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Stellarator Simplification using permanent magnets

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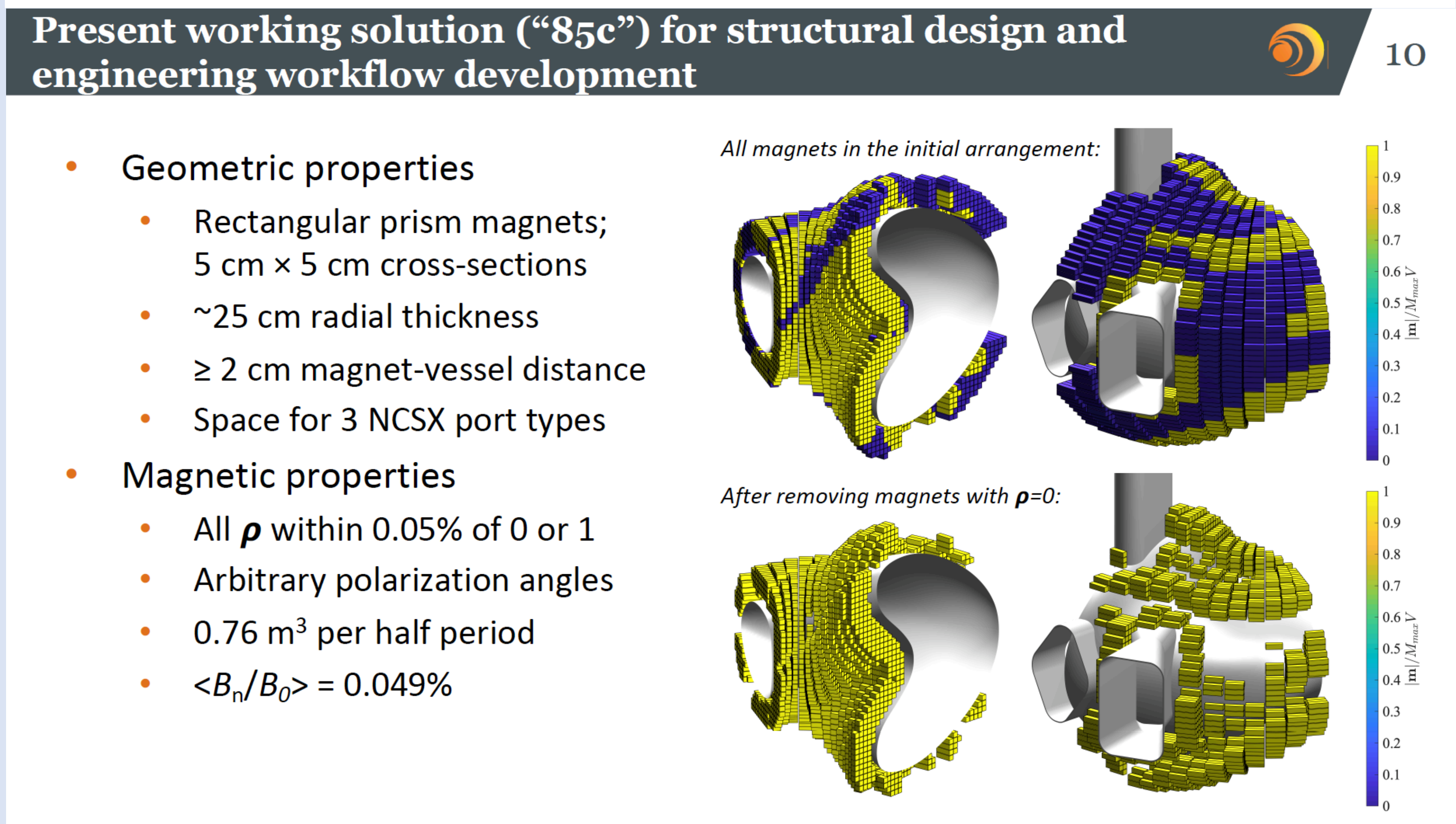
ABSTRACT

- A new project has been launched to demonstrate the technical feasibility of using permanent magnets to provide the shaping fields for a quasi-axisymmetric stellarator.
- New physics design tools have been developed to describe to positions and polarization orientations of the magnets
- The equilibrium is chosen so as to reuse parts (vacuum vessel and toroidal field coils from the NCSX experiment
- Virtual engineering is used do rapidly develop structural models
- Discussion of new error field identification techniques is presented

BACKGROUND

- A recent PRL by P. Helander, *et al.,* describes the possibility of using permanent magnets, in tandem with toroidal field coils, to provide the 3D shaping fields for a stellarator
- This spawned several publications that investigated methods for actually designing such a system
- These design codes have been employed within a virtual engineering framework to enable rapid design optimization.
- Errors are analyzed using a new error identification scheme.



