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# Progress in the Neutral Beam Heating Experiment on the Globus-M Spherical Tokamak

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**Introduction.** In previous experiments, the neutral beam with energies of up to 30 keV and power of up to 0.6 MW was used on the Globus-M spherical tokamak. Effective heating of plasmas has been demonstrated [1]. For moderate densities, the ion temperature increased up to 0.6 keV and exceeded the electron temperature. With growth of plasma density, the increase in the stored energy of electron component was observed. In assistance of neutral beam injection in Globus-M it was possible to achieve record values of average density of $1.2\times10^{20}$ m$^{-3}$ that corresponds to Greenwald limit for a plasma current of about 200 kA. Experimental studies of the beam particle slowing down in plasma showed that the mechanism governing the deceleration of fast ions is satisfactorily described by the classical theory of Coulomb scattering, at least in the energy range below critical. The further progress in experimental research is connected with improvement of neutral beam injector parameters and development of diagnostics.

**1. NB injector upgrade and second NP analyzer installation**

The renovation of the ion source IPM-1 [2] was performed in order to improve neutral beam parameters. New set of grids for the ion optical system was installed. The curvature of the grids was increased to provide a smaller beam width in the area of launching port. The beam height was also reduced by means of ion optics tuning. As a result, the beam footprint does not exceed 4 cm in horizontal direction and 24 cm in vertical one. That corresponds to at least 2 cm gap between beam edge and docking unit wall. At the same time the power density on the beam axis became half as much again. The dependence of the optimal ion beam current upon the accelerating voltage for hydrogen and deuterium beams is shown in fig. 1. Taking in account the efficiency of the ion beam neutralization we have achieved about 1.0 MW and 0.8 MW beam power for hydrogen and

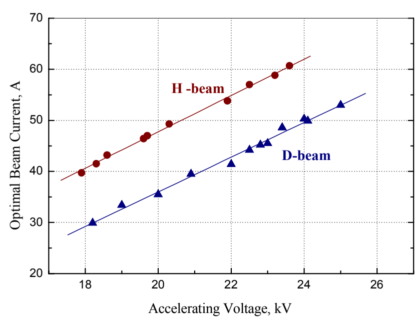


Figure 1. Optimal beam current versus acceleration voltage for hydrogen and deuterium beams for IPM-1 ion source.

deuterium beams correspondently. Further rise of the beam power (about 30%) is possible by means of increasing accelerating voltage up to design parameters. Corresponding extension of the gap between electrodes in the ion optic system is required.

Second neutral particle analyzer ACORD-M was installed on Globus-M in the mid plane. It is equipped with a single mass array of 12 energy channels ($E_{12}/E_1$~7). The analyzer allows to measure only one detailed energy spectrum of hydrogen or deuterium atoms for a tokamak shot. In future, we plan to equip the analyzer with a second array of detectors for simultaneous measuring spectra of both isotopes. One can see from fig. 2, that the new analyzer is aimed tangentially to circumference with a radius of 0.3 m (heating beam is injected into plasma at the same distance from the tokamak axis) and allows to investigate beam particle deceleration starting with the injected neutral beam energy.

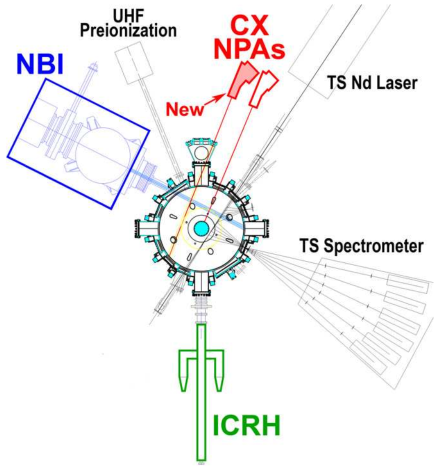


Figure 2. Auxiliary heating and basic diagnostic layout on Globus-M.

