Cosθ 16 T dipole for FCC

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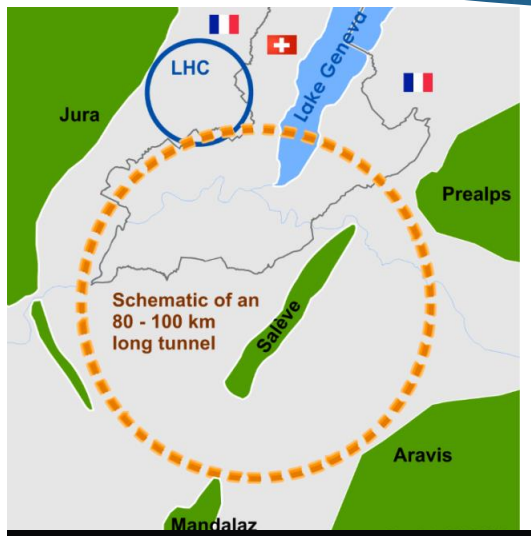
Outlook

- Introduction on FCC project
- EuroCirCol within FCC
- Cosθ layout
- Magnetic design
- Mechanical design
- Conclusions and future developments

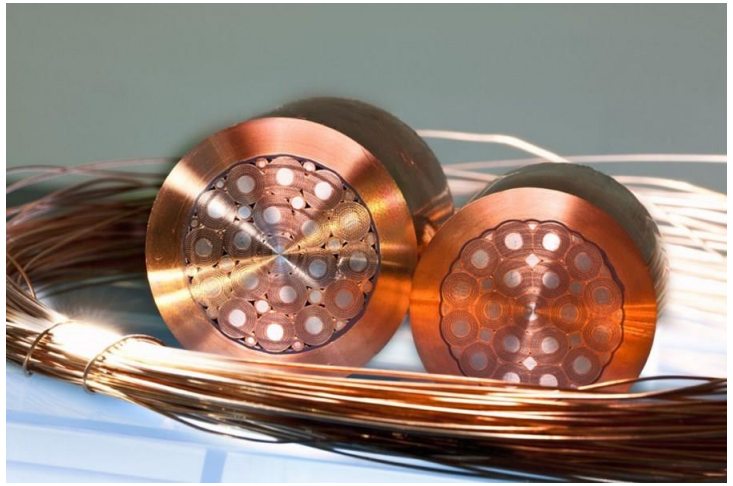
Future Circular Collider (FCC)



- **Future Circular Collider (FCC)**
  Circumference: 90 -100 km
  Energy: 100 TeV (pp) 90-350 GeV (e^+e^-)
- **Large Hadron Collider (LHC)**
  Large Electron-Positron Collider (LEP)
  Circumference: 27 km
  Energy: 14 TeV (pp) 209 GeV (e^+e^-)

LHC p=7 TeV, L=27 km → B=8 T

FCC p=50 TeV, L=100 km → B=16 T

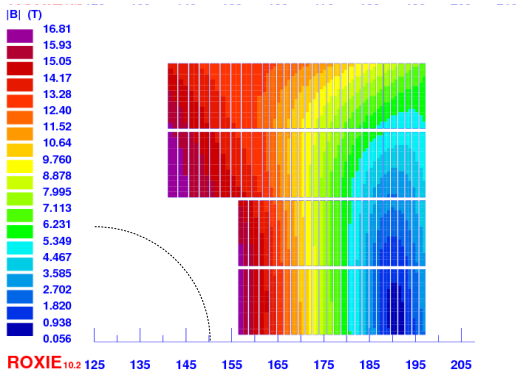


Nb_3Sn brittle after thermal treatment, in particular at room temperature.

