Overview and Progress on Divertor Heat Load Assessment and Design

T.K. Mau
University of California, San Diego
H. McGuinness (RPI), A. Grossman, X. Wang, R. Raffray (UCSD)
L.P. Ku (PPPL)

ARIES-CS Project Meeting

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Outline

- Divertor Assessment : Objectives, Tools and Strategy
- Work Plan : Task List, Deliverables, and Milestones
- Re-assessment of alpha particle heat load on LCMS using particle exit locations in real space
- Summary and future work

Objectives of Divertor Assessment

- To develop a divertor concept for the compact stellarator reactor [island, ergodic, swept, radiative, gas target, etc.]
- To determine the location of the divertor plates and other plasma facing components for a reference CS configuration
- To evaluate the heat load distribution on the divertor and and PFCs due to thermal and alpha particle fluxes
- To design the divertor to satisfy both physics requirements and engineering constraints

Tools for Divertor Assessment

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

- In addition to thermal heat flux, supra-thermal alpha particle loss also needs to be considered, which entails a separate set of computations.

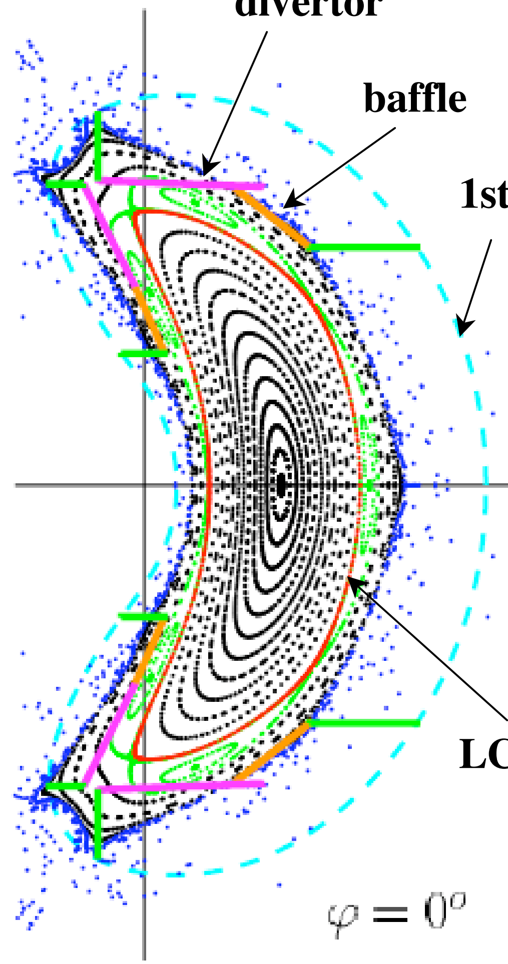
- A list of existing and modified codes to be used:
  - **PIES + VMEC** : Optimizes CS magnetic and plasma configuration
  - **MFBE** : Calculates magnetic field for finite-beta equilibrium
  - **Gourdon** : Traces magnetic field lines inside and outside of LCMS
  - **GEOM** : Establishes location and geometry of divertor plates and PFCs
  - **ORBIT3D** : Determines energy spectrum and exit points on LCMS of lost alpha particles

- Code(s) to be created:
  - A **post-processor** to Gourdon to calculate heat load distribution on divertor plates and PFCs

