Update on Fracture Analyses and Literature Review for Ferromagnetic Loads

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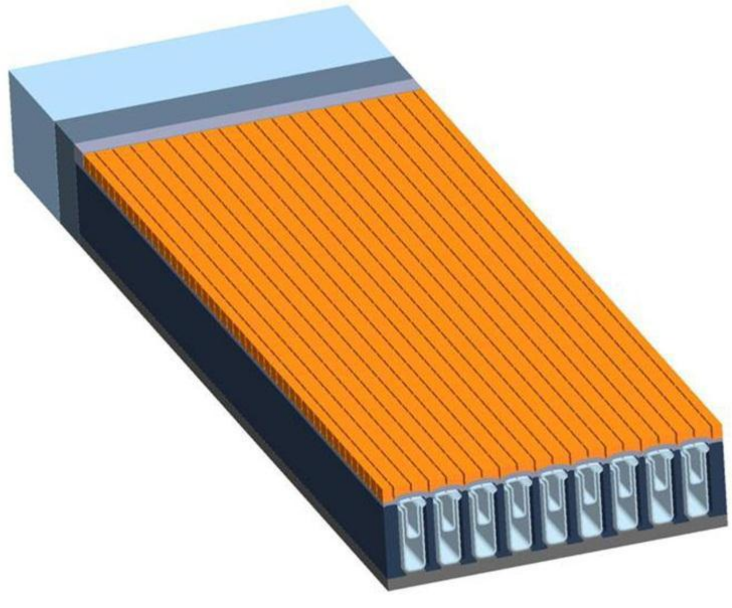
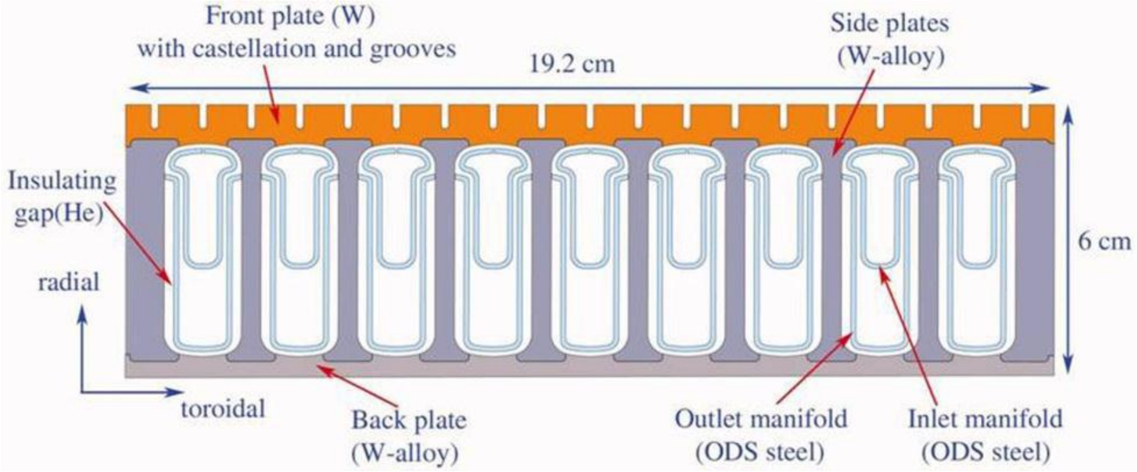
Outline

- 3-D Analysis of Flat Plate Divertor
  - High stress areas
  - Crack locations
  - Thermal stress included
  - Consider full power and cool-down
- Literature Review of Ferromagnetic Loads in Tokamaks

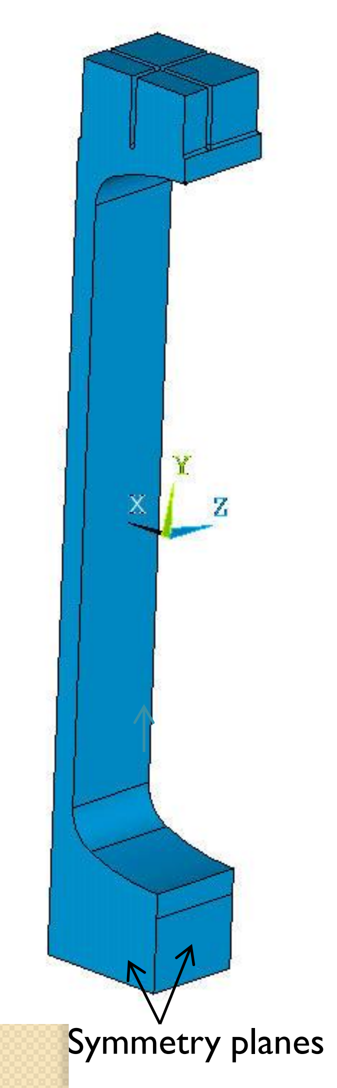
Fracture Studies for ARIES Plate-Type Divertor Concept

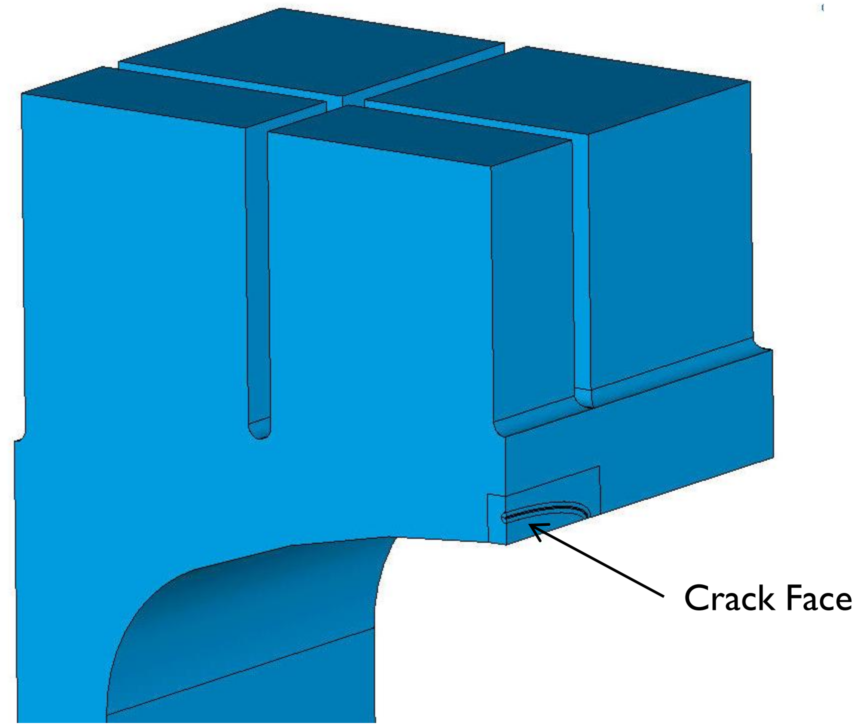
Tungsten HCFP(Helium-cooled Flat Plate) divertor





