U.S. MAGNET DEVELOPMENT PROGRAM

BERKELEY LAB

US Magnet Development Program

Current status of a shell-based utility structure

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U.S. DEPARTMENT OF ENERGY | Office of Science

The goal

- Shell-based Utility Structure
  - Pre-stress for ~17T operation (Nominal 16T, design target 17T)
    - Tunable via key shimming
    - Peak stress of 180 (?) MPa (150 MPa assembly)
    - Requirement on pole separation or tensile stress
  - Rapid and reproducible assembly/disassembly
  - Compatible with existing 4-layer Cos-theta coil design
  - Adjustable to variety of coil designs with minimum modifications
- Design limits and sensitivity
  - Magnet outer diameter
  - Coil design compatibility and combined mechanical/magnetic design
  - Sensitivity of mechanical performance
    - Dimensions, tolerances, friction, etc.

Current 4-layer Cos-theta coil

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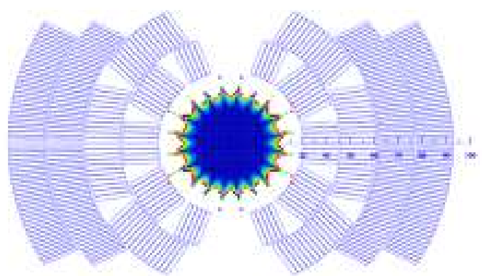
Coil field



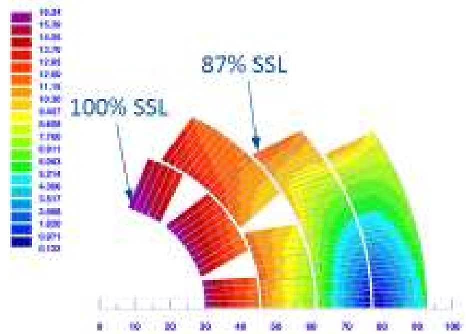


TABLE III. NORMAL RELATIVE HARMONICS (10^{-4} OF THE DIPOLE COMPONENT)

Harmonic	Value
b_3	0.0018
b_5	0.0154
b_7	0.0523
b_9	0.0612

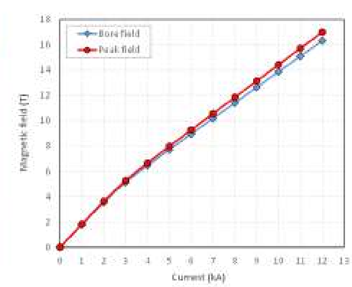
Cable parameters

Parameter	Unit	Inner coil	Outer coil
Strand diameter	mm	1.000	0.700
Number of strands		28	40
Strand J_c(12T, 4.2K)	A/mm^2	2850	2650
Cu/non-Cu ratio		1.13	
Bare mid-thickness*	mm	1.870	1.319
Bare width*	mm	15.10	
Radial insulation thickness	mm	0.150	
Azimuthal insulation thickness	mm	0.125	
Keystoning angle	deg	0.804	

*After reaction

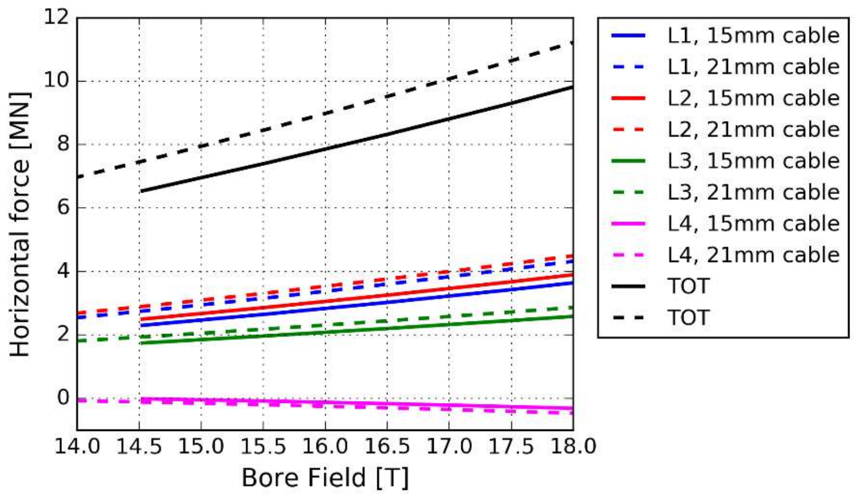
Magnet parameters

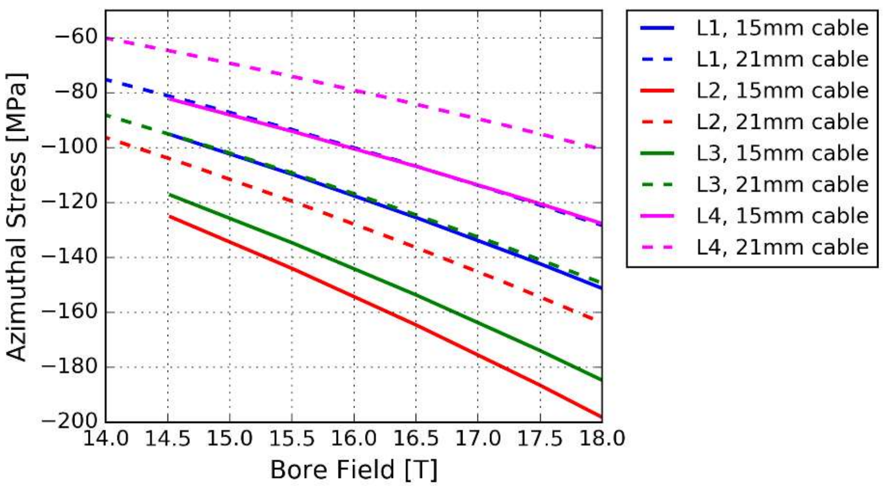
Parameter	Unit	Value
Peak bore field at 4.2 K	T	15.61
Peak coil field at 4.2 K	T	16.25
Peak current at 4.2 K, I_c	kA	11.34
Inductance at I_c	mH/m	25.61
Stored energy at I_c	MJ/m	1.65
Horizontal Lorentz force per quadrant at I_c	MN/m	7.36
Vertical Lorentz force per quadrant at I_c	MN/m	-4.50



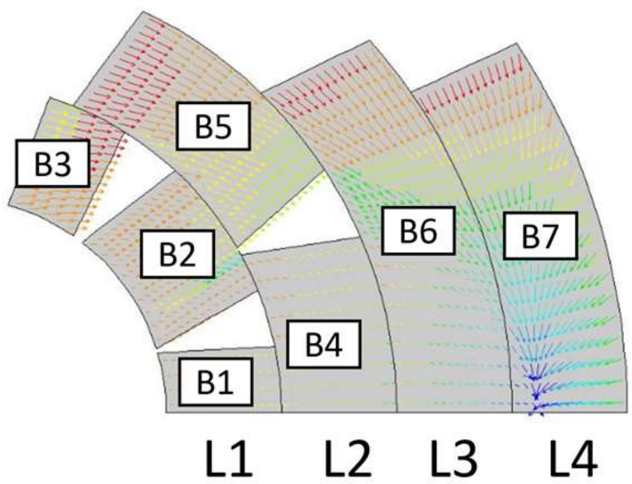
Magnetic forces vs cable width

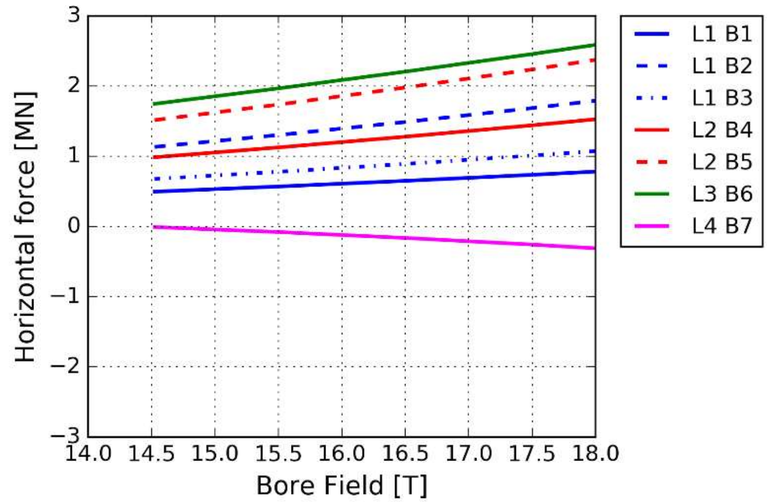
- Quantities
  - Horizontal magnetic force
  - Azimuthal stress on the mid-plane based purely on magnetic force accumulation and cable width
- Cable width
  - 15.10 mm (solid line)
  - 21.13 mm (dashed line)
  - Coil ID fixed
    - Only radial coil dimensions changed
    - Azimuthal coordinates of each block are not changed
    - Number of turns not changed
    - Bigger coil not optimized
- What do we get
  - L2 shows higher stress than L1 ?
  - High azimuthal stress in L3 ?
  - Wider tape *seems to reduce* stress by <30MPa ?
- What we are missing
  - Layers impregnated together
  - Friction between coils
  - Coil deformation and bending
  - Horizontal force accumulation
  - Structure...