## 2. Study of a beam particle deceleration

In previous experiments [3] we could measure noticeable suprathermal particle fluxes during NBI heating only at energies below so called critical energy $E_c$. At energies higher than $E_c$, the beam particles are primarily decelerated due to collisions with electrons, their scattering angles are small and the analyzer which line of sight is directed along the tokamak major radius, i.e. perpendicular to the injection direction, cannot detect them. With the help of "longitudinal" analyzer, we recorded fluxes of particles with energies up to energy of main component of the neutral beam (see fig. 3). Three peaks corresponding to energy components of injected beam arise immediately after beam switching on. Some time later (in our case about 5 milliseconds) the spectra become smoother due to deceleration of beam particles and remained unchangeable till the moment of beam switching off. Typical thermalization time for the beam particles with energy of about 20 keV is close to 10 ms for

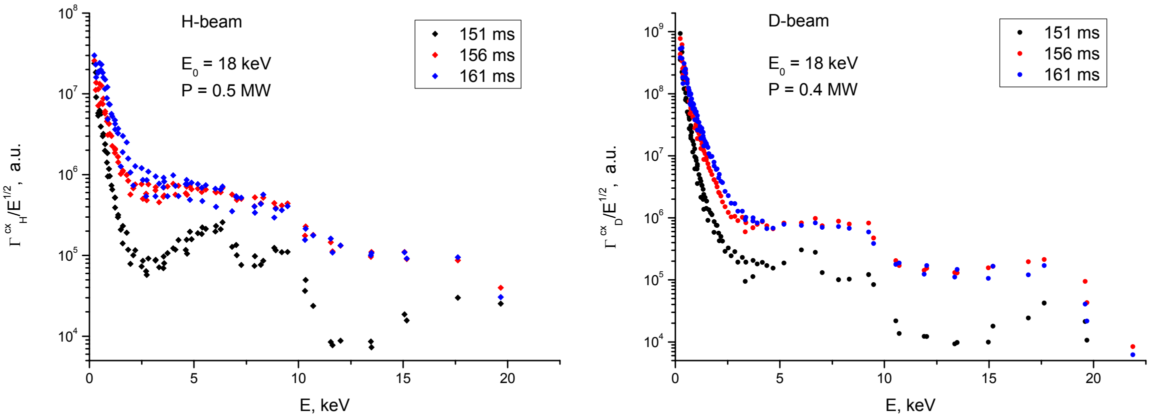


Figure 3. Fluxes of particles recorded with help of "longitudinal" analyzer during hydrogen (left) and deuterium (right) neutral beam injection. The beam is switching on at 150 ms.

Globus-M usual plasmas and is in a good agreement with theoretical predictions. Some visible step in spectra near 10 keV energy range in case of deuterium beam can originate from worse confinement of fast deuterons in comparison with protons [4].

**3. Beam heating experiment results**

Considerable dependence of the ion temperature growth on the plasma column position along major radius was found in the NB heated shots in Globus-M. Usually plasma column center is shifted for 3-4 cm inside from the geometrical center of the vacuum vessel. By means of magnetic system we can increase this value up to 7 cm without significant reduction of plasma parameters for ohmically heated target plasmas. Series of experiments with deuterium beam (21 keV, 0.5 MW) was performed for the plasma with different column shift along major radius. Plasma current was about 200 kA and averaged electron density maintained in a range of $2\text{-}3\times10^{-19}$ $m^{-3}$. The injection switched on at 140 ms. At once ion temperature (see fig 4) began to increase from its initial level of about 150 eV in the ohmic phase and reached maximum value in 20 ms. In the case of a lower column shift (3-4 cm) we had weak temperature rise by 200 eV. Increase in the plasma shift towards the tokamak axis led to a temperature growth by 400 eV or more. It should be note that mentioned above temperature increase was not linear function of the plasma column major radius and has step-wise nature. At the same time electron temperature changed insignificantly in any case. There are two reasons for this behavior. On the one hand, reduction of the plasma major radius leads to decreasing of the plasma volume and increase in auxiliary heating power density. However in our case the difference in plasma volume does not exceed 40% and could not explain the effect entirely. On the other hand, as is shown in [4], the level of so called "first orbit losses" is a strong function of beam energy and sighting parameter. For the same energy the higher the sighting radius (within reasonable limits) the better fast particle confinement. Therefore, we surmise that the reduction of the major plasma radius leads to improvement in confinement of the fast ions and partly explains better ion heating.

