Divertor Configuration and Heat Load Assessment For ARIES-CS

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OUTLINE

- Modeling Code - STELLA
- Base Case Scenario, so far
- Removing wall strike points by shaping wall
- Balance of heat load between IB and OB plates
- Determination of peaking factor
- Summary and strategy for further improvement

Divertor Design Guidelines

- **Physics** : Connection length ~ 100 - 300 m for > 60% divertor radiation
  $T_{e,div}$ ~ 15 - 20 eV, $n_{e,div}$ ~ 4-6 x 10^{14} cm^{-3}
  $T_{e,sep}$ ~ 200-300 eV, $n_{e,sep}$ ~ 6-8 x 10^{13} cm^{-3}
  (assuming 2.5-5.0% Carbon)

- **Location** : Upper and lower tips of plasma cross-section at □=0^o
  (flux expansion region)

- **Size** : Percentage coverage of first wall < 15% (tritium breeding)
  Toroidal extent : $-25^o \le$ □ $\le +25^o$ (B/S/C space constraint)

- **Heat removal constraint** :
  Peak heat load: $W_{pk} \le 10$ MW/m^2
  Heat load distribution: peaking factor □ $\le W_{pk} A_D / P_{div}$
  A_D = target plate area
  P_{div} = power reaching plate

Modeling Tool -- STELLA

- Field line tracing code developed by Tom Kaiser (LLNL) for NCSX
  - Assumes stellarator symmetry, including target plates
  - Traces on MFBE-generated 3D magnetic field geometry
  - Launches field lines on surface conformal to true LCMS
  - Includes finite cross-field diffusion
  - Tracks strike points of field lines on target plates, first wall and shadow region (baffle)
  - Calculates field line (connection) lengths, and angle of inclination to plate
  - Calculates local heat load peaking factor
  - Presently, limited capability of modeling poloidally curved target plates

    $\longrightarrow$ load distribution results not reliable for curved plates

Parameters Used in Field Line Tracing

- **For the latest design phase,**

Number of field lines launched = 8,000

Field line launched location:

- At toroidal cross sections at $\phi = 0^o, 30^o, 60^o, 90^o$
- Launch locations are uniformly distributed poloidally on a conformal surface offset 1 cm from the LCMS in an MFBE-generated finite-β equilibrium.
- Field lines are launched in opposite toroidal directions.

Diffusion coefficient used = 1 m^2/s

- to model cross-field transport of the heat flux

Heat Load Peaking Factor Evaluation

- Associate each field line *i* traced with a constant power value: $P = P_{div} / N$, where N is number of field lines traced, and P_{div} is the conduction power loss from plasma reaching the plate.
- Heat load contribution to incremental area *j* of divertor plate: $P \sin\square_{ij} / \Delta A_j$, where $\square_i$ is field line inclination angle to surface, and ΔA_j is incremental area.
- Sum up all field line contributions to each incremental area to obtain heat load distribution: $$W_j = \sum_i P \sin\square_{ij} / \Delta A_j$$
- Angle of intersection should be low enough to spread the heat load over a larger area, thus help lowering the peaking factor
- The peaking factor for each incremental area $\square_j$ is then defined as

$$\square_j = \sum_i \sin\square_{ij} / \Delta A_j \Big/ \sum_j \sum_i \sin\square_{ij} / \Delta A_j$$

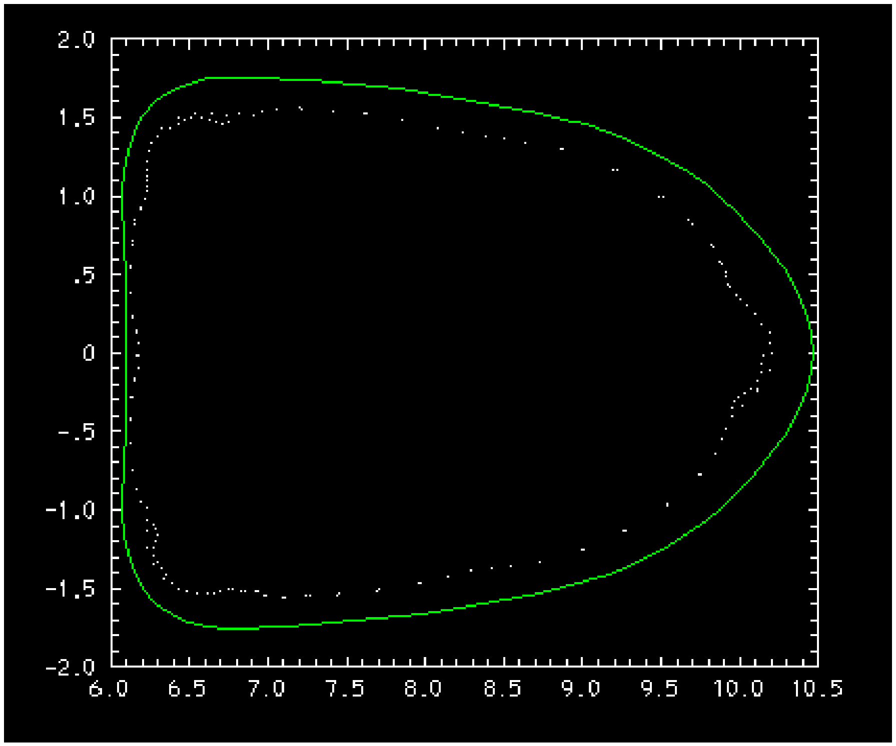
and the overall peaking factor is: $\square$ **= Max {$\square_j$}.**

