AN UPDATE ON
DIVERTOR HEAT LOAD ANALYSIS

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OUTLINE

- Divertor design strategy
- Recent progress in divertor heat load analysis
- Alpha particle gyro-orbits in 3-D magnetic topology
- A divertor-related issue
- Summary and future work

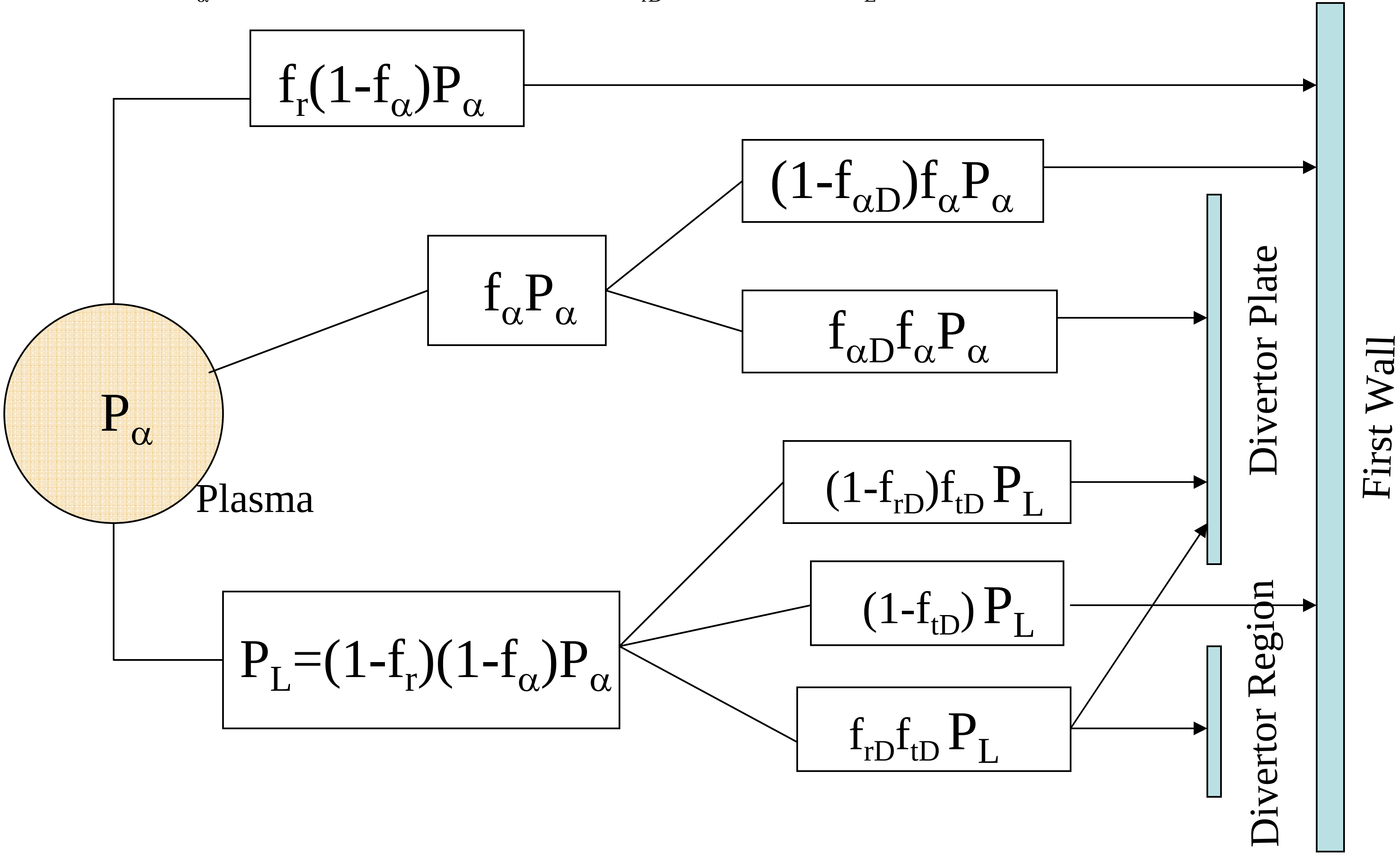
General Plasma Heat Flow Diagram

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



$f_r(1-f_\alpha)P_\alpha$

$(1-f_{\alpha D})f_\alpha P_\alpha$

$f_\alpha P_\alpha$

$f_{\alpha D} f_\alpha P_\alpha$

P_α

Plasma

$(1-f_{rD})f_{tD}\,P_L$

$(1-f_{tD})\,P_L$

$P_L=(1-f_r)(1-f_\alpha)P_\alpha$

$f_{rD}f_{tD}\,P_L$

Divertor Plate

Divertor Region

First Wall

Divertor Engineering Design Criterion

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

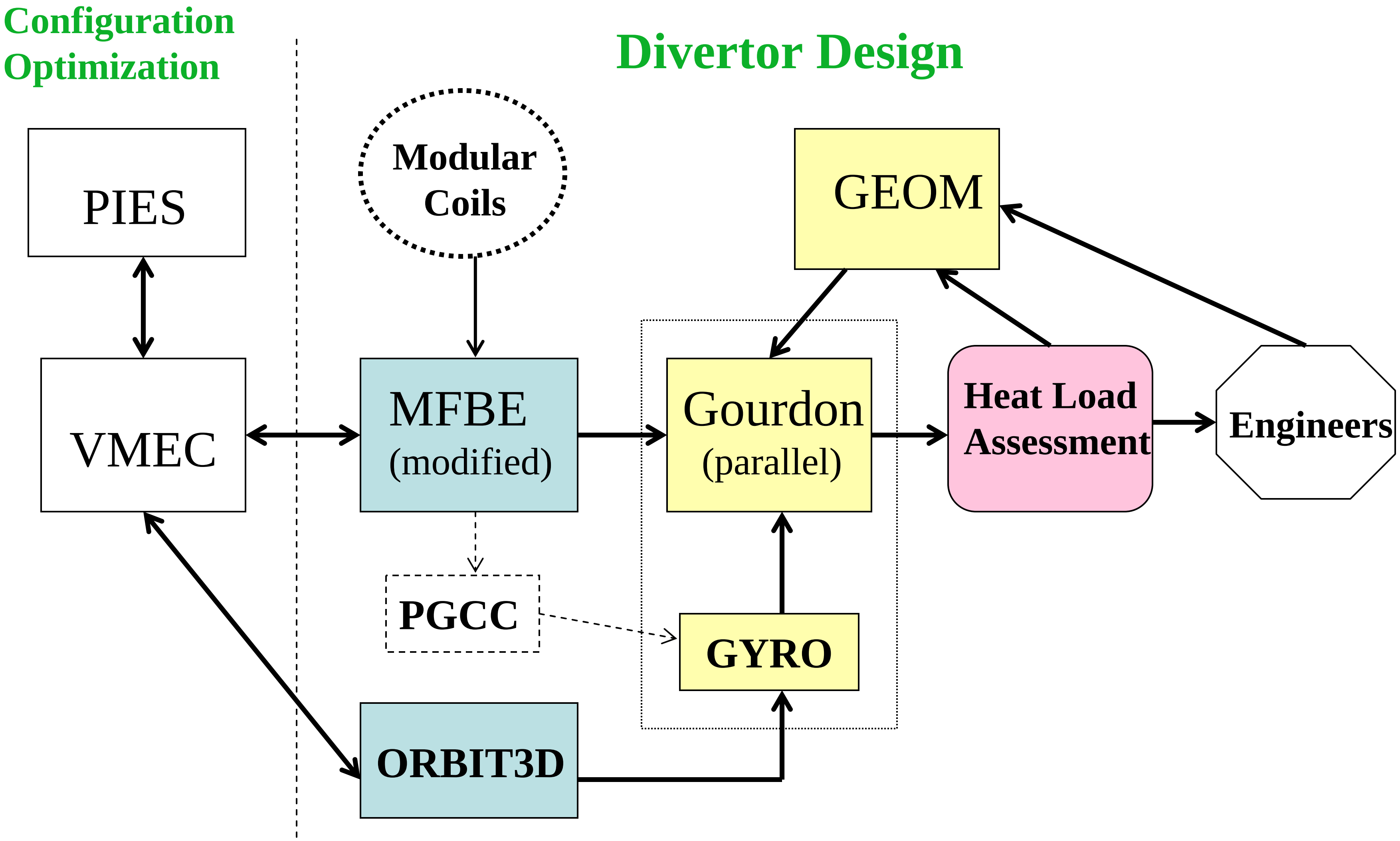
- Divertor design criterion:

$$P_{div}\sin\theta_g/A_D < W_{pk}/\eta$$

where W_{pk} = divertor peak heat load limit
η = heat load peaking factor
θ_g = average grazing angle to divertor plate
A_D = total divertor plate area

