Assessment of Neutron Production in Neutral Beam Injector of TCV Tokamak

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Abstract. Neutral beam (NB) injector for the TCV tokamak has been designed to produce a deuterium beam with energy 30 keV, equivalent current up to 50 A, and pulse duration 2 s. The injector operation is accompanied by generation of fast neutrons produced in deuterium-deuterium collisions via a nuclear fusion reaction D(D,n)3He. Main sources of the neutrons are a beam neutralizer and a deuterium-saturated surface of beam dump. Measurements of the neutron yields from the both sources were produced on the prototype of TCV injector in the Budker Institute of Nuclear Physics. Neutron yields from neutralizer and beam dump are equal to $9.5x10^8$ s^{-1} and $2.3x10^9$ s^{-1} for the nominal parameters of the injector (30 kV, 50 A).

INTRODUCTION

Powerful beams of hydrogen or deuterium atoms (neutral beams) are widely used for plasma heating in fusion facilities [1-5]. Neutral beam (NB) injector for the TCV tokamak has been designed to produce a deuterium beam with energy 30 keV, equivalent current up to 50 A, and pulse duration 2 s [6-7]. The injector operation is accompanied by generation of fast neutrons produced in deuterium-deuterium collisions via a nuclear fusion reaction $D(D,n)^3He$. Monoenergetic neutrons with energy of 2.45 MeV, which are produced in this reaction, may represent a biological hazard. This study is aimed at the neutron flux estimate and assessment of the corresponding levels of radiation exposure during the beam operation.

Another motivation for the study of neutron production is concerned with development of linear magnetic traps for fusion. Up-to-date projects of linear trap - based fusion facilities, such as neutron source for material testing [8-10] or fusion-fission reactor [11-13], are based on the injection of powerful neutral beams with energies 30-60 keV to target plasma. Since NB injectors are intended to place outside main neutron shield of the facility, the level of neutron radiation from the injectors should be estimated for safety provision. This is especially important in the case of injection of mixed deuterium-tritium beams, proposed recently for decreasing of tritium consumption and overall cost of the facility.

There are two major neutron sources in the NB duct, except less important ones like the beam scrapers and the electrodes of the ion optical system. These the most important are a beam neutralizer and deuterium-saturated beam dumps. In the injector, initially formed ion beam is neutralized via charge exchange in a gas coming out from the ion source to the neutralizer. Neutron yield from the neutralizer can be easily estimated using known beam energy and

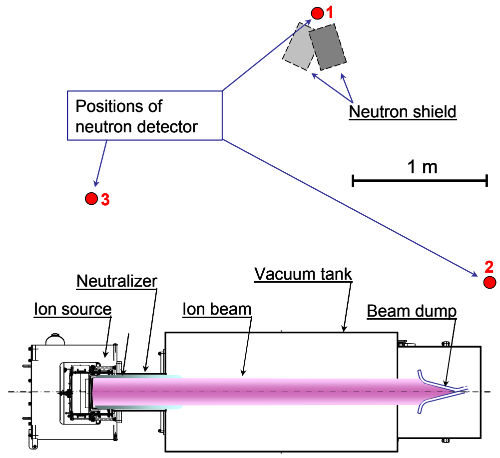

FIGURE 1 Scheme of experimental setup (top view)

current and measured or calculated value of deuterium line density $\langle n_{tar} l \rangle$. On the contrary, deuterium density in the target surface layer $\overline{n}_D$ and, accordingly, neutron yield from the beam dump depends on the properties of subsurface layer, that can't be predicted exactly because of strong modification of the target material by ion irradiation. So experimental measurement of neutron yield is required for assessment of neutron production in ion beam dump.

EXPERIMENTAL SETUP

Measurements of neutron yield were performed on the experimental testbed at the Budker Institute, Novosibirsk. Scheme of the testbed is shown in Fig.1. Ion source of TCV injector and beam dump unit were mounted on the opposite ports of vacuum tank. The tank equipped by integrated cryogenic pump with pumping rate 80 m^3/s. The ion source produced a deuterium beam with energy up to 28 keV and current in the range of 10-50 A. Due to presence of deuterium molecular ions in the plasma emitter the ion source, the beam composed of several fractions of particles with energies equal to full, half, and one-third of accelerating voltage. The ratio of fluxes of different fractions, measured by Doppler Shift Spectroscopy system [14-18], was $F_E / F_{E/2} / F_{E/3} = 0.5/0.3/0.2$, that corresponds to the relative current of full energy ions equal to $I_F=0.7 \cdot I$. Deuterium gas, puffed to a plasma emitter of the ion source, outflows via ion-optical system to neutralizer cell, and then was captured in the cryopump of the vacuum tank. Expected deuterium line density in the neutralizer was in order of $10^{15}cm^{-2}$.

