Divertor and Alpha Particle Physics Analysis for ARIES-CS

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TOPICS

- Divertor design criteria
- Plate geometry and heat load analysis tool
- Plate location and geometry, and thermal heat load
- Alpha particle model and heat load on divertor
- Summary of results and conclusions

Divertor Design for The ARIES-CS Power Plant

- ARIES-CS configuration was based on the NCSX-like coil and plasma shape with three field-period.
- ***The main design parameters:***

  Major radius, R=7.75 m;

  Aspect ratio A=4.5;

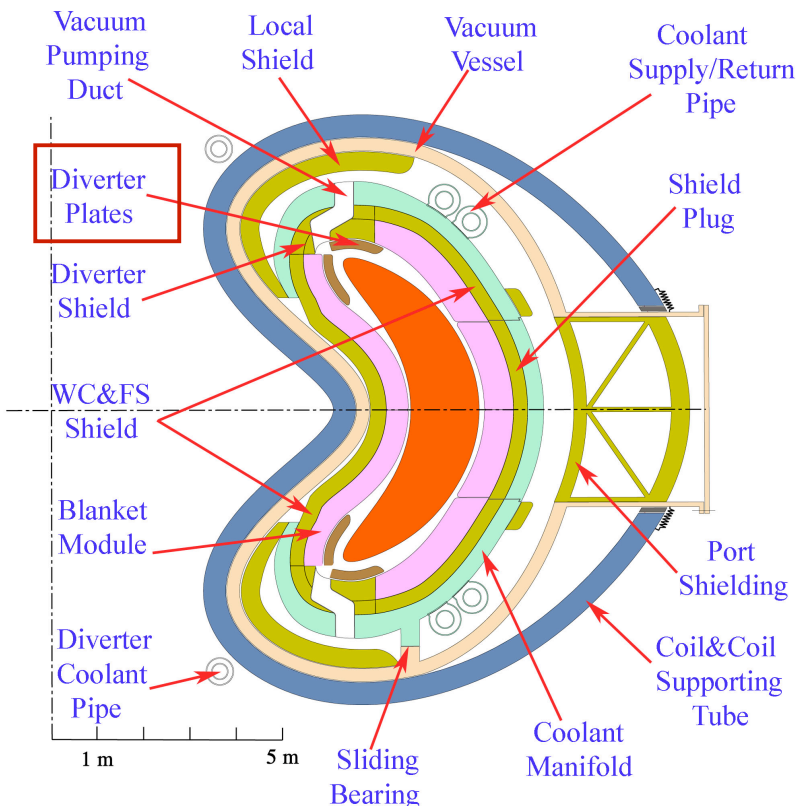
  Plasma magnetic field B=5.7 T;

  Number of modular coils=18;

  Min, coil-plasma distance=1.3 m;

  Fusion power=2.4 GW;

  Avg./max. wall load=2.6/5.3 MW/m2



- Particle and heat flux control is an important issue for the ARIES-CS design.
- Designing a divertor configuration in a complex 3D magnetic geometry is a challenging problem.

Divertor Design Guidelines/Constraints

- **Physics** : Connection length ~ 100 - 300 m for > 60% divertor radiation

  $T_{e,div} \sim 15 - 20$ eV, $n_{e,div} \sim 4\text{-}6 \times 10^{14}$ cm^{-3}

  $T_{e,sep} \sim 200\text{-}300$ eV, $n_{e,sep} \sim 6\text{-}8 \times 10^{13}$ cm^{-3}

  (assuming 2.5-5.0% Carbon)

- **Location** : Region of maximum flux expansion

  [First wall should be sufficiently far away from the plasma to avoid obstructing field lines from striking plates.]

- **Size** : Coverage of first wall < 15% (tritium breeding)

  Toroidal extent : $-25^o \leq \square \leq +25^o$ (B/S/C space constraint)

- **Heat removal constraint** :

  Peak heat load: $W_{pk} \leq 10$ MW/m^2 (surface material)

  Heat load distribution: peaking factor $\square \leq W_{pk} A_D / P_{div}$

  A_D = target plate area

  P_{div} = power reaching plate

Divertor Heat Load Includes Alpha Particle Loss

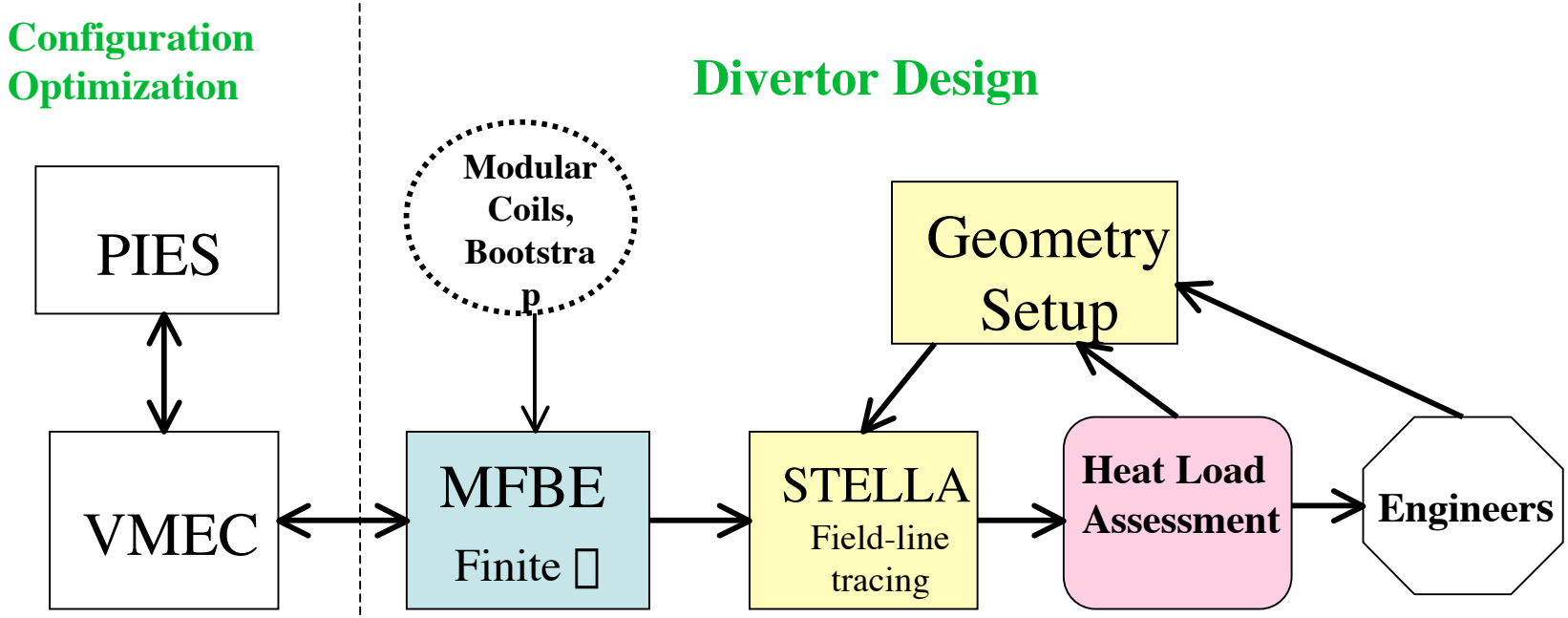
- The divertor heat load consists of thermal transport, alpha particle loss and radiation. The two particle losses are dominant and may have highly nonuniform heat load distribution on the target plates.

