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Fusion Engineering and Design 34-35 (1997) 53-58

Fusion Engineering and Design

Alpha particle loss diagnostics in TFTR and tokamak reactors

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Abstract

Measurement of alpha particle loss rates to the first wall is of importance in planning tokamak fusion reactors, since large loss rates can adversely affect performance. A set of scintillator-based probes has been operated in TFTR to measure alpha particle losses during its DT campaign. A sample exposure probe has also provided alpha particle loss data under some conditions. These technologies, along with infrared imaging and Faraday cups, may be adaptable to alpha particle loss measurements in ITER or other reactor-scale tokamaks. Constraints on detector operation in a reactor environment are discussed. © 1997 Elsevier Science S.A.

Keywords: Alpha particle losses; TFTR; Tokamak

1. Introduction

Future tokamak reactors, such as the International Thermonuclear Experimental Reactor (ITER) [1], plan to operate in the ignited plasma regime, where alpha particles produced by the fusion reactors maintain the plasma at an adequate temperature for ongoing fusion, and also heat the incoming fuel. Such devices will have a large alpha power, e.g. 300 MW in ITER. Significant levels of energetic alpha particle loss from the plasma would be of concern for two main reasons: first, due to diminished self-heating of the plasma and possible extinguishing of the burn; and second, due to the large amount of energy deposited on the first wall by the alphas, which might cause melting or other damage. To understand the mechanisms which cause alpha particle loss from tokamak plasma, fast ion loss measurements have been made on the Tokamak Fusion Test Reactor (TFTR) and a number of other tokamaks [2-8]. From these measurements, alpha particle loss processes have been identified, loss models have been tested and predictions for reactor-scale devices can be made. By the same line of argument as noted above, alpha particle loss detectors will be an important diagnostic for reactor-scale tokamaks.

Section 2 of this paper briefly describes two types of alpha particle loss detectors used in TFTR. This is followed, in Section 3, by a discussion of the possible methods of measuring alpha particle loss in future devices and a consideration of the constraints imposed upon such detectors by the reactor environment.

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PII S0920-3796(96)00690-4

2. Escaping alpha diagnostics in TFTR

The TFTR diagnostic of alpha particle loss [2,9] consists of a set of four probes at a single toroidal angle and at poloidal angles of 20°, 45°, 60° and 90° below the outer midplane. The probe at 20° below the outboard midplane can be moved radially to provide a measurement of the scrapeoff distance for the fast ions there [10]. The other probes are fixed in position, with their apertures at a minor radius ~ 1.5 cm larger than the limiter minor radius. The probes measure fast ions with gyroradii between 2 and 12 cm and pitch angles between 45° and 83°, where the pitch angle is defined as $\chi = \arccos(v_{tor}/v)$. The structure of the probes is shown schematically in Fig. 1. Each is essentially a metal box with a planar scintillator inside on top and a set of two apertures on one side. Alpha particles (and other fusion products or fast ions) that are on trajectories which pass through both apertures are dispersed according to gyroradius and pitch angle in the plane of the scintillator. Fast ions which strike the scintillator produce visible light. A set of lenses at the bottom of the box focuses light from the scintillator into a coherent fibre optic bundle outside of the vacuum vessel, which transmits the image of the scintillator to detectors which are in a radiation-shielded location.

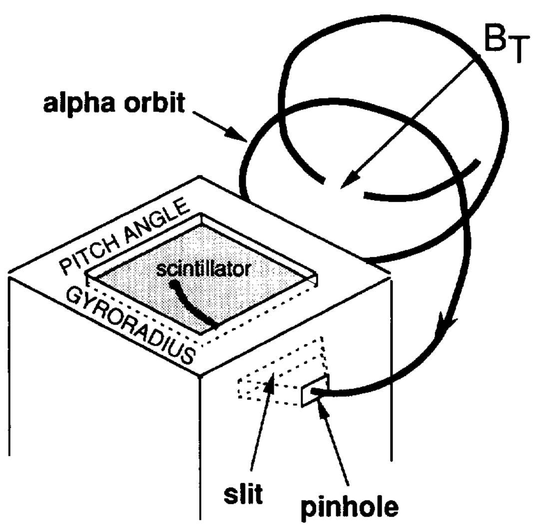

Fig. 1. Schematic diagram of the escaping alpha probes in TFTR. The two apertures disperse fast ions according to their pitch angle and gyroradius on to the scintillator.