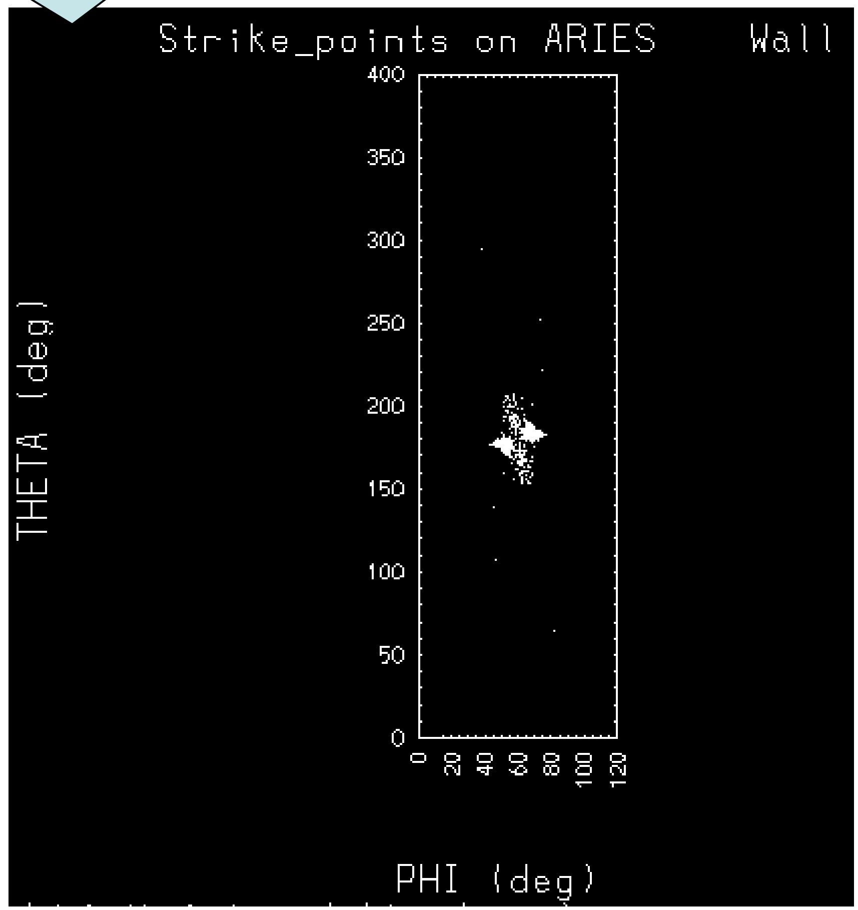
Wall Cannot be Too Close to the Plasma

> 10% of FLs strike wall in

150° < [?] < 210°
40° < [?] < 80°

Plasma-wall at [?] = 60° plane





Gap is set at 5cm at IB mid-plane
from engineering constraint.

Shaping of the Wall to Remove Wall Strike Points

- By pushing the wall back where the strike points are, one should be able to have those field lines travel further and intersect the plates.

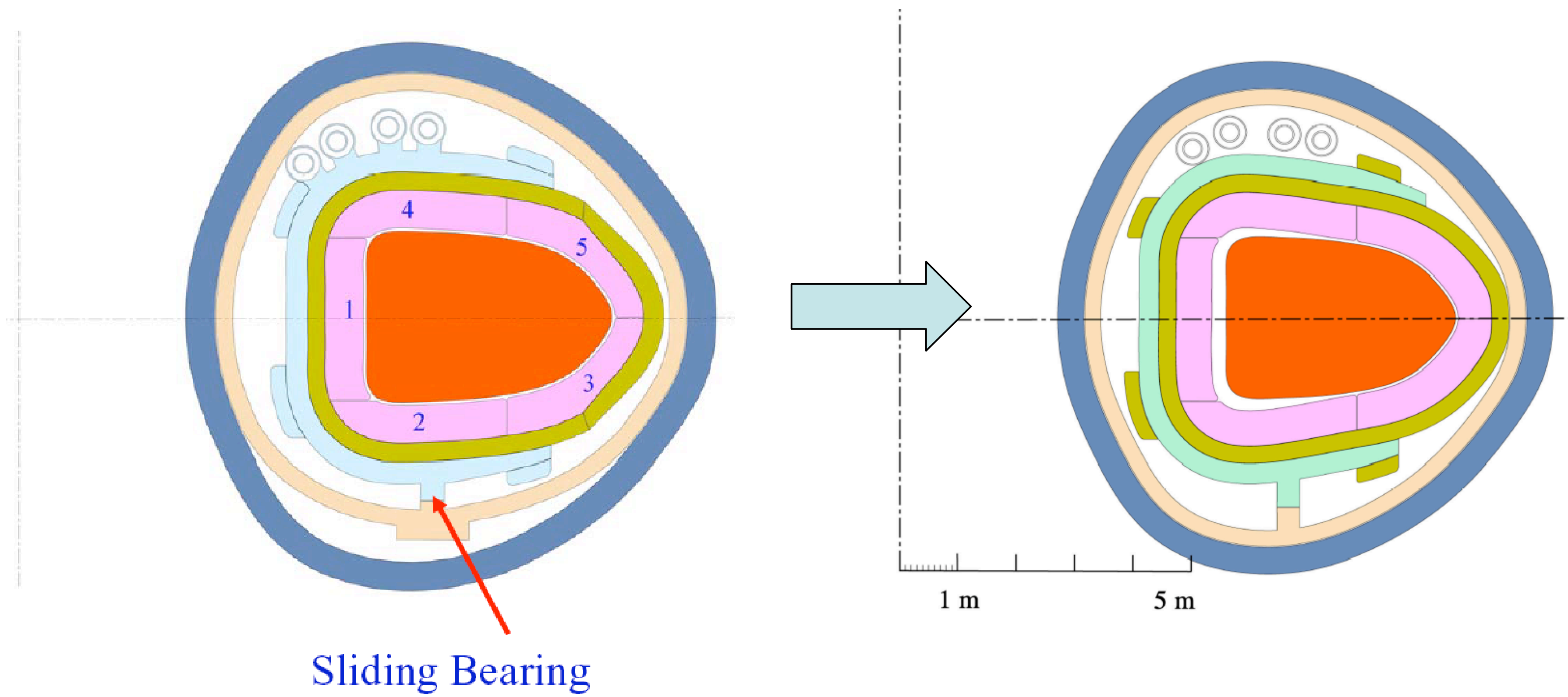
- Engineering constraint stipulates that □, the plasma-wall gap, is:
  - □$_1$ = 5 cm @ □ = 180^o for all □
  - □$_2$ = 45 cm at the plate locations
  - □$_3$ = 15 cm everywhere else.

