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T.W. PETRIE, M.E. FENSTERMACHER,[†] and C.J. LASNIER[†]

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[†]Lawrence Livermore National Laboratory

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T.W. Petrie,[1] M.E. Fenstermacher[2] C.J. Lasnier[2]
[1]General Atomics, P.O. Box 85608, San Diego, CA 92186
[2]Lawrence Livermore National Laboratory, Livermore, CA

ABSTRACT

Advanced tokamaks use D-shaped cross-section plasmas to optimize fusion performance. In turn, the divertor (which handles heat and particles) must operate efficiently in these shaped plasmas. In this paper, we report on recent experiments at the DIII–D National Fusion Facility that compare the advantages/ disadvantages of 1) double-null (DN) versus single-null (SN) configurations, 2) particle pumping at low and high density, and 3) open versus tightly baffled divertors. The focus of this paper will be on the important engineering consequences of these physics results for future tokamak designs. Accurate control over the magnetic balance is required by the plasma shaping coils for DN (and near-DN) operation because of the strong sensitivity of the heat flux to small changes in magnetic balance. Alternatively, additional protective armor may be needed for each divertor. We show that precise control over the strike point location by the coil system is important for lower density (attached) plasma operation, but much less so for higher density (detached) operation. We also find that minimizing the angle between the divertor structure and the divertor plasma legs is very useful in reducing the peak divertor heat flux for lower density (attached) plasmas but is of limited benefit for higher density (detached) plasmas. Finally, the physics results imply that significant heating and damage at the divertor "slot" opening may occur, even if several heat flux scrape-off lengths are allowed for clearance.

I. INTRODUCTION

To be competitive, a power plant based on the tokamak concept must be able to produce electricity economically. Two important considerations which have a direct bearing on this are 1) that the tokamak have an adequate plasma confinement time, τ_E, for plasma ignition and 2) that a sufficiently high volume-averaged toroidal beta, β_T, be accessible for fusion power production.[1] Higher values of both τ_E and β_T are more readily achieved as the plasma shape becomes increasingly D-shaped (or "triangular"), i.e., when the radial location of the X–points are drawn closer to the tokamak centerpost. Since higher overall triangularity is achieved more naturally in the double-null (DN) shape than in a single-null (SN) shape [Fig. 1(a,b)], the wide interest in adopting the DN configuration as the basis for future generation high performance tokamaks is understandable.

Since most of the experimental and theoretical work to-date has focused on SN issues, the design of high performance tokamaks based on the DN concept relies on extrapolations of SN plasma behavior, including the common assumption that the physics processes in one divertor of a DN are the mirror image of the other. Recent experimental work done in DN at the DIII–D National Fusion Facility show that asymmetrics are present and should be accounted for in future designs. In this paper we review the results of these DIII–D studies and their implications for future tokamak design.

In Section II, we show that a delicate sensitivity of the divertor and main plasma to even minor changes in the magnetic balance near DN can have a major impact on the engineering requirements of the DN design. Other factors also demand consideration. In Section III, we explore the conditions under which the poloidal field coils must have precise control over the divertor strike point locations in order to provide adequate particle pumping. In Section IV, we discuss some limitations to how "closed" a baffled divertor can safety be [e.g., Fig. 1(c)]. In Section V, we examine implications for future tokamak design.

