# EuroCirCol Cosθ 16 T dipole

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# Outlook



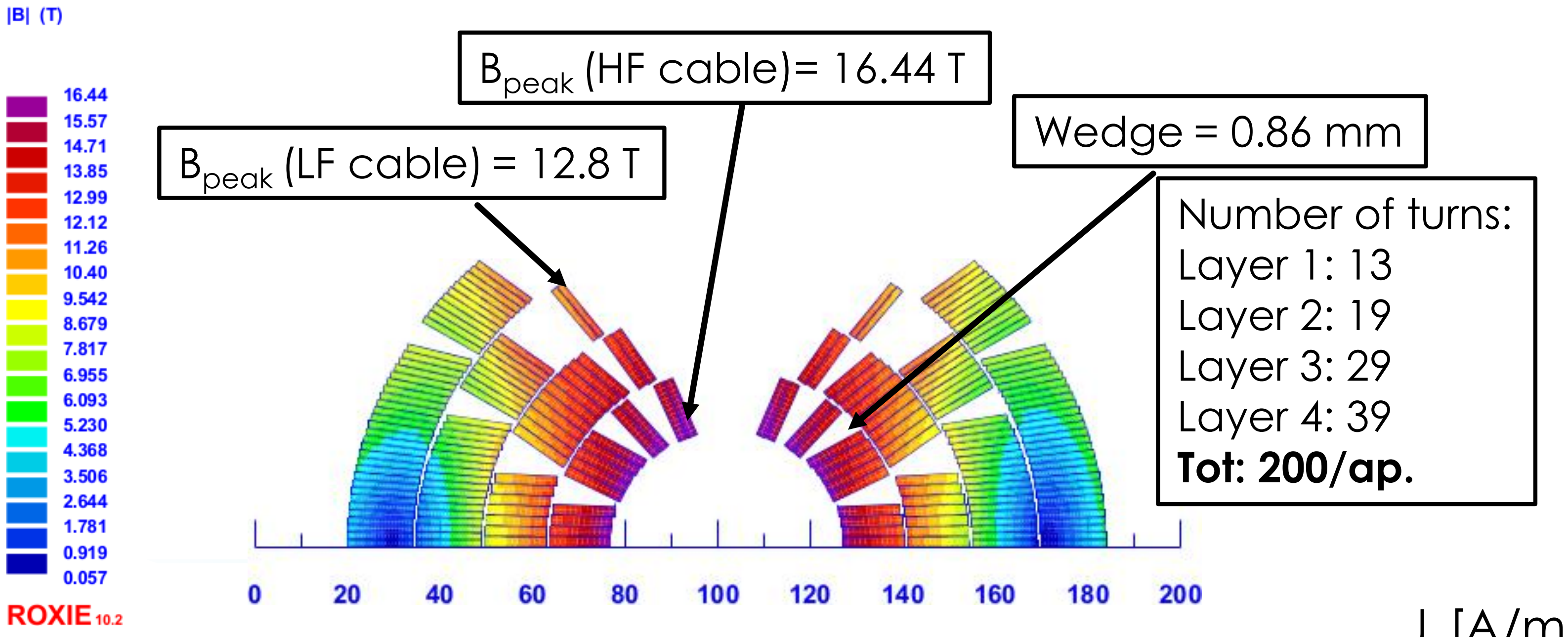
- Magnetic design
  - 2D and 3D magnetic model
  - Field qualty & peak field
- Mechanical design
  - VM stress
  - Contact pressure to the pole
  - Preliminary 3D mechanical design
- Conclusions and Future Work

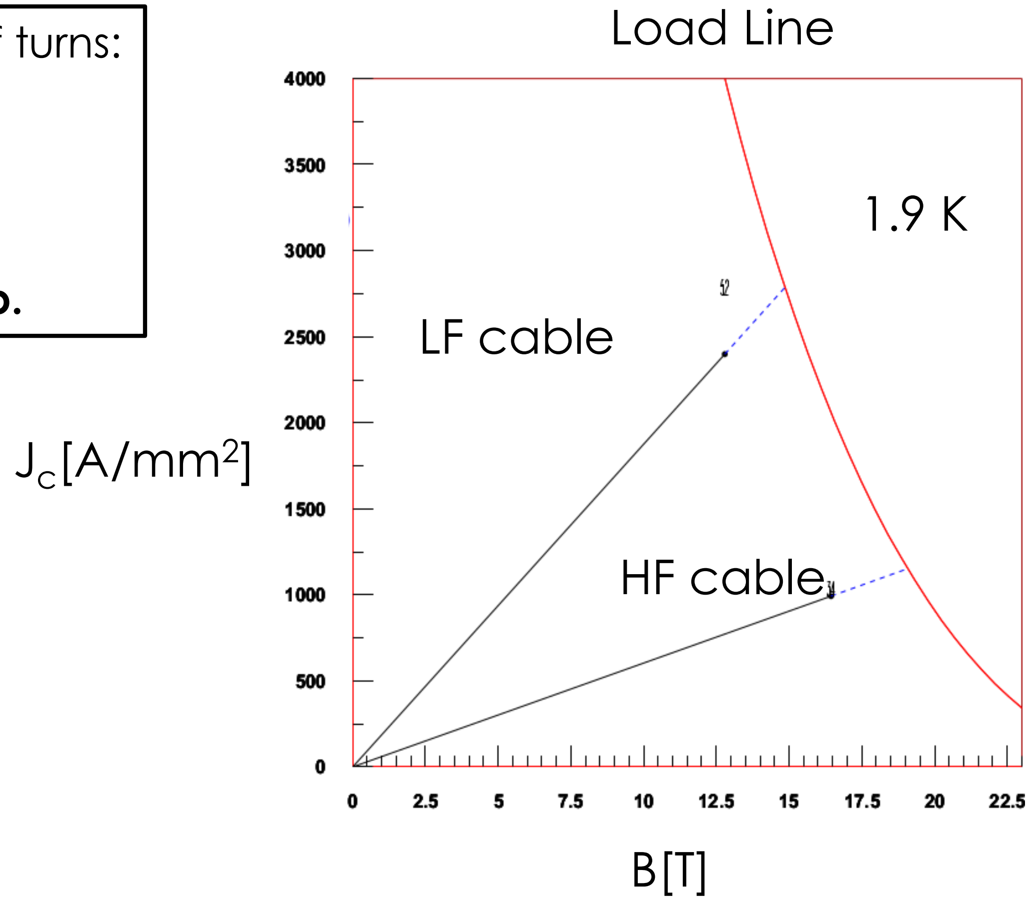
# Design parameters



| Constraints for the magnet design | |
|---|---|
| Bore inner diameter | 50 mm |
| Beam distance | 204 mm |
| Material | $Nb_3Sn$ |
| Bore nominal field | 16 T |
| Operating temperature | 1.9 K |
| Operation on the load line | 86 % |
| Maximum strand number per cable | 40 |
| Cable insulation thickness | 0.15 mm |
| Cu/NCu | $\geq$ 0.85 |
| Field harmonics (geometric/saturation) | $\leq$ 3/10 units |
| Yoke outer radius | 300 mm |

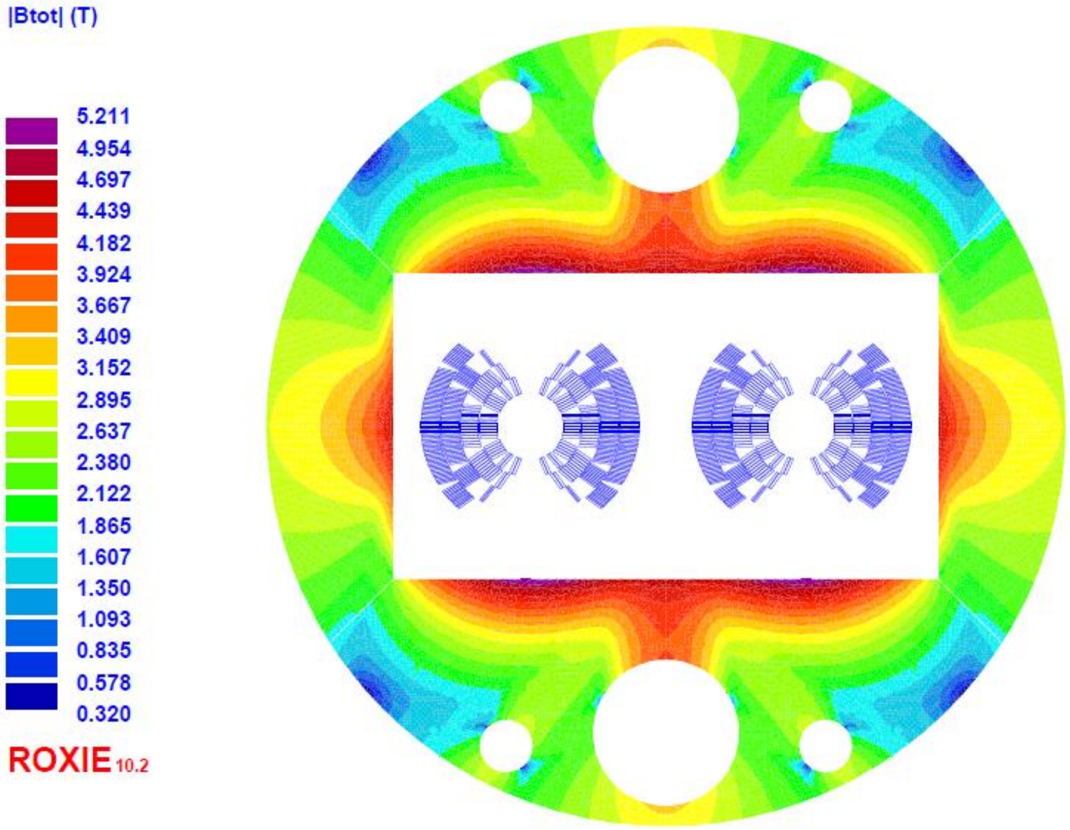
# Magnetic model



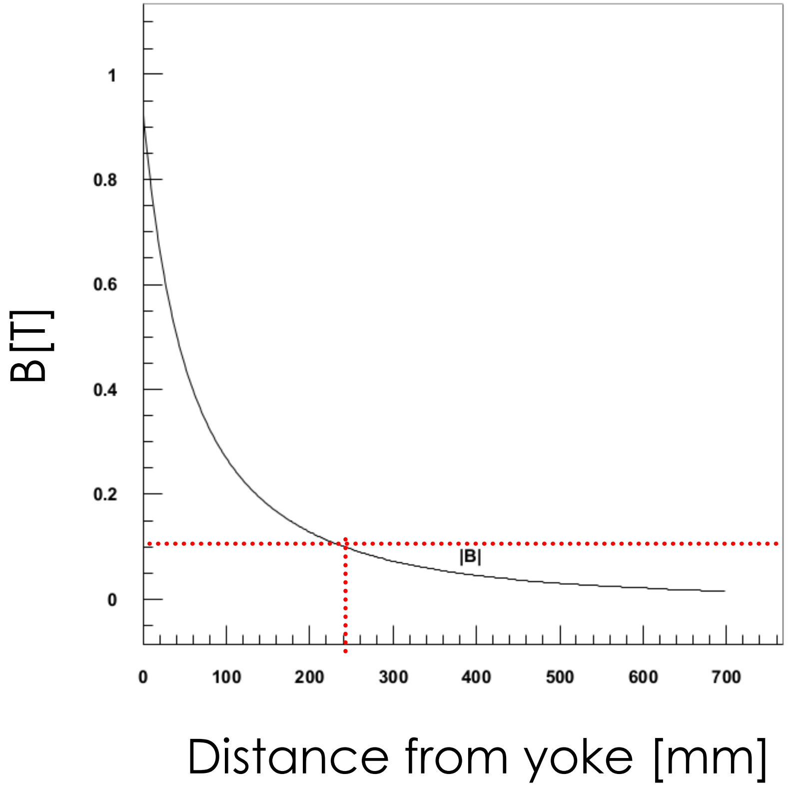




| | HF Cable (inner) | LF Cable (outer) |
|---|---|---|
| Strand number | 22 | 38 |
| Strand diameter | 1.1 mm | 0.7 mm |
| Bare width | 13.2 mm | 14 mm |
| Bare inner thickness | 1.892 mm | 1.204 mm |
| Bare outer thickness | 2.007 mm | 1.3261 mm |
| Insulation | 0.15 mm | 0.15 mm |
| Keystone angle | 0.5° | 0.5° |
| Cu/Ncu | 0.82 | 2.1 |
| Operating current | 11390 A | 11390 A |
| Operating point on LL (1.9 K) | 86 % | 86 % |

# Magnetic model

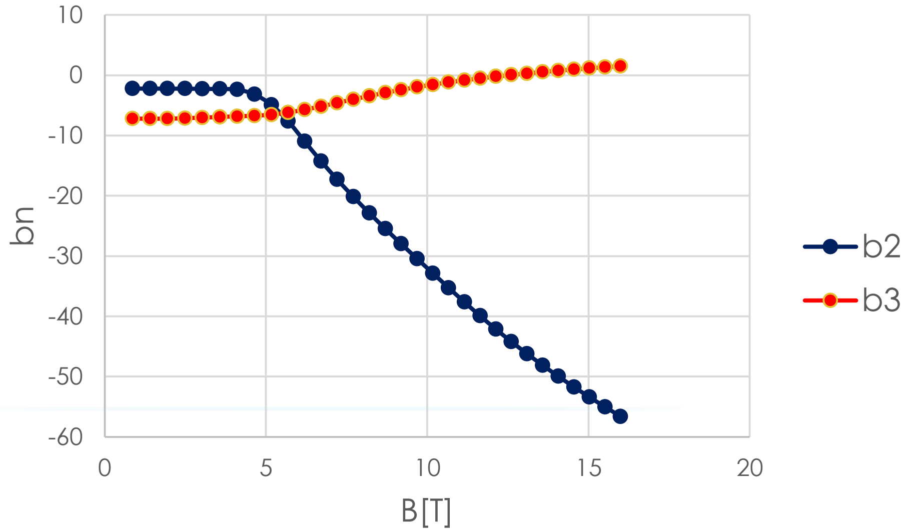


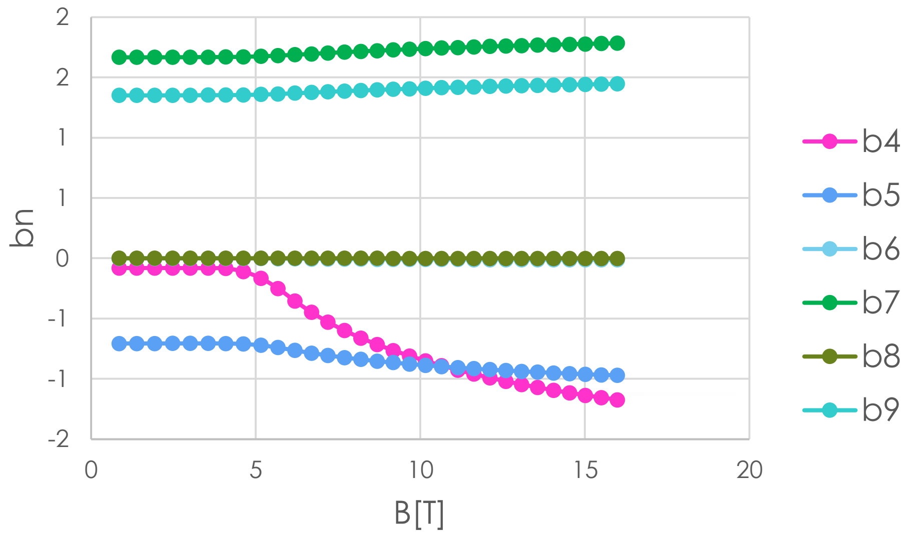

Fringe field along r




Outer yoke radius: 300 mm
B=0.1 T @ 245 mm from the yoke
(545 mm from the center)

