

AN UPDATE on DIVERTOR DESIGN and HEAT LOAD ANALYSIS

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OUTLINE

- Divertor design criteria, tools, etc.
- Results of an example divertor design
 - Target plate geometry
 - Peaking factor, line incident angle, line length
 - Example of projected peak heat load
- A short update of alpha heat load studies
- Summary and future work

Divertor Design Criteria

- The divertor is conceived to consist of a number of plates around the torus between the plasma LCMS and the first wall, at some distance from the plasma to prevent impurity influx from the edge.
- The divertor plates mainly intercept heat flux escaping from the plasma, and help remove the collected heat.
- For the divertor to survive in this environment, the major design criterion is :

$$P_{\text{div}} / A_D < W_{\text{pk}} / \square$$

where P_{div} is power reaching divertor plates, A_D is total plate area, W_{pk} is peak heat load and $\square$ is the heat load peaking factor.

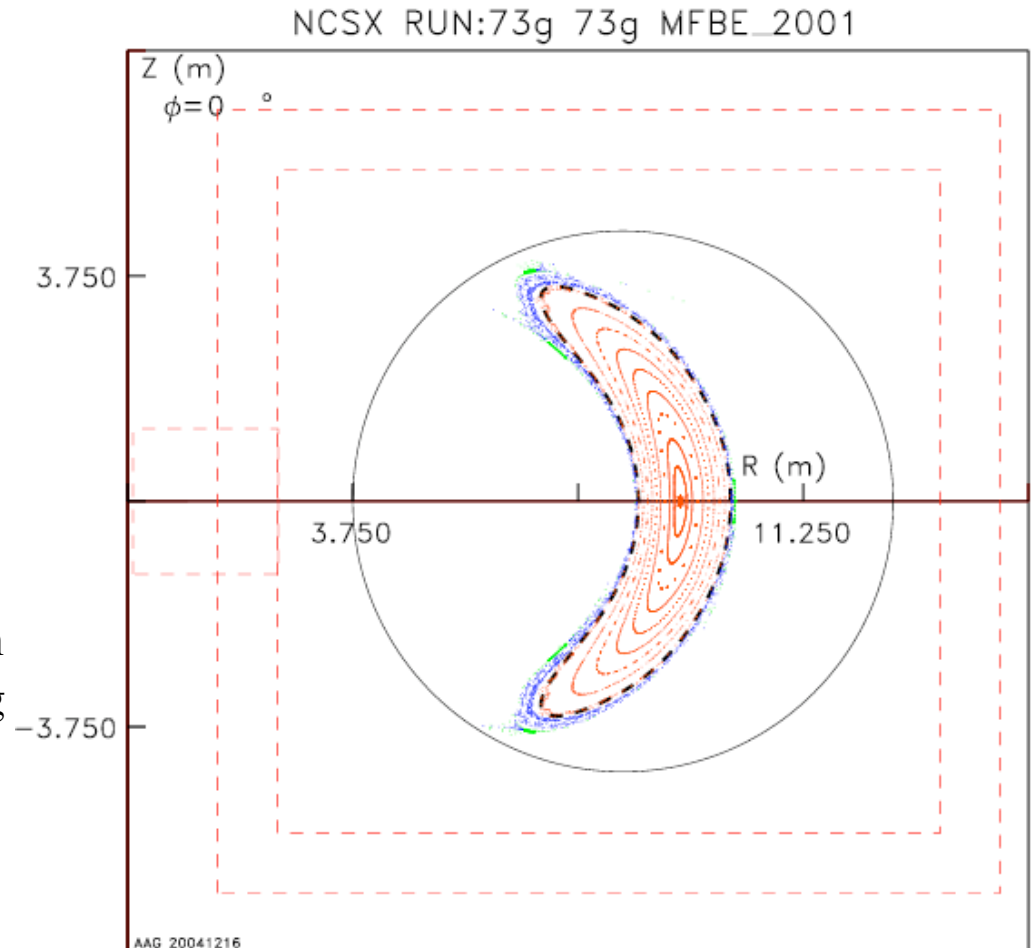
- Since W_{pk} is a fixed engineering limit, designing a divertor plate (location and surface topology) with the lowest possible $\square$ is of critical importance to allow the divertor to handle high heat with the least amount of high Z plate material.
- On the other hand, P_{div} can be lowered by higher core and SOL radiation, and perhaps lower alpha particle loss.

