Survey of Features in Radiative Power Loss Profiles in TFTR

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J. Schivell, C. E. Bush*, D. K. Mansfield, S. S. Medley,
H. K. Park, and F. J. Stauffer**
*Princeton Plasma Physics Laboratory
Princeton, NJ 08543 USA*

Abstract

Although the total radiated power in TFTR is often as high as 70% of the heating power, most of the radiation is concentrated near the surface of the plasma, and the interior loss is almost negligible. Fractional radiative loss declines during neutral beam heating. As the high-density limit is approached, under practically any conditions, a bright band of radiation ("marfe") appears on the inner side of the plasma column. Marfe evolution has been tracked for various conditions of heating, magnetic field direction, and fueling. In enhanced-confinement discharges a peculiar bright band, distinct from a marfe, appears in the lower, outside part of the vacuum vessel, outside of the limiter radius. With pellet fueling, marfe evolution occurs at a higher average density, and an intense peak often appears in the plasma center, consisting of impurity radiation plus working-gas bremsstrahlung. In high density ohmically heated cases with pellet fueling radiative power loss exceeds heating power in the center.

Introduction

TFTR has very good coverage of radiative power loss, as do other tokamaks of its generation. TFTR has two nearly orthogonal bolometer arrays (Figs. 1, 2), six additional bolometers for measuring toroidal variation, and two which look along a tangent to a major circumference. Each array contains two parallel rows of detectors: the first, or primary, row consists of bare platinum detectors, while the second consists mostly of carbon-black-coated detectors, interspersed with filtered detectors that cannot receive visible, UV, or X-radiation. This set of bolometers makes possible multiple measurements of radiation-loss profiles, identification and tracking of local bright features--such as marfes and other concentrations--and separation of contributions to the signal.

Previous reports have discussed the bolometer detector and electronics system [1], the initial performance of the bolometers [2], the toroidal variation of radiated power [3], the behavior of the radiation losses during neutral beam heating [4,5], fast-ion losses (measured by the tangential bolometers) [6], bright radiation bands (marfes) [7-9], a reconstruction method for combining the chord-integral profiles from the two arrays and determining the local radiation intensity [10], and the use of the bolometer arrays in the study of detached plasmas [11-13]. There have also been a spectroscopic study [14] and X-ray studies [15,16] of impurity behavior and trends with neutral beam heating in TFTR. There was also a preliminary report on analyzing local features in the radiated power [17]. The present report surveys the behavior of radiation-loss radial profiles on TFTR and the most important of the numerous and distinctive local bright features that are seen. New information on marfe behavior is presented, as well as on a bright feature which appears during the enhanced confinement mode ("supershots" [18]) and radiated power behavior after pellet injection.

*Permanent address: Oak Ridge National Laboratory

**Permanent address: University of Maryland

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Before TFTR began operation, it was not really known what radiation-loss behavior to expect in this new region of tokamak size and power. In particular, it was not known how serious the losses would be in the power balance [19]. As it turns out, whenever the vacuum vessel is reasonably well conditioned, the radiative losses are quite mild, and the radial profile of radiation is hollow, with the loss near the plasma center being approximately 15% or less of the central heating power per unit volume [2]. The majority of the radiation is from near the outside of the plasma, where it can be regarded as benign--in the sense that it helps produce a uniform distribution of the plasma power outflow. The other interesting outcome is that with neutral beam heating, the total power radiated does not increase in proportion to the heating power--the fraction radiated decreases slowly with increasing power[4,5]. Typically, only 30% of the heating power is lost by radiation during high-power neutral beam heating.

The surprise that came with observing radiation profiles on TFTR was the frequency of occurrence and the dramatic prominence of local bright features. The fact that we have two practically orthogonal arrays makes it possible to determine the location and extent of these features and to track them when they move. The first feature noticed was the marfe [7-9], and we have been able to study the poloidal drift and evolution of marfes under various conditions. In detached plasma cases [11-13] the two arrays give excellent confirmation of the symmetry, as well as the radius and intensity, of the radiating shell. A strange feature that has been observed consistently in plasmas in the enhanced confinement mode [18] is an intense streak of radiation in the lower, outer part of the vacuum vessel, distinctly outside the limiter radius. (Unfortunately, there is no theory for this feature.) In normal discharges--without either of the above local effects--on the inner-bumper limiter (IB), we see directly in front of the bumper an intense cloud of radiation loss, which dominates the inner half of the vertically viewed radiation profile. This local effect typically accounts for about one-half of the total radiated power. At the highest densities achieved with pellet injection we see a strong central radiation peak, confirmed by both arrays. This peak consists partly of bremsstrahlung from both the working gas and the impurities. Other surprising features are occasionally seen in the radiation profiles, some understandable and some not.

