Operation of a tangential bolometer on the PBX tokamak

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Abstract

A compact 15-channel bolometer array that views plasma emission tangentially across the midplane has been installed on the PBX tokamak to supplement a 19-channel poloidal array which views the plasma perpendicular to the toroidal direction. By comparing measurements from these arrays, poloidal asymmetries in the emission profile can be assessed. The detector array consists of 15 discrete 2-mm x 2-mm Thinistors, a mixed semiconductor material whose temperature coefficient of resistance is relatively high. The accumulated heat incident on a detector gives rise to a change in the resistance in each active element. Operated in tandem with an identical blind detector, the resistance in each pair is compared in a Wheatstone bridge circuit. The variation in voltage resulting from the change in resistance is amplified, stored on a CAMAC transient recorder during the plasma discharge, and transferred to a VAX data acquisition computer. The instantaneous power is obtained by digitally smoothing and differentiating the signals in time, with suitable compensation for the cooling of the detector over the course of a plasma discharge. The detectors are "free standing," i.e., they are supported only by their electrical leads. Having no substrate in contact with the detector reduces the response time and increases the time it takes for the detector to dissipate its accumulated heat, reducing the compensation for cooling required in the data analysis. The detectors were absolutely calibrated with a tungsten-halogen filament lamp and were found to vary by $\pm 3\%$. The irradiance profiles are inverted to reveal the radially resolved emitted power density from the plasma, which is typically in the 0.1 to 0.5 W/cm³ range.

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1. Introduction

Bolometric measurements are a simple and reliable method of obtaining knowledge of the total radiated power loss from a plasma, and are an essential diagnostic for understanding the energy balance in tokamaks. Operating together with spectroscopic instrumentation, information on the influx, species, and quantity of impurities can be obtained. Due to such utility, long-pulsed tokamaks have employed metal resistance^{1,2} bolometers to record the power losses from radiation while thermistors³ and pyroelectric detectors⁴ have been employed on smaller devices.

Measurement of radiated power distributions in a toroidal plasma using a tangential view is beneficial because of complications which can arise in tokamaks with noncircular cross sections. This is particularly true in a device such as PBX⁵ due to both the presence of the bean-shaped cross section and an expanded boundary divertor. A simple Abel inversion of the irradiance profiles calculated from poloidal array data is ambiguous because of both the unknown path length for each line of sight resulting from the time-varying noncircular cross section and the presence of significant emission along chords which view the periphery of the plasma near the divertor region. To address these ambiguities, an array of bolometers was installed in a tangentially viewing configuration to complement an existing poloidal array. For a tangential view, the required symmetry is toroidal rather than poloidal. Assuming such symmetry, an Abel inversion provides unambiguous profiles of radiated power as a function of major radius in the midplane.

The detectors employed here are "free standing," i.e., they are supported only by their electrical leads and have no substrate backing. Heat dissipation through a substrate provides larger signals by virtue of a higher operating temperature and bias current. However, the absence of a backing shortens the response time of the detector and increases the time it takes for the detector to dissipate its accumulated heat. This latter point is important because the corrections due to detector cooling (see section III) which are made during the data reduction contribute less to the final result, thereby reducing the error in the measurement.

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This paper presents a discussion of thinistor detectors and their calibration and operation, the design philosophy and physical geometry of the PBX tangential bolometer array, electronic amplification of the signals, data reduction, and application to measurement of radiation in the divertor region in PBX.

II. Detector and circuit characteristics

The essential characteristic of a bolometer is that the resistance of the detector is sensitive to the change in detector temperature which in turn is proportional to the time integral of the applied heat flux, $\int dt \Phi$. The principal radiative power loss in most tokamaks is line radiation emitted in the 1 to 2000 Å spectral range from highly ionized impurities. A wide variety of materials are good absorbers of radiation in this spectral range. For example, platinum bolometers have recently been developed and installed in the larger tokamak experiments such as TFTR.⁶ Although such metallic bolometers are highly resistant to hard radiation and can withstand repeated vacuum vessel baking (neither of which are requirements on PBX), they have a lower thermal sensitivity than semiconductor bolometers and have a high reflectivity in the visible spectrum, making calibration more difficult. Thinistor detectors were chosen for this application following their successful use on the PDX/PBX poloidal bolometer. While they are designed specifically for infrared detection, they have been used successfully as an absorber of VUV radiation.

