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STUDY OF HOT-ION PLASMA CONFINEMENT IN THE GAS-DYNAMIC TRAP

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1. Introduction

The study of hot anisotropic ion confinement is one of the key elements of the experimental program on the gas-dynamic trap (GDT) [1]. Hot ions are produced in the trap by 45^0 injection of six 13-17 keV neutral beams into collisional target plasma. The total injected power was up to 4.5 MW, pulse duration 1.2 ms. The behavior of hot ions with mean energy 3-10 keV and peak density of $0.5\text{-}1.0\times10^{13}$ cm^{-3} was studied in detail in the experiments with plasma-ß up to 30 %. The method of confinement study consists essentially in comparison of the measured ion parameters with those predicted by computer simulations based on theory of Coulomb collisions. Self-sufficient set of diagnostics for measurements of fast ion parameters has been developed [2]. In parallel Monte-Carlo transport code was developed for numerical study of the fast ions [3].

For fast ion plasma component the ion mean free path of scattering into the loss cone is much greater than mirror-to-mirror distance. Confinement of these hot sloshing ions with a small pitch-angle spread is the critical issue for the GDT-based neutron source [4] for fusion materials irradiation testing.

To measure the local energy distribution function of fast ions, we applied the method of artificial target [5]. The diagnostic neutral beam (DNB) injector in combination with an electrostatic charge-exchange particle analyzer (CXA) was used to measure the effective ion drag time in the target plasma. Additionally the measurements of DD neutron flux were used to monitor the hot ion density profile along the GDT axis. Comparison of the hot ion relaxation times, measured experimentally and obtained numerically, allowed us to conclude that two-body Coulomb collisions dominate the relaxation of anisotropic fast ions. Anomalous hot ion energy losses as well as angular scattering were not yet observed in GDT experiments in this high-ß regime.

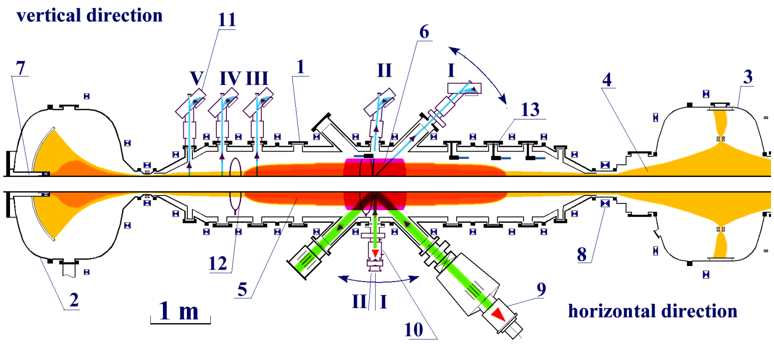

Fig.1: *The GDT layout. 1 – central cell, 2 – expander, 3 – cusp cell, 4 – target plasma, 5 – hot ions, 6 – test ions, 7 – plasma gun, 8 – mirror coil, 9 – NB-injector, 10 – DNB, 11 – electrostatic analyzer, 12 – diamagnetic loop, 13 – scintillation detector.*

2. Global energy balance

The detailed description of the global energy balance data of the fast ions and target plasma was previously presented in [6]. It was shown that at the high-ß regimes of the GDT operation the global characteristic times of electron drag and charge-exchange were 0.3-0.8 and 6-10 ms respectively. The new diagnostic method was apply to infer the fast ion energy confinement time from the temporal evolution of the mean energy of test ions. The diagnostic neutral beam was aimed at approximately 85^0 to the magnetic axis at the GDT midplane (position II in Fig. 1) to provide test ions build up. It was injected at 0.61-0.74 ms after the main NBs start. The test ions were localized within ~100-cm long zone near midplane. Their pitch-angles were close to the injection angle (85^0 in respect to the machine axis) thus allowing to separate the charge-exchange particles resulted from the test ions and those from the main fast ion population whose pitch-angle distribution is peaked near 45^0. Any CXA signal at 85^0 is, therefore, believed to be due to the test ions. The global time of energy losses of the test ions was calculated from temporal behavior of test ion mean energy. At 0.65-1.0 ms after the main NBs start the measured energy relaxation time was about 0.7 ms (Fig.2(b)), that is close to that of the main hot ion population and to that calculated for the given experimental conditions.

