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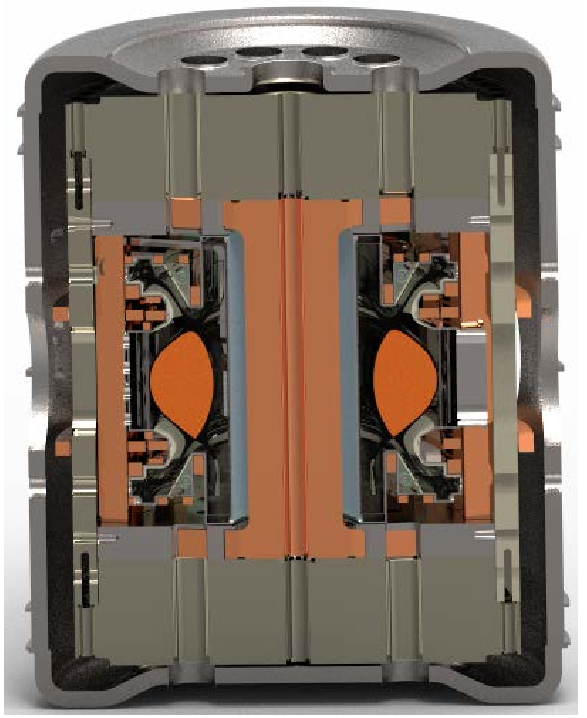
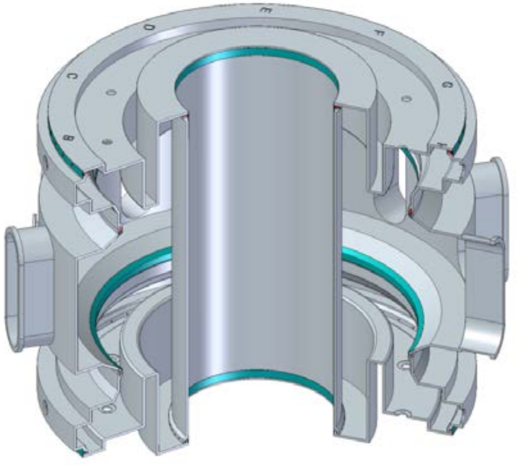
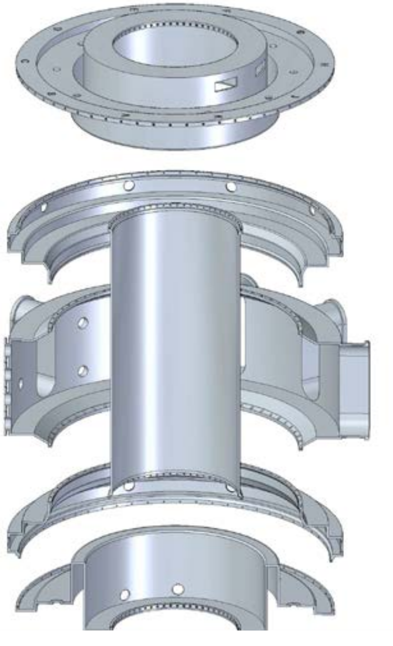
Structural Analysis of the Advanced Divertor eXperiment's Proposed Vacuum Vessel







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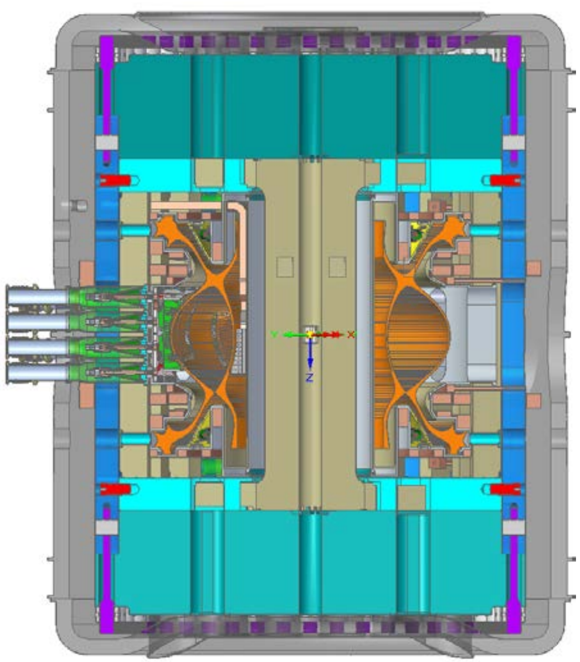
Introduction

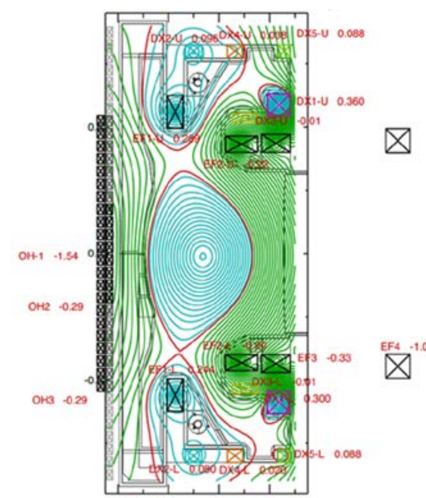
- Fusion Power could provide a zero carbon clean energy source
- Magnetic Fields can be used to hold and compress hot plasma – like the sun – in a device called a tokamak.
- This process is well understood