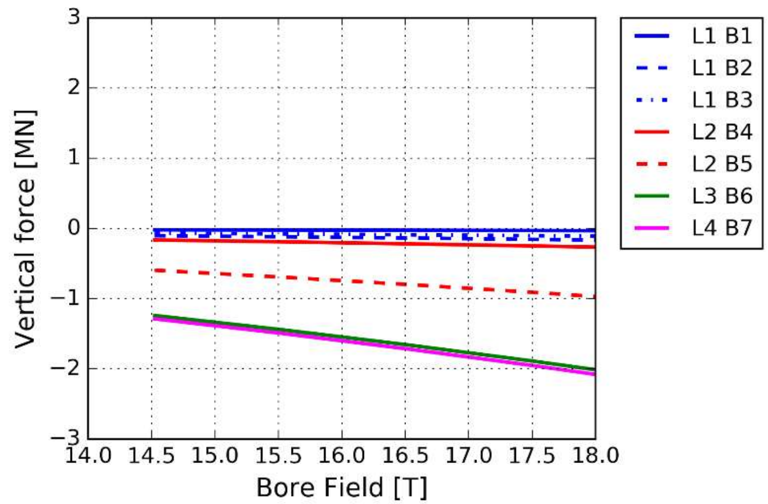


Forces per block
15.1 mm cable





- In the coil L1+L2 block B5 shows highest vertical force and contributes to a high peak stress in block B1
- L1+L2 compress L3+L4 against structure and high vertical force in L3+L4 does not deform the coil and stress is not high



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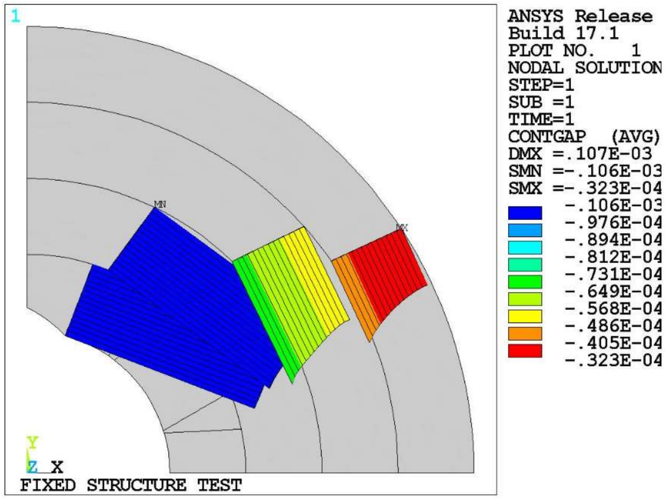
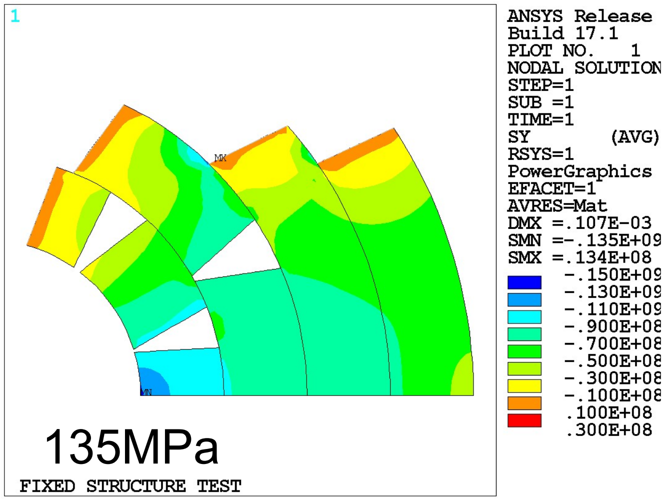
Fixed structure
No pre-load

- Structure and poles infinitely rigid with fixed displacement
  - Not contracting due to cool-down
  - Contact with friction
- Coil not bonded to the pole
  - Not contracting due to cool-down
  - Properties for 4.3K
  - Layers 1&2 bonded together
  - Layers 3&4 bonded together
  - Layers 2&3 in contact with friction
- Conclusions
  - Stress concentration in mid-plane of layer 1
    - 135 MPa at 15 T
    - 174 MPa at 17 T
  - Stress in layers 2-4 < 90MPa contrary to magnetic analysis estimate
    - Bonded coils
    - Interaction between layers and structure





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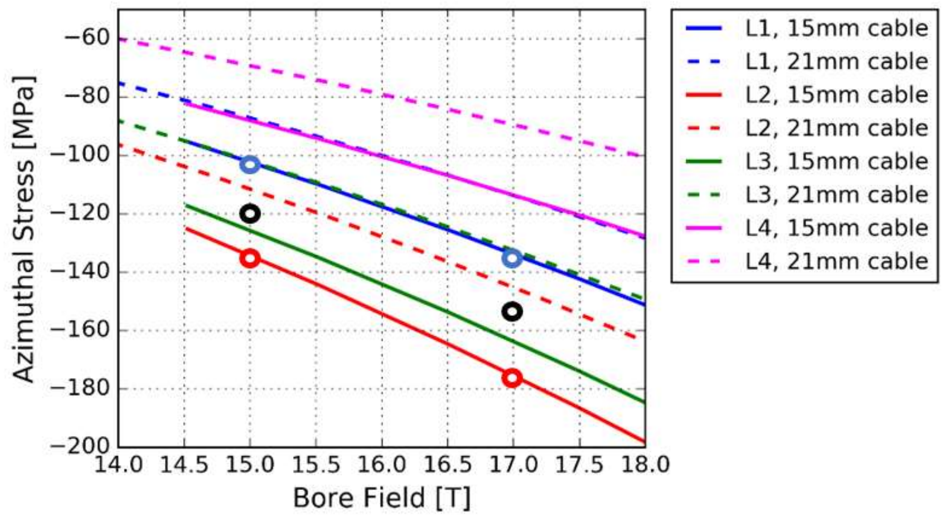
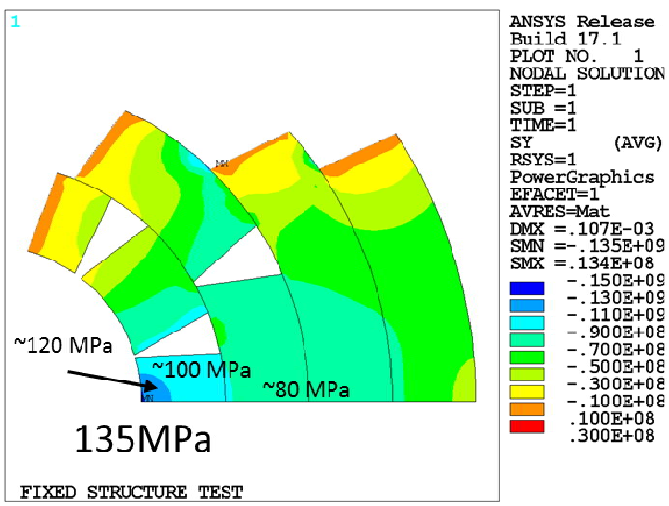
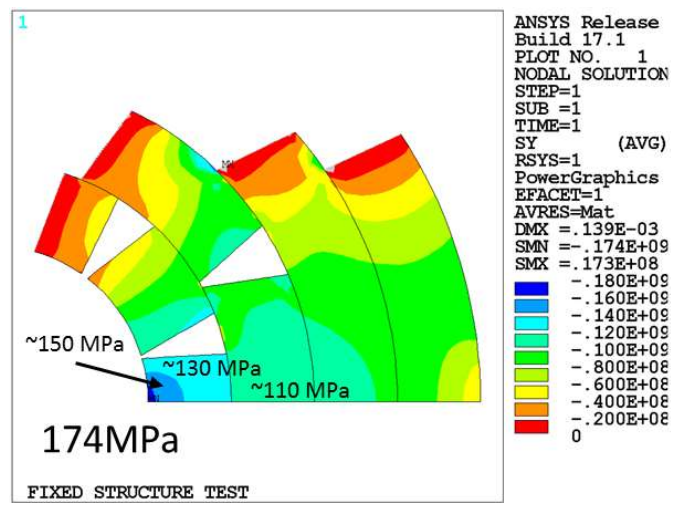
Fixed structure, No pre-load
Comparison with previous estimation