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.

Poincare 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 $\phi = 0^\circ$:
 - 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:
 $P = P_{\text{cond}} / N$, where N is number of field lines traced, and P_{cond} is the conduction power loss from plasma.
- Heat load contribution to incremental area j of divertor plate:
 $P \sin \alpha_{ij} / \Delta A_j$, where α_{ij} 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:

$$W_j = \sum_i P \sin \alpha_{ij} / \Delta A_j$$

Angle of intersection α_{ij} should be as small as possible to spread the heat load over a larger area, thus help lowering the peaking factor

- The peaking factor for each incremental area Δ_j is then defined as

$$\Delta_j = \sum_i \sin \alpha_{ij} / \Delta A_j \bigg/ \sum_j \sum_i \sin \alpha_{ij} / \Delta A_j$$

and the overall peaking factor is: $\Delta = \text{Max} \{\Delta_j\}$.

Parameters Used in Field Line Tracing

- **For the latest design phase,**

Number of field lines launched $> 30,000$

Field line launched location:

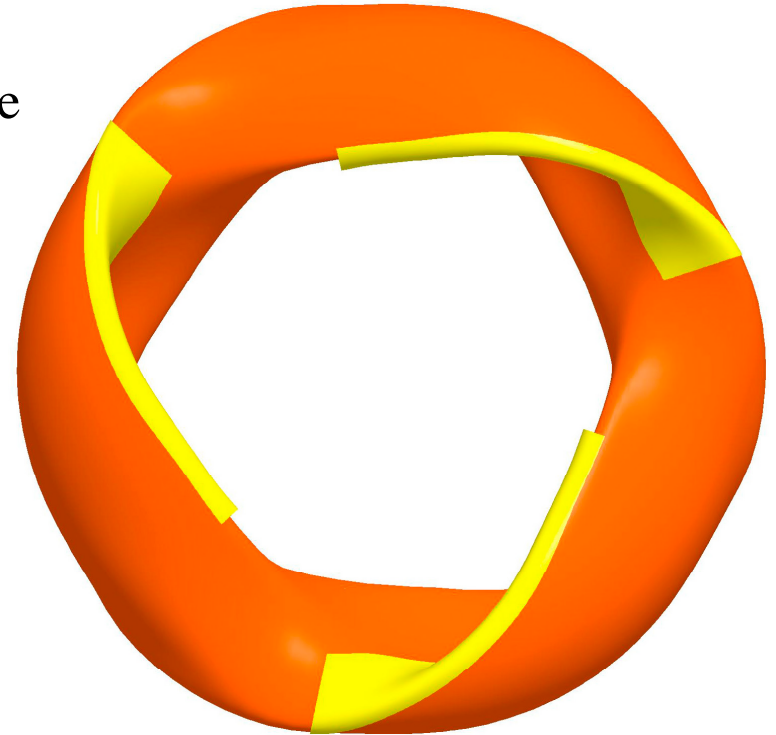
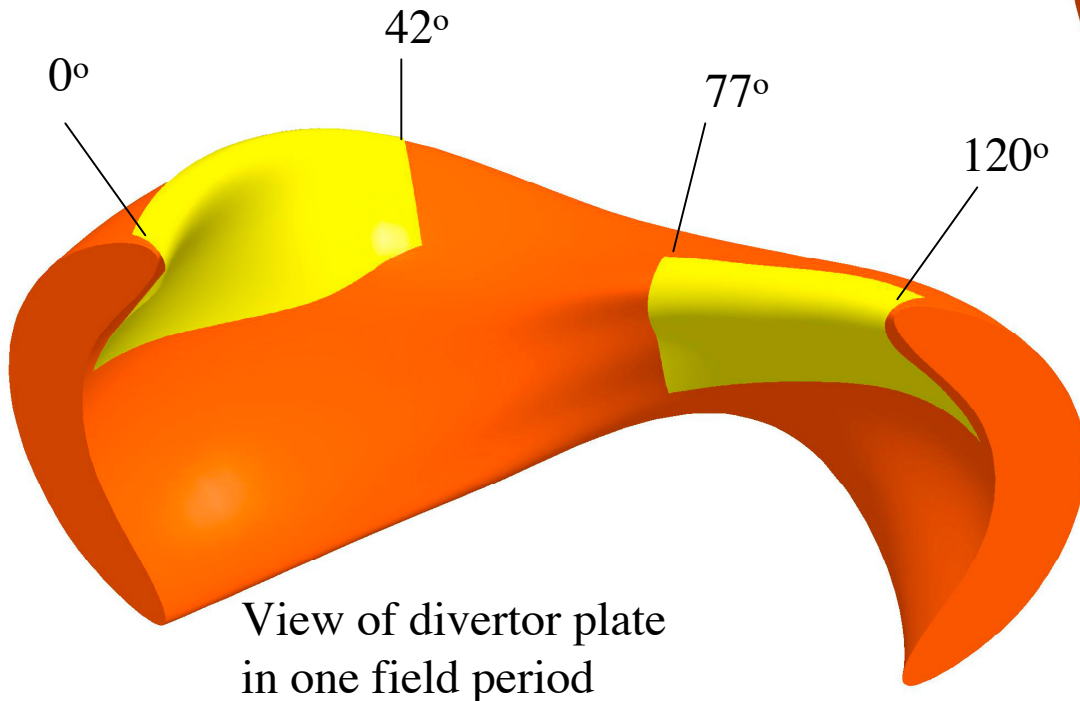
- At toroidal cross sections at every 30°
- At each toroidal cross section, launch locations are randomly distributed poloidally, and randomly placed between 0 and 1 cm. outside LCMS.

