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WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

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2D Sensitivity Study and Critical Tolerances of CD1 Magnet

26 June 2017

Summary

- **2D Mechanical modelling of CD1 dipole with ANSYS**
- **Design's objectives**
- **Baseline Design (+ excursus on CD2)**
- **Nominal Design vs. Material Properties**
- **Mechanical tolerances**
- **Parametric Study**
- **Conclusions**

Summary

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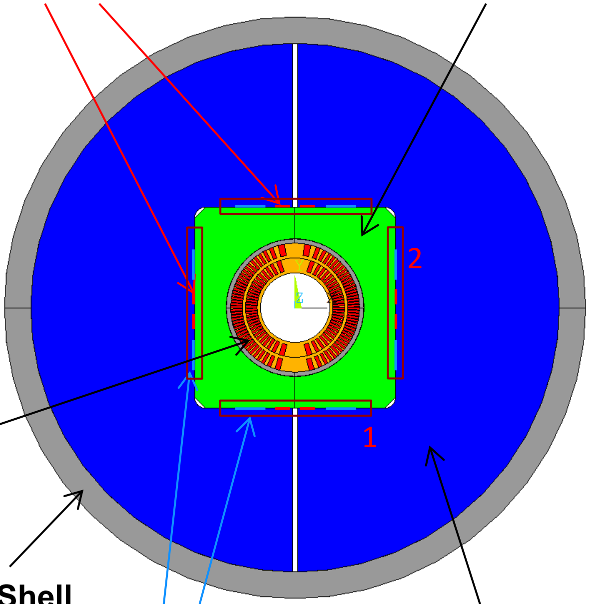
2D Mechanical modelling
Setup of the numerical simulations (ANSYS)

The simulation is divided in 5 load steps:

1. Vertical bladders inflation (max 40 MPa pressure) and vertical keys insertion
2. Vertical bladders deflation and horizontal bladder inflation (max 40 MPa pressure) with horizontal keys insertion
3. Horizontal bladders deflation-> assembly at room temperature
4. Cool down of the assembly to 1.9 K
5. Operation->Lorenz forces acting on the conductor according to short sample limit (1.9 K, 12 T)



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Design's Objectives

- **What we care the most**
  - Limit the maximum stress on the conductor
  - Keep the maximum stress of the mandrel below 0.2% yield stress

Material	Stress limit (MPa)	
	293 K	4.2 K
Coil	130	130
Al-Bronze	250	400

  - Guarantee:
    i. pad/pad contact interface
    ii. Extra margins for steel pads configuration (using in the simulations Lorenz force maps associated to ultimate load (12 T, I_{ss}=20 kA at 1.9 K))

- **For the other materials of the assembly**
  - Aluminum for external and coil assembly shells (Al 7075)
  - Ferromagnetic Iron yoke
  - Steel for the pads (316LN)

Material	Stress limit (MPa)	
	293 K	4.2 K
Al 7075	480	690
Ferromagnetic Iron	180	720
Austenitic steel 316LN	350	1050

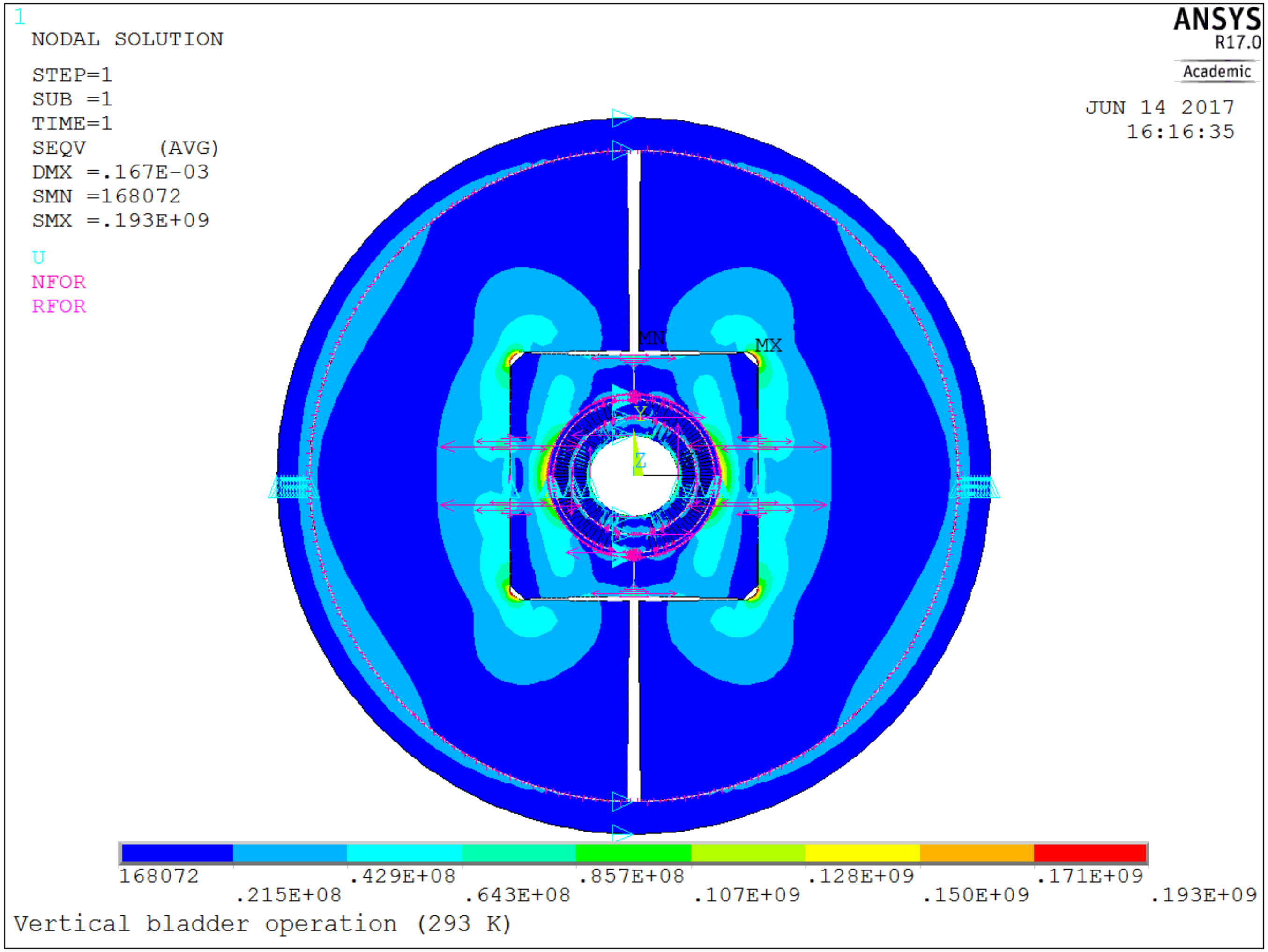
- 2D Mechanical modelling of CD1 dipole with ANSYS
- Design’s objectives
- **Baseline Design** (+ excursus on CD2)
- The Design vs. Material Properties
- Mechanical tolerances
- Parametric Study
- Conclusions

The Magnet

The Magnet

Vert. bladder operation

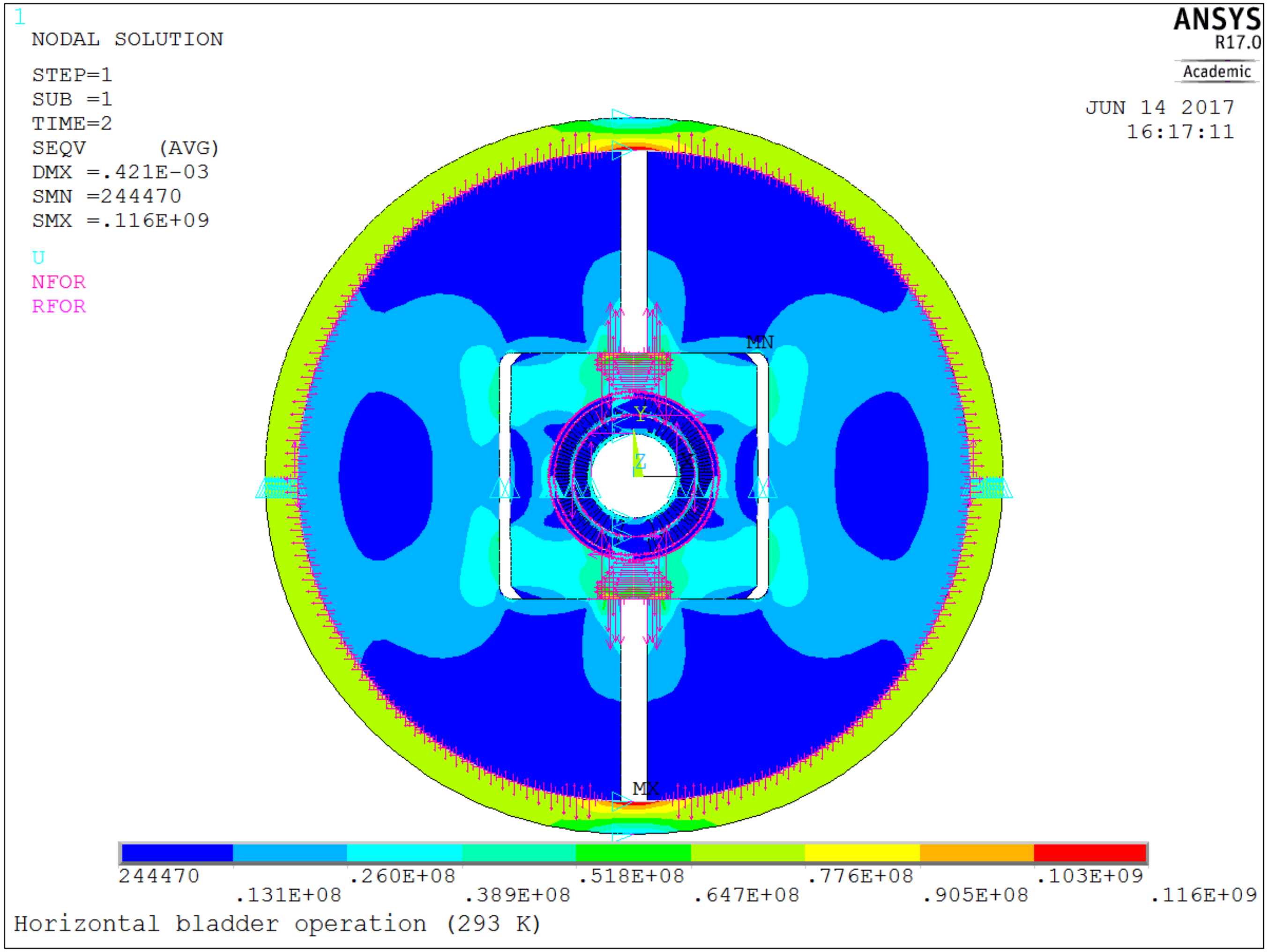
Room temp. steps



The Magnet

Hor. bladder operation

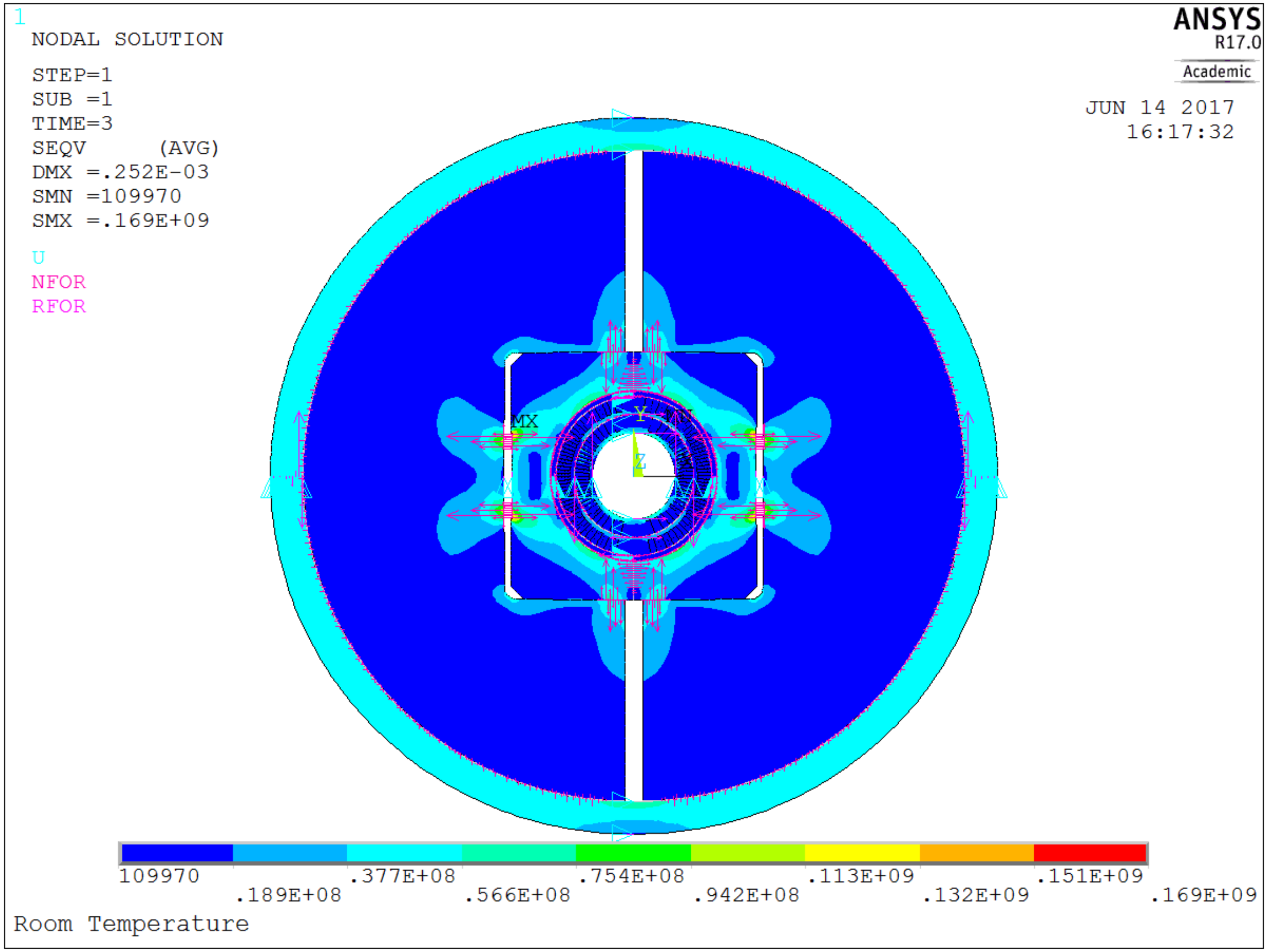
Room temp. steps



The Magnet

Assembly - room temp.

