EXPERIMENTS ON HIGH-β PLASMA CONFINEMENT IN GAS DYNAMIC TRAP

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Abstract

The paper reports on the present status of the Gas Dynamic Trap (GDT) experiment and plasma parameters recently achieved with increased neutral beam power. The measurements indicated plasma beta approaching 0.3 in the vicinities of the turning points of energetic sloshing ions. Energy balance of the energetic sloshing ions with maximal density of 10^{13} cm^{-3} and energies ~ 5-7keV was studied in detail in the regimes with high beta. It was observed that relaxation and losses of the energetic ions are dominated by classical Coloumb scattering. Also discussed in the paper is power balance of the bulk plasma heated by the neutral beam injection.

1. INTRODUCTION

The Gas Dynamic Trap (GDT) (see Fig.1) is an axisymmetric plasma confinement device with the high mirror ratio variable in the range of 12.5-100. To provide MHD stability of the entire plasma axisymmetric min-B cells are attached from both ends of the device. The plasma confined in the central cell is essentially collisional and contains hot ion minority produced by oblique injection of high-power neutral beams (NBs) into the relatively cold target plasma. The plasma in the external stabilizing cells are fed by bulk plasma losses from the central cell. Studies of low beta (5-10%) plasma confinement in GDT are reported elsewhere [1-3]. Main objective of the GDT research program is to generate adequate plasma physics database for the GDT-based neutron source for material irradiations [4]. In order to provide 14MeV neutron flux approaching 2MW/cm^2 in the testing zones plasma beta in the device should be as high as ~0.7. So far, confinement of high-β plasma, relevant to operational conditions in the GDT-based neutron source, was not studied. To address those problems we increased injected neutral beam power and improved vacuum conditions in the GDT.

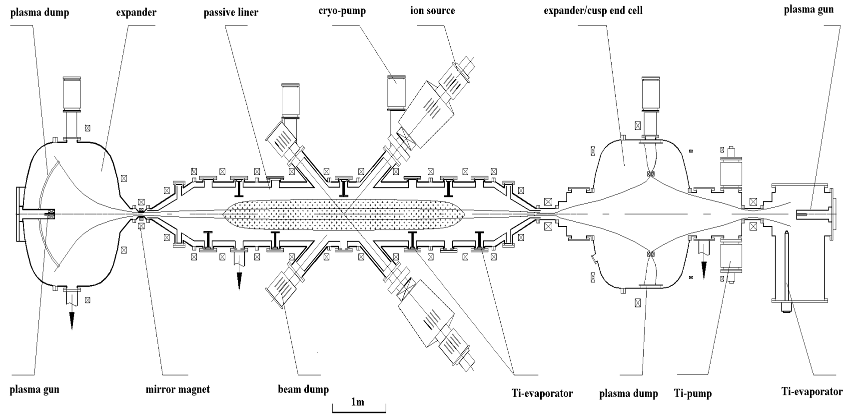

FIG.1 General layout of the GDT.

The GDT parameters are listed in Table1. Recently, the currents of each of six NB injectors were equalized by their increasing to 37 eq. A. (as it was for the better injector), for 15.5 -17keV energy thus providing full injection power of up to 4.3MW in 1.2ms pulses. Due to the equalizing the injected currents and beam energies for the injectors located at different azimuths better axial symmetry of the injection was achieved. It resulted in smaller disturbances and induced losses of the target plasma during the initial stage of neutral beam heating. With increase the injected NBs power plasma energy was also increased more than 1.5 times in comparison with that previously achieved.

2. SLOSHING IONS CONFINEMENT AND RELAXATION IN THE HIGH-β REGIMES

In stable regimes of confinement with cusp end cell [3] and when titanium was deposited onto the first wall, heating up of bulk electrons to temperatures of 120eV was observed. Reduction of charge-exchange losses and increase of target plasma temperature enabled to increase the density of fast ions with the mean energy of 5-8keV to 10^{13} cm^{-3} near the turning points.

Distribution function of the energetic ions over energies was locally measured at the midplane of GDT using "artificial target" method [5]. Relaxation of the fast ions in the target plasma was simulated using Monte-Carlo code which incorporates classical Coloumb collisions. Simulation results were find to be in reasonable agreement with the experimental data on the fast ion distribution over energies and pitch angles as well. The measured fast ion energy content, with an accuracy of ±10%, close to that predicted by the code for the given parameters of target plasma.

