Measurements and Calculations of Isotopic Exchange between Deuterium and Tritium and Their Implications to Neutral Beam Injection

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ABSTRACT

The hydrogen isotope exchange in some beamline components of a tritium injector is analysed using the local mixing model. Various implantation and cleanup scenarios using tritium, deuterium and hydrogen beams are discussed. The model is also used to interpret D(t,n)α neutron measurements during the cleanup of beamline elements after the First Tritium Experiment (FTE) at JET.

INTRODUCTION

Tritium inventory in the beamline components of the tritium neutral beam injectors is important for the handling of those components after tritium injection and for tritium accountability. During the injection of tritium beams, large amounts of tritium will be implanted into beamline components (dumps, scrapers, calorimeters). Implanted tritium can be removed using deuterium cleanup pulses after tritium injection. A computer code based on the local mixing model [1] was developed to interpret hydrogen isotope exchange during hydrogen bombardment of actively cooled CuCrZr beam panels. The code was previously used to interpret hydrogen-deuterium exchange in the beam dump panels of the JET Neutral Beam Test Bed [2,3]. In this paper we present results of the computer simulation of tritium implantation and tritium recovery using deuterium and hydrogen beams.

II. EXPERIMENTAL RESULTS

In the First Tritium Experiment at JET [4], tritium was introduced into the plasma entirely by tritium beams. Two PINIs of one of the JET Neutral Injectors [5] (NIB 8) were operated with tritium gas. Beam history around the FTE, relevant for tritium implantation and subsequent cleanup of tritium from beamline components, is given in Table I. The estimated activities of the beamline components, assuming 100% implantation of energetic tritium during various phases of tritium operation, are summarised in Table II.

Table I
NIB 8 beam history around FTE.

Phase	T- beam commissioning	FTE	Cleanup phase 1	Cleanup phase 2
Beam	100% T	100% T	100% D	100% D
Beam type	deflected	synchronous	undeflected	deflected
Extr. voltage	78 kV	78 kV	55 kV	~80 kV
Extr. current	27 A	27 A	20 A	40 A
Time	1 s	6.7 s	30 s	144 s
Exposed component	calorimeter ion dumps	ion dumps scrapers	calorimeter	calorimeter ion dumps

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Table II
Tritium inventory in NIB 8 after FTE.

Component	Absorbed activity (Ci)
Calorimeter	10 ± 1
Ion dumps	60 ± 5
Box and duct scrapers	15 ± 3
TOTAL	85

Ion beam dumps and calorimeter were cleaned after the last tritium pulse by using deuterium beams. The progress of tritium recovery was monitored by measuring neutrons from the D(t,n)α reaction. One of the neutron counters from the torus diagnostic system was used for this measurement.

In the first cleanup phase, the calorimeter was cleaned within 30 beam seconds using undeflected 55 kV deuterium beams. In the second phase, the deflected ~80 kV deuterium beams were used to clean the dumps and the calorimeter. Measured neutron yield during the cleanup of beamline components is given in Fig. 1.

The tritium cleanup procedure by deuterium beams was also monitored by measurement of the activity of the gas regenerated from the injector cryopumps - ~70 Ci was recovered. Bearing in mind the uncertainties (~10%) which can be applied to both, the assumed total activity of the beamline components (Table II) and the measured activity of the tritium gas, we can conclude that essentially all of the implanted tritium was recovered. This also implies that the depletion of the implanted tritium through the diffusion at room temperature can be neglected, since the cleanup of the

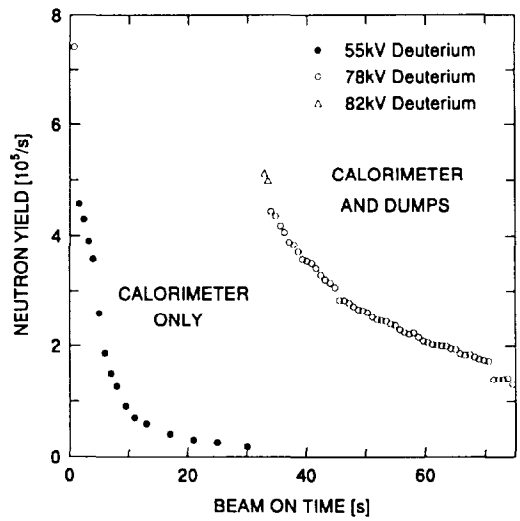

Fig. 1 Cleanup of the tritium injector with deuterium beams after the FTE using undeflected (solid symbols) and deflected beams (open symbols).

injector box using deuterium beams started two days after the FTE.

