High Luminosity LHC

Single Aperture Orbit Corrector: Progress on MCBXFB design

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November, 19th 2014

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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Index

- Magnet and cable specifications.
- Magnetic design.
- Protection.
- Mechanical design.
- Conclusions.

Magnet and cable specifications

MCBXFB Requirements

MCBXFB requirements	
Magnet configuration	**Combined dipole (Operation in X-Y square)**
Minimum free aperture	**150 mm**
Integrated field	**2.5 Tm**
Baseline field for each dipole	**2.1 T**
Magnetic length	**1.2 m**
Working temperature	**1.9 K**
Nominal current	**<2500 A**
Field quality (without iron saturation effect)	**<10 units (1e-4)**
Iron geometry	**MQXF iron holes**

Strand & Rutherford Cable

Strand parameters		
Cu:Sc	1.75	-
Strand diameter	0.48	mm
Metal section	0.181	mm^2
Nº of filaments	2300	-
Filament diam.	6.0	µm
I(5T,4.2K)	200-210* (prev. 203)	A
Jc	2800-3300* (prev. 3085)	A/mm^2

* Extracted from strand March-14
(Data provided by Luc-Rene Oberli)

Cable Parameters		
No of strands	18	-
Metal area	3.257	mm^2
Cable thickness	0.845	mm
Cable width	4.370	mm
Cable area	3.692	mm^2
Metal fraction	0.882	-
Key-stone angle	0.67	deg
Inner Thickness	0.819	mm
Outer Thickness	0.870	mm

Insulation

- 1st option: Fibre glass sleeve
  - Easier assembly
  - Need validation test of a suitable binder: PVA under study because ceramic binder failed at the tests carried out.
- 2nd option: Polyimide tape
  - Better cooling.
  - Difficult assembly.

Magnetic Design

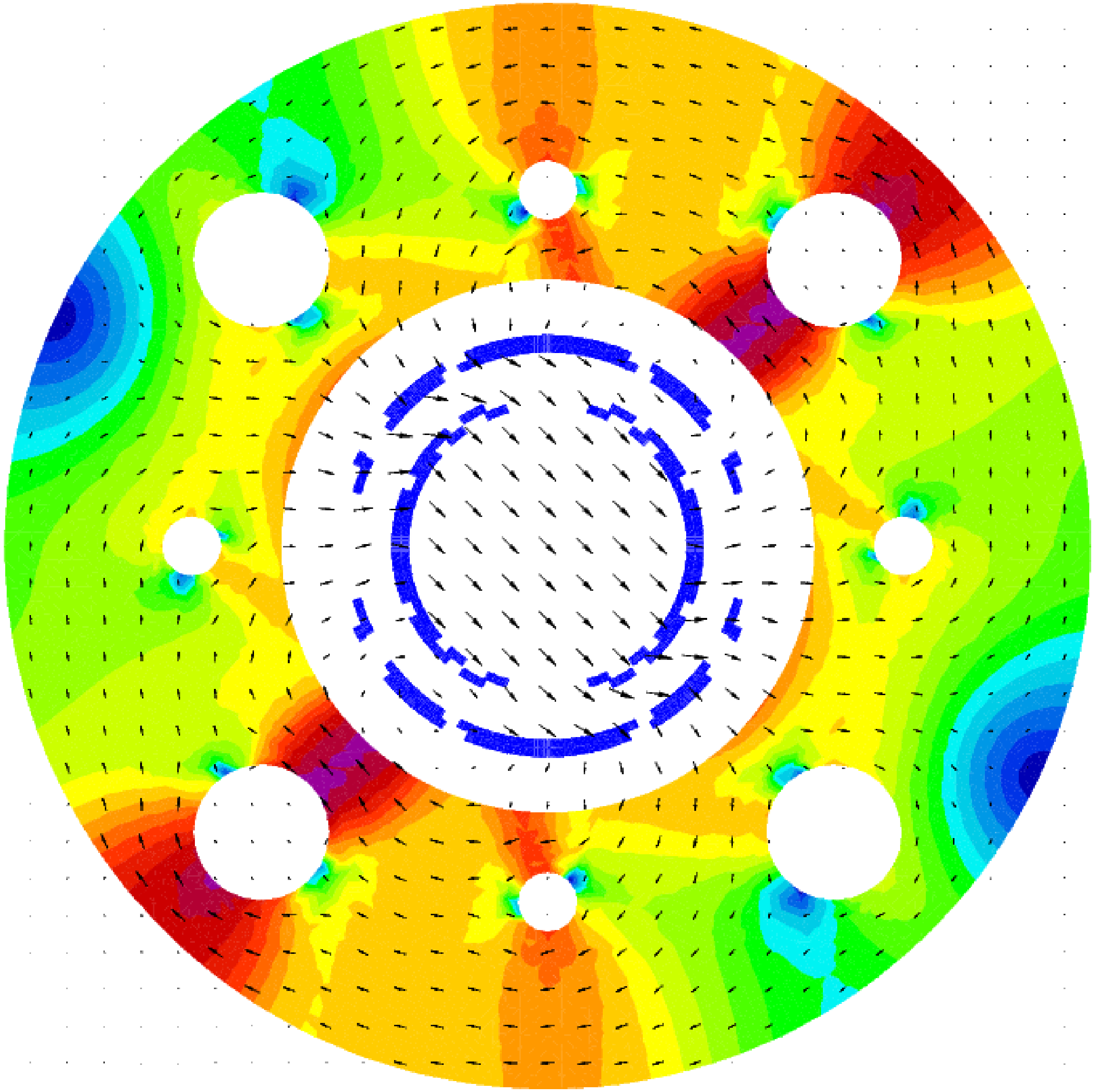
Magnet configuration

- Cosine theta:
  - Winding and assembly procedures are well-known.
  - Long coil ends (similar to the aperture diameter).
  - High number of turns (large aperture and small cable).
- Superferric:
  - Field quality is not achievable within the available space (iron saturation and large aperture).
  - Very simple configuration.
- Canted cosine theta:
  - Lack of experience in case of high fields.
  - Magnet protection in case of quench.
  - Large radial forces (same as cosine theta case).
  - Azimuthal forces support and good field quality.

Single layer & Double layer designs VS old MCBX (same central field comparison)

Inner coil (ID) & Outer Coil (OD) parameters	Units	Single layer design	Double Layer design (Small Collars)	Double Layer design (Large Collars)	Old MCBX (Series Model, both coils powered)
Nominal field 100% (ID)	T	**2.13**	**2.13**	**2.13**	**2.13**
Nominal field 100% (OD)	T	**2.11**	**2.12**	**2.12**	**2.12**
Nominal current (ID)	A	**2450**	**1250**	**1560**	**362.5x8=2900**
Nominal current (OD)	A	**2150**	**1036**	**1340**	**331.25x8=2650**
Coil peak field	T	**4.27**	**3.95**	**3.93**	**3.817**
Working point	%	**60%**	**44.7%**	**48.1%**	**39.54%**
Torque	10^5 Nm/m	**0.92**	**0.98**	**1.19**	**-0.455**
Conductors height (h)	mm	**4.37**	**2x4.37**	**2x4.37**	**13.2 (8)**
Mean stress at the coil and collar nose interface	MPa	**135**	**70**	**82**	**38**
Aperture (ID)	mm	**Ø150**	**Ø150**	**Ø156,2**	**Ø90**
Aperture (OD)	mm	**Ø180**	**Ø200**	**Ø218**	**Ø116.8**
Iron yoke Inner Diam.	mm	**Ø230**	**Ø250**	**Ø300**	**Ø180**
Iron yoke Outer Diam.	mm	**Ø540**	**Ø540**	**Ø610**	**Ø330**
Number of conductors used (1st quad)	-	**162**	**357**	**324**	**800**

Current Magnetic Design



Larger collars in order to increase the stiffness of the assembly and make them self-supporting.

Saturation at nominal current for both dipoles causes the increasing of sextupoles:

- **Δb3= 37 units**
- **Δa3= 24 units**

Possible options?

- **Offsetting the zero at higher current for partial compensation.**
- **Iron geometry changes effectiveness to be studied.**

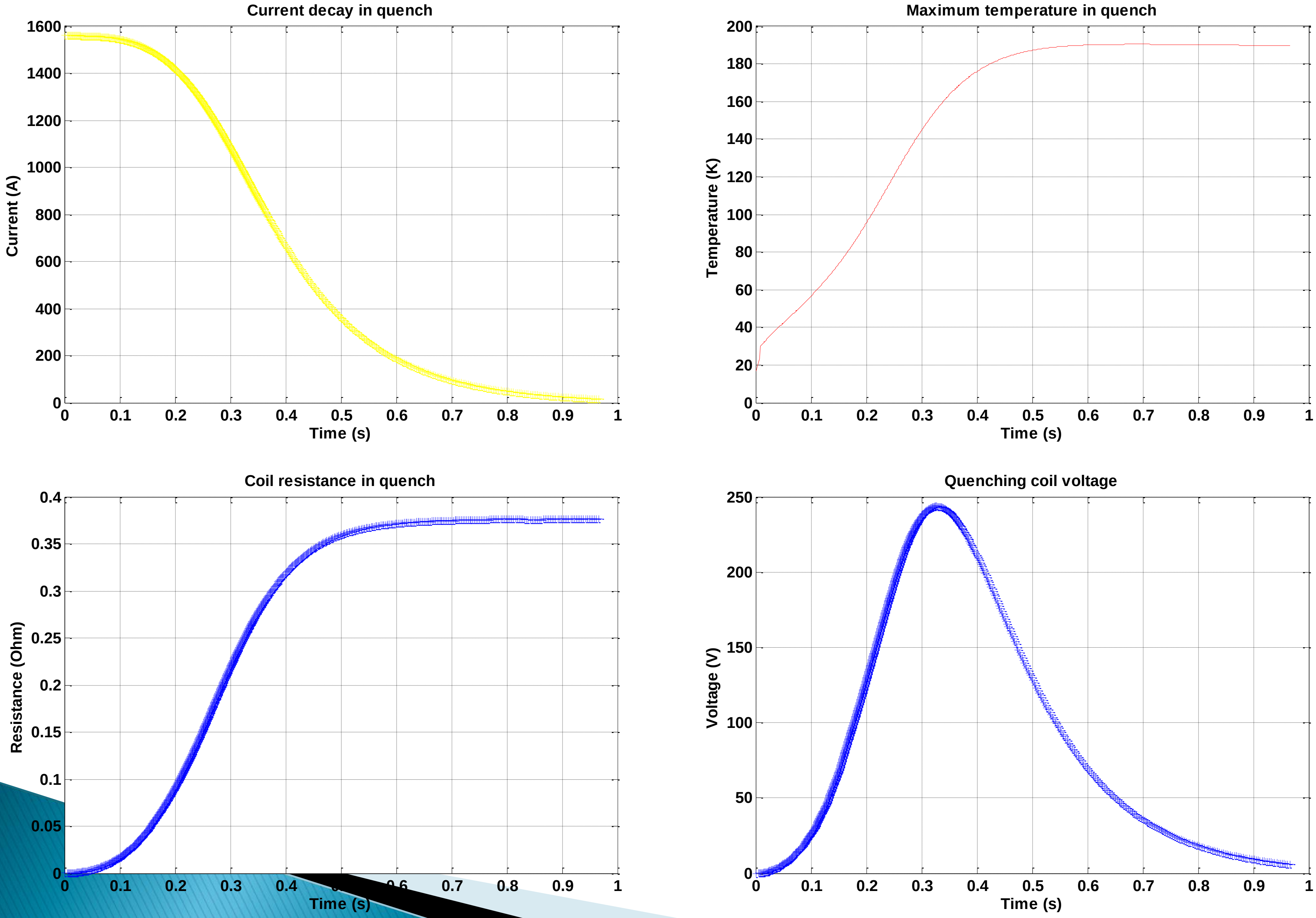
Protection

CIEMAT in-house developed code based on finite difference method : Optimistic assumptions of the model

- Rutherford cable is modeled as a monolithic wire with the same metallic area, discarding the voids or internal volumes filled with resin.
- The wedges are not modeled.
- Quench origin is placed at the innermost turn, although it is not where the peak field is placed when both coils are powered.
- A uniform magnetic field is assumed in the wires, equal to the peak field.