Present working solution ("85c") for structural design and engineering workflow development

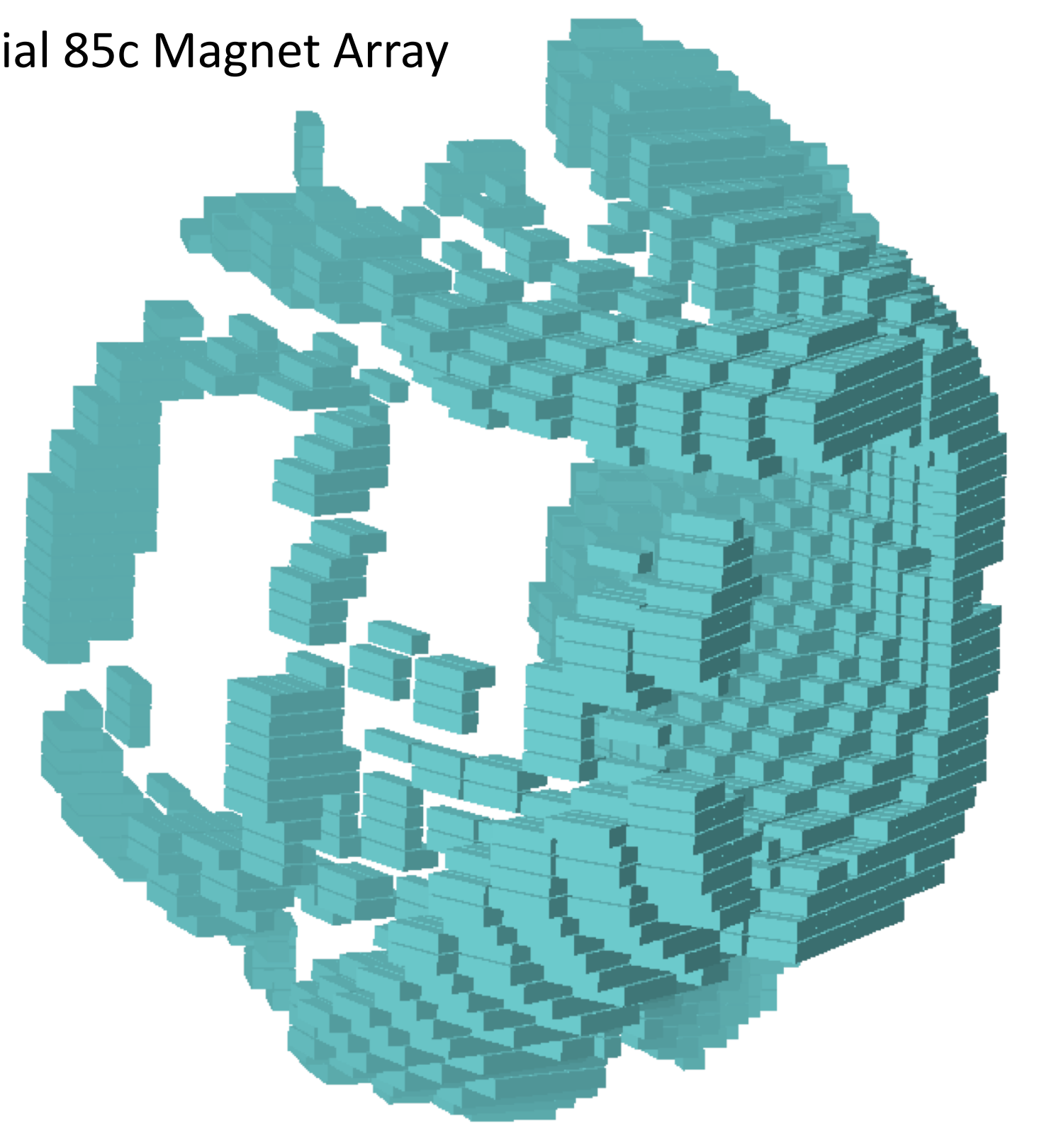
- Geometric properties
  - Rectangular prism magnets; 5 cm × 5 cm cross-sections
  - ~25 cm radial thickness
  - ≥ 2 cm magnet-vessel distance
  - Space for 3 NCSX port types
- Magnetic properties
  - All ρ within 0.05% of 0 or 1
  - Arbitrary polarization angles
  - 0.76 m^3 per half period
  - $\langle B_n/B_0 \rangle$ = 0.049%