Strategy for Divertor Design

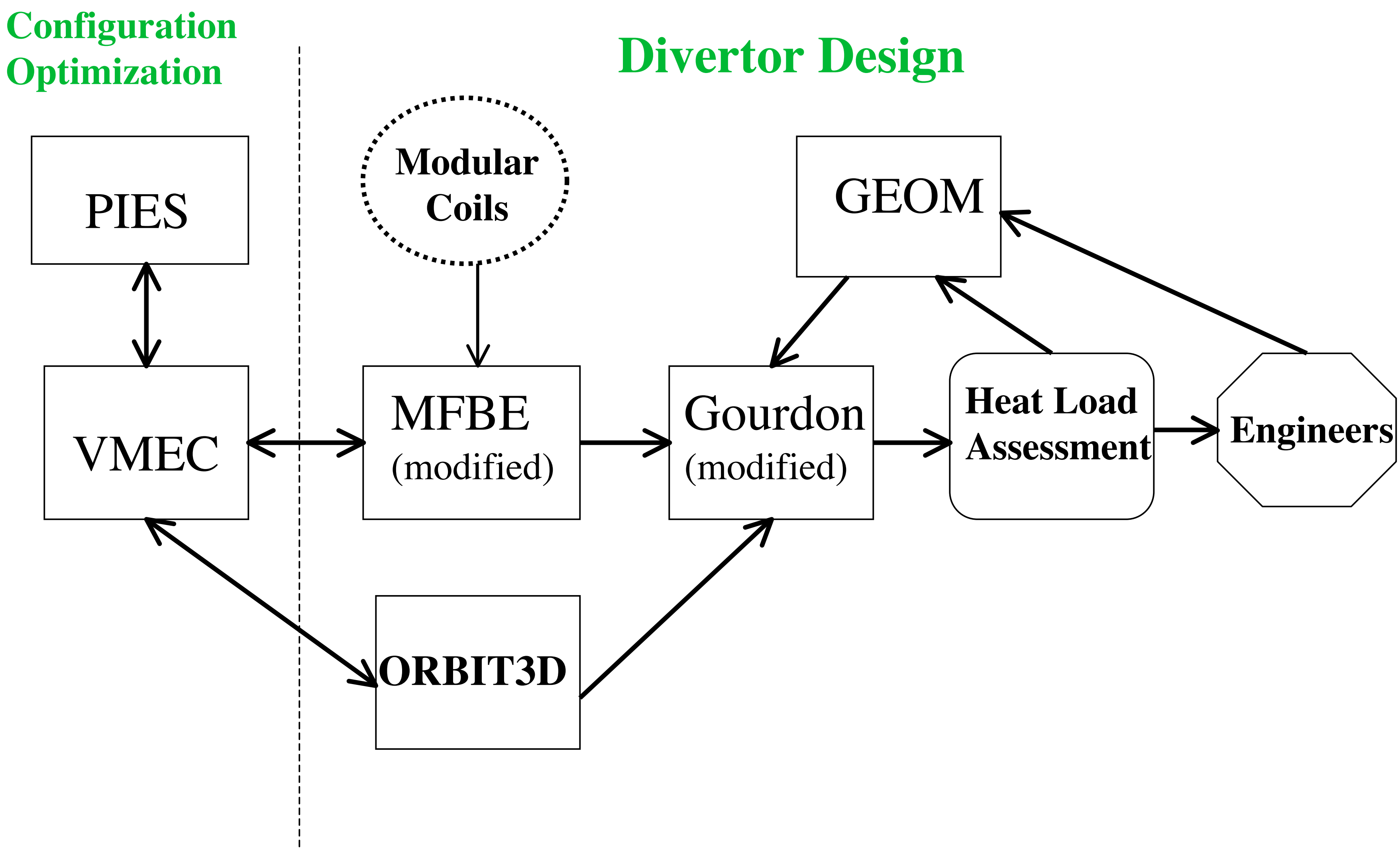
- **Prerequisite**: Develop an acceptable CS equilibrium (devoid of resonant island structures inside the LCMS) [PIES];

  Create corresponding free-boundary VMEC equilibrium



- Use MFBE to calculate magnetic field both inside and outside LCMS; use GOURDON to trace field lines and re-determine LCMS; adjust toroidal flux until the two LCMS's are reconciled.
- Use GEOM to initiate divertor plate locations.
- Use GOURDON to trace field lines outside LCMS until they strike divertor plates.
- Use ORBIT3D to calculate alpha particle exit points; Use modified Gourdon to determine alpha strike points on various intercepting plates
- Evaluate thermal and alpha heat load distribution on plates.
- Use GEOM to adjust plate locations and geometry until heat load is within engineering limits.