Diffusion coefficient used $= 0.1 \text{ m}^2/\text{s}$

- to “mimic” cross-field transport of the heat flux

Divertor Design Result

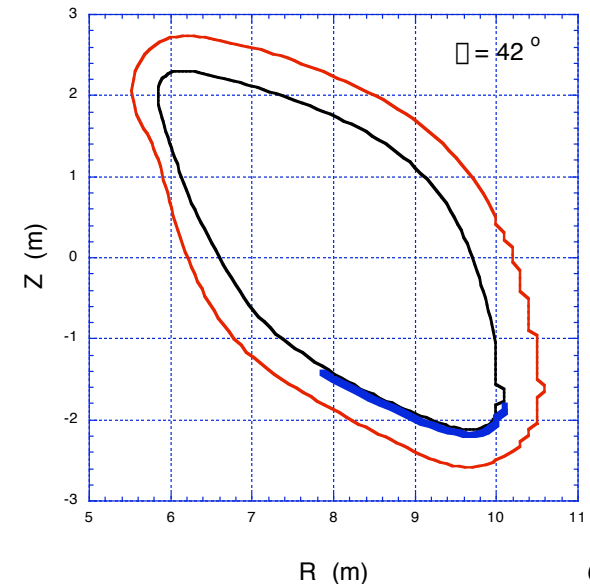
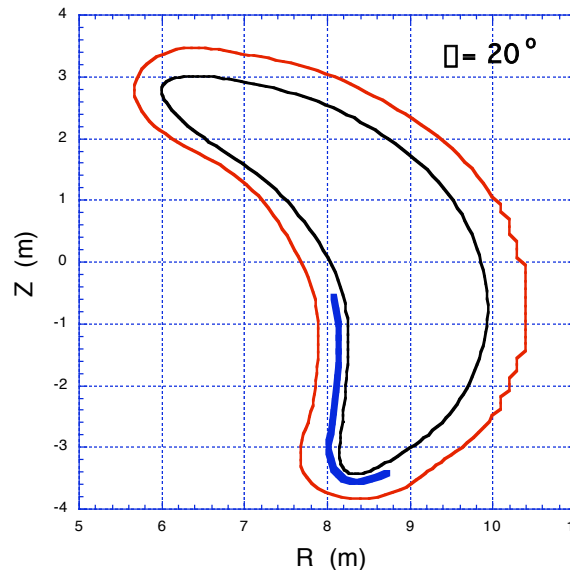
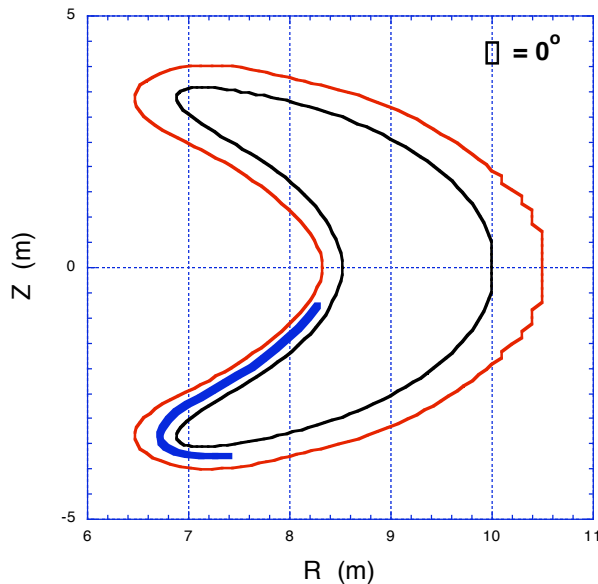
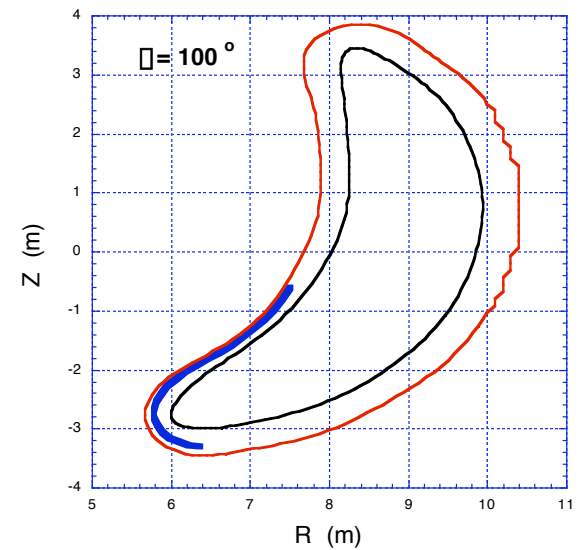
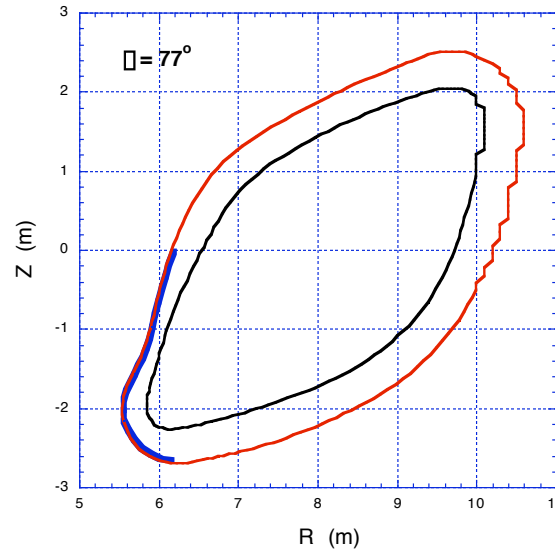
- Plate toroidal extent = 87°
Plate poloidal extent $\sim 20\%$ of circumference
- Surface area per plate = 40 m^2
As a comparison, LCMS area = 807 m^2
Plasma coverage fraction = 15% .