# Field Quality (geometrical + iron saturation)



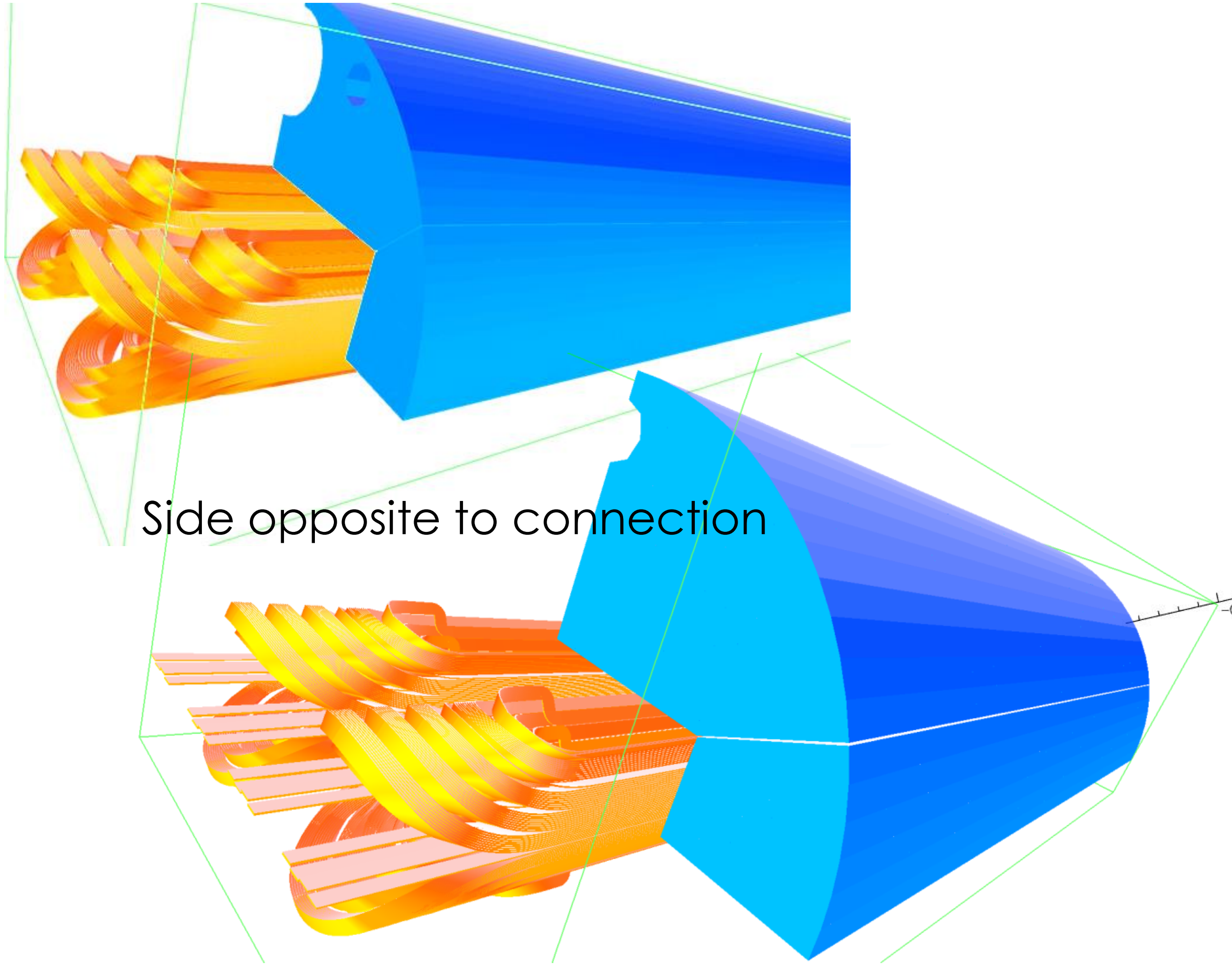

| B | b2 | b3 | b4 | b5 | b6 | b7 | b8 | b9 |
|---|---|---|---|---|---|---|---|---|
| 16T | -56.6 | 1.5 | 1.2 | -1.0 | -0.01 | 1.8 | -0.001 | 1.4 |

# 3D magnetic end design



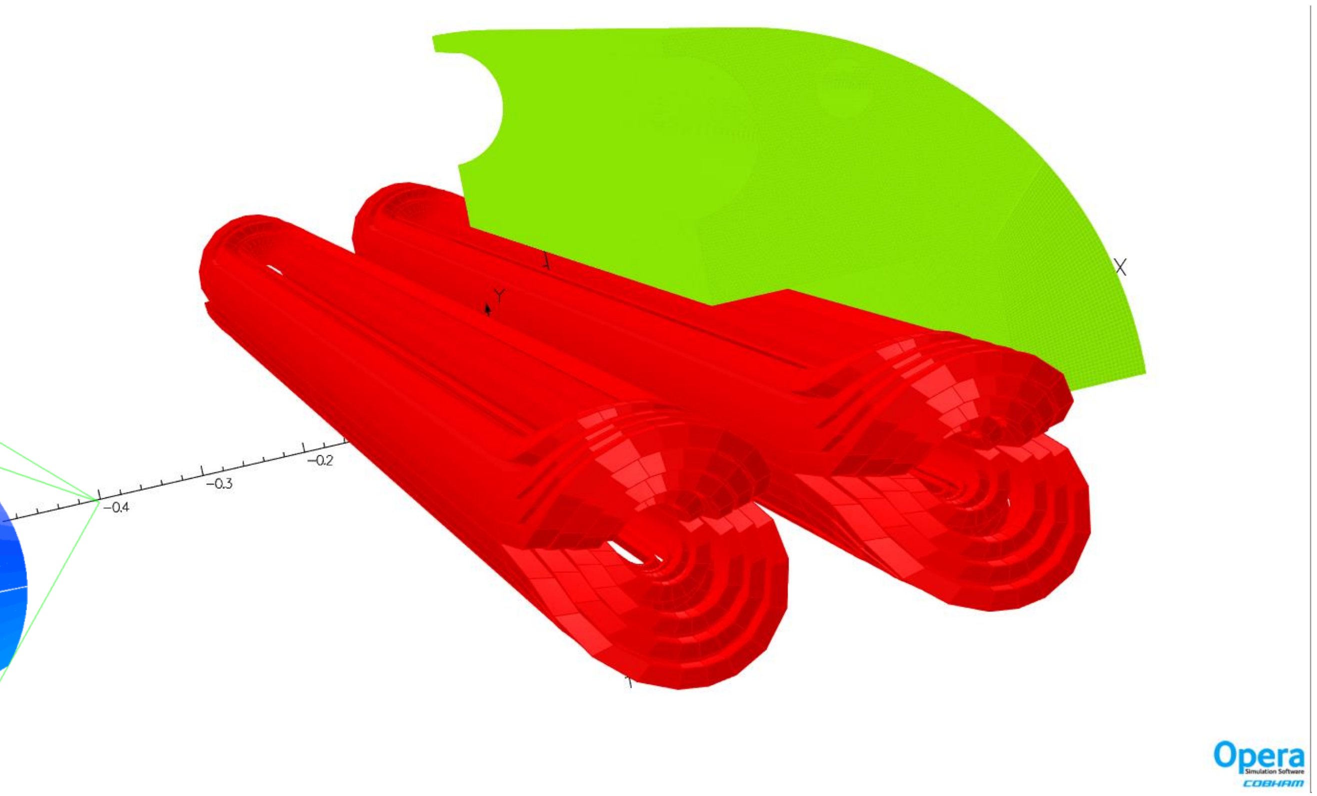
Roxie

Connection side

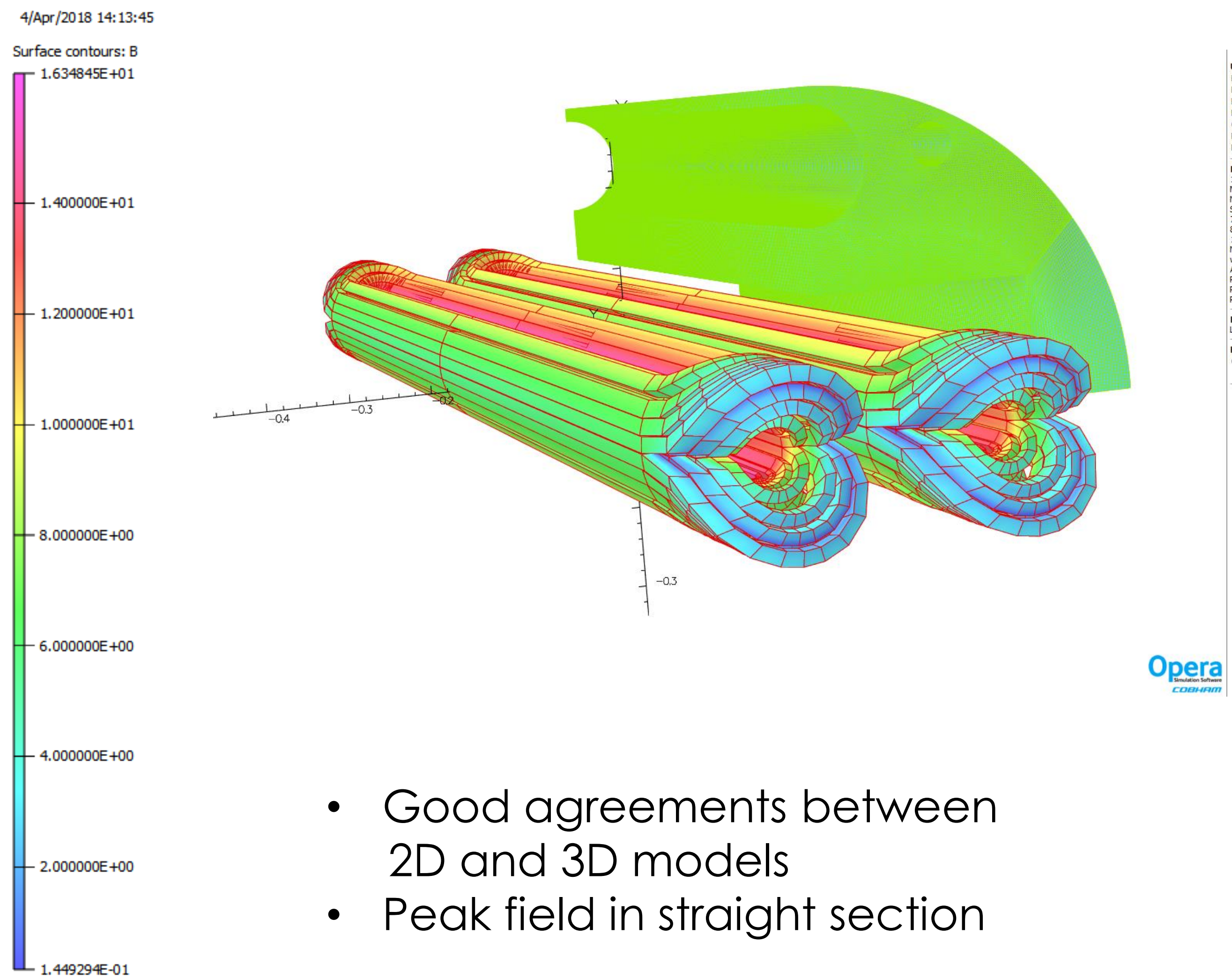


Side opposite to connection

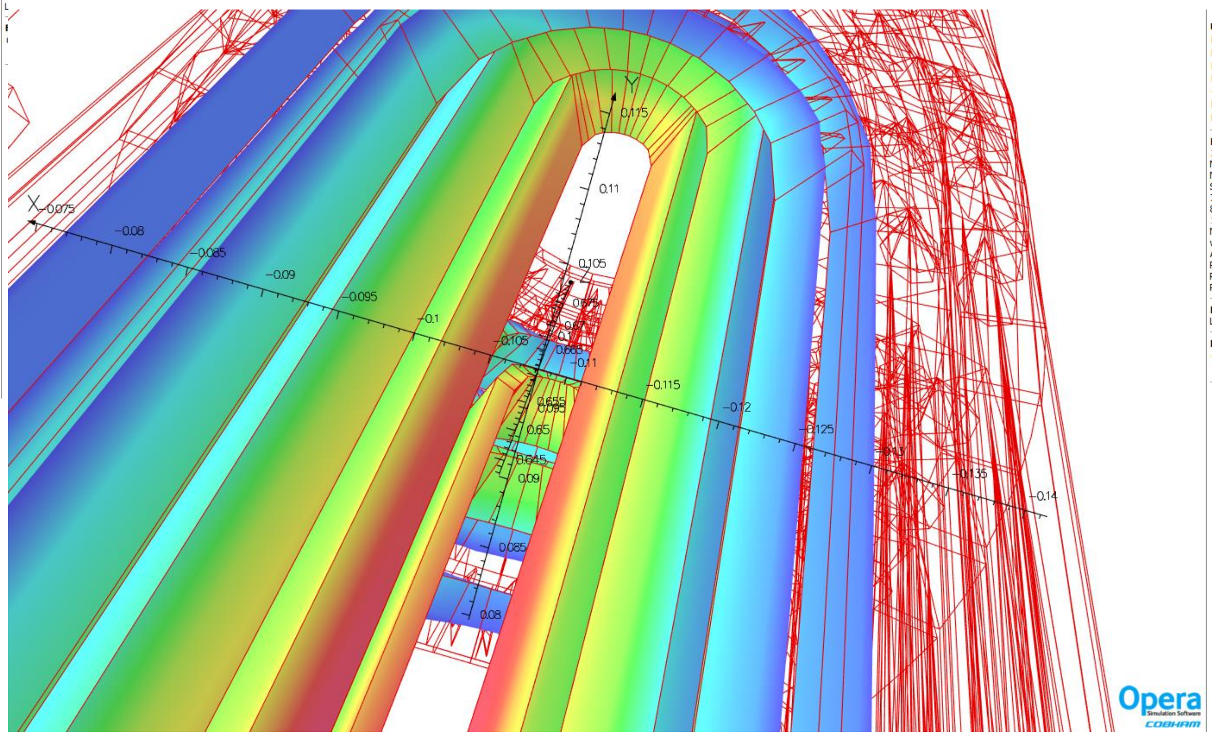
Opera



# 3D magnetic end design




$B_{peak}$ = 16.39 T (Opera)
16.44 T (Roxie 3D)
16.44 T (Roxie 2D)



