PAUL SCHERRER INSTITUT

PSI

CHART

Swiss Accelerator Research and Technology

Douglas Martins Araujo on behalf of the CHART Team

CHART2/MagDev Results and Roadmap - Technical Review

Stress-Managed Cosine Theta Road Map 4-Layers, 2-Layers, Subscale and BigBoX

Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI.

Agenda

- Stress-Managed Magnet Concepts
- ETHZ – PSI Collaboration: MagNum
- 4 Layers Stress-Managed Magnet – 14.5 T option
- 2 Layers Stress-Managed Magnet – 10/12 T options
- Subscale Stress-Managed Magnet – 5 T
- BNL/MDP – PSI Collaboration
  - Stress-Managed Insert Coil - BigBoX
- Panoply of Devices and Main Parameters
- Next Steps

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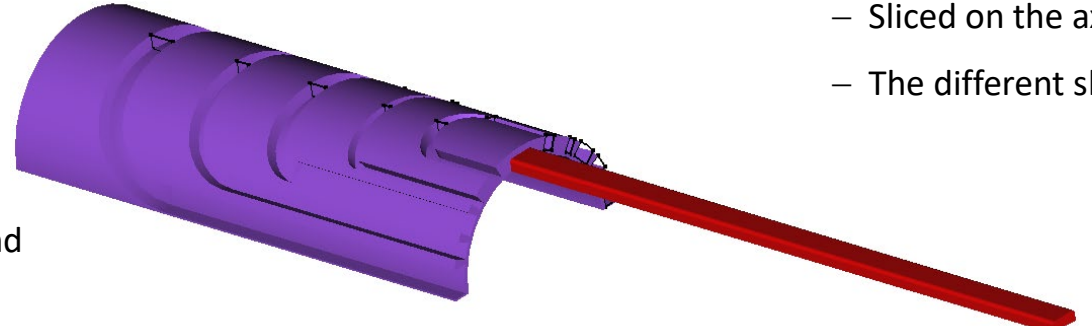
Stress-Managed Magnet Concepts

- WAX (or similar materials) impregnated coils
  - Low crack energy release
  - Low debonding energy release
- Stress-Managed CT by A. Zlobin et Al.
  - Cable in channel
- Cable sliding in the channel
- Turns sliding with respect to each other

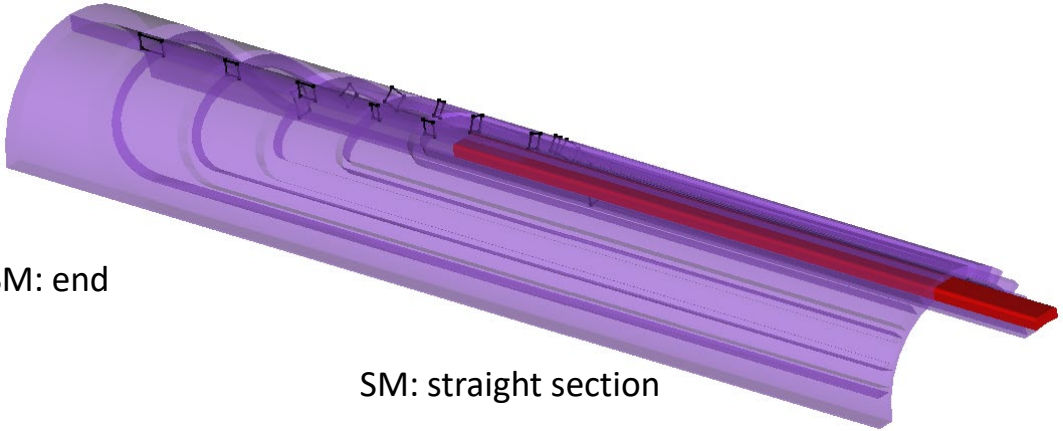
Courtesy of A. Zlobin

Stress-Managed Magnet Concepts

- Backbone and sliced SM structure



SM: end



SM: end

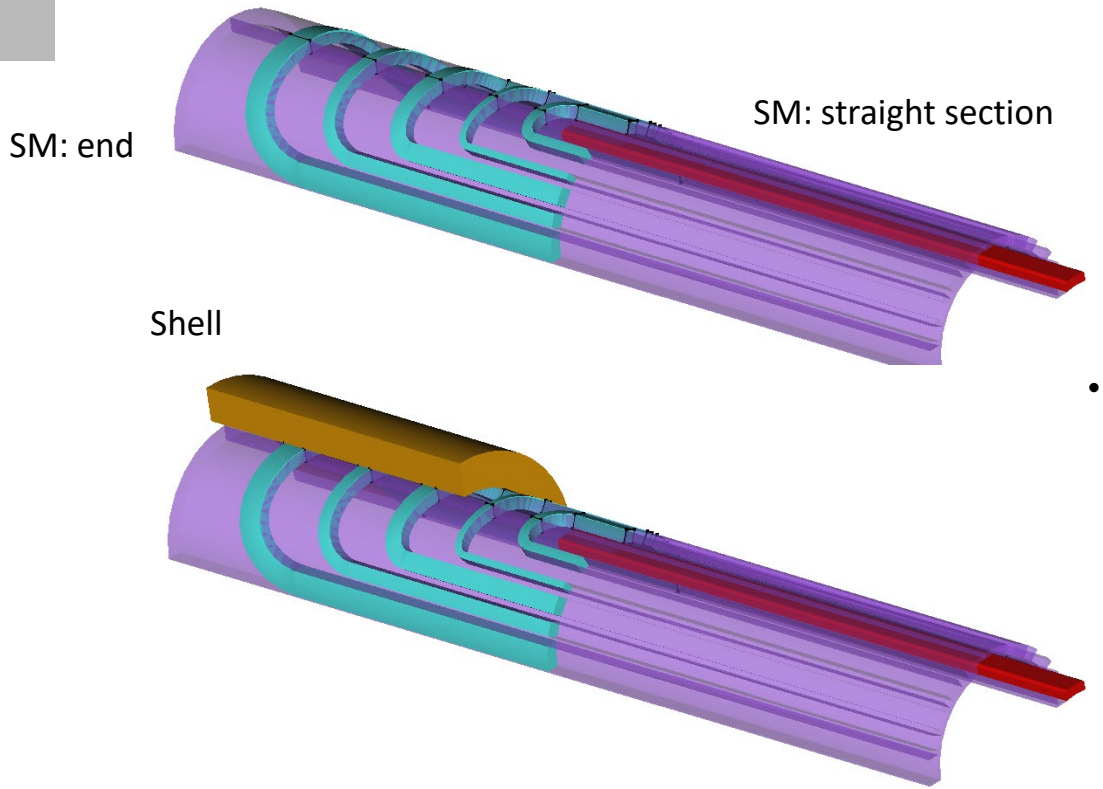
SM: straight section

- Stress-management structure
  - Sliced on the axial direction
  - The different slices are connected on the backbone

- Backbone
  - Magnet handling
  - Alignment
  - Connecting SM structure

Stress-Managed Magnet Concepts

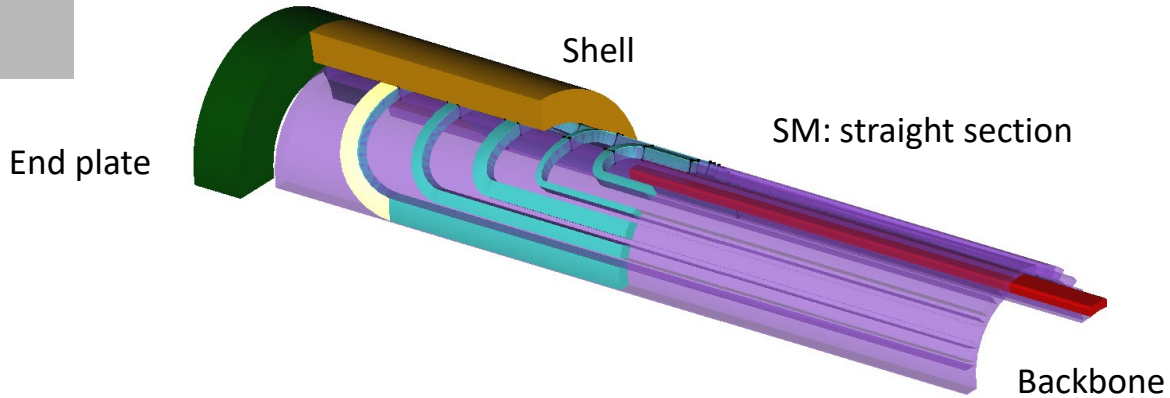
- Coil in channels and shell

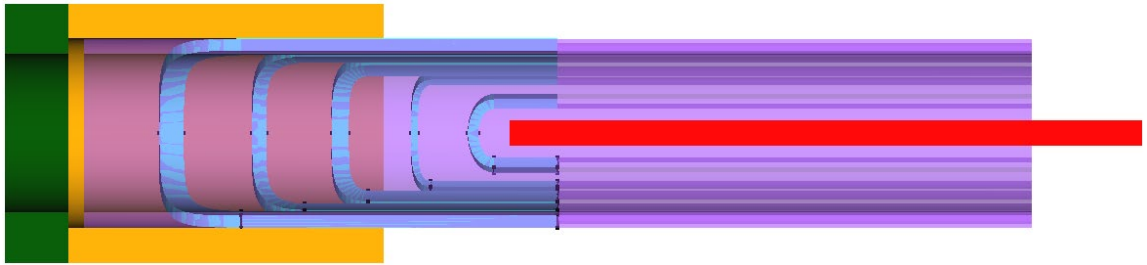


- **Continuous** half shell
  - Made of stainless steel as the SM structure to match thermal contraction
  - Holding the axial Lorentz forces
  - Decoupling of the coil its axial load from the transversal structure

Stress-Managed Magnet Concepts

- End plate connected





- SM structure
  - Made of stainless steel and spliced to allow HT movement
- Backbone
  - Magnet handling and connecting the SM structure different pieces
- Shell
  - Holding the axial Lorentz forces
- End plate
  - Connected to the shell for axial stiffness

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  – Stress-Managed Insert Coil - BigBoX
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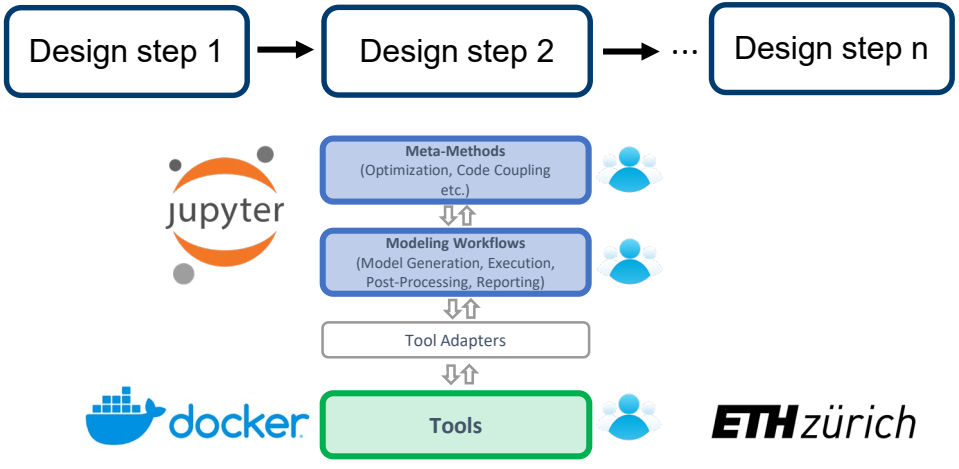
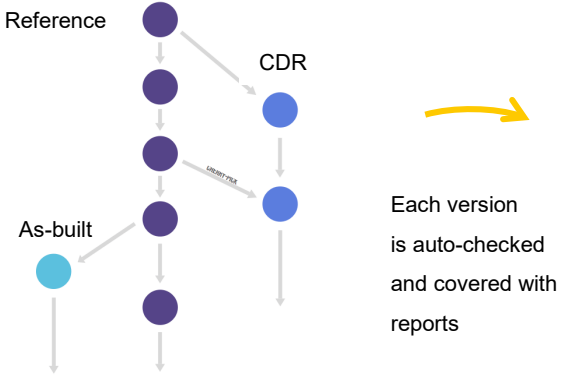
MagNum Project: Multi-Model and Multi-Scale Design **Workflows**

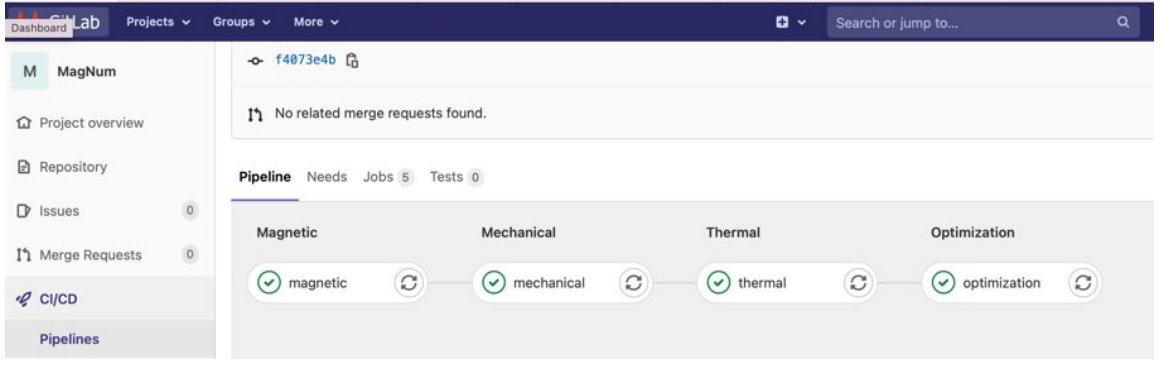
M. Maciejewski

- The modelling workflows are implemented in ***interactive Notbooks*** (Jupyter Notebook).
- Each workflow starts from a generic magnet geometry and parameter input.
- Workflows and have defined interfaces implement different alternative tools and modeling depths.
- Interfaces enable flexible coupling of numerical tools and streamlining of complex workflows.
- An automated modelling pipeline integrates design versions and workflows (GitLab).





Each version is auto-checked and covered with reports



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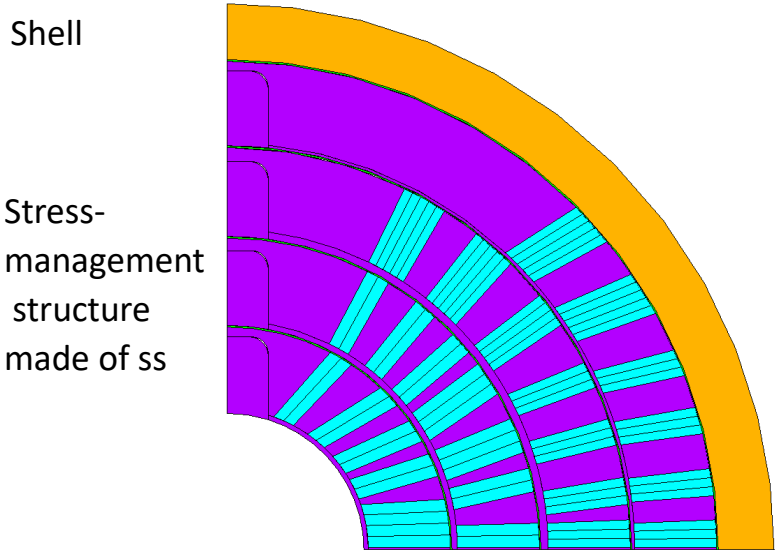
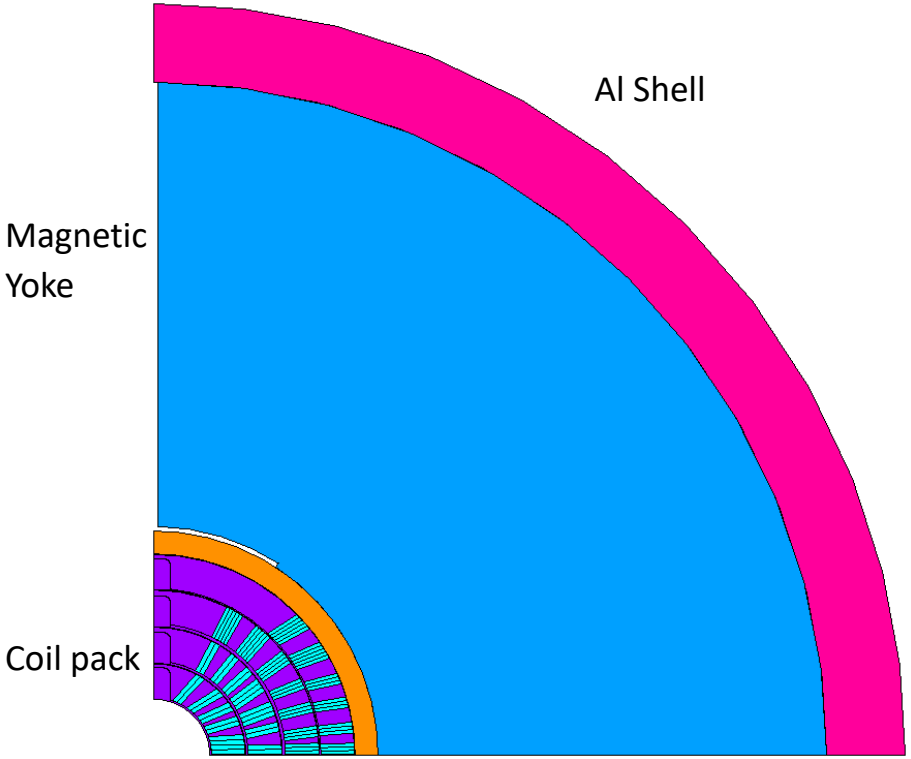
4 Layers Stress-Managed Magnet: Cross Section

