results are summarized in final Section 5.

2. GDT device and diagnostics

The GDT device consists of a long solenoidal central cell with mirror plugs at both ends (see Fig. 1). The mirror ratio can be varied in the range of 12.5-75. To provide the MHD stability of the plasma axisymmetric cusp-like MHD anchor is attached to the one end of the central cell. The plasma start-up is accomplished during ~2.9 ms by injecting a hydrogen plasma along the field lines from one end. For that purpose a gas-puffed washer-stack plasma gun is installed inside the end tank. Subsequently, the target plasma column with an initial temperature of 3÷5eV and density of $6\div20\cdot10^{13}$cm^{-3} is heated up by Neutral Beam (NB) injection which at the same time provides the desired fast ions. The total time of plasma gun operation is up to 4.0 ms. Detailed description of the GDT device and review of experimental results are given in [12,13]. Table 1 lists the main parameters of the facility.

Parameter	Value
Mirror to mirror distance	7 m
Magnetic field: at midplane in mirrors	 up to 0.22 T 2.5-15 T
Density of the target plasma	$1\text{–}20\times10^{13}$cm^{-3}
Radius of the target plasma	8 – 15 cm
Injection energy of NB	12.5 – 17.5 keV
Pulse duration of NB	1.1 ms
Total injection power of NB	3.9 – 4.1 MW
Injection angle of NB	45^0
Density of fast ions	up to $1.\times10^{13}$cm^{-3}
Mean energy of fast ions	5 – 8 keV
Plasma β	15 – 20%

Table 1 Parameters of the GDT facility

2.1 The Neutral Beam system

The GDT NB-system consists of six START-3 injectors [14]. Injectors are azimuthally arranged in two groups on opposite sides of the central cell. The azimuthal angle between injectors in the group is 30°. The injection angle of NBs is 45° to the machine axis. The used injectors have relatively high current density (≈0.5A/cm^2) and small fraction of molecular ions (<10%). Last year the NB-heating system of has been upgraded, that includes the following improvements: plasma sources with two gas valves were installed to achieve higher gas efficiency, the new control system was employed to control NB-injectors and to monitor the injector parameters, the ion-optic systems were renewed, the NB power supplies have been improved. These modifications resulted in significant improvement of the parameters of NB-system. The current of the each neutral beam is set to be 48-55 eq. Amp.. The energy of neutrals is 12.5-17.5 keV, the duration of the NB pulse is 1-1.2 ms, and the total NB-power exceeds 4 MW. Note that before the modification the typical value of the total NB-power was 2.2-2.5 MW The angular divergence of neutral beams are: $\alpha_{\perp}\approx1°$ in the direction perpendicular to machine axis, and $\alpha_{\|}\approx2.5°$ along the axis.

2.2 First wall and vacuum conditions

In order to decrease the charge-exchange losses of fast ions, the reduction of the neutral gas recycling at the chamber wall is an essential demand. For that purpose, an array of electric-arc Ti-evaporators has been installed inside the central cell of the device. The system and its application procedure have been optimized to allow the fast (just before experimental shot) and homogeneous coating of the wall surface at any time. In order to improve the adhesion of the film on the background wall, the inner surface of the chamber has been covered by stainless steel panels, which have been exposed to several special treatments. The installed evaporation system allows performing the experiments with neutral beam injection, producing fast ions with a mean charge-exchange lifetime up to

10 ms. That has been mainly achieved by the drastic reduction of the fast neutral recycling at the chamber wall. The base pressure during the experiments is sustained at a level of about 0.5-1.1·10^{-5}Pa. The detailed description of the vacuum system, Ti-evaporation system, wall preconditioning procedure, and the experiments concerning to study of the dynamics of the neutral gas in GDT by the NB injection has been previously published [15].

2.3 Diagnostics

Neutral beam attenuation detectors are used to measure the trapped power of neutral beams. The energy contents of the target plasma and of the fast ions were determined by the diamagnetic loops located at the midplane and beyond the turning point of the fast ions. The charge-exchange and radiation losses from the plasma were measured by a set of pyro-bolometers. The time resolution of the bolometers is 10µs. Near to the midplane the fast ions are partially neutralized by charge-exchanging with injected neutral beam and leave the plasma within rather small interval of pitch angles near the injection angle of 45°. The bolometer located at the midplane is used in conjunction with a movable collimating tube aimed to separate the charge-exchange of the fast ions and radiative losses from the plasma column. The detailed description of this diagnostic has been published in [7].

