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IN THE DIVERTOR REGION IN PBX

By

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Measurement of emitted power in the divertor region in PBX

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Abstract

In strongly indented PBX plasmas, radiated power profiles are calculated by combining data obtained from two bolometer arrays in order to study poloidal asymmetries arising from plasma indentation and characterize emission from the divertor region. A compact, 15-channel bolometer array that views the plasma tangentially along the midplane complements a 19-channel array that scans the plasma vertically in a poloidal plane. Assuming that radiated power density is constant along a magnetic flux surface, the contribution to the irradiance viewed by the poloidal array from the region inside the separatrix can be calculated from the midplane measurements. The difference between this contribution and the measured poloidal distribution is assumed to originate in the expanded boundary divertor. In general, the total radiated power loss constitutes 40% of the total input power, and is independent of beam geometry. However, the radiation profiles in the main plasma and divertor region depend on operating conditions such as beam geometry and gas puffing rates. Radiation from the main plasma accounts for 20% of the input power and radiation from the divertor region accounts for 20%. Accumulation of impurities during neutral-beam-heated discharges can cause peak radiation levels to exceed 1 W/cm^2 , leading to a thermal collapse of the plasma.

MASTER

I. Introduction

The Princeton Beta Experiment (PBX) is a medium-sized tokamak ($R = 145$ cm, $a = 35$ cm, $I_p \leq 500$ kA) experiment designed to study the effect that strong indentation of the plasma cross section has on the maximum attainable beta values.¹ The PBX neutral beam system consists of four co-injecting beam lines which can inject up to a total power of 5 MW. Two are oriented for near-perpendicular ($\perp$) injection with a tangency radius of 35 cm and the other two are oriented for tangential ($\parallel$) injection with a 135 cm tangency radius. A unique feature of PBX is the presence of an active "pusher" coil located at the inboard midplane of the vacuum vessel. This permits indentation of the toroidal plasma along its inner radius, resulting in a bean-shaped cross section, as shown in Fig. 1. The plasma can be bounded by a free magnetic separatrix whose X-point is located inside the close fitting passive stabilizers, giving rise to a region surrounded by the separatrix and the nearest wall, i.e., an expanded boundary divertor. During intense neutral beam heating, the presence of this divertor results in H-mode operation² similar to that observed with a closed divertor configuration in the predecessor of PBX, the PDX device.^{3,4} In PBX, H-mode operation is characterized by a sudden increase in electron density and stored energy in the main plasma and an increase of up to 50% in the energy confinement time. However, under these conditions, the influx and accumulation of impurities in the center of the plasma often becomes excessive, leading to intense radiative cooling and subsequent thermal collapse of the plasma.^{5,6} This accumulation can be controlled to some extent by moderate gas puffing at the plasma edge.⁷

To quantify the effects of impurity behavior in PBX and to further characterize the expanded boundary divertor, the radiated power distributions in PBX are being studied with bolometer arrays. Measurement of the radiated power distributions in PBX is complicated by the presence of the expanded boundary divertor and the bean-shaped cross section as shown in Fig. 1. A simple Abel inversion of the

irradiance profiles calculated from poloidal array data is ambiguous because of the unknown path length for each chord 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 this ambiguity, a complementary array of bolometers was installed in a tangentially viewing configuration.⁸ For a tangential view, the required symmetry is toroidal rather than poloidal. Assuming such symmetry, an Abel inversion provides unambiguous profiles of radiated power vs. major radius in the midplane. Furthermore, assuming that radiative emission is a constant along a flux surface, the radiated power density inside the separatrix can be computed. Using these values, the contribution to the irradiance which originates from the region inside the separatrix, as viewed by each chord in the poloidal array, is calculated. This contribution is subtracted from the total measurement, i.e., the emission integrated along the entire viewing chord, and the emission from the region outside the separatrix, particularly from the divertor region, can be determined. The divertor radiation is calculated from the upper half of poloidal bolometer array as shown in Fig. 1. Data from the lower chords indicate that the radiation profiles are up/down symmetric.

