Operating experiences with the TFTR escaping alpha detectors

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This paper reviews the operating experiences obtained with a set of scintillator-based escaping fast ion detectors which have been used successfully for several years on the TFTR tokamak. There have been several operational problems which need to be resolved before these detectors are used to measure 3.5 MeV DT alphas in 1993. The main problem has been overheating by edge plasma heat flux for large major radius plasmas, when the detectors were not shadowed by the adjacent limiter. Other problems have been due to runaway electron-induced x-ray flux and scintillator and foil damage.

I. INTRODUCTION

A schematic drawing of the two-dimensional (2D) escaping MeV ion scintillator detector is shown in Fig. 1. High energy ions escaping from the tokamak plasma approach the 1 in.×1 in. detector on helical orbits with relative large gyroradii (2–11 cm). Some of these ions enter the pinhole and pass through the slit inside the detector box, where they are dispersed according to their gyroradius ρ (as in a magnetic spectrometer) and pitch angle χ (with respect to the toroidal magnetic field). The existing array of four such detectors on Tokamak Fusion Test Reactor (TFTR) was specifically designed to measure escaping alpha particles during the DT experiments.

A prototype 2D imaging detector was operated on TFTR in 1987,[1] based on a generically similar plastic track detector previously used on the Princeton Large Tokamak (PLT),[2] and on scintillator response tests on TFTR in 1986.[3] An array of 2D scintillator detectors was installed in the TFTR vessel in 1988. Several interesting results on escaping DD fusion products were obtained from this fixed detector array at poloidal angles of 45°, 60°, and particularly at 90°.[4,5]

The radial positions of the apertures were 102±1 cm from the center of curvature of the "rf limiter," which was at that time a poloidal ring of radius 99 cm located about 120° toroidally from the detectors. Before 1991 there was no significant damage to these detectors due to heat flux, and the maximum temperature near the scintillator was $<100\pm10$ °C, well within the operating range of the ZnS(Ag) scintillator.[6] In 1989 an additional movable probe-mounted detector was installed at a 20° poloidal angle.[7]

After the 1990 run, a new rf limiter was installed 45° toroidally in the escaping particle (co) direction from this fixed poloidal array. As discussed previously,[8] this nearby limiter would have blocked nearly all of the ion orbits which had previously been detected. Thus for the 1991 run the three detectors in the fixed array were moved radially inward 2–3 cm so that their apertures were at 100.2±0.1 cm from the nominal center of curvature of the rf limiter, which is only about 1 cm behind the nominal rf limiter surface at a radius of 99 cm.

It was anticipated that this inward repositioning would cause additional heat loads on the detector, so a protective "mushroom" was installed as well.[8] The counterfacing side of each detector was completely shielded by protective graphite mushrooms, and above the scintillator there was a protective graphite "cap," the top of which was nominally 0.2 cm outside the rf limiter radius.

II. OVERHEATING OF THE DETECTORS

There was an unanticipated heat flux from the unshielded co-facing side of the detector during the 1991 run. Indications of the overheating of the detectors came from thermocouples, an infrared TV (IRTV) camera, and from a post-run damage assessment.

The thermocouples were mounted outside of the detector box opposite the apertures (away from direct plasma flow); thus they measured the time-averaged temperature of the detector inside the nearly "blackbody" formed by the protective graphite mushroom.[8] For an $R=2.615$ m run the detector boxes reached 150–200 °C over 25 pulses with 15–25 MW of neutral beam injection (NBI) (No. 58480-58505, with no NBI within No. 58488-91), while for an $R=2.45$ m run they reached only 60–70 °C over 30 consecutive pulses with 20–25 MW of NBI (No. 59636-59666). Detector overheating (>100 °C) was observed only for the larger major radius plasmas with $R\simeq2.6$ m (R is the center of the outermost magnetic flux surface).

The other direct measurement of detector temperature was made using the survey IRTV diagnostic on TFTR,[9] which viewed only the 90° mushroom and co-facing unprotected side of the detector box. During the $R=2.615$ m shot sequence above, the surface temperature was only at least 670 °C when the internal temperature was only 50–100 °C (this is an underestimate since the size of the hot spots were less than the pixel size of the IRTV). This surface temperature did not vary significantly when the neutral beam varied from 11 to 20 MW, suggesting that the surface was in radiative equilibrium at this temperature, or that the plasma shape varied such as to reduce the local heat flux at high power. No observable temperature rise in this same region was seen for $R=2.45$ m plasmas, implying a surface temperature <300 °C.

The worst overheating damage can be seen in the photograph of the 60° detector shown in Fig. 2, which represents the integrated effect of 10 000 shots in the 1991 run.