- Launching only from the □ = 0^o plane for an improved convex poloidal plate configuration, we have the following comparison:

□$_1$, □$_3$	#FLs to wall	#FLs to plates	#FLs to shadow		total #FLs
5, 15 cm	138	1506	94		1738
5, 20 cm	112	1530	96		1738
20, 20 cm	0	1623	115	□□□□	1738

- Moving the wall away at □ = 180^o and □ = 60^o removes all wall strike points.

Since there is enough space, IB first wall can be pushed back around □ = 60° to eliminate/minimize field lines striking wall.



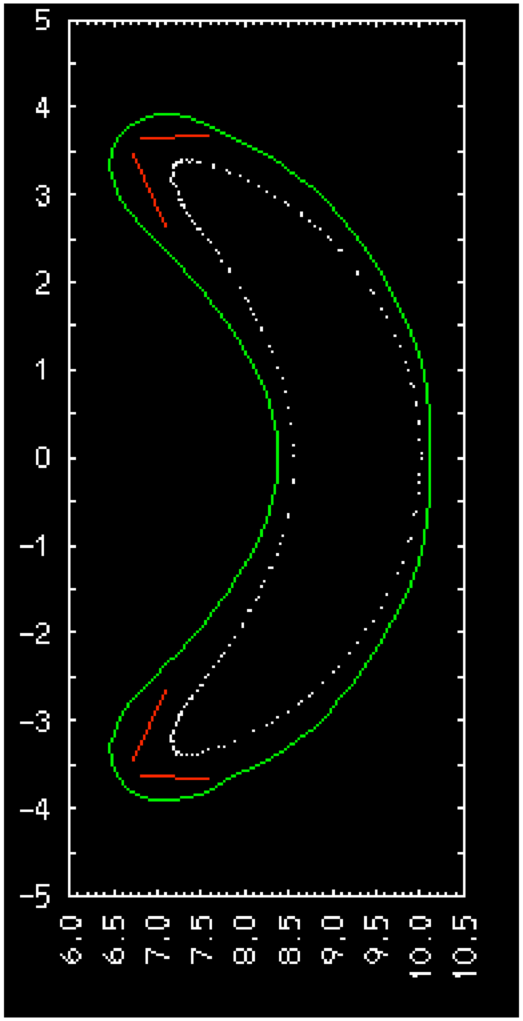
Field Line Strike Points for Baseline Flat Plate Configuration

Plate geometry: -25° ≤ □ ≤ +25°; □□ = 20° ; Edge of plate is 20 cm from LCMS/VMEC

