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ELMING H-MODE PLASMAS**

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JULY 1994

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ABSTRACT

We account for $\geq 85\%$ of the injected power in DIII-D during single-null diverted ELMing H-mode discharges. Core plasma radiation accounts for $\leq 18\%$ with the rest flowing through the scrape-off layer to the inboard and outboard divertors. The total power roughly splits in an in:out ratio of 1:1.3. Of the power entering the outboard divertor 75% leaves as direct heat flux to the divertor target plates with the rest in the form of radiation. In the inboard divertor, however, 75% of the power leaves as radiation with the rest as divertor target plate heat flux and charge exchange losses. The in:out ratio remains constant over a range of injected power and plasma current and even as divertor conditions change due to gas puffing.

1. INTRODUCTION

In this paper we report on power accounting in the DIII-D tokamak during ELMing H-mode in a single-null configuration. In a reactor the power leaving the plasma discharge will be very large (Post [1]), presenting a serious challenge in the design of plasma facing components. An accurate accounting of the magnitude and location of heat fluxes from the plasma is needed to understand current divertor operation and to produce a workable design for future higher power tokamaks. Current experiments which test new divertor techniques and operating regimes also need an accounting of power to test their effectiveness. Finally, accurate power accounting is important for benchmarking edge plasma computer codes (Rognlien [2]). These codes will aid in design of the next generation of divertors and need to be cross checked with existing experiments.

For this paper we study ELMing H-mode plasmas. These plasmas provide attractive reactor scenarios with their high confinement and ELMing behavior which limits density and impurity accumulation to produce a steady-state discharge. We are studying single-null plasmas because they are our best diagnosed configurations and secondly, the current design for ITER calls for a single-null plasma.

We will show that we account for $\geq 85\%$ of the injected power, P_{inj} . A fraction of this power, $\leq 18\%$, is lost as radiation in the plasma core, P_{core} . The rest flows through the scrape-off layer (SOL) and into the inboard and outboard divertors where it exits as direct heat flux to the divertor plate, P_{plate} , and divertor radiation, P_{rad} , with a lesser amount carried out by charge-exchanged neutrals, P_{cx} . Previous work showed much greater heat flux, P_{plate} , by a factor of 4 to 8, to the outboard divertor than the inboard (Hill [3]). This study confirms that result, but we also find the opposite asymmetry in P_{rad} . With a greater value of P_{rad} in the inboard divertor than the outboard the total power flow, P_{plate} plus P_{rad} , is more nearly balanced at an in:out ratio of approximately 1:1.3. This ratio is maintained over variations in plasma current and input power and with changes to divertor conditions with gas puffing.

We will discuss the diagnostics and analysis tools used for this study in Section 2. Section 3 will present the power balance data for single-null ELMing H-mode discharges with variations in input power, plasma current and gas puffing. A discussion of the results will follow in Section 4.

2. DIAGNOSTICS

Power leaving the plasma is measured by two diagnostic sets, bolometers for power, and IR TV cameras for power flux to plasma facing surfaces. The bolometer diagnostic consists of two 24-channel arrays providing complete plasma coverage. Each detector channel consists of two 50- Ω platinum foil resistors, arranged in a bridge configuration. A more complete description of the DIII-D bolometer array design is given in Leonard [4]. The signal measurement electronics are of the same design of those previously installed on TFTR (Schivell [5]). The detectors are sensitive to all radiation leaving the plasma, including neutral particle flux. The views of the two arrays, shown in Fig. 1, are designed to give complete plasma coverage and yet retain good resolution in the divertor.

The radiated power in a toroidal projection of a bolometer viewing chord can be approximated by $P = 2\pi R K P_d r \Delta\theta$ where K is a constant of the aperture and detector geometry, $\Delta\theta$ is the poloidal width of the viewing chord, P_d is the power on the detector, r is the distance from the aperture to the center of radiation and R is the major radius at the center of radiation. Because of the flat response arrangement of the viewing chords (Leonard[4]) and the complete coverage, the total radiation can be calculated using the above relation and summing over detector channels of a single array. For chords viewing the core plasma, r is assumed to be the distance from the aperture to the tangent magnetic flux surface. For the divertor chords r_i is assumed to be the distance to the divertor because of the very intense radiation in that region. The total radiated power is measured by summing over the chords of the lower array, with the divertor radiation determined by summing only over the lowest of these chords which view the divertor. The remaining chords of the lower array measure P_{core} . The upper array is used to determine the inboard and outboard fractions of the measured divertor radiation.

Power flow to plasma facing surfaces is determined from surface temperature measurements obtained from four IRTV cameras sensitive in the 8–12 μm band (Hill [6]). The surface

temperatures are converted to heat flux using a one-dimensional uniform slab model. These cameras provide coverage of the divertor target, the inner wall, and the upper divertor, or ceiling, area. Power flux to the outer wall is not routinely measured.

