Princeton University: Plasma Physics Laboratory

To:	Distribution	Date:	October 24, 1996
From:	Stanley M. Kaye	Subject:	NSTX Divertor Heat Flux Estimates
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The purpose of this memo is to provide the Physics guidance for heat fluxes to the divertor plates and center stack, for various operating scenarios, to the engineers. It is a follow-up to previous memos by P. Mioduszewski and R. Maingi, and recent draft memos by me.

The average heat flux at any target plate, other than the center stack, can be estimated as the ratio of the power to the target plate, P_{target}, to the area intercepted at the target plate, A_{target}, so that

$$< q_{target} >= \frac{P_{target}}{A_{target}}. \quad (1)$$

Following the 7/11/96 memo by Maingi and Mioduszewski (M&M), the power to the target plate is given by (slightly modified)

$$P_{target} = P_{aux}(1 - f_{rad,core})(1 - f_{rad,div,i})\frac{f_{div,i}}{f_{div,tot}}/N_{div} \quad (2)$$

where

P_{aux}=auxiliary heating power
$f_{rad,core}$=fraction of power radiated in the core
$f_{rad,div,i}$=fraction of power radiated in the i^{th} divertor region (inner or outer)
$\frac{f_{div,i}}{f_{div,tot}}$=fraction of power flowing to the i^{th} divertor region (inner or outer)
N_{div}=number of divertors (=1 for SN, =2 for DN or outer plates in ND).

The area of the target is given by

$$A_{target} = 2\pi R_{sp}\Delta^{div} \quad (3)$$

where

R_{sp}=radius of the strike point, and
Δ^{div}=power flux width at the target plate, given by

$$\Delta^{div} = \Delta^{mp} f_{flux}(1 + f_{\frac{PFR}{SOL}})/sin\alpha \qquad (4)$$

where

Δ^{mp}=power flux width at the midplane
f_{flux}=flux expansion factor
$f_{\frac{PFR}{SOL}}$ accounts for additional area in the private flux region
α=angle of incidence of separatrix at the target plate in the poloidal plane.

The average power flux to the center stack is given by

$$< q_{cs} >= \frac{P_{cs}}{A_{cs}} \qquad (5)$$

where the surface area of the center stack onto which the power flows is given by

$$A_{cs} = 4\pi R_{cs} h \qquad (6)$$

where

R_{cs}=outer radius of the center stack (0.175 m), and
h=half-height of the vertical extent onto which the power flows (1 m) - based on equilibrium calculations,
giving $A_{cs} = 2.2\ m^2$.

Given the above relations, the power fluxes to the divertor plates can be estimated.

I) Natural Divertor

We start with the Natural Divertor configuration. Based on DIII-D results for inner wall limited discharges (Jackson et al., 1996), we assume the scenario that the total amount of non-core-radiated power is evenly split between the center stack and the outer divertor plates. For this and other configurations, it is assumed that 30% of the auxiliary power is radiated in the core, and we take $P_{aux} = 6MW$. Consequently, 2.1 MW is deposited on the center stack, giving an average heat flux of $< q_{cs} >\simeq 1\ MW/m^2$.

The heat flux profile for DIII-D is shown in Fig. 1 (the "well-limited" case in Fig. 9b of Jackson et al., Phys. Plasmas, 3 (1996) 1005); this is to be used for the NSTX heat flux profile on the center stack. Note that the profile extends across an equivalent 2 m vertical extent. The heat flux values in the figure have to be renormalized to reflect the NSTX estimate of 2.1 MW total impinging on the center stack.

The heat flux to the outer divertor plates in the ND configuration can be computed using Equations 1 to 4. As the ND configuration is up-down symmetric, the power flow to each of the outer divertor plates will be 1.05 MW/m^2. The divertor power width and target area can be computed from Eq. 4 under the following assumptions:

Parameter	Outer Plate
Δ^{mp}	1.0 cm (from M&M)
f_{flux}	5 (conservative from M&M)
R_{sp}	0.65 m
$f_{\frac{PFR}{SOL}}$	0.33 (from M&M)
α	45° (from equilibrium flux plot)
Δ^{div}	0.094 m
A^{outer}_{target}	0.38 m^2

Table 1: Natural Divertor Configuration

For a flat power flux profile across the 9.4 cm divertor power width, the average heat flux is 2.8 MW/m^2. If a more realistic power deposition profile is used, such that $q(x) = q_{peak}e^{-x/\Delta^{div}}$, then $q_{peak} = 4.3\ MW/m^2$ for $\Delta_{div} = 0.094\ m$.

