Constraints on escaping alpha particle detectors for ignited tokamaks[a)]

S. J. Zweben, R. Boivin, S. L. Liew, D. K. Owens, J. D. Strachan, and M. Ulrickson
Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543

(Received 9 May 1990; accepted for publication 9 May 1990)

Several modifications to existing escaping alpha scintillation detectors in TFTR will be needed before they could be used on ignited tokamaks such as CIT or ITER. The main difficulties are the large heat flux at the desired detector locations and the accumulated radiation damage to the scintillator itself. Constraints imposed by these problems can probably be overcome by using remotely movable (and removable) detectors.

I. INTRODUCTION

Escaping alpha particle diagnostics could be used in ignited tokamaks to determine the net alpha heating power (i.e., the neutron-inferred alpha source rate minus the escaping alpha power) and the characteristics (space-time-energy-pitch angle distribution) of alpha heat and particle flux to the wall and divertor plates. This paper describes our preliminary ideas concerning the design of escaping alpha detectors for ignited tokamaks such as CIT or ITER, based mainly on experience with escaping MeV-ion scintillation detectors in TFTR. Final designs for such detectors for ignited tokamaks have not yet been attempted.

II. TYPES OF ESCAPING ALPHA ORBITS

Several different physical mechanisms can bring fast alpha particles to the tokamak wall, as summarized in Table I. Ideally, the escaping alpha detectors should be able to measure and distinguish each of these.

The simplest alpha loss mechanism is the first-orbit loss, which occurs when the alpha is born within a banana width $\Delta_\alpha \approx q\rho_\alpha$ from the wall, where q is the local magnetic safety factor (≈ 3) and ρ_α is the alpha gyroradius (2.5 cm for CIT and ≈ 5 cm for TFTR and ITER).[1-3] For this mechanism, the alpha gyrocenters approach the wall nearly along a magnetic field line (see below), and their impacts are distributed (at least for circular tokamaks) with a weak maximum near 90° below the outer midplane (in the ion grad-B drift direction). The energy of these orbits is very nearly the alpha birth energy of 3.5 MeV, and their pitch angles (with respect to the plasma current direction along B) are about 40°–60°. For high current tokamaks like CIT or ITER the expected first-orbit loss flux of alphas of this type is nearly equal to the fraction of alphas born within Δ_α of the wall, which is maximally $\approx 5\%$ for the (highly unlikely) case of flat source profiles, but more likely a negligible $10^{-3}\%$ for a normal parabolic-to-the-sixth source profile.

The next-simplest alpha escape mechanism is toroidal field ripple-induced diffusion of trapped alpha orbits.[4] This process allows confined trapped alpha orbits born in the "stochastic region" outside $\approx a/2$ to diffuse to within Δ_α of the wall, leading to alpha loss fractions on the order of $\approx 1\%$ for 25 MA ITER plasmas (and $\approx 10\%$ for 10 MA CIT-type plasmas).[5-7] The trajectories of these orbits as they approach the wall are similar to prompt loss orbits, making them somewhat difficult to distinguish from prompt losses in present experiments. The main distinguishing feature of this type of loss is that it should be highly localized just below the outer midplane.[8] Another distinguishing feature is the pitch angle distribution, which should peak at angles roughly 10°–20° lower than those for first-orbit losses (since the banana tips should be located just above the plasma center instead of to the small major radius side as for first-orbit loss). A possible distinguishing feature is also the energy spectrum, which should show a slight decrease in energy for the temporarily confined ripple diffusion losses (but only by less than 10%, which is difficult to measure with the scintillator detectors).

A third type of alpha loss is due to "ripple trapping" of alphas in the magnetic wells between the toroidal field coils. These particles have $\approx 90° \pm 10°$ pitch angles and drift nearly vertically downward into the wall at about $\delta_V \approx \pi\rho_\alpha^2/R \approx 0.3$ cm/orbit for TFTR.[9] They occur mainly through conversion of ripple-diffusing trapped orbits into ripple-trapped orbits near the plasma edge. Recent calculations for ITER suggest that this mechanism could produce the dominant local alpha particle and heat flux to the wall (with an average alpha heat load of 0.1 MW/m^2).

The last type of alpha loss is that due to plasma instabilities, which could produce a wide variety of space-time loss patterns. For example, high-frequency Alfven modes (at about 0.1–1.0 MHz) might cause losses similar to plasma-generated ripple diffusion, while low-frequency "fishbones" may eject bursts of alphas on a timescale of $\approx 10\ \mu$s. Instability-induced loss should be diagnosed with detectors having good time resolution (up to 1 MHz) and wide pitch angle resolution (to near 0° pitch angle), since passing particles might also be lost to either the wall or to the divertor plate.