- **L1 and L2 potted**
  - Average stress in 1st block similar to average stress from L1 and L2 magnetic forces
- **Peak stress ~20MPa higher due to bending**
- **17T shows stress ~30MPa higher than 15T**
  - Requires ~30MPa more pre-load at CD and MF

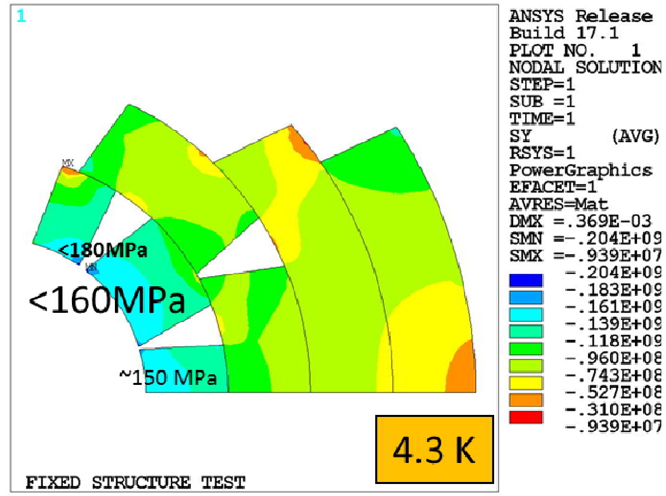


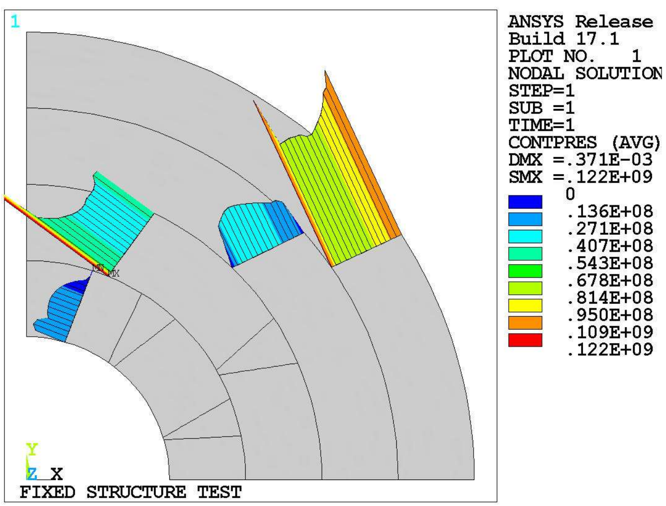


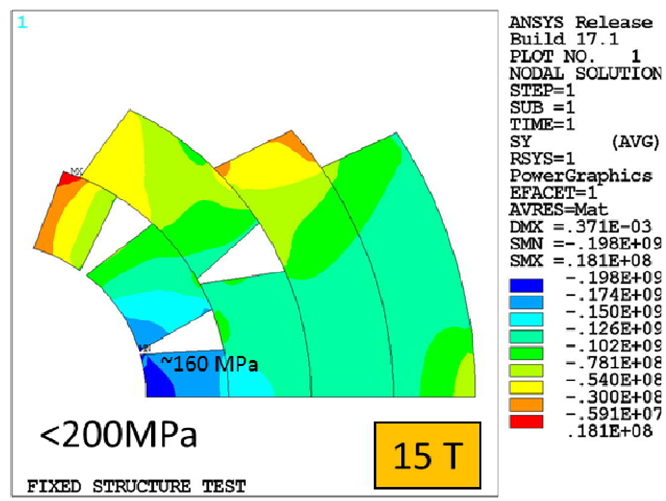


Fixed structure
Pre-load for 15 T

- Rigid structure
  - Shrinkage modeled by contact element offset (-365um)
  - Structure does not deform due to MF
- Coil and pole shrink during cool-down
- Coil can separate from the pole
- Horizontal magnetic force: 7 MN/m
- Total pole reaction force at cool-down: -8.7 MN/m
- Reaction force in each pole at 15T:
  - -0.3, -0.8, -1.6, -1.5 MN/m

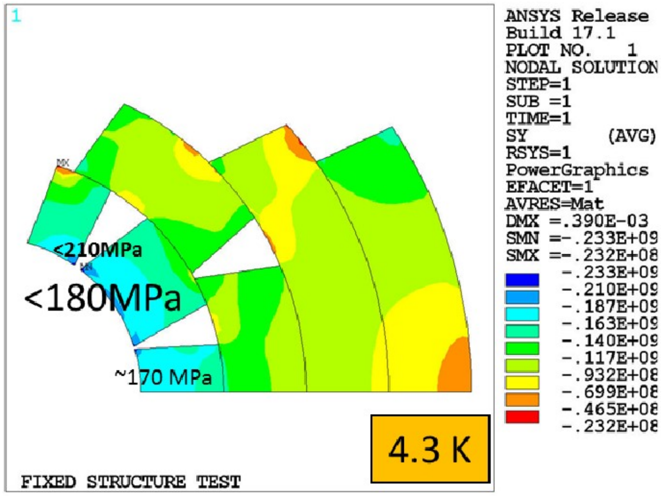


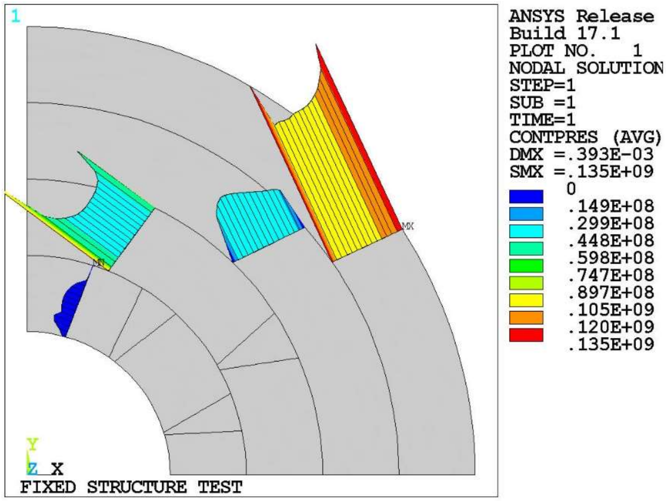


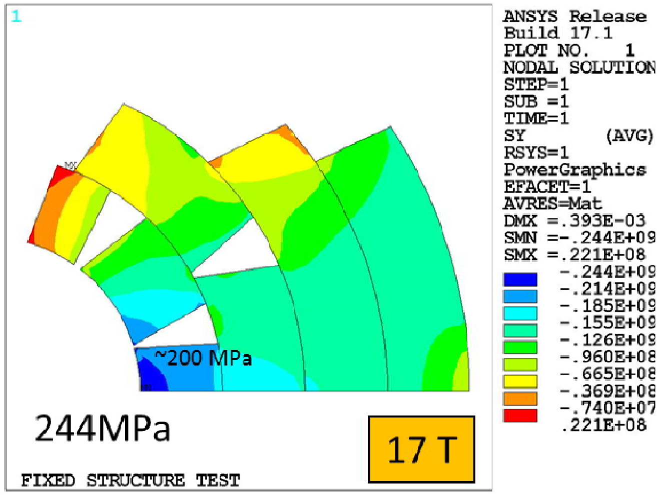


Fixed structure
Pre-load for 17 T

- Rigid structure
  - Shrinkage modeled by contact element offset (-385um)
  - Structure does not deform due to MF
- Coil and pole shrink during cool-down
- Coil can separate from the pole
- Horizontal magnetic force: 9 MN/m
- Total pole reaction force at cool-down: -10.7 MN/m
- Reaction force in each pole at 17T:
  - -0.2, -0.8, -2.0, -1.6 MN/m