- A more uniform heat load (lower η) will permit a higher P_{div}.
  P_{div} can be lowered by more radiation from the core (higher f_r) and in the divertor region (higher f_{rD}).

Divertor Design Tools and Strategy Flowchart



Recent Progress on Divertor Design

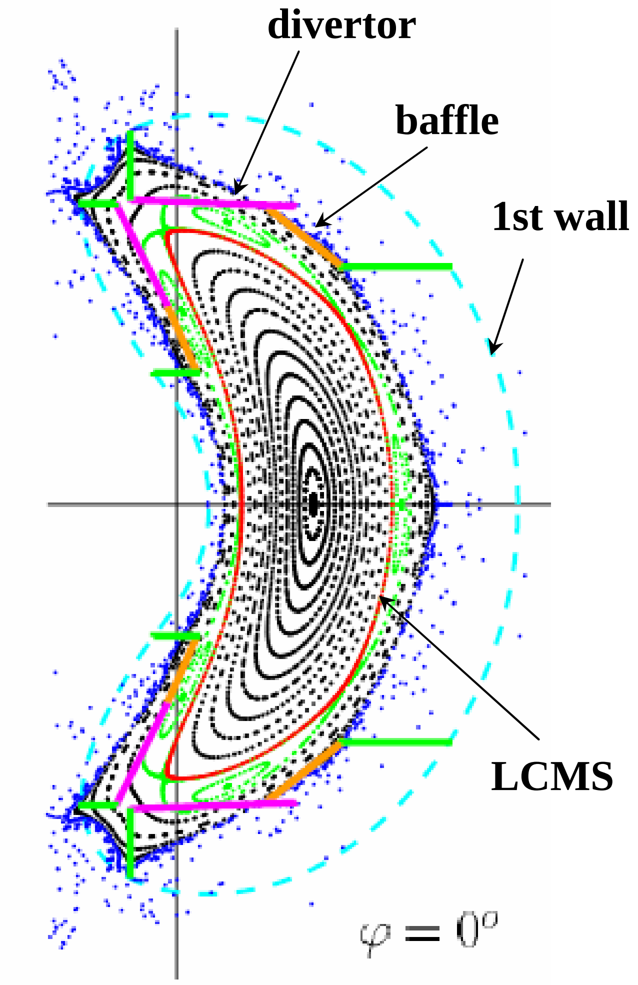
- **Prerequisite**: An acceptable NCSX-based equilibrium (good flux surfaces inside LCMS, manageable α loss) has been developed and used in divertor analysis. Optimization of an MHH2 configuration is on-going. [L.P.

- A 3D magnetic field table for the plasma and the SOL region was generated using MFBE. [Grossman]

- Further improvements have been made to the GOURDON field line tracing code. [McGuinness]

- Field line footprints have been obtained at imaginary first wall conformal to LCMS and at test divertor plates. Plate and first wall locations are specified in the GEOM code. [McGuinness]

- Alpha particle gyro-orbits have been computed inside and outside LCMS by coupling GYRO to the 3D magnetic field table. [Mau]