  high magnetic field => hot, dense plasma => magnetic fusion

Tokamak with plasma shown in center



Magnetic Fields used to create a “bottle” to hold and compress the hot plasma

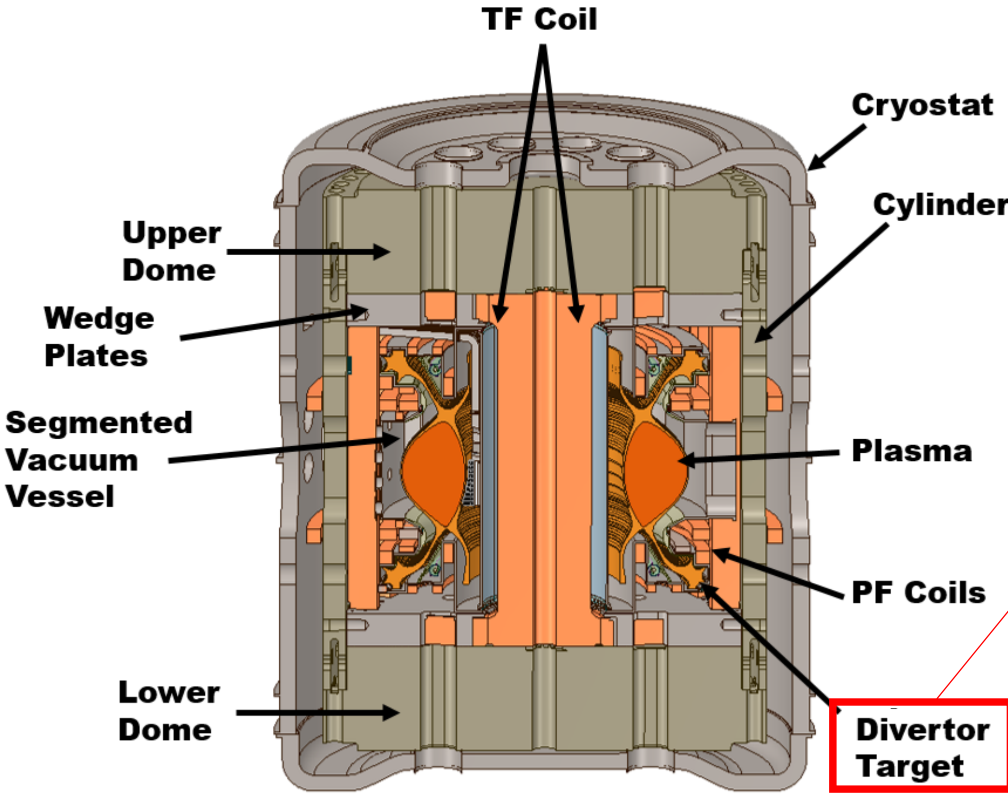


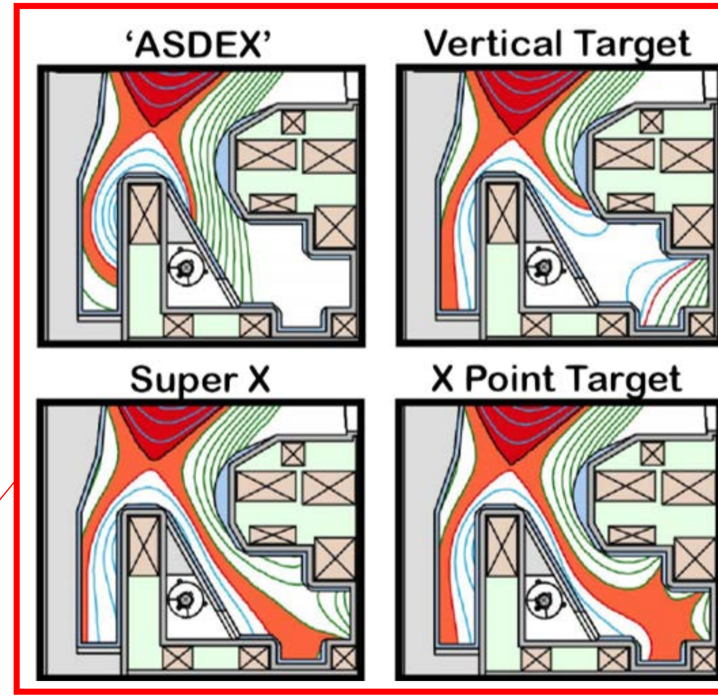
New Machine Proposal

- MIT and collaborators are proposing the ***Advanced Divertor and RF tokamak eXperiment*** (ADX) as a new facility to test technologies for
  - accepting heat exhaust (divertor) and
  - driving plasma current (RF antennas)

  at reactor relevant power densities and heat fluxes in compact device.
- COMSOL is used to analyze loads and stresses on the new vacuum vessel design.

ADX designed to test multiple divertor configurations





- Divertor accepts heat and particle exhaust from the core plasma.
- More advanced designs are needed for a fusion reactor.
- ADX will test multiple advanced divertor configurations designs at reactor level heat and particle exhaust

Massachusetts Institute of Technology

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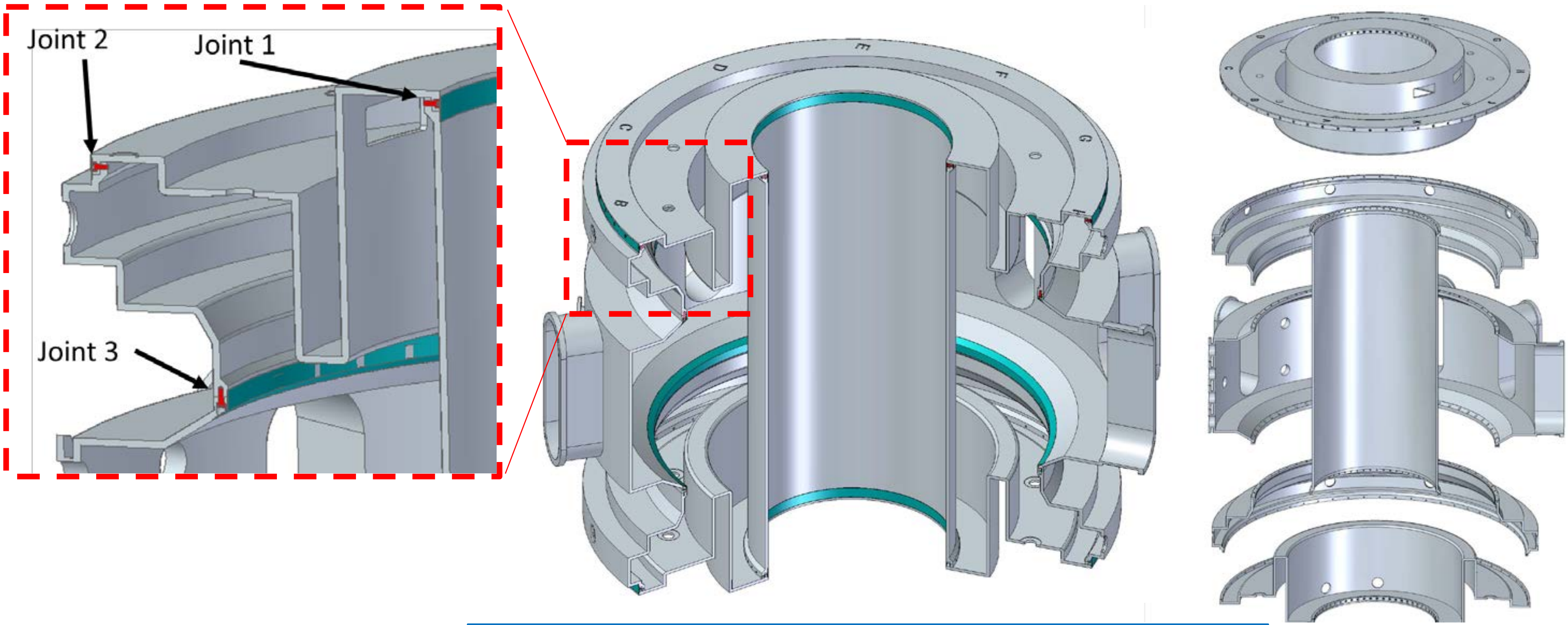
ADX

ADX vessel is comprised of an inner cylinder and 5 shells bolted together



This design must survive the loads induced in it during a plasma disruption.

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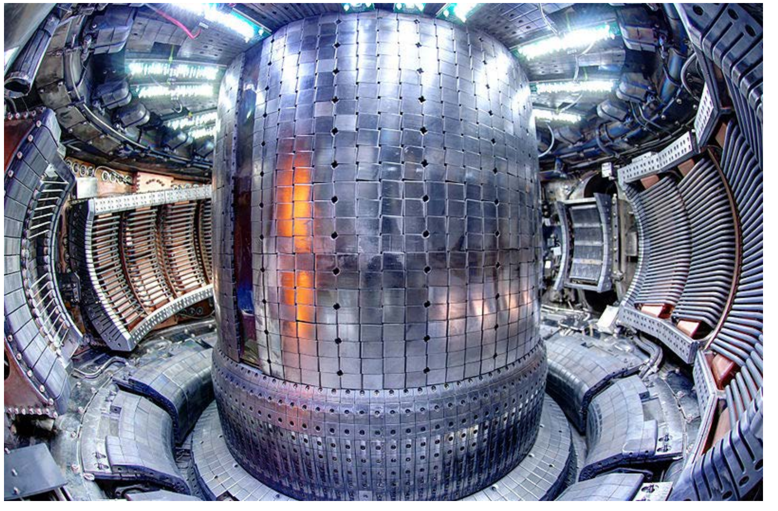
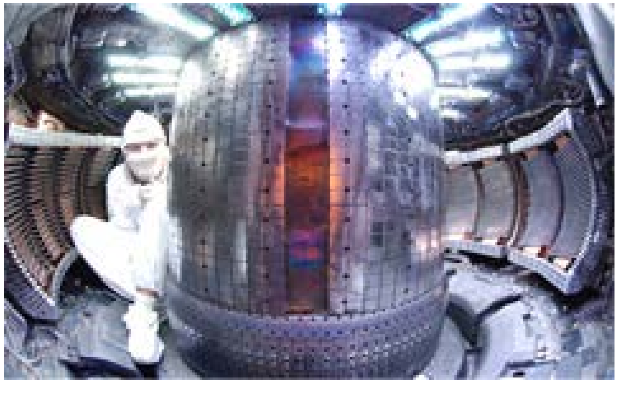
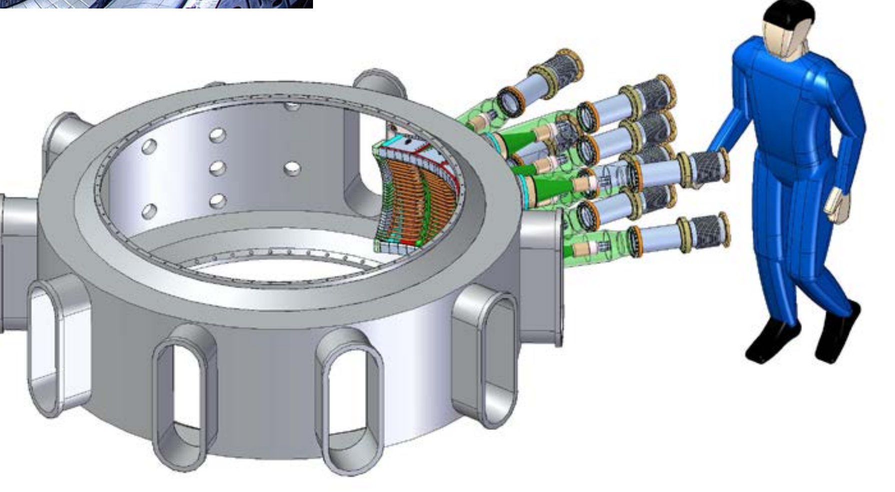
Advantageous for initial installations







