Plasma heating and neutron production in the TUMAN-3M

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Introduction

The idea of a powerful neutron source based on a compact tokamak, where plasma is heated by injection of a neutral beam of energetic particles, is widely discussed [1, 2, 3, 4, 5]. In a compact tokamak, where both a tokamak size and a value of magnetic field are relatively small, the enhanced beam power losses may take place. The additional beam power losses can occur during thermalization of fast ions in plasma. In recent experiments of D-injection into D-plasma on TUMAN-3M an investigation of direct fast particles losses and their losses during thermalization was carried out by means of two diagnostics: neutron flux diagnostic [6] and neutral particle diagnostic, which includes two analyzers of charge-exchange atoms ACORD-12 and CNPA-07 [7, 8]. The results of the modeling of the neutron flux intensity obtained with ASTRA and NUBEAM code [9, 10] are presented. While increasing the beam power some additional beam power losses associated with the beam attenuation during transportation into plasma were detected. To improve the conditions for the transportation of the beam into the plasma a new beam connecting duct of large cross-section was built. The experiment showed that the use the new connecting duct results in the increase of neutron rate $R_n$ up to 60%.

Experiment

A new IS-1 ion source was installed as a part of the plasma injection research program to study parametric dependence of the neutron yield on main plasma and beam parameters. IS-1 power exceeds the power of the former IS-2 ion source by almost twice at the same beam energy $E_b$. It should be noted that IS-1 have emission surface area larger than that of IS-2. In the first experiments, where IS-2 was used, it was found that with increasing $E_b$ a saturation of ion temperature $T_i$ at the beam energy above $E_b = 19$ keV took place. A slowing down of neutron flux rate $R_n$ with increasing $E_b$ was also observed [11]. However, modeling of the neutron flux intensity $R_n$ with ASTRA and NUBEAM codes showed that $R_n$ should grow in a wide energy range $E_b$ from 12 to 30 keV. Operation of the more powerful ion source IS-1 aggravated the situation. Instead of the predicted twofold increase, the value of $R_n$ in the experiment was even lower than one obtained with less powerful IS-2 ion source [11]. An
absence of the expected doubled $R_n$ after the replacement of IS-2 by IS-1 can be explained by a growth of effective charge $Z_{eff}$ and also by a dilution of the background plasma ions by the fast ions. It was also suggested that the power of the neutral beam obtained by IS-1 is attenuated when it passes inside the connecting duct between the injector and the tokamak, since the cross-section of the connecting duct was slightly smaller than size of the beam. Simulation of 20 keV beam attenuation during its transportation through the old connecting duct predicts significant losses in the beam power up to 20-50%.

In order to estimate the effect of reconstruction of the connecting duct on the beam power attenuation the neutron flux rates were compared in the experiments with the old and the new connecting ducts. The parameters of the plasma and the injection beam were the same in both cases. Figure 1 shows the time evolution of $R_n$ for the old and the new connecting ducts. In both cases, the IS-1 ion source was used. The experiment showed that the use of new connecting duct led to an increase in $R_n$ by 60%, which agrees well with the results of the simulation.

With the new connecting duct and use of IS-1 ion source the dependence of $R_n$ on $E_b$ was measured. In figure 2 the experimental $R_n$ in comparison with results of NUBEAM and ASTRA code modeling are shown as function of $E_b$. Good agreement of the experimental data and simulations is observed in the range below $E_b = 20$ keV. Further increase of the beam energy results in a deficit of the neutron flux growth in comparison with the model prediction.

Additional information on the capture of the beam fast ions and their thermalization in plasma was obtained from the measurements of spectra of charge-exchange atoms. Results of such measurements performed earlier with old (narrow) connecting duct for the beam energy $E_b = 10.8$ keV and $E_b = 18$ keV were presented in [11]. Those experiments demonstrated a noticeable deficit of fast atoms in the energy range of 5–10 keV for $E_b = 18$ keV in comparison with $E_b = 10.8$ keV. The difference could be explained either by a blocking of the neutral beam in the connecting duct or by an enhanced ion orbit losses in the case of IS-1 operation at increased energy. Results of the recent experiments with IS-1 performed with the
new connected duct at beam energy $E_b = 12.5$ keV and $E_b = 20$ keV are shown in figure 3. The experiment demonstrated that the relative behavior of charge-exchange atoms spectra for the two energies $E_b$ corresponded to the theoretical prediction. Temporary evolution of $R_n$ in discharges with different value of initial beam energy $E_b(0)$ was shown in figure 4.

An unexpected result was obtained when measuring the ion temperature $T_i$ for the two beam energies $E_b = 12.5$ keV and $E_b = 20$ keV. In the both cases $T_i$ increased by 110 eV up to 330 eV. This ion temperature behavior is surprising. Discussions are continued. An increase of the sawtooth oscillations amplitude of central electron temperature $T_e(0)$ at $E_b = 20$ keV in comparison with $E_b = 12.5$ keV was observed. $T_e(0)$ was monitored by soft X-ray detectors.

The influence of the horizontal displacement of plasma column on the efficiency of fast beam particles capture was also investigated. Comparison of the charge-exchange atoms spectra measured at different horizontal plasma positions demonstrated a small difference in their shapes (see figure 5). This indicates a similar thermalization conditions, independently on plasma position. The main difference in the spectra is in absolute values of charge-exchange atom fluxes. The inward shift also led to change in neutron rate $R_n$. Figure 6 shows dependence of $R_n$ on horizontal plasma position. The electron temperature slowly grew with increasing displacement of the plasma column inward. A similar behavior of the electron temperature and the neutron flux was also observed with an old connecting duct and a low-power ion source IS-2 [12]. Thus, the growth of the neutron flux and the charge-exchange atom fluxes with increasing shift of the plasma column towards the interior may be caused by an increase in the thermalization time of fast ions.

Summary
In this paper, we have presented experimental results on plasma heating and neutron yield where a new, more powerful, ion source was used. To improve conditions of the transportation of a powerful beam, a new connecting duct was made with two-fold increase cross-section compared with the old connecting duct. As a result, the gain in the neutron yield was increased by 60%. Surprisingly small rise in T_i was found after E_b was increased from 12.5 keV to 20 keV.

Good agreement of the experimental data and simulations is observed in the energy range below E_b = 20 keV. Further increase of the beam energy results in a slowing of the neutron flux growth in comparison with the model prediction.

It was found that plasma shift inward leads to increase in the flux of neutrons owing to an improvement of conditions for capture of fast ions, slowing of the fast ions thermalization on electrons (due to an increase in electron temperature), and reduction of the impurity content. The detected increase in fluxes of charge-exchange atoms is connected with an increase in the quantity of fast ions and, to some extent, with an increase in the density of the neutral target.

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References:

5. B.V. Kuteev et al, 2017, Nucl. Fusion, 57, 076039
11. V.A. Kornev, L.G. Askinazi, A.A. Belokurov et al., Nuclear Fusion, 57 (2017), 12, # 126005, DOI: http://dx.doi.org/10.1088/1741-4326/aa7d13