Prompt charge exchange loss from the neutral beam injection can be detected by bolometric systems. To prevent detection of power loss from the perpendicularly injected beams, the poloidal bolometer array was tilted a few degrees off a direct radial view in the co-injected direction. This eliminated an overestimation of radiated power which occurred in PDX.⁹ Similarly, the tangential array was oriented to view in the co-injected direction to prevent detection of fast charge-exchange from the parallel beams.

The discussion presented in this paper will include 1) quantitative measurement of radiated power density profiles in the region inside the separatrix; 2) assessment of poloidal asymmetries in the radiated emission profile that originate

outside the separatrix; 3) calculation of the quantity of radiation originating in the divertor and; 4) determination of the spatial distribution of emission in the divertor.

The bolometric measurements presented in this study were obtained from a specific series of high plasma current discharges covering a 1 to 5 MW range of neutral-beam-injected power. This allows a comparison of divertor emission as a function of beam power and geometry.

II. Radiated power in the plasma core

In general, radiated power density at the center of the plasma ranges from 0.1 to 0.5 W/cm³. Until the very end of the discharge in cases where there is strong impurity accumulation, the value of total power radiated from the main plasma remains about 20% of the total input power over a wide range of injected power and beam injection geometry. Unlike the total radiated power, the emission profiles in the midplane are quite dependent on beam injection geometry. In general, the emission profile is more hollow for predominantly $\perp$ cases than for predominantly $\parallel$ cases. This relation is illustrated in Fig. 2 for a particular case of 2 $\perp$, 1 $\parallel$ injection and 1 $\perp$, 2 $\parallel$ injection. The profile is hollow with a central power density of 90 mW/cm³ for the mostly $\perp$ injection case, whereas for the predominantly $\parallel$ injection case, the radiation profile increases towards the outer major radius with a central emission density of 160 mW/cm³. The asymmetry of the radiation profile to the larger major radius, though more evident in this case than in general, is similar to the asymmetry in the electron density profile seen in both PDX and PBX.¹⁰

During the final stage of the discharge, radiation is often observed to peak sharply (10 cm half-width) in the center of the plasma and radiated power can exceed 1 W/cm³. This rise in central radiation and subsequent rapid peaking is consistent with X-ray and spectroscopic measurements of an increased impurity influx leading to severe impurity accumulation, especially for high-Z metallic species such as Ni, Fe, and Ti.⁶ As an example, a discharge in which the emission profile sharpens during

the course of significant impurity accumulation is shown in Fig. 3 (a). For 200 msec after the onset of injection, the emission profile is flat or even slightly hollow with power densities of 30-40 mW/cm³. About 60 msec later the power density increases to 200 mW/cm³ and is broadly peaked (30 cm half-width). Metallic impurities then rapidly accumulate in the center of the plasma, and within 40 msec, the emission profile is very strongly peaked (half-width 15 cm) and the peak power density is about 1.8 W/cm³. In the case shown here, the radiated power becomes comparable to the input power to the electrons at the center of the plasma and causes the plasma to thermally collapse. The final rapid peaking can be mitigated to some extent by gas puffing which reduces the central radiated power density to less than 400 mW/cm³ as shown in Fig. 3 (b). In this case, the profile is more hollow with edge power densities about 100 mW/cm³. This results in greater total radiated power than the case without gas puffing. At 650 msec, the peaking is far less evident, but both discharges abruptly end at 720 msec when the neutral beam injection ends.

III. Divertor radiation

As discussed in Sec. I., the radiated power outside the separatrix is derived by 1) projecting the measured power density averaged about the magnetic axis in the midplane onto the magnetic flux surfaces; 2) calculating the irradiance that the poloidal bolometer viewing chords would observe; and 3) subtracting the irradiance originating in the plasma region inside the separatrix from the poloidal bolometer signals. The projection onto the flux surfaces is approximate since the density is known to not be a constant along a field line and some poloidal asymmetry is often seen in the midplane radiation profiles, as in Fig. 2. Outside the separatrix, it is assumed that the emission is uniformly distributed in the region between the separatrix and the nearest physical boundary, generally the passive stabilizing conductors or the pusher coil. In general, the results of this analysis indicate that there is a large amount of power being radiated outside the main plasma. Regardless of beam geometry and power of the injected

beam, the amount of radiation emitted from the divertor region is approximately 20% of the total input heating power. These quantities are comparable to the amounts of power radiated from closed boundary divertors in PDX or ASDEX.^{11,12}