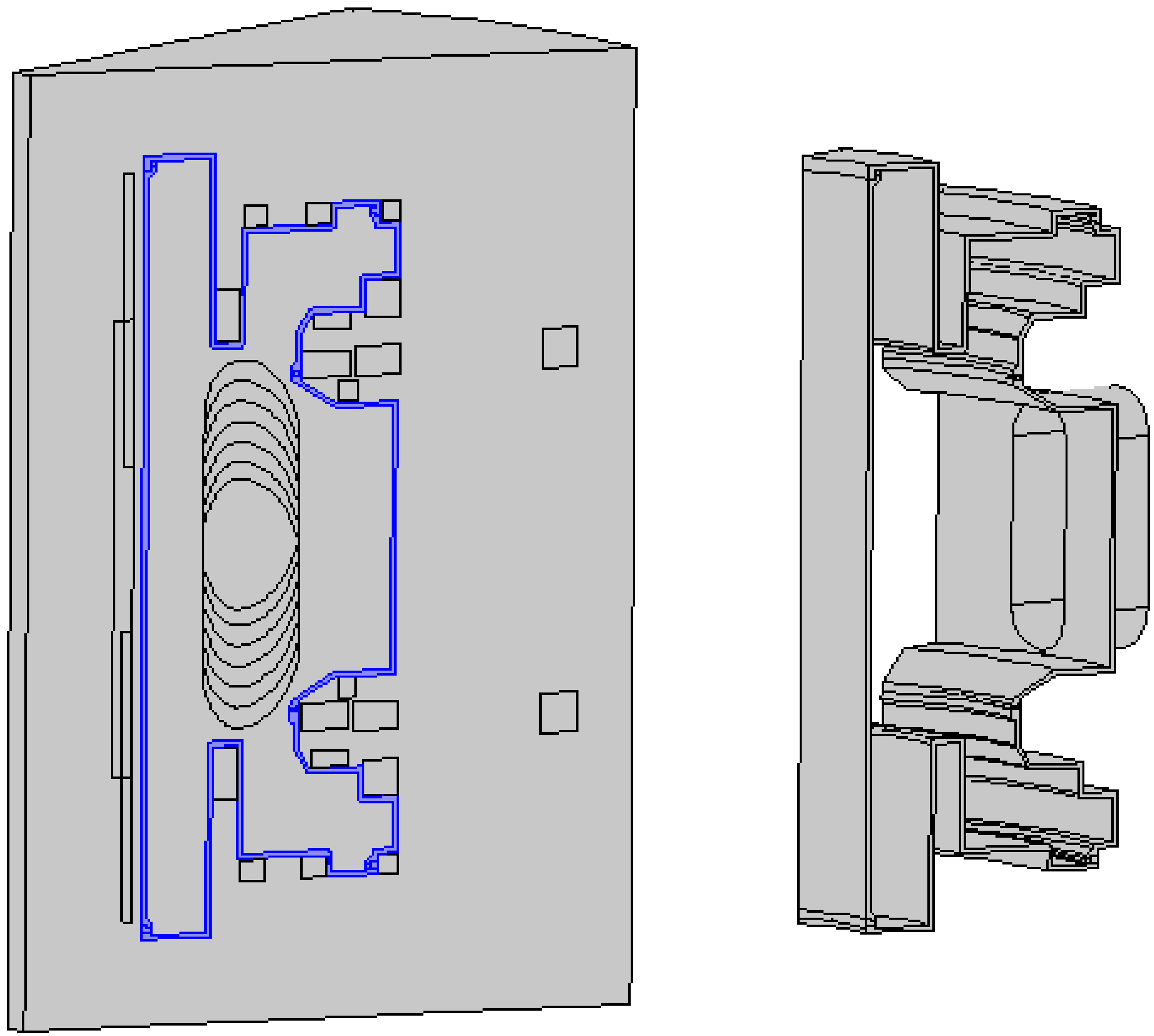
COMSOL used to predict Loads and Stresses During a Disruption

- Magnetic Fields (mf) physics used to simulate the plasma collapse and predict the resultant fields, eddy currents and Lorenz forces.
- A Vertical Displacement Event (VDE) where the plasma moves from its equilibrium position before losing its current is chosen as the design scenario.
- COMSOL is used to simulate both the plasma motion and the current quench.
- Forces are then mapped to the solid mechanics module where stresses and displacements are predicted

Vacuum Vessel

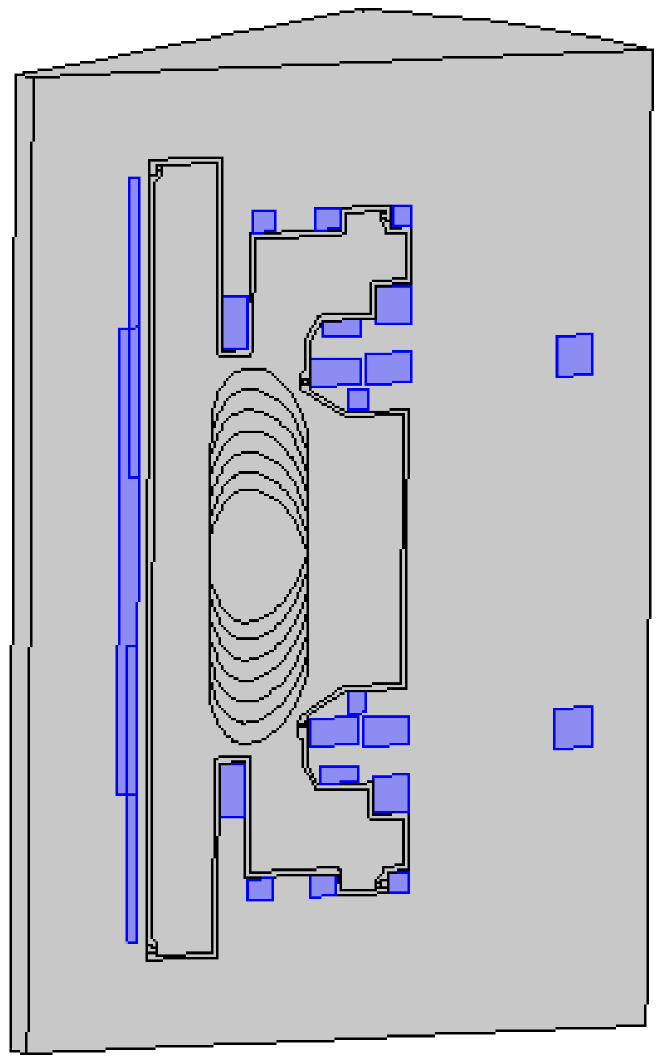
Material: Inconel 625
(low conductivity,
high strength)

Need to determine
loads, stresses and
displacements during a
plasma disruption

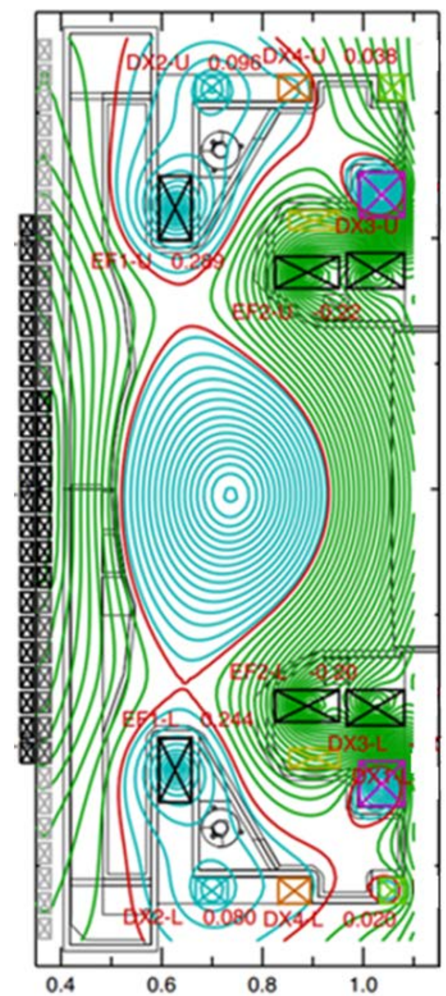


Poloidal Field Coils

Coil Currents needed to hold plasma in equilibrium are provided from an ACCOME simulation and input to COMSOL as External Current Density

