HEAT LOAD ON DIVERTORS IN NCSX

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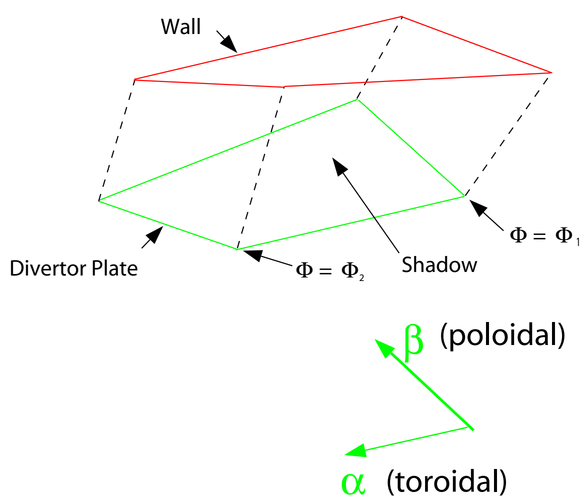
Introduction

We have continued our investigation of the effect of divertors in NCSX and extended it to include the ARIES-CS reactor-study design. We use magnetic field data generated by either the PIES 3D MHD or VMEC/MFBE equilibrium codes, and find that results for comparable equilibria from the two codes agree to within statistical uncertainty.

Field lines are followed numerically from a starting surface just outside and conformal with the LCMS until they strike a divertor structure or the first wall, or exceed a prescribed length (taken to exceed the desired connection length). Effects of particle scattering are mimicked by diffusing field-line trajectories with a diffusion coefficient of 1 m^2/s. The relative location of field-line start points and strike points is observed to obey exact stellarator symmetry.

Localized power deposition on divertors is estimated by assuming the energy flux to be proportional to the density of field-line strike points, which implicitly includes a proportionality to the sine of the angle of incidence. Heat load sensitivity to variation in divertor design can be investigated by systematic variation of the size, shape, location and orientation of candidate design plates, each of which can be constructed of an arbitrary number of quasi-flat quadrilateral segments.

Divertor Model



The intersection of a divertor plate with a poloidal plane is assumed to be a straight-line segment whose end-points vary linearly with toroidal angle, Φ, sweeping out a non-planar quadrilateral surface in 3D for $\Phi_1 < \Phi < \Phi_2$.

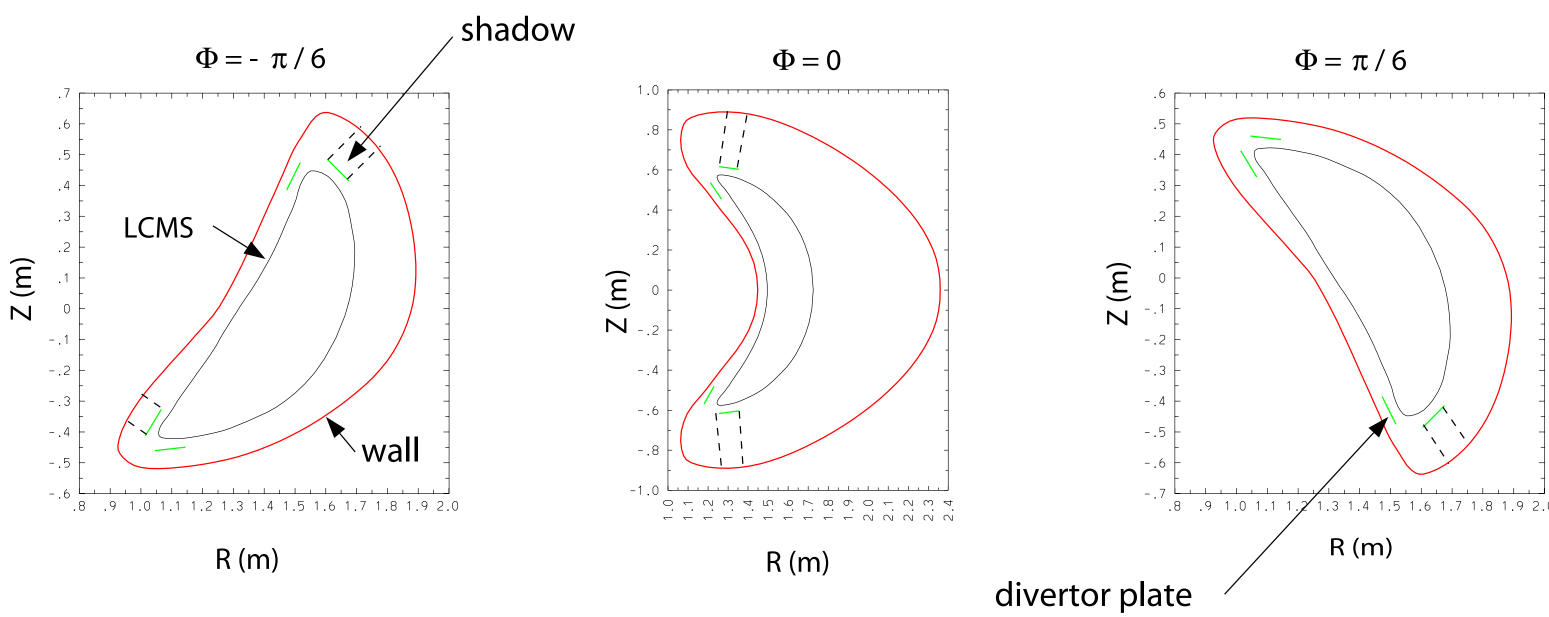
The hexahedral volume between the plate and the wall is called the "shadow" region.

A field line is followed until it intersects a divertor plate, enters a shadow region or hits the wall.

Current calculations include four divertor plates/period, centered at the upper and lower ends of the banana-shaped LCMS at $\Phi = 0, 2\pi/3, 4\pi/3$.

In order to visualize field-line strike points on the (non-planar) divertor plate, it's mapped to the unit square with coordinates $0 < \alpha$(toroidal), β (poloidal) < 1.

Divertor Plate Poloidal Cross Sections



Computational Protocol

In the heat-load study, 16000 field lines were launched from starting curves in poloidal planes at $\Phi = 0, 30, 60, 90$ deg and followed parallel or anti-parallel to the magnetic field until hitting a divertor plate or the wall, entering a shadow region, or exceeding 300 m in length. Field-line diffusion (D = 1 m^2 / s) was used to mimic the effect of particle scattering.