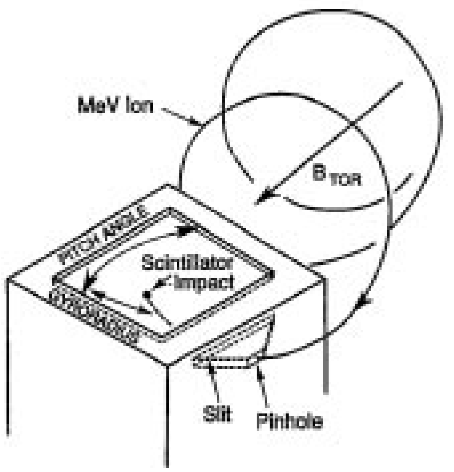

FIG. 1. Schematic drawing of the escaping alpha scintillator detector. This detector box was enclosed in a heat shield for the 1991 run, but was unprotected from the co-side (from which the escaping ions come).

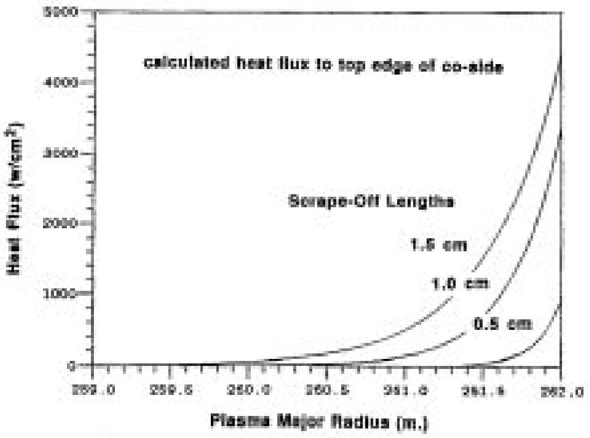

FIG. 3. Model of co-side heat flux vs plasma major radius position for the 45° detector for various scrape-off layer thicknesses. The relative heat flux increases dramatically for $R > 2.59$ m because the field lines connected to the detector move inward radially past the co-side rf limiter. The absolute value in W/cm^2 is an estimate for a high power beam discharge.

A significant part of the graphite and tantalum cap has been melted on the co-side edge. About 0.5 cm^3 of graphite was also eroded from the edge of the graphite cap of the 45° detector, and there is evidence that the braze to the tantalum melted. The stainless steel detector boxes of the 60° and the 45° detectors were also slightly melted by the co-side plasma heat flux. A small hole was melted through the top of the co-side of the 45° detector box, and the quartz scintillator just inside this spot was cracked (as was the 60° scintillator).

Analysis of the pattern of the damage shown in Fig. 2 implies that the average heat flux on the edge of the graphite cap heat flux was 2 kW/cm^2, with a radial scrape-off layer distance for power of about 1 cm. Note that the 90° detector cap suffered only very minor surface erosion and no damage to the detector.

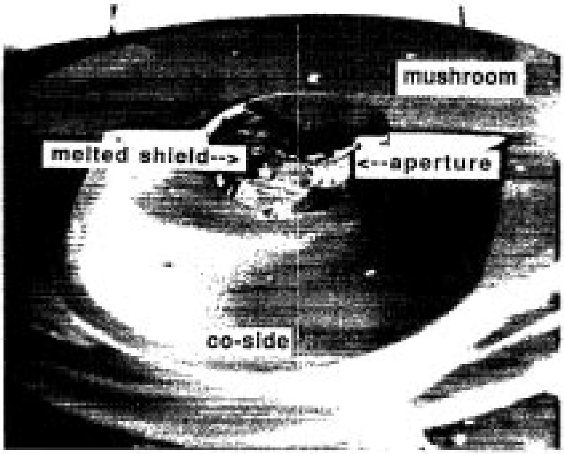

FIG. 2. Damage to the 60° detector during the 1991 run, during which the mushroom top was 0.1 cm behind the rf limiter radius. There was significant melting of the soft x-ray shield and graphite cap, and slight melting of the stainless steel detector box due to plasma heat flux from the co-side.

III. CAUSES OF DETECTOR OVERHEATING

The damage to the 45° and 60° detectors such as shown in Fig. 2 was caused by plasma heat flux in the scrape-off layer coming from the co-direction with respect to the plasma current (the same direction as the escaping fast ion orbits). No attempt had been made to shield heat from this direction, since it was thought that the magnetic field lines from this direction were always originating from the wall and not from the plasma edge.

However, this was evidently not the case for the large major radius plasmas, as described above. These observations motivated a recent reanalysis of the heat flux expected from the co-side to an object in the scrape-off region, with results for the 45° detector shown in Fig. 3 (the other detectors had similar results).