- At the reactor plasma operating point, it is assumed that
  - Alpha power loss fraction = 5%
  - Core radiation loss fraction = 75%
  - SOL radiation fraction (edge+divertor) = 75%

- Power balance, for the reference ARIES-CS reference point, results in 23.6 MW of thermal particle power incident on the divertor plates, and 23.6 MW of alpha power loss from the plasma.

- Most of this power should be intercepted by the target plates, with the rest going to the region behind the plates (or baffles) or striking the first wall.

Divertor Design Tools and Strategy



- The divertor will be designed on a CS equilibrium optimized for highest beta and lowest alpha loss.
- Initial target location, size, and shape are determined based on thermal heat flux consideration to maximize interception with minimum peak load.
- Target geometry is further optimized to accommodate the intercepted alpha loss power while satisfying peak heat load limit.

Main Modeling Tool -- STELLA

- Field line tracing code developed by Tom Kaiser (LLNL) for NCSX
  - Assumes stellarator symmetry, including target plates
  - Traces field lines on MFBE-generated 3D magnetic field geometry:

$$\frac{dR}{ds} = \frac{B_R}{B} \quad ; \quad \frac{dZ}{ds} = \frac{B_Z}{B} \quad ; \quad \frac{d\phi}{ds} = \frac{1}{R}\frac{B_\phi}{B}$$

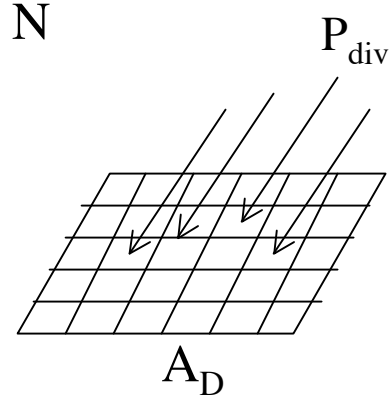
  - Launches field lines from surface conformal to last closed magnetic surface (LCMS) until they strike a plasma facing component
  - **Records positions of field line strike points on target plates, first wall and shadow region (behind plate)**
  - Calculates field line (connection) lengths, and angle of inclination to plate
  - Calculates and plots field line strike points and heat load peaking factor profile on divertor plate

Heat Load Peaking Factor Evaluation

- Associate each field line with a fixed power value: P_{div} / N

  P_{div} = total particle power incident on divertor target

  N = total number of field lines striking target



- Target area A_D is divided into $n_\alpha \times n_\beta$ segments.
- Heat load to each segment *j* of area A_j located at (α,β) is

$$W_j(\alpha,\beta) = (N_j / N) P_{div} / A_j$$

N_j = number of field lines striking segment

  – The effect of the angle (θ) of intersection of the field line with the segment surface is implicitly included in the number of field lines intercepted ($N_j \sim \sin\theta$).

- Average heat load is $\langle W \rangle = P_{div}/A_D$. The peaking factor for each segment is then

$$\Phi_j(\alpha,\beta) = W_j / \langle W \rangle = \left(N_j / A_j\right) / \left(N / A_D\right)$$

- The target peaking factor is: $\Phi = \mathbf{Max}\ \{\Phi_j\}$ for $1 \le j \le n_\alpha \times n_\beta$ which is to be minimized.

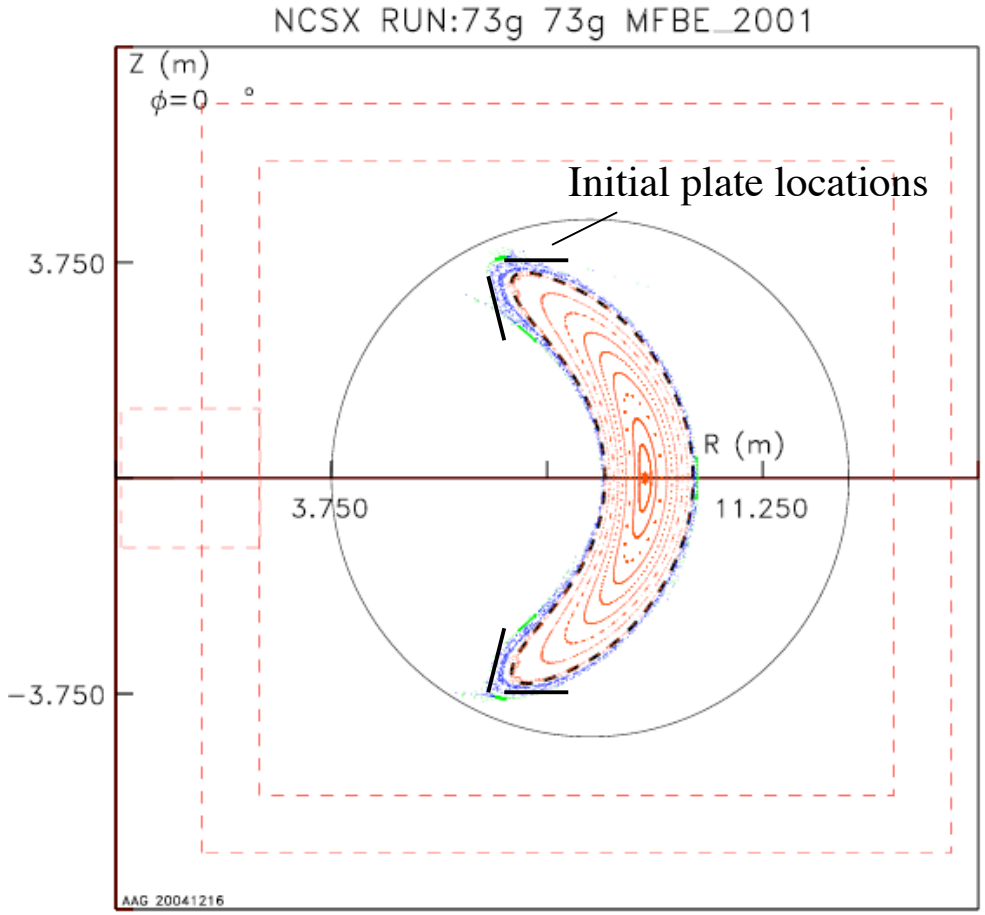
- **Peak heat load is $W_{pk} = \Phi \langle W \rangle \longrightarrow$ Minimize P_{div}/A_D.**

Poincaré Plot of Field Lines Outside LCMS Provides Guidance for Initial Placement of Divertor Plates

- **Most desirable poloidal location**: outside tips of crescent shaped plasma cross section at $\phi = 0^{o}$, and extended toroidally on a surface conformal to LCMS:

  - Local flux expansion zone ensures spreading of field lines (and heat load).