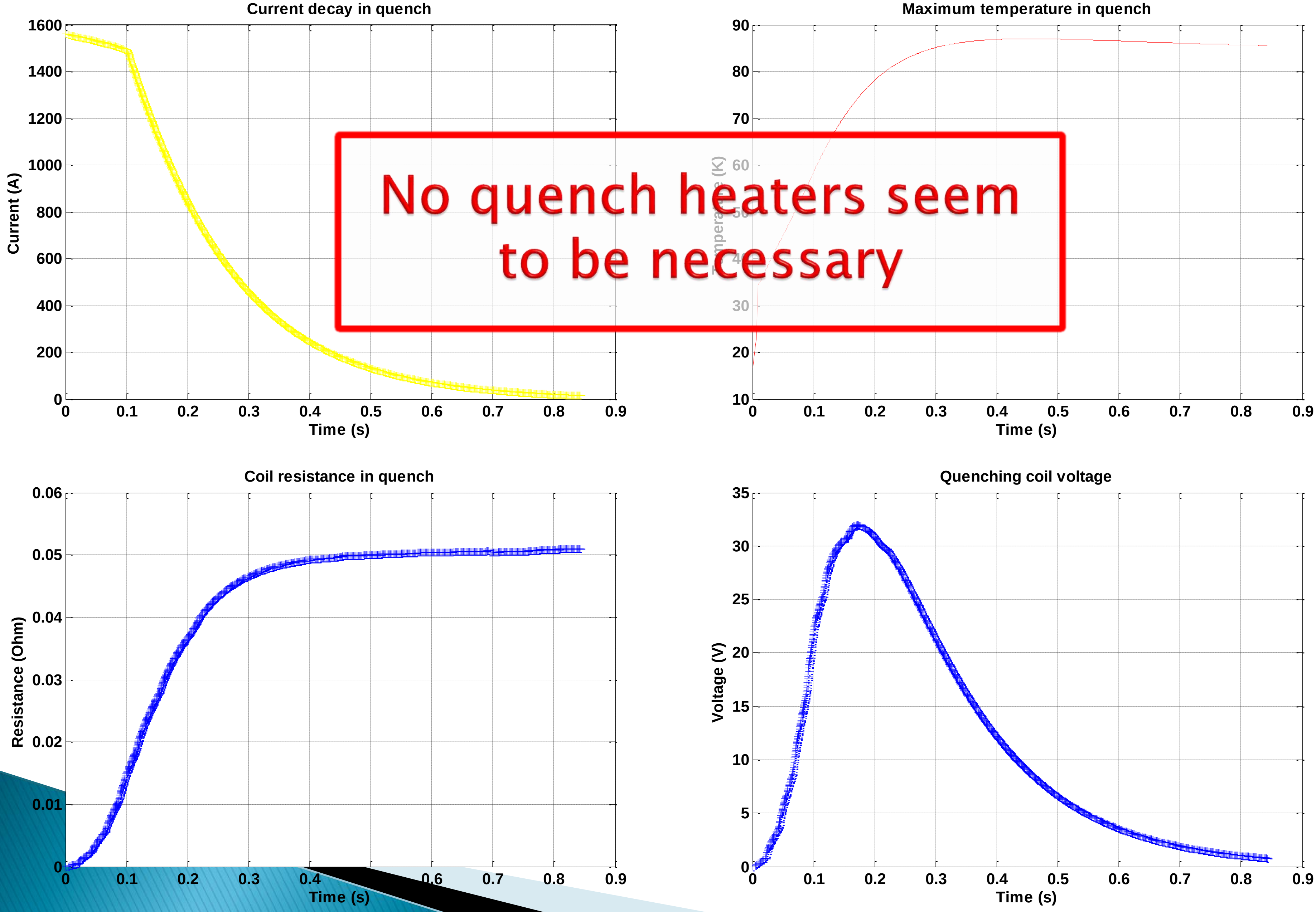
MCBXFB: No damping resistance included

Preliminary



MCBXFB: Damping resistance = 0.3 Ω (0.1 s delay)

Preliminary



No quench heaters seem to be necessary

Mechanical Design

Mechanical design: Challenges to face

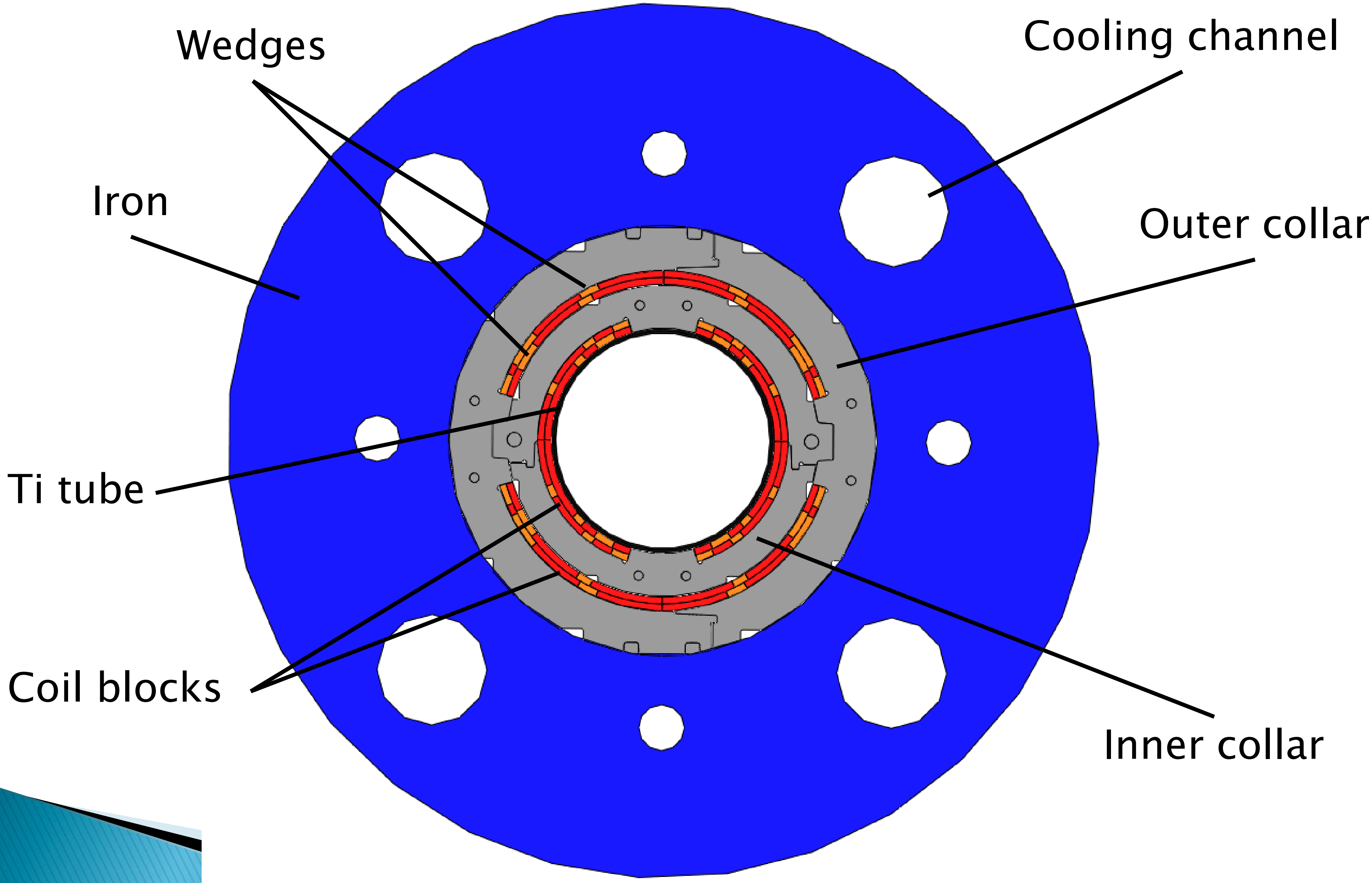
- As a combined dipole that requires a square range of operation in X and Y axis, a large torque arises when both coils are powered.
- Due to the expected radiation dose a solution based on mechanical clamping is required to mechanically fix the coils and guarantee the magnet performance.
- Other major challenges:

Challenge	Solution proposed
Large radial deformations of the assembly	Large self-supporting collars
Large azimuthal displacements of the coils	Azimuthal interference at collar noses
Radial inward forces at the inner dipole	Inner titanium tube

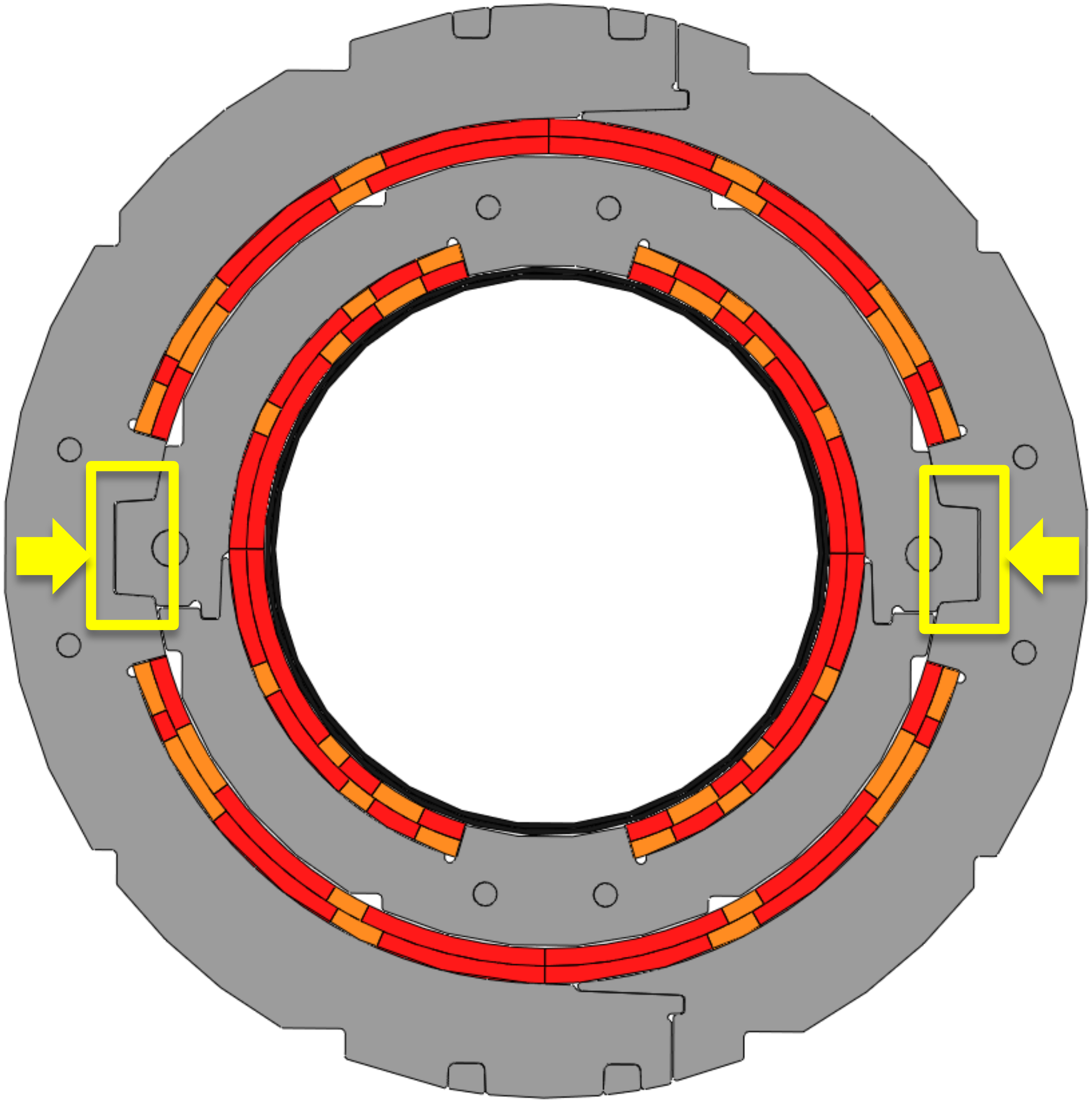
- Mechanical model
  - Powered with 108% of nominal current for sizing purposes.
  - Material properties used:

	Material	E [Gpa]	u [-]	CTE [K^{-1}]
Coils & spacers (Impregnated)	**NbTi+Cu**	**40**	**0,0032**	**$1.1*10^{-5}$**
Collars	**StainlessSteel**	**$193_{293K}/210_{4.3K}$**	**0,0028**	**$0.983*10^{-5}$**
Inner tube	**Ti**	**130**	**0,0017**	**$0.603*10^{-5}$**

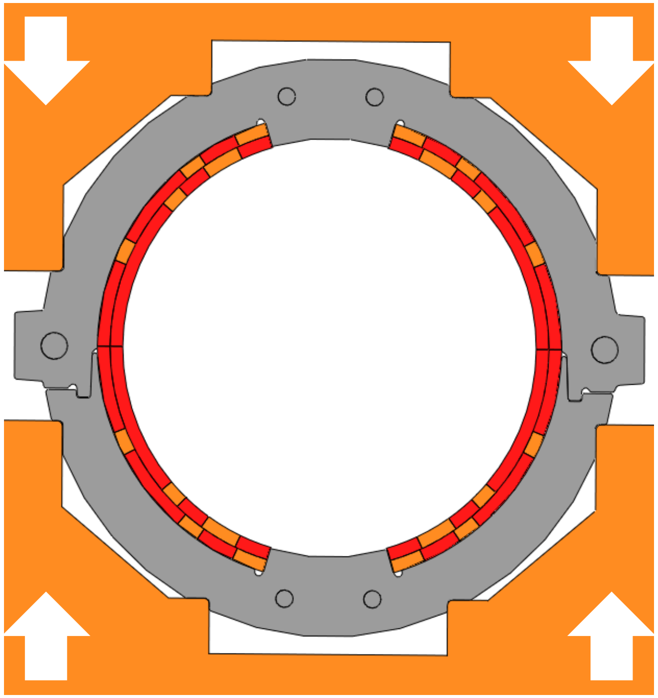
Mechanical model



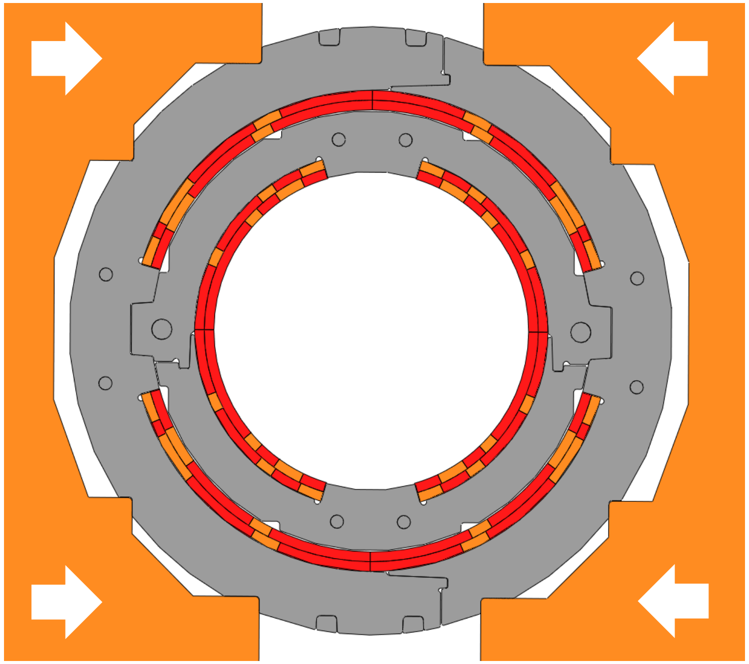
Mechanical model



Mechanical assembly

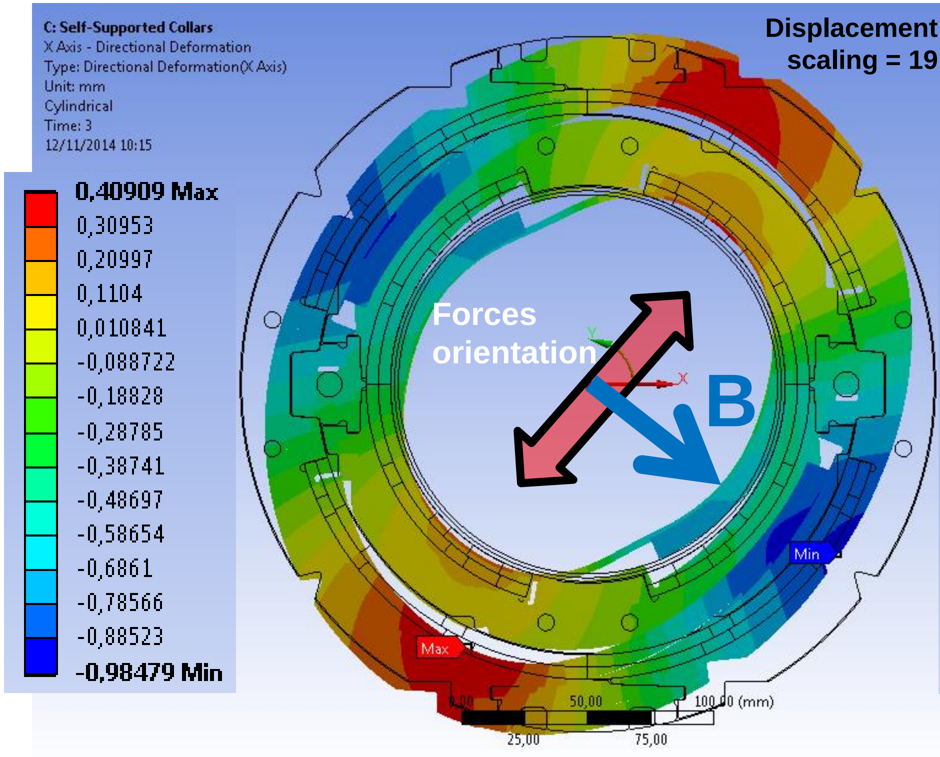


- **Challenging nested assembly due to the inner dipole deformation after collaring.**
- **Other solutions under evaluation.**



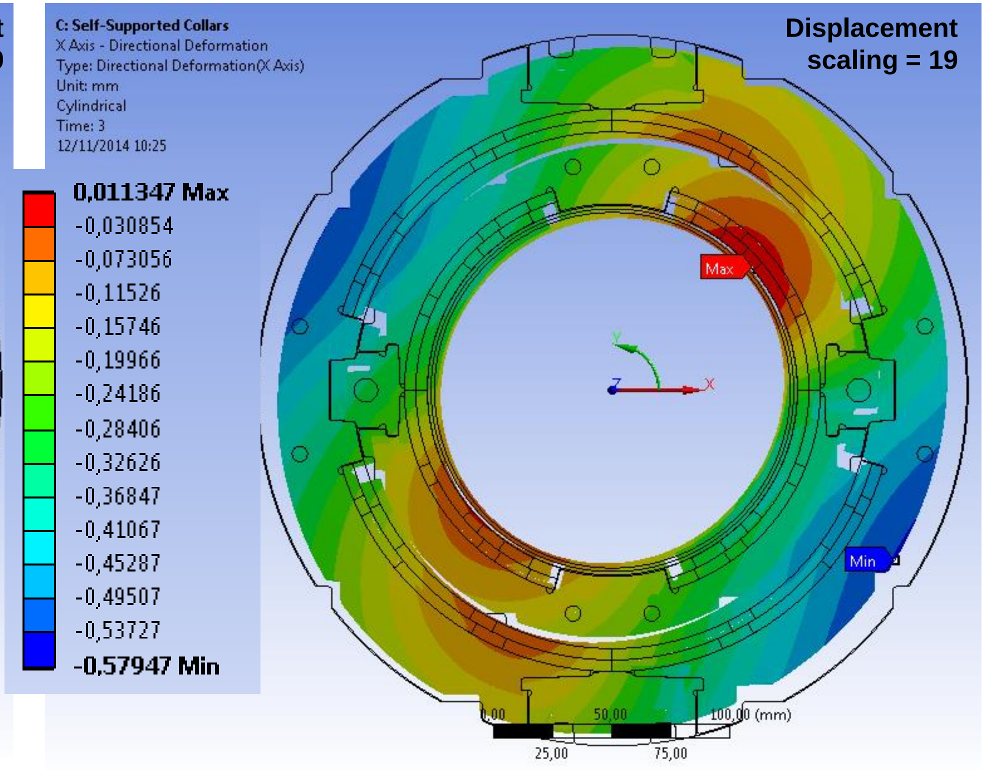
Results: Large radial collar deformations

Outer Collar Diam.= 275 mm



C: Self-Supported Collars
X Axis - Directional Deformation
Type: Directional Deformation(X Axis)
Unit: mm
Cylindrical
Time: 3
12/11/2014 10:15

Outer Collar Diam.= 300 mm



C: Self-Supported Collars
X Axis - Directional Deformation
Type: Directional Deformation(X Axis)
Unit: mm
Cylindrical
Time: 3
12/11/2014 10:25

Ellipticity ≅ 1.4 mm **VS** **Ellipticity ≅ 0.6 mm**

Currently evaluating if iron support is needed

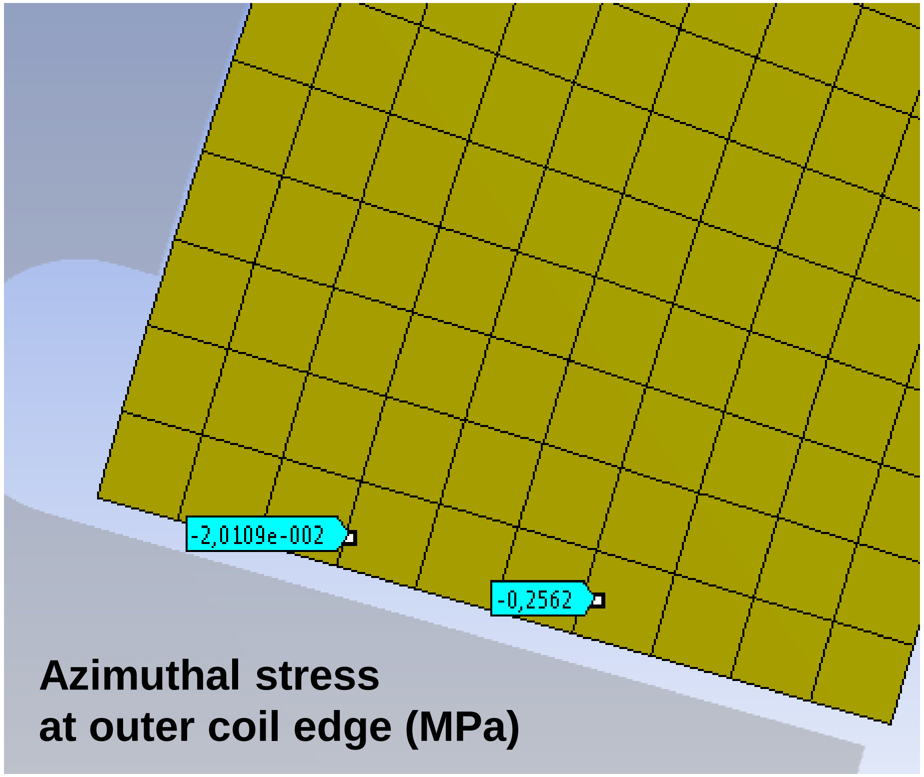
Field quality effect (Ansys2Roxie) :