The particular detectors employed are model 43K1C225/1 Thinistors,⁷ thick-film flake thermistors, manufactured by Victory Engineering Corp., Springfield, NJ. The detector medium is a 40-μm-thick layer of a nickel manganite spinel, a polycrystalline mixed oxide semiconductor material. The high surface area-to-mass ratio and very low heat capacity of the detector results in a submillisecond thermal time response. The detector resistance is $25 \text{ k}\Omega \pm 20\%$ (@ 25°C), and its negative temperature coefficient is approximately -4%/°C. The relationship between detector resistance and temperature is exponential ($R/R_{25^\circ\text{C}} \propto e^{-K\Delta T}$ where $1/K$ is 25°C for temperatures between 0° and 50°C).

Analysis of the data would be simplified if the detector resistance were proportional to its temperature. This can be realized if the temperature excursion is restricted to less than about 2°C, because the exponential relationship between detector temperature and resistance can be linearized in this range. The maximum temperature excursion expected during a PBX discharge for this detector can be calculated from the specific heat, which we measured by optically applying a known quantity of heat to the detector and recording the rise in temperature:

$$\Delta T/\Delta E = (2 \pm 0.7)^\circ\text{C/mJoule},$$

where ΔT is the temperature excursion and ΔE is the incident energy. The maximum incident power expected on the detector during a PBX shot is about 0.5 mW. Assuming this to be the average power over the one half-second duration of neutral beam injection, the quantity of incident energy is 0.25 mJoule and, therefore, the temperature excursion is expected to be less than 0.5°C, small enough to assume that the relationship between detector temperature and resistance is linear, and large enough to cause a 2% change in detector resistance. The gain of the electronics is set so a 0.5°C temperature change corresponds to the full dynamic range of the transient recorder, 5 V. The greatest observed temperature increase during operation on PBX was 0.4°C.

A constant bias current, i_{bias} , is sent through the detector and the accumulated heat is measured from the variation in bias voltage across the detector due to the changing resistance. Since the output signal is proportional to $i_{bias}\Delta R$, it is desirable to operate the detectors at high bias potentials. However, it should be kept in mind that the detector's differential sensitivity, $dR/dT \propto -KR$, decreases along with resistance. A fundamental criterion for a maximum bias voltage arises from the fact that detector resistance decreases (and heat dissipated in the detector increases) exponentially with temperature, while dissipative cooling increases only linearly. The linear cooling curve and exponential applied power curve for three values of bias voltage are shown in Fig. 1. If excessive bias heating raises the detector's temperature beyond its capacity to dissipate it, the detector resistance continues to decrease, increasingly large currents are

driven, and the detector overheats, as shown by the fact that curves (a) and (d) in Fig. 1 do not intersect. A marginal condition, known as the "rollover" in the voltage-current characteristic, is defined by the highest bias voltage which allows equalization between the bias heating, $(V_{bias}^2/R_{25^\circ C})e^{K\Delta T}$, and dissipative cooling, $C\Delta T$, where C is the cooling dissipation constant, as shown by the intersection of curves (b) and (d) in Fig. 1.

A value for the dissipation constant is provided by the manufacturer (0.5 mW/°C for this detector in still air @ 25°C); however, no conduction losses to the air are present when operating in a vacuum, though radiation and conduction through the leads still provide a heat sink. From the Stefan-Boltzmann radiation law, the radiative dissipation for an 8 mm² black-body radiator at 30°C is 0.05 mW/°C. To determine the total dissipation constant, we optically heated the detector to a known temperature and calculated the dissipated power, by knowing the specific heat and measuring the temperature decay. The dissipation constant for a free-standing detector with double adjacent leads *in vacuo* is found to be 0.16 ± 0.05 mW/°C.