Divertor plates and plasma viewed from bottom

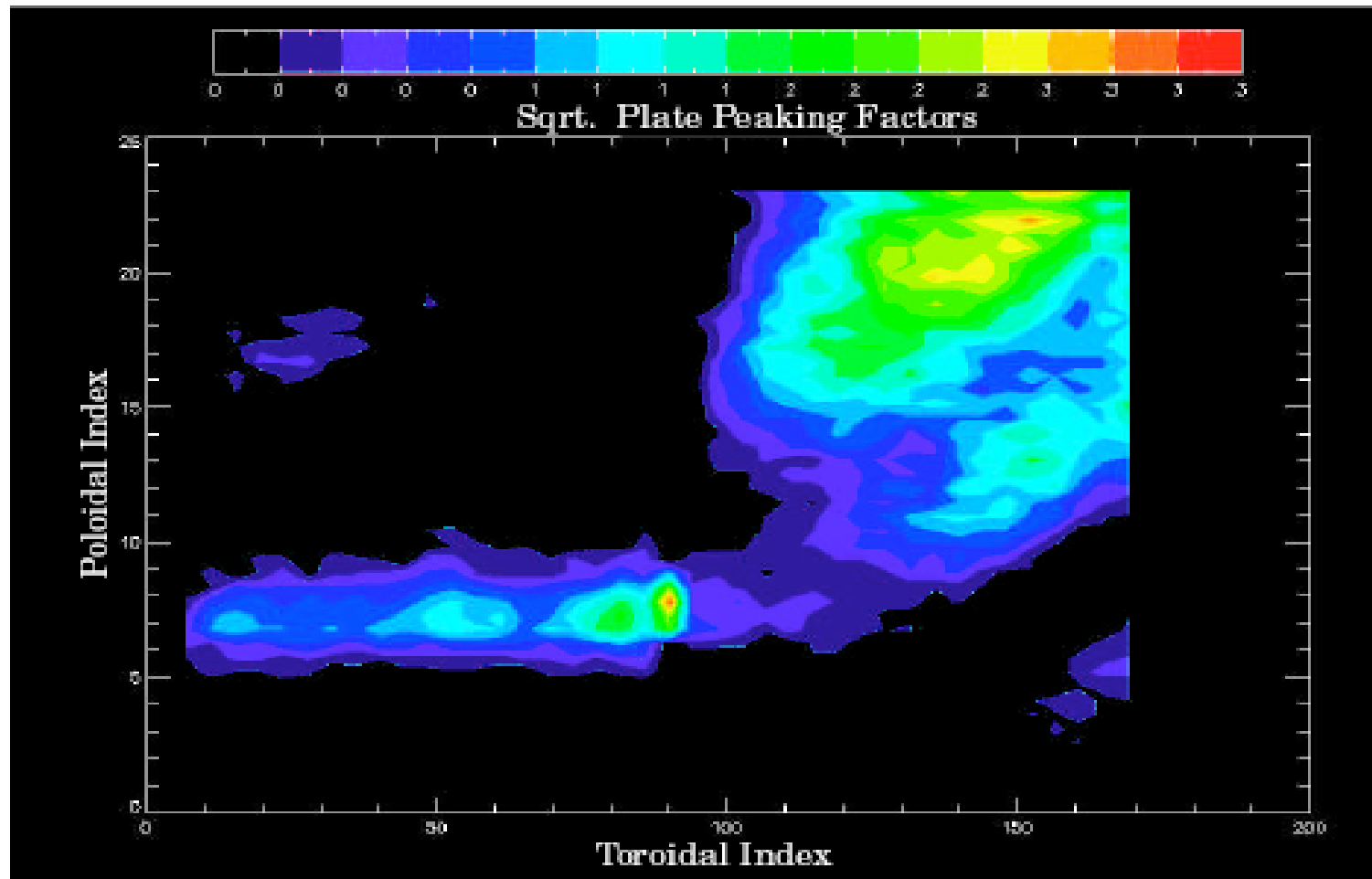
Plate Profile Roughly Conformal to LCMS

- Plate is conformal to LCMS at each toroidal plane, to ensure shallow intersection angle.
- Plate has asymmetric tilt to LCMS in toroidal direction to ensure maximum field line capture.



Distribution of Peaking Factor on Divertor Plate

- Maximum peaking factor $\square = 14$, in two locations.
- There are 40 sections in toroidal and toroidal coordinates, a total of 1600 regions.
- Each unit in poloidal index corresponds roughly to 1% of poloidal circumference.



Additional Comments on Peaking Factor Evaluation

- An extensive analysis was carried out to determine heat load peaking factor. The main issue are the optimum size of the regions for the plate and the number of field lines traced where the value of $\square$ converges.

These have been determined to be:

Number of sections in toroidal direction = 40

Number of sections in poloidal direction = 40

Number of field lines traced = 30,000

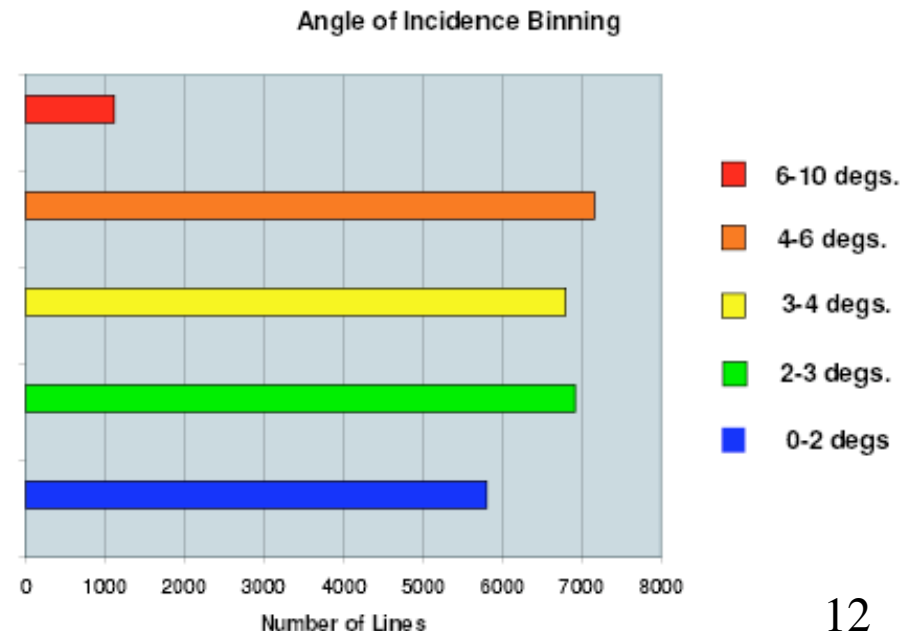
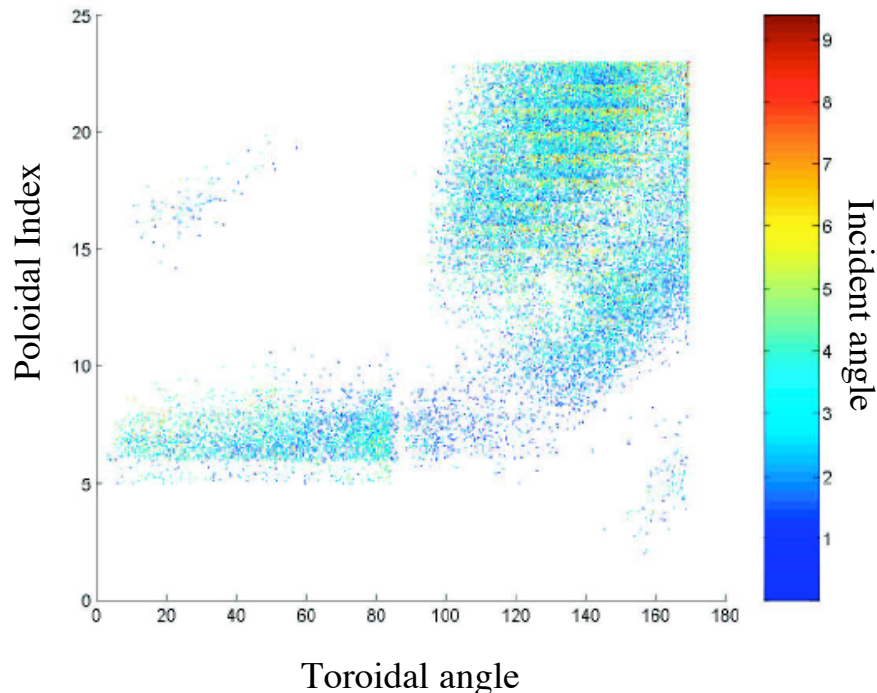
- Roughly one quarter of the plate surface, in the upper part of the first half, intercept little or no field lines. The part can presumably be removed without affecting its performance, thus lowering the coverage fraction.

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.