The observations in this report are believed not to be affected (except in specific cases discussed below) by the following backgrounds and uncertainties: power delivered to the bolometer by charge-exchange neutrals, tangential loss of circulating beam ions by charge exchange, enhancement of radiation intensity near the movable limiter (ML), infrared light from the IB, and light reflections from the wall. Charge-exchange neutral power flux into the bolometer arrays is estimated by the transport code TRANSP [20] to be small, 5-10% in the largest, beam-heated cases. Measurements on PLT with the Low-Energy Neutral Spectrometer [21-23] found a very small fraction--much less than 1%--of the power outflow in neutrals. In any case, the power delivered by charge-exchange neutrals is real power outflow--it simply is subtly distorted because it does not share with optical radiation the properties of transparency and isotropy. Tangential loss of fast ions [6] cannot be seen by the arrays and is not considered in this report. An extreme case of charge exchange losses, apparently caused by a neutral beam which passes in front of an array, is discussed below. The enhanced radiation near the ML does not affect inverted profiles because, for ML discharges, we use the measured profiles from the horizontal (H)-view array, which is far from the ML (Fig. 2). In principle, infrared radiation from the IB would constitute a background for the profiles. To date there have been no hot spots on the IB--except during disruptions--as hot as 300 °C. The radiation at this temperature would be equivalent to 15 kW/m² from the plasma. But this would be in high-power beam-heated cases in which a typical measured signal is 200 kW/m². Furthermore, the bare platinum detectors, which are used for all of our results, are very insensitive to infrared.

The signals from the shiny and black detectors have differed only on rare occasions. From this we conclude that, as a rule, (1) visible and near-UV light are a small part of the radiated power, and (2) since wall reflection should be small in the shorter wavelengths, reflections are not a problem.

In all of the plots of chord-integral power, array positions 1 and 21 are fictitious chords with signal identically zero, which have been added to fix the profiles at the vessel wall. In the vertical (V) view position 1 is on the inner side of the plasma, and position 21 is

on the outer side. In the horizontal (H) view position 1 is at the bottom, and position 21 is at the top. The scale of minor radius shows the radius to each chord, with negative merely signifying radii to chords inward of, or below, the plasma center. In the H view the plasma center is normally always at position 11, but in the V view the plasma center varies. The vertical dashed lines indicate the limiter radius.

In this paper, we use the term "emittance" to mean radiated power per unit volume, typically in units of W/m^3 .

Normal Profiles and Trends

The typical profiles of radiation loss in TFTR have evolved over time, reflecting the changing operation conditions. During the first two and one-half years plasma operation was primarily on the ML, a set of three large, curved assemblies of graphite tiles at one toroidal location, on the large-major-radius side of the plasma. For the first one and one-half years the tiles were coated with titanium carbide, and the effects of titanium on the radiated power were evident. After the TiC was removed, the radiated power behaved differently as a function of density, and the radiation was less intense at the middle values of radius [2]. As the machine became well conditioned and I_p and n_e were raised, the typical profiles became more difficult to understand. Overall intensity was low, and there were bumps and peaks that were glaringly asymmetric about the plasma center. Since the installation of the inner bumper limiter (IB)—a toroidally complete wall of graphite tiles—in the summer of 1985, most of the plasmas have been run on that limiter. The measured profiles have entirely different shapes.

The characteristic profiles seen in the first era are discussed in [2]. The principal observations are as follows: 1) Radiated power is peaked toward the outside of the plasma and is a quite small term in the power balance within the inner half of the minor radius. 2) Variations of total radiated power and radiated power from $r < a/2$ with density are both affected by the presence of titanium—when the limiter had a coating of TiC, radiated power was a strongly falling function of density; after the TiC was removed, radiation became a mildly rising function of density. 3) As expected from radiation rates as a function of temperature [24], radiation loss at medium radii in TFTR is strongly affected by the presence of titanium.

Figures 3(a,b) show a set of measured profiles from the two arrays from an early discharge with plasma current $I_p = 1.0 \text{ MA}$ and line-average density $\bar{n}_e = 1.5 \times 10^{19} \text{ m}^{-3}$. From the point of view of confirming the measurements, it was reassuring to see how similar the Abel-inverted profiles, Figs. 3(c,d), are. There are three, and for the most part four, separate half-profiles which invert to practically the same result. The persistent features of the radiation per unit volume are 1) a sharp peak near the plasma edge, 2) a dip near $r = 0.55 \text{ m}$, 3) an inner peak near $r = 0.35 \text{ m}$, and a deep central dip with a radius of about 0.2 m . The central dip also is present in plasmas with a much smaller major radius (centered at a different location in the V view), showing that it is not an instrumental effect. This narrow, deep dip is contrary to expectations, since impurity transport and the broadness of the temperature and density profiles should smooth out radial variation of the radiated power in the plasma center [25]. The $r = 0.35 \text{ m}$ peak is apparently from metals, since it is generally much reduced in discharges with a bare carbon limiter [2]. The noise level (rms) in the inverted result is only 2 kW/m^3 , but the systematic distortions of the profiles appear to lead to errors of more like 10 kW/m^3 .