The scintillator material is P46 ($Y_3Al_5O_{12}$:Ce), which was selected for DT operation in TFTR based on its performance characteristics. It has excellent linearity at high fluxes and prolonged resistance to damage from accumulated alpha fluence [11-13]. The light from the scintillator is split between several detectors, including a photomultiplier, which gives the total alpha particle loss rate to each probe, and an intensified video camera, which gives an image of the light pattern on the scintillator, from which the pitch angle and gyroradius dependence of the loss can be inferred.

This scintillator detector system has been in operation since 1988 and has produced results from both DD and DT discharges in TFTR. The principal results have been as follows: (1) observation of losses in the 90° detector in both DD and DT discharges which match those predicted by a model of first orbit loss [14]; (2) observation of stochastic ripple diffusion loss of DD and DT fusion products to the 20° detector, which showed qualitative agreement with numerical models [15-17]; (3) observation of MHD-induced losses of DD and DT fusion products [18]; (4) observations of fast ion losses due to collective instabilities driven by neutral beam ions or ICRF H-minority tail ions [19,20]; and (5) measurements of fusion product and fast ion losses due to ICRF fast waves and ion Bernstein waves [21].

A second escaping alpha detector was recently developed to look exclusively at alpha particle loss from DT discharges [22]. This is a sample exposure probe [23-25], located at 90° below the midplane, that traps collected alpha particles in nickel foils. The probe is cylindrical and has two rows of apertures, each row consisting of eight apertures spaced equally around its circumference. Each aperture is 6 mm in diameter and 6 mm deep, providing some pitch angle resolution. Inside each aperture is a stack of 1 μm thick nickel foils, 10 layers deep. The discrete layers provide some energy resolution since more energetic alpha particles can penetrate more deeply into the stack. Typically, these foils are exposed for the duration of one DT discharge, and then extracted from the vessel. They are then analyzed by placing the foils in a vacuum chamber, melting the layers one by one, and measuring the partial pressure of helium in the chamber that results when the alpha particles are released from the foil.

The sample exposure probe provides an absolutely calibrated measure of the alpha particle losses. Measurements have been made both at low and high current. The measurements from the lower current case ($I_p = 1.0$ MA) are in good agreement with the first orbit loss model in magnitude, pitch angle and energy. However, the measurements at higher current ($I_p = 1.8$ MA) show an apparent loss of partially thermalized alphas considerably larger than first orbit loss. This latter loss is not seen by the scintillator probes [14], but has features similar to the anomalous delayed loss [26] seen in DD plasmas.

3. Options for escaping alpha particle measurements in reactor-scale tokamaks

It is desirable to measure alpha particle losses from reactor-scale tokamak plasmas to ascertain the magnitude of loss to the wall and to learn whether previously unforeseen losses are occurring. The latter could damage the wall if the losses are large enough. The environment of a reactor plasma, however, places several constraints on the type of detection technique which can be used.

An estimate of the alpha flux to the ITER wall from first orbit loss can be made by taking the loss rate to be $\sim 1\%$ of the source rate [1], giving a loss of $\sim 5 \times 10^{18}$ α/s. If this is spread over one-quarter of the wall area, ~ 250 m^2, it yields a flux of $\sim 2 \times 10^{16}$ α/m^2/s. For a Faraday cup detector, this is 320 nA/cm^2. Expressed in terms of heat flux, it is 11 kW/m^2. Stochastic ripple diffusion loss of alpha particles in ITER will be larger than first orbit loss, with calculations ranging from 2 to 5% of the source rate when collisional effects are included [17]. These losses will be localized both toroidally and poloidally, resulting in local fluxes several times higher than that from first orbit loss [1].

