Experimental Evidence of High-Beta Plasma Confinement in an Axially Symmetric Gas Dynamic Trap

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In the axially symmetric magnetic mirror device gas dynamic trap (GDT), on-axis transverse beta (ratio of the transverse plasma pressure to magnetic field pressure) exceeding 0.4 in the fast ion turning points has been first achieved. The plasma has been heated by injection of neutral beams, which at the same time produced anisotropic fast ions. Neither enhanced losses of the plasma nor anomalies in the fast ion scattering and slowing down were observed. This observation confirms predicted magneto-hydrodynamic stability of plasma in the axially symmetric mirror devices with average min-B, like the GDT is. The measured beta value is rather close to that expected in different versions of the GDT based 14 MeV neutron source for fusion materials testing.

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This Letter reports on the first experimental evidence of the stable plasma confinement near the predicted stability threshold for ballooning MHD interchange modes in the gas dynamic trap (GDT) device in Novosibirsk. A plasma with energetic ions has been produced by neutral beam injection and on-axis plasma β exceeding 0.4 has been measured near the turning points of the fast ions. The gas dynamic trap configuration [1,2] has been proposed as a possible approach to an open-ended fusion reactor or, as a near-term perspective, as a 14 MeV neutron source [3] for fusion materials testing. The GDT-based reactor would produce power in a long, axially symmetric, high-β, magnetic solenoid. End losses from the solenoid are reduced by a strong increase in the magnetic field at the end mirrors under the condition that the mirror to mirror length exceeds the ion mean-free path of scattering into a loss cone. In the gas dynamic trap, the rate at which ions are lost out of the ends is of the order of an ion-acoustic speed V_{T_i}. The resulting plasma lifetime can then be roughly estimated as $\tau = (RL/V_{T_i})$, where L is the machine length, and R the mirror ratio [1,2]. The lifetime appropriate for fusion applications can be achieved by increasing both the mirror ratio and the machine length.

A more near-term application of the GDT concept is a 14 MeV neutron source for fusion materials development [3,4]. For this purpose, energetic D and T ions with anisotropic angular distribution should be produced in GDT providing high neutron flux density in localized regions. These energetic ions are produced by angled injection of ≈ 100 keV deuterium and tritium neutral beams at the center of solenoid. In contrast to the GDT-based reactor, quite a moderate electron temperature of 0.5–1 keV is sufficient to generate neutron flux as high as 2 $\mathrm{MW/m^2}$. For a given temperature of the warm plasma and energy of the beams, the fast ion angular distribution remains quite narrow, and centered on the initial value of the pitch angle during their slowing down to considerably lower energies. This results in formation of sharp fast ion density peaks near the turning points where the ions spend a sufficiently large fraction of a bounce time. The neutrons are mainly produced in collisions between the fast ions and, accordingly, the neutron flux density is also strongly peaked in the same regions that house the testing zones. A gas dynamic trap has the advantages of confining high-β plasmas which produce a higher 14 MeV neutron flux density (up to 4 $\mathrm{MW/m^2}$) than would other plasma based sources. This property of GDT is vital to the high performance of the source and, therefore, should be experimentally proven. Note that for a magnetic mirror with quadruple minimum-B (min-B) field, MHD stable confinement of a plasma with $\beta \geq 1$ has been already demonstrated [5].

Earlier gas dynamic trap experiments [6], in which a low temperature gun-produced plasma was studied, successfully demonstrated confinement of a MHD interchange stable plasma with $\beta \leq 0.1$. The stability in an axially symmetric gas dynamic trap was established with remote stabilizing cells. Our present experiments then demonstrate that plasma β can be further increased up to the predicted stability limit for ballooning interchange modes or even higher without enhancement of radial losses. A stability limit of slightly less than 0.4 was predicted [2] for those modes in a gas dynamic trap with the magnetic field optimized for stability of flutelike interchange modes, as in the case of the GDT device. With special provisions made so that magnetic field profile is optimized to improve the stability against the ballooning perturbations, the stability limit could be further increased up to 0.7–0.8 [2].

