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ABSTRACT.

The neutral particle analyzer ISEP (Ion SEParator) NPA [1] was applied to measure the tritium neutral flux during Tritium Trace Experiment (TTE) on JET [2]. The energy dependence (in the 5 – 28 keV energy range) of the tritium neutral flux rise time after a short ~ 100 ms tritium gas puff into deuterium plasmas has been observed for the first time. The dependence has been interpreted as being due to the penetration of the tritium ions from the plasma boundary into the core and has been used for the calculation of the tritium diffusion coefficient and convective velocity values.

1. INTRODUCTION

Study of the ion particle transport in high-temperature plasmas is one of the most important areas of research towards the fusion reactor. However, notwithstanding all the progress in this area, some of the issues remain unclear. In particular the ion particle transport is of the greatest interest in the regimes with enhanced core confinement (internal transport barrier and optimized shear plasmas) – the regimes which are envisaged as one of the possible scenarios for the first fusion tokamak-reactor ITER [3]. The experimental determination of the ion transport coefficients is a complex problem. Diffusive and convective parts of the particle flux can not be separated by the analysis of the equilibrium density profiles. This difficulty can be overcome by perturbing the plasma density and examining the resulting plasma response [4]. The perturbation can be induced by sawtooth [5], neutral beam [6] or pellet injection [7], gas puffing [8]. The latter is one of the most widely used methods, because it allows to generate reasonably small density perturbations which at the same time are detectable. The perturbation can be further reduced and the sensitivity of the method increased if the puff is made of gases different from the bulk ions and the plasma response is detected by the diagnostics which signal is proportional to the puffed gas concentration.

Of the upmost interest in view of the particle transport studies of future thermonuclear plasma main components are the tritium trace (~1%) experiments (TTE) [9, 10]. To retrieve the information on the tritium behavior in such experiments the neutron cameras were widely used to detect 14 MeV DT neutron fluxes. Another possible method for tritium transport studies is the analysis of the tritium neutral fluxes measured by the NPA. Particularly in [11] the reconstruction of the minority density profile from the charge-exchange spectra shape was demonstrated and the requirements for the accuracy of the main plasma measurements and their influence on the reconstruction accuracy were formulated. In this paper we present the first results on the measurement of the tritium transport coefficients, performed by the analysis of the tritium neutral spectrum evolution in JET discharges with tritium puffing into deuterium plasmas [2].

2. EXPERIMENTAL SETUP

The ISEP neutral particle analyzer was used to measure the tritium atomic fluxes [1]. Several unique features of ISEP NPA make it well suited for the measurements in TTE plasma scenario. The analyzer provides the simultaneous measurement of all the hydrogen isotope neutral fluxes (H^0, D^0,

T^0) in the thermal energy range, has low sensitivity to the background radiation ($\leq 10^{-7}$ cm^2/n), high detection efficiency for the neutral particles (~0.03 for E_T = 5keV and ~0.1 for E_T = 28keV) and good mass resolution (suppression of neighbour D^0 and T^0 masses is better than 1000). Moreover, the pulse height analysis implemented in ISEP preliminary data acquisition system allows separating the actual signal from the noise by pulse height analysis. These characteristics of the analyzer ensure the satisfactory counting rates while measuring relatively low neutral fluxes of a certain isotope in the presence of the ten-hundredfold more intensive fluxes of another isotope and a large radiation background.

The experimental layout of the diagnostic is shown in Fig.1. ISEP NPA (KR2) is located in the Octant 3 of JET tokamak. The NPA is installed 28cm above the tokamak mid-plane and its line of sight views the plasma centre in the horizontal direction. The neutron cameras (KN3) used for the tritium transport study and components of the additional plasma heating system (neutral beam injectors, ICRH antenna) are also shown in the figure. Tritium was introduced by the gas puffing valve GIM15 through the equatorial port of the Octant 6.

The time traces of the main plasma parameters of the typical TTE scenario discharge (optimized shear plasma, Pulse No: 61161) are presented in Fig.2. Neutral beam heating power P_{NBI} was about 15MW, ion-cyclotron heating power P_{IC} used together with NBI to sustain the optimized shear configuration of the plasma was about 2MW. The central electron density reached the value of $n_e(0) \sim 4\times10^{19}$ m^{-3}, the electron temperature $T_e(0) \sim$ 7keV, and the ion temperature $T_i(0) \sim$ 12keV. At the time t = 10.4s the tritium was puffed into the plasma. Puff duration was equal to 100ms, the total amount of the tritium introduced into the plasma was $\sim 2.8\times10^{20}$ particles. Rate of 14MeV DT-neutrons reached the value of $R_{dt} \sim 4\times10^{16}$ neutrons/s with the total neutron rate $R_n \sim 5\times10^{16}$ neutrons/s. Nevertheless this tritium puffing did not disturb the plasma significantly because no noticeable change of the global plasma parameters such as density and temperature was observed.