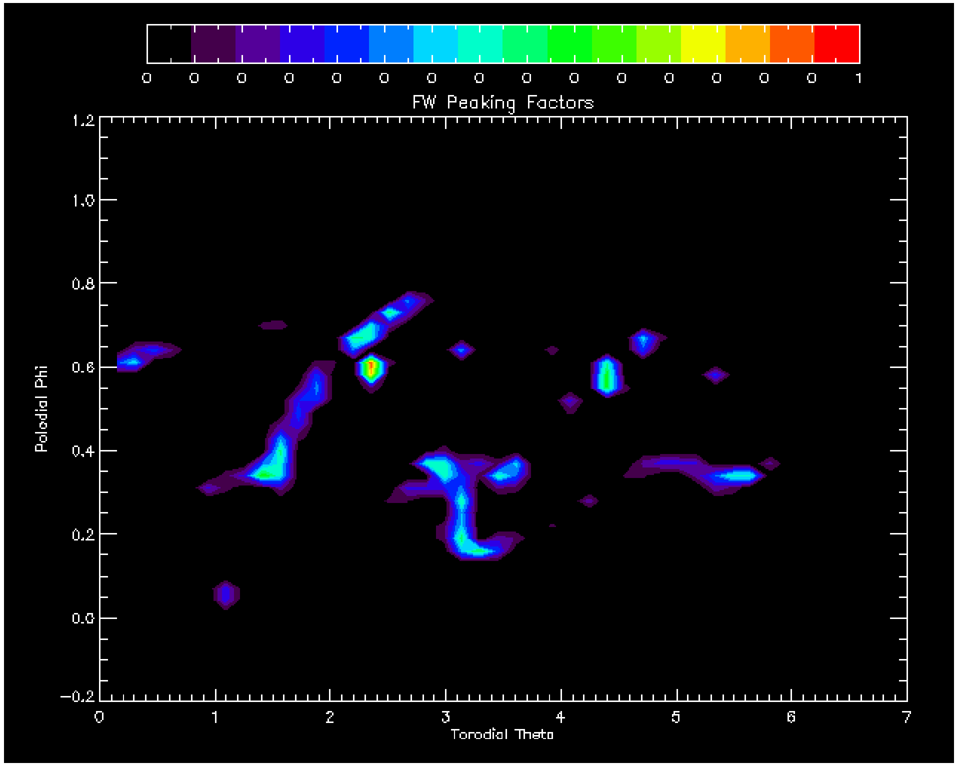


W7-X Example

Highlights of Progress in Locating Divertor Plates

(McGuinness)

- The parallelized GOURDON code was successfully run on SEABORG, and closed flux surfaces inside LCMS and ergodic field lines in SOL have been obtained.
- As a first step towards defining possible divertor plate locations, field line footprints on a first wall conformal with LCMS and with ~5 cm offset has been obtained. A roughly periodic pattern with 3 slanted strips in the $\theta - \phi$ plane is shown.



- A graphic package for display of target plates (and their locations) and heat load distribution has been developed.

Modeling Heat Flux due to Nonthermal Alpha Loss

- Due to non-axisymmetry of the magnetic topology, a significant fraction of fusion alphas can be lost from the plasma before thermalization.

- A kinetic approach is required to model this alpha heat load. Instead of the guiding center approach, the gyro-orbit of the energetic alphas should be taken into account, especially in the narrow scrape-off layer with $\rho_{c\alpha} \sim \Delta_{sol}$, since it governs their strike points on the PFC's; also of concern are local hot spots, and blistering of surface materials that depend on the angle of incidence of the alphas.

- For a complicated 3D magnetic field profile found in CS's, we follow a representative set of energetic alphas from birth in the core to eventual thermalization inside the LCMS or to striking the PFC's (divertor plates and first wall).

GYRO - A Single-particle Gyro-orbit Code

- The GYRO code directly solves the equation of motion

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

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,ϕ,z), the equation can be written in the form:

$$\begin{aligned} \frac{d\dot{r}}{dt} &= \frac{q}{m}\left(r\dot{\phi} B_z - \dot{z} B_\phi \right) + \frac{(r\dot{\phi})^2}{r} \\ \frac{d(r\dot{\phi})}{dt} &= \frac{q}{m}\left(\dot{z} B_r - \dot{r} B_z \right) - (r\dot{\phi}) \frac{\dot{r}}{r} \\ \frac{d\dot{z}}{dt} &= \frac{q}{m}(\dot{r} B_\phi - r\dot{\phi} B_r) \end{aligned}$$

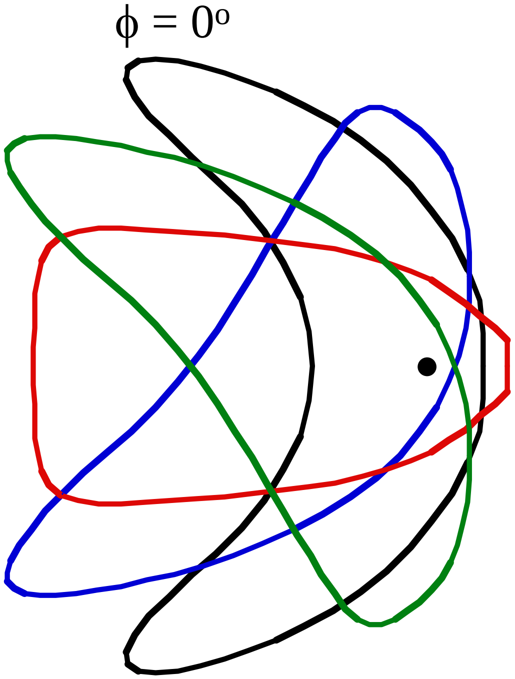
where are solved with the standard Runga-Kutta method to h^4 accuracy.

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.

  This was reported in the Feb. 05 meeting.

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



- Initial conditions:

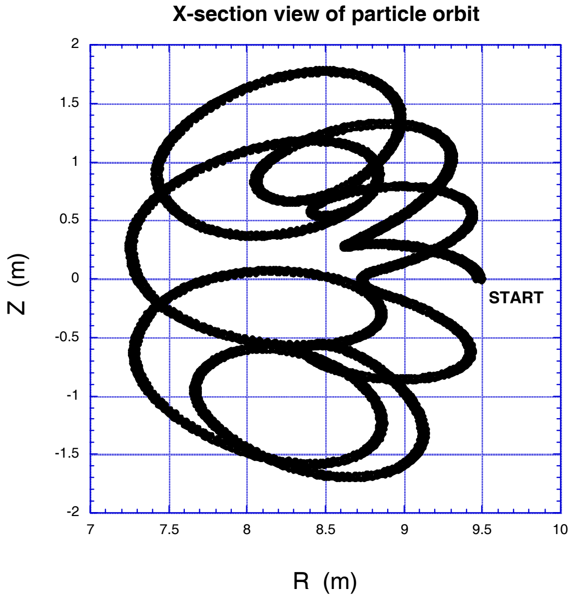
  particle energy E_o (= 3.5 MeV)