Fraction to plates, wall, baffle = 0.935, 0.003, 0.062

Average connection length to plates = 233 m

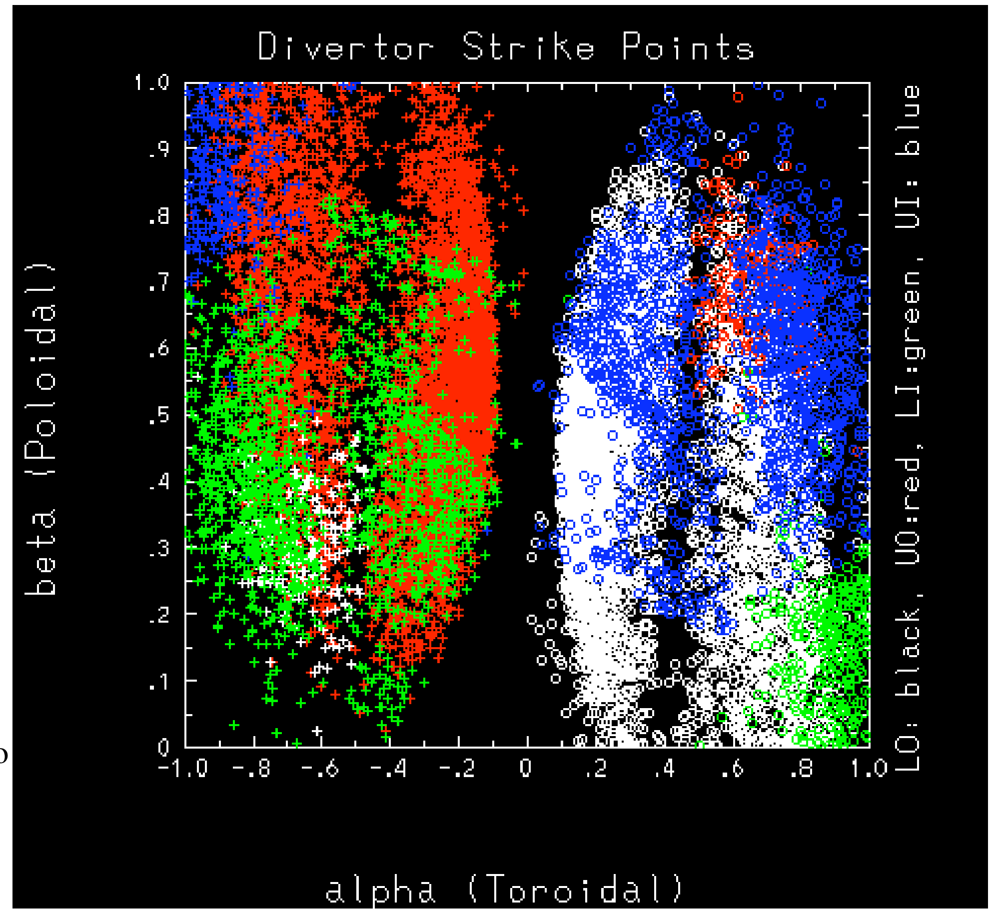
Z (m)



R (m)

