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Formation and confinement of compact fast ion plasmoid in the gas dynamic trap.

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The gas dynamic trap (GDT) is an axially symmetric mirror device with the long central cell for confinement of two-component plasma with anisotropic pressure [1]. The most perspective near-term application of the GDT concept is a 14 MeV neutron source for fusion materials development [2]. For this purpose, 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 GDT experiment, fast ions with anisotropic angular distribution are produced by 45° injection of six 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 fast ions population, particle lifetime is determined by the charge exchange and slowing down in the target plasma. In recent experiments stable confinement of two-component plasma with the fast ion energy content of about 0.9 kJ was successfully demonstrated [3]. Table 1 summarizes the basic parameters of the gas dynamic trap.

Characteristics of the neutron yield in the turning points strongly depend upon the

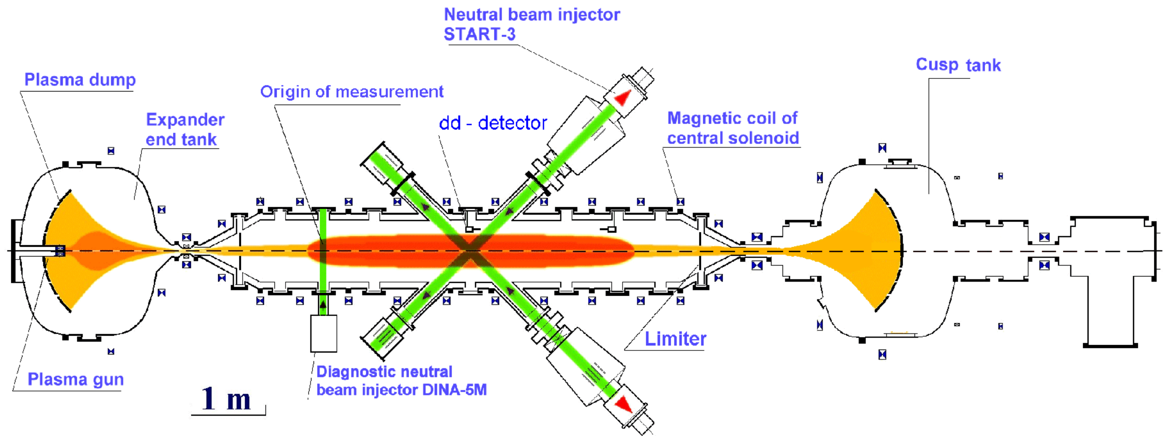

Fig 1 The GDT layout.

spatial distribution of fast deuterons in that regions. The spatial profile of fast ion density has been studied by different methods: MSE spectroscopy [3], active charge-exchange diagnostic [4] and measurement of D-D fusion product fluxes.

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	1.1 ms
Total injection power	≈ 3.8 MW
Injection angle	45°
Fast ion density in the turning point	$\approx 2\times 10^{19}$ m^{-3}
Mean energy of fast ions	10 keV
Total energy contents	≈ 0.9 kJ
Maximal local β	≈ 0.4

Table 1

The radial profile of magnetic field reduction (or diamagnetism) $\Delta B/B$ is shown in Fig. 2. (blue bars). The distinctive feature of this experimental profile is its small radial width that is about 7 cm at 1/e level mapped onto the GDT midplane. It is only slightly greater than the fast deuteron gyroradius (≈5.6 cm) calculated for the magnetic field 0.25 T and an ion mean energy 10 keV. At the same time, the guiding center density profile of trapped deuterium ions (red curve on Fig. 2), calculated from target plasma profile and beam parameters, has about two times greater radial extent of 12÷15 cm. This paper describes the study of formation and equilibrium confinement of such compact fast ion plasmoid in the GDT experiment.

