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HIGH PRESSURE PLASMA CONFINEMENT AND STABILITY IN GAS DYNAMIC TRAP

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The paper reviews recent results obtained in the studies of high beta plasma confinement in Gas-Dynamic Trap (GDT) device. Successful application of Ti-gettering and increase of NB injection power and duration enable to obtain a plasma as high as 30%. Enery balance and stability of this high beta plasma with a density of ~3 10^{13} cm^{-3} were thoroughly studied. Confinement of more dense plasma with steeper density gradients was also studied in the experiment with on-axis gas puff in the central cell.

INTRODUCTION

One of the key issues to be studied in the experiments on GDT device is the MHD and micro-stability of multi-component plasma with high β. It is essential that for the GDT-based neutron source plasma confinement is to be nearly classical one. Successful application of Ti-gettering and increase of NB injection power and duration provided excess to obtaining plasma with β value as high as 30%. It enable us to study plasma energy balance and stability in these regimes with a bulk plasma density of ~3 10^{13} cm^{-3} and fast ion density of up to 10^{13} cm^{-3} in the turning points and compare the plasma parameters with the code predictions. Additionally, confinement of more dense plasmas with steeper density gradients was studied in the experiment with on-axis gas puff in the central cell.

EXPERIMENTAL SETUP

The experimental setup is schematically shown in Fig.1. The vacuum chamber consists of a cylindrical central cell 7 m long and 1 m in diameter (1) and two expander tanks attached to the central cell at both ends (2,3). GDT has an axisymmetric magnetic field configuration that is produced by a set of coils mounted on the vacuum chambers (4). Both mirror coils of the GDT are composed of two parts inserted one into another (5). The outer coil is supplied in series with central cell coils whereas the inner coil is powered independently and produces an additional field of up to 10 T. These inserts provide a variable mirror ratio ranging from 12.5 to 100 when the central magnetic field is set to be up to 0.22 T.

In the recent years remote anchor cells of two different types were experimentally tested. The first is an expander end cell in which the plasma from the mirror throat freely expands along decreasing magnetic field to the end walls. By energizing the proper coils of the end tank we were able to perform experimental runs that switched between expander and cusp end cell configurations without opening the device to air.

Plasma start-up is initiated by injection of the hydrogen plasma along the field lines from one end during ~2.9 ms by making use of a gas-puffed washer-stack plasma gun installed inside the end tank. Subsequently, the target plasma column with an initial temperature of 3–5 eV and a density of $6–20\times10^{13}$ cm^{-3} is heated up by the Neutral Beam injection which at the same time provides the fast ions. The total time of plasma gun operation is up to 4.0 ms. an additional plasma gun was installed behind the cusp end cell to vary the plasma parameters in the cusp independently. A more detailed description of the GDT device is given in [1-4]. The GDT NB-system consists of six injectors that are azimutally arranged in two groups on opposite sides of the central cell. The azimuthal angle between the injectors of one group is 30^0. The neutral beams are injected at 45^0 to the axis. The current of each neutral beam amounts to 48-55 equivalent Amps, the energy of neutrals is in the range of 12.5–17.5 keV, the duration of the NB pulse is 1–1.2 ms, and the total injected power exceeds 4 MW. The angular divergence of the neutral beams is: $\alpha_{\perp}\approx1^0$ in the direction perpendicular to the machine axis, and $\alpha_{||}\approx2.5^0$ along the axis. In order to decrease the charge-exchange losses of fast ions it is essential to reduce the neutral gas recycling at the chamber wall.

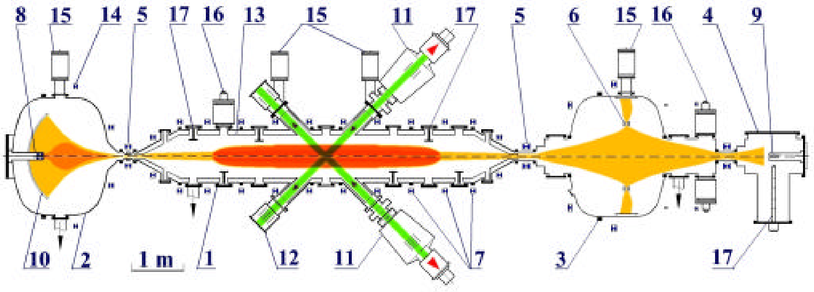

Fig.1 The GDT layout: 1-central cell vacuum vessel; 2-expander end tank; 3-cusp end tank; 4-end tank; 5-mirror coils; 6-cusp coils; 7- central cell coils; 8-plasma gun; 9-additional plasma gun; 10-plasma dump; 11-neutral beam injectors; 12-beam dumps; 13-first wall liner; 14-expander coils; 15-cryopumps; 16-Ti-getter pumps.

