POSSIBLE FURTHER STEPS FOR UPGRADING THE GDT DEVICE

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Recent upgrade of the neutral beam system has resulted in considerable improvement of the plasma parameters in the gas dynamic trap experiment. With injection of 5 ms, 20 keV, 4.5 MW neutral beams the electron temperature approaching 250 eV was obtained. At the same time maximal plasma beta attained about 60%. Further progress in plasma temperature and pressure could only be possible with considerable increase of the magnetic field in the central solenoid and re-optimization of its profile to improve stability of high-beta plasma, as well as with extension of the neutral beam pulse. Possible steps in this direction are considered in this paper.

I. INTRODUCTION

Hot ion energy content, electron temperature and plasma pressure in the Gas dynamic trap (GDT) have been significantly improved after upgrading of the neutral beam injection system which now provides 4.5 MW power incident on the plasma in a 5 ms pulse [1]. However, the plasma energy and electron temperature did not saturate indicating that plasma did not reach steady state yet. The reason is that since the electron temperature now exceeds 200 eV, the proton or deuterium collisional slowing down times are comparable with the total injection time. This is one of the limitations of the present experiments. Another one is associated with high $\beta \approx 0.6$ near the turning points, which is close to the ballooning instability threshold of 0.7-0.8 predicted numerically for GDT [2]. Therefore, further accumulation of hot sloshing ions which provide the dominant contribution to the plasma pressure, may be hampered by the onset of the ballooning instability. This problem can be solved by reducing the local β in the hot-ion turning region. One more possible difficulty is MHD instability of the central cell plasma. In the present experiments neither a cusp nor an expander are used to provide this stability. Instead, enhanced radial transport caused by the growth of the flute modes is suppressed by sheared plasma rotation at the periphery driven by biasing of end plates and plasma limiters. Enhancement of the hot plasma pressure would increase the instability drive, and therefore it is not clear enough whether this suppression would be sufficient or not. Moreover, this stabilization mechanism requires continuous gas puffing to sustain dense plasma at the periphery of the hot plasma column, which leads to enhanced charge-exchange losses of hot ions. Therefore, it is beneficial to reduce the instability drive in order to facilitate reduction of radial transport with the sheared rotation at the periphery or stabilization of the plasma by a conducting limiter or by other means.

In this paper we consider several possibilities of improving the current GDT parameters without substantial reconstruction of the device.

II. INCREASE OF NBI PULSE LENGTH

In the present experiments with 5 ms injection steady state is not achieved. While the electron temperature seems close to saturation at the level about 200 eV by the end of the neutral beam injection, the diamagnetic loop installed near the hot-ion turning region and picking a signal proportional to the hot ion energy content shows linear growth at a rate $dW_f/dt \approx 0.4$ kJ/ms until the end of injection when it is about 2 kJ [1]. The hot-ion density in the turning regions reaches $5{\cdot}10^{19}\ \mathrm{m}^{-3}$ which gives for $T_e = 200$ eV the slowing down time of 2.4 ms for hydrogen ions and 4.8 ms for deuterium ions which is comparable with the NBI pulse length. Duration of the beam should exceed the ion slowing down time several times in order to let maximum accumulation of hot ions in the central cell of GDT. We believe that extension of the pulse duration to 20 ms will be sufficient to achieve plasma steady state in GDT. Moreover, provided the same energy accumulation rate 0.4 kJ/ms, an "optimistic" estimate gives maximum hot-ion energy content about $0.4{\times}20 \sim 8$ kJ without account for β limit. Of course, limiting β will be achieved as well, and it will provide a good test of the ballooning instability threshold.

In order to make more quantitative predictions for variation of the plasma parameters with extended neutral beams, we considered space-averaged simple balance equations for two ion populations and electrons. These simulations are now in progress to optimize shot scenario for obtaining maximal electron temperature.

III. MAGNETIC FIELD OPTIMIZATION

By optimization of the magnetic field we mean such rearrangement of the field that allows one to improve certain parameters of the plasma. For example, it may be an increase in hot-ion energy content near β limit, or reduction of the MHD instability drive. Field optimization takes local variation of the field which does not require large change in total magnetic field energy.

III.A. Reduction of local β in the ion turning regions

As it was mention above, β is close to its maximum possible value in the sloshing ion turning regions. By definition, $\beta = 8\pi n\langle\varepsilon\rangle/B_v^2 \propto p_{hi}/B_v^2$, where $\langle\varepsilon\rangle$ is the average transverse energy of hot ions in the turning region, n is the hot-ion density, B_v is the vacuum magnetic field at the turning point and p_{hi} is the local hot-ion pressure. Therefore, if we want to decrease β keeping the same axial distribution of the magnetic field, we may increase the magnetic field. This is the most straightforward way which also allows keeping the same $B(z)$ profile, but it requires new coils and new power supply for the magnetic system, because the present one already works at its maximum.

