EFDA–JET–PR(09)07

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** See annex of F. Romanelli et al, "Overview of JET Results",*
(Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).

Preprint of Paper to be submitted for publication in
Plasma Physics Reports

ABSTRACT.

A neutral particle analyzer [11] operating in the MeV energy range was used to measure a flux of tritium atoms emanating from the hot-ion H-mode deuterium plasma heated by the deuterium neutral beams, producing DD fusion tritons. We found that tritons of ~ 0.3–1.1MeV were largely neutralized by the beam atoms and the beam halo atoms. This enabled us to find the localized energy distribution function of the DD fusion tritons in the plasma bulk. Simulation of the triton energy distribution function showed that MeV ions in JET hot-ion H-mode plasma equilibrate classically.

1. INTRODUCTION

The discovery of high energy atomic hydrogen fluxes in JET plasmas [1, 2] has greatly stimulated Neutral Particle Analysis (NPA) in the MeV energy range on large tokamaks. This diagnostic was first successfully applied to study the formation of high energy ion tails in H/He_3-minority ICRF-heated plasma [3, 4, 5]. Later, the main efforts were focused on the fusion product confinement in a tokamak [6, 7, 8]. Of special interest is the fact that these measurements are directly related to the alpha-particle physics for the future fusion reactor [9], so NPA was introduced as one of the basic diagnostics for ITER [10].

In this paper we present NPA measurements of the energy distribution function of DD fusion tritons in hot-ion H-mode D-beam/D-plasma discharges. It has been found that fast tritons are mainly neutralized by the neutral beam and the beam halo neutrals. The contribution of impurity ions to this process appear to be rather small. Therefore, this experimental layout can provide a local spatial measurement and allow evaluation of the source volume of DD fusion tritons in the plasma bulk. The results obtained are compared with theoretical predictions.

2. TIME EVOLUTION OF A T^0 IN MEV ATOMIC FLUX

A flux of T^0 MeV atoms originating from DD fusion tritons was measured using a neutral particle analyzer described in [11]. The NPA was installed on top of the torus and its line-ofsight intersected the plasma bulk and the beam line of a neutral octant 4 injector [1].

Since a T^0 atomic flux has an extremely low intensity, we combined the data of six similar shots to get a reasonable statistics. A series of hot-ion H-mode deuterium NBI (D^O)-heated Pulse No's: 41646, 41653, 41656, 41657, 41658, 41659 ($B_t = 3.4T$, $I_p = 3.8MA$) was analyzed. The time evolution of the plasma parameters for one of the discharges is presented in figure 1.

For all the discharges, the power from the octant-4 injector was reasonably constant, lying in the range $P_{NBI4} = 8.2–9.7MW$ (ED-beam ~ 75keV).

Since the analyzer operates in intensive neutron and gamma radiation of the machine it is necessary to distinguish the particle signal from the induced noise. Figure 2 shows the typical pulse height distributions detected in energy channels 3 ($E_T = 480keV$) and 5 ($E_T = 720keV$) of the NPA, integrated over the six shots for the time interval Δt = 13.0 - 14.0s.

One can see well-defined particle signals peaked at the pulse amplitudes 10-12, which differ from neutron and γ-ray noise. Possible contamination of the signals by protons or by He_3 ions produced at the same d-d fusion reaction is considered to be negligible. The corresponding peaks of these particles should appear on the pulse height distributions around the pulse amplitudes 5-6. The absence of the peaks is not surprised. The proton signal is strongly rejected in the NPA by mass resolution [11]. In turn the neutralization probability of He_3^{++} ions in plasma is much less than the neutralization probability of hydrogen isotopes [3, 8]. Therefore we consider the detected particle signal as a pure tritium signal.

The time evolution of the T^O atomic fluxes of different energies is illustrated in figure 3 (upper half) with the time resolution Δt = 0.5s. One can notice a time delay of the flux maximum with decreasing energy which corresponds to the thermalization process of tritium ions.

