ELSEVIER

Journal of Nuclear Materials 290–293 (2001) 1093–1096

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Effect of magnetic geometry on ELM heat flux profiles

C.J. Lasnier [a,b,*], A.W. Leonard [b], T.W. Petrie [b], J.G. Watkins [c]

[a] Lawrence Livermore National Laboratory, Livermore CA 94551, USA
[b] General Atomics, P.O. Box 85608, San Diego CA 92186-5608, USA
[c] Sandia National Laboratories, Albuquerque NM, USA

Abstract

In this paper, we explore how precisely the magnetic up/down symmetry must be controlled to insure sharing of edge localized mode (ELM) heat flux between upper and lower divertors in a double-null tokamak. We show for DIII-D, using infrared thermography, that the spatial distribution of Type-I ELM energy is less strongly affected by variations in magnetic geometry than the time-averaged peak heat flux in attached discharges. The degree of control necessary to share ELM heat flux deposition equally between divertors was less stringent than the control needed to balance the time-averaged heat flux. ELM energy is transported more than four times further into the scrape-off layer (SOL) than the time-averaged heat flux. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: ELM; Heat flux; Divertor; Thermography

1. Introduction

In future high-power tokamaks, a prominent design consideration is coping with ELM heat flux on the divertor plate. If the ELM energy flux exceeds 1.5 MJ/m^2 per ELM, ablation of the divertor plate will be unacceptably high [1]. One strategy is to make a double-null tokamak and attempt to share the ELM heat flux between the upper and lower divertors. However, the sharing of the ELM heat flux between the upper and lower divertors is strongly affected by the magnetic balance between the divertors.

In addition, some tokamaks that are nominally single null have a secondary X-point inside the vacuum vessel. For this type of design, we need to know how much energy will be deposited by ELMs on plasma facing components near the secondary null. If the deposited energy is too large, the wall components will be damaged, while if the energy is too low we will not be taking advantage of the ability to share the ELM energy load between the upper and lower surfaces to prevent excessive heating and ablation of components in the primary divertor.

In DIII-D, the up–down magnetic balance is expressed by the quantity dr_{SEP}, which is the radial distance at the outer midplane between the two flux surfaces connected to the two nulls. A dr_{SEP} value of −4 cm represents a lower single null, $dr_{SEP} = +4$ cm represents an upper single-null, and $dr_{SEP} = 0$ represents a magnetically balanced double-null. Intermediate values of dr_{SEP} show corresponding degrees of interaction with the upper and lower divertor plates.

The benefits of sharing heat flux between two divertors apply to the time averaged heat flux as well as the ELM heat flux. The magnetic control required to achieve heat flux sharing is a critical part of the design for a high-power tokamak with double-null divertor configuration, or with a secondary null which could direct significant heat flux to the nearby wall [2]. We investigated whether the sharing of ELM heat flux required the same degree of magnetic control as the time-averaged heat flux. This is of particular concern in the ITER device in which the planned poloidal field coils are outside the toroidal field coils.

2. Experimental method

We changed the up–down magnetic balance dr_{SEP} between upper and lower divertors and observed the

* Corresponding author. Tel.: +1-619 455 4150; fax: +1-619 455 3569.
E-mail address: lasnier@apollo.gat.com (C.J. Lasnier).

PII: S0022-3115(00)00502-X

effect on the distribution of ELM heat flux on divertor surfaces. The value of dr_{SEP} was varied from one discharge to the next, or within a single discharge. We used ELMing H-mode discharges with plasma current of 1.4 MA, toroidal field of 2.0 T, ion $\nabla\mathbf{B}$ drift downward, and core density approximately 5×10^{13} cm^{-3}, with attached divertor plasma.

Heat flux was measured using infrared thermography with two cameras, one viewing the upper divertor and the other viewing the lower divertor. The heat flux profiles on the surface were calculated from the surface temperature data using a method similar to that discussed in previous publications [3,4]. However, for this calculation the temperatures were not time-averaged before being used to calculate heat flux. From the heat flux profiles we calculated the energy deposited on the surface by integrating the heat flux radially, toroidally assuming symmetry in that direction, and over the time of the ELM (typically 2–3 ms).

The camera views and divertor geometry are shown in Fig. 1. The cameras are actually at two different toroidal locations, but are shown on the same cross-section for simplicity. Each camera gives surface temperature profiles with a time resolution of 125 μs.