All magnets in the initial arrangement:

After removing magnets with $\boldsymbol{\rho}$*=0:*

Design Objectives for Conceptual Design

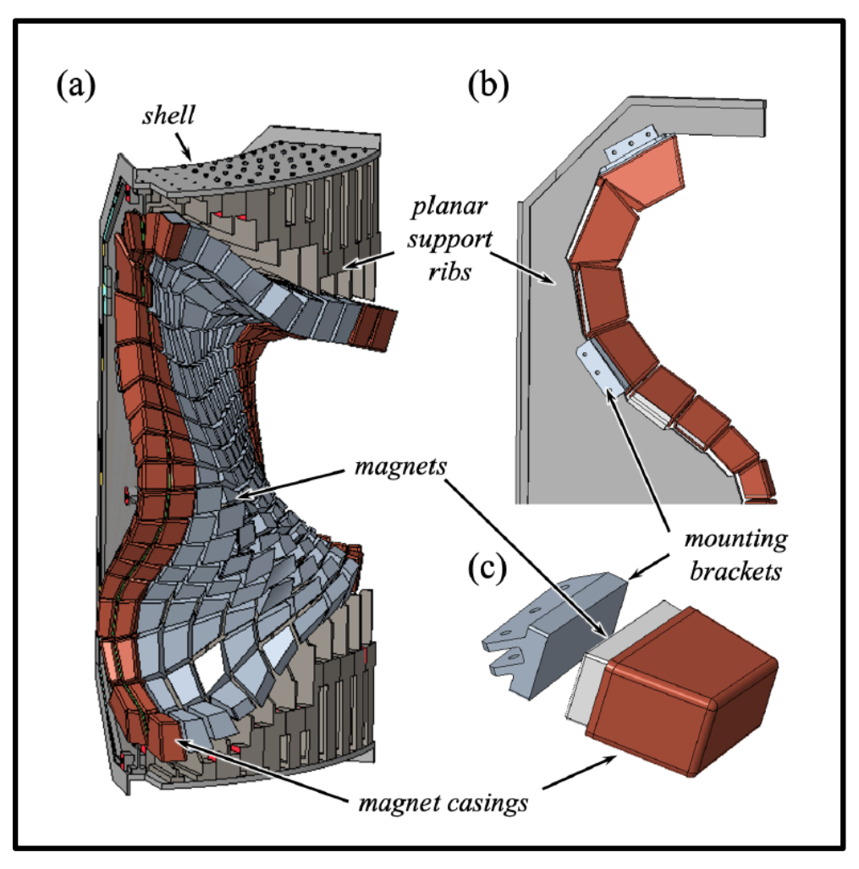
- Create a structure to support the Trial 85c Magnet Array
- Determine requirements for future magnet arrays
  - Array compatible with structural design concept
  - Vacuum Vessel Clearance
  - TF Coil Clearance
- General Notes:
  - Magnet array is formed from a regular grid in a cylindrical coordinate system.
  - Individual permanent magnets have see loads between 10 - 700 lbs