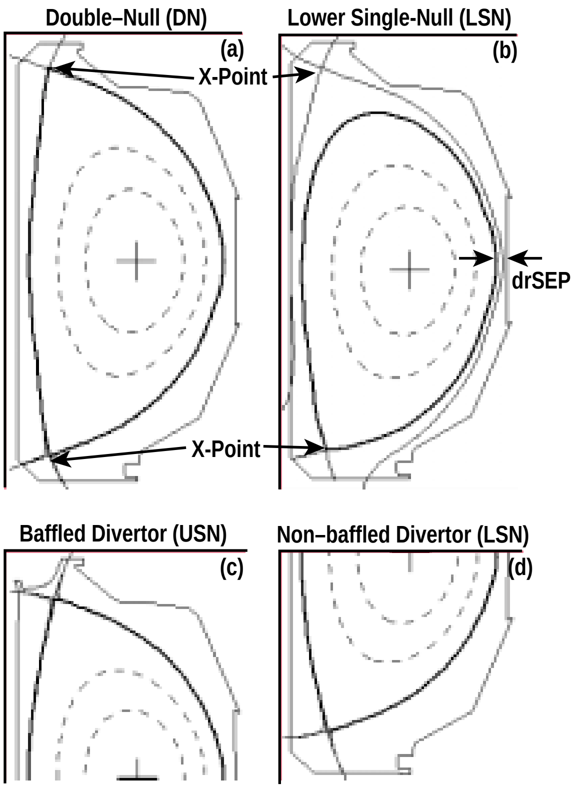

Fig. 1. (a) Double-null (DN) and (b) Single-null (SN) cross-sections in DIII–D. In either case, the upper and lower X–points lie within the vessel. Also shown are representations of (c) a baffled ("slot") divertor and (d) a non-baffled ("open") divertor. Characteristic parameters in this report are: I_P = 1.4 MA, B_T = 1.6-2.1 T, P_{inj} = 3-8 MW, a = 0.6 m, R_M = 1.68 m, q_{95} = 3-5.

The results discussed in Sections II-IV depend not only on details of the magnetic geometry, but also on whether a divertor plasma is "attached" or "detached."[2] For "Attached" plasmas, the heat flow in the divertor is dominated mainly by electron conduction, whereas for "detached" plasmas, the heat flow is dominated by convection and radiated power. For the purposes of discussion below, an "attached" divertor is when the maxima in the measured heat flux and particle flux profiles are coincident with the divertor separatrix strike point; typically, this occurs for lower density discharges. A "detached" divertor is when the maxima of these profiles are located well away from the divertor separatrix strike point; this typically occurs during deuterium gas puffing at higher density.

II. SENSITIVITY TO MAGNETIC BALANCE NEAR DN

In this section, we show that important divertor properties depend critically on the magnetic balance of the configuration, To quantify the degree of "divertor imbalance" (or equivalently, to what degree the shape is "double-null" or "single-null"), we introduce a parameter drSEP, which we define as the radial distance between theupper divertor separatrix and the lower divertor separatrix, as determined at the outboard midplane If drSEP=0, the configuration is a magnetically balanced DN [e.g., Fig. 1(a)].; if drSEP = -4.0 cm, the last closed flux surface is denfined by the separatrix through the lower X–point [Fig. 1(b)]. In all the data presented, the ∇B ion drift is toward the lower divertor.

A. Heat Flux Behavior

Precise control of the magnetic balance is essential for sharing the power exchange between divertors in the DN (and near-DN). Figure 2 shows that the balance in the peak heat flux to the <u>outboard</u> divertors in attached plasmas depends strongly on drSEP (i.e., on the magnetic balance) between drSEP = –0.5 cm and + 0.5 cm. This width of about 1 cm is approximately twice the measured scrape-off width of the parallel heat flux at the outboard midplane, as might be predicted by simple geometry and heat flow by conduction arguments.[3] Three other important features of Fig. 2 include: (1) Magnetic balance does <u>not</u> imply peak heat flux balance between the divertors. In Fig. 2 magnetic balance leads to the parallel peak heat flux density to the lower divertor being approximately twice that of the upper divertor. (2) Up/down balance in the peak heat flux density occurs for drSEP ≈ +0.25 cm, in the direction opposite the ∇B

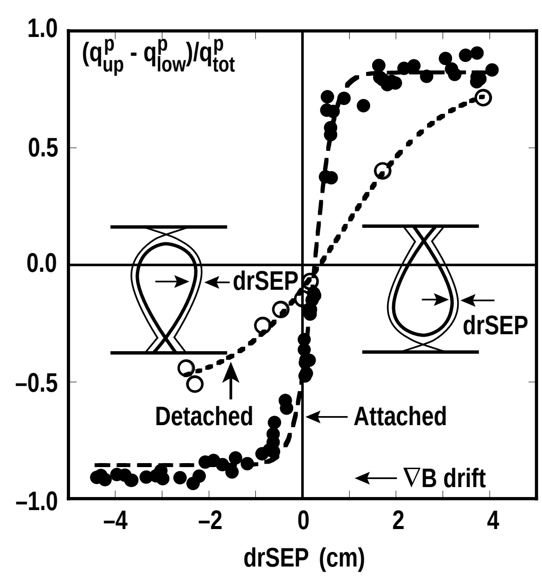

Fig. 2. The peak heat fluxes at the lower outer divertor target (q^p_{low}) and upper outer divertor target (q^p_{up}) vary more strongly with drSEP in attached plasmas (closed circles) than in detached plasmas (open circles). Note: $q^p_{tot} = q^p_{low} + q^p_{up}$.

drift (see below). (3) The peak heat flux shared by the outboard divertors in detached (high density) discharges near drSEP=0 is much less sensitive to magnetic balance.