- Stress-management structure
- No room temperature pre-load
- Independent layers
- Backbone structure for handling and axial stiffness



- **Example** of Magnet structure

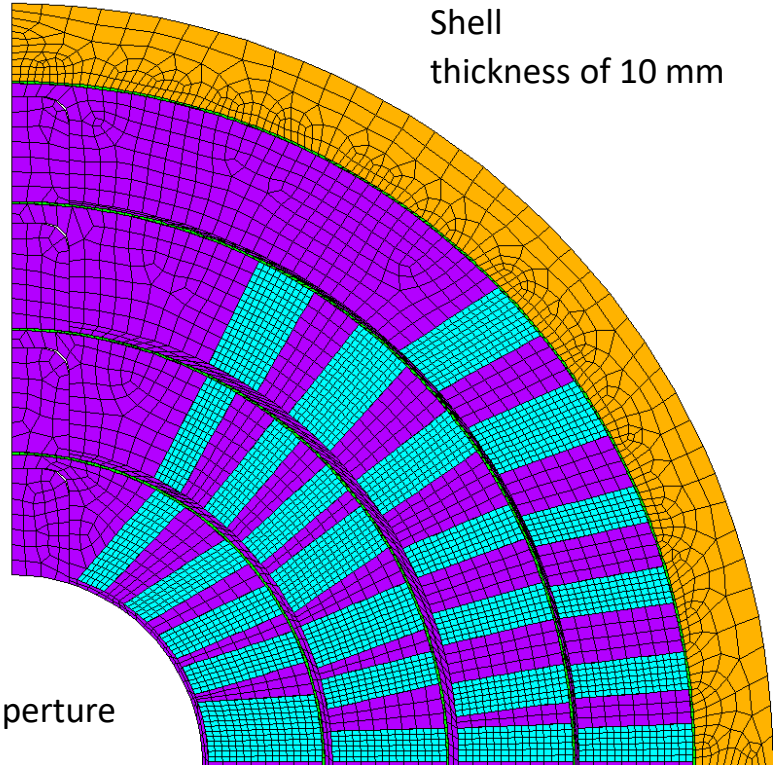


4 Layers Stress-Managed Magnet: Mesh

- Mesh

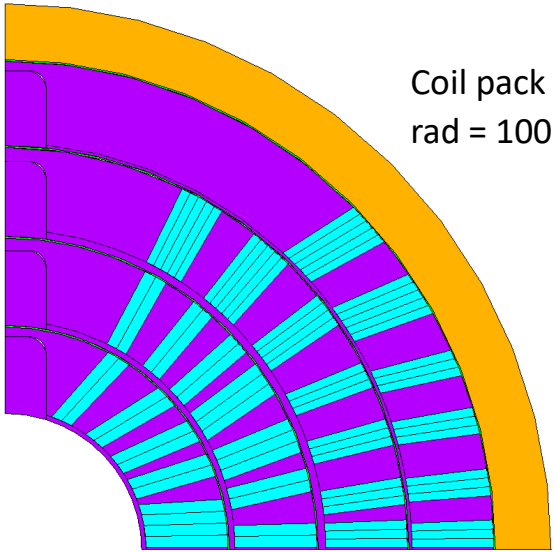
Shell
thickness of 10 mm

Inter-
layer
Insulation
of 300 um



25 mm aperture

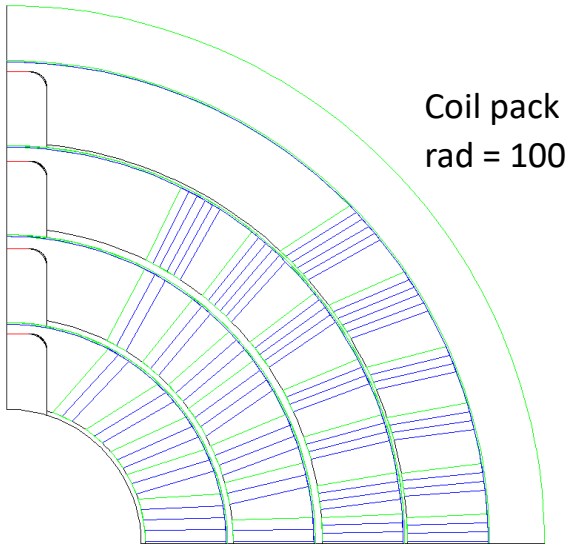
- Variable layer spar thickness
- Max of 5 turns per slot
- Spars and ribs forming one piece (CCT-like)
- Graded solution



Coil pack (with inner shell)
rad = 100 mm

4 Layers Stress-Managed Magnet: Contacts

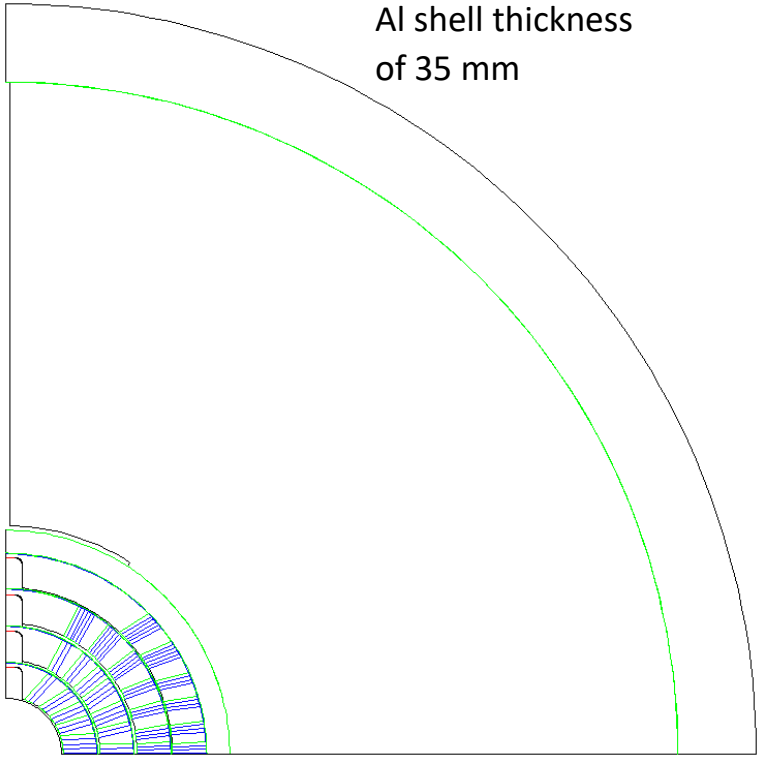
- Bonded contact: backbone to SM-structure
- **Sliding contacts**: between turns and inner slot side
- Detaching contacts: between layers and turns to slot



Coil pack (with inner shell)
rad = 100 mm

Yoke rad
of 300 mm

Al shell thickness
of 35 mm



4 Layers Stress-Managed Magnet: Existing Cable Parameters (Summers fitting)

- HF cable (28 x RRP-150/169 subelement's size = 52 um)

- Bc20(4.2 K) = 28.9 T
- C = 3.79E+10
- Tc0 = 18 K

- Dia = 1 mm
- Cooper% = 48%

- width 14.7 mm
- keystone angle = 0.79 degrees
- mid-thickness = 1.8 mm

- LF cable (40 x RRP-108/127 subelement's size = 41 um)

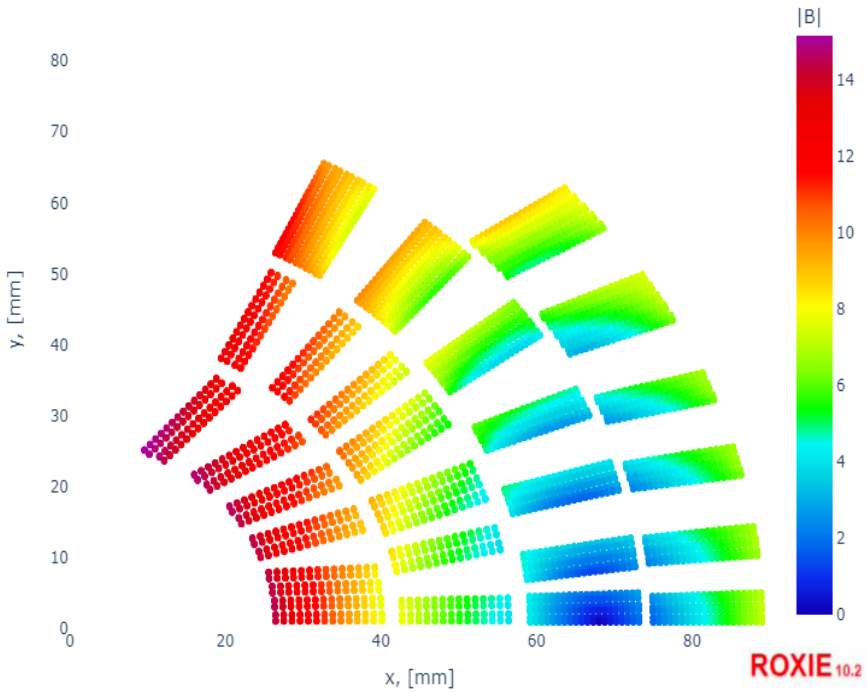
- Bc20 = 28 T
- C = 3.85E+10
- Tc0 = 18 K

- Dia = 0.7 mm
- Cooper% = 53%

- width 14.7 mm
- keystone angle = 0.79 degrees
- mid-thickness = 1.3 mm

4 Layers Stress-Managed Magnet: Cable Parameters

- Roxie analysis



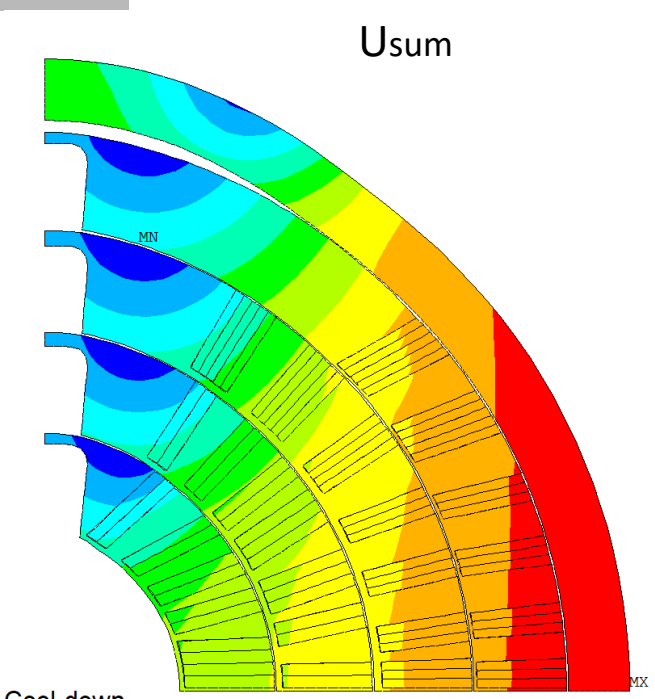
Layer	Turns
1	12
2	16
3	26
4	22

Multi pole	Units
b3	2
b5	3
b7	6

Parameter	Value
B_0	14.5 T
B_p	15.2 T
I_{op}	16.5 kA
T_{op}	1.9 K
Margin at T_{op}	14 %
F_r at I_{op}	2.1 MN/m
F_θ at I_{op}	6.2 MN/m

4 Layers Stress-Managed Magnet: Mech Analysis Coil Pack Displacement

- After cooling down
- At nominal field (14.5 T / 16.5 kA)

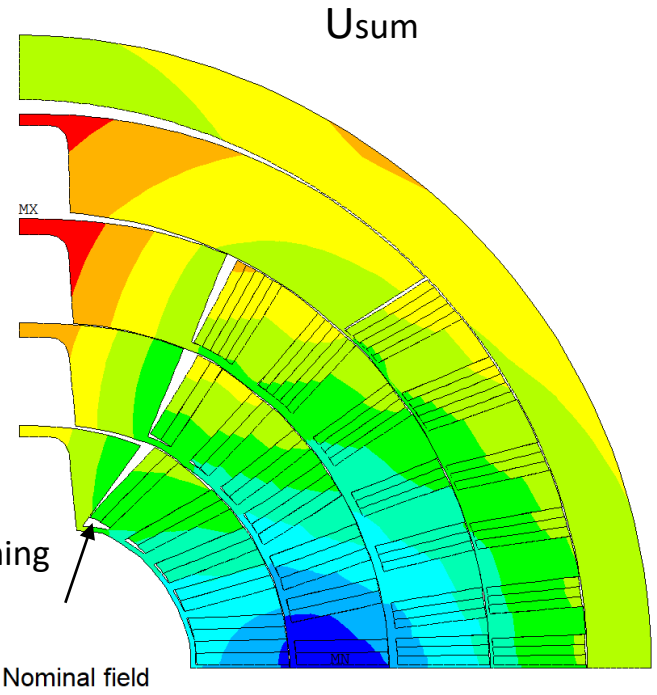


Cool-down

ANSYS 2021 R1
Build 21.1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
USUM (AVG)
RSYS=1
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.578E-03
SMN =.560E-04
SMX =.578E-03
.560E-04
.114E-03
.172E-03
.230E-03
.288E-03
.404E-03
.462E-03
.520E-03
.578E-03

Opening

Gap



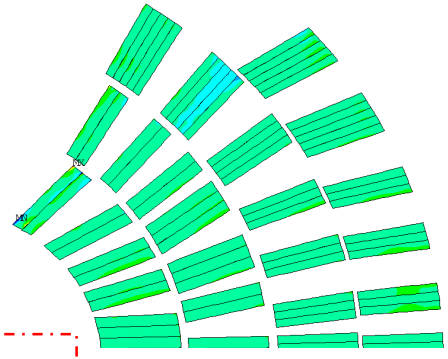
Nominal field

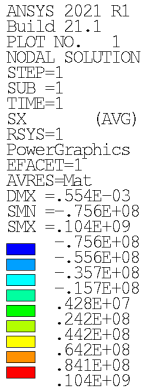
ANSYS 2021 R1
Build 21.1
NODAL SOLUTION
STEP=2
SUB =1
TIME=2
USUM (AVG)
RSYS=1
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.384E-03
SMN =.261E-05
SMX =.384E-03
.261E-05
.450E-04
.873E-04
.130E-03
.172E-03
.257E-03
.299E-03
.341E-03
.384E-03

4 Layers Stress-Managed Magnet: Mech Analysis
Coil stresses

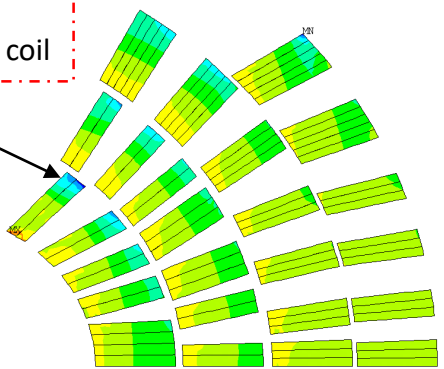
- After cooling down

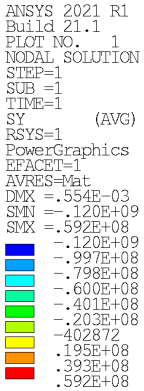
Coil properties from epoxy impregnated coil





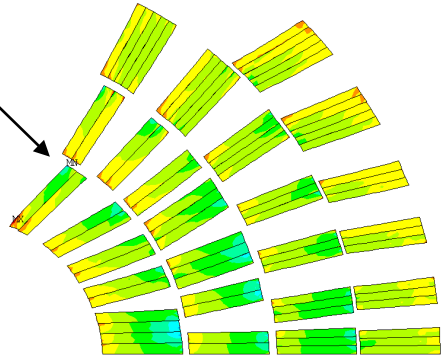
120 MPa

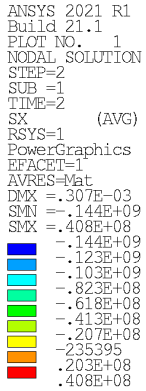




- At nominal field (14.5 T / 16.5 kA)