The time for a steady state τ_{st} of the fluxes to be established can be estimated from the equation [16, 17]:

$$\tau_{st}(v) \approx \frac{\tau_s}{3} \ln \left(\frac{v_o^3 + v_c^3}{v^3 + v_c^3} \right) \tag{1}$$

where τ_S is the time of slowing down, v_o is the initial velocity of tritons in the DD fusion reaction and v_c is the critical velocity, at which the triton slowing down by electrons and ions becomes equalized. For the plasma parameters considered (see section 3), these times are equal to $\tau_S \sim 0.5$s for $E_T = 720$keV and $\tau_S \sim 1.3$s for $E_T = 380$keV and are found to be in good agreement with the experimental values of $0.75^{+/-0.25}$s and $1.50^{+/-0.25}$s, respectively. However, in spite of the continuous NBI heating phase up to t = 16.0s (see figure 1), the atomic fluxes started to decay within the time interval Δt = 13.0–14.0s, the exact time depending on the energy. In order to explain this phenomenon, we evaluated the combined parameter S_{To}, which is approximately proportional to the production rate of fast tritium atoms originating from the DD fusion tritons:

$$S_{T^0} \propto S_n ABS_{beam} ABS_{T^0} \tag{2}$$

where S_n is the DD neutron production rate and the coefficients ABS_{beam} and ABS_{To} correspond to the absorption of the neutral beam and T^0 atoms, respectively. Figure 3 (lower half) shows the time evolution of the combined parameter for tritons of energy $E_T = 380$ keV. Taking into account the time behavior of the neutron emission rate (see figure 1), we can conclude that the drastic decay of T^0 flux after t = 14.0s is largely due to absorption which, in turn, results from a continuous increase in the plasma density.

3. THE NEUTRALIZATION PROBABILITY OF FAST TRITONS

Charge-exchange spectrum of To atoms, integrated over the time Δt = 13.0–14.0s and averaged over the six shots is shown in figure 4. A number of charge-exchange processes should be taken into account to obtain the total neutralization probability for fast tritium ions. This is necessary to derive their energy distribution function from neutral particle measurements. The cross-sections of all the charge-exchange reactions which can make a contribution to the neutralization are presented in figure 5 [12, 13, 14, 3].

Calculations were made for the plasma parameters as follows: $n_{eo} = 3.5\times10^{13}$ cm^{-3}, $T_{eo} = 8$keV, $T_{io} = 7$keV, $Z_{eff} = 1.4$, $P_{NBI4,D} = 9.5$MW (the power ratios of the beam fractions are E1 / E2 / E3 = 0.83 / 0.13 / 0.04). The bare impurity ion densities in the plasma bulk were measured by charge-exchange recombination spectroscopy, with their average values for this series of shots being $n_{He}{}^{2+}/n_{eo} = 1.3\%$, $n_{Be}{}^{4+}/n_{eo} = 0.41\%$ and $n_C{}^{6+}/n_{eo} = 0.8\%$. A Monte-Carlo code procedure was used to calculate the density distribution of D^o beam halo atoms, whose contribution to the neutralization was found to be substantial (~80% of the average beam density). The densities of He^+, Be^{3+} and C^{5+} impurity ions produced by the neutral beam were evaluated using the approach described in [3, 15]:

$$n_{z-1} \approx n_z K_{Ro} \frac{\tau_{esc}}{\tau_{cx}} \tag{3}$$

where n_z is the density of bare impurity ions, $\tau_{esc} = \Delta l_{beam} / v_{z-1}$ is the time of H-like ion escape from the “active” volume. Δl_{beam} is the beam dimension along the toroidal field and v_{z-1} $(cm/s) = 1.6.10^6$ $[T_{z-1}\,(eV)/\,\pi/A]^{1/2}$ is the average velocity of the directed motion of ions with the temperature T_{z-1} and atomic weight A. The coefficient $K_{Ro} = 1/(1-exp(-2\pi R_o/\,\lambda)$ takes account of the species returning to the line-of-sight of the NPA running around the torus, where R_o is the major radius and λ is the mean free path of the species produced by absorption. The time for the charge-exchange reactions between the bare impurity ions and the beam and beam halo atoms τ_{cx} is given by the equation:

$$\tau_{cx} = \left(\sum_i <\sigma v>^i{}_{cx,beam}\, n^i{}_{beam} + <\sigma v>_{ex,\,alo} \int \frac{n_{halo}(l)dl}{\Delta l_{halo}} \right) \tag{4}$$

where $<\sigma v>^i{}_{cx,\,beam}$ and $<\sigma v>_{cx,\,halo}$ are the charge-exchange rates of He^{2+}, Be^{4+} and C^{6+} impurity ions reacting with the beam and beam halo atoms, respectively. Since the mean free path of He^+, Be^{3+} and C^{5+} impurity ions is much longer than the beam halo size $\lambda >> \Delta l_{halo}$, these ions have enough time to reach the line-of-sight of the NPA moving along the toroidal magnetic lines even if they are produced by the halo atoms far from the beam. Therefore, the total line integral of the halo distribution along the toroidal field (“l” is the appropriate coordinate) should be included in equation (4). Note that in infinite limits this integral yields a halo density from a simple ion balance $\int n_{halo}(l)dl/\,\Delta l_{beam} = {}_i\Sigma <\sigma v>^i{}_{cx,\,beam} n^i{}_{beam} / <\sigma v>_{ie}$ where $<\sigma v>^i{}_{cx,\,beam}$ is the charge-exchange rate between the bulk deuterium ions and the beam atoms, $<\sigma v>_{ie}$ is the electron ionization rate of He^+, Be^{3+} and C_{5+} ions. A summation is made over the different beam energy fractions.

Thus, the total neutralization probability of tritons can be defined as:

$$\begin{aligned} P_{tot}(E_{T^+}) = v_{T^+} [\sum_i n^i{}_{beam}\, \sigma^i{}_{cx,beam}(E^i{}_{rel}) + n_{halo}\, \sigma_{cx,halo}(E_{T^+}) + n_{He^+} \sigma_{cx,\,He^+}(E_{T^+}) \\ + n_{Be^{3+}}\, \sigma_{cx,\,Be^{3+}}(E_{T^+}) + n_{C^{5+}}\, \sigma_{cx,\,C^{5+}}(E_{T^+})] \end{aligned} \tag{5}$$

where σ_{cx} are the charge-exchange cross-sections for tritons interacting with D^o_{beam}, D^o_{halo}, He^+ Be^{3+} and C^{5+} particles and E^i_{rel} is the energy of relative motion of the beam atoms and the tritons, $E^i_{rel} = E_{beam} + E_T^+$ (the beam line is normal to the NPA line-of-sight); finally, n_{halo} means the beam halo density within the area scanned by the NPA. The energy dependence of the neutralization probability of all the species is presented in figure 6. It is seen that the most significant contribution to the neutralization of DD fusion tritons is made by the neutral beam and the beam halo neutrals. So this case is very close to the classical "active" charge-exchange diagnostics (with use of a neutral beam). The localization of the charge-exchange target primarily depends on the experimental layout and the beam halo size. We have estimated the spatial resolution here to be approximately ± 30cm.

4. THE ENERGY DISTRIBUTION FUNCTION OF DD FUSION TRITONS

The calculated neutralization probability can be further used to derive the energy distribution of tritium ions from the measured charge-exchange spectrum $d\Gamma_{T^o}(E)/dE$ given in figure 4. This can be done using the equation:

$$f_{T^+,NPA}(E) = 4\pi P_{tot}^{-1}(E)\,\frac{d\Gamma_{T^o}(E)}{dE} \qquad (6)$$