Operation with the DN may significantly relax the cooling requirements at the inboard divertors compared to a SN. The fraction of the peak flux at the outboard divertor target to that of the inboard divertor target is constant (≈2.5×), except near magnetic balance (drSEP=0), where this ratio is much larger [Fig. 3(a,b)]. This is due in part to the geometry of the DN[3] and possibly to reduced power losses on the inboard side when "unfavorable curvature" of the outboard side of the plasma is severed from the "favorable curvature" of the inboard side of the plasma when the DN forms.[4,5] Figure 3(a,b) shows additional asymmetries; even though near magnetic balance $q^p_{out} >> q^p_{in}$ in both divertors, these ratios are still significantly different for each of the divertors. This means that the design of one of the DN divertors may not necessarily be appropriate for the other divertor in DN.

These asymmetries in the heat flux distribution are believed to be related to E×B poloidal drifts and the ∇B drifts.[6-8]

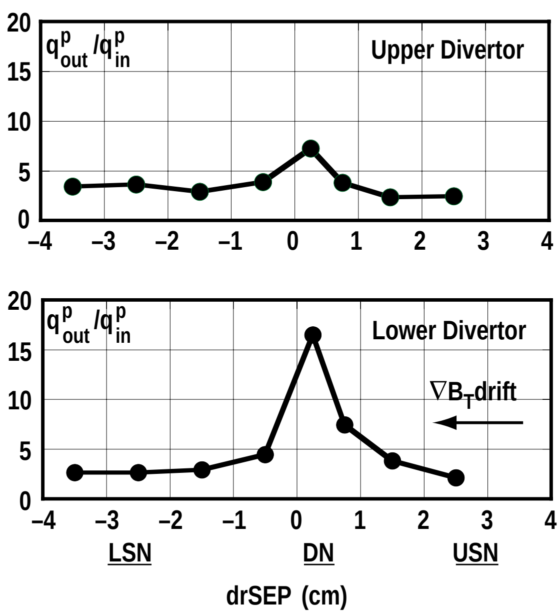

Fig. 3. The ratio of peak heat flux to an outer divertor target (q^p_{low}) to that of its corresponding inner divertor tar get (q^p_{low}) occurs near DN in both (a) upper and (b) lower divertors. The configurations cover lower single-null (LSN), DN, and upper single-null (USN). The ∇B-drift is toward LSN, for both (a) and (b).

B. Particle Flux Behavior

Precise control over the magnetic balance may be less of an issue for particle pumping in attached DN divertors, the variation of the peak particle flux with magnetic balance near the DN is slower than observed for the peak heat flux (i.e., in Fig. 2).[3] The upper/lower divertor asymmetries we observe with the particle flux is qualitatively consistent the E×B poloidal and ∇B drifts mentioned above.

C. Maintenance of Good Energy Confinement

Precise control over the magnetic balance during the early stages of the plasma discharge is required to maintain its H–mode confinement properties, if the DN shape is used. This is shown in Fig. 4 for three identically-prepared discharges; the ∇B direction is toward the lower divertor. For t > 1.75 s, one of the plasma discharges is drawn into a near-DN biased slightly toward the upper divertor (drSEP = +1 cm), the second is drawn into a near-DN biased slightly toward the lower divertor (drSEP = -1 cm), and the third remains a balanced DN (drSEP = 0), as shown in Fig. 4(a). While "slippage" in the magnetic balance from the DN to the lower SN (drSEP = -1 cm) has only a small effect on line-averaged density or stored energy, the slippage in the magnetic balance from the DN toward the upper divertor-biased shape degrades energy confinement and density sharply [Fig. 4(b,c)].

