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Confinement of High-Beta Plasma with Anisotropic Ions in a Gas Dynamic Trap

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Development of structural materials for fusion reactor core is one of the primary objectives of controlled fusion research. To attain this objective a dedicated 14 MeV neutron source with a flux of 1-2 MW/m^2 is mandatory. An axially symmetric mirror trap confining high energy anisotropic deuterium and tritium ions is considered as one the most attractive approaches for the development of the neutron source for fusion materials testing. This concept has been proposed by Mirnov and Ryutov [1] and the experimental studies of this concept is under way at the Gas Dynamic Trap (GDT) mirror device [2]. In the projected neutron source, an angled injection of ≈100 keV deuterium and tritium produces a population of anisotropic fast ions, which oscillate back and forth between the turning points near the end mirrors ("sloshing" ions). Ion density is peaked in the turning points leading to a high neutron flux density from the localized regions that house the testing zones.

In the GDT experiment, fast ions with anisotropic angular distribution are produced by 45° injection of 17 keV D-beams into a warm target plasma. Fig. 1 shows the general layout of the gas dynamic trap. The temperature and density of the target plasma correspond to the conditions, at which the mirror-to-mirror distance is much longer than the ion mean-free-path of scattering into a loss cone. Confinement of this collisional plasma component is determined by its collisional losses through the mirrors. For the "sloshing" ions population, particle lifetime

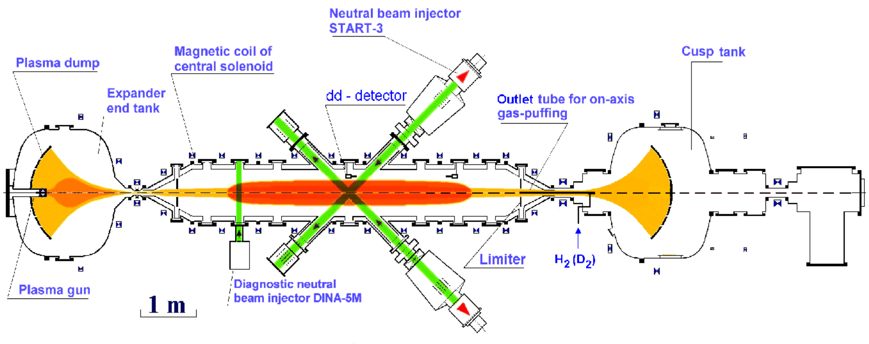

Fig 1 The GDT layout.

is determined by the charge exchange and slowing down in the target plasma. Characteristics of the neutron yield in the turning points strongly depend upon the spatial distribution of fast deuterons in that regions. Table 1 summarizes the basic parameters of the gas dynamic trap. In recent experiments stable confinement of two-component plasma with the fast ion energy content of ≈0.9 kJ was successfully demonstrated [3]. The maximal local plasma β achieved the value exceeding 0.4 as it was measured in the fast ion turning point region by the MSE diagnostic [4]. The radial profile of magnetic field reduction (or diamagnetism) ΔB/B is shown in Fig. 2. Red curve demonstrates the calculated diamagnetism profile using the MCFIT code [5]. The severe difference between the experimental and model profiles could be explained by significance of finite-beta effects (reduction of magnetic field in the hot-ion plasma core) and possible drift motion such as E×B drift. That effects are not considered in the MCFIT code. The distinctive feature of the experimental profile shown in Fig. 2 is its small radial width (≈7 cm). It is only slightly greater than the fast deuteron gyroradius (≈5.6 cm) calculated for the magnetic field 0.25 T and an ion energy 10 keV. At the same time, profile of trapped deuterium ions has more than two times greater radial extent of about 18÷20 cm. Further study is required to obtain the information on fast ion equilibrium formation and possible mechanisms of peripheral particle losses. Experiments described in the paper were performed

Parameter	***Value***
Mirror to mirror distance	7 m
Magnetic field at midplane	0.28 T
In mirrors	2.5 ÷1.5 T
Target plasma density	$(3 \div 6)\times 10^{19}$ m^{-3}
Radius at midplane	≈7 cm
Electron temperature	≈100 eV
Energy of deuterium beams	17 keV
Beam pulse duration	1 ms
Total injection power	≈3.8 MW
Injection angle	45°
Fast ion density in the turning point	≈2×10^{19} m^{-3}
Mean energy of fast ions	10 keV
Maximal local β	≈0.4

Table 1

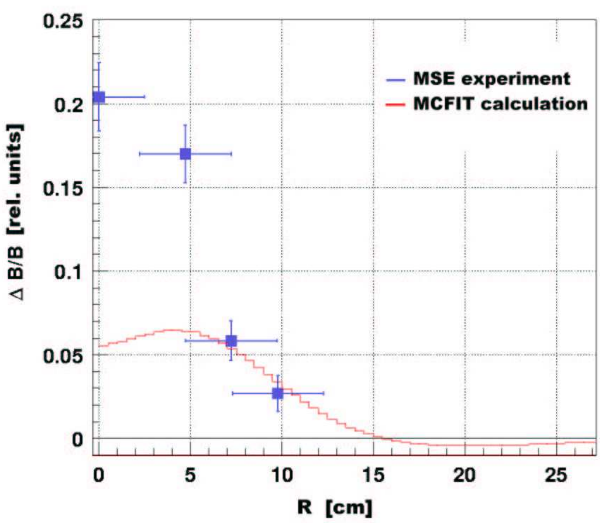

Fig. 2 Radial profile of plasma diamagnetism in the fast ion turning point.

