EPFL

EDIPO 2
Staggered racetracks
3D magnetic analysis

X. Sarasola

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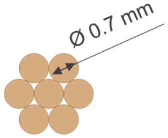
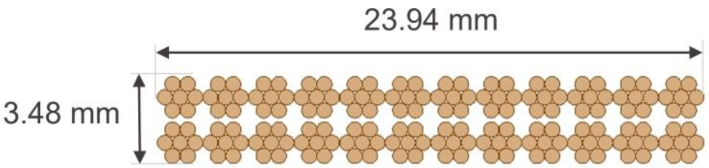
SWISS PLASMA CENTER

Cable design

- Bruker strand:
  - $j_{c,nc}$ = 2600 A/mm^2 at 12 T and 4.2 K
  - Cu:nCu = 1.0
- Same cable used for all coils
  - First stage:

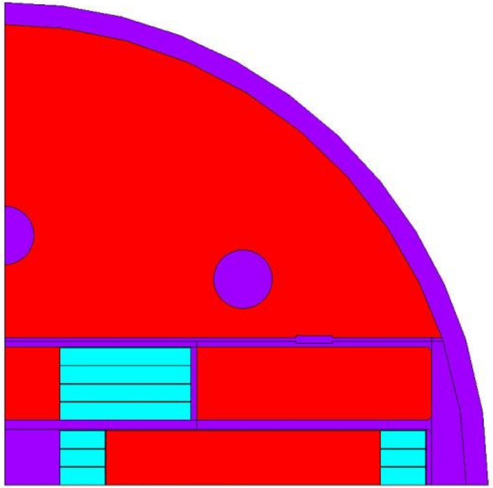


  - Second stage: 24×(6+1), 0.7 mm

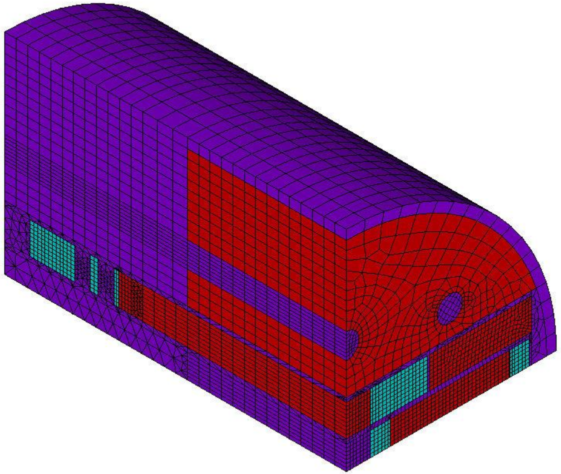


Magnet design

- 144×144 mm^2 aperture
- Two sets of flat racetrack coils:
  1. Side coils: one pair of coils each made of 6 pancakes: 16 turns/pancake
  2. Vertical coils: one pair of coils each made of 4 pancakes: 46 turns/pancake
- Iron parts in red: iron yoke limited to the straight section of the side coils
- 50 mm wide spacers at the coils' ends



EDIPO, magnetic 2D model

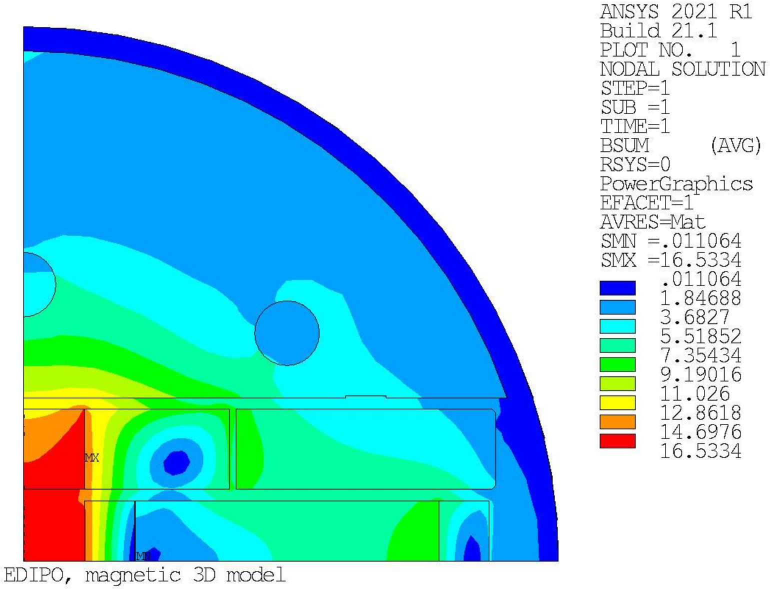


EDIPO, magnetic 3D model

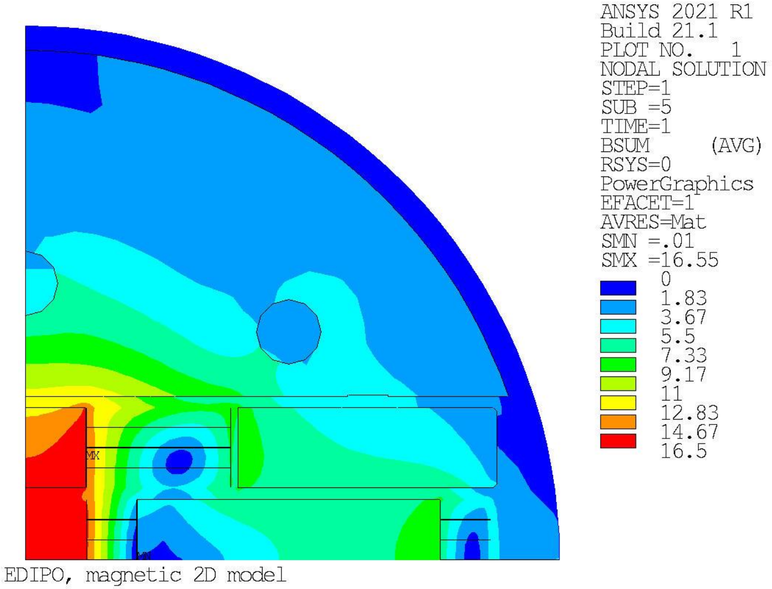
Comparison 3D vs 2D

	3D	2D
I_{op} (85%×I_{ss})	17.410 kA	17.316 kA
$B_{center\ aperture}$	15.01 T	15.03 T
B_{coil}	15.04 T	15.07 T
E_{total}	19.7 MJ	11.4 MJ/m

Magnetic 3D model



Magnetic 2D model



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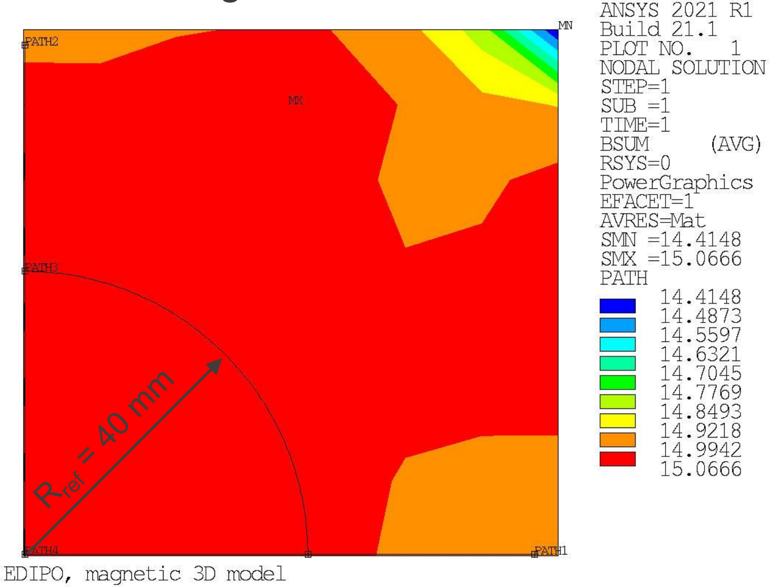
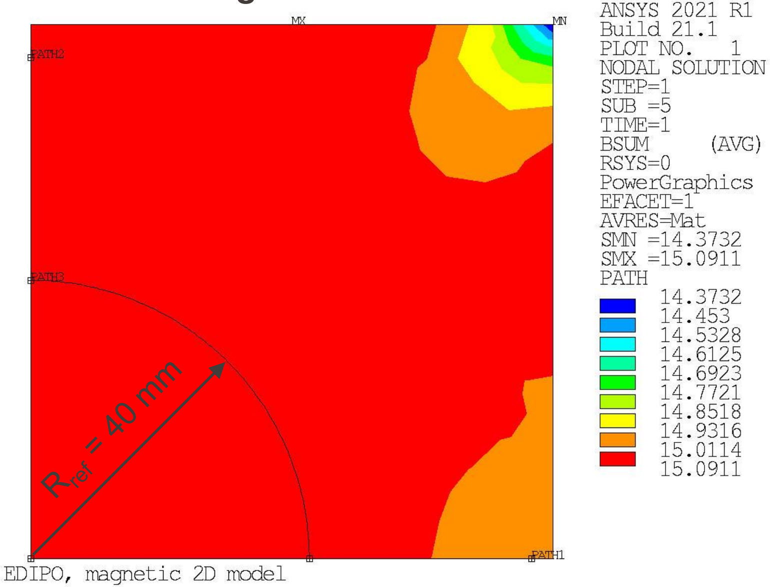
Field in the aperture

- B field plotted along 4 paths:
  - Path 1 along x axis of the aperture
  - Path 2 along y axis of the aperture
  - Path 3 around a circumference of R=40 mm
  - Path 4 along z axis

