35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-2.103 (2008)

Analysis of Density Dependence of Neutron Rate in NBI Experiments on TUMAN-3M

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Introduction

The low toroidal field of the tokamak TUMAN-3M complicates plasma heating by Neutral Beam Injection (NBI) due to degradation of fast ion (FI) confinement. Recent experiments [1, 2] were aimed at study of fast ion confinement and mechanisms of losses of FI in co-NBI heating scenario with emphasis on density dependence of neutron rate. Measurements of 2.45 MeV D-D neutron flux were used for FI confinement study. Since the bulk ion temperature of the deuterium plasma in TUMAN-3M is rather small (~180 eV) the measured 2.5 MeV neutrons are produced exceptionally by beam-plasma D-D reactions and therefore are very sensitive to FI fraction. FI confinement time was estimated from the decay time of neutron rate after NBI switch-off. The measured decay times was compared with calculated one assuming classical slowing down.

Experiment

The TUMAN-3M is a relatively low aspect ratio (R/a=2.3) toroidal device. The plasma major and minor radii are 0.53 m and 0.23 m, respectively. The operational parameters for beam heated plasma were as follows: $B_T \leq 0.7$ T, $I_p \leq 170$ kA, $\bar{n}_e \leq 4 \cdot 10^{19}$ m^{-3}, $T_e(0) \leq 0.5$ keV, $T_i(0) \leq 0.2$ keV.

The plasma was heated by 0.35 MW of deuterium neutral beam injection with the accelerating voltage of up to 22 keV. The beam was injected tangentially with the minimum distance from the major axis R_{imp}=0.42 m. Central electron temperature $T_e(0)$ was monitored by means of soft X-ray detectors [3]. The 12- channel neutral particle energy analyzer ACORD-12 [4, 5] was used for the measurements of ion temperature and energetic neutral particle fluxes in toroidal and radial directions.

The time evolution and the absolute value of the 2.5 MeV neutron rate in the range $10^8 \div 10^{12}$ n·s^{-1} were measured by two ^{3}He filled neutron detectors with 0.1÷0.5 ms time

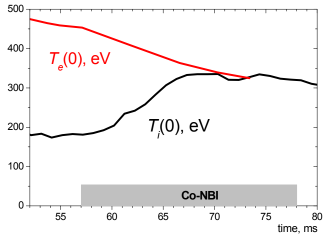

Fig. 1 Temporal evolution of electron and ion temperature

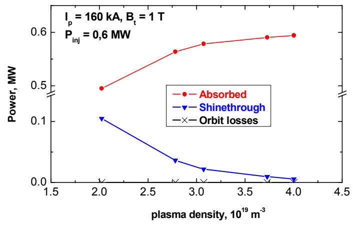

Fig. 2. The dependence of absorbed power on plasma density

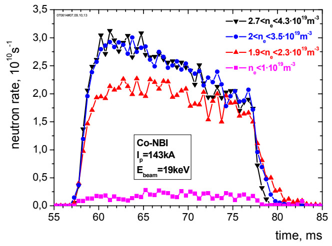

Fig. 3. The temporal evolution of neutron rate at different values of plasma density

resolution [6]. This detector has low sensitivity to HXR emission and high efficiency of neutron flux registration. This type of neutron detector was employed to study FI confinement.

The co-NBI resulted in the central ion temperature increase from 180 to 350 eV during heating pulse (figure 1), the electron temperature $T_e(0)$ did not change as compared to the ohmic value at similar density. In order to model the effect of NBI heating on plasma parameters the transport simulations with ASTRA code [7] were performed. It was found that the shine-through losses are governed mainly by the plasma average density (figure 2), whereas the first orbit losses are mostly defined by the plasma current magnitude and its direction [8]. The simulations of absorbed, shine-through and orbit loss powers prove that density exceeding $2{\cdot}10^{19}$ m^{-3} is needed to minimize shine-through losses. These losses at average $n_e \geq 3{\cdot}10^{19}$ m^{-3} were found to be less than 5 % (figure 2). The simulation result was confirmed by neutron measurements.