To prevent thermal instability, an even more stringent limitation than the roll-over condition is imposed: the detectors are operated just below the "self-heating" point, defined to be where the detector resistance begins to change value markedly (10-20%) due to bias heating. A specification for the self-heating point is also provided by the manufacturer (1-2 mW for this free-standing detector in air) and this corresponds to an operating temperature equal to 2-5°C above ambient air. To maintain this operating temperature in a vacuum, the input power must be kept in the 0.25 to 0.5 mW range (taking the lower limit of our measured dissipation constant, 0.1 mW/°C). An adequately low bias potential (3 V for this detector) is chosen to meet this criterion and also ensures operation at a temperature well below the roll-over point so that the detector cooling losses increase faster with temperature than the bias heating, thereby establishing a thermal equilibrium. Satisfaction of this condition is illustrated by operating the detector at the intersection of curves (c) and (d) in Fig. 1.

The active detector is situated in a bridge circuit along with a reference detector, as shown in Fig. 2. The active and reference detectors comprise the upper elements, and a pair of monolithic current source transistors form the lower elements. When the bridge becomes unbalanced, due to heating and consequent change in resistance of the active detector, the difference in the voltage is amplified 120 times by an instrumentation amplifier. The signal is conditioned with a low-pass two-pole Butterworth filter which exhibits flat response with a high frequency cutoff of about 100 Hz. With a transient recording rate equal to 1 kHz, this frequency response is low enough to prevent aliasing.

A "voltage set" potentiometer is used to apply a positive voltage (typically 4 V) at the top of the bridge. The "bias voltage," V_{bias} , is set with a potentiometer and provides a reference voltage (typically 1 V) to the summing point of an operational amplifier. This amplifier also senses the voltage drop across the reference detector and causes both current source transistors to drive the necessary current to maintain the set bias voltage at the bottom of the reference detector. The actual bias voltage is the difference between the "voltage set" and the "bias voltage" values.

Since the bias feedback affects both detectors identically, either the reference or active detector must be additionally adjustable, so that the detectors can be kept in balance, defined by the output signal being equal to zero. A "manual null" potentiometer is used to adjust the current only through the active detector to maintain a coarse balance. Fine balance is maintained by sensing the difference between the voltages across the reference and active detectors, i.e., the output signal. The signal from the instrumentation amplifier is integrated through an operational amplifier that is referenced to ground. This is summed with the bias voltage output and is applied to the current source transistor in the reference leg, so that the output signal is forced to zero. One second before the discharge, a signal is sent to a solid state relay which disengages this "autonulling" feedback for a few seconds. A very low loss integrating capacitor (not shown in the schematic) is used to keep the feedback level at the point required for zero output at the instant autonulling is turned off. This prevents the baseline from drifting when the

autonulling is disengaged. The detector drift (in the absence of a plasma) over a few seconds is insignificant compared to the actual signal levels. Coarse balance is performed with the autonulling disengaged.

The amplifiers are situated in the experimental area about 20 feet from the detectors and were connected via 15 three-wire cables. The cable assembly is encased in a braided tube for RFI shielding. The signals are recorded for each channel on a LeCroy 8212 data logger at a 1 kHz sampling rate which resides in a CAMAC crate next to the amplifiers.

III. Relative calibration of the detectors

The detectors were calibrated in the near IR/visible spectrum with a 1000 W tungsten-halogen lamp. The FEL1000-W coiled filament bulb⁸ was operated at an absolute temperature of 3,200° K. The detector emissivity, not available from the vendor, was assumed to be unity in the visible. Nearly all surfaces are perfectly absorbing at normal incidence in the VUV region. The filament was focused at infinity to provide nearly collimated light at the detectors. A calibrated surface absorption power calorimeter with a 1-in. diameter was used to measure the irradiance at the detectors. Power measurements ranging from 31 to 32 mW were recorded as the calorimeter was moved along the detector housing, corresponding to an incident power of 0.19 to 0.20 mW on the detector, approximately the power levels observed in PBX. A mechanical shutter was used to illuminate the detectors for 200 msec. The time derivatives of the signals were digitally computed and compared to the incident power levels. It was found that the calibration of the 15 detectors used on PBX was in the 0.034 ± 0.001 W/(V/ms) range, i.e., the detector/amplifier response varied by about $\pm 3\%$. The voltage calibration constant is dependent on the detector current, which is set by the voltage set and bias settings, so calibration and operation must occur without altering these values.