The distribution function is presented in figure 7, along with the isotropic distribution function predicted by theory for the classical slowing down of tritons [16, 17]:

$$\begin{aligned} f_{cl}(E) &= f_0\,\frac{3}{2\ln\left[1+\left(E/E_c\right)^{3/2}\right]}\,\frac{E^{1/2}}{\left(E^{3/2}+E_c^{\,3/2}\right)},\ E \le E_0 \\ f_{cl}(E) &= f_{cl}\,exp\left(-\frac{E-E_0}{\left(T_i E_0\right)^{1/2}}\right),\ E > E_0 \end{aligned} \qquad (7)$$

where E_o and E_c are the birth energy for the DD fusion reaction and the critical triton energy, respectively. The coefficient f_o in the former equation defines the production rate of DD fusion tritons. We have found this parameter from the experimental data on the DD neutron emission rate and define it as $f_o = S_n\,\tau_{se}/V$, where V is the average source volume of DD tritons. In the series of discharges presented, the contribution of DD neutrons is about 75% of the total neutron yield. Within the time interval considered, $\Delta t = 13.0-14.0$s, the DD neutron emission rate is $S_n \sim 6\times10^{15}$ n/s and the slowing time is $\tau_{se} \sim 1.6$s.

The volume V is a free parameter to fit the theoretical distribution function to the experimental one. The best fitting is shown in figure 7 by a dashed line and corresponds to $V \sim 20\text{m}^3$ which is about 20% of the total plasma volume. This value is comparable with that evaluated from measured neutron emissivity profiles and is found to be quite reasonable, because most of the tritons in this case are produced by interaction between the slowing beam ions and the bulk plasma ions.

Consequently, the source volume of tritons appears to be primarily determined by the neutral beam length and confinement of the beam ions rather than by the ion temperature and the density profiles.

SUMMARY

- A flux of T^o MeV atoms originating from DD fusion tritons was measured in hot ion H-mode Dbeam/D-plasma discharges;
- The neutralization target for fast tritons is found to be determined mostly by the neutral beam and the beam halo neutrals. Thus, a neutral particle analyzer allows local measurements to be made in the plasma bulk with a spatial resolution equal to ± 30cm;
- The deduced energy dependence and the time behavior of the distribution function of DD fusion tritons are found to agree well with the theoretical predictions;
- The average source volume of DD fusion tritons is evaluated to be about $20m^3$ (20% of the total plasma volume), which is comparable with that obtained from the measured neutron emissivity profiles.

ACKNOWLEDGEMENTS

The authors are grateful to M. von Hellermann and M.Tunklev for the analysis of CX spectroscopy data on bare impurity densities and to N. Jarvis and P. van Belle for the analysis of neutron emissivity profiles and discussions of the results. We also thank to P. Morgan for a careful reading of the paper and helpful suggestions. This work, supported by the Wuropean Communities under the contract of Association between EURATOM/UKAEA was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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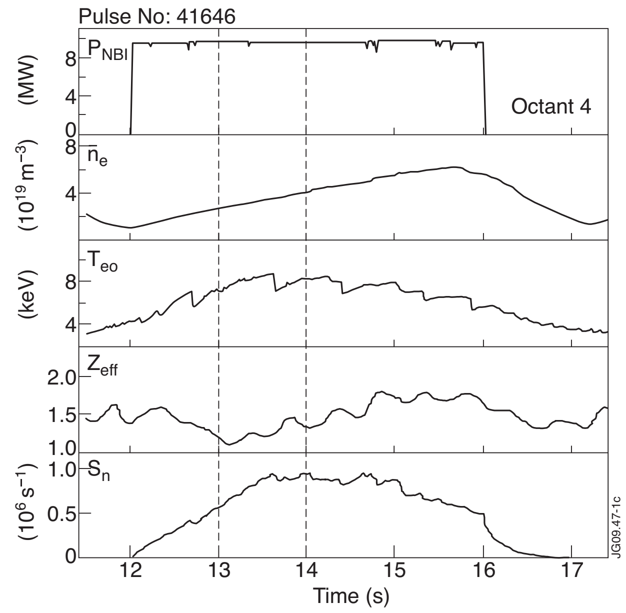

Figure 1: The typical time evolution of the main plasma parameters in a D-beam/Dplasma discharge. Dotted lines, the time interval used to evaluate the energy distribution function of DD fusion tritons.