  - Much larger number of field lines passing through the region increases chance of interception by divertor plates located there.



Specific Strategies for Maximizing Heat Load Performance

- Start with a flat plate (projected onto a poloidal cross section).

- Distribute the power uniformly among plates:

  - ✓ Start with all plates equally offset from LCMS
  - ✓ Then adjust individual plate offset distances

  while keeping the connection length to all plates within acceptable limits.

- Reduce the peaking factor on the plates:

  - ✓ Tailor surface topology to smooth out local high peaks
  - ✓ In general, make the plate surface more conformal to the LCMS.

- Adjust location and surface topology iteratively to achieve or approach desired results.

Modeling Thermal Heat Flux with Field Line Tracing

- Launch field lines from a surface conformal to the MFBE-determined LCMS with a small radial offset distance, at f = 0, 30, 60, and 90°.

- Presently, the start points are uniformly spaced on the surface.

- For each field line launched in the +ve toroidal direction, there is a corresponding field line launched in the -ve direction.

- Radial diffusion of the heat flux is modeled with a non-zero diffusivity set to $D_{\Box} = 1\ cm^2/s$. For every $\Box s$ advance in field line length, there is a random transverse displacement given by

$$\Box R = \Box\Box \cos(\Box); \quad \Box Z = \Box\Box \sin(\Box)$$

$$\Box\Box = (24 D_{\Box} \Box s / v_{th})^{1/2} \Box$$

with ($\Box$,cos$\Box$) uniformly distributed on [0,1].

Reference Divertor Plate Configuration

Plate geometry: 4 plates per period
Plate toroidal extent: $-25^o \leq \phi \leq +25^o$;
Plate poloidal extent: $\Delta\theta = 20^o$

$\phi = 0^o$

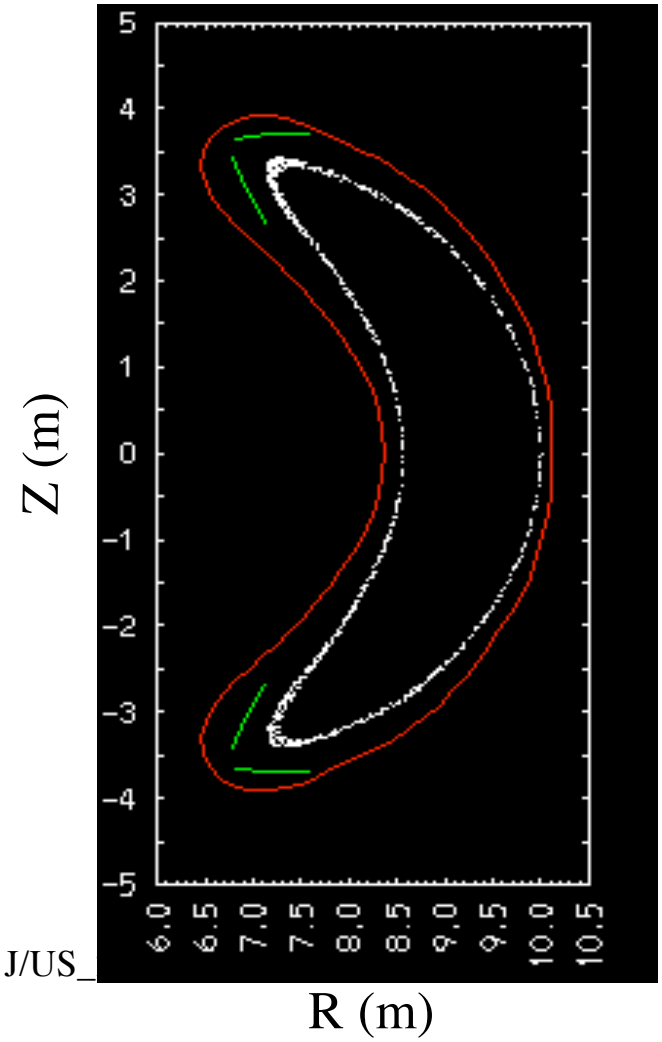
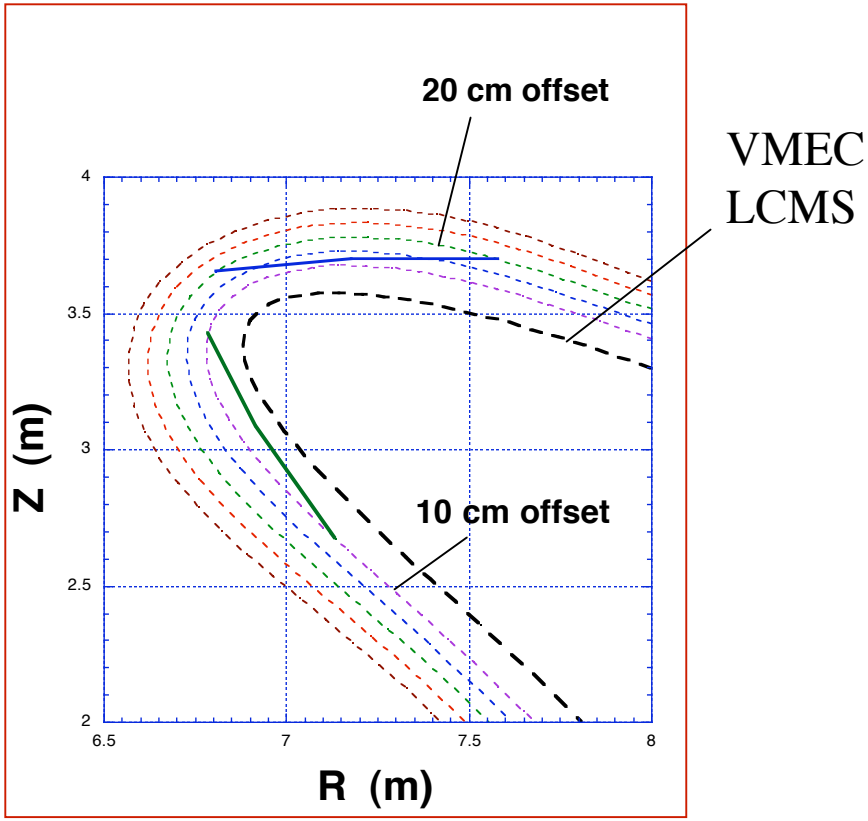