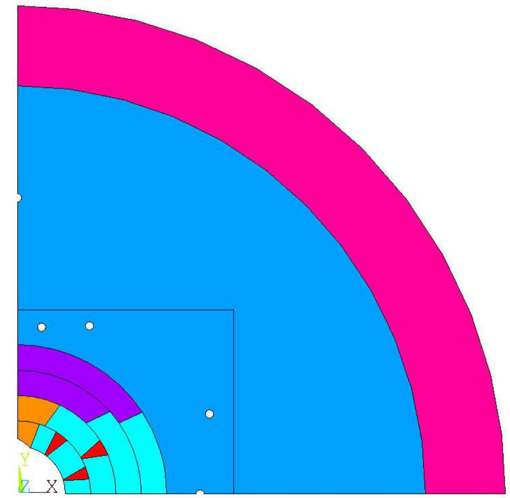


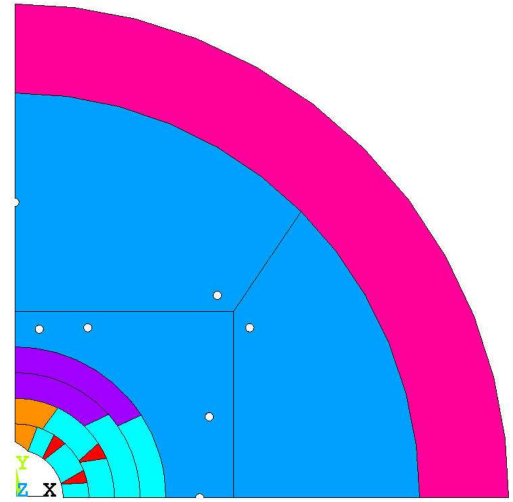




Exploration of shell parameters

- Two types of yoke configurations investigated
  - Dipole yokes
  - Quad yokes
- Shell parameter space
  - OD range: 600-800 mm
  - TH range: 55-75 mm
- Pre-load target
  - Pole reaction force 2MN/m higher than magnetic forces
  - Adjusted using key shim
- Quantities
  - Shell and pole reaction forces (RT, CD)
  - Shell stress
  - Pre-load key shim
  - Bladder pressure
    - Dipole yokes bladder surface D/2
    - Quad yokes bladder surface 0.7D/2





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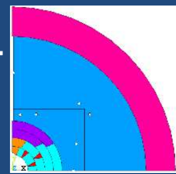
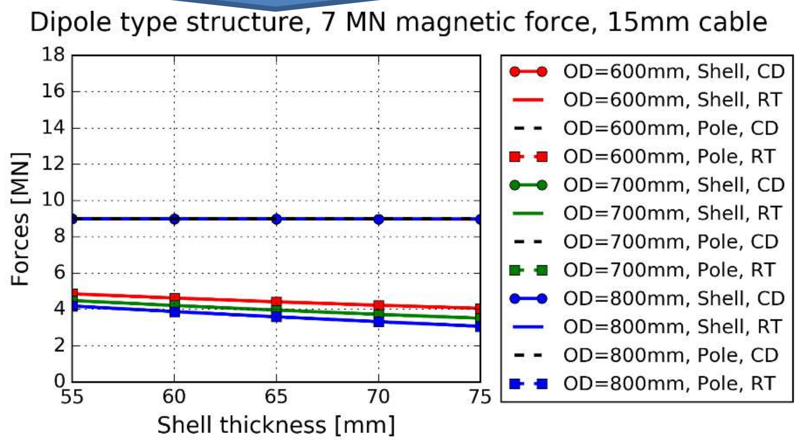
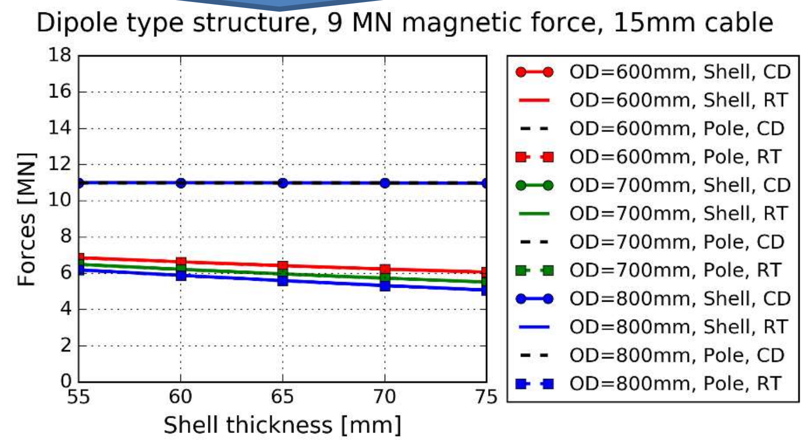


Dipole yokes
Forces, Shell stress

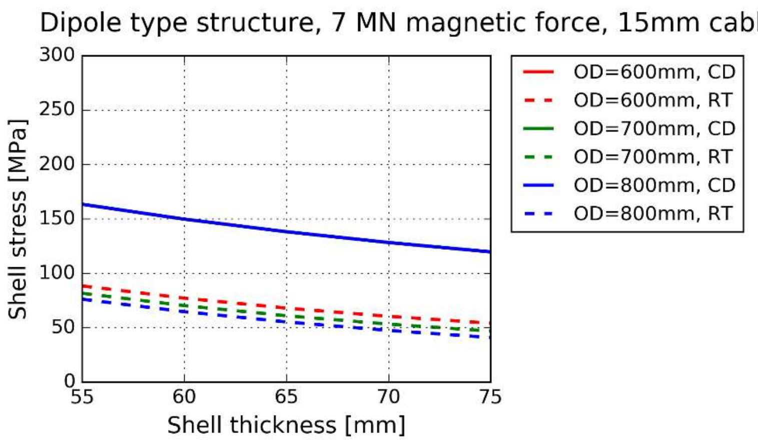
15T

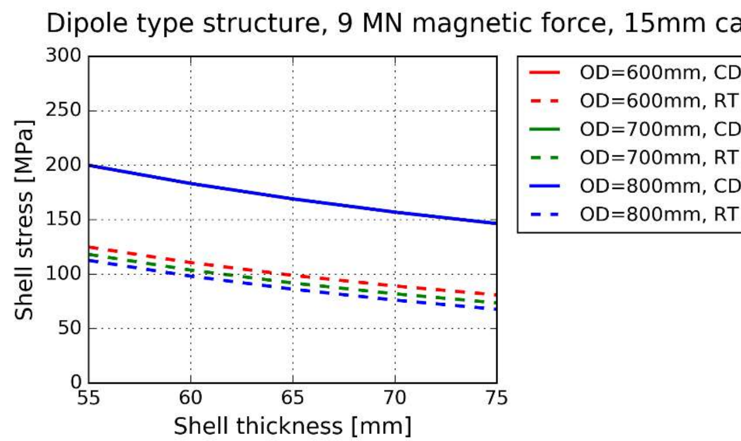


17T

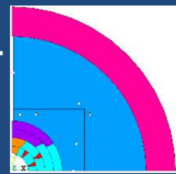


RT key adjusted to the same pre-load after cool-down (2MN/m more than magnetic forces)
Reaction force in the shell equal to the reaction force in the pole