3. EXPERIMENTAL RESULTS

The typical time evolution of deuterium and tritium neutral fluxes (energy of atoms ~15keV) measured by ISEP NPA in JET shots with a small tritium puff is shown in Fig.3. During the puff the behavior of the deuterium time trace does not change, but the tritium flux rapidly increases and then gradually diminishes to the initial level.

It is important to notice that the tritium signal detected by the analyzer can be impaired by the gamma and neutron emissions, which can change abruptly during the tritium puff (see Fig.2). The influence is reduced by the abovementioned pulse height analysis of the signal pulses arriving from the ISEP NPA detectors (see section 2). For example, in Fig.4 the amplitude spectra of the deuterium and tritium signals for E_D = 18.9keV and E_T = 9.4keV energy channels of the analyzer, integrated over (10.5−11.5) s time interval, are presented. It can be seen that by setting the lower threshold of the detection to 25th, ADC channel one can reliably separate the valid signal (Gaussian-like distribution around 40th channel) from the low-amplitude noise (exponentially dropping distribution from 12th to 25th ADC channel).

Shown in Fig.5 is the main experimental result obtained during the study of the tritium neutral flux response to the tritium gas puffing. For the first time in experiments of such a kind, the energy dependence of the neutral fluxes rise time has been detected. Such behavior of the neutral fluxes can be due to the two physical processes: gradual heating of tritium ions and/or penetration of the tritium ions from the plasma boundary into the core.

In the first case, after the puffing and ionization of the tritium gas, a cold fraction of the tritium ions is formed inside the plasma with temperature much lower than the temperature of the bulk ions. Charge-exchange of these ions will lead mainly to the formation of neutral fluxes of the lower energies. Then, as tritium ions heat up, more energetic neutral fluxes arise. To evaluate the input from this process, the time needed by the cold tritium ions to reach the temperature of the thermal deuterium has been estimated. For parameters of the selected plasma shot ($n_D(0) = 4\times10^{19}$ m^{-3}, $T_D(0) = 12$keV) this time is about 30ms, which is considerably less than the characteristic time of the tritium neutral flux evolution (200–400ms). Thus, in further analysis it was considered that the observed dependency is induced mainly by another process – the penetration of the tritium ions into the plasma.

In this case the explanation is as follows. Neutral particle fluxes of the higher energy range come from deeper regions of the plasma. On the one hand, this is due to the ion temperature usually being peaked in the center; on the other hand the plasma transparency is better for the atoms of higher energies. A combination of these two factors leads to appearance of a maximum in the probability of the atoms to leave the plasma (so called atomic emission function) at a certain radius. Moreover the position of this maximum depends on the neutral particle energy. In particular, in Fig.6 the results of the calculation of the neutral tritium emission function profiles at different tritium energies are shown. It is seen from the figure that 5keV neutral fluxes carry information on the peripheral r ~ (0.7–0.9)a plasma area, while the faster particles with the energy of 28keV - on deeper area, closer to the plasma center r ~ (0.2–0.6)a. After the puffing and ionization of the initial tritium gas, the secondary tritium ions slowly penetrate from the boundary to the center rapidly heating up to the surrounding plasma local temperature. The rise of the tritium density in the hotter but deeper regions of the plasma is slower than in the peripheral region. This leads to a slower response of the high energy tritium neutral fluxes compared to the fluxes of the lower energies.

4. RESULTS OF MODELING

DOUBLE code has been applied to reconstruct the time evolution of the tritium ion profiles from the experimental data [12]. The code allows to model the neutral particle fluxes of the thermal energy range emitted by plasma itself or induced by the neutral beams. In our case in spite of the powerful enough neutral beam injection, the contribution of the beams into ISEP NPA signal appears to be negligible, obviously due to the long distance from the neutral injectors to the line of sight of the analyzer. Besides, to exclude the influence of the tritium gas source from the modeling, we have chosen (10.9–11.4s) as the time interval after the switching off the tritium gas valve when the tritium fluxes decay have been observed.