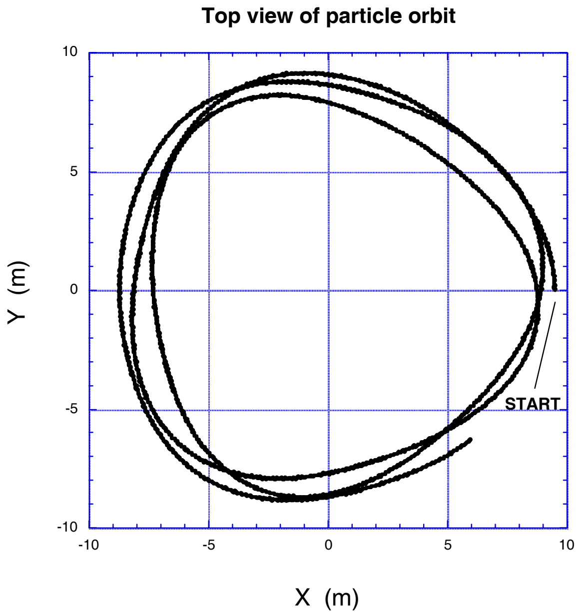
  toroidal velocity v_ϕ (> 0)

  velocity pitch $p = v_\perp/v_\|$

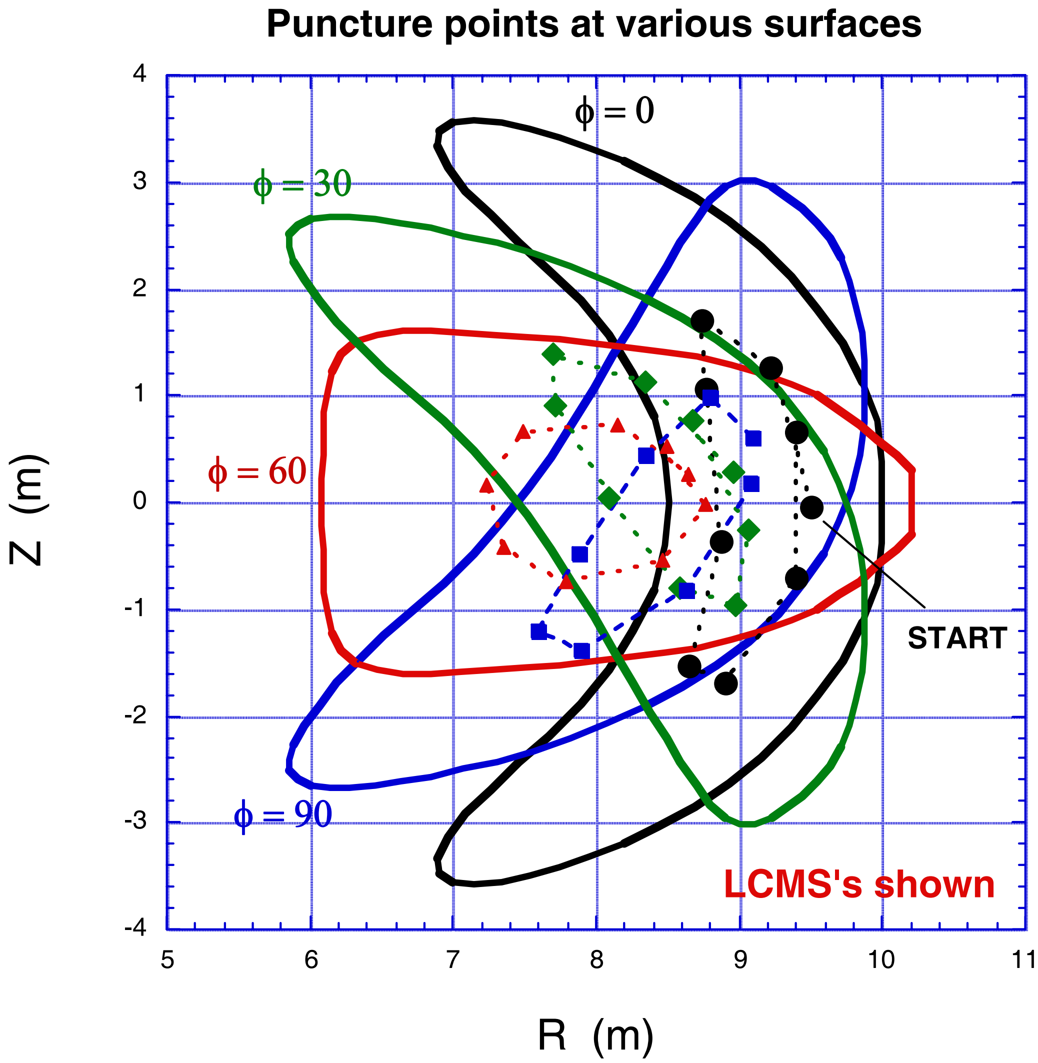
  starting location: R = 9.5 m, $\phi = 0.$, Z = 0 m. : on OB midplane

