Study of fast ion confinement using 2.45 MeV *D-D* emission in TUMAN-3M

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Introduction

Recent experiments on NBI heating in the TUMAN-3M tokamak were carried out at magnetic field B_t=1 T, what is higher, than in previous experiments [1], where B_t was 0.7 T At higher toroidal field B_t and plasma current I_p the electron temperature T_e was observed to increase [2], what resulted in plasma heating efficiency increase.

One should expect an increase in the amount of fast ions (FI) in the NBI application phase at higher toroidal field. The increase should occur, firstly, because of reduction of orbit losses and, secondly, due to increased slowing down time at higher T_e.

Measurements of 2.45 MeV D-D neutron fluxes I_n were utilized to study FI confinement studying the conditions of increased B_t and I_p. The neutron diagnostic is very sensitive to FI fraction since the bulk ion temperature of the deuterium plasma in TUMAN-3M is small (~180 eV) and the measured 2.5 MeV neutron flux is produced in beam-plasma D-D reactions. In the presented study the FI confinement time was estimated from the decay time of I_n after NBI switch-off.

Experiment

The target plasma parameters in the experiments were as follows: $R_0 = 0.55$ m, $a_l = 0.22$ m, $B_t \leq 1$ T, $I_P \leq 190$ kA, $n_e \leq 5 \cdot 10^{19}$ m^{-3}, $T_e(0) \leq 0.75$ keV, $T_i(0) \leq 0.2$ keV. The deuterium beam power was 0.4 MW, the accelerating voltage was up to 25 keV. The beam was injected tangentially in co-current direction with the impact parameter of $R_{imp} = 0.42$ m. Central electron temperature $T_e(0)$ was monitored by soft X-ray detectors [3]. The twelve channel neutral particle energy analyzer ACORD-12 [4, 5] was used for the measurements of $T_i(0)$ and energetic neutral particle fluxes in radial direction. The evolution and the absolute value of the 2.5 MeV D-D neutron emission was measured by two ^{3}He filled neutron detectors with 0.1 ÷ 0.5 ms time resolution [6].

The increase of toroidal field B_t from 0.7 T to 1 T leads to electron temperature increase from 400-500 eV to 550-650 eV. Further increase in the T_e up to 650-750 eV was observed with the plasma current increase from 160 kA to 190 kA.

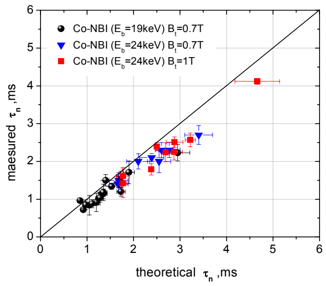

Fig. 1 Comparison of the experimental τ_n with calculated one at different E_b

The slowing-down time of fast ions was derived from the measurements of neutron rate. The e-folding time for decay of neutron emission (τ_n) after beam turn-off has been measured for the set of discharges. For the beam-target regime, when Coulomb interactions between the energetic ions can be ignored, the decay time τ_n is given by [7, 8]

$$\tau_n = \frac{\tau_{se}}{3} \cdot \ln\left(\frac{E_b^{3/2} + E_c^{3/2}}{E_n^{3/2} + E_c^{3/2}} \right), \qquad (1)$$

$$E_c = 14.8 \cdot A_f \cdot T_e \cdot \left(\frac{Z_i^2}{A_i} \right)^{2/3} \qquad \tau_{se} = 6.3 \cdot 10^{14} \cdot \frac{A_f \cdot T_e^{3/2}}{Z_f^2 \cdot n_e \cdot \ln\Lambda_e},$$

where τ_{se} is the slowing-down time, if only interaction with electrons is taken into account, E_n is the energy at which the fusion reaction cross section drops by factor of e from its value at the beam injection energy E_b and E_c is the critical energy at which the electron and bulk-ion contributions to the FI slowing-down are approximately equal. Since T_e increases as a result of B_t and I_p increase in ohmic regime τ_n is expected to became longer (see expression 1 derived from the theory of Coulomb interactions).

Figure 1 shows an observed values of τ_n vs theoretical ones calculated using expression (1) for values of E_b = 19 кэВ at B_t = 0.7 T and E_b = 24 кэВ at B_t = 0.7 T and B_t = 1 T. The figure suggests that FI slowing down is essentially classical at both energies: E_b = 19 кэВ and E_b = 24 кэВ. Growth of T_e at similar n_e leads to increase in τ_n by factor of 1.5.

