Plasma Heating by Neutral Beam Injection in the TUMAN-3M Tokamak

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Experiments on Neutral Beam Injection (NBI) on the TUMAN-3M [1] have been started in 2004 [2]. The development of NBI is aimed on the increase in experimental resources of the tokamak. Study of a transport barrier formation in the presence of NBI heating is planned. Utilization of the Heavy Ion Beam Probe diagnostic in the NBI experiments is expected to provide important data on effect of the radial electric field on transport barrier formation. Study of the plasma stability at high β is planned as well.

Although the NBI system is able of producing more than 600 kW power with the energy of 30 keV and pulse duration up to 28 ms, in the described experiments P_{NBI} was limited by 330 kW at E_{NB}=22 keV with pulse duration 20ms. The experiments have been performed in the co-injection geometry using Deuterium beam. Target plasma parameters were as follows: R_0=0.53 m, a_l=0.22 m, B_T=0.7 T, I_p<170 kA, $\bar{n}$ <4 10^{19} m^{-3}, $T_e(0)$=(0.3-0.5) keV, $T_i(0)$=(0.15-0.2) keV, working gas – Deuterium, operation regimes – ohmic heating, ohmic *H*-mode. In order to reduce impurity influx during the NBI pulse, the entrance port was conditioned with a several hundreds of NBI shots without/with plasma. Further improvements of the vessel and entrance port conditions have been achieved by boronization. In the shots obtained after the boronization Z_{eff} increase during the NBI application was small.

Typical waveforms of the major plasma parameters in the shot with co-injection of 290 kW NBI and without boronization are presented on Fig.1. NBI resulted in the increase in the loop

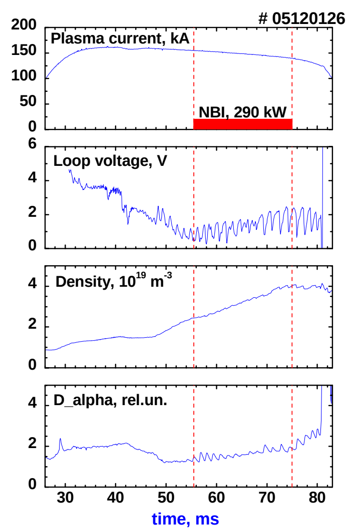

FIG.1. Plasma current, loop voltage, average density and D_α emission in the shot without boronization. Red vertical lines represent interval of 290 kW NBI.

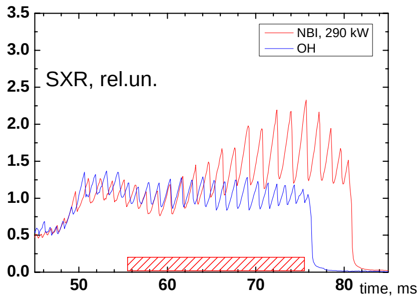

FIG.2. SXR emission in the NBI heated (red) and ohmic (blue) shots with the same densities.

voltage Up, average density $\bar{n}$, D_α emission indicating enhanced impurity/working gas influx due to interaction with vessel and entrance port walls. Rough estimations showed 2-fold increase in Z_{eff} during NBI from initial value of 1.5. SXR emission increases during NBI as shown on Fig.2, athough T_{e0} is constant ($\bar{n}$ is similar in OH and NBI shots). The increase confirms Z_{eff} rise. A moderate ion heating was observed in these experiments. The central ion temperature $T_i(0)$, measured by the Neutral Particle Analyzer, was increased from 180 to 350 eV in the shots in the nonboronized vessel, see Fig.3. Boronization of the vessel resulted in the reduction of both the initial ohmic $T_i(0)$ and the increase in the $T_i(0)$ during NBI pulse: $T_i^{OH}(0)$ and $\Delta T_i(0)$ were found to be 150 eV and 100 eV, respectively. Although up to 70% of beam power was absorbed by electrons, the electron temperature increase was even smaller than ion one (negligible within the measurement accuracy). An essential increase was observed in the electron density during the NBI pulse applied to plasma before the vessel boronization. Thus, the major effect of NBI power absorption is the increase in the energy content due to the density increase rather than temperature rise. According to the diamagnetic measurements shown on Fig.4 the increase in the perpendicular stored energy during NBI was up to factor of 2.5 as compared to the initial level. Measured energy confinement times are in good agreement with ITER98(y,2) scaling in the all regimes under consideration (ohmic *H*-mode, NBI *H*-mode: boronized/nonboronized).

The SXR measurement of sawteeth inversion radius allowed estimation of the current profile evolution caused by the NB absorption. The measurement has shown some peaking of j(r) in the co-injection scenario. Seemingly, the peaking indicates appearance of noninductively driven current in the vicinity of magnetic axis. The fraction of driven current could be estimated as ~ 10% of total plasma current, that agrees with the ASTRA transport simulation predictions.