For qualitative interpretation of the tritium transport a simple model has been used, where the radial flux of the ions is a sum of the diffusive and convective terms:

$$\Gamma = -D\frac{\partial n}{\partial r} + Vn$$

where – is the ion radial flux, n is the ion density, D is the diffusion coefficient and V is the convective velocity. In the model it has been assumed that plasma has an elliptic shape, that the D and V transport coefficients are constant over the plasma radius and no toroidal effects have been taken into account. The experimental tritium ion profiles reconstructed from the measured tritium neutral fluxes are shown in Fig.7 for the three time points t = 10.9s, 11.1s and 11.4s. It should be noted that a good agreement of the time evolution of the profiles with the neutron diagnostic data was pointed out before [13]. The solid lines show the best fit to the experimental data in the frame of the model. The following values of the transport coefficients have been obtained from the fit: the convective velocity is equal to V = –0.5 m/s, where the negative sign indicates an inward pinch, and the diffusion coefficient is equal to D = 0.1 m^2/s, which is close to the neoclassical values of this parameter. The value of diffusion coefficient well agrees with the previous studies of the ion transport in hydrogen plasmas with deuterium puffing [11].

CONCLUSIONS

For the first time the energy dependence of the rise time of the neutral tritium fluxes in the experiments with a small tritium gas puffing into deuterium plasmas (Tritium Trace Experiment) has been observed. The dependency has been interpreted as a consequence of the tritium ions penetration from the plasma boundary into the core;

Time evolution of the tritium density profile has been reconstructed from the experimental tritium neutral fluxes;

In the frame of a simple diffusive model the values of the tritium ion transport coefficients have been obtained: the convective velocity is equal to V = – 0.5m/s and the diffusion coefficient is equal to D = 0.1m^2/s.

ACKNOWLEDGEMENTS

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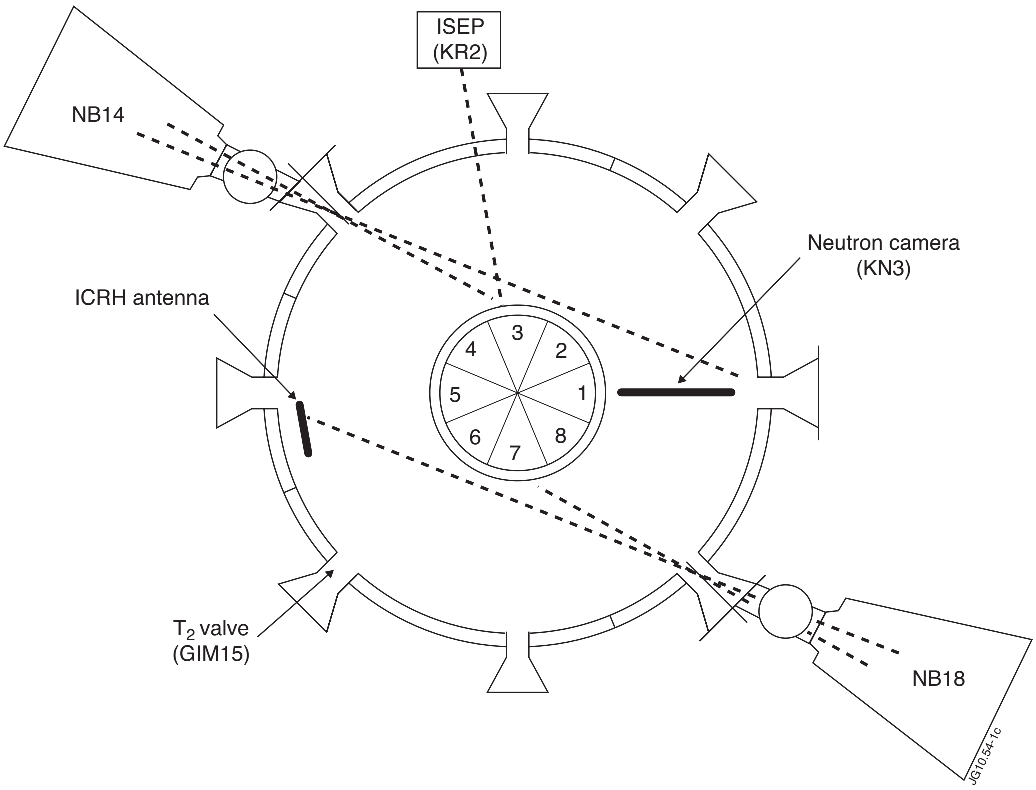

Figure 1: Experimental layout of the Tritium Trace Experiment (TTE) on JET: GIM15 is the valve for the pulse tritium gas puffing, ISEP (KR2) is the neutral particle analyzer, KN3 is the neutron camera (view area of the camera is shown in the figure), NBI4 and NBI8 are the neutral beams of the Octant4 and Octant8, respectively.