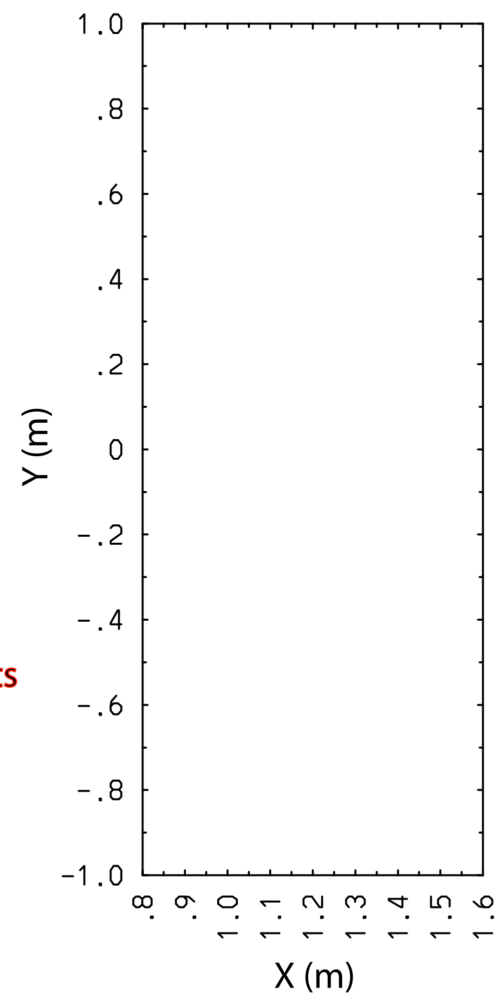
The field-line starting points were uniformly spaced in arc-length on a closed curve slightly larger (by 0.6 cm) than and conformal to the LCMS. A total of 2000 lines were followed in each direction for each initial toroidal angle.

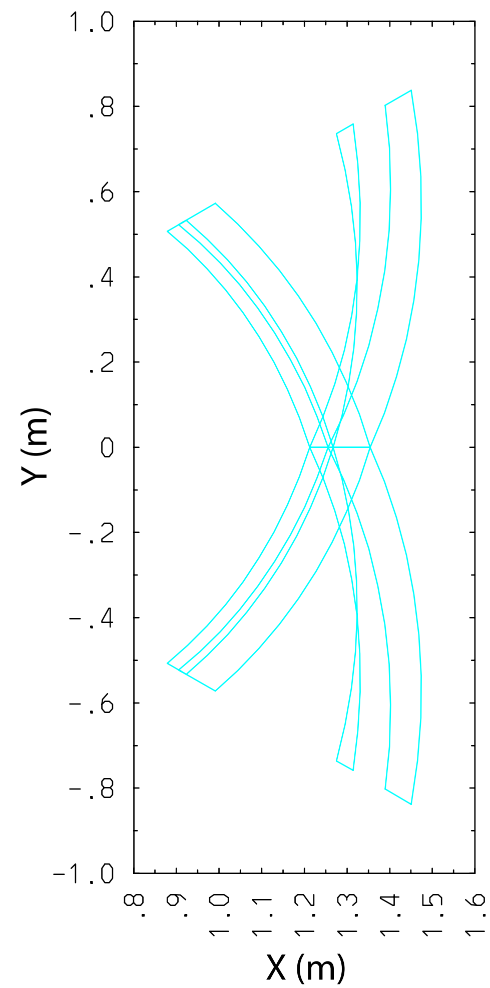
Each divertor plate consisted of 2 toroidal segments with a poloidal width of .10 m, and a toroidal extent of 30 deg, corresponding to a total toroidal length of approximately 1.5 m, and a resultant area of roughly .15 m^2. They were centered toroidally at $\Phi = 0, 120, 240$ deg, and located about 2.5 cm from the banana tips of the plasma surface.