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 2.45 MeV neutron has the similar value since cross section for both reactions are almost equal. Fusion product yield is proportional to the deuteron density squared multiplied by the plasma column cross section. Accordingly, neutron flux profile should be significantly

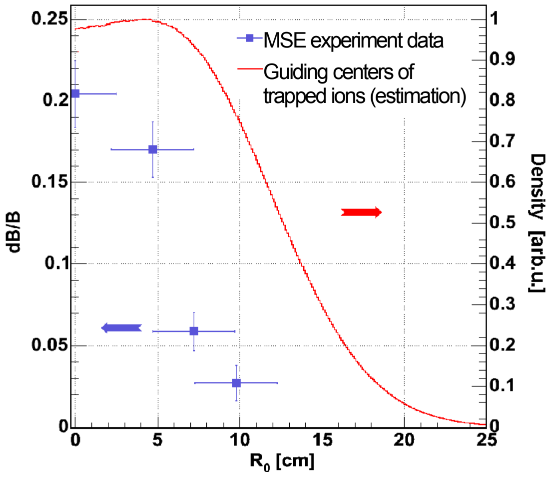

Fig.2 Radial profile of plasma diamagnetism in the fast ion turning point (blue) and estimated density of trapped ion guiding centers (red).

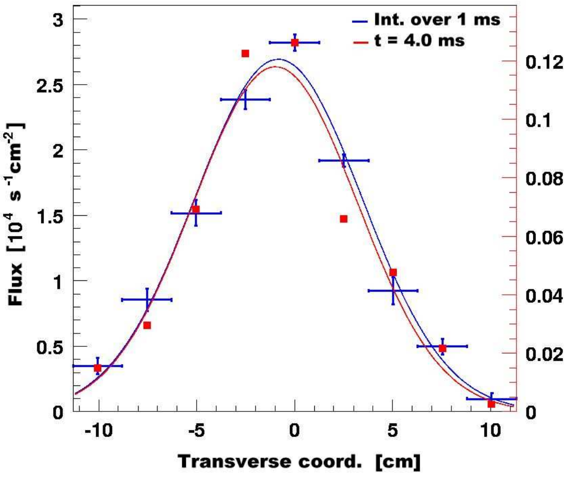

Fig.3 Transverse profiles of fusion 3.02 MeV proton flux. Red - t=4.0 ms, blue - time integrated. Measured in the fast ion turning point.

narrower than the ion density profile. For Gaussian distributions, the 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. In this case relative velocity of interacting deuterons can be less 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.

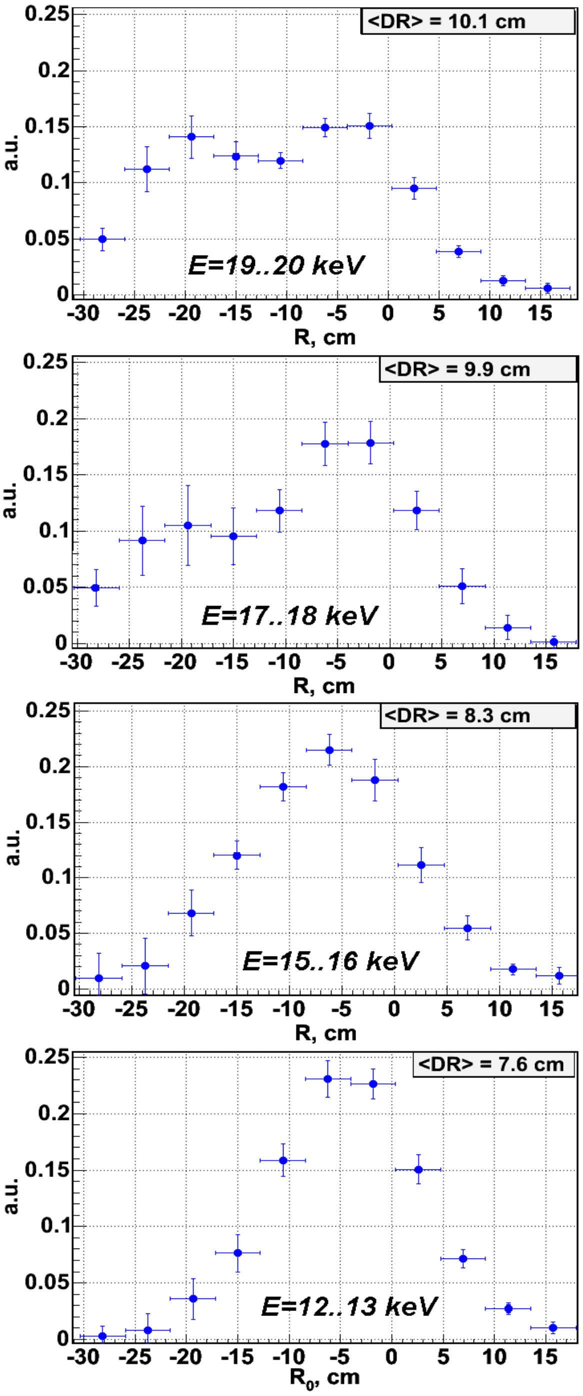

Fig.4 Transverse profiles of CX neutrals flux from the fast ion turning point measured at 90°. Profiles for four different energies are shown..