Particle Orbit with p = 1

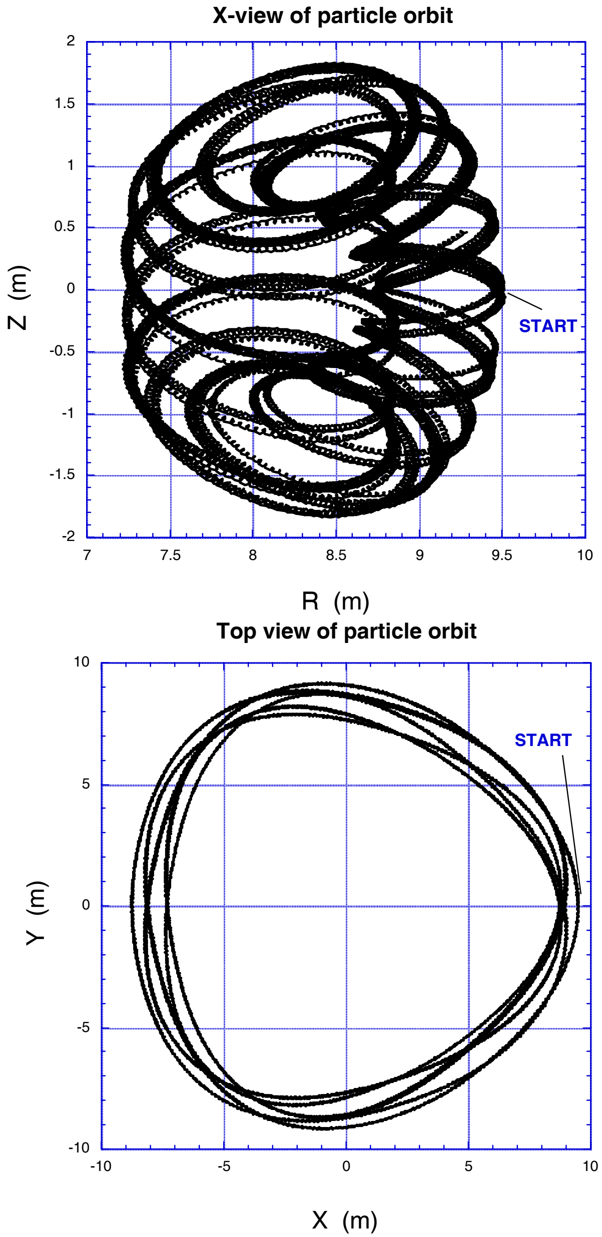

X-section view of particle orbit


Top view of particle orbit

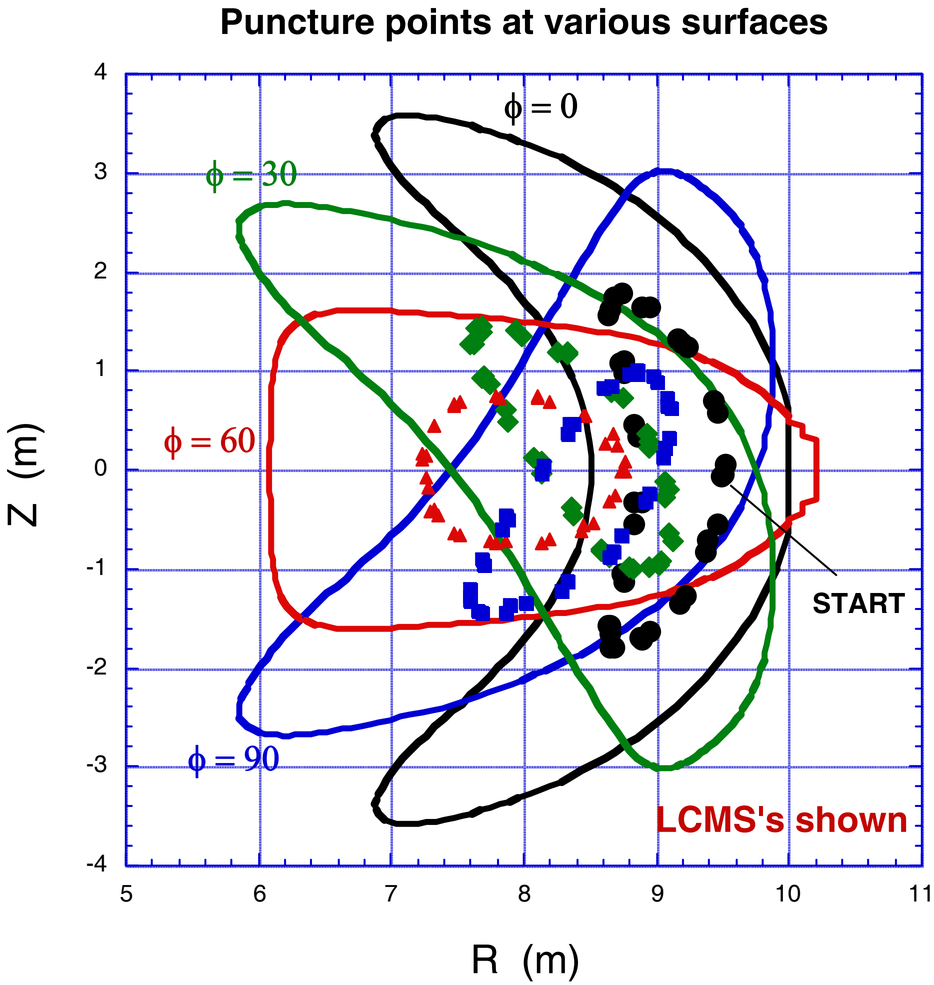
Particle appears to be circulating and confined to a closed flux surface.


Puncture points at various surfaces

Particle Orbit with p = 2



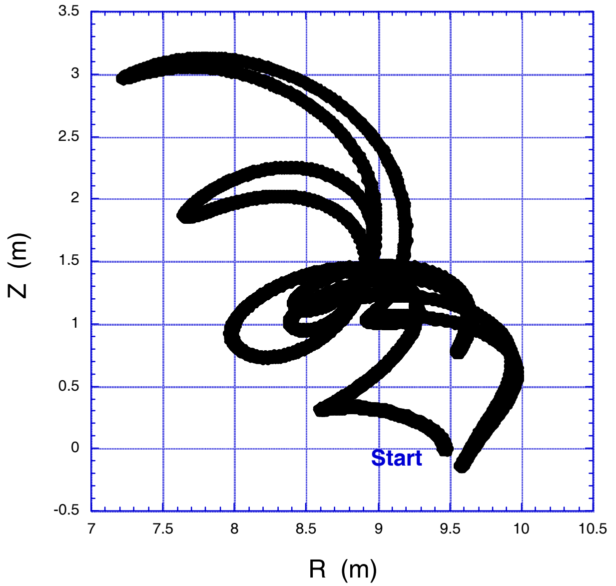
Particle appears to be circulating and confined to the same flux surface. The puncture points clearly define closed flux surfaces, like field line tracing.



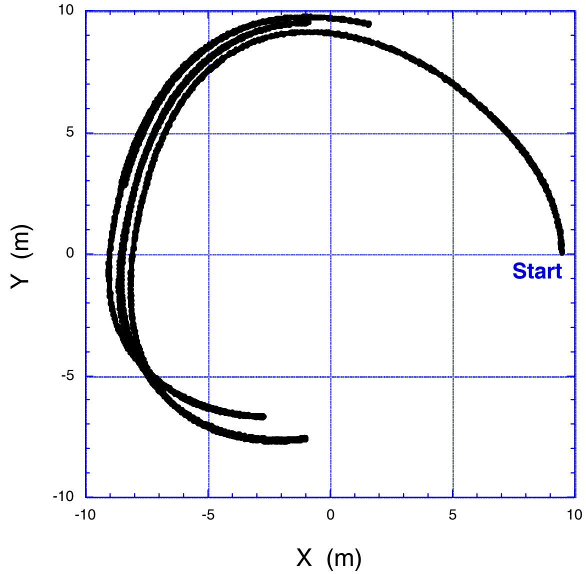
Particle Orbit with p = 5

Particle appears trapped in magnetic well and drifts radially outward until it almost reaches the LCMS.