$□_o$+10°

$□_o$-10°



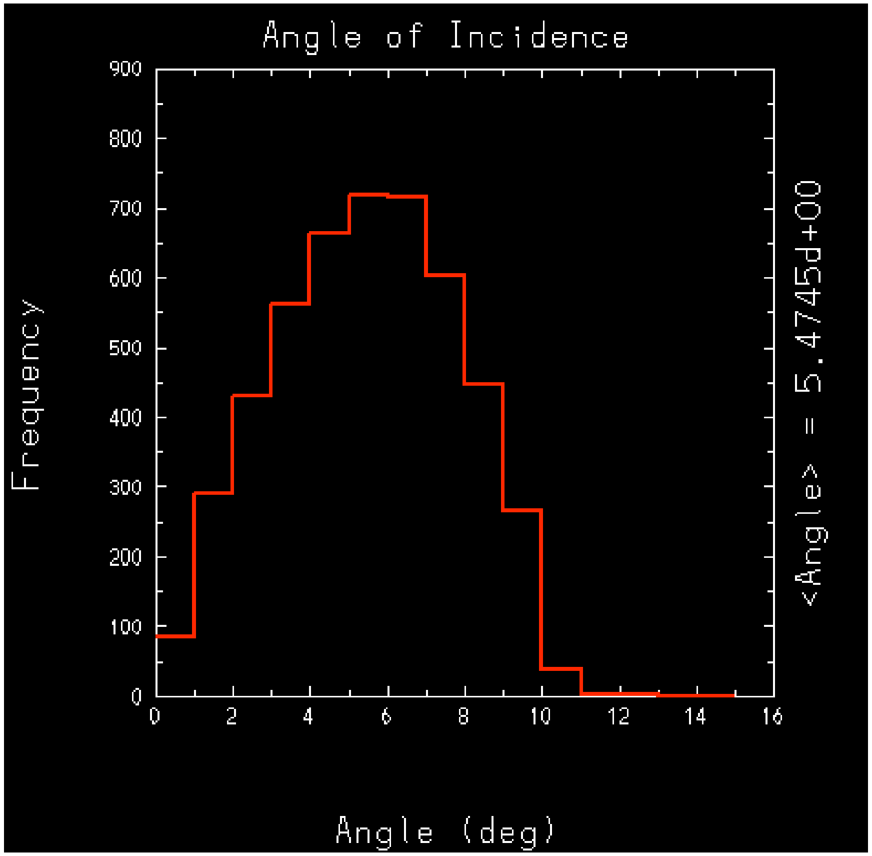
-25°

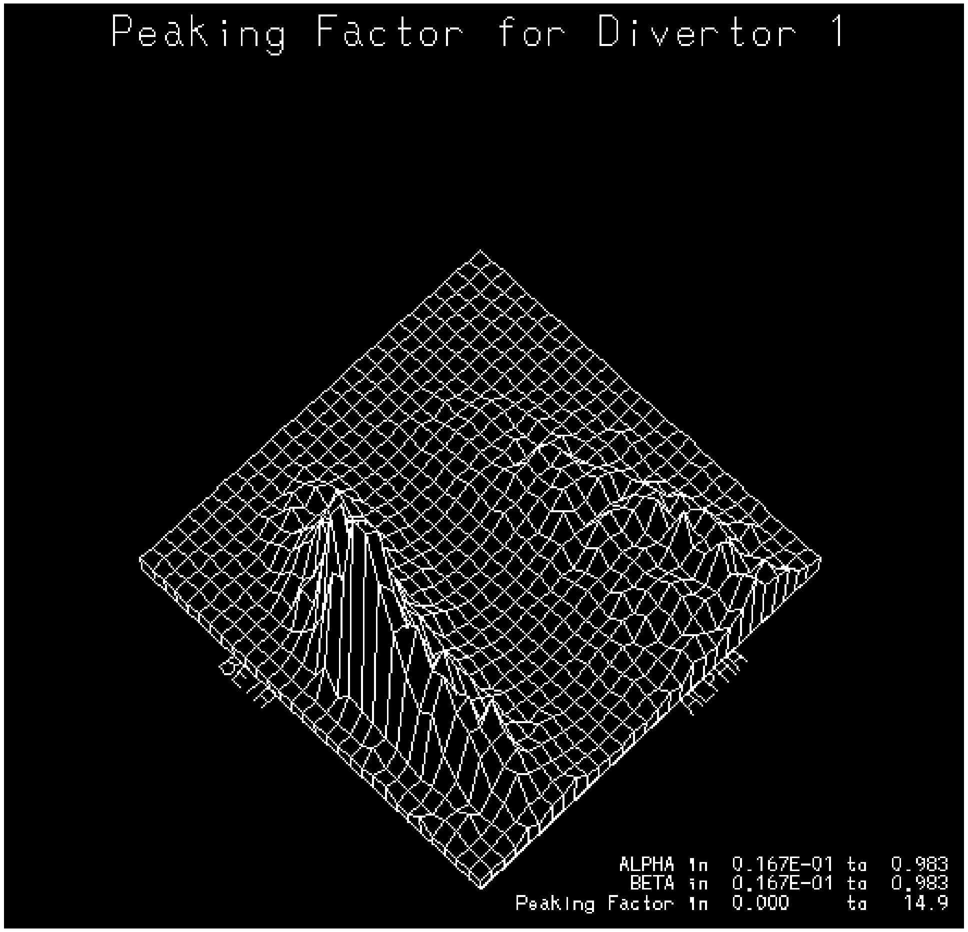
+25°

Normalized Heat Load Distribution for Lower OB Half-Plate

Half-Plate : $0^o \leq \square \leq 25^o$ Divided into 30 x 30 zones.

Average inclination angle = 5.47 ^{o}; Load Peaking Factor = 14.9





Heat Load Distribution Among 8 Half-Plates

Divertor Half-Plate	Area* (m^2)	Load Fraction	Ave. Incl. Angle	Peaking Factor
Lower OB (+)	2.08	0.354	5.47^{o}	14.9
Lower OB (-)	1.62	0.016	1.91^{o}	44.4
Upper OB (+)	1.62	0.016	1.91^{o}	44.4
Upper OB (-)	2.08	0.352	5.47^{o}	14.9
Lower IB (+)	2.36	0.021	4.32^{o}	32.6
Lower IB (-)	2.11	0.110	4.05^{o}	12.9
Upper IB (+)	2.11	0.110	4.05^{o}	12.9
Upper IB (-)	2.36	0.021	4.32^{o}	32.6

(+) : $0^{o} \leq$ □ $\leq 25^{o}$; (-) : $-25^{o} \leq$ □ $< 0^{o}$

* : Scaled to <R> = 7.75 m.

Estimated Peak Heat Load for 8 Half-Plates

- For the latest ARIES-CS reference point, after radiation in the core and in in the divertor region, 24.5 MW of thermal power will approach the plates, 95% will actually hit the plates. 7.76 MW of thermal power will hit the 8 half-plates for one field period.

Divertor Half-Plate	Load Fraction	Incident Power(MW)	Peak Heat Load (MW/m^2)
Lower OB (+) Lower OB (-)	0.354 0.016	2.75 0.12	19.7 3.3
Upper OB (+) Upper OB (-)	0.016 0.352	0.12 2.73	3.3 19.6
Lower IB (+) Lower IB (-)	0.021 0.110	0.16 0.85	2.2 5.2
Upper IB (+) Upper IB (-)	0.110 0.021	0.85 0.16	5.2 2.2

Balance of Heat Load between IB and OB Plates

- With "equal" distance between plasma and plate, it is noted that the OB plates intercept a much larger portion of the thermal power.

- By moving the OB plates further from and/or IB plates closer to the plasma, it appears possible to equalize the distribution of power, provided the connection length to the inner plates are within acceptable limits.

