Fast Particle Confinement and NBI Heating Study on Globus-M

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Introduction. Previous experiments demonstrated an effective auxiliary NB heating of small size low aspect ratio plasmas in the spherical tokamak Globus-M [1]. Also it was shown, that the principal channel of the beam power losses is related to the first-orbit losses [2]. As it follows from the beam particle trajectory simulations, the direct losses (i.e. shine-through and first-orbit losses) can reach the value of 25% and 50% or more for hydrogen and deuterium beams correspondently in typical discharge conditions (B_T ~ 0.4 T, $<n_e>$ ~ 2-6 $\times 10^{19}$ m^{-3}). Plasma density rise leads to decrease of the shine-throw losses and contrary increases the first-orbit losses. Increasing of the beam energy also leads to a higher rate of direct losses. Latest results on the fast particle confinement study in the NB heated plasmas are reported in the paper.

1. Novations in the spherical tokamak Globus-M layout

Some renovation of the ion source IPM-1 for the NB injector was performed in order to provide reliable operation with maximal accelerating voltage of 30 kV. The gap between grids was enlarged from 4.0 up to 5.1 mm. As a result, we could provide about 1 MW of neutral beam power.

Essential improvement of the OH plasma target parameters was achieved by means of embedding the error field correction system and therefore minimizing the effect of locked modes on Globus-M [3]. The β_t parameter obtained with the help of EFIT reconstruction of magnetic measurements [4] reached the value of 14.5% for the high density discharges with the line averaged density of about 1×10^{20} m^{-3} under B_t = 0.4 T [5].

Novel data on the electron plasma component was obtained due to upgrade of Thomson scattering diagnostics [6]. Five additional spatial channels together with a new collecting optic scheme were put into operation last year. Now together with data from a movable Langmuir probe we can measure complete electron density and temperature profiles across the plasma column. Significant asymmetry of profiles along the major radius was found for the majority of shots.

As in previous experiments we used two neutral particle analyzers (ACORD type [7]), which were installed in the Globus-M mid plane. One of them, which was aimed along tokamak major radius, provides data for the ion temperature determination. Another one is aimed tangentially to circumference with a radius of 0.3 m (impact radius of the heating beam is the same) and allows to investigate beam particle deceleration starting with the injected neutral beam energy. Corresponding experimental layout is shown in fig. 1.

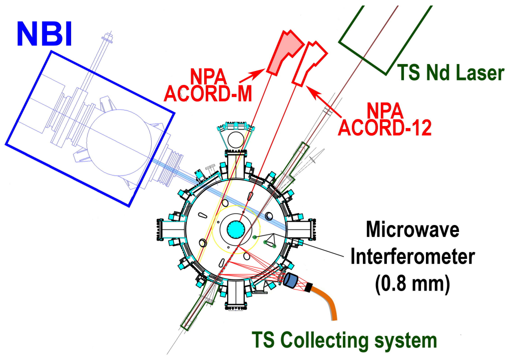


Figure 1. NB heating and basic diagnostic layout on Globus-M

2. Fast particle distribution investigation

The primary reason for the high level of first-orbit losses in the spherical tokamak is a relatively low toroidal magnetic field, especially on the outer side of the plasma column. In Globus-M it is deteriorated by the smaller size of plasma cross section, compared to MAST and NSTX. Thereby the fast ions have large gyro-radii up to 4-8 cm comparable with the plasma minor radius of 24 cm. As a result high energy ion orbits deviate significantly from the magnetic surfaces and could cross plasma border.

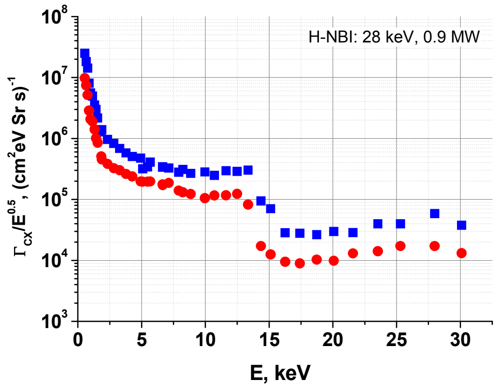
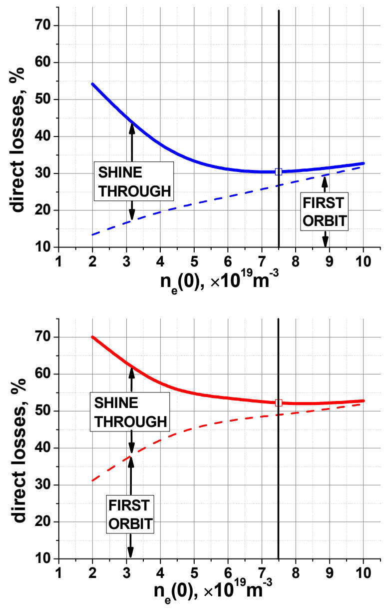