Since the resistance of these detectors is sensitive to the accumulated heat rather than instantaneous power, the loss of heat from radiative cooling over the course of the measurement must be taken into account. If the resistance to temperature relationship of

the detector is linear then the time rate of change in bias voltage, V , is:

$$dV/dt \propto dT/dt \propto (\Phi - \Gamma), \quad (1)$$

where Γ is the exiting heat flux due to the cooling of the detector. It is assumed that in the absence of heating, the temperature of the detector decays exponentially in time, t :

$$T(t) \propto e^{-\beta t}, \text{ and} \quad (2)$$

$$\Gamma \propto dT_{loss}/dt = -\beta T, \quad (3)$$

where β is the cooling rate. Since voltage is proportional to temperature, β is determined from the equation $dV_{loss}/dt = -\beta V$ or mathematically from the slope of the line $\beta = -\Delta \ln(V)/\Delta t$, for the case when $\Phi = 0$, (i.e., during the cooling phase). Substituting $\Gamma = -\beta V$ into Eq. (1) and rearranging:

$$\Phi = A(dV/dt + \beta V), \quad (4)$$

where A is the detector power calibration factor discussed in this section. In a vacuum, $1/\beta$ is measured to be 3.1 ± 0.1 seconds. Measured cooling time constants in still air are found to be 0.5 seconds, indicating that cooling due to radiation and conduction through the leads is small compared to surface conduction.

IV. Detector geometry and *in situ* absolute calibration

The design criteria for this detector system include the desire for a compact apparatus which would share a PBX vacuum vessel flange with an existing diagnostic. Secondly, the array must provide a full view of the plasma across its midplane with a spatial resolution of about 5 cm. The 15-channel tangential array, as depicted in Fig. 3, views the major radius from 107 cm (inner armor) to 189 cm (outer limiter).

Prompt charge-exchange loss from the neutral beams which are injected to heat the plasma can be detected by bolometric systems, resulting in an overestimate of total radiated power, as was observed in PDX.⁹ To prevent detection of this spatially directed power loss from the perpendicularly injected beams, the poloidal bolometer array is tilted a few degrees off a direct radial view in the co-injected direction. Similarly, the tangential array is oriented to view in the co-injected direction to prevent detection of fast charge-exchange particles from the tangentially injected beams. The position of the

resulting tangential system with respect to the poloidal bolometer and the neutral beam lines is shown in Fig. 4.

The 15 active detectors are equally spaced 1.06 cm apart, center to center, in a linear aluminum housing that is mounted on a 4.5-in. copper gasket-type vacuum flange, as shown in Fig. 5. The 2-mm x 2-mm detectors are not backed with any substrate and are suspended by four double-adjacent electrical leads connected to posts on a TO-5 style base mount, as shown in Fig. 6. The electrical connections are through the supporting leads and the electrodes extend down opposite edges underneath the detector flake. The detector housing is bored to allow insertion of the base mount and a 2-mm-diameter hole is drilled to allow plasma radiation to strike the active detector area. An identical mount that contains the blind reference detectors is placed immediately behind the active mount, but faces away from the plasma. Each active/reference pair is connected to a common return, and comprises the upper elements of the electrical bridge. With suitably insulated vacuum flange bolts, electrical isolation from the vacuum vessel is obtained by replacing the usual copper gasket with a Vespel ring. This breaks any ground loops to provide greater immunity from EMI. Vacuum isolation from the rest of the tokamak is provided by an 8-in. diameter, manually operated gate valve. There is no separate pumping system for the detector assembly.