Equatorial-Plane Projection of Divertors and Strike Points

Divertor-Plate Hits

Shadow-Region Hits

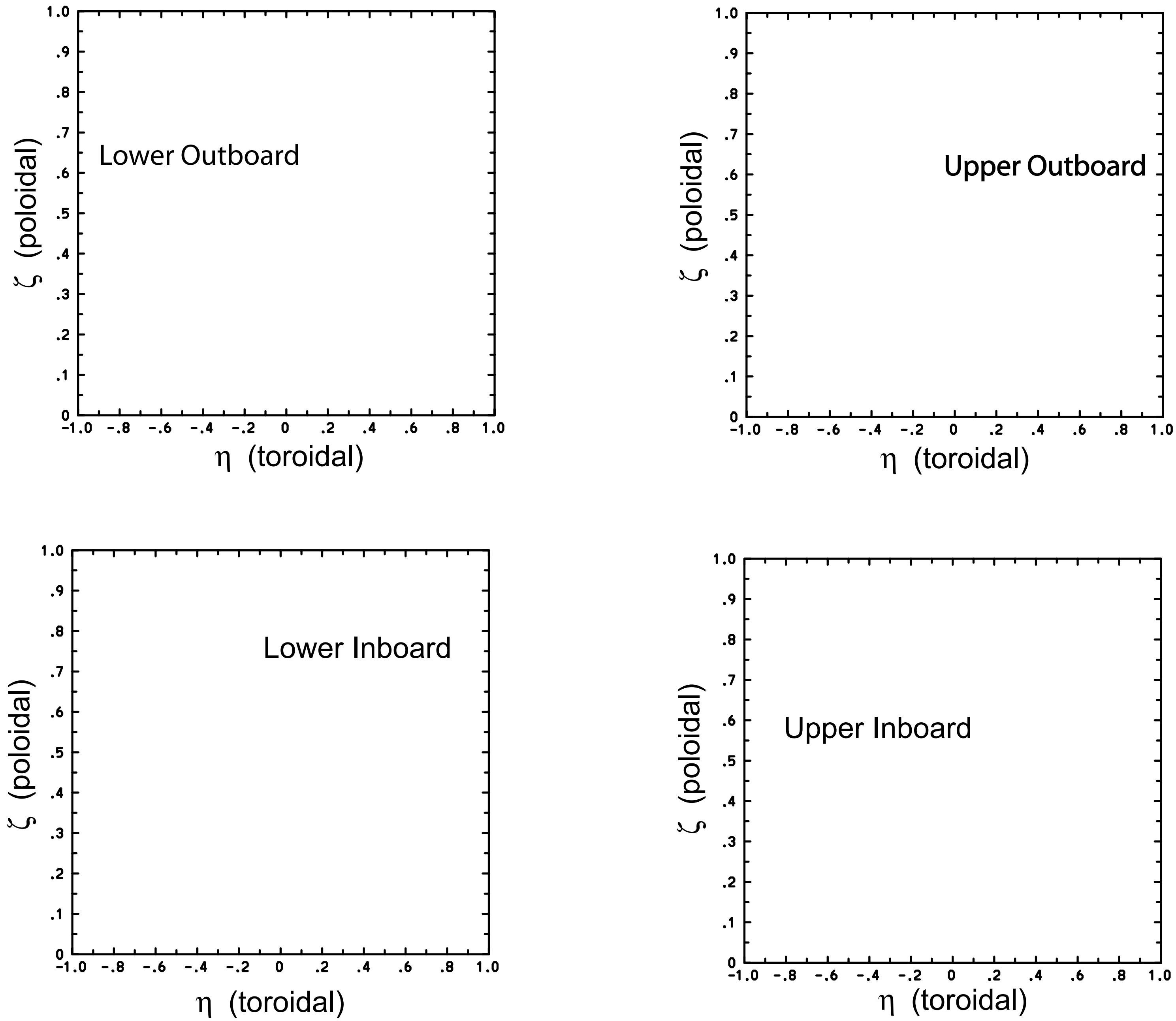




Lower Plates

Upper Plates

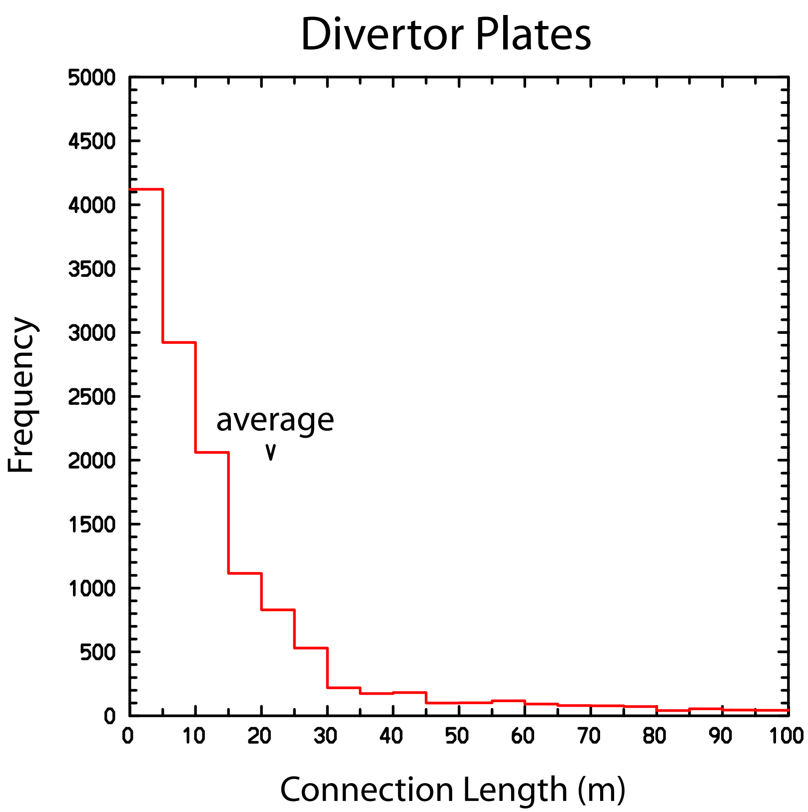
Strike Points on Divertor Plates

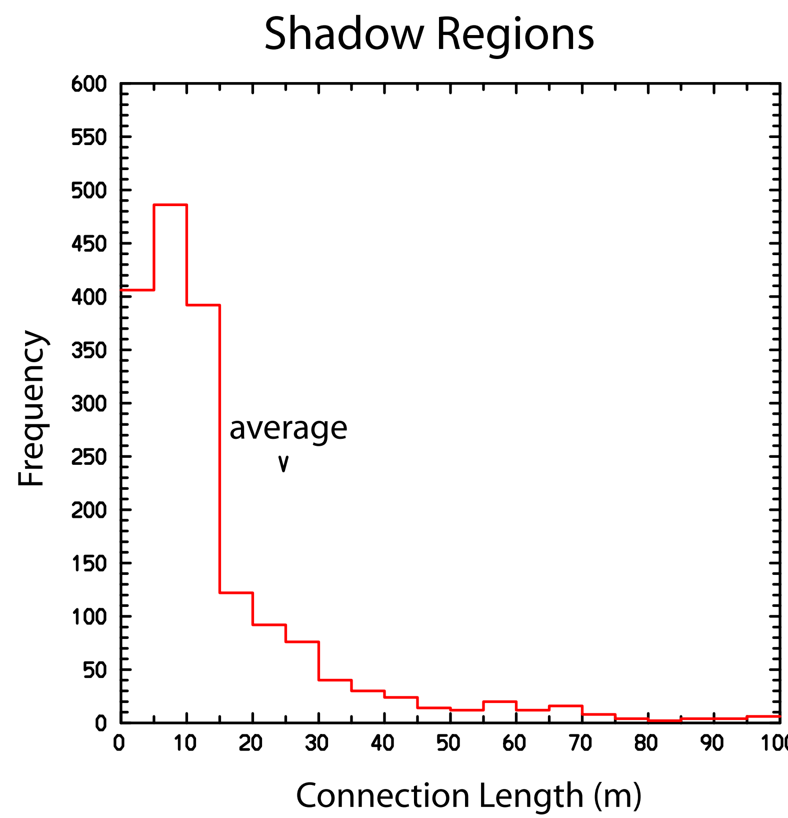


Field Line Termination Statistics
(15394 field lines)

