Methods for the measuring surface tritium inside TFTR using beta decay

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(Presented on 9 May 1994)

Three potential methods for evaluating the surface tritium content of the TFTR vacuum vessel are described, each based on a different technique for measuring the *in situ* beta emission from tritium. These methods should be able to provide both a local and a global assessment of the tritium content within the top ~1 μm of the inner wall surface. © *1995 American Institute of Physics.*

I. INTRODUCTION

Locating and recycling unburned tritium fuel from the inner walls of DT tokamaks like TFTR, JET, and ITER is important since their in-vessel inventory tritium needs to be minimized. Described here are three potential techniques for *in situ* measurements of the surface tritium on the TFTR tokamak vacuum vessel wall.

Tritium produced from DD reactions has already been measured on graphite wall tiles removed from TFTR, JET, and other tokamaks by counting the tritium beta emission using a *p-i-n* diode or channeltron detector.[1] Beta emission from tritium implanted in surfaces has also been measured by using a phosphor screen and image intensifier,[2] and by focusing the secondary electrons created by tritium betas using an electrostatic lens.[3] These methods are excellent for determining the surface tritium concentration of samples removed from the tokamak, but they cannot (yet) be used for TFTR DT since the tritiated wall tiles cannot be removed before the run is over.

Measurements of the surface tritium contamination in TFTR should be made during the DT experimental run, the tritium clean-up campaign, and prior to decommissioning. Strong spatial nonuniformities of the tritium concentration can be anticipated based on previous retention measurements of deuterium in TFTR[4,5] and tritium in JET.[6] For example, higher tritium concentrations are expected on the inner carbon bumper limiter (which contacts the plasma) than on the recessed metal walls.

The betas emitted by tritium decay have a broad Fermi spectrum with a maximum energy of ~18 keV and an average energy of 5.6 keV. Since the maximum range of tritium betas in carbon is ~3 μm,[7] all tritium measurements made using beta detection are restricted to tritium within a surface layer ~1 μm thick. Therefore, these measurements provide a *lower limit* to the tritium inventory. At least half of the tritium is expected to be in codeposited layers $\geq$1 μm thick or in cracks between the carbon wall tiles,[4,5] neither of which would be directly visible via beta detection (see Sec. VI).

The tritium inventory inside the TFTR vessel is restricted to $\leq 2\times10^4$ Ci. Assuming that $\sim 1\times10^4$ Ci is within ~1 μm of the vessel surface area of $\sim 10^6$ cm^2, the averaged beta emission rate should be $\sim 4\times10^8$ betas/cm^2 s, which corresponds to a current of $\sim 6\times10^{-11}$ A/cm^2 or a power of $\sim 3\times10^{-7}$ W/cm^2.

II. DIRECT BETA DETECTION WITH MAGNETIC STEERING

The principle of this method is illustrated in Fig. 1. A beta detector is inserted into the bottom of the vessel at the end of a movable probe. The horizontal and vertical magnetic fields of the tokamak are applied without a plasma or fill gas. The betas emitted from the wall are "steered" by the magnetic field onto the probe head, allowing the wall to be scanned poloidally and possibly toroidally (with an additional toroidal field component).

The betas emitted at the wall will spiral across the magnetic field and travel freely along the magnetic field toward the detector. The spatial resolution at the wall will be determined by the Larmor radius of the electrons in the applied magnetic field. The gyroradius ρ of a 10 keV electron with a pitch angle χ with respect to a magnetic field B(G) is ρ(cm) $\sim 3.4(100\ \mathrm{G}/B)\sin\chi$. Thus the viewing diameter at $B = 100$ G is about $2\rho \sim 6$ cm, which is suitable for examination of the ~2 m high inner bumper limiter. The available magnetic-fields of 10–100 G can be scanned during a standard TFTR

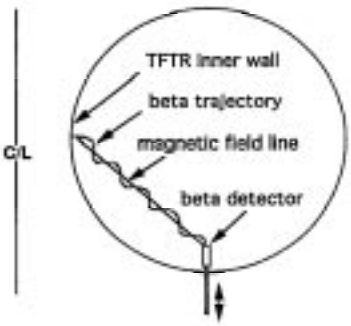

FIG. 1. Schematic view of the TFTR vacuum vessel illustrating magnetic steering of tritium betas emitted from the inner wall onto a removable beta detector. The applied horizontal and vertical magnetic fields of ~100 G can be scanned to form a map of the surface tritium on the vessel inner wall. A similar probe mechanism could be used with a biased electrode to measure the ionization current made by the tritium betas in a neutral filling gas.