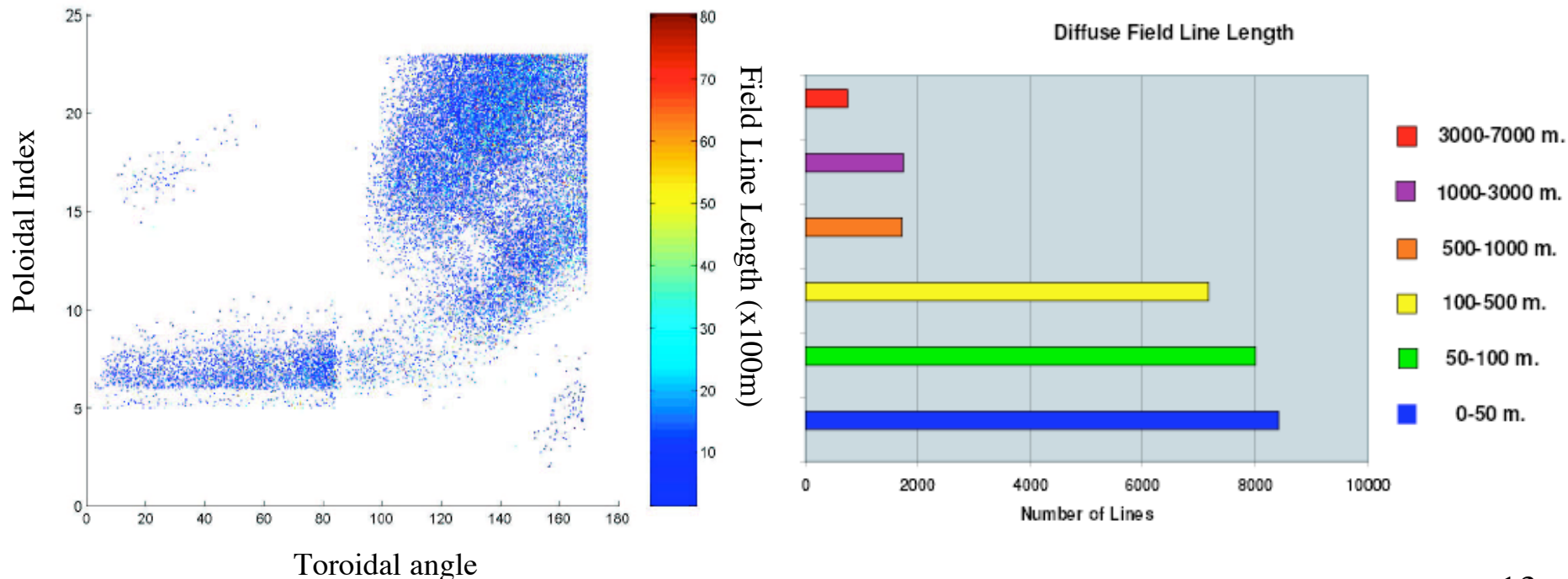
Average angle of incidence = 3.3°

Highest angle of incidence = 9.9°