Magnetic 3D model



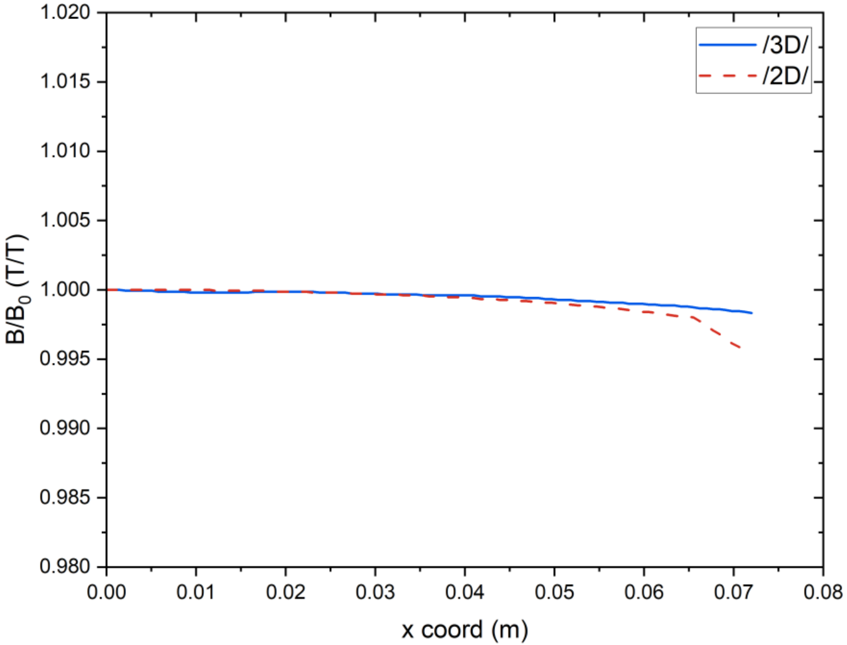
Magnetic 2D model



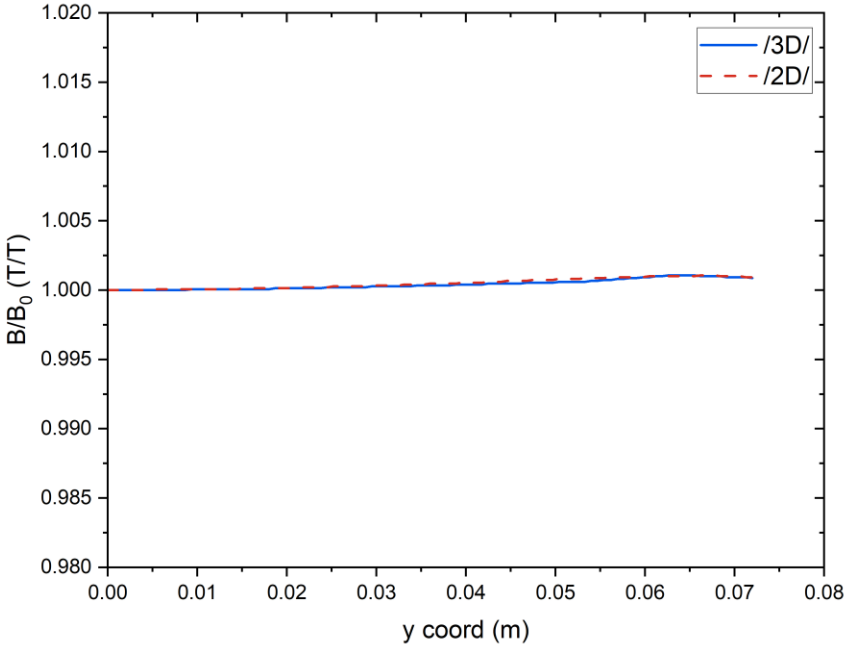
Field along paths 1 and 2

- Good agreement between 2D and 3D

Path 1 (x axis of the aperture)



Path 2 (y axis of the aperture)



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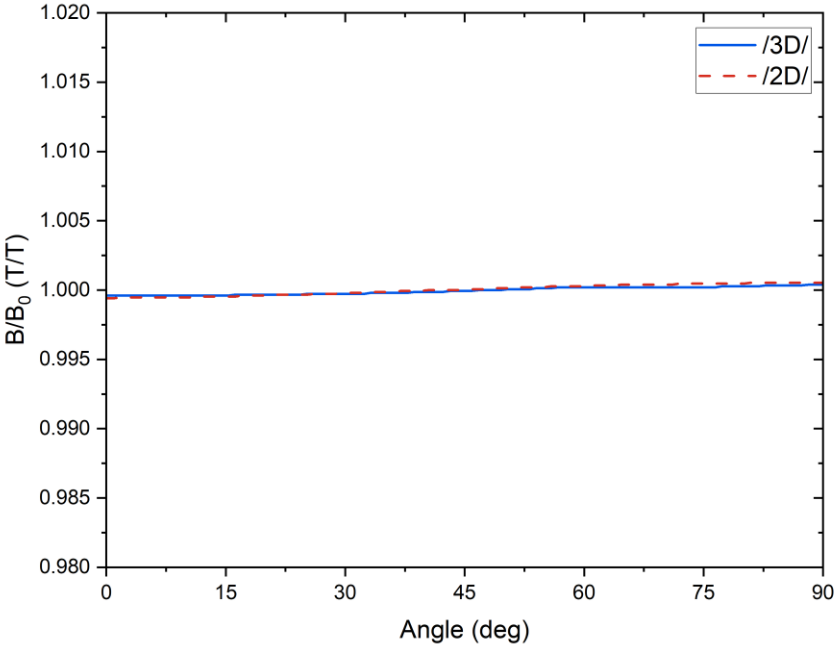
Field along paths 3 and 4

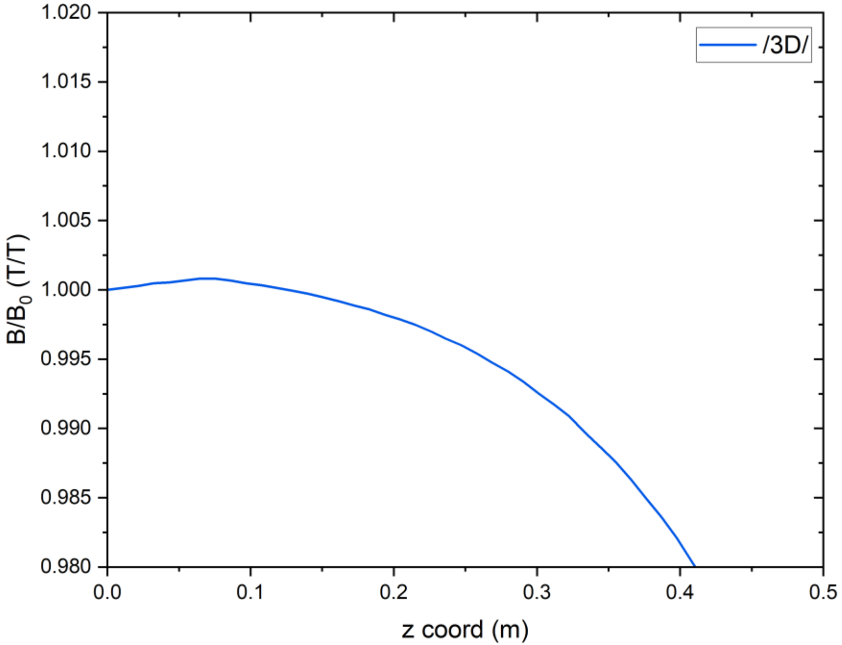
- Homogeneity along the z axis:
  - 1% drop of the field at z = ±0.331 m
  - 2% drop of the field at z = ±0.411 m

Large end spacers and a limited length of the iron yoke are required to bring the peak field in the coils to the straight section, but reduce the homogeneous field length

Path 3 (around circumference of R=40 mm)



Path 4 (z axis of the aperture)