Plate poloidal extent is represented By three points.
Mid-point of OB(IB) plates is 12(5) cm offset from LCMS

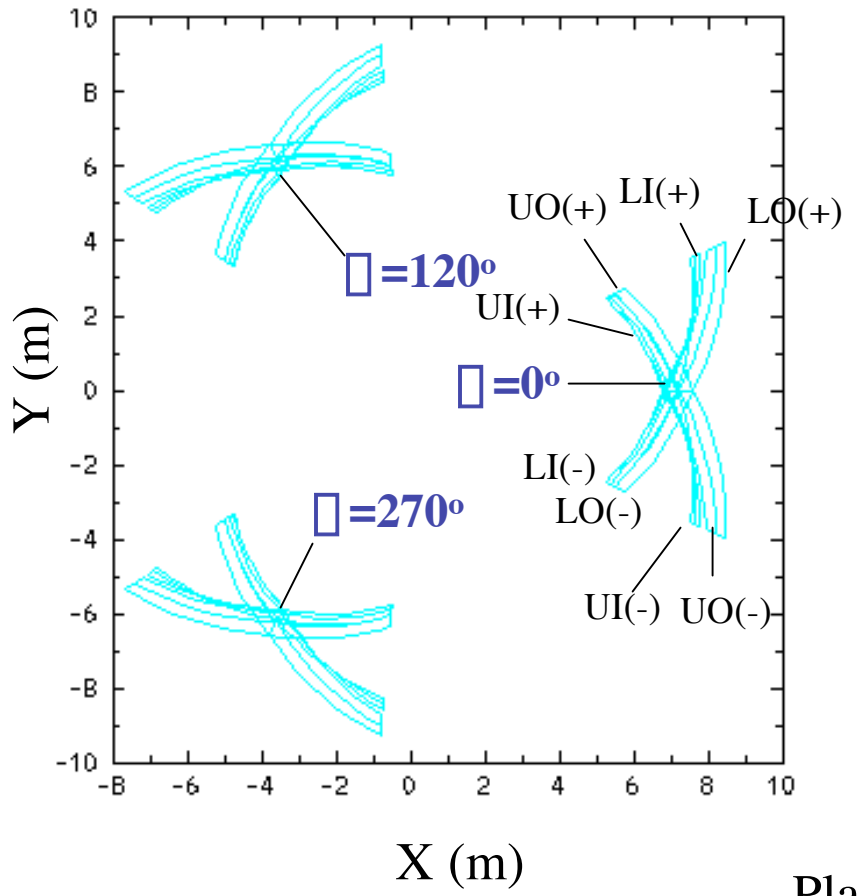


Reference Divertor Plate Geometry

Each plate consists of two half-plates

(+) : $0^o \le \phi \le 25^o$
(-) : $-25^o \le \phi < 0^o$ or $95^o \le \phi < 120^o$

Top View of Plates



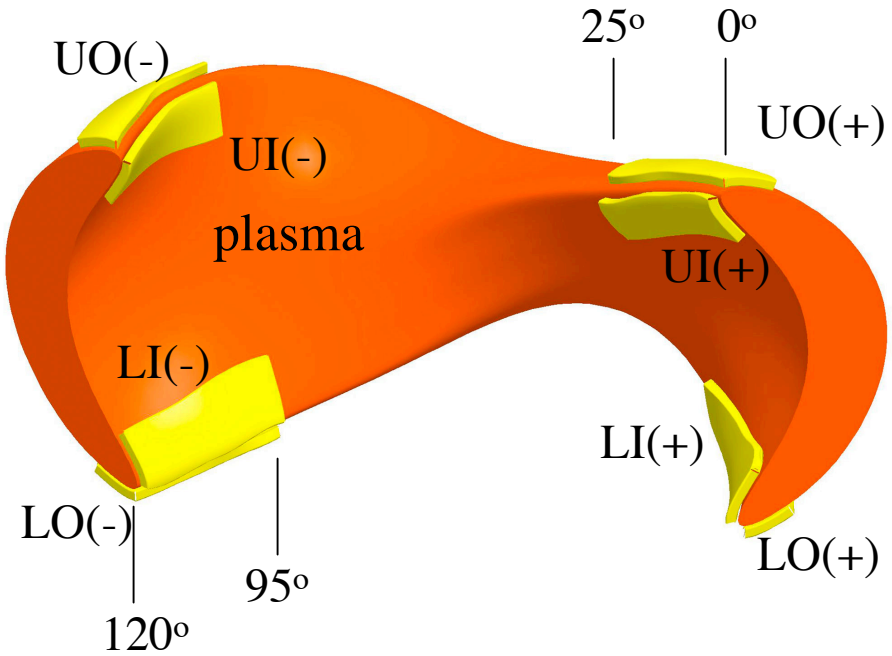


Plate area = 50 m^2 = 7% surface coverage

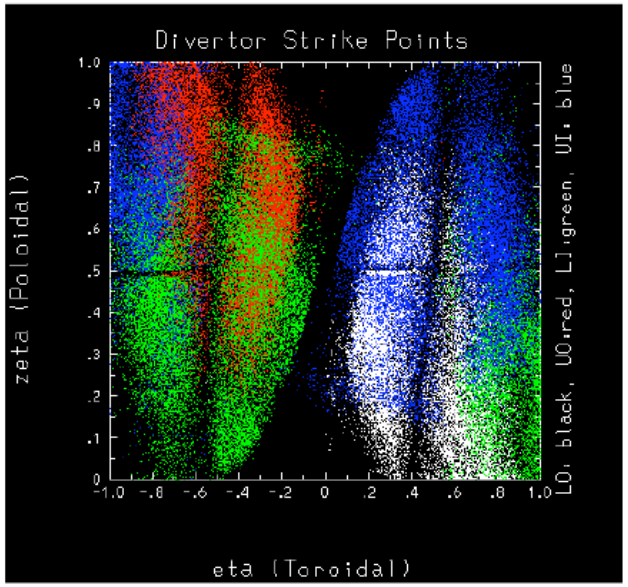
Thermal Heat Load Distribution on Reference Divertor

60x60 grids in each plate are used; each segment contains I/2 divertor unit.