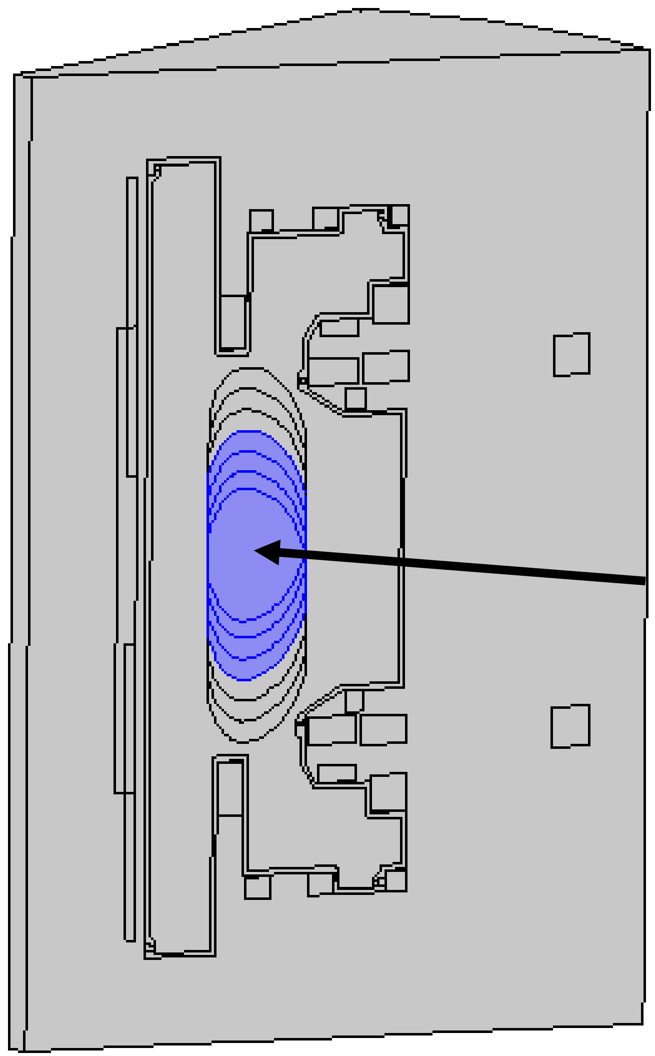


ACCOME SIMULATION



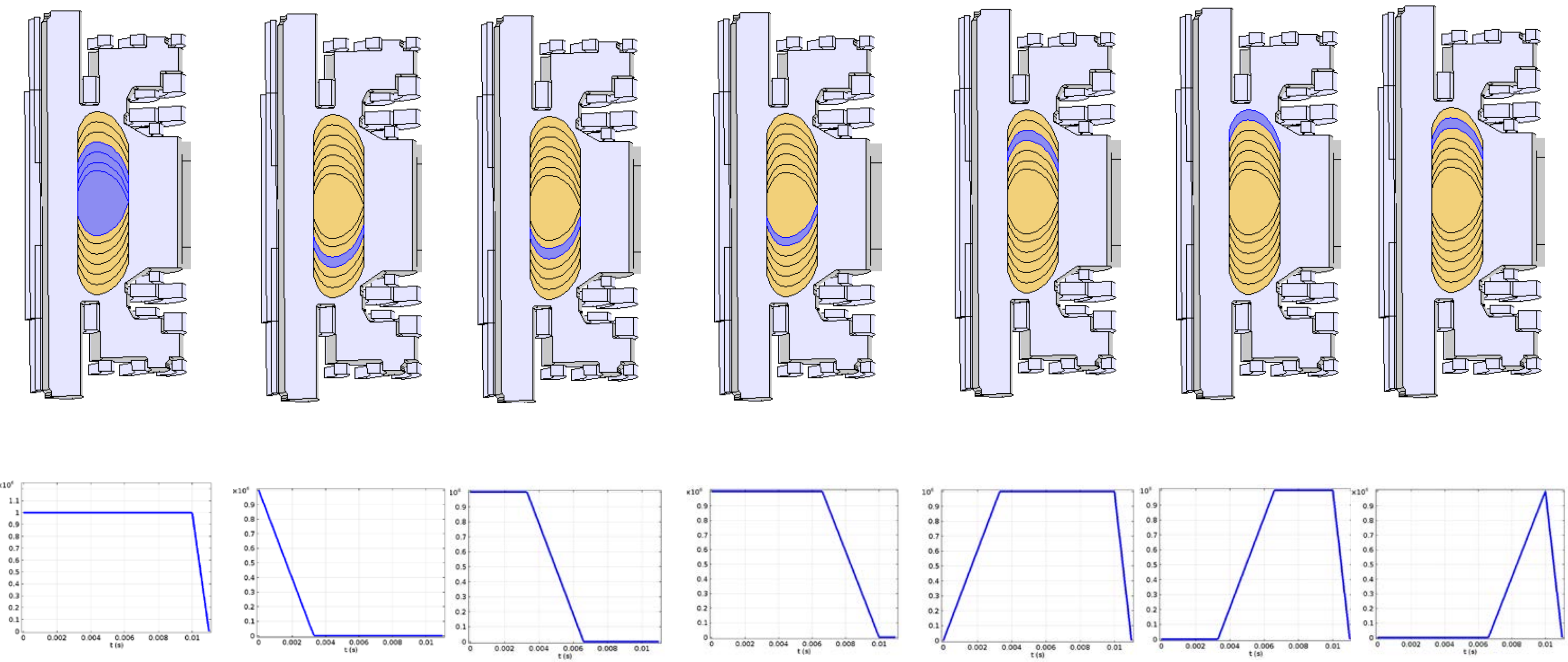
Plasma

- The ADX plasma is carrying 1.5 MA of current.
- During a vertical displacement event (VDE) the plasma drifts upward for 10 ms and then loses all of its current in 1 ms.
- This causes rapidly changing magnetic fields which in turn create eddy currents and large Lorenz Forces in the surrounding conductive structures (such as the vessel)