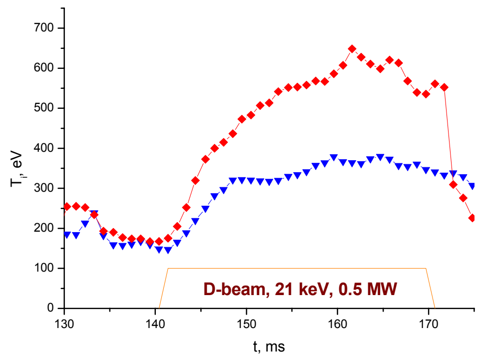


Figure 4. Temporal evolution during NB injection into plasmas shifted towards tokamak axis on 4 cm (blue) and 7 cm (red).

As was mentioned above, we achieved 1 MW of auxiliary power for hydrogen beam. Together with ohmic power, it corresponds to 2.5-3.0 MW/$m^3$ of specific power density in Globus-M plasmas. The inner surface of the tokamak vacuum vessel is fully coated with graphite tiles [5]. In the framework of the ICRH programme the graphite coating was removed from outer ring of the vessel (about 40% of inner surface) and we were able to compare NB heating under these conditions. In both cases plasma current was maintained near level of 180-200 kA and averaged electron density was about 3-4×$10^{-19}$ $m^{-3}$. In 10 ms after neutral beam switching on, we could see significant drop in loop voltage. In case of fully coated vessel, it was noticeable and reached minimum level of about 1.1-1.2 V. The electron temperature remained unchanged and was about 500-550 eV, the ion temperature approached electron one, or may slightly overcame it. In any case, plasma stored energy excelled electron density in growth rate. Absence of graphite tiles substantially influenced on stability of plasma discharge. Majority of shots were accompanied by internal reconnection events (IRE) and further degradation of plasma parameters. In addition, it was difficult to maintain discharge strongly shifted towards the tokamak axis. Spectroscopic diagnostic pointed to increase of the spectral line luminosity with wavelength of 468 nm, which corresponds to ions of Fe, Ni, Ti and He. We interpret the situation as effect of heavy impurity incoming from unprotected stainless steel surface during NB pulse. All subsequent experiments were carried out with a full graphite installation. Ion temperature of about 750 eV (see fig. 5) was achieved for the moderate level of input beam power of about 0.5 MW. Deuterons with energy of 20 keV were injected into deuterium plasma with the current of 200 kA and initial target density of 2×$10^{-19}$ $m^{-3}$. The plasma column was shifted inside along the major radius for a distance of 6 cm. Ion temperature growth continued all 20 ms during NB pulse.

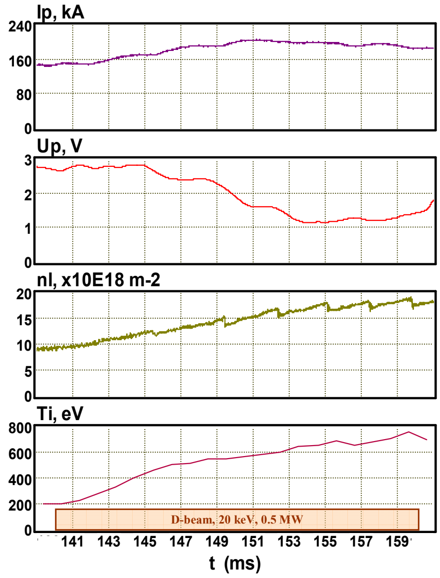

Figure 5. Temporal evolution of plasma parameters in shot #20436 with record ion temperature.

**Conclusions.** A very high level of specific power density up to 3 MW/$m^3$ was achieved in Globus-M plasmas. At the same time, high efficiency of NB plasma heating by means of shot optimization was shown for moderate power level. In future, we plane to provide reliable operation of NB injector with ultimate parameters, develop plasma-shaping technique and as a result achieve discharges with enhanced density and beta parameters.

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