Half-plate	LO(+)	UO(-)	LI(+)	LI(-)	UI(+)	UI(-)
Load fraction (%)	24.7	25.0	6.7	18.3	18.4	6.7
Inc. power (MW)	1.74	1.76	0.47	1.29	1.30	0.48
Area (m^2)	2.20	2.20	2.20	2.02	2.02	2.20
Av. Load [MW/m^2]	0.79	0.80	0.21	0.64	0.64	0.22
Peaking factor(60x60)	13.13	12.99	19.24	9.63	9.60	19.08
Std. Deviation	0.11	0.11	0.19	0.16	0.16	0.19
Pk. Heat Load [MW/m^2]	10.38	10.40	4.14	6.15	6.16	4.16

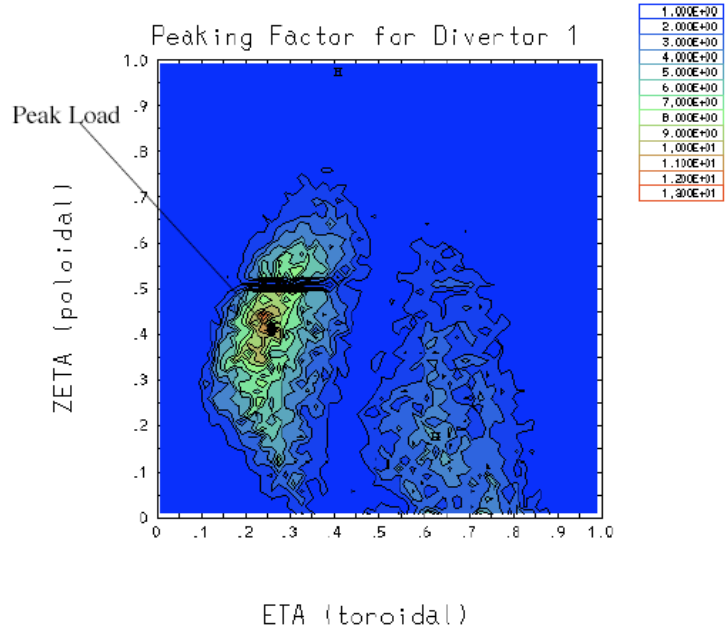
128K field lines are launched with 107631 hitting plates (89.6%), shadow region (10.3%) or wall (0.1%). There are no strike points on LO(-) and UO(+) half-plates.

Strike Points for Thermal Field Lines on Plates



Thermal Peaking Factor for Half-Plate LO(+)

Highest Peak Heat Load (10.4 MW/m^2)



Sensitivity of Peaking Factor with # of Field Lines

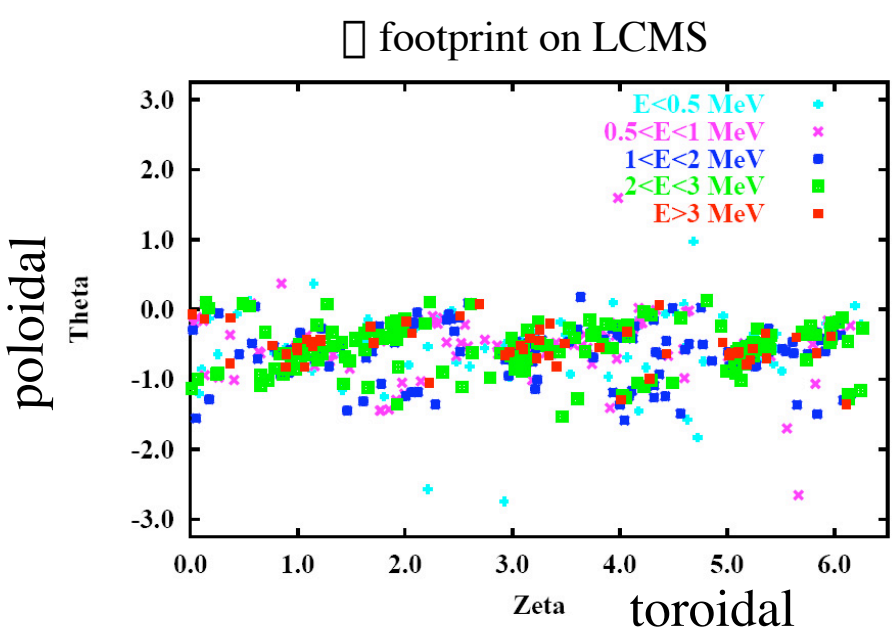
Case (A) : Thermal, ~110K field lines
Case (B) : Thermal, ~ 12K field lines

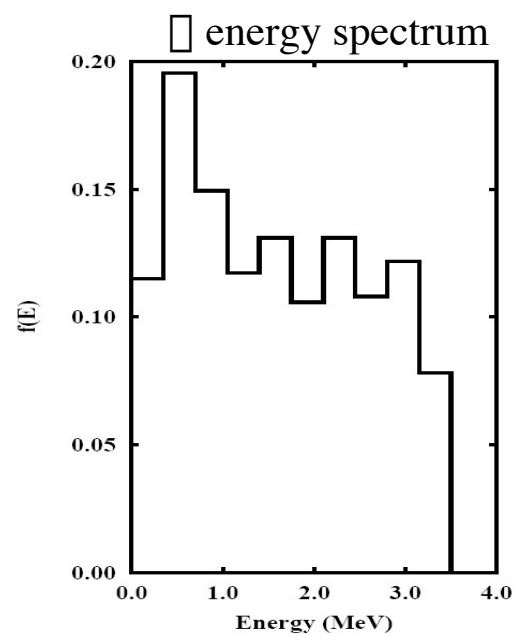
More field lines lead to lower peaking factors and lower peak heat loads, to varying degree.

Half-plate	LO(+)	UO(-)	LI(+)	LI(-)	UI(+)	UI(-)	
Peaking factor(60x60)	13.13	12.99	19.24	9.63	9.60	19.08	(A)
Std. Deviation	0.11	0.11	0.19	0.16	0.16	0.19	
Pk. Heat Load [MW/m^2]	10.38	10.40	4.14	6.15	6.16	4.16	
Peaking factor(60x60)	14.33	15.20	37.75	14.20	14.11	37.32	(B)
Std. Deviation	0.30	0.29	0.38	0.38	0.38	0.38	
Pk. Heat Load [MW/m^2]	11.32	12.16	7.93	9.09	9.03	7.84	