Precise control over magnetic balance at higher density may also be required in order for the discharge to avoid inadvertently falling out of H–mode. As with the example in the previous paragraph, significant degradation in both energy confinement and plasma density occurs, when the magnetic balance changes from a balanced DN to a near- balanced DN biased toward the upper divertor i.e., the divertor opposite the ∇B drift direction.

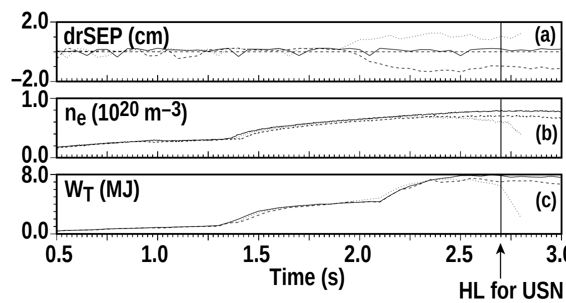

Fig. 4. (a) Though prepared identically, the plasmas diverge to LSN, DN, and USN at t=1.9 s. (b) The line-averaged density and (c) plasma stored energy are affected. The time that the USN falls out of H–mode (HL) is shown. The ∇B drift direction is toward the LSN.

III. SENSITIVITY TO THE LOCATION OF THE DIVERTOR STRIKE POINTS TO PARTICLE PUMPING

A. Non-baffled Divertor

Precise control of the location of the divertor strike points is essential for adequate particle pumping under certain operating conditions. The removal of helium ash and other impurities from the plasma environment is an important issue for long pulse and steady state tokamaks. In previous studies it was found for more non-baffled ("open") divertors that the location of the separatrix strike point with respect to the pumping aperture is much more important to particle pumping for attached divertor plasmas than for the detached plasmas.[9,10] In attached plasmas, most of the recycling occurs near the separatrix strike point. It follows that effective pumping should occur only when the separatrix strike point is near the pumping aperture; in DIII–D, this separation for strong pumping is typically a few centimeters. For high density (detached) plasmas, recycling occurs over a much wider region of the divertor, so that the separatrix strike point is not required to be close to the pumping aperture for effective particle pumping.

B. Baffled Divertor

For a low density attached plasma, efficient pumping requires precise control over the separatrix strike point locations, since the pumping rate falls off significantly as the strike point- pumping aperture distance increases.[11] For higher density, detached plasmas, however, particle pumping is insensitive to the gap distance between the location of the strike point and the pumping aperture. As with the "open" divertor, precise control over the separatrix strike locations is less important. An example of such insensitivity for a baffled divertor is shown in Fig. 5(a,b). For these two shots, the separatrix strike points are located either on the sloped "dome" or on the "flat" surface inside the slot. Particle pumping is done from the outboard cryo-pump, as shown in Fig. 5(a). The same D_2 gas puff program is applied to each shot [Fig. 5(b1)]. The rate at which particles are pumped is similar for both shots [Fig. 5(b2)]. Important performance characteristics, such as line-averaged density [Fig. 5(b3)] and the energy confinement nomalized to H–mode[11] [Fig. 5(b4)], between the start of gas injection (t = 2.3 s) and a timeslice well into the gas puff phase (t = 3.4 s) are similar, even though the separatrix strike point is >10 cm from the baffle pumping aperture in the dome case and at a different vertical height. (Ultimately, "overpuffing" will degrade confinement properties for both discharges.)