Figure 2. Spectra of charge-exchange atoms for normal 0.4 T (blue, #24593-24597) and for reduced 0.32 T (red, #24585-24591) toroidal magnetic fields



(a)

(b)

Figure 3. Calculated dependences of shine-through and first-orbit losses on plasma density for normal 0.4 T (a) and for reduced 0.32 T (b) toroidal magnetic field

First of all we compared energy distribution of the fast passing ions in shots with normal toroidal magnetic field of 0.4 T and in shots with reduced by about 20% field (0.32 T). Conformably the plasma current was decreased to 160 kA from its original value of 200 kA to save permanent magnetic configuration for a numerical calculations. We tried to keep all other plasma parameters the same. The line averaged density was about 4.0 $\times 10^{19}$ m^{-3}. Corresponded spectra of charge-exchange atoms, which leave plasma in tangential direction, are shown in fig. 2. Each spectrum has two visible steps correlating with full and half beam energies. At the same time the spectrum corresponding to a stronger magnetic field is about two times higher than the one corresponding to a lower magnetic field. If it is assumed, that nonionized atoms have similar distribution along analyzer line of sight (nothing points out to the contrary), the difference should be caused mainly by the level of direct losses of fast ions.

The beam particle trajectory simulations were performed to estimate fast ion losses. Poloidal magnetic field configuration was reconstructed by means of the EFIT code for the corresponding shots. Electron density and temperature profiles were measured with the help of Thomson scattering diagnostics. Neutral deuteron distribution in plasma was reconstructed by DOUBLE code [8]. Calculated dependences of shine-through and first-orbit losses on plasma density are represented in fig. 3. One can see that total value of direct losses for the shots with decreased toroidal magnetic field are half as high again as for the shots with usual value of field for the similar discharge conditions. That confirms our thesis about strong dependence of the direct fast ion losses level on the toroidal magnetic field in a spherical tokamak. Field reduction leads to narrowing the area in plasmas where arising fast beam ions do not leave the column. Contrary, increasing of the toroidal field should improve fast ion confinement. Figure 4 demonstrates direct losses dependence upon magnetic field magnitude. One can see that 50% B_t increase up to design limit of 0.6 T will be enough to reduce the losses significantly.

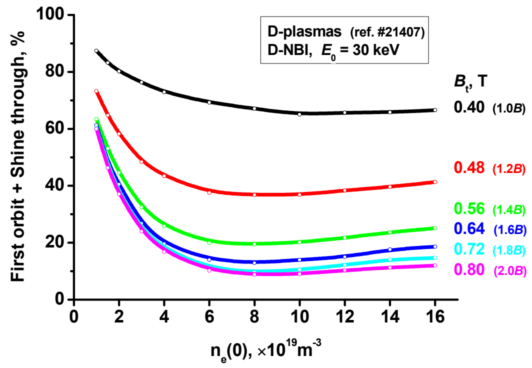


Figure 4. Calculated direct losses dependence on plasma density for normal and for increased magnetic fields

Taking into account strong influence of the error field compensation on the OH plasma performance we examined effect on the NB heated discharge. Figure 5 demonstrates CX spectra for two cases, when correction coils were switched on and off. Slowing down particle spectra are alike.