B field in the coils

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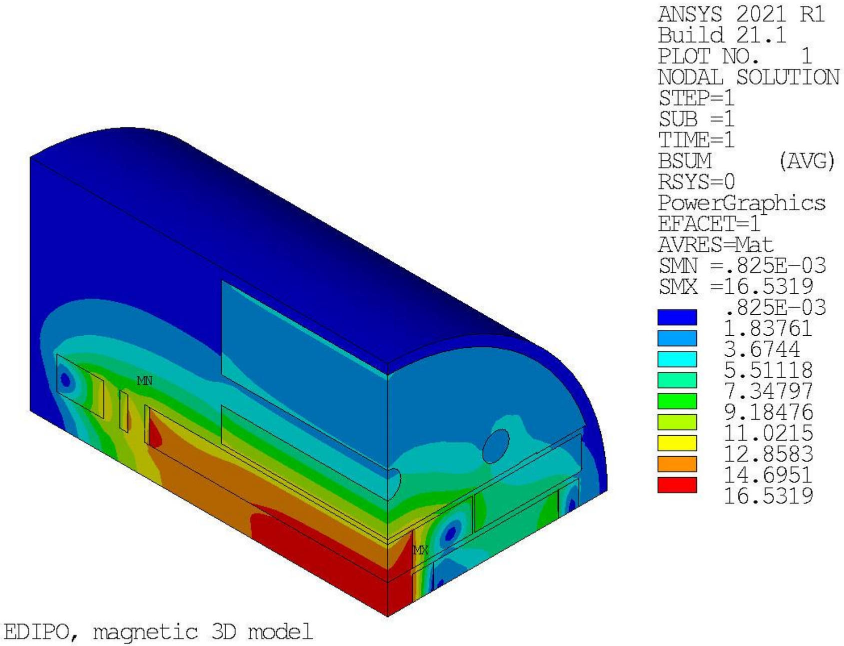
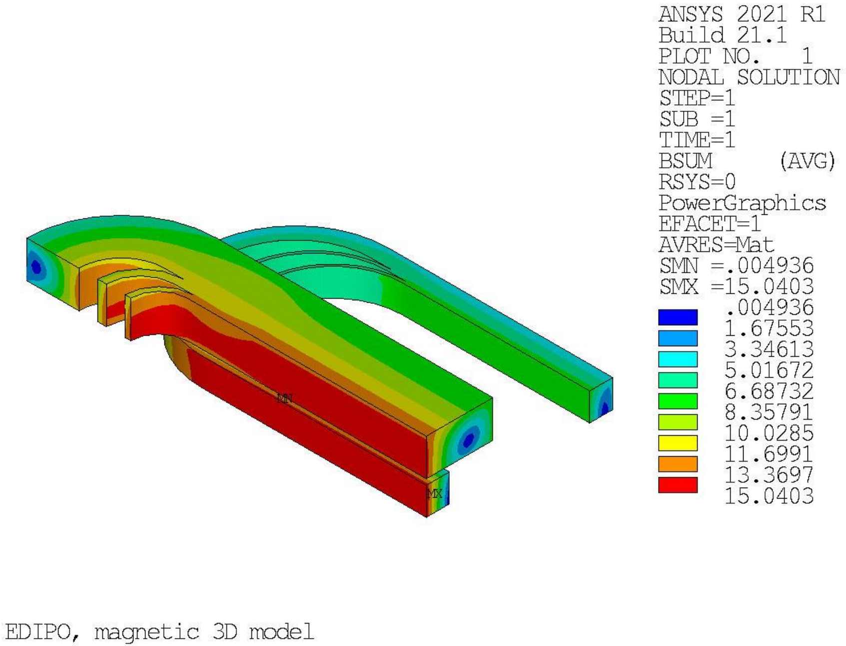
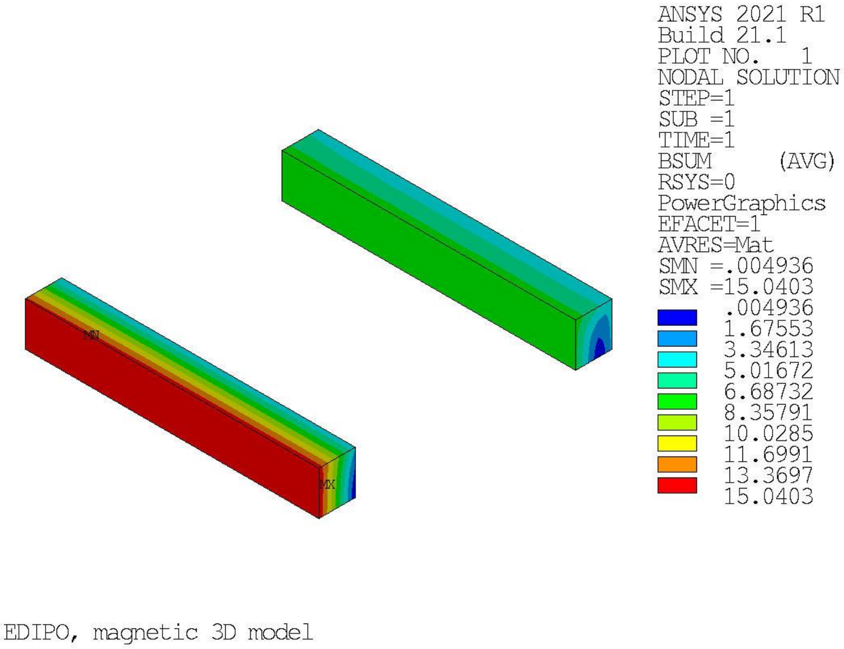




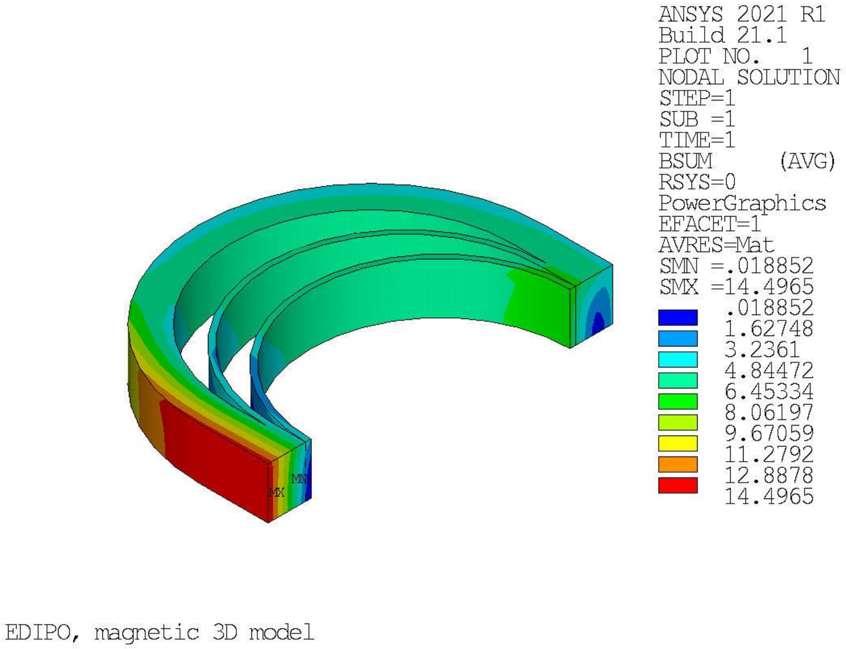
B field in coil 1: straight section vs ends

- 50 mm wide spacers in the coil ends
- The difference in peak field is 0.54 T

Straight section (B_{max} = 15.04 T)



Coil ends (B_{max} = 14.50 T)



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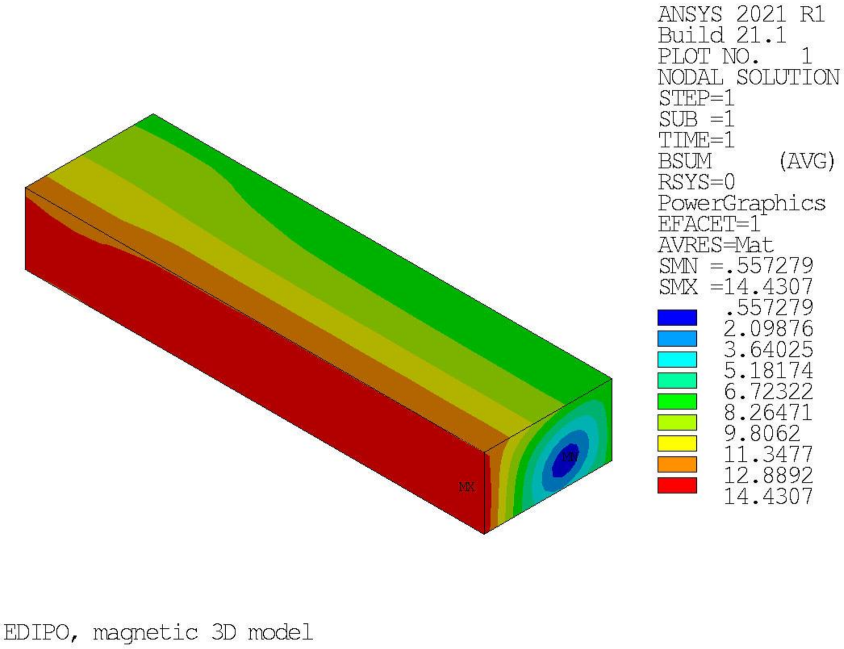
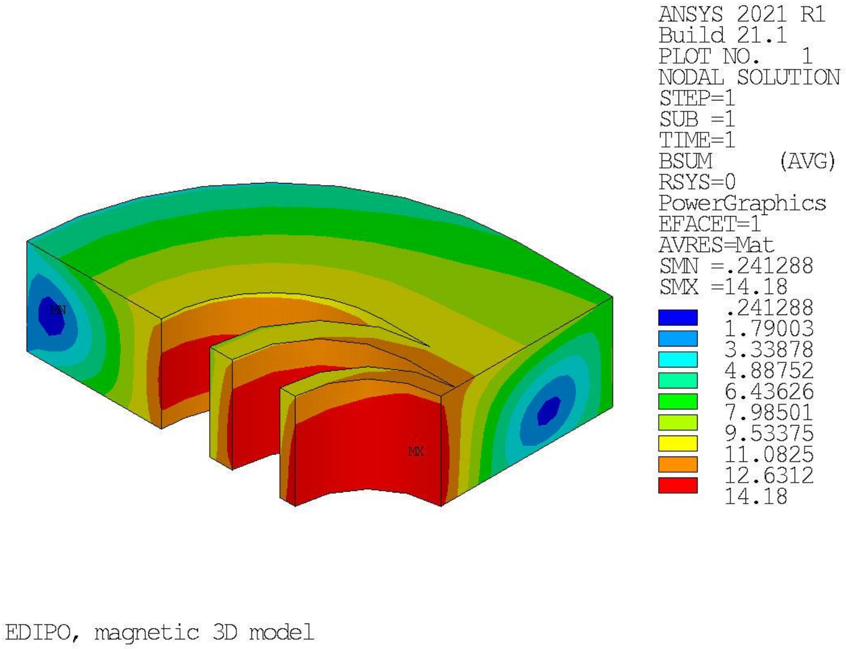
B field in coil 2: straight section vs ends

- 50 mm wide spacers in the coil ends
- The difference in peak field is 0.25 T

Straight section (B_{max} = 14.43 T)



Coil ends (B_{max} = 14.18 T)

