Edge Particle and Heat Flux Control For Compact Stellarator Reactors

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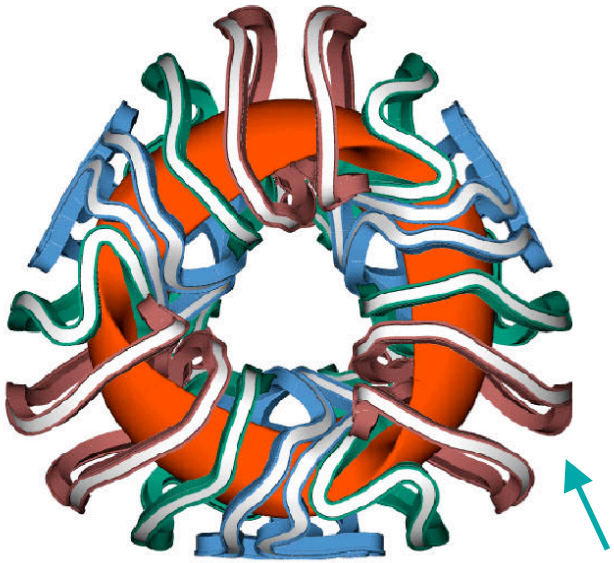
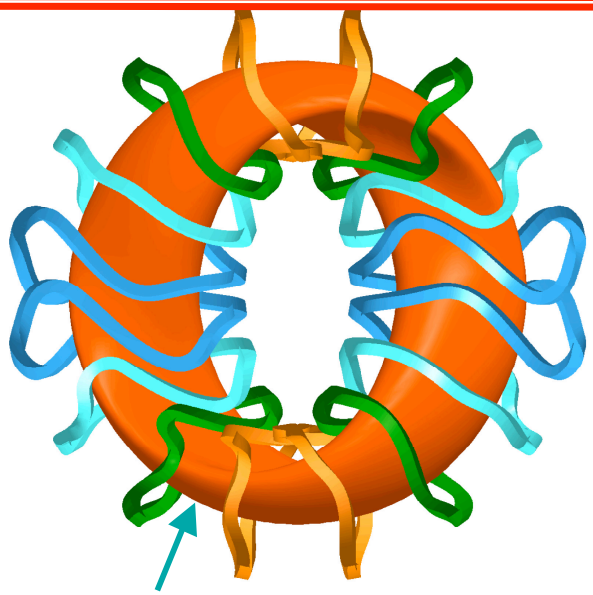
Two Representative Configurations for ARIES-CS Phase II Studies





Parameter	3-field period (NCSX)	2-field period (MHH2)
Coil-plasma distance, Δ (m)	1.2	1.4
<R> (m)	8.3	7.5
<a> (m)	1.85	2.0
Aspect ratio	4.5	3.75
β (%)	4.1	4.0
Number of coils	18	16
B_o (T)	5.3	5.0
B_{max} (T)	14.4	14.4
Fusion power (GW)	2	2
Avg. wall load (MW/m^2)	2.0	2.7

Particle and Heat Flux Control is an Important Issue for ARIES-CS Power Plant Study

- **Particles and heat transported from the plasma** need to be handled (or diverted) while maintaining acceptable heat loads and erosion rates on all plasma facing components (PFCs).

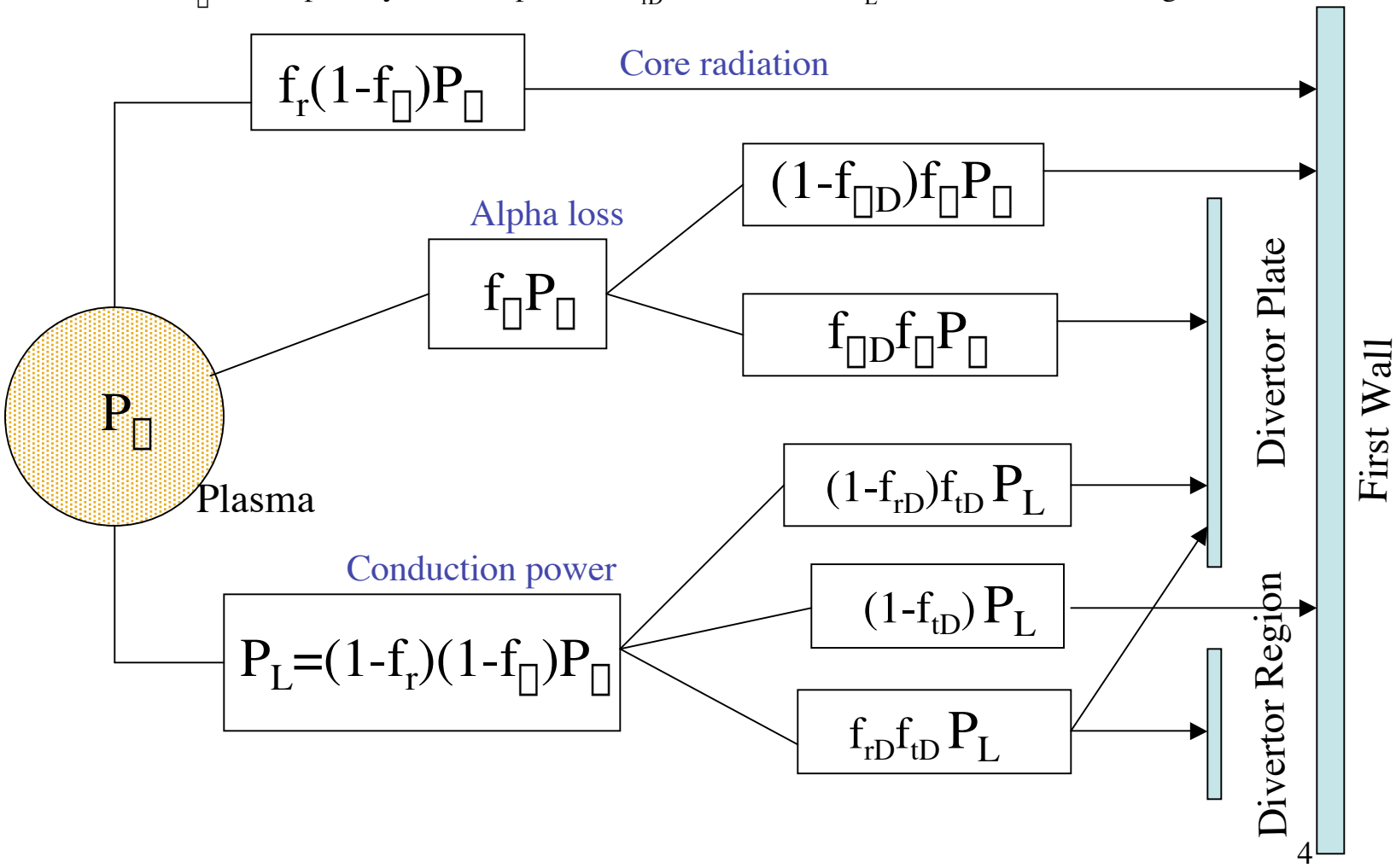
- Because of non-axisymmetry of the magnetic geometry, a significant number of **energetic alpha particles** escape the plasma that need to be withstood by the PFCs.

- To intercept the bulk of the heat flux while maintaining particle control, we propose to use strategically located divertor target plates between the last closed magnetic surface (LCMS) and the first wall, designed to satisfy the peak heat load limit of 10 MW/m^2 for these plates.

- In the talk, we will focus on the handling of heat fluxes due to conduction power loss and non-thermal alpha particles ejected from the plasma.

Plasma Heat Flow Diagram

P_{α} = alpha power from fusion reactions; f_{α} = fraction of alpha power lost from plasma
f_r = fraction of plasma heating power radiated from core
P_L = lost thermal power from core ; f_{tD} = fraction of P_L intercepted by divertor plates
$f_{\alpha D}$ = fraction of P_{α} intercepted by divertor plates; f_{rD} = fraction of P_L radiated in divertor region



Divertor Engineering Design Criterion

- Total heat to divertor plates: $P_{div} = [(1-f_{rD})f_{tD}(1-f_r)(1-f_{\square})+f_{\square}f_{\square D}]P_{\square}$
  Total heat to first wall = $[f_r(1-f_{\square})+(1-f_{tD})(1-f_r)(1-f_{\square})+(1-f_{\square D})f_{\square}]P_{\square}$

- Divertor design criterion:

$$P_{div} / \square_D < W_{pk} / \square$$

where W_{pk} = divertor peak heat load limit (=10 MW/m^2)
$\square$ = heat load peaking factor
A_D = total divertor plate area

- Design a divertor (location and geometry) with a more uniform heat load (lower $\square$) will permit a higher P_{div} while satisfying peak heat load constraint.

