In-vessel tritium measurements using beta decay in the Tokamak Fusion Test Reactor

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Tritium on the inside walls of the Tokamak Fusion Test Reactor was detected by configuring the vacuum vessel as an ionization chamber and measuring the secondary electron current from the tritium beta decay. The vessel was typically filled with ≈5 Torr of dry nitrogen and the secondary electron current was collected by an internal electrode biased to about +15 V with respect to the vessel wall. The measured variations of the collected current with gas pressure, bias voltage, and applied magnetic fields are described, as well as an *in situ* calibration made by injecting a known amount of tritium gas. Improved versions of this diagnostic may be useful to track the in-vessel content of surface tritium in future fusion devices. © *1999 American Institute of Physics.* [S0034-6748(99)56301-6]

I. INTRODUCTION

Knowledge of the tritium inventory inside deuterium–tritium (DT) fusion machines is critical to assuring efficient utilization of this scarce fusion fuel and for meeting regulatory requirements for the safe operation of the plant. Currently this inventory is evaluated as the difference between the tritium input and exhaust from the vacuum vessel; however, as the tritium flow rates and run times become longer, this procedure will become increasingly difficult and inaccurate.

The goal of this work was to measure the tritium content on the first wall surface of the Tokamak Fusion Test Reactor (TFTR) vacuum vessel by using the beta emission from tritium decay. Since these betas have a range of only ≈1 μm in the carbon first wall material, only the tritium on the top ≈1 μm surface of the wall can be detected this way. To measure this beta emission rate, the TFTR vacuum vessel was configured as a large ionization chamber using an existing electrode to collect the ionization current of the betas. The chamber was filled with dry nitrogen gas to a pressure of about 5 Torr and the collected current was measured periodically during and after the DT run between 1995 and 1997.

II. PRINCIPAL OF THE MEASUREMENT

The principal of this measurement is the same as a conventional gas ionization chamber.[1–4] The vessel is filled with dry nitrogen gas and some of the betas emitted by the tritium on the first wall create ionization in the gas. The ionization current is collected by biasing an electrode inside the vessel with respect to the chamber ground. The electric field should ideally be high enough to collect all the charge, but low enough to avoid charge multiplication or avalanching. A similar principal is used in commercial tritium detectors.[5] Other techniques for tritium detection on surfaces have been developed based on direct measurement of the beta energy spectrum or current,[6,7] but these could not be implemented on TFTR during or shortly after the DT run due to a lack of access to the vacuum vessel.

Tritium betas are created with a broad energy spectrum up to 18 keV with an average energy of ≈5.7 keV. The amount of energy needed to produce an electron–ion pair is typically 35 eV. Therefore a single tritium beta source would ideally produce ≈200 electrons, which corresponds to an ionization current of 1 μA/pCi.

However, there are several features of this particular measurement which cause the collected current to be much less than the total in-vessel tritium inventory times 1 μA/pCi. First, the range of tritium betas in the first wall material (carbon) is only ≈1 μm, whereas the depth of the tritium in the co-deposited layers on the first wall may be up to 10–100 μm thick in places,[8] so only ≈1%–10% of the tritium betas inside such layers would enter the gas and cause ionization. Second, the toroidal geometry of the vessel and the limited range of tritium betas in the gas inhibit the collection; for example, the range of tritium betas at 4 Torr of N_2 is ≈1 m, while the vessel diameter is ≈7 m. Third, the electric field strength was relatively small to avoid potential arcing, so that the processes of recombination, electron attachment, and diffusion may further inhibit secondary electron collection in this experiment.

III. EXPERIMENTAL SETUP ON TFTR

The experimental setup is shown schematically in Fig. 1. The TFTR vacuum vessel ($R=2.6$ m, $a=1$ m) is filled with dry nitrogen gas and a dc voltage up to +100 V is applied between the electrode at the top and the grounded vessel wall. The current through the electrode was measured by a Keithley digital microammeter. The neutral gas pressure was measured by an ionization chamber below 10^{-4} Torr and a capacitance manometer above this pressure.