Fortunately, there is another way to reduce β in the turning regions, namely to decrease the hot-ion pressure locally. Since $W_f \propto \int p_{hi}\,dV$, we may try to change $p_{hi}(z)$ distribution in order to reduce the peak pressure in the turning regions which are most critical in terms of β, while keeping the same integral W_f or making it even larger. Thus we may redistribute the hot ions along the axis between the turning points. To decrease the local hot-ion pressure in the turning region we should increase the volume of this region which means increasing of its length. Conservation of the fast-ion magnetic moment $\mu = mV_\perp^2/2B$ in its motion from the midplane to the turning point yields

$$\frac{1}{B(z_t)} = \frac{\sin^2\theta_0}{B_0},$$

where B_0 and θ_0 are the magnetic field and the ion pitch-angle at the midplane. Let us change angle by $\Delta\theta$ and calculate the shift of the turning point

$$\Delta z_t \approx -\Delta\theta \frac{B(z_t)}{\frac{dB}{dz}(z_t)} \frac{2\cos\theta_0}{\sin\theta_0}.$$

This expression shows that to increase the length of the turning region, one should either increase the angular spread of hot-ion distribution function or reduce the magnetic field gradient near the turning point. Variation of the injection pitch-angle θ_0 is not possible on one hand since it would require reconstruction of the beam injection lines, and on the other hand it does not result in any significant change in turning point position. Angular width $\Delta\theta$ cannot be varied in a wide range, since it is determined by the optimal operational regime of the injectors. Therefore, we can increase Δz_t by reducing the magnetic field gradient either by shifting positions of the coils which determine the field near the turning region or by varying currents in these coils. To obtain quantitative evaluation of this effect we need to calculate pressure distribution along the device axis.

To be more specific, let us assume a model hot-ion distribution function of the form $f(\varepsilon,\theta) = f_0\delta(\varepsilon-\varepsilon_0)\exp(-(\theta-\theta_0)^2/\Delta\theta^2)$, where ε_0 is the injection energy, δ is the Dirac delta-function, θ_0 is the pitch-angle of injection at the midplane and $\Delta\theta$ is the width of the angular distribution. Using this DF one can analytically calculate the axial profile of the pressure components parallel and transverse to magnetic field if the angular width is small enough. Then the ratio of the total pressure at the turning point and at the midplane is

$$\frac{p(z_t)}{p(0)} \approx \sqrt{\frac{2}{\pi}}\Gamma(5/4)\sqrt{\frac{\cos\theta_0}{\sin^3\theta_0}}\frac{1}{1+\cos^2\theta_0}\frac{1}{\sqrt{\Delta\theta}}.$$

In GDT the beams are injected at the midplane at $\theta_0 = 45°$, so for realistic $\Delta\theta = 5°$ angular spread the pressure peaking is $p(z_t)/p(0) \sim 2.3$ which is very close to the experimental estimate. In order to decrease β we need to reduce this pressure peaking by proper variation of the magnetic field profile $B(z)$.

Figure 1 demonstrates how correction of currents in several coils can reduce pressure peaking in the turning region. One half of the device from the midplane to the mirror is shown. In these calculations the currents in several coils are multiplied by corresponding factors that are shown above the coils in the plot.

The turning point for the ions injected at 45° is situated at mirror ratio $R = 2$, which occurs at $z \approx 189$ cm from the midplane. Smoothing of the magnetic field in both turning regions reduces the maximum pressure by a factor of 1.46 for the same total number of hot ions. It means that it is possible to reduce local β significantly maintaining the same energy content. In practice, such magnetic field rearrangement can be performed by adding few coils with moderate currents.

In the above calculations we have implicitly assumed that the magnetic field profile is known. However, this is true only in the low-β limit when magnetic field depression by the plasma diamagnetism is small, and we can use the vacuum magnetic field instead of the real one.

Therefore, the presence of a high-β plasma may substantially influence the smoothed magnetic field profile which in turn may cause undesirable distortions in the pressure profile and local β. We should be also aware that such manipulations with magnetic field may worsen MHD stability of the plasma, but this issue is beyond the scope of this paper.