The dependence of the neutron emission on plasma density was studied in the range of $(0.5\div3.5){\cdot}10^{19}$ m^{-3}. At densities lower than $2{\cdot}10^{19}m^{-3}$ large fraction of the fast particles are not captured in plasma because of shine-through losses and energetic ion charge exchange losses, so the increase in of n_e is followed by the neutron rate rise (figure 3). Density increase over $2.0{\cdot}10^{19}m^{-3}$ resulted in neutron flux saturation and further evolution of neutron flux depends weakly on plasma density. At any given values of plasma current and beam energy there is an optimal value of plasma density, at which FI losses reaches its minimal level. For I_p=145 kA and E_{beam}=19 keV the optimal density is $(2.0\div2.5){\cdot}10^{19}m^{-3}$. The $T_e(0)$ decreases during NBI at high plasma density (figure 1). The decrease in electron temperature results in increase in collision frequency between fast ions and electrons, this leads to the decrease beam of the slowing down time. It results in the neutron rate decrease. The summarized data are displayed in the figure 4. Neutron emission saturates at the high plasma density (higher than $2{\cdot}10^{19}m^{-3}$) and agrees with prediction of the simulations (figure 2).

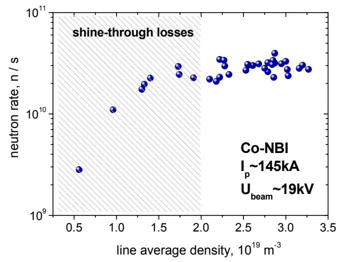

Fig. 4 Neutron emission as a function of the line average density

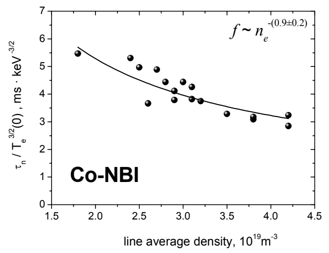

Fig. 5 Measured τ_n normalized to the electron temperature as a function of the line average density

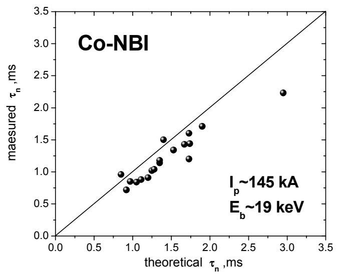

Fig. 6 Comparison of the experimental τ_n with calculated one

The e-folding decay time of neutron emission (τ_n) after NBI swith-off has been measured in the set of discharges; τ_n is the time while energy of FI is sufficient to produce fusion reactions. For the beam-target regime, where Coulomb interactions among the energetic ions can be ignored, the decay time τ_n is given by [9, 10]

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

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

where τ_{se} is the electrons slowing-down time, E_n is energy at which the fusion cross section is reduced by 1/e from value at the injection energy E_{beam} , and E_c is the critical energy at which the electron and bulk-ion contributions to the slowing-down rate are approximately equal.

Dependence of measured τ_n on plasma density is shown in the figure 5. This dependence indicates that the fast-ion slowing down process has essentially the classical variations with $n_e(0)$ and $T_e(0)$.

Measured decay time was compared with the one calculated assuming classical slowing down (see Eq. (1)). Figure 6 shows the relation between the predicted and observed values of τ_n. The measured values are slightly less than the predicted values, with the deviation tending to increase at larger τ_n.

Summary

Temporal evolution and the absolute value of the rate of 2.5 MeV D-D neutrons in the range $10^8 \div 10^{12}$ n·s^{-1} were measured by two ^{3}He filled neutron detectors with 0.1÷0.5 ms time resolution. The detectors has low sensitivity to HXR emission and high efficiency of neutron registration (~5%).

The dependence of neutron rate on plasma density in the experiments with deuterium neutral beam injection into deuterium plasma was studied on the TUMAN-3M.

FI confinement time was estimated from the decay time of neutron fluxes after NBI switch-off. Dependence of measured τ_n on plasma density indicates that the fast-ion slowing down process has essentially the classical variations with $n_e(0)$ and $T_e(0)$. The good agreement of the measured and calculated decay times suggests the absence of anomalous FI losses.

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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