OSPO VSIP MFEM-Based Tokamak Equilibrium Solver

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Georgia Tech

Team Overview

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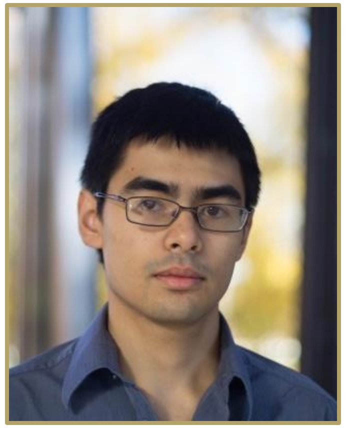

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Saisruthi Bandla

Background

Goal

Milestones

Next Steps

Project Background

Plasma, the 4th state of matter, is a hot, ionized gas containing free electrons and charged particles. A key application of plasma is fusion—where atomic nuclei combine to release immense energy.

Fusion Uses

Energy Generation
Abundant power with minimal environmental impact

Space Propulsion
Faster and longer-distance space travel

Scientific Research
Study plasma & fundamental particle interactions

Prior to achieving these benefits, there are some key challenges that need to be addressed

Saisruthi Bandla

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Plasma Fusion Challenges

Confinement
Develop devices that can contain and withstand high temperatures

Maintain Equilibrium
Plasma expands and cools—stabilization keeps it hot long enough for fusion

Popular State of the Art Solutions

MFEM Project Focus

Magnetic Confinement
Uses strong magnetic fields to trap plasma

Ex: International Thermonuclear Experimental Reactor (ITER) – constructing a Tokamak, a donut-shaped fusion reactor device

Inertial Confinement
Uses lasers/beams for rapid compression

Ex: National Ignition Facility (NIF) - building an inertial confinement fusion device that uses powerful lasers to enable fusion

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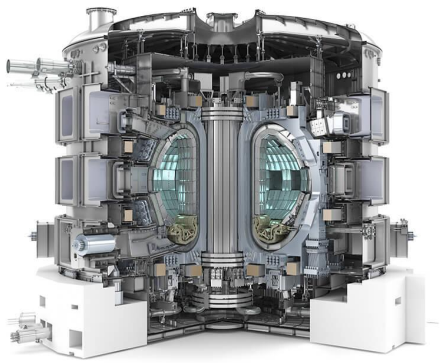
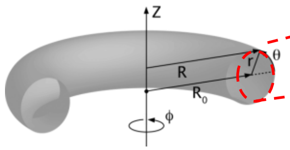
MFEM Project Goal

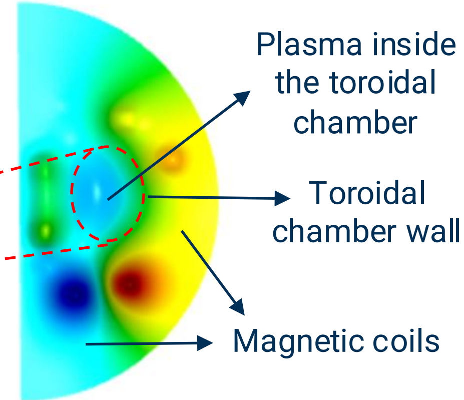
Goal: Develop a free boundary tokamak equilibrium solver for the magnetic confinement fusion community



Tokamak



Toroidal plasma chamber of tokamak



Magnetic flux simulation

Equilibrium

Stabilize plasma and avoid contact with walls

- Modeled by Grad–Shafranov (GS) equation, which describes magnetohydrodynamic equilibrium in axisymmetric, toroidal plasmas

Free Boundary

Unknown plasma shape & boundary conditions

- Modeled using MFEM, an open-source finite element library for solving partial differential equations on unstructured 2D and 3D grids

Develop a tokamak plasma equilibrium solver using MFEM library

Saisruthi Bandla

Internship Contributions

- **Milestone 1**
  Run serial/parallel MFEM on PACE
- **Milestone 2**
  Determine & visualize ITER's magnetic flux
- **Milestone 3**
  Contribute to the first pull request
- **Milestone 4**
  Generate a mesh and interpolate solution
- **Main Goal: Milestone 5**
  Add a writer for EFIT data
- **Milestone 6**
  Fix other issues & bugs in the code

Janani Murugan

Internship Contributions: Milestones 1 - 3

Milestone 1

Run serial/parallel MFEM on PACE

- Use Phoenix cluster on PACE to install and compile MFEM
- Visualize solutions using GLVis, a finite element visualization tool

Milestone 2

Determine & visualize ITER's magnetic flux

- Install gslib, compile a provided example using the GS solver
- Visualize the resulting solution representing the magnetic flux of an ITER device

