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Comparison of High Density Discharges Heated Ohmically and with NBI in the Globus-M Spherical Tokamak

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In the previous campaigns significant ion heating effect was demonstrated during neutral beam injection experiments on the Globus-M spherical tokamak. Ion temperature two-three times increase was measured at low and moderate densities [1]. Predictive ASTRA simulations, confirmed by experiments, shown poor electron heating at such a regime. One of the most attractive fusion relevant scenarios is a high plasma density regime as the fusion power depends squarely on density. First experimental results obtained near Globus-M density limit during OH and auxiliary NBI heating are presented in the current report. The permanent improvement in the vessel conditioning makes possible to operate at currents in excess of 230kA and high average densities in the target OH regime. The densities ~(6-7)$\cdot 10^{19}$ m^{-3} were achieved at the final stage of the discharge. One of the experimental difficulties specific for high density regime operation was the practical microwave interferometer limit of measurements set by the refraction of microwave ray with 1mm wavelength. Globus-M has rather big plasma cross-section (~1m×0.5m) and difficulties arose with microwave interferometer probing along vertical (~1m) chord). The practical limit of measurable average density is dependent on plasma shape and usually ~6-7$\cdot 10^{19}$ m^{-3}. Routine operation of multipulse Thomson scattering diagnostics resolves this problem. The problem of discharge reproducibility which is essential during high density regime operation was also significantly simplified, as the laser pulse train of 10-20 pulses makes possible the recording of temperature and density spatial and temporal evolution during one machine

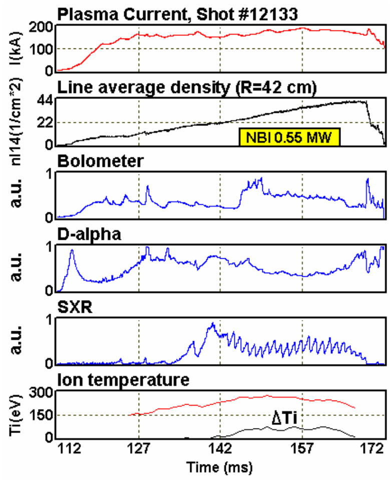

Fig.1. Plasma parameter waveforms in NBI shot with high puffing rate

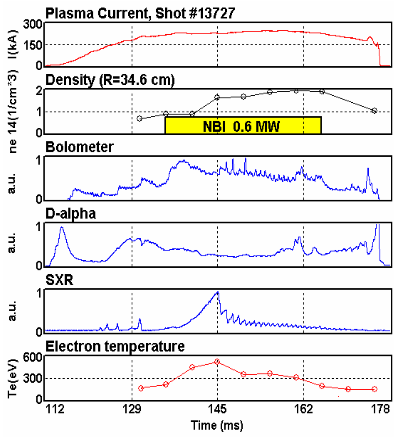

Fig.2 Plasma parameter waveforms in NBI shot with ultimate puffing rate

shot. Usually in experiments with significant density increase the auxiliary heating source is necessary. We used neutral beam injector with deuterium beam injected co-current. The power was in the range of 0.45-0.5MW at the beam energy of 28-29keV. The experiments were performed at conditions: toroidal magnetic field – 0.4 T, major and minor radii ~0.33-0.35 m and ~0.22-0.23 m respectively, plasma current – 0.18-0.25 MA, safety factor at 95% flux surface 3.5-5, plasma elongations ~1.5-1.7. Magnetic configuration was mainly limiter one with a few OH shots when plasma detached from the central column and exhibited separatrix configuration. In the shots with NB injection inner wall limiter configuration was typical. The density was increased at the different rates with external deuterium gas puffing valve. High rate ~55 litter torr/sec and ultimate rate ~100 litter torr/sec, which definitely disrupt the target OH discharge. It's worth noting, that in conditions of high density experiment the density was basically controlled externally by the gas puff and the contribution of the walls can be neglected. It was achieved due to mentioned above accurate wall conditioning in combination with boronization. Another important part of experimental scenario was the cycle of high density shot followed by low density shots to prevent wall saturation by deuterium. Neutral beam was injected at two different discharge time points – at 135 ms "early beam heating" and 10 ms later "normal beam heating". Beam injection lasted for 20-30 ms. Typical waveforms of plasma parameters at "normal" beam heating, high puffing rate at the plasma current below 200 kA are shown in Fig.1. Fortunately in this particular case line averaged density increase up to 7.2 10^{19} m^{-3} was measured by interferometer. Also the well pronounced ion temperature increase is seen, which is novel for high density range in Globus-M.

The highest densities were achieved at higher plasma currents, "early beam heating" and ultimate gas puffing rate. The plasma current was increased up to 230-250 kA and the neutral beam power was about 0.5 MW, which was approximately equal to the OH power.

Fig.2 demonstrates the time dependence of routine plasma parameters (current, D-alpha, bolometer, SXR intensity) together with kinetic parameters measured by Thomson scattering and NPA diagnostics.

Variation of central electron density and temperature, measured at the point ~5cm away from the column axis are shown. It is seen that central electron density reached very high value of $\sim 2\cdot 10^{20}$ m^{-3} before the end of the NB pulse. During such an experiment also weak current drive effect is seen, as the current with NBI increased by ~5% compared to OH discharge at the same loop voltage.