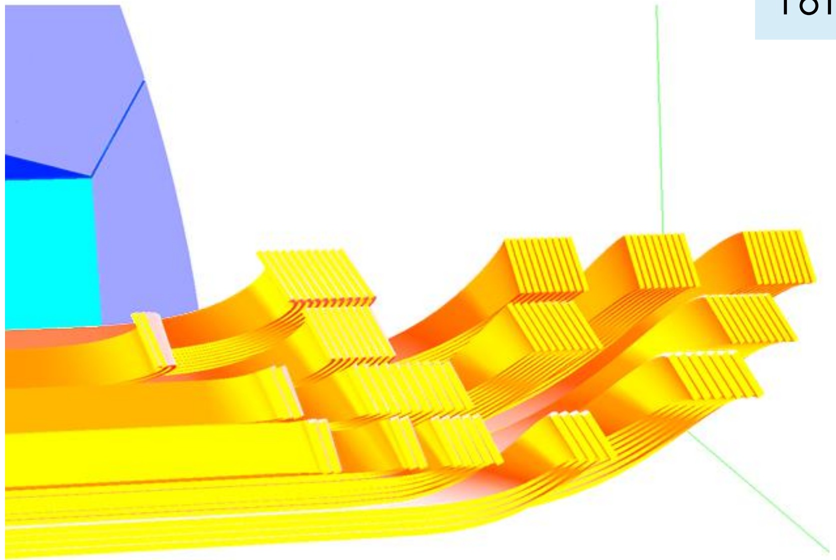

- Good agreements between 2D and 3D models
- Peak field in straight section

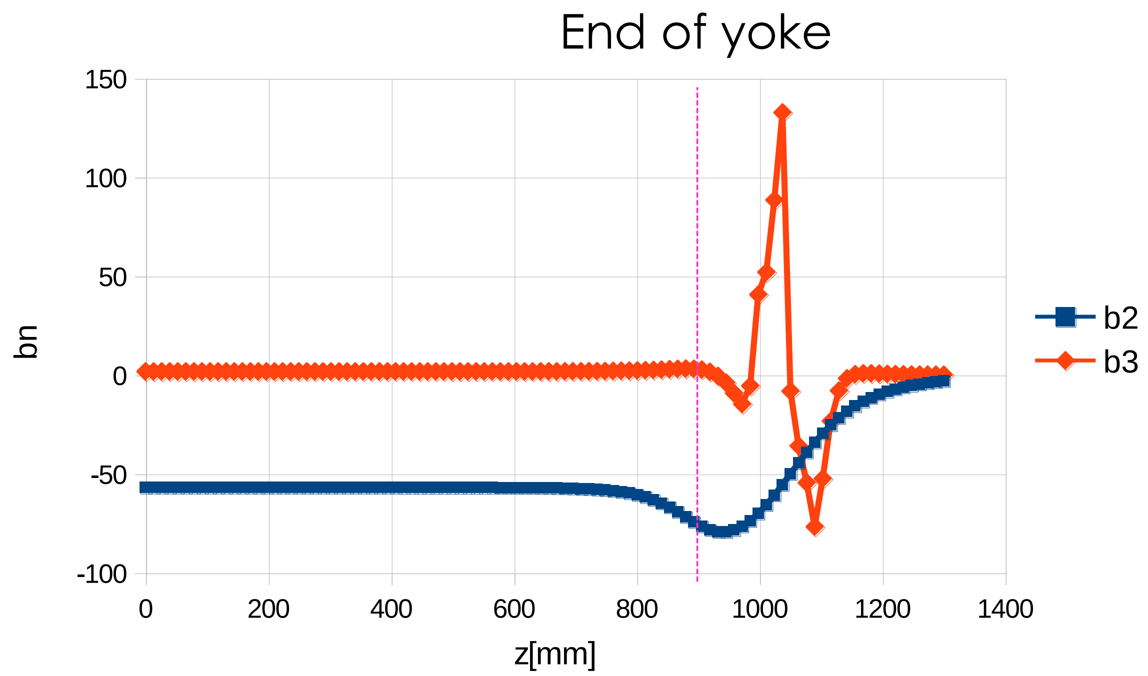
# 3D magnetic end design



NORMAL 3D INTEGRAL RELATIVE MULTIPOLES

| B | b2 | b3 | b4 | b5 | b6 | b7 | b8 | B9 |
|---|---|---|---|---|---|---|---|---|
| 16T | -65.3 | 2.1 | -1.2 | -0.6 | -0.01 | 1.7 | -0.0002 | 1.4 |






Iron Length: 890 mm
Magnetic length:1032 mm
Physical length: 1100 mm

# Mechanical constrains

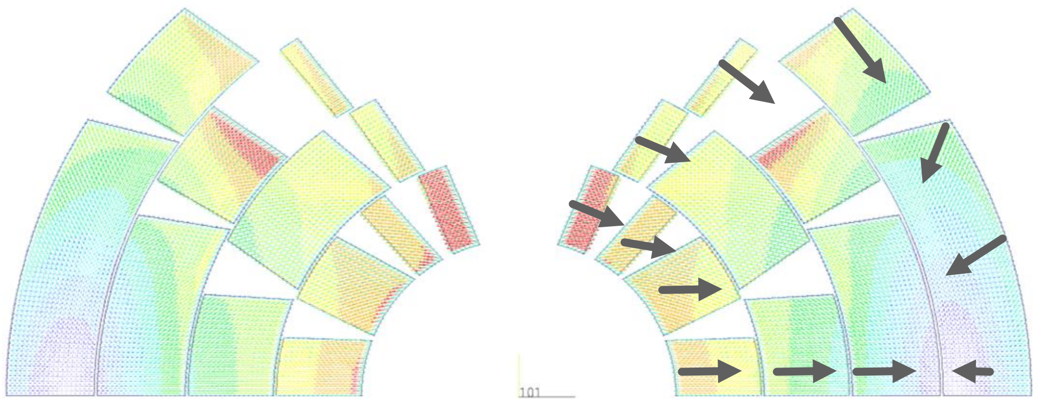


- Stress in the conductor < 150 MPa @ RT, < 200 MPa @ 1.9 K
- Stress on mechanical structure < yield strength
- No detachment between coil and pole

| MATERIAL | Stress limit [MPa] RT | Stress limit [MPa] 1.9 K | E [GPa] RT | E [GPa] 1.9 K | ν | α RT→1.9K |
|---|---|---|---|---|---|---|
| Coil | 150 | 200 | | | 0.3 | |
| Radial dir | | | 30 | 33 | | $3.1\ 10^{-3}$ |
| Azimuthal dir | | | 25 | 27.5 | | $3.4\ 10^{-3}$ |
| Austenitic steel (316LN) | 350 | 1050 | 193 | 210 | 0.28 | $2.8\ 10^{-3}$ |
| Al7075 | 480 | 690 | 70 | 79 | 0.3 | $4.2\ 10^{-3}$ |
| Ferromagnetic iron | 230 | 720 | 213 | 224 | 0.28 | $2.0\ 10^{-3}$ |
| Ti6Al4V | 800 | 1650 | 115 | 126 | 0.3 | $1.7\ 10^{-3}$ |

# Lorentz Forces



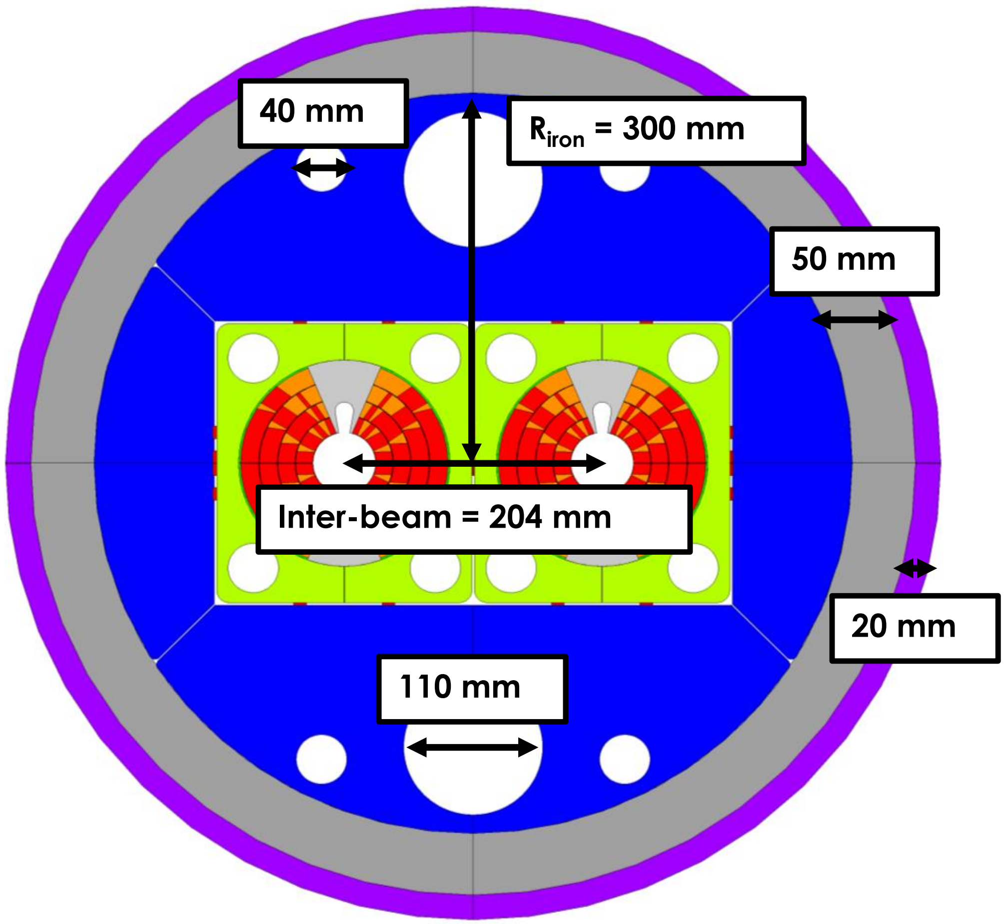



| RH | FX sum (MN) | FY sum (MN) | Fθ sum (MN) | σθ sum (MPa) |
|---|---|---|---|---|
| 1 | 2,1 | -0,1 | -1,2 | -90,5 |
| 2 | 2,3 | -0,5 | -1,6 | -120,4 |
| 3 | 2,0 | -1,1 | -1,8 | -125,9 |
| 4 | 0,3 | -2,0 | -2,1 | -145,8 |
| Total RH | 6,8 | -3,7 | -6,7 | -118,0 |
| **LH** | **FX sum (MN)** | **FY sum (MN)** | **Fθ sum (MN)** | **σθ sum (MPa)** |
| 1 | -2,1 | -0,2 | 1,3 | -92,9 |
| 2 | -2,4 | -0,6 | 1,7 | -125,9 |
| 3 | -2,2 | -1,2 | 2,0 | -136,9 |
| 4 | -0,7 | -2,3 | 2,4 | -166,9 |
| Total LH | -7,4 | -4,2 | 7,3 | -127,9 |
| **total winding** | **-0,6** | **-7,9** | **0,6** | **/** |

In cosθ configuration, Lorentz forces push the coil:

- Outward in the radial direction
- Toward the midplane in the azimuthal direction