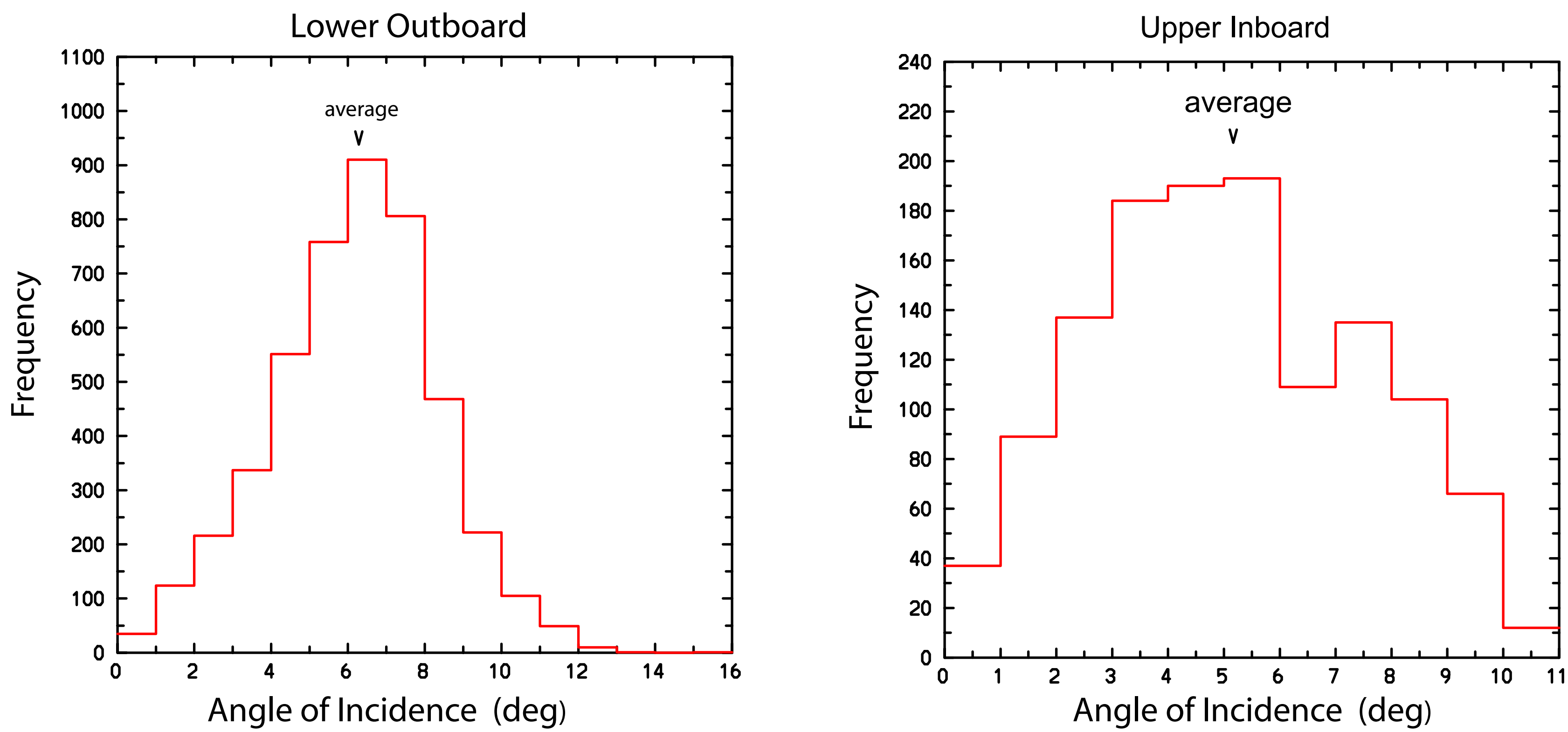
Segment	Hits	Fraction	<Inc. Angle> (deg)	Area (cm^2)
LO (+)	4593	.30	6.2	743
UO (+)	4	.00	0.8	653
LI (+)	22	.00	2.2	688
UI (+)	1256	.08	5.1	642
UO (-)	4596	.30	6.2	743
LO (-)	4	.00	0.8	653
UI (-)	22	.00	2.1	688
LI (-)	1220	.08	5.1	642
Shadow	3763	.24		
Wall	4	.00		

Connection Lengths





Angle of Incidence



Heat-Load Peaking Factor

The power flux on an element of area of divertor plate i is

$$\Delta P_i(\alpha,\beta) = \frac{\Delta N_i(\alpha,\beta)}{N} P_0$$

where P_0 is the total power leaving the plasma flowing along field lines, N is the total number of field lines followed and $\Delta N_i(\alpha,\beta)$ is the number of field lines incident on the area element. The area element centered at (α,β) is

$$\Delta A_i(\alpha,\beta) = J_i(\alpha,\beta)\Delta\alpha\Delta\beta,$$

where J_i is the Jacobian of the transformation from 3D space to the dimensionless surface coordinates on plate i. The energy flux on ΔA_i is

$$\Delta W_i(\alpha,\beta) = \frac{\Delta P_i(\alpha,\beta)}{\Delta A_i(\alpha,\beta)} = \frac{\Delta N_i(\alpha,\beta)}{N} \frac{P_0}{\Delta A_i(\alpha,\beta)}.$$

The single-plate peaking factor, $\mathcal{P}_i$, is defined as the ratio of $\Delta W_i(\alpha,\beta)$ to the plate average $\langle \Delta W_i \rangle = (P_0/N)(N_i/A_i)$, where A_i is the area of and N_i the total number of field lines hitting plate i, respectively. Thus

$$\mathcal{P}_i(\alpha,\beta) = \frac{\Delta W_i(\alpha,\beta)}{\langle \Delta W_i \rangle} = \frac{\Delta N_i(\alpha,\beta)}{\Delta A_i(\alpha,\beta)} \frac{A_i}{N_i}.$$

Its maximum value over (α,β) is the overall single-plate peaking factor for plate i,

$$\mathcal{P}_{i,max} = \max[\mathcal{P}_i(\alpha,\beta)].$$

In order to make plate-to-plate comparisons, it's necessary to normalize to the average over all plates:

$$\overline{\mathcal{P}}_i(\alpha,\beta) = \frac{\Delta N_i(\alpha,\beta)}{\Delta A_i(\alpha,\beta)} \frac{\sum_i A_i}{\sum_i N_i},$$