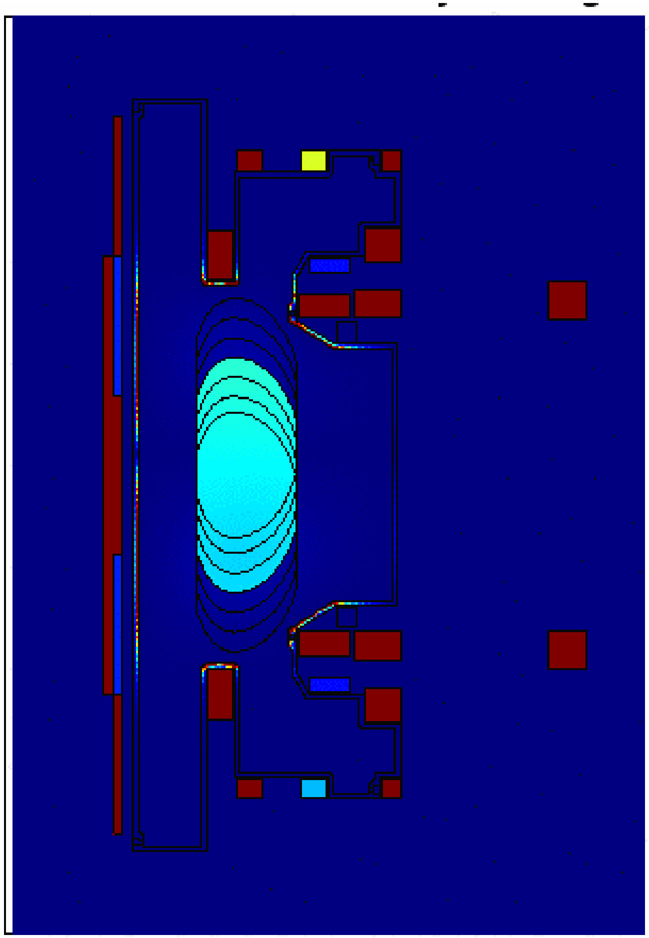


Purple Volume represents plasma position at equilibrium

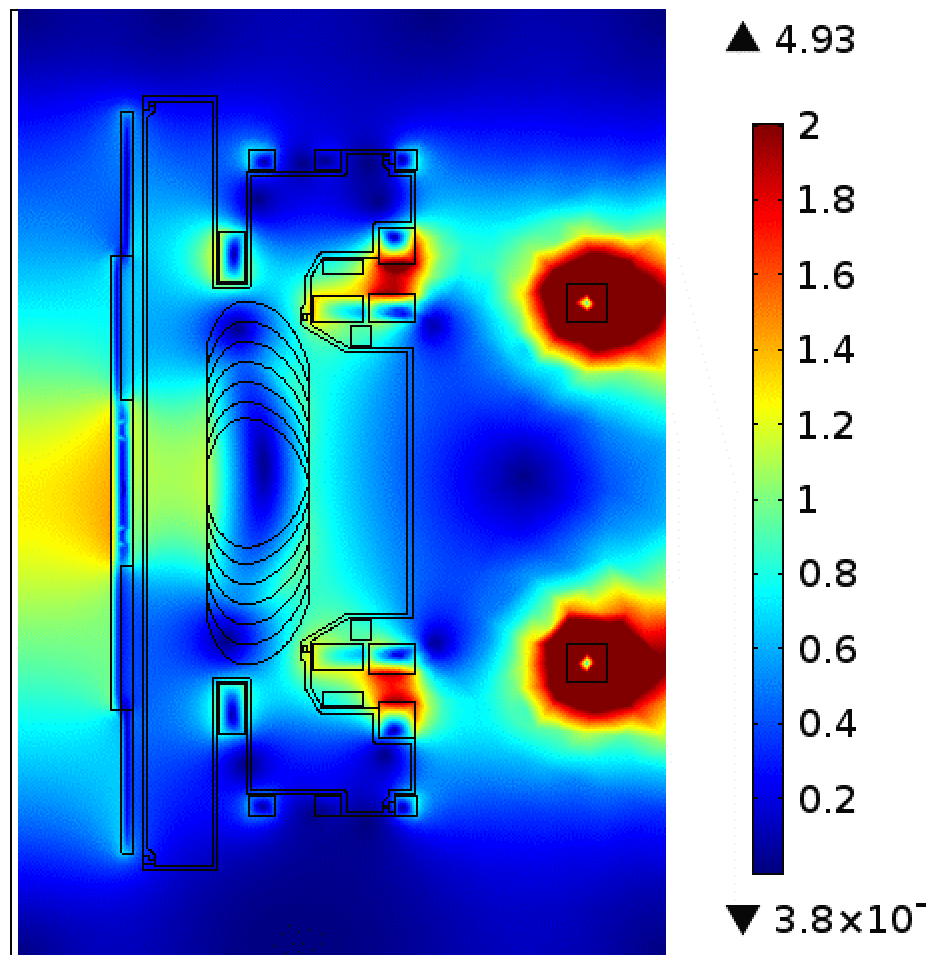
Plasma motion and Current change are modeled by applying different time histories of current to different volumes



Current Density (A/m2)
During VDE Disruption showing plasma rise, current quench and eddy currents in vessel



B Fields (T) during VDE Disruption



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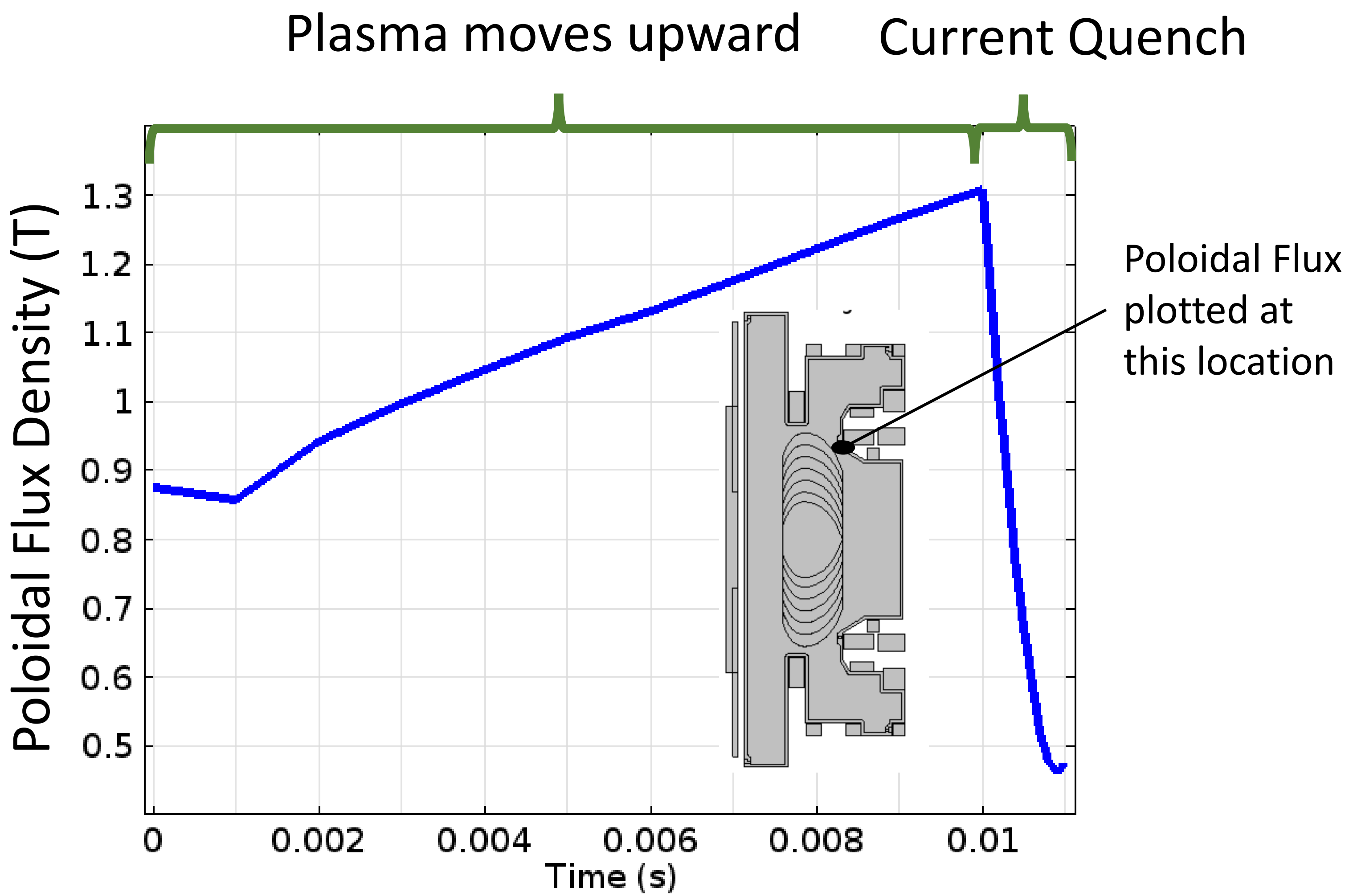
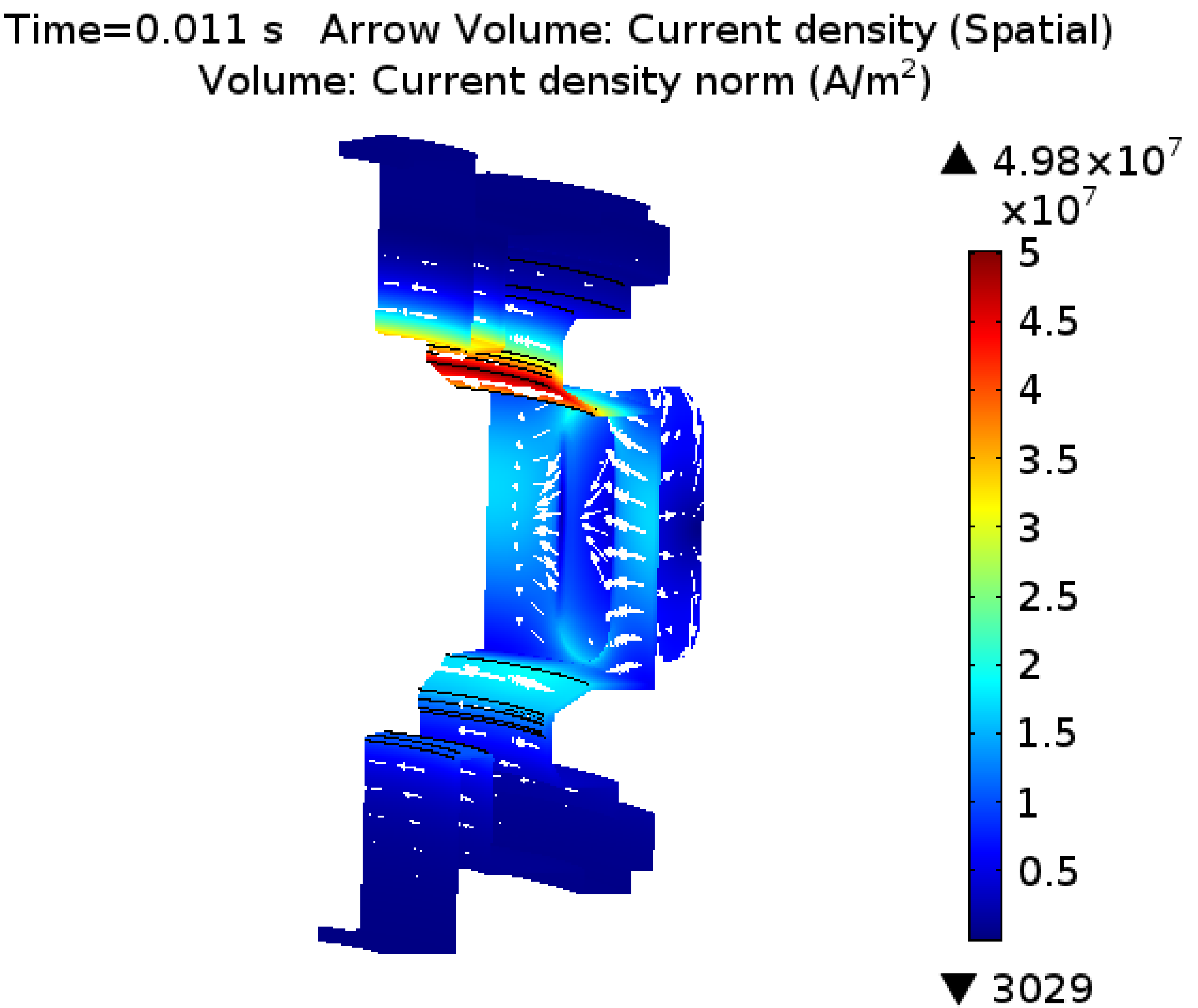
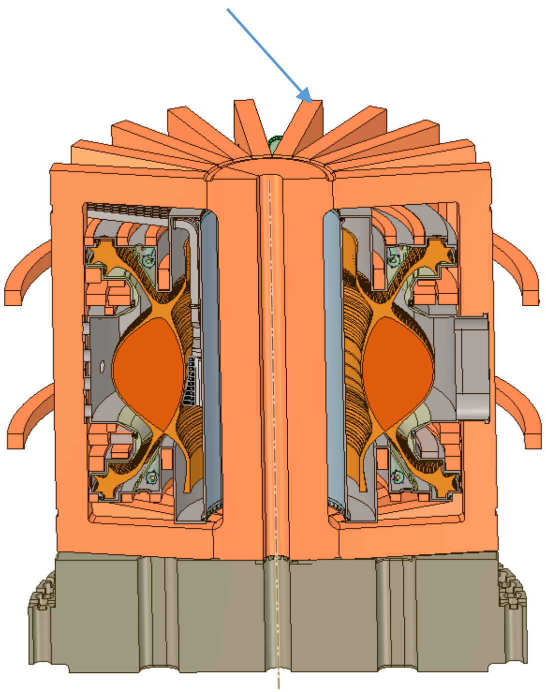
Poloidal Flux increases as plasma moves closer to vessel then drops quickly during current quench