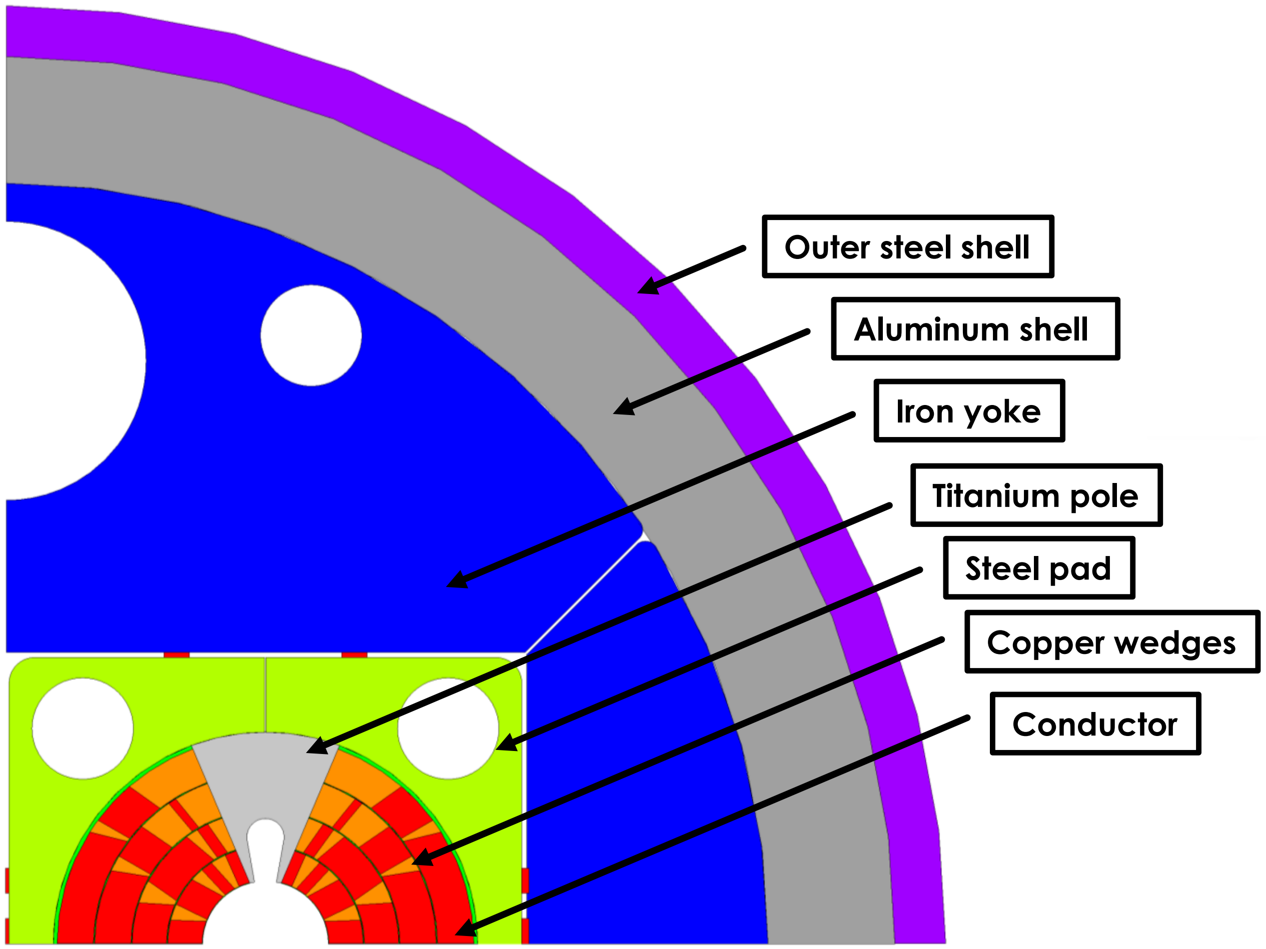
# Cosθ mechanical layout



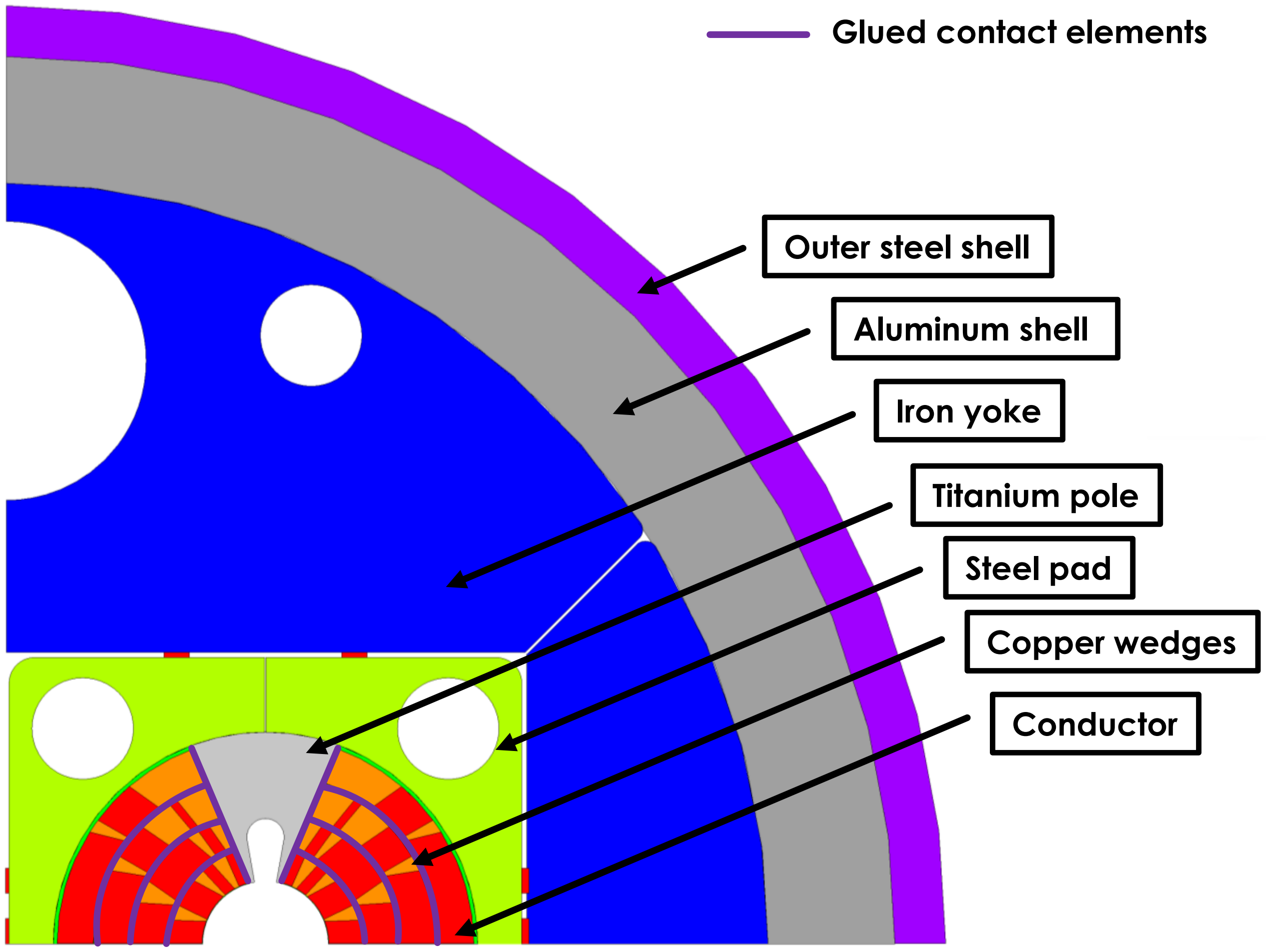

- Yoke outer diameter: 600 mm
- Al alloy shell thickness: 50 mm
- SS shell thickness: 20 mm
- Outer magnet diameter: 740 mm
- Inter-beam distance: 204 mm

# ANSYS mechanical models



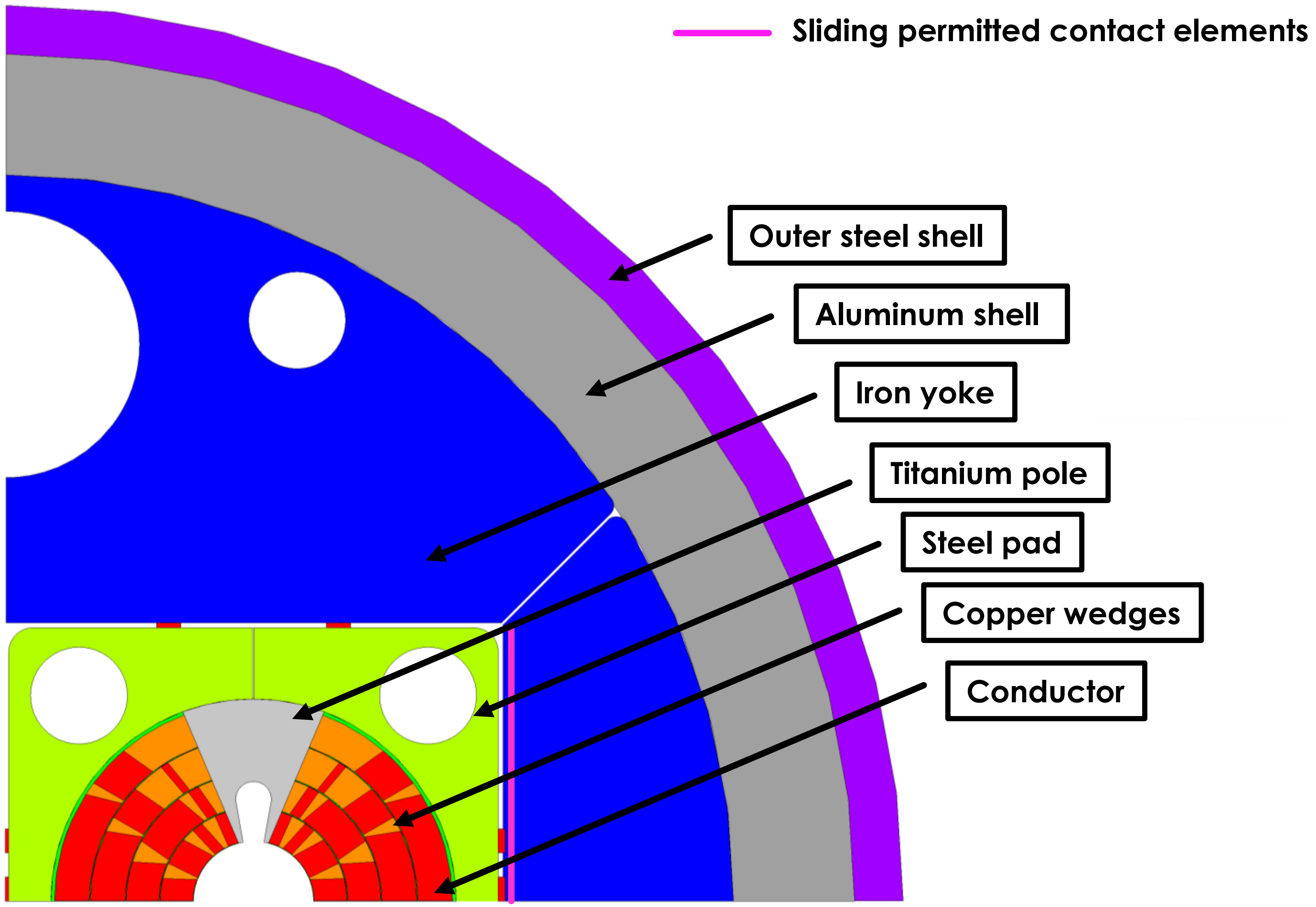


# Mechanical analysis



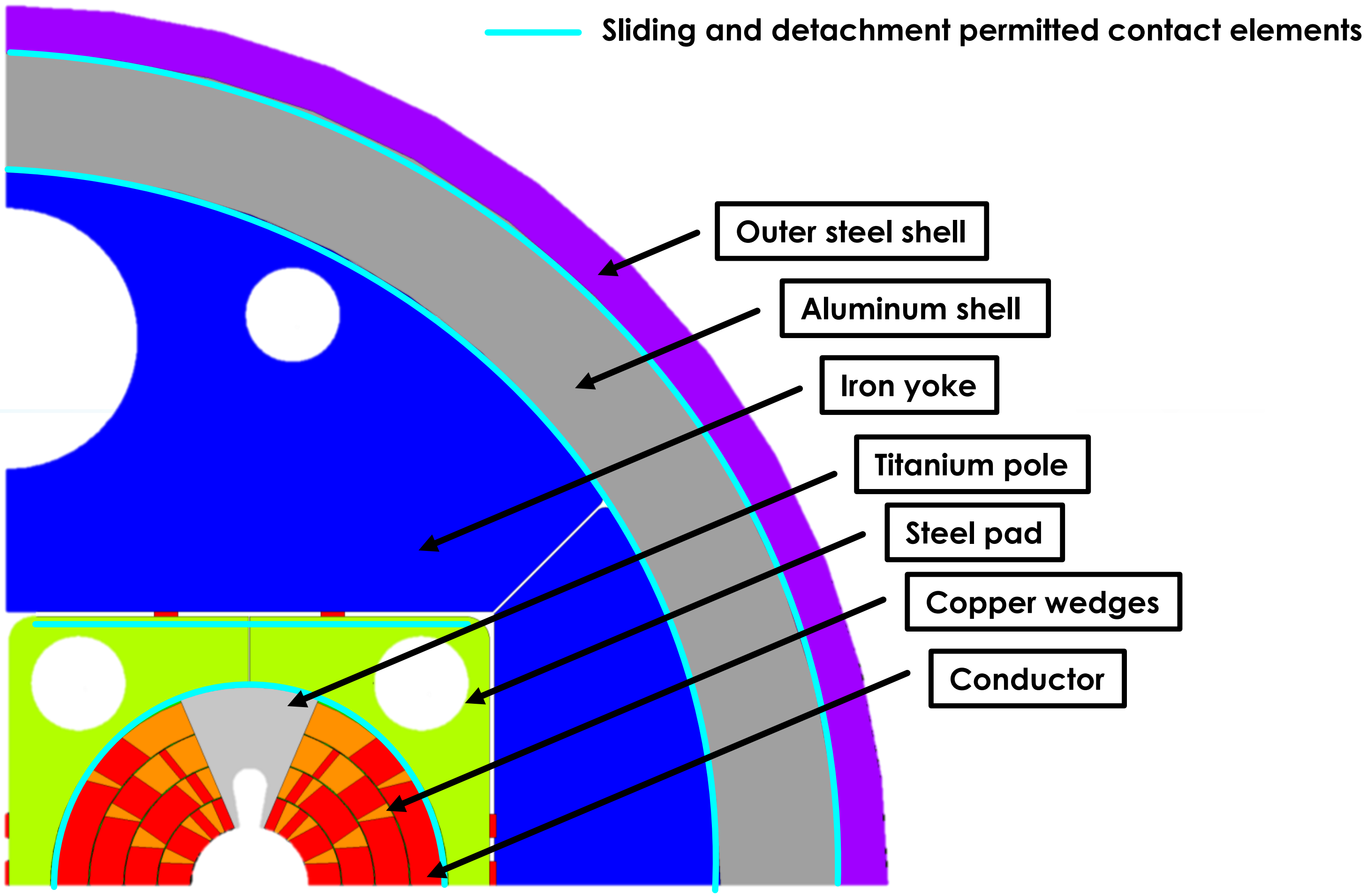
# Mechanical analysis



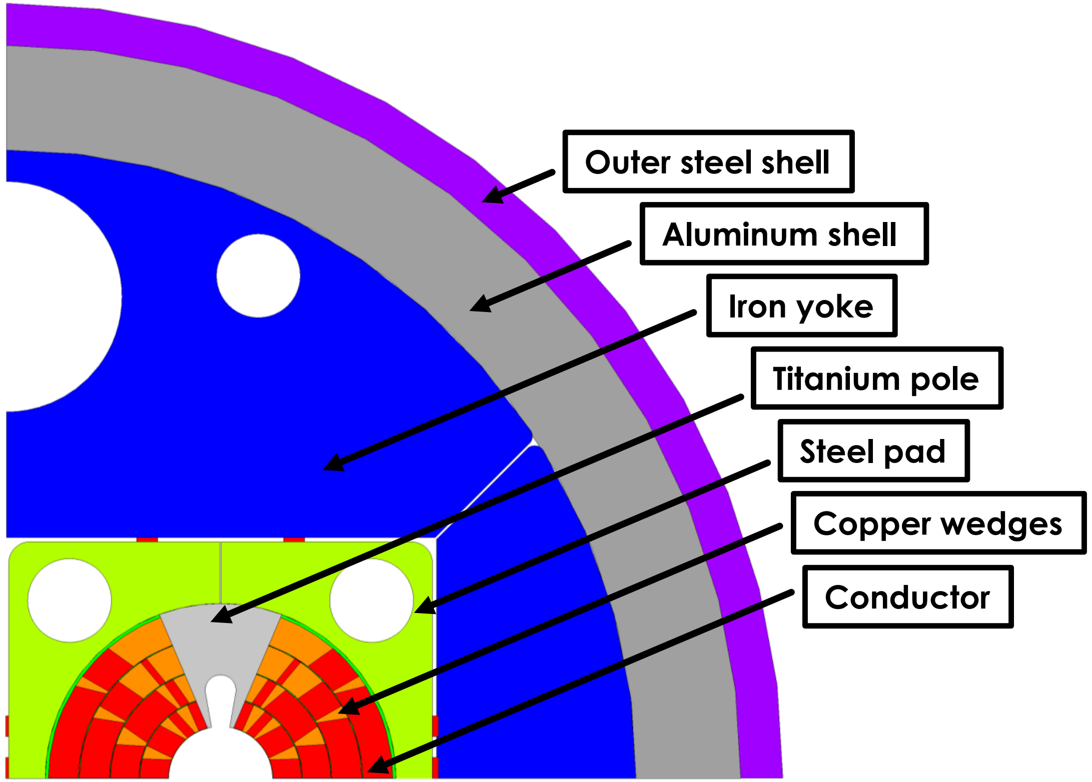


# Mechanical analysis





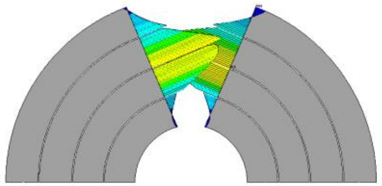
# Mechanical analysis



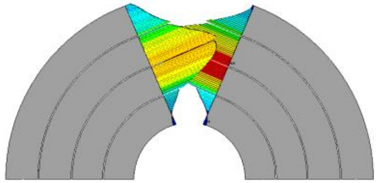

- Step 1: assembly (key insertion)
- Step 2: assembly under compression of SS shell 0.2 mm per side cut on midplane
- Step 3: cooling down
- Step 4: energization to 16 T (application of Lorentz forces to the conductor elements)