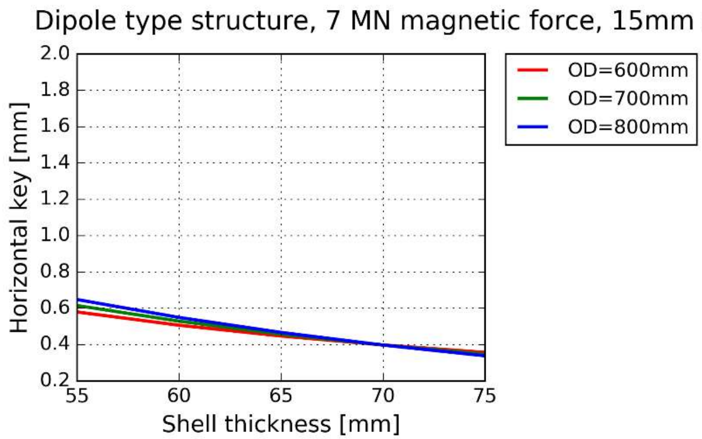


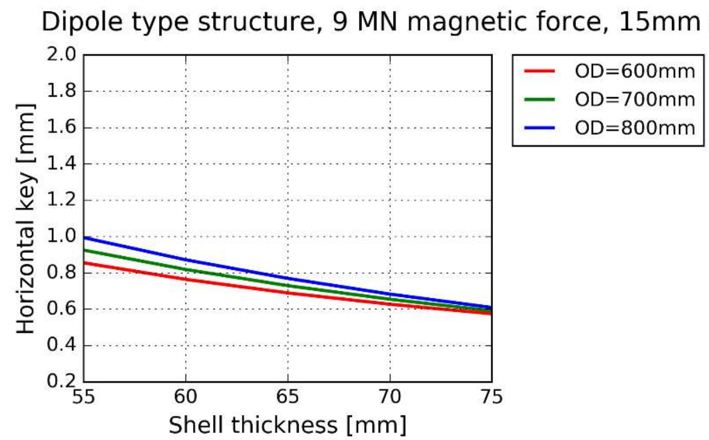


Dipole yokes
Horizontal key, bladder pressure

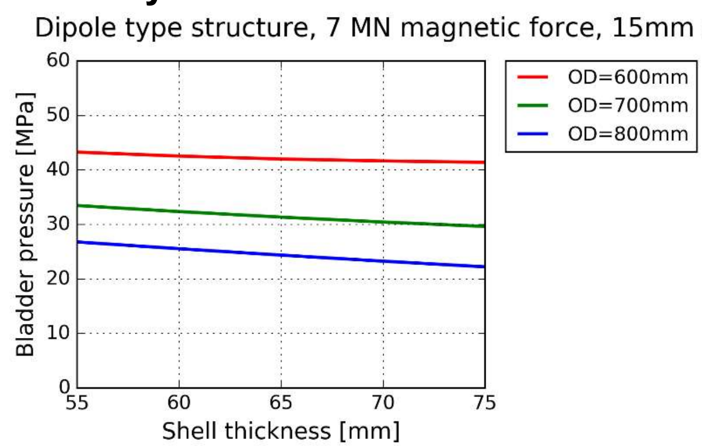


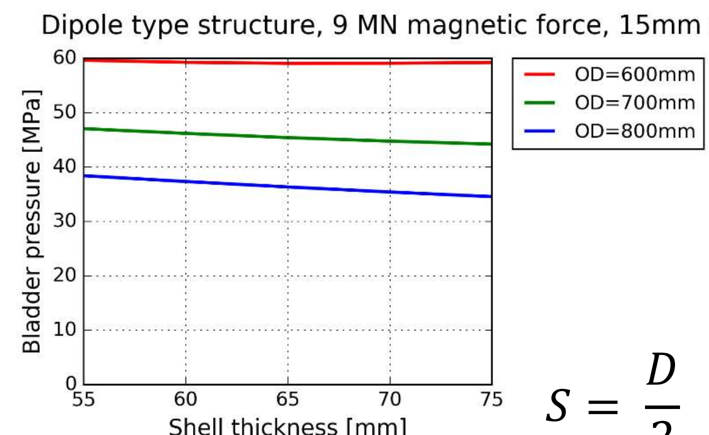
15T **17T**





RT key adjusted required to reach the pre-load
Only half of diameter used for the bladders





$$S = \frac{D}{2}$$

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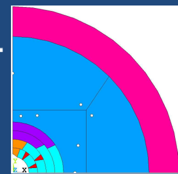
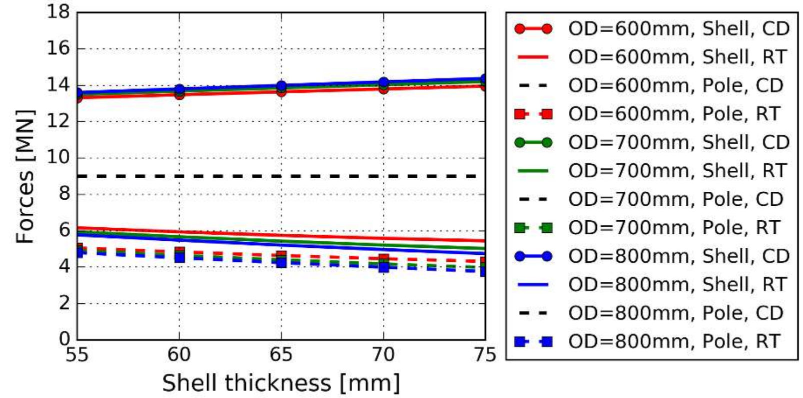


Quad yokes
Forces, Shell stress

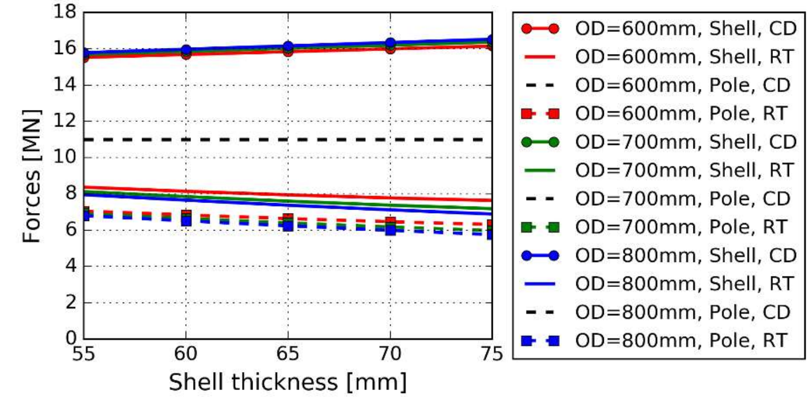
15T

Quad type structure, 7 MN magnetic force, 15mm cable



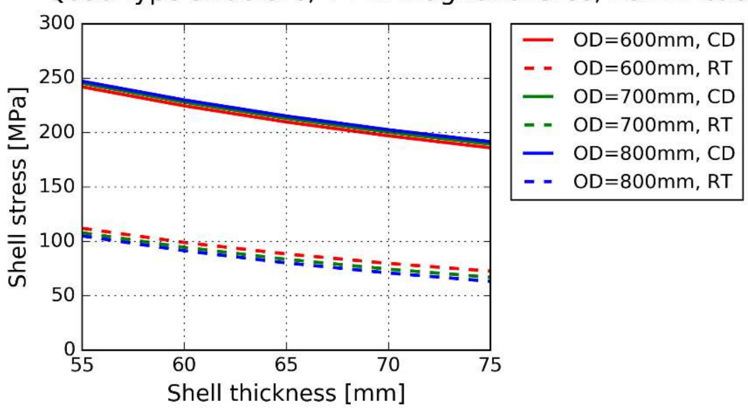
17T

Quad type structure, 9 MN magnetic force, 15mm cable

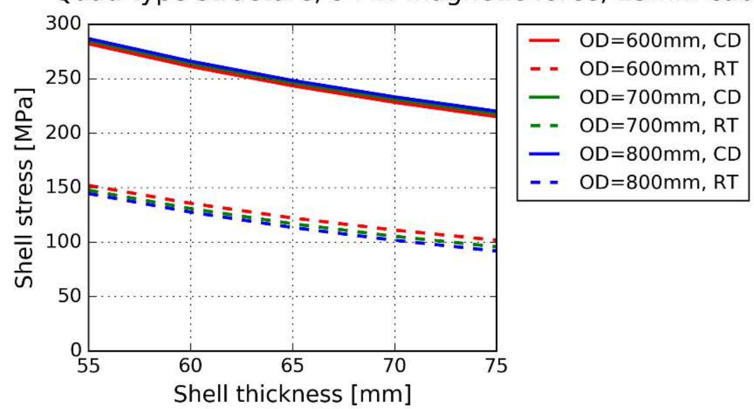


RT key adjusted to the same pre-load after cool-down (2MN/m more than magnetic forces)
Reaction force in the shell higher due to pre-load locked by the top/bottom yoke

Quad type structure, 7 MN magnetic force, 15mm cable



Quad type structure, 9 MN magnetic force, 15mm cable



Quad yokes
Horizontal key, bladder pressure

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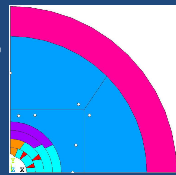
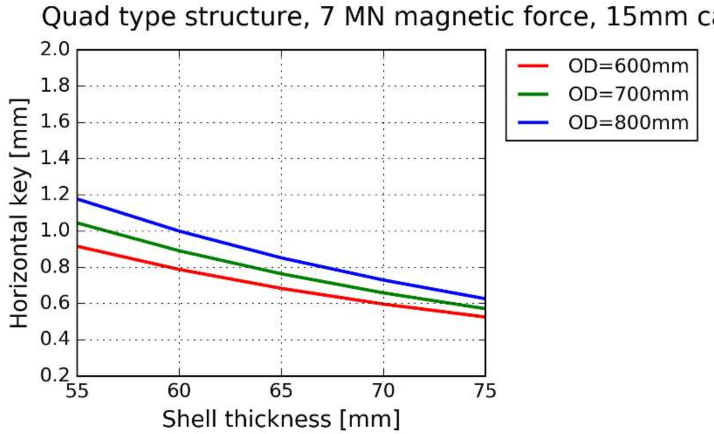
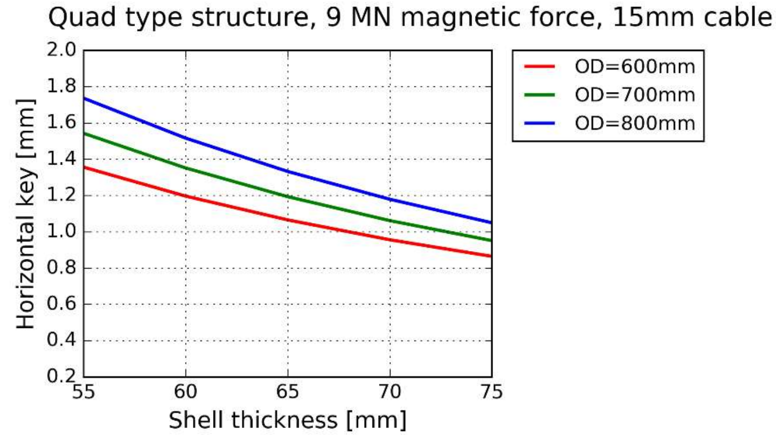