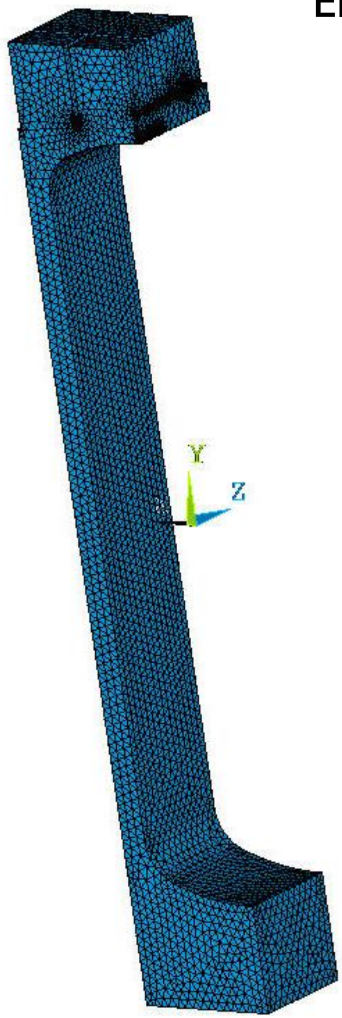
3-D Model Geometry and Crack Location

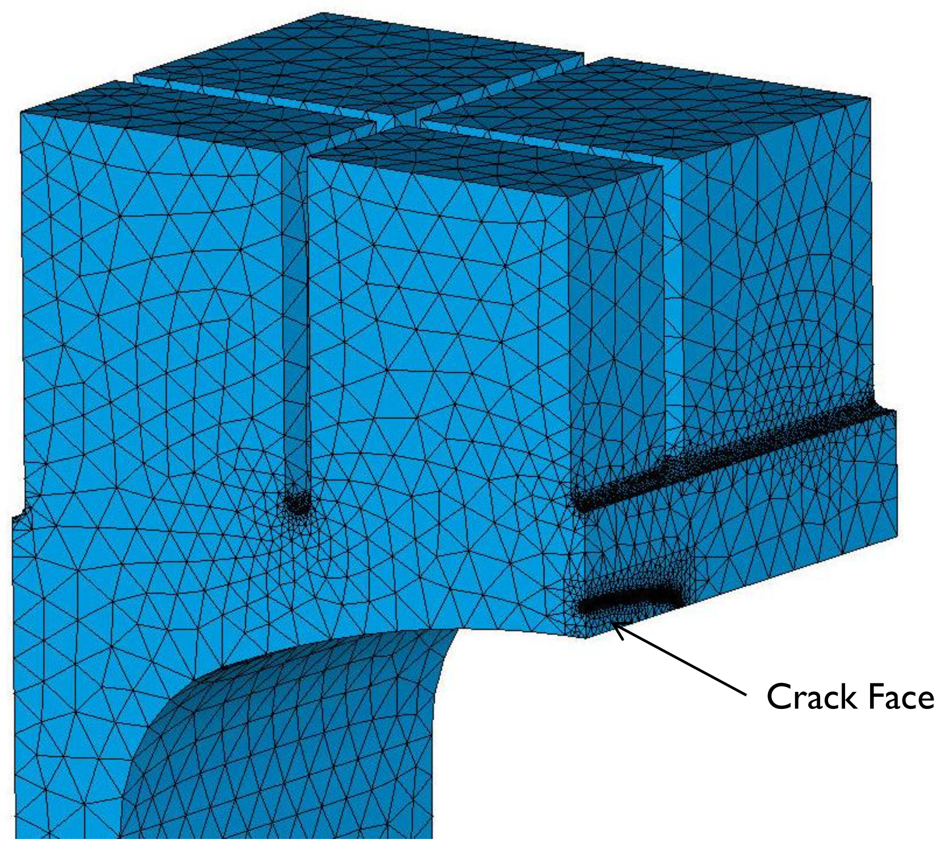




Finite Element Mesh

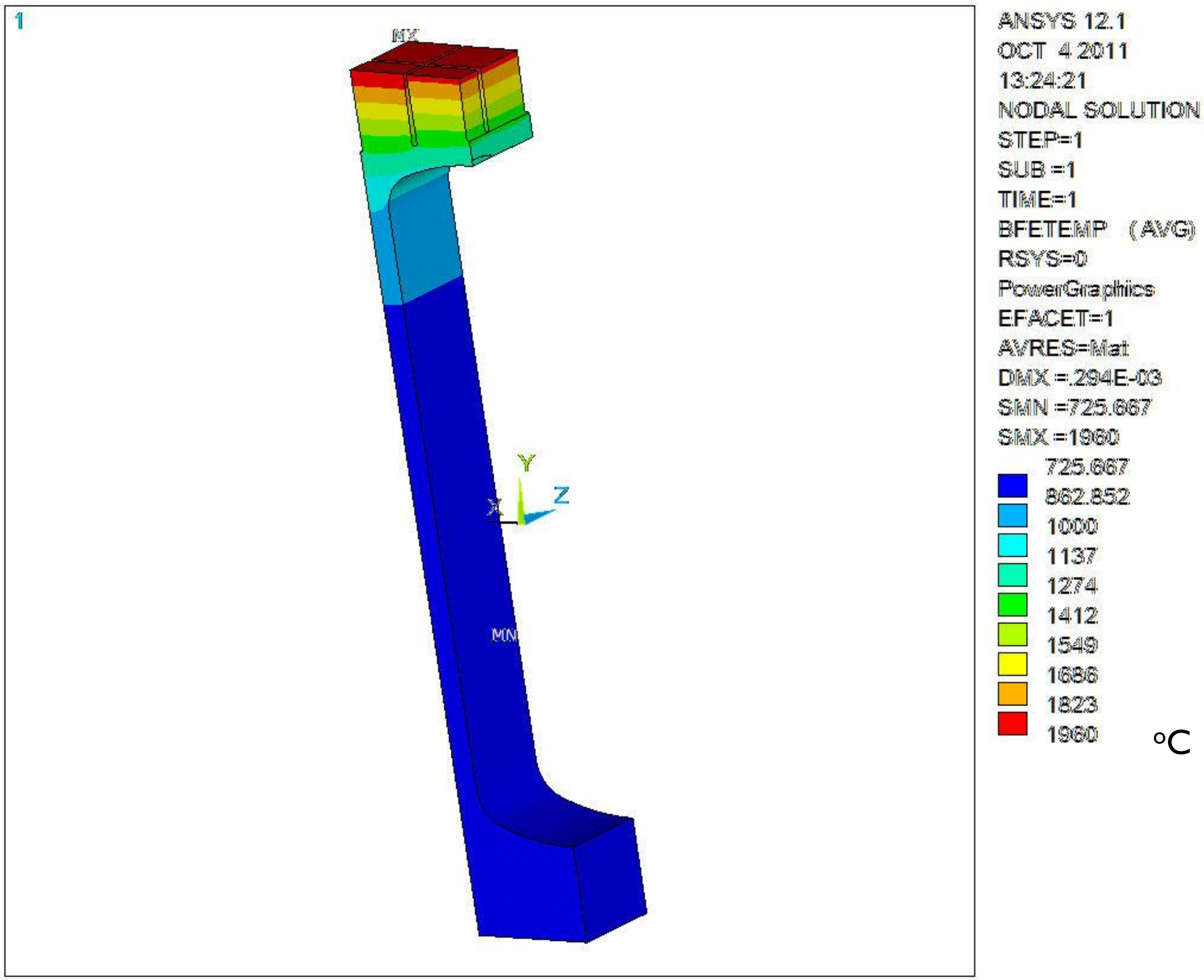
Nodes   553787
Elements. 387972





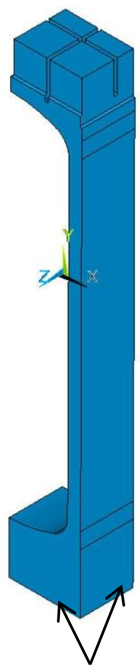
Temperature Distributions Simulated Using ARIES Design Loads with Simplified Convection Cooling

q"=11 MW/m^2
q'''=17.5 MW/m^3
P=10 MPa
$T_{coolant}$=600 ^oC
Max. T_{armor}= 2000 ^oC
Max. $T_{structure}$=1310 ^oC
Min. $T_{structure}$=725 ^oC