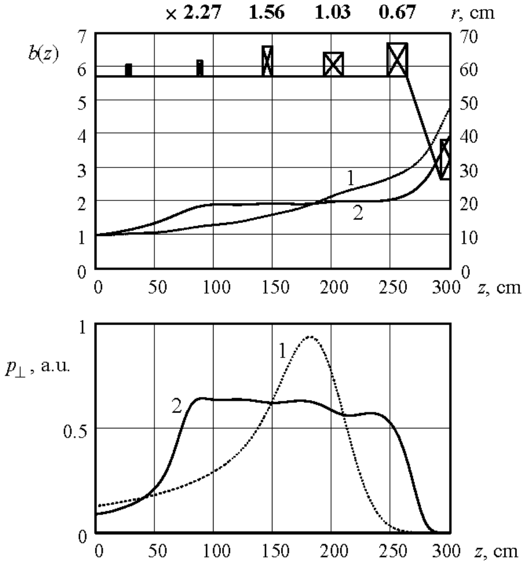

Fig.1. Axial profiles of magnetic field $b = B/B_0$ and pressure $p_\perp$. Labels 1 and 2 refer to the present GDT system and the corrected magnetic system, respectively.

III.B. Improvement of MHD stability

We estimated plasma stability in the GDT central cell against flute modes using a stability criterion which is valid for small scale perturbations in low-β plasma in the paraxial limit [3]

$$\int (p_\perp + p_\parallel)\frac{\kappa}{rB^2}dz > 0, \tag{1}$$

where r and $\kappa \approx d^2r/dz^2$ are the field line radius and curvature. For collisional plasma in a mirror trap with large mirror ratio the plasma pressure is isotropic, and perturbation energy is minimum for the magnetic field profile of the form [2]

$$B(z) = \frac{B_0}{1 - \frac{z}{z_m}\left(1 - \frac{1}{R}\right)}, \tag{2}$$

where B_0 is the magnetic field at the midplane, R is the mirror ratio and z_m determines the distance between the mirrors. The magnetic system of GDT was designed to reproduce this optimal profile. However, in the current experimental conditions it is the anisotropic hot ion population which makes the dominant contribution to the pressure. Figure 2 shows the axial profiles of κ/rb^2 for the present GDT magnetic system, the calculated total pressure for the model ion DF used above, and their product which determines the perturbation energy (1).

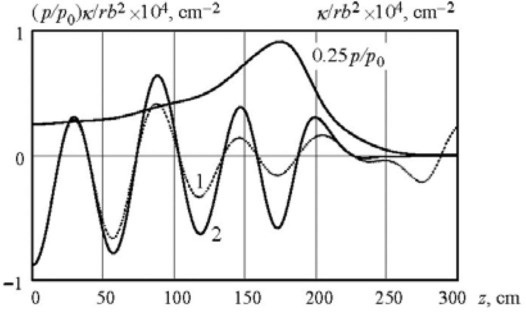

Fig.2. Axial profiles of hot ion pressure p/p_0, κ/rb^2 (1) and their product (2).

Since the real GDT magnetic field is produced by discrete coils, it has notable ripples, and the curvature is oscillating along the device axis. As one can see, the plasma pressure is peaked in the region of negative curvature which is unfavorable for stability, since it makes the negative perturbation energy larger in magnitude.

Therefore, the magnetic field profile should be optimized to minimize the perturbation energy (1) for this $p_{hi}(B)$. To do this we shift the existing coils while keeping the same currents and calculate the perturbation energy. The optimal coil shifts are shown in Fig. 3.

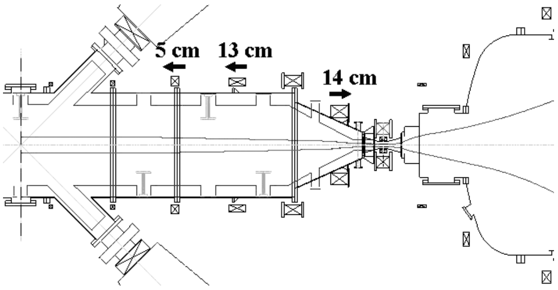

Fig.3. Coil shift improving pressure-weighted curvature.

This relatively small variation of coil positions results in such reshaping of the magnetic field that curvature is made positive over a large portion of the hot-ion turning region (see Fig. 4).

While the total perturbation energy is still negative, its absolute value is 2.7 times smaller than for the present coil system. In the present experimental scenario, radial plasma losses are controlled by sheared plasma rotation at the periphery provided by a biased limiter, which requires relatively large density of the warm periphery plasma to provide sufficient axial electric currents. Reduction of the MHD drive will allow us to reduce the halo density, thus improving hot-ion confinement in the central cell.