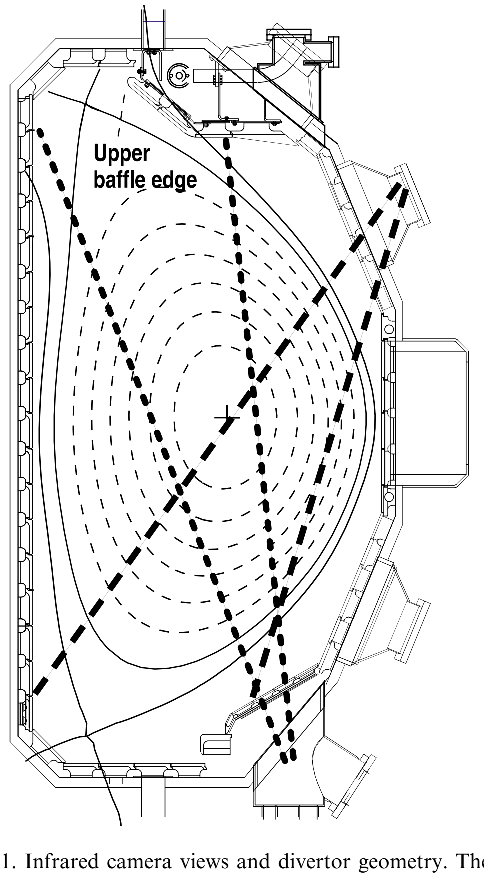

Fig. 1. Infrared camera views and divertor geometry. The dashed lines show the view of the lower divertor, and the dotted lines depict the view of the upper divertor. The cameras are actually located at different toroidal positions.

3. Analysis

We used the energy deposited by an ELM to calculate the energy balance ratio between the upper and lower divertors as $R_E = (E_{up} - E_{low})/(E_{up} + E_{low})$. Here E_{up} and E_{low} are the energies deposited on the upper and lower divertor plates, respectively, by a single ELM. This value approaches unity for an upper single-null and −1 for a lower single-null. The ELM energies are obtained by integrating the surface heat flux over the radial profile and over the duration of the ELM, and assuming toroidal symmetry.

In Fig. 2(a) we plot R_E versus dr_{SEP} for ELMs. Each point on the plot represents R_E for a single ELM. In

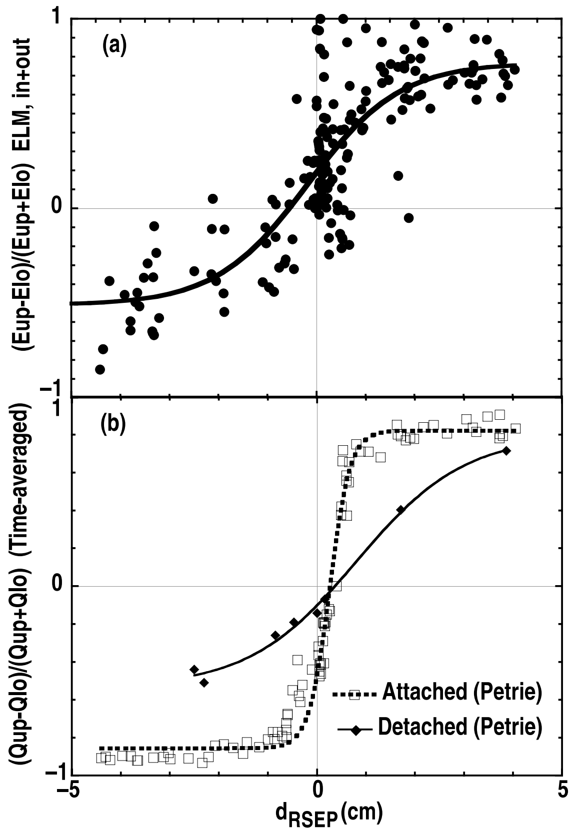

Fig. 2. (a) ELM Energy balance ratio versus dr_{SEP} for attached divertors and; (b) heat flux balance ratio versus dr_{SEP} for peak attached heat flux (time-averaged), and peak detached heat flux (time-averaged). The curves are hyperbolic tangent fits. The qualitative behavior of the ELM energy with varying dr_{SEP} is similar to the time-averaged attached peak heat flux, but the scale length to change from one divertor to the other is much greater, and similar to the detached time-averaged peak heat flux.

