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PERFORMANCE OF THE TFTR BOLOMET

By

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PERFORMANCE OF THE TFTR BOLOMETERS

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ABSTRACT

For the past year we have been making use of a horizontally viewing 19-channel array and a bolometer which views a narrow cross-sectional slice of the plasma. More recently, we have also obtained results from a second, vertically viewing array. Software has been developed to translate the data from general plasma and array locations to plasma minor radius and to do the Abel inversion with an antisymmetrical term included. Experience has been obtained on the noise and response-time characteristics, as well as the accuracy of total radiated power and radial profiles. Representative cases of radiated power profiles and local power balance are presented, as well as comparisons with other measurements of impurity concentration and trends with electron density and limiter coating. Although most of the ohmic-heating input power leaves by radiation, most of this loss occurs near the outer part of the plasma. Also, the behavior of power profiles during neutral beam injection and disruptions is discussed briefly.

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I. INTRODUCTION

TFTR employs a number of bolometers to measure the total power lost from plasmas by impurity radiation. There are two arrays which measure radiated power profiles in minor radius and six individual bolometers which measure cross-sectional slices at various locations around the torus. The detectors and electronics, which have been described elsewhere,¹ are of a new design, dictated by the environmental requirements of TFTR. In this report we discuss the deployment of bolometers on TFTR, the data reduction to total radiated power and radial profiles, and uncertainties in the results. We show a number of interesting results obtained to date: persistent features in the profiles, the significance of radiated power loss in the local power balance, trends in radiated power as a function of electron density and limiter coating, the effect of limiter coating on the radiated power profile, and the behavior of the profile before, during, and after a current disruption.

II. DETECTOR AND ELECTRONICS

The TFTR bolometers are based on a platinum-foil grid used as a sensitive resistance-temperature detector. This detector was chosen in order to satisfy the environmental requirements of neutron and gamma radiation, bakeout temperature, and high vacuum. Because of the low resistance and resistance-temperature coefficient of the platinum grid, a rectangular-wave ac bridge circuit was developed to read out the resistance changes with minimum sensitivity to electrical pickup. This type of bolometer has proven to be rugged, accurate, and relatively immune to electrical noise, its main limitation being a time response limited to approximately 1 ms (in our configuration). A bolometer for the Joint European Torus, employing a similar kind of detector, has been described in Ref. 2.

Since the publication of Ref. 1, there have been two developments in the design. The platinum sensor that we finally chose consists of four layers: platinum laminated to kapton and die-cut to the grid shape, which is in turn mounted on an uncut laminate of platinum and kapton. The bare uncut platinum sheet is the side of the detector which faces the plasma. This choice was made in order to avoid the unknown spectral absorption of kapton. The arrays have duplicate sets of detectors adjacent to the primary sets, in which the platinum has been coated with a layer of carbon black. This enables us to estimate the amount of the radiated power signal which is due to light in the visible and near ultraviolet. As it turns out, there has been no difference seen between the coated and bare detectors. In the future many of these will be cleaned off and employed with appropriate filters to measure neutron and gamma heating of the detectors and synchrotron radiation.

III. LOCATIONS

There are two bolometer arrays on TFTR (see Fig. 1). One looks in horizontally and the other down vertically. Each one is a fan shaped array of 19 lines of sight in a plane perpendicular to the magnetic axis. The horizontally and vertically looking arrays are located 162 degrees apart toroidally, and the vertically looking one is 36 degrees toroidally from the rail limiter. The resolution in minor radius is 0.11 m. The range in angle between the extreme lines of sight is 75 degrees. The detectors in the horizontally looking array are exposed to the plasma through a rectangular aperture such that the solid angle for the detector on the midplane is 8.4×10^{-3} sr and for the detectors at the extremes is 6.7×10^{-3} sr [the midplane value multiplied by $\cos(75^\circ/2)$]. The vertically looking array has separate apertures in the two transverse directions - the solid angles range from 9.5

$\times 10^{-3}$ sr to 5.4×10^{-3} sr.

The "wide-angle" bolometers are located as shown in Fig. 1. Each of these has a long, narrow slit so that a detector can see a slice 0.1-0.2 m thick in the toroidal direction and the full width of the plasma in the radial direction. Results from the wide-angle bolometer adjacent to the horizontally viewing array (at "Bay T") are mentioned below. Detailed results from the wide-angle bolometers will be discussed elsewhere.

IV. DATA REDUCTION

After the raw data has been smoothed in time and converted to chord-integral power,³ the result is plotted as a function of angle and time and can be inverted at each time by the Abel transformation to power radiated per unit volume as a function of minor radius. The algorithm used is a modest generalization⁴ of a method by K. Bockasten⁵ in which the necessary integral over radius is done by interpolating the intervals between measured data with local cubics. In our case, fixed angles between lines of sight, the calculation reduces to multiplying the set of data by a matrix which is always the same and scaling the results by the inverse of the largest chord radius.

Because there is twice as much data from each array as necessary to determine a cylindrically symmetric radiated-power profile, we go a step farther and also analyze the data according to a model in which the power emission per unit volume is in the following form: $E(r, \theta) = E_0(r) + E_1(r) \cos \theta$, where $\theta = 0$ is in the direction transverse to the direction the array is looking. This $E(r, \theta)$ is a simple model which seems reasonable to use for data which is mildly asymmetric in either intensity or centering in the array field of view. Adopting a method of F. Pohl,⁶ we transform the chord-

integral data into their symmetric and antisymmetric components and invert each component. The results are the functions $E_0(r)$ and $E_1(r)$, respectively.