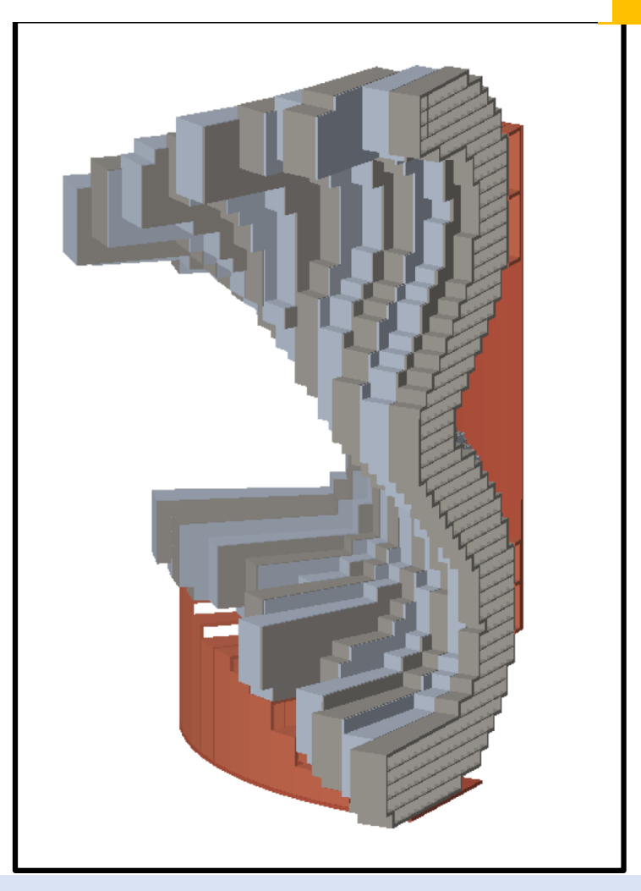


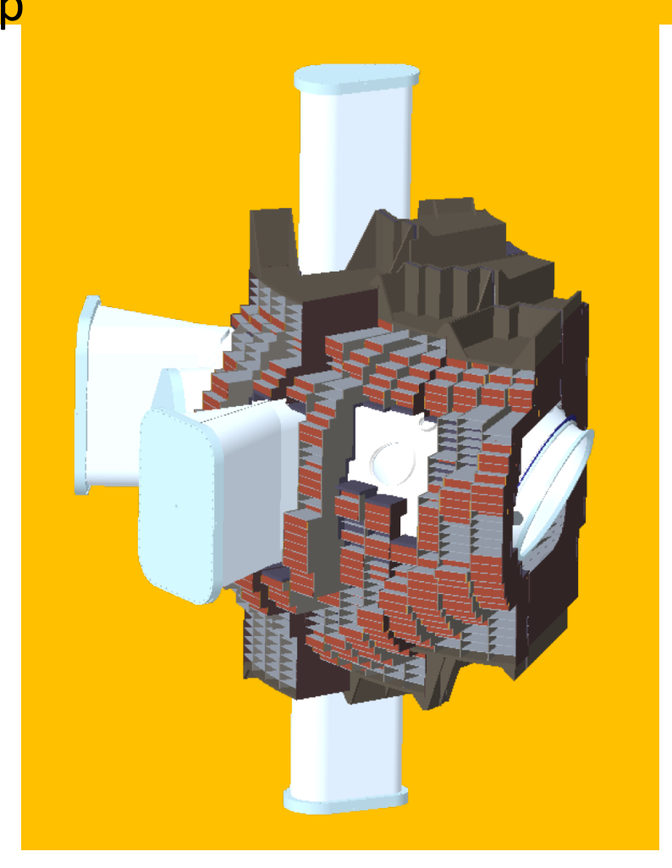
Trial 85c Magnet Array

Designs Considered

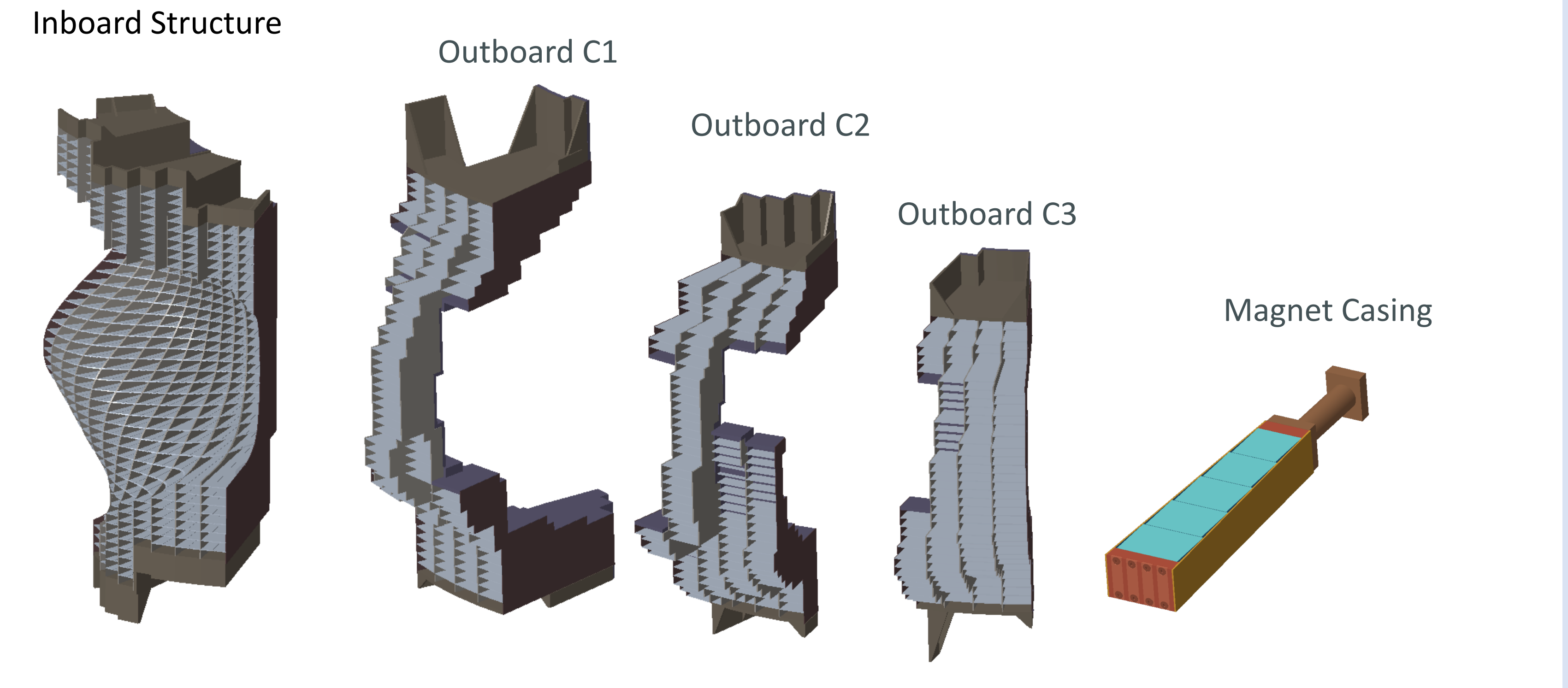
- Magnets Normal to Vessel
  - Complicated geometry produced voids in array that reduced magnet strengths
  - Design difficult to assemble
- Honeycomb array
  - Large forces to assemble wedges
  - Risk of ejecting magnets while building
  - Tolerance stack up between wedges
- Post-office-box
  - Magnets assembled into casings
  - Casings controlled throughout insertion process
  - Fewer large assemblies to handle
  - Plate design improves tolerance stack up