III. MODEL

The time evolution of the hydrogen isotope density inside a metallic (copper) target during the implantation of hydrogen, deuterium or tritium is calculated using the local mixing model [1]. Details of the calculations are described elsewhere [3], and only the basic assumptions are summarised here.

It is assumed that the local concentration of implanted hydrogen atoms is limited to a maximum value of n_{sat}, which is inversely proportional to the copper surface temperature [3]. The diffusion of implanted atoms is neglected and the only free parameter in the model is the saturation concentration.

Fast hydrogen atoms slow down in the host lattice and when they come to rest they are stored in a saturable trap. If the local concentration of hydrogen isotopes is below saturation level, the number of deposited hydrogen atoms can be determined from the corresponding range distributions [6]. If the incoming particle comes to rest within the saturated region, one implanted (trapped) 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.

In the case of deuterium beams, neutrons are emitted in collisions of deuterium atoms with previously implanted tritium atoms. Slowing down of deuterium in copper is calculated using the stopping power formulas [7]. The total neutron yield can be calculated by using the total cross-section for the D(t,n)α reaction [8], the energy of the deuterium particles during the slowdown, and the calculated density distribution of implanted tritium atoms.

IV. TRITIUM RECOVERY AFTER THE FTE

For simplicity, only the cleanup of the calorimeter is considered, as the calorimeter was exposed to undeflected beams during the initial cleanup. This improves the accountability. It is assumed that the calorimeter panels were fully saturated with deuterium before tritium implantation, with deuterium to copper atomic ratio of 1:10 ($n_{sat} \cong 8.5\times10^{21}$ atoms/cm^3). This saturation concentration is lower than the one found in the literature [9], accounted for by the increase in temperature (~400°C) of the calorimeter panels exposed to energetic deuterium or tritium beams [3].

The calorimeter was exposed to tritium beams only during the commissioning phase. Charging and subsequent cleanup of the NIB 8 calorimeter after the FTE was simulated using beam parameters given in Table I. Incident particle densities required for the simulation were derived from the measured beam profiles.

The total neutron yield was calculated for the first phase of the cleanup process (55 kV deuterium beam). Since no attempt was made to derive total neutron count rates from measured values, the calculated neutron yield was normalised to experimental data. The result is shown in Fig. 2. The time evolution of the tritium density distribution inside the copper target during cleanup is given in Fig. 3. Note that the tritium saturation density was not reached during the charging of the calorimeter since the total tritium implantation time was only 1 second.

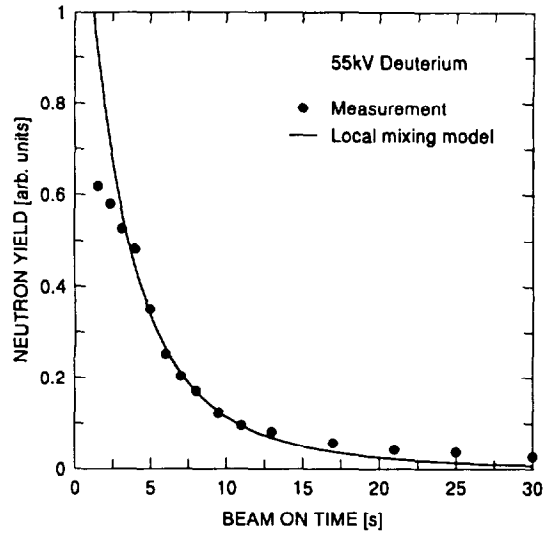

Fig. 2 Calculated and measured neutron yield during NIB 8 calorimeter cleanup after the FTE using 55 kV deuterium beams.