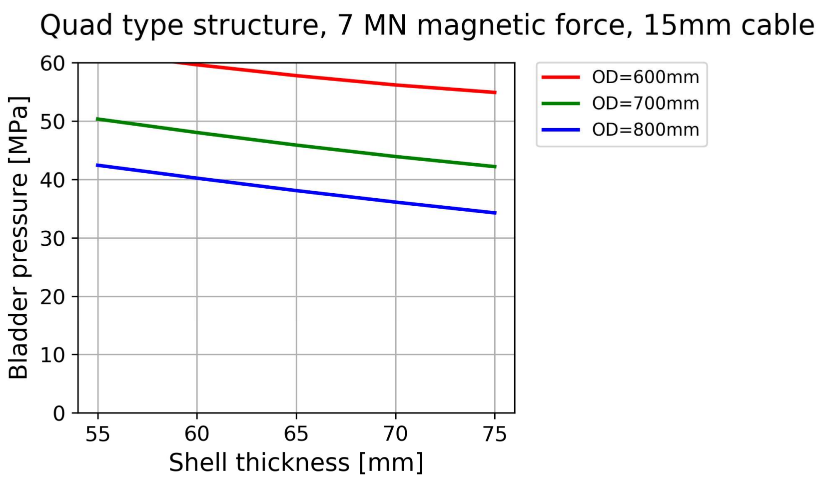
15T

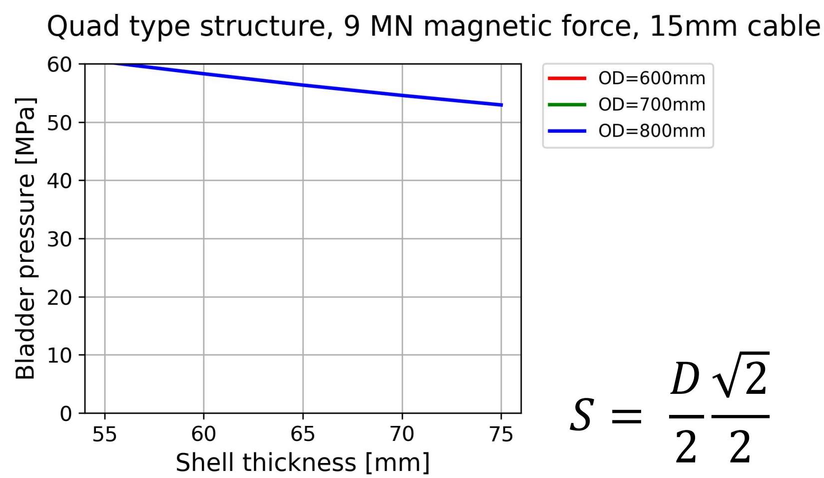


17T



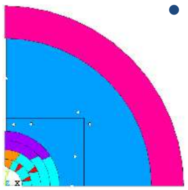
Thicker shim required due to intercepted force
Usable bladder space smaller than in dipole yokes structure



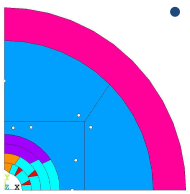


$$S = \frac{D}{2}\frac{\sqrt{2}}{2}$$

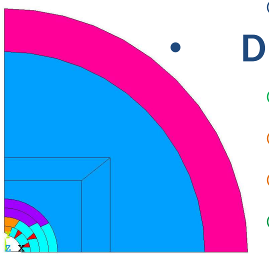
Summary
Other structure types



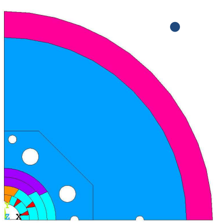
- Dipole yokes
  - Sufficient bladder space
  - Full reaction force from the shell goes to coil pre-load
  - Vertical corner keys increase stress in the structure
  - Low number of components
  - Adjustment with 2 key types



- Quad yokes
  - Limited bladder space, bladders less efficient
  - Top/bottom yoke limits vertical and intercepts part of the pre-load
  - Vertical corner keys increase stress in the structure
  - Quad yokes assembly
  - Adjustment with 2 key types



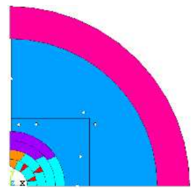
- Dipole yokes, quad pads
  - Sufficient bladder space
  - Top/bottom pad limits vertical and intercepts part of the pre-load
  - Vertical corner keys increase stress in the structure
  - Simple yoke assembly, more components in the coil-pack, bigger OD required
  - Adjustment with 2 key types

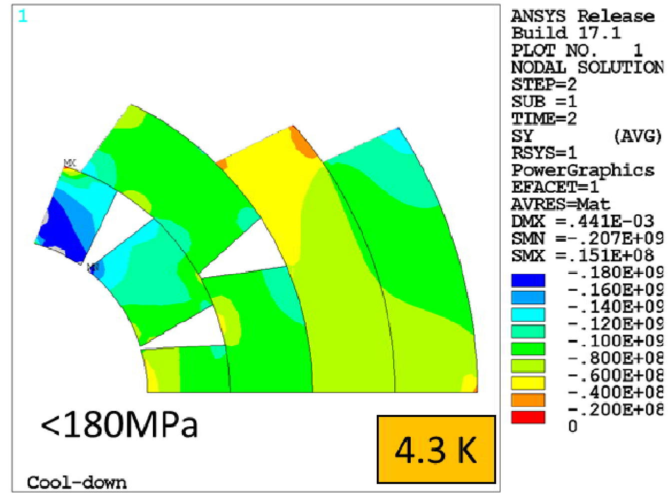


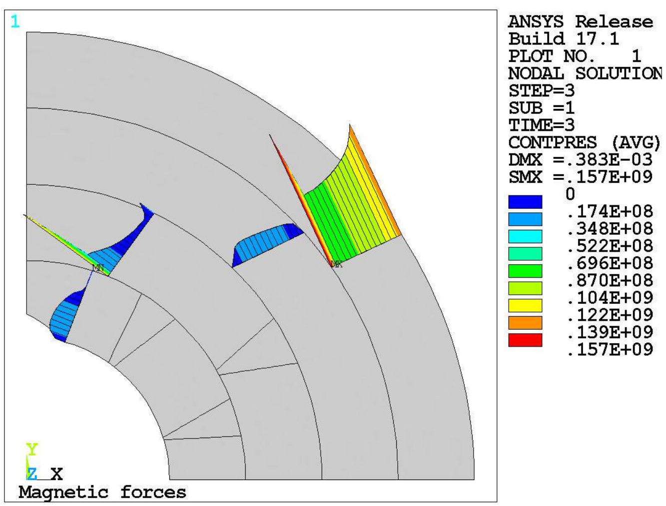
- Dipole yokes, octagonal coil-pack
  - Sufficient bladder space, diagonal bladders less efficient but increase total surface
  - Full reaction force from the shell goes to coil pre-load
  - Force transfer radially, low stress in the structure
  - Low number of components
  - Adjustment with 3 key types

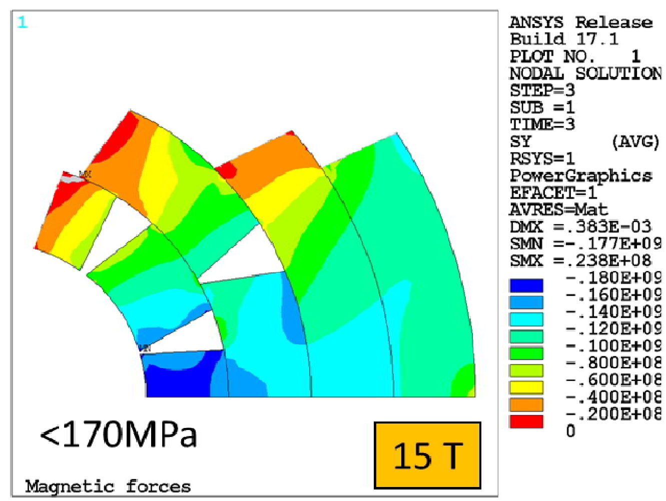
Shell based structure – example 1
Dipole yokes