An existing glow discharge cleaning probe was used for all these measurements. Its electrode was cylindrically shaped with a diameter of ≈4 cm and a length of ≈6 cm

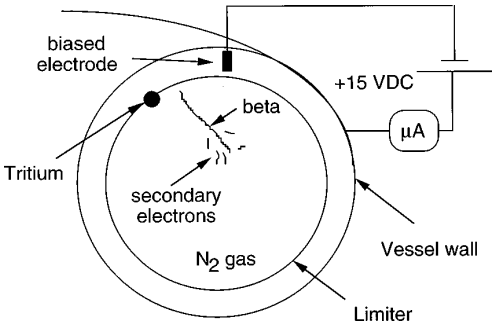

FIG. 1. Experimental setup for measuring the secondary electron current generated by tritium betas inside the TFTR vacuum vessel. The electrode is biased typically +15 V with respect to the vacuum vessel ground, and the chamber is typically filled with ≈4 Torr of dry nitrogen. No plasmas or external magnetic fields are present during these measurements.

located at the top of the vacuum chamber. The tip of this probe was approximately flush with the local first wall structures, but about ≈8 cm behind the (remote) limiter radius. At this location the electrode had a line-of-sight view of ≈1/3 of the entire TFTR vacuum vessel first wall.

These measurements could only be made when the vacuum vessel was filled with dry nitrogen. This was done once in 1995 (about 1.5 years after the start of the DT run), and several times near and just after the end of the TFTR DT run (2 years after that). The experimental setup was identical in all these runs.

IV. EXPERIMENTAL RESULTS

For a given state of the tritium on the TFTR wall surface (i.e., at a given time), the current collected by the circuit in Fig. 1 depended on both the neutral gas fill pressure and also on the electrode bias voltage. The typical dependence of the collected current on the dry N_2 gas fill pressure is shown in Fig. 2, and the dependence on the bias voltage for various fill pressures is shown in Fig. 3.

The collected current was very small at the base pressure of $\approx 10^{-8}$ Torr ($\leqslant 1$ μA), but increased as the pressure was raised up to ≈4 Torr, and then slowly decreased for higher fill pressures, as illustrated in Fig. 2. The location of this peak in pressure was approximately constant for all the runs. Qualitatively, this can be interpreted as a lack ionization targets at pressures much below 4 Torr, and a gradual inhibition of the collection process at higher pressures (see Sec. IV).

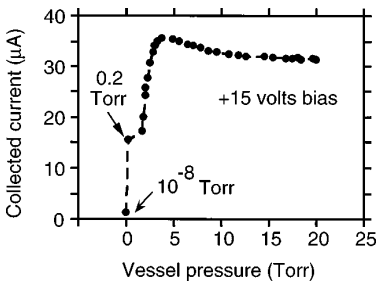

FIG. 2. Variation of the collected current from tritium betas vs nitrogen gas fill pressure at an electrode bias of +15 V dc. The collected current peaks at about 4 Torr and decreases slowly for higher pressures. This particular measurement was made in the middle of the TFTR DT run (3/95).

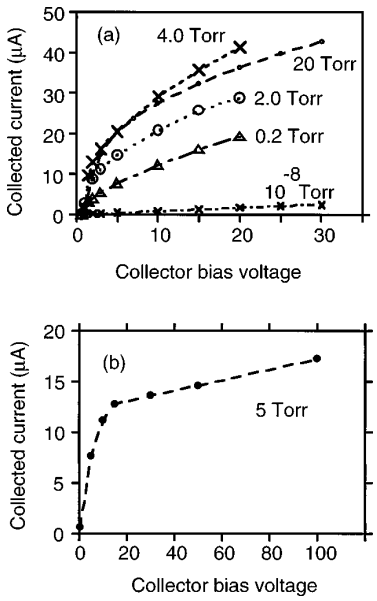

FIG. 3. Variation of the collected current from tritium betas vs the electrode bias voltage for various fill pressures. The measurements in (a) were made during the DT run in 3/95, and the measurements in (b) were made after the DT cleanup campaign in 4/97. The latter had a larger range of applied bias, and shows a plateau similar to an ideal ionization chamber above voltages of ≈15 V dc.