Milestone 3

Contribute to the first pull request

- Clean-up MFEM code by fixing issues with member initialization, variable usage, etc

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Internship Contributions: Milestones 4 - 6

- Background
- Goal
- **Milestones**
- Next Steps

Milestone 4

Generate a mesh and interpolate solution

- Using the solution from the original triangular mesh, generate a 2-D cartesian mesh and interpolate the plasma solution onto this mesh

Milestone 5

Add a writer for EFIT data

- Using G-EQDSK file format, develop an EFIT writer, code used to reconstruct plasma equilibrium

Milestone 6

Fix other issues & bugs in the code

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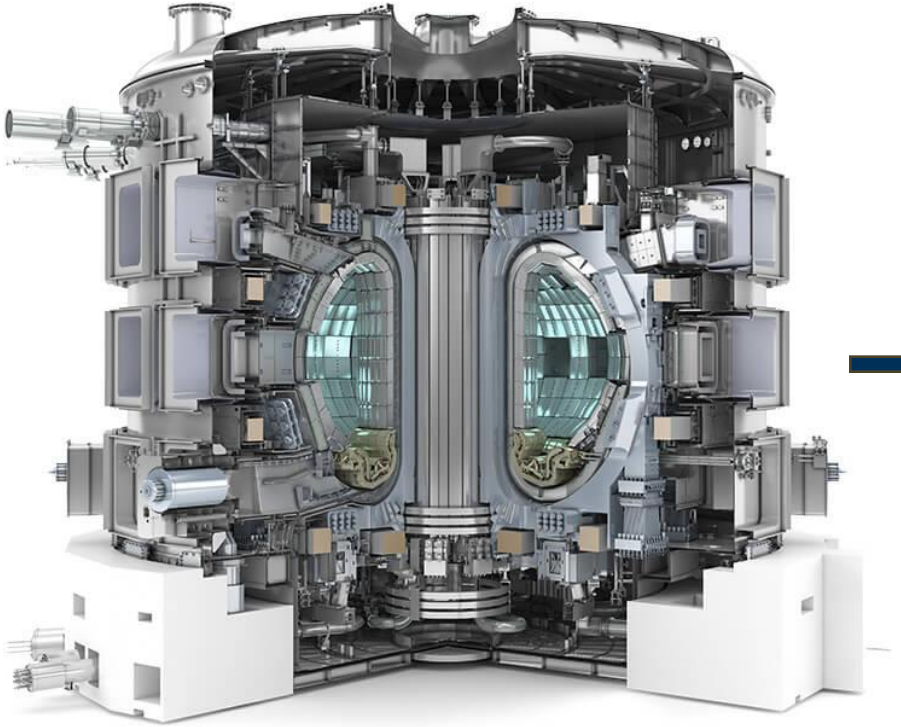
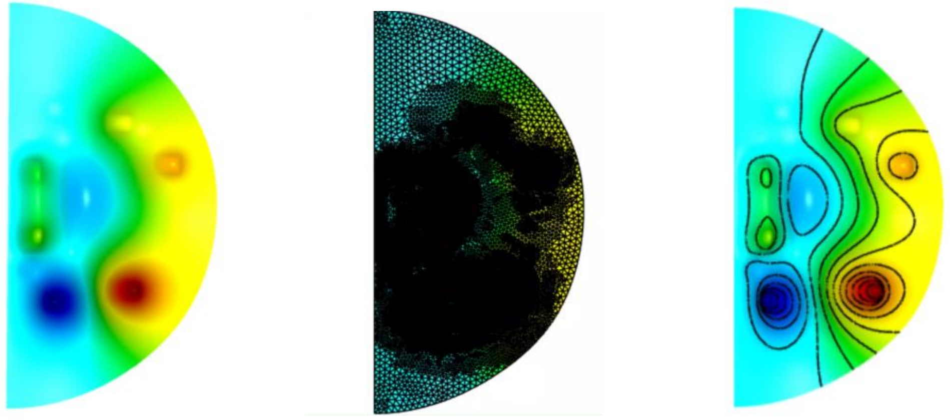
Milestone 2 Results

Determine & visualize ITER's magnetic flux



Cross-sectional view of the plasma chamber and magnetic coils



Regular View | Mesh View | Contour View

A triangular mesh was used here for flexibility in modeling the complex geometry. However, a quadrilateral structured mesh is much preferred in engineering practices.