  P_{div} can be lowered by inducing more radiation
  (a) from the core (higher f_r), e.g., by setting up a radiating mantle inside LCMS
  (b) in the divertor region (higher f_{rD}), e.g., trace impurity or gas injection

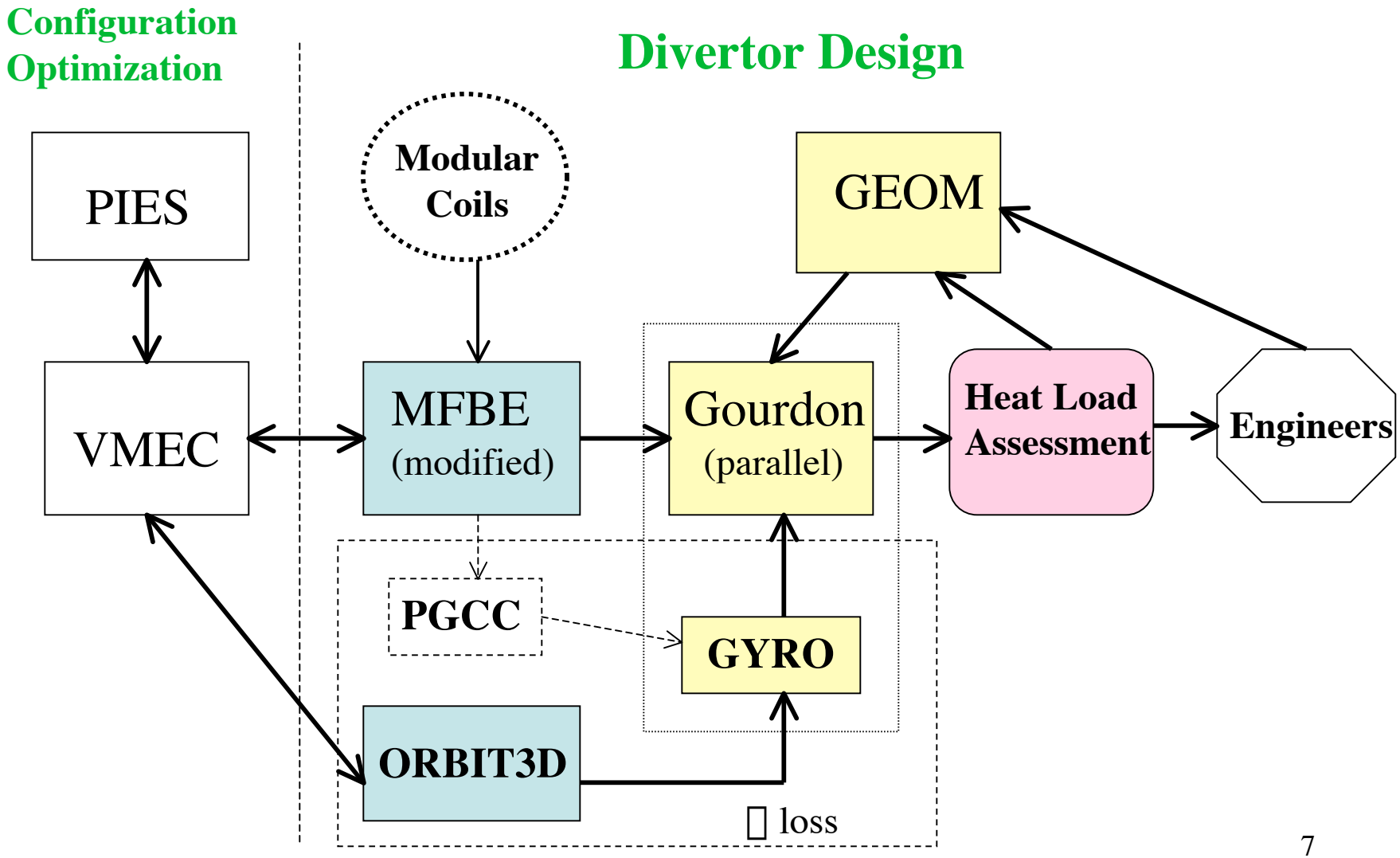
Tools for Divertor Design

- Because of the complex 3-D magnetic geometry, a suite of highly sophisticated computer codes are required to carry out the divertor design for the compact stellarator reactor:

  - **VMEC+MFBE** : Calculates magnetic field including finite-beta effects both inside and outside the LCMS.
  - **GOURDON** : Traces magnetic field lines inside and outside of LCMS.
  - **GEOM** : Establishes location and geometry of divertor plates and first wall.
  - **GOURDON/GEOM :** Determines (1) locations where field lines intersect the divertor plates and first wall, (2) angles of intersection and (3) field line lengths from LCMS to first wall.
  - A **suite of codes** to calculate the Fourier representation of first wall and plate surface topology.
  - A **suite of graphic routines** for displaying results.

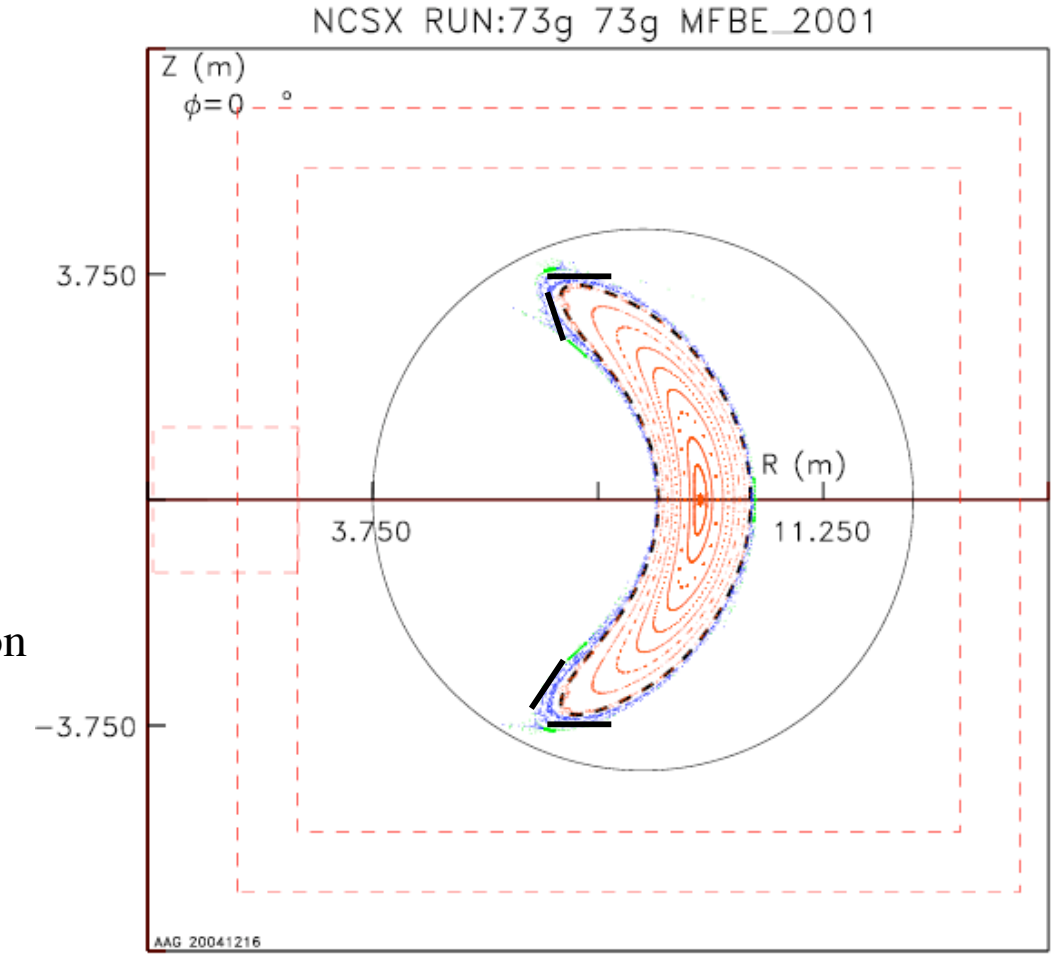
- MFBE, GOURDON, and GEOM are codes originated from Garching, Germany. [Erika Strumberger]

Divertor Design Strategy Flowchart



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

- Most desirable poloidal location: outside tips of crescent shaped plasma cross section at $\phi = 0^o$:
  - 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 intercepting divertor plates located there.