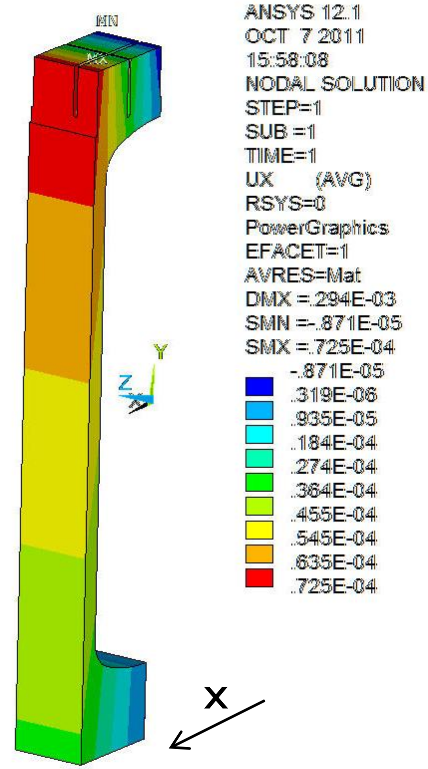
Structural Boundary Conditions Adjusted to Not Over-Constrain Model

Planar rotations in x and z direction simulate panel bow

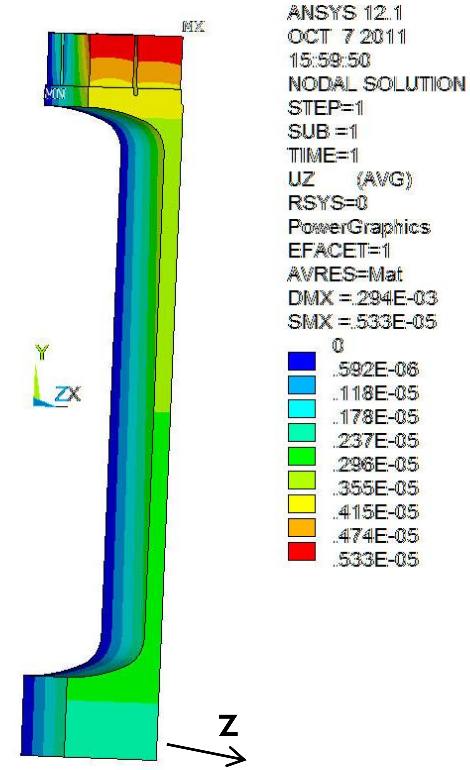


Surfaces must remain planar but may rotate

Free surface displacements



X-displacement

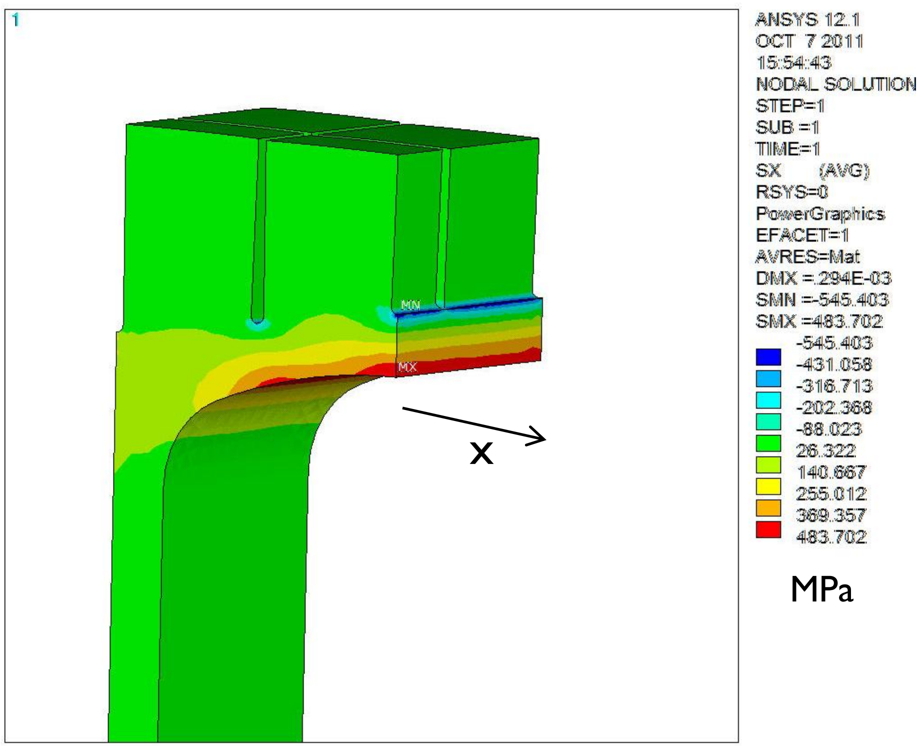


Z-displacement

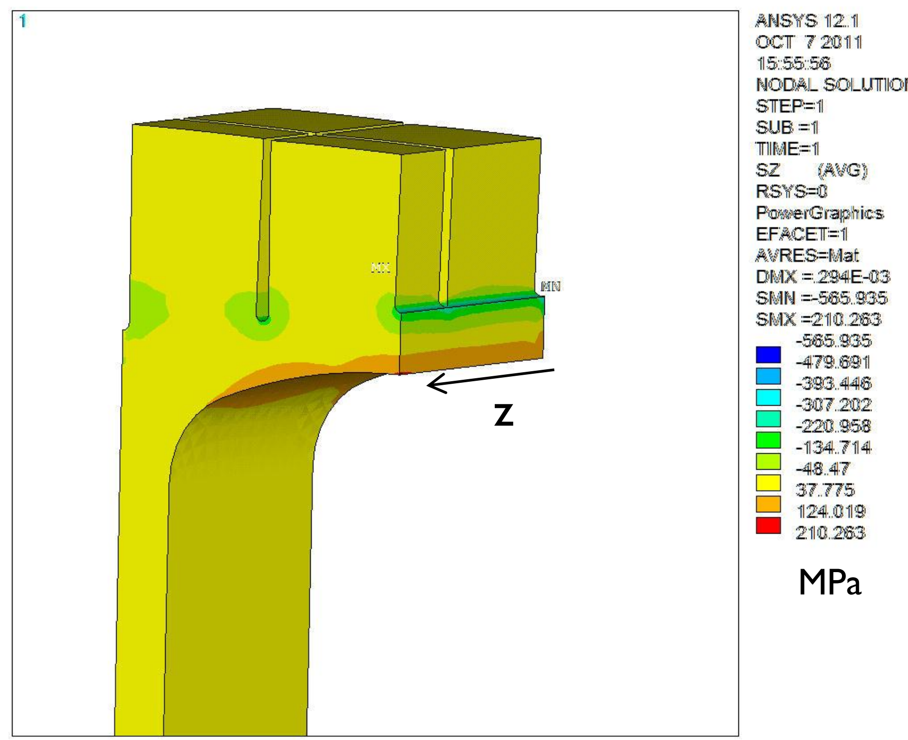
Stresses in Uncracked Structure

- X stresses are similar to 2-D model results
- Z stresses are ~ 100 MPa near crack vs highly compressive for plane strain and zero for plane stress 2-D assumptions