Diagnostic Neutral Beam:	
Energy of atoms	15 keV
Current	20 Atom Amperes
Pulse duration	120 µs
Current density	~0.5 Atom A/cm^2
Radius in the focus point	3 cm
Electrostatic Analyzer:	
Angle	45°±5°
Spatial resolution	8×6×2.5 cm^3
Angular resolution	0.35°
Energy range	2.8-20 keV

Table 2 The parameters of the diagnostics to measure the local energy distribution functions of fast ions.

The Thomson scattering system based on a ruby laser was used to measure the radial profile of electron temperature [8]. The diagnostics based on a charge-exchange of the 25 keV D^0 beam has been developed to monitor of the time evolution of the radial density profile [9]. The spatial resolution of the diagnostic is 1.5 – 2.0 cm; the time resolution is 50 µs. The set of fast inverse magnetron ionization gauges was used for the measurement of the time evolution and spatial distribution of neutral gas density [15].

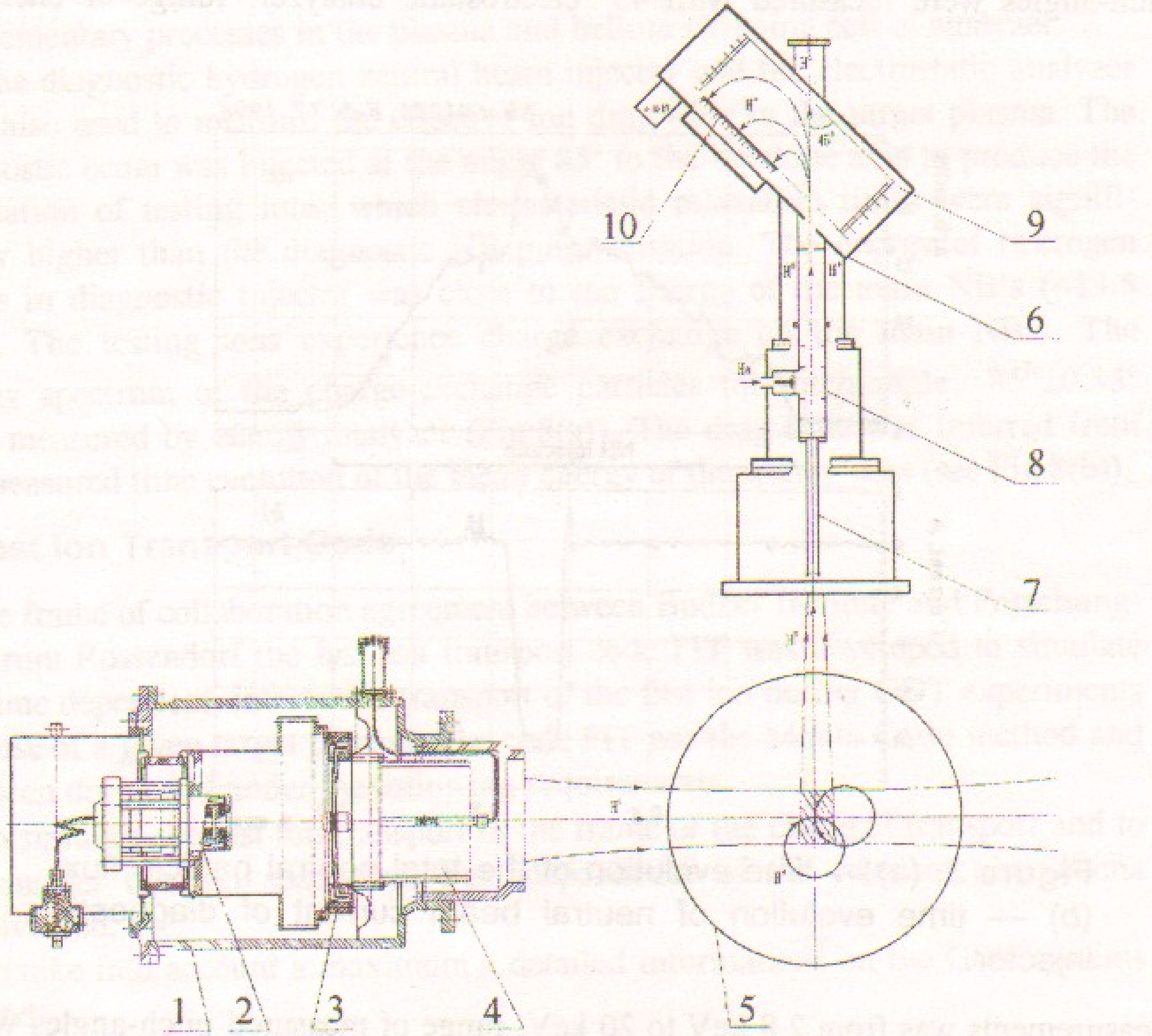

Figure 2. Layout of the diagnostics to measure the local energy distribution function of fast ions.
1 – diagnostic NB injector, 2 — plasma source, 3 – focusing ion-optic system, 4 – charge-exchange cell, 5 – plasma, 6 – electrostatic analyzer, 7 — collimator, 8 — stripping cell, 9 — electrostatic 45° analyzer, 10 — MCP.