Divertor Design Strategy Flowchart



Initial Activities of Divertor Working Group

- A divertor working group was formed and met on Oct. 21-22. Members include R. Raffray, T.K. Mau, A. Grossman, X. Wang (UCSD) and H. McGuinness (RPI).
- A work plan for CS divertor assessment and design was developed, with objectives, task list, deliverables and schedule for task completion.
- At the meeting, it was concluded:
  - The divertor design concept will be based on optimized CS configuration and on the field line structures outside LCMS.
  - To model □ heat load, it is necessary to include finite gyro-radius effects since $\square_{c\square} \sim \square_{sol}$
  - Detailed divertor modeling including neutrals and impurities should be performed during the design integration phase.
  - Code development/enhancement should be done with presently available reference configurations, in parallel with configuration optimization.
  - UCSD and RPI will collaborate on this effort and maintain same modeling capabilities.

Divertor Assessment Tasks - I

- Modify GEOM to adapt to CS configurations [Hayden]
  - Need Fourier representation of first wall - 5 cm offset from LCMS

  Deliverable: GEOM adapted to CS, runs on Seaborg

  Due: Done

- Modify Gourdon to run on IBM Seaborg at NERSC [Art, Hayden]
  - Latest Gourdon code is parallelized and coupled to GEOM, runs on T3E, a Cray machine at NERSC that has been retired; Need to convert to IBM Seaborg platform.

Deliverable: Parallelized Gourdon code that runs on Seaborg platform

Due: Dec. 15 -- Interim report on status of this task

Jan. 31 -- time for completion (best estimate at this time)

Divertor Assessment Tasks - II

- Initially, run MFBE/Gourdon for 1-2 existing reference CS [Art, Hayden]
  - **3-field period**, NCSX based [provided by Long-Poe]

  Deliverable: MFBE magnetic field grids and LCMS reconciled to VMEC

  Due: before Jan. 1
  - **2-field period**, MHH2 [TK, Lao]

  Deliverable: Finite-beta, free-boundary VMEC equilibrium

  Due : before Jan. 1

- Write post-processor code to calculate heat load distribution on PFCs. [Hayden, Art, TK]

  Deliverable: post-processor code

  Due: Jan. 31, 05, present best estimate

Divertor Assessment Tasks - III

- Create graphics display for foot prints and heat load distribution on PFC's [Hayden, Art, Wang]
  - Create IDL module, or use Excel, AVS/IBM, or Pro-E

  Deliverable: graphics module for display

  Due: Feb. 15 (using Excel or IDL)

- Run MFBE/Gourdon for improved CS equilibria

  Due: As needed

Divertor Assessment Tasks - IV

- Build interface between ORBIT3D and Gourdon to create lost alpha particle starting points for field line tracing or particle following.

  [TK, Art, Hayden]

  Deliverable: Conversion of alpha exit points from Boozer to cylindrical coordinates

  Due: Done

- Modify Gourdon by adding a branch of direct solution to equation of motion for α's

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

  in a spatially varying magnetic field. [TK, Hayden, Art]

  Deliverable: Modified Gourdon to include finite gyro-orbits

  Due: Feb. 15 (best estimate)

- Develop finite beta VMEC equilibrium with acceptable alpha energy loss fraction (<< 35%). [TK, Long-Poe, Lao, Paul]

Divertor Assessment Tasks - V

- Run GEOM to locate and shape the divertor plates, and other PFC’s to satisfy engineering constraints (including thermal and alpha particle heat loads). [Hayden, Rene, Art, TK]

  Deliverable: divertor plate location and geometry with heat load distribution

  Due: April 2005

Divertor Assessment Tasks - VI

- Detailed modeling in the SOL and divertor region, including neutrals and impurities, to determine plasma parameters and heat flux profile
  - Depending on the connection lengths to the divertor plates, we can use either one- or 2-point model for quick analysis as in Gourdon post-processing,

    or invoke Monte Carlo diffusion model in Gourdon

    (with $D_{\perp}$~1-10 m^2/s ?)
  - Depending on availability of resources, we might want to consider using EMC3 and/or Eirene code.

Due : During integrated design analysis.