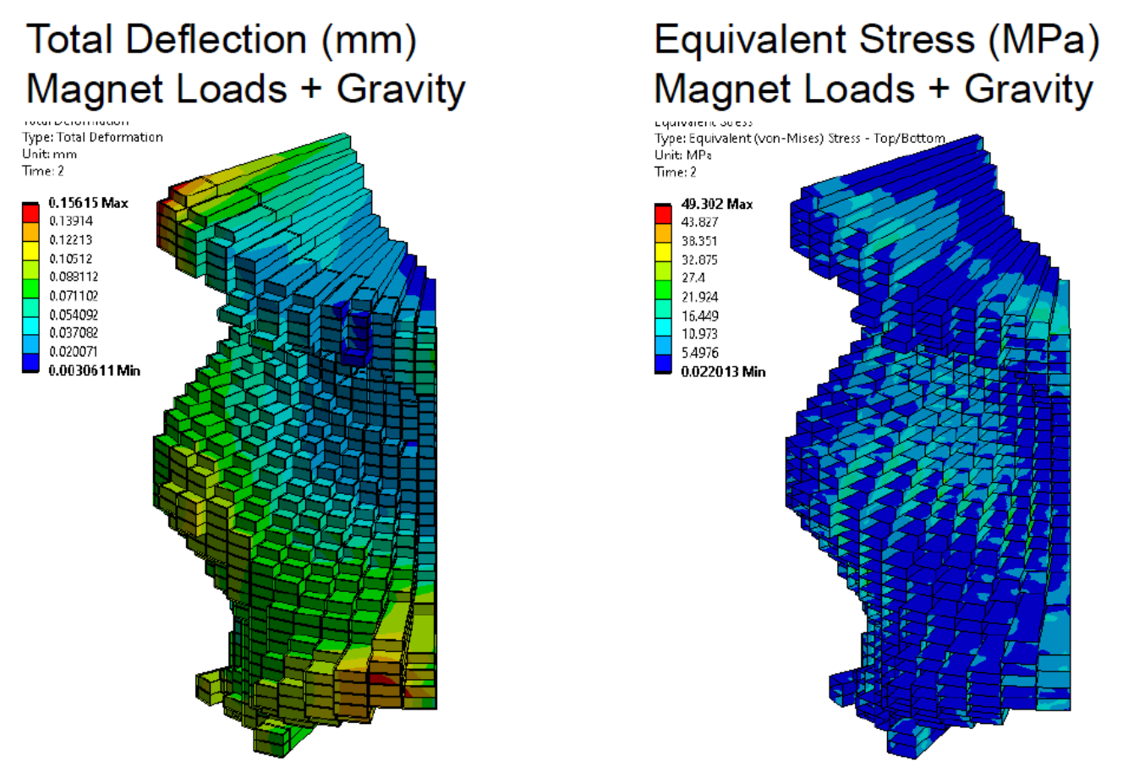


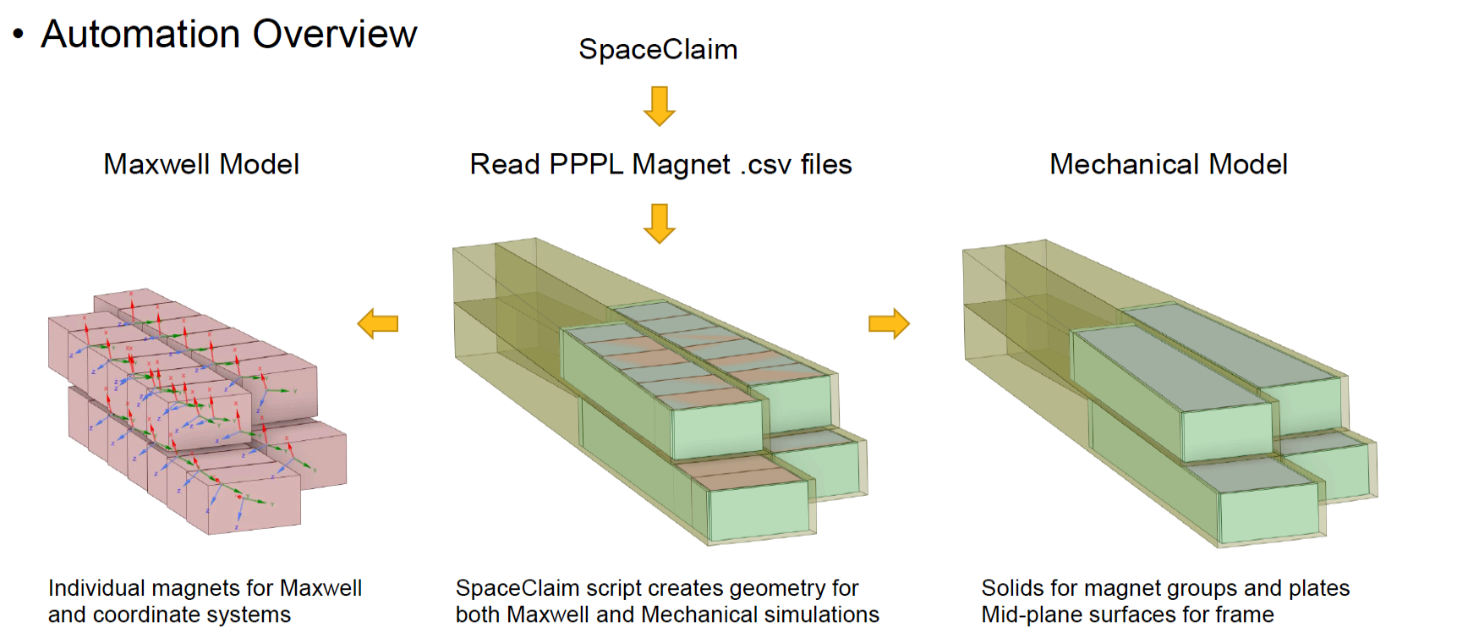
Key Components of the Design



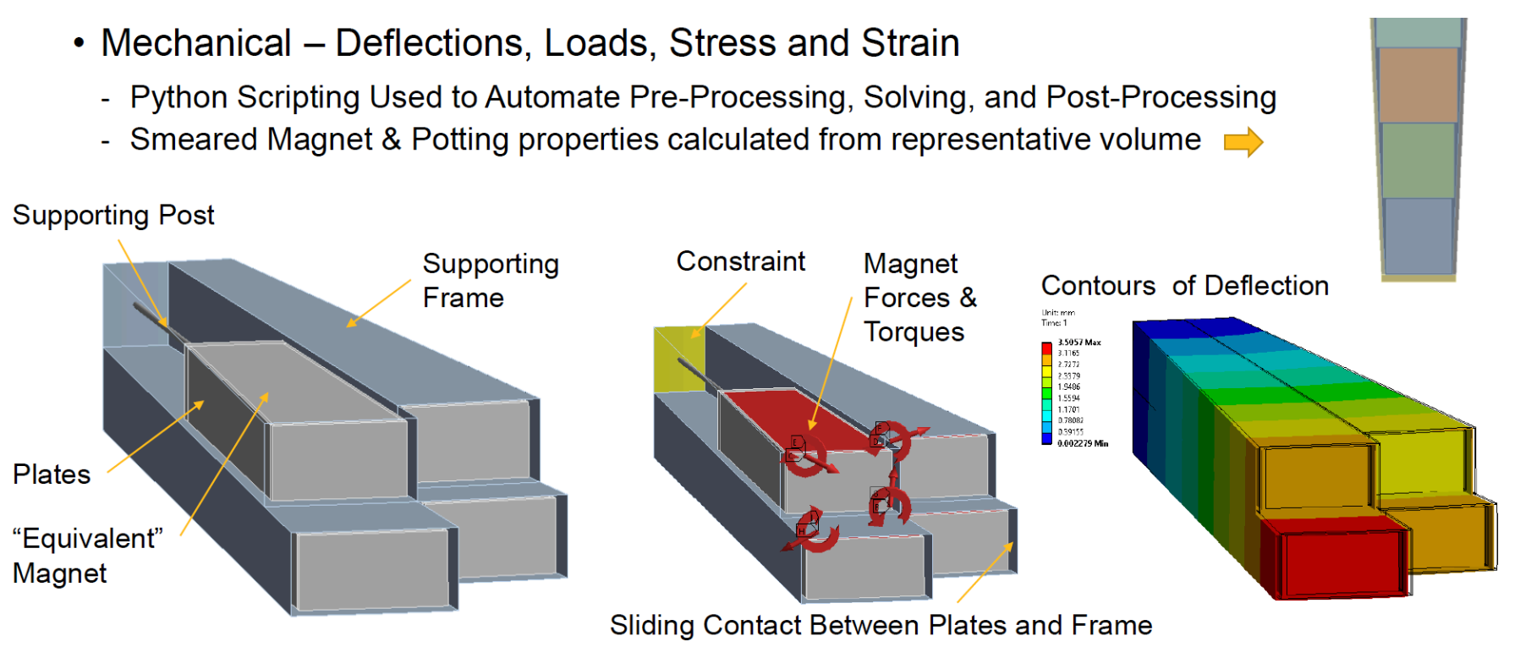
Permanent Magnet Structure Generated Through Virtual

- Starting with magnet locations from physics definition file
- Virtual engineering defines entire mechanical structure with fields from magnets with real physical material characteristics
- Enables rapid design variations for optimization