A typical set of profiles from the second era—no Ti, ML operation—with $I_p = 2.2 \text{ MA}$ is shown in Figure 4. These profiles are not as simple to interpret. Two time slices are shown to demonstrate the evolution during the discharge. In the horizontal (H) view there are peaks which are glaringly asymmetric about the midplane. The profiles measured by the black-coated bolometer sensors are the same, which tends to confirm that these odd peaks are not instrumental effects. The large, fairly broad peak in the outer half of the vertical (V) view is apparently due to a plume of impurities which comes off the ML. From one plasma condition to another the intensity of this peak is broadly correlated with power throughput. The increase on the inner side is probably the same radiation as seen in the growing peaks in the upper half of the H view. When these types of profile distortion are present, the Abel inversion becomes dubious. The top and bottom halves do not agree.

except in an approximate way. When the inversion procedure is applied, one often obtains a significantly negative emittance in the center. This is understandable, since the sharp peaks appear to be local effects, probably on the plasma edge, and do not fit the cylindrically symmetric model which is the basis of the inversion. The V profiles are typically unusable, with large negative emittances implied for the plasma center. Usually in these cases we either average the top and bottom halves of the H view for Abel inversion or abandon any attempt at inversion.

Figure 5 is a typical set of profiles from a discharge on the IB. This discharge had $I_p = 2.2$ MA and $n_e = 2.9 \times 10^{19} \text{ m}^{-3}$, and the total radiated power was 45% of the heating power--in spite of the large peak on the inner side of the V view. Because of the large amount of light from the vicinity of the IB, the H view has a large background and, therefore, is useless for Abel inversion. We use the outer half of the V view instead; however, what is apparently the "tail" of the inner-bumper light (in the vicinity of positions 9-11) leads to a spurious central peak in the inverted result. It is a matter of judgement at what position outside the center the tail becomes negligible. Two-dimensional reconstruction (below) reconciles the two profiles, but the emittance at the plasma center is still quite uncertain. This problem aside, the emittance as a function of radius and the local power balance are similar to those in discharges on the ML.

The trend of radiated power loss with neutral beam heating [4,5] is that the loss increases more slowly than proportional to the beam heating power. That is, the fraction radiated decreases. In the TFTR enhanced-confinement, or "supershot," mode the fraction radiated behaves in a quite similar way and tends toward 25-30% as heating power approaches 20 MW. Unfortunately, the difficulties with the observed profiles make the determination of the total radiation from, say, $r < a/2$ rather uncertain. Therefore, one cannot reach any detailed conclusions about the trend of the inner one-half-radius radiated power. However, we can state that it is small--about 5-10% of the total heating power--and that this fraction shows little, if any, dependence on heating power.

Marfe Behavior and Plasma Detachment from the Limiter

Marfes have been observed in a number of tokamaks[9]. In TFTR marfes stand out dramatically in the radiation profiles. The fact that there are two practically orthogonal arrays makes it possible to track the marfe position, and measure the power and size, from bolometer measurements alone. These observations are confirmed by pictures from the Plasma TV [26] and the behavior of signals from the Multichannel InfraRed Interferometer (MIRI)[27]. Marfes often drift up or down the inner side of the plasma, and at the time when the horizontally-viewing bolometer array shows one crossing the midplane, the 1-mm interferometer provides clear confirmation by losing count of fringes. Normally, the H and V arrays show consistent peaks, although occasionally inconsistencies arise.

The experience on TFTR has been that there is a rather long list of parameters which influence marfe behavior. The list includes:

- n_e
- I_p and dI_p/dt
- impurity content
- fueling gas flow
- pellet fueling
- neutral beam heating
- neutral beam direction
- toroidal field direction

With all of these influences operating, perhaps it is not surprising that we have observed a wide variety of marfe behavior. Efforts to determine the patterns and rules of marfe behavior have met with mixed success.

The specific observations that are clear in TFTR are the following:

(1) the evolution of the marfe as a discharge is pushed closer to the high-density limit, first drifting up (or down, depending on the toroidal field direction) the inner side of the plasma, then leading to a brightly radiating, symmetric shell and detaching from all limiters [11-13],

- (2) the stability of the detached plasma state--even spontaneously detached plasmas persist in equilibrium for as long as several seconds, until the discharge conditions are changed,
- (3) the reversal of the evolution, back to an earlier state, usually when neutral beam heating is added to the discharge, but also under conditions of added edge heating, such as I_p ramp-up,
- (4) reversal of the drift direction when the toroidal field is reversed,
- (5) occasional drift to the bottom, outer quadrant of the plasma cross section,
- (6) driving the marfe up or down the inner side, depending on the mix of co- and counter-injection (Co-injection is in the same direction as the plasma current, and counter- is in the opposite.),
- (7) presence of marfes in both limiter cases: discharges on the ML and discharges on the IB (In the latter case the marfe is superimposed on the bright cloud which covers the IB.),
- (8) multiple bright streaks, which may or may not be marfes, at high plasma current (2.2-2.5 MA).