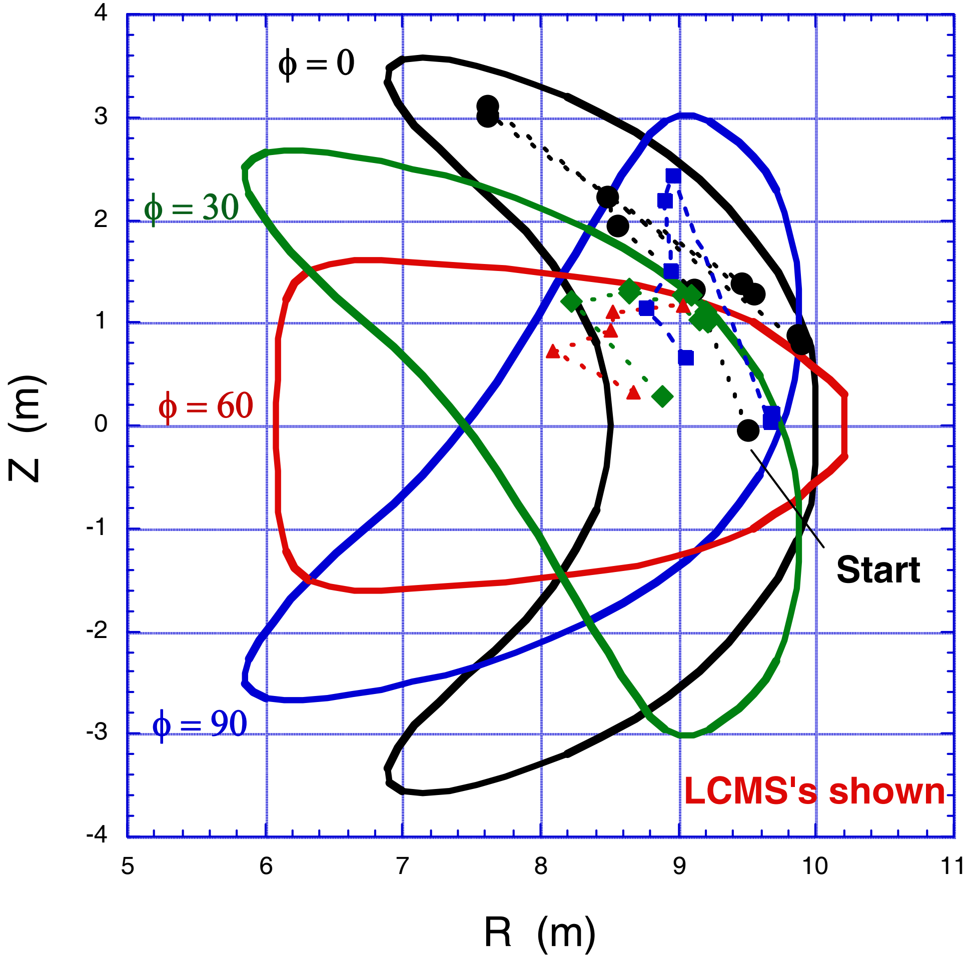
X-view of particle orbit



Top view of particle orbit

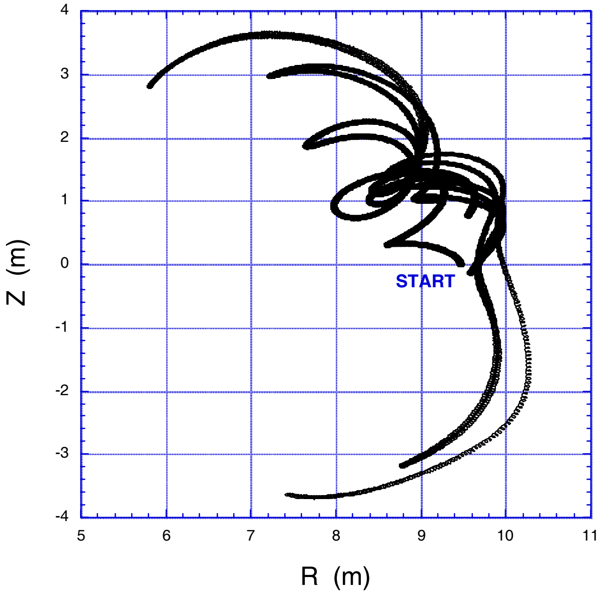


Puncture points on various surfaces

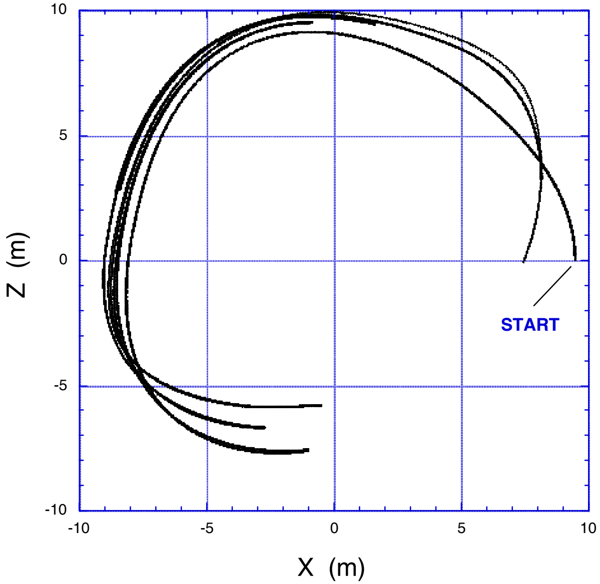


Following Particle Orbit with p = 5 to 1st Wall with 5 cm Offset