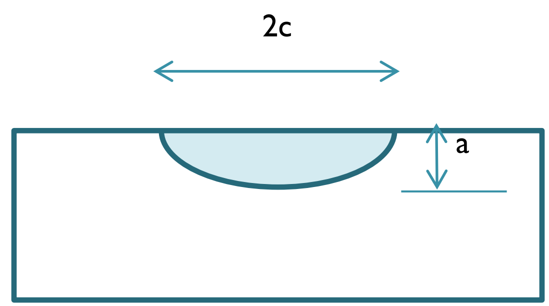
X-Direction Stresses

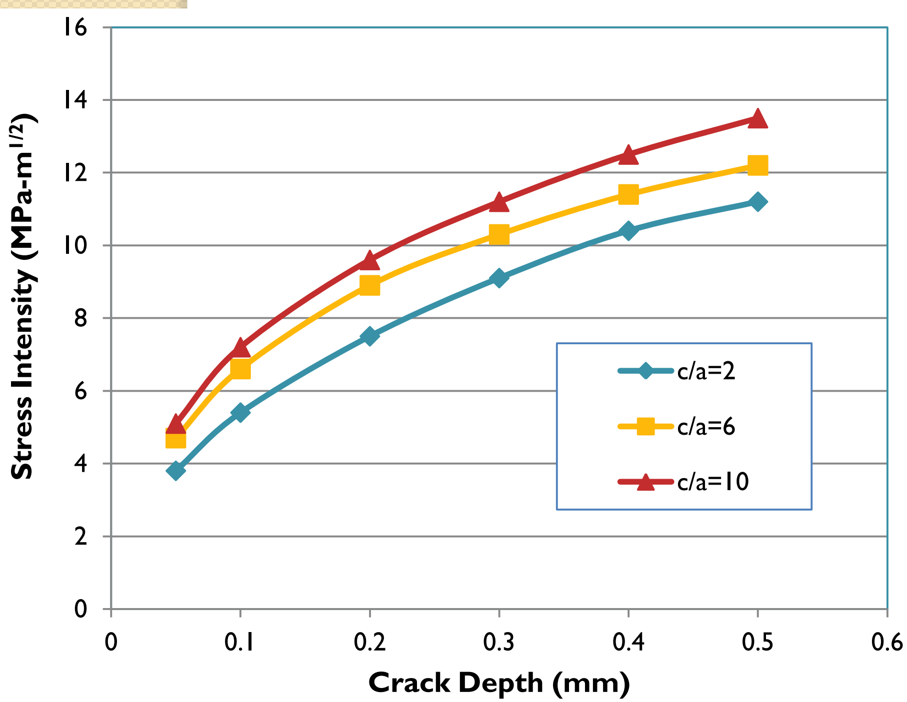


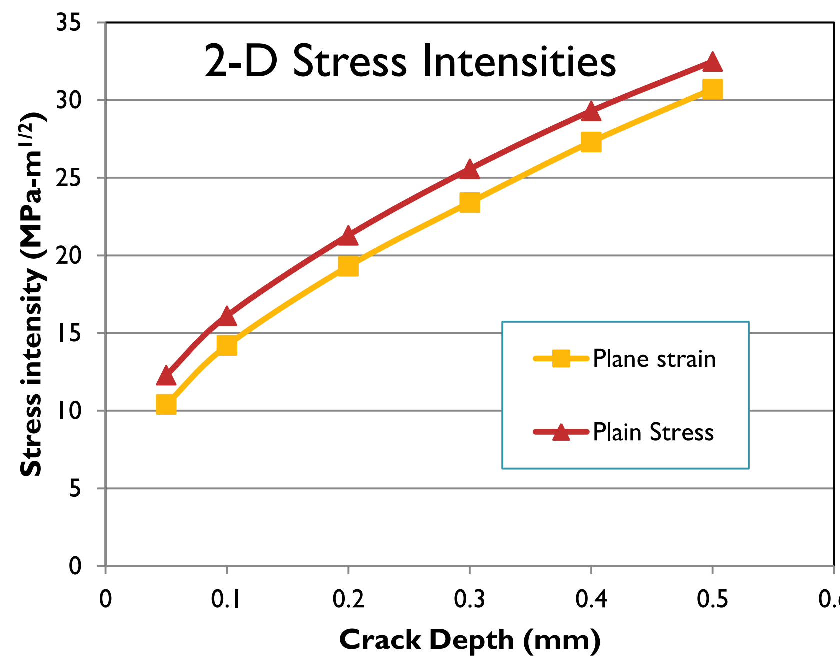
Z-Direction Stresses



Stress Intensities for 3-D Models Significantly Lower then 2-D Results







Conclusions

- As expected, 3-D results indicate lower stress intensity factors due to finite crack length and more realistic stresses
- We still have to do some convergence studies to verify the results

Ferromagnetic Loads in Tokamaks

- Ferritic steels structures will experience magnetic loads in tokamaks
- Previous work focused on static fields
- There has been very little work since
- Questions remain regarding transient fields

References

- H. Attaya, G.L. Kulcinski, and W.G. Wolfer, "Analysis of Forces on Ferromagnetic Components Used in Magnetic Fusion Reactors," J Nuc Mat, 122&123 (1984) 96
- T.A. Lechtenberg and C. F. Dahms, "Magnetically-Induced Forces on a Ferromagnetic HT-9 First Wall/Blanket Module," J Nuc Mat 122&123 (1984) 140
- L.R. Turner, "Electromagnetic Computations for Fusion Devices," COMPUMAG-Tokyo Conference, 1989

Ferromagnetic Effects

- Toroidal field ripple is reduced
- Forces in the presence of field gradients
- Temperature gradients can be an issue due to the temperature dependence of saturation magnetization