TABLE 1. The parameters of GDT experiment

Parameter	Value
Magnetic field at midplane	0.22 T
Total length	11m
Trapped NBI power (15.5-17keV beam energies)	2.4-2.6 MW
Fast ion energy content	520-700 J
Bulk plasma energy	170-230 J
Electron temperature	85-110eV
Radiated power	20-50kW
Electron drag power in limiter shadow	220kW
Power released on limiters	300kW
Plasma radius	8.5cm
Bulk plasma density	1.0-10×10^{13} cm^{-3}

The fast ions global energy balance in high-β regimes is illustrated by Fig.2. NB-injected power (P_{inj}) was determined by measuring of a drain current and an 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 from beam attenuation measurements. The fast ion energy content (W_F) was inferred from the diamagnetic loops data.

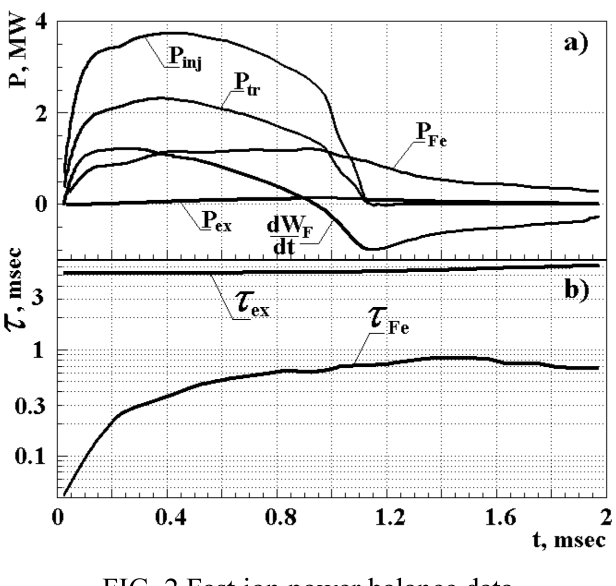

FIG. 2 Fast ion power balance data

The power of charge-exchange losses (P_{ex}) were measured by bolometers located on the first wall of central cell. Subsequently the electron drag power (P_{Fe}) was derived using the energy balance equation:

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

In parallel, the Monte-Carlo (FIT — fast ion transport code) [6] and Fokker-Planck (FPM — fast particles model) [7,8] codes were applied to calculate the fast ion characteristics. As inputs for these codes we used the measured parameters of neutral beams and those of the target plasma and spatial density distribution of neutral gas in the central cell.

The comparison between the measured and calculated temporal variation of fast ion energy content shows, that within the measurement accuracy the experimental and simulated data are almost identical (Fig.3). It demonstrates that the relaxation rates of the fast ions in a plasma background are essentially defined by Coulomb collisions with a bulk plasma and charge-exchange. The same results has been obtained previously in the studies of lower density energetic ions relaxation [3,9]. The global characteristic times of electron drag and

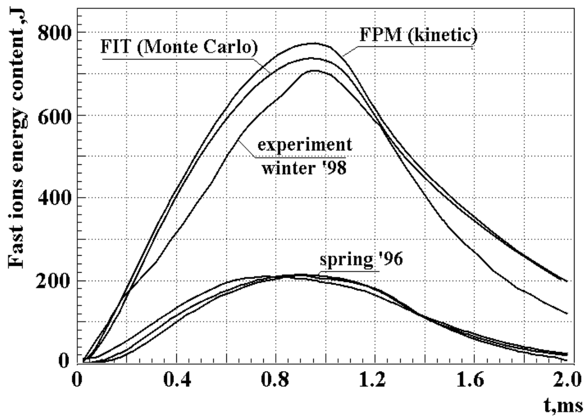

FIG. 3 Fast ion energy content vs. time: simulations using FIT and FPM codes and experimental data measured before (spring'96) and after (winter'98) NB-system upgrade.

charge-exchange of fast ions were calculated from the energy balance data by making use of the following relationships:

$$\tau_{Fe} = {}^{W_F}\!/_{P_{Fe}} ; \tau_{ex} = {}^{W_F}\!/_{P_{ex}} .$$

Initially, when NBs start up, the electron drag time was as low as 10-20μs provided the electron temperature being of some eVs and plasma density of 3-13×10^{13} cm^{-3}. Later on the electron temperature increases up to 100 eV causing the electron drag time increase up to 0.3-0.8ms. The charge-exchange losses were measured to be negligibly small during NB injection (τ_{ex}=6-10 ms).

In Fig.4 the local energy distribution functions of fast ions are presented at different time points after the start of NBI. From measurement of the energy spectra one can determine the mean energy of ions, that was estimated to be 5-8 keV. The angular distributions of ions with different energies were also measured and compared to those obtained by numerical simulations. This comparison did not reveal any significant anomalies in fast ion slowing down and scattering rates.