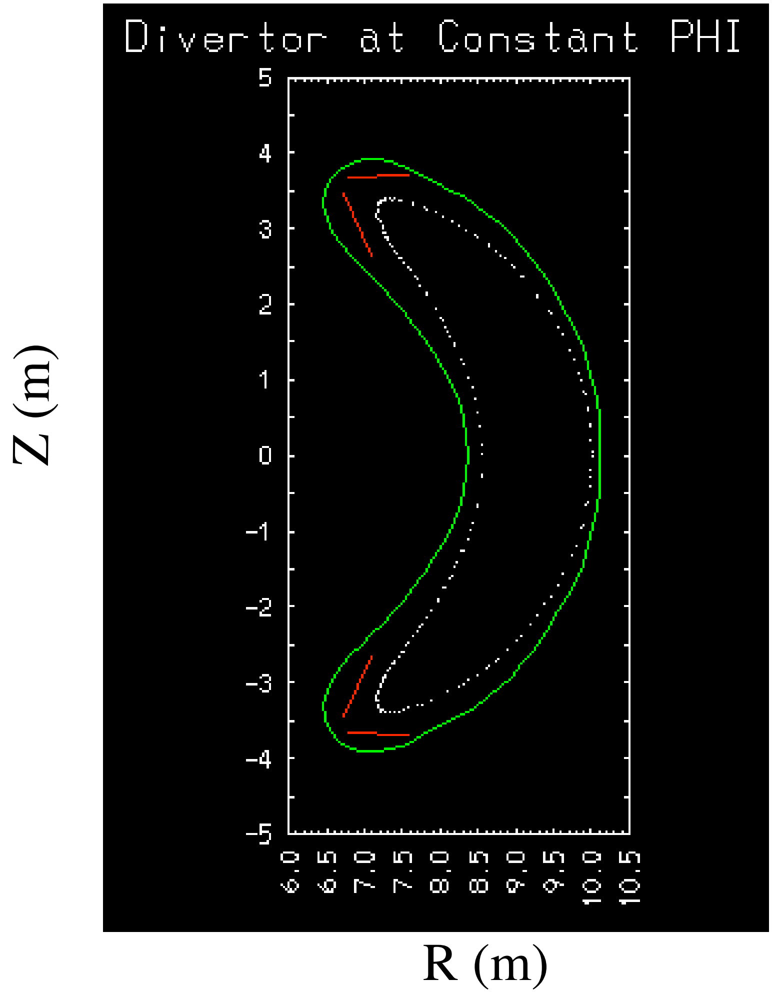
- This has been verified, to some extent, with the convex poloidal plate configuration:

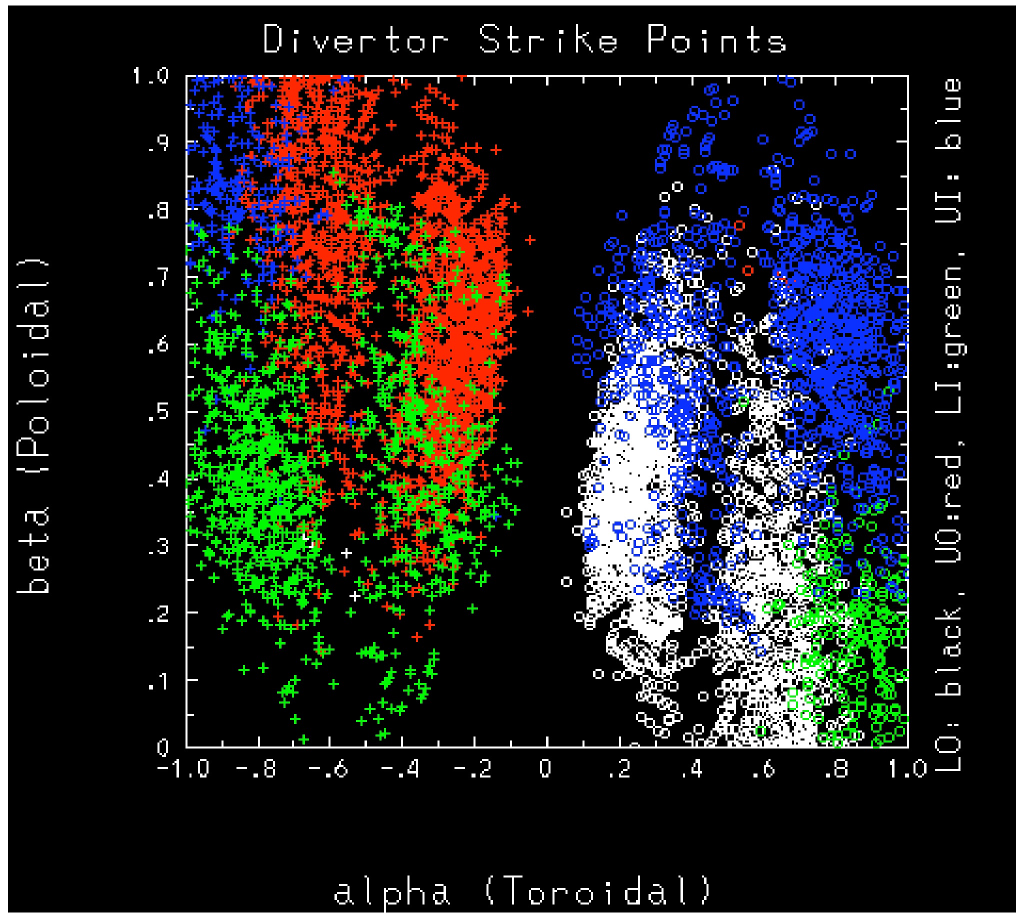
Case 1: mid-point of OB plate is 15 cm from LCMS — P(IB)/P(OB) = 0.39
< C.L. > = 228 m

Case 2: mid-point of OB plate is 17 cm from LCMS — P(IB)/P(OB) = 0.47
< C.L. > = 184 m