FAST ION RELAXATION AND CONFINEMENT

Hot ion confinement in high-ß regimes was studied by comparison of the global and local parameters of the fast ions measured experimentally with those predicted by computer simulations. To realize this approach a self-sufficient set of diagnostic methods for studying the fast ions has been developed [5]. As an example of application of this approach, Fig. 2, 3 show calculated and measured parameters of the fast ions in the GDT central cell. The fast ion energy and angular distributions were inferred from the energy spectrum of charge-exchange neutrals with spatial resolution of ~4 cm. For comparison the results of FIT [5] code simulation are also shown.

The experimental data and estimated values of the fast ion angular spread for the given experimental conditions are presented in

Fig. 2 as functions of ion energy. These data allow to conclude that the measured angular spread of the ions is quite well explained by their Coulomb interaction with the bulk plasma particles. From this observation it can be further concluded that within the measurements accuracy (~15%) micro-instabilities which could cause significant additional scattering of fast ions were not yet observed in GDT experiment in these high beta shots.

The global energy distribution functions of the fast ions were obtained by integration of experimentally measured functions over pitch-angles and the central cell volume. These are shown in Fig. 3 as measured during and after the NB injection. It is seen that the distribution evolves over time so that ions accumulate in the low energy range as provided by the dominant process of the ion slowing down on bulk plasma electrons. Comparison of these distributions with those simulated by the numerical codes show that losses to the radial limiters and to the loss cone are not significant. Classical character of the fast ion relaxation in high-β plasma was also confirmed by the measurements of the angular distributions of the fast ions shown in Fig. 4 together with the distributions simulated by the FIT code. Note that the angular spread at high energy (14-18 keV) is close to that in the main NBs. The angular spread of the ions with energies 3-5 keV was approximately 3 times larger than that for the injection energy. Therefore the conclusion can be drawn that confinement of the fast ions is good enough that was also confirmed by measurements of their energy balance which are summarized in the table.

Fast ion energy content, within the measurement accuracy (about 15%), is in reasonable agreement with the simulation results and do not exhibit any significant differences compared to the case of low β shots.

Generally, the measurements indicate that the fast ions have relatively narrow angular spread. Therefore the longitudinal fast ion density profile (and the resulted neutron flux) is to be peaked near the turning points. This is one of the basic features of the GDT-based neutron source [6]. This peaking was additionally studied by the measurements of axial profile of D-D fusion products in the shots with deuterium neutral beams with the energy 13-17 keV and total power up to 3 MW. It was observed that the decay time of accumulated fast deuterons is ~1.5 time longer than for H^+ ones. The fusion products (2.45 MeV neutrons and 3.02 MeV protons) emission were measured by an array of scintillation detectors equipped with retractable collimators. While not collimated the detector sees ~2π solid angle. When collimated by a mask with slits oriented perpendicularly to the machine axis, the detector essentially measures the DD proton linear specific yield with a spatial resolution ~ 20 cm. The measured proton flux profile is presented in Fig. 5 in which the estimated flux for 3^0 angular spread of the fast D^+ ions is also shown for comparison. Reasonable agreement between experiment and simulation results was noted that is considered to be an additional important argument supporting the main conclusions about classical character of fast ion relaxation in the GDT-experiment with high-ß plasma.

The hot ions with maximum density of about 10^{13} cm^{-3} and mean ion energy of about 8 keV was produced in GDT with the 4 MW neutral beam injection. At the same time plasma ß reaches almost 30%.

Parameter	Value
NB injected power	3.1–3.7 MW
Trapped power	1.6–2.2 MW
Fast ion energy contents	520–650 J
Charge-exchange losses	150±30 kW
Losses to loss cone	<50 kW
Electron drag power: in plasma core in plasma halo	1.15±0.1 MW ~930 kW ~220 kW
Energy confinement time: global energy balance data test ions relaxation [7] estimated value	 550–750 μs 774±36 μs ~700 μs

Fast ion energy balance data

GLOBAL ENERGY BALANCE OF THE HIGH-β TWO-COMPONENT PLASMA

The results of the global energy balance studies for high-β regimes at 0.6 ms after NBI start shown that about 60% of injected fast atoms were trapped and transformed into sloshing ions. The dominant fast ions energy losses channel was electron drag. The main channel of the plasma energy losses was the longitudinal losses through the mirrors (43% of electron drag power). The losses to the limiters were about 26%. Heat sink to the plasma gun muzzle (27%) significantly contributes to the energy losses in near-axis region.

The following conclusions can be drawn from the measured energy balance measurements in the high-β shots:

- fast ions energy losses are dominated by classical electron drag and charge-exchange losses as it was previously measured in low plasma-β regimes;

- the measurements of the angular and energy distribution functions are explained quite well by Coulomb interaction with the target plasma particles;
- enhanced scattering or energy losses due to micro-instabilities were not observed in the GDT experiment;
- for electron temperatures ~100 eV the energy losses from the target plasma are increased in the near-axis region presumably due to heat sink to plasma gun located in the expander;
- for the radii 8-12 cm longitudinal losses from the target plasma are dominated by collisional outflux through the mirrors;
- the measured transverse lifetime of the plasma exceeds 40 Bohm transverse lifetime.