The collected current increased with bias voltage as shown in Fig. 3. The data in Fig. 3(a) were taken up to a bias voltage of +30 V dc at various fill pressures (all on the same day in 1995), and the data of Fig. 3(b) were taken up to a bias voltage of +100 V dc at one fill pressure (after the DT run). The current–voltage characteristics are similar to a standard ionization chamber, but without a perfectly flat ''plateau'' region where the current is independent of bias voltage (i.e., when all the charge is collected without multiplication). However, since the collected current increases by only ≈30% over the range 15–100 V dc, we used 15 V as a standard voltage for these measurements.

A summary of the five runs of this experiment is shown in Fig. 4, all at a constant bias voltage of 15 V dc and a constant fill pressure of ≈4 Torr N_2. The collected current was highest just after the last day of TFTR operation, and decreased by a factor of ≈6 during the subsequent month of the tritium cleanup campaign. On the same plot is an estimate of the total in-vessel tritium inventory, based on the difference between tritium input into and exhaust from the vessel.[8] The estimated inventory decreased by only ≈20% during this time, so the tritium detected using the ionization current was not simply proportional to the total tritium inventory in the vessel. This is not too surprising since most of the inventory left after the cleanup campaign was likely to be deep inside co-deposited layers or in inaccessible places such as the gaps between the carbon tiles on the first wall.

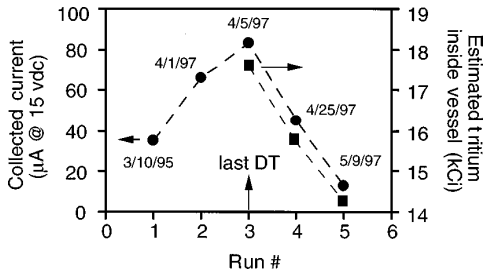

FIG. 4. Variation of the collected current for the five times this experiment was run during and after the TFTR DT campaign. In all cases the bias was +15 V DC and the fill pressure was ≈4 Torr N_2. The largest signal occurred just after the last DT shot, after which it decreased by a factor of ≈6 during the subsequent cleanup campaign. The estimated total tritium inventory inside the TFTR vacuum vessel is also shown (note suppressed zero).

A special measurement was made to check the sensitivity of the collected current to the presence of small dc magnetic fields, which are always present at the few Gauss level in TFTR due to a weak magnetization of the floor structure. As shown in Fig. 5, the collected current decreased by less than 10% for applied vertical or horizontal magnetic fields of ≈10 G, so the weak magnetic field present for the measurements of Figs. 2–4 did not significantly affect those results.

On the last run day of this experiment (5/9/97) there was initially 80 mTorr of moist air left in the chamber before the 5 Torr of dry nitrogen was added, and the observed collection current of ≈6 μA at 15 V dc was much lower than expected. An additional 1 Torr of air was added to check its effect, and the collection current dropped to less than 1 μA. Later that same day the vessel was pumped out to $\approx 10^{-4}$ Torr and refilled with dry nitrogen, and the collected current went back up to ≈13 μA (as shown in Fig. 4). This effect of moist air in reducing the collection efficiency was most likely due to the water vapor or oxygen, which should be avoided in ionization chambers due to their electron capture.[2,3]

V. CALIBRATION AND BACKGROUNDS

Using the *a priori* calibration factor of ≈1 μCi/pA discussed in Sec. II, the maximum collected current of ≈100 μA just after the end of the DT run corresponds to a tritium activity of ≈100 Ci. This is only about 1% of the estimated tritium inventory inside the vacuum vessel at that time. This is not too surprising since the measured ionization current comes only from the tritium on top ≈1 μm the surfaces, and probably from tritium only within about 1 m of the biasing electrode, which is the range of betas in the gas. However, given the complex geometry and single-point measurement, the effective collection area is not really known.