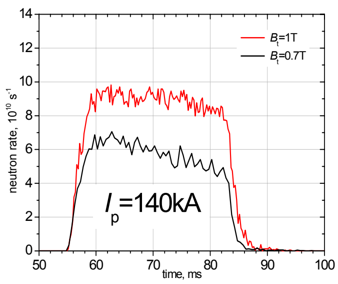

Fig. 2 The temporal evolution of neutron rate at different values of B_t

The temporal evolution of neutron rate in two shots with different values of B_t is shown in the figure 2. Energy of fast ions was 23.5 keV and n_e was similar in the both shots. As mentioned above the increase of B_t from 0.7 T to 1 T results in growth of T_e, thus observed increase in the neutron rate could be explained by larger FI fraction in the conditions of longer slowing down time (see expression 1).

The increase of plasma current at high B_t from 140 kA to 179 kA leads to both the increase in T_e and the improvement of capture efficiency of fast ions. The temporal evolution of neutron rate at different value of I_p is shown in the figure 3. The value of neutron rate increases by factor of 1.5 at $I_p = 179$ kA as compared with $I_p = 140$ kA.

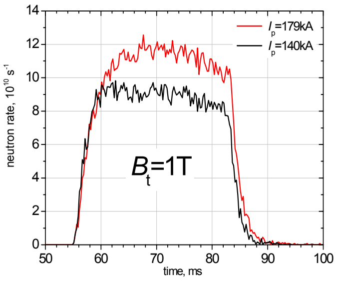

Fig. 3 The temporal evolution of neutron rate at different values of plasma current

At similar discharge parameters neutron rate strongly depends on fast ion energy E_b since cross-section of d (d, ^{3}He) n reaction is exponential function of E_b. It also depends on capture efficiency, which degrades at high energy. Some dependence of charge exchange and shine-through losses on energy may play role in neutron rate dependence on beam energy. Experimentally observed value of I_n saturates at high energy of injected beam. The dependence of the neutron emission on beam energy was studied in the range of 15 ÷ 24 keV.

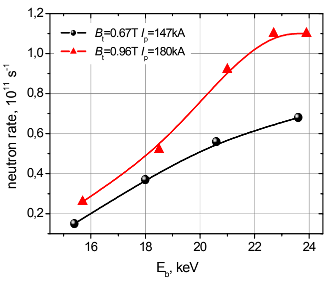

Fig. 4 Measured neutron rate as a function of the E_b

Measured neutron rate as a function of the E_b for two values of toroidal field is shown in the figure 4. The triangle points correspond to $B_t = 0.67$ T and $I_p = 147$ kA. The circular points correspond to $B_t = 0.96$ T and $I_p = 180$ kA. The plasma density was similar in both cases. The evolution of I_n as function of the E_b shows that effect of B_t is not very strong at $E_b < 20$ keV. The further increase of E_b results in considerable difference in I_n. The increase of B_t up to 0.96 T leads to substantial growth of I_n at $E_b > 20$ keV. E_b increase over 23 keV resulted in neutron flux saturation. So the further increase of B_t is required for fast ions to be efficiently captured for $E_b > 23$ keV.

The growth of ion temperature during NBI at high B_t was observed by means of neutral particle analyzer ACORD-12 [2]. Neutron rate and NPA fluxes measurements suggest that the rise in ion temperature during NBI is due to increase of capture efficiency and longer slowing down times of fast ions at high magnetic field.

Summary

At $B_t = 1$ T the maximum value of I_P was increased up to 190 kA. The increase of B_t (from 0.68 T to 1 T) and I_P resulted in $T_e(0)$ increase (from 400 eV to 700 eV) in ohmic phase. The B_t increase, followed by T_e increase, significantly improved conditions for fast particle capture and confinement.

The improvement of plasma parameters at high B_t leads to increase of fast ion slowing-down time τ_n. As result at similar n_e neutron rate decay time τ_n increases by a factor of 1.5. The slowing-down time of fast ions was derived from the measurements of neutron rate decay time.

From the analysis of neutron rate behavior at low and high magnetic field it is concluded that the capture efficiency was increased. The value of neutron rate increases by a factor of 1.5 at $B_t = 1$ T and $I_p = 179$ kA, as compared with $B_t = 0.67$ T and $I_p = 140$ kA.

The increase of B_t leads to substantial growth of I_n at $E_b > 20$ keV. I_n saturates at $E_b > 23$ keV. The further increase of B_t is required for fast ions to be efficiently captured at $E_b > 23$ keV.

The continuous growth of ion temperature during NBI pulse at high B_t was observed. It is suggested that the rise of ion temperature during NBI is due to increased fast particle capture efficiency and longer slowing down time at high magnetic field.

We conclude that B_t strongly effects NBI heating in small tokamaks.

Acknowledgements

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