- **Δb3= 9 units**
- **Δa3= 6 units**

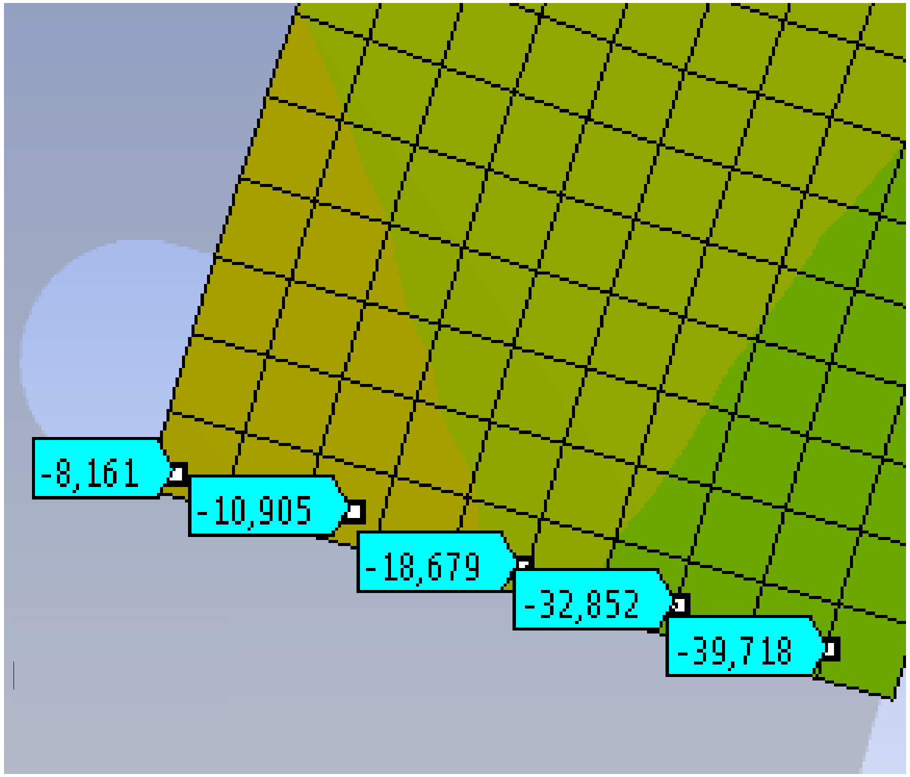
Results: Large azimuthal coil displacements

Outer Collar Diam.= 275 mm
Interference = 0.2 mm

Outer Collar Diam.= 300 mm
Interference = 0.2 mm



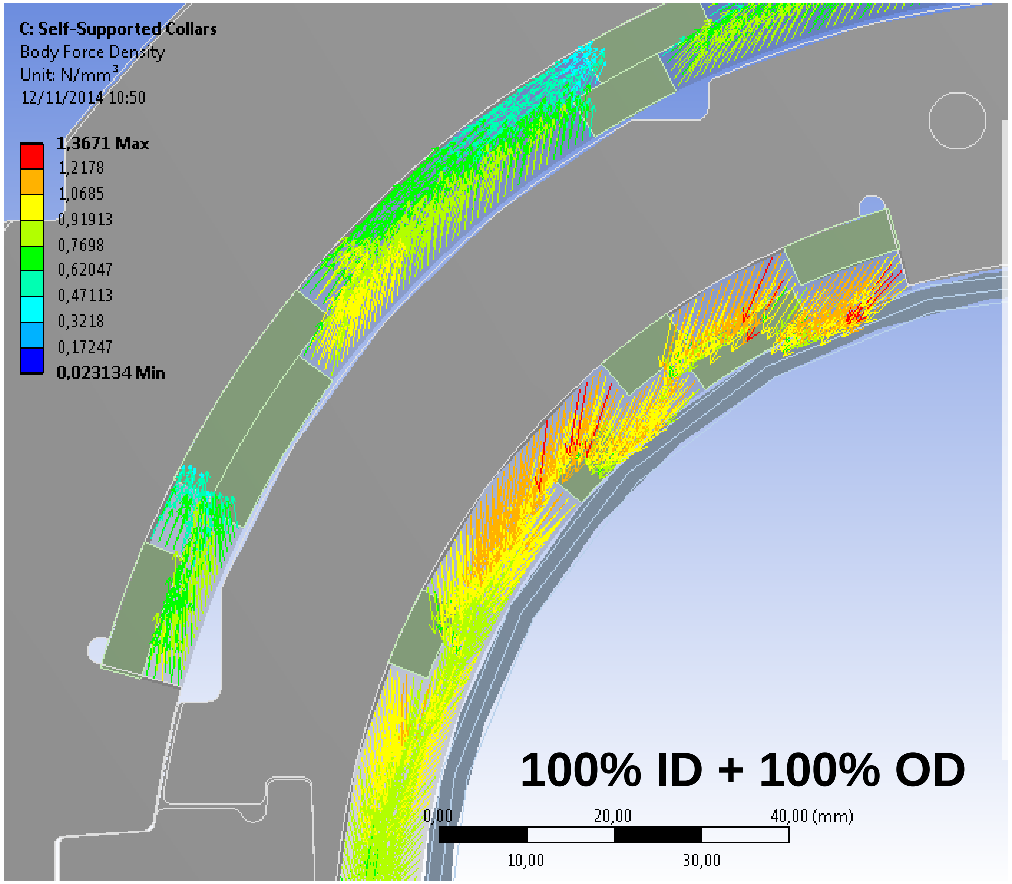
Azimuthal stress at outer coil edge (MPa)



The coils separates from the collar VS The coils stay attached to the collars

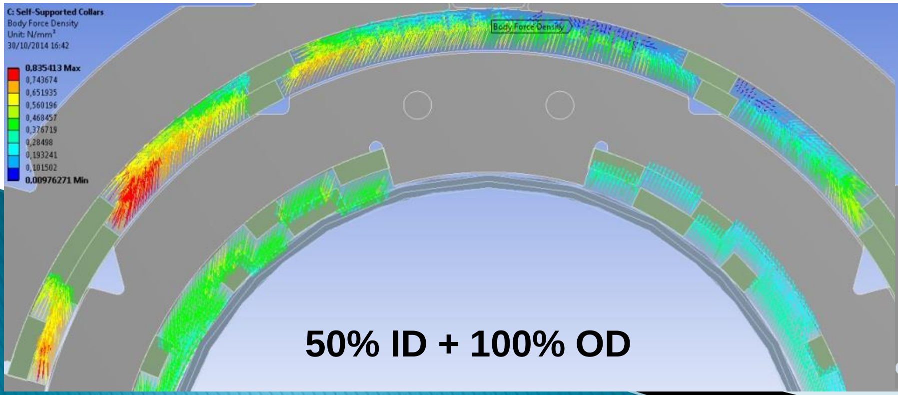
Azimuthal interference value to be further evaluated

Results: Radial Inward Forces at Inner Dipole

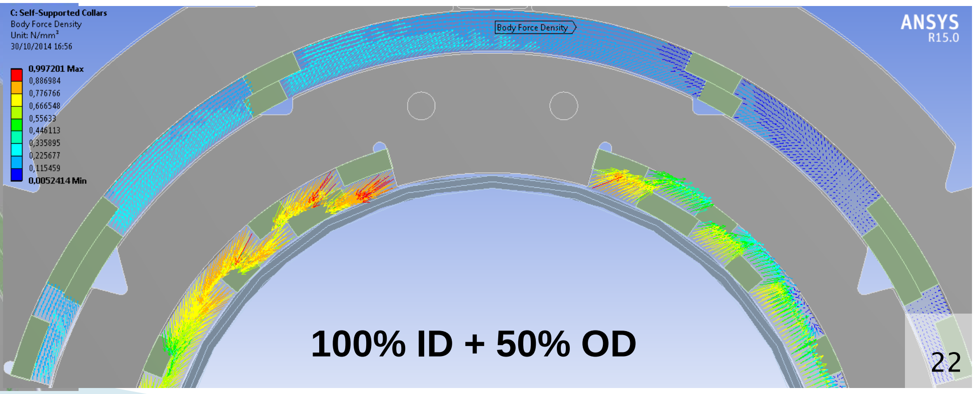


100% ID + 100% OD

- Due to the combined dipole configuration, radial inward forces appear in the inner coil (upper blocks), causing the coils to deform into the aperture.
- Checking other possible powering scenarios, forces at outer dipole are always outwards.
- An inner titanium tube was proposed given its low contraction factor.



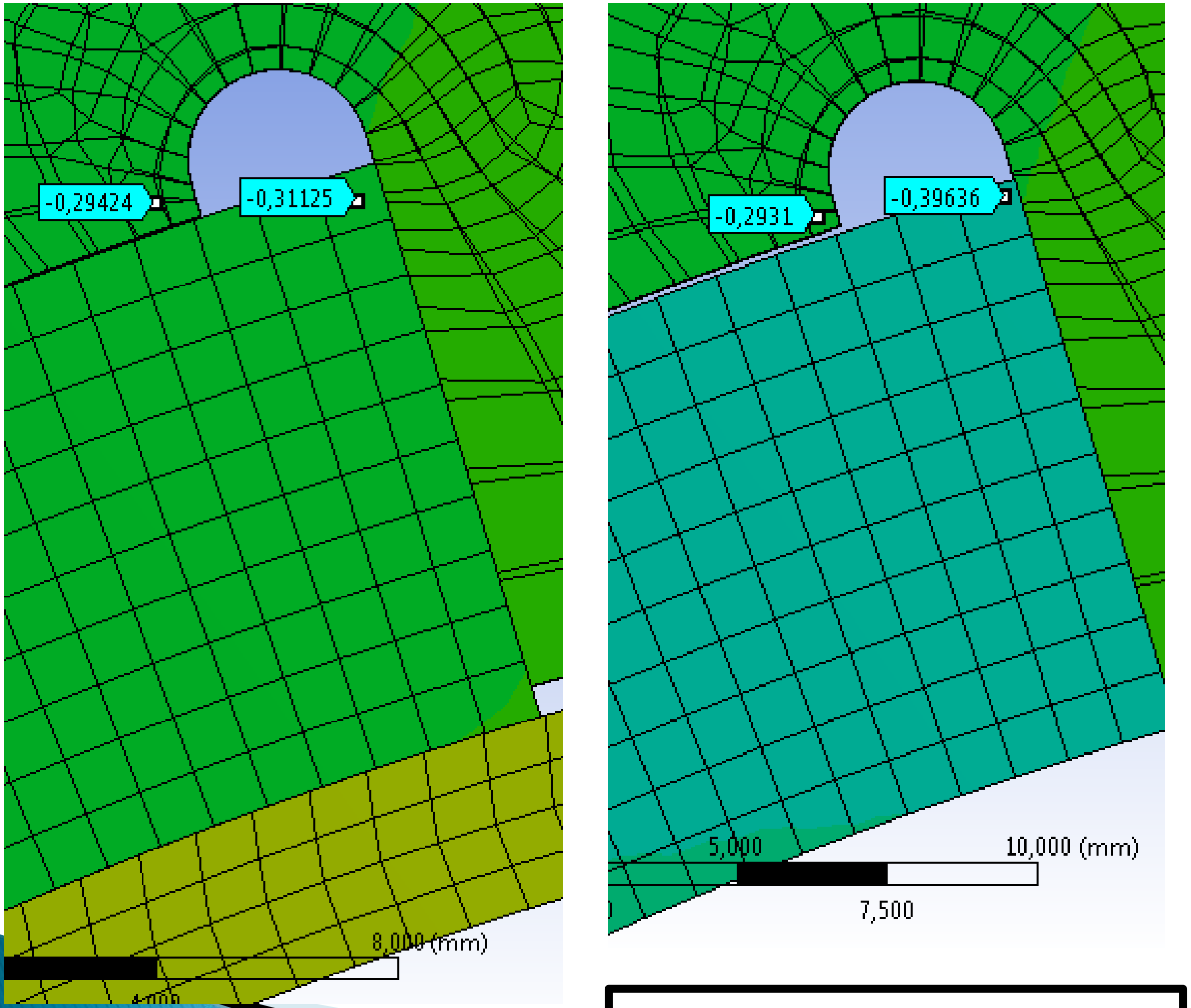
50% ID + 100% OD



100% ID + 50% OD

Results: Radial Inward Forces at Inner Dipole

With Tube **VS** **Without tube**



Tube performance under evaluation

Outer Collar Diam.= 300 mm
Interference= 0.2 mm
Frictionless contact
between coil and collar nose