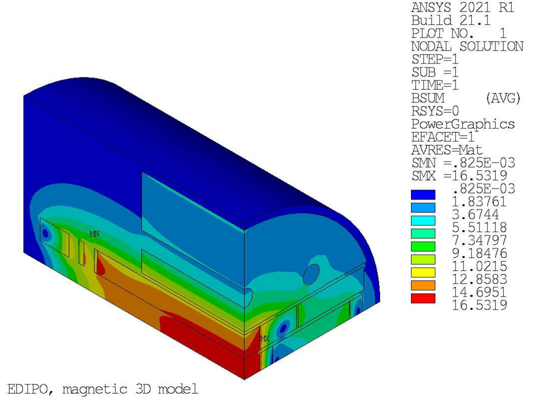


Magnetostatic 3D analysis

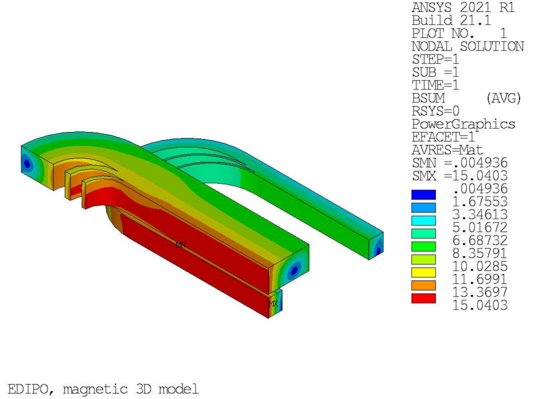
	$I_{op} = 0.85 \times I_{ss}$	$I_{op} = I_{max}$	
Cable layout	24×(6+1), 0.7 mm diam		
Number of turns	Side coils: 2×6×16 Vertical coils: 2×4×46		
Total number of turns, n_{total}	560		
Total area of insulated conductor	52886		mm^2
Operating current, I_{op}	17.41 (85%×I_{ss})	18.00 (87.9%×I_{ss})	kA
B field in the center of the aperture, B_0	15.01	15.46	T
Peak B field in the coils, B_{peak}	15.04	15.51	T
Total ampere-turns, I_{total}	9.75	10.08	MAt
Total magnet stored energy, E_{total}	19.7	21.0	MJ
Magnet self-inductance, L	129.8		mH
Engineering current density, j_{eng}	184.3	190.6	A/mm^2
Copper current density, j_{Cu}	538.6	556.8	A/mm^2

$I_{op} = 0.85 \times I_{ss}$

B field in the magnet



B field in the winding pack

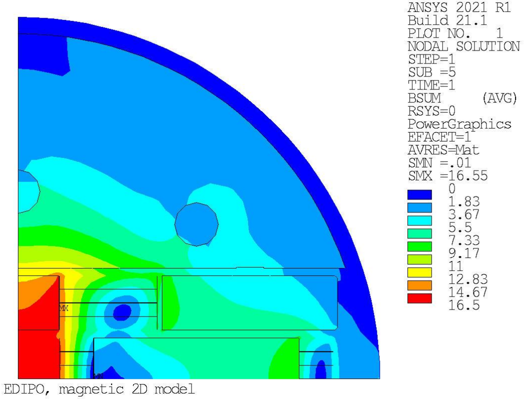


Magnetostatic 2D analysis

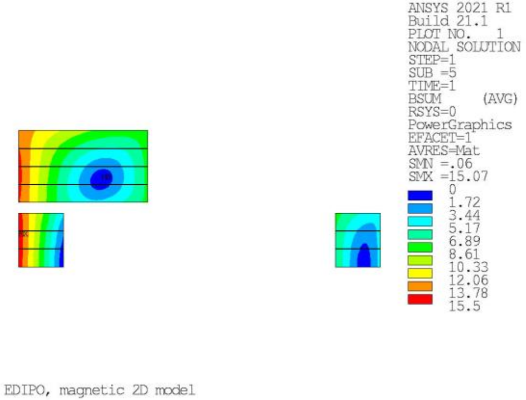
	$I_{op} = 0.85 \times I_{ss}$	$I_{op} = I_{max}$	
Cable layout	24×(6+1), 0.7 mm diam		
Number of turns	Side coils: 2×6×16 Vertical coils: 2×4×46		
Total number of turns, n_{total}	560		
Total area of insulated conductor	52886		mm^2
Operating current, I_{op}	17.316 (85%×I_{ss})	18.00 (88.4%×I_{ss})	kA
B field in the center of the aperture, B_0	15.03	15.56	T
Peak B field in the coils, B_{peak}	15.07	15.61	T
Total ampere-turns, I_{total}	9.70	10.08	MAt
Total magnet stored energy, E_{total}	11.44	12.33	MJ/m
Magnet self-inductance, L	76.1		mH/m
Engineering current density, j_{eng}	183.4	190.6	A/mm^2
Copper current density, j_{Cu}	535.7	556.8	A/mm^2

$I_{op} = 0.85 \times I_{ss}$

B field in the magnet

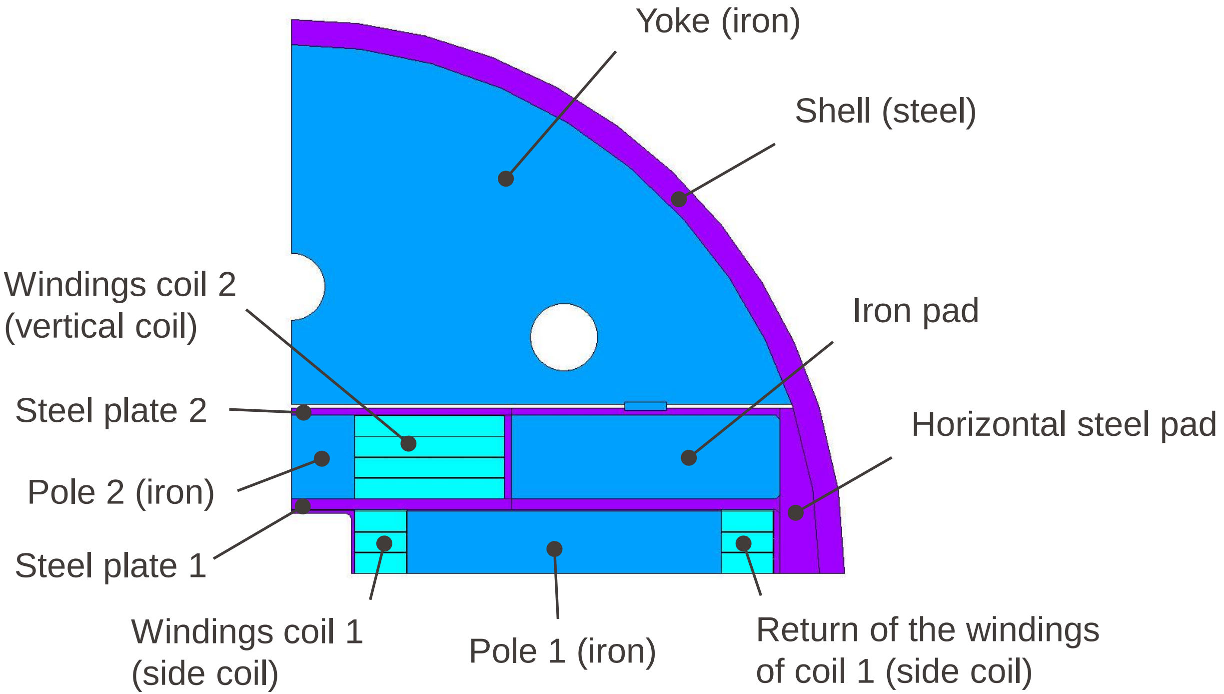


B field in the winding pack



Mechanical 2D analysis

- Three loading steps:
  - Room temperature
  - Cool-down
  - Powering



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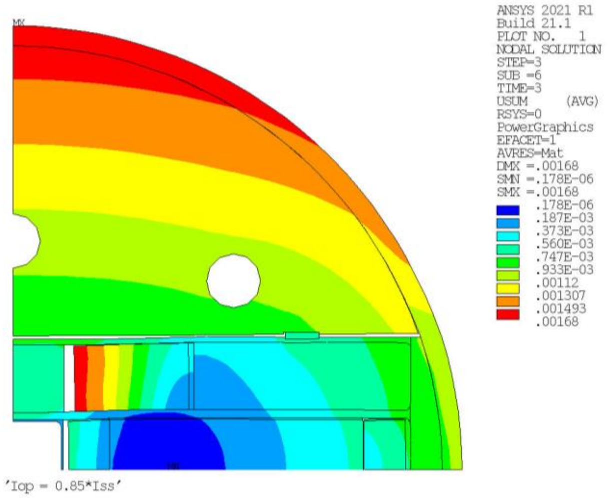
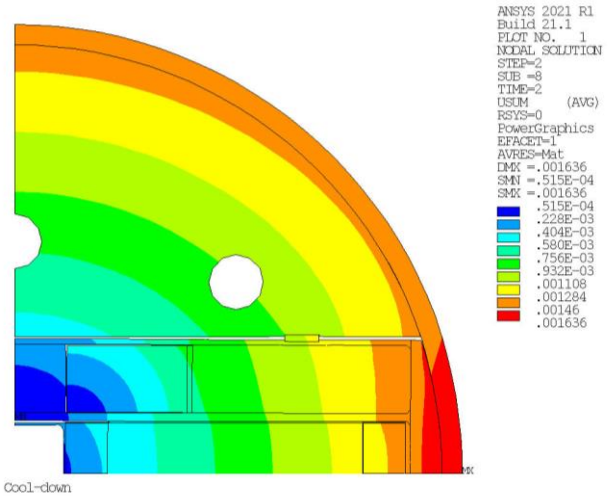
Displacement (magnet)