Heat Load Peaking Factor Evaluation

- Associate each field line *i* traced with a constant power value:
  $P = P_{cond} / N$, where N is number of field lines traced, and P_{cond} is the conduction power loss from plasma.
- Divide plate surface into a large number N_r of regions. Heat load contribution to each region *j* of divertor plate is $P \sin\theta_{ij} / A_j$, where θ_{ij} is field line inclination angle to surface, and A_j is region area.
- Sum up all field line (N_j) contributions to each region to obtain heat load distribution:

$$W_j = \sum_{i=1}^{N_j} P \sin\theta_{ij} / A_j$$

  Angle of intersection should be sufficiently small to spread the heat load over a large area, thus help lowering the peaking factor
- The peaking factor for each region Φ_j is then defined as

$$\Phi_j = \sum_{i=1}^{N_j} \sin\theta_{ij} / A_j \Big/ \sum_{i=1}^{N_r} \sum_{i=1}^{n_j} \sin\theta_{ij} / A_D$$

  and the overall peaking factor is: Φ **= Max** $\{\Phi_j\}$, for $1 \le j \le N_r$.

Parameters Used in Field Line Tracing

- **For this initial study phase,**

Number of field lines launched > 30,000

Field line launched location:

- At toroidal cross sections at every 30°
- At each toroidal cross section, launch locations are randomly distributed poloidally, and randomly placed in a 1-cm thick zone outside LCMS.

Diffusion coefficient used = 0.1 m^2/s

- to model cross-field transport of the heat flux

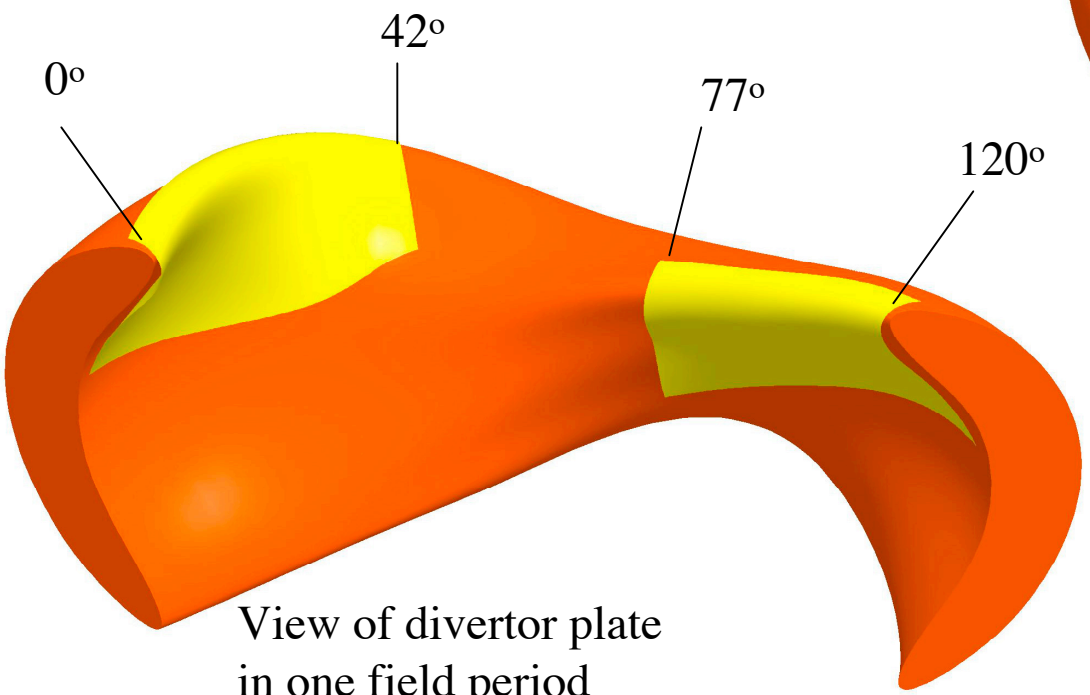
The target plate is divided into 1600 regions, with 40 divisions each in the poloidal and toroidal coordinates.

Initial Example of a Divertor Configuration

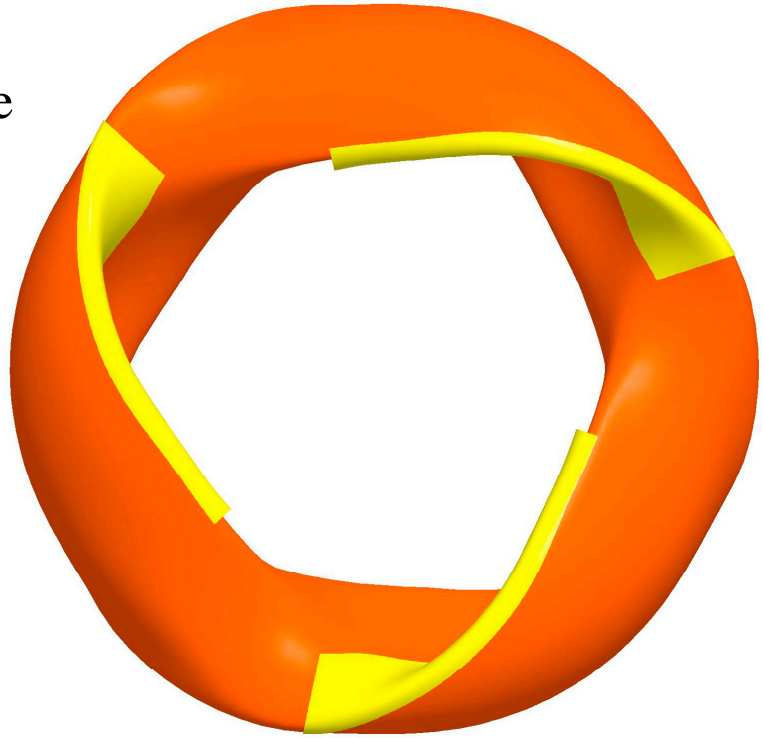
- Plate toroidal extent = 87°
  Plate poloidal extent ~ 20% of circumference

- Surface area per plate = 40 m^2
  As a comparison, LCMS area = 807 m^2

  Plasma coverage fraction = 15%.