Improved Flat Plate Configuration

- The endpoints of the OB plates are pushed back to 30 cm from LCMS, to shift heat load to the IB plates.
- P(IB)/P(OB) = 0.64 @□ = 30 cm vs P(IB)/P(OB) = 0.39 @ □ = 20 cm





Heat Load Performance for Improved Flat Plate

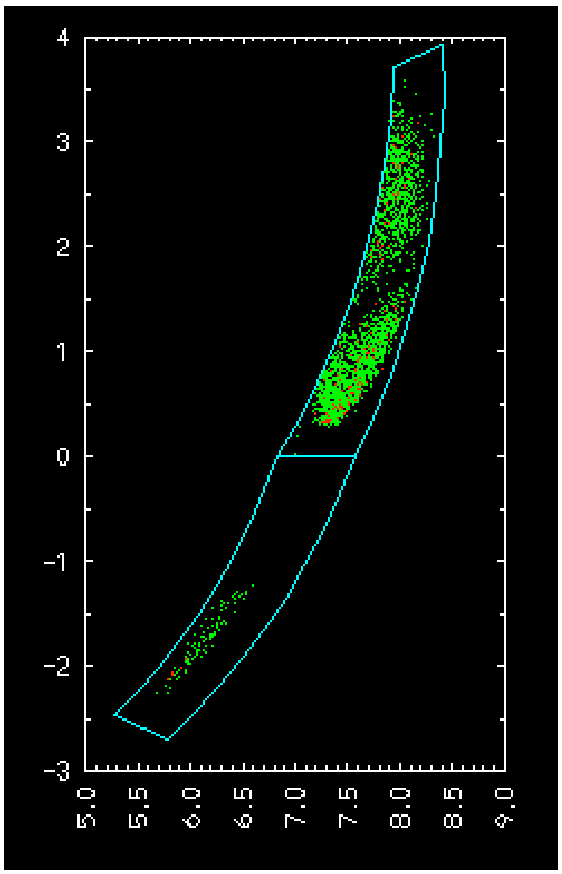
- The gain in lower load fraction is somewhat offset by a resultant higher peaking factor.
- Heat load distribution needs to be considered together with balance of load among various plates.

Divertor Half-Plate	Load Fraction	Peaking Factor	Peak Heat Load (MW/m^2)
Lower OB (+)	0.304	16.1	17.3
Lower OB (-)	0.0	-	0
Upper OB (+)	0.0	-	0
Upper OB (-)	0.303	16.1	17.2
Lower IB (+)	0.033	37.7	4.2
Lower IB (-)	0.162	16.2	9.7
Upper IB (+)	0.162	16.2	9.7
Upper IB (-)	0.034	37.7	4.2

Varying Surface Topology to Spread Heat Load

- We have only begun to explore this option by using 3 points to define the plate surface in poloidal and toroidal extent.

2 pt : flat, LO plate

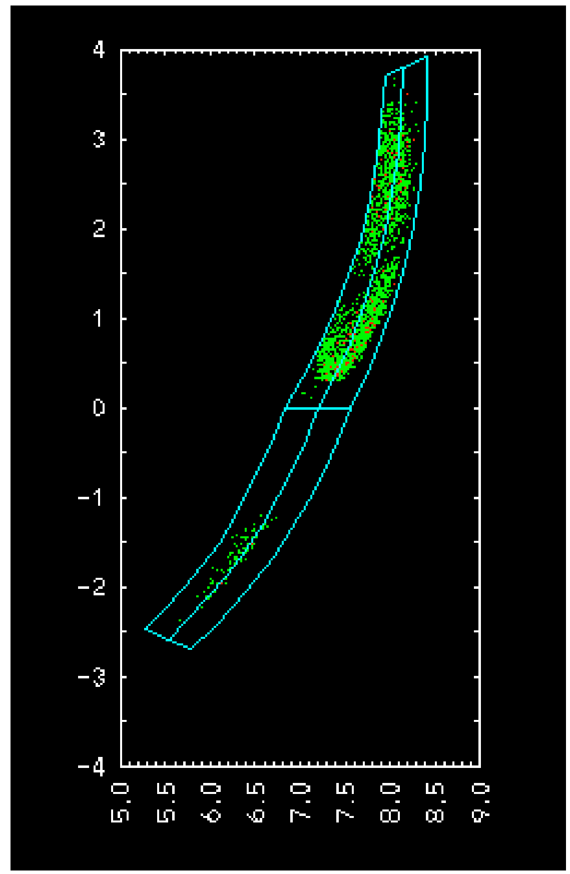


Y (m)

X (m)

Top View

3 pt : non-flat, LO plate



Y (m)

X (m)

Peaking Factor Determination

- Case Study: Flat plate with end-points 20 cm from LCMS

- Launched 8000 and 16000 field lines, and assessed peaking factors for 2 generic plates receiving the most number of strike points.