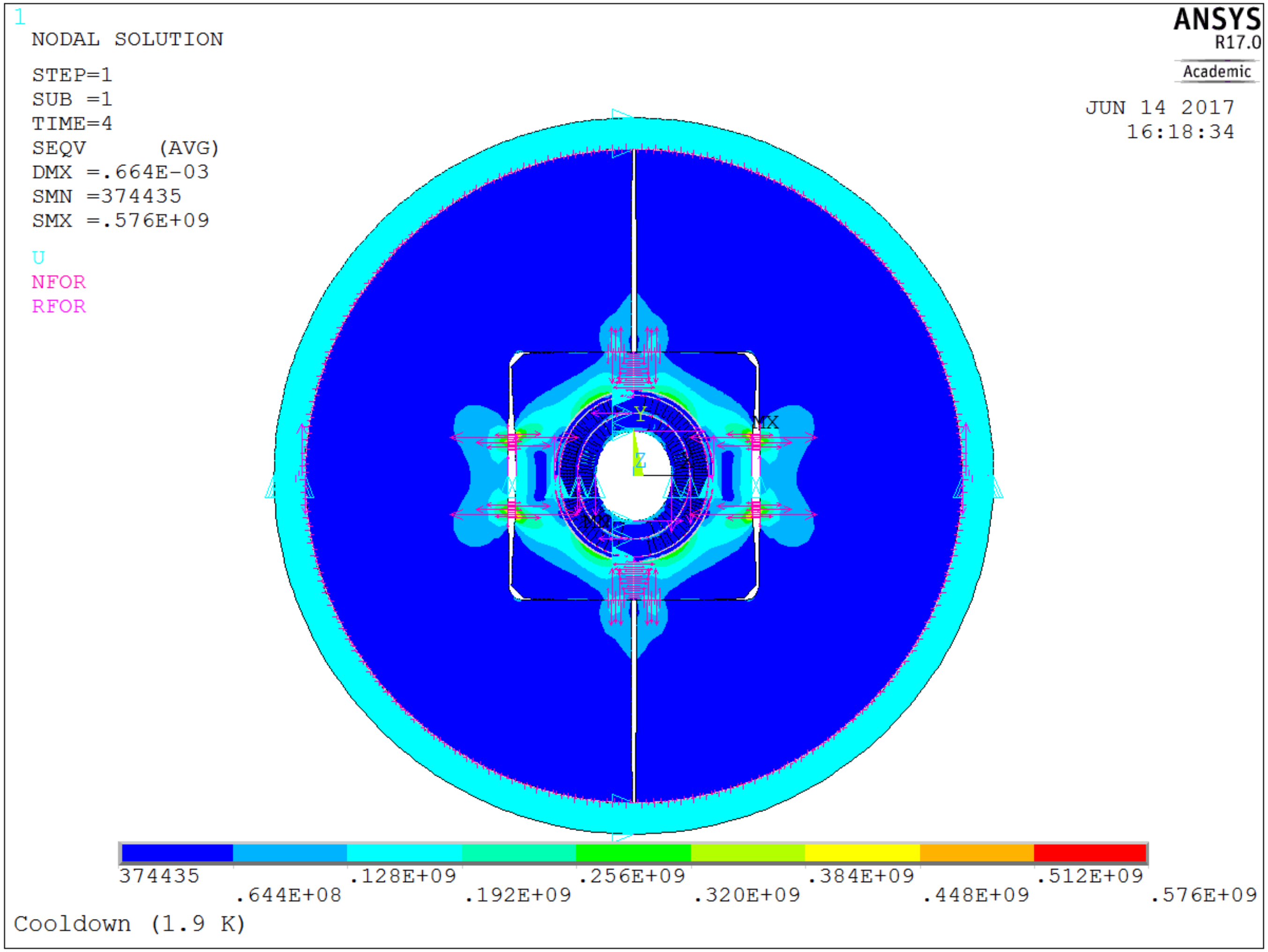
Room temp. steps



The Magnet

1.9 K steps

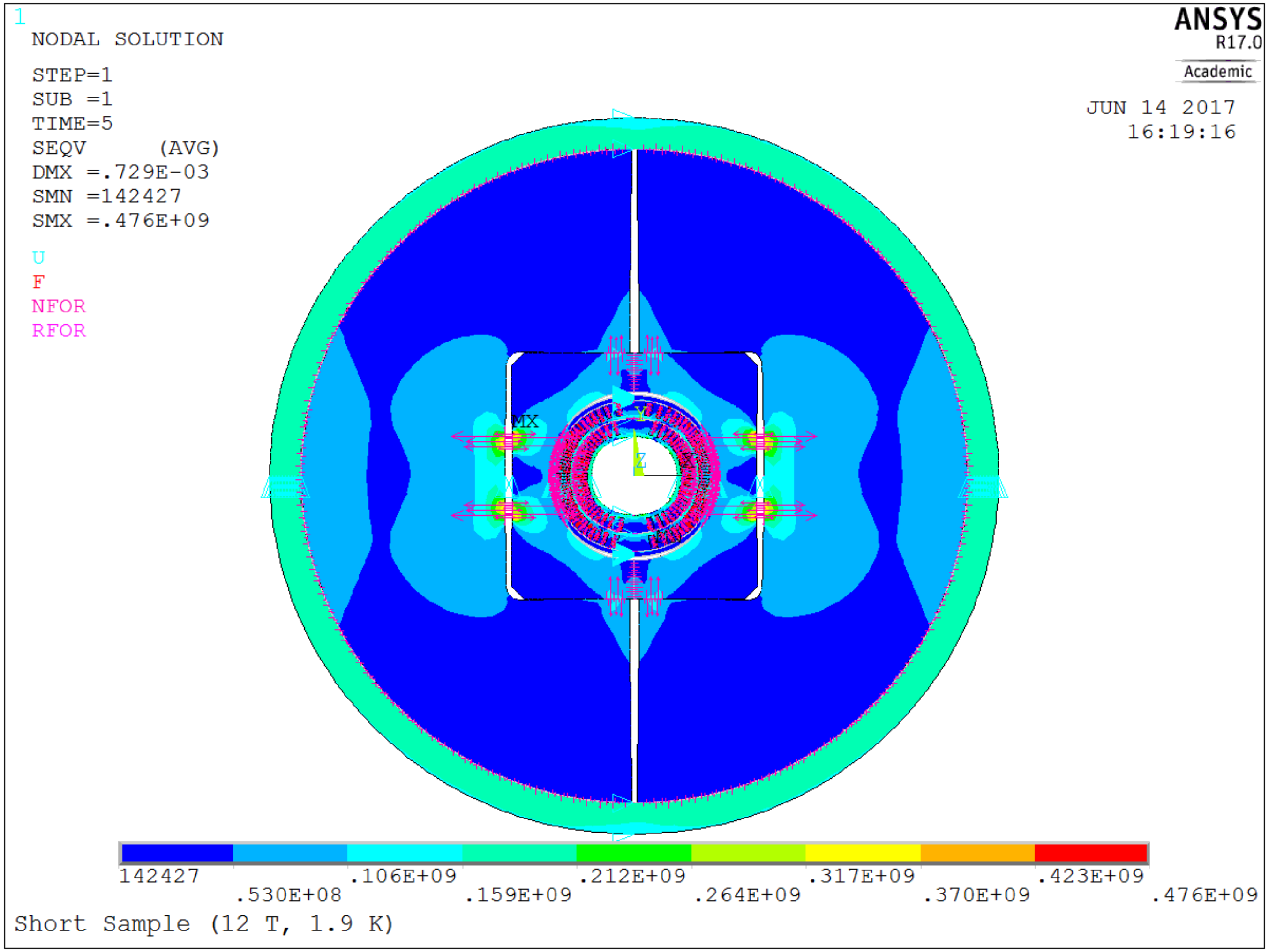
Cool down 1.9 K



The Magnet

Operation at short sample limit (1.9 K, 12 T)

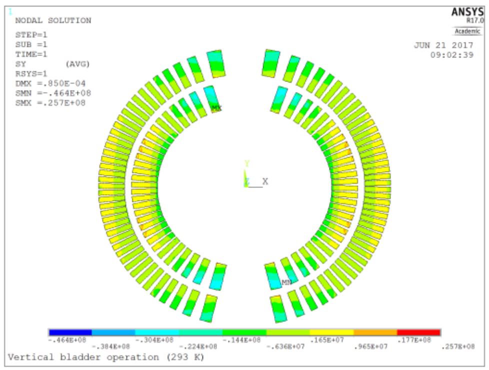
1.9 K steps



The Coil

Room temp. steps (σ_θ - Azimuthal)

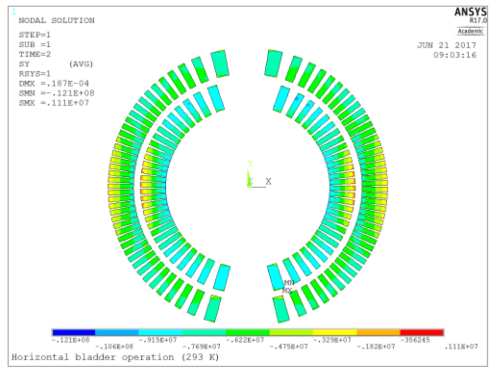
Vert. bladder operation



Cable σ_θ = [- 46.4, 25.7] MPa

Cable σ_v^{max} = 45.6 MPa

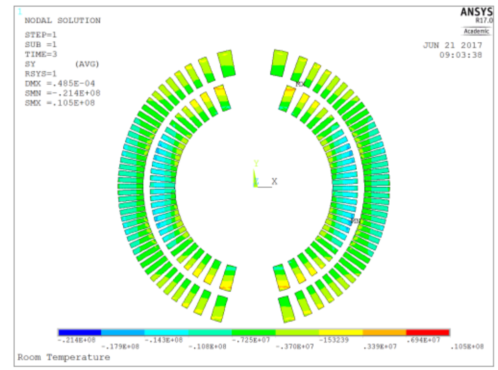
Hor. bladder operation



Cable σ_θ = [-12.1, 1.1] MPa

Cable σ_v^{max} = 11.6 MPa

Assembly - room temp.

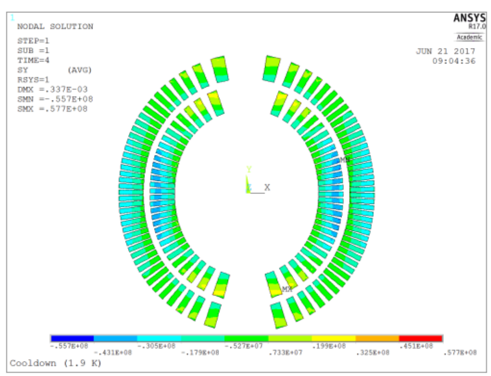


Cable σ_θ = [-21.5, 10.5] MPa

Cable σ_v^{max} = 19.8 MPa

Cool down and operation steps (σ_θ - Azimuthal)

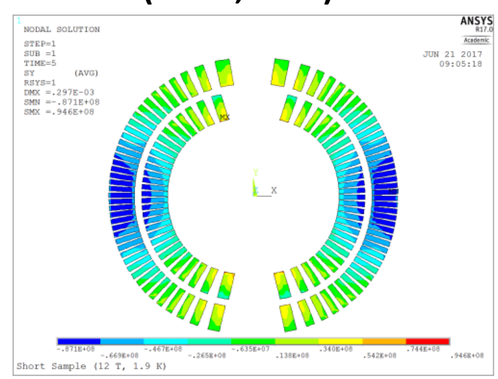
Cool down 1.9 K



Cable σ_θ = [-55.7, 57.7] MPa

Cable σ_v^{max} = 66.4.5 MPa

Operation at short sample limit (1.9 K, 12 T)



Cable σ_θ = [-87.1, 94.6] MPa

Cable σ_v^{max} = 101 MPa

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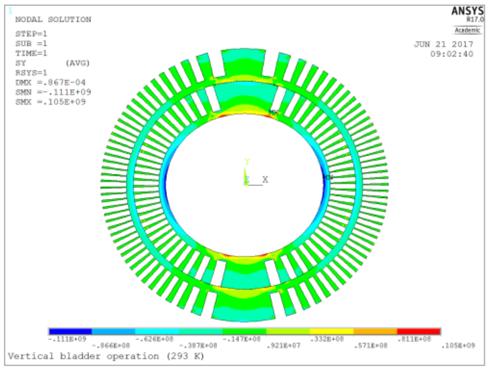
The Former

Room temp. steps (σ_θ - Azimuthal)

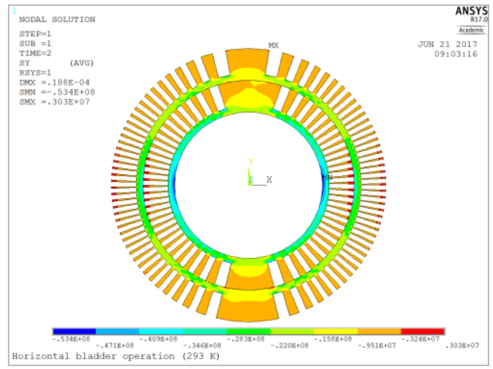
Vert. bladder operation



Former σ_θ= [-110.6, 105.0] MPa

Former σ_v^{max} = 110.6 MPa

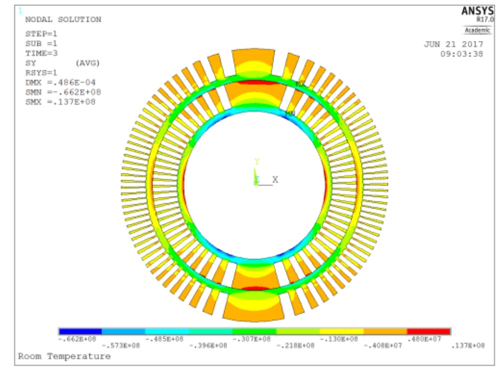
Hor. bladder operation



Former σ_θ = [- 53.4, 3.0] MPa

Former σ_v^{max} = 53.4 MPa

Assembly - room temp.