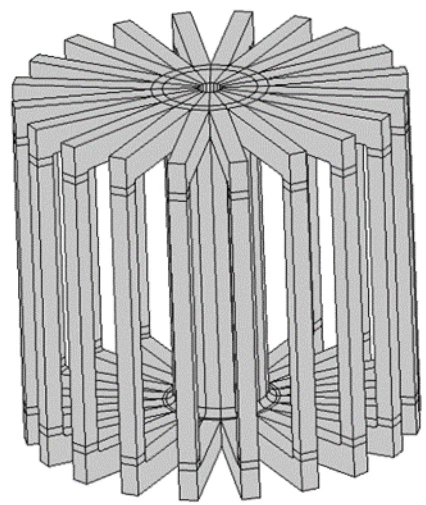
Eddy Currents Generated During Disruption

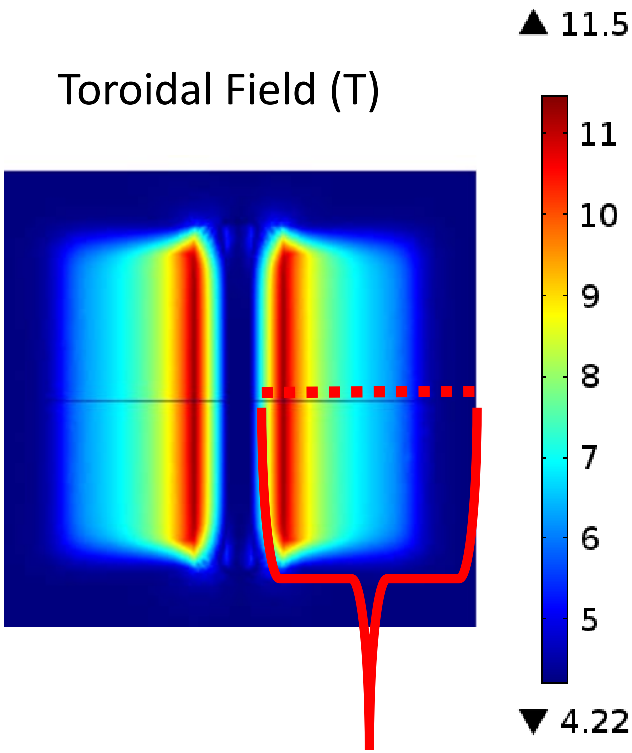


Toroidal Field Predicted in separate model and used to calculate Lorenz Forces in Solid Mechanics Module



Model of TF Coil built to predict toroidal field





Read out Field as a function of radial position and save as an interpolation table

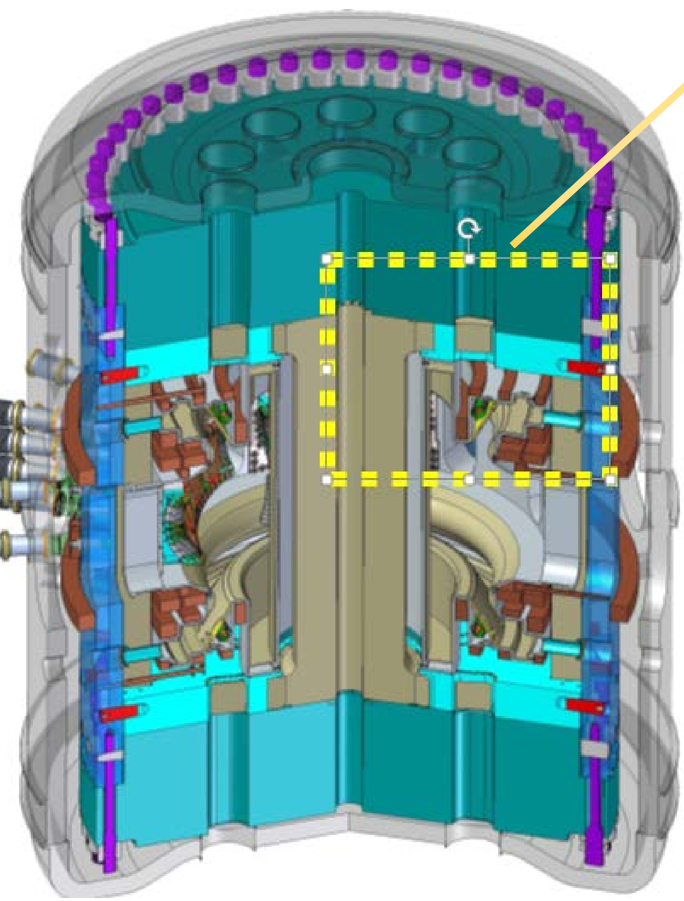
Forces Calculated as

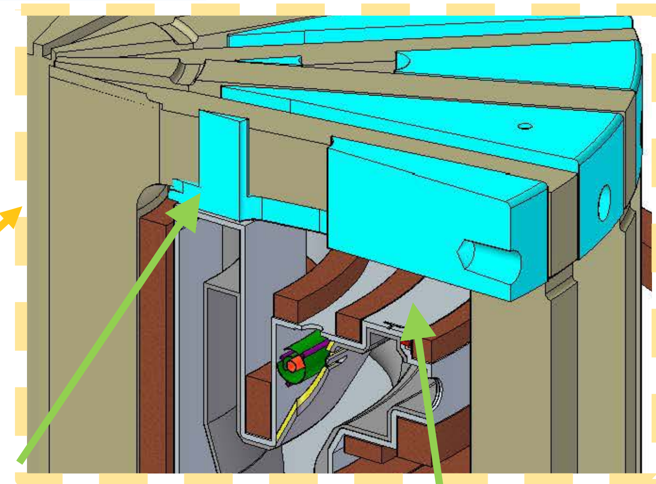
F = J x B

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} mf.Jx \\ mf.Jy \\ mf.Jz \end{bmatrix} \times \begin{bmatrix} mf.Bx \\ mf.By + B_{ToroidalTable}(r) \cdot \cos(\theta) \\ mf.Bz + B_{ToroidalTable}(r) \cdot \sin(\theta) \end{bmatrix}$$