- Both sets of coils are pulled radially outward:
  - Side coils detach from the test well
  - Vertical coils detach from their poles
- Pole 2 is pulled toward the midplane

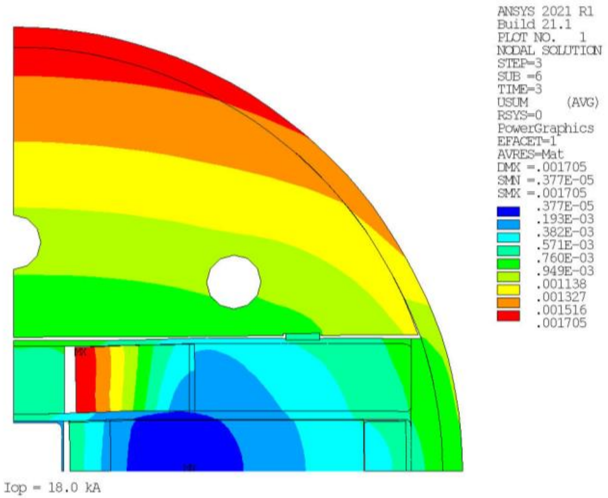
$I_{op} = 0.85 \times I_{ss}$



Cool-down



$I_{op} = 18.0$ kA



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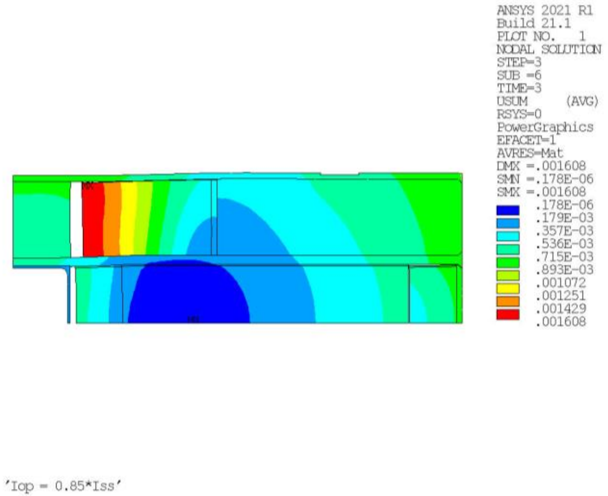
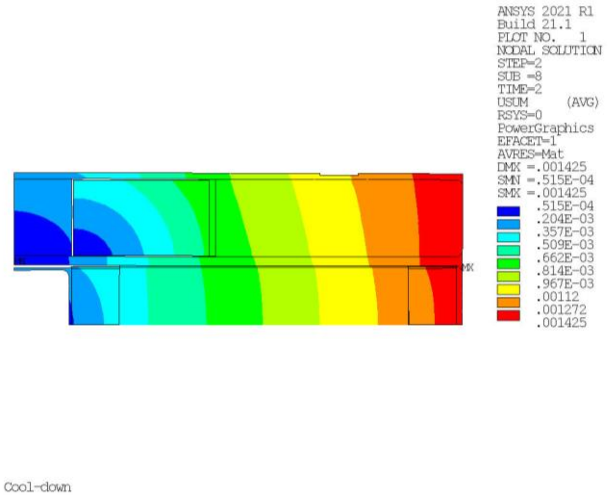
Displacement (coil pack)

- Both sets of coils are pulled radially outward:
  - Side coils detach from the test well
  - Vertical coils detach from their poles
- Pole 2 is pulled toward the midplane

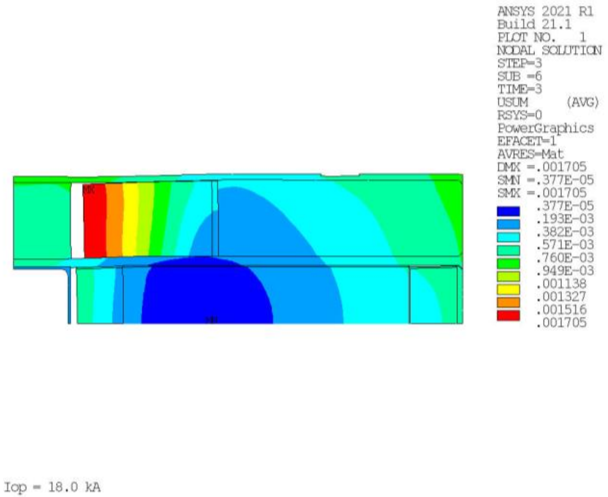
$I_{op} = 0.85 \times I_{ss}$



Cool-down



$I_{op} = 18.0$ kA



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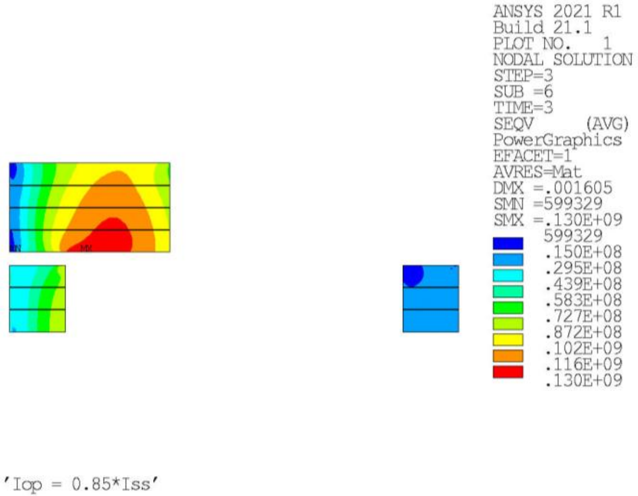
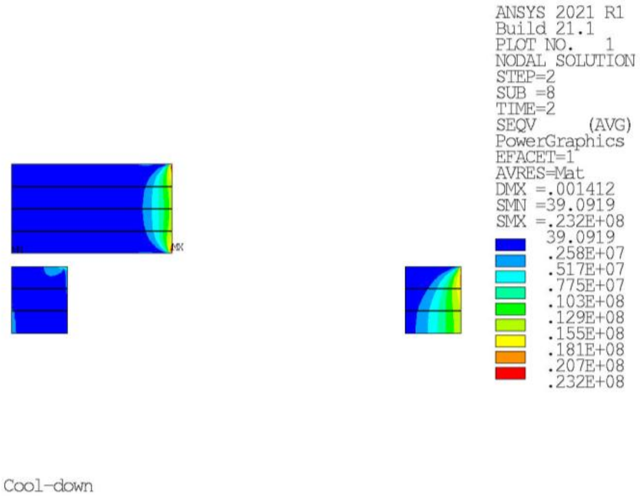
Von Mises stress in the coils

- Very modest stress after cool-down
- $\sigma_{eq} \leq 130$ MPa at $I_{op} = 0.85{\times}I_{ss}$
- $\sigma_{eq} \leq 139$ MPa at 18.0 kA
- More modest stress in the high field region

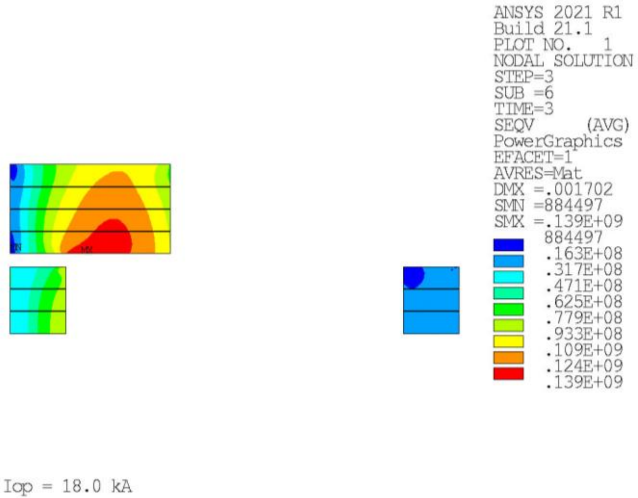
$I_{op} = 0.85{\times}I_{ss}$



Cool-down



$I_{op} = 18.0$ kA



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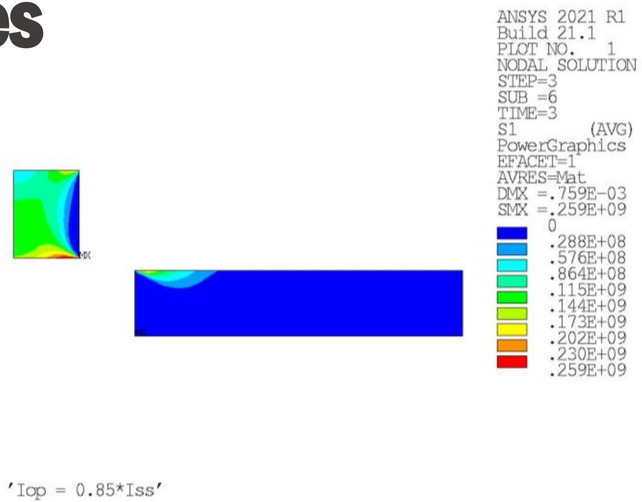
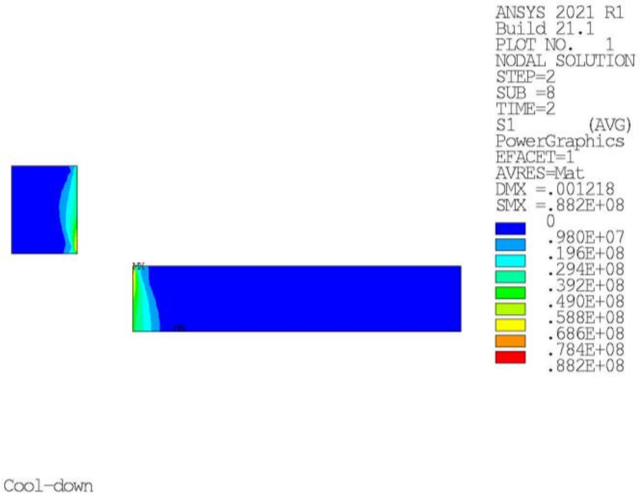
Max principal stress in the poles