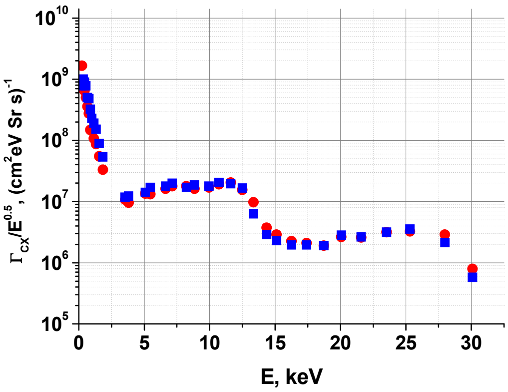


Figure 5. Spectra of charge-exchange atoms with (red, #26071-26076) and without (blue, #26087-26090) error field correction

3. Improved plasma shots

Several steps were made to improve plasma performance. First of all we tried to overcome maximal ion temperature achieved in previous experiments. We used deuterium plasmas with relatively low averaged density of about 1×10^{19} m^{-3} as a target and made efforts to restrain density rise during NB injection. Also we moved plasma column inward to tokamak axis for 3-4 cm from its usual position. Earlier it gave a positive result, as we assume, due to reduction of the plasma volume (higher specific power) and increase of the effective impact radius and gap between plasma boundary and outer wall (lower first orbit losses). As before we injected 25 keV deuterium beams with power of 0.7 MW. Significant rise of the ion temperature up to 0.85 keV was measured by NPA (see fig. 6).

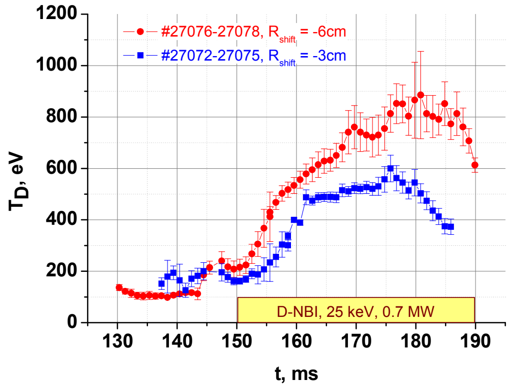


Figure 6. Record ion temperature measured by NPA in shifted plasma column

Another noticeable result was achieved with the help of the error field correction system. As it was mentioned before the field correction does not affect the beam direct losses, but improves target plasma performance. Injection of the hydrogen beam (29 keV, 1.0 MW) led to 18% of toroidal beta for the regular magnetic field of 0.4 T. At the same time normalized beta came close to 6.4 % m T/MA (see fig. 7).

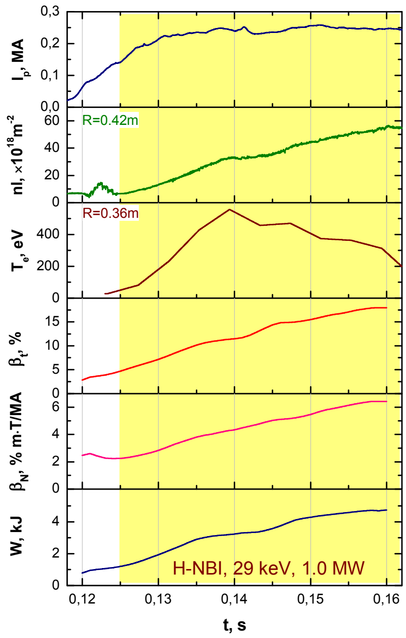


Figure 7. Time evolution of plasma parameters in shot #26435 with maximal toroidal beta

Conclusions

The direct loss of fast ions during neutral beam injection is the principal cause of deterioration of the auxiliary NB heating in a small size spherical tokamak. Raise of the toroidal magnetic field is a reliable way to increase efficiency of the beam injection heating as well as ohmic plasma performance. Now toroidal field of 0.6 T on the column axis is the design limit for the tokamak magnet. As it seen from the simulation, that value should significantly improve NB heating efficiency on Globus-M.

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References:

[1] *V.B.Minaev, et al.* // 35th EPS Conf. on Plasma Phys., 2008, ECA vol. 32D, P1.110
[2] *F.V.Chernyshev, et al.* // 35th EPS Conf. on Plasma Phys., 2008, ECA vol. 32D, P2.097
[3] *Yu.V.Petrov, et al.* // Plasma Physics Reports, 2010, vol. 36, No.6
[4] *V.K.Gusev, et al.* // Technical Physics, 2006, vol. 51, p. 987
[5] *M.I.Patrov, et al.* // 36th EPS Conf. on Plasma Phys., 2009, ECA vol. 33E, P5.153
[6] *S.Yu.Tolstyakov, et al.* // This Conference, P5.137
[7] *A.B.Izvozchikov, et al.* // Technical Physics, 1992, vol. 37, p. 201
[8] *Afanasyev V.I., et al.* // JET-R-(00)04, 2000