X-view of paticle orbit

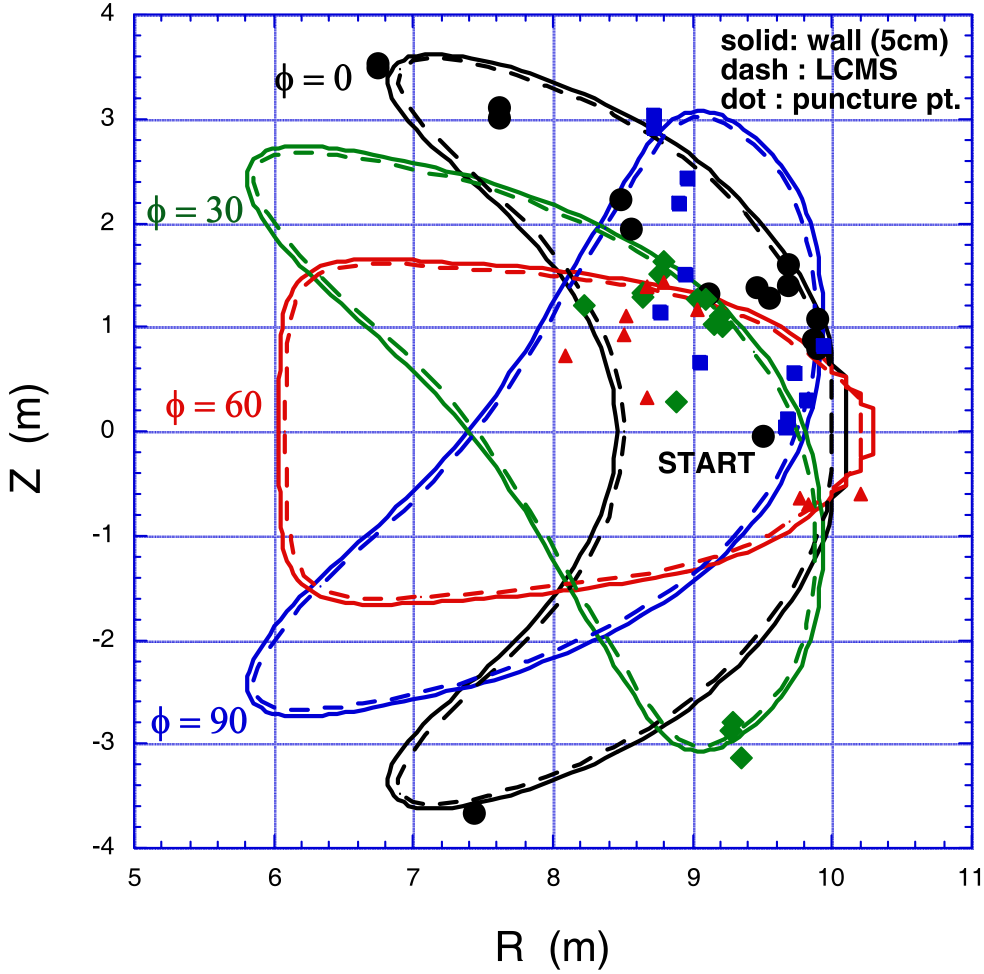


Top view of particle orbit

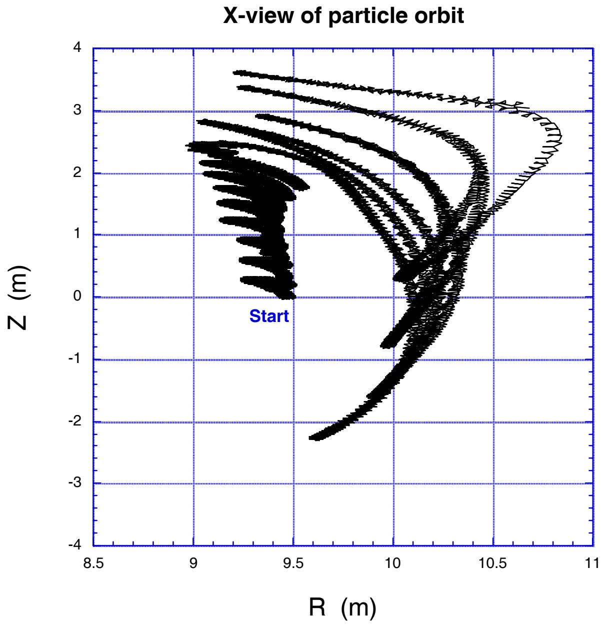


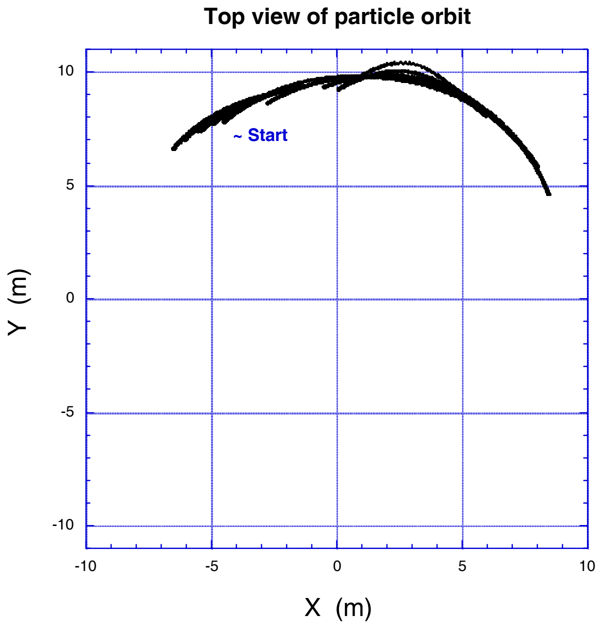
Particle is lost from plasma (LCMS) and hits first wall 5 cm away. Exact locations of loss and strike cannot be determined yet.

