Isotope Exchange in High Heat-flux Components of the JET Tritium Neutral Beam Injector

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1. INTRODUCTION

Accumulation and release of tritium in actively cooled structures exposed to high fluences of energetic particles (at energies up to 160 keV in JET) have been studied during the recent DT experiments (DTE1). This retention of tritium is of importance in terms of tritium accountability, activation and decontamination of components, and as a possible source for contamination of the cooling water. To develop an understanding of the underlying physics and to benchmark predictive models for tritium retention, release and migration is a prime condition for ignition devices which have to handle large quantities of tritium safely.

Exchange between implanted and incident particles of different isotope (D and T) may be observed experimentally from the beamline neutron emission during pulses in which beams are not injected into torus but impinge on the calorimeter (*Async* pulses). It was previously shown [1] that neutron emission data could successfully be described by a "local mixing model" [2-3] taking into account the stopping function for the incident particles.

2. EXPERIMENT

A neutron detector was placed near the JET Octant 8 neutral beam injector [4] to monitor neutrons from D(t,n)α and D(d,n)^{3}He nuclear reactions caused by collisions of beam particles from the JET Positive Ions Sources (PINIs) [4] with deuterium and tritium atoms implanted into beamline elements (ion dumps, calorimeters, beam scrapers etc.).

Neutron data were recorded during the entire DT experiment (May 1997 - February 1998), but only data from *Async* beam pulses can be used for monitoring hydrogen isotope exchange in beamline components. During *Sync* beam pulses, when beams are injected into the JET plasma, the neutron detector was in saturation caused by high flux of neutrons originating from plasma fusion reactions.

In the *Async* mode of injector operation, the majority of detected neutrons are produced in collisions of beam particles with T (D) atoms implanted into calorimeters and full energy ion dumps. The contribution of other beamline components (fractional ion dumps, neutralisers, etc.) can be neglected due to lower beam energies and/or considerably lower particle fluxes. It was also established that the neutron detector signal is dominated by neutrons from the calorimeter. The location of the detector with respect to the injector beamline components is such that the detection efficiency for neutrons originating from the full energy ion dumps is much lower than for calorimeters. This is caused by larger distance and by scattering of neutrons while passing through injector components.

Large quantities of tritium, deuterium and hydrogen were implanted into different beamline components during the JET DT experiment and the results are summarised in Table 1. The amount of injected particles N was calculated as $N = (f_1 + 2f_2 + 3f_3) I_{ext} \Delta t$, where f_1, f_2 and f_3 are ion species fractions (H^+, H_2^+ and H_3^+) extracted from the source, I_{ext} is the extracted ion

current and Δt is the beam pulse length. Neutralisation efficiency for the three beam components (full, half and third energy) was taken into account when calculating implanted quantities of three hydrogen isotopes into various beamline elements. Typical injection energies for hydrogen, deuterium and tritium beams were 110, 140, and 155 keV, respectively.

Table 1. Injected quantities of hydrogen, deuterium and tritium (in Coulombs, 1C=6.24×10^{18} atoms) during the DTE experiments.

Period	20/05/97 to 18/09/97			19/09/97 to 02/02/98		
Gas	Hydrogen	Deuterium	Tritium	Hydrogen	Deuterium	Tritium
Upstream components	0	43047	1709	29955	83531	10864
Full energy ion dumps	0	103925	3518	75241	202139	22726
Fractional ion dumps	0	28541	836	38768	55274	5290
Calorimeter	0	44855	3449	16723	37448	10973
Calorimeter back-panel	0	1417	38	796	3749	469
Box scraper	0	5678	152	3184	14988	1877
Duct scraper	0	4259	114	2388	11241	1409
Injected to plasma	0	51484	1427	30017	141173	17867
Total	0	283206	11243	197072	549543	71475

3. RESULTS

Measured neutron rate during *Async* beam pulses for the second part of DTE1 is shown in Figure 1. Data are shown for Quadrant 4 only (PINIs 7 & 8) and similar results were obtained for *Async* pulses for the remaining three quadrants of the JET Octant 8 neutral injector.