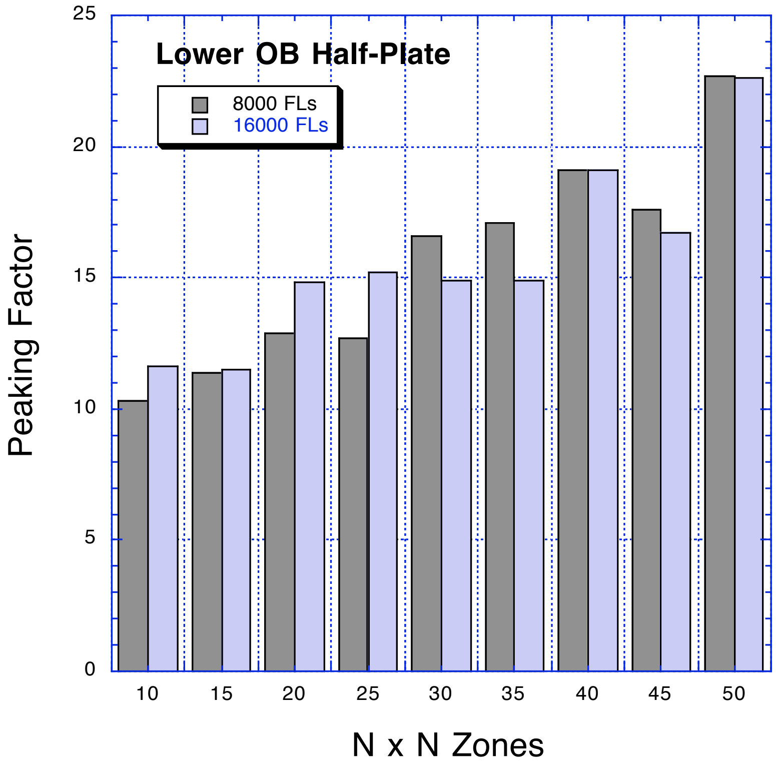
  ✓ Lower OB half-plate: 2423, 4825 strike pts. Respectively
  ✓ Upper IB half-plate: 743, 1503 strike pts. Respectively

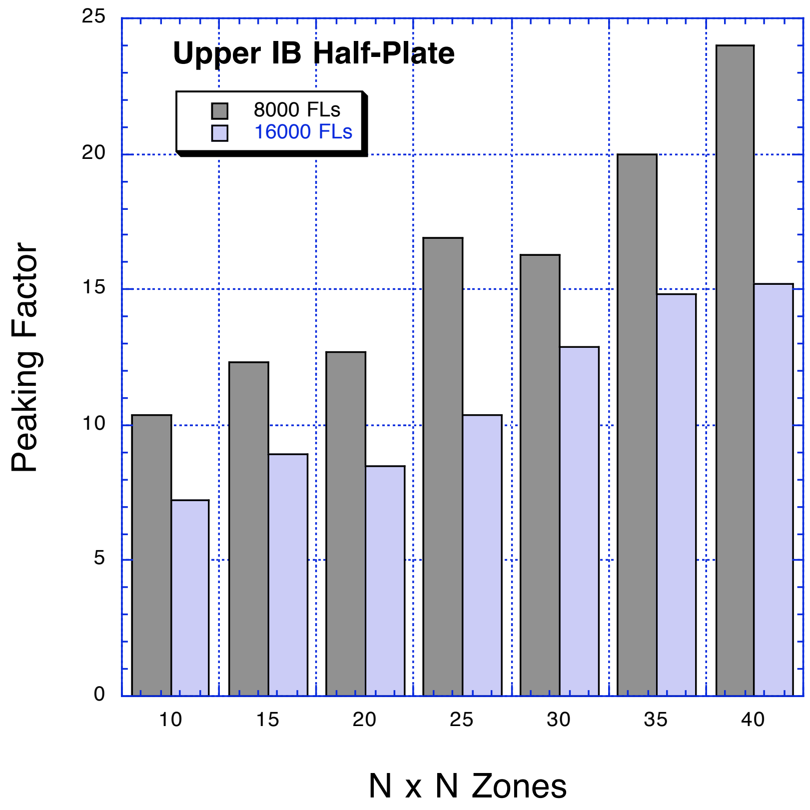
- Peaking factors are evaluated for various N x N zones on the plate(s)

Peaking Factors for Two Major Half-Plates

As functions of

- Total number of field lines launched
- Number of zones on the half-plate





Observations and Comments on Peaking Factor

- For the same number of launched FLs, peaking factor (p.f.) tends to increase as NxN, number of zones, increases; but, that is when the uncertainty also increases since the number of strike points decreases.
- Larger number of FLs should give better estimate of p.f. since strike points in zone increases.
- This is a postulate: For the same number of FLs launched, if the p.f. does not vary much over a range of NxN, then that p.f. value is a reasonable estimate of the p.f. for the plate.
- Conversely, for the same NxN, if the p.f. does not vary much over a range of FLs launched, that p.f. is a reasonable estimate of the p.f. for the plate.
- Based of this set of postulates, then from the histograms, for the lower OB half-plate, the p.f. is ~ 15, while for the upper IB half-plate, there is insufficient data to conclude what a reasonable p.f. should be.

Strategy to Further Target Improve Performance

- The plate geometry developed so far needs further improvement in design.

- Adjust the radial location of IB and OB plates to try to equalize the distribution of heat among IB and OB plates, thus lowering peak heat load on the OB plates.

- When the code is ready for curved plate heat load analysis, we will try to determine the best plate solution by taking this option into consideration, and write it into the final report.

- We will also further develop and devise an algorithm to solidify determination of the plate peaking factor, for the final report.