To measure the local energy distribution function of fast ions, we applied the method of artificial target [16,17]. To serve this diagnostic special hydrogen neutral beam injector was installed in the central plane of the device at the distance of 1.2 m from the axis (see Fig.1). To obtain the enhanced neutral flux density, ion-optic system, which provides the beam focusing, was used [17]. The neutral beam was employed as a charge-exchange target for fast ions. The distribution function of charge-exchange neutral particles over energies and pitch-angles were measured with 45° electrostatic analyzer. Range of energy measurements was from 2.8 keV to 20 keV, range of measured pitch-angles was 45°±4°. Figure 2 shows the layout of the diagnostic, Table 2 lists the main parameters of the diagnostic. The local measurements were rather difficult, because heating hydrogen neutral beams are injected at the same place and provide high charge-exchange background level. However, it is convenient to measure the angular spread in this region because the angular spread here is minimal.

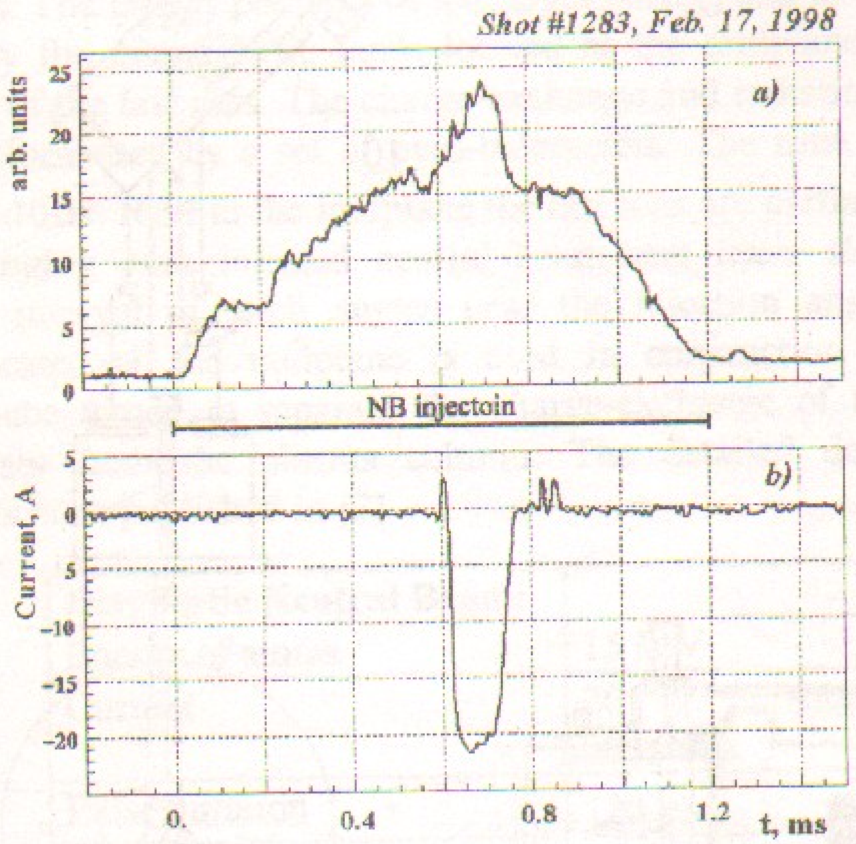

Figure 3. (*a*) — time evolution of the total neutral particle flux; (*b*) — time evolution of neutral beam current of diagnostic injector.

Figure 3 shows the typical time evolution of the total neutral particle flux measured by analyzer together with time evaluation of diagnostic NB current. The background observed is associated with the charge-exchange of the fast ions with the heating beam atoms. Since the neutral fluxes due to diagnostic beam were relatively small, the fluctuations of background neutral fluxes played an important role. The required accuracy of the measurements of the distribution function (±10%) was reached by averaging the data over several experimental shots. We calculated the distribution function of the fast ions over energies using measured distribution function of neutrals, taking into account cross-sections of the elementary processes in the plasma and helium stripping cell of analyzer.