Starfire

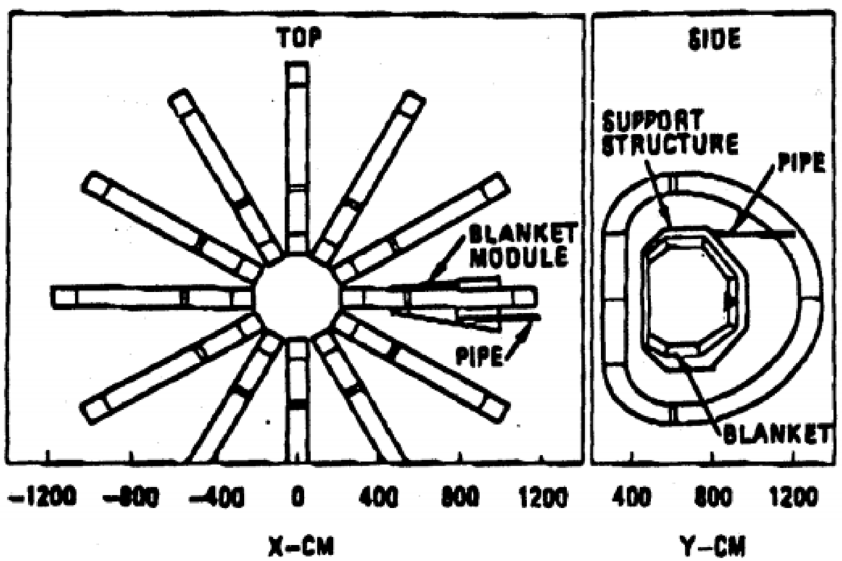


Fig. 4 Schematic of the location of module and coolant pipe with respect to the toroidal field magnets in (a) top view and (b) side view

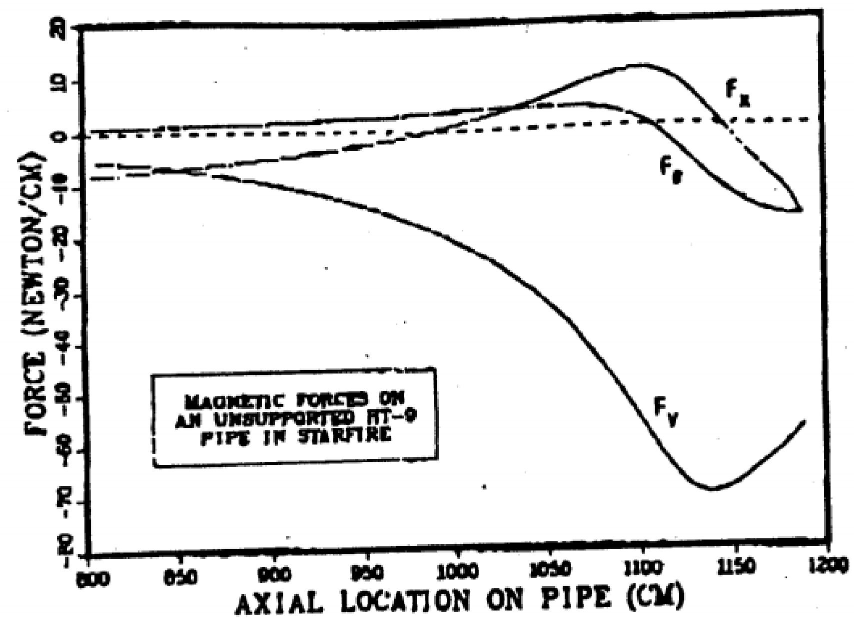


Fig. 5 Magnetic force distribution for a coolant pipe in Starfire at 0.86 m from the center of the TF magnet

ref T. Lechtenburg et al, "An assessment of Magnetic Effects in Ferromagnetic Martensitic Steels for Fusion Machines"

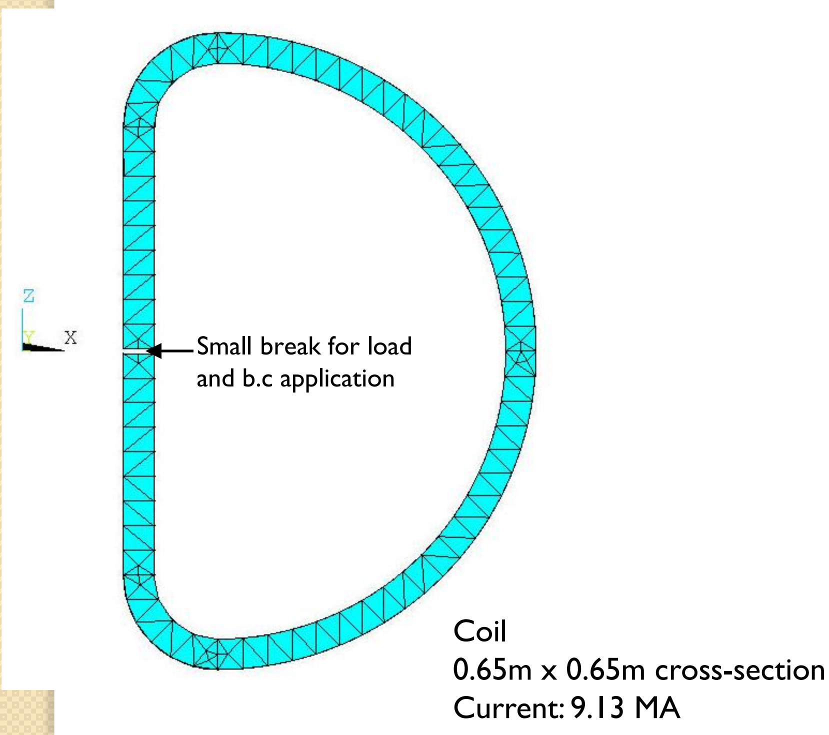
ANSYS Capabilities

- Field ripple effects (ferromagnetic inserts)
- Forces

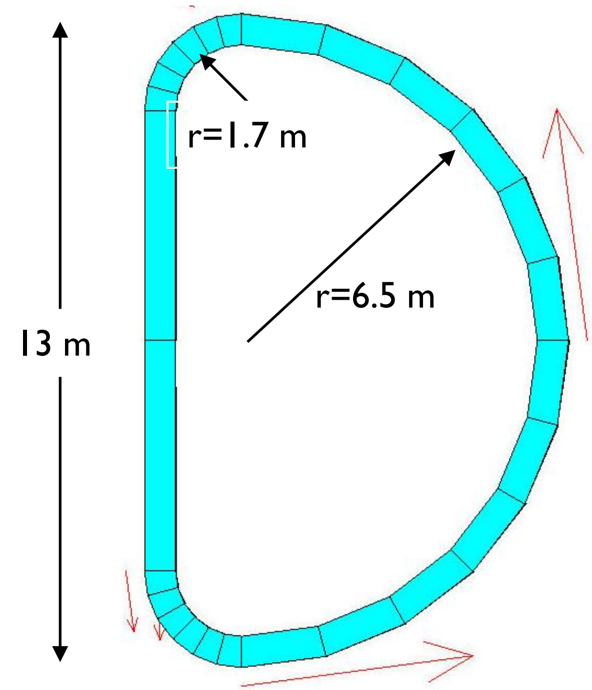
ITER-Like Magnetic Analysis

- First modeling strategy use SOLID96 tetrahedral elements connected with the 3-D tetrahedral mesh. Current density is solved for in first load step.
- Second strategy used SOURC36 primitive used to supply current source data to magnetic field problems. Identical simplified coil D-shape geometry created with only 6 elements not connected to rest of mesh.