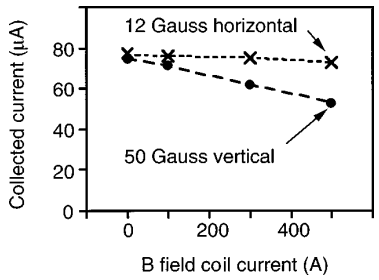

FIG. 5. Variation of the collected current with externally applied vertical and horizontal magnetic fields. The current was reduced by <10% at external fields of ≈10 G, so the presence of a few Gauss stray field during the measurements in Figs. 2–4 was not significant.

To help clarify this situation, an *in situ* calibration was made by adding 400 Ci of tritium gas to the TFTR vacuum chamber at 4 Torr of N_2. The collected current rose from 83 to 103 μA in response to this tritium input, which had no significant effect on the total gas pressure. *If* this new tritium source was distributed over surfaces of the vessel with the same spatial distribution as the tritium from the previous DT run, then the initial current of 83 μA would correspond to ≈1600 Ci of tritium on the entire surface of the vessel. This implies that the electrode is normally collecting only ≈10% of the tritium on the top 1 μm of the TFTR wall surfaces. However, the actual spatial distribution of the added tritium gas on the wall and/or in the gas phase is not known, so this interpretation of this calibration is still very uncertain.

The only potential background in this experiment is the ionization current created by the neutron-activated metal components of the vacuum vessel, mainly from gammas with an energy in the MeV range (carbon does not become activated). The gamma radiation level just outside the vessel wall during these measurements was typically ≤100 mR/h, which corresponds $\leq 10^{-7}$ W of energy deposited in the chamber gas at 4 Torr. This is much smaller than the expected energy deposition of $>10^{-2}$ W due to tritium betas emitted into the gas from the inner wall surfaces. Thus the background due to ionization from the background activation of the wall should be negligible.

VI. SUMMARY AND FUTURE DIRECTIONS

This article described the first attempt to diagnose the tritium content of a tokamak using the ionization current created by its beta emission. To do this, the TFTR vacuum vessel was configured as a large ionization chamber with a neutral gas at a pressure of ≈5 Torr of nitrogen and an internal electrode biased at 15 V. The largest collected current of ≈100 μA corresponded to the detection of ≈100 Ci of tritium, which was only ≈1% of the estimated tritium inventory inside the vessel at that time. This difference was most likely due to the limited range of tritium betas in the wall and in the chamber gas. An *in situ* calibration with a known tritium gas input implied that this current corresponded to a total surface tritium content of roughly 1600 Ci. This ionization current decreased by a factor of ≈6 during the tritium cleanup campaign, while the estimated tritium content decreased by only ≈20%. This result was consistent with expectations that the majority of the tritium is buried underneath co-deposited layers of thickness ≥1 μm, which prevent the betas from entering the chamber gas.

At present these measurements provide only a qualitative and relative measure of the tritium on the surface of the first wall, so obviously many aspects of this method should be studied further and improved. Clearly, the dependence of the collected current on bias voltage and gas pressure needs to be better understood through a detailed analysis of the diffusion, recombination, and electron attachment processes. To improve the measurement, multiple electrode locations could be tried, or the gas composition might be optimized to allow collection from a larger area. Some of this work could be done on a small test chamber to simulate the tokamak environment, e.g., using a lower gas pressure to maintain the relevant ratio of chamber size to beta range.

The usefulness of this method could also be extended by having a controllable means to release the tritium from the co-deposited layers into the chamber gas, perhaps using a surface heating method.[9] However, it should be noted that the operation of any such ionization chamber would be significantly affected by the strong toroidal field of a superconducting tokamak, which could not easily be turned off for such measurements. To avoid this problem, or to check the results from such measurements, it would also be interesting to try *in situ* detection using a scintillating gas to visualize the location of the tritium on the walls.[4]

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