Input to Solid Mechanics model under Body Load

Restraints in Vessel Model based on Geometry

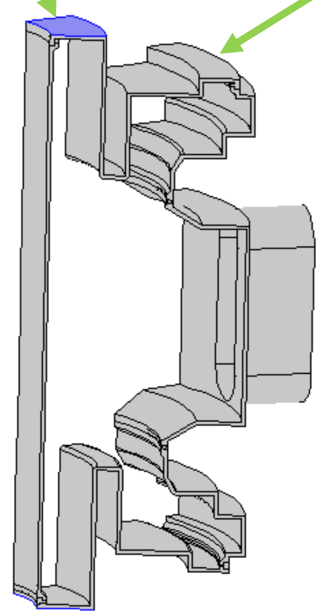


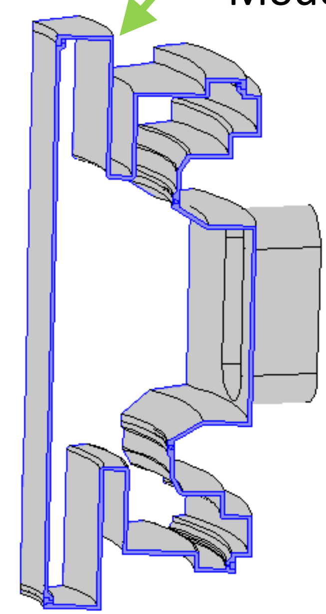


Wedge Plate holds Vessel Here

No support here

Cyclic Symmetry on Model Edges





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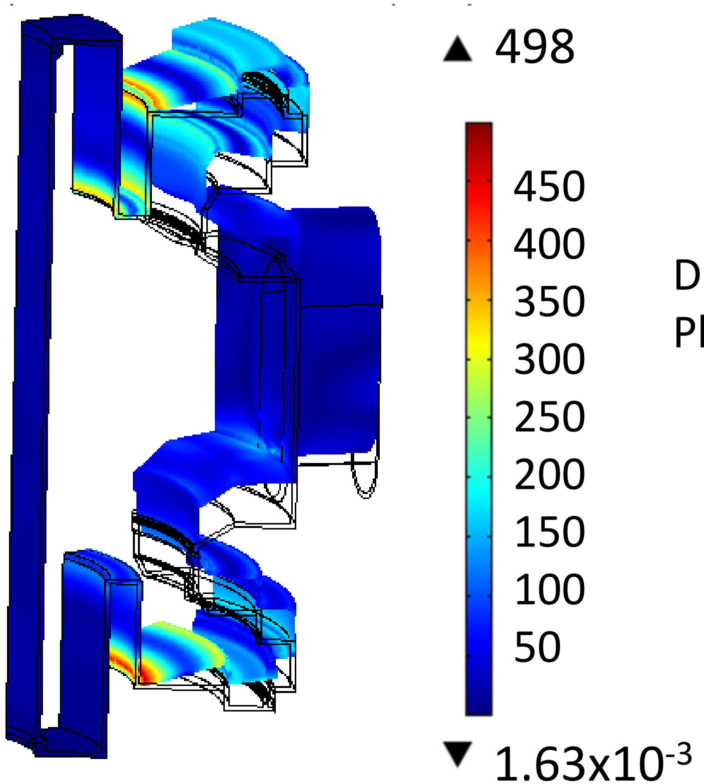
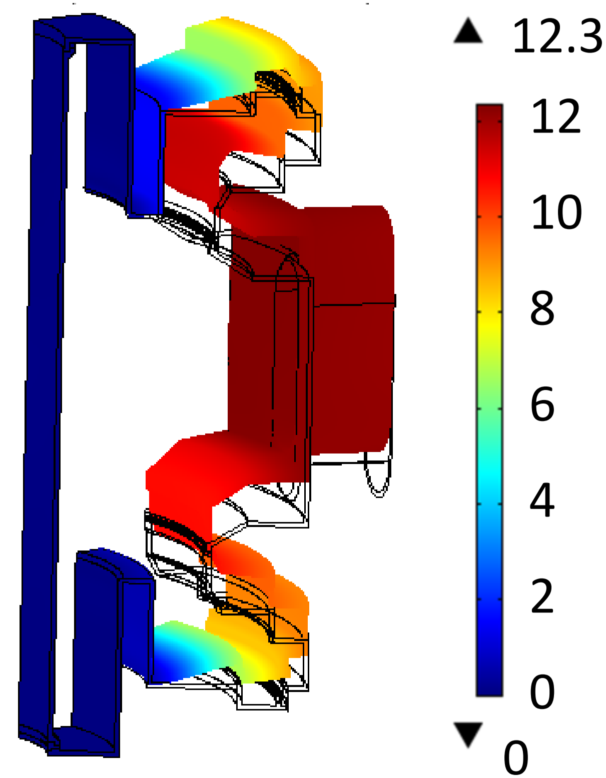
Stress and Displacement as Designed

Von Mises Stress (MPa)



Deformation Plotted 10X

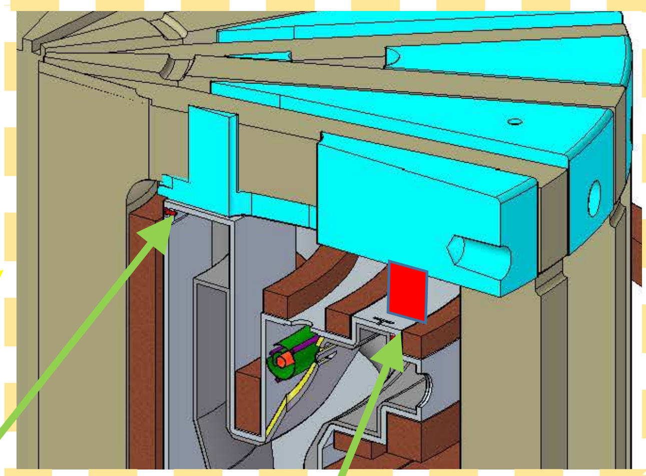
Displacement (mm)

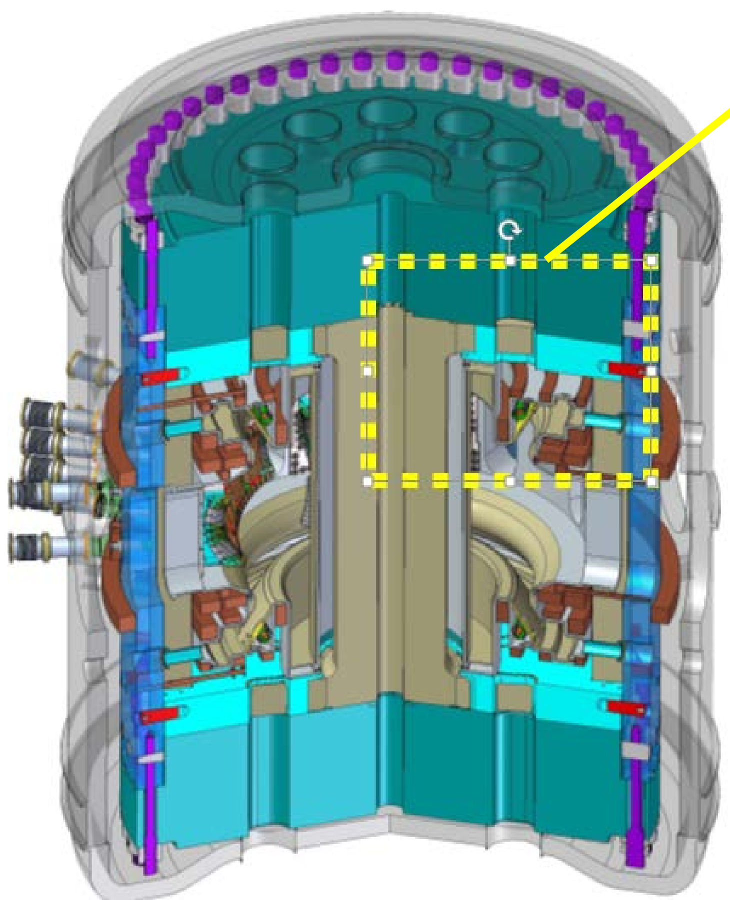


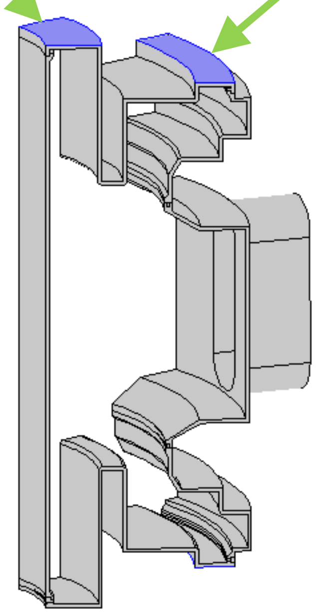
Inconel 625 Yield = 460 MPa
2/3 Yield = 306 MPa