Coil modeled with SOLID96 Elements
1207 elements

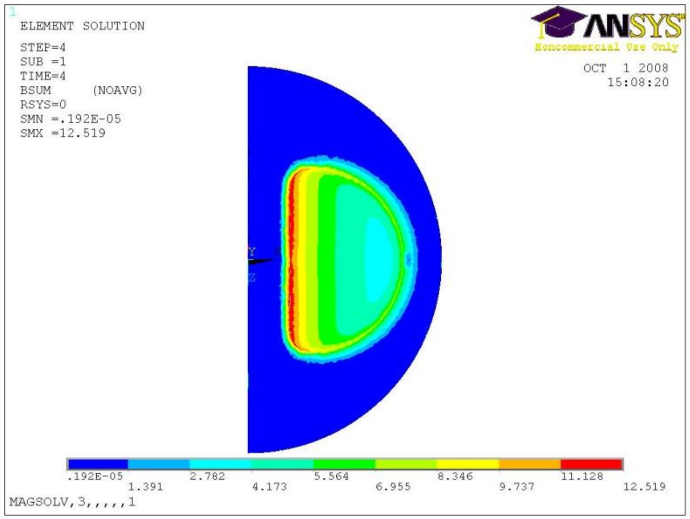


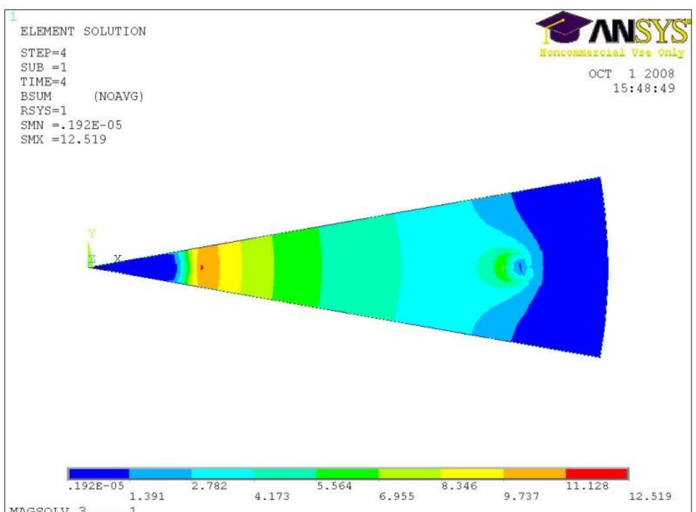
Coil modeled with SOURC36 Elements
6 elements



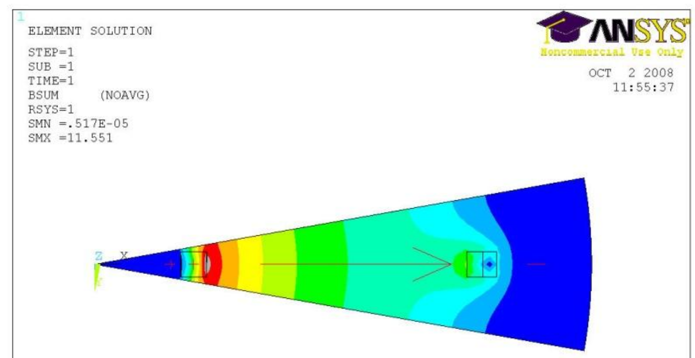
Methods Produce Nearly Identical Results
Magnetic Flux Density (B)

Results using SOLID96 Elements





Results using SOURC36 Elements



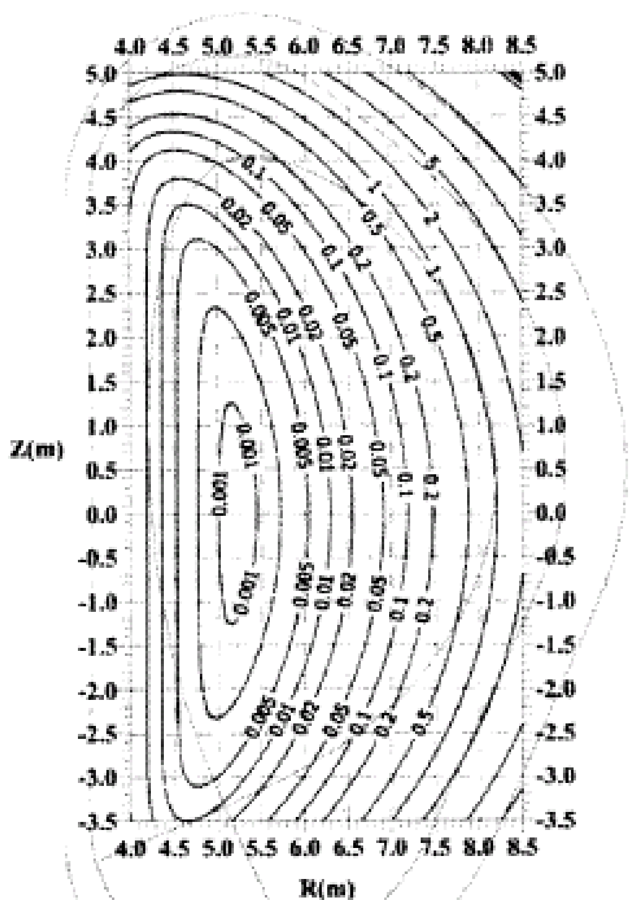
ITER Field Specifications

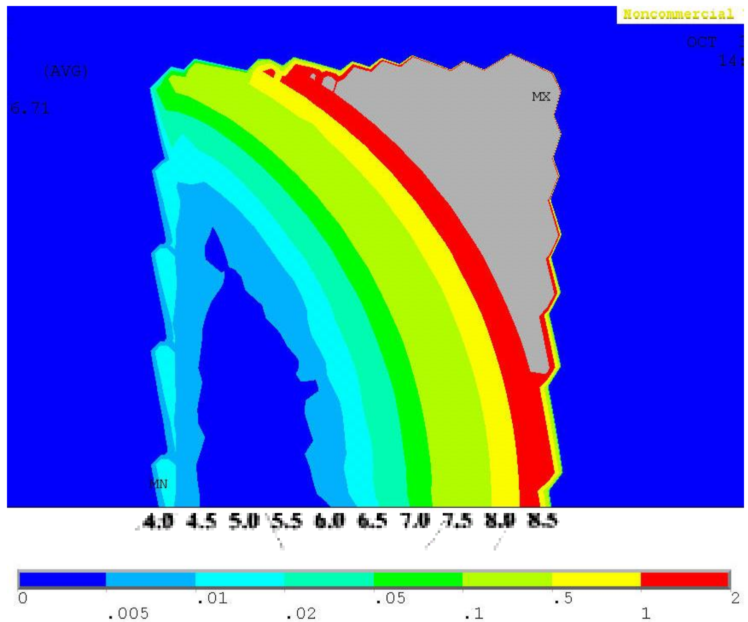
Max Field in coils – 11.8 T

Field at r = 6.2m – 5.3 T

Field Toroidal Ripple Predictions Uncompensated Results

- Ripple measures toroidal variation of the field between the 18 magnets.
- ANSYS results correlate well with published ITER results for ripple values above 0.02%. Below this value solution error appears to dominate.