The diagnostic hydrogen neutral beam injector and the electrostatic analyzer were also used to measure the effective ion drag time in the target plasma. The diagnostic beam was injected at the angle 85° to the machine axis to produce the population of testing ions, which characteristic relaxation times were significantly higher than the diagnostic NB pulse duration. The energy of hydrogen atoms in diagnostic injector was close to the energy of the main NB's (~13.5 keV). The testing ions experience charge exchange on the main NB's. The energy spectrum of the charge-exchange particles for pitch-angle −85°±0.35° were measured by energy analyzer (Fig.8(a)). The drag time was inferred from the measured time evolution of the mean energy of the testing ions (see Fig.8(b)).

3. Fast Ion Transport Code

In the frame of collaboration agreement between Budker Institute and Forschungscentrum Rossendorf the fast ion transport code FIT was developed to simulate the time dependent, interactive transport of the fast ion during GDT experiments for case of a given target plasma. The code FIT use the Monte Carlo method and has been developed under the following requirements

- to simulate the fast ion transport in the frame of the classical transport and to consider the full space and time dependence of the relevant phenomena involved,
- to take into account a maximum a detailed informations on the GDT systems and
- to produce a maximum of results per run.

The general scheme of the code is of standard type: stochastically independent fast ion histories are generated in course of which the scoring of results is performed by summing up contributions to well-defined estimators for each quantity of interest. Having simulated *N* particles histories a final result for each quantity is computed as the average of the estimates scored by each of them and the statistical error of the result is calculated from the mean quadratic deviation of the individual estimates from their mean value. The main disadvantage of the method is due to the fact that this statistical error converges with $N^{-1/2}$ only. The main components of the code are

- generation of neutral atoms on the emission surface of neutral beam injectors;
- ionisation of the NBI atoms by charge exchange, electron and ion impact;
- flight of ion in given magnetic field;
- interaction with the target plasma (energy losses and scattering of the flight direction);
- interaction with the neutral gas and generation of fast atoms.

FIT offers a great spectrum of physical quantities that may be estimated. The results represent the quantities of interest as discrete distributions over user-defined phase space grid over a sequence of time intervals. The main result functions are: fast ion energy content, NB trapped power, charge-exchange loss power, electron drag power, energy and pitch angle distribution functions of fast ion in magnetic tube defined by radial interval at the GDT midplane.

The NEUSI and TUBE codes were use additionally to calculate the space and time distribution of the neutral gas for simulation of fast ion charge-exchange. The detailed description of FIT, TUBE and NEUSI codes have been published in [10].

4. Results of experimental and numerical study of the fast ion confinement

4.1 The global energy balance

The fast ion global energy balance is illustrated by Fig.4(a). NB-injected power (P_{inj}) was determined by measuring of ion current and accelerating voltage of each injector. Then, ion beam power was multiplied by the measured neutralization efficiency of the beam which varies in the range of 0.82-0.85 for different injectors. Trapped NB power (P_{tr}) was determined using the beam attenuation measurements. The fast ion energy content (W_F) was determined based on the diamagnetic loops data. The power of charge-exchange losses (P_{ex}) were measured by an array of pyro-bolometers. Subsequently the electron drag power (P_{Fe}) was calculated using the energy balance equation:

$$P_{Fe} = P_{tr} - \frac{dW_F}{dt} - P_{ex}.$$

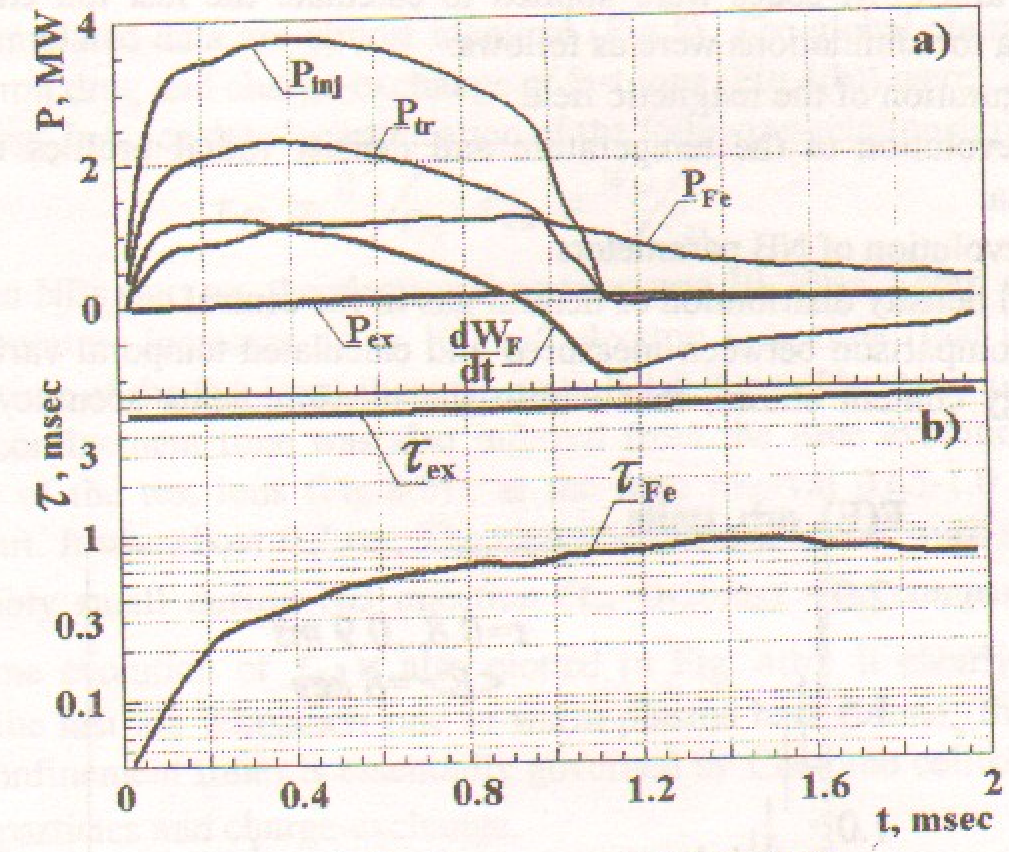

Figure 4. Fast ion power balance data.

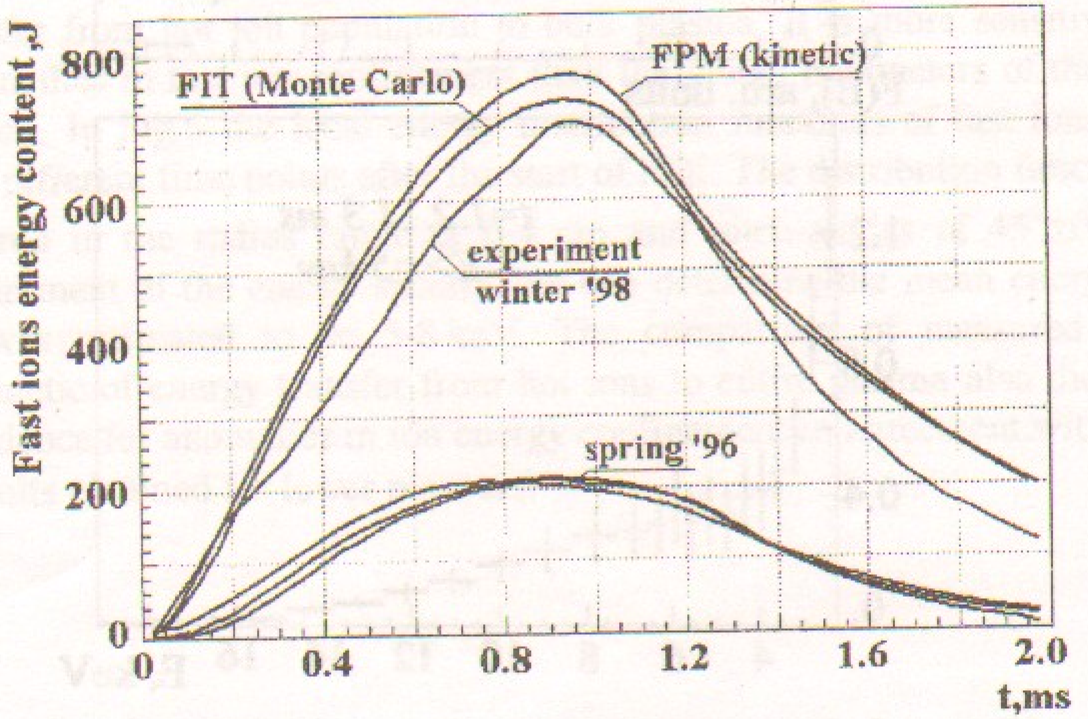

Figure 5. Fast ion energy content vs. time. Simulations (FIT — Monte-Carlo code, FPM — Fokker-Planck code) and experimental data, before (spring'96) and after (winter'98) NB-system upgrade.

The FIT and FPM codes were applied to calculate the fast ion characteristics. Input data for simulations were as follows:

- configuration of the magnetic field;
- time evolution of the temperature and density radial profiles of the target plasma;
- time evolution of NB parameters
- spatial density distribution of neutral gas in the central cell.