- **The inclusion of the titanium tube helps to decrease the inward displacement of the inner dipole coil from 0,1 mm to less than 0,02 mm.**
- **It is intended to prevent a sudden slipping movement of the coil under Lorentz forces, because some friction is always present.**
- **Even such a small movement, if sudden, might likely trigger a quench.**
- **This frictionless case illustrate the worst scenario possible. If the movement were continuous, no pipe would be necessary.**

Conclusions

Conclusions (I)

- Magnetic Design:
  - Single layer and double designs were studied. Double layer design showed as the most suitable option to meet the requirements.
  - To Be Done:
    - Deal with sextupoles appeared due to iron saturation.
    - Persistent current and magnetization effect to be studied.

- Protection
  - Preliminary results suggest that a dump resistor would be enough to manage quench at both MCBXF models.
  - To be done: Refine the model.

Conclusions (II)

- Mechanical design:
  - The challenges faced at this magnet were radial inwards forces at the inner dipole, large azimuthal coil displacements and large radial deformations of the assembly.
  - A solution based on self supporting collars and an inner titanium tube has been proposed and is currently being assessed.
  - To be done: Evaluate if iron support is needed, inner titanium tube performance and azimuthal interference value.

- Manufacturing techniques
  - To be done:
    - The coils will be fully impregnated coils but a compatible binder is still needed (PVA under study).
    - Challenging assembly of nested collars. Short model needed to validate the method.

Next year activities

- March 2015: Finish magnetic and mechanical detailed design.
- October 2015: First Coil fabrication.
- December 2015: Short mechanical model.

Thanks
for your attention

Annexes

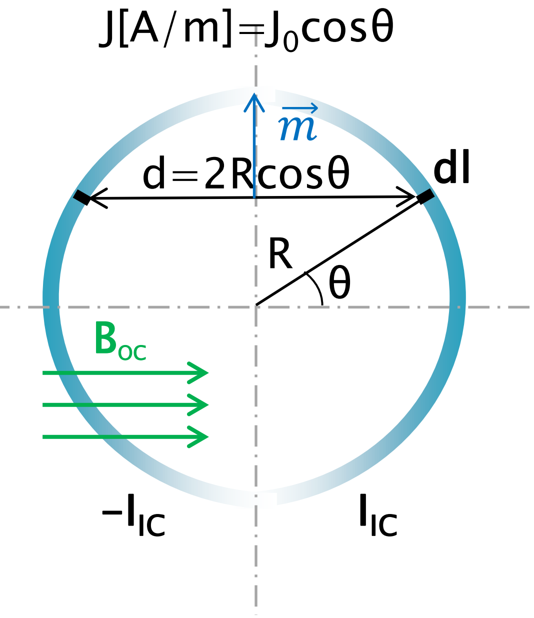
Considerations on a MCBXFB design based on a canted cosine-theta coil configuration

- Comparing the main challenges in the case of MCBXFB design for both designs:
  - **The torque between nested dipoles**:
    - It will be the same for both designs.
  - **The separation of the pole turn from the collar nose due to the Lorentz forces**:
    - It does not happen in the CCT dipole (azimuthal forces support).
    - In the pure cosine-theta it can be overcome with a small interference between the collar nose and the pole turn of the coil.
  - **The elliptical deformation of the support structure under Lorentz forces**:
    - In a CCT dipole the outer formers should hold the outwards radial forces coming from the inner layers, which complicates significantly the assembly and fabrication.
    - The assembly of two nested collared coils is not easy, but seems more affordable.
- The CCT configuration has not been broadly used up to now, so other open questions are:
  - The handling of the axial repulsive forces between layers.
  - The influence of the cable positioning accuracy on the field quality.
  - The training of a large and high field superconducting dipole.
  - The protection of the magnet in case of quench.
  - Formers materials to be used (insulation, stiffness and easily machining required).
  - Coils impregnation.

Single layer & Double layer designs VS old MCBX (same central field comparison)

Inner coil (ID) & Outer Coil (OD) parameters	Units	Single layer design	Double Layer design (Small Collars)	Double Layer design (Large Collars)	Old MCBX (Series Model, both coils powered)
Nominal field 100% (ID)	T	**2.13**	**2.13**	**2.13**	**2.13**
Nominal field 10% (ID)	T	**0.214**	**0.214**	**0.218**	**0.2156**
Non-linearity (ID) [$B_{100\%}$-10·$B_{10\%}$]/10·$B_{10\%}$·100]	%	**-0.47%**	**-0.61%**	**-2.29%**	**-1.2%**
Nominal field 100% (OD)	T	**2.11**	**2.12**	**2.12**	**2.12**
Nominal field 10% (OD)	T	**0.212**	**0.2154**	**0.219**	**0.2156**
Non-linearity () [$B_{100\%}$-10·$B_{10\%}$]/10·$B_{10\%}$·100]	%	**-0.47%**	**-1.58%**	**-3.2%**	**-1.67%**
Nominal current (ID)	A	**2450**	**1250**	**1560**	**362.5x8=2900**
Nominal current (OD)	A	**2150**	**1036**	**1340**	**331.25x8=2650**
Coil peak field	T	**4.27**	**3.95**	**3.93**	**3.817**
Working point	%	**60%**	**44.7%**	**48.1%**	**39.54%**
Torque using Roxie Forces	10^5 Nm/m	**0.92**	**0.98**	**1.19**	**-0.455**
Torque using Analytical Equation	10^5 Nm/m	**0.93**	**1.03**	**1.13**	**0.45**
Difference Roxie vs Analytical Eq.	%	**+1.68%**	**+4.13%**	**-4.72%**	**-1.1%**
Conductors height (h)	mm	**4.37**	**2x4.37**	**2x4.37**	**13.2 (8)**
Mean radius (ID)	m	**0.0775**	**0.08**	**0.0825**	**0.0518**
Mean stress at the coil and collar nose interface	MPa	**135**	**70**	**82**	**38**
Aperture (ID)	mm	**Ø150**	**Ø150**	**Ø156,2**	**Ø90**
Aperture (OD)	mm	**Ø180**	**Ø200**	**Ø218**	**Ø116.8**
Iron yoke Inner Diam.	mm	**Ø230**	**Ø250**	**Ø300**	**Ø180**
Iron yoke Outer Diam.	mm	**Ø540**	**Ø540**	**Ø610**	**Ø330**
Number of conductors used (1st quad)	-	**162**	**357**	**324**	**800**

Some useful expressions to understand where mechanical stresses come from



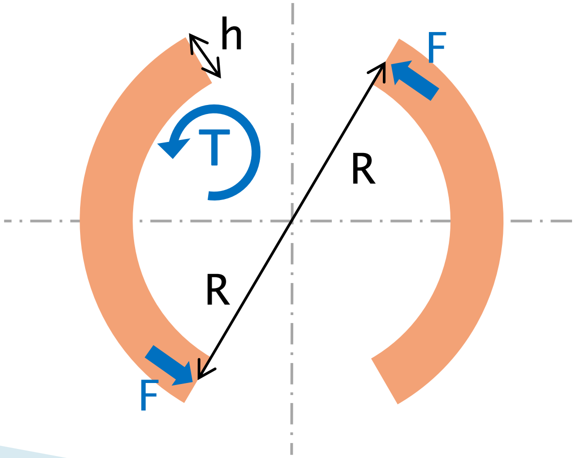
$$I_T = \int_{-\pi/2}^{\pi/2} J\,\mathrm{dl} = \int_{-\pi/2}^{\pi/2} J_0 \cos\theta\, R\,\mathrm{d}\theta = 2J_0 R \;\Rightarrow\; J_0 = {}^{I_{IC}}/_{2R}$$

$$\frac{T}{l} = \frac{\vec{m}\times\vec{B}}{l} = \frac{B_{OC}}{l}\int_{-\pi/2}^{\pi/2} S\cdot I = B_{OC}\int_{-\pi/2}^{\pi/2} 2R_{IC}\cos\theta\, J_0 \cos\theta\, R_{IC}\,\mathrm{d}\theta$$

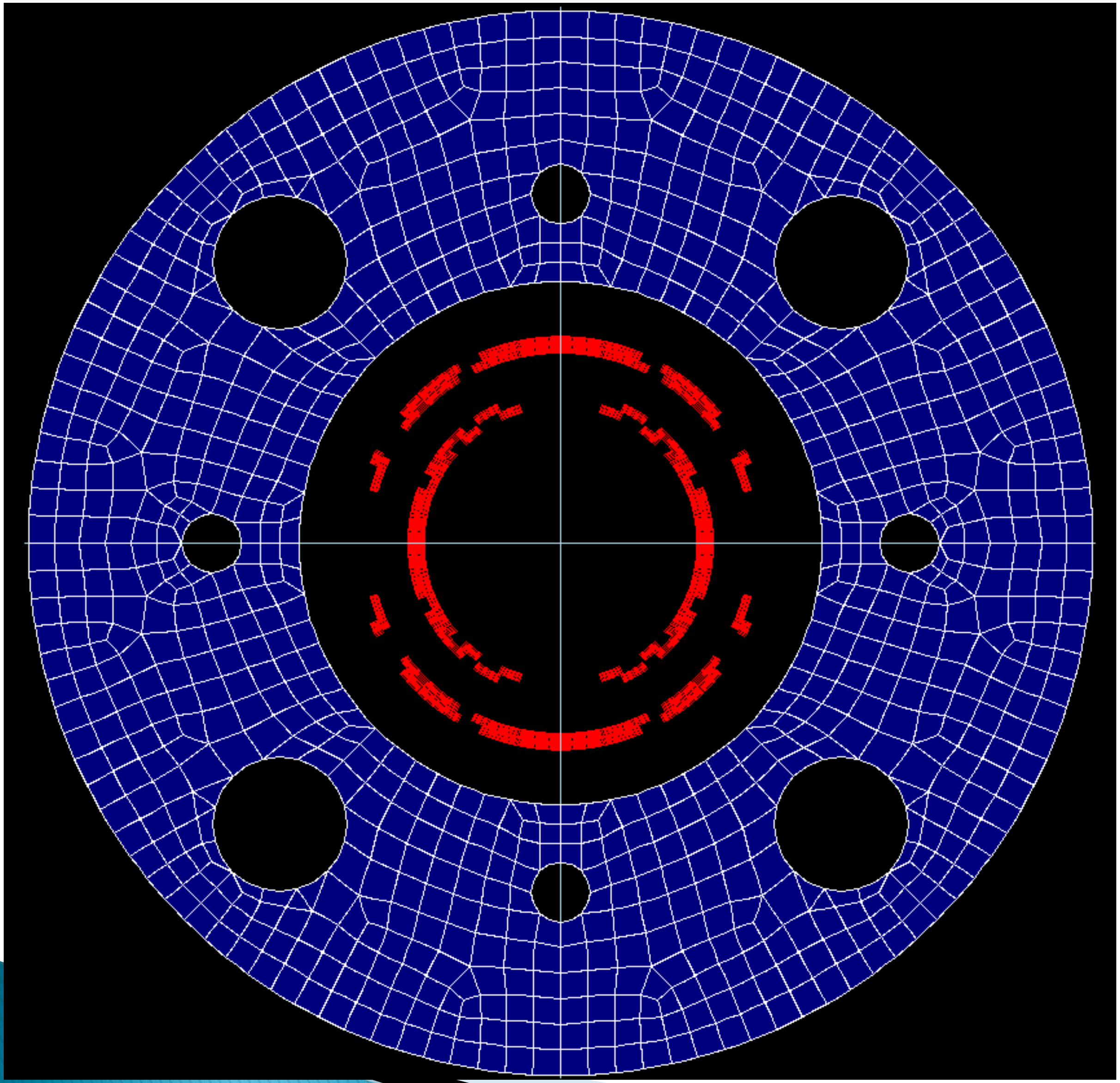
$$\boldsymbol{{}^{T}/_{l}{}^{*} = \frac{\mu_0\pi}{8} I_{IC} I_{OC} \frac{R_{IC}}{R_{OC}}\left(\frac{{R_Y}^2 + {R_{OC}}^2}{{R_Y}^2}\right)} \;\Leftarrow\; \boldsymbol{{}^{T}/_{l} = \frac{\pi}{2} R_{IC} B_{OC} I_{IC}}$$