3. BULK PLASMA ENERGY LOSSES

To evaluate the central cell energy confinement time in the high beta regimes we define $\tau_\perp = \frac{W_{cc}}{P_\perp}$, where W_{cc} is energy stored in the bulk plasma, determined by diamagnetic loops, and $P_\perp$ is the transverse power losses from the bulk plasma. Energy losses from collisional bulk plasma under neutral beam heating were evaluated in the high performance shots by direct bolometric measurements of the power released on the limiters, less the power released by finite-orbit fast ions in the halo plasma located in the limiter's shadow. The former portion is not directly measured, we determined it from fast energy balance data. The magnitude of the various terms used to evaluate the global energy confinement time of the bulk plasma is given in Table I. The difference between the total power absorbed by the limiters (300kW) and Electron Drag Power (EDP) of fast ions in the halo plasma gives for the radial power flux from the core plasma the value of about 100kW. In the same experimental conditions the bulk plasma energy content amounts to 170J. This corresponds to energy confinement time of the heated plasma of 1.7ms. In accordance with the data given in Table I, taking the plasma radius a=8.5cm and B=0.2T, T=85eV, one obtains that the characteristic Bohm confinement time $\tau_{Bohm} = {}^{a^2}\!/_{6D_{Bohm}}$, where $D_{Bohm} = {}^{cT}\!/_{16eB}$, equals to 0.045ms and is at least 37 times less than the observed value. This observation reasonably correlates with the results obtained previously for lower plasma temperatures. Note that this ratio between the plasma lifetime and

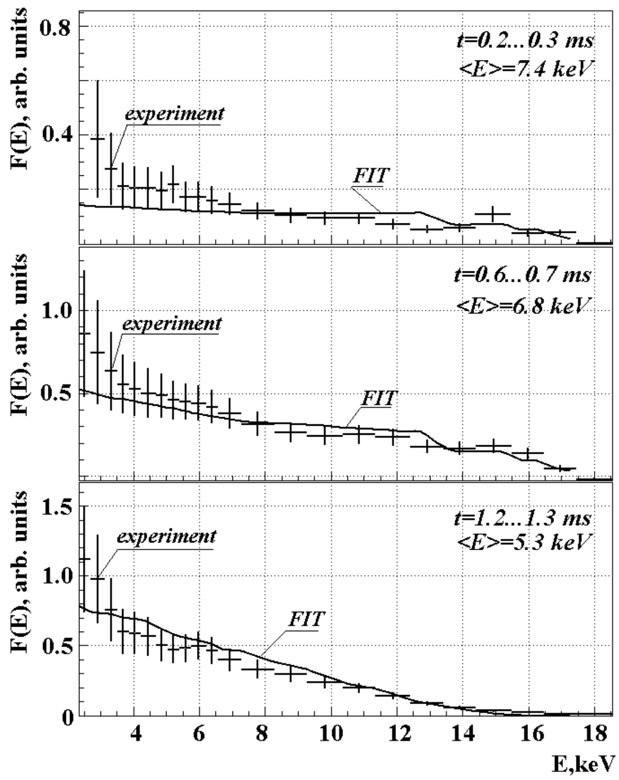

FIG. 4 Local energy distribution functions of fast ions on the GDT axis (r=0...4cm)

characteristic Bohm time is considered to be favorable for the operational parameters of the GDT-based neutron source.

Axial losses from the central cell plasma were also measured and found to be in reasonable agreement with the theory applicable to a collisionless regime of plasma flow beyond the mirrors [6]. An assessment of power balance of the cusp stabilized central cell plasma indicates that these axial power losses account for at least 60% of the EDP for mirror ratio of 12.5.

It was observed that the electron temperature profile in the high performance shots has a well pronounced minimum on axis, indicating enhanced energy losses from the near-axis region. This region is well mapped along the field lines onto the plasma gun, so it can be concluded that this temperature reduction is attributed to heat sink onto the gun. Local energy balance data indicate that about 30% EDP are lost due to this mechanism for plasma temperatures in the range of 80-110eV. For smaller temperatures this energy losses become less significant [3,9].

4. CONCLUSIONS

Plasma β in GDT central cell was increased up to 30% with higher NB power. Measurements of local distribution of fast ions over energies and pitch angels 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 $\approx 30\,\tau_{Bohm}$ 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 noted that these losses are tolerable when scaled to the operational parameters of the GDT-based neutron source.

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