Figure 6 illustrates a number of the interesting points of marfe behavior. In this discharge the current was constant until 3.0 s, followed by an 0.5 s ramp up, followed by neutral beam injection for 0.5 s. There was a gas puff from 1.5 to 2.0 s. The plasma was created at a major radius of 2.9 m and moved in to 2.48 m to contact the IB just before 0.5 s. In the radiated-power profiles a marfe is observed as soon as contact is made. The peak in intensity is centered between H array positions 12 and 13, 1-1/2 steps [approx. 6°] above the midplane. In the V view, the peak is buried in the usual IB bright sheet. The marfe is practically stationary until the gas puff, when it drifts up. It then develops into a detached plasma. The inner-bumper bright sheet disappears, the profiles from both arrays become nearly symmetrical, and the total radiated power (not shown) becomes 100% of the input power. The detached plasma, which occurred spontaneously after the gas puff, is completely stable and persists until the plasma current is ramped up. During the ramp the plasma reattaches to the IB and a marfe redevelops, which drifts down the inner side of the discharge to approximately the same location as the marfe early in the discharge. Then, during neutral beam injection, the marfe rapidly becomes much more intense and drifts down to settle in at a location approximately 17° below the midplane. There is a peak in the V view at a consistent location.

Spontaneous detachment has been seen frequently in cases with high "safety factor," q , when the density is pushed to a high value. These cases reverse-evolve into a marfe when neutral beam power is injected. Other typical behavior includes marfe drift and detachment when plasma current is ramped down--or decays because of an ohmic heating (OH) primary current interruption. Current ramp-down is used to produce detached plasmas for study [11,12].

Marfes have also been observed to drift underneath the plasma and to the lower, outer side. One such case is shown in Fig. 7, where the changing mix of co- and counter-beam heating moves the marfe down, then up, then down again. In this case, when the marfe moves down during the second co-beam-only phase, it continues under the plasma and starts up the outside, as evidenced by the peak on the outer side of the V view and the increase at positions 6 and above in the H view. The effect of co-, counter- mix on marfe location will be described in more detail below. We have not seen marfes drifting over the top of the plasma column.

In order to combine the data from the two fan-array views, a specialized emittance reconstruction method was developed [10]. It is based on the assumption that the asymmetric features are on the inner side of the plasma, near the surface. The cross section of the vacuum vessel is divided into zones of constant emittance. In the interior of the plasma the zones are annuli; on the inner aspect of the plasma the zones near the surface are annuli subdivided poloidally into angle intervals approximately 10° wide. The emittances in the

zones are adjusted iteratively for the optimum fit to the measured profiles. Thus, marfe intensity and poloidal location and extent can be found quantitatively; in addition, the profile of emittance throughout the interior of the plasma can be found, in spite of the background from marfes and the IB bright sheet of radiation. One limitation is that the accuracy of the result for the central radiated power is very low, because the emittance from the center is usually about an order of magnitude lower than the background emittance. Another limitation is that, because of the geometry of the fan arrays, we cannot determine an upper limit on the marfe thickness in minor radius, except when it is in the upper part of the inner aspect of the plasma. We assume that it is no thicker when it is in the lower part. As an example, the reconstructed emittances for the six times of interest in Fig. 7(a-h) are plotted in Fig. 8.

Using the zone reconstruction method, we can trace the development of marfe power and location as a function of time. The discharge in Figs. 7 and 8 is particularly interesting because of its varying amounts of co- and counter-injected beam. The toroidal field was in the counter-clockwise (positive) direction. Figures 7(i-l) show marfe location, beam power and mix, and marfe power and poloidal extent as functions of time. Location, θ_{marfe} , is the angular position above or below the midplane. The width is the full width at half maximum intensity. The marfe emittance we estimate depends on how thick we estimate the emitting layer to be in the radial direction. For the case in Figs. 7 and 8, at 3.1 s, the peak marfe emittance, averaged over a 0.2 m layer, is 2 MW/m^3 . Our interpretation of this case is as follows: Before beam injection begins, the marfe, which is radiating approximately 1 MW while the ohmic input is 2 MW, is in a fairly advanced state of evolution. Since the TF is positive, the marfe is in the upper part of the inner side of the discharge. During the initial beam-heating phase, the additional heating reverses the marfe evolution, driving the marfe down to -60° . When the beam goes off, the marfe starts up again, but the motion is accelerated by the turn-on of the 2 MW of counter-beams. In the third beam phase, which is all co-, the marfe moves down to -65° within the first 150 ms, growing broader during the motion. It settles in at that location for the next 250 ms, but then, for some unknown reason, it drifts under the plasma column. It develops into a disruption after the beam is shut off. Comparing the latter two beam phases, we conclude that counter-beam heating has a vastly different effect on marfe location than co-beam heating. The total beam power is the same; the marfe power is similar; the marfe average emittance is even more nearly the same. But the location changes from near the top of the plasma to near the bottom. We have also observed a case, with negative TF, in which the neutral beam power was kept at 5 MW for 1.5 s, but was alternated co-, counter-, co- at 0.5 s intervals. A marfe clearly moves from upper to lower to upper locations during these three periods. These cases are the clearest comparisons of counter- and co-injection. In other cases the effects appear to be diluted by various factors--for example, a more nearly balanced beam power.

We have also used the zone reconstruction method to analyze a number of scans of plasma density and current, to determine the trends in marfe power under various conditions. As others have reported [7-9], we find that marfes occur as density is pushed up near its limit for a given plasma current, and that marfe power increases, the closer the density is to the limit.