- Within allowable limits at I_{op}=0.85×I_{ss}
  - $\sigma_1 \leq$ 259 MPa
- Slightly above limits at I = 18.0 kA
  - $\sigma_1 \leq$ 289 MPa

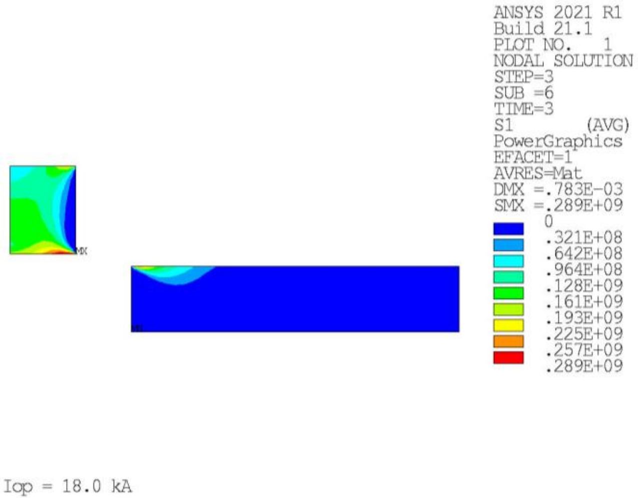
I_{op} = 0.85×I_{ss}



Cool-down



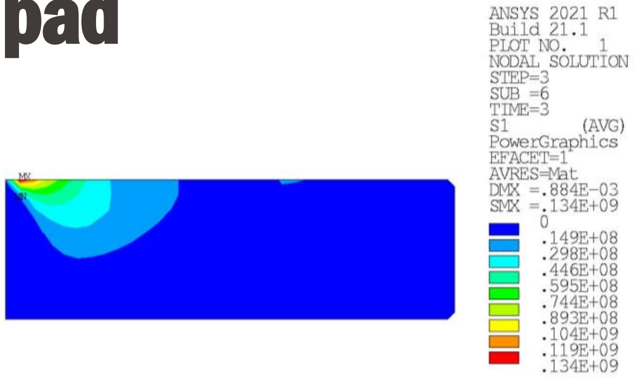
I_{op} = 18.0 kA



Max principal stress in the iron pad

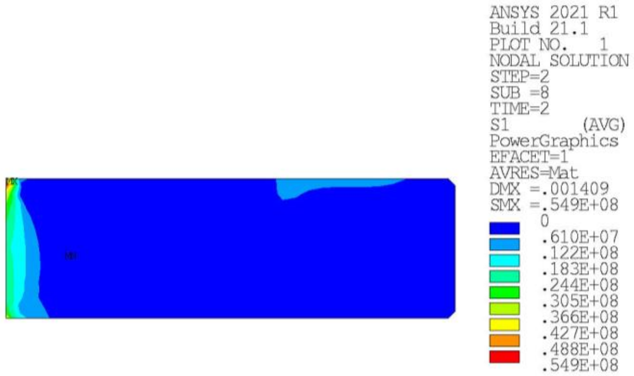
- Always within allowable limits:
  - $\sigma_1 \leq 134$ MPa at $I_{op} = 0.85 \times I_{ss}$
  - $\sigma_1 \leq 148$ MPa at 18 kA

$I_{op} = 0.85 \times I_{ss}$



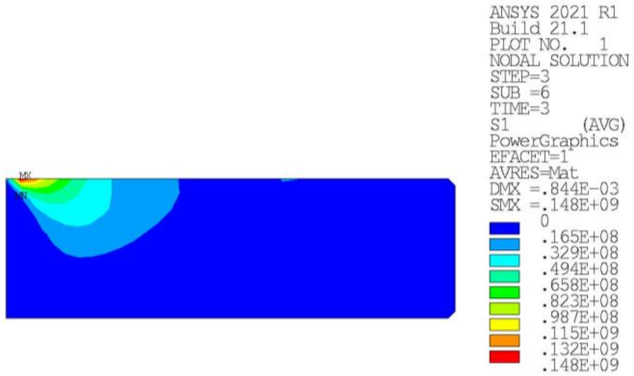
'Iop = 0.85*Iss'

Cool-down



Cool-down

$I_{op} = 18.0$ kA

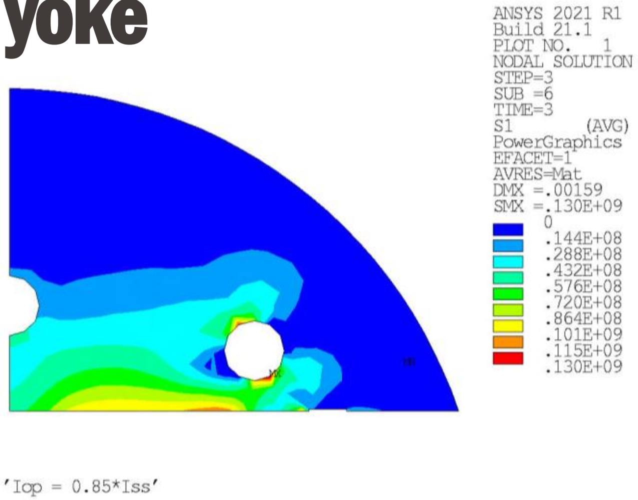


Iop = 18.0 kA

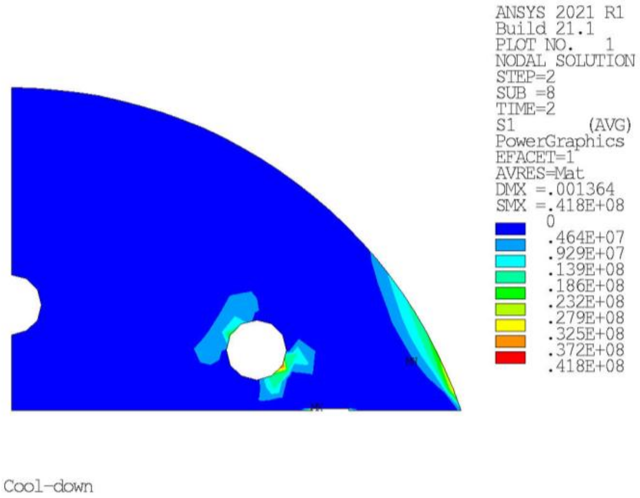
Max principal stress in the iron yoke

- Always within allowable limits:
  - $\sigma_1 \leq 130$ MPa at $I_{op} = 0.85 \times I_{ss}$
  - $\sigma_1 \leq 134$ MPa at 18 kA