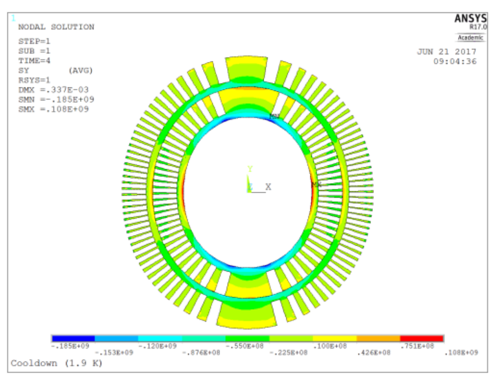


Former σ_θ = [-66.2, 13.7] MPa

Former σ_v^{max} = 65.9 MPa

Cool down and operation steps (σ_θ - Azimuthal)

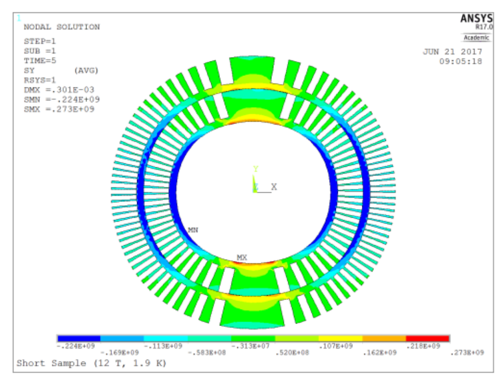
Cool down 1.9 K



Former σ_θ = [-185.2, 108]MPa

Former σ_v^{max} = 184.8 MPa

Operation at short sample limit (1.9 K, 12 T)



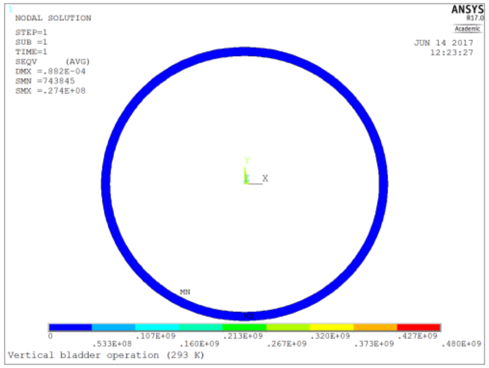
Former σ_θ = [-224.0, 273.0]MPa

Former σ_v^{max} = 271.6 MPa

The Protective Coil Pack Shell

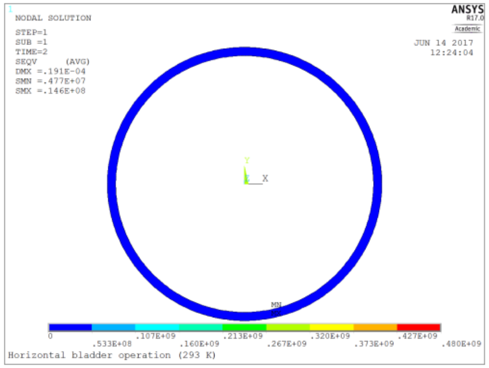
Room temp. steps

Vert. bladder operation



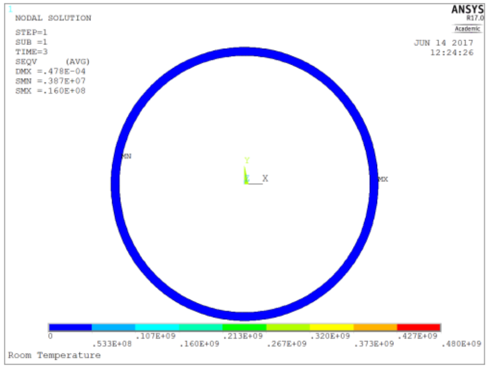
Prot. Shell σ_v^{max} = 27.4 MPa

Hor. bladder operation



Prot. Shell σ_v^{max} = 14.6 MPa

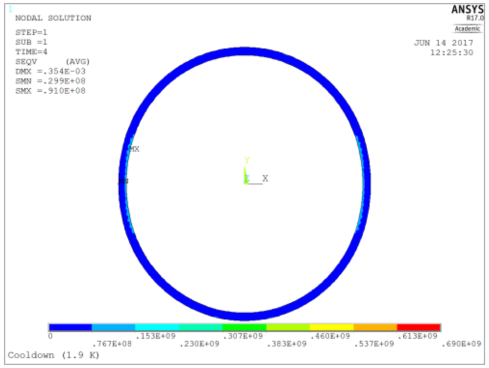
Assembly - room temp.



Prot. Shell σ_v^{max} = 16.0 MPa

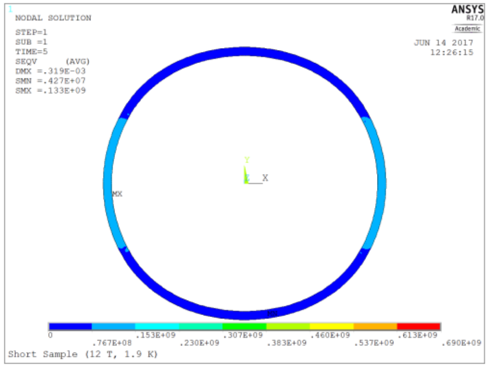
Cool down and operation steps

Cool down 1.9 K



Prot. Shell σ_v^{max} = 91.0 MPa

Operation at short sample limit (1.9 K, 12 T)

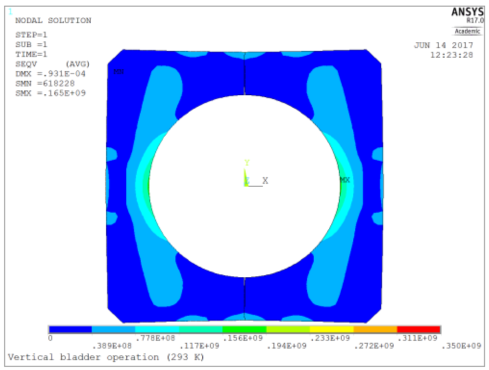


Prot. Shell σ_v^{max} = 133.5 MPa

The Steel Pads

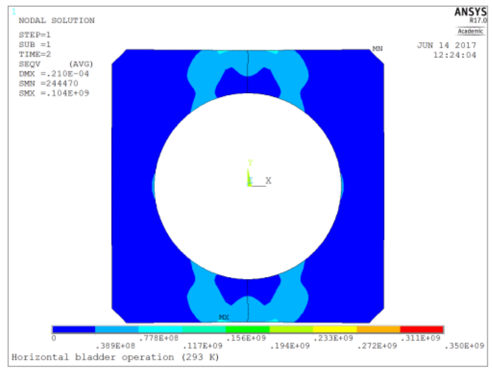
Room temp. steps

Vert. bladder operation



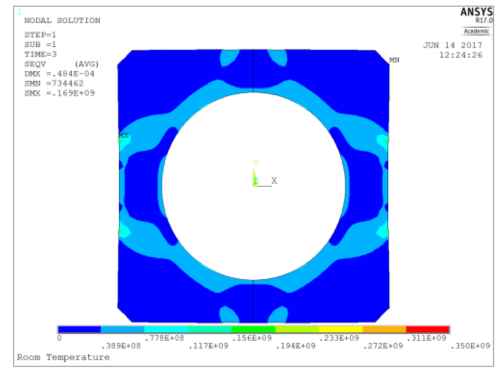
Pads IR σ_v^{max} = 165.5 MPa

Hor. bladder operation



Pads IR σ_v^{max} = 48.0 MPa

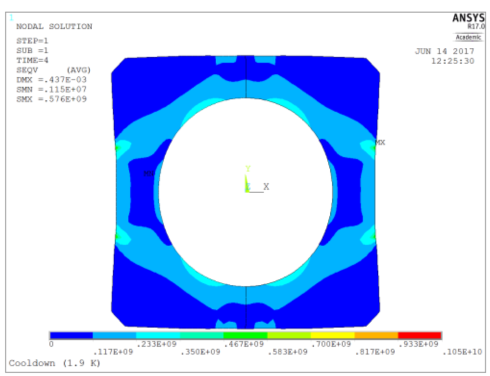
Assembly - room temp.



Pads IR σ_v^{max} = 80.6 MPa

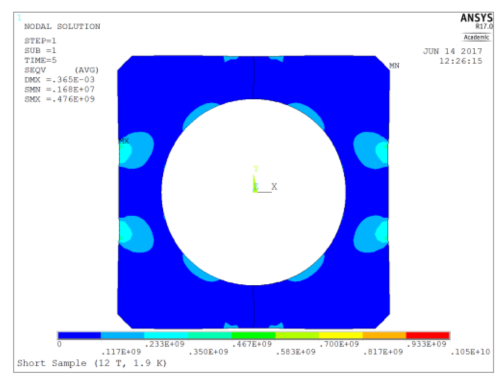
Cool down and operation steps

Cool down 1.9 K



Pads IR σ_v^{max} = 316.3 MPa

Operation at short sample limit (1.9 K, 12 T)

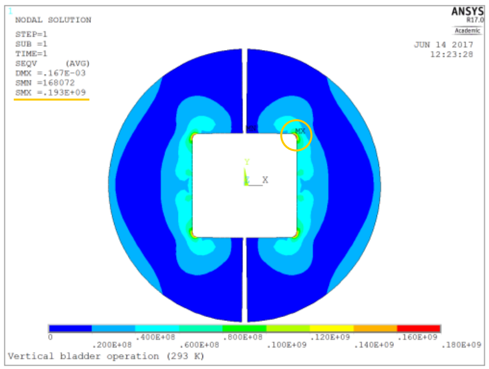


Pads IR σ_v^{max} = 161.0 MPa

The Iron Yoke

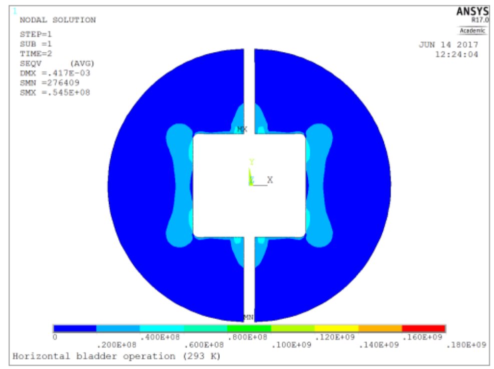
Room temp. steps

Vert. bladder operation



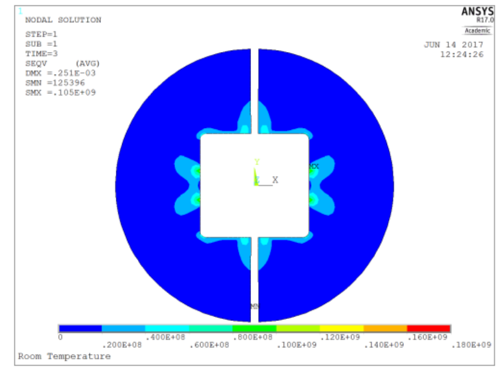
Yoke σ_v^{max} > 180 MPa

Hor. bladder operation



Yoke σ_v^{max} = 54.5 MPa

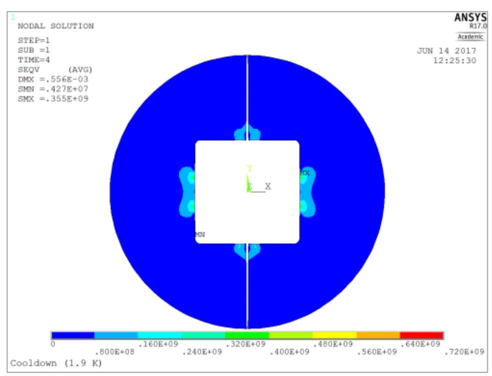
Assembly - room temp.



Yoke σ_v^{max} = 105.0 MPa

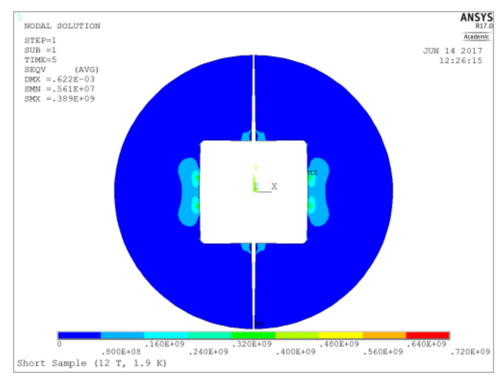
Cool down and operation steps

Cool down 1.9 K



Yoke σ_v^{max} = 355.0 MPa

Operation at short sample limit (1.9 K, 12 T)



Yoke σ_v^{max} = 389.0 MPa

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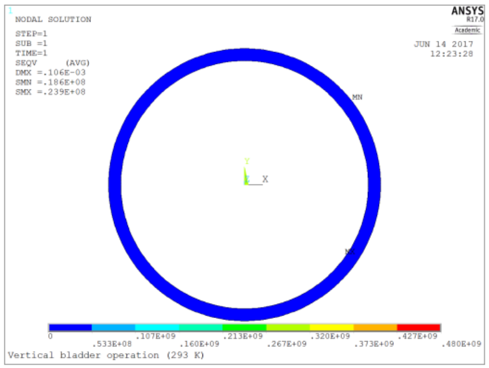
The Support Shell

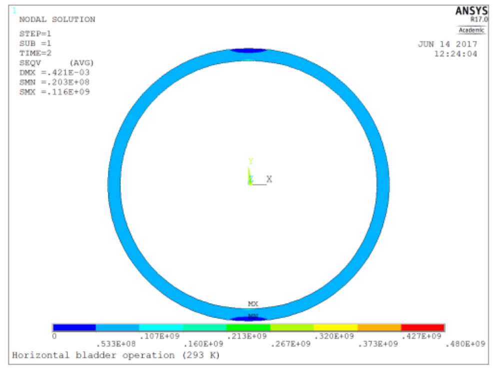
Room temp. steps

Vert. bladder operation



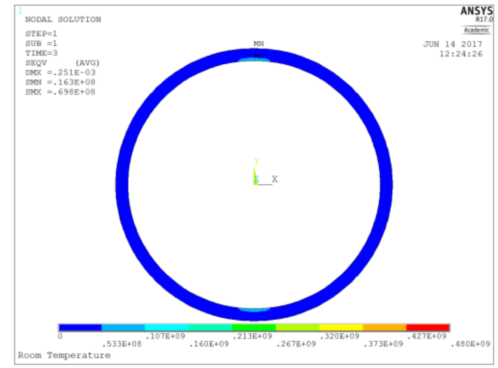
Shell σ_v^{max} = 23.9 MPa

Hor. bladder operation



Shell σ_v^{max} = 116.3 MPa

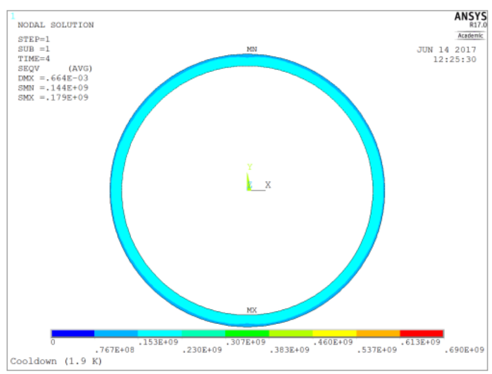
Assembly - room temp.