The distribution of radiated power in the divertor region is plotted vs. poloidal bolometer channel for a single $\parallel$ and $\perp$ injected beam in Fig. 4. For both injection geometries, a broad maximum in radiated power is centered 25 cm from the X-point towards the upper passive stabilizer plates. Recordings of H_α emission show that the recycling in the edge plasma is strongly concentrated in this same region of the divertor which is magnetically connected to the outside edge of the plasma. As was found in PDX-diverted plasmas¹³, the power flow along the separatrix into the divertor region appears to be strongly asymmetric with most of the power flowing out along the larger major radius side of the plasma. The detailed distribution of radiated power in the divertor is sensitive to discharge conditions. For the $\perp$ case, the radiation is more uniformly distributed with more radiated power emitted from the region between the X-point and the pusher coil. This is consistent with the speculation that beam shine-through during $\perp$ injection provides moderate fuelling on the inboard plasma side and/or impurities are produced from beam impact on the inner armor.

Variations in divertor emission also occur for cases where the amount of hydrogen gas puffing is altered. In an effort to control the strong density rise in an H-mode plasma, the gas fuelling rate was often dropped to nearly zero after the H-mode transition. In the case of little or no gas puffing, substantial quantities of metallic impurities often accumulate in the center of the plasma.⁷ Figure 5 shows the variation in the distribution of radiated power in the divertor region for the cases of no and moderate gas puffing (10-20 torr-l/s). For both cases, the edge radiation is again peaked between the X-point and the top of the vacuum vessel, and the peak power density is about 0.44 W/cm^3 , comparable to that in the center of the main plasma. In both cases, the peak of the radiation profile is located between the X-point and the top

of the vacuum vessel. However with moderate gas puffing, the distribution is more broadly distributed throughout the divertor region.

IV. Discussion and Summary

Although there are variations in the distribution of radiated power in both the main plasma and edge regions for different operating conditions, the total radiated power is approximately a constant fraction of the total input power. A summary of the radiation power balance for both the main plasma and divertor plasma regions, depicted in Fig. 6, shows that total emission is roughly independent of beam geometry. Radiation from the main plasma, ranging from 0.3 to 0.9 MW, accounts for approximately 20% of the total input power. Poloidal asymmetries observed by the poloidal bolometer array are ascribed to emission along the plasma periphery, particularly from the expanded boundary divertor region. Assuming no appreciable emission in the outer scrape-off region (as evidenced by the midplane profile), there is a greater quantity of emission from the divertor region than in the main body of the plasma. Emission from the divertor region, ranging from 0.4 to 1.2 MW, accounts for roughly another 20%, combining for a total radiation loss of 40%. Because of the presence of several small (2-cm high) graphite rail limiters on the passive stabilizers which are not viewed by the bolometer arrays, this may be an underestimate of the total radiation losses. Under some conditions, the plasma TV diagnostic shows substantial interaction between the edge plasma and these protective rails. In addition to this loss, the remaining 60% of the input power presumably is absorbed as thermal energy by the passive stabilizers (which act as the divertor neutralizer plates) and the graphite armor covering the pusher coil. In open divertor PDX discharges, it was observed that a similar fraction of the input power was deposited on the neutralizer plates.⁹

Radiated power density in the center of the plasma ranges from 0.1 to 0.5 W/cm³ and can rise as high as 1.5 W/cm³ during a thermal collapse of the discharge.

The emission profiles are more hollow with $\perp$ injection than with $\parallel$ injection, possibly indicating that there is a greater proportion of low-Z impurities with perpendicular injection. There may, of course, also be a change in the impurity transport in the core of the plasma which leads to impurity accumulation. For both $\perp$ and $\parallel$ beam injection geometries, radiation in the divertor region is concentrated between the X-point and the stabilizer plates. However, for the $\perp$ injected case, the divertor emission profile is more uniformly distributed about the X-point, with more radiation between the X-point and the pusher coil.