Alpha Heat Load Assessment Using F.L. Tracing

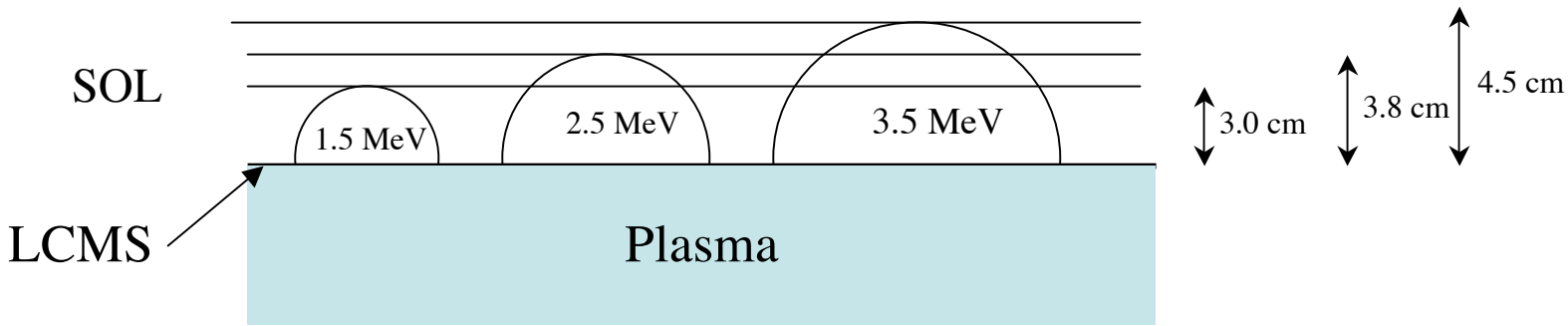
- We note that alphas escape the plasma almost exclusively through the lower OB quadrant of the LCMS.
- Also the alpha energy spectrum gives approximately equal numbers of escaped particles with <E> = 1, 2, 3 MeV.
- According to ORBIT3D calculations, particles with <E>=1 MeV exit with toroidal drift in either direction, while those with <E> = 2, 3 MeV escape with toroidal drift in the +ve direction. [Ku]





Alpha Heat Load Assessment Using F.L. Tracing (Cont'd)

<E>=1 MeV : 0.5 < E < 1.5 MeV; <E>=2 MeV : 1.5 < E <2.5 MeV; <E>=3 MeV : 2.5 < E < 3.5 MeV



- Since energetic α's have gyro-radii $\rho_{c\alpha}$ ~ SOL width, particle trajectories must be described by drift and gyro orbits to accurately locate strike points. So instead of implementing a time consuming gyro-orbit code, we launch field lines from semi-circle with radius $\rho_{c\alpha}$ centered at the alpha exit point on the lower OB quadrant of the LCMS. This is equivalent to launching field lines from the shell of thickness $\rho_{c\alpha}$ from the plasma surface.

- Since P_{div} N, # of field lines $\longrightarrow$ N(1MeV):N(2MeV):N(3MeV)=1:2:3

Alpha Heat Load Assessment Using F.L. Tracing (Cont'd)

- Gathering the above conditions, the field line launching scheme for alpha heat load assessment is as follows:

  (1) ~50% of field lines are launched from 4.5 cm thick shell for $\langle E_{\alpha} \rangle$ = 3 MeV particles, in +ve toroidal directions.
  (1) ~33% of field lines are launched from 3.8 cm thick shell for $\langle E_{\alpha} \rangle$ = 2 MeV particles, in +ve toroidal direction.
  (3) ~17% of field lines are launched from 3.0 cm thick shell for $\langle E_{\alpha} \rangle$ = 1 MeV particles, in both toroidal directions.

  This is the **asymmetric alpha launch case**.

- We also obtain results where all alpha field lines for the three energies are launched in both directions. This is the **symmetric alpha launch case.**

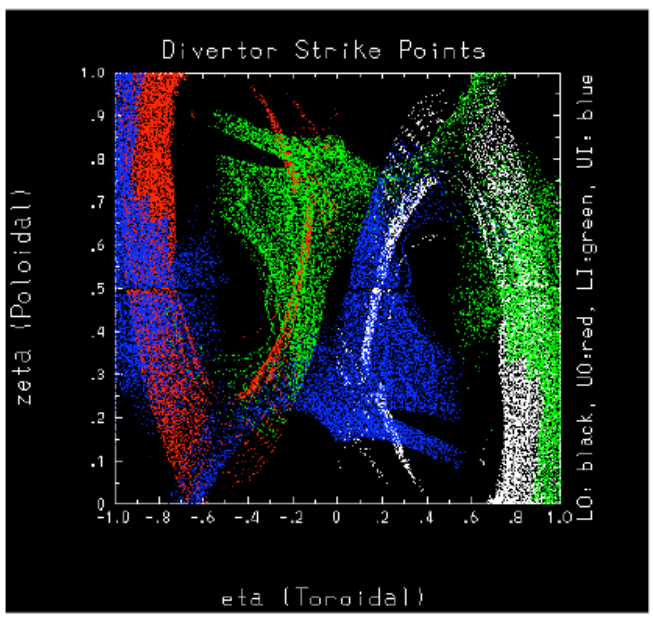
- Since for the reference design point, incident thermal and alpha powers are the same, the same number of field lines should be traced for both incident fluxes.

ALPHA Particle Heat Load Distribution on Reference Divertor with ASYMMETRIC Field Line Launch

Half-plate	LO(+)	UO(-)	LI(+)	LI(-)	UI(+)	UI(-)
Load fraction (%)	14.6	27.9	2.9	3.0	25.0	26.5
Inc. power (MW)	0.873	1.668	0.173	0.179	1.495	1.585
Area (m^2)	2.20	2.20	2.20	2.02	2.02	2.20
Av. Load [MW/m^2]	0.397	0.758	0.079	0.089	0.740	0.720
Peaking factor(60x60)	42.36	11.77	30.05	18.82	9.78	14.64
Std. Deviation	0.09	0.12	0.22	0.27	0.14	0.12
Pk. Heat Load [MW/m^2]	16.82	8.92	2.37	1.68	7.24	10.54

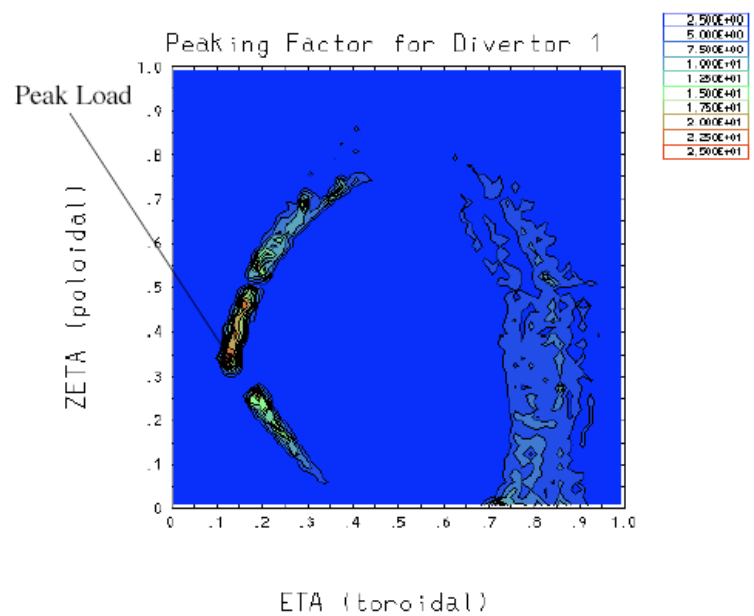
108975 field lines are launched from the lower OB quadrant of plasma surface, with 76.0% hitting plates, 21.2% entering shadow region, and 2.8% hitting wall.