Shell σ_v^{max} = 69.8 MPa

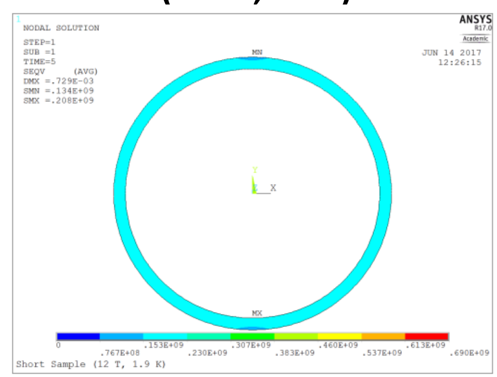
Cool down and operation steps

Cool down 1.9 K



Shell σ_v^{max} = 179.0 MPa

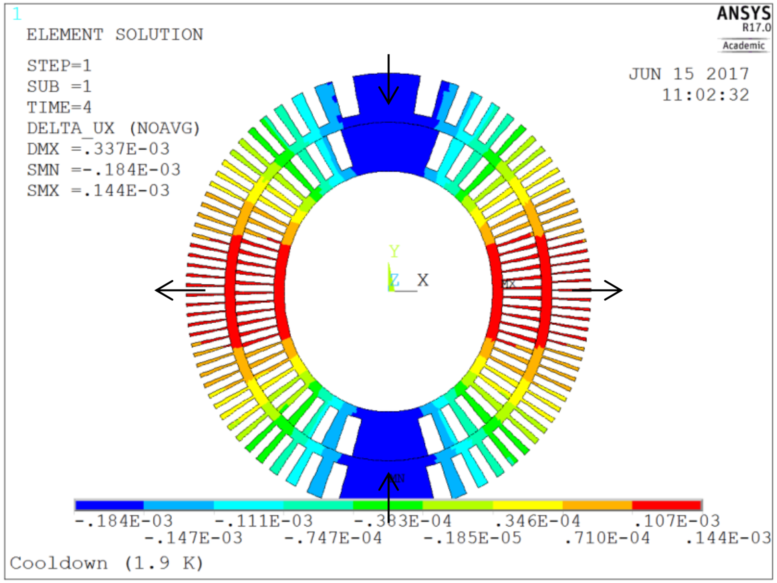
Operation at short sample limit (1.9 K, 12 T)



Shell σ_v^{max} = 208.0 MPa

Former Displacement

Radial displacement difference of the former between cool down and short sample load steps



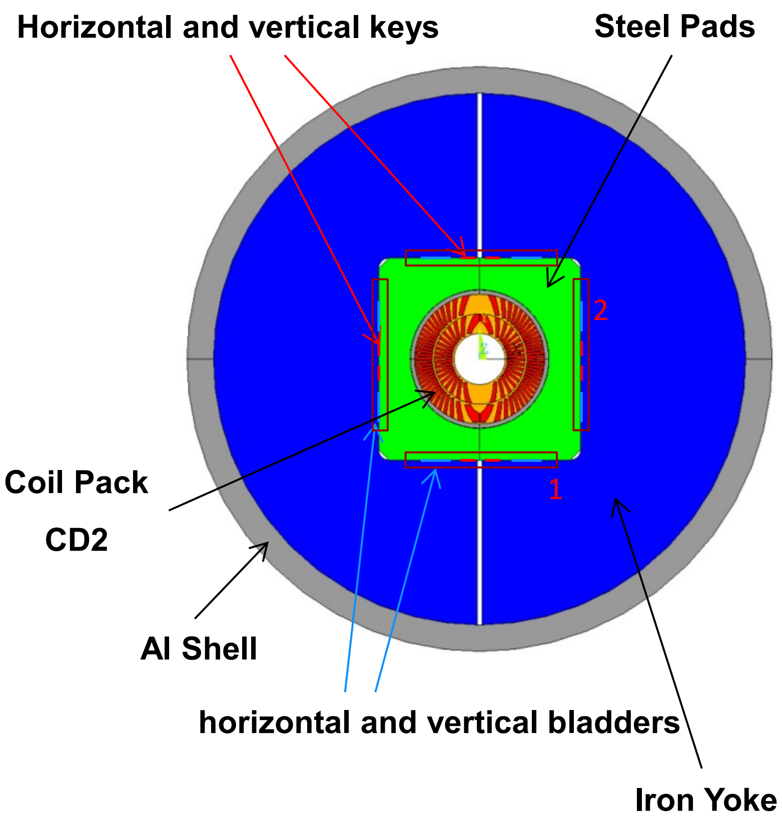
- **The arrow indicates the radial movement direction from cool down to operation on X and Y axes**
- **Along Y axes the coil pack squeeze of roughly of 180 μm**
- **Along X axes the coil pack expand of roughly of ~ 140 μm**

- 2D Mechanical modelling of CD1 dipole with ANSYS
- Design's objectives
- Baseline Design **(+Excursus on CD2)**
- The Design vs. Material Properties
- Mechanical tolerances
- Parametric Study
- Conclusions

CD2 mechanical structure

The CD2 design:

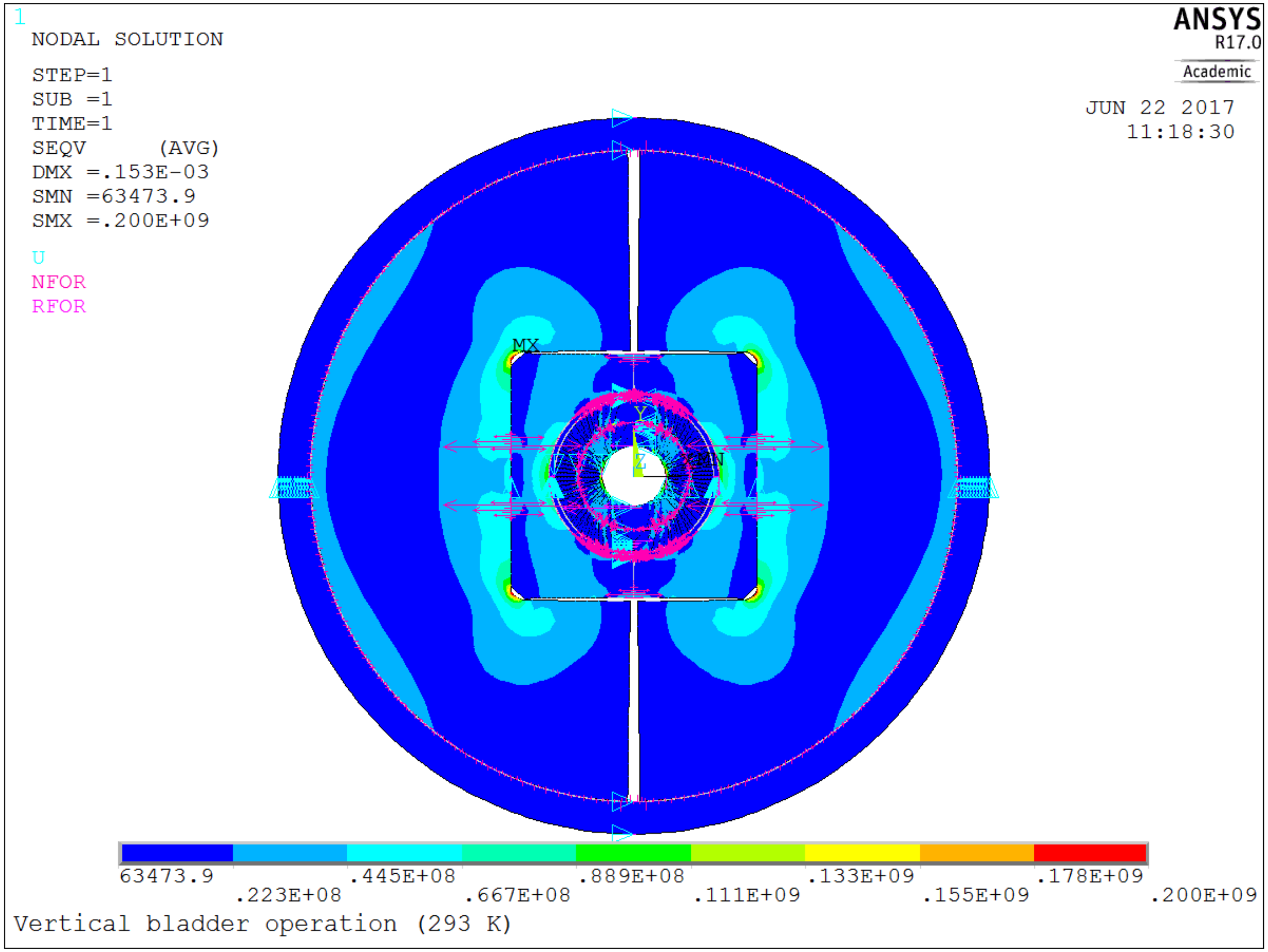
1. Same Layer-2 OD =122 mm of CD1
2. Inclined cable channels
3. Same Bladder and Key structure of CD1
4. 2D Simulations -> 5 steps (as for CD1)and same B&K config.
   - Operation->Lorenz forces acting on the conductor according to test condition (4.2 K, 10.5 T) , limited by the test station I_{max}=22 kA