The GDT magnet and neutral beam systems are shown in Fig. 1. The vacuum chamber consists of a cylindrical central cell 7 m long and 1 m in diam and two expander tanks attached to the central cell at both ends. A set of coils mounted on the vacuum chambers produce an axisymmetric magnetic field with a variable mirror ratio ranging from 12.5 to 75 when the central magnetic field is set to 0.28 T. The basic parameters of the device and the plasma parameters typical for the operational regime used are listed in Table I.

The finite-β plasma in central solenoid is stable against magnetohydrodynamic instabilities because along a magnetic field line the minimum-B axially symmetric end cells provide a favorable pressure-weighted curvature. To ensure this stability, a sufficiently high density plasma is maintained in the end cells by collisional losses of the warm plasma from central solenoid.

In these experiments, the GDT plasma is heated and fast ions were produced by six deuterium neutral beams. We used the deuterium beams instead of the hydrogen ones, which are routinely injected, in order to slightly increase the beam trapped fraction and obtain additional diagnostic capabilities. Neutral beam currents in excess of 250 equivalent atomic amperes were injected with an accelerating voltage 15–17 keV. The beam duration of each injector is set to 1 ms. About 2.6 MW have been trapped by the solenoid plasmas.

The initial plasma is produced by a ≈ 3 ms pulse from a washer stack hydrogen-fed plasma gun. The gun is located in one of the end tanks beyond the mirror throat. Under standard conditions, the plasma density reached $(5–7) \times 10^{19}$ m^{-3} within ≈ 3 ms, after that the gun current was terminated and the plasma had begun to decay. The electron temperature of the gun-produced plasma 3–10 eV was nearly constant across the radius. The radial density profile was well fitted by a Gaussian with characteristic scale length of 6–7 cm which slightly changed with magnetic field strength in the gun. During the beam injection, significant broadening of the density profile has been observed. Further experiments revealed that this broadening, which was accompanied by considerable target plasma losses, is associated with a plasma rotation caused by radial electric field. The electric field magnitude is determined by a drop of ambipolar potential across the plasma radius. Under typical conditions of the experiments, an ambipolar potential with on-axis magnitude of ≈ 150 V develops as the electron temperature increases.

To avoid the negative consequences of plasma rotation, a significant improvement has been introduced into a plasma shot scenario. Namely, in these experiments we employed a set of biased radial limiters and radially segmented end walls to control electric field in the plasma. While varying the electric field strength, we observed the maximum in plasma energy and diamagnetism. This maximum corresponds to the radial limiter biasing at 120–150 V, while the radial end wall segments were electrically floating. The limiter potential in the optimum is essentially close to on-axis plasma potential at the end of the beam injection. In this case, when

TABLE I. The parameters of GDT device.

Parameter	Value
Mirror to mirror distance	7 m
Magnetic field at midplane	up to 0.28 T
In mirrors	2.5–15 T
Target plasma density	$(3–6) \times 10^{19}$ m^{-3}
Radius at the midplane	6–7 cm
Electron temperature	≈ 90 eV
Energies of deuterium neutral beams	15–17 keV
Pulse duration	1 ms
Total injection power	3.9–4.0 MW
Injection angle	45°
Fast ion density in turning point regions	$\approx 10^{19}$ m^{-3}
Mean energy of fast ions	≈ 10 keV
Maximal local plasma β	0.4

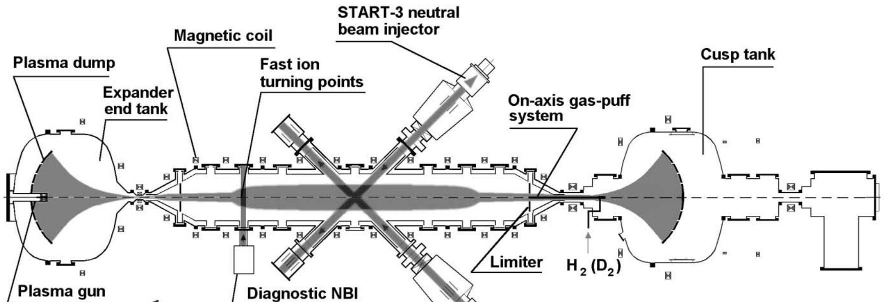

FIG. 1. The GDT layout.

the radial potential drop was minimized, the radial extent of the target plasma remained almost unchanged during the neutral beam injection, which indicates that no gross instability precludes the production of high-β, multicomponent plasma in a gas dynamic trap configuration.

