PROGRESS ON
DIVERTOR HEAT LOAD ASSESSMENT

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Divertor Assessment Objectives

• Develop divertor concept

• Locate divertor plates and other PFCs

• Evaluate heat load distribution (thermal & alphas)

• Optimize design to within physics and engineering limits
Status of Tasks for Divertor Design

- **Prerequisite**: Develop an acceptable CS equilibrium (devoid of resonant island structures inside the LCMS) and create free-boundary VMEC equilibrium.  
  [Ku, Garabedian, Mau] ✓✓ (achieved)

- Create 3D magnetic field table for inside and outside LCMS with MFBE; re-determine LCMS with Gourdon, and adjust toroidal flux until LCMS agrees with VMEC. [Grossman] ✓✓
- Initiate divertor plate locations with GEOM. [McGuinness] ✓ (making progress)
- Use GOURDON to trace field lines outside LCMS until they strike divertor plates. [McG] ✓
- Calculate alpha particle exit points with ORBIT3D. [Mau] ✓
- Follow alpha gyro-orbits outside LCMS with GYRO-CS until reaching divertor. [Mau] ✓
- Evaluate thermal and alpha heat load distribution on plates. ——> Algorithm/Post Processor
- Adjust plate locations and geometry until heat load limit is satisfied.
Divertor Heat Load due to Alphas

• To model the alpha heat load, the gyro-orbits of the energetic alphas should be taken into account, since $\frac{c}{\alpha} \sim \frac{\alpha}{\text{sol}}$; also of concern are local hot spots, and blistering of surface materials which depends on angle of incidence.

• Propose to add to Gourdon a direct solution to equation of motion for $\alpha$’s

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

in a 3D spatially varying magnetic field.

• We have created a stand-alone code, GYRO-CS, that solves the equation in cylindrical coordinates:

$$\frac{dr}{dt} = \frac{q}{m} \left( r \hat{\alpha} B_z \cdot \hat{z} B_\alpha \right) + \frac{(r \hat{\alpha})^2}{r}$$

$$\frac{d(r \hat{\alpha})}{dt} = \frac{q}{m} \left( \hat{z} B_r \cdot \hat{r} B_z \right) \cdot \left( r \hat{\alpha} \right) \hat{r}$$

$$\frac{d\hat{z}}{dt} = \frac{q}{m} \left( \hat{r} B_\alpha \cdot r \hat{\alpha} B_r \right)$$

where $B = B(r, \alpha, z)$. A standard Runga-Kutta method of order $h^4$ is used.
Testing GYRO-CS on a Tokamak-like Magnetic Geometry

- GYRO-CS is first tested on an axisymmetric magnetic geometry to make sure it is correct results.
- Assume a tokamak with concentric, circular flux surfaces:
  \[ R_o = 5.0 \text{ m}, \ a = 2.25 \text{ m}, \ B_o = 3 \text{ T}, \ I_p = 2 \text{ MA}. \]
  \[ B_{\|} = B_o \frac{R_o}{R} \]
  \[ j_{\|} = j_o \left[ 1 - \left(\frac{r}{a}\right)^2 \right]; \quad r^2 = Z^2 + (R-R_o)^2 \]
  \[ B_{\|} (r) = 0.4 \ I_p(\text{MA}) \ (r/a^2) \left[ 1 - 0.5 \ (r/a)^2 \right] \]

- Initial conditions:
  particle energy \( E_o \)
  velocity pitch \( p = v_{\|}/v_{\parallel} \)
  starting location \( R = 6.0 \text{ m}, \ \| = 0., \ Z = 0 \text{ m.} \) : OB midplane
Results for $\parallel$ Particles with $E = 0.035$ MeV

- passing particles with circular drift orbits coincident with flux surfaces
- trapped particle orbits observed at $p = 5.0$ with small banana width
Results for $\otimes$ Particles with $E = 0.35$ MeV

- Circulating orbits are displaced inwards for $v_\parallel > 0$ and outward for $v_\parallel < 0$.

- Trapped orbits have finite banana width.

- Gyro-orbits are visible from pictures.
Results for \( \square \) Particles with \( E = 3.5 \text{ MeV} \)

- Severe displacement of circulating orbits
- Large gyro-orbits are displayed. \( (\square \sim 10 \text{ cm}) \)
- Very fat banana orbits for \( v_\parallel < 0 \) and \( p = 0.5 \)
- Trapped orbits drift radially outward.
Addition of a Moderate Non-Axisymmetry

- We add a small ripple field to the toroidal field component: \( B_0 \cos(N \phi) \) where \( \phi \) is ripple size and \( N \) is the number TF coils.

- This results in the gyro-orbit radius clearly being modulated along the particle trajectory.
Future Plans for GYRO-CS

• In a simple tokamak configuration, GYRO-CS reproduces particle orbits that are well known, indicating that GYRO-CS is working well.

• The code is now ready to be incorporated into the Gourdon code.
  
  – An algorithm will be developed to transition from drift orbits calculated either by ORBIT3D or PGCC, to full gyro-orbits using GYRO-CS at or near the LCMS.
  
  – The fast ion Monte-Carlo code, LOCUST, from Culham Laboratory has a similar feature.
Recent Progress and Future Tasks for Divertor Heat Load Assessment

- A 3D magnetic field table has been generated for the ARIES-CS 3-FP configuration using MFBE. The corresponding table for a 2-FP case will be calculated.

- A gyro-orbit code in cylindrical coordinates, GYRO-CS, has been written and tested successfully with a tokamak magnetic topology. This needs to be incorporated into GOURDON.

- The parallelized GOURDON code has been successfully compiled on SEABORG/NERSC, and closed flux surfaces and LMCS have been traced for the 3-FP case. Field line tracing should be done from LCMS to divertor plates set up by GEOM.

- A post-processor code should be set up to compile the data from GOURDON to calculate the heat flux distribution on all intercepting plates. This can be a subroutine in GOURDON.

- A cross-field diffusion model should be incorporated into the parallelized GOURDON code.

- A fixed boundary VMEC capability has been added to UCSD with the help of Lang Lao, and a 2-FP VMEC equilibrium with imposed iota profile was generated. Interfacing to ORBIT3D code is on-going.