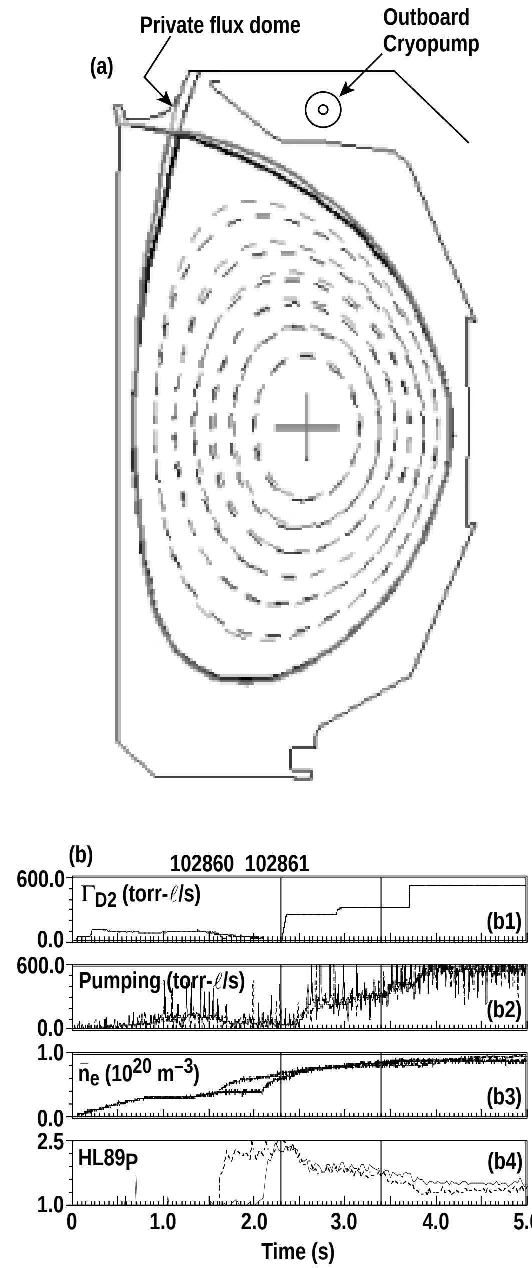

Fig. 5. (a) USN configurations have their outer separatrix strike points on the "dome: and "flat" surfaces inside a baffled divertor. The "flat" cases are the solid lines and the "dome" case is dashed. (b1) An identical deuterium gas puffing program produces a near identical response in (b2) particle pumping. Similar behavior in (b3) line-averaged density and (b4) energy confinement normalized to ITER89p L–mode scaling[12] shows insensitivity to the outer divertor strike point position. The vertical lines at t=2.3 s and t=3.4 s define the timeslices used for Fig. 6.

IV. RELATED ISSUES

A. Heat Flux on a Sloped Divertor Surface

The technique of reducing heat flux by sloping the divertor structure with respect to the incident separatrix flux surface is found to be both effective and predictable for attached plasmas. In attached plasmas, the peak heat flux for the above “dome” case is about a factor of 2.5 less than that of the “flat” surface case, in accordance with the predictions from simple geometric arguments for the exposed wetted surfaces.

Contouring or shaping the divertor to minimize the peak heat flux is less effective for detached plasmas. Detachment occurs with deuterium gas puffing in both “dome” and “flat” surface cases at high density. A well established result for configurations similar to the “flat” surface case is that the peak heat flux at high density is significantly lower (typically ≈3×) than its low density, attached counterpart;[2] this was, in fact, observed here [Fig. 6(a)]. However, little additional reduction in the peak heat flux between low (attached) and high (detached) density is observed for the dome case [Fig. 6(b)]. While direct particle heating of the divertor by conduction is the main mechanism for heating the divertor target in attached plasmas, most of the divertor heating in high density detached plasmas is due largely to hydrogenic or impurity radiated power. This radiated power sets a lower limit on how much the *total* heat flux (i.e., particle + radiated contributions) can be reduced, and measured divertor radiated power for the dome and slot cases is approximately the same. This means that the dome and slot peak heat flux will have similar heat flux profiles in detachment.

B. Heat Flux Reduction <u>Outside</u> the Slot

Substantial heat flux may strike the conformal structure outside the “slot”, even when the plasma near the separatrix strike point inside the slot is detached. In Fig. 7(a), for example, the 1.5 cm SOL flux surface (as measured from the outboard midplane) intersects the top of the baffle at the entrance to the slot. For this discharge, we consider the heat flux at three times: (1) prior to deuterium puffing (attached), (2) shortly after detachment with gas puffing, and (3) high density detachment during gas puffing. The heat flux distribution in the pre-puff case can be estimated from geometric arguments. During neutral deuterium gas puffing, the peak heat flux inside the slot was reduced by a factor of 3-4 from its original (pre-puff) value. Yet, the heat flux at the entrance to the slot (approximately two power scrapeoff lengths outside the separatrix) is unchanged [Fig. 7(b)]. In low density attached plasmas, electron heat conduction to the divertor