View of divertor plate
in one field period

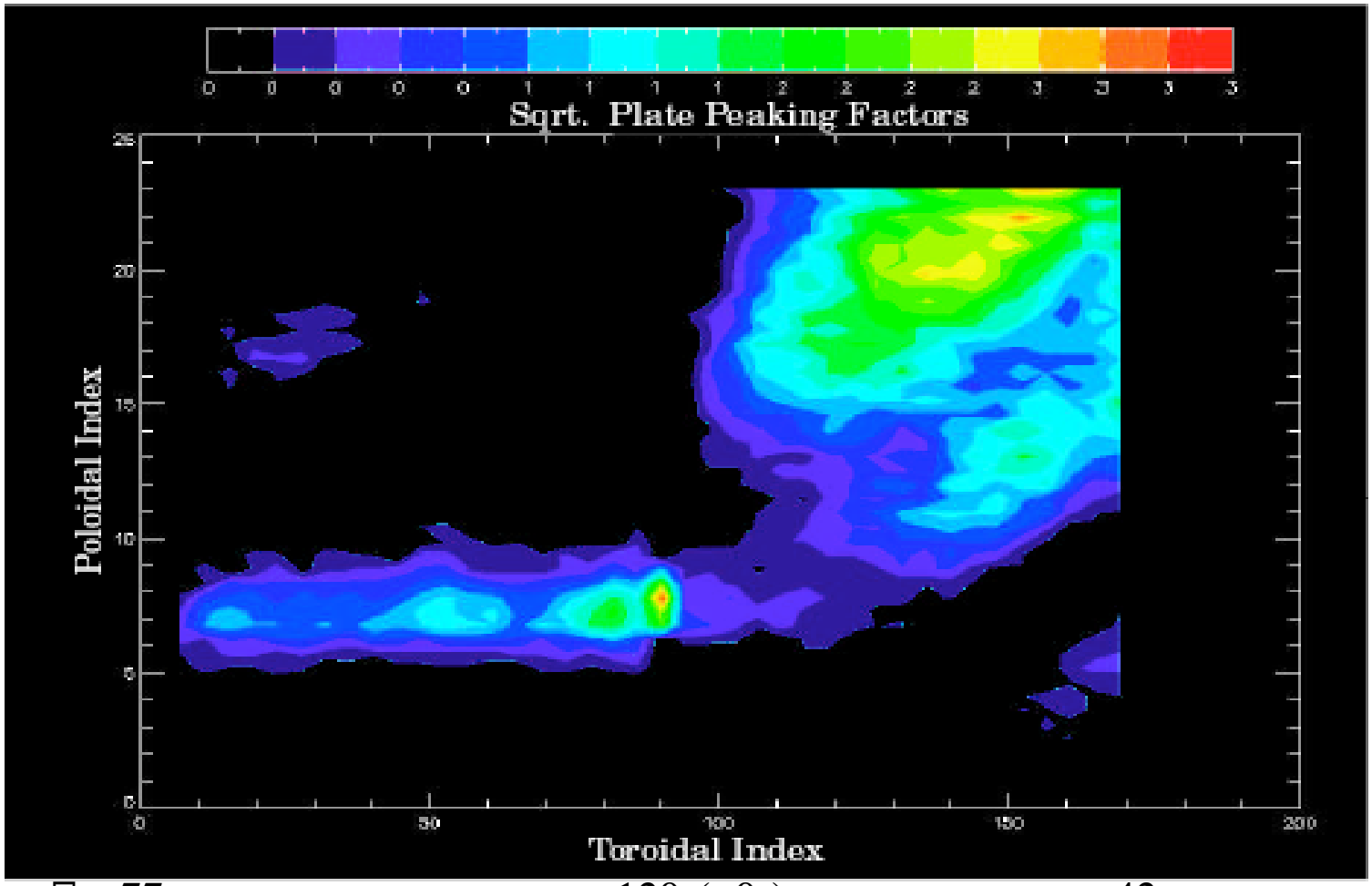


Divertor plates and plasma
viewed from bottom

Distribution of Peaking Factor on Divertor Plate

- Maximum peaking factor $\square$ = 14, found in two locations.
- Each unit in poloidal index corresponds roughly to 1% of circumference.
- Square root of $\square_j$ is shown in order to bring out the distribution details.

IB, top



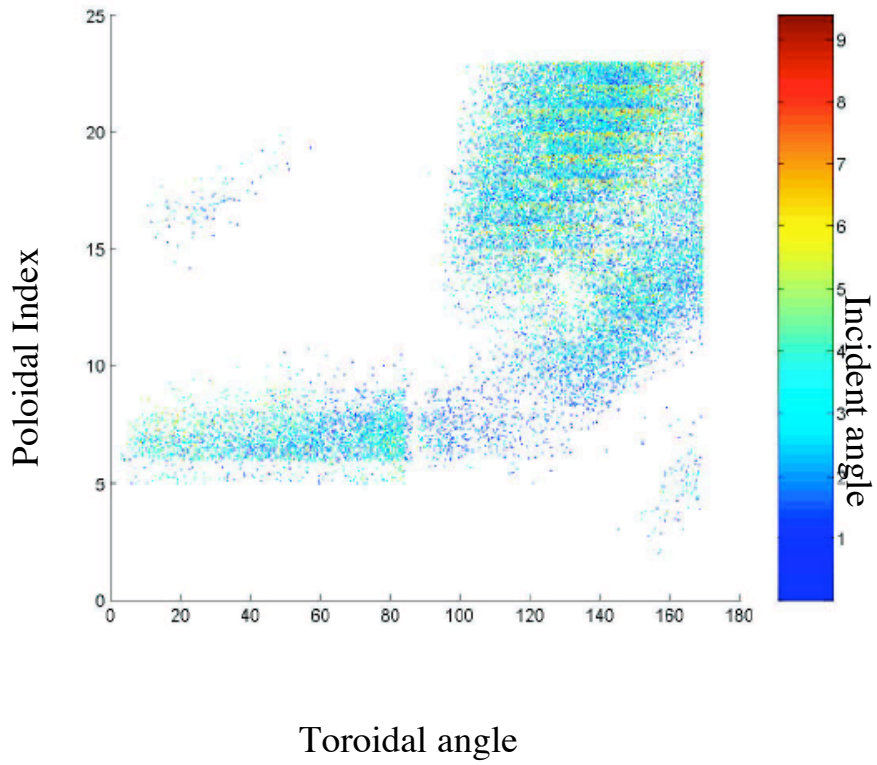
OB, bot.

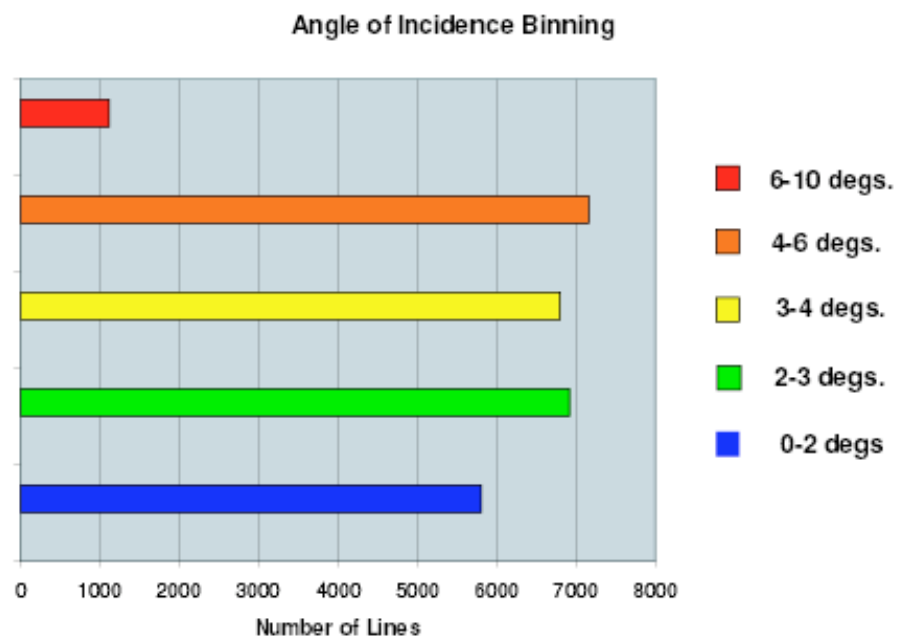
$\square$ = 77° 120°(=0°) 42°

Field Line Angle of Incidence is Small

- The angles of incidence of the lines to the plate are relatively small because the plate shape is roughly conformal to the LCMS.