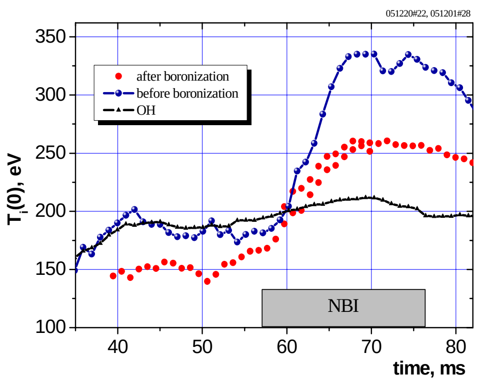

FIG.3 Central ion temperature behaviour in the ohmic regime (black), NBI heated plasmas without boronization (blue) and after boronization (red).

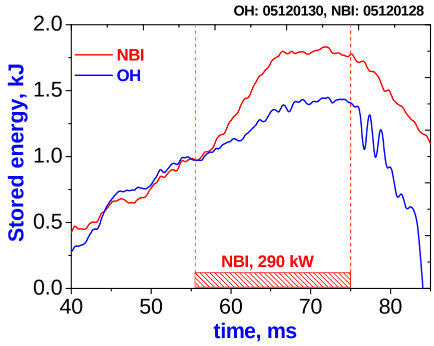

FIG.4. Diamagnetic measurements of the stored energy in ohmic (blue) and NBI (red) heated plasmas. Increase in the energy content is within 20% at the same density. Since T_e does not change the increase indicates ion heating.

In the nonboronized vessel the NBI heating was accompanied by essential increase in the total number of particles, although external gas puffing was switched off simultaneously with NBI application. Evidently, the density growth was caused by impurity influx. In agreement with the above observation, the average Z_{eff} increased as was evidenced by loop voltage evolution through NBI. Clear peaking of the electron density profile n(r) was observed as well. Since central particle source from the NB is negligible the n(r) peaking could be attributed to $Z_{eff}(0)$ increase due to accumulation of impurities. The increase in the central SXR emission is in line with assumption of essential Z_{eff} peaking during NBI. The impurity influx was suppressed by the vessel boronization and by the entrance port conditioning with NBI pulses. In the best achieved conditions the total number of particles did not increase and Z_{eff} was close to 1 during the NBI heating phase.

Application of NB heating was found to effect MHD stability of the plasma. Practically all high density shots are terminated by disruptions, but shots with NBI were systematically longer than the ohmic ones in the similar vessel conditions, see example shown on Fig.2. Although global stability was better in auxiliary heated shots, the level of MHD activity registered by high frequency magnetic probes was higher. Bursts of wide spectrum MHD oscillations were observed during NBI. The bursts strongly correlated with sawtooth crashes. Example of the MHD bursts is shown on Fig.5. Further analysis is necessary to identify origin of the bursts.

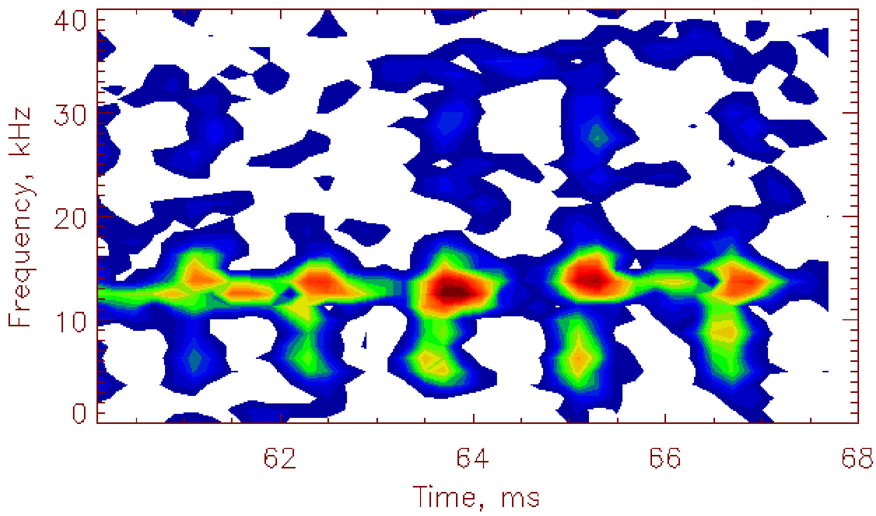

FIG.5. Spectrogram of the MHD bursts observed during the NBI heating in the TUMAN-3M.

Summary

NBI heating experiments were successfully started in the TUMAN-3M tokamak. Stored energy increases by 20% as a result of 2-fold ion temperature increase during NBI. Indications of noninductive current drive by NBI were observed using SXR multi-chord diagnostic. NBI in unboronized vessel allows more effective ion heating. Bursts of wide spectrum MHD oscillations were observed during NBI.

References

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