The TCV injector is equipped by a separating magnet, which deflects residual ions after neutralizer to a special collector. The separating magnet was not engaged in these experiments allowing the beam of non-neutralized ions and neutrals impinging the beam dump. Thus, the interpretation of the results was more straightforward since the residual

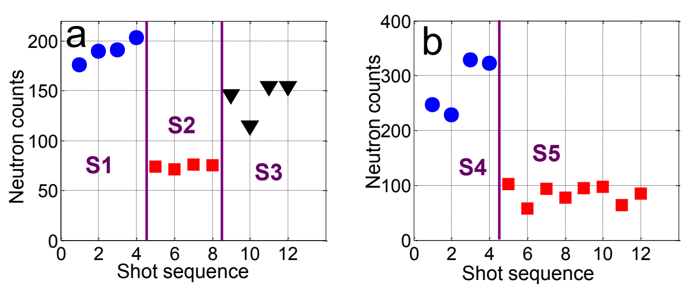

FIGURE 2 Determination of an origin of the neutrons. a) – experimental run with a neutron shield, S1 – unshielded detector, S2 – detector is shielded from beam dump, S3 – detector is shielded from neutralizer; b) – measurements with different positions of the detector, S4 – detector in the position 2 (see Fig.1) near beam dump, S5 – detector in the position 3 near neutralizer.

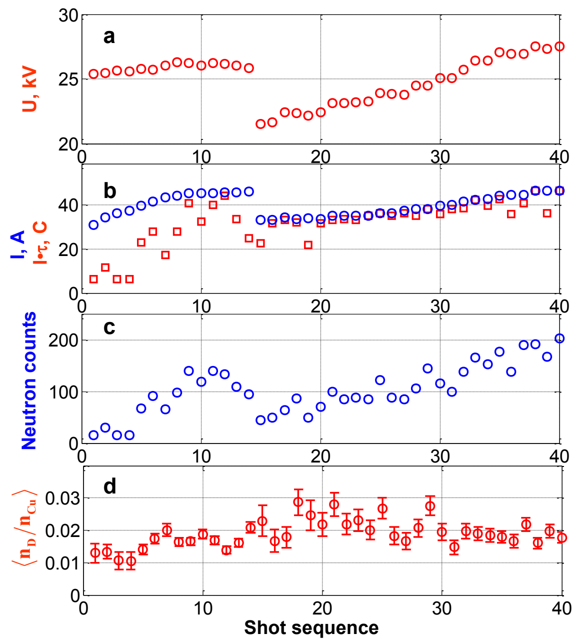

FIGURE 3 Beam parameters and relative neutron yield for one-day shot sequence, a) beam voltage; b) circles - beam current, squares – beam charge integrated over shot duration; c) number on neutrons detected by the counter during the shot; d) estimated relative concentration of deuterium in the bulk of copper beam dump plates.

ion collectors were not irradiated and the beam dump was the dominant source of neutrons. The beam current density on the beam dump was higher compared with standard operation, because the residual ions were not deflected. Therefore, the measurements were done with the pulse duration limited to 0.3 s to avoid occasional overheating and melting of the beam dump surface.

Neutron flux was measured by scintillation counter with digital neutron/gamma discrimination [19-20]. The counter consists on the cylindrical stilbene crystal 30 mm in diameter and 30mm long, PMT Hamamatsu R6231-100 and a fast ADC with digital processing unit. Apart from primary neutrons from the area of neutron generation the stilbene scintillator can detect neutron-inducted gamma rays, multiple scattered neutrons, and muons of cosmic ray background. Discrimination of neutrons from the background by scintillation pulse shape analysis is used for provision of spatially-resolved measurements and prevention of overestimation of a neutron flux.

NEUTRON FLUX EVALUATION

Two special experimental runs were performed for determination of an origin of neutrons. Beam parameters in every run was kept close to constant. A number of neutrons counted by the detector during a pulse of injector were shown in Fig.2. In the first run the detector was sequentially shielded from neutrons born in the neutralizer and beam dump by 30-cm-width paper block with calculated neutron shielding efficiency about 90% (Fig.2a). In the second experimental run the counter was moved to positions 2 near beam dump and position 3 near neutralizer (Fig.2b). Both these experiments shown that neutrons is predominantly produced in the beam dump.

In the bulk of the measurements the neutron counter was placed in the position 1 (see Fig.1). Number on neutrons counted during the shot along with shot parameters is shown in Fig.3 for one experimental day.