The chord-integral power data from each half of an array is integrated over radius to obtain the total radiated power, as a function of time, for each half of the plasma, and $E_0(r)$ is integrated over the volume to obtain the total radiated power vs. time. In order to interpret the data from wide-angle bolometers, it is necessary to model the plasma column and its position and calculate the amount of power falling on the detector. The resulting scale factor to convert detector power to total radiated power depends on plasma major radius, but only slightly on the profile $E_0(r)$ [less than 10% for drastic changes in the shape of $E_0(r)$]. However, it is affected by asymmetry in the longitudinal direction ($\sin\theta$ term).

V. UNCERTAINTIES

The root-mean-square noise on a detector signal is equivalent to an absorbed power of $100 \mu\text{W}/\text{cm}^2$ when the bandwidth is set to 50 Hz.¹ For the Bay T wide-angle bolometer this implies an uncertainty of 4 kW in the measurement of total radiated power. For the arrays, the corresponding figure is $2 \text{ kW}/\text{m}^2$ in the chord-integral power measurement. Propagating the noise through the Abel inversion, we calculate that the uncertainty in the radiated power per unit volume at the plasma center is approximately $10/r_{\text{max}}$ times the uncertainty in the typical chord integral, where r_{max} is the largest chord radius. Substituting $r_{\text{max}} = 1.0 \text{ m}$, we obtain $20 \text{ kW}/\text{m}^3$ as the root-mean-square variation in the central radiated power at 50 Hz bandwidth. Because of the nature of the Abel inversion, the uncertainty in the central value is the largest. The uncertainties become less as a function of radius. The observed noise level in the result agrees with this estimate. The analysis software

employs time averaging of the signals with an adjustable width. When the width is set to 100 ms, the bandwidth is reduced by a factor of 10. For most cases on TFTR this is sufficient. With this smoothing the chord-integral noise is reduced to 0.2 kW/m^2 and the central radiated power random variation to 2 kW/m^3 . The volume-integrated power has a variation of approximately 20 kW rms with 50 Hz bandwidth. The total radiated power obtained from the horizontally viewing array agrees with that measured by the adjacent wide-angle bolometer to within 4%.

VI. PROFILE FEATURES

There is a very persistent, deep central dip in the inverted profiles, which was not expected. This feature is confirmed in two ways: first, the inversion of the separate halves of each array results in a similar dip at the center, and second, the dip appears in both arrays' views of the plasma, with approximately the same depth and width (Fig. 2). There is also a central dip under many conditions in discharges with smaller limiter radius, although the dip is narrower. The vertical view shows that a central dip appears in the profile even when the plasma center is located in a completely different part of the array field of view.

Another feature, which has appeared recently, is a dip in the vicinity of 0.55 - 0.60 m minor radius. This also appears to be confirmed by both sides of both arrays (Fig. 2), although the profile from the upper half of the horizontal view is not clear on this point. Since the dominant metal impurity has been changed from titanium to nickel, possibly the appearance of this dip could be due to a separation of the peaks in the radiated power profile due to metal and light impurities.⁷

VII. POWER BALANCE AND TRENDS

Radiated power is 60-100% of the ohmic-heating input, with the majority of cases falling above 80%. The radial profile of radiation loss can be compared with the profile of ohmic input, as in Fig. 3. Radiation loss is dominant only in the outer portion of the plasma.

There are clear trends with density and limiter surface. Figure 4 shows the results for discharges with a minor radius of 0.83 m and a current of 1.4 MA. During the earlier period when the limiter rails were coated with titanium carbide, soft X-ray measurements^{8,9} indicated that titanium was a significant impurity and that its concentration was a steeply falling function of density. With the removal of the coating from the limiters, the amount of titanium has dropped by about a factor of 50. Now the radiated power seems to be more influenced by the amount of carbon and oxygen. This view is supported by a comparison of radiation profiles, Fig. 5, for discharges with the same current and density in the two run periods, and also by the trends in the radiated power from the inner one-half radius of discharges, Fig. 4(b). Radiated power from impurities of medium atomic number is believed to be dominant at inner radii.⁷ Recent observations with injection of 1.15 MW of neutral beam into a plasma of line-average density $1.5 \times 10^{19} \text{ m}^{-3}$ show radiated power of 70 kW/m³ at 0.25 m radius, but only 45 kW/m³ at 0.75 m, probably indicating that the metal concentration has been increased significantly.

VIII. DISRUPTIONS

Figure 6 shows the plasma current and density vs. time, as well as the radiated power profiles at several times, for a discharge which disrupted. The radiated power profile shows modified behavior well before the disruption. At 1.02 s there is already a doubling of the local radiated power in the lower part of the discharge. By 1.32 s the edge power has increased by more than a factor of 4. When the disruption occurs, power is seen beyond the limiter radius. Afterward, for a surprisingly long time (0.1 s), there is a bright, shrinking light. The profiles from the vertical view indicate that this bright object is not a hot area on the inner wall.

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FIGURE CAPTIONS

- Fig. 1 Locations of bolometers on TFTR (plan view). Rail limiter and gas feed locations are also shown. Usually the gas is fed in only at location ("Bay") F.
- Fig. 2 Full-asymmetric inverted profiles for (a) the horizontal view and (b) the vertical view of a recent large plasma.
- Fig. 3 Ohmic-heating power profile and radiation loss profile for a typical discharge (TiC-coated limiter).
- Fig. 4 (a) Ohmic input power and total radiated power, and (b) radiated power integrated only out to $1/2$ of the minor radius, for a number of discharges of varying density, all with plasma current of 1.4 MA, under two different conditions of limiter surface.
- Fig. 5 Radiation-loss profiles for two discharges with the same current and density but different limiter surfaces.
- Fig. 6 Inverted profiles (horizontal view) before, during, and after a disruption. Part (a) is the plasma current, and part (b) the density, as a function of time. Note the change of scale for the power for part (g) and later.

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Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

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