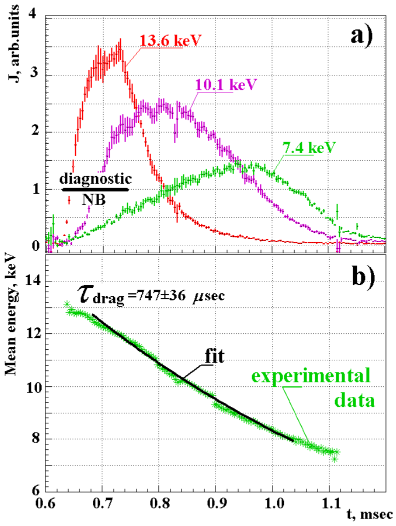

Fig. 2: a) The signals from different channels of the energy analyzer; b) mean energy of the test ion population vs. time.

3. Distribution function of the fast ions

The measured energy distributions of fast ions exhibit the kinetics of energy transfer from the hot ion population to the bulk plasma. It is believed to be more sensitive to possible anomalies in the fast ion relaxation than their global parameters. The fast ion energy and angular distributions were inferred from the energy spectrum of charge-exchange particles. There are essentially three major sources of the charge-exchange neutrals in the GDT: interaction of the fast ions with the residual gas, with the main neutral beams, and with the «artificial charge-exchange target», produced by the separate DNB [5]. Note that the «artificial target» allows to measure the local energy distributions.

In Fig.3 the local energy distribution functions of fast ions at the GDT midplane are presented at different time points after the NBI start for on-axis region and at radius 8.5 cm. The distribution functions were measured with the spatial resolution of 4 cm for pitch-angles of 45°±0.35°. The data from the plasma periphery exhibit less number of particles in the energy range 3-6 keV. We explain that by higher ratio of electron drag time to the charge-exchange time at the plasma periphery compared to that in the near-axis region. The relaxation of the energy distribution function after NBs switch off (see Fig.3(b)) reasonably corresponds to the estimated electron drag time.

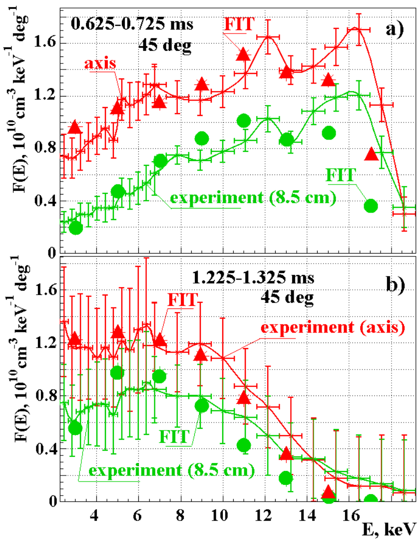

Fig.3: The local energy distribution functions of fast ions. Radii range 0-4 cm and 6.5-10.5 cm, pitch angles range 45°–0.35°; a) at NB injection; b) after NB injection

The near-axis energy distributions of the fast ions for the pitch-angles of 40-48^0 were measured at the midplane using the artificial target method. These were also measured at different position along the machine axis (positions III-V in Fig.1). The view line of the energy analyzer at these positions was perpendicular to the axis allowing to measure the energy distribution function of the fast ions whose turning points were close (along the device axis) to the location of the CXA. The corresponding pitch-angles projected to the device midplane were 46.7^0, 38.2^0 and 31.7^0 with angular resolution ~1^0. The fast neutrals at positions III-V are resulted from the fast ion charge-exchange on the background gas. The usage of diagnostic injector to produce the artificial target was ineffective here due to the problems with separation the charge-exchange flux from the main population of the fast ions and the additional population, produced by the trapped DNB particles.

The fast ion angular distributions were inferred from the energy spectrum measurements at different pitch-angles. Experimentally measured and modeled angular distributions for a set of energy intervals are shown in Fig.4. Note that the angular spread at high energy (14-18 keV) is close to that of 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. The experimental data and the estimated values of the fast ion angular spread for the given experimental conditions are presented in Fig.5 as functions of ion energy. The results refer to the time interval 0.6-0.8 ms after NBI start when the mean electron temperature was ~70 eV. The measured angular spread of the ions is quite well explained by their Coulomb interaction with the bulk plasma particles. The microinstabilities which could cause the additional scattering of ions were not yet observed in these experiments.

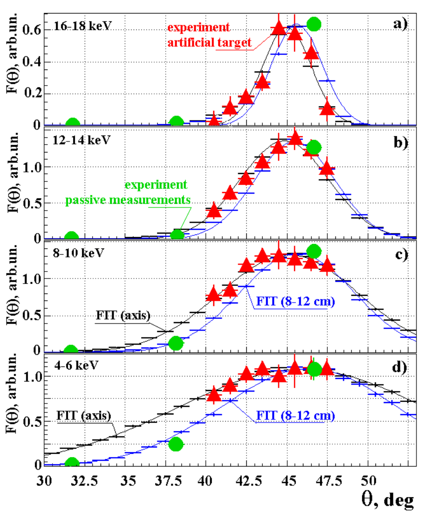

Fig. 4: The angular distribution of fast ions for various energy intervals at 0.6-0.9 ms.