The model of Fig. 3 shows that the heat flux to the co-side of an object at the toroidal location of the detectors varies dramatically with the plasma major radius. When the plasma position is $R < 2.59$ m, the field lines from the co-side of the detector tilt radially outward by up to 10° when moving toward the co-side limiter, so plasma flow from that direction is blocked (as assumed previously). However, when $R \simeq 2.6$ m, the outer magnetic flux surfaces are nearly concentric with the nearest co-side rf limiter (centered at $R = 2.61$ m and about 2 m away toroidally), so that the detectors tops are within the power radial scrape-off width of this limiter. Further, when $R > 2.6$ m the field lines can entirely miss the nearest co-side limiter, and so accumulate heat flux over a very long connection length, resulting in a larger heat flux and scrape-off layer thickness. The results of this model agree at least qualitatively with the observed thermocouple readings versus R and damage patterns.

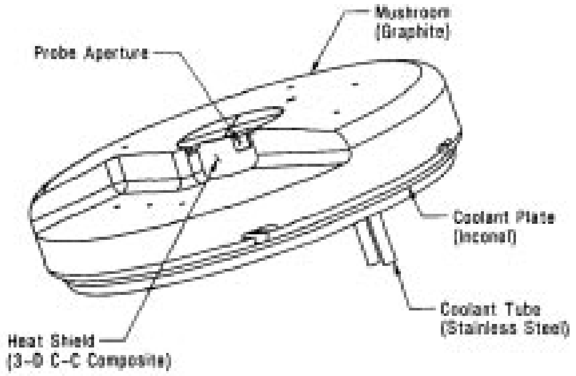

FIG. 4. New design of the escaping alpha detectors. There is now a cylindrical heat shield protecting the detector from the co-side, and the bottom of the graphite mushroom is actively cooled with water lines. The damaged detectors at 45° and 60° were also replaced and retracted about 0.5 cm for the 1992 run.

Another factor contributing to the damage of the 45° and 60° detectors was the neglect (in the original design) of the effect of toroidal field ripple on the detector positioning. Since the detector tops were in the low-B field (between coils), whereas the co-side rf limiter was in the high-B field region, the magnetic field lines extended outward in minor radius by about 0.5 cm between the co-side rf limiter and the detectors. Thus the tops of the 45° and 60° detectors were magnetically a few mm farther inside the rf limiter than assumed, adding to the damage at the tips of the detector boxes.

IV. IMPROVED DETECTOR DESIGN TO AVOID OVERHEATING

The three fixed position detectors were changed for the 1992 run as illustrated in Fig. 4. The main improvement is a carbon composite heat shield protecting the detector boxes from the co-side, which should be able to withstand a heat flux of 1.5 $\mathrm{kW/cm^2}$ for up to 2 s. This shield has a cutout which is carefully designed to let ions into the aperture with $\chi \simeq 45°–90°$ and $\rho > 2$ cm.

The other major change is active cooling of the graphite mushroom by water lines through a metal plate attached to its bottom. This is to insure that residual heat flow (from either side) does not cause the detector temperature to exceed ≈ 100 °C. The heat-damaged 45° and 90° detectors will also be moved radially outward by about 0.5 cm to compensate for the toroidal field ripple. This should still allow all relevant ions to enter the aperture unblocked by the rf limiter.

Just in case the water cooling is insufficient to keep the scintillator temperature from ratcheting above 150 °C, the scintillators will also be changed from ZnS(Ag) (P11) to ZnS(Cu) (P31), which maintains half of its response up to 350 °C.[6] The brightness of the green ZnS(Cu) scintillator is comparable to the blue ZnS(Ag); however, the new scintillator has about 50 kHz time response instead of about 100 kHz for the older one.[6,10]

V. OTHER OPERATIONAL EXPERIENCES

(a) Hard x rays from high energy runaway electrons occasionally cause the scintillators to light up, usually just after a major disruption. The runaway-induced light is usually quite uniform across the scintillator, so has been useful as a check of the scintillator alignment in the camera field of view.

(b) The scintillators themselves were slightly damaged during the 1988–1989 run, when they were left in place for two years. This damage was a set of <0.5-mm-diam fern-like patterns on the phosphor surface, possibly caused by arcing during discharge cleaning. Since there were relatively few of these, the average scintillator light emission over a $\approx 1\ \mathrm{cm} \times 1\ \mathrm{cm}$ area was reduced by $\lessdot 10\%$. However, no visible surface damage was seen for two different sets of scintillators used in the same detectors during the 1990 and 1991 runs, implying that this damage was not due to fusion product ions.

(c) There was a small hole in the foil of the 90° detector during the 1991 run, which allowed some escaping neutral beam ions to hit the scintillator (these ions could be distinguished by their small ρ and rapid appearance at NBI turn on and disappearance at NBI turn off). Post-run examination showed that the hole was due to a mechanical tear, probably incurred during assembly and not by erosion in service. Note that the foil can be intentionally removed to study beam ion loss.[11]

ACKNOWLEDGMENTS

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