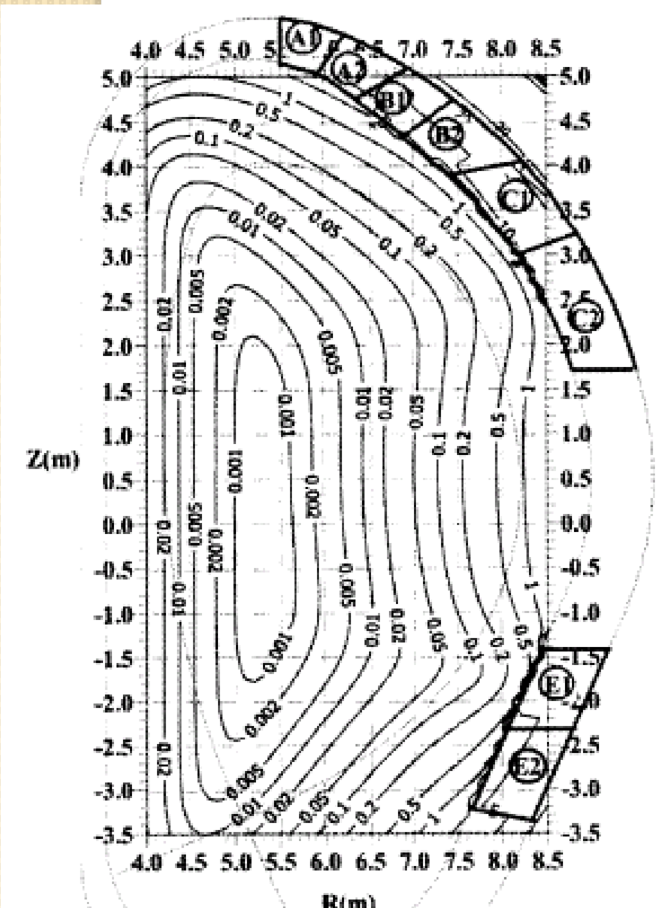


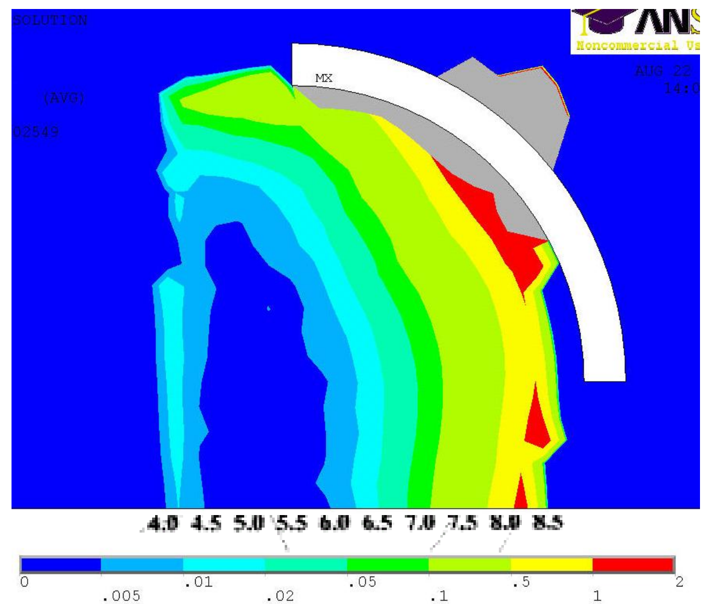


$$\%Ripple = \frac{B_{max}-B_{min}}{B_{max}+B_{min}} \times 100$$

Field Toroidal Ripple Predictions
Ripple Reduced using Ferromagnetic Inserts

- Simplified representation of ferromagnetic inserts reduces ripple to similar proportions as the optimized ITER design.

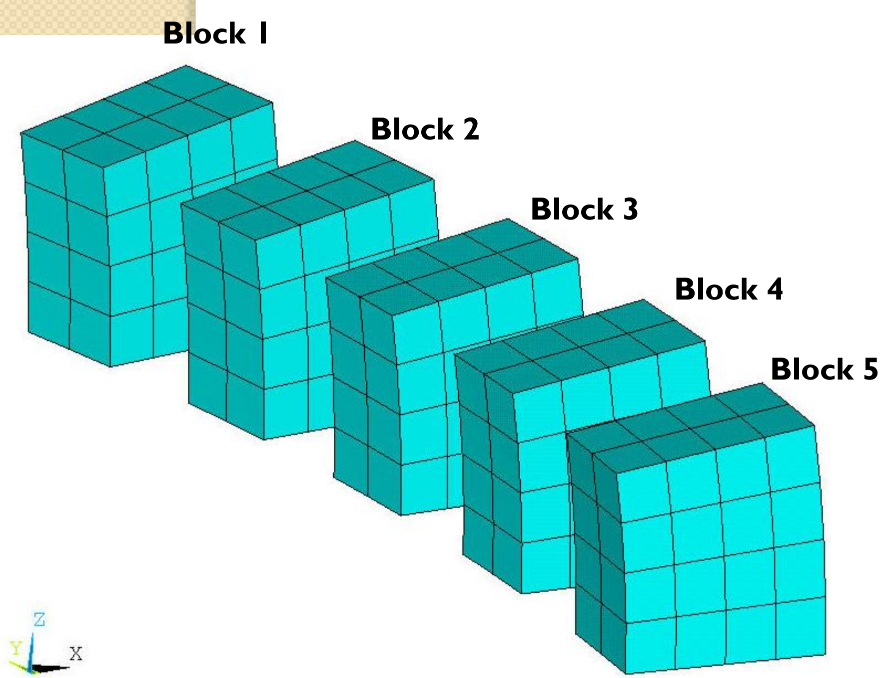




$$\%\text{Ripple} = \frac{B_{max}-B_{min}}{B_{max}+B_{min}} \times 100$$

Magnetic Forces on the Ferromagnetic Inserts

- Inwall shield blocks are typically 0.4m x 0.3m. The ferromagnetic shield blocks will be subject to magnetic forces from the field coils.
- The published maximum forces due to magnetization acting on a ferromagnetic insert block are 18.2 kN in the poloidal direction and 7.1 kN in the outward direction normal to the block surface.
- Forces calculated by ANSYS are significantly higher.