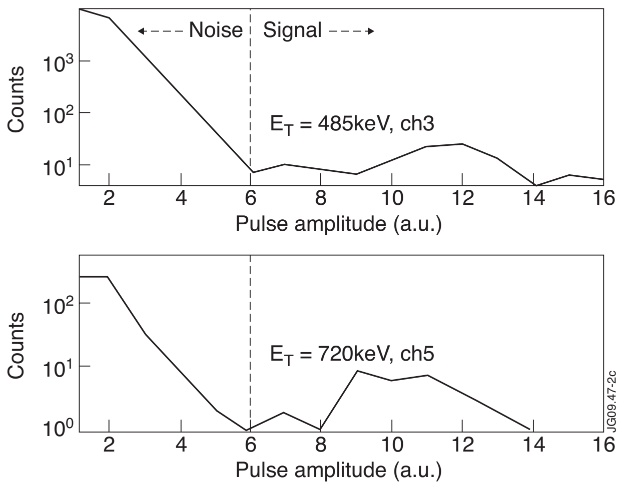

Figure 2: The pulse height distributions measured in NPA channels 3 and 5 and integrated over six similar discharges (see figure 1) for the time Δt = 13.0s–14.0s.

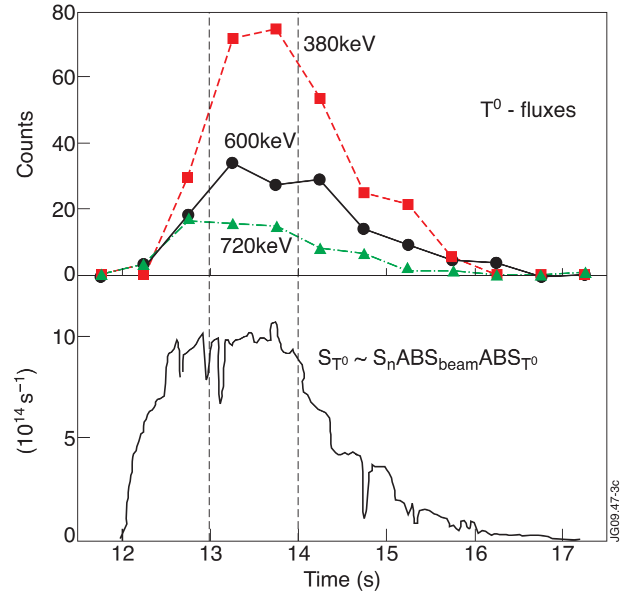

Figure 3: The time evolution of T^o fluxes (upper half) and the combined parametero S_{T^o} (lower half) which are proportional to the T^o production rate. The coefficients ABS_{beam} and ABS_{T^o} correspond to the absorption factor of the beam (E = 76keV) and the T^o flux (E = 380keV), respectively.

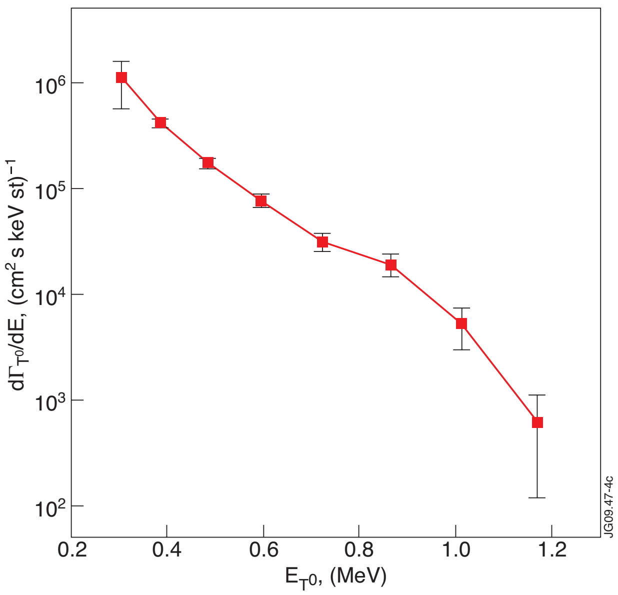

Figure 4: The charge-exchange energy spectrum of T^o atoms for the time Δt = 13.0s–14.0s.