Since we began observing marfes, the toroidal field (TF) has been in the positive (counter-clockwise) direction for two periods and in the negative direction for two. The marfe drift direction for forward evolution is controlled by the direction of the TF--when the TF is positive, marfes drift up as they evolve, and when the TF is negative, they drift down. The plasma current has been in the negative direction for only one week. This reversal appeared to have no effect on the marfe drift direction, although we would have preferred a clearer example. Figure 9 shows such a case. TF is negative, and so is plasma current. As the plasma reaches the IB, the marfe develops at a location slightly inward from the bottom of the discharge [Fig. 9(a), (d)]. As the density is raised--after 2.4 s--the marfe drifts under the bottom and toward the outside. This motion seems consistent with a downward drift direction.

We note that the marfe drift direction with forward evolution is the same as the ion ∇B drift direction.

We have also looked at the quantitative correlation between marfe power and location. We took a sample of 66 OH discharges with marfes and reconstructed the marfe at the equilibrium analysis time for each shot. Data were from a number of density scans, all with

the plasma running on the IB. Plasma currents ranged from 0.9 to 2.2 MA. About 30% of the cases had one or more pellets injected. There was a continuous range of marfe width, extending to broad radiation enhancements which covered most of the inner side of the plasma. Thus, it was necessary to make a cut on width. We chose to cut at a full width of 70° . The marfe location is the number of degrees poloidally above the midplane, multiplied by the sign of the TF to take into account the reversal of marfe motion with TF. The total marfe power divided by the width was taken as the average intensity. Relative intensity is this average intensity divided by the total heating power. The units are $(\text{degrees})^{-1}$. Figures 10(a), for deuterium plasmas, and 10(b), for helium, show practically the same trend--that is, that marfe location is rather well correlated with relative intensity. Correlation with absolute intensity or with total marfe power is not as good, and if the sign of the TF is not taken into account, the points are scattered. All of the points in Fig. 10 had positive I_p and no gas feed at the analysis time.

With neutral beam heating, marfe location is correlated with beam direction and TF direction. Based primarily on qualitative observation, we find that marfes are located low on the inner side during co-injection and high during counter-, when the TF is positive. When TF is reversed, the corresponding marfe locations are reversed (*e. g.*, case mentioned above). Generally, we have not seen marfe evolution during beam heating. This may be due to the fact that the high-density limit is not normally approached in TFTR during neutral beam heating.

Marfe radiated power during neutral beam heating ranges as high as 3-4 MW (*e. g.*, Fig. 7), while the largest marfe emittance that has been seen in TFTR--in either OH or NB discharges--is approximately 2 MW/m^2 . For beam-heated, pellet-fueled discharges marfe power divided by total heating power increases with average electron density and has become as high as 40%.

All of the above observations were made on plasmas limited by the IB. We attempted to produce plots of trends of marfe position vs. intensity for ML discharges, but were unable to find any sequence of shots in which marfe power progressed smoothly from density to density. Instead, we must rely on the behavior of individual marfes as a function of time. They did, indeed, increase in intensity as they drifted toward transition into detached plasma. An example is shown in Fig. 11. (In this case the dip in intensity as the marfe passed through the midplane was apparently caused by a momentary dip in the rate of gas feed. The gas flow was controlled by feedback from the 1-mm interferometer; when the marfe reached the midplane, it caused the density signal to jump up, momentarily reducing the gas flow sharply.) Generally, marfe behavior in ML plasmas is the same as in IB plasmas. Marfe drift and growth happen together; the usual behavior is growth and drift on the way to detachment. The direction of drift during the evolution to detachment is the same as the sign of the TF. The emittance of marfes in ML discharges is similar in magnitude to that in IB discharges. A surprising feature, which appears correlated with high I_p or low q , is the appearance of what may be multiple marfes. Figure 12 shows such a case in a pellet-fueled shot, but similar features have been seen in discharges without pellets. They have not been seen in plasmas on the IB.

Discharges of reduced (less than 82 cm) minor radius made by placing the magnetic center closer to the IB exhibit marfes at high density, just as full-size discharges do. However, in small discharges made on the ML, no marfes have been seen, even though we reached the high density limit and disruption. This comparison suggests that the amount of space between the plasma and the wall may be important in marfe formation.

Below-Limiter Radiation Streak (BLRS)

In June, 1986, after thorough conditioning[28] of the vacuum vessel and IB, and operating with current in the range 0.7 - 1.1 MA to minimize the target plasma density, a regime of improved energy confinement at high neutral beam power was discovered in TFTR ("supershots" [18]). In that regime we observed a quite surprising phenomenon in the profiles of radiated power. There is an intense signal which appears at the very bottom of the H array, approximately 0.15 m outside the limiter radius (*cf.* Fig. 1). An example of this phenomenon is given in Figs. 13 and 14. The corresponding peak in the V profile--at or near position 15--indicates that this feature is centered at a major radius of $R = 3.1 \pm 0.1 \text{ m}$. The

shape and behavior of this streak are similar, regardless of whether the plasma is limited by the IB or the ML. The intensity (chord-integral emittance) is roughly correlated from shot to shot with the neutron yield of the discharge and with the poloidal β . The temporal behavior of the Below-Limiter Radiation Streak (BLRS) intensity is also approximately correlated with that of the neutron yield and β .