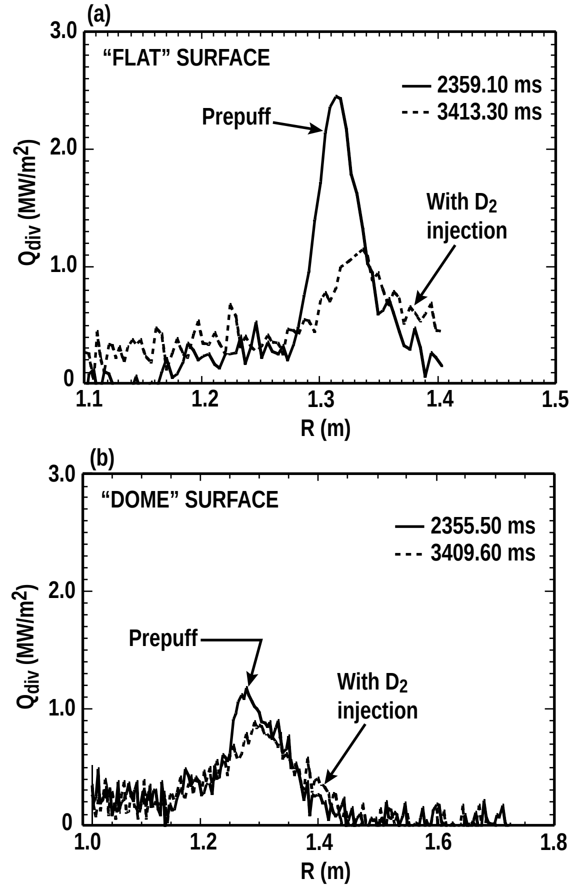

Fig. 6. (a) Radial heat flux for the “flat” surface case shown in Fig. 5 at attached and detached timeslices. (b) Radial heat flux for the "dome" surface case (see Fig. 5) at attached and detached timeslices.

plates is responsible for the peaked heat profile near the separatrix strike point prior to introducing a radiating divertor. Since electrons can be efficiently cooled by enhancing the radiation in the divertor, the peak heat flux found under the separatrix strike points can be reduced significantly using radiative divertor approaches. Even if the divertor radiates enough power to significantly reduce structural heating, however, surface heating on the top of the baffle may not be damped appreciably. The formation of a strong radiating zone above the baffle top is difficult, primarily due to the relatively low density ($\lesssim 1\times10^{19}$ m^{-3}) typical along field lines in the far SOL. In addition, “deep” into the SOL the energetic ions may become an important contributor to the heat flux, since the ion temperature scale length in the SOL in DIII–D can be several times that of the electron temperature scale length. While radiated power enhancement in the SOL and divertors may be effective for cooling the electrons, cooling energetic ions once they are in the SOL much more difficult. Moreover, fast ions, which may be a contiributor