CD2 Magnet

Room temp. steps

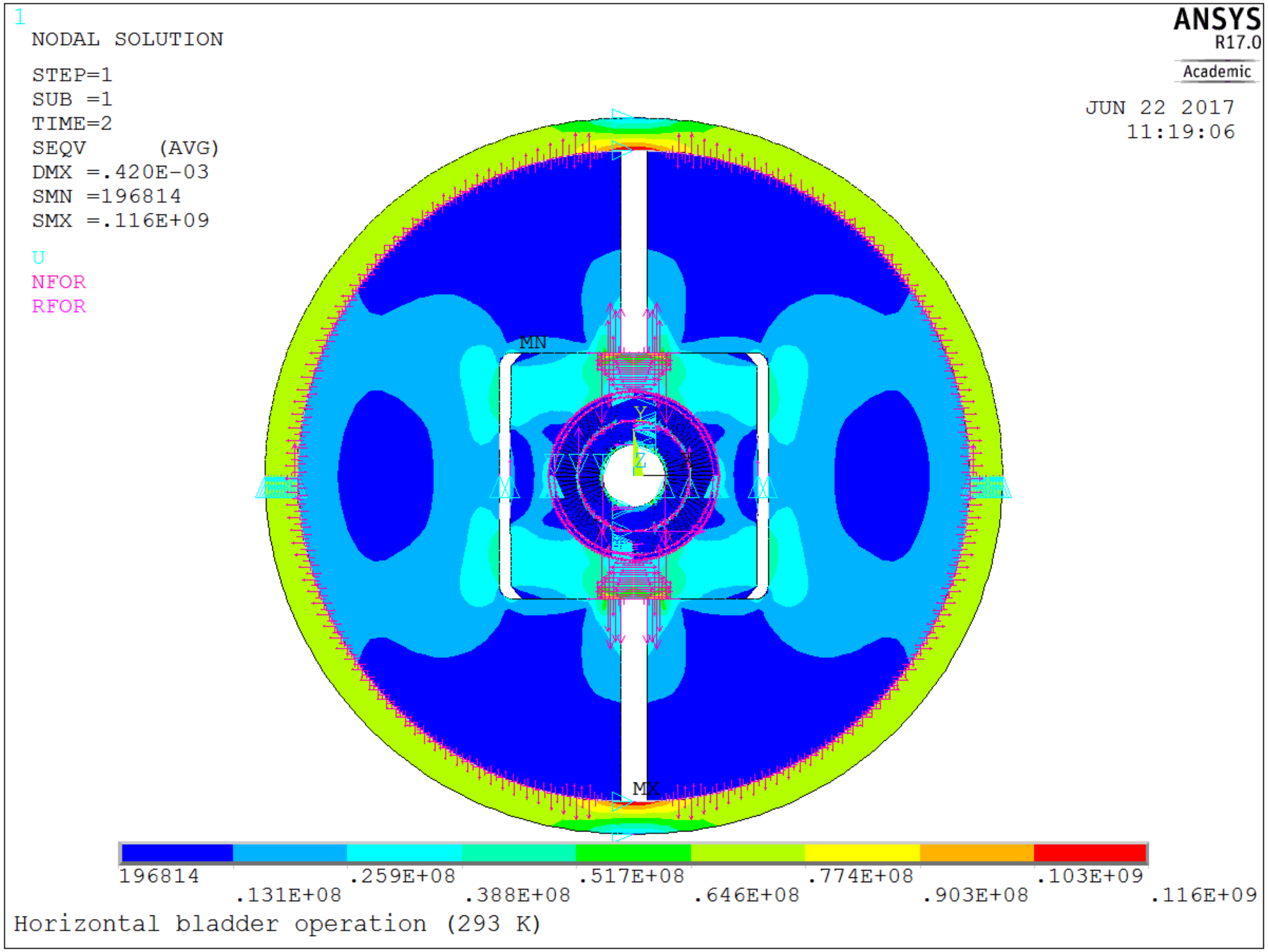
Vert. bladder operation



CD2 Magnet

Hor. bladder operation

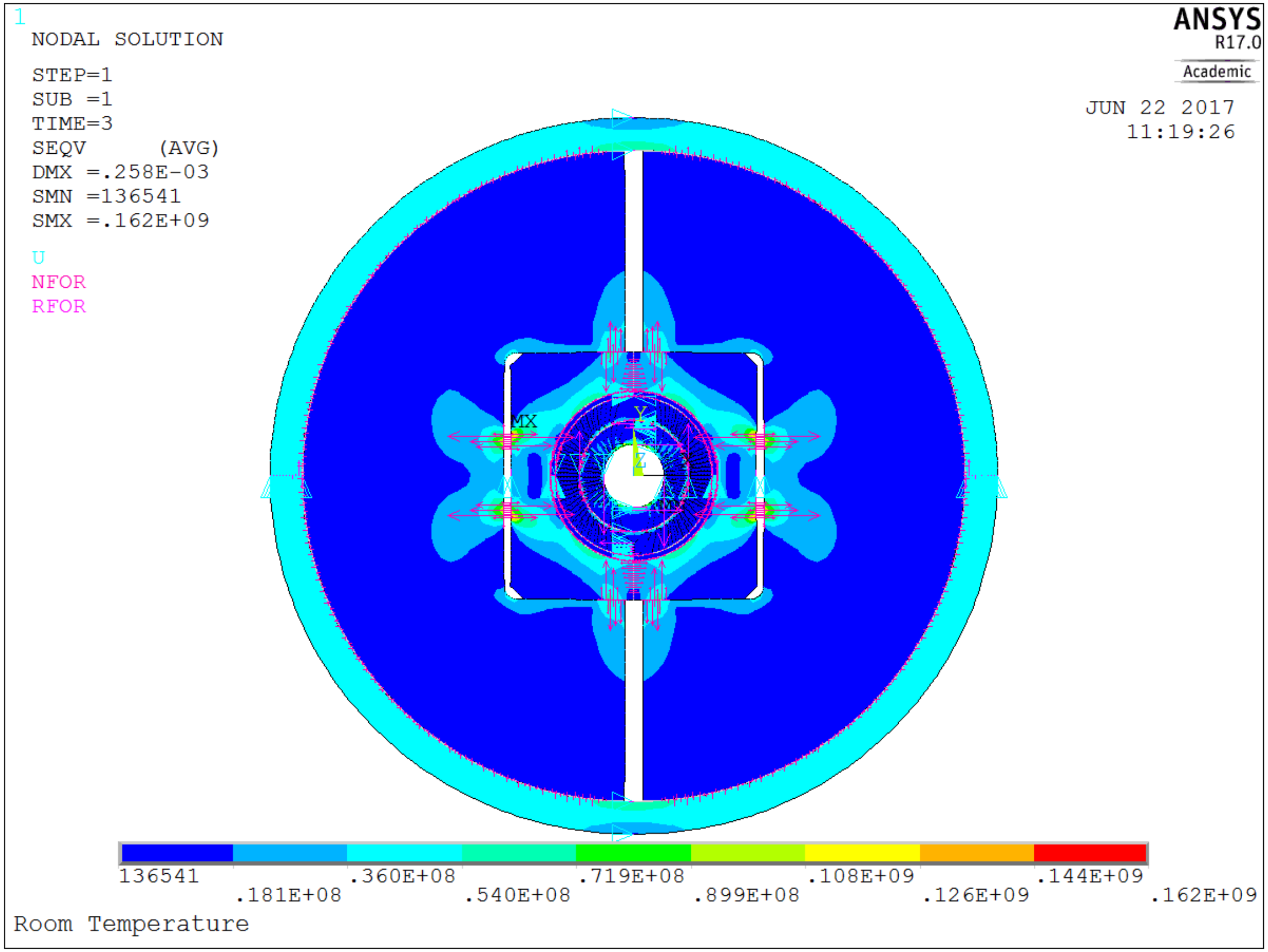
Room temp. steps



CD2 Magnet

Room temp. steps

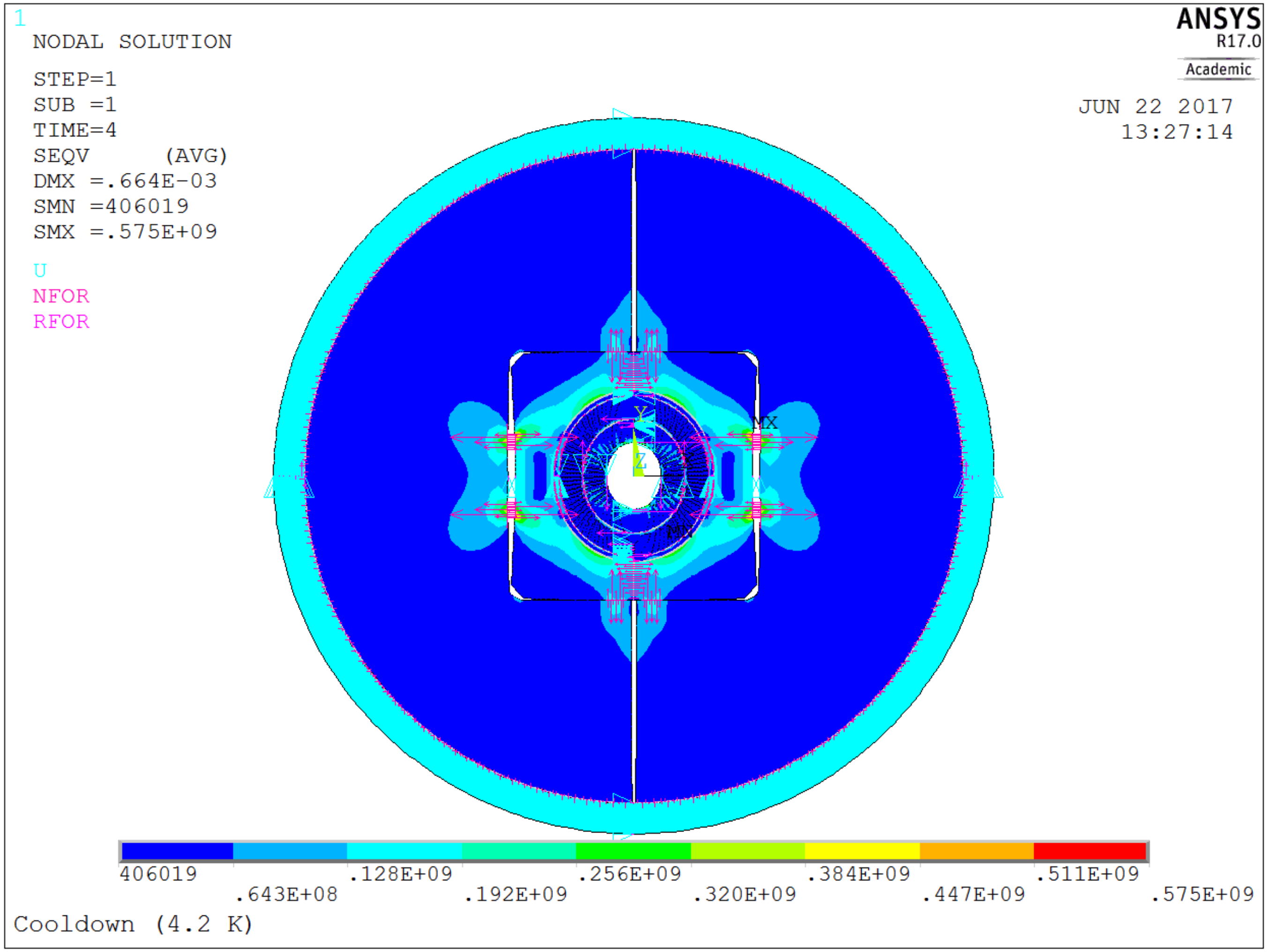
Assembly - room temp.



CD2 Magnet

Cool down 4.2 K

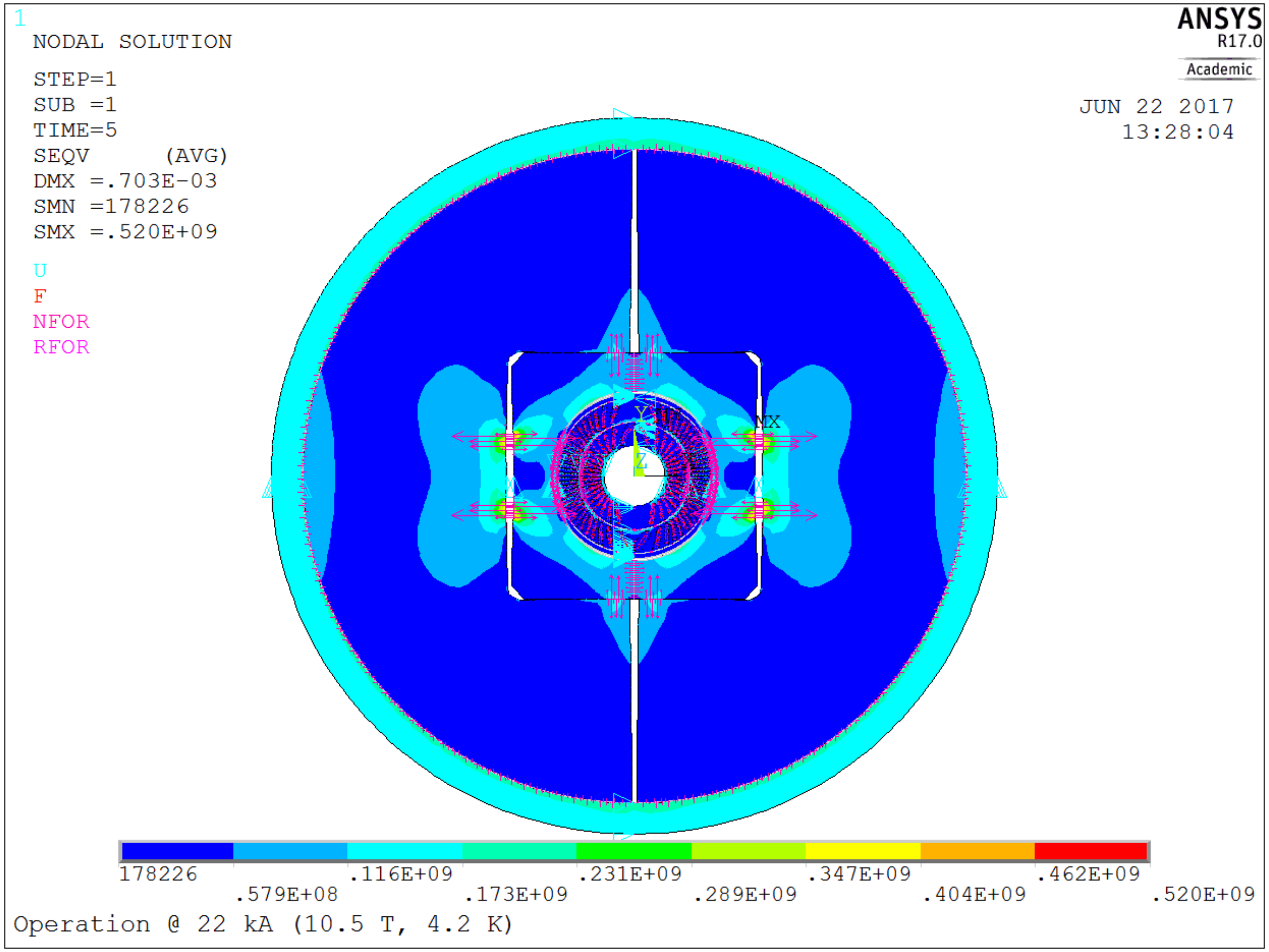
4.2 K steps



CD2 Magnet

4.2 K steps

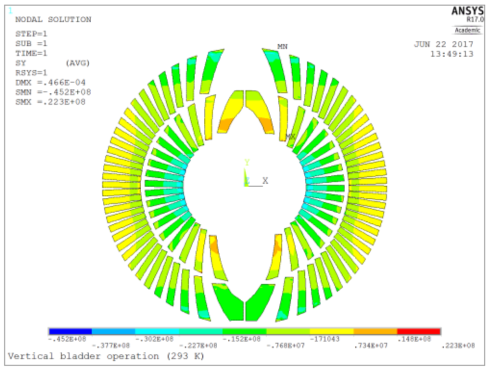
Operation (4.2 K, 10.5 T)



CD2- The Coil

Room temp. steps (σ_θ - Azimuthal)

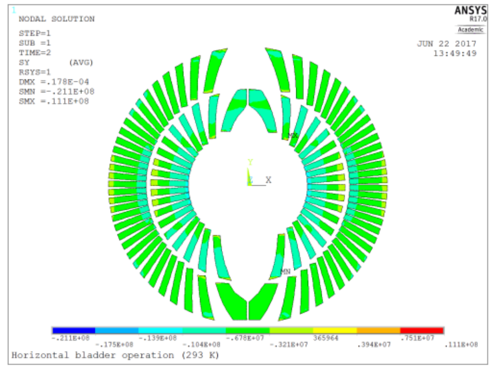
Vert. bladder operation



Cable σ_θ = [- 45.2, 22.3] MPa

Cable σ_v^{max} = 46.2 MPa

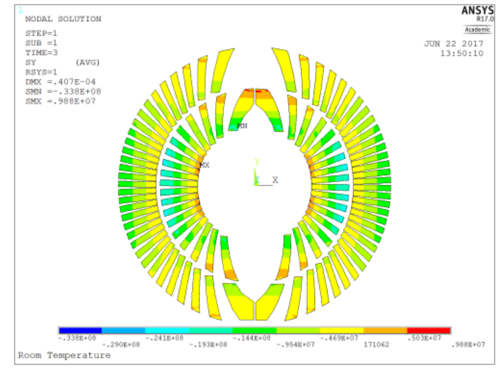
Hor. bladder operation



Cable σ_θ = [-21.1, 11.1] MPa

Cable σ_v^{max} = 20.8 MPa

Assembly - room temp.