Strike Points for Alpha (AS) Field Lines on Plates



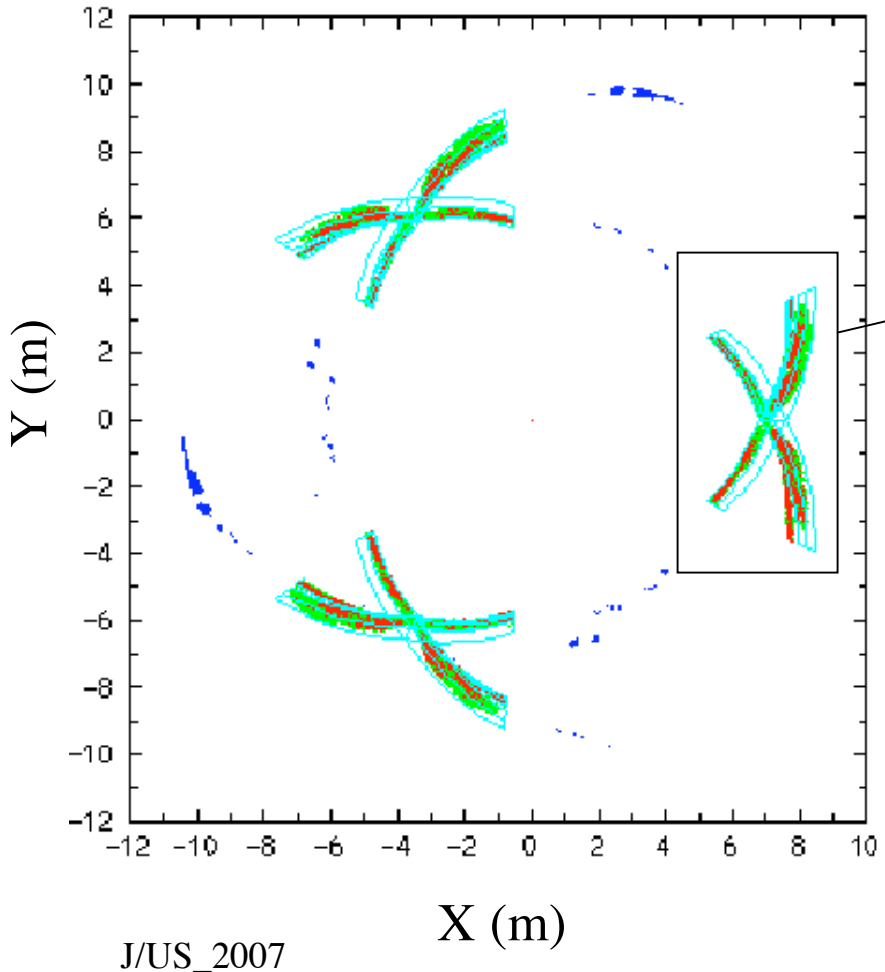
Alpha (AS) Peaking Factor for Half-Plate LO(+)

Highest Peak Heat Load (16.8 MW/m^2)

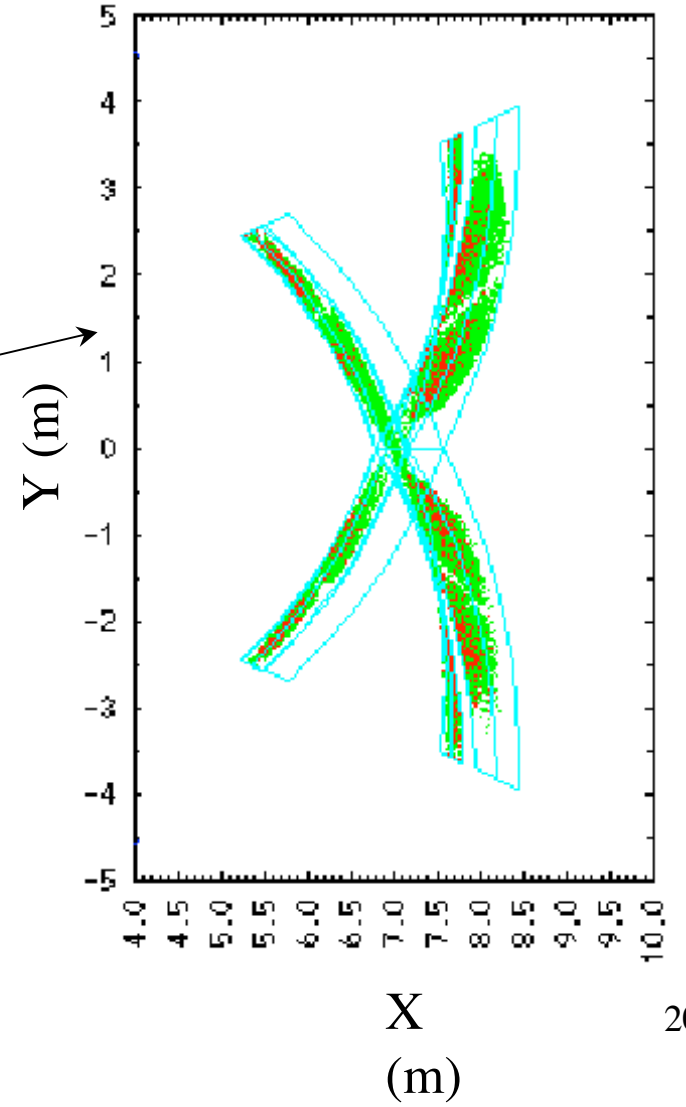


Thermal and Alpha Strike Point Distribution on Plates, Shadow Region and Wall

Top View



green: divertor; red: shadow; blue: wall



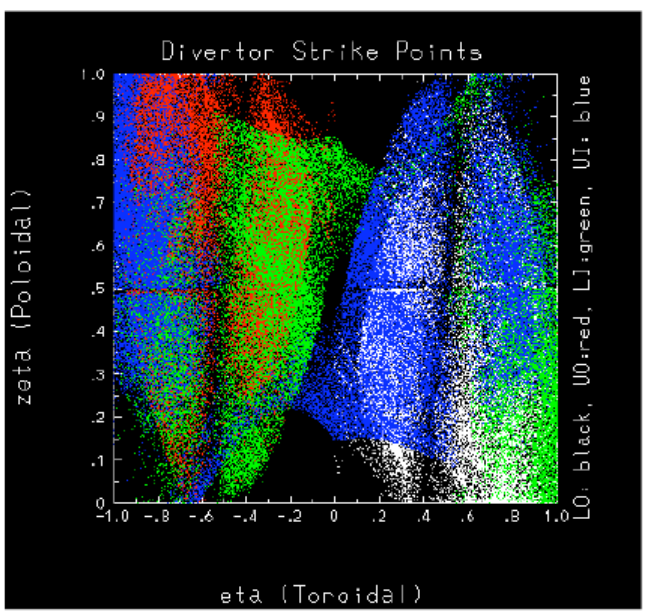
COMBINED Heat Load Distribution on Reference Divertor with ASYMMETRIC Alpha Particle Field Line Launch