The fast initial decrease in the neutron yield can be explained by the efficient replacement of implanted tritium with deuterium around the mean projected range (Fig. 3). Tritium that was implanted deeper into the copper is removed very slowly due to the lower penetration depth of deuterium. The removal of deeply implanted tritium cannot be monitored using neutron detection, as decelerated deuterons do not have sufficient energy to produce a measurable neutron signal. At higher deuteron energies (78 kV), deeply implanted tritium is removed somewhat faster, but the amount of tritium retained in the copper target after 90 beam seconds is still ~5% of its initial value. We can expect that the amount of the retained

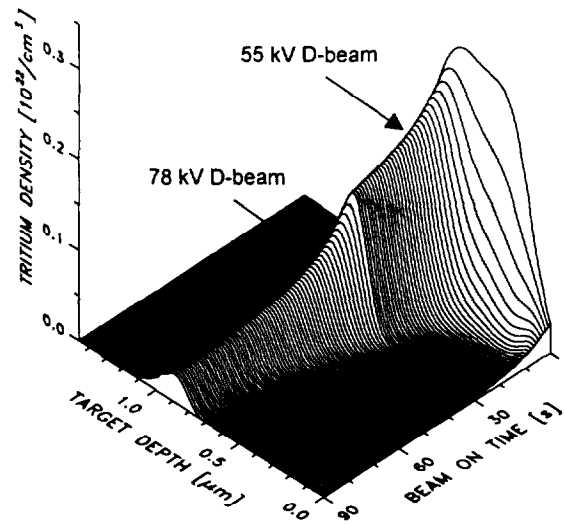

Fig. 3 Time evolution of calculated tritium density during calorimeter cleanup using 55 kV and 78 kV deuterium beams.

tritium in the injector ion dumps is also ~5%. Higher values can be expected for the box scrapers and the duct scrapers, as they are exposed to the lower beam densities, and are consequently cleaned with lower efficiency (see next section). This is in agreement with the difference between the measured activity of the recovered tritium gas and estimated implanted tritium activity.

Higher deuterium beam energies are required for the complete removal of implanted tritium. Note that the cleanup time is considerably longer than the implantation time.

V. LONG TERM TRITIUM OPERATION

The amount of tritium implanted into the beamline components during the active phase of JET will significantly exceed the values of the FTE. Different tritium implantation and cleanup scenarios were simulated using much longer implantation times.

The saturated hydrogen isotope concentration used in the simulation was n_{sat}= 8.5×10^{21} atoms/cm^3 (n_{sat}:n_{Cu}=1:10). In the simulation copper target was exposed to energetic tritium beams for a period of 100 seconds and the cleanup process using deuterium or hydrogen beams was simuleted for 1000 seconds. Incident particle densities were limited to the electrical equivalent of 20 mA/cm^2 perpendicular to the copper surface. This current density corresponds to a power density of 1.3 kW/cm^2 for 70 kV beams. The same incident particle density was used in the implantation and in the cleanup phase. Beams with extraction voltages in the range 60-80 kV, and with fixed species composition of 83%, 10%, and 7% (full, half and third energy) were considered.

Results are presented only for normal incidence beams. The variation of the angle of incidence has little effect on the amount of retained tritium if the flux of beam particles perpendicular to the surface is maintained constant.

The first considered case was the implantation of 70 kV tritium beams into copper and subsequent cleanup using 80 kV deuterium beams. Range distributions of tritium and

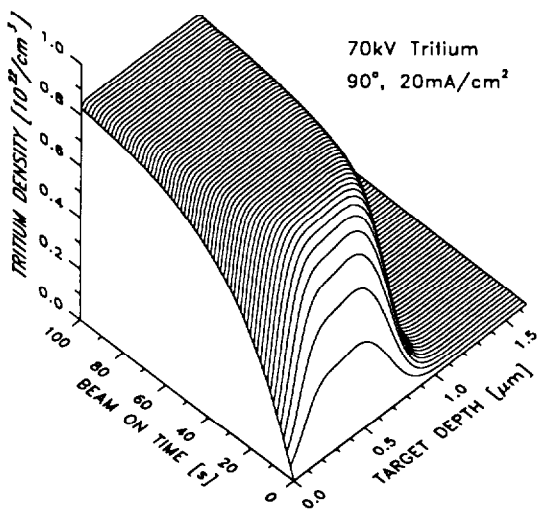

Fig. 4 Simulated time evolution of the tritium density distribution during implantation of 70 kV tritium beam into copper target.