From the measurement of the energy and angular distributions one can determine the mean energy of ions, which was estimated to be 5-8 keV during the NB injection. The comparison of measured and simulated kinetics of the energy transfer from the hot ions to the bulk plasma also did not give any evidence for anomalies in the ion energy loss rate in agreement with the previous results obtained for the lower plasma parameters.

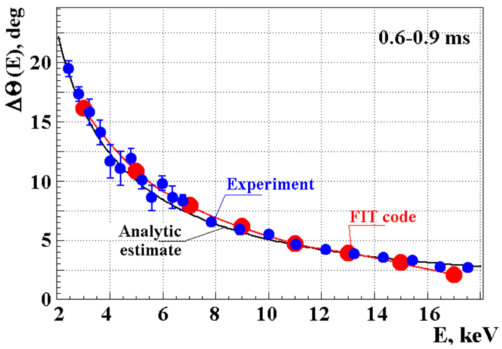

Fig. 5: *Angular spread of fast ions vs. energy.*

4. Fusion products measurements

The measurements indicate that the fast ions have relatively narrow angular spread. Therefore the longitudinal fast ion density profile is to be peaked near the turning points. This circumstance is very important for the GDT-based neutron source [4]. To experimentally prove this peaking special measurements of DD fusion products were carried out. Deuterium neutral beams with the energy 13-17 keV and total power up to 3 MW were injected into GDT plasma instead of H^0-beams. The global characteristics of this regime such as the injected and trapped NB-powers (P_{inj}, P_{tr}), total plasma energy (W_F+Wp) and DD neutron flux density at the detector position (Q) are shown in Fig.6. From the decay time of accumulated fast ion energy content it was calculated that the global energy lifetime of fast D^+-ions is ~1.5 time longer than for H^+ ones. The longitudinal profiles of the fusion products (2.45 MeV neutrons and 3.02 MeV protons) emission were measured by a scintillation detector (Fig.1). The detector was used with and without a special collimator. Without the collimator it sees ~2π solid angle. When collimated by a slit array oriented perpendicularly to the machine axis the detector essentially measures the DD proton linear specific yield with a spatial resolution ~20 cm. The experimental results of proton flux measurements are presented in Fig.7. The estimated flux for 3^0 angular spread of the fast D^+ ions is also shown for comparison.

The detailed comparison of the experimental data on the DD products measurements and numerical simulation is presented in [7]. 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.

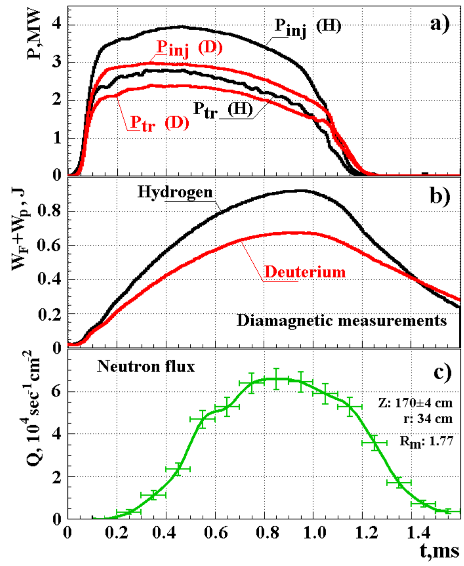

Fig.6: Global plasma characteristics.

5. Conclusions

The following conclusions can be drawn from these studies:

- The hot-ion population with peak density up to 10^{13} cm^{-3} and mean energy 5-8 keV was formed in the GDT under injection of the 4.2 MW neutral beams, at the same time maximal plasma-ß reaches 30%.
- For this high-ß regime fast ion energy loss and scattering rate are dominated by binary Coulomb collisions with target plasma particles and charge-exchange.

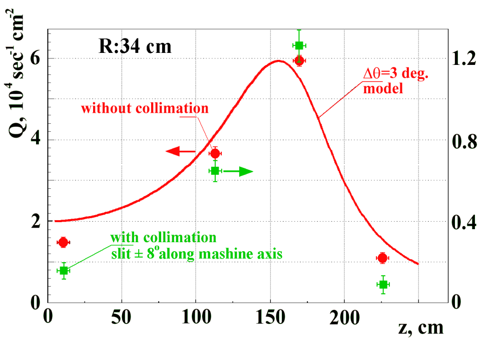

Fig.7: Flux of 3.02 MeV proton on the scintillation detector

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