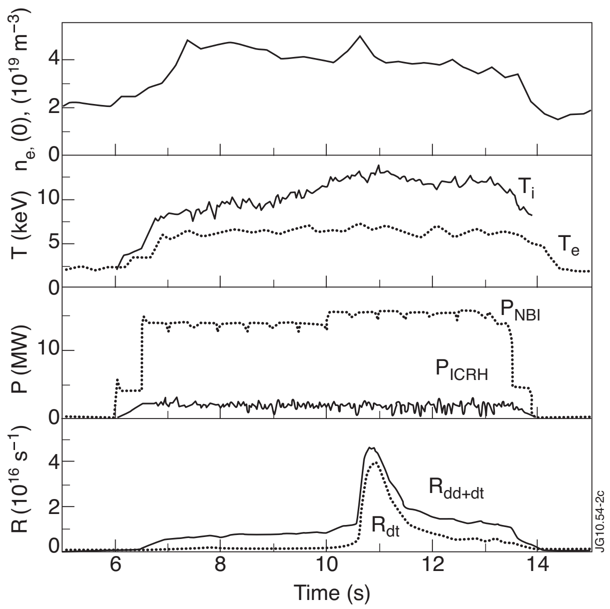

Figure 2: Temporal behavior of the main plasma parameters of the Pulse No: 61161: $n_e(0)$ is the central plasma density, T_i and T_e are the ion and electron temperatures, P_{NBI} and P_{ICRH} are the NBI and ICRH powers, R_{dt} and R_{dt+dd} are the DT neutron yield rate and the total rate of the DT and DD neutron yield.

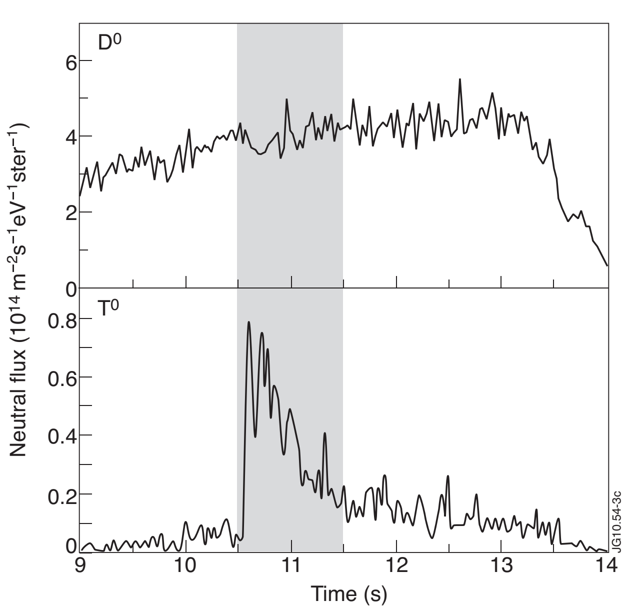

Figure 3:Time traces of the neutral fluxes of the deuterium (D^0) and tritium (T^0) measured with use of ISEP analyzer in plasma Pulse No: 61161. Tritium gas was puffed within the time interval 10.4 – 10.5s. The hatch area indicates the time interval† over which the pulse height distributions were collected.

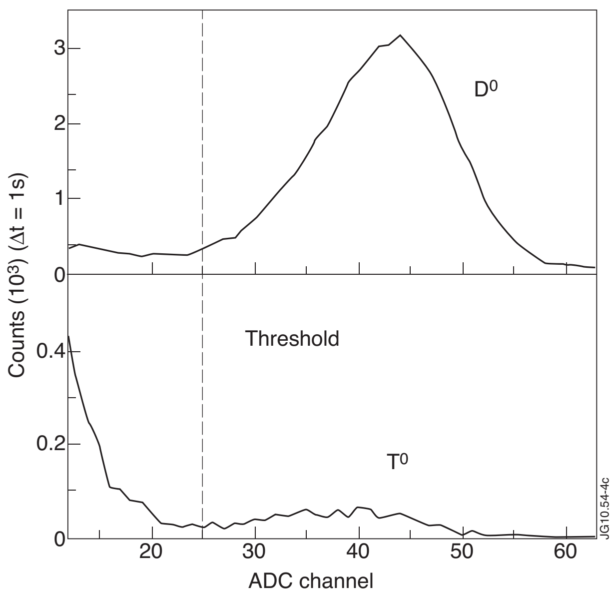

Figure 4: Pulse height distributions of the deuterium (D^0) and tritium (T^0) atoms measured in the analyzer energy channels E_D = 18.9 keV and E_T = 9.4keV, respectively.