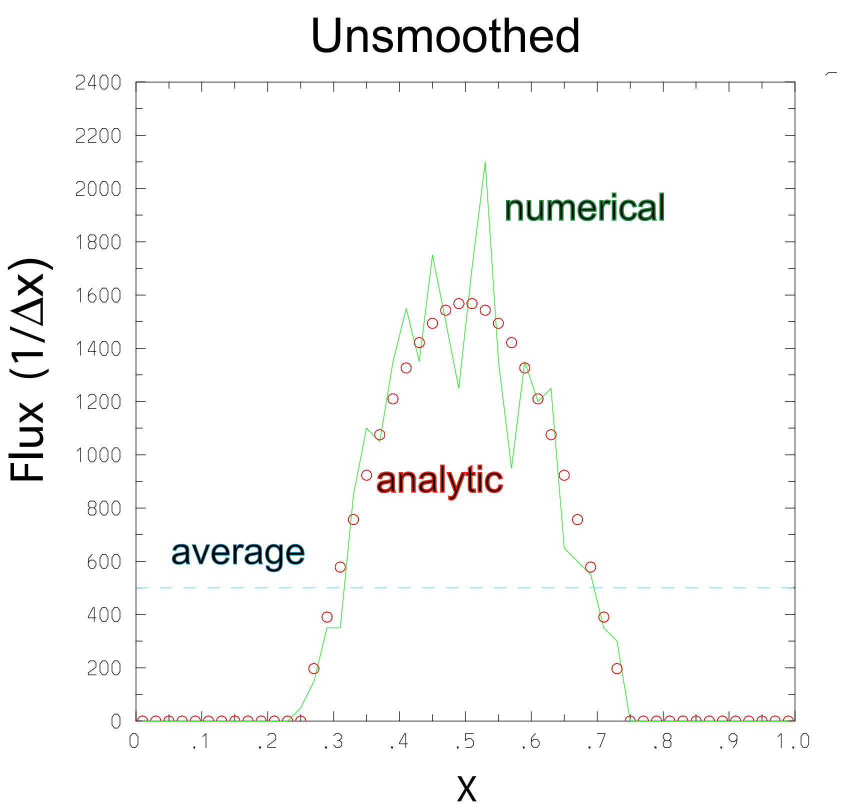
$$\overline{\mathcal{P}}_{i,max}(\alpha,\beta) = \max[\overline{\mathcal{P}}_i(\alpha,\beta)].$$

Heat-Load Profile

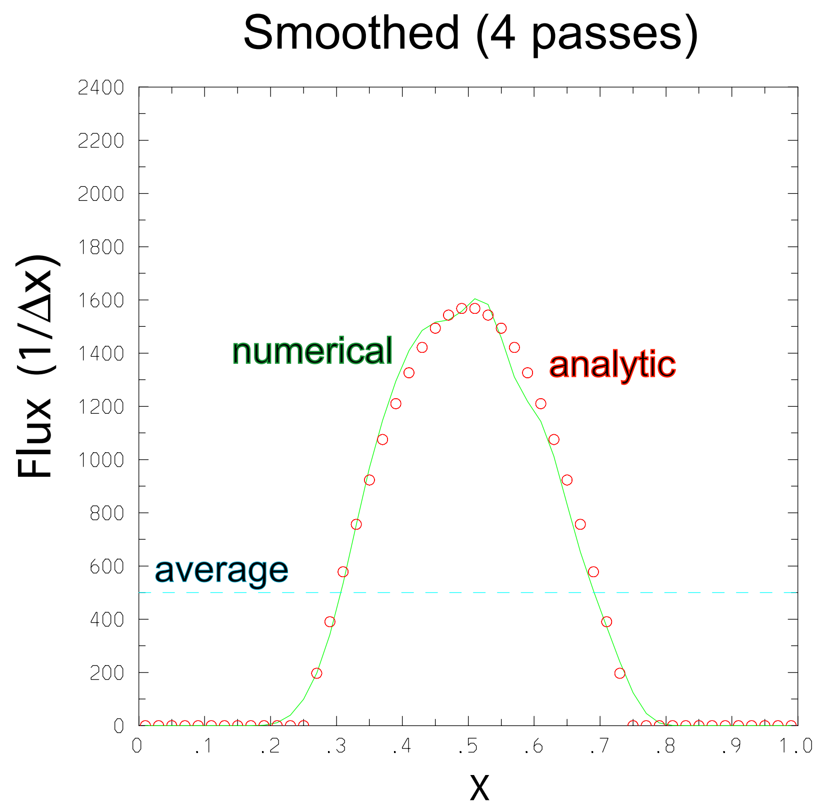
$$H = \Delta W_i(\eta,\zeta) / P_0$$

Half-Plate	max(H) $(1/m^2)$	ave(H) $(1/m^2)$	ave(ΔA) (cm^2)
Lower Out.	10.7 +/- 19%	4.0 +/- 1.5%	1.87
Upper In .	7.5 +/- 24%	1.3 +/- 2.8%	1.60

An integral-preserving diffusive filter suppresses short-wavelength statistical noise