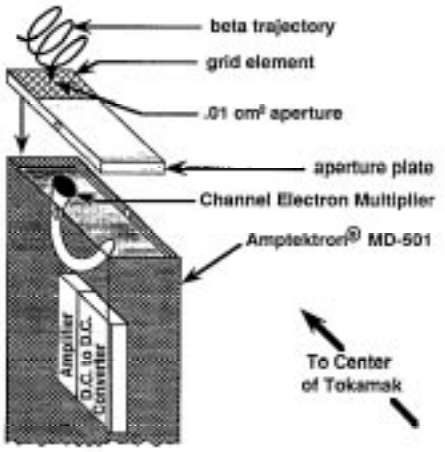

FIG. 2. Detector geometry used for beta detection with magnetic steering. The Amptektron channeltron detector can count ~10 keV betas with high efficiency up to a rate of $\approx 10^5$ counts/s. The biased grid is used to suppress secondary electrons emitted from the wall, and the aperture is used to limit the beta count rate.

shot cycle time of ~8 s to create a map of the tritium concentration along the surface of the inner bumper limiter.

The design of a prototype detector and probe "head" for use in TFTR is shown in Fig. 2. The aperture has a large solid angle ($\sim 2\pi$ sr) to collect betas over the widest possible range of pitch angles. A biasable mesh grid over the aperture is used to repel low-energy ($\leqslant$100 eV) secondary electrons, which may be made in the passage through the wall.[3] The prototype detector is an Amptektron channel electron multiplier with a built in high-voltage power supply and pulse forming electronics.[8] This detector has no intrinsic energy resolution, so for the initial experiments the pulse signals will be converted into an analog signal proportional to the count rate, with a time resolution ~1 ms. Later iterations may be made using a p-i-n diode detector, which has good energy resolution.[1]

The expected beta flux steered toward this detector should depend only weakly on the magnetic-field strength, since the magnetic fields will not focus or defocus the beta stream. However, the beta flux through the aperture will depend on the ratio of the electron gyroradius ρ to the aperture diameter d, the aperture solid angle Ω, and the angle of the field line. For the first TFTR prototype with $d \sim 0.1$ cm $\ll \rho$ and $\Omega \sim 2\pi$, the collected beta flux per unit aperture area should be similar to that emitted directly at the wall area which is magnetically connected to the detector.

Thus the expected count rate in this detector is $\sim 10^6$ counts/s for $d = 0.1$ cm, which is near the limit for pulse counting. This detector has already been bench-tested using a small tritium beta source, which for calibration purposes can be mounted onto the probe head itself or near its retracted position in the shielded basement area. An additional *in situ* calibration may be obtained by introducing low pressure tritium gas into the vessel while the magnetic fields are pointed into an area of low tritium beta emission; for example, a tritium gas level of ~100 Ci at a pressure of $\leqslant 10^{-4}$ Torr should be readily detectable.

This method would mainly be useful for determining the spatial distribution of the tritium on the wall, rather than the total tritium inventory in the vessel. The need to integrate these local signals over the whole wall area would introduce at least a factor-of-2 uncertainty in the total surface inventory.

III. BETA DETECTION USING TFTR AS AN IONIZATION CHAMBER

A method more likely to provide an accurate measurement of the *total* surface tritium inventory $\leqslant 1$ μm deep is based on an ionization chamber,[9] which is the operating principle of most commercial tritium detectors. An ionization chamber works by collecting the electron-ion pairs made by any ionizing radiation in passing through a neutral gas; typically the ionization rate is ~30–40 eV/ion, i.e., ~200 ions/tritium beta. Tritium ionization chambers generally measure the small current (~1 pA/μCi) drawn between biased walls (~10–20 V) of a small chamber (~1000 cm^3) filled with gas at near atmospheric pressure containing tritium, with an uncertainty of ~20%.