We are confident that the observed peaks are not due to background from X-rays or other penetrating radiation or to electronic pick-up. The detectors for which the impurity radiation is filtered out see no signal during the occurrence of this effect. When we closed the array shutters, the effect went away with the rest of the signals. Where pairs of shiny and blackened detectors view the BLRS, they yield the same signal, indicating that (1) the radiation from this feature is predominantly not in the visible or near UV, and (2) it is seen on two independent channels looking at the same plasma--that is, it is not due to an anomaly of the bottom detector channel. The fact that there are corresponding peaks in both the H and the V views is the strongest confirmation of the effect. The location in the two profiles--measured 162° around the torus--puts an upper limit of approximately 20° on the rotational transform of the BLRS. However, since these are low-current discharges, rotational transform of the magnetic field at the plasma surface is only 30° . Therefore, we cannot rule out that the BLRS follows the field lines.

Comparisons with other diagnostics do not suggest an obvious model. The MIRI interferometer, which has ten parallel, vertical lines of sight, sees a shoulder on the density profile at $R \sim 3.1$ m under conditions for making supershots. The occurrence of this shoulder is anticorrelated with the BLRS. In other types of discharge we have seen an impurity plume on the visible-light Plasma TV. However, the BLRS does not behave very much like an impurity plume. It is definitely on the bottom only. In the H view, which is toroidally 126° away from the ML, it is quite intense and concentrated. One would probably expect an impurity plume from the ML to dissipate significantly at that distance. In a normal discharge with an impurity plume (for example, Fig. 4) there is no sign of a peak at the bottom of the H profile. Finally, the BLRS is concentrated outside of the limiter radius, where densities should be low.

Also, BLRS is not a marfe. It does not reach the bottom, outside location by drifting there. It occurs at low density. Finally, marfes do not go below the ML.

Since BLRS intensity is correlated with poloidal β , we collected data for a large number of discharges and looked for trends. The total power radiated by the BLRS is estimated by multiplying the peak chord-integral emittance by the estimated width and the circumference at $R_p \approx 3.1$ m. In Fig. 15 the power is plotted against β from the diamagnetic measurements. For fixed I_p and R_p , BLRS radiated power, P_{BLRS} , rises with β_p . Parts (a) thru (c) are for cases of $I_p = 600$ to 800 kA, inclusive, with R_p increasing from (a) to (c). Parts (d) and (e) are for $I_p = 900$ to 2000 kA, at corresponding major radii. There is no clear correlation with I_p . It does appear that, the further toward the outside of the torus the plasma is, the higher power is radiated by the BLRS. (Note that high β causes even plasmas limited on the IB to bulge out enough to contact the ML.) These observations would tend to support an interpretation of the BLRS as some sort of impurity plume. However, there are some aspects of BLRS behavior which are not what one would expect from impurity plumes--for example, there is no clear correlation between BLRS power and plasma vertical position.

It should be noted that total radiated power, as a fraction of heating power, behaves completely differently from the BLRS--total radiated power is a slowly falling function of β .

Something like the BLRS is seen even in a reduced-size plasma, made by setting $R_p = 2.3$ m, which puts the outer edge more than 30 cm from the ML (Fig. 16). The characteristic prominent peak is seen in the V view in the vicinity of $R = 3.05$ m. In the H view there are three candidates for the corresponding peak. There is the bump in the lowest two positions, outside the plasma, the peak at 6, and the peak at 16 and 17. Near the end of the neutral beam injection there is even a marfe on the upper inner side of the plasma, as confirmed by a drop of more than 100% in the 1-mm interferometer signal. Sorting this all out appears nearly impossible.

The TF direction was negative for these BLRS observations, and the plasma current was in the positive direction. The ion ∇B drift was downward.

In supershots made with the TF and plasma current reversed, the usual BLRS

disappears, and, instead, a round hump appears at the top of the H profile.

Radiation losses after pellet injection

The prominent radiation-loss features with pellet injection [29] are marfes and a central peak. Pellet injection is the only condition in TFTR under which a central radiation peak appears. In some cases it is so intense that we can see the central radiation in the visible-light Plasma TV image--as a bright column in the center of the plasma.

Marfe behavior is practically the same as that in gas-fueled discharges. However, the density profiles resulting from pellet injection are highly peaked. Therefore, we would expect that marfe power would be smaller for a given line-average density. This is, in fact, observed. Nevertheless, the trend of marfe location with marfe intensity is the same in the pellet cases as in the gas-fueled.

After the injection of multiple pellets an intense central radiation peak is quite common. An example is given in Fig. 17. The appearance of the peak in the center of both views confirms the identification and the central location in the plasma. (The three tall spikes in the H array data are due to the fact that the pellets are injected into the plasma on the midplane directly in front of that array. The affected bolometer channels recover from saturation within 40 ms.) The peak in both views typically lasts for about 1 s, and has an emittance of as much as 0.4 MW/m^2 . The electron density is, of course, highly peaked. Bremsstrahlung estimated for the fuel plus impurities is typically 0.04 MW/m^2 . In some cases the radiation losses per unit volume exceed the OH power, the electron temperature profile is hollow, and the center temperature drops to $0.75\text{--}0.8 \text{ keV}$. These cases are probably in thermal collapse, in which the impurity ions recombine partially and thus radiate more efficiently.

