*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-1.146 (2007)*

Confinement of NBI-originated fast ions in TUMAN-3M

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Experiment

The low toroidal field and small aspect ratio of the tokamak complicate the task of plasma heating by Neutral Beam Injection (NBI) due to enhanced ion orbit losses and MHD-induced losses. The orbit losses are strongly increased in the Counter-injection heating scenario. Recent experiments on the TUMAN-3M tokamak [1] were aimed at study of confinement of fast ions (FI) and mechanisms of their losses in Co- and Counter-NBI heating schemes.

The target plasma parameters in the experiments were as follows: $R_0 = 0.53$ m, $a_l = 0.22$ m, $B_T \le 0.7$ T, $I_p \le 170$ kA, $\bar{n}_e \le 4 \cdot 10^{19}$ m^{-3}, $T_e(0) \le 0.5$ keV, $T_i(0) \le 0.2$ keV. Deuterium neutral beam (P_{NBI}<0.4 MW, E_0<25 keV) was injected tangentially with the minimum distance from the major axis R_{min}=0.42 m [2]. The Co- and Counter-injection scenarios were attained by changing the plasma current direction. Measurements of the ion temperature and tangential and perpendicular spectra of charge exchange neutrals were performed using 12-channel neutral particle analyzer ACORD-12 [3]. D-D neutron detector was employed to study FI tail behavior. MHD oscillations during NBI were detected by Mirnov coils and by high frequency magnetic probe inserted in the SOL region.

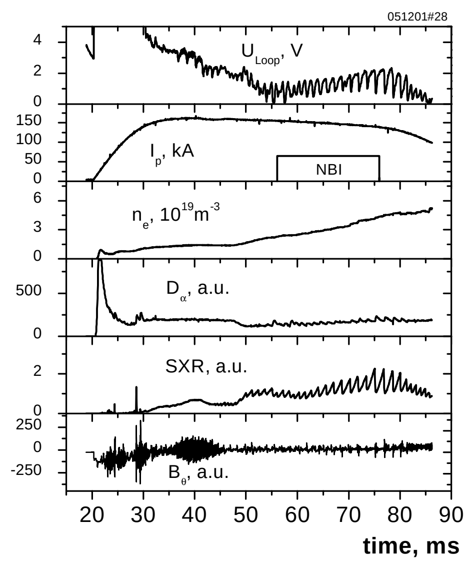

Fig.1. Evolution of the main plasma parameters in the shot with Co-NBI.

Typical waveforms of the main plasma parameters in the shot with 290 kW Co-NBI heating are presented on Fig.1. The increase in the loop voltage and average density indicate enhanced impurity influx caused by NBI [2]. Our estimations have shown 2-fold increase in Z_{eff} during NBI pulse. In the Co-NBI, the central ion temperature $T_i(0)$ was found to increase by a factor of 2 from 180 eV to 350 eV, see Fig.2. The electron temperature $T_e(0)$ did not change as compared to the ohmic value at similar density. These observations are consistent with the measured 20% increase in the stored energy W_{dia}, see Fig.3.

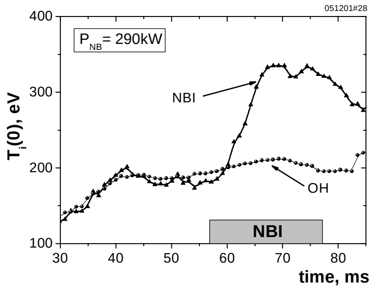

Fig.2. $T_i(0)$ evolution in ohmic (OH) and Co-NBI (NBI) shots.

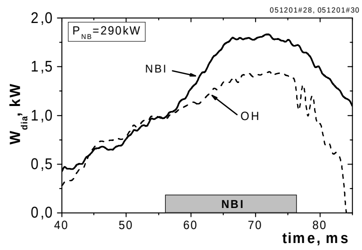

Fig.3. Diamagnetic stored energy in the ohmic (OH) and Co-NBI (NBI) shots.