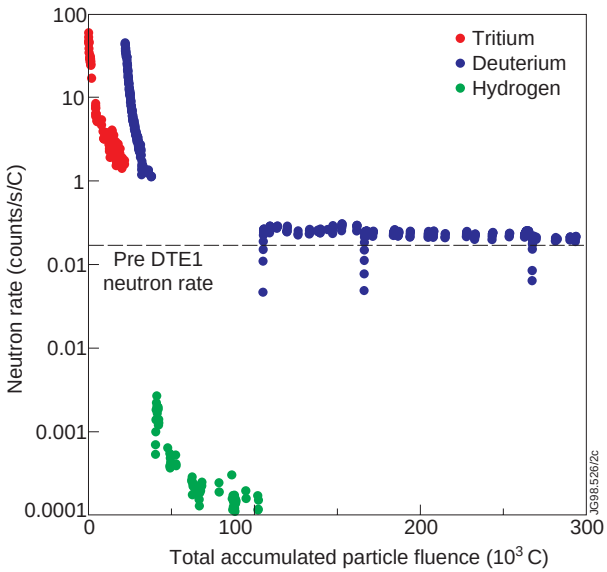

Figure 1. Neutron rate for Quadrant 4 Async *pulses during the second part of DTE1.*

Second part of the DTE1 was preceded by a long deuterium operation so it is justified to assume that the beamline elements were practically saturated with deuterium atoms. The fall in the neutron rate during tritium injection is caused by the reduction of the number of implanted deuterium atoms through isotope exchange with incoming tritium atoms. Tritium operation was followed by a long cleanup phase (both *Sync* and *Async*) when large quantities of deuterium and hydrogen were injected. The decrease in the neutron rate during the cleanup phase illustrates the reduction of tritium retained in calorimeter panels via isotope exchange with incoming deuterium and hydrogen atoms. Very

low neutron count rate during hydrogen injection can be attributed to small quantities of deuterium (0.1%) present in the hydrogen beam. The gaps in the neutron data correspond mainly to *Sync* operation. At the end of the cleanup phase the neutron rate was just slightly above the pre DTE1 neutron rate (indicated by dotted line in Figure 1). Pre DTE1 neutron rate was measured using the same neutron detector and 140 keV deuterium beams prior to tritium injection. Points below the pre DTE1 level correspond to lower deuterium beam energies occurring during restarts of the injector.

4. DISCUSSION

Time evolution of hydrogen isotope densities inside beamline elements can be calculated using the local mixing model. This model assumes that the local concentration of hydrogen isotopes cannot exceed a given saturation level which is dependent on temperature. When the saturation level is reached one hydrogen isotope atom is instantly released for each incoming atom without being trapped in the adjacent non-saturated region. In this case, the release rate equals the deposition rate and reflects the local implanted isotope mixture.

Details of the model and the computer code used to calculate implantation profiles were described elsewhere [1,5]. The code can handle beams combined of up to three hydrogen isotopes with given full, half and third energy fractions. Slowing down of fast particles inside metallic (copper) target is calculated using stopping power formulas [6]. Finally, the total neutron yield is calculated using the total cross-sections for $D(t,n)\alpha$ and $D(d,n)^3He$ nuclear reactions [7], the energy of deuterium and tritium particles during the slowdown, and the calculated density distribution of implanted deuterium and tritium atoms.

For the reasons mentioned earlier, only calorimeter was considered in the calculation. The cleanup phase of the DTE1 started after long tritium operation and in the calculation it was assumed that the calorimeter panels were fully saturated with tritium. The saturation concentration of hydrogen in copper was set to be 20%. Saturation concentration is temperature dependent and the value used here is slightly higher than the one used in our previous calculations [1,5] to account for short pulses and relatively low temperatures of calorimeter panels. Beam energies used in the simulation were 140keV for deuterium and 110keV for hydrogen, which represent the averages of the actual values used in the experiment. In the case of hydrogen injection it was assumed that the beam was contaminated with 0.1% of deuterium.

Measured neutron yield during the cleanup phase of the JET Octant 8 injector is compared to calculation in Figure 2. To make comparison possible, both experimental and calculated data were normalised to pre DTE1 neutron rate. The agreement between the measured and calculated neutron rates is acceptable bearing in mind the simplicity of the model and complicated geometry of the actual experiment.