ANSYS Magnetic Force Results

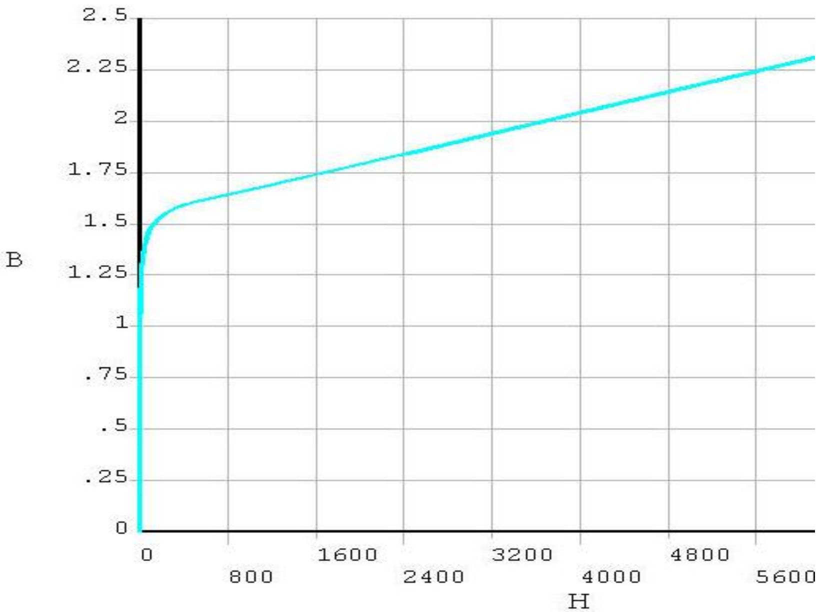
	Block 1	Block 2	Block 3
Fx (kN)	-94.9	-18.1	68.2
Fy (kN)	59.9	-111.1	0.0
Fz (kN)	-19.0	6.4	36.3
Fsum (kN)	113.8	112.7	77.2

Due to symmetry, forces in Blocks 4 and 5 are equivalent to forces in 2 and 1

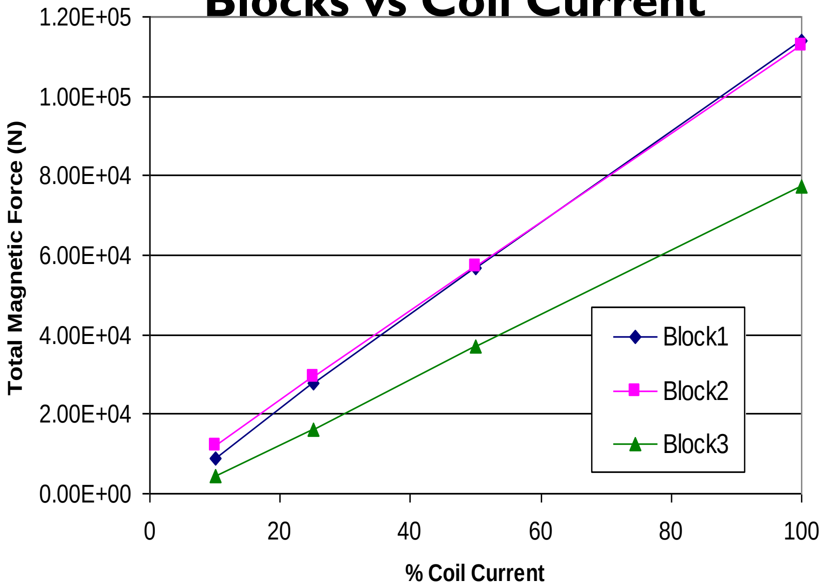
Variation of Magnetic Force with Coil Current

- B-H curve for SS430 used in ANSYS analyses is highly nonlinear shows saturation around 1.5T
- Magnetic forces vary nearly linearly with coil current (and magnetic field)

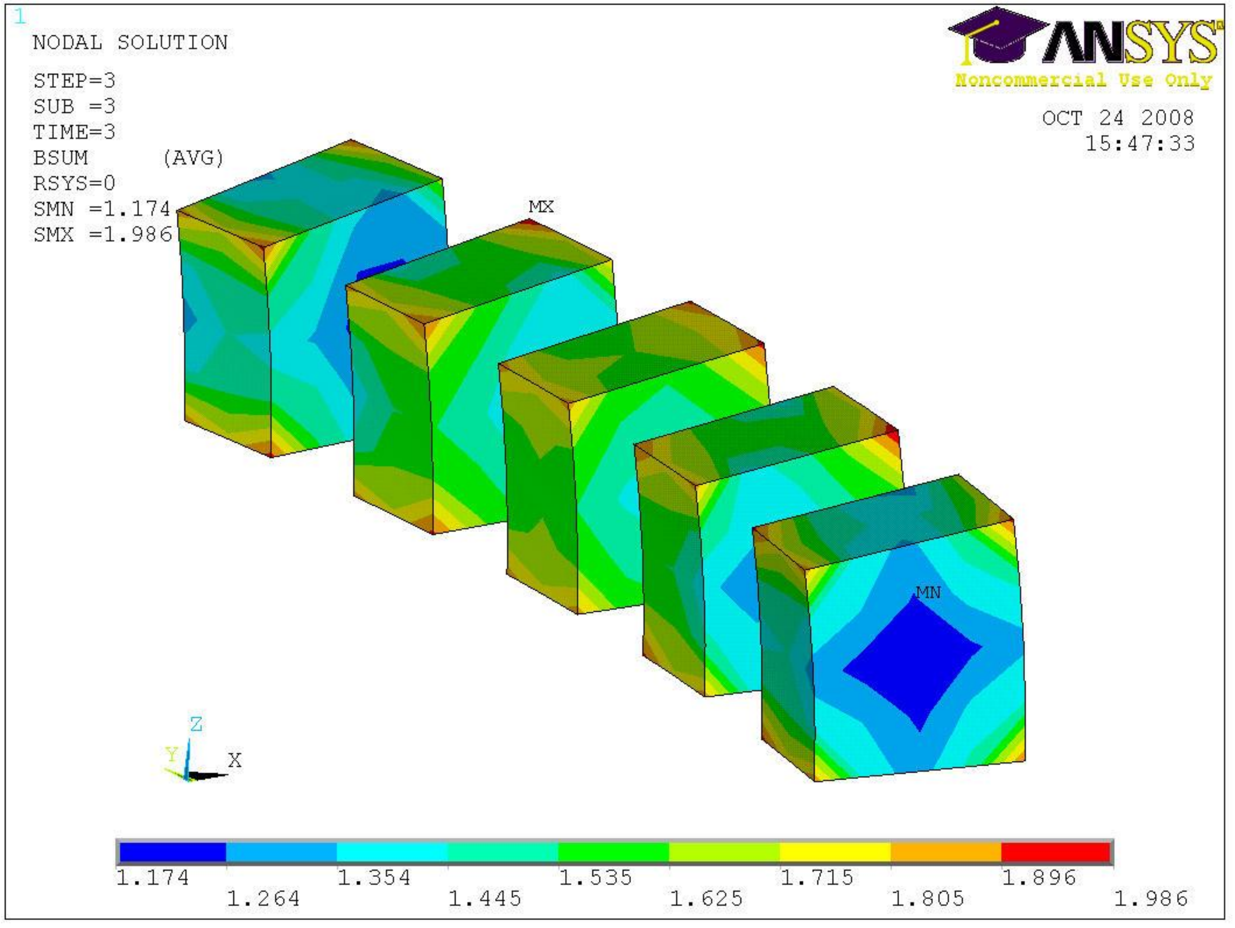
B-H Curve for SS430



Total Magnetic Force on Blocks vs Coil Current



Magnetic Flux Density (B) in Ferromagnetic Inserts



Conclusions

- Ferromagnetic loads are generally found to be non-negligible, but manageable
- We can do ferromagnetic calculations with ANSYS, though more benchmarks would be required
- This includes ripple and force calculations
- We have not tried transient calculations