Fig. 1. Viewing chords of the two bolometer arrays in the DIII-D vessel. Each ray represents the bounds of a viewing chord.

3. POWER BALANCE IN ELMING H-MODE

The standard discharge of this study is a lower single-null configuration with magnetic flux surfaces similar to that shown in Fig. 1. For this study the plasma current is varied from 1.0–2.0 MA, and the input power, P_{inj} , varied from 4–18 MW with a constant 2.1 T toroidal magnetic field. The toroidal field direction is for the ∇B drift towards the x-point. This parameter regime is typical standard single-null operation for DIII-D that is easy to achieve and reproducible. The discharge easily attains H-mode and rapid ELMs soon develop which keep the density constant for the duration of the discharge, about 3 seconds. The stored energy and other global parameters remain constant over this period. The ELM frequency changes with these parameters, but the ELMs remain frequent enough to maintain steady-state conditions. The plasma density does not change with variations in P_{inj} , but does typically vary proportionally with plasma current during ELMing H-mode.

The chord-averaged radiated power profile during the steady-state phase is shown in Fig. 2. While the chord-averaged radiation is strongly peaked in the divertor, the radiation intensity is relatively flat over the bulk of the core plasma. The core plasma radiation has a flat profile at $\leq 0.1 \text{ W/cm}^3$ while the divertor is radiating strongly at $\leq 3.0 \text{ W/cm}^3$. The upper bolometer array shows that the divertor radiation is dominated by the inboard leg. The large and small peaks are aligned with the inboard and outboard divertor legs as determined from magnetic flux reconstructions.

The heat flux profile to the divertor floor and center post for a typical discharge at 10.2 MW is shown in Fig. 3. The heat flux peaks strongly on the outer strike point at $\sim 350 \text{ W/cm}^2$, with a much lesser peak at $\sim 80 \text{ W/cm}^2$ on the inboard strike point. There is also some significant power delivered to the lower center-post near the inboard divertor. These profiles are typical of all discharges in this study.

Fig. 2. Chord-averaged radiated power profiles for the (a) upper and (b) lower arrays for a standard single-null plasma discharge. The power in each channel is calculated assuming the center of radiation is the center of the discharge.

P_{rad} and P_{core} described above will contribute to surface heat flux measured by the IRTV. It is important to subtract this contribution when calculating P_{plate} . An estimate of this heat flux from an inversion of typical radiation measurements is also shown in the heat flux profile in

Fig. 3. An estimate of this contribution is subtracted from the IRTV data when calculating P_{plate} .

Fig. 3. The heat flux profile as measured by the IRTV cameras to (a) the divertor floor, and (b) the centerpost. The dotted line is the heat flux to surfaces that would result from the inverted radiation profile.

The radiated power losses in the core plasma, P_{core} , are calculated by summing over the channels that do not view the divertor. For our series of discharges P_{core} was measured at

approximately 18% of P_{inj} over variations in plasma current and P_{inj} . The impurity levels contributing to P_{core} were measured in the core plasma with charge-exchange-recombination (CER) spectroscopy for a 1.6 MA 10.2 MW discharge. The impurities found contributing to P_{core} were a carbon fraction of 2.0% a helium fraction of 2.5% and oxygen fraction of 0.2%. The radiation profile from these impurity levels, along with the main plasma ions was modeled with the MIST (Hulse [7]) code. This modeling produced a radial profile in minor radius flat over the bulk of the core plasma at $\leq 0.03 \text{ W/cm}^3$ due mostly to bremsstrahlung. The predicted radiation is also peaked at 0.10 W/cm^3 near the separatrix where impurity line radiation dominates. The width and amplitude of this peak is determined by impurity transport levels for which educated estimates must be made. The bolometer chords viewing the core plasma were inverted to obtain a radial radiation profile as a function of magnetic flux surface. The inverted profile has a greater central value than the modeling at 0.045 W/cm^2 . The inverted data also showed a peaking in edge radiation near the separatrix with similar magnitude but somewhat narrower in minor radius than the MIST modeling. The total power, P_{core} , predicted by MIST was 1.2 MW compared to the measured value of 1.6 MW. The discrepancy in width of the edge radiation is due to uncertainty in the impurity transport values used in the simulation. Uncertainties in the measured central radiation intensity arise from the difficulties of inversion of a hollow profile. The simulation is consistent, though, with the inverted measurements in that both have a hollow profile and similar total power.