Ideally, the TFTR vacuum vessel could be made into a large ionization chamber by biasing an electrode attached to a probe similar to that in Fig. 1. The vacuum chamber would be filled with a standard tokamak gas such as helium to a pressure just large enough to stop the tritium betas (~10 Torr), to minimize the gas load on the tritium recovery system and the ionization produced by background radiation. The expected ionization current would be $\sim 10^{-3}$ A for a tritium inventory of ~1000 Ci, which is easily measurable.

The bias voltage should be large enough to prevent recombination or diffusion of the ions, but small enough to avoid gas multiplication (to simplify calibration). The appropriate voltage depends on the type and pressure of the gas and on the chamber geometry,[9] but is likely to be in the range of ~10–100 V. The current–voltage characteristic of the TFTR chamber will be measured directly to identify the plateau region characteristic of an ionization chamber.

This ionization current would be a simple measure of the total tritium content $\leqslant 1$ μm from surface, and could be calibrated with samples of tritium gas (see Sec. I). However, some tritium beta ionization may not be collected by this electrode due to diffusion or recombination, or to geometric effects due to small magnetic fields inside the vessel (~10 G). It may therefore be useful to have another electrode at a different location to cross-check this measurement.

IV. SCINTILLATOR DETECTOR USING A FILL GAS

A third possible method to measure tritium inside TFTR would be to fill the chamber with a scintillating gas and observe the light emission with discrete detectors or TV cameras. This technique could provide good spatial resolution if the pressure was raised high enough, e.g., the tritium beta range is ~0.3 cm in helium at atmospheric pressure. Scintillation light from tritium beta decay in solid phosphors is used in exit signs (~20 Ci) and watch dials (~0.2 Ci).

The scintillation processes in gases is due to molecular excitation and subsequent photon emission. The efficiency is highest for inert gases and increases with their atomic number; for example, He and Ar make ~1000 photons per 4.7 MeV alpha at atmospheric pressure.[9,10] Noble gases emit predominantly in the ultraviolet ~300–400 nm, but a small percentage of nitrogen mixed with a noble gas can shift its emission partially into the visible. This efficiency is ~0.1% for conversion of alpha particle energy into photons, and is presumably similar for betas.

Thus the betas emitted from ~10 000 Ci of tritium inside the vessel would produce at least ~0.3 mW of UV light, or $\sim 10^{-11}$ W/cm^2 sr when stopping in a scintillating gas. If this emission were at 400 nm and imaged at $f/2$ with an optical transmission of 0.5 onto an imaging detector with quantum efficiency of 0.2, it would result in about four electron-hole pairs per second per 20 μm×20 μm pixel. The emission could be increased by gas multiplication using an inserted electrode, although probably with a loss of spatial resolution.[11] The UV emission can be converted to visible using a small amount of nitrogen or organic gas,[10] or with a fluorescent UV-visible converter just outside a vacuum window.

V. RADIATION BACKGROUNDS INSIDE THE TFTR VESSEL

Measurements of tritium beta decay activity inside the TFTR vessel must take into account the background due to the decay of residual radioactivity in the tokamak structure caused by the DT neutrons.[12] The primary residual decay product inside the vessel is γ rays, which have a broad energy spectrum with a maximum ~100 keV, with a peak energy ~2–3 MeV. The total γ ray flux inside the vessel 1 day after a series of DT discharges producing $\sim 10^{19}$ neutrons is calculated to be $\sim 2\times 10^5$ γ/cm^2 s, but is ~10× less than this after 1 month of cooling.

These γ rays can interact directly with a detector to produce background counts; however, the probability of such a direct interaction is low. For example, for the Amptektron detector the probability of counting a ~2 keV x ray is ~2%–3%[8] and decreases with increased energy, so this background should be small compared to the estimated beta count rate of $\sim 10^5$–10^6 s^{-1}, even at the end of the DT run ($\approx 1\times 10^{21}$ neutrons). Similarly, the direct γ-ray background in the gas-filled methods should be small due to the low ionization rate of the high-energy gammas.