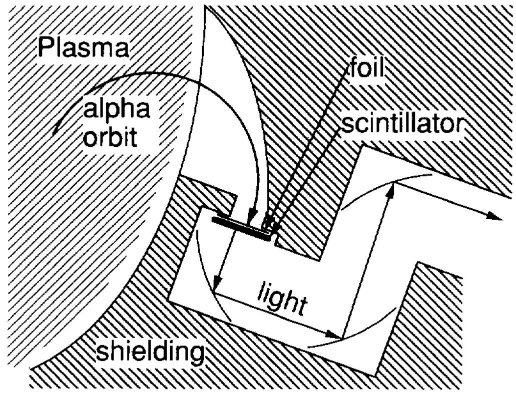

Fig. 2. Poloidal cross-section of a possible scintillator-based alpha loss detector for ITER. A groove several meters in length extending toroidally in front of the detector is necessary to allow alpha particle orbits to enter it.

The candidate methods for detection of alpha loss are scintillators [2,9,27–29], exposure samples [6,22,30], infrared imaging [31], Faraday cups [32,33] and silicon barrier diodes (SBDs) [3,5–8]. The scintillator-based detectors could be of a design similar to that used in TFTR. One possible arrangement is sketched in Fig. 2. Exposure samples could include a wide variety of materials and configurations, but would operate on the principle described in Section 2. A possible layout is shown in Fig. 3. Infrared imaging would yield a measurement of the temperature over a range of positions on the first wall of the device, showing hot spots

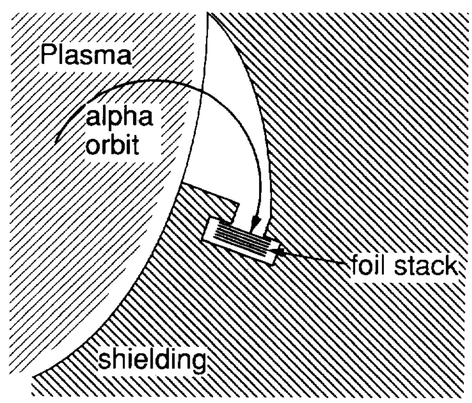

Fig. 3. Poloidal cross-section of a possible sample exposure alpha loss detector for ITER. The geometry required is similar to that for the scintillator detector.

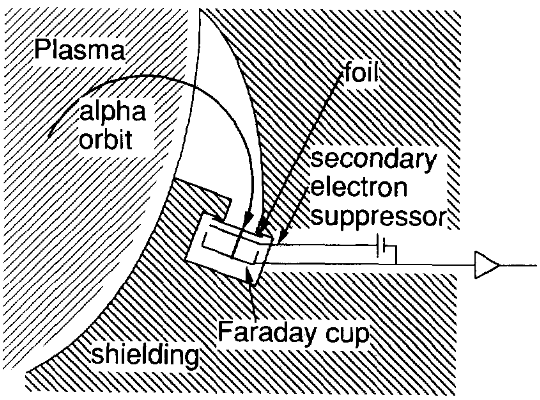

Fig. 4. Poloidal cross-section of a possible Faraday cup alpha loss detector for ITER.

caused by localized alpha particle loss. (Thermocouples in the first wall could also provide this sort of information, but imaging would provide many more data points with much better time resolution than thermocouples could. Hence, of these two, only imaging need be considered.) Faraday cups would measure the alpha particle current incident upon them, and a possible arrangement is shown in Fig. 4. SBDs would generate an electrical pulse for each alpha particle incident upon it, and might be used in place of the Faraday cup in Fig. 4.