There are two novel effects observed in Globus-M during high density experiments. The first one is definite electron heating by NB. Previously we couldn't observe such a heating as the power absorbed by electrons at low and moderate densities is small. It becomes a considerable fraction of OH power only at high average densities. Recently it was reported [1] that beam power fraction absorbed by electrons increase with density (Fig.3).

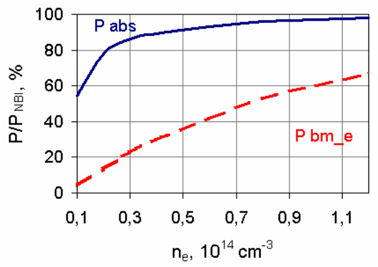

Fig. 3. Total power absorption and power absorbed by electrons vs average density

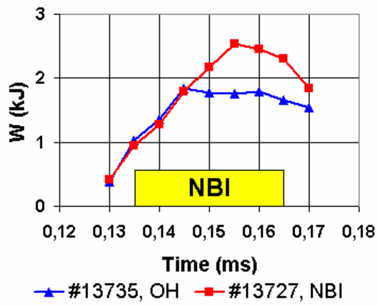

Fig.4 Electron energy content in the plasma during NB heating (red) and OH high density regime

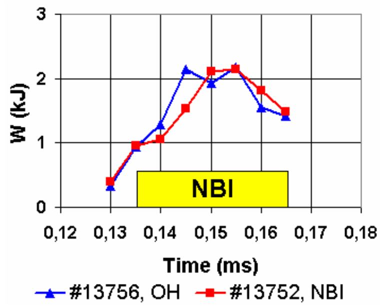

Fig.5 Electron energy content in the plasma during NB heating – red and OH moderate density regime

At the average density of ~ $0.6\cdot 10^{20}$ m^{-3} the additional electron heating power reaches $P_{bm\_e}\sim 0.2$ MW for the total beam power of ~0.5MW which is significant fraction of the OH power, P_{OH} ~ 400kW at the final stage of the discharge. So, the contribution of the beam should be visible, if no significant degradation of confinement takes place. Fig.4 shows the electron energy content variation in NBI heated discharge compared to high density OH discharge.

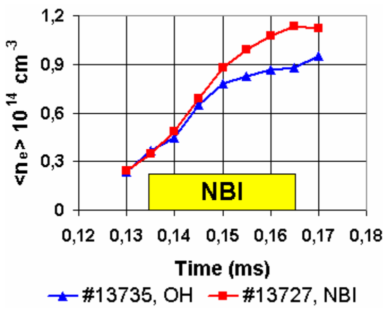

Fig.6 Temporal variation of the average density in OH and NB heated discharges with high density ,TS data.

The above mentioned density range is crucial for electron heating in the Globus-M tokamak as the density decrease nearly cancels the effect. Electron energy content variation in NB heated discharge compared to OH discharge at the density lowered by 25% is shown in Fig.5.

The second effect is the achievement of highest up to date density in Globus-M. Absolute densities of about $2{\cdot}10^{20}$ m^{-3} were observed at the central part of the plasma column. It is difficult currently to satisfy high precision demands on TS scattering density measurements as the absolute Raman scattering calibration was not made yet. Keeping in mind the relative calibration of n(R) profile by the link to the line integrated density profile measured by microwave interferometer at the OH phase of the discharge we obtain the density temporal dependence shown in Fig.6.

Volume averaged density value in this experiments approaches to $1.2{\cdot}10^{20}$ m^{-3}. The Greenwald limit at 170 ms is ~ $1.5\ 10^{20}$ m^{-3}.

Finally, a few remarks on plasma column MHD stability at such a regime could be made. Global plasma column stability is conserved for the whole duration of the discharge, in other words the NB injection makes the discharge more stable by stabilizing IREs, which are specific for high current (low $q_{95}{\approx}3.5$) OH discharges. The second specific instability is snake instability in high density discharges. Formerly it seemed to create a density limit [2]. The typical behavior of SXR intensity pattern during snake development in the Globus-M discharge is shown in Fig.7.

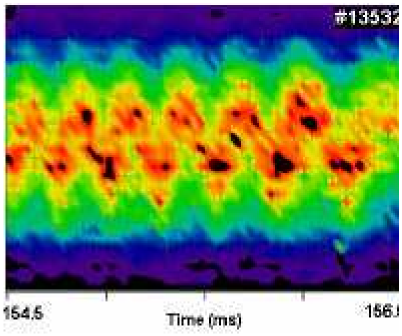

Fig.7 SXR intensity behavior shows the development of m=1/n=1 structure in OH discharge

Snakes don't occur at ultimate puffing rate in high density NB heated discharges.

The reason for the current termination at the final stage of the discharge is not understood yet either in OH or in NB heated discharges.

Efficient heating of electrons was observed in the Globus-M for the first time during NB injection of ~0.5 MW, ~30 keV beam. Very high density $n_{eo}{\approx}2{\cdot}10^{20}$m^{-3} was achieved at low magnetic field ~0.4 T and low $q_{95}{\approx}3.5$ values.

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