An 8-mm x 9-mm aperture is placed 360 mm in front of the active array to image the plasma onto the detectors. No baffles or blackened surfaces were employed because of the low reflectivity of steel in the VUV. The distance from this aperture to the point of tangency of the central detector's line of sight is 2.08 m, providing effective magnification of 5.8 and a chord separation equal to 61 mm at the point of tangency. To maximize the optical throughput, the imaging aperture is made as large as possible without having the the field of view of adjacent chords overlap. With an aperture whose dimensions are 8 mm x 9 mm, the width of the field of view for each chord is 58-mm (i.e., the zones do not quite overlap) and the height of the viewing zone is 64 mm.

For the above geometry, the relation between emission from the plasma and the

light flux incident on the detector can be calculated. Assuming that the plasma is optically thin and radiates isotropically, the intensity of emission is the volume integral of the power density, ϵ in W/cm³, distributed over all solid angles:

$$d\Phi/d\Omega = (\iint dA \int \epsilon dl) / 4\pi \text{ W/sr}, \quad (5)$$

where the area integral is over the surface viewed by the detector and the line integral is along the detector's line of sight through the volume. The area integral can be simplified if the plasma is an extended source (i.e., if the limitation on plasma area viewed by the detector is determined by an external aperture rather than the plasma extent). In this case, the differential area dA is equal to the differential viewing solid angle limited by the aperture, $d\Omega_{slit}$, multiplied by R^2 where R is the distance from the plasma element to the central detector.

The light flux on the central detector, Φ_{det} (in W), is equal to the plasma intensity integrated over the differential solid angle subtended by the detector, the latter of which is given by:

$$d\Omega_{det} = dA_{det}/R^2, \quad (6)$$

where dA_{det} is the detector differential area. Multiplying Eq. (5) by Eq. (6) and substituting for dA , the total light flux on the detector is:

$$\Phi_{det} = (\iint dA_{det} \int \epsilon dl) / 4\pi. \quad (7)$$

This is the result for an extended source viewed by an optical system whose etendue or optical throughput is given by the expression in parentheses in Eq. (7). If it is assumed that the detector size is small, i.e., $d\Omega_{slit} = \text{constant}$ and the source emission does not vary across the detectors field of view, then the flux on the detector is:

$$\Phi_{det} = (A_{det} \Delta\Omega_{slit}) / 4\pi \int \epsilon dl, \quad (8)$$

where $\Delta\Omega_{slit} = A_{slit}/R_{slit}^2$, A_{slit} is the area of the aperture, and R_{slit} is the distance from the central detector to the aperture. A factor of $\cos^4\theta$ (where θ is the angle between the line of sight and the normal to the surface of the detector) arises for off-axis detectors because they are farther from the imaging aperture and they view the aperture and the plasma obliquely.

For a detector area equal to 0.0314 cm^2 , an aperture area of 0.72 cm^2 , and an aperture-detector distance of 36 cm, the irradiance, or line integral, of plasma power density for the central channel is:

$$E = \int \epsilon(l) dl = 7.2 \times 10^5 \Phi_{det} \text{ W/cm}^2. \quad (9)$$

When the detector power calibration is included, the conversion from measured signal to plasma irradiance for all 15 channels is in the $(2.5 \pm .1) \times 10^4 \text{ (W/cm}^2\text{)/(V/ms)}$ range. Inverting Eq. (9) to obtain the local power density as a function of major radius along midplane is discussed in section V.

Since emissivity of the detector material in the visible/near IR spectral region is most likely less than unity, while the emissivity in the soft X-ray/VUV region is nearly unity, calibration with a filament lamp provides only a relative calibration among the detector elements in the array. However, an absolute calibration of the array is provided *in situ* through a comparison with a bolometer channel at the midplane, which measures the radiated power *radially* integrated along the midplane of the torus (though at a different toroidal location). The value of this radial bolometer is that it consists of a thermistor that is mounted on a relatively massive copper substrate, a material whose specific heat and mass density are well known. A reliable absolute calibration is obtained by measuring the rise in detector temperature following an *electrically* applied heat pulse of known power, and comparing this with the value calculated from the specific heat. Then, the computationally integrated midplane power profile from the tangential array data can be scaled from the value found by the actual radiated power from the plasma, as measured with the calibrated detector. Peaked emission profiles are examined so that edge effects such as plasma interaction with the inner limiter are small enough to be negligible. This comparison with the calibrated channel provides calibration constants for the tangential array in the $(1.2 \pm 0.05) \times 10^4 \text{ (W/cm}^2\text{)/(V/ms)}$ range. If the discrepancy between this value and that found with the filament source is due solely to the emissivity in the visible/near IR, the total emissivity of this detector material for light emitted from tungsten filament heated to $3,200^\circ\text{K}$ is calculated to be 0.48 ± 0.04 .