Activation γ rays can also produce fast electrons on the inside surface of the vessel due to Compton scattering or the photoelectric effect, and nontritium beta decays may also occur in the surface materials of the wall. The effective probability for creating Compton electrons is relatively small, e.g., <0.03 electrons/γ in carbon.[13] Nontritium beta decays should be negligible for the carbon inner wall where most of the tritium betas are expected, but some higher energy betas may come from decay of activation products in the metallic wall surfaces.

VI. TRITIUM BELOW THE SURFACE LAYER

All the tritium beta decay measurements described above are limited to a surface layer ~1 μm thick from which tritium betas can escape. Since the tokamak wall can be eroded and codeposited over a greater depth, depending on the number of high powered discharges, it would also be useful to make *in situ* measurements of the this subsurface tritium. Previous surface analysis[4,5] suggests that ~50%–90% of the tritium in the TFTR wall may eventually reside in this subsurface codeposited layer by the end of the DT run.

Subsurface tritium could potentially be measured by a controlled evaporation of a selected surface layer, e.g., by the laser release method. The newly exposed surface can be measured with the methods of Secs. II or IV, and the released tritium can be measured by the beta decay methods above, by a residual gas analyzer, or by spectroscopic means[14] in the presence of an ohmic plasma.

For evaluating the tritium inventory inside the TFTR vessel during the post-DT clean-up campaign, it may be sufficient to show a relative decrease, e.g., by a clean-up campaign with HeO glow discharges. After this period the extent of subsurface tritium will also be evaluated by removing samples of wall material for *ex situ* analysis, and by measuring tritium pumped from the vessel into the gas holding tank.

ACKNOWLEDGMENTS

We thank R. J. Hawryluk and K. M. Young for helpful comments. This work was supported by DOE Contracts Nos. DE-AC02-CHO-3073 and DE-AC04-94AL85000.

[1] W. R. Wampler and B. L. Doyle, Nucl. Instrum. Methods (to be published).
[2] T. Ida and Y. Ikebe, Nucl. Instrum. Methods Phys. Res. A **253**, 119 (1986).
[3] M. E. Malinowski and R. A. Causey, J. Vac. Sci. Technol. A **6**, 2310 (1988).
[4] W. R. Wampler *et al.*, J. Vac. Sci. Technol. A **6**, 2111 (1988).
[5] M. Ulrickson, H. F. Dylla, P. H. LaMarche, and D. Buchenauer, J. Vac. Sci. Technol. A **6**, 2001 (1988); M. Ulrickson, Proceedings of the IEA Large Tokamak Workshop on Tritium Experiments, 1992 (unpublished).
[6] P. Andrew *et al.*, JET Joint Undertaking, Abingdon, Oxfordshire; D. H. J. Goodall and G. M. McCracken, Nucl. Fusion **33**, 1389 (1993).
[7] R. D. Evans, *The Atomic Nucleus* (McGraw-Hill, New York, 1955).
[8] Amptektron model MD-501, Amptek, Inc., Bedford, Massachusetts.
[9] See e.g., G. F. Knoll, *Radiation Detection and Measurement* (Wiley, New York, 1979).
[10] J. B. Birks, *Theory and Practice of Scintillation Counting* (Macmillan, New York, 1964).
[11] A. J. P. L. Policarpo, Space Sci. Instrum. **3**, 77 (1977).
[12] L. Ku and J. Kolibal, Nucl. Technol. Fusion **4**, 586 (1983); L. Ku and S. Liew, 15th Symposium on Fusion Engineering, Hyannis, MA, 1993 (unpublished).
[13] T. A. Dellin, R. E. Huddleston, and C. J. MacCallum, IEEE Trans. Nucl. Sci. **NS-22**, 2549 (1975).
[14] C. H. Skinn, H. Adler, R. V. Budny, L. C. Johnson, J. Kamperschroer, A. T. Ramsey, and D. P. Stotler, Princeton Plasma Physics Laboratory Report PPPL 2993 (1994).