III. EXTRAPOLATION OF TFTR ESCAPING ALPHA DETECTORS

The TFTR escaping alpha scintillation detectors are located inside discrete carbon-armored boxes just outside the minor radius of the poloidal limiters.[3,10] Eight similar detectors were installed in 1988, several of which have successfully measured the first-orbit loss of alpha-like D-D

[a)]The abstract for this paper appears in the *Proceedings of the 8th Topical Conference on High Temperature Plasma Diagnostics* in Part II, Rev. Sci. Instrum. **61**, 3233 (1990).

TABLE I. Types of escaping alpha orbits.

Loss type	% alphas lost[a]	Location of loss	Pitch angle	Energy	Time dependence
First orbit	$<1\%$	broad poloidal/ toroidal distribution	$\simeq 40°–60°$	3.5 MeV	Slow variations >0.1 s
TF ripple diffusion	$\sim 1\%–10\%$	near outer midplane	$\simeq 40°$ (?)	$\simeq 3.5$ MeV	>0.1 s
TF ripple trapping	$\sim 0.1\%–0.3\%$	TF ripple wells $\simeq 45°$ below midplane	$90° \pm 10°$	<3.5 MeV	>0.1 s
Instability	0%–100% (?)	(?)	any	?	Up to 1 MHz

[a]Approximate range shown for 10–25 MA CIT/ITER plasmas.

tritons and protons (which have orbits nearly identical to the 3.5 MeV alphas).

A. Geometrical constraints

The success of these detectors has so far depended upon the fact that they were located far away toroidally from the poloidal limiters. This is illustrated in Fig. 1, where a typical first-orbit-lost alpha-like ion is shown entering a detector aperture located radially behind a toroidally displaced limiter. The thermal load and scintillator temperature were kept at acceptable levels since the detector box was located in the radial shadow of the limiters, while the alpha-like orbits with a radial angle "σ" could still enter the detector aperture. Even at such relatively well shielded locations, the temperature inside the box near the scintillator occasionally reached ≈ 100 °C during high-power operation, and the surface of the carbon armor reached at least several hundred degrees C in fault conditions (e.g., disruptions).

The radial angle of the alpha orbit gyrocenter with respect to the local magnetic field near the wall can be found from the ∇B and $\nabla \times B$ drifts to be approximately

$$\sigma \approx (\rho_0/R)(\cos\chi + 0.5\sin^2\chi/\cos\chi)\sin\theta, \qquad (1)$$

where ρ_0 is the maximum gyroradius of the particle (at 90° pitch angle), R is the major radius, χ is the pitch angle of the particle with respect to B, and θ is the poloidal angle of the detector (measured from the outer midplane). For TFTR at $B = 50$ kG, $\rho_0 = 5$ cm, $R = 250$ cm, $\chi \approx 40°–60°$, and $\theta = 90°$ this angle is $\sigma \approx 0.02$ rad, thus (easily) allowing the detector aperture to be 3 cm radially behind a poloidal limiter located ≈ 500 cm away toroidally from the detector (as it was during the 1988–1990 TFTR runs). In practice, evaluations of this geometrical constraint were made using the PPPL single-particle orbit code ORBIT,[11] which includes realistic magnetic tokamak fields and simplified 3-D limiter geometries.

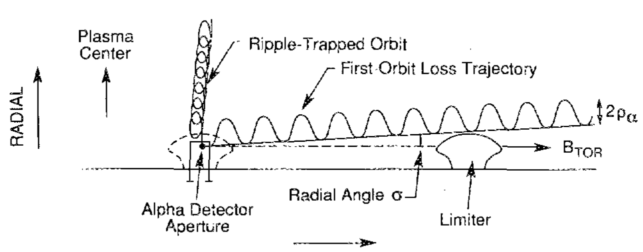

FIG. 1. Schematic view of escaping alpha orbits near the tokamak wall. The first-orbit and ripple-diffusion loss orbits approach the wall at a small radial angle $\sigma \approx 0.02$ rad, thus requiring that the escaping alpha detector be located radially just behind the limiter boundary. Orbits which are ripple-trapped move vertically downward and could be detected farther outward radially, although the vertical drop per orbit is very small (≈ 0.1 cm).