144 MPa





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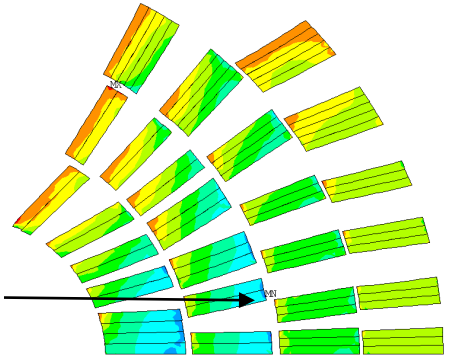
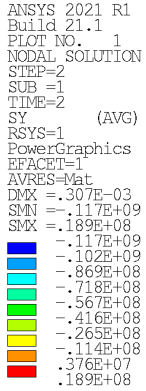


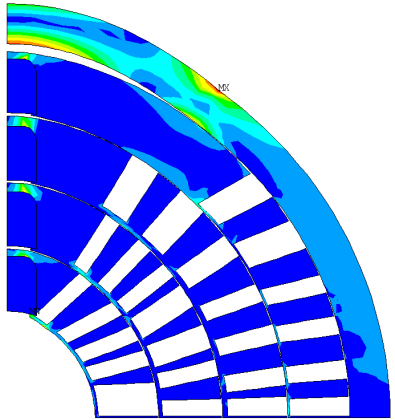
117 MPa

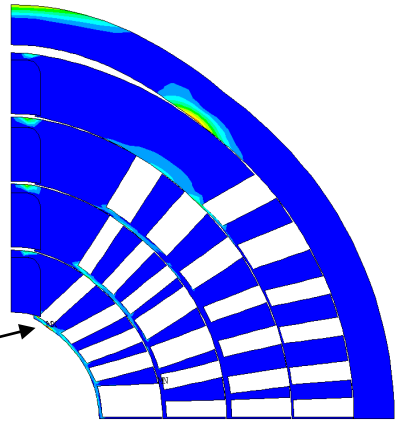


Sθ

4 Layers Stress-Managed Magnet: Mech Analysis
SM Structure and Cylindrical Pads

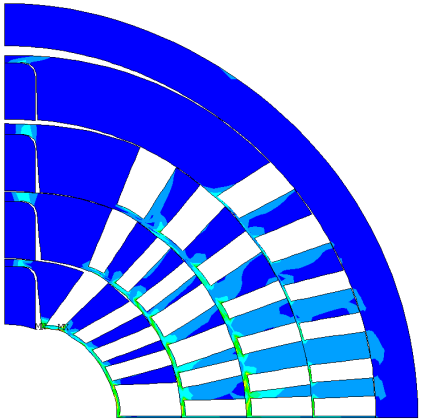
- After cooling down





766 MPa

- At nominal field (14.5 T / 16.5 kA)



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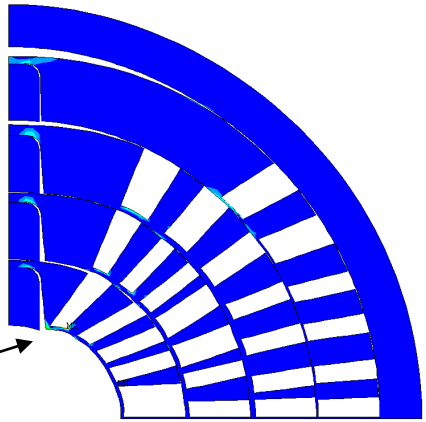
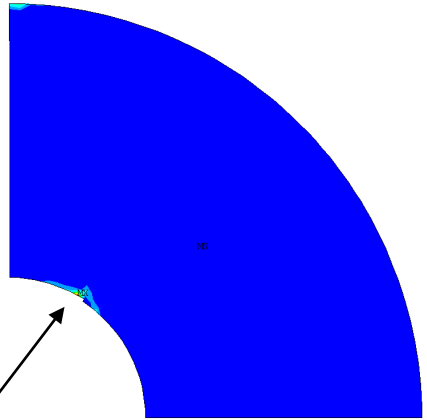


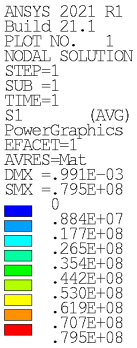
925 MPa

S1

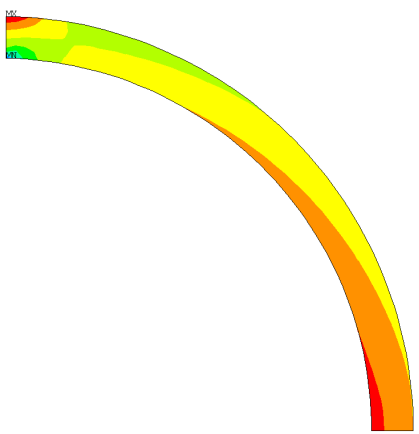
4 Layers Stress-Managed Magnet: Mech Analysis Yoke and Shell

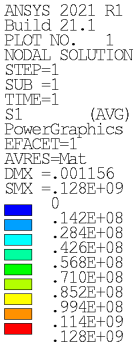
- After cooling down



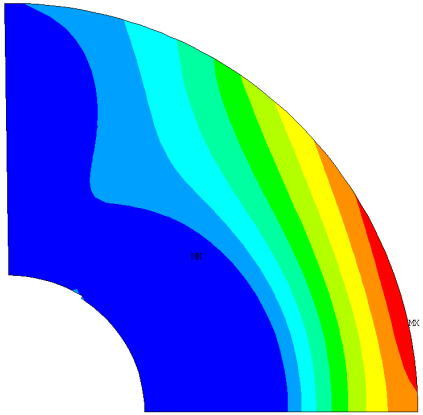


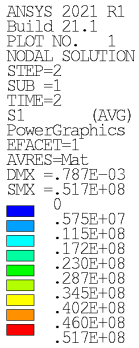
80 MPa





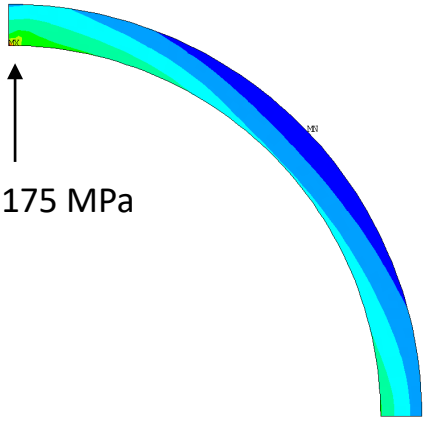
- At nominal field (14.5 T / 16.5 kA)

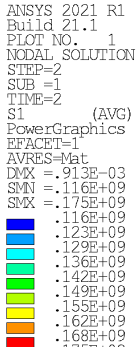




S1

175 MPa

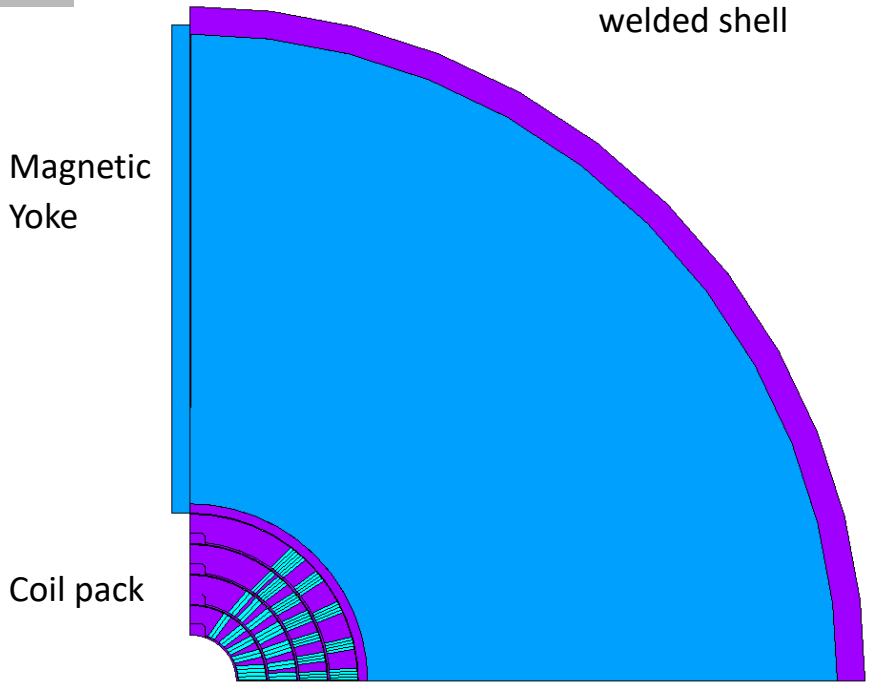




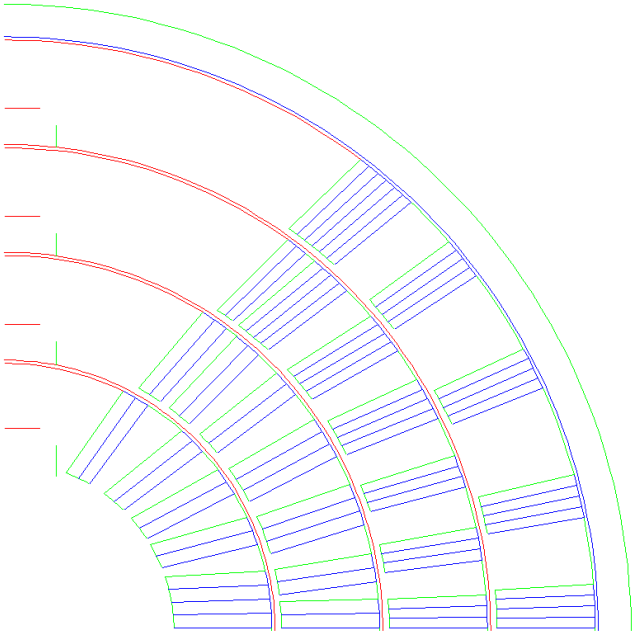
Sθ

4 Layers Stress-Managed Magnet: alternative structure

- **Example** of Magnet structure



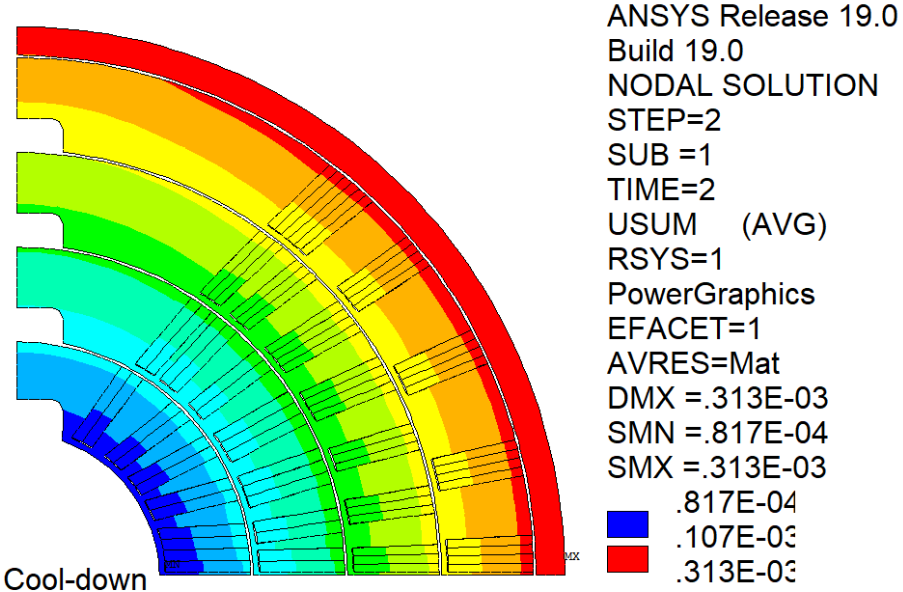
- Bonded contact: backbone to SM-structure and **last ribs**
- **Sliding contacts**: between turns and inner slot side
- Detaching contacts: between layers and turns to slot



4 Layers Stress-Managed Magnet: alternative solution - Coil Pack Displacement

- After cooling down

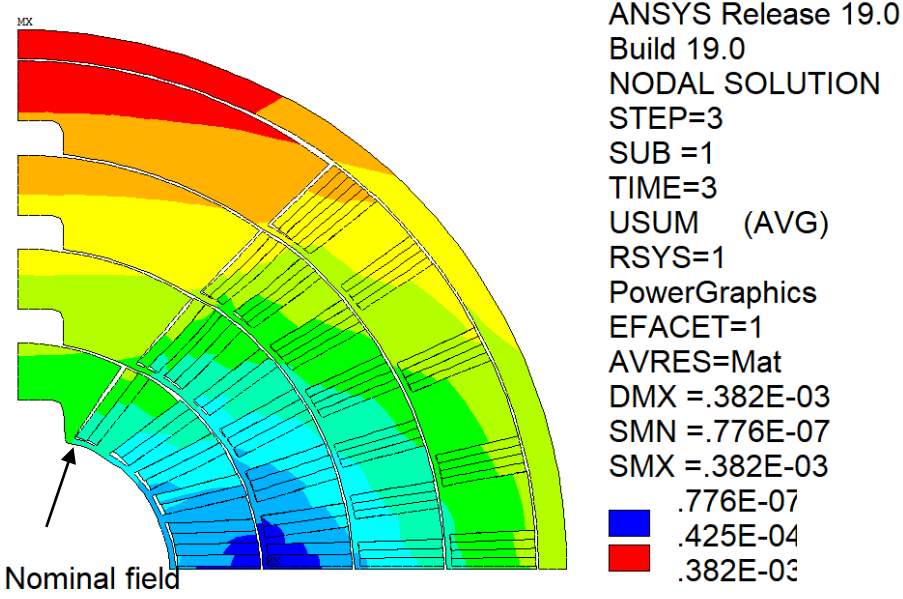
Usum



Cool-down

- At nominal field (14.5 T)

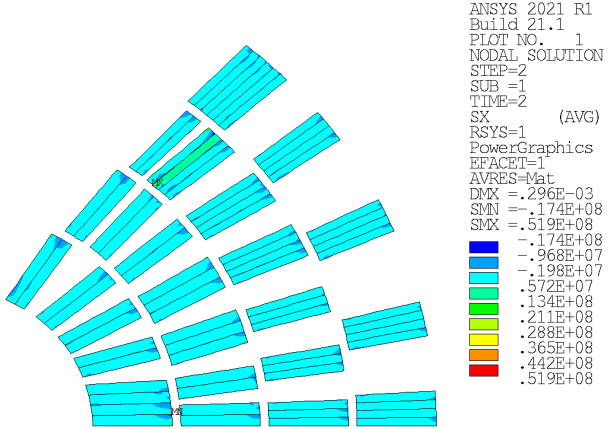
Usum

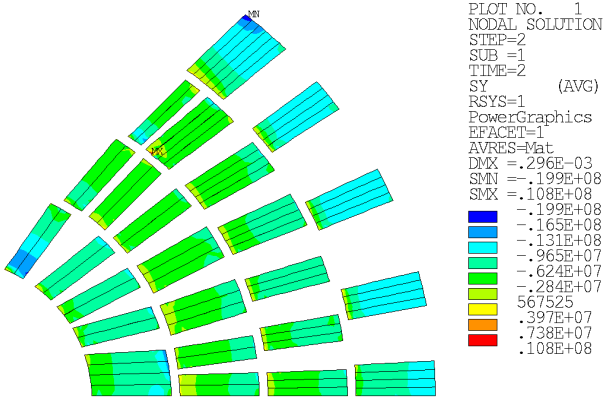


Nominal field

4 Layers Stress-Managed Magnet: alternative solution - Coil stresses

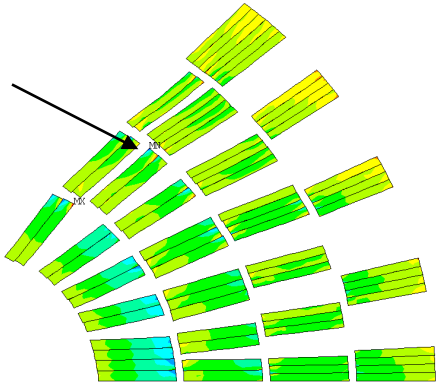
- After cooling down



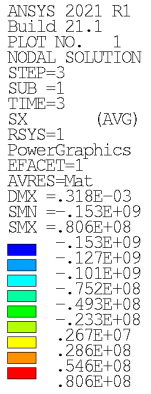


- At nominal field (14.5 T)