Both stress and displacement are too large => Need to add reinforcements

Add Support Block to connect OD of Vessel to Wedge Plate



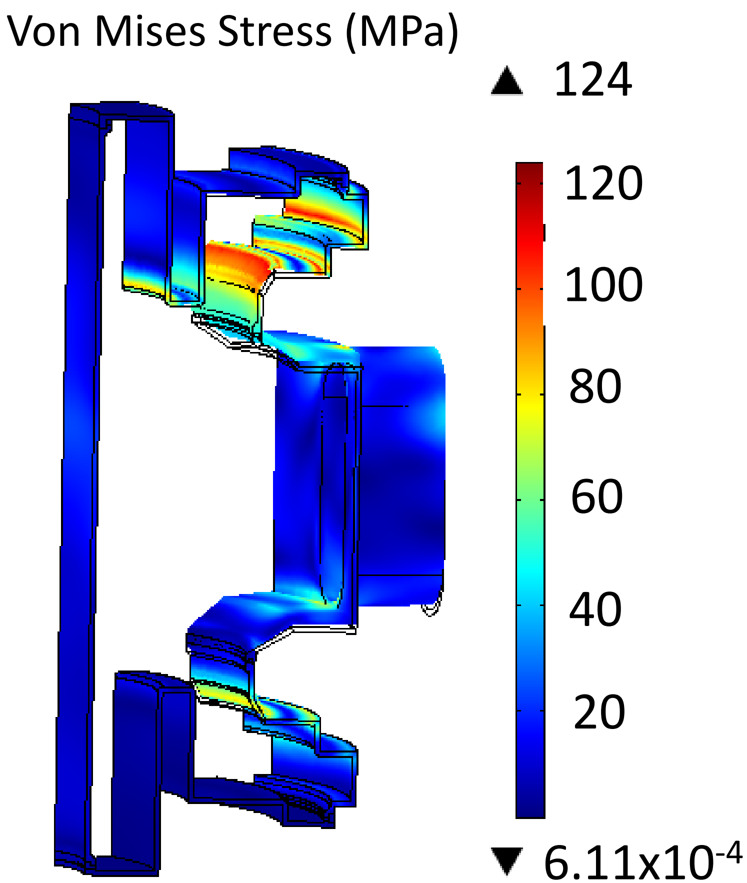


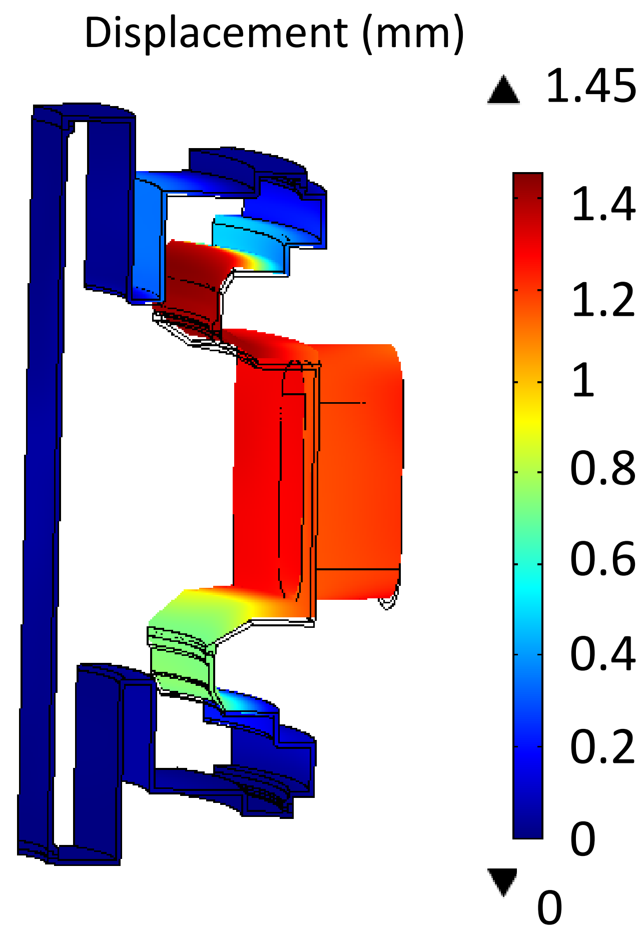


Wedge Plate holds Vessel Here

Add support block here

Added Blocks bring Stress down to allowable levels for 1.5MA/6T Design Point





Inconel 625 Yield = 460 MPa

2/3 Yield = 306 MPa

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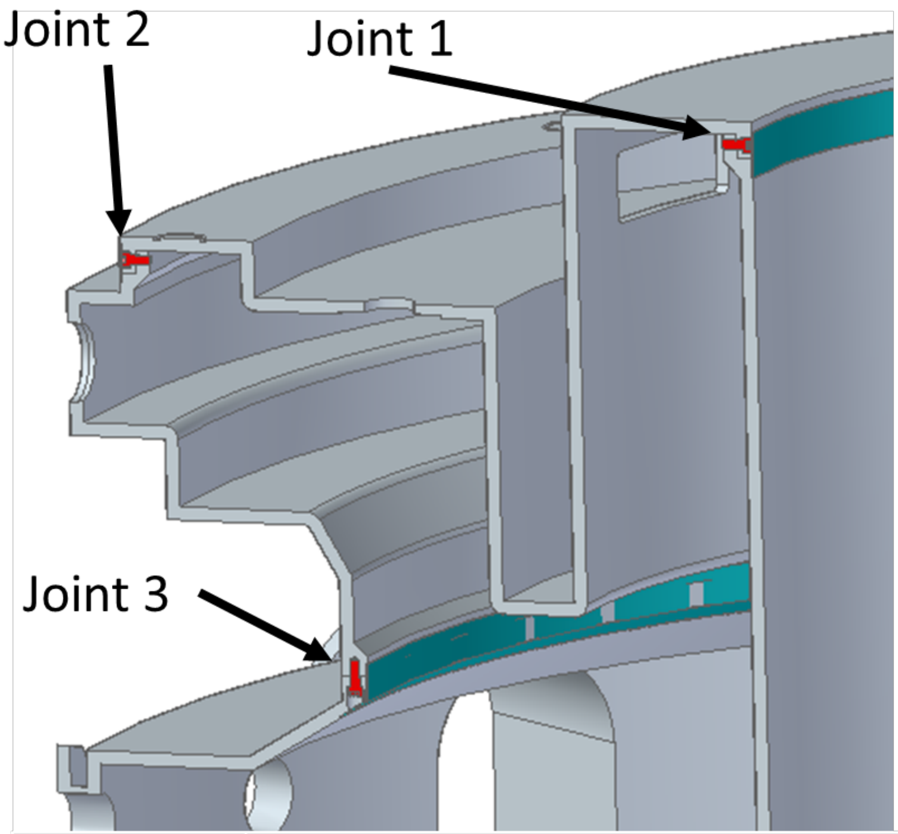
Bolted Joints will stay Closed



Joint	Number of Bolts Required to Carry max Load During VDE
Joint 1	3
Joint 2	32
Joint 3	18

Bolt Stress Calculations:
Integrate Stress on Joint Area to get Force (N) that bolts will need to carry.

Compare this load to:
\# of bolts * preload on bolts
(Grade 8, 3/8" bolts preloaded to 36 kN)

Max load seen by any joint $=1.1\text{x}10^6$ N

ADX designed with 60 bolts per joint

Summary

- COMSOL used to model the magnetic fields, eddy currents and Lorenz forces generated in the design for the ADX Vacuum Vessel during a plasma disruption.
- COMSOL results on initial design show stresses above allowable limits (2/3 yield), and COMSOL used to test proposed restraints to reduce stress.
- With additional restraints, ADX Vessel is within allowable limits for stress and displacement.
- Bolted Joints will remain closed