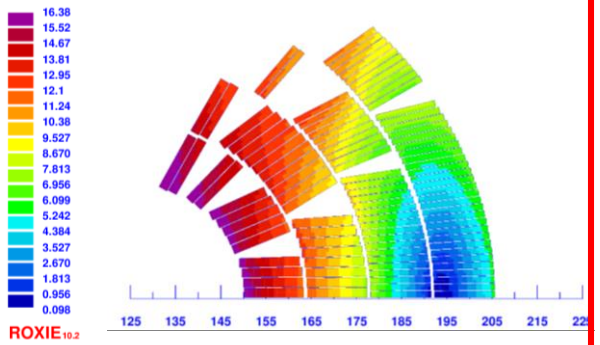
EuroCirCol project

Aim: provide a conceptual design for a hadron collider to the FCC project.
WP5 will deliver the conceptual design for the 16 T bending dipoles, 50 mm aperture.
3 configurations are currenlty being studied:

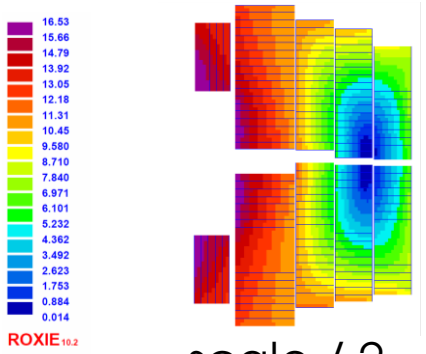
CEA Block coil



INFN Cosθ coil



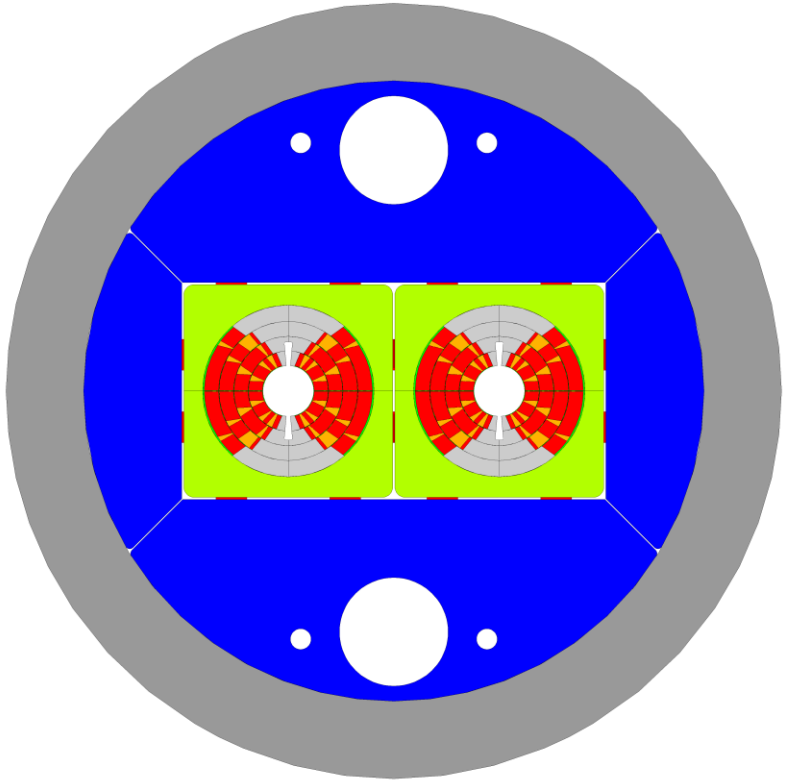
CIEMAT Common coil



scale / 2

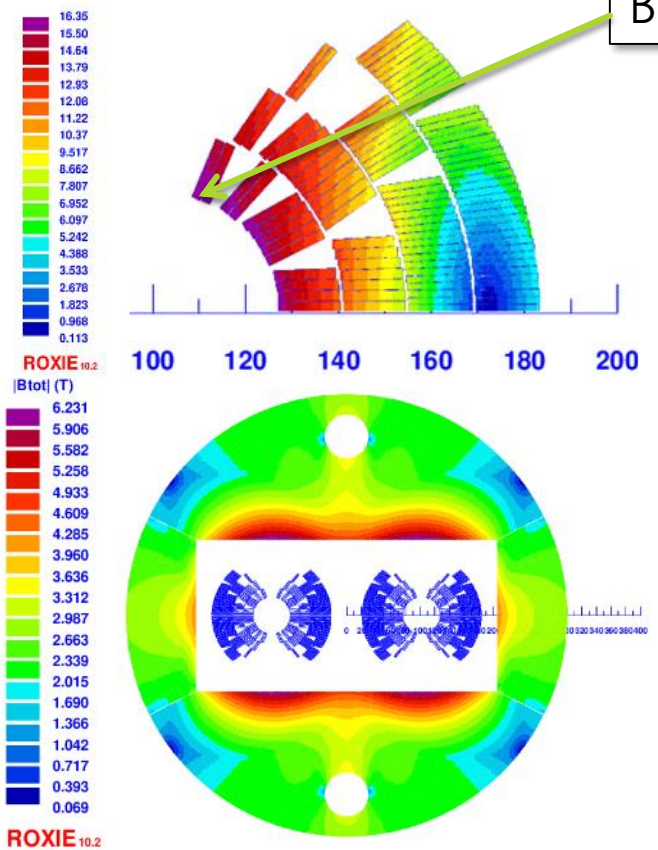
Conductor performance assumption: 2300 A/mm^2 @1.9 K@ 16 T, RRR=100, d_{strand}^{MAX}=1.2 mm
Cu/non CU_{MIN}=0.8:1, Margin 14 %