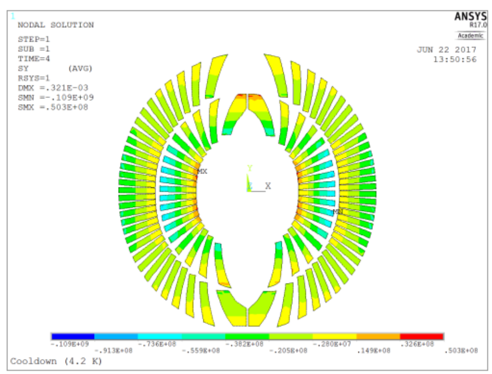


Cable σ_θ = [-33.8, 9.8] MPa

Cable σ_v^{max} = 33.0 MPa

Cool down and operation steps (σ_θ - Azimuthal)

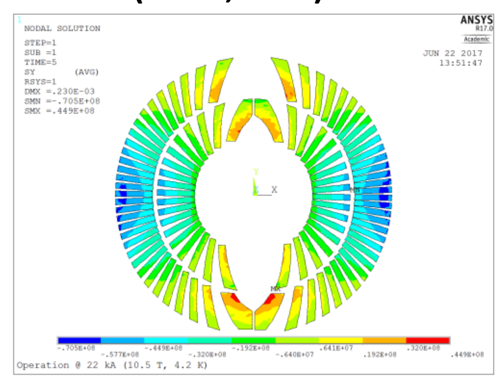
Cool down 1.9 K



Cable σ_θ = [-109.0, 50.3] MPa

Cable σ_v^{max} = 102.0 MPa

Operation at short sample limit (1.9 K, 12 T)



Cable σ_θ = [-70.5, 44.9] MPa

Cable σ_v^{max} = 72.4 MPa

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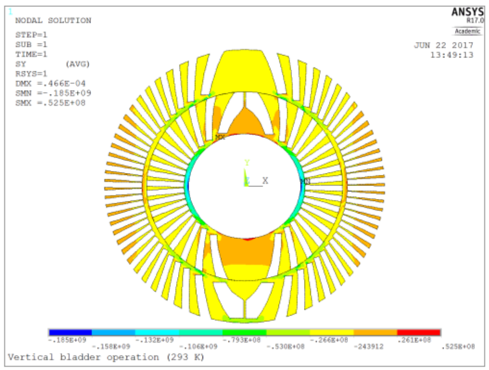
CD2-The Former

Room temp. steps (σ_θ - Azimuthal)

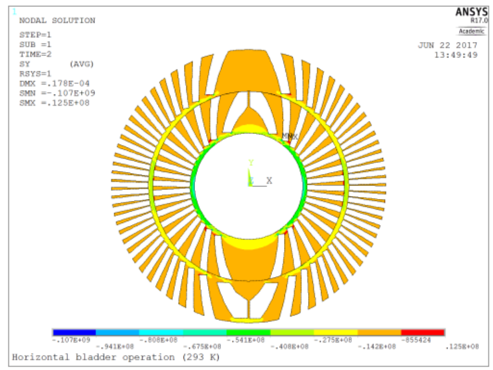
Vert. bladder operation



Former σ_θ= [-185.0, 52.5] MPa

Former σ_v^{max} = 185 MPa

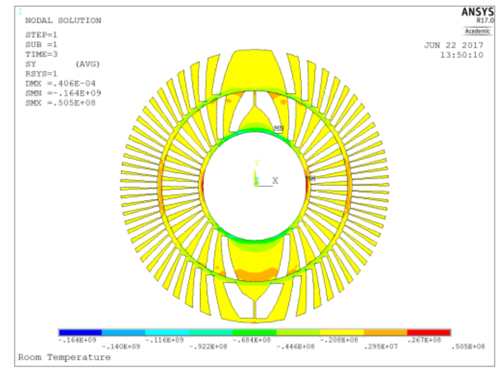
Hor. bladder operation



Former σ_θ = [- 107.0, 12.5] MPa

Former σ_v^{max} = 100 MPa

Assembly - room temp.

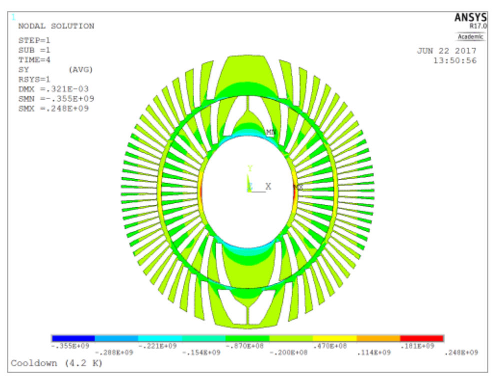


Former σ_θ = [-164.0, 50.5] MPa

Former σ_v^{max} = 158 MPa

Cool down and operation steps (σ_θ - Azimuthal)

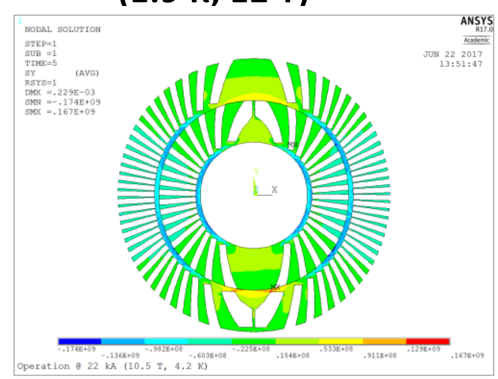
Cool down 1.9 K



Former σ_θ = [-355.0, 248.0]MPa

Former σ_v^{max} = 340 MPa

Operation at short sample limit (1.9 K, 12 T)



Former σ_θ = [-174.0, 167.0]MPa

Former σ_v^{max} = 175.0 MPa

- 2D Mechanical modelling of CD1 dipole with ANSYS
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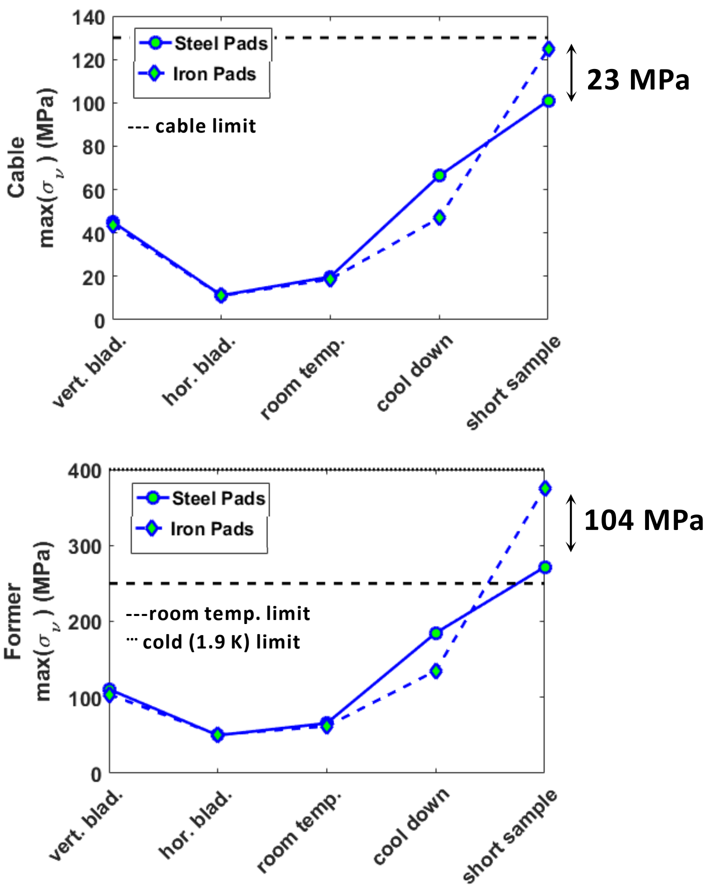
- **Nominal Design vs. Material Properties**
- Mechanical tolerances
- Parametric Study
- Conclusions

Pads: Steel vs. Iron

Von Mises (σ_v) maximum stresses

cable and former for the 5 load steps



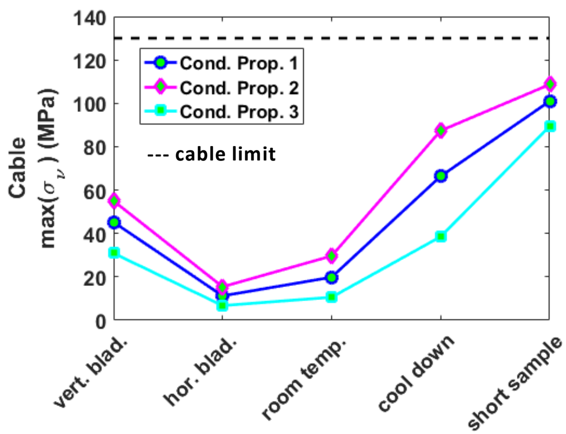
Why steel instead of iron

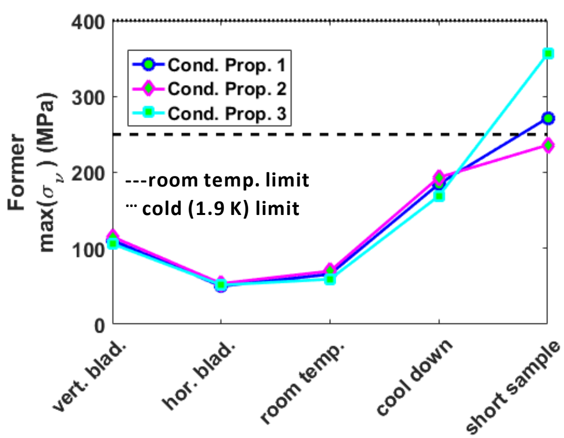
- Thermal contraction of steel higher than iron
- Thermal contraction of steel much closer to the one for the coil pack
- For the iron pads, after cool down the differential thermal contraction gives a smaller value of pre-stress leading to higher maximum stress at operating conditions

Conductor's Mechanical Properties

Von Mises (σ_v) maximum stresses

cable and former for the 5 load steps





Mechanical Properties for comparison

Used for simulations

Cond. Prop. 1	
E (GPa)	
293 K	4.2 K
EX=33	EX=30
EY=27.5	EY25
GXY=21	GXY=21

Cond. Prop. 2	
E (GPa)	
293 K	4.2 K
EX=54	EX=54
EY=44	EY=44
GXY=21	GXY=21

Cond. Prop. 3	
E (GPa)	
293 K	4.2 K
EX=14	EX=14
EY=7.74	EY=7.74
GXY=21	GXY=21

The only remarkable differences are

- **7.7 MPa higher peak stress for Cond. Prop.2 on the cable at short sample operating condition**
- **85 MPa higher peak stress for Cond. Prop.3 on the former at short sample operating condition**

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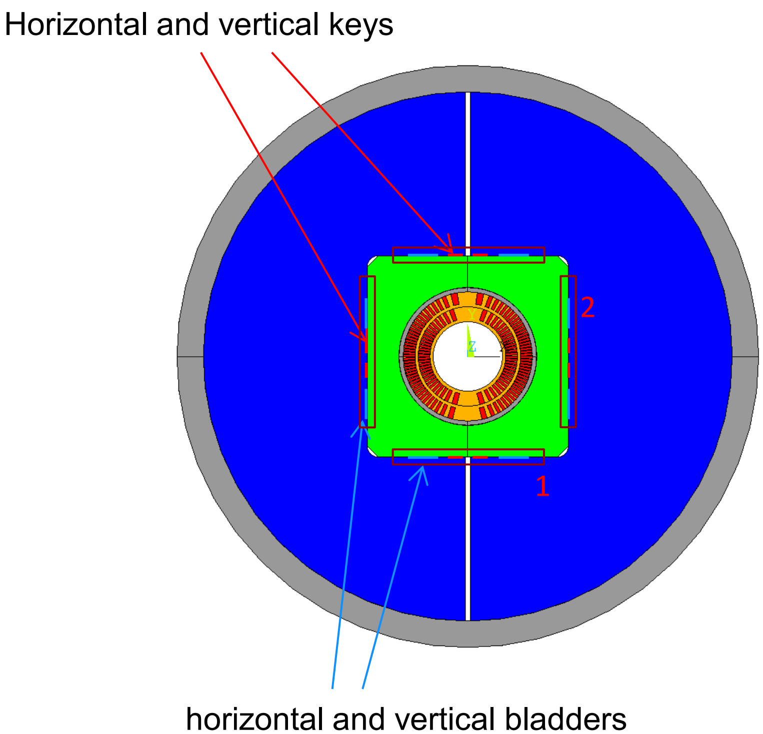
Mechanical Tolerances

Tolerances of interest:

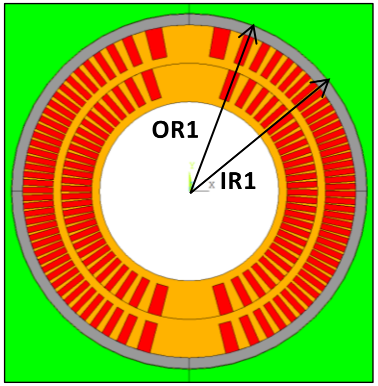
- Mismatch between radii of coil and pads assemblies (OR1-IR2) ≠ 0 (**coil/pad radial**)
- Horizontal key tolerance (**hor. key**)
- Vertical key tolerance (**vert. key**)
- Pad/pad interface contact (**pad/pad cont.**)

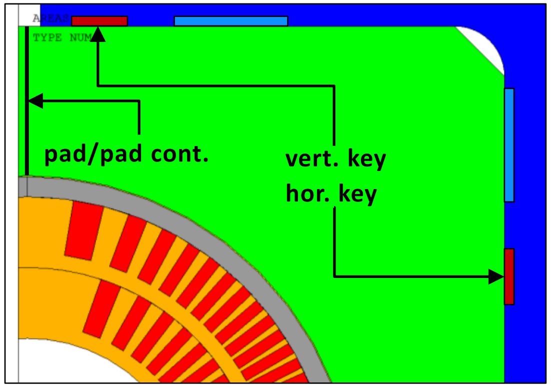
Use ANSYS contact technology

- (**coil/pad radial**) < 0 → gap
- (**coil/pad radial**) > 0 → compression
- **(hor. or vert. key)** < 0 → undersize key
- **(hor. or vert. key)** > 0 → oversize key
- (**pad/pad cont.**) < 0 → undersize pads
- (**pad/pad cont.**) > 0 → oversize pads



Coil pack





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Parametric study and design's objective