# Contact Pressure at Pole

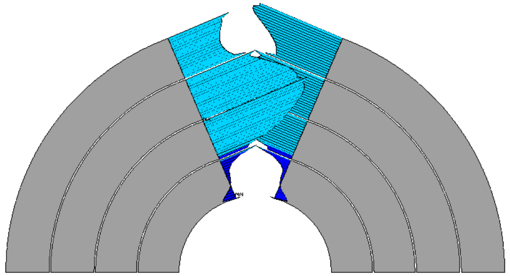
***ASSEMBLY***



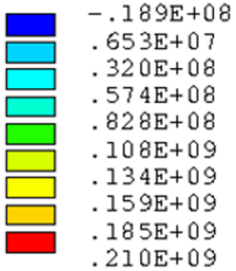
***COOL DOWN***



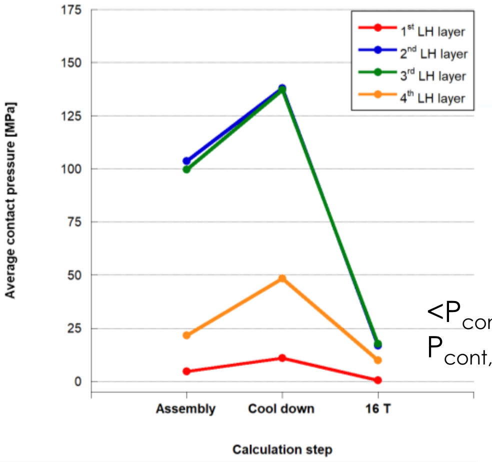
***16 T***



Contact pressure [Pa]

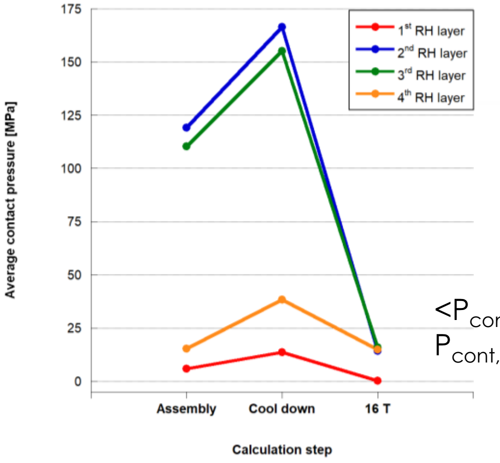



**LEFT**




$<P_{cont,1°layer}$ (16 T)$>$ = 2 MPa
$P_{cont,1°layer}$ (16 T) $|_{mid\text{-}point}$ = 1 MPa

**RIGHT**



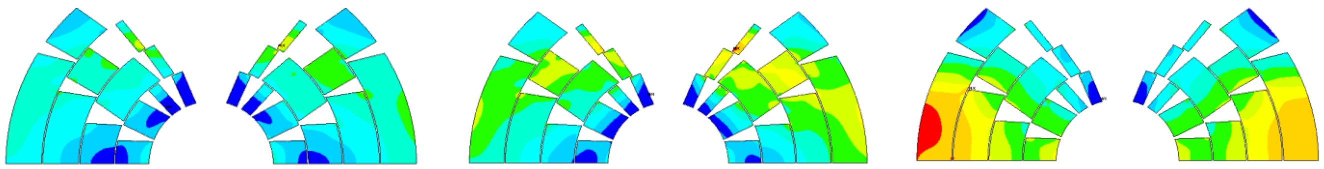

$<P_{cont,1°layer}$ (16 T)$>$ = 2 MPa
$P_{cont,1°layer}$ (16 T) $|_{mid\text{-}point}$ < 1 MPa

- Contact pressure increases after cool down (Al + SS shell shrinking)
- $P_{cont,med}$ > 0 for 1° layer after energization at 16T

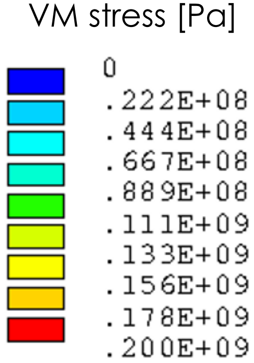
# VM stress in the conductors



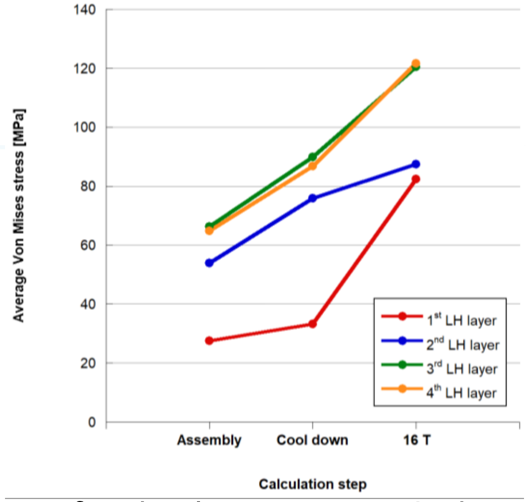
***ASSEMBLY*** ***COOL DOWN*** ***16 T***



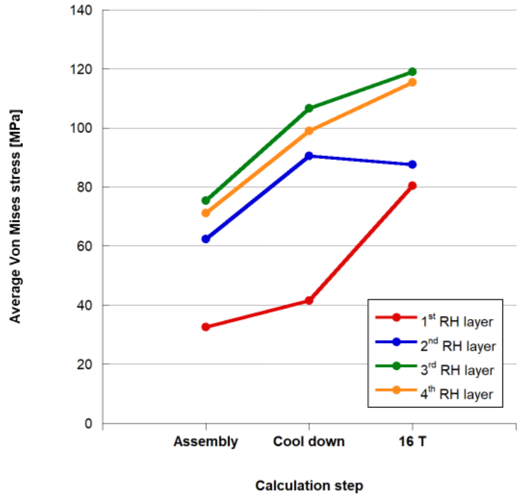
$\sigma_{VM,max}$ = 145 MPa $\sigma_{VM,max}$ = 192 MPa $\sigma_{VM,max}$ = 199 MPa




**LEFT**




**RIGHT**



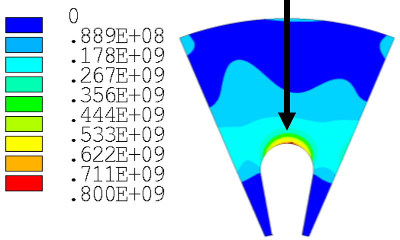

- VM stress far below current degradation limit (150 MPa @ RT -200 MPa @ 1.9K)
- Localized hot spot due to wedge edges after cooling down
- After energization, the high stress region is located in the fourth layer (low field region), VM(peak field region)< 50 MPa

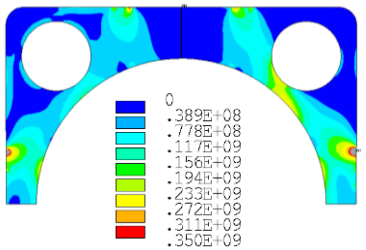
# VM stress in the mechanical structures

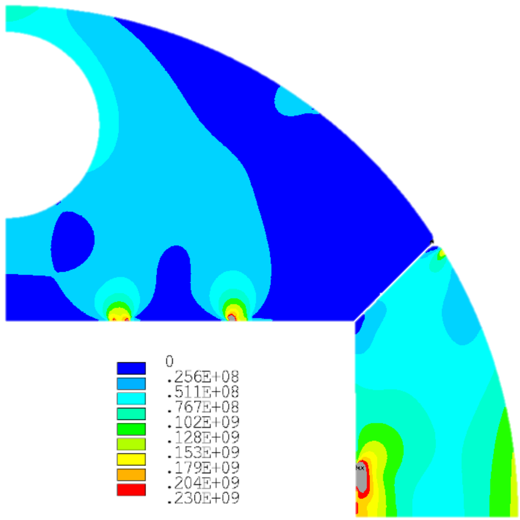
## ***ASSEMBLY***

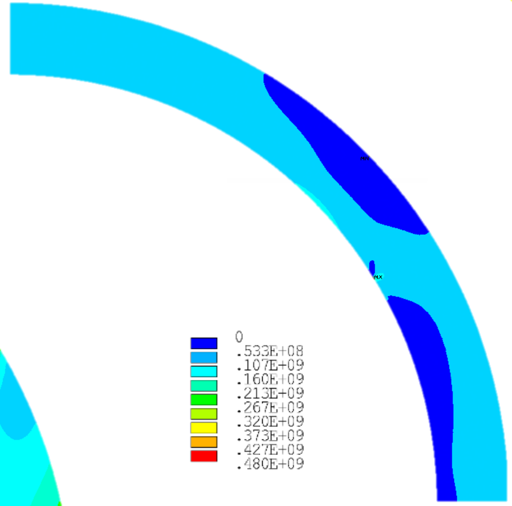
| MATERIAL | Stress limit [MPa] RT |
|---|---|
| Austenitic steel (316LN) | 350 |
| Al7075 | 480 |
| Ferromagnetic iron | 230 |
| Ti6Al4V | 800 |

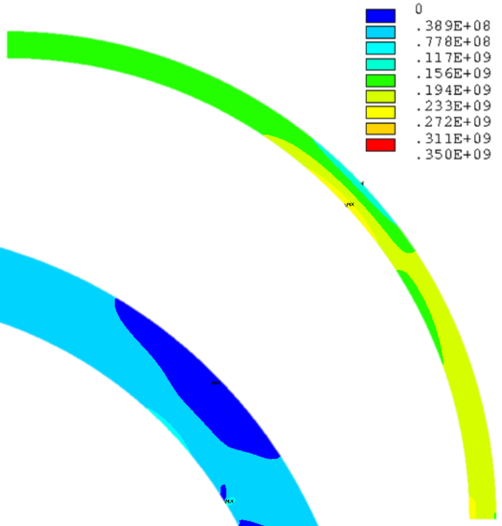
$\sigma_{VM,max} = 749$ MPa



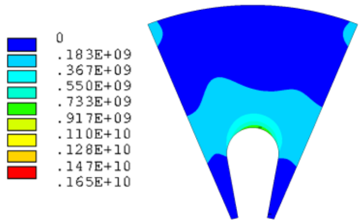



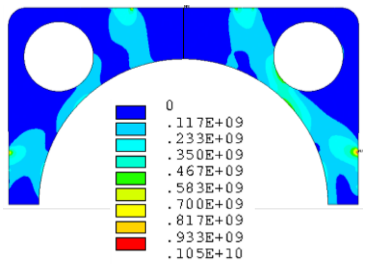



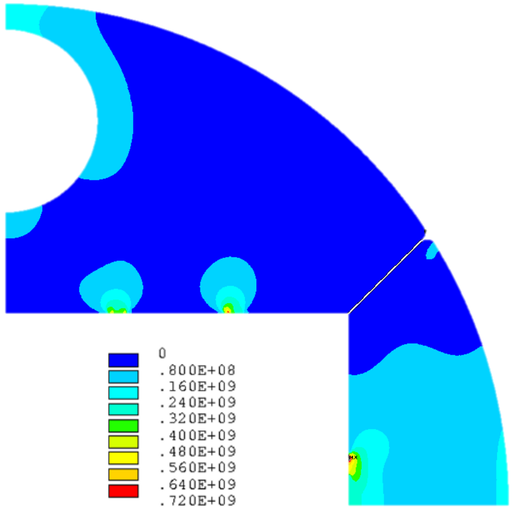
# VM stress in the mechanical structures

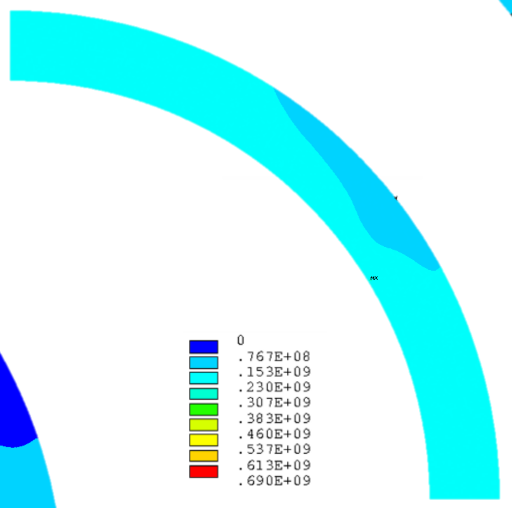
## ***COOL DOWN***

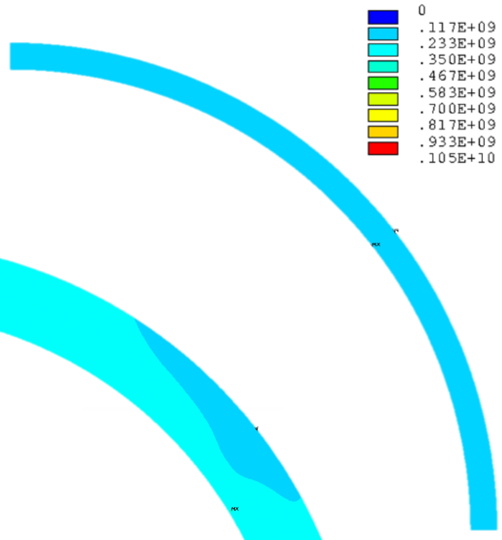
| MATERIAL | Stress limit [MPa] 1.9 K |
|---|---|
| Austenitic steel (316LN) | 1050 |
| Al7075 | 690 |
| Ferromagnetic iron | 720 |
| Ti6Al4V | 1650 |