Cosθ coil layout



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	≥ 0.85
Field harmonics (geometric/saturation)	≤ 3/10 units
Yoke outer radius	300 mm

Magnetic design



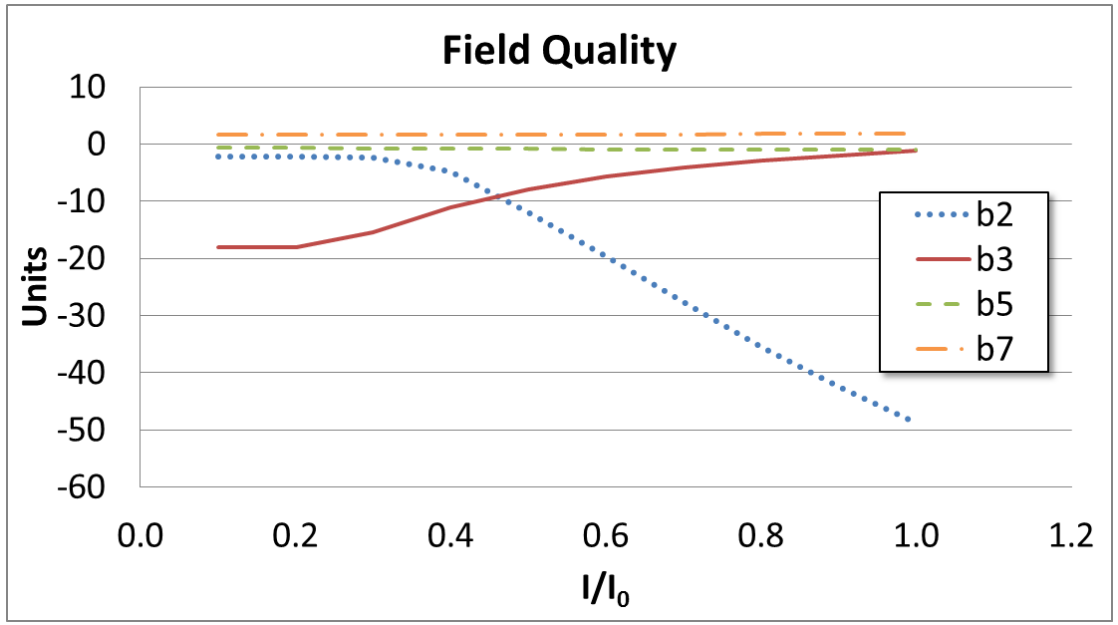
B_{peak}: 16.35 T

Number of turns:
Layer 1: 13
Layer 2: 19
Layer 3: 29
Layer 4: 39
Tot: 200/ap.