Fast ion confinement in Co-NBI scenario

The presence of fast ion population in the Co-NBI scheme had been established by the NPA measurement of the CX spectra [3]: the high energy tail extends up to the NB energy E_0=22 keV indicating good-enough confinement of FI. Fast ion confinement time was estimated from comparison of the measured and simulated neutron fluxes. Since the bulk ion temperature of the deuterium plasmas in TUMAN-3M is rather small the measured neutron flux is governed by beam-plasma D-D reactions and therefore is very sensitive to FI fraction. Decay time of the flux after NBI switch off is directly connected with FI confinement time. Figure 4 presents comparison of the measured and simulated neutron fluxes. In the Fokker-Planck simulations of FI distribution function the only classical slowing down was taken into account. Thus, the good agreement of the measured and simulated decay times suggests the absence of any anomalous FI losses. Some difference between the shapes of flattop on Fig.4 may be explained by the increasing orbit losses due to gradual reduction of the plasma current in the experiment which was not taken into consideration in the simulations.

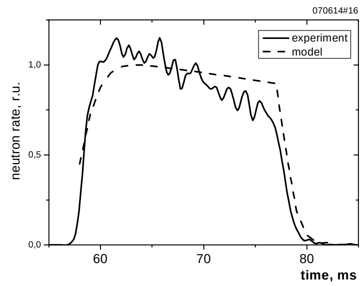

Fig.4. Experimental and simulated evolution of neutron rate during Co-NBI.

In some shots with high Co-NBI input power and high density the fishbone activity was observed, which further proves the presence of FI population. The fishbones manifested themselves as bursts of high frequency MHD oscillations and as a temporary increase in the NPA flux at high energy coinciding with sawtooth crashes. The charge exchange flux increases during the burst since FI are expelled from the core to the plasma edge, where target neutral density is much higher. Typical example of the fishbone activity is presented on Fig.5. Each burst was accompanied by the

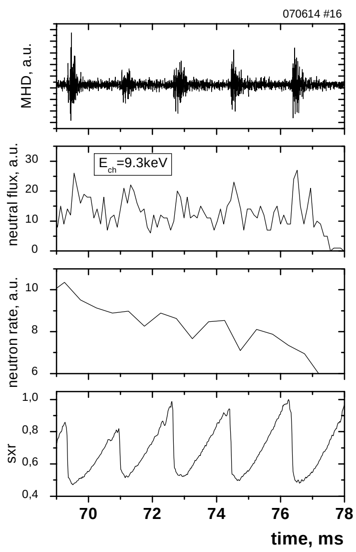

Fig.5. Fishbone activity as seen by fast magnetic probe, FI neutral flux, neutron rate. Sawtooth crashes coincide with fishbones.

moderate drop in the neutron rate. The relatively small drop suggests small direct FI losses during the fishbone event. Clear connection of the fishbones with the NBI-originated fast ions is illustrated on Fig.6. Here, MHD burst amplitude increases during Co-NBI pulse and decays after it with a time constant close to classical slowing down time τ_{se}=8 ms.

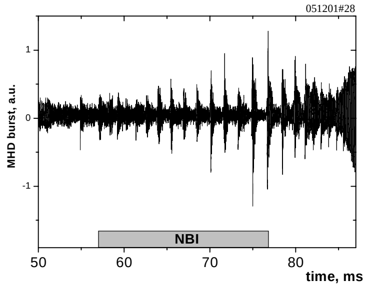

Fig.6. Fishbone instability development during Co-NBI heating.

Another observation confirming the existence of essential fraction of FI in the Co-NBI heating scenario was some increase in the sawtooth period following the NBI application, see Fig.7. Since there was no noticeable difference in the density between Co-NBI shots and Counter-NBI and OH ones we suppose the increase in the sawtooth period in former case is due to partial ST stabilization in the presence of fast ions. Similar effect was observed in other tokamak experiments [4].