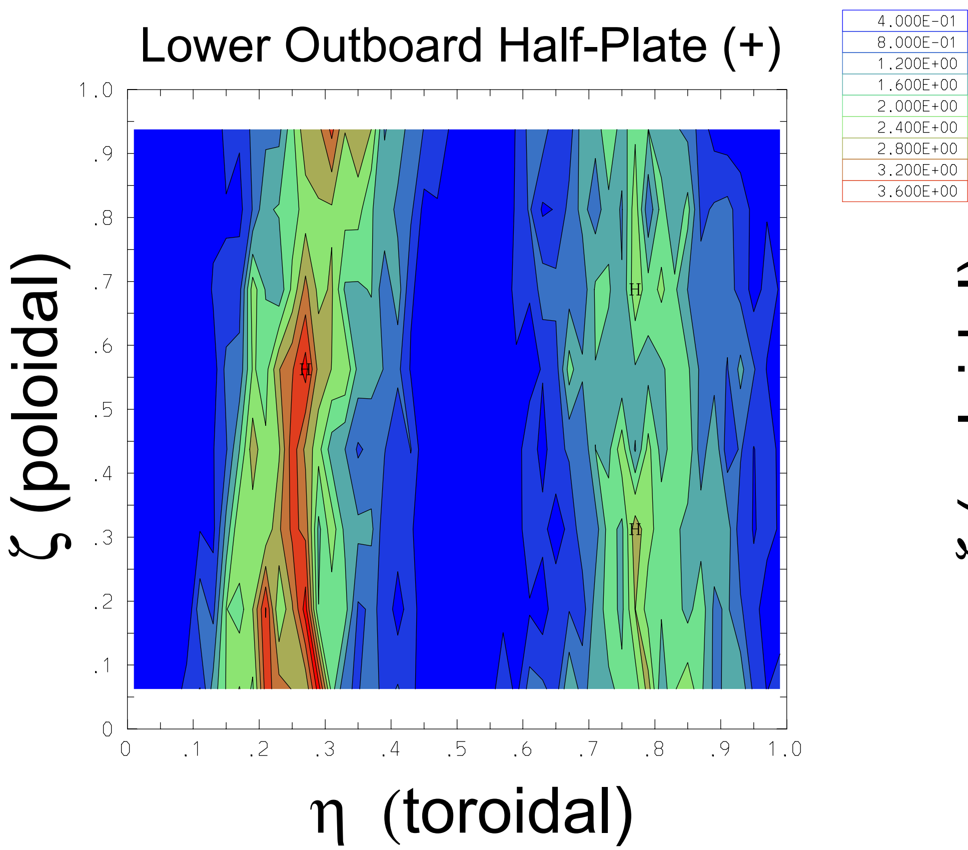


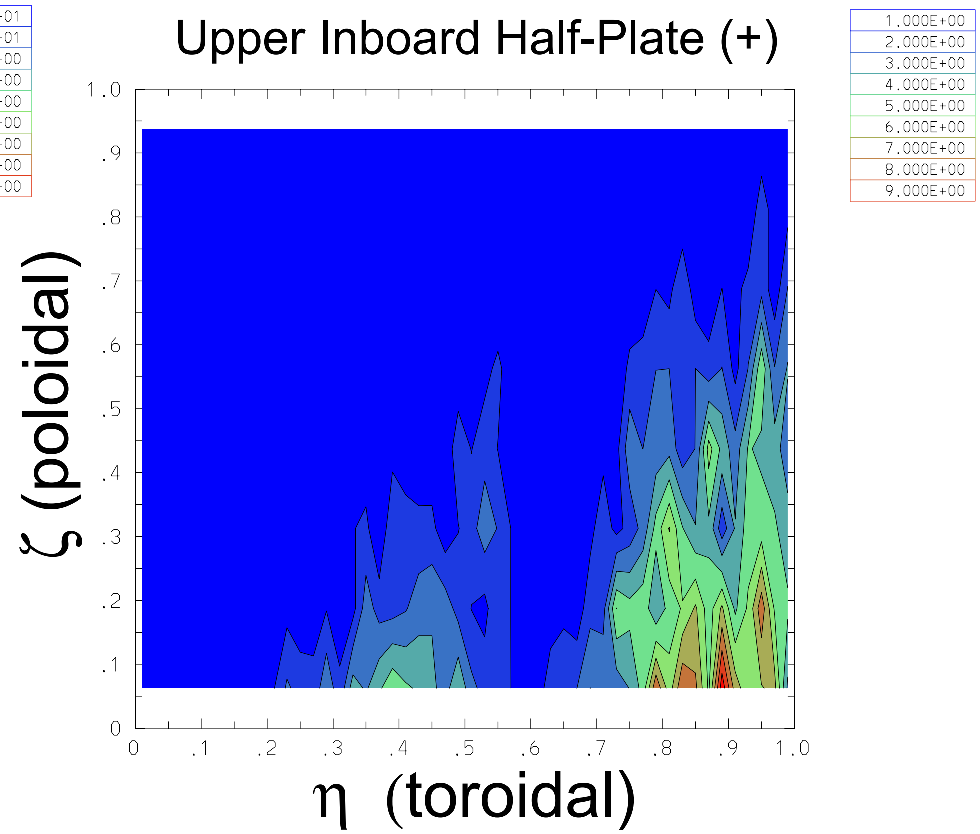
Peaking Factor error = 34%



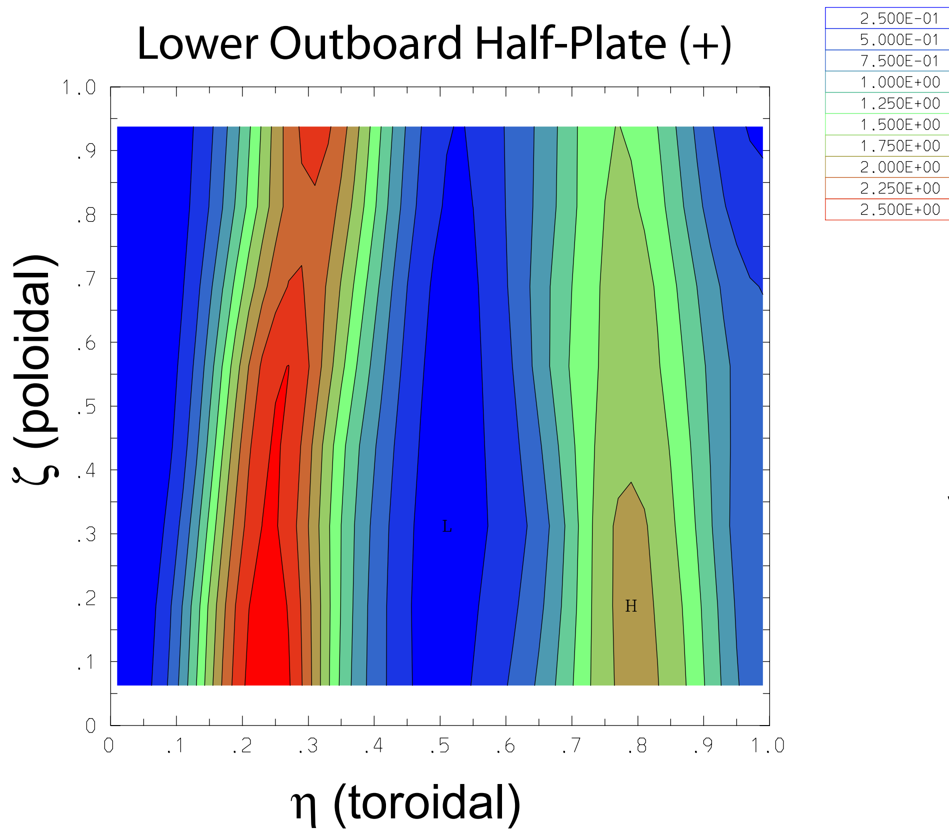
Peaking Factor error = 2%

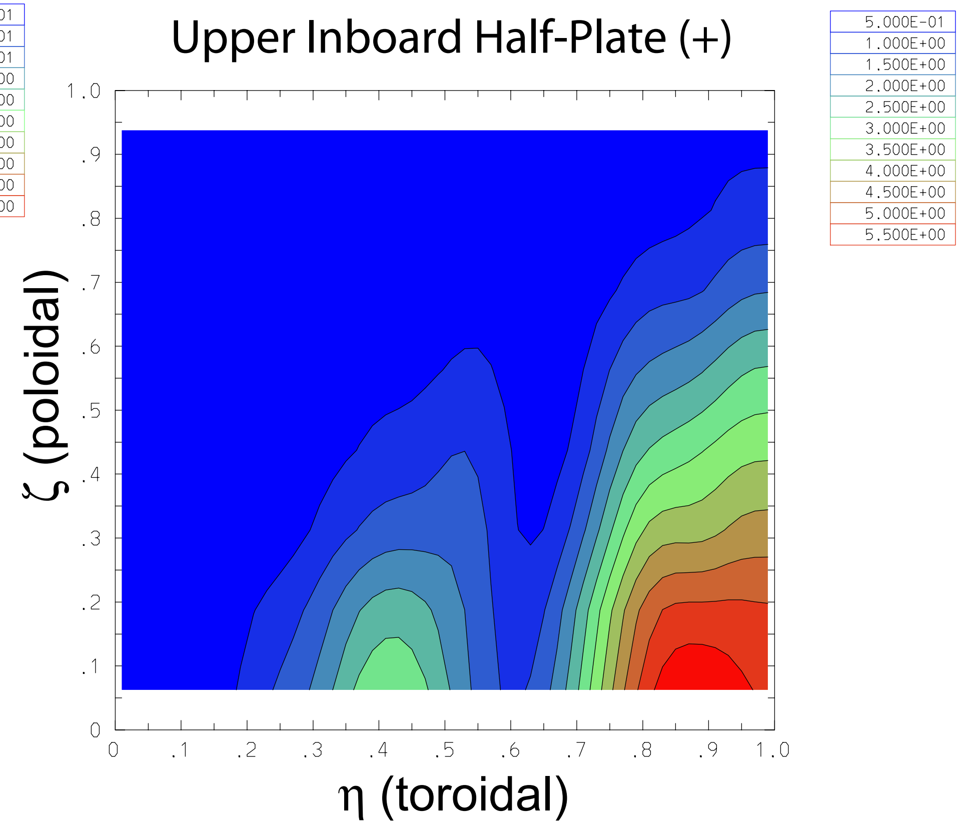