- **Use a ± 100 µm tolerance on the parameters of interest with a 50 µm step (five values for each parameter, reasonable computation time)**
- **Nominal values of the parameters**
  - coil/pad radial gap equals to 0.0 mm
  - hor. key interference of 0.3 mm
  - vert. key interference of 0.0 mm
  - pad/pad contact gap equal to 0.0 mm
- **For any combination of the parameters tolerances:**
  - **Maximum stress on the conductor below 130 MPa**
  - **Maximum stress on the former below 250 MPa at room temp and 400 MPa. at 1.9 K**
  - **The pad/pad interface has to be in contact during all the operating conditions.**

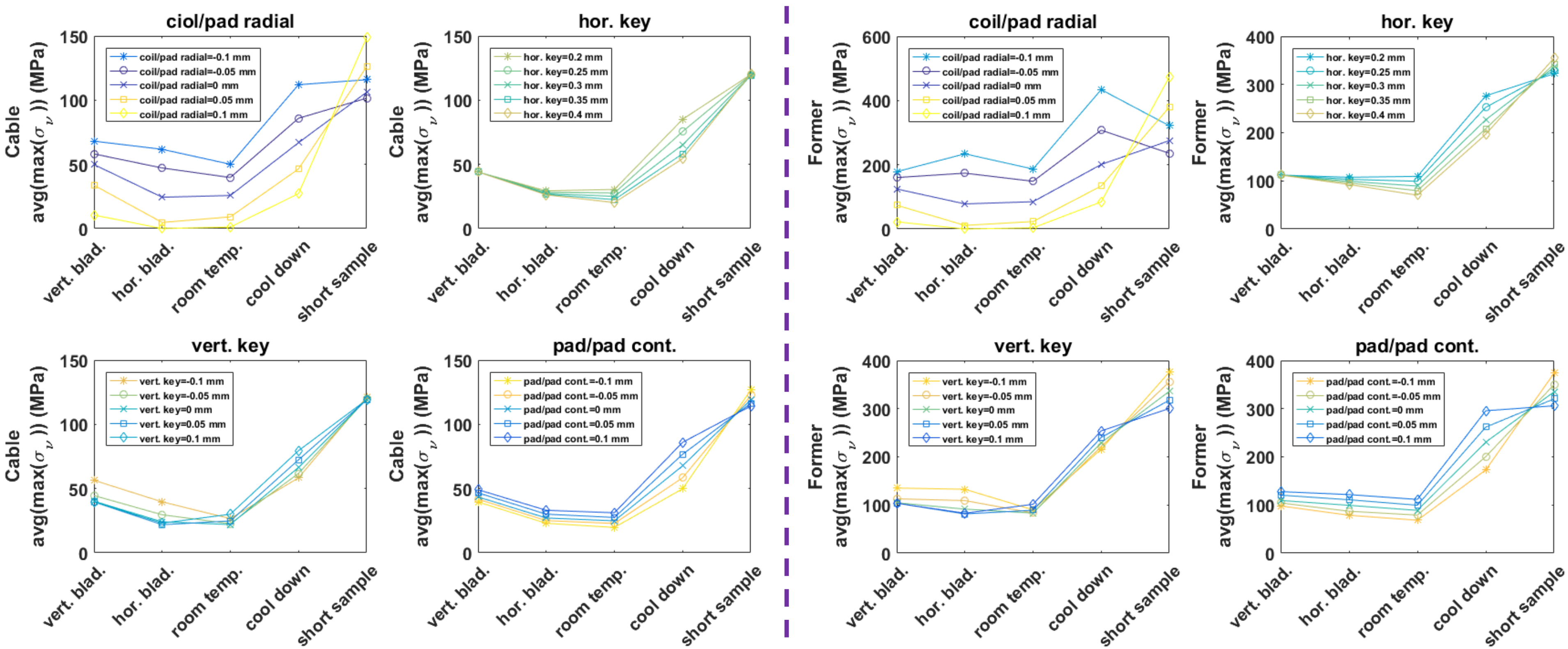
- **If any of the maximum allowed stresses on the conductor and on the former are exceeded, the parameters combination is considered to be harmful for the magnet operation**

- **A pad/pad interface not in contact during all the steps**

Sensitivity to Parameters
One-factor-at-the-time

One-factor-at-the-time (quick check of important parameters)

- Average the stress values over all the simulations runs for a given param. value and load step
- Display the average as a function of the load step and param. value
- Color map identify the spread on the results



- Coil/pad radial mismatch has the larger influence on maximum stresses
- Horizontal and vertical keys tolerances have a minor influence
- Pad/pad contact tolerance can play a rule

We can restrict ourselves to the interactions between two parameters

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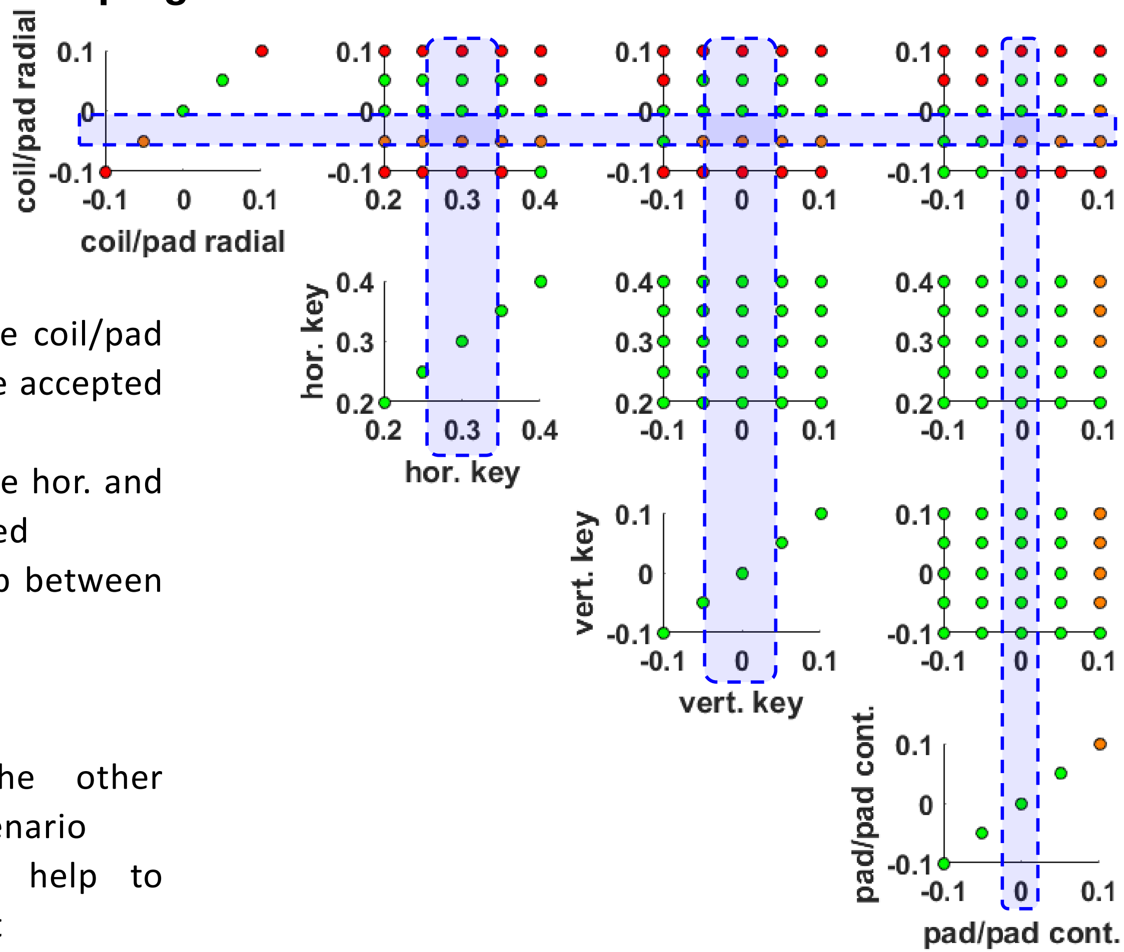
Sensitivity to Parameters
Two Parameters Analysis

Varying two parameters while keeping the others at their nominal value:

- All good
- Pad/pad interface
- Stresses values exceeded



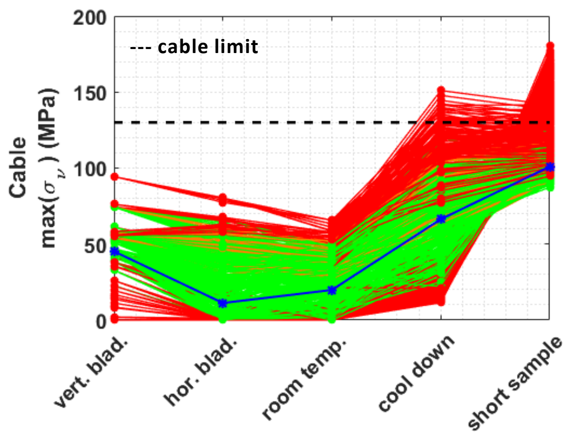
- **FIRST ROW**
  1. ± 100 µm tolerance on the coil/pad radial mismatch can not be accepted (required below 50 µm);
  2. A ± 50 µm tolerance on the hor. and vert. key must be considered
  3. Better to leave a small gap between coil and pad (≤ 50 µm)

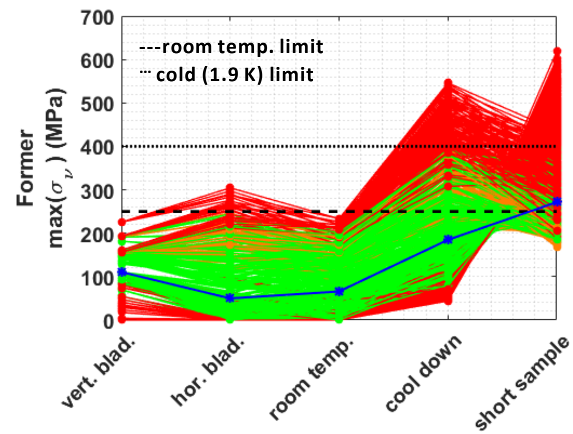
- **2nd, 3rd and 4th ROWS**
  1. Any combination of the other parameters gives a safe scenario
  2. Using tighter tolerances help to guarantee pad/pad contact

A Glance to the Overall Results

Results from full parametric study

- Within the requested limits
- Pad/pad interface contact not guaranteed (at room temp.)
- Stresses values exceeded the design limits
- Nominal design





Need to verify that tolerances from two parameters analysis allow to stay within the stress limits!

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Defining Tolerances

Target tolerances (according to the procurement of mechanical parts)

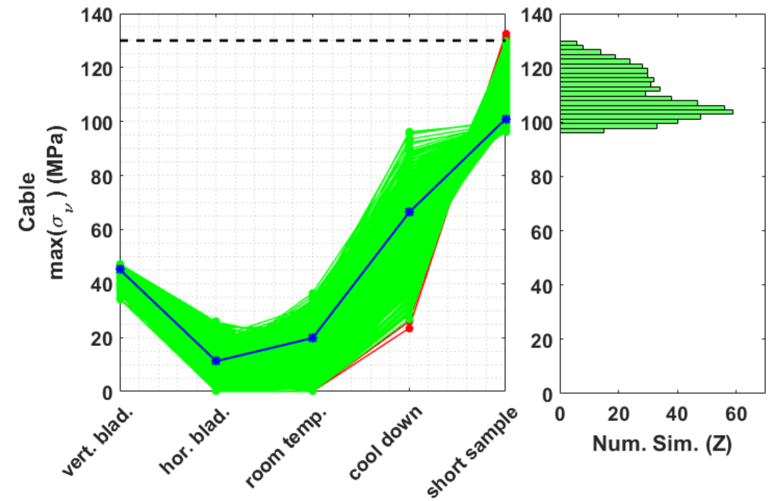
- coil/pad radial → [-40, 0] µm
- hor. key → ± 50 µm
- vert. key → ± 50 µm
- pad/pad contact → ± 25 µm

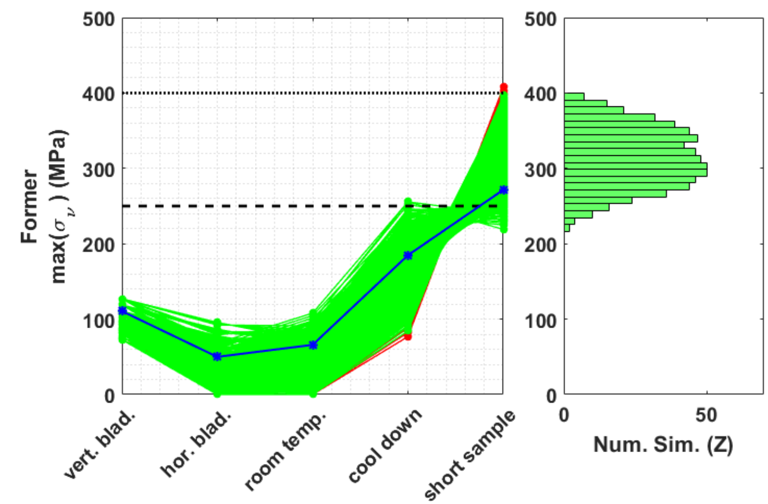
4 simulations runs above limit -by a small amount- out of 625 simulations (5 values per tolerance):

coil/pad radial (µm)	hor. Key (µm)	vert.key (µm)	pad/pad contact(µm)	Cable (Mpa)	Former (Mpa)
-40	25	25	25	130.46	
-40	25	50	13	130.115	
-40	27.5	50	13	132.6	407.85
-40	27.5	50	25	131.23	402.36

THIS IS NOT GOING TO BE A PROBLEM: WE HAVE EXTRA MARGINS!