Puncture points on various surfaces

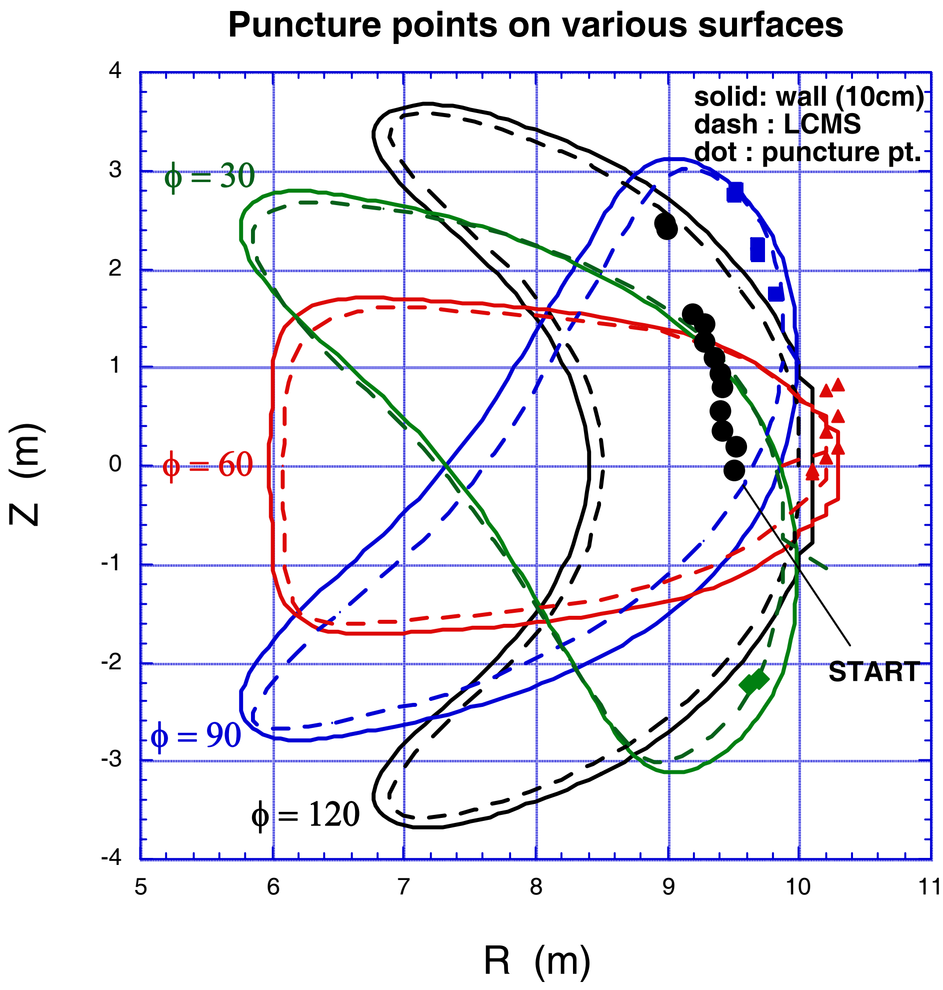


Following Particle Orbit with p = 10 to 1st Wall with 10 cm Offset





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.



Future Plans for GYRO

- In a typical CS configuration, GYRO reproduces particle orbits that are passing (confined) and trapped (unconfined), indicating that the code is working well.

- 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 now ready to be incorporated into the GOURDON code.
  - An algorithm will be developed to use results from drift orbit calculations inside the plasma (ORBIT3D or PGCC) to start full gyro-orbit tracking (GYRO) when the particle reaches the LCMS.
  - Features in GOURDON can be interfaced with GYRO to determine particle exit points from LCMS and strike points on first wall.

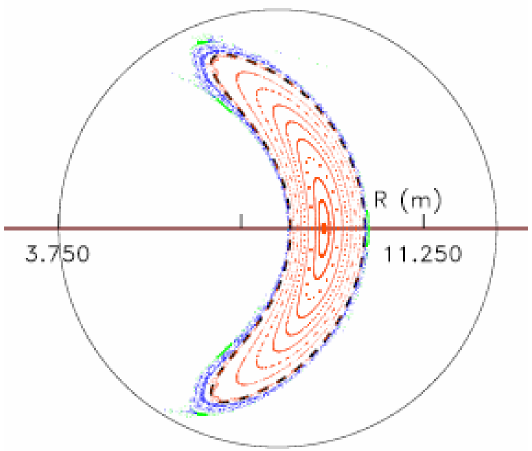
Ergodic or Island Divertor for NCSX-based Configuration?

- Ergodic divertors attempt to use local flux expansion zones to locate the target plates with favorable heat load profiles.

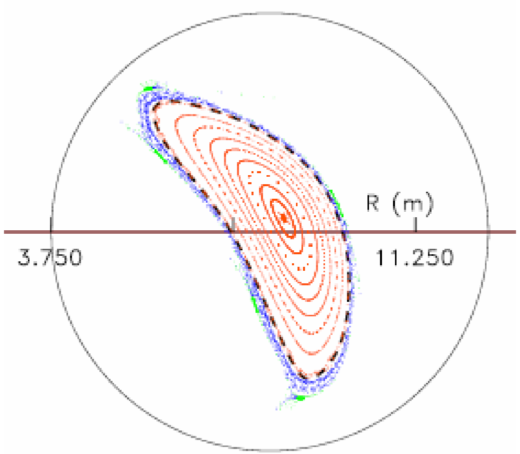
- Island divertors make use of island topology similar to SN tokamak divertors, except with helical X-lines. Confinement of recycled particles in closed islands allows for high n, low T near target.

- NCSX-based configuration shows only remnants of 3/5 islands, so an ergodic divertor will have to be considered for now.

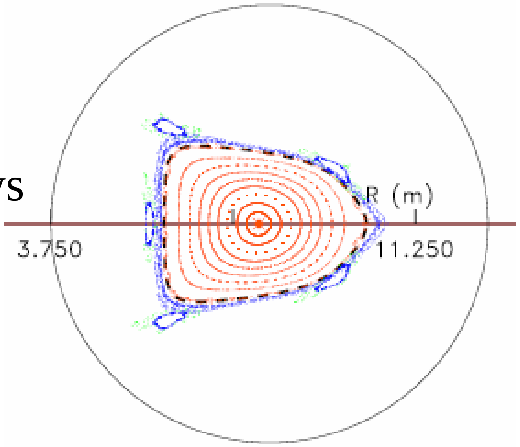
$\phi = 0^o$



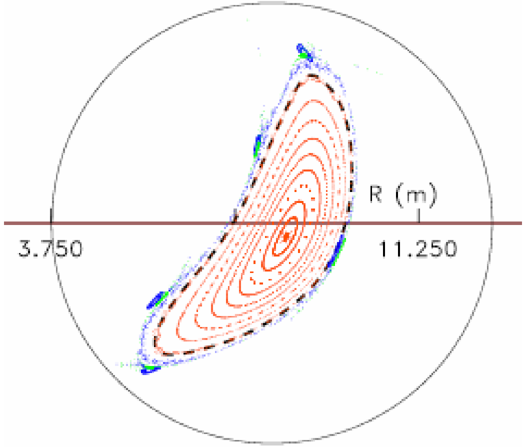
$\phi = 30^o$



$\phi = 60^o$



$\phi = 90^o$



- To take advantage of island divertors, an extra coil set or modified edge iota will be required to result in prominent island structures outside LCMS.

Summary and Future Tasks

- The GYRO gyro-orbit code in cylindrical coordinates has been tested successfully with a 3D compact stellarator magnetic topology. Unconfined alpha orbits have been followed from inside the plasma to the first wall.

  This will be incorporated into GOURDON to track particles in the SOL to the PFCs (target plates and first wall).
- Field lines have been traced with GOURDON from LCMS to first wall (and divertor plates) set up in GEOM. Initial field-line footprints on imaginary first wall provide useful guidance for divertor plate locations.

  Target plate location will be optimized and heat load distribution calculated.
- A post-processor code has been set up to compile results from GOURDON to calculate heat load distribution on all intercepting plates.
- A cross-field diffusion model has been incorporated into the parallelized GOURDON code.

  Testing of this model will be performed in the near future.
- So far, divertor heat load analysis has been on the 3-FP NCSX-based case.

  The corresponding analysis for an acceptable MHH2 case should be carried out.

  ⇨ An archive of “attractive” CS equilibria should be set up so these cases can be investigated for possible divertor configurations.