153 MPa

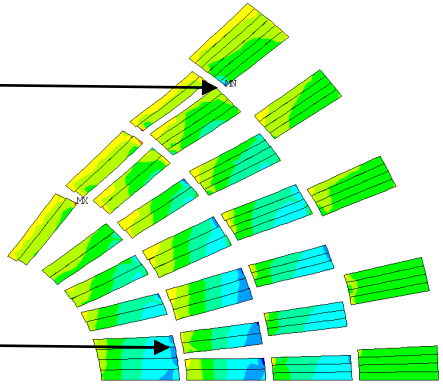


Sr

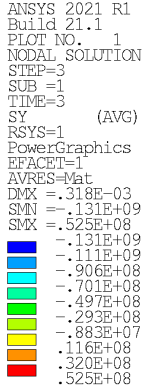


130 MPa

110 MPa

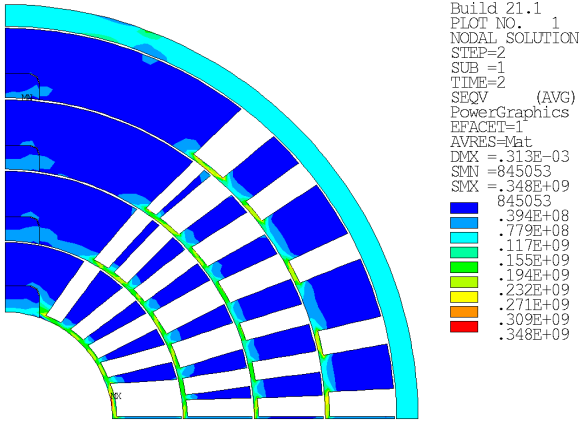


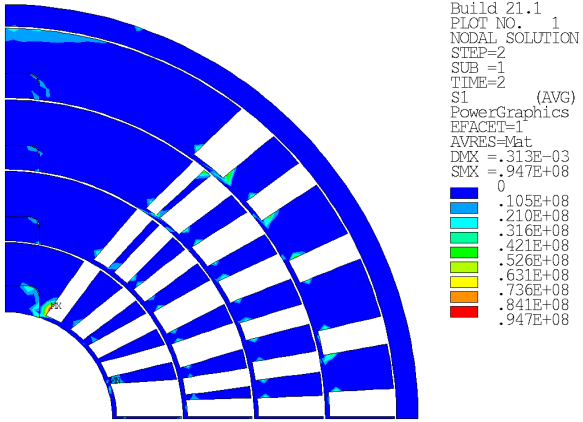
Sθ



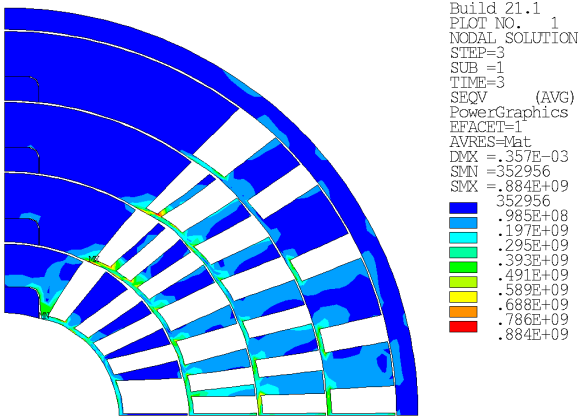
4 Layers Stress-Managed Magnet: alternative solution - SM Structure and Cylindrical Pads

- After cooling down

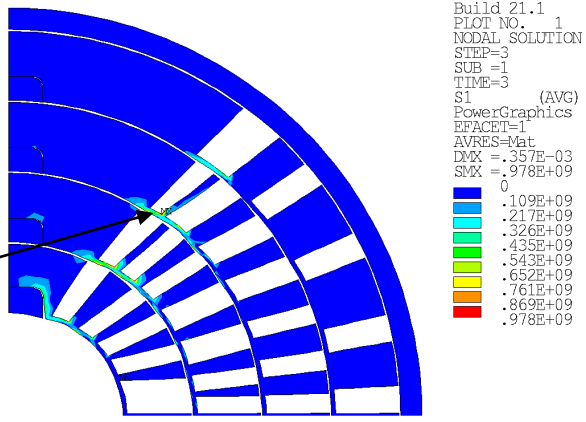




- At nominal field (14.5 T)



Seqv

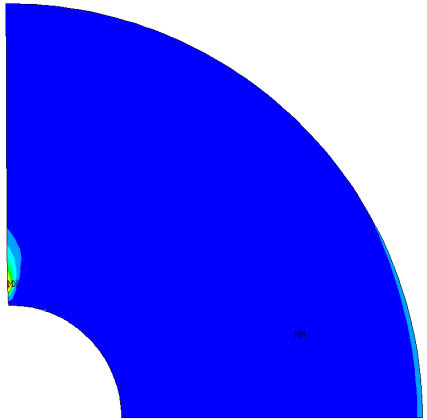


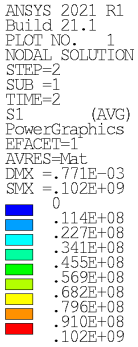
978 MPa

S1

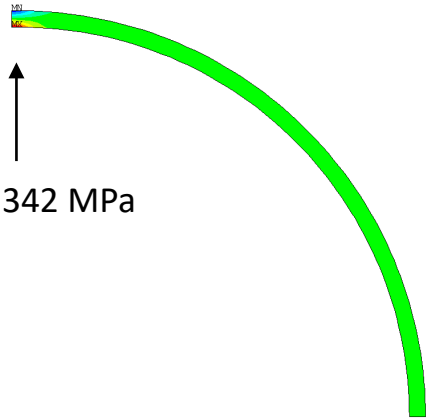
4 Layers Stress-Managed Magnet: alternative solution - Yoke and Shell

- After cooling down

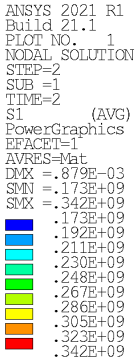




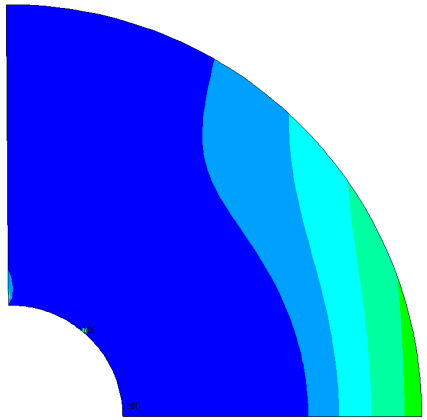
100 MPa

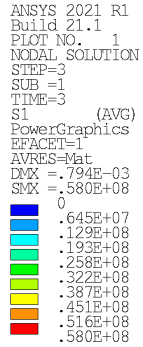


342 MPa

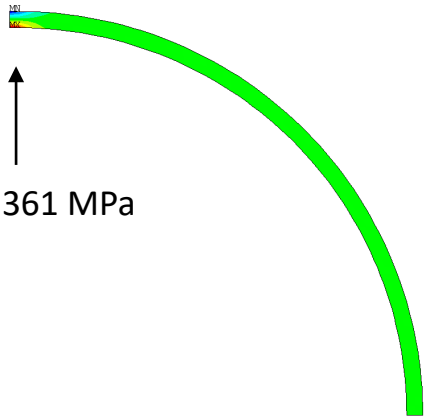


- At nominal field (14.5 T)

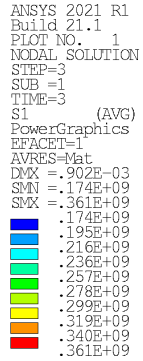




S1



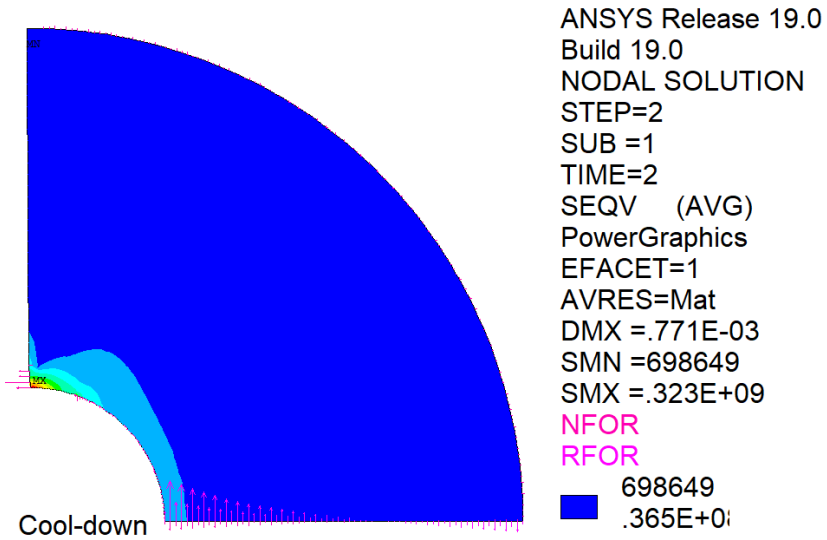
361 MPa



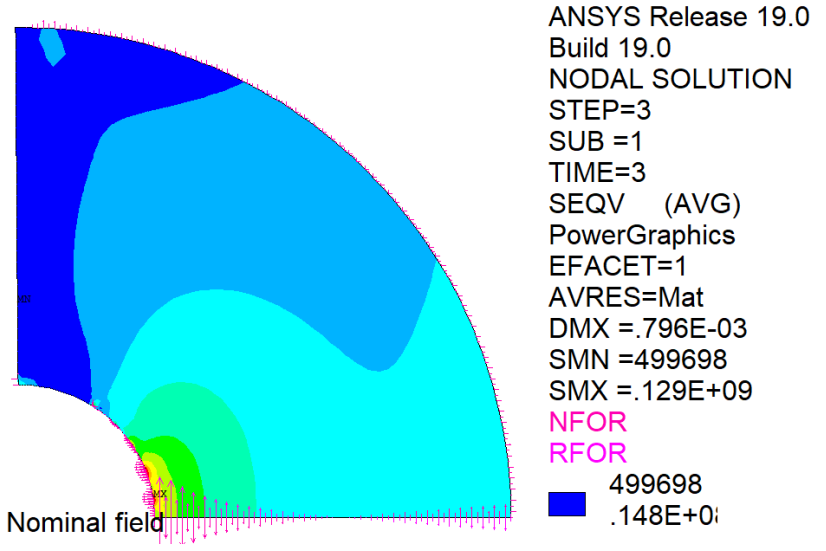
Sθ

4 Layers Stress-Managed Magnet: alternative solution – **Closing** Yoke

- After cooling down



- At nominal field (14.5 T)



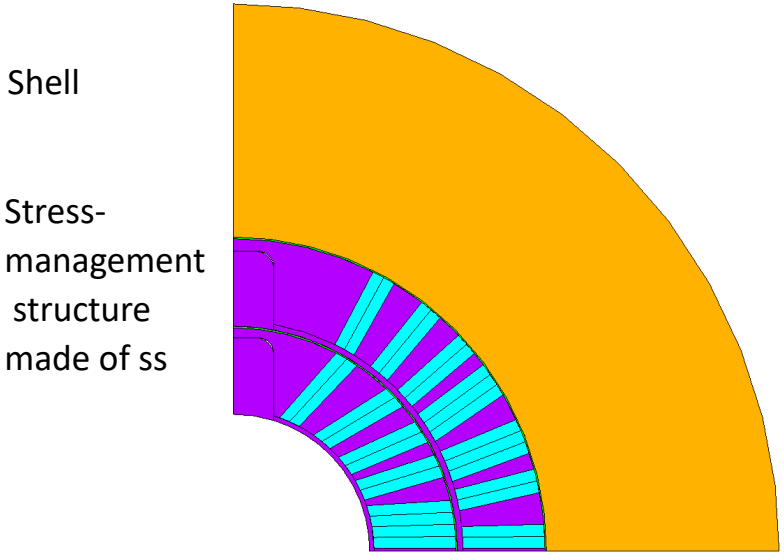
Agenda

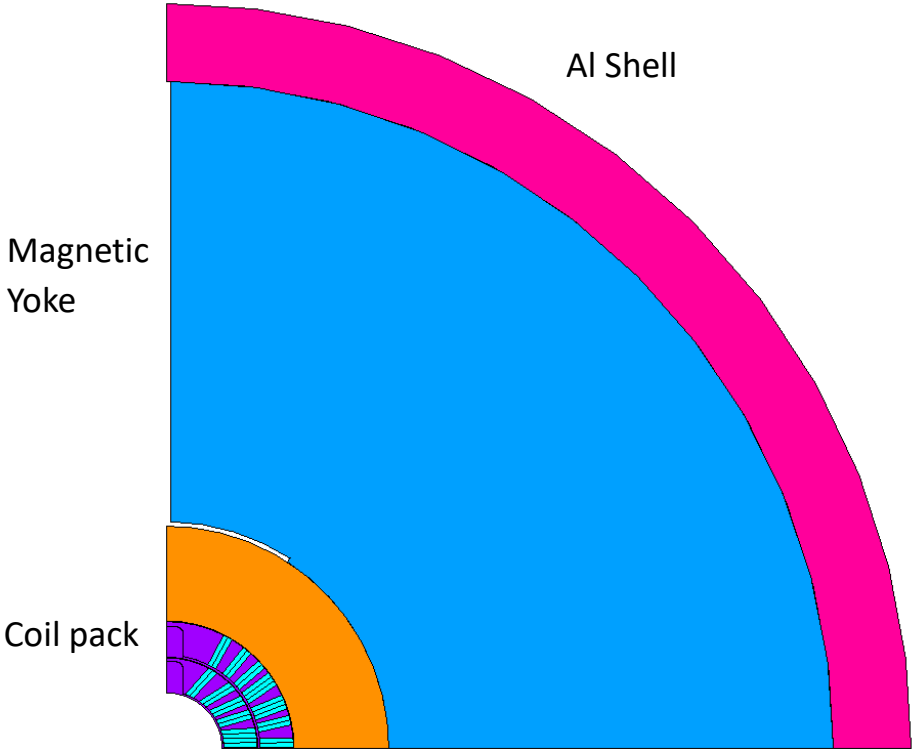
- Stress-Managed Magnet Concepts
- ETHZ – PSI Collaboration: MagNum
- 4 Layers Stress-Managed Magnet – 14.5 T option
- 2 Layers Stress-Managed Magnet – 10/12 T options
- Subscale Stress-Managed Magnet – 5 T
- BNL/MDP – PSI Collaboration

  – Stress-Managed Insert Coil - BigBoX
- Panoply of Devices and Main Parameters
- Next Steps

2 Layers Stress-Managed Magnet: Cross Section

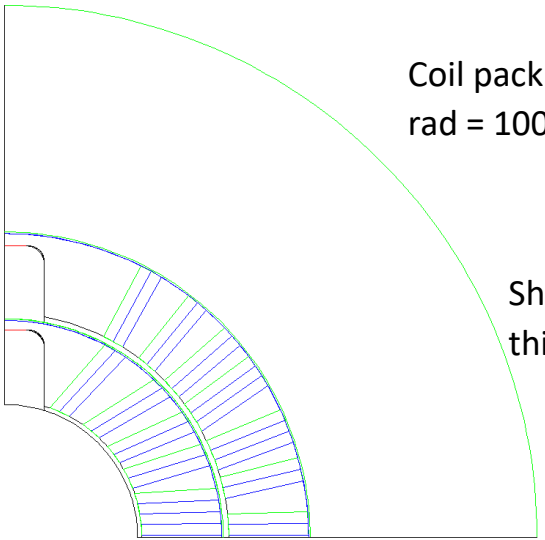
- From the 4 layers solution we take layers 1 and 2
- The shell is thicker which would allow re-using the magnet structure





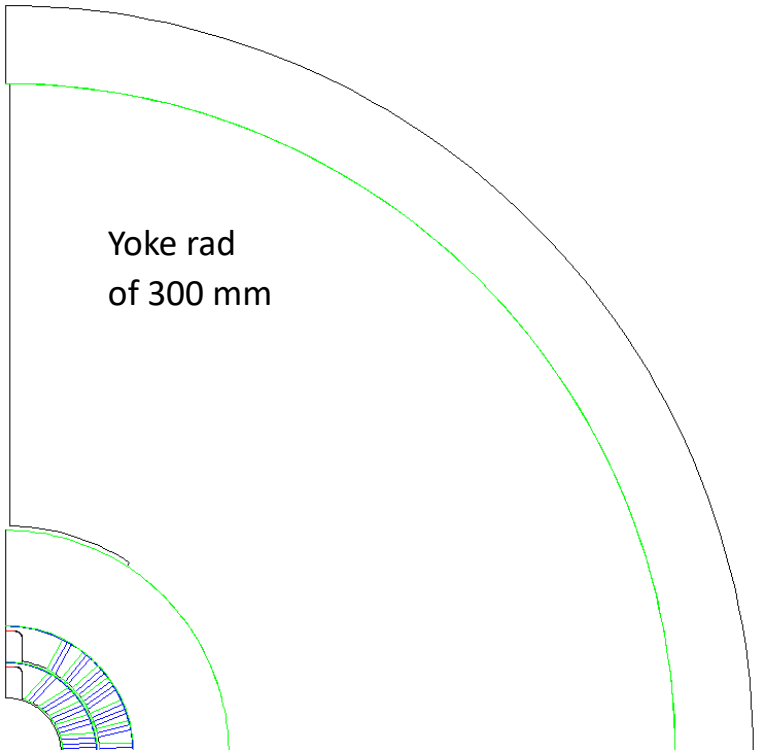
2 Layers Stress-Managed Magnet: Contacts