	HF Cable (inner)	LF Cable (outer)
Strand number	22	37
Strand diameter	1.1 mm	0.7 mm
Bare width	13.2 mm	13.65mm
Bare inner thickness	1.892 mm	1.204 mm
Bare outer thickness	2.072 mm	1.3231 mm
Insulation	0.15 mm	0.15 mm
Keystone angle	0.5°	0.5°
Cu/NCu	0.9	2.2
Operating current	11230 A	11230 A
Operating point on LL (1.9 K)	86 %	86 %

Magnetic analysis

High-order harmonics at 16 T						
b2	b3	b5	b7	b9	b11	b13
−48.8	−1.2	−1.0	1.7	1.4	1.0	−0.2



- All harmonics are **within constraints**
- b2 optimization **not yet** performed
- **Persistent currents** will be evaluated in the next months, together with a more detailed design of the **iron yoke**

Mechanical Constraints

- 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	$1.7\ 10^{-3}$

Critical Current Measurements of High-J_c Nb_3Sn Rutherford Cables under Transverse Compression

B. Bordini, P. Alknes, A. Ballarino, L. Bottura, L. Oberli

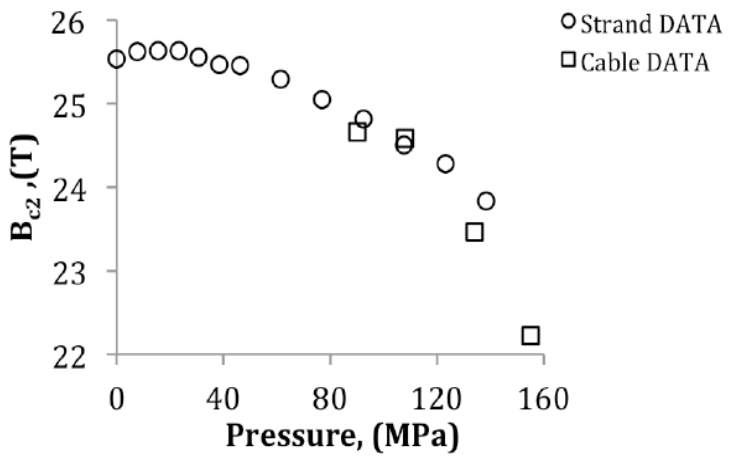
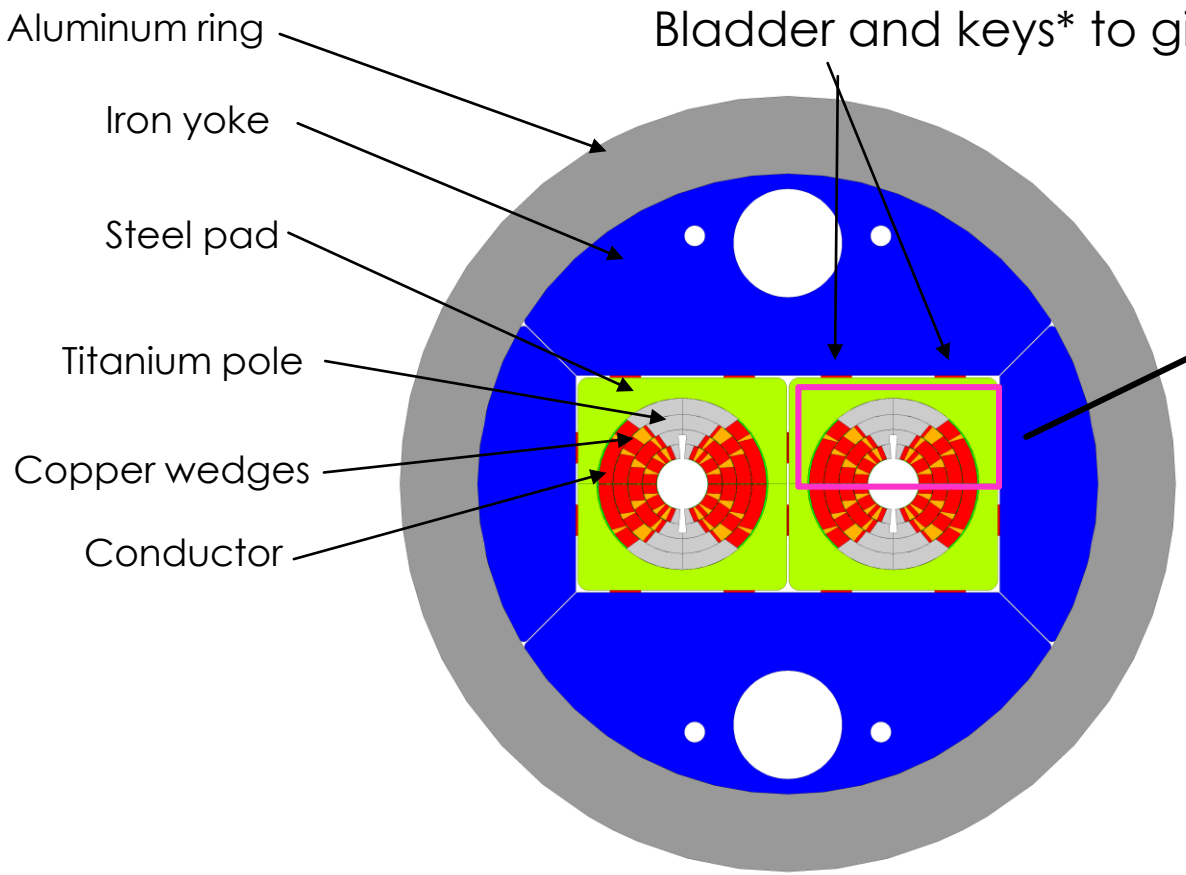
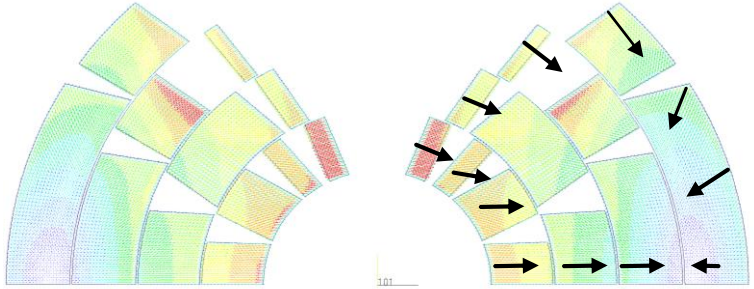