Heat-Load Peaking Factor
(unsmoothed)



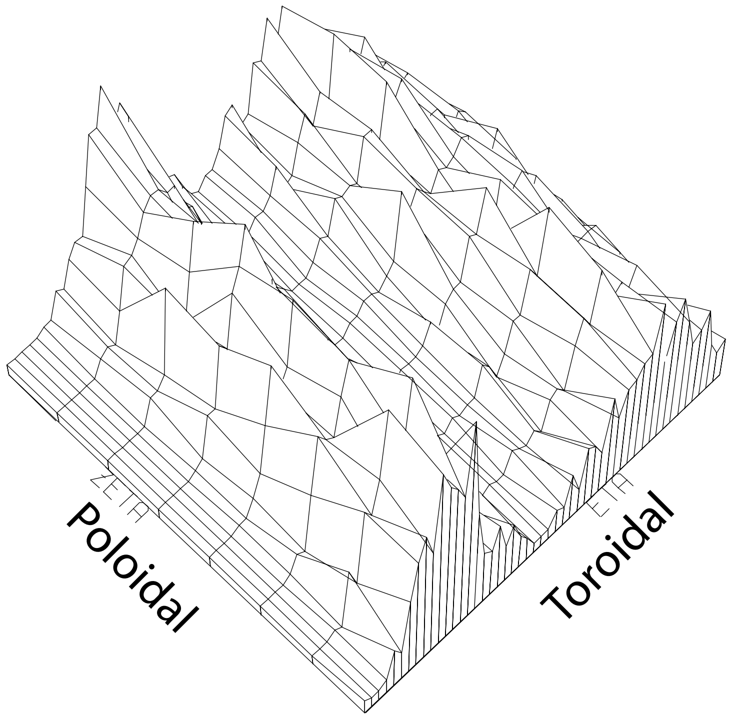


Heat-Load Peaking Factor
(smoothed)





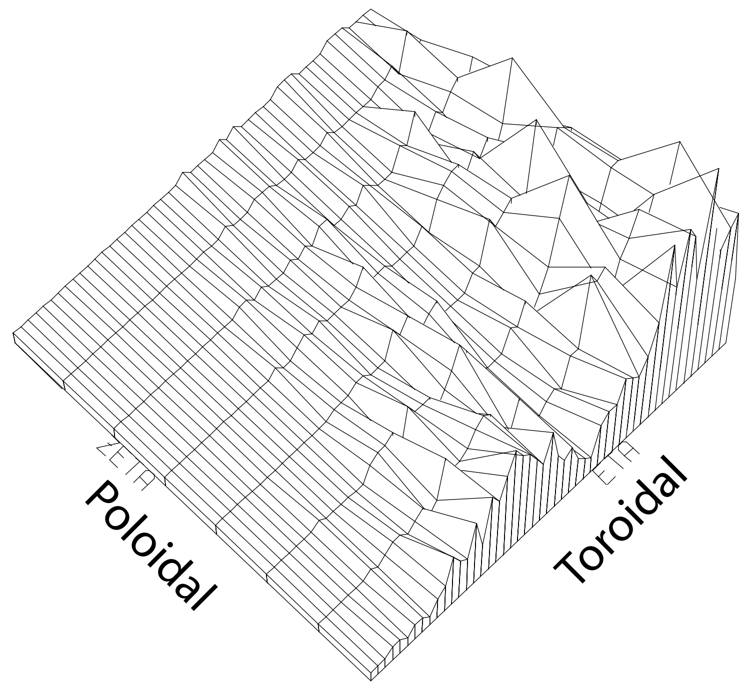
Heat-Load Peaking Factor
(unsmoothed)