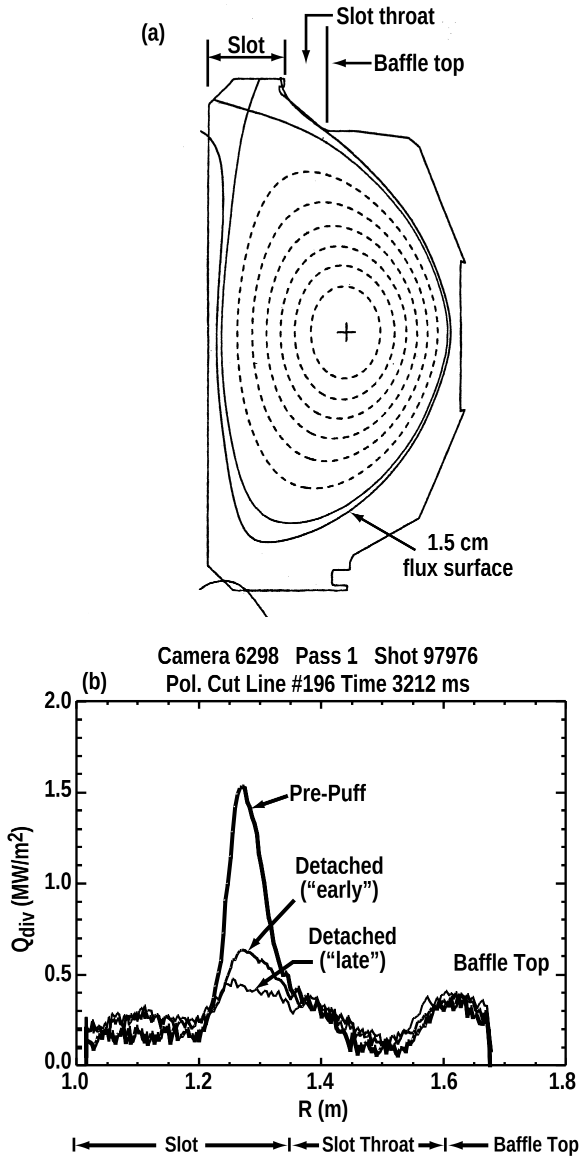

Fig. 7. (a) An USN divertor has its 1.5 cm scrape-off layer flux surface intersect the top of the baffle. (This shot was taken prior to the installation of the "dome".) (b) The radial heat flux profiles for three timeslices are shown.

to the heat flux far out in the SOL, could cause substantial sputtering of closed conformal divertor structures.

V. SUMMARY AND IMPLICATIONS

The results from recent DIII–D experiments identify several issues that should be carefully considered when designing future, high performance tokamaks. Below, we highlight some of these issues.

A. Sensitivity of Tokamak Performance to Magnetic Balance

For attached DN plasmas, it is important that the plasma shaping coils be able to maintain adequate control of magnetic balance to high tolerance or that the divertors have sufficient protective armor to withstand a possible loss of control over magnetic balance. For detached plasmas, however, precise control over magnetic balance may not be as critical an issue for heat flux balance. Interestingly, the steep dependence of peak heat flux sharing with magnetic balance does have a positive feature, because this sensitivity, in conjunction with "real time" divertor heat flux meaurements (e.g., with infrared cameras), provides an accurate means to track magnetic balance during the discharge.

Experiments on DIII–D also showed that the ratio of peak heat flux between the outer and inner divertor targets rises sharply in lower density attached DN plasmas. Such strong out/in heat flux asymmetries for DNs may sufficiently relax the cooling requirements for handling the power flow to the inboard divertors and make active cooling of the inboard divertors unnecessary. This would be an advantageous feature for high triangularity, low aspect ratio tokamaks. At the very least, it would appear that the cooling requirements for the inboard divertor targets in DN would be reduced (compared with SNs).

Adequate feedback control of the magnetic balance is recommended in order to minimize the loss of good confinement in shapes near DN, where even small changes in magnetic balance can significantly change confinement properties. This sensitivity can be especially crucial during the early stages of the plasma discharge, where the evolving nature of the discharge makes precise magnetic control difficult.

Finally, experiment has shown that particle flux to the outboard divertors is less sensitive to changes in magnetic balance near DN. This suggests that variation in particle pumping as magnetic balance "slips" near DN will be less of an issue than the variation in heat flux would be.

B. Active Particle Pumping

Precise control over the strike point location is important if lower density, attached plasma operation is planned. Precise control over the separatrix strike point locations is less important, if high density, detached operation is envisioned. For both baffled and non-baffled cases, strong particle pumping is possible at low density only if the separatrix strike point is near the pump aperture. On the other hand, strong particle pumping in high density detached plasmas is insensitive to the gap between separatrix strike point and pump aperture and this would provide considerable flexibility in how to position the separatrix strike points in the divertors.

C. Related Issues

Minimizing the angle between the divertor structure and the separatrices is useful in reducing the peak heat flux, if attached plasma operation is planned. For detached plasmas, however, this procedure appears to be much less effective. Sloping (or contouring) the divertor surfaces with respect to the separatrix flux surface in attached divertor discharges lowers the peak heat flux in the divertor in the manner predicted by simple geometric arguments.

Finally, it is important to carefully consider that there can be appreciable heat flux at the entrance to a "divertor slot", even under high density, highly radiating divertor conditions where the peak heat flux inside the slot has been reduced significantly. In addition to this, energetic ions in the SOL can be a source of erosion of materials at the slot entrance. Because of this inefficient energy exchange between electrons and ions in the SOL, the energetic ions in the SOL not only makes reducing the heat flux at the slot entrance difficult, but also may make the issue of physical sputtering on the structure itself problematical.

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