* Linear Iron

$$\boldsymbol{\sigma_{\theta\,cond} = \frac{F}{A} = \frac{T/2R}{lh} = \frac{T/l}{2Rh}}$$



Current Magnetic Design



Considerations used due to…

Mechanical analysis
- Thicker collars.
- Larger aperture.
- Larger main posts.

Manufacturing
- Less than 55 conductors per block.
- Iron rod holes.

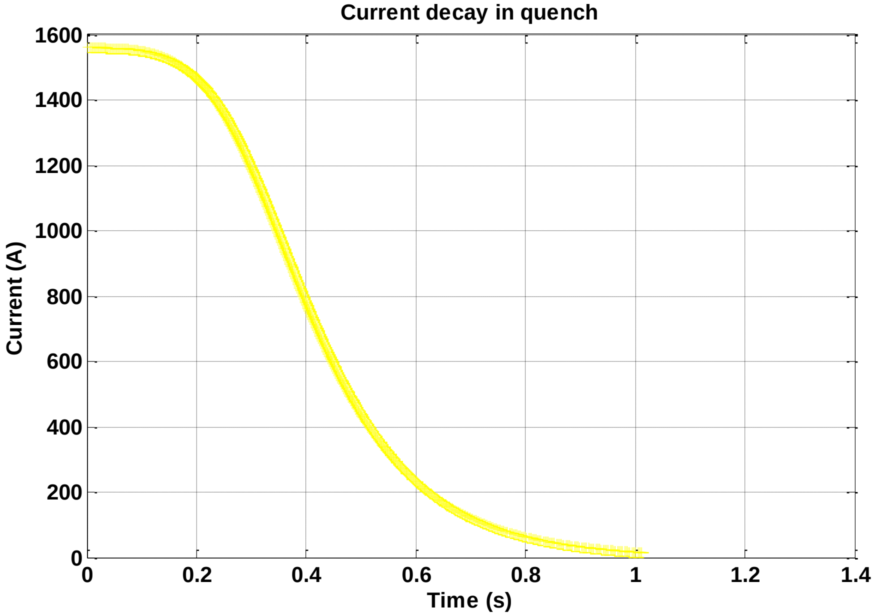
Geometry
- Material contraction.

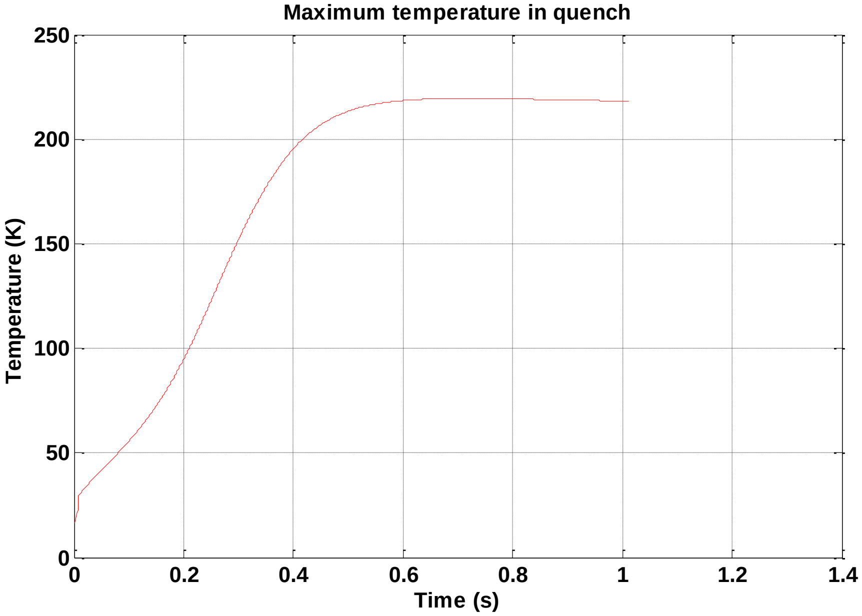
Insulation
- Insulation layer at the mid-plane.
- New insulation thickness.

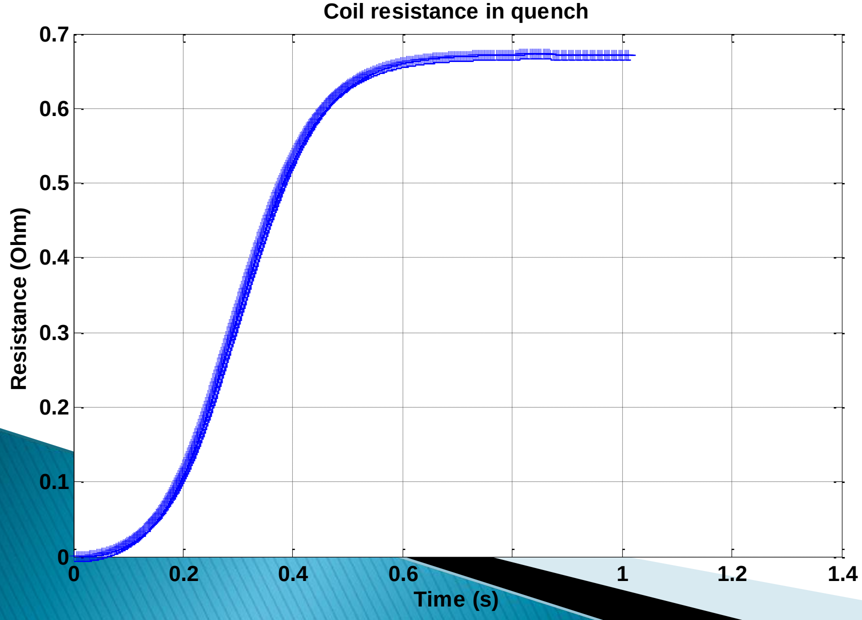
Integration
- MQXF holes and outer diameter

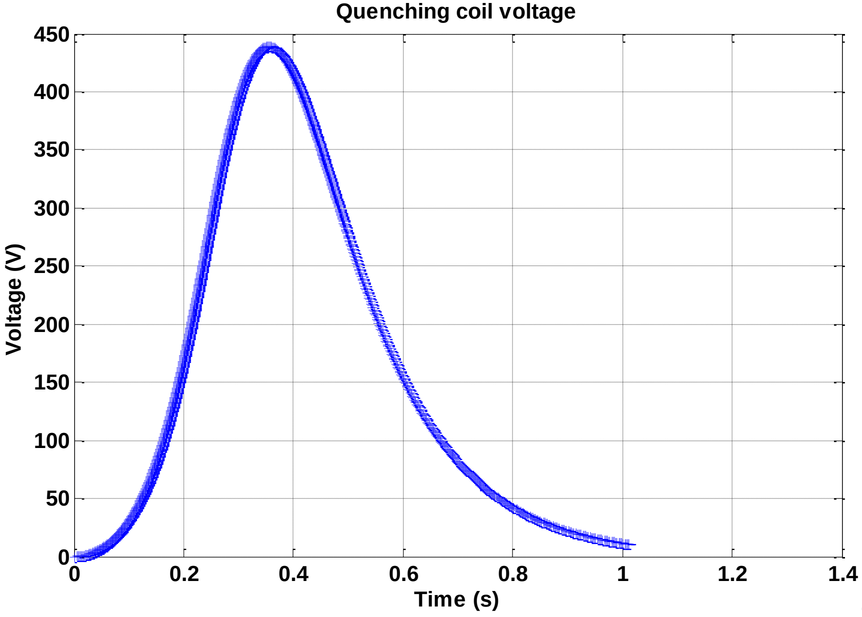
MCBXFA: No damping resistance included

Preliminary


Current decay in quench

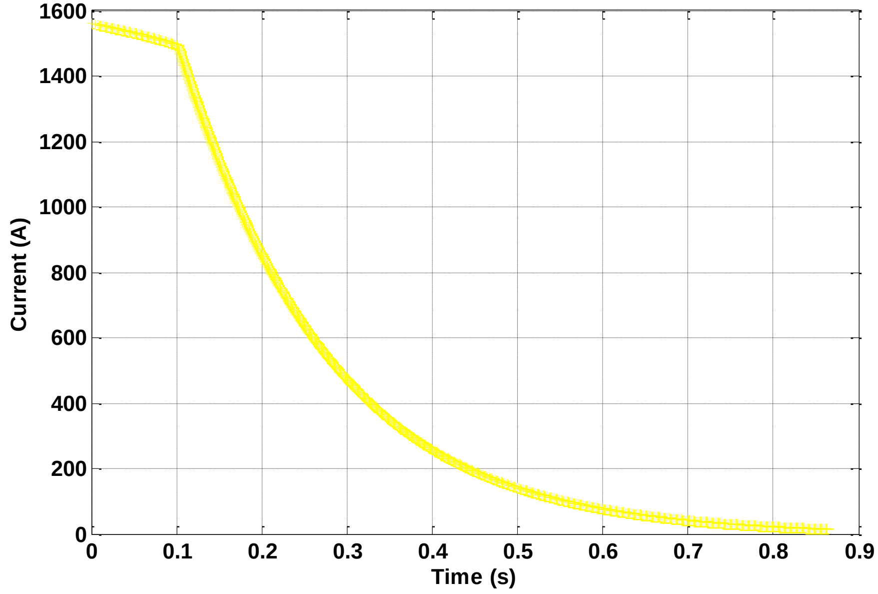

Maximum temperature in quench


Coil resistance in quench

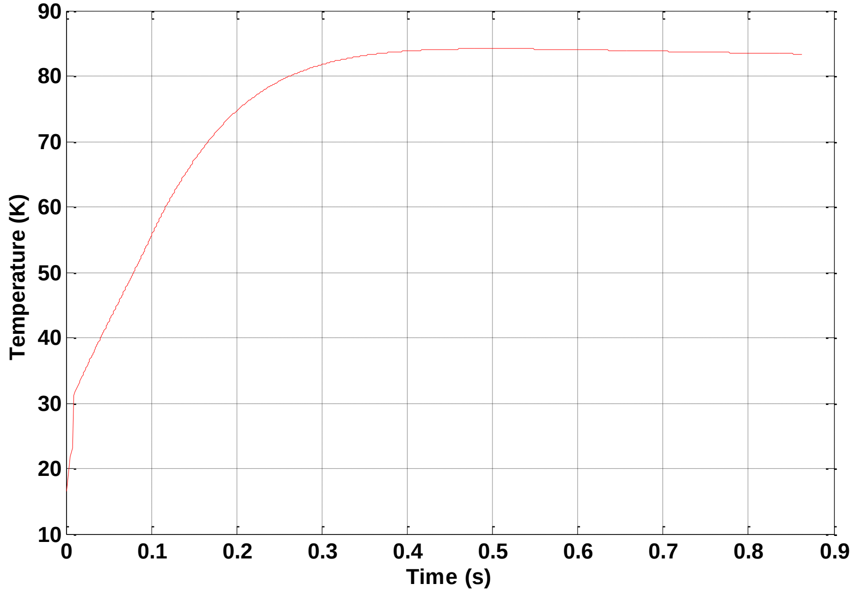

Quenching coil voltage

MCBXFA: Damping resistance = 0.3 Ω (0.1 s delay)