- Bonded contact: backbone to SM-structure
- **Sliding contacts**: between turns and inner slot side
- Detaching contacts: between layers and turns to slot



Coil pack (with inner shell)
rad = 100 mm

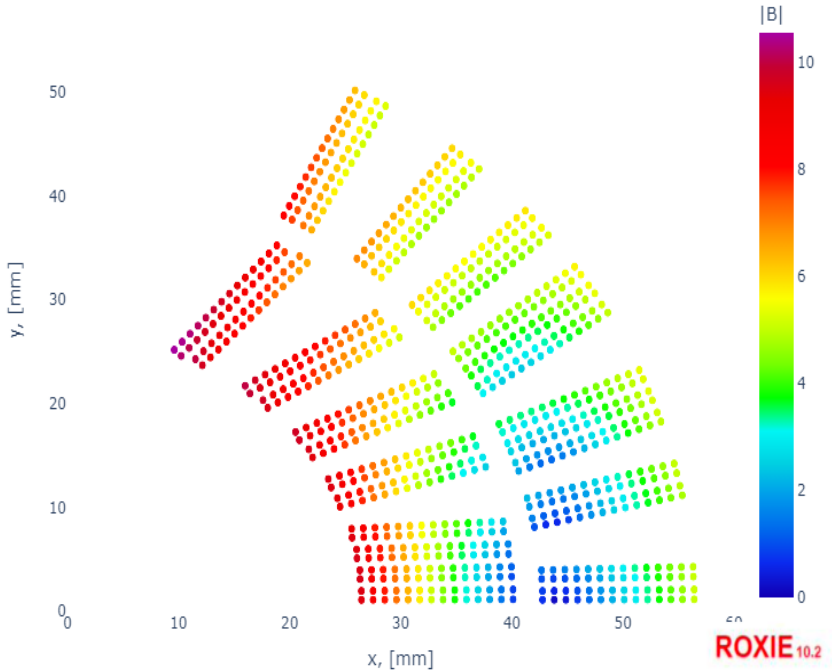
Shell
thickness of 43 mm



Yoke rad
of 300 mm

2 Layers Stress-Managed Magnet: Cable Parameters

- Roxie analysis



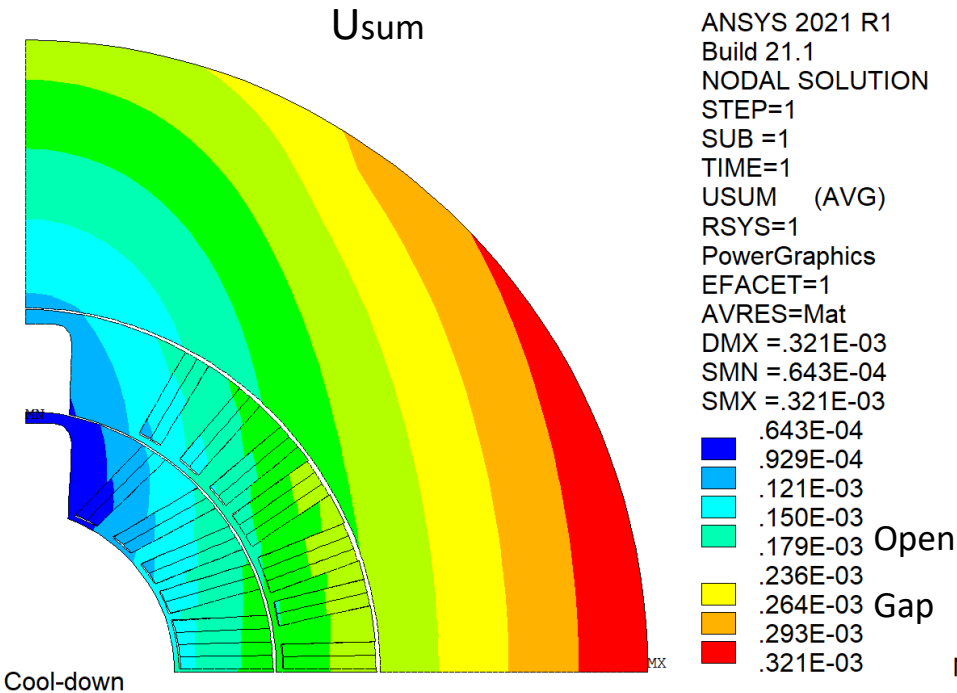
Layer	Turns
1	12
2	16

Multi pole	Units
b3	8
b5	3
b7	11

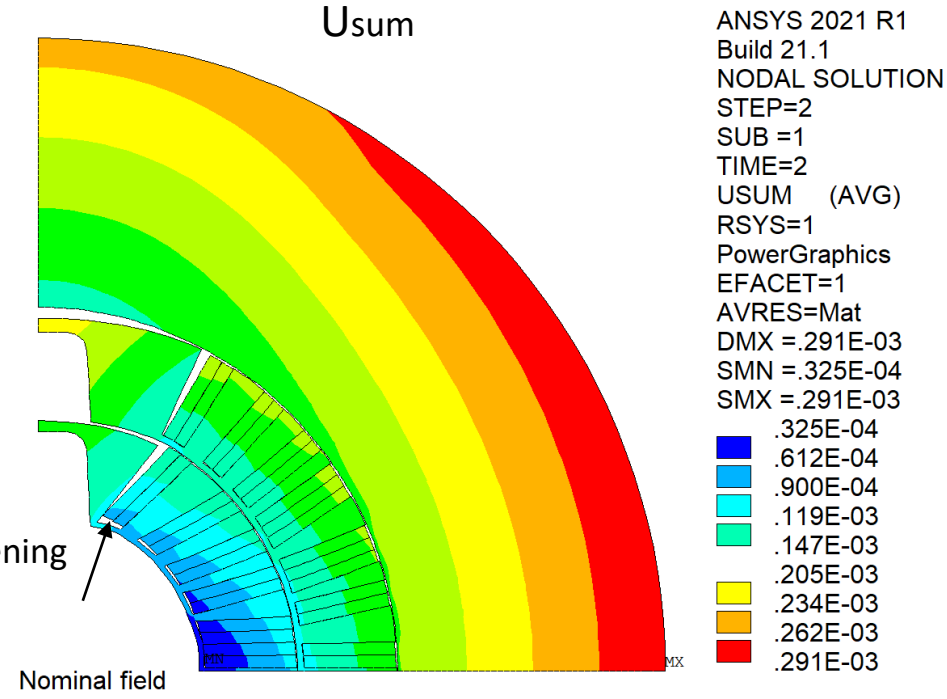
Parameter	Value
B_0	10/12 T
B_p	10.5/12.6 T
I_{op}	20/**24** kA
T_{op}	1.9 K
Margin at T_{op}	30/14 %
F_r at I_{op}	0.7 MN/m
F_θ at I_{op}	2.1 MN/m

2 Layers Stress-Managed Magnet: Mech Analysis Coil Pack Displacement

- After cooling down

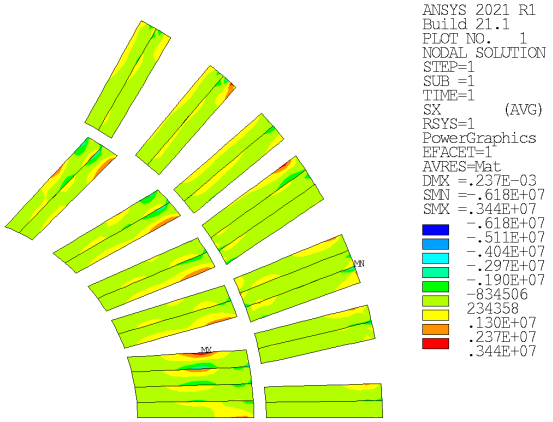


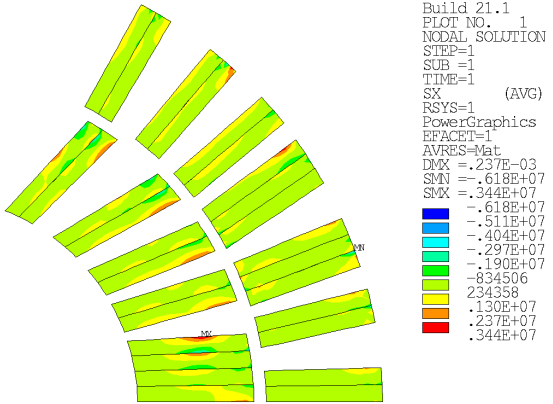
- At nominal field (12 T / 24 kA)



2 Layers Stress-Managed Magnet: Mech Analysis Coil stresses

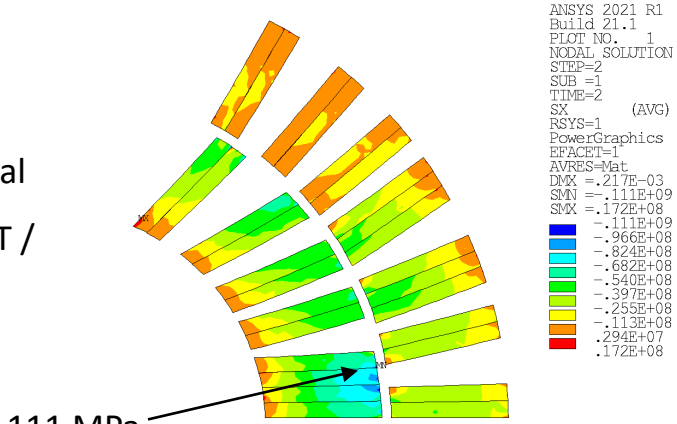
- After cooling down





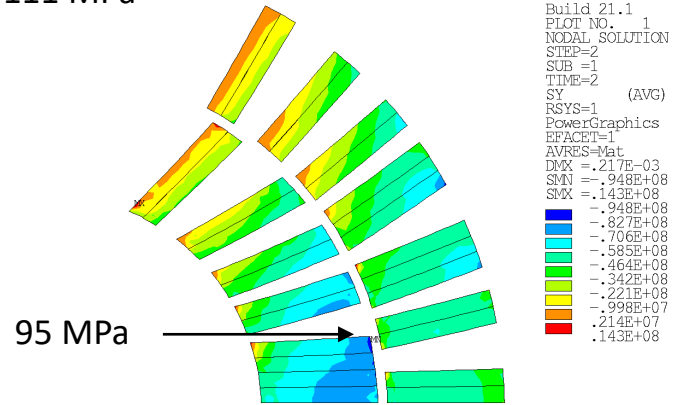
- At nominal field (12 T / 24 kA)

Sr



111 MPa

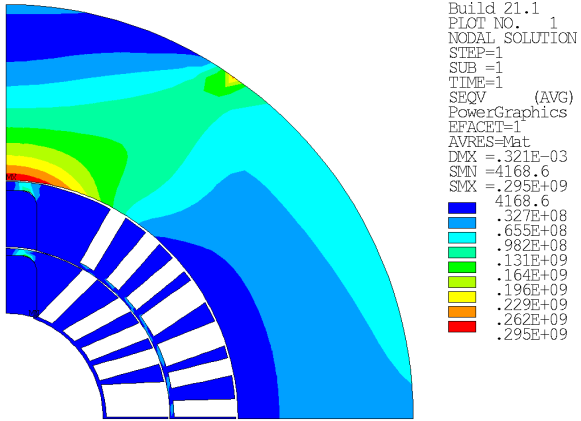
Sθ

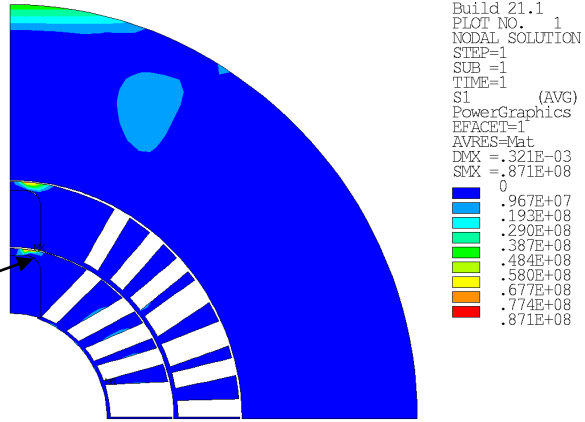


95 MPa

2 Layers Stress-Managed Magnet: Mech Analysis SM Structure and Cylindrical Pads

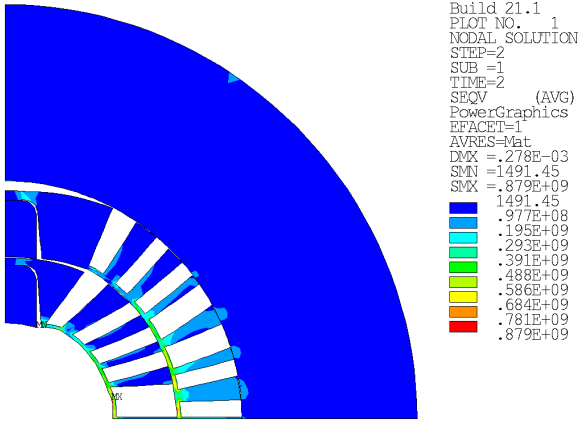
- After cooling down





871 MPa

- At nominal field (12 T / 24 kA)



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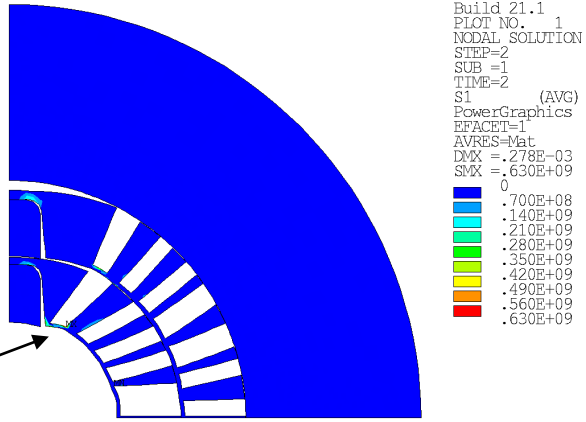
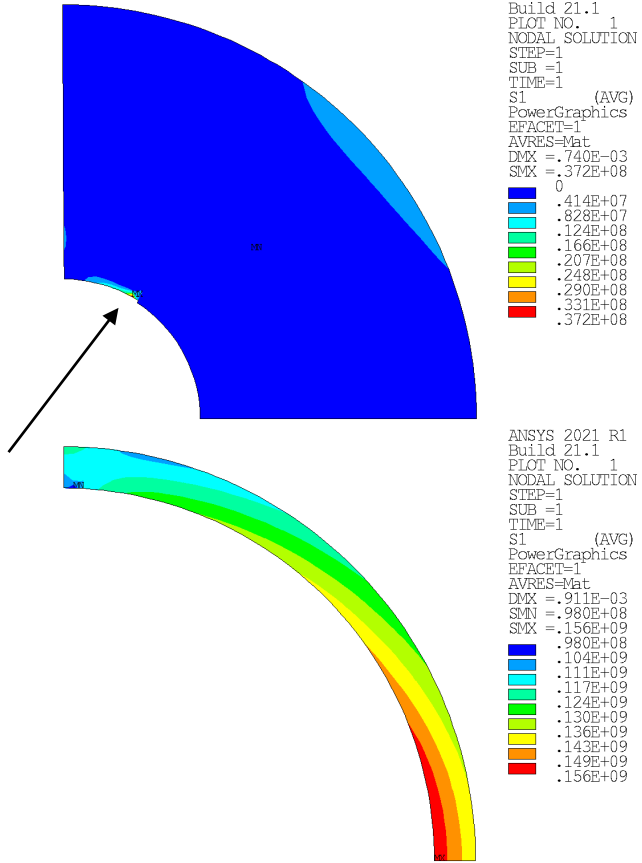