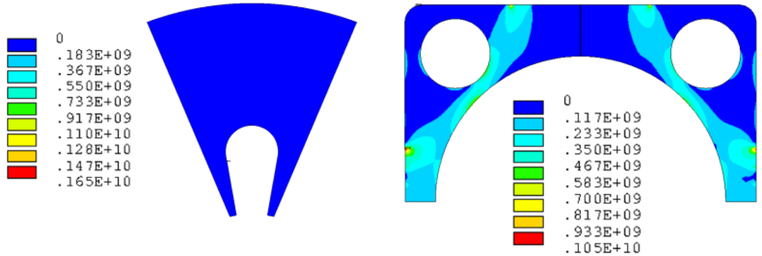



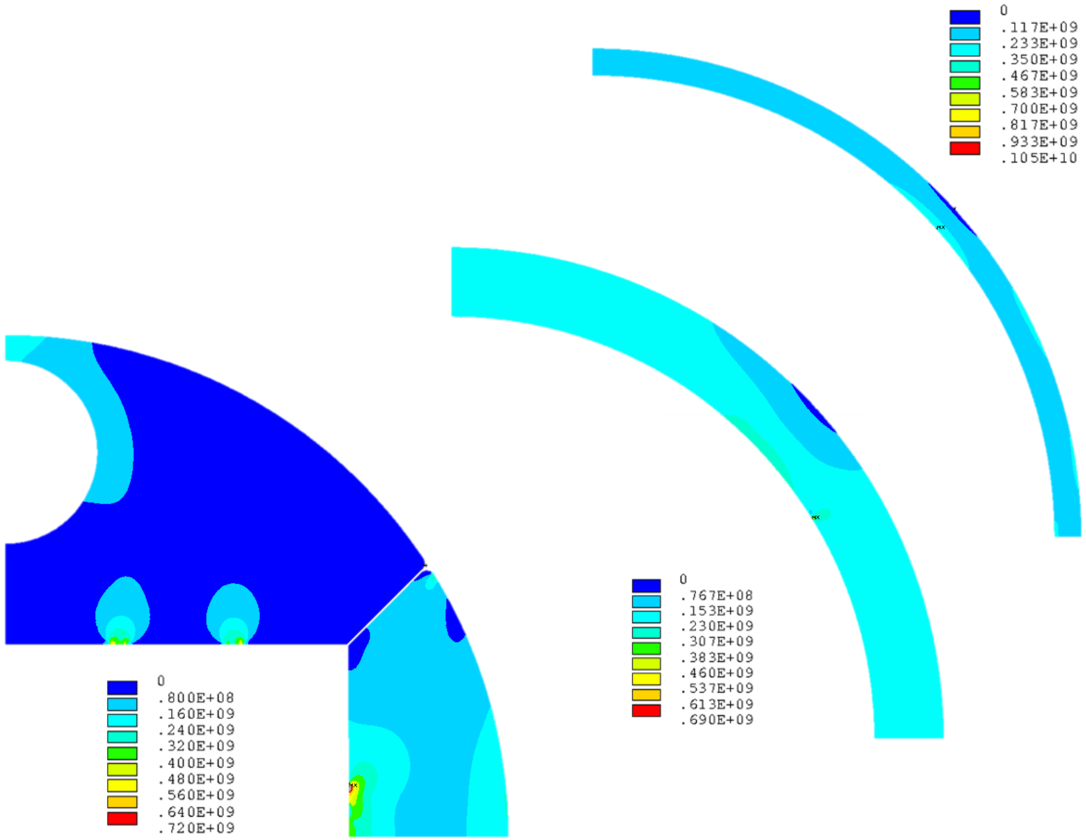



# VM stress in the mechanical structures

## ***ENERGIZATION***

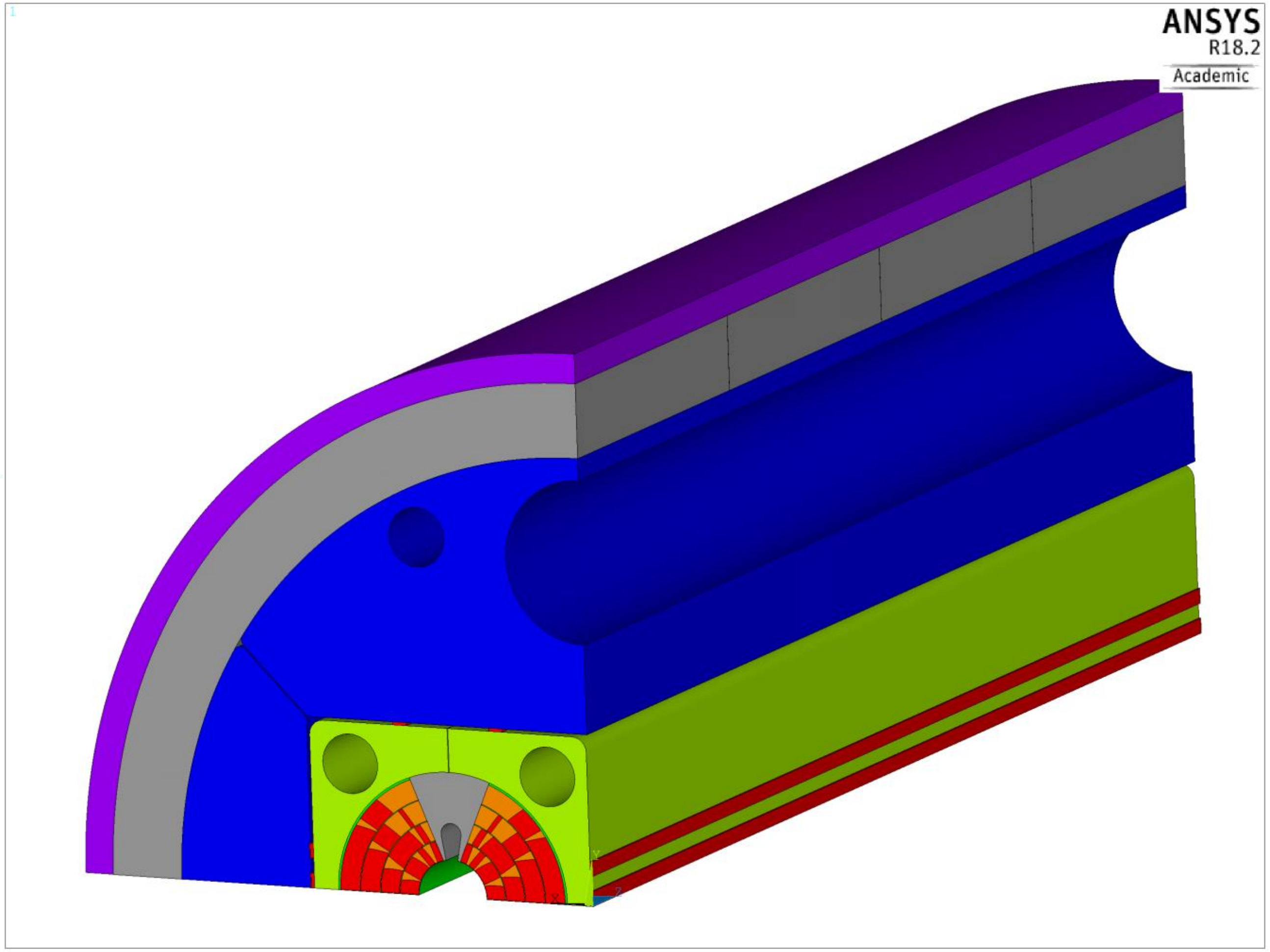
| MATERIAL | Stress limit [MPa]<br>1.9 K |
|---|---|
| Austenitic steel (316LN) | 1050 |
| Al7075 | 690 |
| Ferromagnetic iron | 720 |
| Ti6Al4V | 1650 |



# 3D mechanical design

3D mechanical ANSYS model, very preliminary

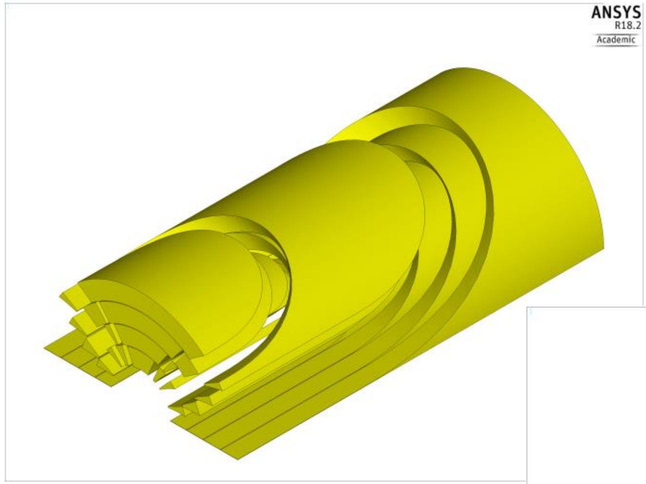


# 3D mechanical design



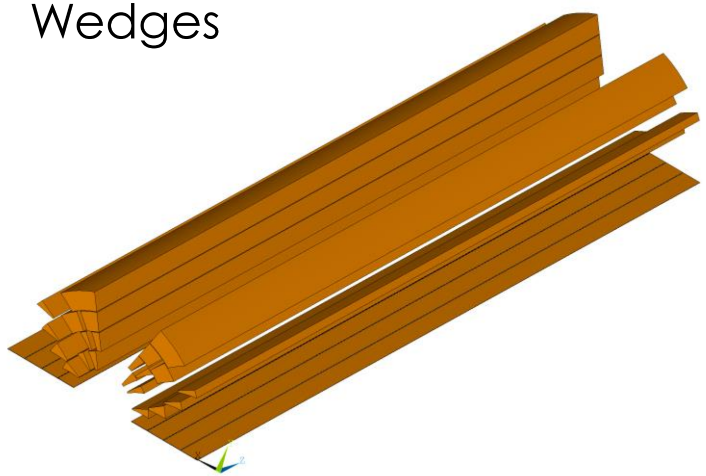
3D mechanical ANSYS model, very preliminary

End spacers ( from Roxie)



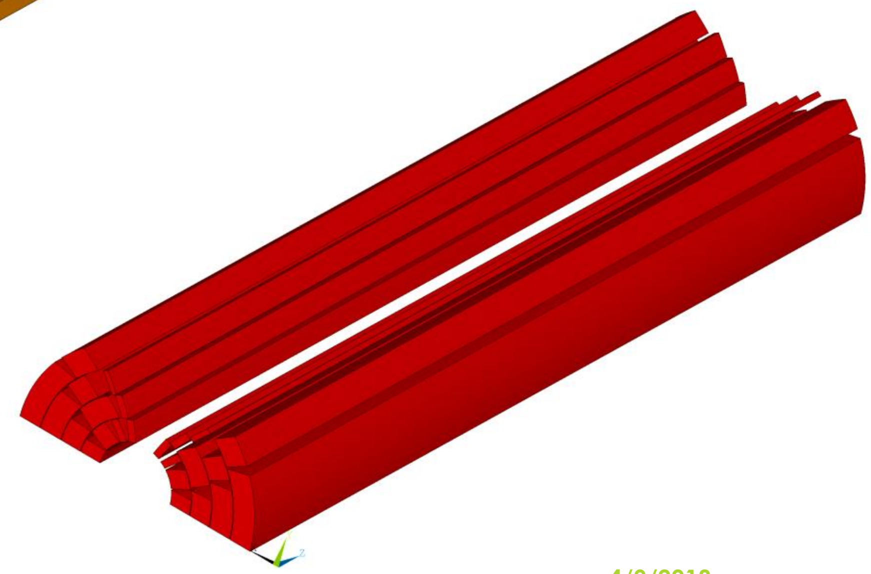

Conductor ends


Wedges



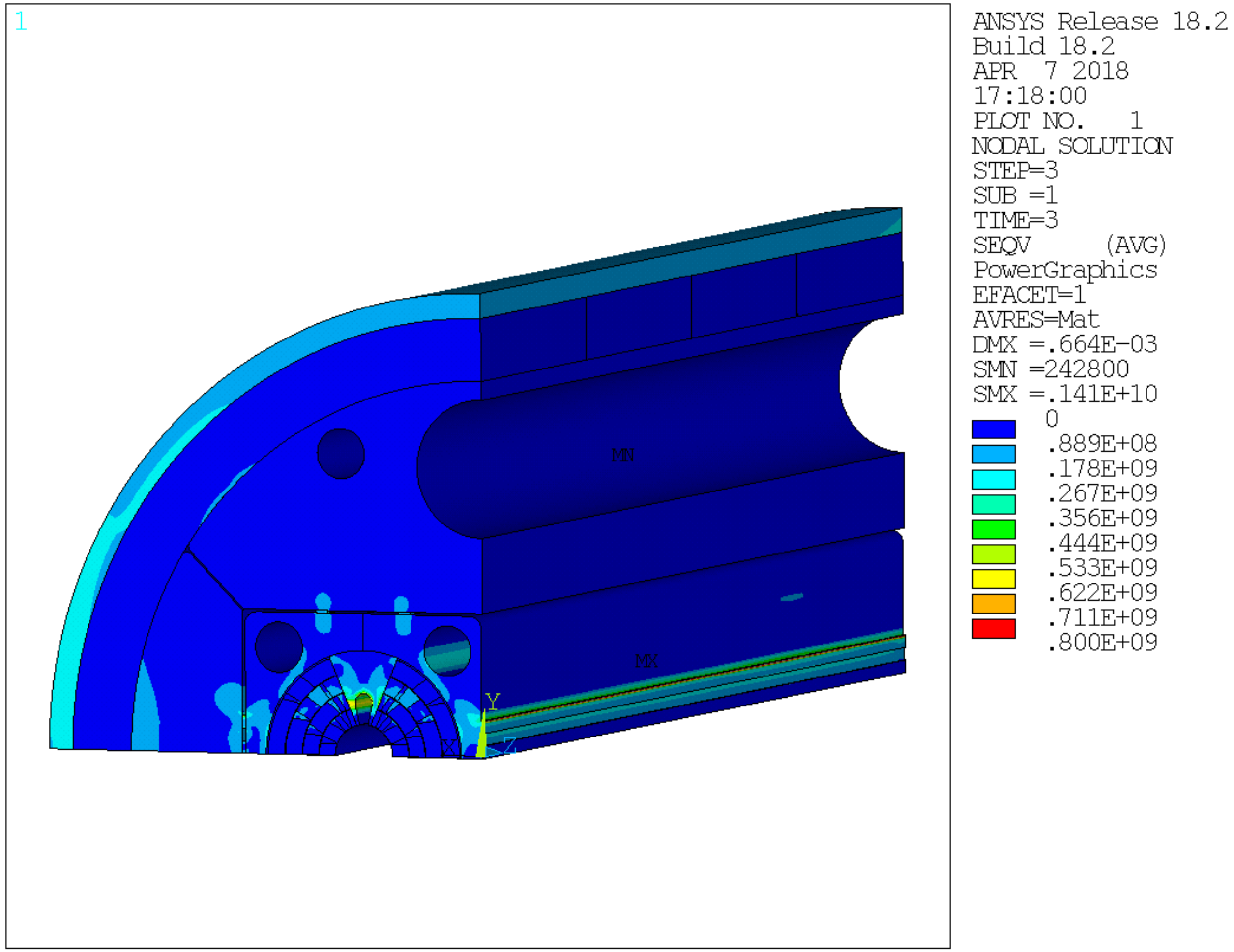
Straight section

Conductors



# 3D mechanical design

3D mechanical ANSYS model, very preliminary



# Conclusions



- We have designed a **4 layer cosine-theta** bending dipole for the FCC, according to the **EuroCirCol** constraints:
  - Able to produce **16 T** bore field
  - Operation point on the load-line is **86%** at 1.9 K
  - **Good** field quality (2D and 3D)
  - **B&K** mechanical structure able to **keep azimuthal pre-stress**, within **stress limits**