Two-parameter model of neutron production is used for quantitative comparison of neutron production in the beam dump and the neutralizer. Experimental data from two-day measurements, that include above-mentioned special runs, were fitted by the model function:

$$F_Y = \eta_1 \cdot 9.28 \cdot 10^{-14} \cdot U^{3.5} \cdot I_F \cdot \tau \cdot \frac{S_0}{4\pi L_1^2} + \eta_2 \cdot 1.63 \cdot 10^3 \cdot U^{4.3} \cdot I_F \cdot \tau \cdot \frac{S_0}{4\pi L_2^2}, \qquad (1)$$

where η_1, η_2 - free parameters of the model, corresponding to line density of deuterium in the neutralizer η_1= $\langle n_{tar}l \rangle$ and mean relative concentration of deuterium in the beam dump η_2=$\langle n_D/n_{Cu} \rangle$; s_0 – effective area of the counter (0.4 cm^2); U, τ - mean accelerating voltage and shot duration, I_F=0.7·I current of full-energy ions, L_1 and L_2 – distances from the counter to neutralizer and beam dump. The coefficients and accelerating voltage dependence in the model function were derived from DD reaction cross-section integration over trajectory of deuterium ions in the gas target and copper beam dump [21].

RMS fitting of experimental data by the model function gives the follows values of the parameters: $\langle n_{tar}l \rangle$=1.98±1.2 ×10^{15} cm^{-2}, $\langle n_D/n_{Cu} \rangle$=1.80±0.48 ×$10^{-2}$ (errors here means standard deviation of corresponding variable rather than accuracy of estimation of its expectance). Neutron yields from neutralizer and beam dump are equal to 9.5×10^8 s^{-1} and 2.3×10^9 s^{-1} for the nominal parameters of the injector (30 kV, 50 A).

Variation of measured points from model prediction is shown in Fig.4. As seen from this figure, this variation (between-group variability) exceeds statistical variation (within-group variability). In other words, the model is not complete experimental data and there are shot-to-shot changes of the parameters values.

We will assume that line density of deuterium gas in the neutralizer stay constant, and the data variation is result of variability of deuterium concentration in the beam dump. The reason of such assumption is that the first parameter is fully controlled by experimental equipment, instead of the second one, which depends on the processes in the beam dump surface. Based on this assumption, it is possible to estimate mean deuterium concentration in the beam plate for every shot. Shot-to-shot behavior of this concentration is shown in Fig.3d. Only moderate sequential change of the concentration is observed, without marked dependence from beam voltage, current, or shot duration. This change lies in the range ±50% for all shots with two times (0.7 - 1.4 MW) varied beam power and six times (from 50 to 300 ms) varied pulse duration.

SUMMARY AND DISCUSSION

Estimated neutron production yield in the nominal regime of TCV NB system operation (30 kV, 50 A) is about 3×10^9 s^{-1}. Neutrons are generated in the beam neutralizer and beam dump, neutron yield from the beam dump approximately two times exceed neutron yield from neutralizer. Mean relative concentration of deuterium atom in the surface of copper dump is about $\langle n_D/n_{Cu} \rangle \approx 0.02$. This concentration remained practically constant during experimental run; despite on sufficient changes in acceleration voltage, beam current density and pulse duration. Stationarity of deuterium concentration in the beam dump and its independence on beam current and voltage, observed in the experiments, are in contradiction with expectations, based on idealized model of deuterium retention in copper, that predict strong dependence of deuterium retention from surface temperature, and, consequentially, beam parameters. One possible explanation of this contradiction is capture and accumulation of deuterium in radiation-induced traps with high bonding energy, the amount of which is determined by the processes of radiation damage and annealing of defects.

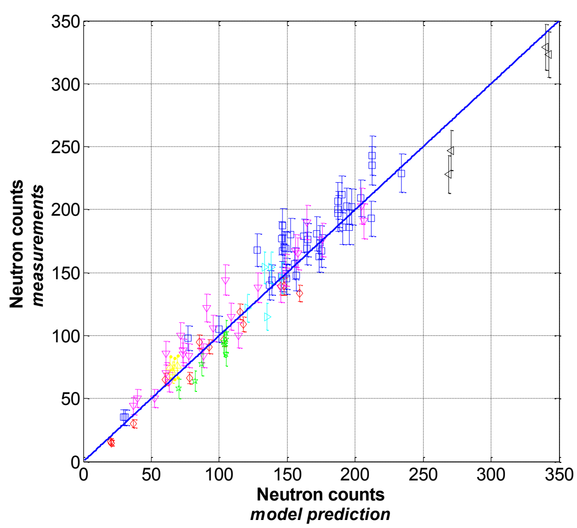

FIGURE 4 Comparison of predictions of the model of neutron yield model with measurements, different symbols correspond to different runs of measurements

ACKNOWLEDGMENTS

This work was supported by Russian Science Foundation (project 14-50-00080).

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