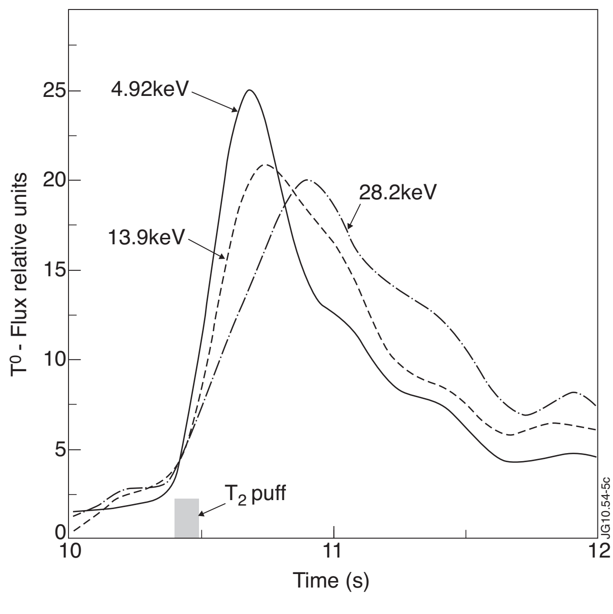

Figure 5: Time evolution of the tritium neutral fluxes of the different energies observed after the pulse tritium puffing into the deuterium plasma.

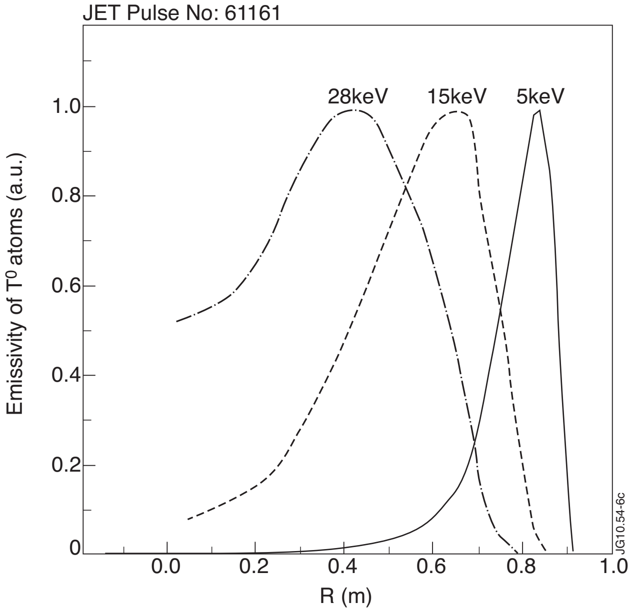

Figure 6: Radial dependence of the probability of the tritium atoms to escape from the plasma calculated for different energies (emissivity functions of the tritium atoms).

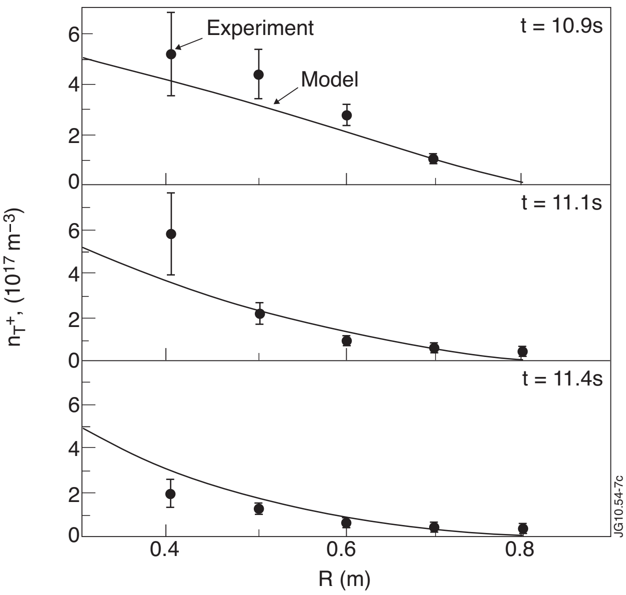

Figure 7: Time evolution of the density profile of the tritium ions reconstructed with use of the energy spectra of the tritium neutral fluxes in comparison with the modeling results.