Study of the Neutral Beam Heated Plasma in the Globus-M Spherical Tokamak

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Introduction. In the first series of NBI experiments performed in Globus-M [1-3] a significant, by a factor of 2-3 rise of the ion temperature in the plasma bulk was observed at moderate values of the plasma average density $\langle n_e \rangle \approx (2\div4)\times10^{19}$ m^{-3}. However, this temperature increase took place only during the initial phase of the NB pulse of 30 ms total length. Whereas during second half of NB pulse in most shots the ion temperature often went down to the initial value of OH regime. The reason of this phenomenon became clear after the magnetic diagnostics upgrade and the routine usage of EFIT analysis in each plasma shot. The results of the magnetic measurement reconstruction revealed a tendency of the plasma vertical displacement towards the vessel lower dome as the current in the central solenoid increased during the negative halfwave. The value of the plasma vertical displacement could exceed 10-15 cm compared with the plasma minor radius and beam vertical length. Note that in these experiments the plasma vertical position was monitored by the feedback control system using a simple bipolar sensor for the measurements of the radial magnetic flux. As a rule, the control system sustained the radial magnetic flux near the preprogrammed zero level. Actually, it appeared to be insufficient for the stabilization of plasma vertical position near the midplane. The reason lies in appreciable asymmetry of the central solenoid construction caused by its manufacture and assembly. Indeed, the axial magnetic field in the solenoid reaches 5-6 T at the end of the plasma shot, and even a small inaccuracy in coil winding can lead to a significant distortion of the poloidal magnetic field in plasma. In this presentation we describe an improvement of the plasma vertical position control, which led to an increase of the ion heating efficiency in the NBI experiments. Also, in the recent experimental campaign the beam injection angle was slightly changed in the mid plane which corresponded to the 3-4 cm shift of the beam impact radius. The results are outlined.

1. Magnetic diagnostics and plasma position control improvement

Fig.1 shows the arrangement of the magnetic flux loops used for the EFIT analysis and the plasma position control. Also, Fig.1 illustrates the contour of the vacuum vessel and the placement of the central solenoid and the PF coils. Due to the close location of the loops relatively the plasma boundary we could use a small number of sensors (21 toroidally closed loops) for the magnetic reconstruction. The analysis revealed [4] that the characteristic accuracy in the definition of the outer magnetic surface position is within 3-4 mm. The radial magnetic flux dipole sensor is shown by two black dots on the vessel domes. To improve the plasma vertical position control the quadrupole sensor was implemented in recent experiments (four green dots in Fig. 1). As the result, a decrease of the plasma vertical shift by a factor of 2 was achieved under the same plasma control conditions. In addition, the routine EFIT analysis allowed to elaborate requirements for the correction of the preprogrammed radial magnetic flux waveform. This reduced the vertical deviation of the plasma current centroid to a level of 2 cm.

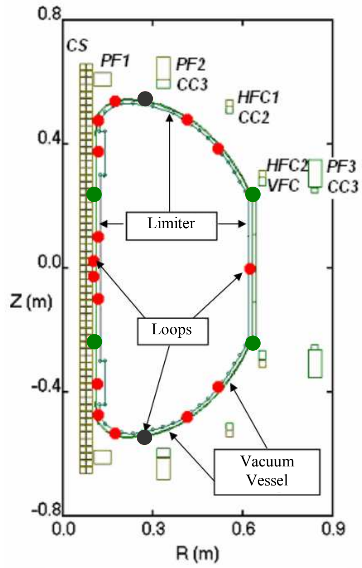

Fig. 1. Location of poloidal flux loops.

2. NBI experiments

Influence of plasma column position on heating efficiency.