Future Group Communications

- The ARIES-CS projects works on a relatively tight schedule to fulfill certain objectives. Therefore, we need a system to monitor progress of the tasks.
  - Create group e-mail list for distribution of interim progress report
  - Conference calls to discuss details of work (as needed)
  - UCSD weekly staff meeting
  - Project meetings (every 3 months)

Re-Assessment of Alpha Heat Load

- We use a VMEC equilibrium for the reference MHH2 16-coil case (L.P. Ku), that assumes

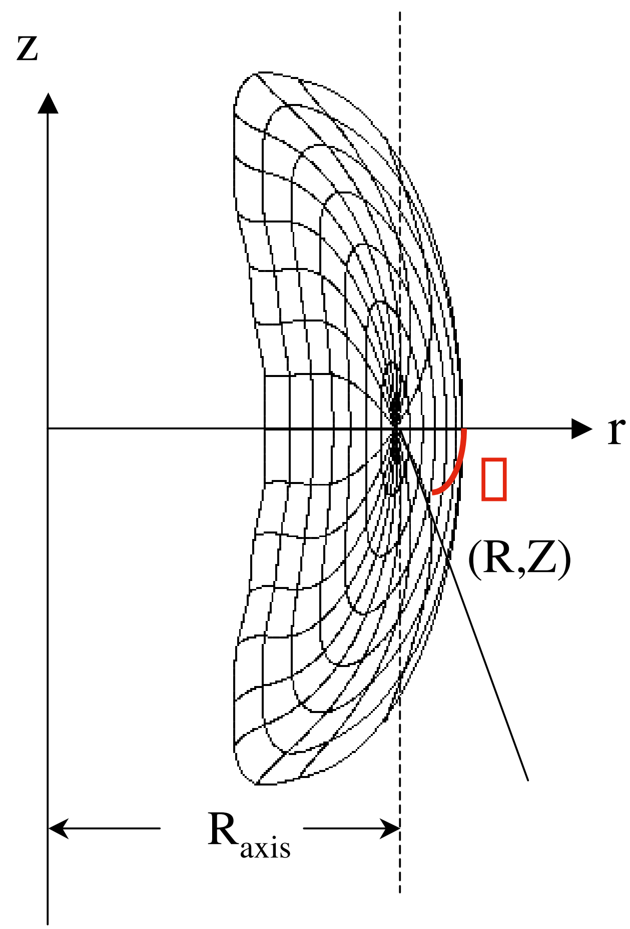
  $p(s) \sim (1 - s^{1.5})^{1.5}$

  $\beta = 4\%$

  There is no net current in the plasma.

- It assumes $B_o = 5.5$ T, R = 7.5 m, and
  $n_e = n_i = 1.3 \times 10^{14} \ (1 - s^2) \ cm^{-3}$
  $T_e = T_i = 11.5 \ (1 - s^2)$ keV