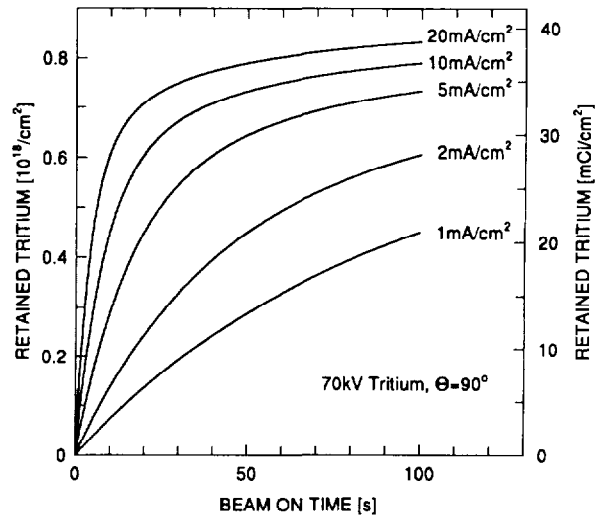

Fig. 5 The amount of retained tritium during tritium implantation into copper for different beam current densities.

deuterium in copper for those beam energies are quite similar, which should lead to efficient tritium cleanup.

The time evolution of tritium density distribution inside the copper target during implantation of 70 kV tritium beam at normal incidence is given in Fig. 4. Tritium saturation in the vicinity of the mean projected range is vary rapid. The saturated region extends gradually, and after 100 beam seconds the saturated region is roughly 1 μm deep.

For the lower incident particle densities, the saturation of the copper target is much slower, and only the region around the mean projected range will become fully saturated with tritium. Nevertheless, the amount of tritium retained in the target (i.e. the integral of tritium density along the total penetration depth) is still considerable (Fig. 5). This means that beamline elements which are not exposed to maximum beam particle densities will still contain a significant amount of tritium after the long tritium implantation. The amount of retained tritium is given per unit area. The corresponding activity is indicated on the right scale of the diagram (10^{18} atoms ~ 45 mCi).

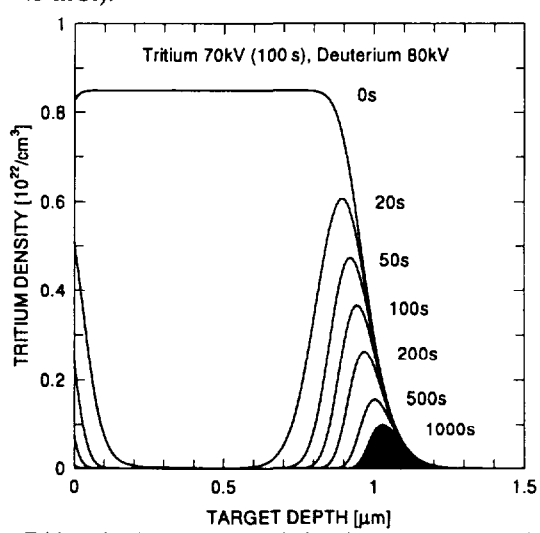

Fig. 6 Tritium density distribution during the cleanup phase using 80 kV deuterium beams at normal incidence, with current density of 20 mA/cm^2.