The comparison between measured and calculated temporal variation of fast ion energy content shows, that within the measurements accuracy the experimental and simulated data are almost identical (Fig.5). The global characteristic times of electron drag and charge-exchange of fast ions (Fig.4(b)) were calculated using the energy balance data by application of the following relationships:

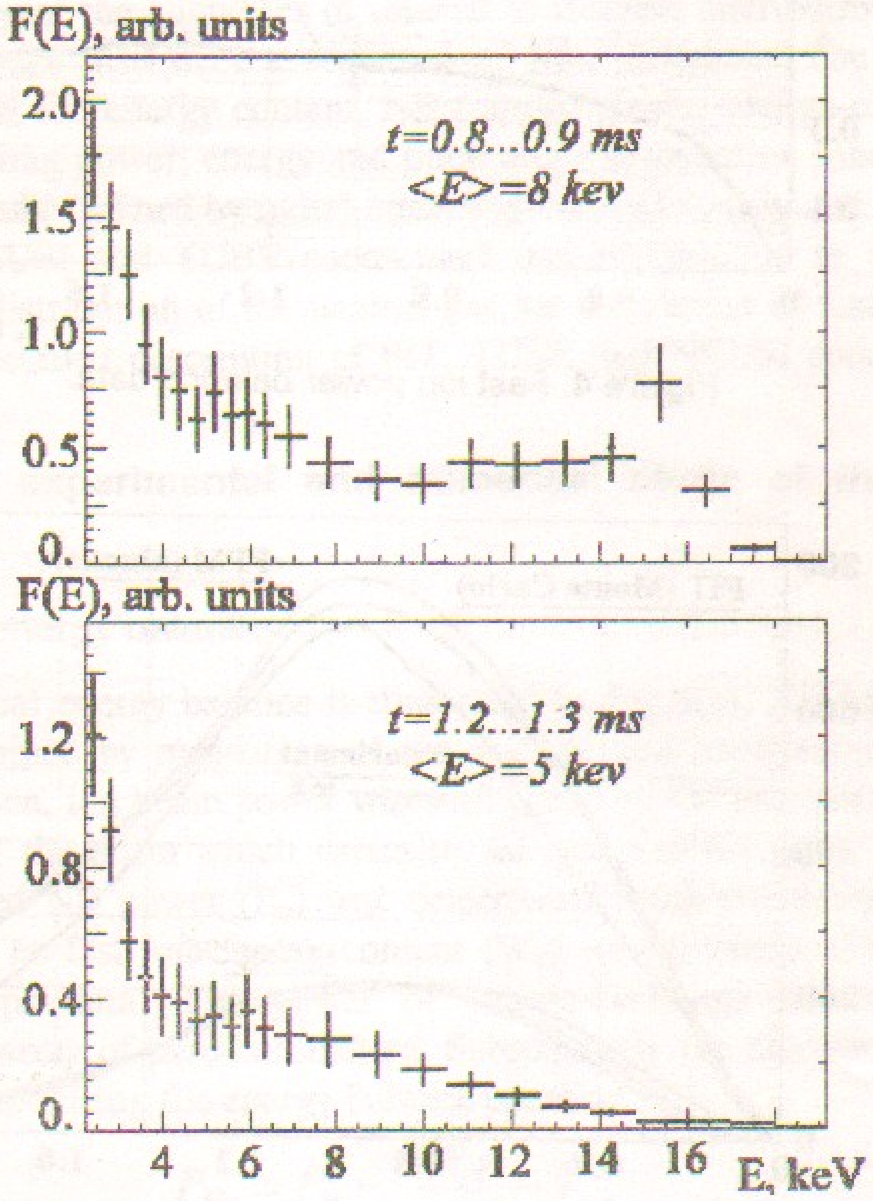

Figure 6. The measured local energy distribution function of fast ions at different time points after the start of NBI. The measurements were performed in the range of radii of 0-4 cm and in the range of pitch angles of 45°±0.35°.

$$\tau_{Fe} = W_F / P_{Fe}\ ;\ \tau_{ex} = W_F / P_{ex}$$

Initially, when NBs start up, the electron drag time was 10-20μs. Later, when the electron temperature increases up to 100 eV, electron drag time (that is energy confinement time of the fast ions) increase up to 0.3-0.8 ms. The value of the fast ions energy confinement time was also inferred from the time evolution of the mean energy of the test ions (Fig.8(b)), at the time interval 0.65-1.0 ms after main NBs start. It was about 0.7 ms. The charge-exchange losses were measured to be negligibly small during NB injection (τ_{ex}=6-10ms). For comparison the calculated time evolution of τ_{Fe} is also plotted in Fig. 4(b). It clearly demonstrates, that the fast ion relaxation rate in warm plasma background (that is fast ion energy confinement time) is essentially governed by Coulomb collisions with bulk plasma particles and charge-exchange.