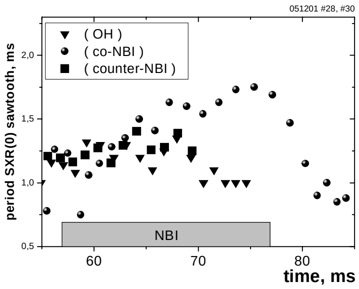

Fig.7. Sawtooth period decreases in ohmic regime and in Counter-NBI, increases in Co-NBI scenario.

Transport modeling performed with ASTRA code [5] has shown good agreement of the ion temperature and stored energy increases in the Co-NBI heating scenario with the experimental observations described in the previous section. In the simulations the classical slowing down was the main mechanism of the FI energy losses. Thus, the above mentioned fast ion observations and transport modeling suggest the absence of anomalous fast ion losses in the Co-NBI scenario.

Counter-NBI experiments

Substantial ion losses are expected in the Counter-NBI scenario. ASTRA simulations predicted the increase in the losses from 9.8% in the Co-NBI scheme to 87 % in the Counter-NBI. Accordingly, the strong impurity influx has been found experimentally. Z_{eff} increased by a factor of 3 during NBI pulse. Because of large losses the amount of confined FI is much smaller in Counter-injection case. Figure 8 presents simulated FI density distribution.

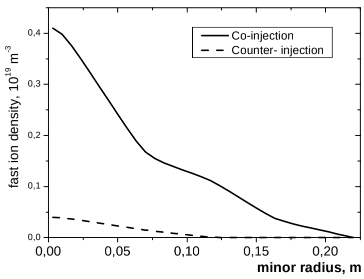

Fig.8. Simulated fast ion density profile in Co-NBI and Counter-NBI scenarios.

Small amount of confined FI resulted in clear reduction in heating efficiency. In good agreement with the transport simulations only a weak effect has been found on central ion temperature in the experiment. No increase in the stored energy was registered. The central ion temperature increase was within 50 eV as seen on Fig.9. Negligible amount of FI has been further proved by absence of fishbone activity and any effects on sawtooth oscillations. In line with the above observations the NPA charge exchange fluxes in Counter-NBI scenario are by more than order of magnitude smaller than in Co-NBI case. Thus, we can conclude the Counter-NBI is not applicable scheme for plasma heating in the current TUMAN-3M parameter range.

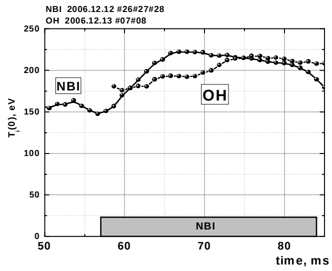

Fig.9. Measurements of the central ion temperature in the Counter NBI scenario.

Summary

Observed 2-fold ion heating and stored energy increase by a factor of 1.2 are in agreement with assumption of good confinement of fast ions and their classical slowing down in the Co-NBI heating with power of 0.3 MW in the TUMAN-3M tokamak. Measurements of the charge exchange fluxes and neutron rate confirm the classical collisional slowing down is the main mechanism determining FI lifetime. Fast ion population effect sawtooth activity by increasing their period. Observed fishbone activity at high density did not result in the substantial enhancement of fast ion losses.

The orbit losses are strongly increased in the Counter-injection scenario resulting in small heating efficiency. Ion heating was within 50 eV (20%) in this scheme. No effect of NBI was found on stored energy. In agreement with the simulations no essential amount of fast ions was detected by NPA. Fishbone instability was not registered in the Counter-NBI scheme.

Acknowledgements

The work was supported by Russian Foundation for Basic Research (Grant No 07-02-01311-a), RF Federal Agency for Science and Innovations (State Contract No 02.518.11.7023) and Russian Academy of Sciences.

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