- Structure configuration:
  - 2 yokes (iron)
  - 2 “collars” (iron)
- Shell OD/TH: 610/55 mm
- Hor. Mag. forces at 15T: 6.7MN/m
- Shell force at CD: 8.7 MN/m
- Pole force at CD: 8.7MN/m
- Pole force at 15T: 2.0 MN/m



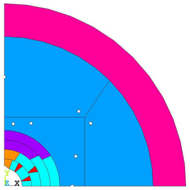


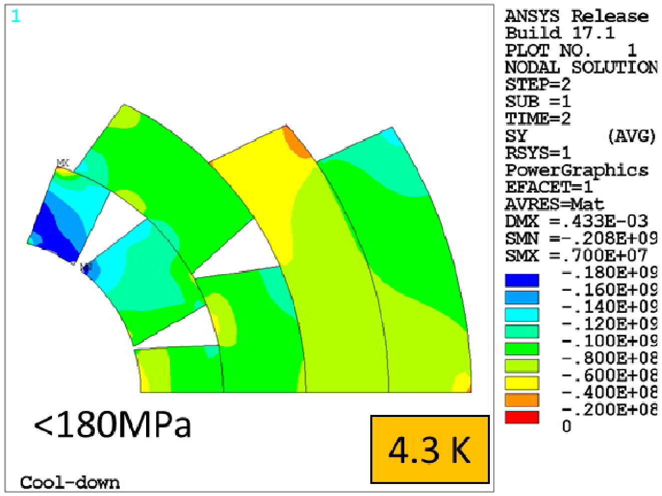


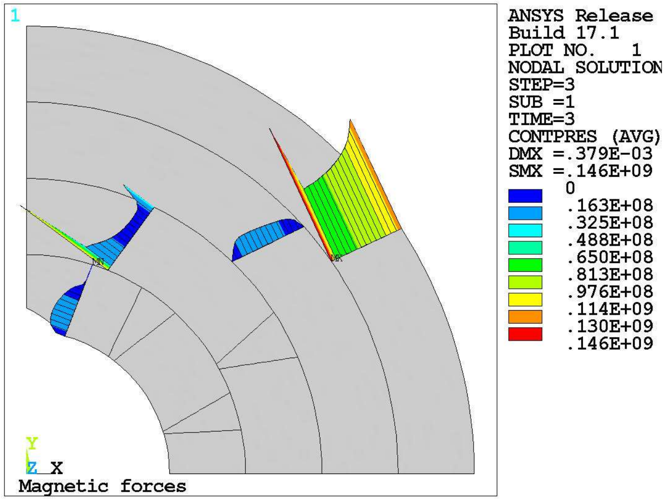


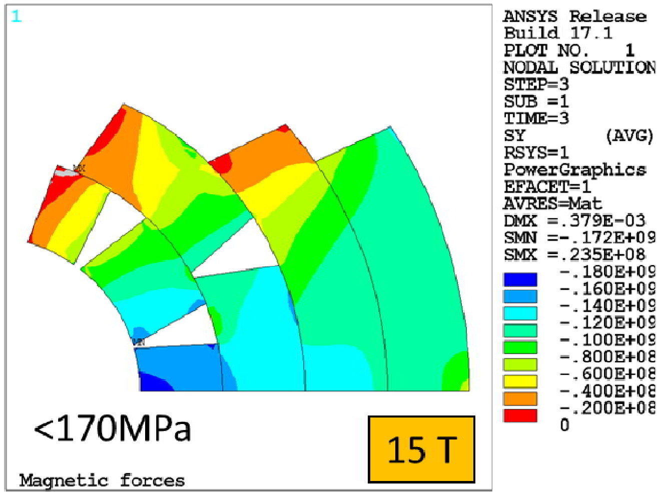
Shell based structure – example 2 Quad yokes

- Structure configuration:
  - 4 yokes (iron)
  - 2 “collars” (iron)
- Shell OD/TH: 610/55 mm
- Hor. Mag. forces at 15T: 6.7MN/m
- Shell force at CD: 12.4 MN/m
- Pole force at CD: 8.4 MN/m
- Pole force at 15T: 2.1 MN/m









Shell based structure – example 3
Dipole yokes, Quad pads

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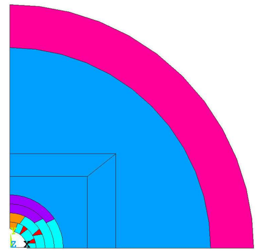
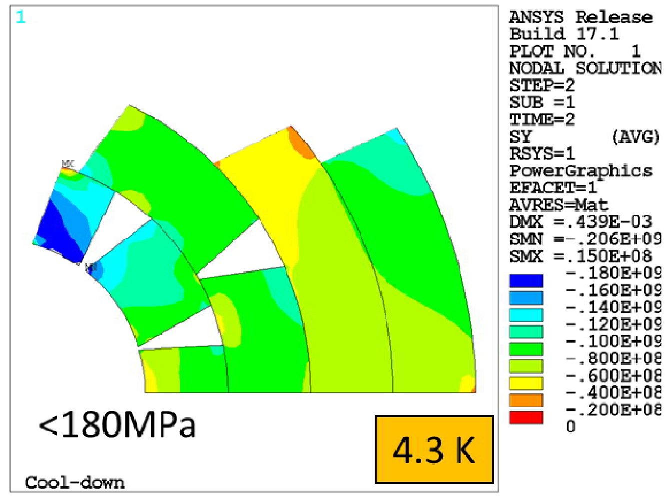
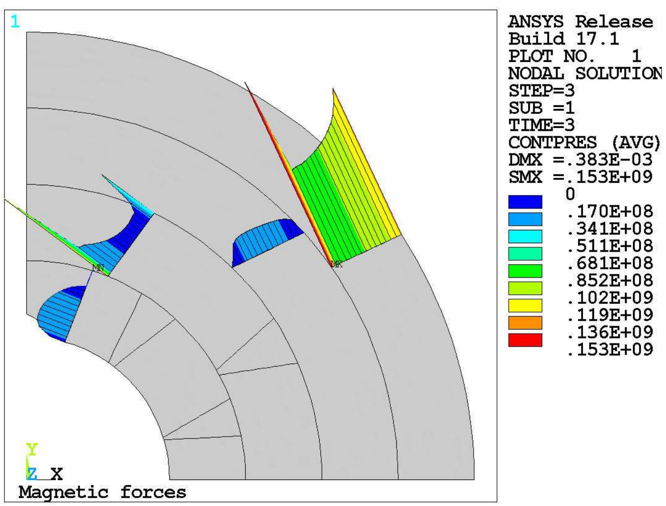
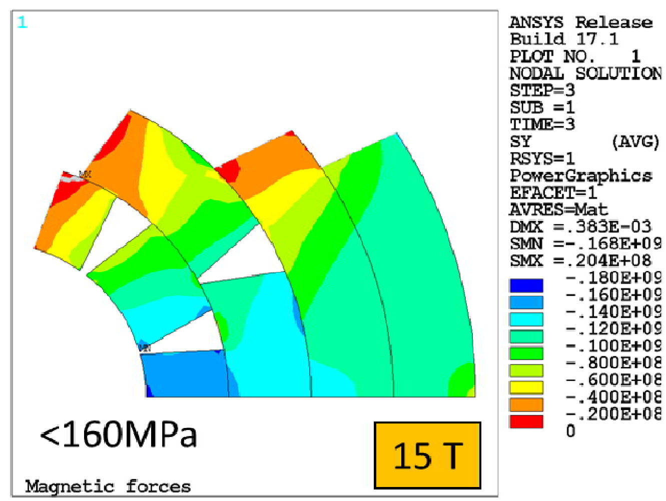
- Structure configuration:
  - 2 yokes (iron)
  - 4 pads (iron)
  - 2 "collars" (iron)
- Shell OD/TH: 850/75 mm
- Hor. Mag. forces at 15T: 6.9MN/m
- Shell force at CD: 12.7 MN/m
- Pole force at CD: 8.5 MN/m
- Pole force at 15T: 2.3 MN/m