Fig.2 illustrates two shots with similar experimental parameters: the plasma current about 200 kA, the plasma averaged density 2-3×10^{19}m^{-3}, the toroidal magnetic field near the plasma axis 0.4 T. In both cases the deuterium beam with the energy of 24-25 keV and the power of 0.4 MW was injected into the deuterium plasma. The plasma vertical position was derived from the EFIT analysis. The plots of magnetic fluxes in Fig.2 correspond to the beginning and the end of the NBI pulse. In the left picture (shot #11939) the plasma vertical displacement reaches the value of 14 cm near the end of NBI pulse whereas the neutral beam footprint half-height $h/2 \approx 10$ cm. In this shot the dipole sensor for the horizontal magnetic flux was used. The control system kept the plasma vertical position according to the preprogrammed horizontal magnetic flux near a zero level. As the result, the combination of the central solenoid asymmetric stray field and the horizontal field produced by the executive control coils HFC (see Fig.1) formed the single null magnetic configuration shifted to the vessel lower dome. The ion temperature (measured by the 12 channel neutral particle analyzer) increased only during first 10 ms of the NB pulse. Then the temperature rather decreased, which can be associated with a rise of shine-through and first-orbit losses.

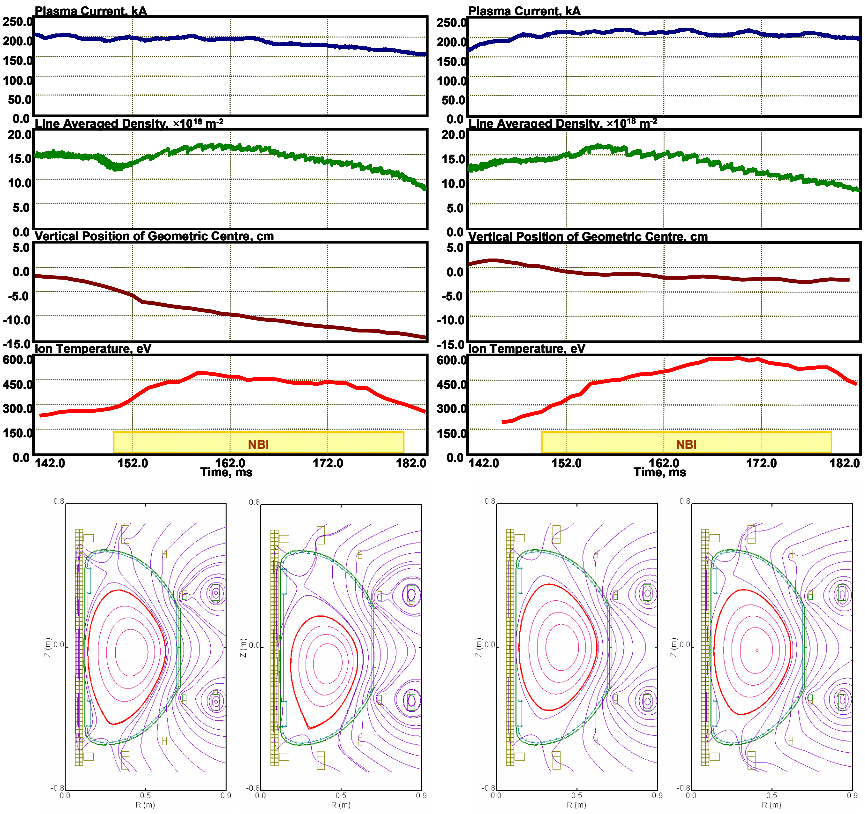

Fig. 2. Influence of plasma column shift on ion heating during NB injection in shots #11939 (left) and #17563 (right). Results of plasma magnetic surface reconstruction by EFIT code in the beginning and in the end of NB pulse are shown in the bottom.

In the right picture (shot #17563) the plasma magnetic configuration was sustained near the midplane during the NB pulse. This result was achieved using the quadrupole sensor consisting of four magnetic flux loops and by the correction of the preprogrammed horizontal magnetic flux made on the base of magnetic measurements followed by EFIT processing. The absolute value of the ion temperature reached 600 eV and even exceeded the electron temperature. Some drop in the ion temperature at the end of the NBI pulse can be associated with approximately 20% decrease of the NBI power and change of electron-ion heat balance.