A remarkable behavior of the central peak is that it typically sharpens up over time (of order 1 s) after the pellet. Figure 18 shows the detailed behavior of the discharge of Fig. 17. In the measured chord-integral emittance it is clear that the central peak narrows and grows in intensity. Since this central peak is prominent, the two-dimensional reconstruction handles it well. The reconstructed central emittance, $E_{\text{rad}}(0)$, rises by a factor of at least 3, while $n_e(0)$ is falling slowly and $T_e(0)$ is rising slowly. In coronal equilibrium $E_{\text{rad}} = R(T_e)n_en_i$, where $R(T_e)$ is the radiation rate, and n_i is the impurity density. For the dominant impurities, carbon and oxygen, $R(T_e)$ is falling with increasing T_e or at its minimum at these temperatures [24]. Thus, we might normally expect $E_{\text{rad}}(0)$ to be falling here. Detailed modeling of the impurity and working-gas transport has been done with the Multi-Ion Species Transport (MIST) code and other codes [30]. The diffusion coefficient, D , near the plasma center is quite low--about $10^{-5} \text{ m}^2/\text{s}$. Without an inward convection effect the impurity density profile would be quite broad, and we would not see such a narrow central radiation peak as we do--in spite of the central electron density peak. What appears to be happening is that the light impurities in the discharge are being concentrated in the center after the central electron density is raised by pellet injection. The overall fraction of light impurities remains about 5%. Similar inward convection of impurities has been observed in other tokamaks [31, 32]. The concentration of metals--Cr, Ni, Fe--is quite small, only about 10^{-5} , as determined from UV spectroscopic evidence [30].

Other Features Seen

During one experiment at quite low current and density ($I_p = 580 \text{ kA}$, $\bar{n}_e = 0.75 \times 10^{19} \text{ m}^{-3}$), with only co-beams used, the beam sources were on for 0.5 s each, two at a time, in a sequence that lasted 1.5 s. When the third pair was turned on, the total radiated-power signal took a sharp, 33% step upward. In the H array, only certain channels looking near the plasma center had a sharp step. (None of the V-array signals had a sharp step.) An example is given in Fig. 19. Now, the detectors in the arrays are actually in two rows, with two positions in one row, then two in the other row, and so on. Detectors at positions 2, 3, 6, 7, 10, 11, 14, 15, 18, and 19 look 5.5° in the co-direction--that is, behind co-drifting beam ions--and detectors at positions 4, 5, 8, 9, 12, 13, 16, 17, and 20 look 13.5° in the counter-direction--or toward co-drifting ions. The counter-looking detectors at 8, 9, 12, and 13 see a large step at 3.0 s, when the third set of sources is turned on. They also are higher than their immediate neighbors during the earlier beam-heating

phases. These effects are interpreted as follows: One of the beam sources injects along a trajectory which passes in front of the H array. When that source is turned on, at 3.0 s, it generates a "halo" of neutrals, which enhances the loss of co-drifting beam ions. (They have diffused in momentum space, and they can leave at an angle to the tangential direction.) Before 3.0 s, apparently there is enough neutral density near the array to cause some enhanced loss of co-drifting ions. Operation at higher density probably dilutes this effect.

Finally, one more dramatic feature was seen in the run in which the plasma current was reversed to put most of the neutral beam power in the counter-direction. Under this condition we often observed very high radiated power, $\sim 1.5 \text{ MW/m}^2$, near the top and bottom edges of the IB.

Conclusions

There are surprisingly many local features which appear in the radiated-power profiles. Some, such as marfe behavior and the Below-Limiter Radiation Streak, are interesting and await full theoretical understanding. Others are merely troublesome backgrounds. The ability to determine the local radiated power per unit volume varies from one case to another. With the normal inner-bumper bright cloud or with marfes one can invert the outer half of the V profile (although there remains the choice of whether to average the radiation loss around each flux surface). When the BLRS appears, it is superimposed on the V-outer half profile, and we therefore cannot resolve either the BLRS shape or the main-plasma local radiation profile. With marfes, unless the marfe is on the lower, outer side of the plasma, the marfe shape and the main-plasma profile can be determined by a two-dimensional reconstruction technique [10]. In particular, this technique is useful for obtaining the central radiated power when there is a central peak.

We have recently added a tangentially viewing bolometer array to TFTR to resolve ambiguities in difficult cases and to afford an accurate measurement of the central radiation.