4.2 The local energy distribution functions of the fast ions

The measured local energy distribution functions of fast ions show the kinetics of energy transfer from hot ion population to bulk plasma. It is more sensitive to possible anomalies in fast ion confinement than the global parameters of the hot ion population. In Fig.6 the local energy distribution functions of fast ions are presented at different time points after the start of NBI. The distribution functions were measured in the radius range of 0-4 cm and pitch-angles of 45°±0.35°. From measurement of the energy spectra one can determine the mean energy of ions, that was estimated to be 5-8 keV. The comparison of measured and simulated kinetic of energy transfer from hot ions to entire plasma also did not give any evidence for anomalies in ion energy confinement in agreement with the previous results obtained for lower plasma β.

5. Conclusions

The population of the hot ions with high energy content and mean ion energy of 5-8 keV was obtained in GDT experiments by 4 MW neutral beam injection in combination with titanium coating of the first wall between the experimental shots. The confinement of the fast ions was studied both experimentally and numerically using special computer code based on Coulomb collisions. Comparison of the energy confinement time, measured experimentally and obtained numerically allowed us to conclude that two-body Coulomb collisions determine the confinement of the fast ions. Anomalous energy transport of the fast ions, was not yet observed in GDT experiments in this high-β regime.

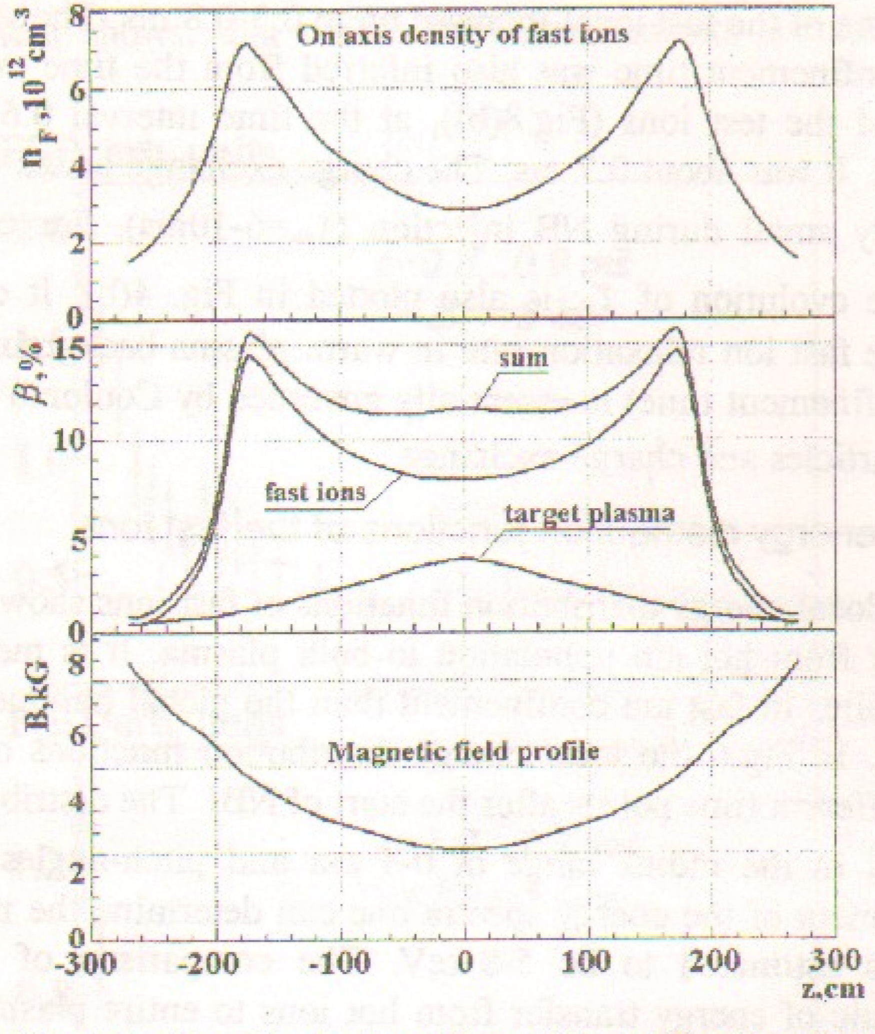

Figure 7. Simulated longitudinal profiles of β and fast ion density assuming the classical Coulomb kinetic of ion scattering.

Unfortunately local angular distribution functions were not measured precisely during these experiments. This circumstance is caused by too small available range of the pitch-angles, which have been monitored by the analyzer of charge-exchange neutrals.