Fig. 2(b) is shown the ratio of time-averaged peak heat fluxes calculated in a similar way: $R_q = (q_{\mathrm{up}} - q_{\mathrm{low}})/(q_{\mathrm{up}} + q_{\mathrm{low}})$ for attached and detached discharges. We use q_{up} and q_{low} to denote the time-averaged heat flux at the peak of the profile on the upper and lower divertor plates, respectively. The averaging time for q_{up} and q_{low} was approximately 65 ms, which included several ELMs in these discharges. The values of q_{up} and q_{low} are local quantities, not integrated radially or toroidally.

Notice that the ELM energy ratio varies much more slowly with dr_{SEP} than the attached peak heat flux ratio, but is similar to the dependence of detached peak heat flux on dr_{SEP}. The scale length of the transition from downward heat flux to upward heat flux for the attached discharges (0.4 cm) is similar to the scale length for heat flux penetration into the scrape-off layer of 0.5–0.6 cm [5]. The dr_{SEP} scale length to change the ELM energy flux deposition is much larger at 1.9 cm. For comparison, the dr_{SEP} scale length for the detached time-averaged peak heat flux is 2.2 cm [6].

It might be expected that the dr_{SEP} dependence of the ELM energy distribution is similar to the dr_{SEP} dependence of the peak heat flux during detachment, as shown in Fig. 2. As pointed out by Leonard in Ref. [7], the heat flux to the divertor plate during detachment is primarily due to ELMs, radiation, and convection. ELMs can assist the transport of energy to the divertor plate by heating the SOL and increasing the thermal conductivity. Since the heat flux to the plate between ELMs is very low, the overall energy transport to the plate can be dominated by ELMs during detached conditions.

Two factors are most important in preventing R_E from reaching −1 or +1. First, the ELM energy deposition still shows some energy in the upper divertor when dr_{SEP} is biased downward. This is primarily because of heat deposited near the edge of the upper pump baffle. The flux surface that is 4 cm from the separatrix when mapped to the midplane did not clear this baffle completely even for large negative values of dr_{SEP}. Even for downward magnetic bias we see residual heat on the edge of the upper baffle. Secondly, the shape of the curve is also affected by the fact that not all of the inner strike point heat flux in the lower divertor was within the field of view of the camera. We estimate that this contributes a few percent error to R_E. These complications depend on the particular geometry of the tokamak and cameras.

Fig. 2 presents the main result of this paper as discussed above. We now examine in more detail the energy deposition profiles for some single ELMs, to show the changes in deposition profile which result from changing dr_{SEP}. This reveals in more detail the behavior shown in Fig. 2.

In Figs. 3 and 4, we show energy flux profiles in the lower and upper divertors, respectively, for values of dr_{SEP} ranging from −3.8 to +3.4 cm. The separatrix positions shown in Figs. 3 and 4 were held constant by the control system as dr_{SEP} was varied. For the largest positive values of dr_{SEP} the energy flux profile in the lower divertor near the separatrix nearly vanishes, but there remains energy flux far from the separatrix. We also see in these profiles where the inner lower energy flux profile was cut off by the edge of the field of view of the camera.

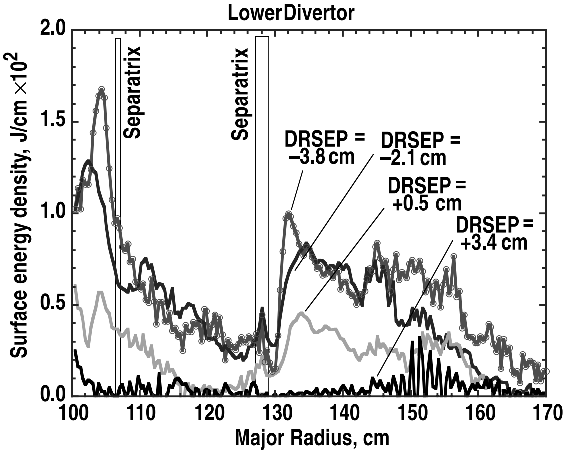

Fig. 3. Lower divertor energy flux profiles for various values of dr_{SEP}. The separatrix locations are shown. For the largest positive dr_{SEP} the energy flux near the separatrix nearly vanishes.