in the regime without remote stabilizing cells that provide favorable pressure-weighted curvature along the magnetic force line. Stability of the finite-beta plasma against magnetohydrodynamic instabilities was maintained by the set of biased radial limiters and segmented end walls (see Fig. 1). Biasing of limiters and end walls to a specific potential (150÷200 V) allowed to suppress destabilizing effect of the radial electric field which develops in plasma due to the gradient of ambipolar potential on different flux tubes. Measured radial profile of the plasma potential is almost flat from the axis to the limiter radius in this regime. It was observed in experiment, that application of biasing potential leads to a significant reduction of transverse plasma losses and increase of the energy content [6].

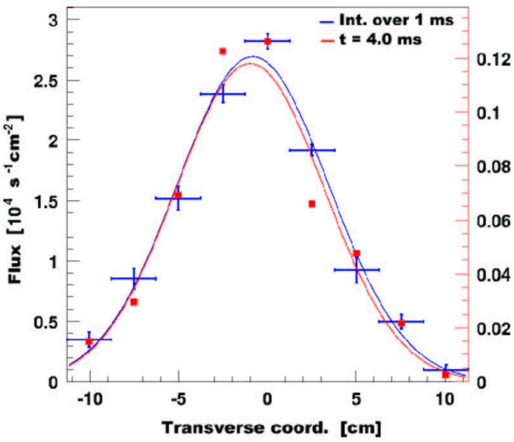

Fig.3 Transverse profiles of fusion 3.02 MeV proton flux. Red - t=4.0 ms, blue - time integrated. Measured in the fast ion turning point.

Fig. 3 shows the radial flux profile of D-D reaction protons with the energy 3.02 MeV, which was measured in the region of fast ion turning point. The flux of 14 MeV neutron has the similar value since cross section for both reactions are almost equal. Neutron yield is proportional to the deuteron density squared multiplied by the plasma column cross section. Accordingly, neutron flux profile should be significantly narrower than the ion density profile. For Gaussian distributions, flux profile width is two times smaller than that of density profile. An additional sharpening of the neutron yield profile could arise if an ion gyroradius is close to the profile radius due to a greater relative velocity of interacting deuterons near the axis comparing with peripheral regions. As it is seen in Fig 3, flux profile shape is nearly constant during the neutral beams pulse within the measurement accuracy.

Under conditions of the GDT experiment, a deuteron gyroradius for the mean energy of 10 keV is close to the characteristic scale of both the plasma density and diamagnetism profiles. Hence the spatial distribution of fast ion guiding center is crucial for the confinement study. The most direct method permitting to solve this task, is recording charge exchange atoms with spatial and angular resolution. Fig. 4 presents the transverse profiles of fast D-neutrals flux generated by charge exchange on the focused diagnostic neutral beam ("artificial target") [7]. Profiles were measured in the "sloshing" ion turning point at 90° to

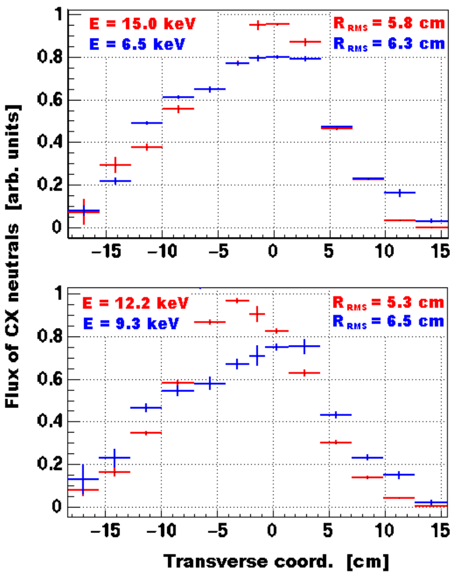

Fig.4 Transverse profiles of CX neutrals flux from the fast ion turning point measured at 90°. Profiles for four different energies are shown.

the machine axis. The profiles shown also feature small radial width, which is only slightly varies for different energies. Upper plot in Fig. 4 demonstrates profiles for the upper and the lower energy recorded. Lower plot presents the most narrow (E = 12.2 keV) and the most broad (E = 9.3 keV) profiles. Observation of neutral flux temporal evolution allows to note that a profile width is unchanged during the beam pulse within the measurement accuracy. At the same time, fast ion density and energy content grow during the entire beam duration. Analysis of the plasma energy and particle balance in these shots provides the basis for the conclusion that no gross losses preclude the production of high-β population of anisotropic fast ions.

In conclusion, in the GDT experiment the on-axis local plasma β as high as 0.4 was deduced against MSE measurements of diamagnetism ΔB/B=0.2 in the turning point of fast deuterons. The profile of magnetic field perturbation is strongly peaked, so its radial extent (7 cm) is close to a fast deuteron gyroradius calculated for the fast ion mean energy of 10 keV. There were observed no indications of either anomalies in fast ion scattering and slowing down, or enhanced radial plasma losses, which might be caused by MHD instabilities.

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