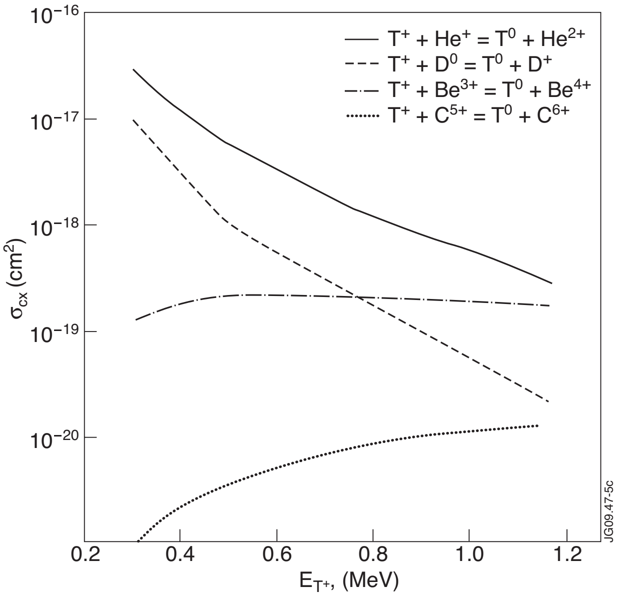

Figure 5: Cross-sections of the charge-exchange reaction of fast tritons

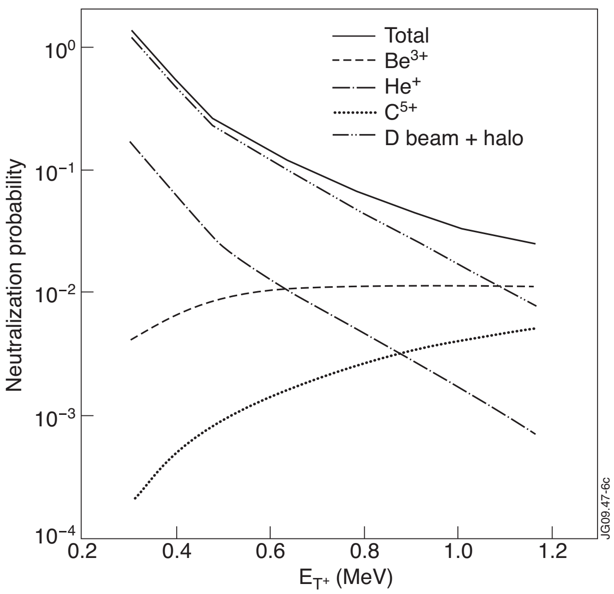

Figure 6: The energy dependence of the neutralization probability of tritium ions produced by D^o neutral beam injection (octant 4).

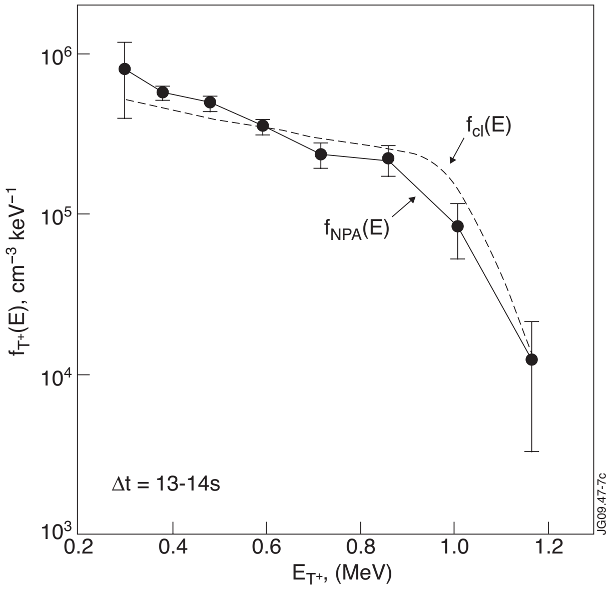

Figure 7: The energy distribution function of DD fusion tritons derived from NPA measurements $f_{NPA}(E)$, as compared with the classical distribution function $f_{cl}(E)$.