630 MPa

S1

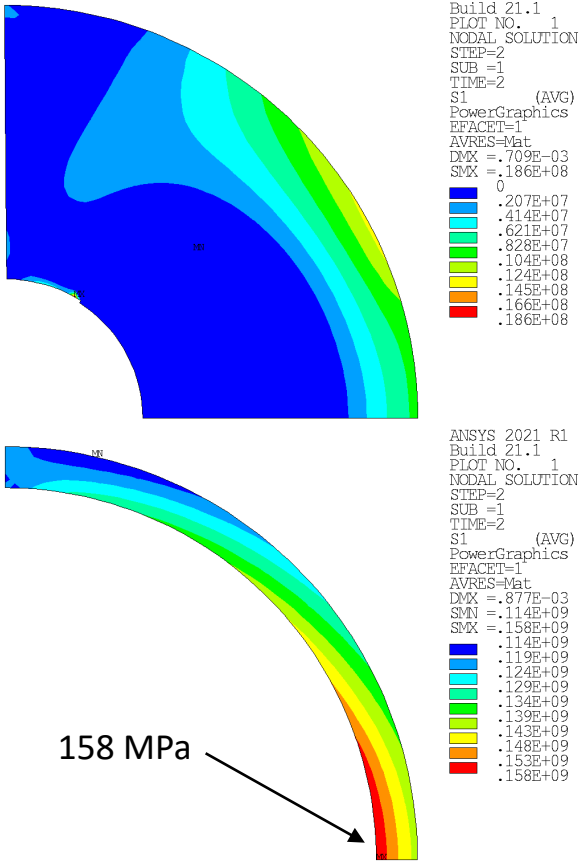
2 Layers Stress-Managed Magnet: Mech Analysis Yoke and Shell

- After cooling down



37 MPa

- At nominal field (12 T / 24 kA)



158 MPa

S1

Sθ

Agenda

- Stress-Managed Magnet Concepts
- ETHZ – PSI Collaboration: MagNum
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- Subscale Stress-Managed Magnet – 5 T
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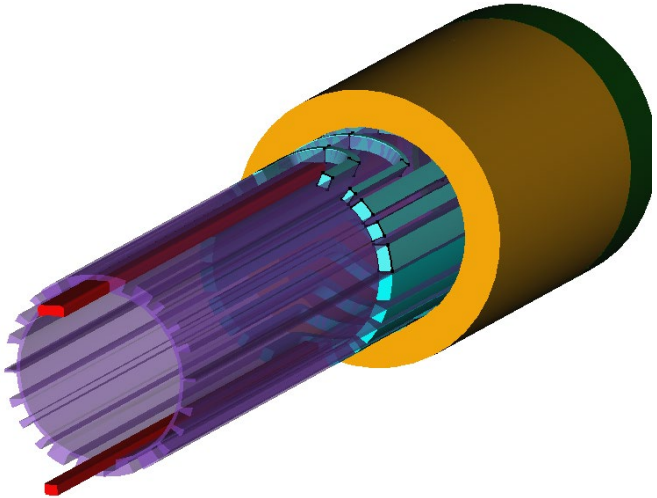
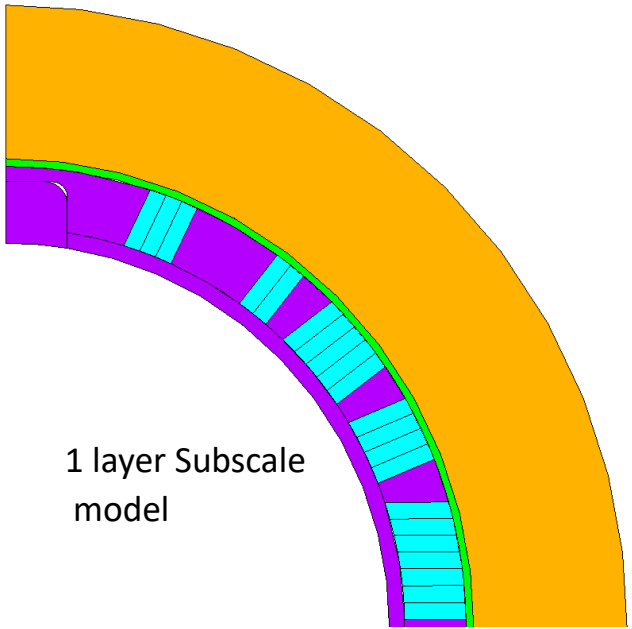
  – Stress-Managed Insert Coil - BigBoX
- Panoply of Devices and Main Parameters
- Next Steps



Stress-Managed Subscale Magnet: Cross Section

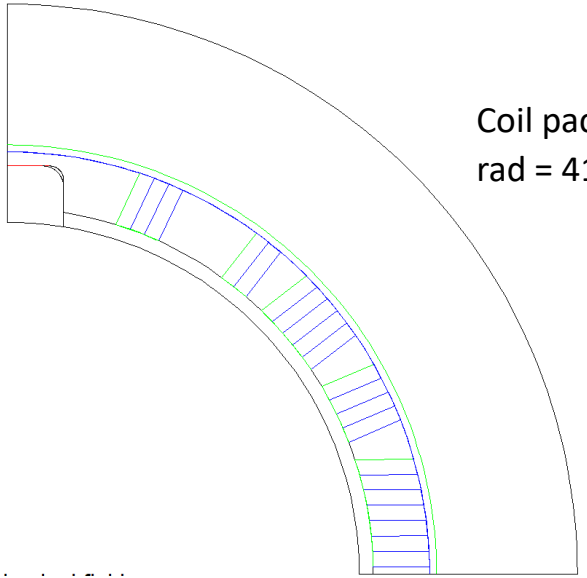
- Subscale Magnet structure
- Fast turnaround
  - **Test facilities**

Shell



1 layer Subscale model

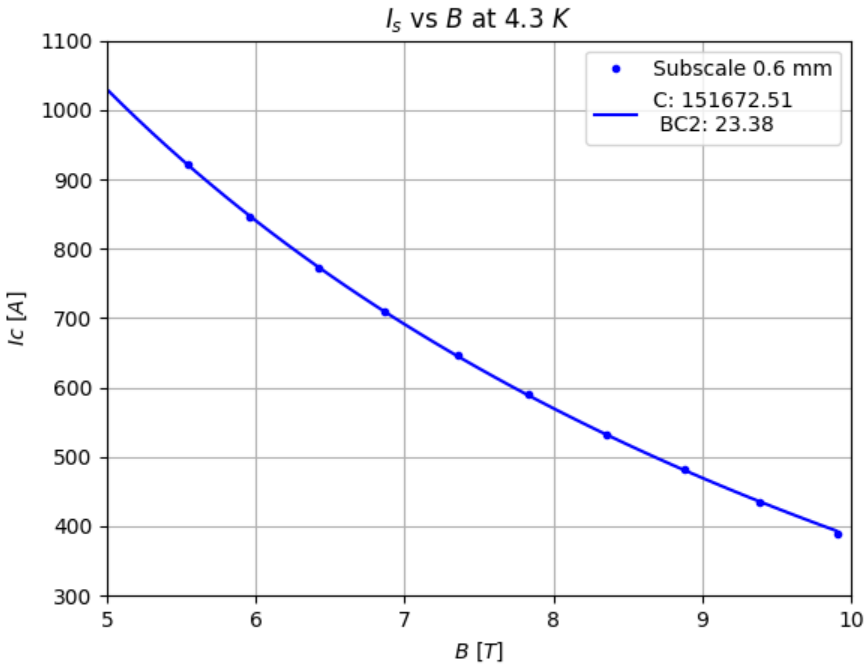
- Bonded contact: backbone to SM-structure
- **Sliding contacts**: between turns and inner slot side
- Detaching contacts: between layers and turns to slot



Coil pack (with inner shell)
rad = 41 mm

Stress-Managed Subscale Magnet: **Cable** Parameters

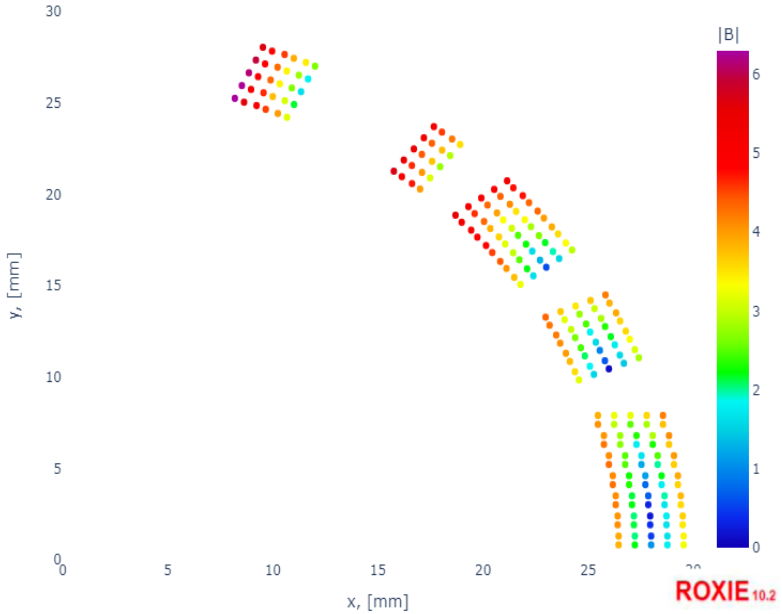
- Number of strands = 11
- Insulation thickness 65 um
- Insulated cable dimensions: 1.1 x 4.0 mm
- Coil unit length: 8 m
- Magnet unit length: 16 m



Courtesy of Diego Arbelaez and I. Pong

Stress-Managed Subscale Magnet: Cable Parameters

- Roxie analysis



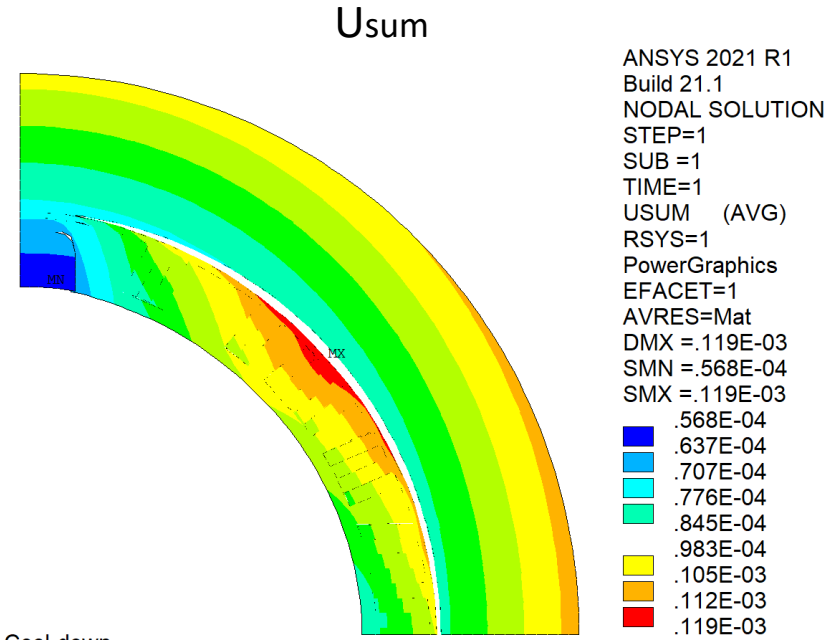
Layer	Turns
1	21

Multi pole	Units
b3	< 1
b5	< 1
b7	< 1

Parameter	Value
B_0	5 T
B_p	6.3 T
I_{op}	10 kA
T_{op}	4.5 K
Margin at T_{op}	5 %
F_r at I_{op}	59 kN
F_θ at I_{op}	467 KN

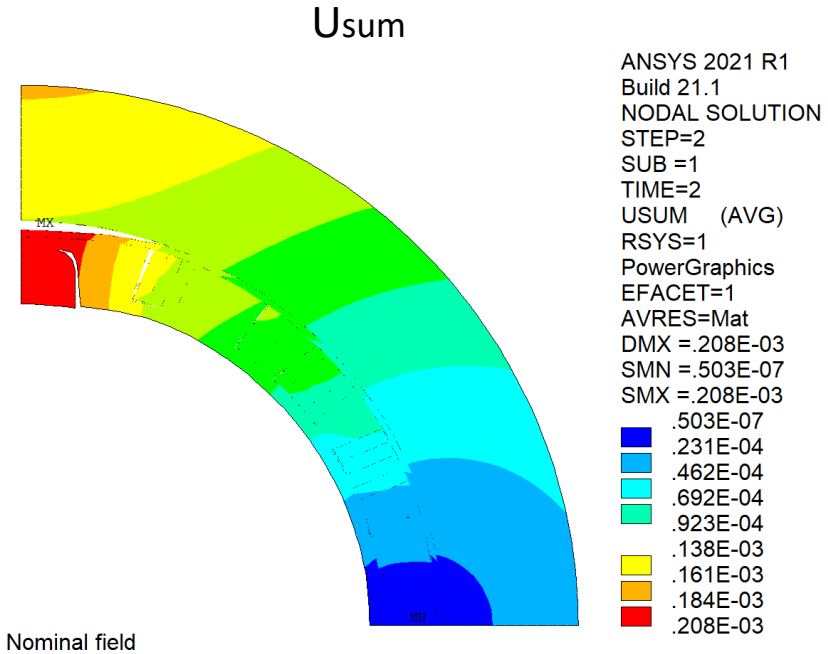
Stress-Managed Subscale Magnet: Mech Analysis Coil Pack Displacement

- After cooling down



Cool-down

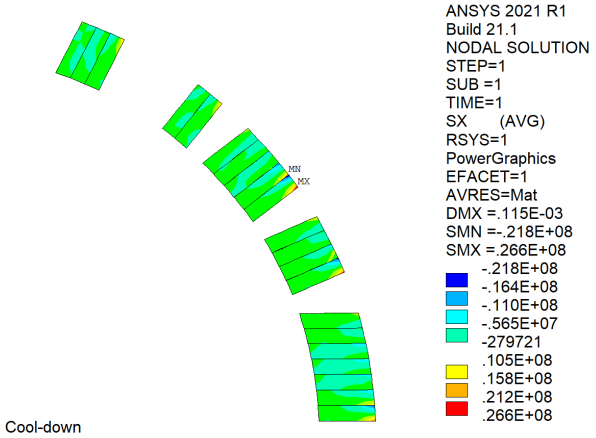
- At nominal field (5 T / 10 kA)

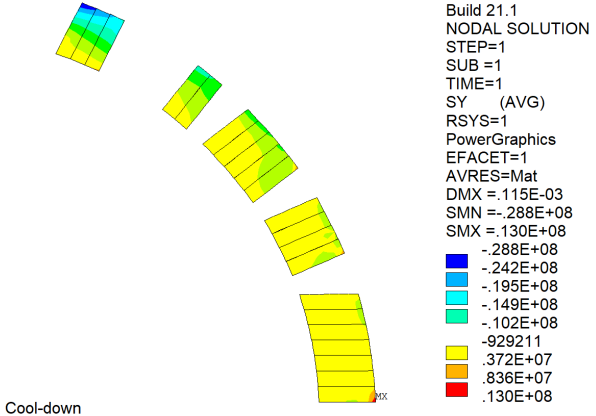


Nominal field

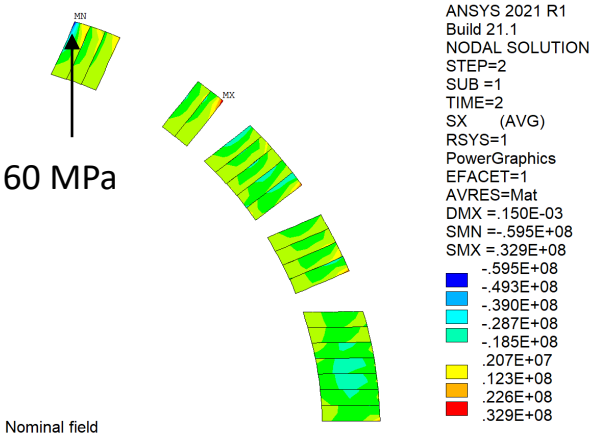
Stress-Managed Subscale Magnet: Mech Analysis
Coil stresses

- After cooling down

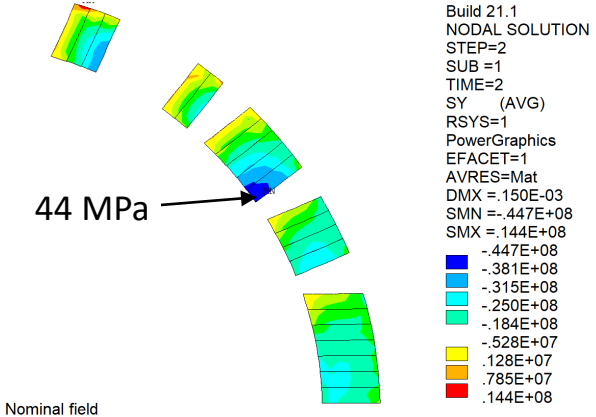




- At nominal field (5 T / 10 kA)