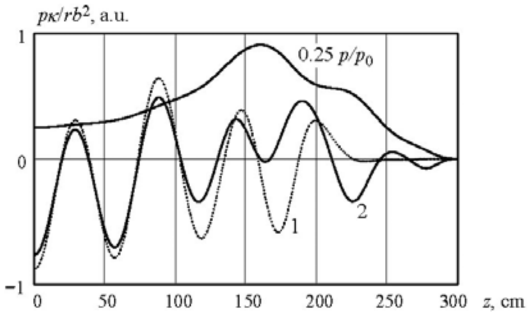

Fig.4. Axial profiles of $p\kappa/rb^2$ in the present GDT (1) and after field correction (2). Also shown is a profile of p/p_0 after field correction.

IV. MAGNETIC FIELD INCREASE

Assuming that all heating power transferred from hot ions to electrons via collisional drag is equal to the axial heat flow of the warm plasma through the mirrors, $W_f/\tau_{ie} \approx Q_{\|}$ and recalling that $Q_{\|} \propto n_e T_e^{3/2}$ and $\tau_{ie} \propto T_e^{3/2}/n_e$, we find $T_e \propto W_f^{1/3}$. On the other hand, for given β, $W_f \propto \beta B^2$. So, another scaling is $T_e \propto B^{2/3}\beta^{1/3}$, and, assuming that maximal plasma beta is determined by the ballooning threshold, the most direct way to increase W_f and T_e is to increase the magnetic field. As far as the GDT coils and capacitor storage already operate at their maximum currents and energy, respectively, in order to increase B we propose to use the existing water-cooled coils with inner diameter of 140 cm from the AMBAL-M machine and additional capacitor storage. These coils can carry 24 kA current in quasistationary regime. We calculated coil positions that provide magnetic field increase ΔB in the central cell including the hot-ion turning regions, with the same axial profile as the original GDT field. Since ΔB is proportional to the coil current, we will be able to estimate the maximum ΔB available for this coil system and the necessary energy.

We set $2N$ additional coils and minimize the averaged square of the difference between the model GDT field with profile (2) and the field of discrete coils with unknown positions and current

$$\min \int_0^{z_{\max}} \left(B_c(z) - \Delta B_{GDT}(z)\right)^2 dz,$$

where integration is performed over the range $-260<z<260$ cm including the turning points at ±190 cm. The GDT layout with the ten optimally placed additional coils is shown in Fig. 5.

With 26.3 kA current in these coils they provide 1.5 kGs additional field in the midplane, i.e. they increase magnetic field in the central cell 1.36 times.

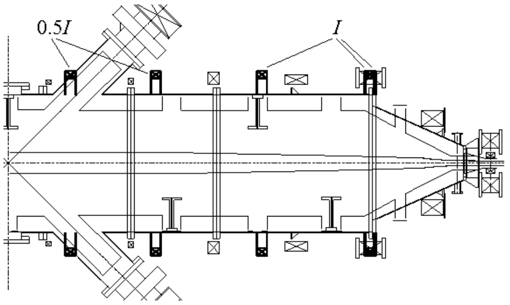

Fig.5. One half of the central cell with 5 additional coils.

According to our scaling, it makes possible to increase W_f by a factor of 2.25 for the same β, and T_e should increase by a factor of 1.3 and may reach 300 eV. For the present GDT magnetic system with 3.0 kGs field at the midplane, the total magnetic field energy is 1.95 MJ. With the additional coils, the energy increases to 3.55 MJ, thus addition of 1.6 MJ is required only to increase the magnetic field to 4.5 kGs neglecting ohmic losses in supplying cables which are inevitable during 1/4 period of LC circuit oscillation until the current maximum is achieved. In the existing system only about 57% of the capacitor storage energy is transformed into the magnetic field energy. Assuming the same proportion, the total additional capacitor energy needed to increase the field to 4.5 kGs field using the additional coils would be about $3.4\times1.55/1.95 = 2.7$ MJ. Such capacitor storage is in principle available at the GDT location in BINP.

V. CONCLUSIONS

Extension of neutral beams from 5 to 20 ms together with increase of magnetic field should provide steady state plasma with significantly enhanced hot-ion energy content and electron temperature. Lengthening of the hot-ion turning region may give additional information about the β limit and increase T_e. Adjustment of the present coil system may significantly improve MHD stability. Increase of the central cell magnetic field by a factor of 1.36 up to 4.5 kGs is possible with available additional coils and capacitor storage.

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