The plasma parameters at the solenoid were measured with a number of diagnostics. The density profile is derived from the measured attenuation of the neutral beams and from the Thomson scattering data near the midplane. The Thomson scattering system also measured electron temperature in the plasma core. These data were combined with those from the probes installed in the shadow of a radial limiter to provide the electron temperature profile. In these experiments, the measured profile was almost constant ($T_e \approx 90$ eV) in the core, with approximately linear reduction out of the limiter edge. Temporal variation of the ion temperature of the target plasma was measured by Rutherford scattering of a diagnostic neutral beam. At the end of beam injection pulse, the ion temperature was close to that of the electrons. The parameters of the fast ions were measured by using an artificial target method [7], neutral particle analyzers, and an array of diamagnetic loops installed at different axial locations inside the solenoid [8]. We estimated the average energy of the beam-produced deuterons to be about 10 keV. The measured angular width of fast ion distribution and their energy distribution well correspond to the results of numerical simulations [7]. We also found that the heated target plasma losses are dominated by the axial ones through the mirrors, as predicted. The diamagnetic loop data in combination with the measured angular and energy distribution of fast ions enabled us to conclude that plasma β, averaged over the entire cross section at the turning points, reached 0.2–0.25.

In order to measure the radial profile of plasma beta in the turning point region we first applied motional Stark effect (MSE) diagnostic, which was recently installed at GDT device [8]. It utilizes the appearance of a Lorentz electric field $\boldsymbol{E} = [\boldsymbol{v} \times \boldsymbol{B}]$ in the frame of reference of a fast atom moving in a transverse magnetic field. For a hydrogen atom, the resulting Stark splitting is linear in the magnetic field. Therefore, it provides a robust method of local magnetic field measurements. By measurements of absolute value of magnetic field in plasma shots and in vacuum ones, one can calculate the plasma diamagnetism as $(\Delta B/B) = [(B_{\rm vac} - B_{\rm plasma})/B_{\rm vac}]$. By using a paraxial approximation, one can further estimate plasma beta as $\beta \approx 2(\Delta B/B)$.

The MSE diagnostic at GDT comprised a diagnostic neutral beam injector [9], which was modified to increase energy from 30 up to 40 keV and the extracted current up to 7 A, and a registration system [10]. The spatial resolution was determined by the beam size and by the viewing angle of the observation system. It was 4.5 and 1.5 cm along the viewing chord and in the perpendicular plane, respectively. The temporal resolution was 200 μs, as it was set up by the duration of the diagnostic beam.

The measured radial profile of the $\Delta B/B$ mapped onto midplane is shown in Fig. 2 together with plasma density profile. Several factors contribute to the relative errors in the field measurements. Horizontal error bars are defined by the spatial resolution of 4.5 cm. The error in the measured value of $|B|$ is due to several factors: shot-to-shot fluctuation of plasma parameters, variation of the beam injection energy, uncertainty in the dispersion calibration, and statistical (Poisson) fluctuation of the recorded beam emission. Fluctuation of plasma parameters (in a series of shots corresponding to the same regime) contributed to an amount of $\approx 2\%$, error due to statistical fluctuation $\approx 3\%$ was calculated by the fitting procedure. The contribution of both other factors to the error in $|B|$ was negligible. Thus the precision of the MSE measurements of $|B|$ is estimated to 4%, and was cross checked by calculation of the statistical deviation in results obtained in separate series of shots. Correspondingly, an error in $|B|$ of 4% leads to error in $\Delta B/B$ of $\approx 10\%$.

According to the data presented in Fig. 2, the magnetic field perturbation amounts to ≥ 0.2 on plasma axis. It allows one to conclude that perpendicular plasma β exceeds 0.4. The distinctive feature of the radial profile is its quite small width. It amounts to about 7 cm at $1/e$ level mapped onto the GDT midplane. This is only slightly larger than the fast deuteron gyroradius ($\rho_i \approx 5.6$ cm) calculated for the magnetic field of 0.25 T and for 10 keV, an energy that is close to the fast ion mean energy.