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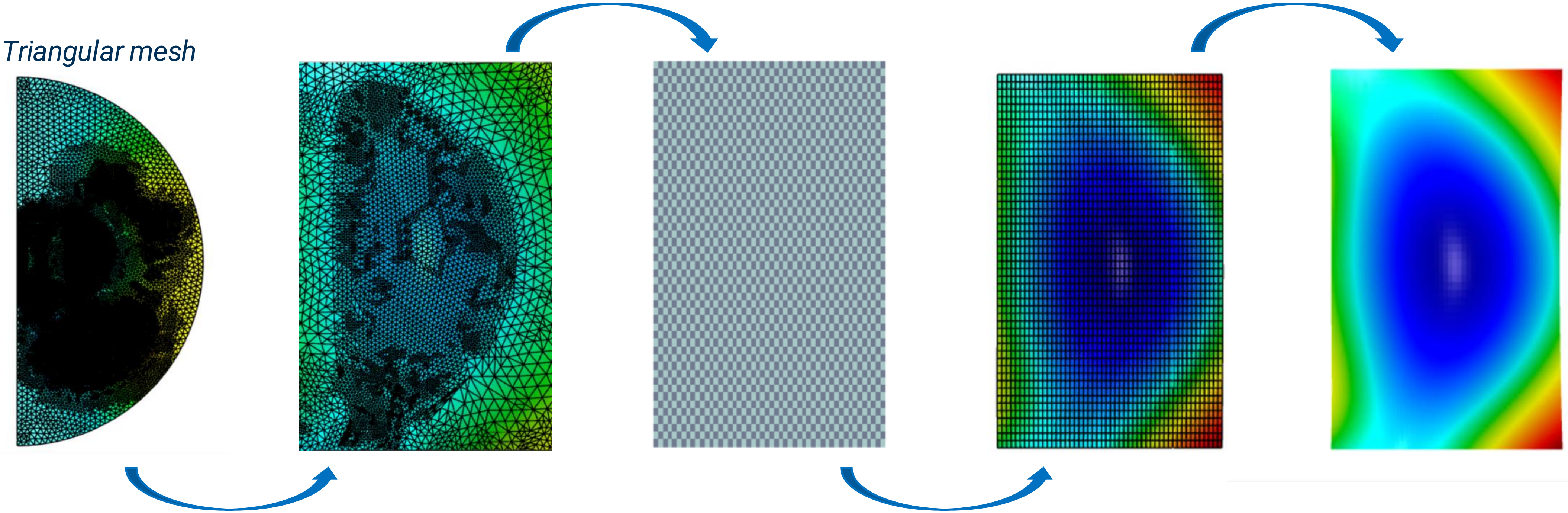
Milestone 4 Results

Generate a Mesh and Interpolate the Solution

Generate a quadrilateral mesh matching the dimensions of the isolated plasma region

Solution without the mesh

Triangular mesh



Isolate plasma region nodes

Interpolate the solution onto the nodes of the quadrilateral mesh

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Milestone 5

- Background
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Add a writer for EFIT data

Using G-EQDSK file format, develop an EFIT writer, code used to reconstruct plasma equilibrium

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Why?

Standardization
Widely used standard in the plasma fusion industry

Portability
Allows for easy sharing of results

Centralization
Important parameters are gathered in one location

Janani Murugan

Milestone 5: Technical Approach

- Background
- Goal
- **Milestones**
- Next Steps

Gather Parameters

- ✓ Computational grid metrics
- ✓ Magnetic axis information
- ✓ Plasma state metrics
- ✓ Plasma boundary metrics
- ✓ Poloidal current and flux
- ✓ Safety factor
- ✓ Limiter grid

Contains properly formatted sub-files for each of the parameters

GEQDSK-generation.cpp

Compute other needed parameters

↓

Append all metrics

↓

Final EFIT file

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Milestone 5: Gather Parameters

Terms Extracted from MFEM

MFEM Code Variable	Documentation Definition
Header	
nx	Number of elements (cells) along the r-axis
ny	Number of elements (cells) along the z-axis
Section 1	
rdim	Width of computational domain in the R direction
zdim	Height of computational domain in the Z direction
rcentr	Reference value of R
rleft	R at left (inner) boundary
zmid	Z at middle of domain
rmagx	R at magnetic axis (0-point)
zmagx	Z at magnetic axis (0-point)
psi_ma	Poloidal flux at magnetic axis
psi_x	Poloidal flux at plasma boundary
bcentr	Vacuum toroidal magnetic field at rcentr
cplasma	Plasma current

MFEM Code Variable	Documentation Definition
Sections 2 - 7	
pres	Plasma pressure
pprime	Gradient of plasma pressure
Section 8	
nbdry	Number of points in the boundary grid
nlim	Number of points in the limiter grid
Section 9	
rbdry_zbdry	R of boundary points
rbdry_zbdry	Z of boundary points
rlim_zlim	R of limiter points
rlim_zlim	Z of limiter points