Average angle of incidence = 3.3°
Highest angle of incidence = 9.9°

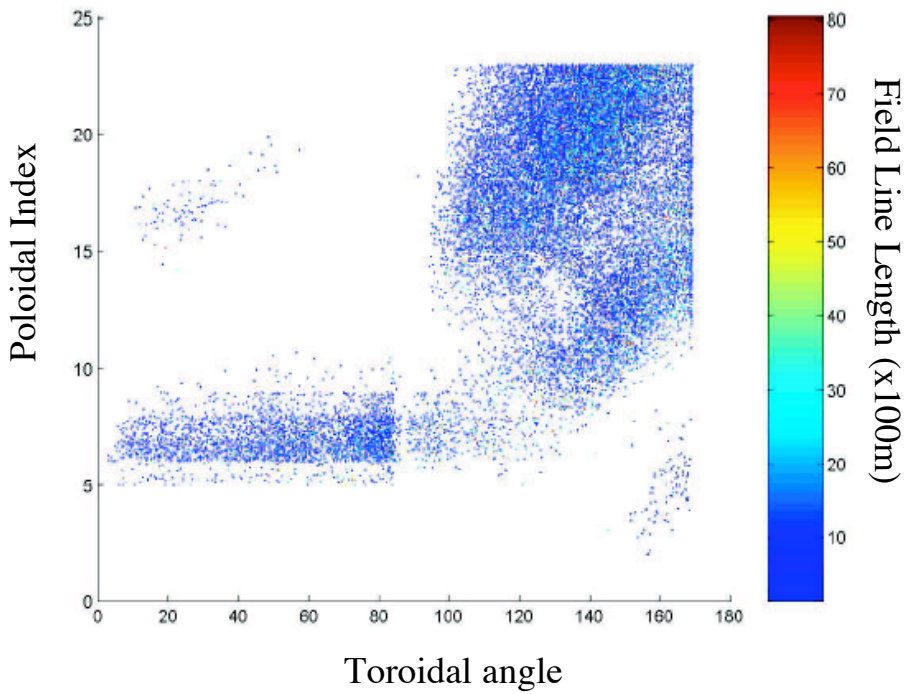


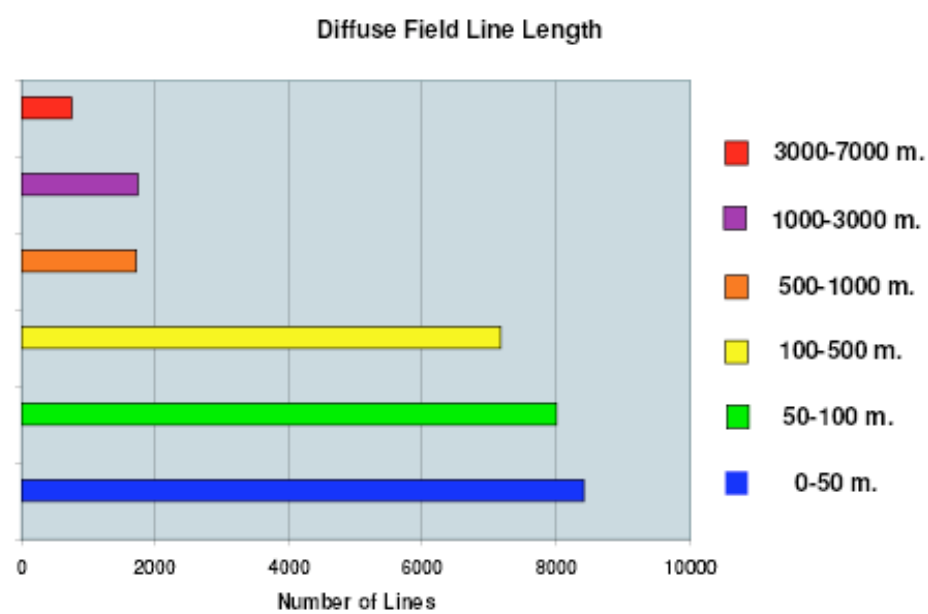


Field Line Length is Crucial in Determining SOL Parameters

- The averaged diffused field line length is found to be 356 m.

- A short field line length implies T is constant along field line from LCMS to target. A long field line length implies conduction dominates over convection along field line, with possible low T and high n near the target, leading to significant radiation near the target.



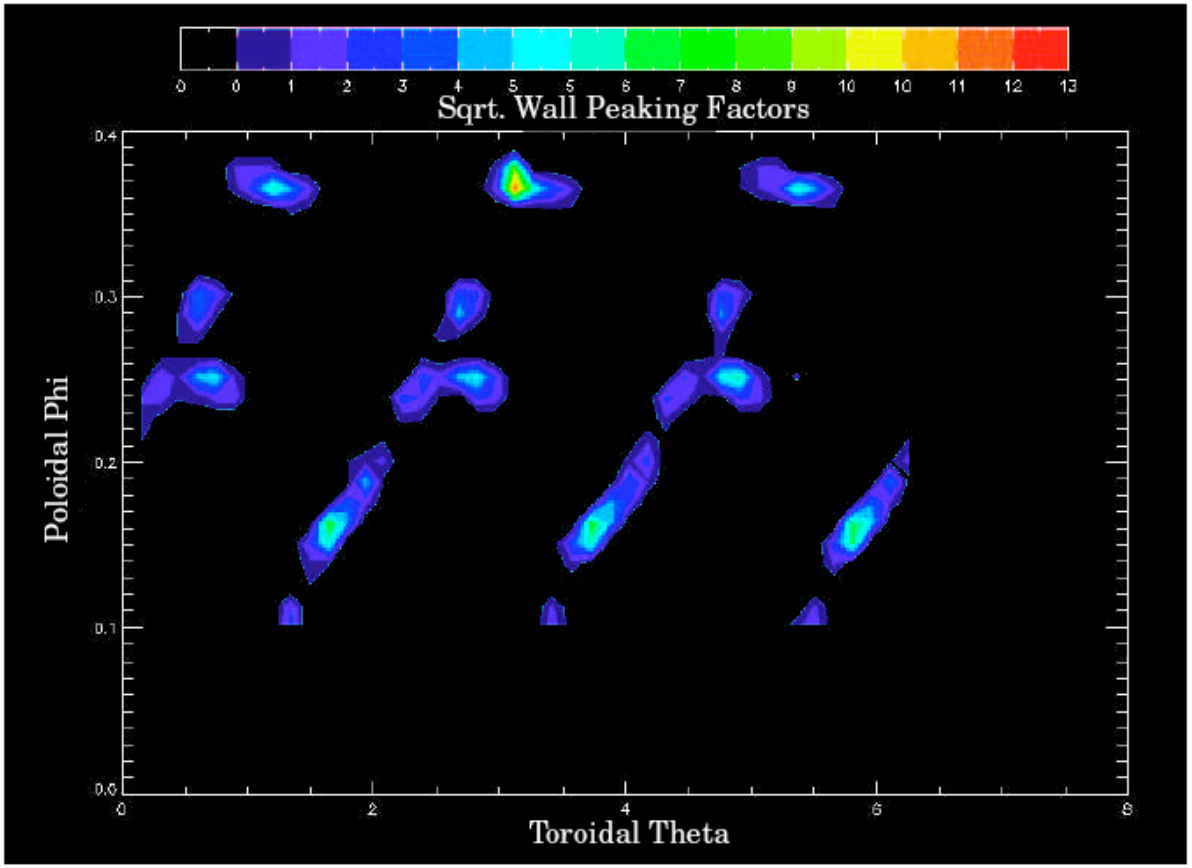


Some Conduction Power Reaches the Wall

- About 6.8% of the field lines miss the divertor targets and hit the first wall. The average LCMS-to-wall line length of 104 m implies many of these lines intersect the wall soon after leaving LCMS.

- The lines hit a very small fraction of the wall, with typical slanted periodic strips.

- Except for one anomalous peak likely due to non-convergence, the likely peaking factor is about 30.



Target Plate Configuration Needs Optimization

- With a load peaking factor of 14, the example target plates can handle a maximum of 86 MW incident power, in order to satisfy the 10 MW/m^2 peak heat load limit.

  The rest of the conduction power must be radiated in the divertor region.

- For the present plate configuration, heat load distribution is uneven, and the plasma surface coverage fraction is too large to maintain a tritium breeding ratio of 1.10.

- **Improvements in the plate location, size and surface topology are being studied using a more systematic approach.**

- Enhanced radiation in the core and in the divertor/SOL region will likely play important roles in the final design of the divertor system.

Assessment of Heat Flux due to Nonthermal Alpha Loss

- Due to non-axisymmetry of the magnetic topology in a stellarator, a significant magnetic field ripple is present along the flux surfaces in the plasma core.
  - → A significant fraction of fusion alphas are either born or "kicked" into orbits that are trapped in these ripples.
  - → Rapid outward diffusion and quick exit from the LCMS before they are thermalized.
  - → Hit PFCs (target plates, first wall), adding to the heat load and/or blistering of component surface materials.

- To study these effects, patterns of alpha particle strike points on the PFCs, including incident angles and energy spectrum, need to be calculated.

- To follow MeV alpha particles outside the LCMS, finite gyro orbits must be taken into account, because gyro radius ~ SOL width. The GYRO orbit code has been created for this purpose.

GYRO - A Single-particle Gyro-orbit Code

- The GYRO code directly solves the equation of motion

$$m_{\square}\frac{d\vec{v}_{\square}}{dt} = q_{\square}\left[\vec{v}_{\square} \square \vec{B}(\vec{r})\right]$$

in the presence of spatially varying magnetic field, and in the absence of collisions. Gyro-motion is included, as opposed to only drift orbits.

- In the cylindrical coordinates (r,□,z), the equation can be written in the form:

$$\frac{d\dot{r}}{dt} = \frac{q}{m}\left(r\dot{\square}B_z \square \dot{z}B_{\square}\right) + \frac{(r\dot{\square})^2}{r}$$

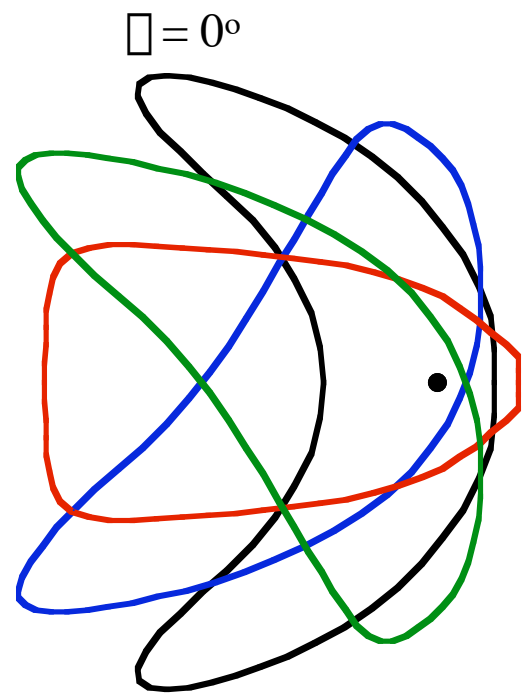
$$\frac{d(r\dot{\square})}{dt} = \frac{q}{m}\left(\dot{z}B_r \square \dot{r}B_z\right) \square (r\dot{\square})\frac{\dot{r}}{r}$$

$$\frac{d\dot{z}}{dt} = \frac{q}{m}(\dot{r}B_{\square} \square r\dot{\square}B_r)$$

where are solved with the standard Runga-Kutta method to h^4 accuracy.