After flowing out of the core plasma and through the SOL, the remaining power splits between the inboard and outboard divertor. In the outboard divertor the power leaves the discharge either as heat flux carried by the plasma to the divertor target, $P_{plate,out}$ or as radiated power, $P_{rad,out}$. For the outboard divertor $P_{plate,out}$ accounts for 27% of P_{inj} with a smaller 10% leaving as $P_{rad,out}$. The relative fractions remain nearly constant as P_{inj} and the plasma current are varied. For the inboard divertor it is radiation that dominates as was seen in the radiation and heat flux profiles. Inboard divertor radiation, $P_{rad,in}$ accounts for 22% of P_{inj} with a lesser 3% showing up as P_{plate} . Carbon, the dominant impurity in DIII-D, and hydrogen radiation most

likely make up the bulk of this radiated power, but the relative fractions have not yet been measured in DIII-D.

The low value and large relative uncertainty for $P_{\text{plate,in}}$ is due in large part to subtracting the contribution of radiation to the surface heat flux measured by the IRTV cameras. In fact, as shown in Fig. 3 the calculated power flux due to radiation is greater than the measured heat flux over much of the divertor heat flux profile. One would expect a greater value for $P_{\text{plate,in}}$ from the plasma conditions at the divertor surface as measured by the divertor Langmuir probes, though this estimate requires a proper interpretation of probe measurements and sheath potential. Also the lower center-post IRTV, with a view farther removed from the inboard divertor but on a lower temperature scale, measures a greater heat flux than much of the inboard divertor. One possible explanation for the low value of $P_{\text{plate,in}}$ is IRTV camera sensitivity. The lower divertor IRTV camera views both strike points, so the camera is set on a high temperature scale as not to saturate the view of the hot outer strike-point. Much of the inboard divertor temperature rise is just above the noise level on this setting. This possible undercounting, though, represents at most 5% of P_{inj} and thus $P_{\text{plate,in}}$ would remain a small part of the global power balance.

The lower center post IRTV camera, Fig. 3(b), farther removed from the divertor strike point measures a direct heat flux of 4%-6% of P_{inj} , after accounting for the radiated power flux. The lower center post power, where charged particle flux should be small, is most likely due to charge-exchange neutral particle loss, P_{CX} . The divertor Langmuir probes indicate that plasma pressure balance is not maintained between the inboard and outboard divertor. Ion-neutral interactions might account for this loss of pressure balance. The DEGAS (Fenstermacher [8]) code has previously shown that charge-exchange power loss can become significant when the divertor electron temperature nears 5 eV. This is the range of electron temperatures at the inboard divertor measured by the divertor Langmuir probes. Charge exchange losses, P_{CX} , would not be expected to be directed only at the lower center post, but would also comprise part of the measured $P_{\text{plate,in}}$. P_{CX} , from the inboard divertor would not be measured as P_{rad} by the bolometer array because of the intervening ionizing plasma.

A total accounting of power for ELMing H-mode in DIII-D can now be summarized. The bolometer arrays and IR TV cameras measure 85% percent of the input power P_{inj} . Radiation in the core plasma, P_{core} , accounts for 18% of P_{inj} . In the outboard divertor 27% of P_{inj} leaves as $P_{plate,out}$ and 10% as $P_{rad,out}$. For the inboard divertor only 3% leaves as $P_{plate,in}$ but 22% leaves as $P_{rad,in}$ with an additional 5% of the power to the center post, $P_{plate,cntr}$. These losses remain roughly constant over the range of parameters of our study and represent the power loss paths for ELMing H-mode in DIII-D. However, 15% of P_{inj} is still missing. This is larger than can be made up for by the previously mentioned uncertainty in $P_{plate,in}$. Measurements of heat flux to the outer wall midplane for a different set of experiments reveal heat flux slightly above that expected from radiation. This excess could make up a significant fraction of the missing power if spread evenly over the outer wall. To not be observed by the bolometer arrays this power would have to be charged-particle loss, presumably fast ions. Ripple loss of ions might possibly account for 1% of P_{inj} but the rest would have to be lost through some other mechanism. Fast ion loss would not be expected to be uniform on the outer wall, so a complete measurement would be necessary to quantify this loss. Uncertainty in P_{inj} might account for much of the missing power. For example, reionization of the neutral beams and subsequent loss in the beam ducts has been estimated at 3%. This value is hard to estimate or measure and could be higher. It is quite possible that 10% of P_{inj} could be lost before absorption in the plasma. It will be difficult to reduce the uncertainty in P_{inj} without direct calorimetric measurements of the neutral beam power entering the vessel.