Reference: https://freeqdsk.readthedocs.io/en/stable/geqdsk.html

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Milestone 5: Gather Parameters

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Terms Generated Through Computation

MFEM Code Variable	Documentation Definition	Method of Calculation
Sections 2 - 7		
fpol	Poloidal current function	f_x + alpha (psi-psi_x)
ffprime	1D array	alpha*fpol
qpsi	Safety factor	Take line integral over several contour lines

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Milestone 5: Safety Factor Calculations

- Background
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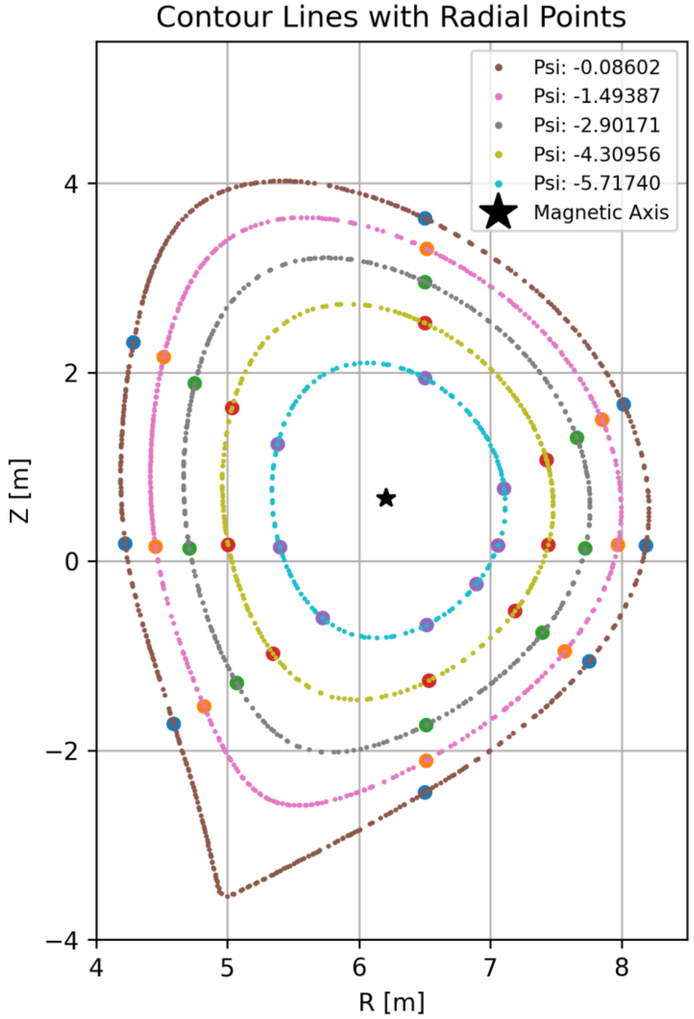

Plot with 5 psi contours, each with 8 radially aligned points

Determine a range of psi values spanning from the magnetic axis to the boundary

↓

For each psi, find the corresponding closed contour line in the plasma solution

↓

On the line, determine the position of x number of equally spaced points

↓

For each point, obtain its coordinates, the toroidal magnetic field, and magnetic field in theta direction

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Perform a line integral around the contour to get the safety factor for the given psi

Repeat for all psi values

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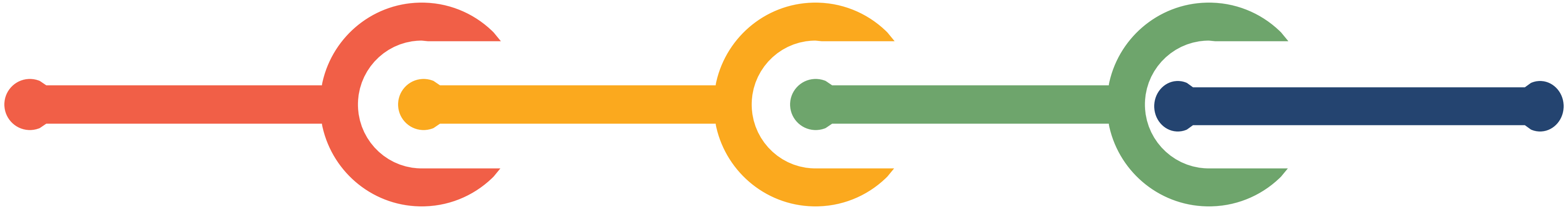
Next Steps



Conduct Testing

Test EFIT writer

Continue Development

Add more functionalities

Expand to Other Tokamaks

Thank You!

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