METHODS FOR THE MEASURING SURFACE TRITIUM INSIDE TFTR USING BETA DECAY

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Methods for the Measuring Surface Tritium
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Abstract

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 $\approx 1\mu m$ of the inner wall surface.

Locating and recycling unburned tritium fuel from the inner walls of DT tokamaks like TFTR, JET and ITER is important since its in-vessel inventory needs to be minimized for radiological safety reasons. In this paper we describe three potential techniques for *in situ* measurements of the tritium residing on the inner surface layer of 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 PIN diode or channeltron detector[1]. Beta emission from tritium implanted in surfaces has also been measured by using a proximity-coupled 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 can not (yet) be used for tiles in the TFTR DT vessel since the tritiated wall tiles can not be removed before the run is over.

Spatially resolved and global measurements of the surface tritium contamination should be made inside the TFTR vacuum vessel during the DT experimental run, the tritium clean-up campaign, and prior to venting for decommisioning. Strong spatial non-uniformities 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 monoenergetic tritium betas in carbon is ≈3 μm[7], all tritium measurements made using beta detection are restricted to tritium within a surface layer ≈1μm thick. Therefore, these measurements provide a *lower limit* to the tritium inventory inside the vessel. Approximately half of the tritium is expected to be in co-deposited layers ≥1μm thick or in

cracks between the carbon wall tiles[4,5], neither of which would be directly visible via beta detection (see Sec. V).

The tritium inventory inside the TFTR vessel is restricted to $\leq 2 \times 10^4$ Ci. Assuming that $\approx 1 \times 10^4$ Ci is within ≈ 1 μm of the vessel surface area of $\approx 10^6$ cm^2, the averaged beta emission rate should be $\approx 4 \times 10^8$ betas/cm^2-sec, which corresponds to a current of $\approx 6 \times 10^{-11}$ amps/cm^2 or a power of $\approx 6 \times 10^{-7}$ watts/cm^2.

I. 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 drive. The horizontal and vertical magnetic fields of the tokamak are applied without a plasma and without any filling gas present. The betas emitted from the wall are "steered" by the magnetic field onto the probe head, allowing the area examined to be scanned poloidally and possibly toroidally (with an additional toroidal field component).

The betas emitted at the wall will spiral around 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 is ρ(cm) $\approx$ 3.4(100 Gauss/B) sin χ. Thus the viewing area at B=100 G is about $2\rho \approx 7$ cm, which is suitable for examination of the ≈ 2 m high inner bumper limiter. The available magnetic field range of 10-100 Gauss can be scanned during a standard TFTR shot cycle time of ≈ 8 sec 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 ($\approx 2\pi$ str) to collect betas over the widest possible range of pitch angles. A biasable mesh grid over the aperture is used to repel low energy (≤ 100 eV) secondary electrons, which may be made in the passage through the wall[3]. The first prototype

detector will be 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 with a time resolution ≈ 1 msec and recorded with a transient digitizer. Later iterations may be made using a PIN 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 $d\approx 0.1$ cm$<<\rho$ and $\Omega\approx 2\pi$, 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 $\approx 10^6$ counts/sec 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 the detector in its retracted position in the shielded basement area. An additional *in situ* calibration may be obtained by introducing a low pressure of 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 $\leq 10^{-4}$ 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 most likely introduce at least a factor of two uncertainty in the total inventory on the wall surface ($\leq 1\mu$m thick).

II. Beta Detection Using TFTR as an Ionization Chamber

The method most likely to provide an accurate measurement of the *total* surface tritium inventory $\leq 1\mu m$ 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 $\approx 30\text{-}40$ eV/ion, i.e. ≈ 200 ions/tritium beta. Tritium ionization chambers generally measure the small current (≈ 1 pA/μCi) drawn between biased walls ($\approx 10\text{-}20$ volts) of a small chamber (≈ 1000 cm^3) filled with gas at near atmospheric pressure containing tritium, with an uncertainty of $\approx 20\%$.

The TFTR vacuum vessel could be made into a large ionization chamber by biasing an electrode attached to a probe head 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), in order to minimize both the gas load on the tritium recovery system and the ionization produced by background radiation. The expected ionization current would be $\approx 10^{-2}$ amps for a tritium inventory of $\approx 10,000$ 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 $\approx 10\text{-}100$ volts. The current vs. 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 $\leq 1\mu m$ 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 small (unknown) magnetic fields inside the vessel (≈ 10 Gauss). It may therefore

be useful to have another electrode at a different locations to cross-check this measurement.

III. Scintillator Detector Using a Filling 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 emission 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 ≈10^{-11} watts/cm^2-str 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 4 electron-hole pairs per second per 20μm x 20μm pixel. Long integration times (10^3 -10^4 s) with cooled CCD detectors would be one possibile imaging technique, although background light and activation gamma induced background in the CCD would be concerns. The emission could be increased by gas multiplication using an inserted electrode, although probably with considerable loss of spatial resolution[11]. The UV emission can be converted to visible using a small amount of nitrogen or organic gas[10], or the camera might be used

with a flourescent UV-visible converter just outside a vacuum window prior to imaging.