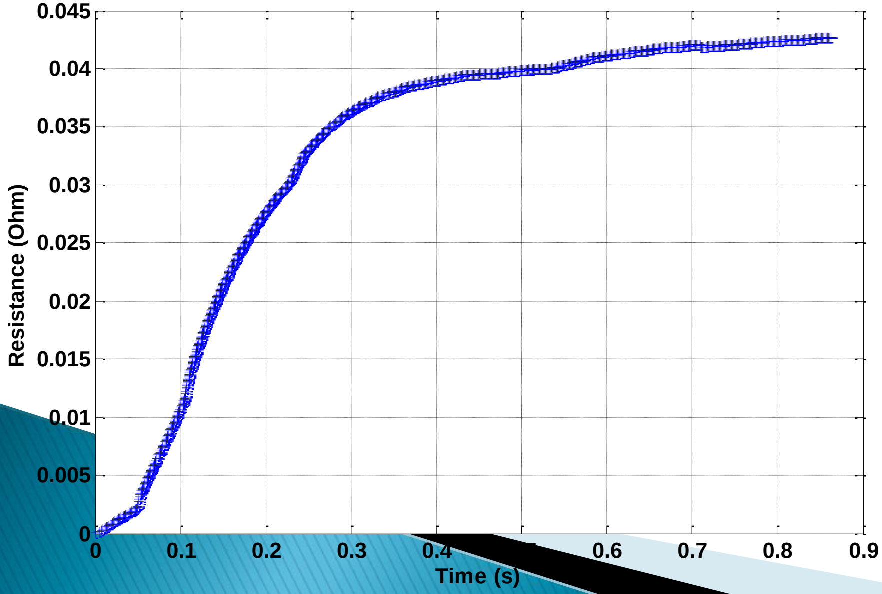
Preliminary



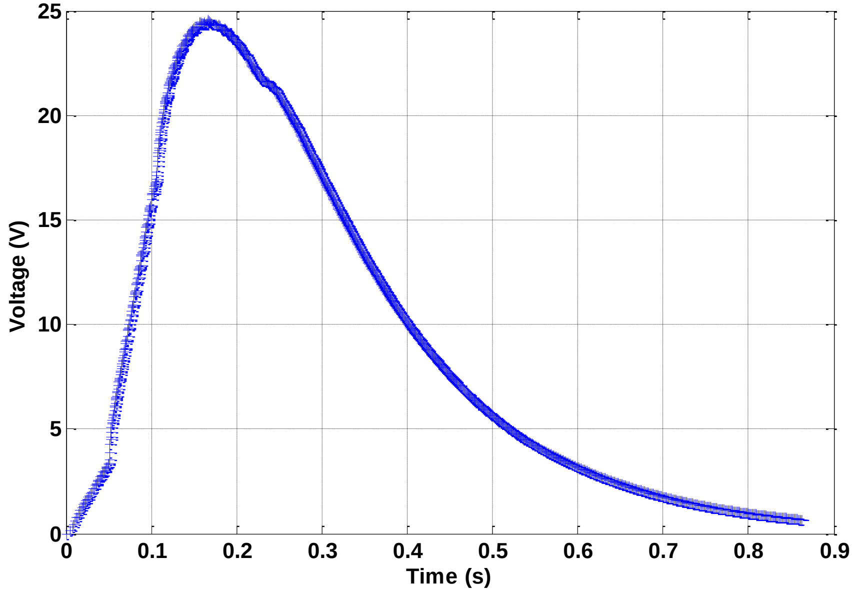
Current decay in quench



Maximum temperature in quench



Coil resistance in quench



Quenching coil voltage

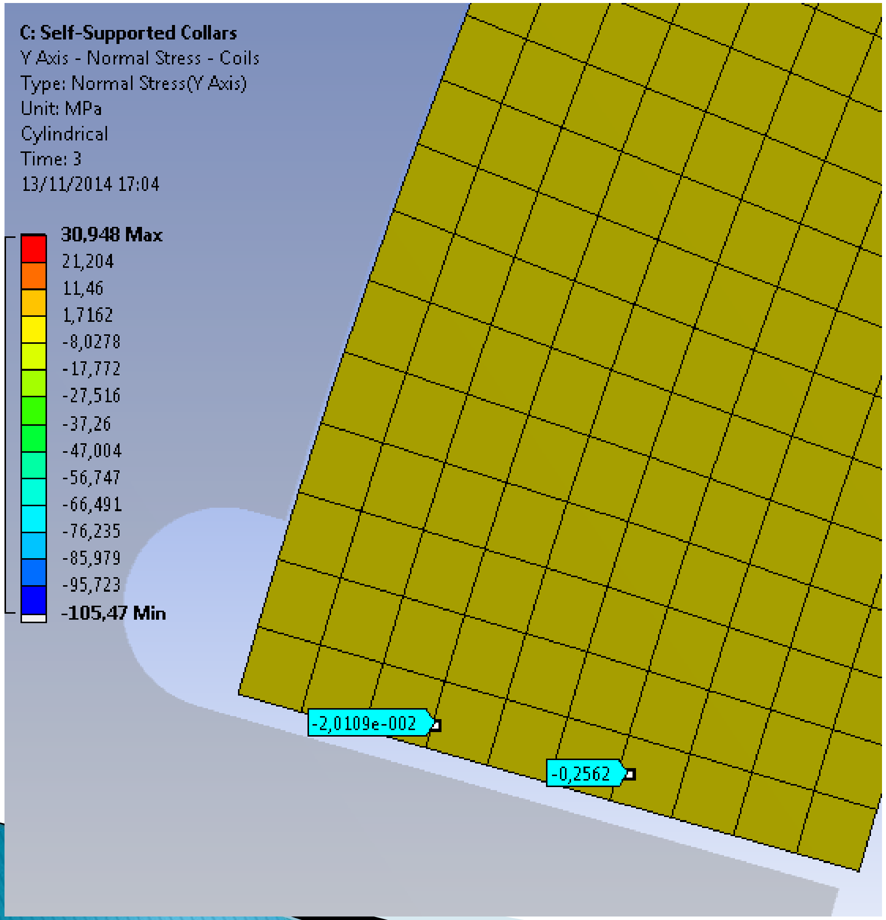
Model settings and convergence challenges

- 2D Ansys Workbench model.
  - 0.5-mm-thick shell elements at the collars.
  - 1-mm-thick shell elements for the rest of the assembly.
- Load steps.
  - t=0-1: Contact offset (pre-stress).
  - t=1-2: Assembly cooldown.
  - t=2-3: EM forces (exported from Maxwell, 108% Nominal current).
- Convergence/stability challenges
  - No symmetry boundary conditions can be used. DOF more difficult to constrain.
  - Many parts involved and linked by contact. Frictional contacts showed better performance that frictionless ones.
  - Techniques used to achieve convergence:
    - Adding extra boundary conditions.
    - Tuning up contact settings at problematic zones (Stabilization dumping factor, Normal stiffness, ramped effects...).

Results: Large azimuthal coil displacements
Outer Collar Diam.= 275 mm, Interference= 0.2 mm

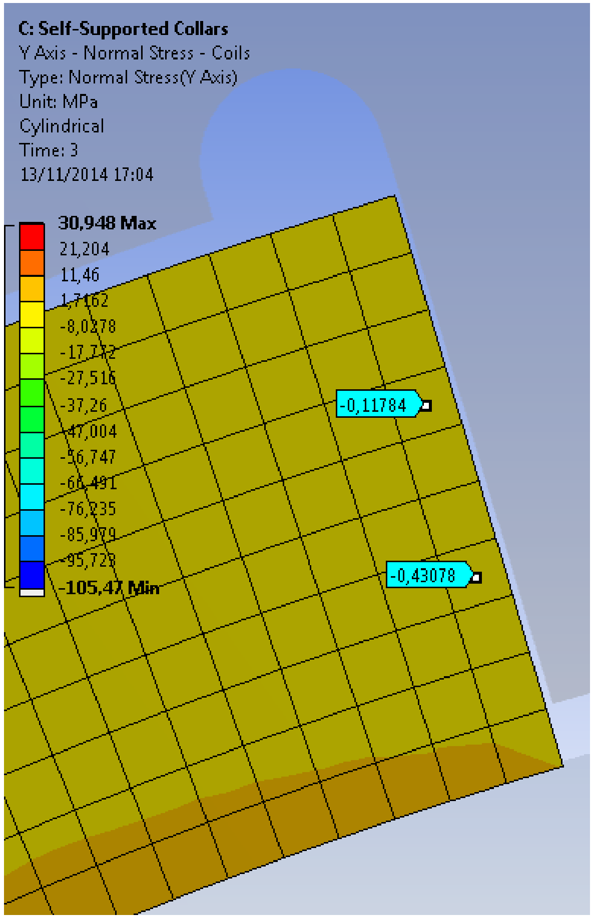
Azimuthal stress

Outer Coil



C: Self-Supported Collars
Y Axis - Normal Stress - Coils
Type: Normal Stress(Y Axis)
Unit: MPa
Cylindrical
Time: 3
13/11/2014 17:04

Inner Coil

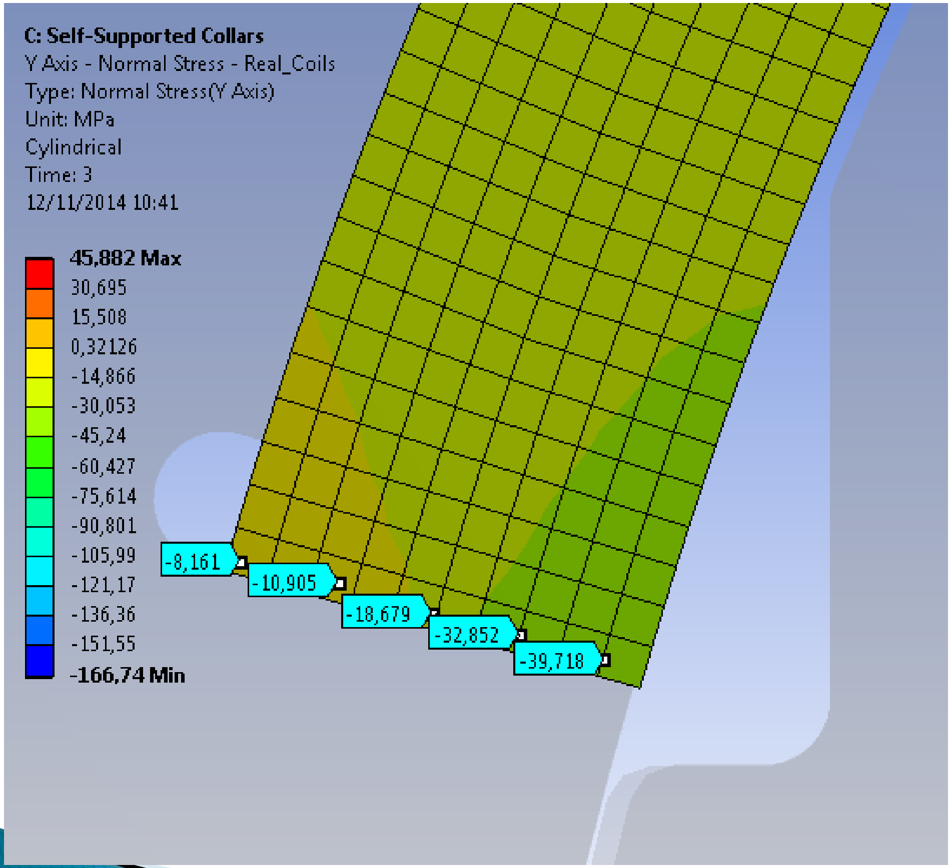


C: Self-Supported Collars
Y Axis - Normal Stress - Coils
Type: Normal Stress(Y Axis)
Unit: MPa
Cylindrical
Time: 3
13/11/2014 17:04