A comparison of total inboard and outboard divertor power can be made by summing the contributions to each divertor leg. Including power to the center post the total power to the inboard divertor is 30% and the outboard 37%. The scatter and uncertainty in the data is at least $\pm 5\%$ for each divertor leg. An in:out ratio of about 1:1.3 is consistent with our data over the range of parameters of the study. This more nearly even balance is in contrast to the large asymmetry observed for P_{plate} alone. The strong radiation in the inboard divertor leads to a much more balanced in:out division of total power. To study the in:out power ratio under

different divertor conditions, radiative divertor experiments are examined. In DIII-D the outboard divertor transitions to a radiative state with heavy puffing of deuterium. When the neutral pressure in the divertor reaches a critical value (Petrie [9], Ghendrih [10]), the outboard divertor suddenly changes state, to one with sharply increased radiation and markedly reduced heat flux. In this radiative state the outboard divertor now radiates as strongly as the inboard. The pre- and post-puffing power balance is summarized in Table I. Because DIII-D has an open divertor configuration, heavy gas puffing results in increased neutral pressure at the mid-plane fueling the core and SOL plasma, increasing radiation from those regions. The remaining power, $P_{inj}-P_{core}$, flowing into the divertor still splits with the same in:out ratio, $\sim 1:1.3$, even though the outboard is now radiating strongly.

Table I. Summary of pre- and post-puffing power balance

Total Power	Pre-Puffing	Post-Puffing
P_{core}/P_{inj}	17%	30%
$P_{plate,in}/P_{inj}-P_{core}$	2%	3%
$P_{rad,in}/P_{inj}-P_{core}$	30%	29%
$P_{plate,cntr}/P_{inj}-P_{core}$	4%	4%
Total in/ $P_{inj}-P_{core}$	36%	36%
$P_{plate,out}/P_{inj}-P_{core}$	42%	19%
$P_{rad,out}/P_{inj}-P_{core}$	12%	30%
Total out/ $P_{inj}-P_{core}$	54%	49%

4. DISCUSSION

Our data has shown the divertor in:out SOL power split to remain roughly constant at 1:1.3 even as conditions are varied. Though we have no underlying principle that would predict this result for all cases we do note the following. Sheath limited power flow to a divertor surface predicts $P_{\text{plate}} \propto nT^{3/2}$ where n and T are the divertor plasma's density and electron temperature. With the SOL a good thermal conductor the divertor with the highest electron temperature should receive the greatest P_{plate} . However, impurity radiation has the opposite temperature dependence with the peak radiation occurring around 5–10 eV. This temperature dependence of the impurity radiation is unstable and may help lead to the observed asymmetries. Thus, the colder divertor should be expected to have less P_{plate} but the power will be traded off for more P_{rad} . But, because the magnitude of the radiation depends on the impurity species and concentration, the tradeoff of P_{plate} for P_{rad} would not necessarily be equal. We only note that it is nearly so for our study.

5. Summary

We have investigated power balance in single-null ELMing H-mode plasmas over a range of injected power of 4–18 MW and plasma current 1.0–2.0 MA. We have accounted for $\geq 85\%$ of the input power. Core radiation accounts for $\leq 20\%$ of the input power with the rest flowing through the SOL to the divertor. The power splits between the inboard and outboard divertor with an in:out ratio of roughly 1:1.3. In the outboard divertor the power leaves the plasma primarily as direct heat flux to the divertor plate with a lesser amount as radiation. For the inboard divertor most power is lost as radiation with a lesser amount of fast neutral losses and direct heat flux.

REFERENCES

- [1] D.E. Post et al., ITER Physics, ITER Doc. Ser. 21 (IAEA, Vienna, 1991) pp. 128–129
- [2] T. D. Rognlien, J.L. Milovich, M.E. Rensink and G.D. Porter, J. Nucl. Mater. **196–198** (1992) 347
- [3] D.N. Hill, M.E. Rensink, A. Futch, D. Buchenauer, T.W. Petrie, M.A. Mahdavi and G. Mathews, J. Nucl. Mater. **176–177** (1990) 158
- [4] A.W. Leonard, W.H. Meyer, B.W. Geer, D.M. Behne and D.N. Hill Rev. Sci. Instrum. to be published
- [5] J. Schivell, G. Renda, J. Lowrance and H. Hsuan, Rev. Sci Instrum. **53** 1527 (1982)
- [6] D.N. Hill, R. Ellis, W. Ferguson, D.E. Perkins, T. Petrie and C. Baxi. Rev. Sci. Instrum. **59** (1988) 1878
- [7] R.A. Hulse, Nucl. Techn./Fusion **3** (1983) 259
- [8] M.E. Fenstermacher et al., Bull. Am. Phys. Soc **38** (1993) 2060
- [9] T.W. Petrie, D. Buchenauer, D.N. Hill, et. al., J. Nucl. Mater. **196–198** (1992) 894
- [10] Ph. Ghendrih, T.W. Petrie, C. Lasnier, A.W. Leonard, R. Maingi, This conference Poster PA2.

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