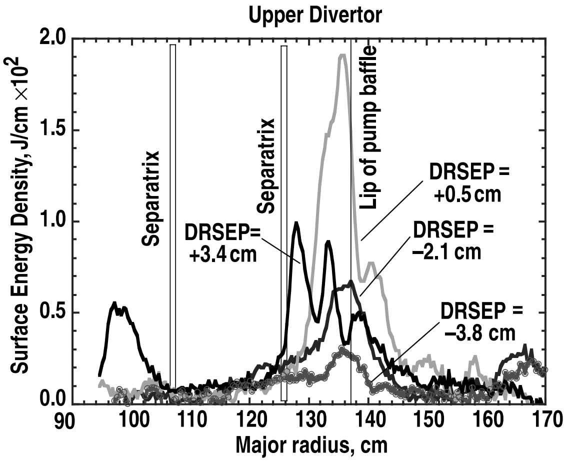

Fig. 4. Upper divertor energy flux profiles for various values of dr_{SEP}. The locations of the separatrix and the edge of the upper pump baffle are shown. For large dr_{SEP}, the heating is peaked near the pump baffle, rather than the broad profile seen in the lower divertor.

The overall heat flux profile in the lower divertor is quite broad. However, we see from the profiles that the peak ELM heat flux does not appear in the private flux region. The observation is consistent with what we expect from the magnetic geometry, with heat primarily flowing along field lines. The conformity of the deposition profiles to the expected positions is evidence that the magnetic flux surfaces are not moving drastically during ELMs in DIII-D.

In the upper divertor profiles we see that for large negative values of dr_{SEP} the peak energy flux is greatly reduced at both the inner and outer strike points. For large positive values of dr_{SEP}, the heating is peaked near the pump baffle, rather than the broad profile seen in the lower divertor. The reason for this difference is not yet completely understood, but seems to depend on the presence of the baffle.

While this effect may be peculiar to DIII-D, similar behavior might be observed in other double-null tokamaks with closed divertors, including some major machines now proposed or in design.

In both the upper and lower divertors, the divertor plate heating near the separatrix is the part of the profile most strongly affected by the change in dr_{SEP}. This is because the flux surfaces near the separatrix change relative position at the midplane when dr_{SEP} is changed. As the heat flux diffuses outward from the main plasma, heat will be directed primarily along the first flux surfaces encountered which connect with a divertor. The flux surfaces farther out which are connected to the other divertor receive less of the heat and so conduct less heat to the corresponding divertor.

4. Conclusions

We find that the ELM heat penetrates more than four times farther into the scrape-off layer than the time averaged heat flux. A correspondingly greater change in dr_{SEP} is necessary to direct the ELM heat flux to the opposite divertor. This means a less precise control system can still exert adequate control over the ELM heat flux balance, compared to the precision required for balancing the time averaged heat flux between two divertors. This bodes well for those future double-null tokamaks that cannot exert fine control over dr_{SEP}, as well as tokamaks designed with a single divertor but still having a secondary null within the vacuum vessel.

Acknowledgements

This work was supported by the US Department of Energy under Contract Nos. DE-AC03-99ER54463, W-7405-ENG-48, and DE-AC04-94AL85000.

References

[1] H.D. Pacher, E9. Disruption and ELM Erosion, Appendix E9, Section 1.7 (Divertor), ITER Design Description Document, ITER No. G 17 DDD 1 96-08-21 W2.1, August 1996.
[2] G. Janeschitz, Physics Issues (Hmode Pedestal, ITBs) for RC-ITER, Memo G 17 MD 117 98-07-16 W 0.2, RC-ITER, 1998.
[3] D.N. Hill, R. Ellis, W. Ferguson et al., Rev. Sci. Instr. 59 (1988) 1878.
[4] C.J. Lasnier, D.N. Hill, T.W. Petrie et al., Nucl. Fus. 38 (1998) 1225.
[5] T.W. Petrie, M.E. Fenstermacher, S.L. Allen, T.N. Carlstrom, R.J. Groebner, C.J. Lasnier, A.W. Leonard, M.A. Mahdavi, R. Maingi, R. Moyer, T.L. Rhodes, D.M. Thomas, J.W. Watkins, W.P. West, and the DIII-D Team, 26th EPS Conference on Controlled Fusion and Plasma Physics, Maastricht, Netherlands, 1999, 23J, pp. 1237.
[6] T.W. Petrie et al., The Effect of Divertor Magnetic Balance on H-mode Performance in DIII-D, these Proceedings.
[7] A.W. Leonard, M.A. Mahdavi, S.L. Allen et al., Phys. Rev. Lett. 78 (1997) 4769.