The first constraint on candidate detectors is the neutron flux at the wall. For ITER, this is an average 1 MW/m^2, or about 4.3×10^{17} $n/m^2/s$. This flux immediately rules out SBDs, which typically fail after an accumulated fluence of $\sim 10^{18}$ n/m^2. Neutrons can produce background light in scintillators, and so these should be made as thin as possible, consistent with stopping the alpha particles fully, ~ 10 μm, in order to minimize the cross-section for interaction. Accumulated neutron and alpha fluence would contribute to damaging the crystalline structure of the scintillators so that they would have to be replaced at intervals, e.g. every few hundred to few thousand full power pulses in ITER for likely candidate scintillators. Optical fibres, such as were used in the TFTR detector system, cannot be used in this environment, since the neutron-induced light would overwhelm the alpha signal. In the TFTR system, the signal to background ratio is about 1:1, with the majority of the background signal being due to neutron-induced light in the optical fibres. In ITER, the average alpha flux to the wall will be half that of TFTR, while the neutron flux will be roughly 10 times larger, meaning that the signal to background ratio would be unacceptably small in a system using optical fibers. In ITER, optical diagnostics of the plasma are designed to use chains of relay mirrors in place of optical fibers. The same technique would need to be used for these detectors.

The neutron flux prohibits the infrared camera for infrared imaging from being in or near the vessel. Hence, a system of relay mirrors will also be required for this diagnostic. Neutrons may produce some background signal in Faraday cup detectors due to charged particles resulting from (n, p) and (n, α) reactions, as well as scattered electrons produced by gamma rays that accompany the neutrons [34]. Exposure samples must be made of materials with small cross-sections for (n, α) reactions.

The second constraint is that of the wall temperature. For ITER, the bulk of the wall is intended to operate at $\sim 200°C$, with significantly higher temperatures possible in the regions of greatest alpha flux. Inorganic scintillators tend to diminish in luminosity as their temperature increases, with most losing 50% or more by 300°C [13]. This may require a thermocouple attached to the scintillator substrate in order to calibrate the light output properly. In contrast, infrared measurements will simply become easier if the wall grows hotter. Temperature should have little effect upon Faraday cup detectors. For exposure samples, too high a temperature can cause the embedded helium to diffuse much more rapidly, resulting in lessened accuracy. For instance, 400°C is the operational limit for nickel samples.

The scintillator, Faraday cup and exposure sample detectors all must occupy some recess in the first wall. To permit alpha particles to enter these detectors, there must be some groove or trench in the wall tiles, so that tiles upstream of the detector do not intercept the alpha flux. This results in tiles with unshadowed corners which may then become excessively hot. Such an arrangement is considerably more difficult in the may then become excessively hot. Such an arrangement is considerably more difficult in the divertor area, where it would mean that some surfaces would be nearly perpendicular to the local magnetic field (and heat flux), rather than at a more tolerable shallow angle.

The infrared imaging approach does not require any such geometrical perturbations to the wall. However, care is required to assure that the observed heat fluxes are in fact due to alpha particle loss and not other phenomena.

A factor in the reactor environment which could affect all of these methods of measurement is the steady erosion and deposition of wall materials by the plasma. The scintillator and Faraday cup detectors should have thin metallic foils in front of them to exclude low-energy particles. Deposition of additional material on the front of these foils can attenuate the alpha flux to the probe. For the exposure sample, additional material on the front surface can cause alpha particles to stop at a shallower depth relative to its original surface, distorting the inferred energy spectrum of the incident alpha particles. Sputtering or coating of the first mirror for the infrared system would impair its calibration and spatial resolution. For the techniques dependent upon thin foils, the ability to measure the thickness and composition of any deposited coating at intervals would be beneficial in improving their calibration. A scintillator detector with some gyroradius resolution might be calibrated simply be measuring the gyroradius of the loss periodically under some standard condition where only birth-energy alpha particles escape.

Of these methods, infrared imaging is probably the easiest to implement. The others, however, can provide more information about the energies or other properties of the incident alpha particles. Under the correct circumstances, it may even be possible to combine types of probes, for instance by electrically isolating a scintillator probe so that the alpha current to the scintillator is measured by an external circuit, as is done with a Faraday cup. Exposure samples could be similarly insulated in order to act as Faraday cups.

Acknowledgements

This work was supported by US DoE contract number DE-AC02-76CH03073.

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