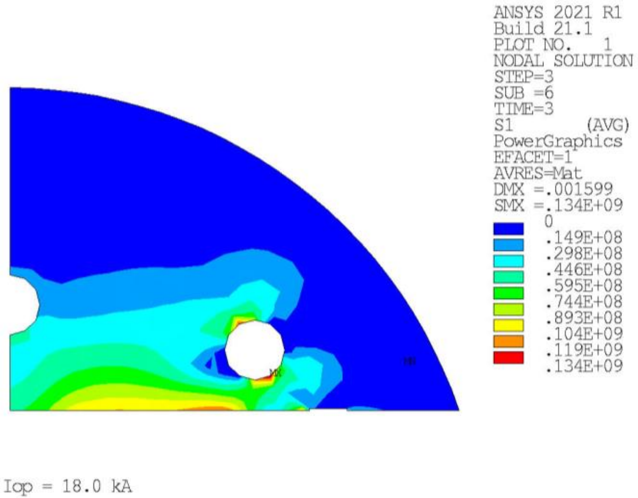
$I_{op} = 0.85 \times I_{ss}$



Cool-down



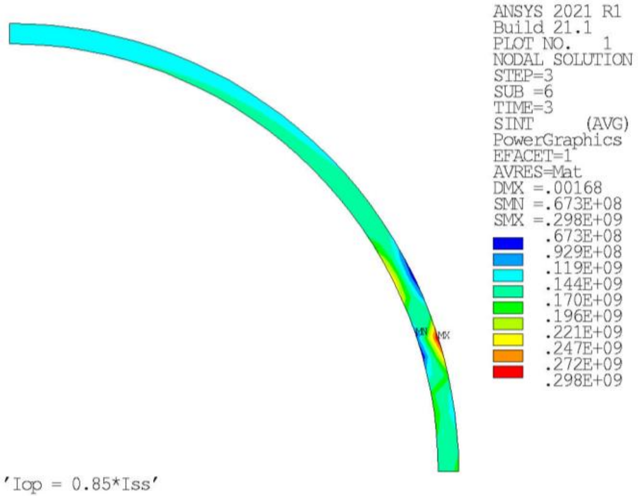
$I_{op} = 18.0$ kA



Stress intensity in the shell

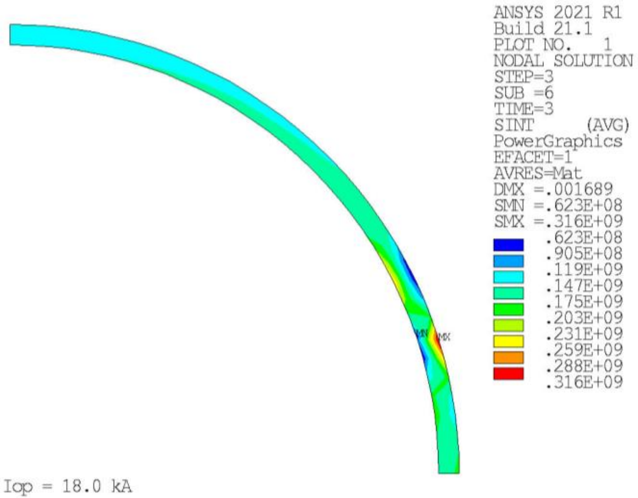
- Always within allowable limits

$I_{op} = 0.85 \times I_{ss}$



Cool-down

$I_{op} = 18.0$ kA



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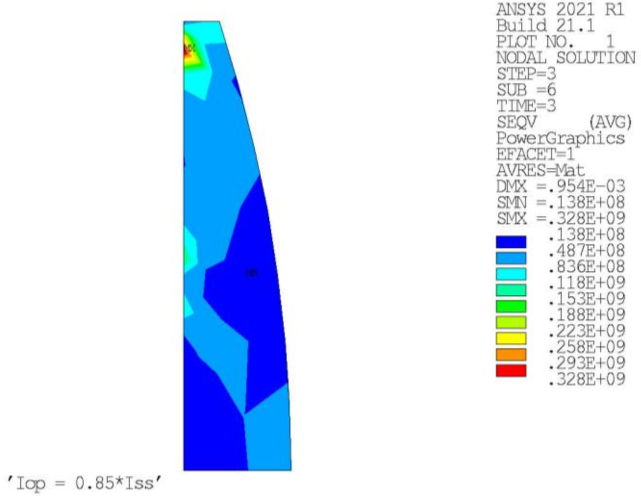
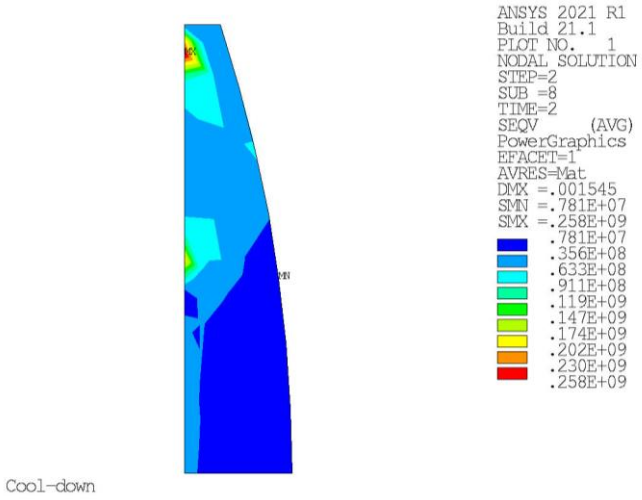
Von Mises stress in the H-pad

- Always within allowable limits

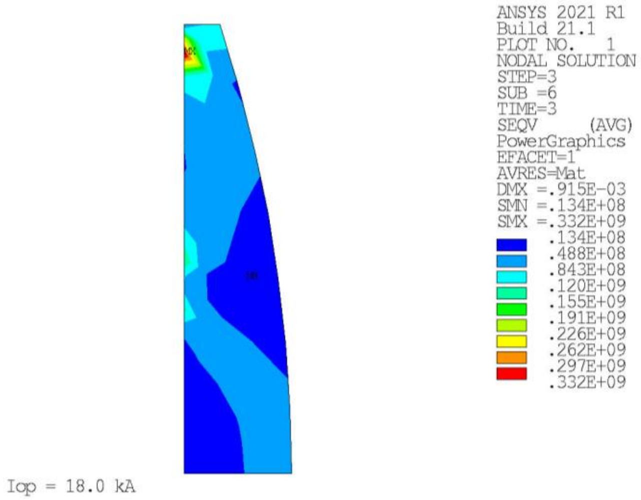
$I_{op} = 0.85 \times I_{ss}$



Cool-down



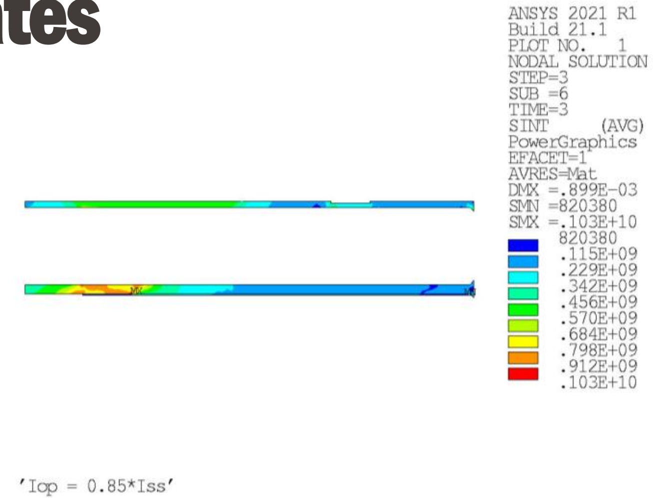
$I_{op} = 18.0$ kA



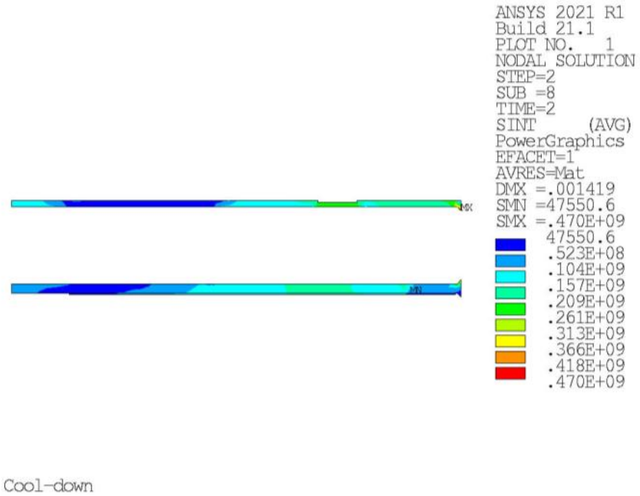
Stress intensity in the steel plates

- The high stress in the steel plate 1 call for the use of a high strength austenitic steel

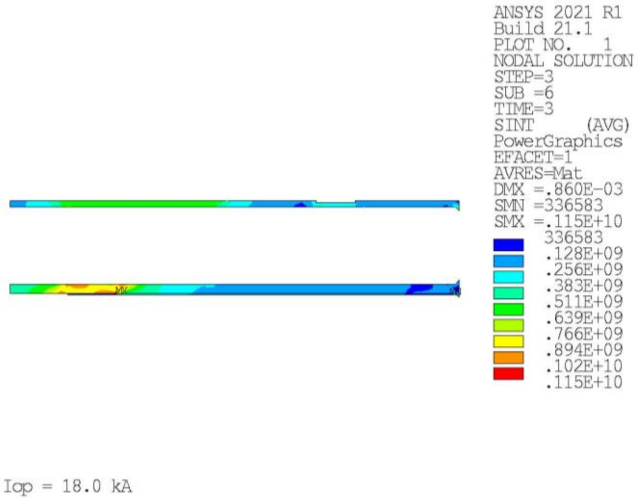
$I_{op} = 0.85 \times I_{ss}$



Cool-down



$I_{op} = 18.0$ kA



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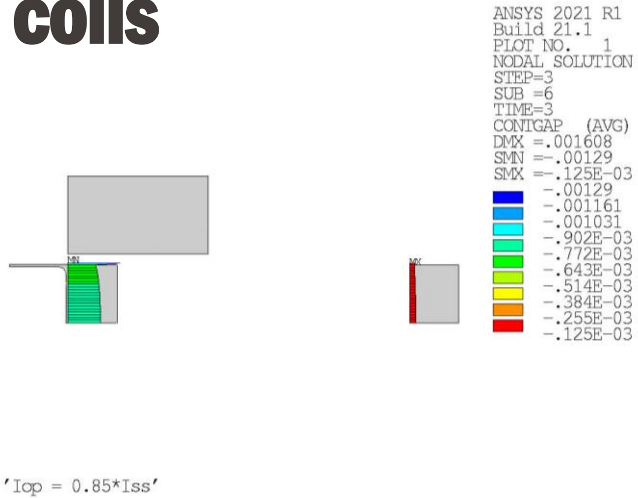
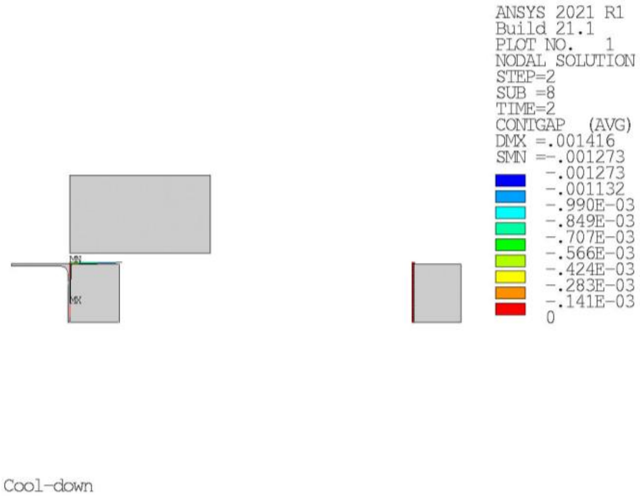
Gap between test well and side coils

- Between the test well and side coils:
  - gap ≤ 0.9 mm at $I_{op} = 0.85 \times I_{ss}$
  - gap ≤ 0.9 mm at 18 kA