II) Double Null Divertor

Here, the power flux to the divertor plates for the DN configuration is estimated. In this case, $N_{div} = 2$, and we again assume that 30% of the 6 MW of input power is radiated in the core, leaving a total of 2.1 MW flowing to each the top and bottom divertor regions of the vessel. For the DN case, the power split is approximately 4:1 so that $f_{div,outer}/f_{div,tot} = 0.8$ and $f_{div,inner}/f_{div,tot} = 0.2$, giving a total power going to each outer and inner divertor regions of 1.7 and 0.4 MW respectively. For the DN configuration

Parameter	Inner Plate	Outer Plate
Δ^{mp}	1.0cm	1.0 cm (from M&M)
f_{flux}	2.5	2.5 (conservative from M&M)
R_{sp}	0.55 m	0.65 m
$f_{\frac{PFR}{SOL}}$	0.33	0.33 (from M&M)
α	60°	60° (from equilibrium flux plot)
Δ^{div}	0.038 m	0.038 m
A^{outer}_{target}	0.13 m^2	0.16 m^2

Table 2: Double Null Divertor Configuration

For a flat profile, this gives:

$< q_{inner} >= 3.1\ MW/m^2$, and
$< q_{outer} >= 10.6\ MW/m^2$.

For a profile such that $q(x) = q_{peak}e^{-x/\Delta^{div}}$, then

$q_{peak,inner} = 4.7\ MW/m^2$ for $\Delta_{div} = 0.038\ m$, and
$q_{peak,outer} = 17.0\ MW/m^2$ for $\Delta_{div} = 0.038\ m$.

Note that we have assumed $f_{rad,div,i} = 0$ in this computation. Observations in Single Null studies indicate that divertor radiation can account for 50% of the total power input into the divertor regions, which would reduce the above estimates by that same factor.

III) Single Null

A simplistic approximation for this case, taken from the TPX Physics Design Description, has an out:in power split of 2:1, so that $f_{div,outer}/f_{div,tot} = 0.67$ and $f_{div,inner}/f_{div,tot} = 0.33$. This means 1.4 MW of power going to the inner divertor region and 2.8 MW going to the outer divertor region ($N_{div} = 1$ in this case, so all the power is flowing to the active divertor region). The divertor characteristics car be computed as before with the following assumptions:

Parameter	Inner Plate	Outer Plate
Δ^{mp}	1.0 m	1.0 cm (from M&M)
f_{flux}	6.5	6.5 (from equilibrium flux plot)
R_{sp}	0.55 m	0.65 m
$f_{\frac{PFR}{SOL}}$	0.33	0.33 (from M&M)
α	70°	60° (from equilibrium flux plot)
Δ^{div}	0.092 m	0.10
A^{outer}_{target}	0.32 m^2	0.41 m^2

Table 3: Single Null Divertor Configuration

For a flat profile, this gives:

$< q_{inner} >= 4.4\ MW/m^2$, and
$< q_{outer} >= 6.8\ MW/m^2$.

For a profile such that $q(x) = q_{peak}e^{-x/\Delta^{div}}$, then

$q_{peak,inner} = 6.9\ MW/m^2$ for $\Delta_{div} = 0.092\ m$, and
$q_{peak,outer} = 10.8\ MW/m^2$ for $\Delta_{div} = 0.10\ m$.

Note that the power widths on the outer and inner divertor plates are comparable. This is somewhat inconsistent with observations indicating broader widths on the inboard side; however, for this estimate these values are used.

Again, is was assumed that $f_{rad,div,i} = 0$. A more sophisticated calculation, and perhaps somewhat more realistic, can be done following the observations of Leonard et al. (1994)

from ELMing Single Null Discharges in DIII-D. These observations folded in power loss through radiation in the divertor and some loss to the center stack in these SN discharges. According to Leonard et al., $f_{div,outer}/f_{div,tot} = 0.57$ and $f_{div,inner}/f_{div,tot} = 0.43$, with 20% of the power to the inner divertor region flowing to the center stack. In the Leonard et al. paper, they also observe $f_{rad,div,inner} = 0.75$ and $f_{rad,div,outer} = 0.25$. This gives a power accounting such that 2.4 MW flows to the outer divertor region, 1.5 MW flows to the inner divertor region, and 0.3 MW flows to the center stack, accounting for the 4.2 MW of non-core-radiated power. Of the 2.4 MW that flows to the outer divertor region, 0.6 MW is radiated, leaving 1.8 MW flowing to the outer divertor plate. Of the 1.5 MW flowing to the inner divertor region, 1.1 MW is radiated, leaving only 0.4 MW flowing to the inner divertor plate.

Using the parameters from Table 3, we have,

For a flat profile:

$< q_{inner} >= 1.25\ MW/m^2$, and
$< q_{outer} >= 4.4\ MW/m^2$.

For a profile such that $q(x) = q_{peak}e^{-x/\Delta^{div}}$, then

$q_{peak,inner} = 2.0\ MW/m^2$ for $\Delta_{div} = 0.092\ m$, and
$q_{peak,outer} = 6.9\ MW/m^2$ for $\Delta_{div} = 0.10\ m$.

The heat flux on the center stack can be computed as in I), assuming the power evenly distributed over an extent of 1 m (as in Leonard et al.), giving an average heat flux of $< q_{cs} >= 0.3\ MW/1.1\ m^2 = 0.27\ MW/m^2$. For a peaked profile such that $q(z) = q_{peak,cs}e^{-z/h}$, where h=1 m, $q_{peak,cs} = 0.43\ MW/m^2$.