V. Data Reduction

The amplified and filtered change in voltage across one of the 15 detectors is shown in Fig. 7 (a) for a PBX discharge with 2.5 MW of neutral beam heating. Typical signals are in the 1-4 V range. Since these detectors measure the time integral of the applied heat flux, the time derivative of the raw data must be performed, as shown in Eq. (4). Because some scatter is always present in experimental data, smoothing of the integrated data must be performed before the derivatives are calculated. Otherwise, the differentiating would amplify this scatter and seriously distort the results. The method employed here uses a cubic spline interpolation which features a local smoothing parameter to approximate the data. The approach is to choose a spline function, $S(x)$, which minimizes the functional:

$$\int_x^{x_n} |S''(x)|^2 dx + \sum_{i=1}^n [y_i - S(x_i)]^2 / \sigma_i^2 - SM, \quad (10)$$

where the y_i 's are the raw data and n is the number of data points. This process establishes a balance between fidelity to the original data as expressed by the second term, and smoothing of the function by usual least squares techniques, as expressed by the first term. The smoothing is accomplished by minimizing the cumulative second derivative or "curvature." If SM is chosen to be zero, the function is a cubic spline interpolation of the data function with no smoothing. If SM is too large, the irradiance profile will become overly flattened. It is best not to choose SM to vary the amount of smoothing, because it is a global parameter. Abrupt changes in the emission rate, such as those present during a disruption, would be lost because the change is as rapid as the detector noise. A local parameter, the relative value of the weights, σ_i , can be used to control the extent of the smoothing in those regions where it is required. There is a relation between the values for σ_i and SM : if σ_i is the estimate of the standard deviation of the data point, then SM should be approximately n .

A particular convenience in using this method lies in the fact that it is available as part of a commercial package of *FORTRAN* numerical routines.¹⁰ It is important that the spline function provide an acceptably accurate approximation of the original curve, even for moderate numbers of data points because the error introduced by the data scatter increases with n . A maximum number of data points of 40 is found to be reasonable.¹¹

Since the PBX shot length can be up to 900 msec, a sampling rate of 1 kHz provides up to 900 data points. The data analysis software has been written so that the user can specify the time interval to be examined, and the program divides the data into 50 equal intervals, performing a simple average in each interval. This data compression provides 50 averaged points for the smoothing routine. In addition to time-averaging, up to 15 shots may be averaged together.

The smoothed raw data display is actually superimposed on the raw data in Fig. 7 (a), and the effect of smoothing is seen to be very slight. The analysis program also provides a plot of the time derivative, as shown in Fig. 7 (b). The σ_j 's are entered into the program as absolute values in volts, and they can be changed uniformly for an entire channel. In addition, the raw, smoothed and differentiated data can be enlarged for each channel and plotted simultaneously, so that the σ_j 's can be adjusted point by point if noise is observed in a particular interval. Typical values for the σ_j 's, the minimum detectable signal above the background amplifier noise, are in the 0.002 to 0.010 V range which corresponds to a minimum measurable temperature of 0.0007 °C. Typical measured voltages are in the 1-2 V range so the signal-to-noise ratio is between 100:1 and 1000:1. Suitably scaled, the time derivative of each of the 15 channels at one instant represents the plasma irradiance profile, a sample of which is shown in Fig. 8. The profiles themselves are smoothed by approximately 5% according to the weights given for each channel because of calibration uncertainties.