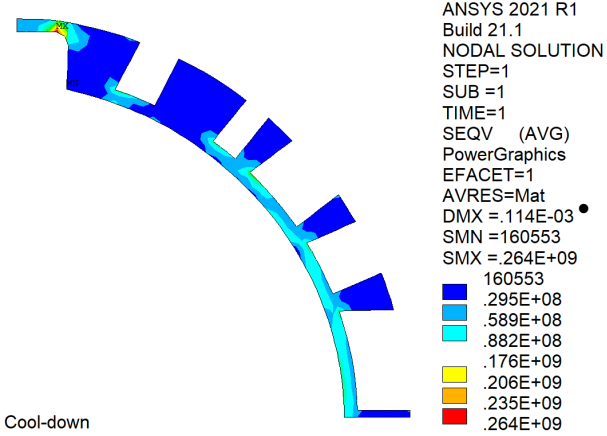
Sr



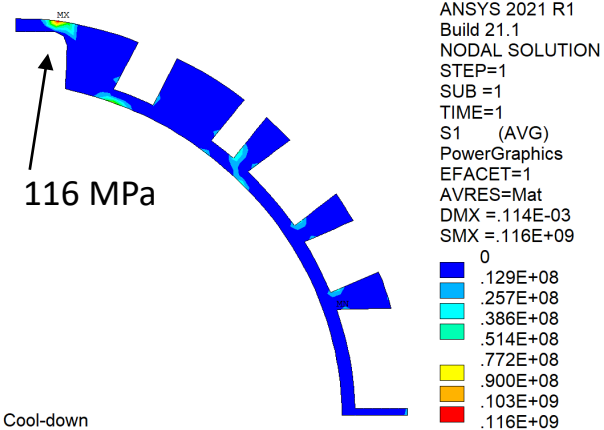
Sθ

Stress-Managed Subscale Magnet: Mech Analysis
SM Structure and Cylindrical Pads

- After cooling down

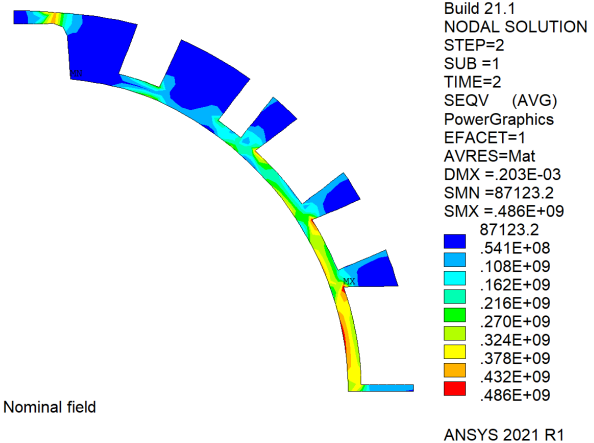


Cool-down



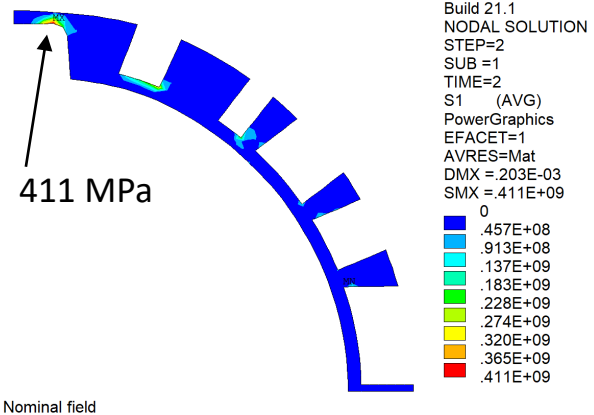
Cool-down

- At nominal field (5 T / 10 kA)



Nominal field

Seqv

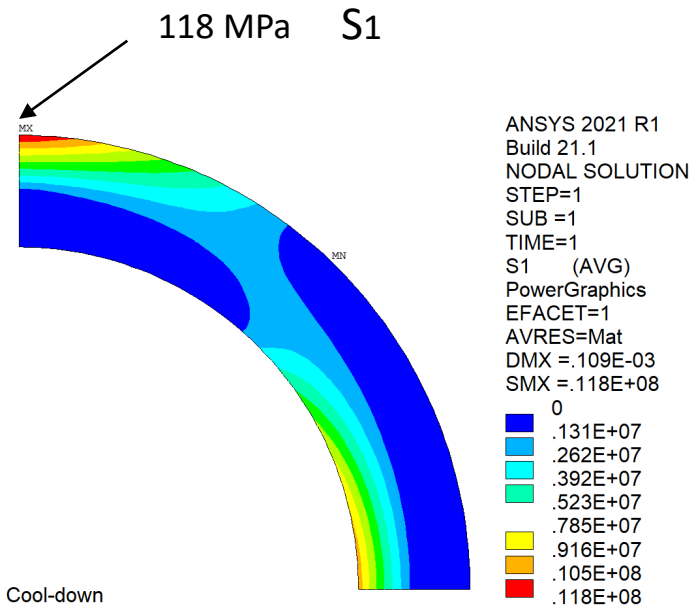


Nominal field

S1

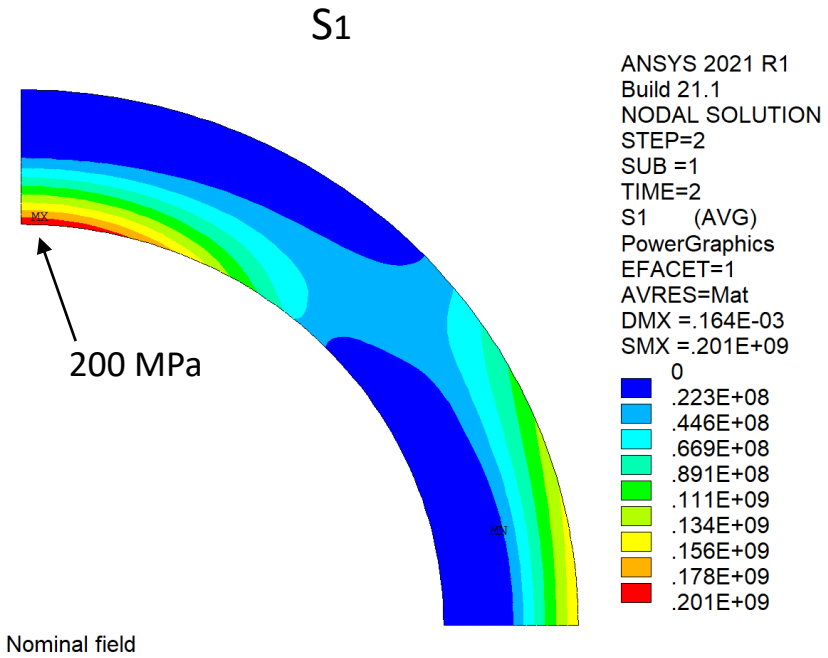
Stress-Managed Subscale Magnet: Mech Analysis
Coil Pack Displacement

- After cooling down



Cool-down

- At nominal field (5 T / 10 kA)



Nominal field

Agenda

- Stress-Managed Magnet Concepts
- ETHZ – PSI Collaboration: MagNum
- 4 Layers Stress-Managed Magnet – 14.5 T option
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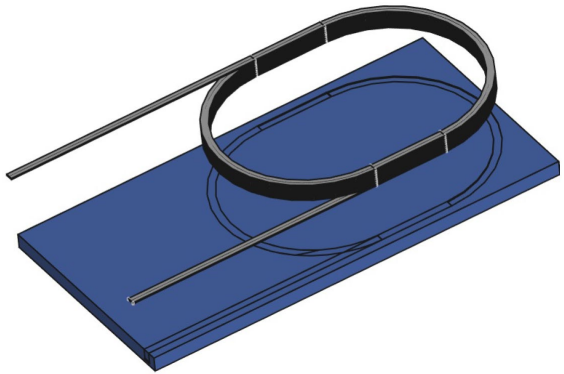
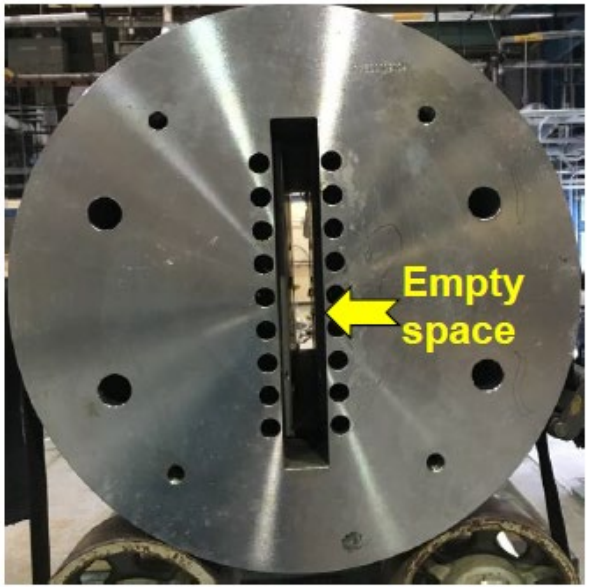
- Subscale Stress-Managed Magnet – 5 T
- BNL/MDP – PSI Collaboration
  - Stress-Managed Insert Coil - BigBoX
- Panoply of Devices and Main Parameters
- Next Steps



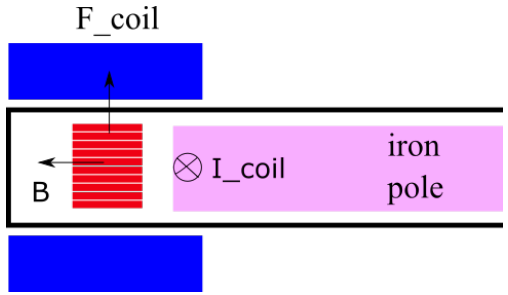
BNL/MDP – PSI Collaboration DCC017

- Common coil dipole
- Free aperture of 30 x 335 mm
- Background field of 10 T
- Rapid-turn around



BigBoX Insert coil on DCC017 Deliverable of MagDev 1

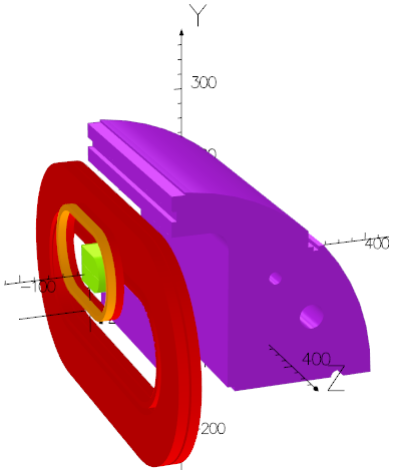
- Cross-sectional view



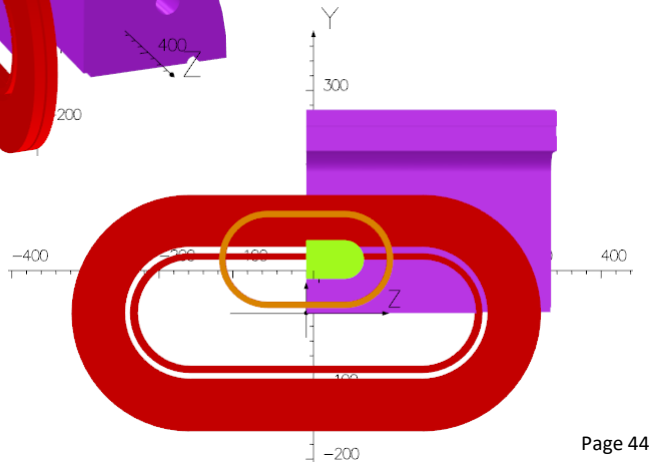
- 3D view

Unit length of 9.6 m

Ends free of Lorentz forces



lateral view



- Evaluating magnet training and limits under stress management conditions:
  - Pre-load free coil
  - Wax performance
  - Stress level
  - SC margin

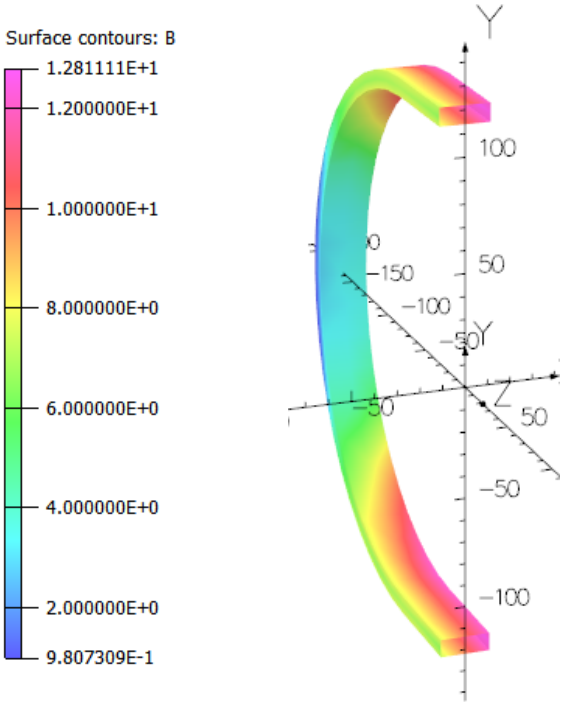
Cable and strand parameters

- **Coil and background parameters**
  - number of turns: 14
  - cable bare width: **7.79** mm
  - cable bare thickness: **1.28** mm
  - insulation thickness: 155.0 µm
  - electrical current: 10 kA
  - background field of 10 T on the x direction

- **Strand parameters**
  - strand diameter: 0.7 mm
  - operational temperature: 4.2 K
  - cabling degradation: 5%
  - Bc20: 28.0 T
  - C: 38500.0 AT/mm2
  - 20 strands per turn

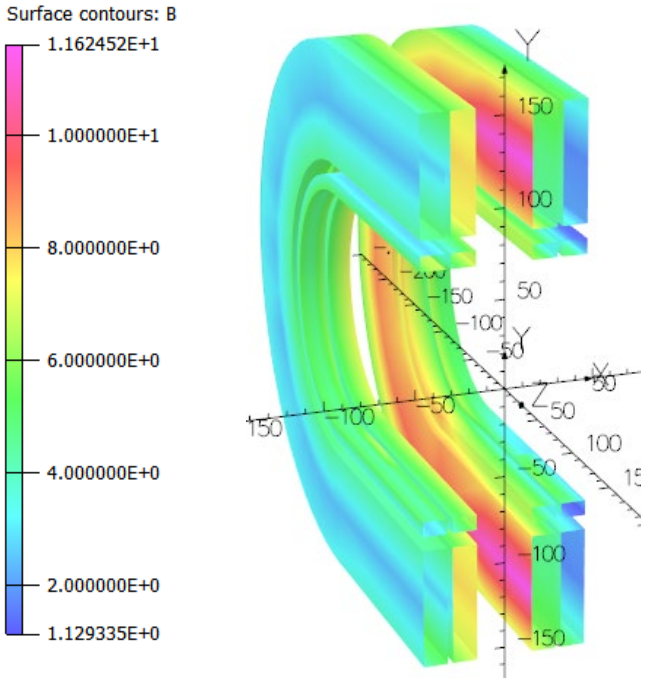
3D magnetic analysis: test coil with 10 kA and background filed

- Test coil peak field of 12.81 T



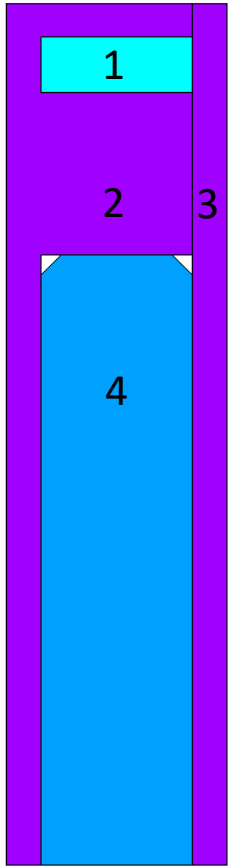
Total load of 834 kN

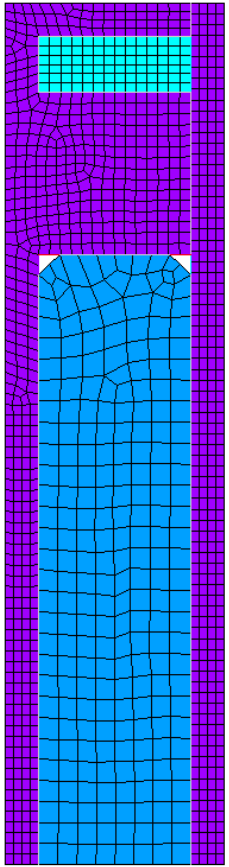
- Common coil peak field of 11.62 T



2D mechanical analysis

- Single coil simplified model
  - Only one straight section is represented
  - Box and cover are made of stainless steel, similar results were obtained with aluminum bronze