Results: Large azimuthal coil displacements
Outer Collar Diam.= 300 mm, Interference= 0.2 mm

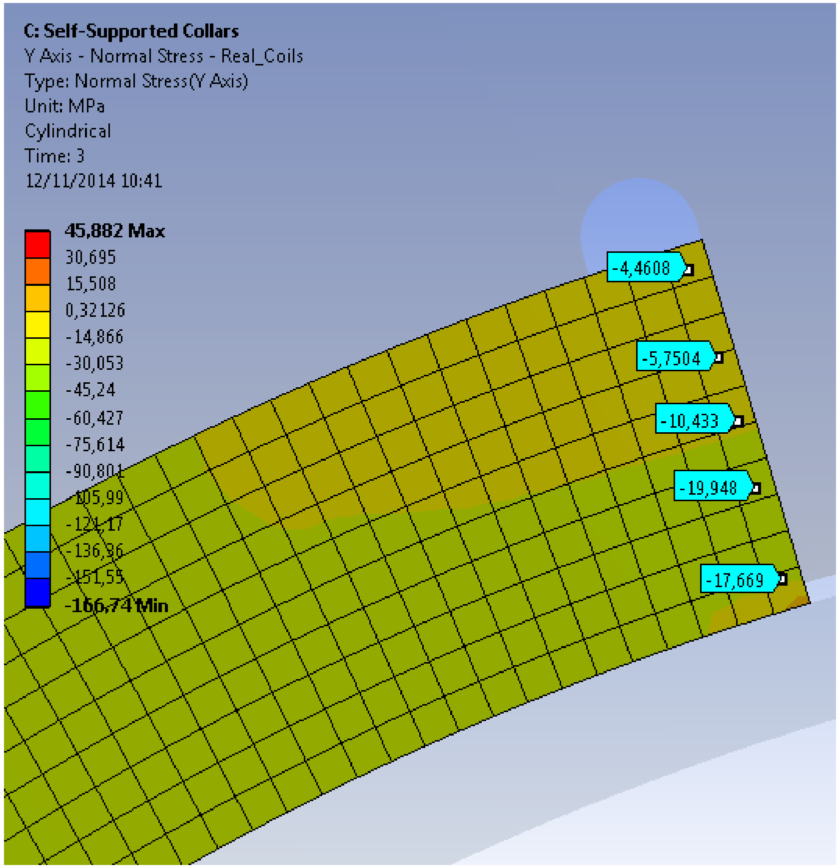
Azimuthal stress

Outer Coil



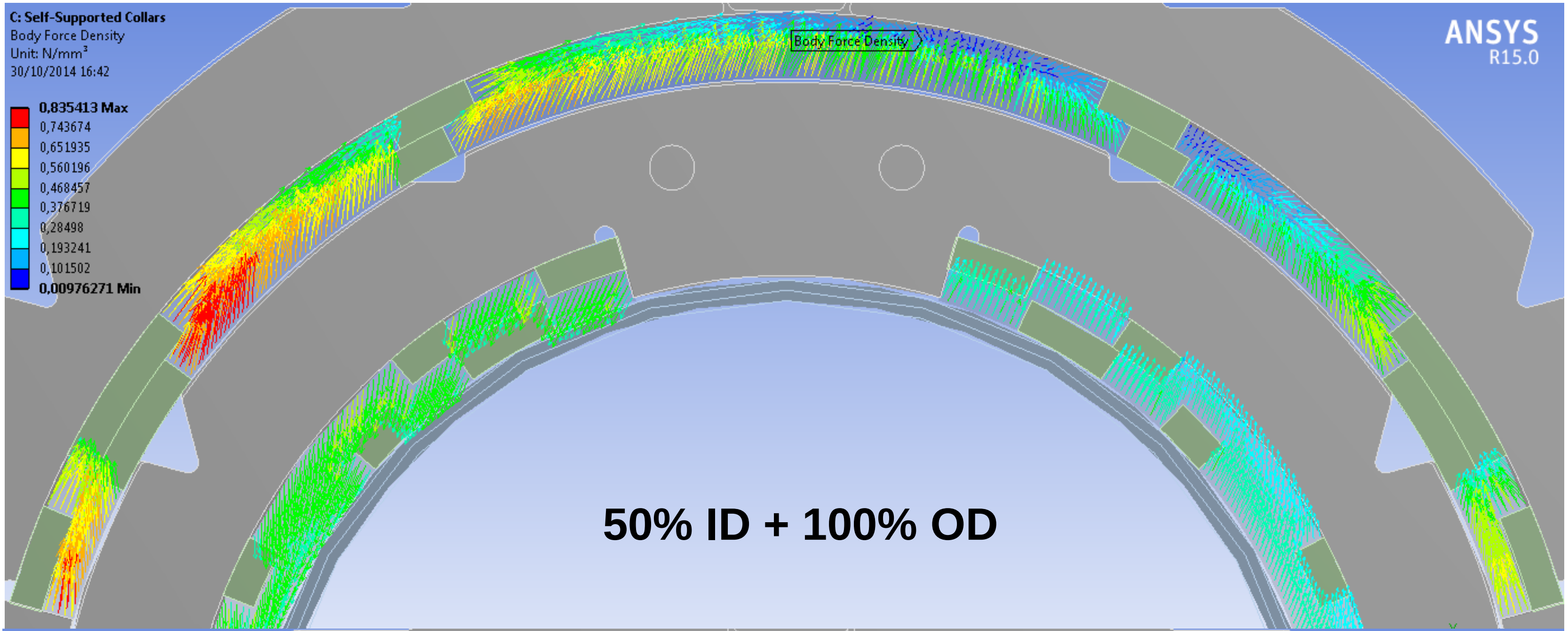
C: Self-Supported Collars
Y Axis - Normal Stress - Real_Coils
Type: Normal Stress(Y Axis)
Unit: MPa
Cylindrical
Time: 3
12/11/2014 10:41

Inner Coil

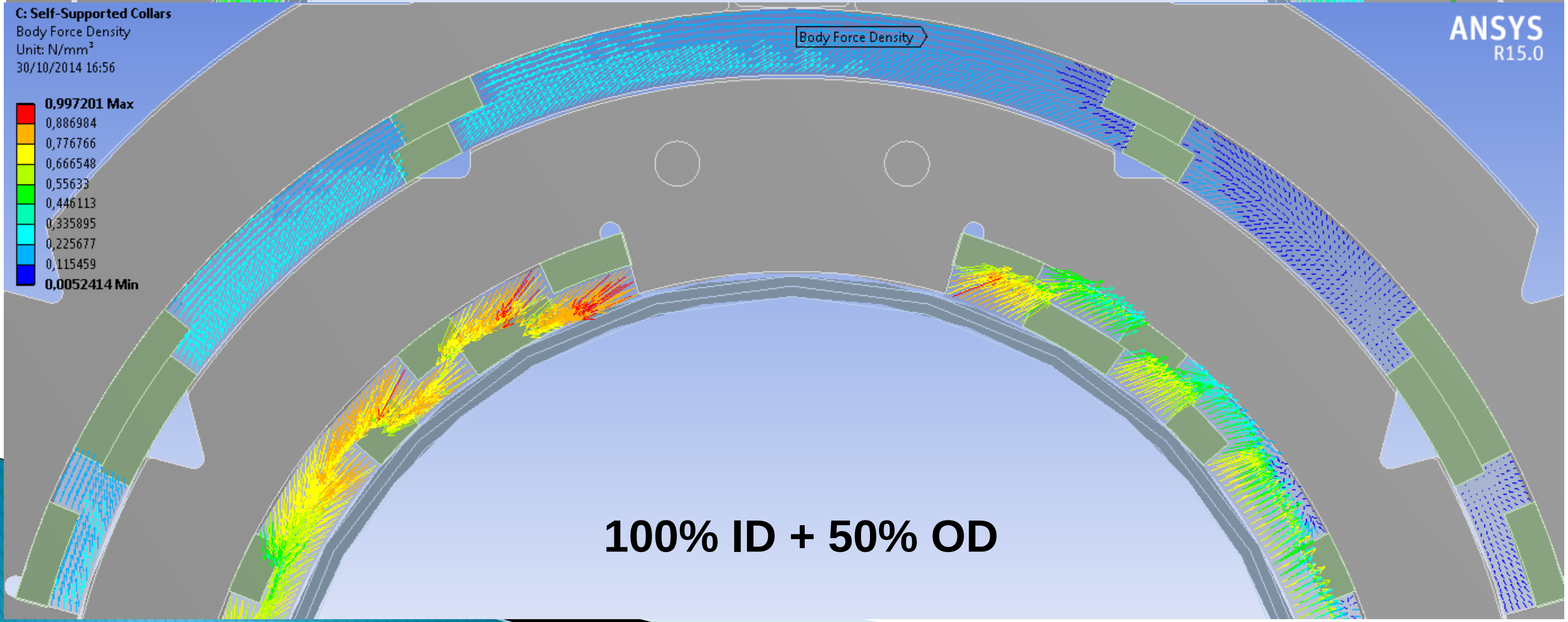


C: Self-Supported Collars
Y Axis - Normal Stress - Real_Coils
Type: Normal Stress(Y Axis)
Unit: MPa
Cylindrical
Time: 3
12/11/2014 10:41

Results: Radial Inward Forces



50% ID + 100% OD



100% ID + 50% OD

Materials

- Cable, wedges and inter-layer insulation: glass fibre sleeve impregnated with binder treatment as hardener (PVA to be studied).
- Wedges: machined from ETP copper.
- End spacers: 3D printed in stainless steel.
- Ground insulation: Polyimide sheets
- Vacuum impregnated coils, radiation hard resin (cyanate-ester blend).
- Collars: Machined by EDM in stainless steel.
- Iron: To be evaluated.
- Connection plate: Hard radiation resistant composite, like Ultem.
- End plates: Stainless steel.
- Inner pipe: Titanium grade 2 if grade 5 is not available.

Winding

- Customized winding machine lent by CERN
  - New beam: 2.5 m long.
  - Electromagnetic brake.
  - Horizontal spool axis.
- Winding process
  - Stainless steel mandrel protected with a polyimide sheet.
  - Binder impregnation and curation.
  - Outer layer will be wound on top of the inner one with an intermediate glassfiber sheet for extra protection.
  - Vacuum impregnation with hard radiation resin.

Assembly

- Collars placed around the coils with a vertical press (custom tooling required).
- Layer of protection between both dipoles, likely a glass fibre sheet
- Innermost turn of the coils will be protected by a stainless steel sheet from the collar nose sliding.
- Iron laminations around the coil assembly.