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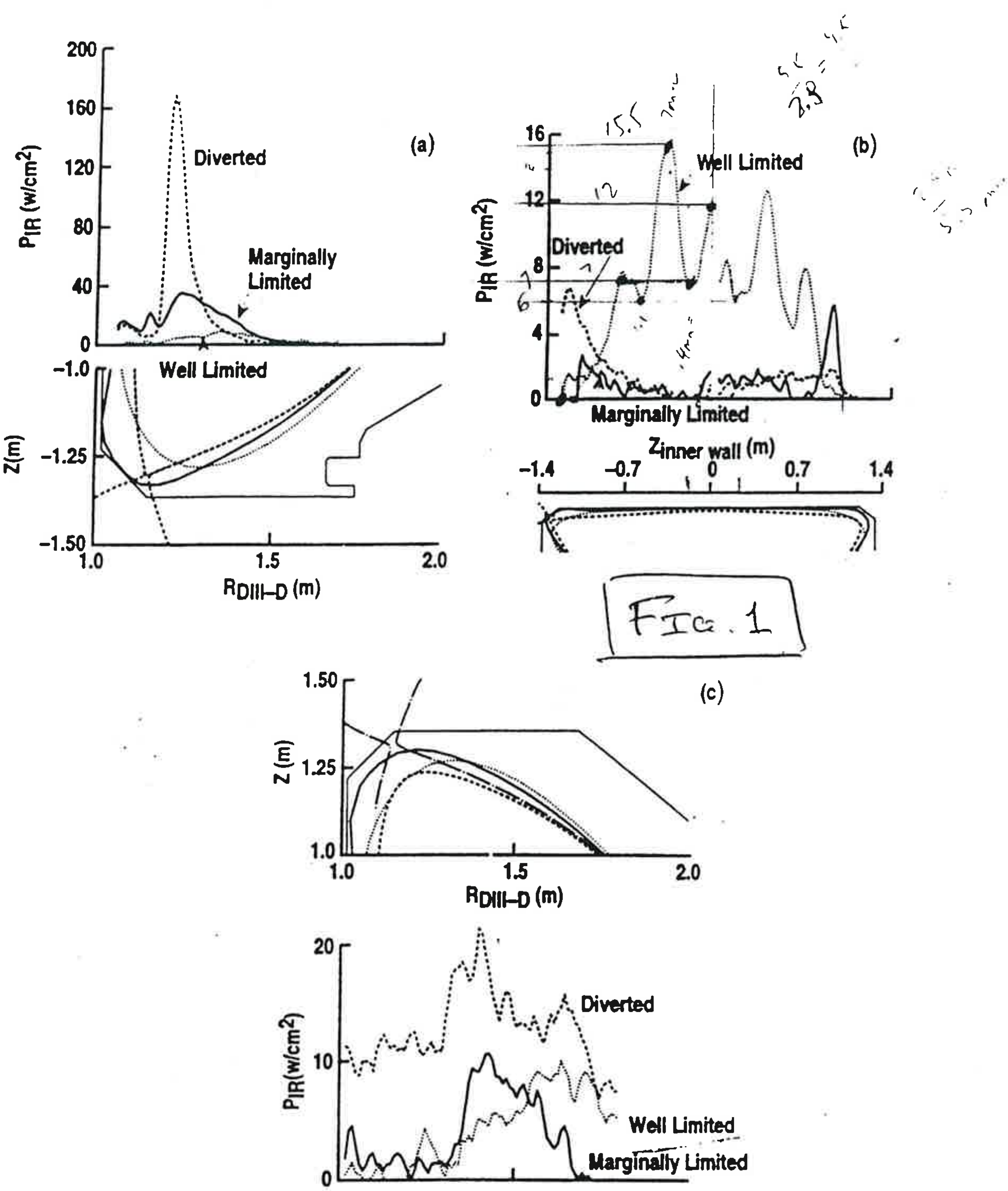

FIG. 9. Comparison of peak heat flux, measured by the IRTV camera, for diverted VH mode (dashed), marginally limited VH mode (solid) and well limited H mode (dot). The $\nabla B \times B$ electron drift is toward the floor in all cases. Profile time was taken at W_{MHD} = 1.1 MJ during the ELM-free phase in all three discharges (1.6 MA, 2.1 T). The LCFS for the three discharges and outline of the DIII-D tiles is also shown: (a) lower divertor region (floor), (b) inner wall, and (c) upper divertor (ceiling). The upper separatrix flux surface for the diverted discharge is shown as a dash–dotted line (c) and is displaced 2.4 mm outboard of the LCFS (dashed line) at the outer midplane.

points. However, a discussion of the feasibility of such designs is beyond the scope of this paper and will require further studies.

We note that in the initial set of experiments described in this paper, shape was not fully optimized for reductions in heat flux, confinement, or maximum I_p. For example, VH-mode confinement scaling was shown to be consistent with previous diverted results, implying that higher triangularity marginally limited discharges may produce further increases in confinement. Also, generated equilibria indicate th: higher values of I_p/q_{95} may be possible with further optimization of discharge shape, which could lead to VH mode at higher plasma currents than previously obtained in DIII-D. Finally, plasma shape can also be further optimized for lower peak heat flux both in marginally and well limited discharges.