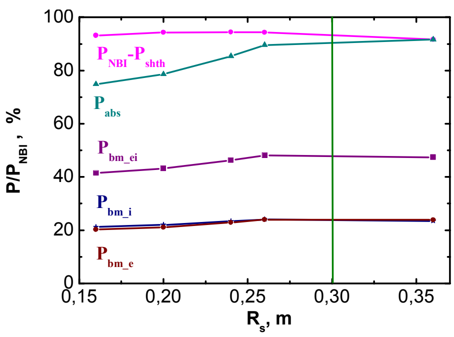

Fig. 3. NB absorbed power versus impact radius. $P_{NB} = 0.6$ MW, $I_p = 0.25$ MA, $n_e = 3\times10^{19} m^{-3}$

Dependence of beam impact radius on plasma heating. Usually we inject the beam tangentially with the impact radius of 30 cm. This beam line was chosen in accordance with preliminary simulations by ASTRA code. The beam power absorption as a function of the aiming radius is shown in Fig. 3. It is steady for radii larger than 25-30 cm and reduces when the beam moves to the inner plasma boundary due to increase of shine-through and first-orbit losses. In recent experiments the beam line was moved by 3-4 cm towards the plasma centre from its initial position (from R_s=30 cm to R_s=33-34 cm). Now it is the maximum possible magnitude restricted by the device design. The time evolution of the ion temperature for the cases of regular and shifted impact radii is shown in Fig. 4. For both shots the ion temperature had similar behavior and reached the same steady state values. This result is in accordance with ASTRA code simulation.

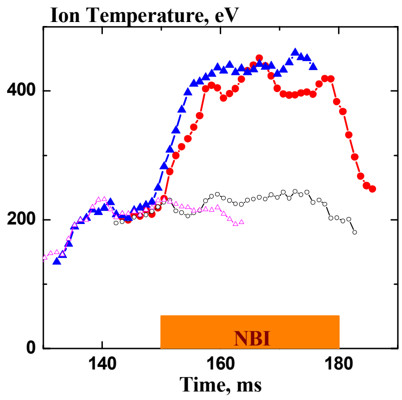

Fig. 4. Ion temperature evolution in shots #16776 (blue, R_s=30cm) and #17023 (red, R_s=33cm) P_{NB} = 0.35 MW, E_{NB} = 23 keV, I_p= 0.2 MA, n_e = (2-3)$\times 10^{19} m^{-3}$

In conclusion we can summarize the present status of the NBI experiment in Globus-M. The NBI has become a routine method for the ion heating of the plasma bulk. This result was achieved after step by step improvement of the vacuum conditions and first wall protection. To date more than 50% of the first wall surface is plated with graphite tiles. By the end of 2006 the protected area will exceed 80%. The existing conditions do not allow to achieve any appreciable electron heating at moderate plasma densities of $(2\div4)\times10^{19}$ m^{-3}. This is partly associated with low absorbed beam power in comparison with the OH power and partly with the plasma impurity contamination. Meanwhile a significant ion heating was observed when the plasma column was sustained near the tokamak midplane. Often the values of ion temperature were larger than the electron temperature values. Approximately the 30% of electron temperature increase was achieved at a high average density $\geq 1\times10^{20}$ m^{-3} close to the density limit [5]. In this range of densities the plasma is not transparent for the charge exchange neutral flux and thus the neutral particle analyzer could underestimate the ion heating in the plasma central region. The next steps on the NBI development in Globus-M are connected with further improvement of the vessel conditioning and the installation of the new ion source capable to increase the beam power up to 1 MW.

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[1] V.B. Minaev, et al., (Proc. 30th EPS Plasma Phys. Conf., 2003) ECA 27A P2-174
[2] V.B. Minaev, et al., (Proc. 31st EPS Plasma Phys. Conf., 2004) ECA 28G P1-190
[3] V.B. Minaev, et al., (Proc. 32nd EPS Plasma Phys. Conf., 2005) ECA 29C P1-103
[4] V.K. Gusev, et al., Technical Physics, Vol. 51 (2006) No. 8
[5] V.K.Gusev et al., to be published in Nuclear Fusion (2006)