CONCLUSIONS

Confinement of a plasma β in GDT central cell with beta up to 30% was studied. Measurements of local distribution of fast ions over energies and pitch angles indicate that there were no noticeable anomalies in fast ion slowing down and scattering. For mirror ratio of 12.5, energy losses from the target plasma are dominated by longitudinal ones. With increasing mirror ratio to 45 it was observed that energy lifetime of the target plasma is about 2 time less than that determined by longitudinal losses through the mirrors. Additional channel of energy losses can be characterized by corresponding lifetime which is estimated to be ≈ 30-40 t_{Bohm} for the representative shot parameters.

In this estimate of the effective plasma temperature is calculated including contribution from fast ions. Exact mechanism of enhanced transverse losses is not identified so far. It is believed that the extra energy losses during NB injection would be caused by residual asymmetry of beam current of injectors installed at different azimuths that still exists. Nevertheless, it should be emphasized that these losses are tolerable when scaled to the operational parameters of the GDT-based neutron source [6].

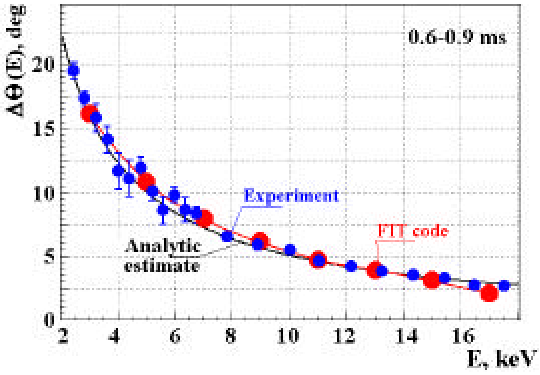

Fig. 2. Angular spread of fast ions vs. energy

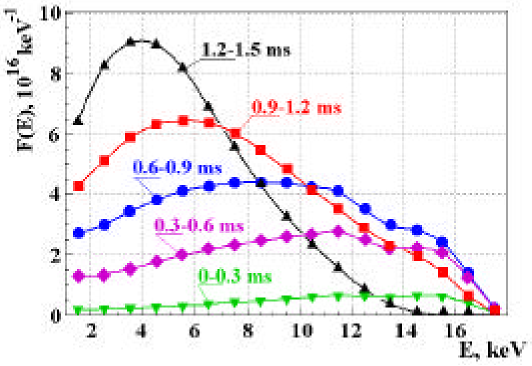

Fig. 3. Global energy distribution functions

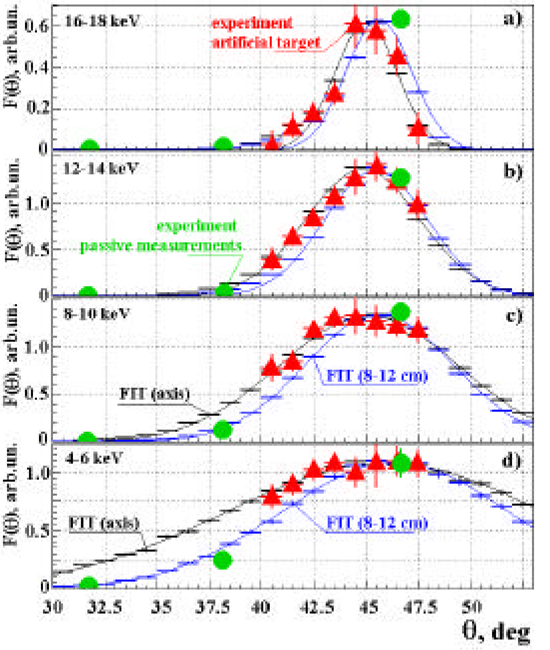

Fig. 4. Angular distribution of fast ions for various energy intervals at 0.6-0.9 ms

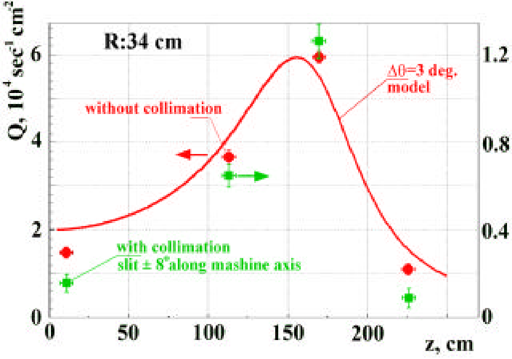

Fig. 5. Axial profile of 3.02 MeV proton flux

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