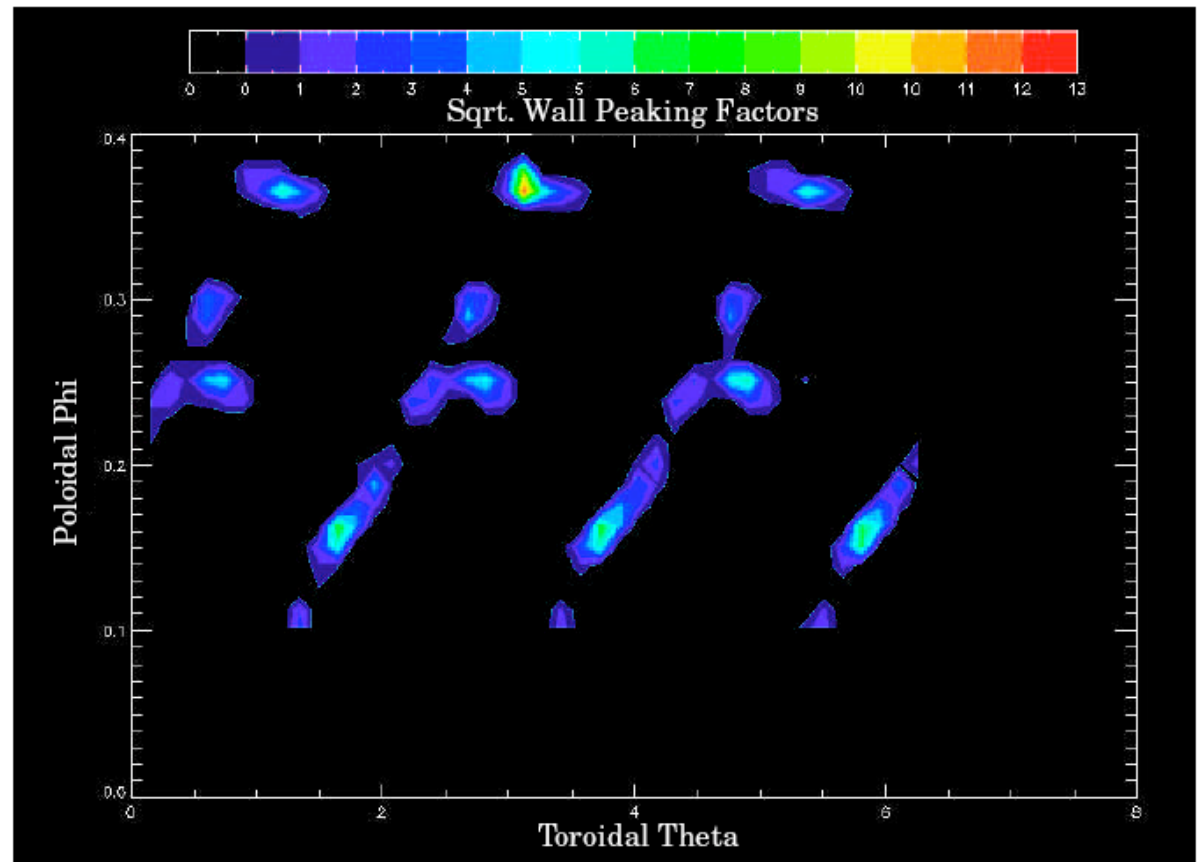
Field Line Length is Crucial in Determining SOL Parameters