For future TFTR runs a new set of poloidal limiters will be installed, one of which is only ≈ 200 cm toroidally (co) from the existing detectors. This in turn requires that the apertures be moved radially inward so that they are no more than about 1 cm radially behind the limiter. This leaves very little room above the aperture for placement of the scintillator itself (≈ 0.5 cm), the tantalum x-ray shield (0.1 cm), and the carbon armor to protect the detector box from plasma heat flux ($\simeq 0.4$ cm). This assumes that no part of the detector or its armor can be inserted farther in radially than the nearby limiter, due to the large plasma heat flux expected to flow along field lines which can heat exposed limiters to > 1500 °C.

B. Heat loading problems

Even though the geometrical configuration with new TFTR limiters will be feasible with the present detector geometry, the decreased distance between the limiter edge and the detector itself will tend to increase the temperature of the scintillator, which might then occasionally exceed its operating temperature (≈ 150 °C for P11, i.e., ZnS[Ag]). Although calculations of heat fluxes behind the limiter shadow are routinely done, the results are contingent on the plasma shape and the edge plasma diffusion rate, and so maximum thermal protection is desirable.

To protect the detector from plasma heat flux an armored "mushroom"-shaped cap is presently being designed, as shown schematically in Fig. 2. This armor can be mechanically and thermally isolated from the detector box, and can be made of 2-D carbon composite in order to channel the heat flow away from the interior. Note that any such armor design for first-orbit or stochastic loss needs to include a cylindrical cut-out in the incoming alpha direction in order to allow a wide range of pitch angles and energies to enter the aperture without being intercepted by the armor itself.

Even without direct plasma heat flux, the wall region of ignited tokamaks will be heated due to radiation, intentional baking, and nuclear heating; thus it seems to be

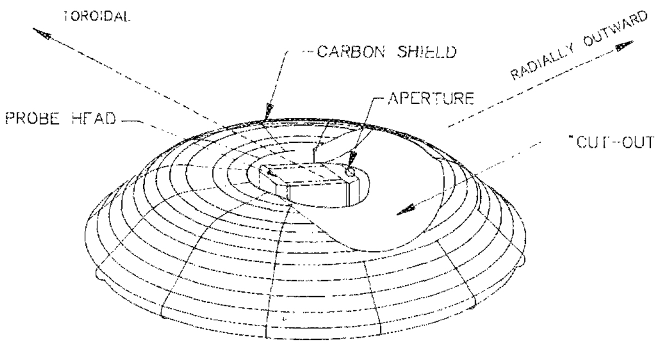

FIG. 2. Schematic view of an escaping alpha detector with a mushroom-shaped carbon armor cap to protect it from plasma heat loads. The detector aperture should be as close as possible to the top of the armor, which itself would be aligned with the other nearby limiters (see Fig. 1). In order for all the escaping alpha orbits to enter the aperture, the armor must have a cylindrical cut-out in the incoming alpha direction.

necessary to use a higher temperature scintillator than ZnS(Ag). We have found that standard phosphors P31 (ZnS[Cu]) and P46 (YtAl[Ce]) both operate at above 300 °C, but both have substantially lower light output per alpha particle than P11 ($\times 2$ and $\times 4$, respectively) and neither has been tried yet (another possibility is a high-temperature glass scintillator). In any case, it will be necessary to carefully monitor the scintillator temperature in future detectors, either with reliable thermocouples (attached to the scintillator plate itself) or with thermoluminescent fiber-optically coupled probes.

In addition, it would be desirable to maintain an *in situ* calibration with a small internal alpha source near the scintillator, particularly to monitor possible accumulated scintillator damage. Some localized blemishes were in fact observed on the ZnS(Ag) scintillators taken from the TFTR vessel after the 1988 + 1989 runs, which was apparently associated with "flaking-off" of some <1 mm sized crystal patches, perhaps due to thermal stress. Although bench tests showed that these patches did not affect the average scintillator response (i.e., $<20\%$ decrease in light output/alpha), the long-term stability of such scintillators in these unpredictable thermal environments cannot be assumed. Alpha calibration sources such as ^{241}Am would need to be rather strong to be detectable, i.e., $\approx 10^{-3}$ Cu/cm^2. Another interesting possibility for calibration would be to create a lithium-doped region on the scintillator or substrate which could create alphas *in situ* using the ^{7}Li(n,α) reaction.

As a last resort, active cooling of the scintillator can be attempted. An actively cooled escaping proton surface barrier detector was briefly operated on the JET tokamak, but concern with disruptive-instability induced damage has limited its use.