Results from parametric study with target tolerances





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- 2D Mechanical modelling of CD1 dipole with ANSYS
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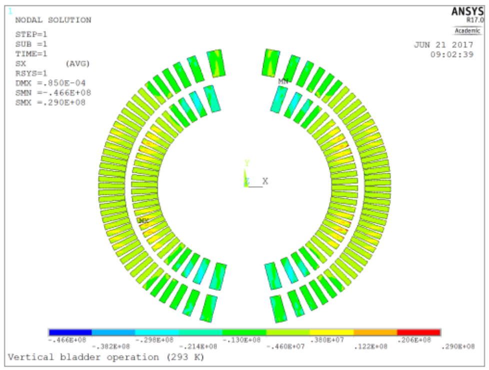
Conclusions

- **A parametric study on the 2D model of CD1 magnet is carried out**
- **Critical tolerances a parameter sensitivity is investigated**
- **Tolerances for technical design are defined**
- **Numerical Results from 2D simulations show the feasibility of the CD1 design**

CD1 - The Coil Radial Stress

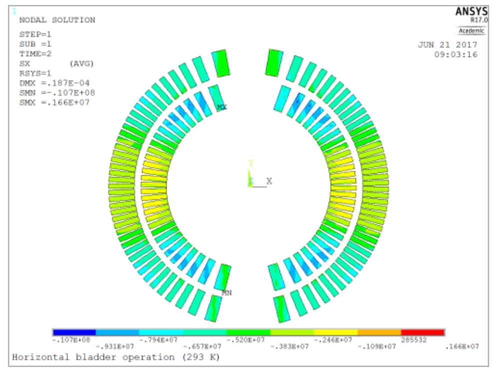
Room temp. steps (σ_r - Radial)

Vert. bladder operation



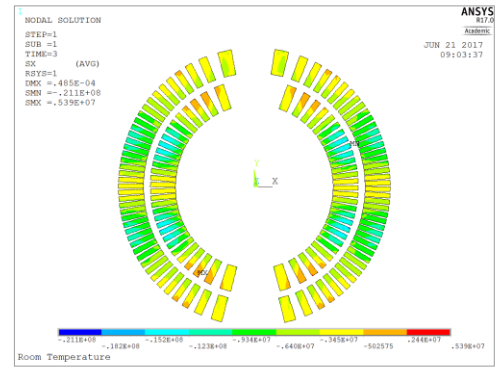
Cable σ_r = [- 46.6, 29.0] MPa

Hor. bladder operation



Cable σ_r = [-10.7, 16.6] MPa

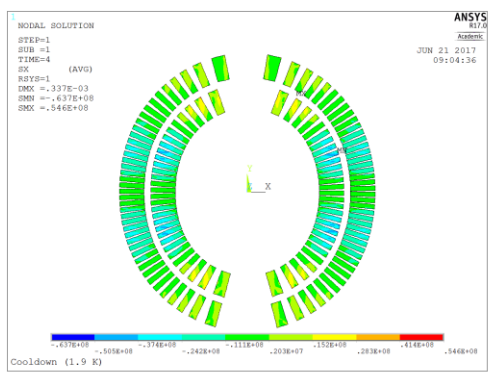
Assembly - room temp.



Cable σ_r = [-21.1, 5.3] MPa

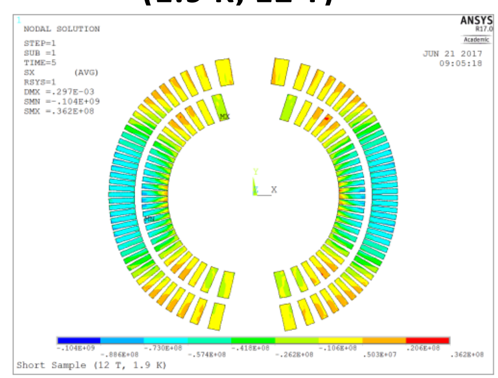
Cool down and operation steps (σ_r - Radial)

Cool down 1.9 K



Cable σ_r = [-63.7, 54.6] MPa

Operation at short sample limit (1.9 K, 12 T)



Cable σ_r = [-104.0, 36.2] MPa

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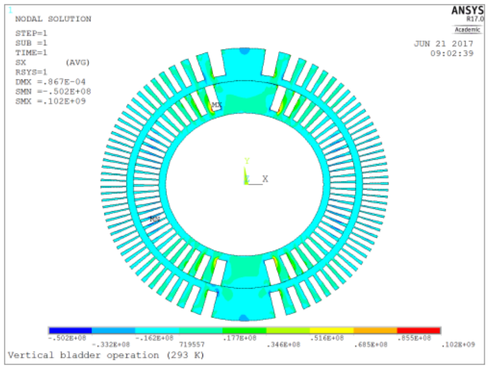
PSI

CD1 - The Former Radial Stress

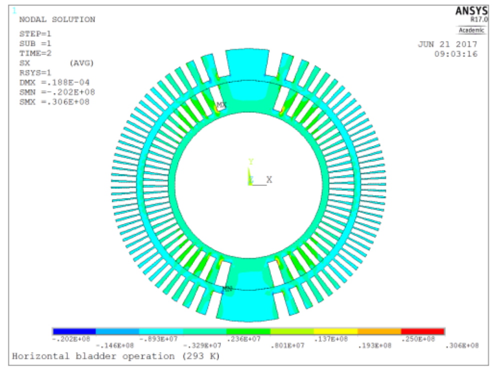
Room temp. steps (σ_r - Radial)

Vert. bladder operation



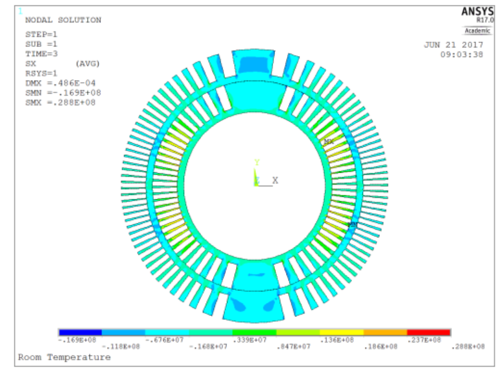
Former σ_r= [-50.2, 102.0] MPa

Hor. bladder operation



Former σ_r = [- 20.2, 30.6] MPa

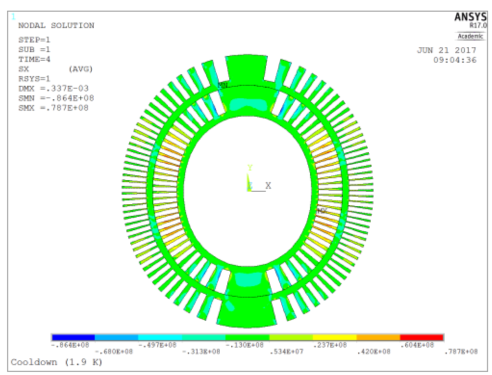
Assembly - room temp.



Former σ_r = [-16.9, 28.8] MPa

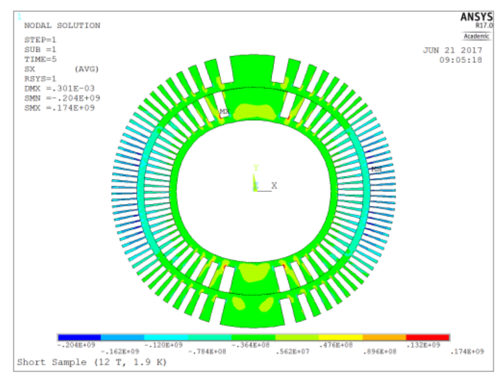
Cool down and operation steps (σ_r - Radial)

Cool down 1.9 K



Former σ_r = [-86.4, 78.7]MPa

Operation at short sample limit (1.9 K, 12 T)



Former σ_r = [-204.0, 174.0]MPa

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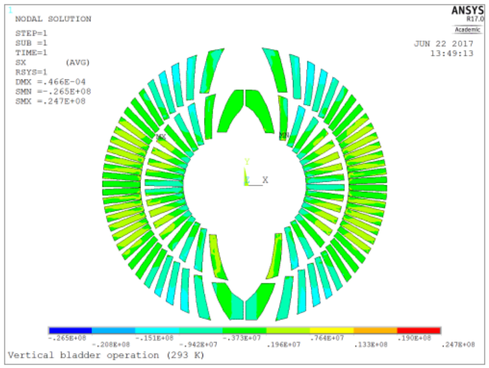
CD2 - The Coil Radial Stress

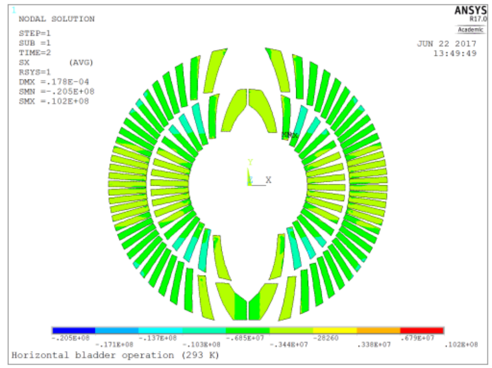
Room temp. steps (σ_r - Radial)

Vert. bladder operation



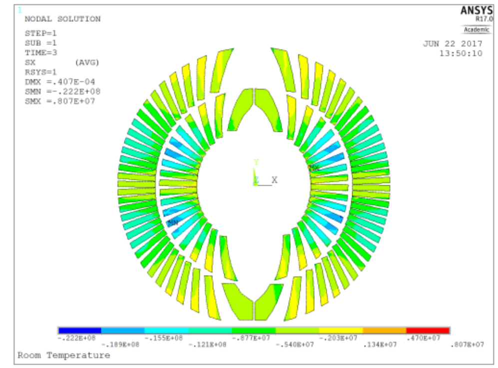
Cable σ_r = [-26.5, 24.7] MPa

Hor. bladder operation



Cable σ_r = [- 20.5, 10.2] MPa

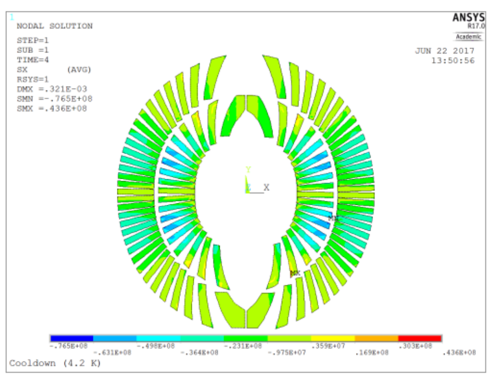
Assembly - room temp.



Cable σ_r = [-22.2, 8.7] MPa

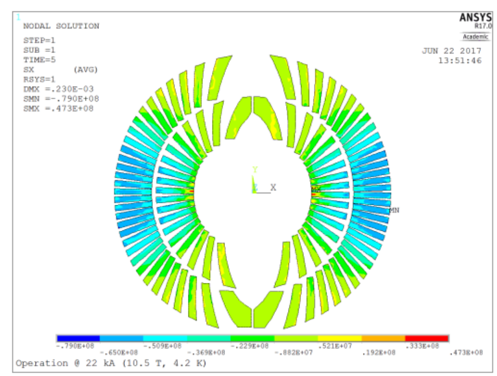
Cool down and operation steps (σ_r - Radial)

Cool down 4.2 K



Cable σ_r = [-76.5, 43.6] MPa

Operation at short sample limit (4.2 K, 10.5 T)



Cable σ_r = [-79.0, 47.3] MPa

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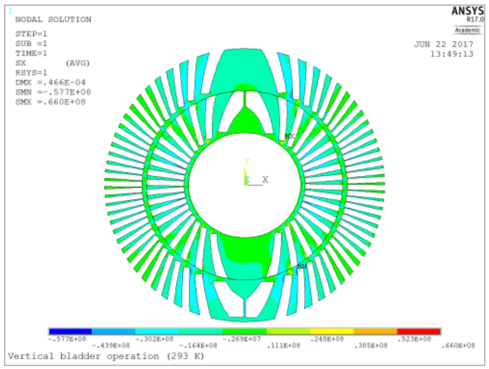
CD2 - The Former
Radial Stress

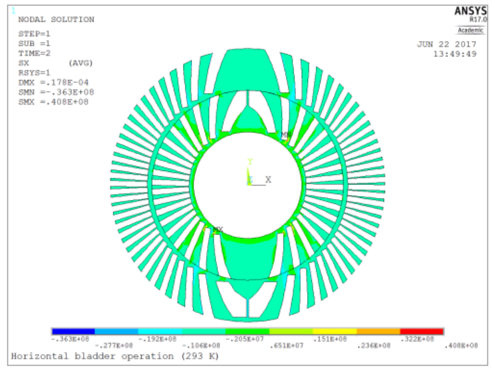
Room temp. steps (σ_r - Radial)

Vert. bladder operation



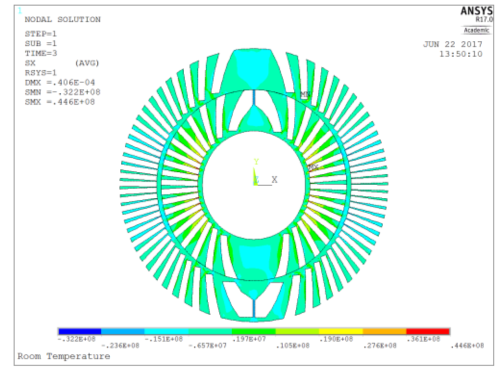
Cable σ_r = [-57.7, 66.0] MPa

Hor. bladder operation



Cable σ_r = [- 36.3, 40.8] MPa

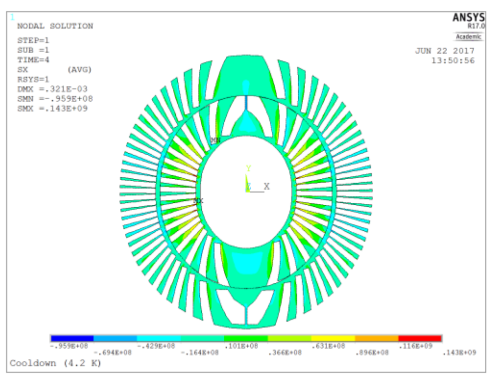
Assembly - room temp.



Cable σ_r = [-32.2, 44.6] MPa

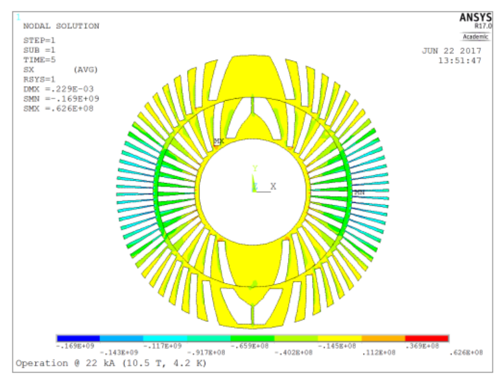
Cool down and operation steps (σ_r - Radial)

Cool down 4.2 K



Cable σ_r = [-95.9, 143.0] MPa

Operation at short sample limit (4.2 K, 10.5 T)



Cable σ_r = [-169.0, 62.6] MPa