Longitudinal beta profile was not yet directly measured. Qualitatively, its variation from the turning point region to midplane can be determined using the axial dependencies of all plasma species. Their contributions are proportional to species density and transverse energy, which vary in a different way for the target plasma and fast ions. In fact, the target plasma density varies only slightly throughout the central solenoid, because only a

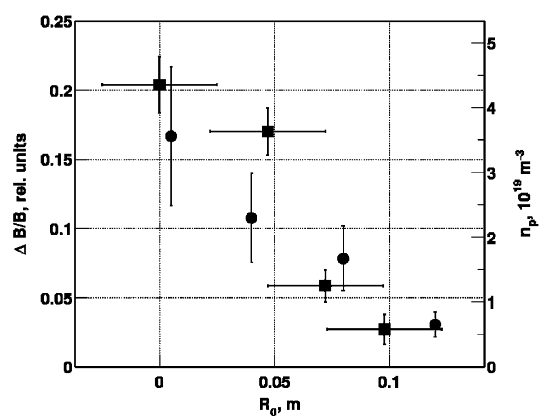

FIG. 2. Radial profile of plasma diamagnetism $\Delta B/B$ and density (circles).

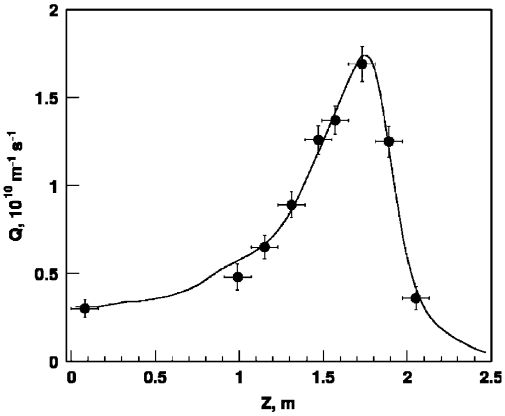

FIG. 3. Axial profile of DD reaction yield as measured from the midplane ($z = 0$).

relatively small density fraction of anisotropic ions is presented. The warm plasma density is otherwise depleted in the regions where the fast ion density is peaked, through development of ambipolar potentials. Taking into account that throughout the solenoid the fast ion density is considerably less than that of the target plasma, its density variation could be ignored.

The contribution of the target plasma to total plasma β is maximal near the center of the device, where the magnetic field is small and falls down longitudinally as the magnetic field increases towards the mirrors. For the measured parameters of the target plasma, its contribution at the center of the device can be estimated as 0.04 and it is negligible near the turning points. In contrast, the fast ion density has strong peaks near the turning points since their angular distribution is anisotropic. This can be seen from the measured axial profile of a specific yield of DD fusion reaction (see Fig. 3). Here, Q is a flux per meter of plasma column length, that is proportional to fast ion density squared multiplied by plasma cross section area. The plasma cross section varies as $1/H$, i.e., it reduces at the midplane by $\sqrt{2 \times 3} \approx 3.5$ times. Near the center, this reduction of fast ion density and partial conversion of their transverse kinetic energies to longitudinal ones result in $\approx 40\%$ smaller fast ion contribution to total β. Accordingly, taking into account the small contribution from the target plasma, one could conclude that total β has a shallow dip $\approx$ 35–40% at midplane.

In conclusion, a previous estimate [7] of the averaged β in GDT as ≈ 0.25 at the turning point of fast ions has been confirmed and elaborated by the first direct measurements of the radial β profile by using recently installed MSE diagnostic. On-axis plasma β as high as 0.4 was deduced against measured magnetic field reduction $\Delta B/B \geq 0.2$. This β value is near the theoretically predicted threshold for the ballooning MHD interchange modes. At the same time, this value is higher than that ever reported for magnetic confinement devices with a long central solenoid, like tandem mirrors [11,12].

The profile of the magnetic field perturbation is strongly peaked, so that its radial extent (7 cm) is close to a deuteron gyroradius calculated for the fast ion mean energy of 10 keV. In these high plasma β shots, there were no indications of either enhanced radial plasma losses, which might be caused by MHD instabilities, or anomalies in fast ion scattering and slowing down. According to the measured axial profiles of the fast ion and target plasma parameters, the total plasma beta exhibits only slight $\approx$ 35–40% variations between the fast ion turning points.

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