C. Radiation damage

Inorganic scintillators like ZnS eventually "burn" under extended particle impact and lose their scintillation efficiency. The TFTR (P11) scintillators were bench tested with continuous exposure to 4.5 Mev alphas from ^{241}Am, and permanently lost about half their light output/alpha at $\approx 10^{13}$ α/cm^2.[9]

With the existing TFTR aperture geometry,[3] the expected ratio of peak alpha flux at the scintillators (per cm^2) to total alpha production rate is $\approx 10^{-7}$–10^{-8} (depending on plasma current). For the 1988 + 1989 TFTR runs, no significant change in the scintillator sensitivity to alphas (i.e., $<20\%$) was observed after they were exposed to a few thousand high-power D-D shots and $\approx 10^{12}$ tritons/cm^2 (@1 MeV). However, for the 100-shot TFTR D-T run the alpha fluence could be up to $\approx 10^{13}$ α/cm^2, implying that either the scintillators need to be carefully monitored with an *in situ* alpha source, or the aperture sizes have to be reduced (or both).

There will also be irreducible scintillator damage due to fast ions created inside the scintillator by the neutron/gamma background, which cannot be shielded from these in-vessel detectors. For example, the (n,α) and (n,p) cross sections for 14 MeV neutrons on ZnS total about 1 barn,[7] which implies eventual scintillator damage after about 10^{18}–10^{19} n/cm^2, which is comparable to the neutron fluence for CIT or ITER.

IV. APPLICATIONS TO CIT OR ITER

Although these mechanical, thermal, and radiation constraints are fairly well defined, there are not yet any final designs for escaping alpha detectors for CIT and ITER. In part, this is because their first-wall designs are still evolving, and alpha detector designs depend crucially on the first wall geometry. In particular, CIT and ITER will probably have very smooth first walls to avoid localized hot spots, thus making the geometrical constraints and thermal problems associated with escaping alpha detectors particularly severe.

There are at least two ways to extrapolate the present TFTR design to these ignited machines. One is to cut a toroidally co-going, few-meter-long inclined "trench" into the local first wall to allow first-orbit and stochastic diffusion losses to reach an aperture 1–2 cm below the normal wall surface (similarly to Fig. 1). The other is to have a movable probe mechanism to transiently insert the probe through a hole in the wall, similarly to the new TFTR midplane detector.[8]

In either case, the heat loading due to plasma flow along field lines will need to be known before a final probe design could be attempted. Note that since CIT and ITER are diverted machines, the plasma heat flux to the first-wall region may be small in normal conditions, but may be extremely large under transient fault conditions (such as a plasma disruption). Thus the thermal loading problems are crucially dependent on the plasma scrape-off layer thickness, the details of the magnetic geometry, and the disruption scenario, and so are difficult to anticipate in advance.

However, given the possibility of thermal damage and the likelihood of long-term radiation damage to the scintillator, it seems desirable to allow for the removal and replacement of the scintillator during DT operation of the machine. Modular probe heads could probably be designed to be replaced from inside the vessel with the standard internal remote manipulators used for first-wall tile replacement.

Detectors for TF ripple-trapped particles can be recessed radially (i.e., vertically) below the nearby wall surface in the minimum-B regions, thus avoiding the plasma heat flow along field lines. In fact, such a recessed "dump" for ripple-trapped alphas might be otherwise desirable to reduce the impurity influx due to these particles. The main difficulty will be to design an aperture which can accept particles which drift vertically only $\delta_V \approx 0.1$ cm for CIT or ITER (see Sec. III).

The optical signals from these detectors will probably have to be coupled out with mirrors, due to the severe radiation damage expected for quartz. Several other optical diagnostics will have similar coupling difficulties.

V. OTHER POSSIBLE DETECTORS

Other possible escaping alpha detectors for CIT and ITER which could avoid the difficulties of the TFTR-type scintillation detector are:

(i) infrared cameras and thermocouples for locating "hot spots" of alpha impact on the wall, particularly at the expected ripple-trapping regions, and

(ii) sample deposition surfaces for time-integrated alpha flux measurement,[12] perhaps configured within removable first-wall or divertor tiles,

(iii) Be(α,n) reactions between the escaping alphas and judiciously located beryllium targets, which could be monitored with collimated neutron detectors.

In the first two cases the alpha flux could be measured in the normal wall configuration, which could be useful for checks of alpha deposition symmetry and damage (note that any alpha samples would need to be protected from plasma deposition and erosion). Unfortunately, neither of these methods would be useful for studying the time-dependent physics of anomalous alpha transport, which could play an important role in future D-T experiments.[13] Thus some form escaping alpha scintillator detector, or nuclear detection like (iii), seems to be necessary for ignited tokamaks, particularly for investigating possible instability-induced alpha losses.

ACKNOWLEDGMENTS

We thank S. Medley and K. Young for helpful comments about CIT. This work was supported by DOE contract No. DE-AC02-76-CH03073.

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