Testing GYRO on a NCSX-based CS Magnetic Geometry

- GYRO was found to give well known results for circulating and trapped particle orbits in an axisymmetric tokamak geometry.



- GYRO is run on an NCSX-based compact stellarator configuration, with
  - $\langle R_o \rangle = 8.5$ m, $\langle A \rangle = 4.5$, $\langle \beta \rangle = 4\%$
  - Number of field periods = 3
  - 3D B-field grids generated by MFBE

- Initial conditions:

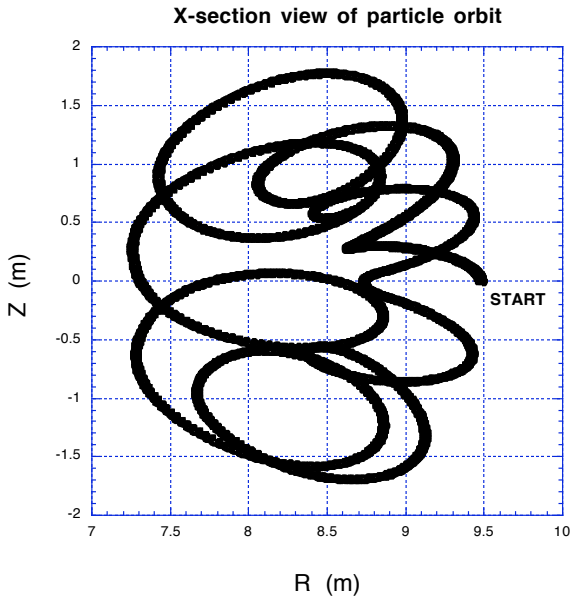
  particle energy E_o (= 3.5 MeV)

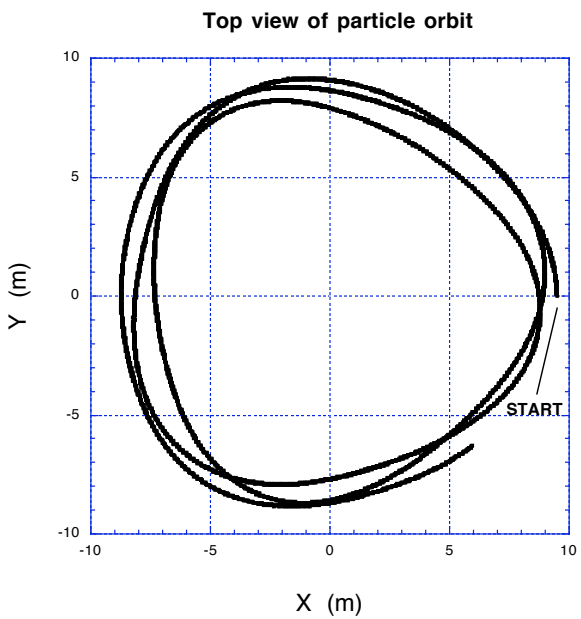
  toroidal velocity v_ϕ (> 0)

  velocity pitch $p = v_\phi / v_\parallel$

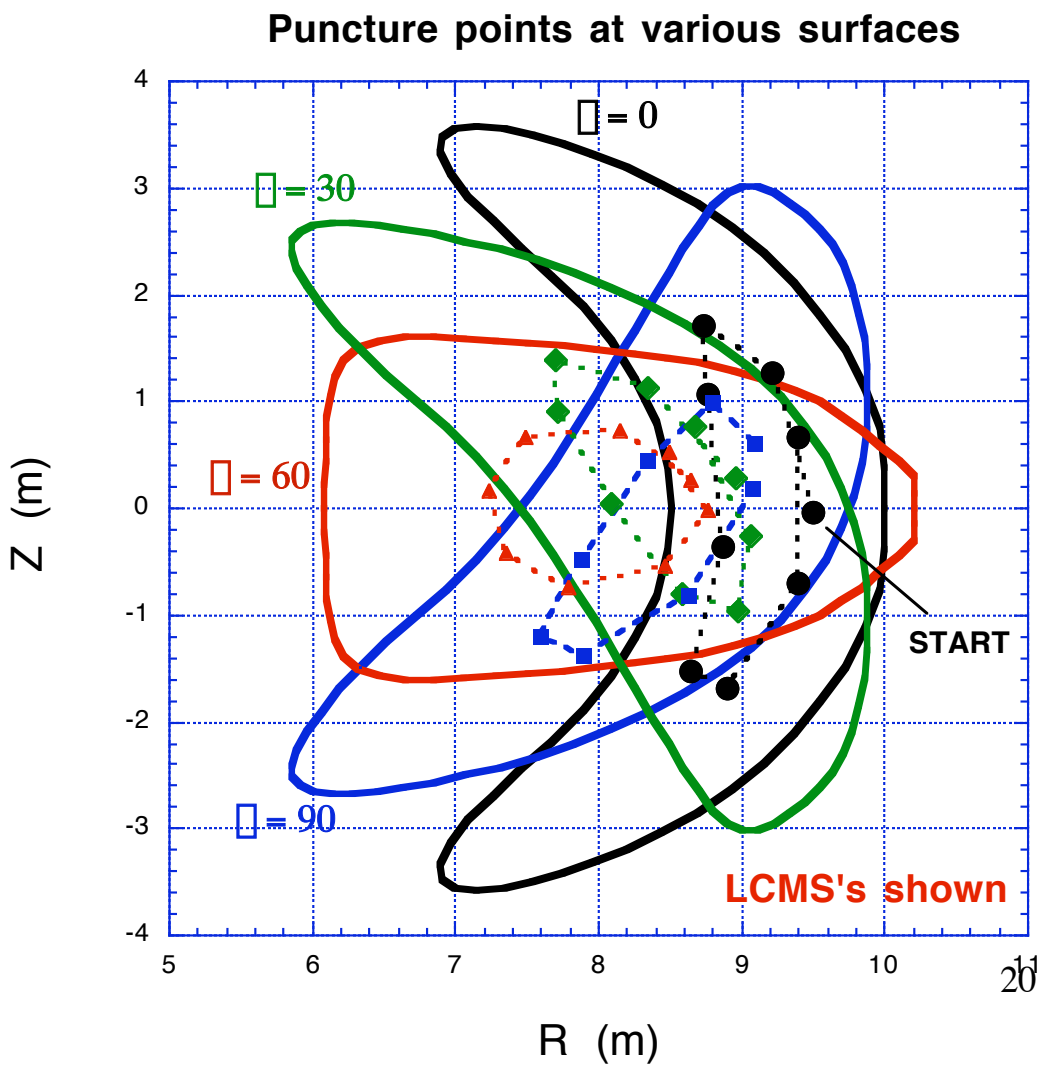
  starting location: R = 9.5 m, $\phi = 0.$, Z = 0 m. : on OB midplane

Particle Orbit with p = 1

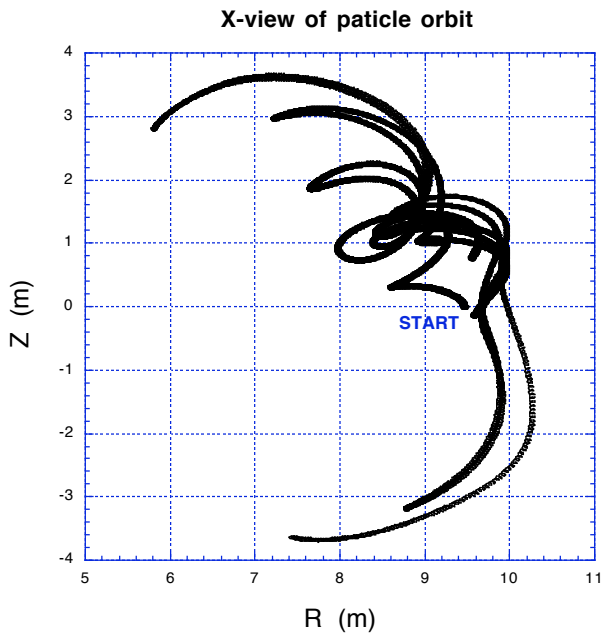


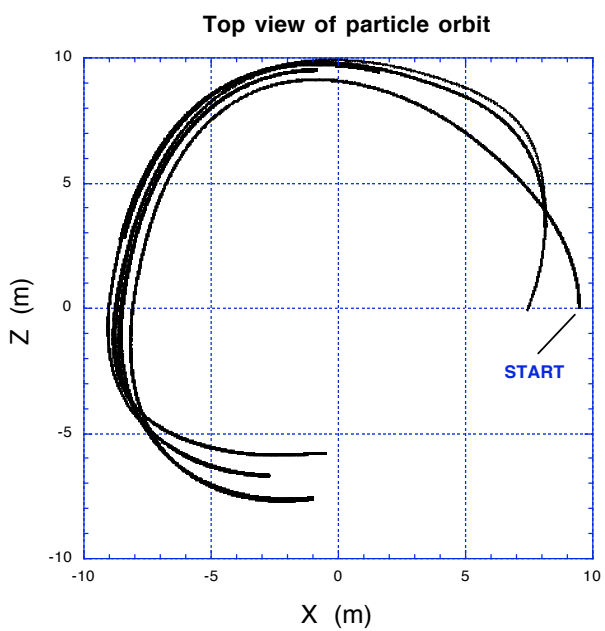


Particle appears to be circulating and confined to a closed flux surface.