There is a similarity in the distribution of emission in the divertor between gas-puffed cases and perpendicular injection, in that the main plasma emission profile is flatter, with less radiation in the center of the plasma, and in that the divertor emission profile is *more uniformly distributed about the X-point*. Significant metallic impurity accumulation in the plasma core is delayed or reduced with gas puffing.

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References

- ¹M. Okabayshi et al., Plasma Phys. Contr. Nucl. Fusion Research 1 (1984) 229.
- ²F. Wagner et al., Phys. Rev. Lett. 49 (1982) 1408.
- ³S. Kaye et al., J. Nucl. Mater. 121 (1984) 115.
- ⁴R. J. Fonck et al., Proc. 4th Inter. Symp. on Heating in Toroidal Plasmas Rome, 1 (1984) 37.
- ⁵K. Ida., R. Fonck, S. Sesnic, R. Hulse, and B. LeBlanc, *Princeton Plasma Phys. Rep.*, PPPL-2315.
- ⁶S. Sesnic et al., J. Nucl. Mater. (in press).
- ⁷K. Ida, Ph.D. Thesis, University of Tokyo (1985), to be submitted to Nucl. Fusion.
- ⁸S. F. Paul, R J. Fonck, and G. L. Schmidt, submitted to Rev. Sci. Instrum.
- ⁹R.J. Fonck et al., J. Nucl. Mater. 128,129 (1984) 330.
- ¹⁰D. Johnson et al., Plasma Phys. and Contr. Nucl. Fusion Research, Proc 9th Inter. Conf. Baltimore, IAEA, Vienna, 1 (1981) 9.
- ¹¹M. Bell et al., J. Nucl. Mater. 121 (1984) 132.
- ¹²E. R. Muller et al., J. Nucl. Mater. 121 (1984) 138.
- ¹³D. K. Owens et al., J. Nucl. Mater. 93,94 (1980) 213.

Figure captions

Figure 1. Flux plot of a typical PBX discharge with an expanded boundary divertor, the region above and to the left of the X-point. The pusher coil with graphite neutral beam armor is shown on the midplane. Also indicated are the locations of the Ni-coated passive stabilizer plates which form the first wall. The poloidal bolometer chords are depicted and the upper channels, as referred to in the text, are numbered.

Figure 2. Power density profiles for 2 $\perp$, 1 $\parallel$ and 1 $\perp$, 2 $\parallel$ injection geometries at 550 msec. Total injected power is 3.5 MW from 350 to 650 msec and total radiated power from the main plasma is 0.6-0.65 MW in both cases.

Figure 3. (a) Emitted power density as a function of major radius and time as measured by the tangential bolometer for the case with no gas puffing. Two perpendicularly oriented neutral beams with a total power of 2.5 MW ($D^0 \rightarrow D^+$) are turned on from 400 msec to 700 msec. (b) Same conditions with moderate gas puffing.

Figure 4. Radiated power density distribution in the divertor at 500 msec for injection of 1.5 MW for both $\perp$ and $\parallel$ beam geometries. Channel five corresponds to the X-point. Negative distance represents distance from the X-point downward to the midplane. Positive distance represents distance from the X-point outward to the top of the plasma region as defined by the passive stabilizers.

Figure 5. Divertor power density distribution at 690 msec vs. poloidal bolometer channel for cases of slight and moderate gas puffing. Two perpendicularly oriented neutral beams inject a total power of 2.5 MW from 400 to 700 msec.

Figure 6. Total radiated power balance vs. incident beam power for various beam geometries. The total radiated power is divided into power radiated from the main plasma region (cross-hatched area), the divertor region. (checkered area), and beam power not absorbed by the plasma (dotted area). The slopes of the lines represent best fits for the various injection powers and geometries.

Figure 1

Figure 2

Figure 3a

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Figure 3b

Figure 4

Figure 5

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Figure 6

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