Fig. 6. Upper critical field at 4.2 K estimated from the critical current measurements under transversal pressure.

Mechanical structures





Lorentz forces tend to push the coil:

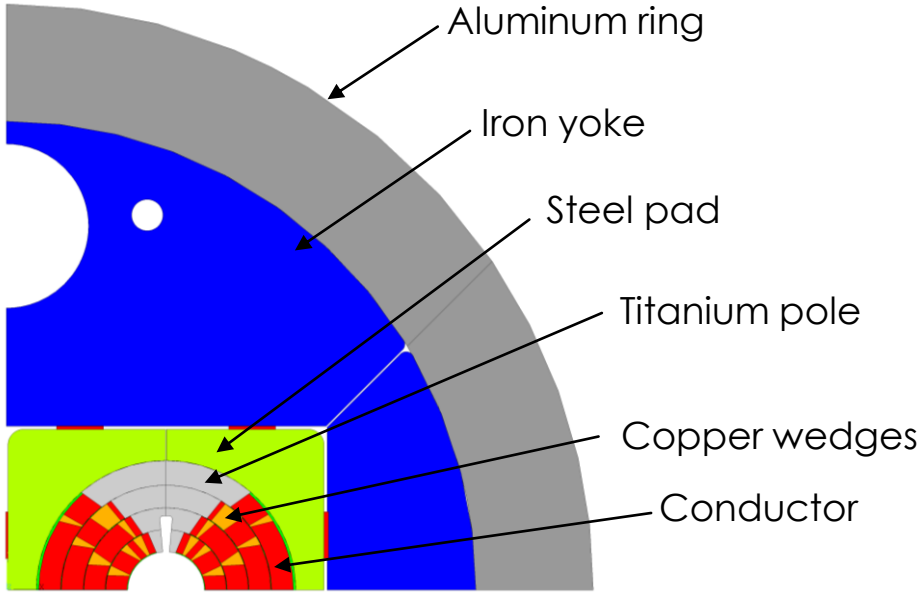
- Outward in the radial direction
- Toward the midplane in the azimuthal direction

Can cause a detachment of the coil from the pole that must be avoided!