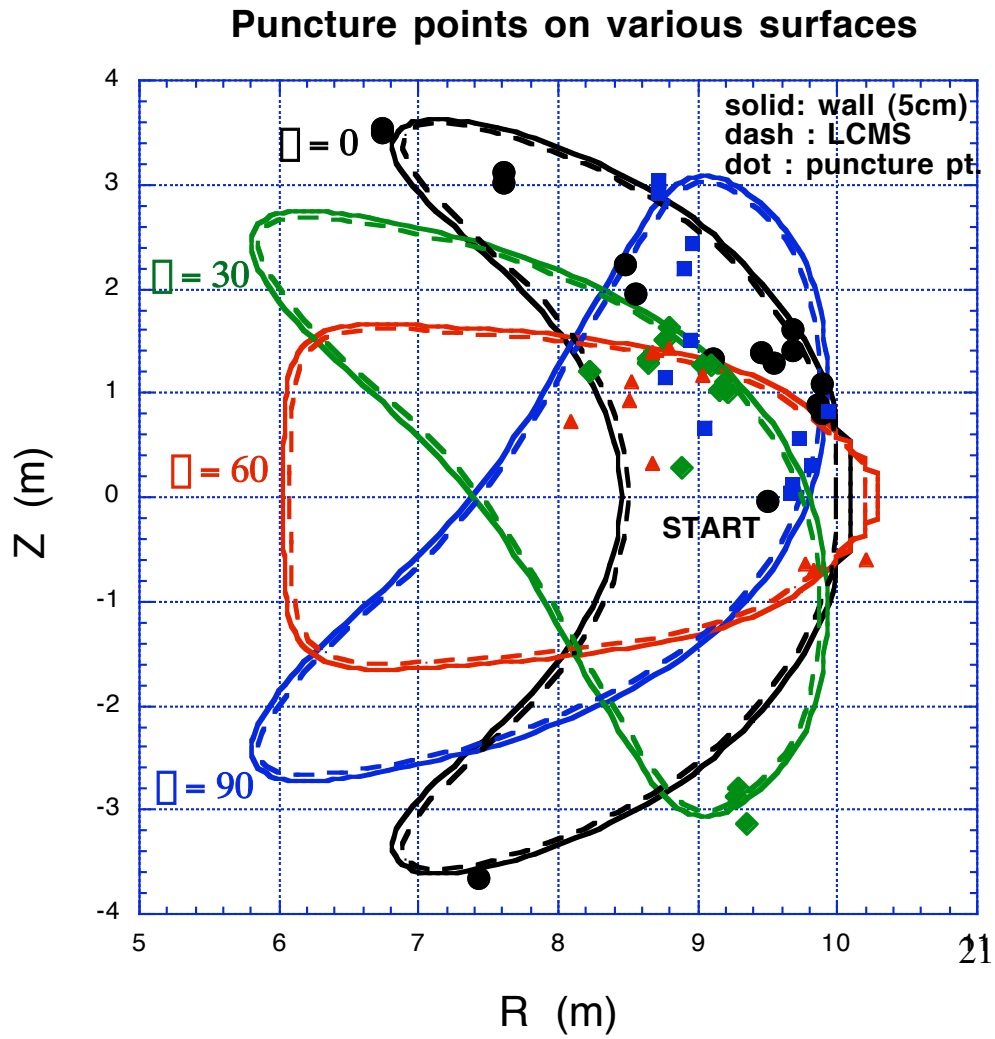


Following Particle Orbit with p = 5 to 1st Wall with 5 cm Offset

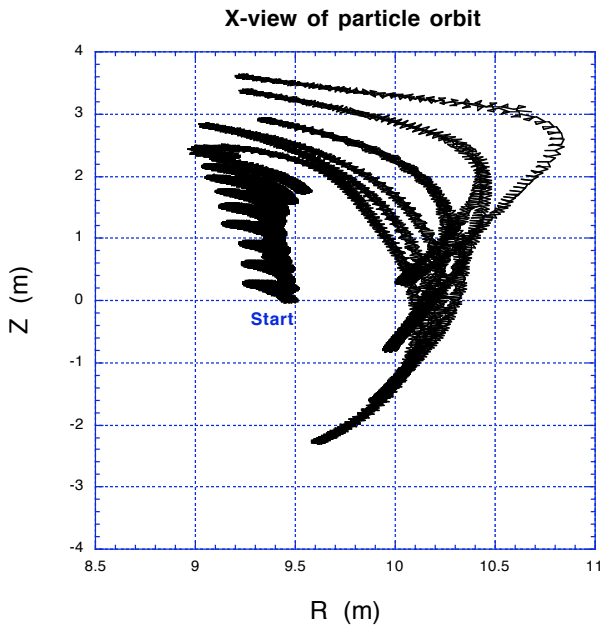


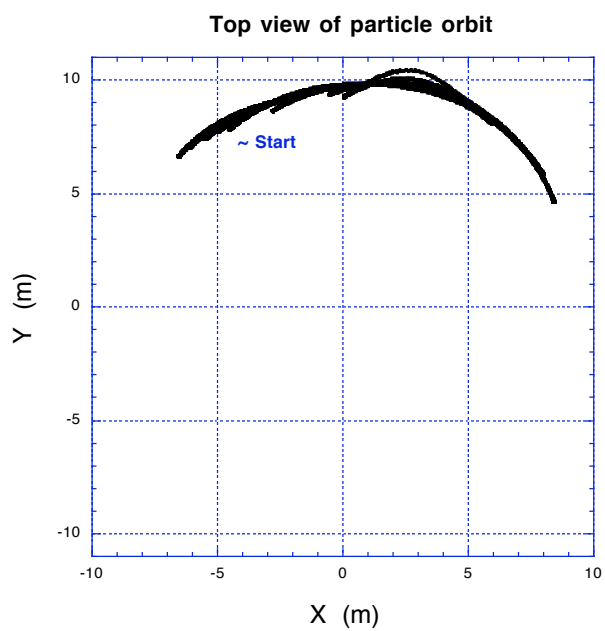


Particle is lost from plasma (LCMS) and hits first wall 5 cm away. Exact locations of loss and strike cannot be determined yet.