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Figure Captions

1. Bolometer array viewing chords on TFTR.
2. Bolometer array locations on TFTR.
3. Chord-integral radiated power (a,b) and results of Abel inversion (c,d) for a discharge in the earlier part of TFTR's history (see text). The Abel inversion for each array has been generalized to use a symmetric and an antisymmetric term. The functional form of the emittance is taken to be $E(r,\theta) = E_0(r) + E_1(r) \cos \theta$ [ref. 2]. The V and H profiles are done separately, with $\theta = \pi$ corresponding to the left half in each case. Parts (a,c) are from the vertically viewing (V) array, and (b,d) from the horizontally viewing (H) array. Vertical dashed lines indicate limiter radius.
4. Chord-integral radiated power for a later case, which also has higher current and density. Part (a) is the vertical (V) view, part (b) the horizontal (H) view. Dashed curves are at 2 s into the discharge, and solid at 3 s. Line-average density is $3.4 \times 10^{19} \text{ m}^{-3}$ at 2 s and $4.3 \times 10^{19} \text{ m}^{-3}$ at 3 s.
5. Chord-integral power profiles from a normal discharge on the IB (a) V, (b) H. Usually, for Abel inversion, the outer half of the V is used. (Time is 3.465 s into the discharge.)
6. Chord-integral radiated power, as a function of position and time, illustrating the phases of marfe behavior. (a) and (b) are profiles for the whole discharge from the V and H arrays, respectively. Parts (c) and (d) contain slices at four times of interest. Part (e) contains the plasma current and line-average density (horizontal midplane) as functions of time. The maximum gas flow was 2.5 torr-l/s. The beam power was 7 MW, all in the co- direction.
7. Chord-integral radiated power as a function of position at six times of interest in a shot with sequenced co- and counter-beam injection. (a)-(d) are V view, and (e)-(h) are H view. Marfe poloidal location (i), radiated power (k), and width (l) vs. time. Beam power and direction are given in (j). $I_p = 1.6 \text{ MA}$ from 1.8 s until disruption at 3.6 s. $R_p = 2.36 \text{ m}$, and $n_e = 5 \times 10^{19} \text{ m}^{-3}$, approximately, at 3.5 s, having ramped up steadily from $t = 0$.
8. Emittance, plotted as the height of a surface, for the six pairs of profiles in Fig. 7. The scale is the same for all six plots. The view is looking in toward the machine axis; R is major radius, and Z is vertical position. The Movable Limiter is shown for orientation only.
9. Marfe behavior in an OH shot with I_p direction reversed. Profiles at eight times of interest are shown. V view is on the left, and H view is on the right.
10. Marfe poloidal location, measured from the intersection of the midplane with the inner side of the plasma, multiplied by the sign of the toroidal field, plotted against marfe relative intensity--power divided by poloidal extent, divided by the total heating power. The plasmas are (a) deuterium, and (b) helium.
11. Isometric plot of H-view chord-integral power for an ML discharge in which a marfe evolves forward. $I_p = 1.4 \text{ MA}$, $B_{TF} = -4 \text{ T}$.
12. Profiles of radiated power at two times in a (pellet injected) discharge that develops multiple streaks. Dashed curve is 280 ms after the second pellet, and solid curve is 240 ms after the third. $I_p = 1.8 \text{ MA}$, Shafranov $q = 3.8$, and $n_e = 6 \times 10^{19} \text{ m}^{-3}$ at the time of the solid curve.
13. Radiated-power profiles from a "supershot," illustrating the Below-Limiter Radiation Streak (BLRS): (a) V, (b) H.

14. Radiated-power profiles at the time of peak BLRS intensity, 4.365 s: (a) V, (b) H. Dashed profiles are for a shot with similar density and beam-heating power, but which does not become "super." Also shown are the temporal variation of β_p (c), neutron source strength (d), and chord-integral emittance on the bottom chord of the H array (e), for the two shots.

15. Power radiated by the BLRS plotted vs. β_p , for three bins of R_p . Full-size IB discharges have $R_p = 2.48\text{ m}$, and full-size ML have $R_p = 2.56\text{ m}$. Parts (a) - (c) contain only values of I_p less than or equal to 0.8 MA. Parts (d) - (e) contain $I_p \geq 0.9\text{ MA}$.

16. Profiles at a time just before the end of beam heating for a supershot with reduced radius. Major radius $R_p = 2.33\text{ m}$, and minor radius $a = 0.67\text{ m}$.

17. Chord-integral radiated power, as a function of position and time, for an OH discharge with injection of three pellets at 2.25, 2.5, and 2.75 s. $I_p = 2.2\text{ MA}$ (from 2.5 to 3.5 s), $B_{TF} = -4.8\text{ T}$, and $q_{Shaf} = 3.35$: (a) H view, (b) V view.

18. Profiles from the discharge of Fig. 17 at five equally spaced times after the third pellet: (a) chord-integral radiated power (center portion), (b) electron density, and (d) electron temperature. Part (c): emittance vs. time at four minor radii, as reconstructed from the two arrays [see text--marfe section]. The minor radius scales have not been corrected for Shafranov shift. The ohmic heating power at $r = 0$ at 3.45 s is calculated to be 0.38 MW/m^3 .

19. Chord-integral radiated power (H view), as a function of time, for twelve individual channels in a discharge with quite low density and neutral beam passing in front of the array.

B6X1139

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

#88X0458

Fig. 8

Fig. 9

#87X0844

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

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