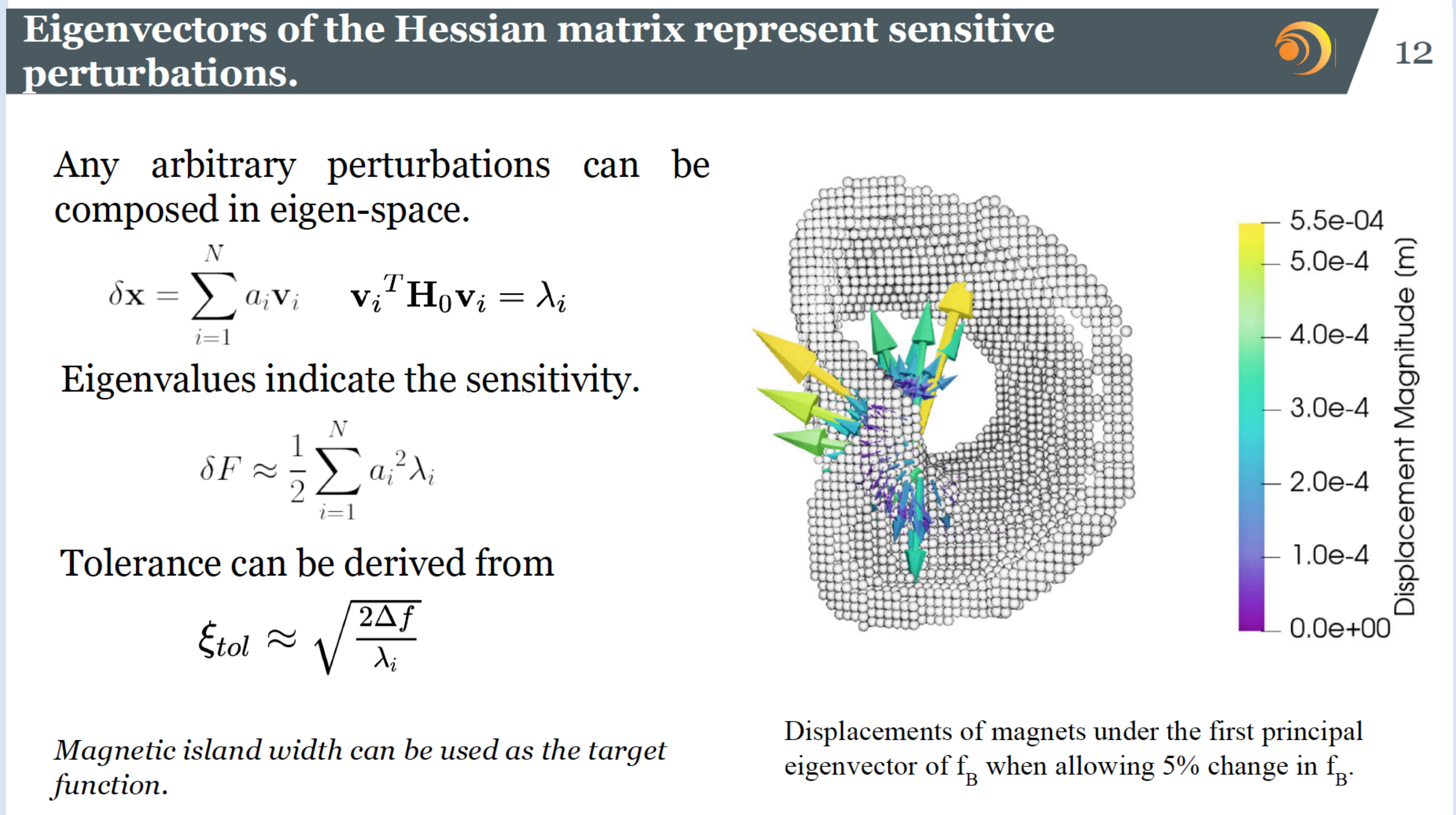




- Automation Overview



- Mechanical – Deflections, Loads, Stress and Strain
  - Python Scripting Used to Automate Pre-Processing, Solving, and Post-Processing
  - Smeared Magnet & Potting properties calculated from representative volume



Eigenvectors of the Hessian matrix represent sensitive perturbations.

Any arbitrary perturbations can be composed in eigen-space.

$$\delta\mathbf{x} = \sum_{i=1}^{N} a_i \mathbf{v}_i \qquad \mathbf{v_i}^T \mathbf{H}_0 \mathbf{v_i} = \lambda_i$$

Eigenvalues indicate the sensitivity.

$$\delta F \approx \frac{1}{2}\sum_{i=1}^{N} a_i{}^2 \lambda_i$$

Tolerance can be derived from

$$\xi_{tol} \approx \sqrt{\frac{2\Delta f}{\lambda_i}}$$

Magnetic island width can be used as the target function.

Displacements of magnets under the first principal eigenvector of f_B when allowing 5% change in f_B.

CONCLUSION

- A project is underway to build a ½-period of the shaping magnets for a 3 period quasi-axisymmetric stellarator that is envisioned to be built in the near future.
- The purpose of this project is to demonstrate the technology can create the appropriate fields within the required accuracy.
- The project is currently at the conceptual design level and is moving into the preliminary design phase.
- Construction is planned to start in early 2022.
- Methods for the design have been developed and error field identification has been performed.