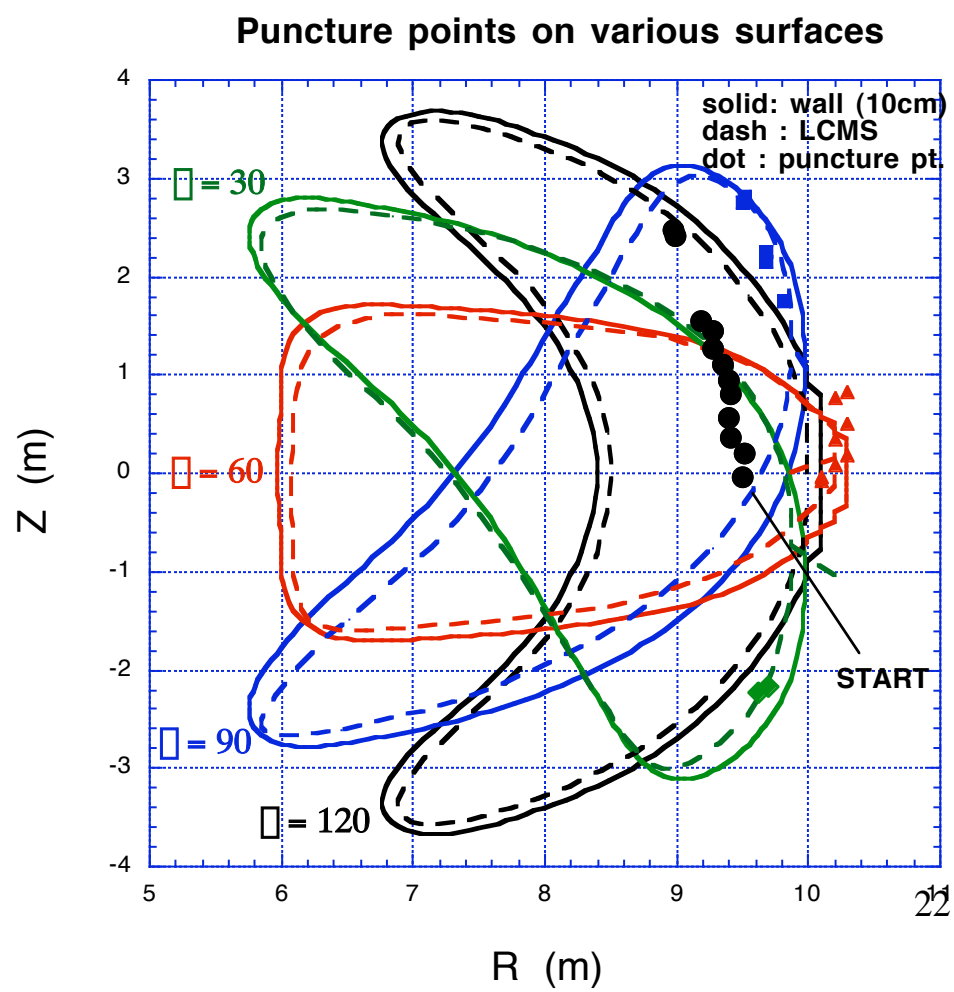


Following Particle Orbit with p = 10 to 1st Wall with 10 cm Offset





Particle appears trapped in a local ripple around $\phi = 120^o$, drifts upward, then trapped in magnetic well before exiting plasma and hitting 1st wall.



Alpha Heat Load Assessment is On-going

- In a typical CS configuration, GYRO reproduces particle orbits that are passing (confined) and trapped (unconfined), confirming that the code is reproducing results similar to those from ORBIT3D.

- As tracking gyro-orbits for energetic α's inside plasma is computationally time-consuming, GYRO is best used in the SOL region where finite gyro-radius effect is important.

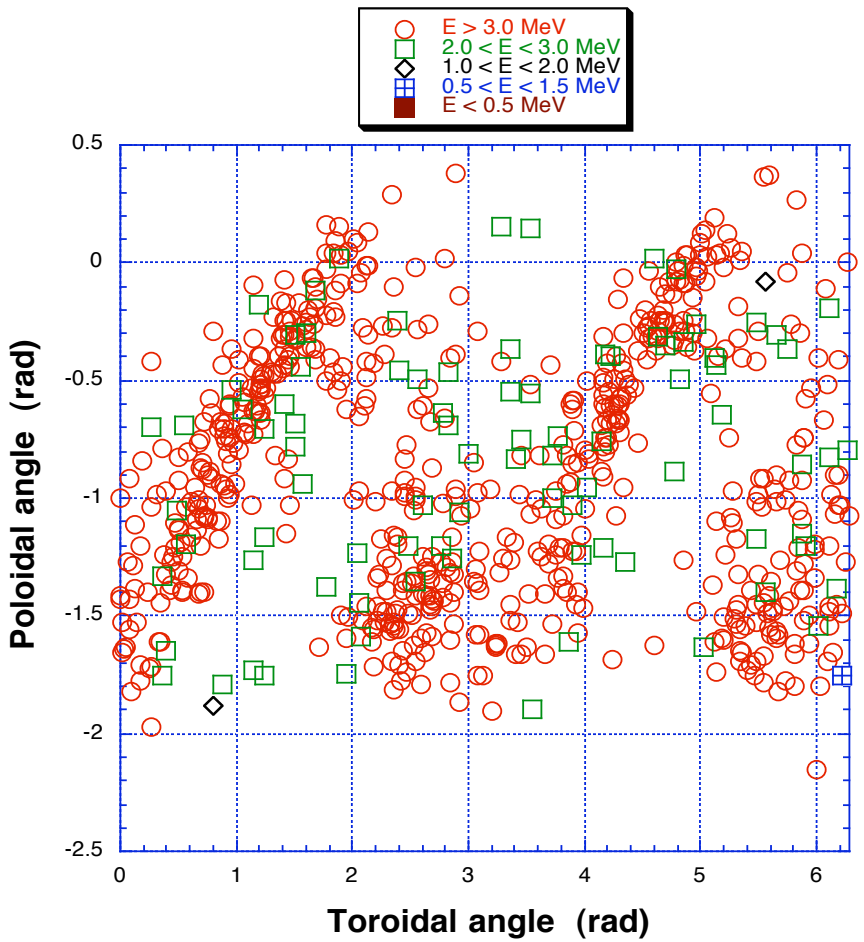
- The code is being incorporated into the GOURDON/GEOM code:

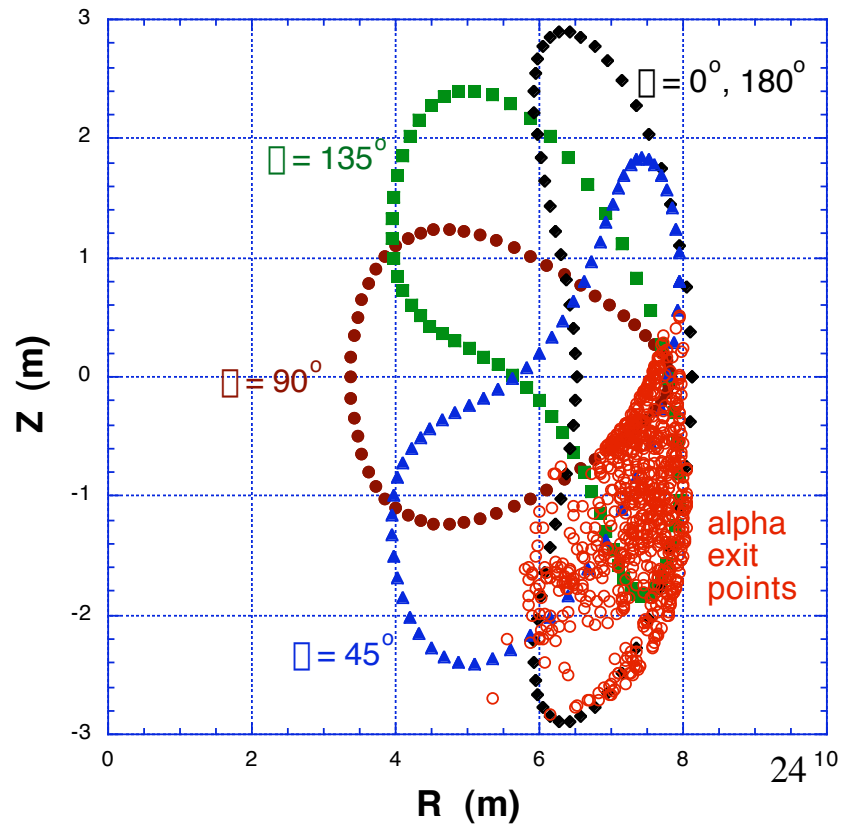
  – to use results from drift orbit calculations inside the plasma (ORBIT3D) to start full gyro-orbit tracking (GYRO) when the particle passes the LCMS.

  – to take advantage of the intersection algorithm inside GOURDON to determine the strike points on the target plates and the first wall.

Typical Alpha Exit Points on LCMS

- For this MHH2 case, the □ footprint has the periodic pattern of slanted strips.
- Most of the □'s exit the LCMS in the lower right-hand quadrant.





Summary

- Edge particle and heat flux control is an important issue for the ARIES-CS study.

- To handle the conduction loss, an example divertor configuration has been obtained for a 3-FP compact stellarator reactor magnetic geometry. It has a calculated heat load peaking factor of 14 and covers 15% of the plasma surface area, to satisfy a peak heat load limit of 10 MW/m^2. It can handle at most 86 MW of incident power.

- This divertor is clearly not optimal. Efforts are on-going to optimize the divertor geometry to achieve lower peaking factor and lower surface area coverage.

- The effect of energetic alpha particles hitting the PFCs is also an important issue.

- We have developed the GYRO code to follow these particles outside the LCMS. We will use GYRO, together with GOURDON/GEOM, to assess the contribution of energetic alphas to the heat load on the divertor targets and the first wall.