ENERGY CONFINEMENT OF FINITE-β PLASMA IN THE GAS DYNAMIC TRAP

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1. Introduction

The paper reports on the results of neutral beam heated high-β plasma confinement studies in Gas-Dynamic Trap experiment [1,2]. The Gas Dynamic Trap (GDT) is an axially symmetric mirror cell with high mirror ratio and a mirror-to-mirror distance exceeding the ion mean free path of scattering into loss cone. In the high-β regimes, the cusp end cell was attached to one end of the central cell to stabilize curvature-driven flute modes [2].

The operational regimes with high plasma beta were achieved with increased neutral beam power and improved vacuum conditions which were obtained by means of extensive Ti deposition on the first wall between shots [3]. Initial plasma with temperature of 3-5eV is produced in the central cell by using a plasma gun located in one of the end tanks. To provide fast ions build up and heat up the central cell plasma the 13-17.5 keV six neutral beams were injected at the midplane of the device at 45^0 to the machine axis. The parameters of the experiment are listed in Table 1. The main objective of the experiments was to study energy balance of injected fast ions and target collisional plasma as well. The obtained data enable us to compare confinement properties of high-β plasma with those of low-β plasma which have been studied in our previous experiments [1,2].

Magnetic field at the midplane	0.22 T
Mirror ratio	15-45
Base pressure	2.5-5.0×10^{-5} Pa
Neutral beam power incident on a plasma duration energy	 3.8-4.2 MW 1.1 msec 13.0-17.5 keV
Trapped NB power	2.2-2.6MW
Electron temperature before NB injection during NB injection	 3-5 eV 90-110 eV
Bulk plasma density	3-13×10^{13} cm^{-3}
Fast ions mean energy	5-8 keV
Max. density of fast ions	10^{13} cm^{-3}
Electron drag power	1.2-1.5 MW
Energy confinement time: of fast ions of target plasma	 0.3-0.8 ms 0.14-0.3 ms
Max. plasma β	20-30 %

Table 1. The GDT parameters

2. Power balance of the fast ions

The fast ions global energy balance is illustrated in Fig.1(a). NB-injected power (P_{inj}) was determined by measuring of drain current and accelerating voltage of each injector. Then, ion beam power was multiplied by the 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 the beam attenuation measurements. The fast ion energy content (W_F) was inferred from the diamagnetic loops data. The power of charge-exchange losses (P_{ex}) were measured by an array of bolometers located on the central cell first wall. Subsequently the electron drag power (P_{Fe}) was calculated from the energy balance equation: $P_{Fe} = P_{tr} - \frac{dW_F}{dt} - P_{ex}$. In parallel, the Monte-Carlo and Fokker-Plank codes were applied to calculate the fast ion characteristics. As the inputs for these codes we used the measured parameters of neutral beams and those of the target plasma, spatial density distribution of neutral gas in the central cell and the magnetic field profile data. The comparison between measured and calculated temporal variation of fast ion energy content and electron drag power shows, that within the measurements accuracy the experimental and simulated data are almost identical. It demonstrates that the relaxation rates of the fast ions in plasma background are defined by Coulomb collisions with bulk plasma particles and charge-exchange. Additionally, an «artificial charge-exchange target» method was used to measure the local distribution function of the ions at the midplane. In fact, the comparison of the measured energy and angular distributions of the fast ions with those simulated did not reveal any significant anomalies in slowing down and scattering rates of fast ions.

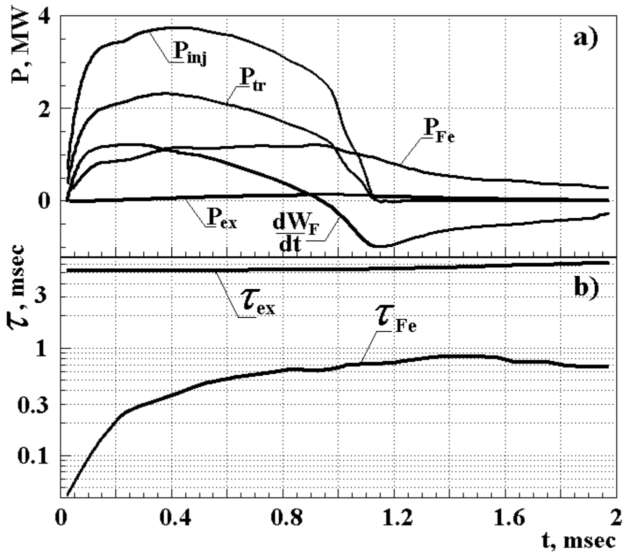

Fig. 1. Fast ion power balance data

The global characteristic times of electron drag and charge-exchange of fast ions (Fig.1(b)) 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 10-20 μs provided the electron temperature being of some eVs and plasma density of $3\text{-}13\times10^{13}$ cm^{-3}. Later on the electron temperature increases up to 100 eV causing the electron drag time increase up to 0.3-0.8 ms. The charge-exchange losses were measured to be negligibly small during NB injection (τ_{ex}=6-10 ms).