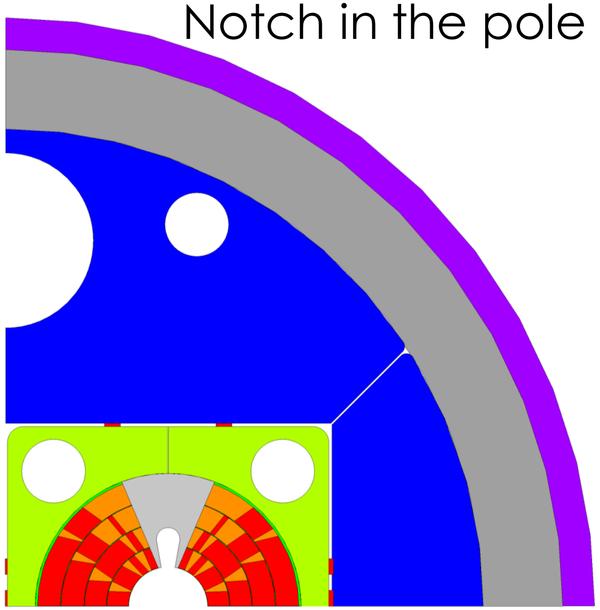
- The magnet is **mature** enough to go in a **more advanced** design phase:
  - 3D mechanical analysis for longitudinal pre-stress
  - Finalization of the **harmonic optimization** (b2 and iron saturation)
  - Starting the development of a **prototype**

Thank you

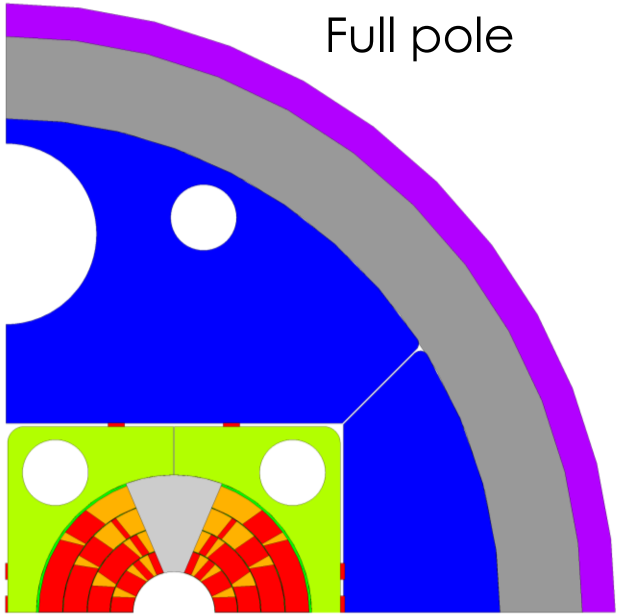
# Displacements Undeformed - Assembly



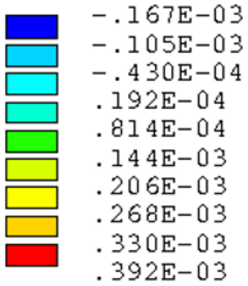
Notch in the pole

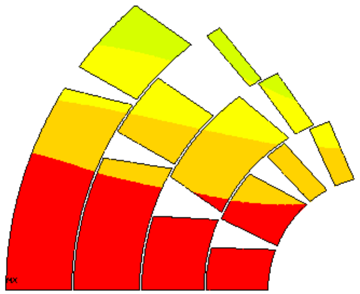


Full pole

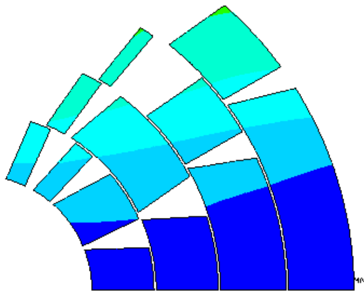


X displacement [m]

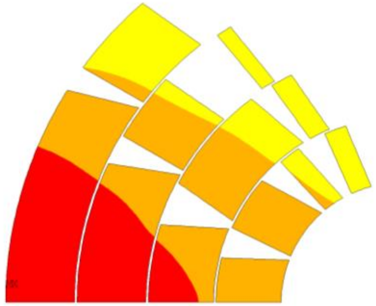


MAX X DISP: 392 μm



MIN X DISP: -167 μm



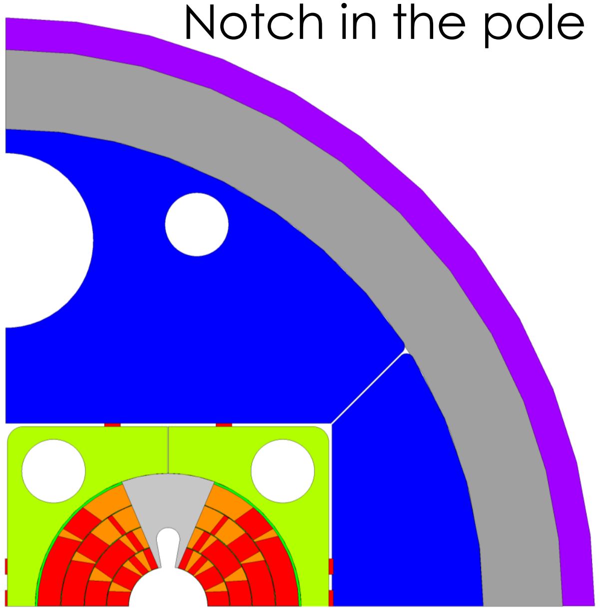
MAX X DISP: 389 μm

MIN X DISP: -10 μm

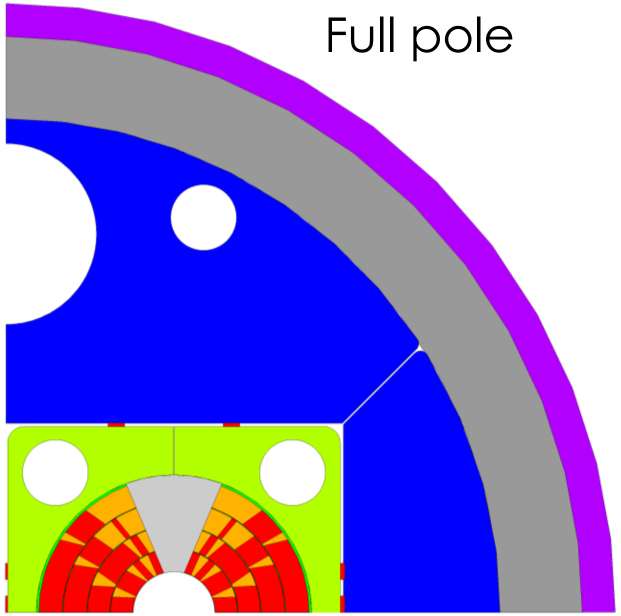
# Displacements Assembly - Cool Down



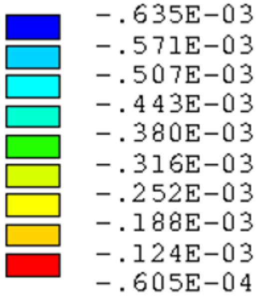
Notch in the pole

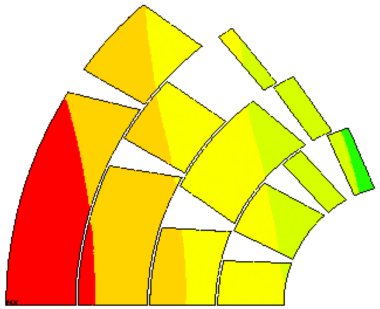


Full pole

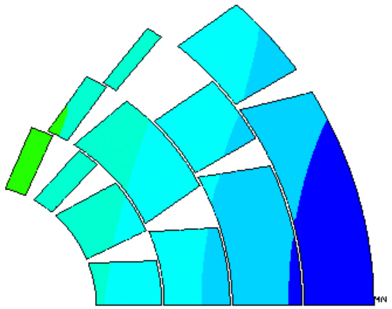


X displacement [m]

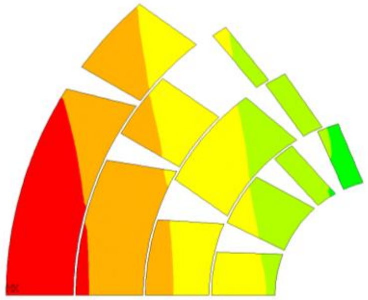


MAX X DISP: 61 μm



MIN X DISP: -635 μm



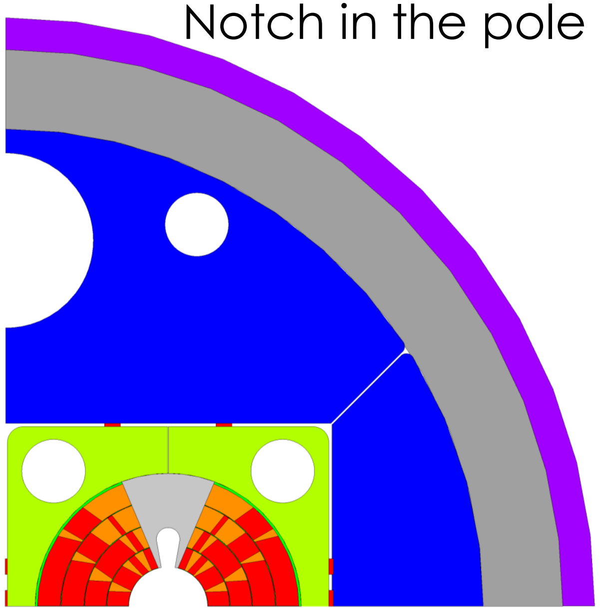
MAX X DISP: 61 μm

MIN X DISP: -640 μm

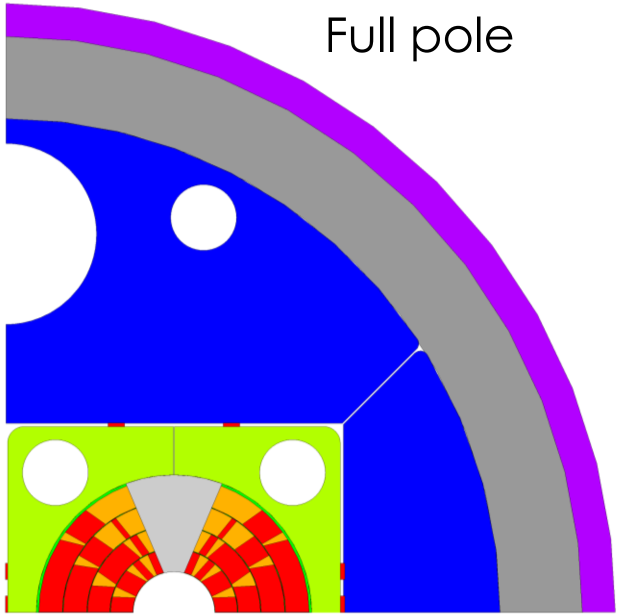
# Displacements Cool Down- Energization 16T



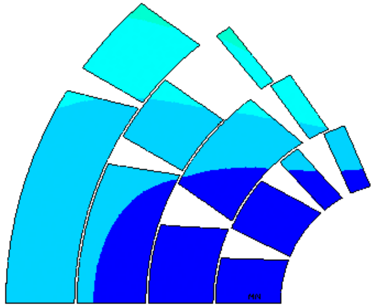
Notch in the pole



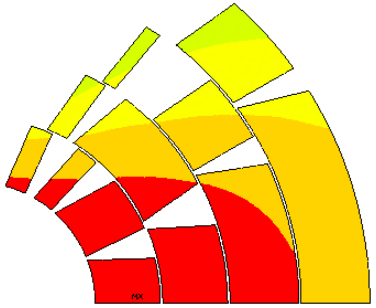
Full pole



Displacement [m]