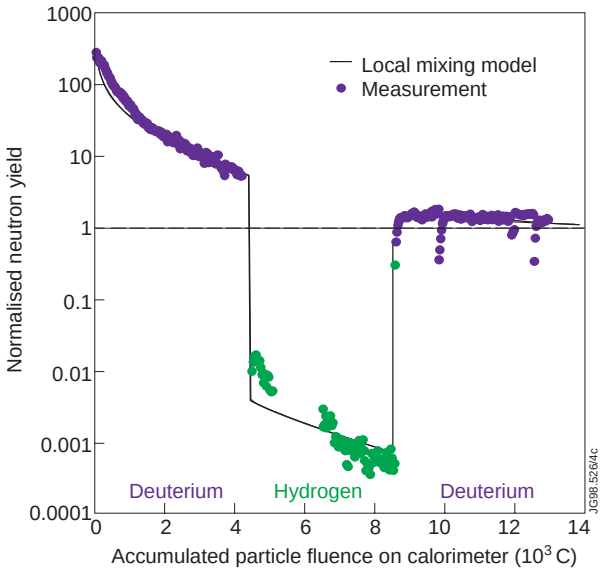

Figure 2. Normalised neutron rate for Quadrant 1 Async *pulses during the cleanup phase.*

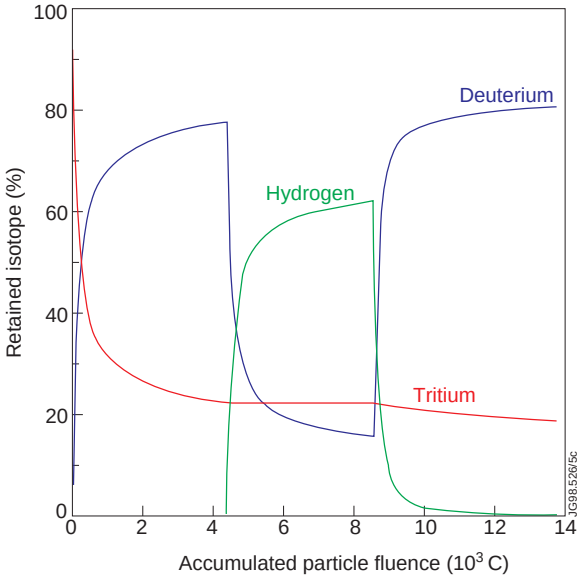

Figure 3. Retained hydrogen isotopes during the cleanup phase of DTE1.

The fact that the neutron rate at the end of the cleanup phase was just slightly above the pre DTE1 level does not mean that the all implanted tritium was removed from the calorimeter panels. This can be seen from Figure 3 where the relative amount of retained hydrogen isotopes is plotted as a function of accumulated particle fluence (100% means fully saturated panel up the penetration depth of 160 kV tritium beam). Around 20% if the initial tritium content is retained at the end for the cleanup phase. Tritium atoms implanted close to the maximum penetration depth can not be reached by the incoming deuterium atoms with smaller penetration depth. In addition, the energy of deuterium atoms close to the end of its trajectory in copper (Figure 4) is not sufficient to produce measurable neutron signal due to energy dependence of the cross section for the D(t,n)α nuclear reaction.

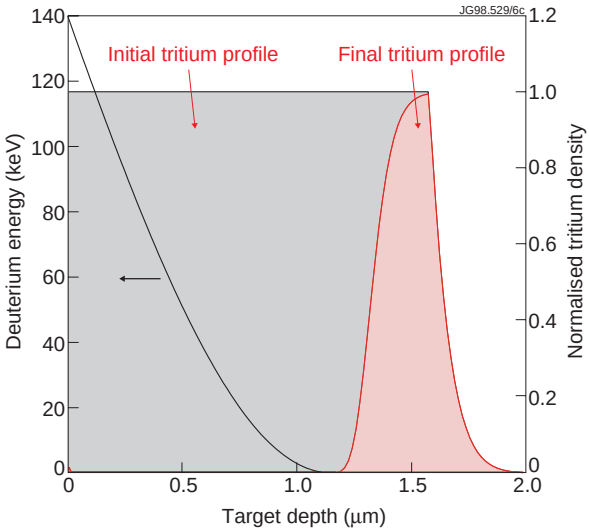

Figure 4. Tritium implantation profile at the end of the cleanup and deuterium slowdown in copper.

At the end of the cleanup phase, the upper limit for the retained tritium within the assumptions of the local mixing model (20% saturation level) is ~0.5_10^{18} atoms/cm_.

The local mixing model can be used to describe qualitatively the hydrogen isotope exchange in the beamline components of the neutral beam injector. It shows that that the implanted tritium atoms can be efficiently removed up to the penetration depth of the incoming fast deuterium atoms, but deuterium beams with energies ~20% higher than tritium beams are required for the complete removal of the implanted tritium.

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