  Initial $n_\alpha \sim (1 - s)^8$

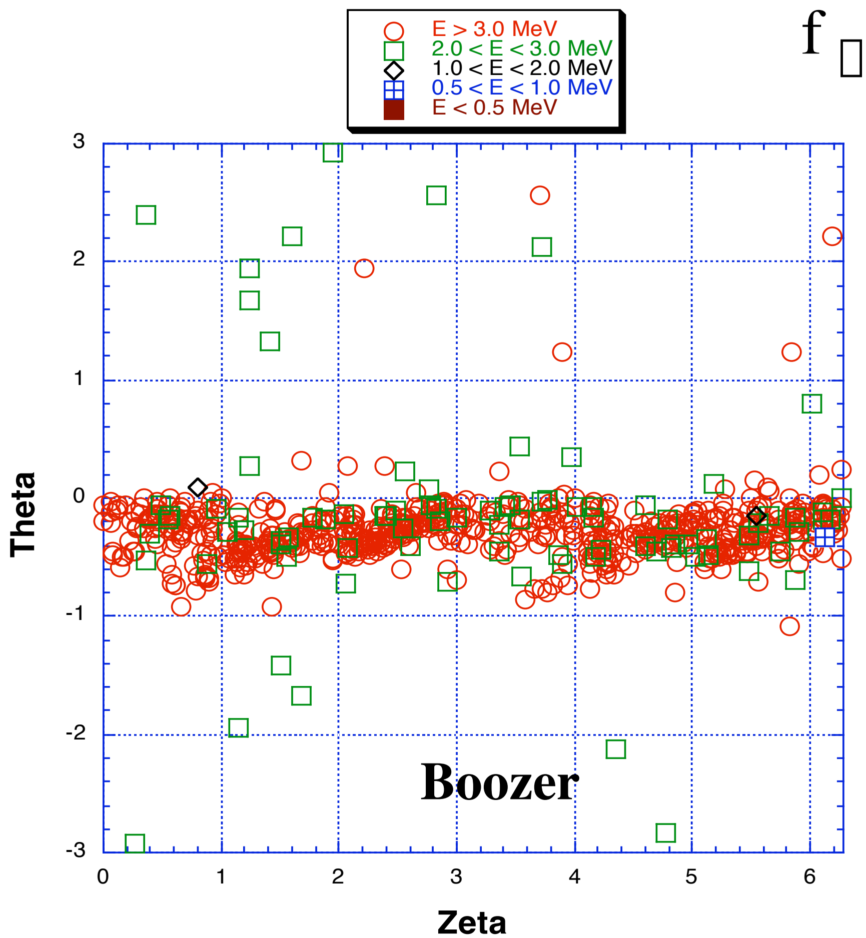


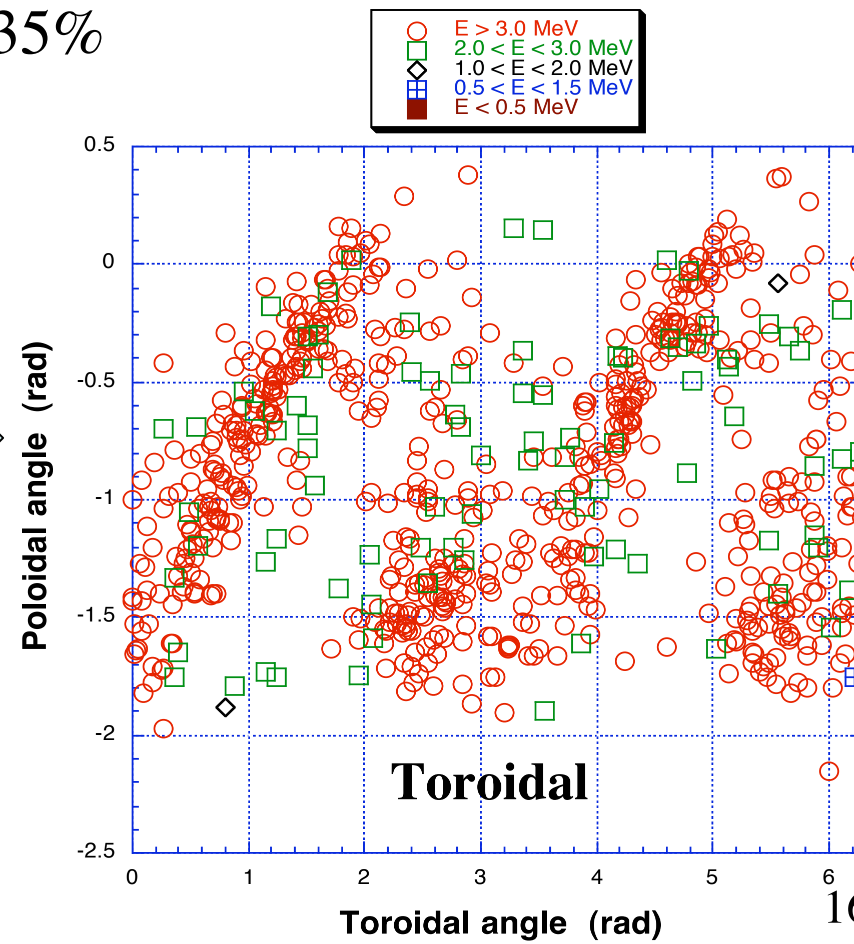
- ORBIT3D is used to calculate alpha particle loss:
  - The sample size used is 2000 particles.
  - Particles are collisionless and slow down on the background plasma.
  - Pitch angle scattering is included.

Alpha Exit Points are Converted from Boozer (□,□) to Toroidal (□,□) Coordinates

- The periodic band-like structure of the alpha foot prints is obtained in (□,□) space, located between -2.0 < □ < 0.5.
- Here, □ is measured from local magnetic axis: □ =Arc tan {$Z/(R-R_{axis})$}.