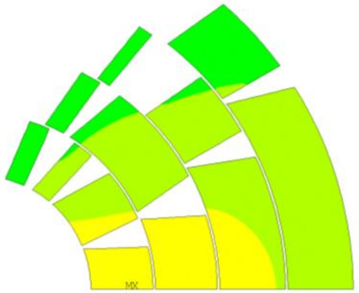



MIN X DISP: -134 μm



MAX X DISP: 401μm

MIN X DISP: - 85 μm

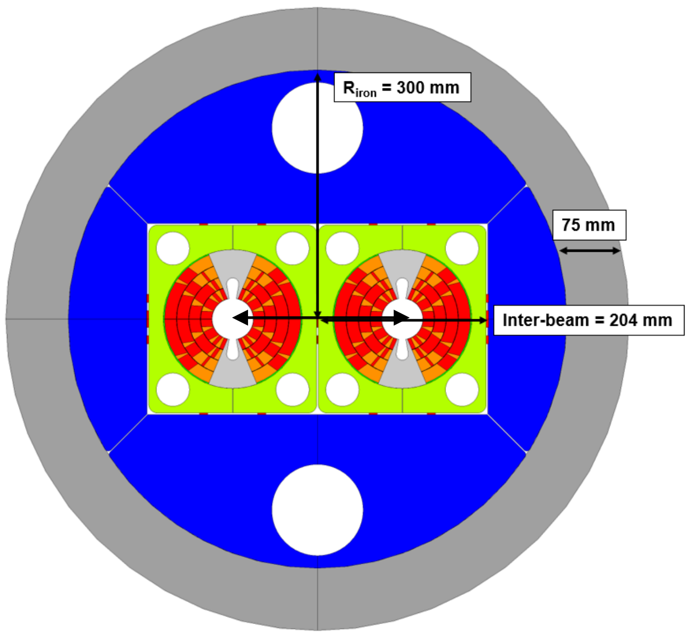


MAX X DISP: 249 μm

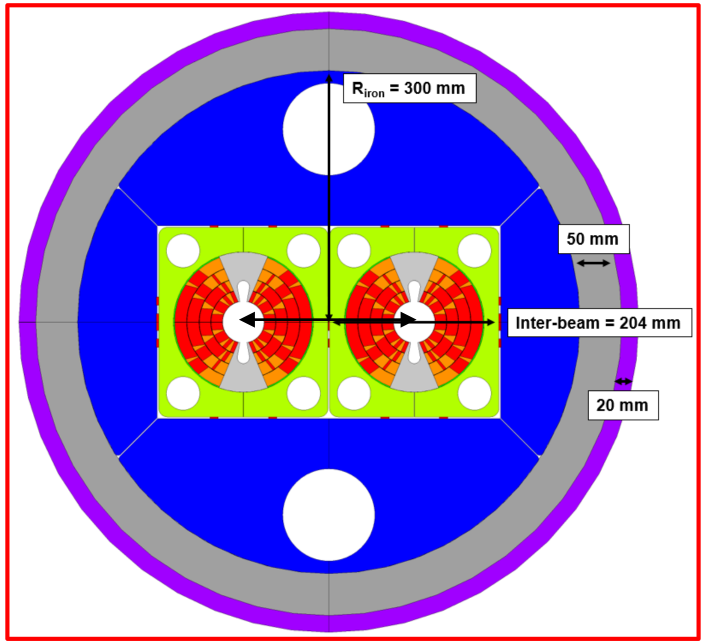
# Cosθ mechanical layout



**_Alluminum shell_**



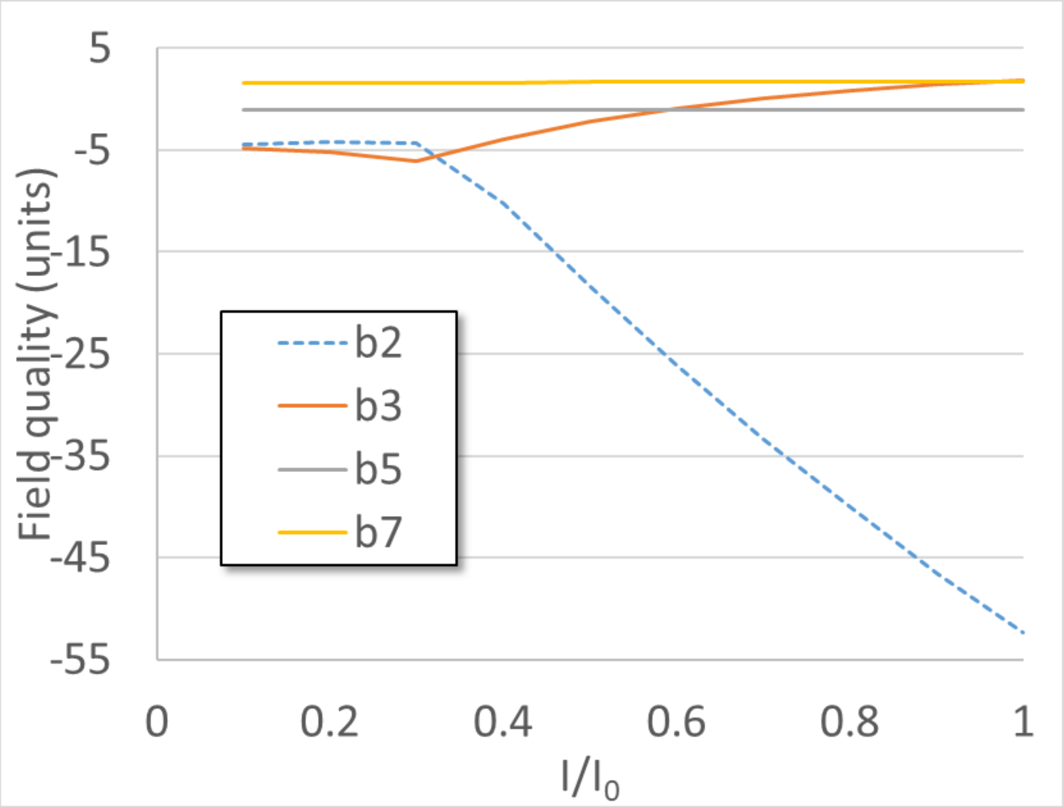

**_Alluminum + SS shell_**

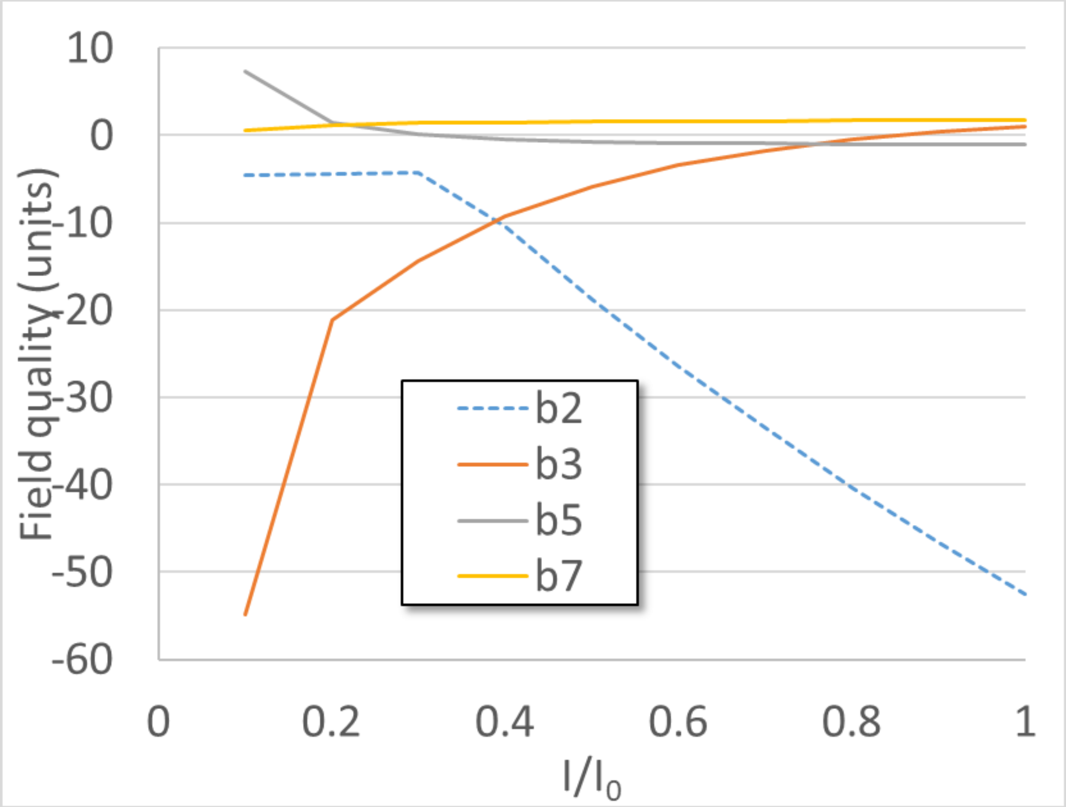



- Yoke outer diameter: 600 mm
- Al alloy ring thickness: 75 mm and 50 mm
- SS shell thickness: 20 mm
- Outer magnet diameter: 750 mm and 740 mm
- New pole design
- Inter-beam distance: 204 mm

# Persistent Currents



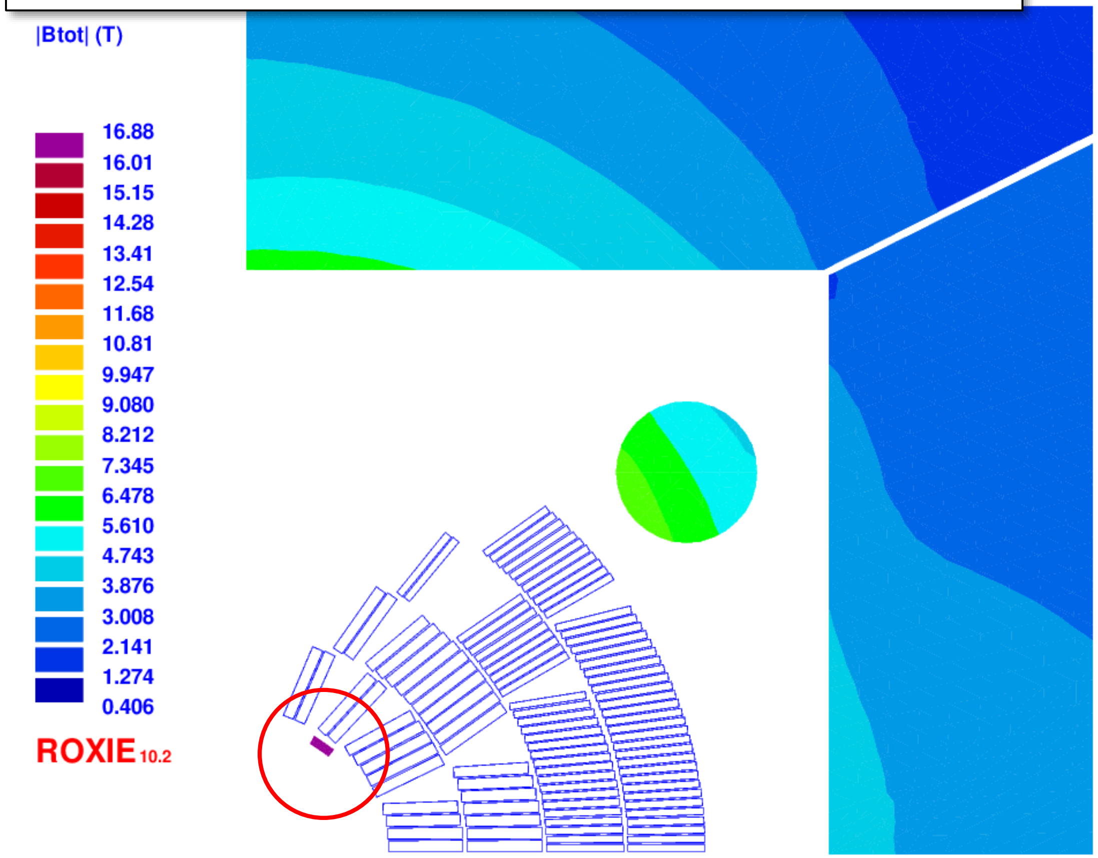


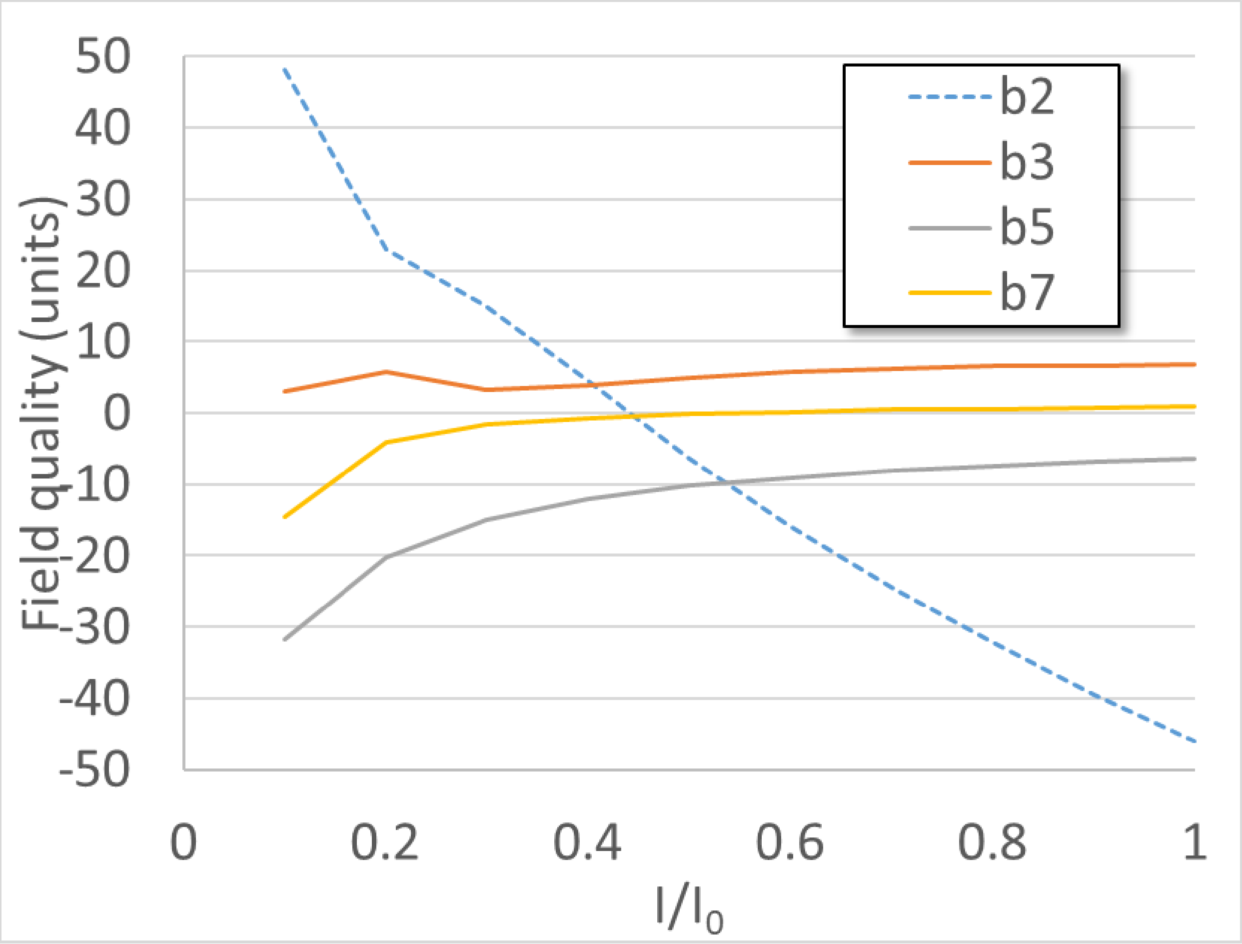




- 50 μm filament diameter
- -50 units on b3 at injection
- +8 units on b5 at injection
- No effect on b2
- Negligible effect at operation current

# Persistent Currents

Possible solution: iron on the beam pipe?




Field quality to be optimized