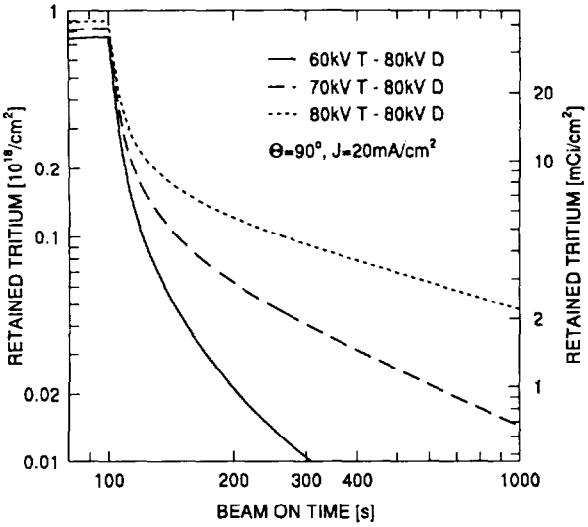

Fig. 7 The amount of retained tritium during the cleanup phase using 80 kV deuterium beams, after the implantation of tritium at 60, 70 and 80 kV for 100 s.

The cleanup process using 80 kV deuterium beams at normal incidence is illustrated in Fig. 6. Initially, tritium replacement with deuterium is very fast. The tritium removal rate decreases gradually, and after 1000 beam seconds the amount of retained tritium is roughly 1.5% of the initial value (shaded area in Fig. 6). It should be noted that the cleanup efficiency is lower for the lower beam particle densities - roughly 3% of the implanted tritium is retained for the beam particle densities equivalent to 1 mA/cm^2.

The cleanup efficiency can be significantly improved if the energy of the deuterium beam used for cleanup is higher than the energy of the tritium beam during implantation. This is demonstrated in Fig. 7, where 80 kV deuterium beam is used to clean the target which was previously saturated with tritium beams of 60, 70 and 80 kV. This implies that the tritium injection energies should be below the nominal maximum of the tritium injector (assumed here as 80 kV), to permit fast tritium recovery using deuterium beams with maximum energies.

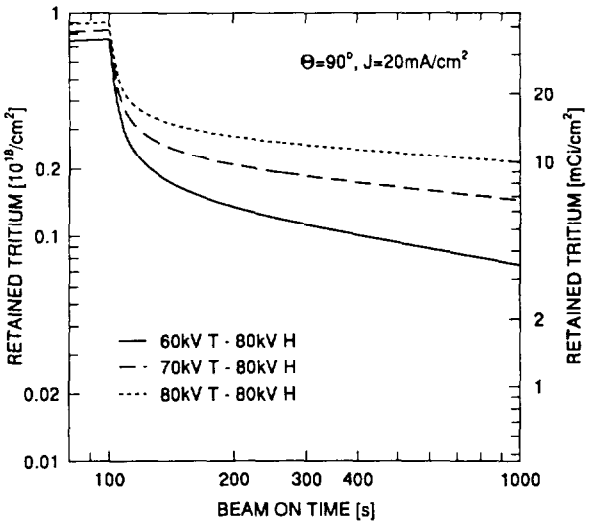

Fig. 8 The amount of retained tritium during cleanup using 80 kV hydrogen beams, after the implantation of tritium at 60, 70, and 80 kV for 100s.

Hydrogen beams are not suitable for cleanup purpose. Due to lower penetration of hydrogen, a considerable amount of tritium can be retained in the target. This is illustrated in Fig. 8, where 80 kV hydrogen beam is used to clean the target which was previously saturated with tritium beams of 60, 70 and 80 kV. Hydrogen beams of much higher energies are required for effective tritium cleanup. Another drawback in using hydrogen beams is the absence of neutrons for monitoring the cleanup process. Helium beams are unsuitable for similar reasons.

VI. CONCLUSIONS

The inventory of tritium in the beam injector can be well understood in the framework of the local mixing model. From the results obtained one can conclude that:

- the depletion of the implanted tritium by diffusion at room temperature is negligible compared to the cleanup with deuterium beams.
- hydrogen saturation densities of the order of 10^{22} cm^{-3} will be achieved during beam injection.
- the saturated region can be 1 μm deep (60-80 kV beams), leading to an activity of ~50 mCi/cm^2 after tritium implantation.
- implanted tritium can be efficiently removed using deuterium beams.
- deuterium beam energies used for cleanup should be roughly 20% higher than the tritium injection energies, to allow fast cleanup of deeply implanted tritium.
- hydrogen and helium beams are not suitable for the injector cleanup, unless significantly higher beam energies can be used.
- neutron detection is useful for monitoring the initial cleanup process.

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