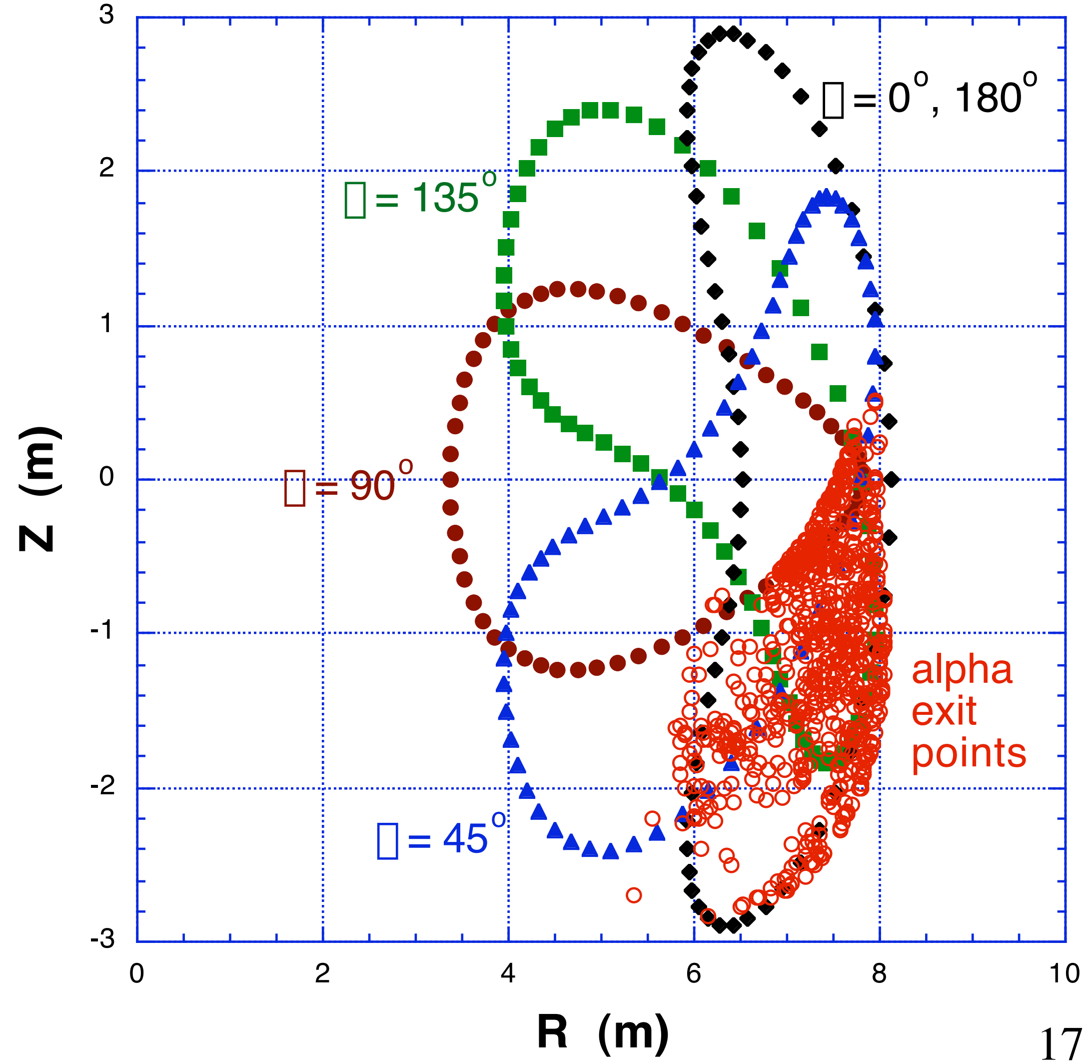
$f_{□,loss} = 35\%$





Projection of Alpha Exit Points onto (R,Z) Plane

- Almost all alpha particles are lost through the OB lower quadrant of the LCMS.