The calculation of plasma power density, ϵ , from the measured irradiance, E , in Eq. (9), is not simple because the variation in power density along the path of integration is not known. However, certain simplifying assumptions make the inversion of the integral

fairly easy. First, the power density is assumed to exhibit toroidal symmetry, i.e., ϵ is a function of major radius only. Then the integral can be stated with its functional dependencies as:

$$E(x) = \int_{-Y}^{+Y} \epsilon(r) dy, \quad (11)$$

where $x^2 + y^2 = r^2$, $Y = (R^2 - x^2)^{1/2}$, and $r \leq R$, where r is the major radius, and R is the major radius of the outer limiter. While the integration path is in the y (chordal) direction, the data are recorded as a function of x (tangency radius), and the desired quantity is a function of r (major radius). The substitution of $y = (r^2 - x^2)^{1/2}$ into the previous equation results in the following integral:

$$E(x) = 2 \int_x^R \epsilon(r) r dr / (r^2 - x^2)^{1/2}. \quad (12)$$

This problem has been examined for cylindrical emitters and has been solved by employing Abel's transformation.¹² However, a problem with this formulation arises because it is the irradiance derivative, $dE(x)/dx$, which is required for the calculation. Similar to the discussion on calculating the time derivative, performing the spatial differentiation can amplify data scatter and distort the profile. Various schemes have been developed to integrate and smooth the raw data before differentiating; however, they often require small amounts of data scatter or require equidistant data points.¹³

Numerical differentiation can be avoided if the power density profile can be described by a "shell" model rather than a smooth function.¹⁴ In this description, the profile is characterized by a series of nested circular shells of constant power density. While the integration path traverses many concentric "shells," the integration can be performed analytically because each shell has a constant power density. Though the assumption of constant power density within a shell results in a coarse approximation of profile, it permits a significant savings in computation time. Calling ϵ_j the constant power density value in the j th shell, and E_j the measured irradiance from the i th channel, the

integral in Eq. (11) can be performed analytically and the irradiance can be represented by a discrete sum:

$$E_i = 2 \sum_{j=i}^n \epsilon_{ij} [(x_j^2 - x_i^2)^{1/2} - (x_{j+1}^2 - x_i^2)^{1/2}] = \sum_{j=i}^n \epsilon_{ij} L_{ij}, \quad (13)$$

where n is the number of chords. The ordering of shells increases towards increasing major radius. The inversion is algebraic and can be performed by computing the inverse of the length matrix, L (the value in the square brackets is actually the path length for the i th channel through the j th shell).

The assumption of toroidal symmetry allows an additional simplification at this point. Because the axis of symmetry for this geometry is the machine axis, rather than the plasma magnetic axis, the distance from the viewing chord to the point of symmetry never changes, i.e., the x_i 's never change. This array of values, L_{ij} , which is a triangular matrix, need be inverted algebraically only once and stored in a data file, so that the power density can be calculated by a simple matrix multiplication:

$$\epsilon_i = \sum_{j=i}^n L_{ij}^{-1} E(x_j), \quad (14)$$

where L_{ij}^{-1} is an element of the inverse of L .

Error propagation due to the combination of the coarse modeling of the profile and uncertainty in the irradiance measurement was tested numerically using several power density profiles. The tests included wide and narrow, peaked and hollow profiles having width of peak (or hollow region) to vacuum vessel diameter ratios ranging from 1/8 to 7/8. Using Eq. (12), the irradiance profiles were calculated exactly or with highly accurate numerical routines, after which $\pm 2.5\%$ random noise was added to each channel. Multiplying the calculated 15×15 inversion matrix by the noisy irradiance profile, the calculated power density was found to agree with the original to within $\pm 8\%$.