The most direct method is recording charge exchange atoms with spatial and energy resolution. Fig. 4 presents the transverse profiles of fast D-neutrals flux generated by charge exchange of fast ions on the focused diagnostic neutral beam ("artificial target") [4]. Profiles were measured in the "sloshing" ion turning point at 90° to the GDT axis. The top plot in Fig. 4 demonstrates profile for the highest recorded energy (E=19-20 keV), that is a upper limit of the injection diapason. The broad measured profile corresponds to estimation of trapped ion spatial distribution. Lower plot present the profile with small radial width, which is only slightly varies for other profiles in measured energy range (up to 6 keV). Values of a profile width for this energies are close both to obtained in $\Delta B/B$ and fusion products yield measurements. The profile width is constant during the neutral beams operation within the measurements accuracy. The conclusion can be made, that stable fast ion equilibrium is formed at the initial stage of beams injection. In the same time, ion density and energy content grow during the entire beam duration. The characteristic time of narrow profile formation can be estimated as a time of slowing down from injection energy to 12 keV. This is about 200 μs for parameters of the GDT experiment.

The analys of energy balance shows that observed phenomena cannot be explained by enhanced fast ions loses from the plasma core. The special experiment with movable limiter in the central cell of GDT illustrates this fact. Fig.5 shows the fast energy content for different limiter position. The movable limiter was located in the region of fast ion motion and did not contact with target plasma. As it is seen, loses of fast ion from radii out of 14 cm (that is great more that fast ion profile width) lead to energy content drop of about two times. The experimental data (red) and numerical simulation of this experiment (blue) provide the basis for the conclusion that no gross losses preclude the production of compact high-β population of anisotropic fast ions.

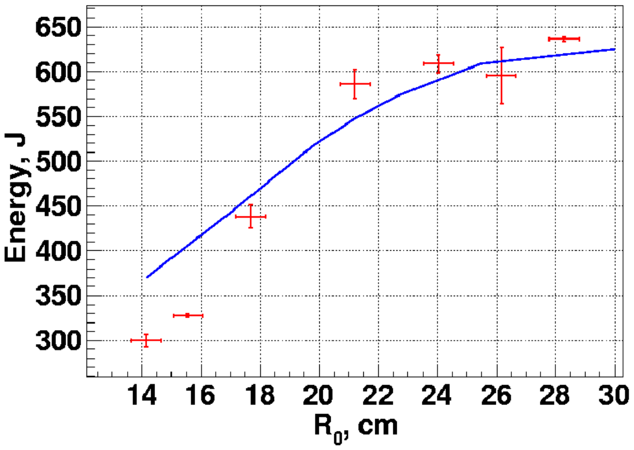

Fig.5 Energy content of fast ions vs movable limiter position: red – experiment data, blue – numerical simulation.

Simplified 2-D theory of fast ion density spatial profiles formation was suggested in [5]. It was shown that the ensemble of ions with a large Larmor radius has the potential energy of interaction caused by the magnetic field perturbation produced by these fast ions. Due to the magnetic momentum conservation this potential energy rises its minimum, when the guiding center spatial distribution is maximally compact. A non-linear interaction of the cold and fast plasma components results in the excitation of **E**×**B** turbulence. The growing kinetic energy of the cold plasma motion comes from the fast ion potential energy. Therefore, this process is accompanied by a self-localization of the fast ions. The self-localization effect is demonstrated by numerical simulation with use the special PIC code. The 2D version of the code described in [6]. The code is based on the equations derived in [5] for the case of small but finite beta. The characteristic time of narrow profile formation, obtained in this simulation equivalent to 10^3 cyclotron periods of fast ion, that is about 250 μs for the GDT experiment. This is in a good agreement with the experimental data. Further theoretical and numerical studying of the problem should be developed to 3-D case.

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