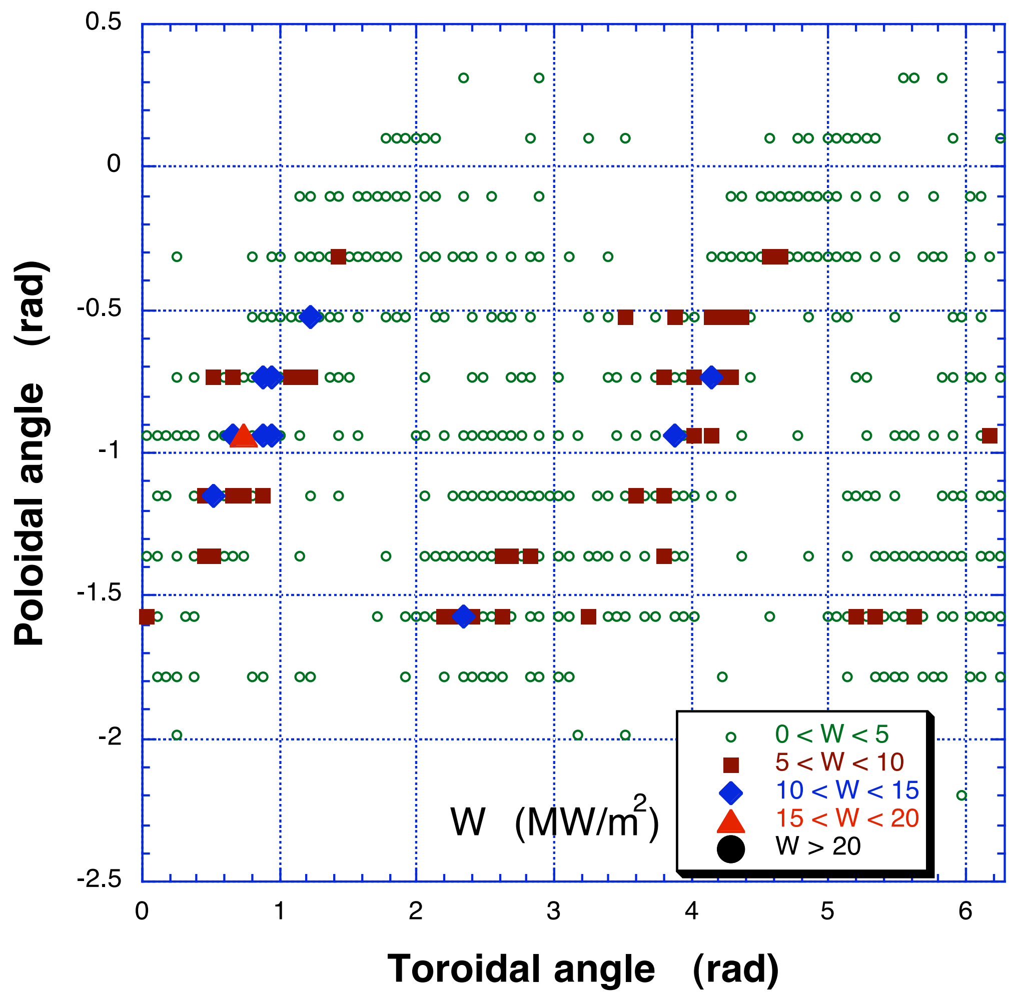
Estimate of □ Heat Load Distribution on LCMS

We divide the plasma surface into rectangular segments, and add up the energy collected in each segment.

For P_{fus} ~ 2000 MW, $P_{□}$ ~ 400 MW, and total power to surface is $f_{□L}$ $P_{□}$, where $f_{□L}$ is fraction of □ energy lost.

Heat load to segment:
W = $f_{□L}$ $P_{□}$ □ (□E/E_{tot})/Area

Peak heat load < 20 MW/m²



Summary and Future Work

- A divertor working group has been formed, and a work plan and strategy for divertor design has been established.
- Coordination among the various members is essential for timely execution of the various tasks.
- Alpha foot points on LCMS have been successfully transformed from Boozer to cylindrical coordinates.

  Heat load distribution on LCMS was re-assessed for an example CS configuration.
- There are two near-term tasks:
  - Obtain finite-beta (with non-zero net current) free-boundary VMEC equilibrium for MHH2 cases for input to MFBE.
  - Develop alpha particle gyro-orbit code and incorporate into Gourdon for following MeV alphas in SOL to PFCs.