Assuming the classical Coulomb kinetic of ion scattering (as the hypotheses that must be verified by future experiments) we used FIT code to calculate longitudinal profiles of plasma β and fast ion density (Fig.7). Note that near by mirror regions (z≈ ±(150-200 cm) density of the fast ions exceeds $8\cdot10^{12}$cm^{-3}, at the same time plasma β reaches ≈20%.

Two approaches to further study of fast ion scattering are currently planned. The first approach consists in essential increase of observed pitch-angle range monitored by the electrostatic analyzer. Essential reconstruction of the GDT central cell is required to realize this idea. Another approach uses the deuterium NB injection instead of hydrogen neutral beams and monitoring of the longitudinal distribution of the neutron flux from D-D fusion reactions. Development of the set of neutron diagnostics is required to realize this approach.

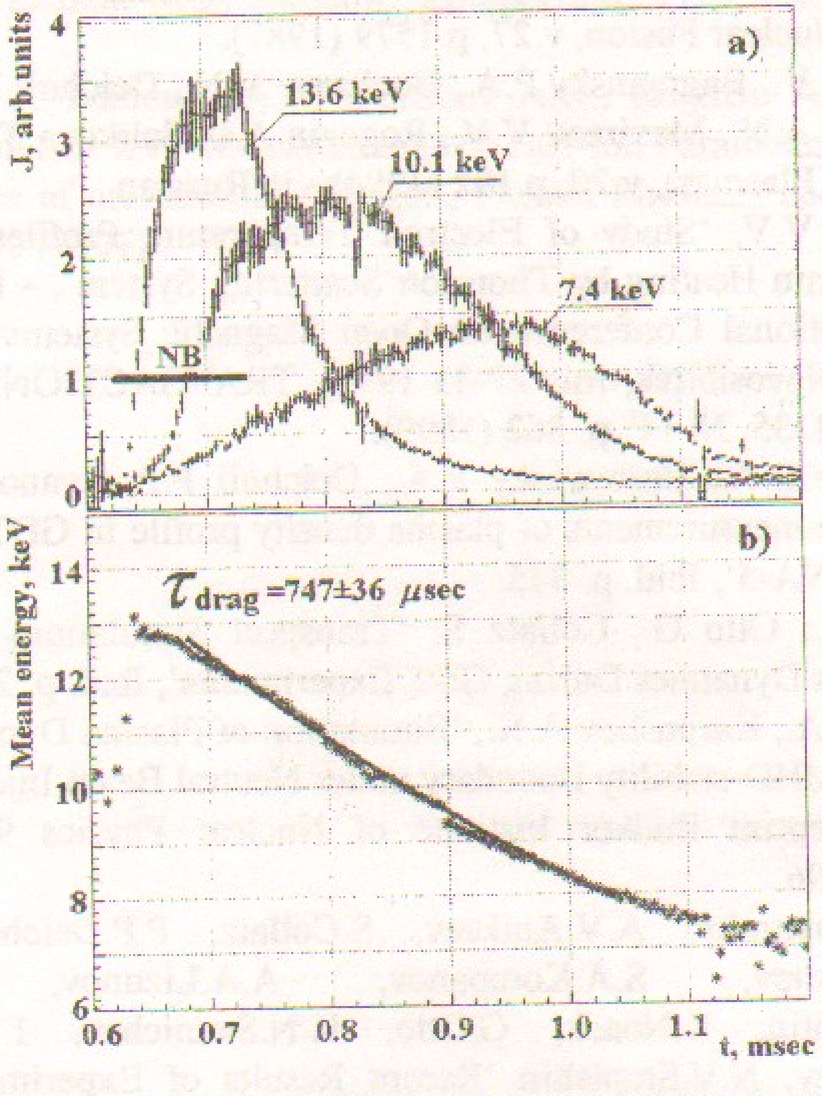

Figure 8. a) The signals from different channels of the energy analyzer
b) Mean energy of the test ion population vs. time.

Acknowledgements

The work was performed in part under the auspices of International Scientific and Technology Center, Research Project number 492.

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S.V. Murakhtin, A.Yu. Smirnov, K. Noack, G. Otto

Investigation of fast ion confinement in the gas-dynamic trap

Budker 99-9

Ответственный за выпуск А.М. Кудрявцев
Работа поступила 5.02. 1999 г.
Сдано в набор 6.02.1999 г.
Подписано в печать 6.02.1999 г.
Формат бумаги 60×90 1/16 Объем 1.4 печ.л., 1.1 уч.-изд.л.
Тираж 130 экз. Бесплатно. Заказ N° 9
Обработано на IBM PC и отпечатано на
ротапринте ИЯФ им. Г.И. Будкера СО РАН
Новосибирск, 630090, пр. академика Лаврентьева, 11.