1 – coil 2 – box 3 – cover 4 – iron pole

Cases

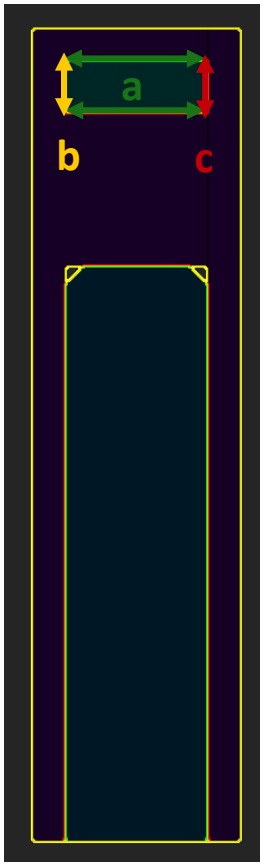
- Model assumptions

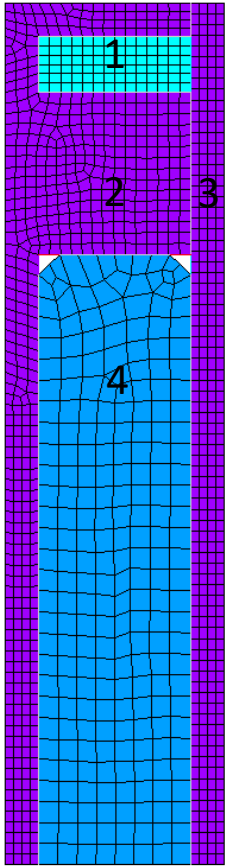
Coil	Pre-load	Interface a	Interface b	Interface c
I	No	Sliding*	Bonded	Detaching

*friction of 0.2

a – coil/box lateral interface
b – coil/box bottom interface
c – coil/cover interface

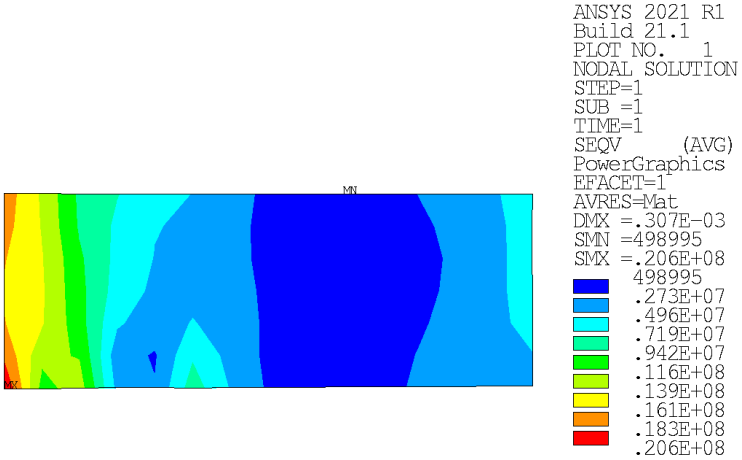
1 – coil 2 – box 3 – cover 4 – iron pole





Selected results - coil

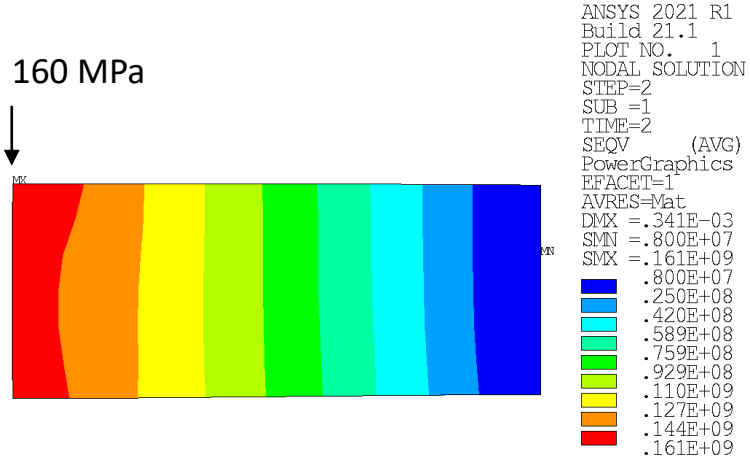
after cooling down



Cool-down

10 kA and background field

160 MPa

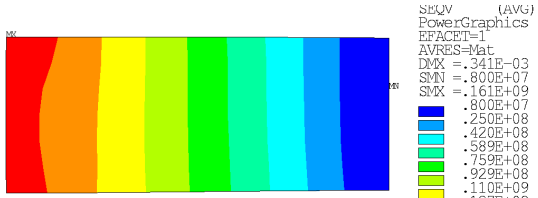


Nominal field

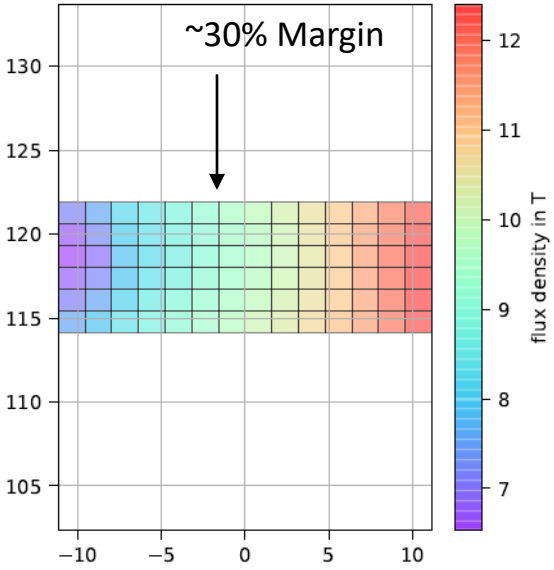
Peak of 160 MPa in compression

Field, force and margin distribution

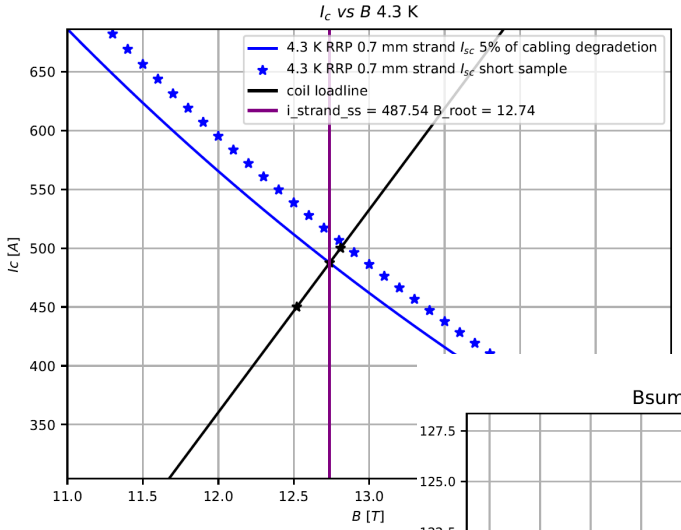
- 2D Mechanical



- 3D Magnetic

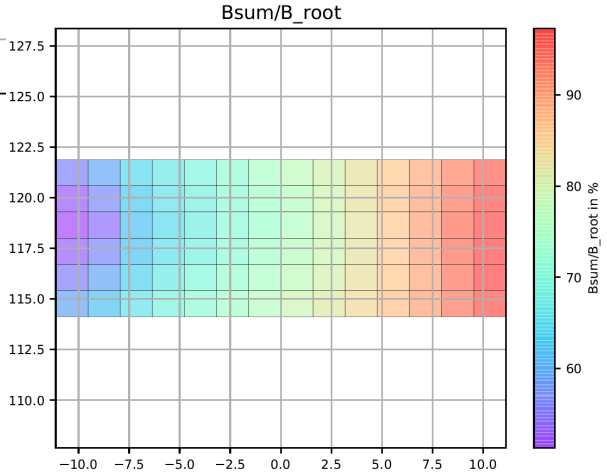


Field computed at element center



- Critical curve and load line

- Local load line

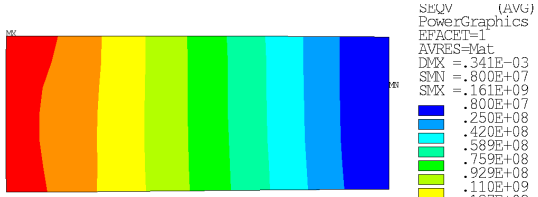


Low field region
160 MPa / 7.0 T

High field region
80 MPa / 12.8 T

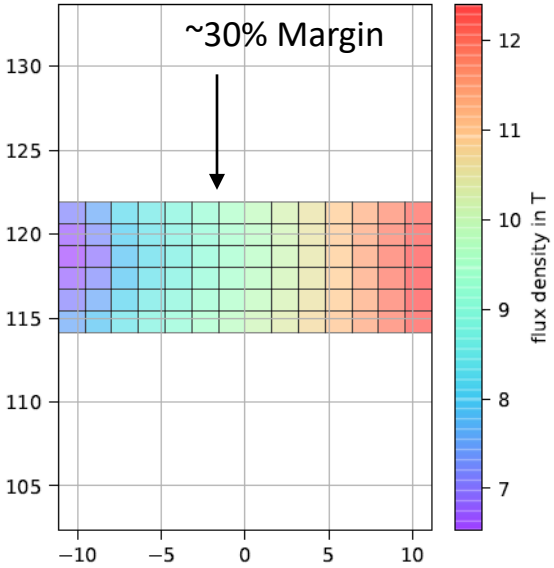
Field, force and margin distribution

- 2D Mechanical

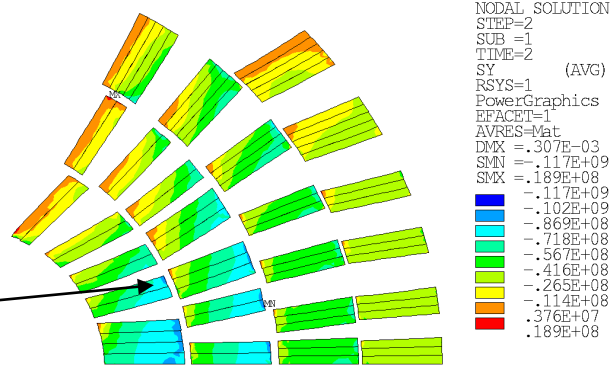


100 MPa

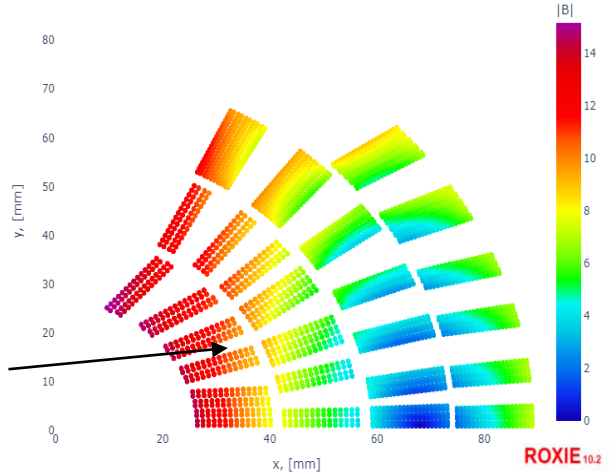
- 3D Magnetic



Sθ



100 MPa



~ 30%

Margin

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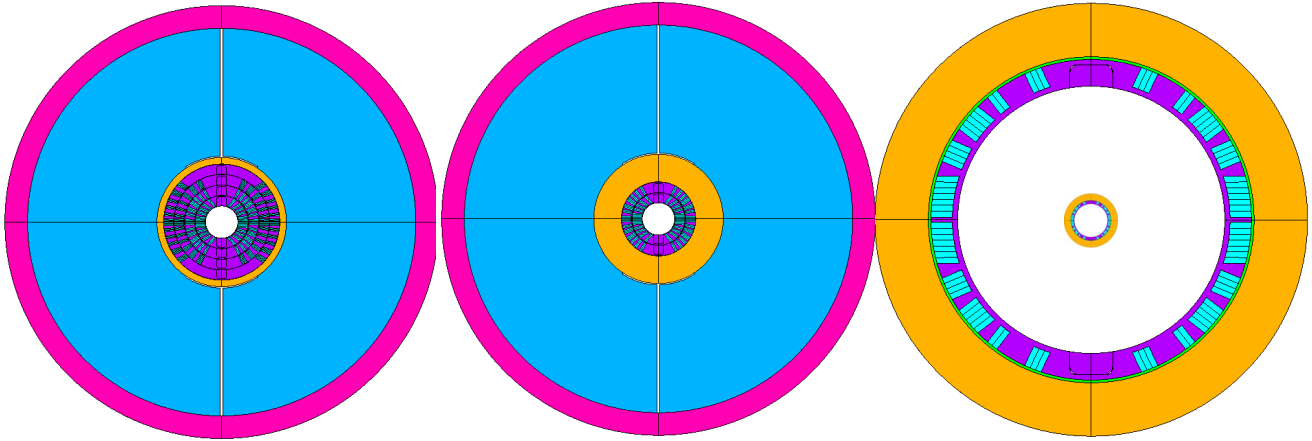
LTS Road Map: Panoply of Magnets and Test Coil

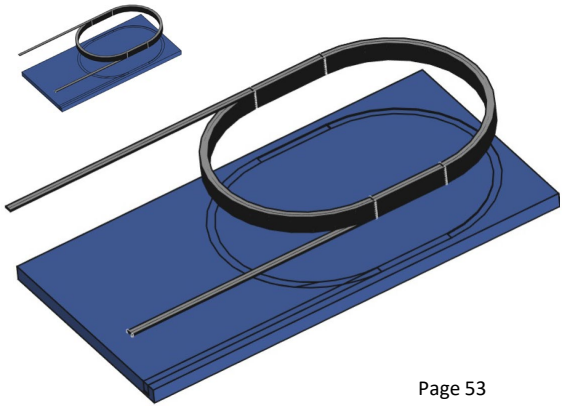
Op Parameter	Value HF/LF
B_0	14.5 T
I_{op}	16.5 kA
S_{θ,r_max}	117/140 MPa

Op Parameter	Value HF/LF
B_0	10 T
I_{op}	20 kA
S_{θ,r_max}	95 MPa

Op Parameter	Value HF/LF
B_0	5 T
I_{op}	10 kA
S_{θ,r_max}	60 MPa

Op Parameter	Value HF/LF
B_p	10 + 2.8 T
I_{op}	10 + 10 kA
S_{max}	80/160 MPa





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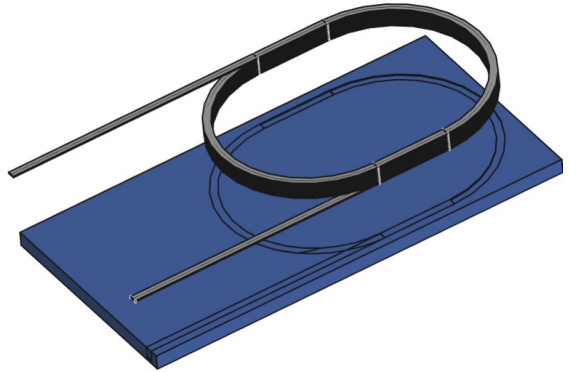
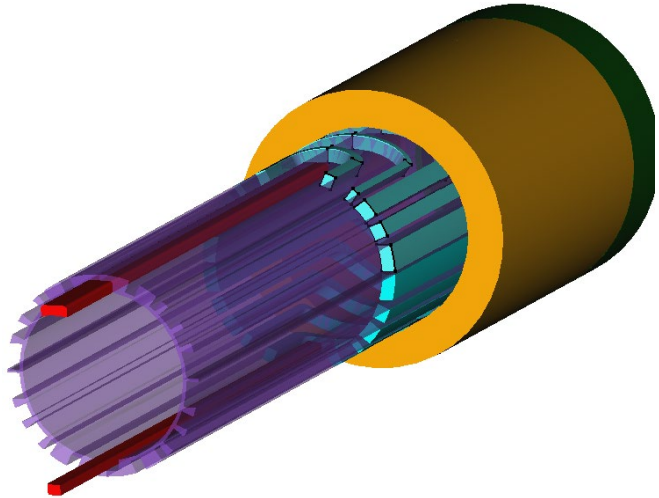
Next Steps (1/2)

- BigBoX
  - Completing the mechanical design
  - Engineering design and manufacturing



- Subscale Stress-Managed Magnet – 5 T
  - 3D coil end optimization
  - Protection
  - Engineering design and manufacturing



Next Steps (2/2)

- Feeding the models with more detailed material characterization
  - 10 stack measurements with Nb_3Sn WAX impregnated cable
  - Coefficient of friction & **Debonding stress**
  - Multi scaling modelling
- Magnet cross-section optimization
  - 4 layers option: further decrease stresses on the SM-structure and coil
  - 2/4 layers option: number of turns on layers 1 and 2 (**12 T with 20 kA**)
  - FCC 16 T option
- 3D analysis: explore SM structure on the ends (backbone and shell)