- 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, implying low T and high n are possible near 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.



Example of Projected Peak Load

- For the present divertor design, what might be a typical peak heat load for a CS reactor?
- Using recent parameters from the systems code,
 - Alpha power = 450 MW
 - Alpha loss fraction = 10%
 - Core radiation fraction = 0.5
 - Fraction of field lines captured by divertor plates = 93%
 - Total plate area = 120 m²
 - Plate peaking factor = 14
 - Calculated peak heat load = 22 MW/m², which is more than twice the engineering limit of 10 MW/m².
- This implies that a semi-detached operation of the divertor may be required to radiate more than half of the conduction power in the divertor region before it reaches the target plate.
Core radiation can also be increased by setting up a radiative mantle.

Issues for the GOURDON/GEOM Code

- The GOURDON/GEOM code is still undergoing test as the divertor design is being developed. There are three issues that still need to be addressed.
- An error in the code causes a few % of the lines to “leak” through the target plate, without registering the strike points. Presently these points are simply thrown out.
- Another error causes strike points with $\pm 0.5^\circ$ of a period boundary, at $\varphi = 0, 120$ and 270° , to be determined incorrectly. Presently, such field lines are simply re-launched, causing a lack of data near the boundaries.
- The implementation of cross-field diffusion in the code must be carefully re-examined, as it has a much stronger effect on field line distribution on the plates and wall than indicated in previous studies (W7-AS, NCSX).

Present Status of Alpha Particle Heat Flux Evaluation

- In our previous meeting, we showed that GYRO reproduces particle orbits that are passing (confined) and trapped (unconfined), indicating that the code is working according to physics prediction.

The lost alphas are followed until they pass beyond the first wall. But details of the strike points (location, incidence angle, etc.) were not calculated.

- Shortly afterward, McGuinness (RPI) ported the GOURDON/GEOM code to UCSD. One purpose is to incorporate GYRO into the code to follow the alpha particles outside the LCMS, and to make use of the intersection algorithm inside GOURDON to determine the strike points on the target plates and the first wall.
- Apparently this task is a bit too ambitious to produce useful results within 2-3 months' time with the resources available at UCSD. Presently, a useful level of familiarization with GOURDON/GEOM has been achieved, and the process of incorporation of GYRO into the code is on-going.

Summary

- An example divertor design has been achieved for a 3FP compact stellarator reactor magnetic geometry.
 - This divertor system consists of three target plates roughly conformal to the LCMS, covering $\sim 15\%$ of the surface area.
 - A field line tracing code is used in the design. About 93% field line capture is obtained, with averaged incidence angle of 3.3 degrees. A power load peaking factor of 14 is obtained.
 - For a typical set of reactor parameters, the peak heat load of 22 MW/m^2 is obtained as compared to the engineering limit of 10 MW/m^2 . This means a semi-detached mode of operation is required to radiate $>50\%$ of of conduction heat loss in the divertor region.
- The incorporation of GYRO into GOURDON/GEOM is on-going, for purpose of calculating the contribution of energetic alphas to the heat load on the divertor targets and the first wall.

Future Work

- Further optimize the present design of the divertor adjusting the shape of the plate surface and by changing toroidal and poloidal extent of the plate.
- Address the three listed issues on GOURDON/GEOM, particularly the effect of diffusion on field line evolution.
- Calculate alpha particle exit points on LCMS for example 3FP finite beta equilibrium with favorable loss fraction.
- Finish the incorporation of GYRO into GOURDON/GEOM, and determine heat load distribution on divertor plates and the first wall.