3. Energy confinement of the target plasma

The radial profiles of the target plasma parameters in the central cell are shown in Fig.3(a). The electron temperature (T_e) near the device axis was measured by Thomson scattering. Target plasma energy content (W_p) was determined by integration the measured local plasma parameters over the central cell volume and, alternatively, by using the data from diamagnetic loops located between the turning points of fast ions and mirror throats. Fig.2(a) illustrates the energy balance of the bulk plasma during NB-heating. Note that the electron drag power was inferred from the fast ion energy balance consideration. It was observed that the sum of the target plasma longitudinal losses and that on the radial limiters (P_{II}^{theory}) was ~2 times less than the measured total energy losses: $P^{EXP} = P_{Fe} - {dW_p}/{dt}$. The theoretically predicted and experimentally measured energy confinement times of target plasma are shown in Fig.2(b). The total radiation losses from the plasma measured by bolometers were less than 100 kW and therefore did not significantly contribute to energy balance. The thermally insulated plates on the limiters were used to measure the total radial energy losses. Characteristic transverse lifetime of the plasma ($\tau_\perp$) was then calculated as a ratio of plasma energy to the power absorbed by the limiter plates. Thus calculated $\tau_\perp$ exceeds 30 τ_{Bohm}. Fig.3(b) shows radial profile of the target plasma losses measured 600 μs after NBI starts. Note that the electron drag power 3-5 times exceeds the calculated longitudinal losses on the axis and

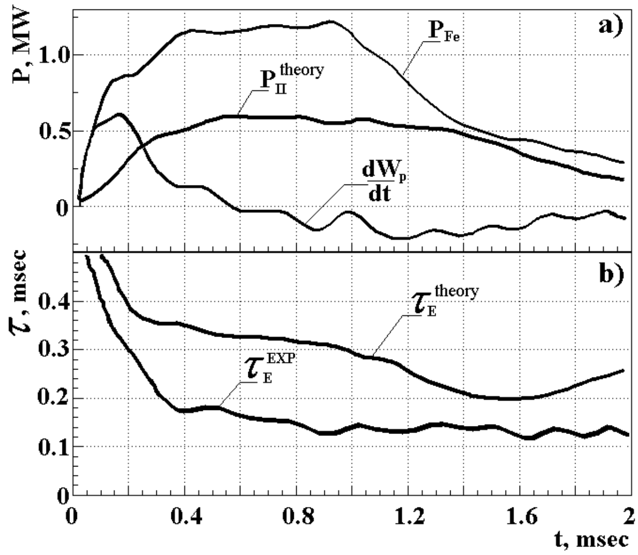

Fig. 2. Power balance of the target plasma

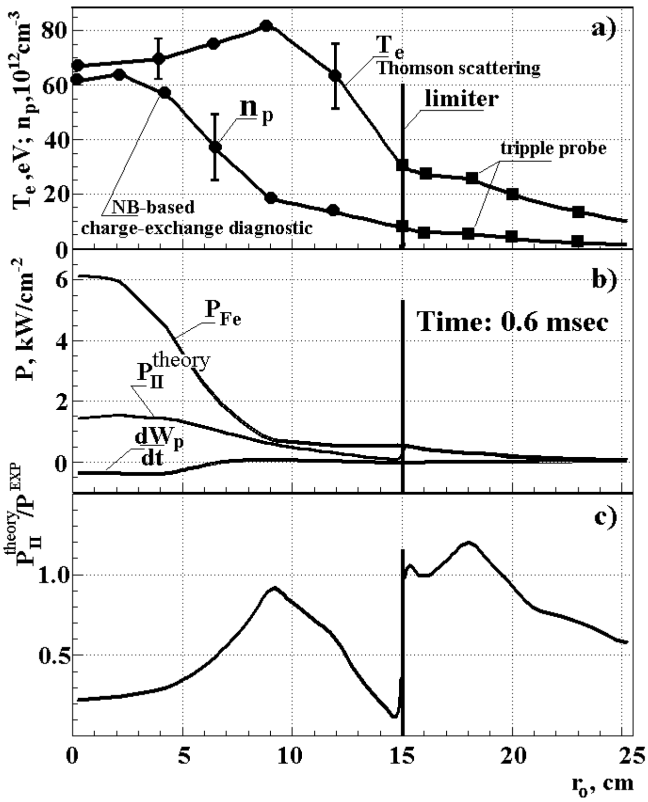

Fig. 3. Local energy balance data

approximately equals to that on the plasma periphery (radii 8-12 cm) (Fig.3(c)). Since the region with the increased near-axis losses is well mapped onto the plasma gun muzzle this increase might be explained by a heat sink to the plasma gun producing the cold dense plasma near the mirror. Another losses channel is the cross-field transport towards (13-15 cm) the plasma halo which mapped on to the limiter. According to the measurements of plasma parameters in halo, the energy confinement here is determined by heat flux through the sheath near the limiter surface which is limited by potential drop across the sheath [4].

4. Conclusion

The plasma β approaching 30% was obtained in the GDT with the higher neutral beam power and titanium deposition on the first wall between the shots. Injection of the 4.2 MW neutral beams with energies 13-17.5 keV and duration 1.1 ms provides the density of fast ions with mean energy 5-8 keV up to 10^{13} cm^{-3} and the electron temperatures 90-110 eV. The following conclusions can be drawn from energy balance measurements in these 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 with lower neutral beam power;
- for high electron temperatures (~ 100eV) the energy losses from the target plasma are increased in the near-axis region presumably by 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.

Acknowledgements

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