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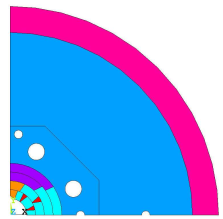
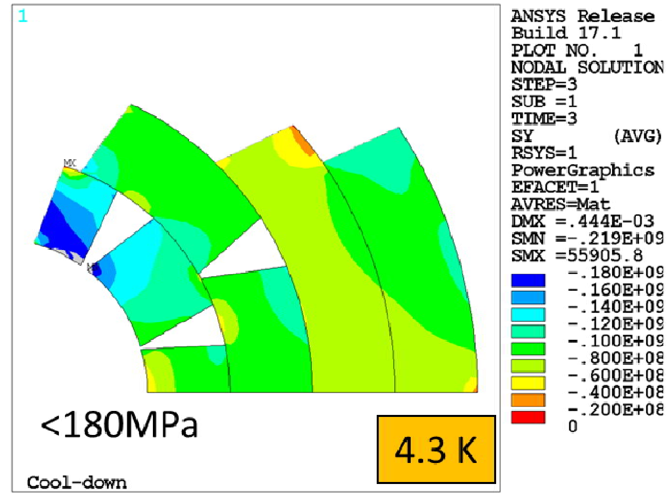
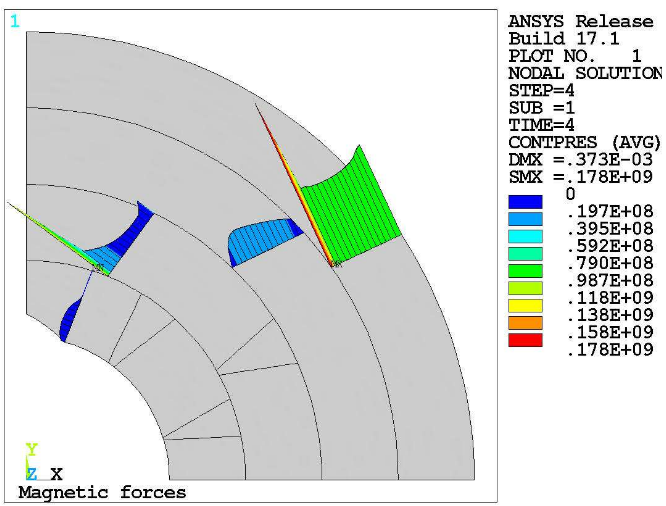
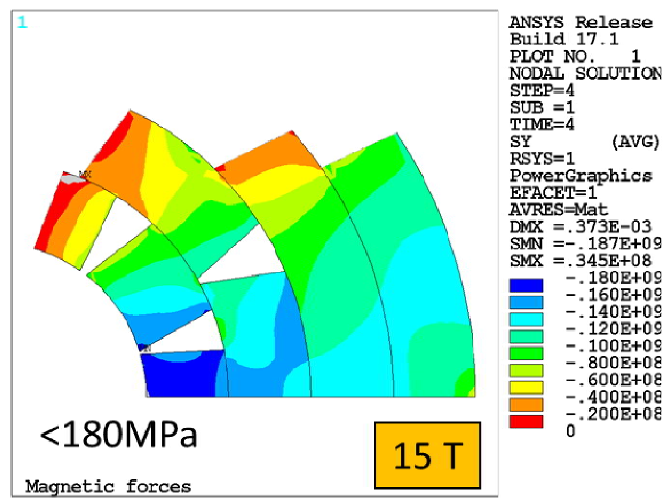
Shell based structure – example 4
Dipole yokes, Octagon coil-pack

- Structure configuration:
  - 2 yokes (iron)
  - 2 “collars” (iron)
  - Octagon coil-pack
- Shell OD/TH: 750/47 mm
- Hor. Mag. forces at 15T: 7.0MN/m
- Shell force at CD: 8.7 MN/m
- Pole force at CD: 8.7 MN/m
- Pole force at 15T: 1.7 MN/m









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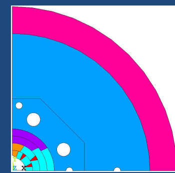
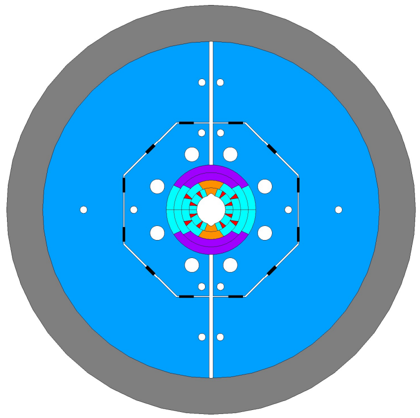
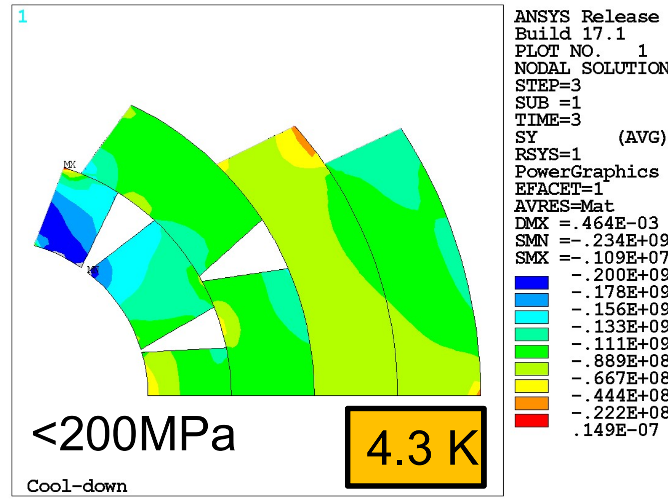
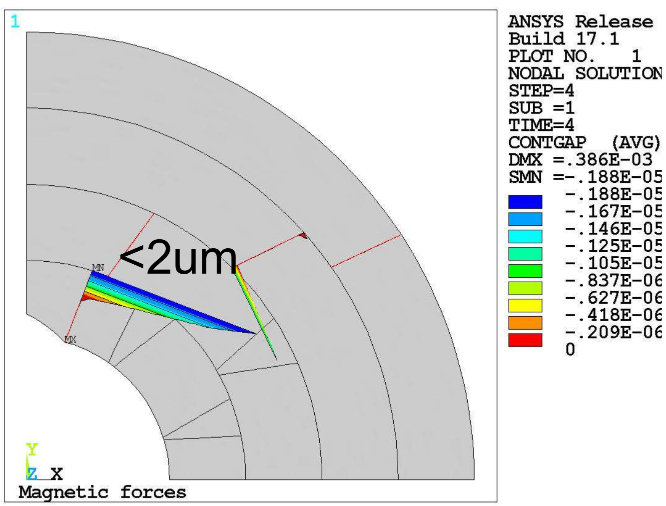


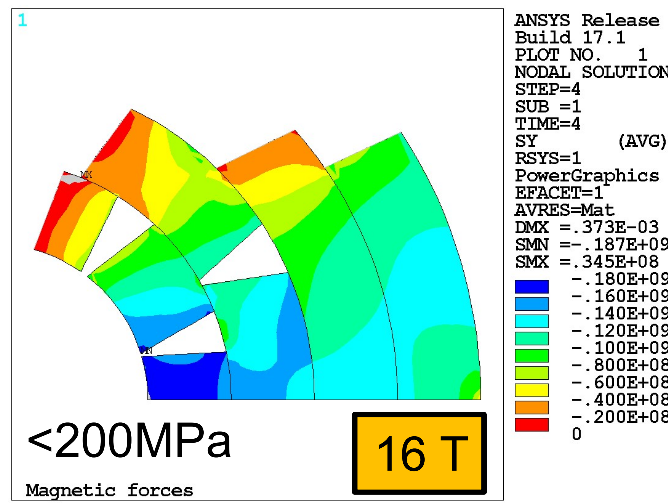
Structure concept optimized for 16T

- Shell OD: 730 mm, TH: 60 mm
- Bladder pressure < 45 MPa
- Coil stress < 80 MPa @ RT
- Structure stress
  - < 180 MPa @ RT
  - < 360 MPa @ CD & 16 T
- 17 T with stress ~230 MPa









Conclusions

- Integrated magnetic and mechanical design is crucial
  - Even simplified mechanical models with fixed OD pre-load can give a good overview of the coil stress limits
- Mechanical limitations of the coil design
  - Wider cable might not solve the problem for CT
  - Stress management in CT coils is an interesting concept
  - Optimization of the coil blocks to minimize the peak stress
  - Other coil designs
- Utility structure
  - Minimum OD limited by space available for bladders (~700mm)
  - Dipole yoke type structures more efficient
  - Structure with octagonal coil-pack
    - Compatible with existing CT design (~180 MPa @ 15T after quick optimization)
    - Shlomo! Let's put CCT inside!
  - Minimum time for engineering design, procurement and parts fabrication
    - 6-8 months

Structure with octagonal coil-pack