Lower Outboard Half-Plate (+)

max($\mathcal{P}$) = 3.8

max($\bar{\mathcal{P}}$) = 8.3

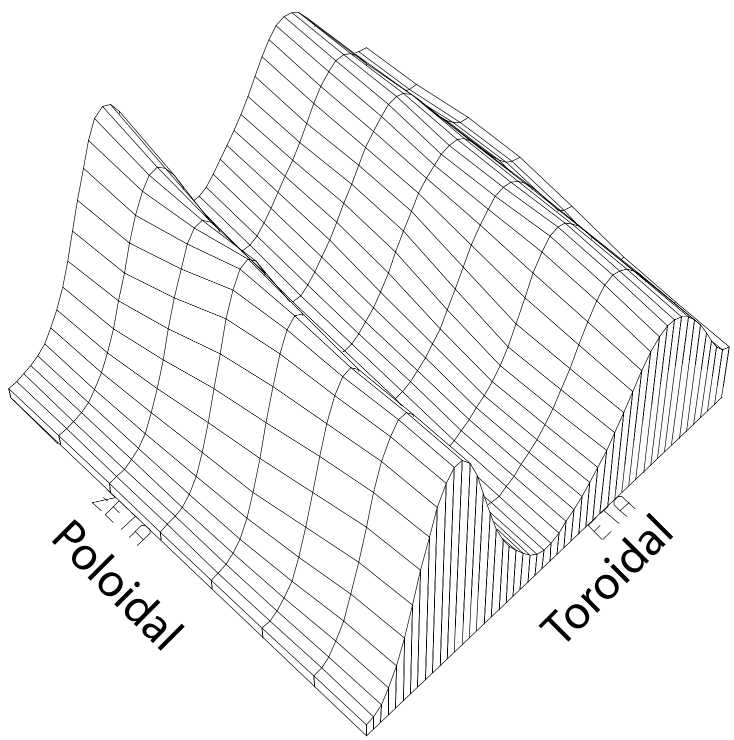


Upper Inboard Half-Plate (+)

max($\mathcal{P}$) = 9.7

max($\bar{\mathcal{P}}$) = 6.7

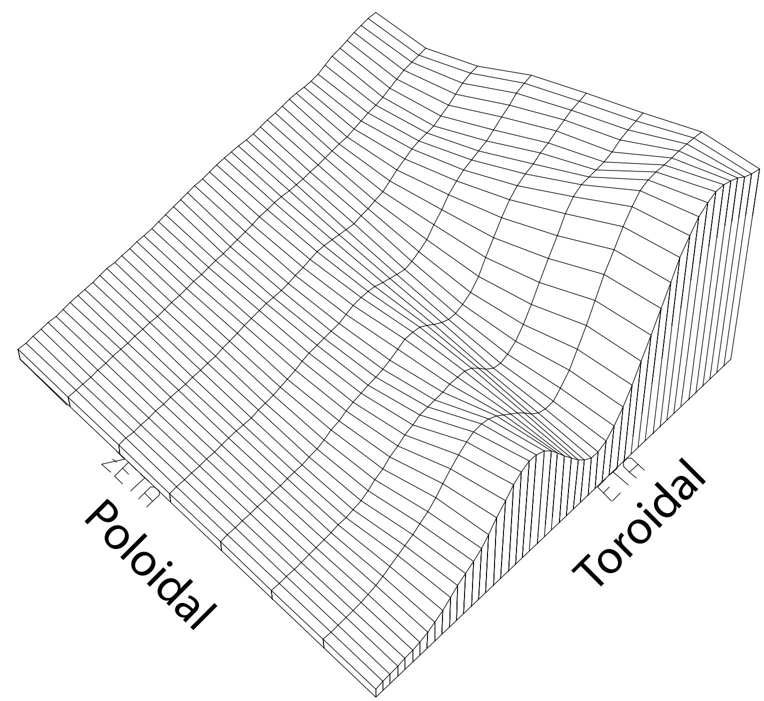
Heat-Load Peaking Factor
(smoothed)



Lower Outboard Half-Plate (+)

max($\mathcal{P}$) = 2.7

max($\bar{\mathcal{P}}$) = 5.8



Upper Inboard Half-Plate (+)

max($\mathcal{P}$) = 6.0

max($\bar{\mathcal{P}}$) = 4.2

Discussion

We continue to investigate the effect of divertors on heat-loading in NCSX using a flexible numerical model of the divertor plates and an interactive and steerable Basis/F90 computer code. Application of these tools to the ARIES-CS reactor study has recently been undertaken by T.K. Mau of UCSD.

For NCSX we find that divertor plates located near the upper and lower tips of the banana-shaped LCMS at $\Phi = 0$, 30, 60, 90 deg are highly effective in collecting field lines: all field lines hit either a divertor plate (76%) or a “shadow” region between a plate and the wall.

While these initial results are encouraging, there is room for significant improvement. In the current design the the ratio of outboard to inboard plate load fraction is about 4:1. A ratio nearer to 1:1 would make more efficient use of the available plate area. The power flow to the shadow regions (24%) needs to be reduced. The strike-point distribution on each plate is highly non-uniform. This may be due to plate areas being shielded by other segments of the same or other plates, but that has yet to be demonstrated conclusively.

Discussion

The connection lengths are too short, a difficulty that probably can be alleviated by moving the plates farther from the plasma, although that could also lead to more field lines hitting the wall. Because computation time is roughly proportional to connection length, it also will increase.

The maximum peaking factor increases monotonically with the number of bins , i.e., the resolution. The maximum resolution necessary from engineering considerations should probably dictate the range of peaking factor to be used. Smoothing the distribution of field-line strike points is beneficial.

The ability to use fully segmented plates has only recently been developed. The additional degree of freedom it affords in plate design should be exploited. T.K. Mau at UCSD has recently begun such an undertaking in the ARIES-CS project.