IV. 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 at $\approx$100 keV and a peak energy of $\approx$2-3 MeV. The total γ-ray flux inside the vessel 1 day after a series of DT discharges producing $\approx 10^{19}$ neutrons is calculated to be $\approx 2 \times 10^5$ γ/cm^2-sec, but is $\approx$10 times 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 an $\approx$2 keV x-ray is $\approx$2-3%[6] and decreases with increased energy, so this background should be small compared to the estimated beta count rate of $\approx 10^5$-10^6 sec^{-1}, even at the end of the DT run ($\leq 1 \times 10^{21}$ 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 non-tritium beta decays may also occur in the surface materials of the wall. The effective probability for creating Compton electrons is relatively small, e.g. <.03 electrons/γ in carbon[13]. The photoelectric effect is more efficient in creating electrons at low γ energy, but the probability of low energy electrons escaping from the inner surface of the vessel is smaller. Non-tritium 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 at other poloidal angles.

V. 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 co-deposited 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 sub-surface tritium. Previous surface analysis[4-5] suggests that ≈ 50-90% of the tritium in the TFTR wall may eventually reside in this sub-surface co-deposited layer by the end of the DT run.

Sub-surface 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. 1 or 3, 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 the particular application of evaluating the tritium inventory inside the TFTR vessel during the post-DT cleanup campaign, it may be sufficient to monitor the surface tritium levels to show that they are diminished substantially from its level at the end of the DT run, e.g. by a cleanup campaign with HeO glow discharges. After this period the extent of sub-surface tritium will also be evaluated by removing small samples of wall material for *ex situ* analysis, and by measuring tritium pumped from the vessel into the gas holding tank.

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Figure Captions

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.

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 ≈10^6 counts/sec. The biased grid is used to suppress secondary electrons emitted from the wall, and the aperture is used to limit the beta count rate.
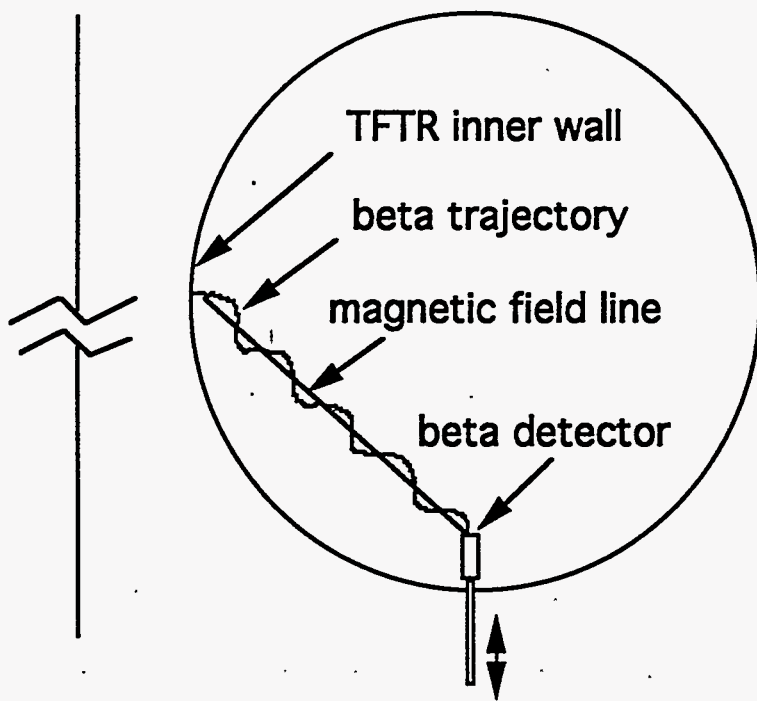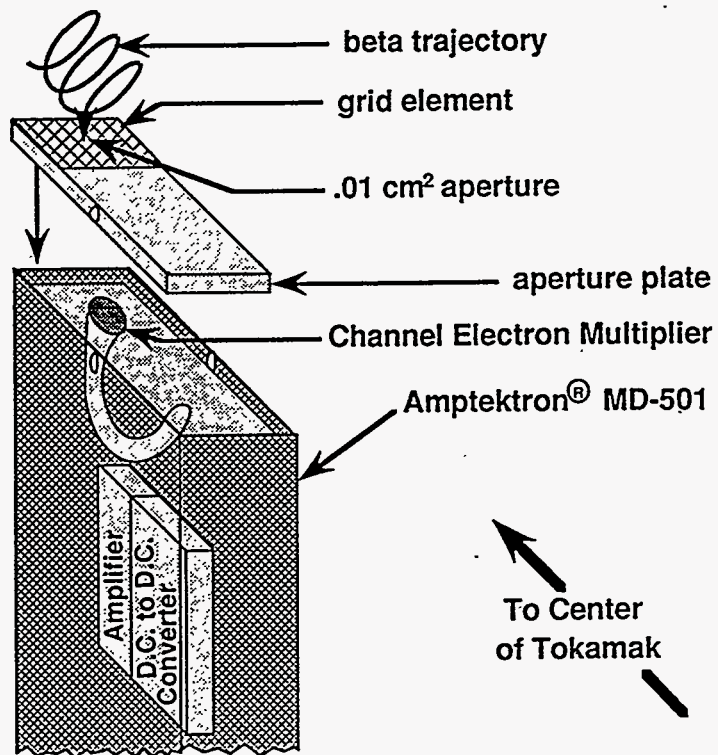
Fig. 1

Fig. 2

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