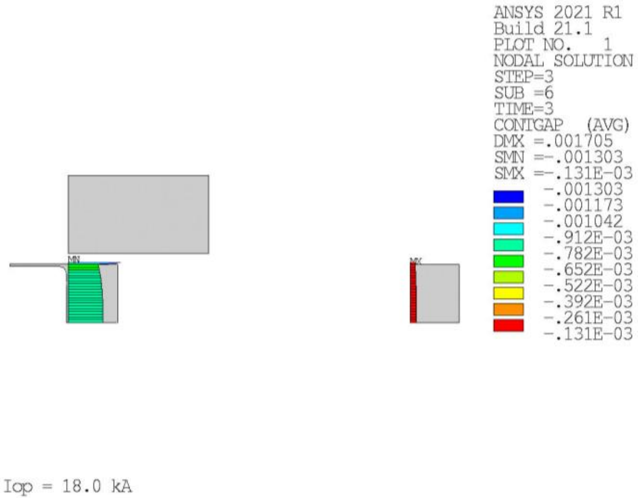
$I_{op} = 0.85 \times I_{ss}$



Cool-down



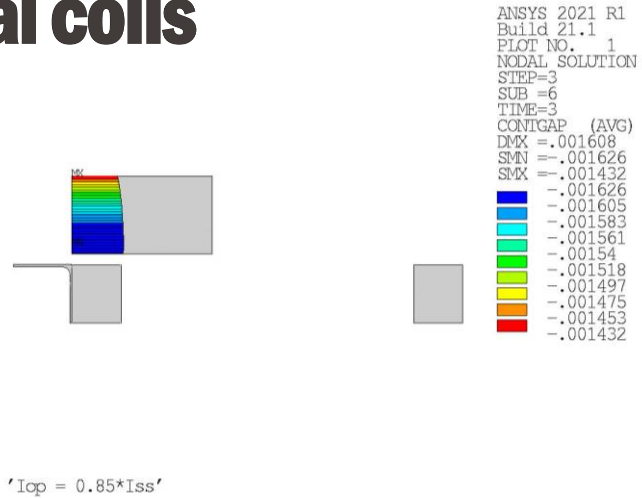
I_{op} = 18.0 kA



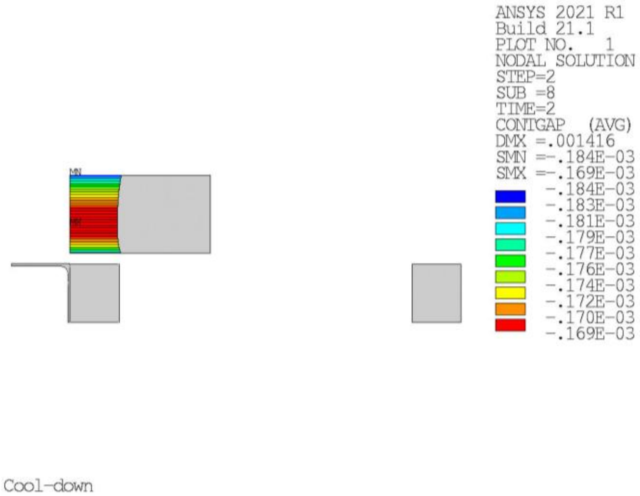
Gap between pole 2 and vertical coils

- Between pole 2 and vertical coils:
  - gap ≤ 1.6 mm at $I_{op} = 0.85 \times I_{ss}$
  - gap ≤ 1.7 mm at 18 kA

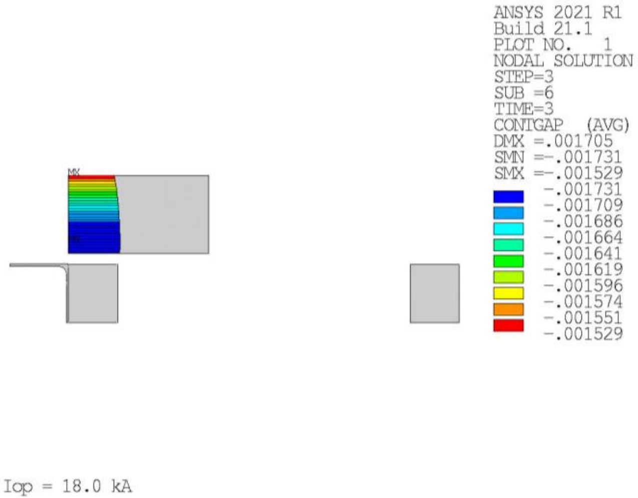
$I_{op} = 0.85 \times I_{ss}$



Cool-down



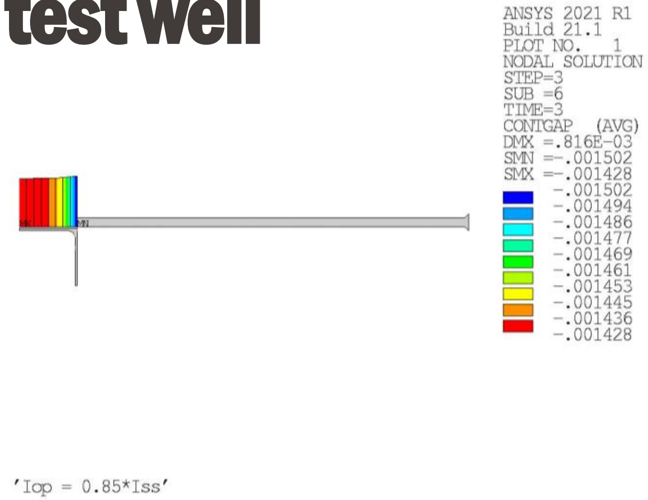
I_{op} = 18.0 kA



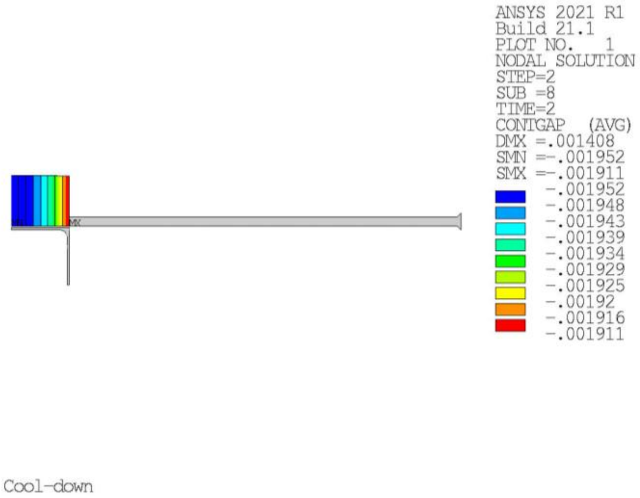
Gap between steel plate 1 and test well

- The steel plate 1 bends, but never touches the test well
- The gap is always higher than 1.4 mm

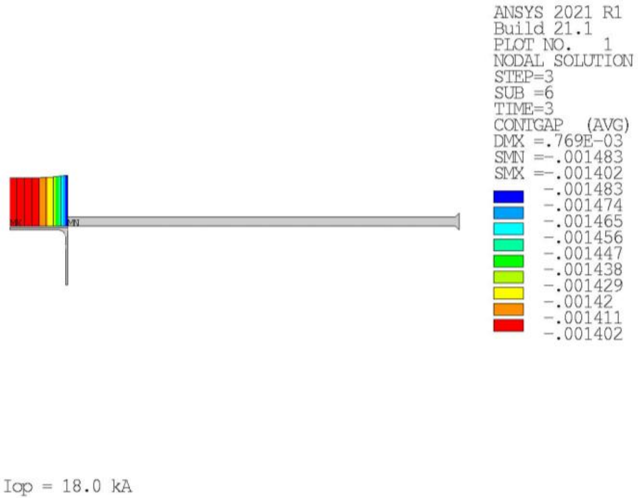
$I_{op} = 0.85 \times I_{ss}$



Cool-down



I_{op} = 18.0 kA

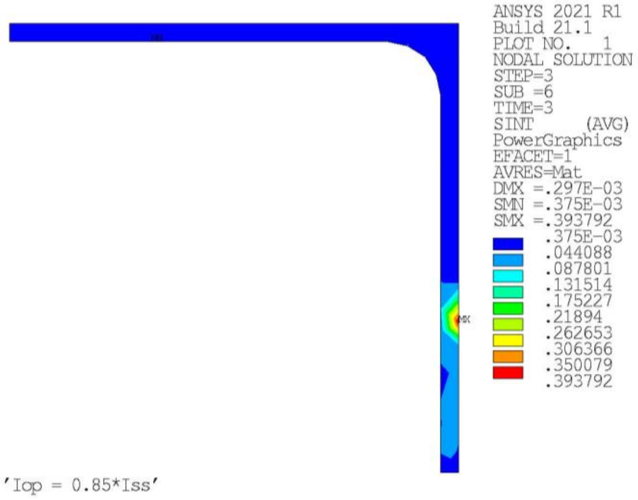


X. Sarasola

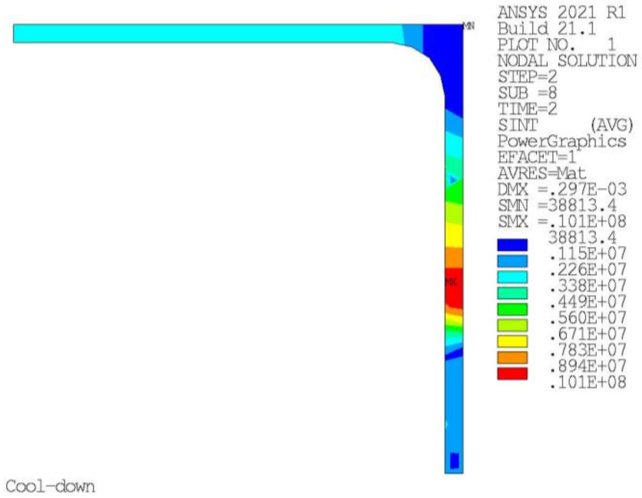
Stress intensity in the test well

- The test well always remains stress-free

$I_{op} = 0.85 \times I_{ss}$



Cool-down



I_{op} = 18.0 kA