Half-plate	LO(+)	UO(-)	LI(+)	LI(-)*	UI(+)*	UI(-)
Load fraction (%)	20.1	26.4	5.0	11.2	21.4	15.9
Inc. power (MW)	2.617	3.437	0.651	1.458	2.786	2.070
Area (m^2)	2.20	2.20	2.20	2.02	2.02	2.20
Av. Load [MW/m^2]	1.189	1.562	0.296	0.722	1.379	0.941
Peaking factor(60x60)	15.48	7.85	17.67	9.49	6.40	13.66
Std. Deviation	0.08	0.10	0.16	0.15	0.12	0.10
Pk. Heat Load [MW/m^2]	18.40	12.26	5.23	6.85	8.83	12.85

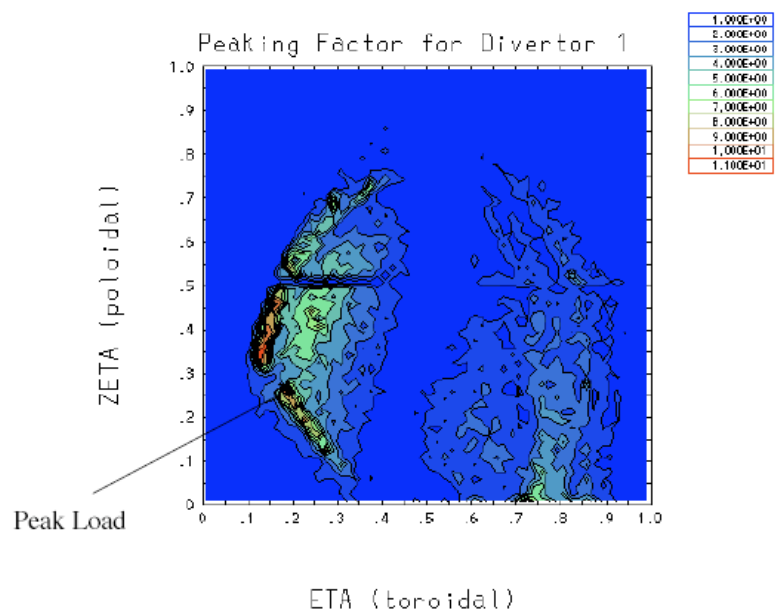
For the reference scenario:

- Total incident power = 47.2 MW
- Total power striking plates = 39.08 MW
  = 13.02 MW / period
- Total power striking shadow(wall) = 7.45 (0.67) MW

Strike Points of Thermal&Alpha (AS) Field Lines on Plates



Total Peaking Factor on Half-Plate LO(+)
Highest Peak Heat Load (18.4 MW/m^2)



ALPHA Heat Loads with Asymmetric (AS) and Symmetric (S) Launch

Half-plate		LO(+)	UO(-)	LI(+)	LI(-)	UI(+)	UI(-)
Load Fraction	[AS]	0.146	0.279	0.029	0.030	0.250	0.265
	[S]	0.219	0.208	0.144	0.142	0.139	0.148
Inc. Power (MW)	[AS]	0.873	1.668	0.173	0.179	1.495	1.585
	[S]	1.316	1.250	0.865	0.853	0.835	0.889
Peaking Factor	[AS]	42.36	11.77	30.05	18.82	9.78	14.64
	[S]	20.30	18.28	17.58	13.43	11.71	17.80
Peak Heat Load (MW/m^2)	[AS]	16.82	8.92	2.37	1.68	7.24	10.54
	[S]	12.14	10.38	6.71	5.67	4.84	7.19

- **Asymmetric launch** results in most alphas striking the upper plates, larger spread in peaking factor (9.8-42.4) and peak heat load (1.7-16.8 MW/m^2) among the half-plates. **Symmetric launch** results in alphas striking more evenly among the plates, with a smaller spread in peaking factor (11.7-20.3) and peak heat load (4.8-12.1 MW/m^2).

COMBINED Heat Loads with Asymmetric (AS) and Symmetric (S) Alpha Launch

Half-plate		LO(+)	UO(-)	LI(+)	LI(-)	UI(+)	UI(-)
Load Fraction	[AS]	0.201	0.264	0.050	0.112	0.214	0.159
	[S]	0.234	0.230	0.103	0.164	0.163	0.105
Inc. Power (MW)	[AS]	2.617	3.437	0.651	1.458	2.786	2.070
	[S]	3.047	2.995	1.341	2.135	2.122	1.367
Peaking Factor	[AS]	15.48	7.85	17.67	9.49	6.40	13.66
	[S]	12.32	9.31	14.29	7.07	6.33	14.37
Peak Heat Load (MW/m^2)	[AS]	18.40	12.26	5.23	6.85	8.83	12.85
	[S]	17.06	12.67	8.70	7.47	6.65	8.86

- **AS launch** gives more uneven spread in strike points and peaking factors among the plates, resulting in one of four plates satisfying the peak heat load limit. **S launch** gives more even spread in strike points and lower peaking factors among the plates, to result in the two inboard plates satisfying the peak heat load limit.

Summary and Conclusions

- We have developed a strategy of optimizing the divertor configuration for a ARIES-CS equilibrium. This involves an iterative procedure that adjusts the location, size and surface topology of a set of divertor plates until all of the physics and engineering criteria are satisfied.

- We have arrived at a divertor design (4 plates/period) at ~0.15 m offset from LCMS, where the plates provide ~7% wall coverage and intersect ≥85% of combined thermal and alpha particle heat flux. The field lines have an average connection length of ~220 m, leading to upstream temperature ≥300 eV at high densities of $\sim 5 \cdot 10^{19}$ m^{-3} and radiated power fraction in SOL and divertors >50%. However, not all plates satisfy the peak heat load limit of 10 MW/m^2.

- From our analysis, alpha heat flux dictates the peak heat load in these plates. This would imply the alpha loss fraction need to be further reduced by making the plasma more collisional. A larger major radius and larger plate area will also help.

- The divertor design for ARIES-CS is challenging. Future efforts on a more rigorous analysis for alpha footprints on the PFCs and a full optimization of divertor plate configuration should be carried out.