The smoothed irradiance profile, multiplied by the inversion matrix, is shown in

Fig. 9 for the data in Fig. 3. Power density values in the range of 0.1 to 0.5 W/cm³ are observed with peak power densities increasing to 1 W/cm³ just before an impurity radiation-induced collapse of the plasma. The power density profile is volume integrated by projecting the value at the midplane onto a poloidal shell characterized by the major radius and minor radius of the plasma and the elongation, indentation, and triangularity of the outer boundary of the plasma. The inner shells of the plasma are described by a Fourier expansion in two variables: a normalized flux coordinate, ρ , and poloidal angle. For a quantity which is a function of the flux coordinate only, the poloidal angle is integrated analytically and the differential volume is represented by 5th-order polynomial in ρ with coefficients determined by the plasma shape.¹⁵ For cases which do not exhibit in/out symmetry, the integration uses an average of the two values on either side of the magnetic axis. The value of volume-integrated radiated power for this case is 0.65 MW, about 25% of the total input power. However, within the centermost 20 cm of the plasma, the radiated power exceeds the input power, inducing a thermal collapse. Increased impurity influx and accumulation, particularly high-Z metallic species such as Ni, Fe, and Ti, is confirmed by VUV spectroscopic measurements at the center of the plasma during the final stage of the discharge.¹⁶

VI. PBX Divertor Results

In addition to providing radiated power profiles in the plasma midplane, the tangential bolometer is used in conjunction with the poloidal array to assess the poloidal asymmetries and calculate emission in the divertor region. Assuming that radiative power density is a constant along a flux surface, these midplane values are projected along each of the closed flux surfaces inside the separatrix and the 2-dimensional radiated power density distribution in the poloidal plane can be calculated. Using these values, the contribution to the irradiance viewed by each chord in the poloidal array, which originates from the region *inside* the separatrix, is determined. This contribution is subtracted from the poloidal bolometer signals and the emission from the plasma outside the separatrix, particularly from the divertor region, is deduced. A detailed discussion of

divertor power measurements on PBX is found in Ref. 17, but a simple illustration is shown in Fig. 10. Assuming a typical path length through the divertor region (0.4 m) and a typical channel width (0.15 m), the profile of radiated power in the divertor can be estimated. The precise location of the region of most intense emission depends on beam geometry, but generally it is found between the X-point and roof of the vacuum vessel. Approximately 20-25% of the input power to the plasma is radiated in the divertor region. This is comparable to the power radiated from the main plasma and is also comparable to the power radiated in the divertors in a closed divertor geometry such as in PDX.⁹

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Figure 1. Heat flow into a thinistor detector due to bias currents (a-c) and dissipation from a thinistor detector (d). Curves (a), (b), and (c) correspond to detector bias voltage values of 6.2, 4.8, and 3.0 V, respectively. (d) The linear cooling curve for a detector whose dissipation constant is equal to $0.1 \text{ mW/}^\circ\text{C}$.

Figure 2. Bridge-electronics schematic. The detectors are depicted as resistors.

Figure 3. Top view of midplane showing orientation of the tangential detector array and aperture; 15 viewing chords cover the major radius of the PBX torus.

Figure 4. Placement of the tangential bolometer array with respect to the radial array and the neutral beams around the PBX torus.

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Figure 6. A thinistor detector showing the four supporting electrical connections.

Figure 7. The amplified voltage drop across one of the 15 active detectors. The smoothed signal is superimposed on the raw data (a). The time derivative of the smoothed data (b).

Figure 8. The 3-D irradiance profile, not smoothed in space, as a function of time.

Figure 9. The spatially smoothed, inverted power density as a function of time.

Figure 10. Irradiance as calculated from tangential array data and measured by the poloidal array for each bolometer channel. The difference between the curves (indicated by the shading) is interpreted as emission originating in the divertor region. Channel #1 corresponds to the midplane. The angle of the line of sight increases with chord number; the X-point of the plasma is viewed by chord #5. Higher channel numbers represent distance from the X-point outward to the top of the plasma region as defined by the passive stabilizers (c.f. Ref. 17).

#86X1853

Fig. 1

I 1138 PDX BOLOMETER BRIDGE

PBX TANGENTIAL BOLOMETER ARRAY
(Top View of Midplane)

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7(a)

Fig. 7(b)

Fig. 8

Fig. 9

Fig. 10

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