*"**The Use of Pressurized Bladders for Stress Control of Superconducting Magnets** " Shlomo Caspi et all (2011)

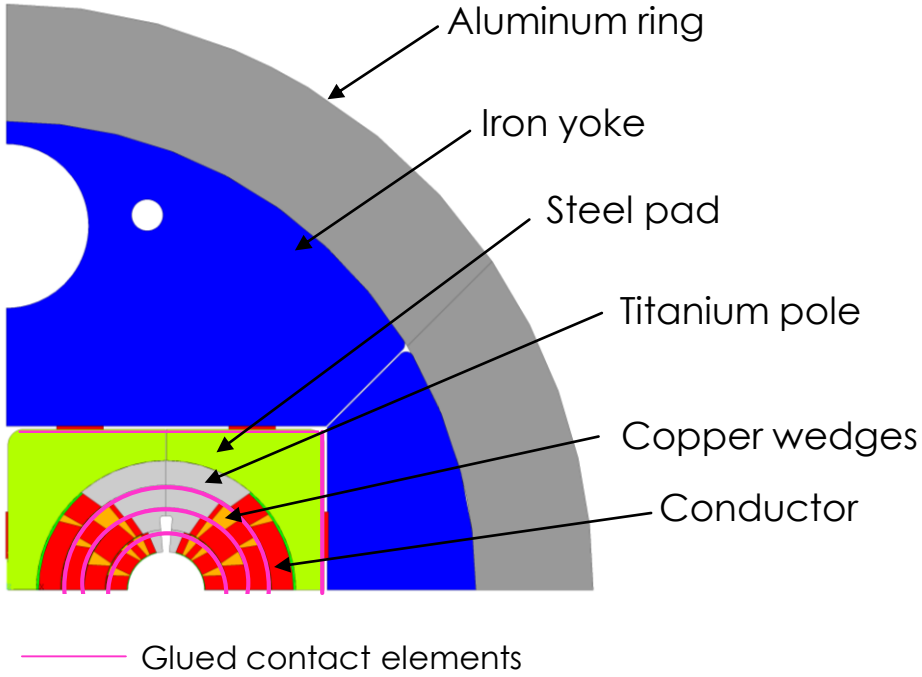
Mechanical analysis

ANSYS model



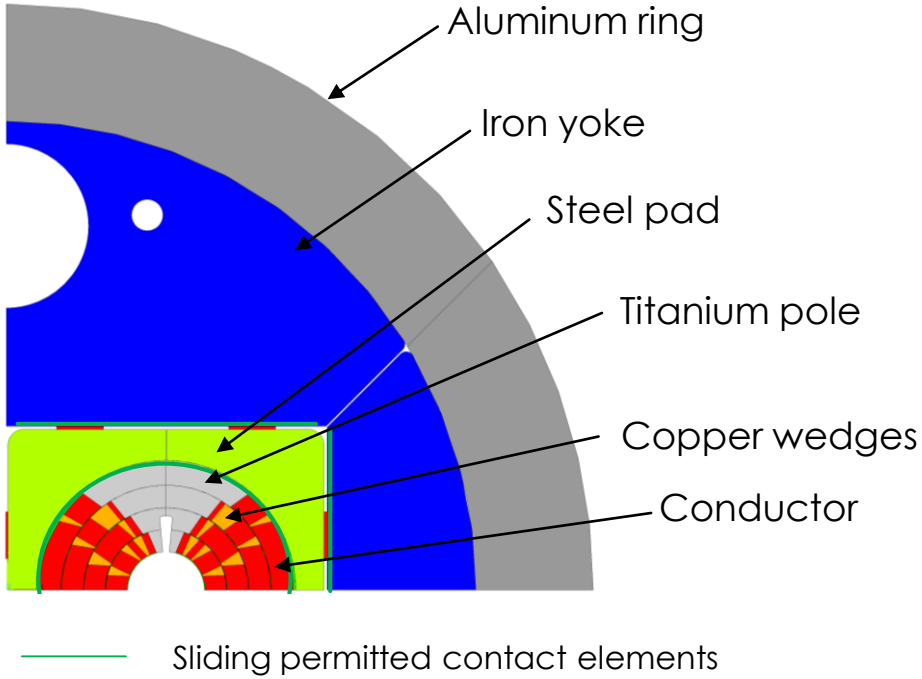
Mechanical analysis

ANSYS model



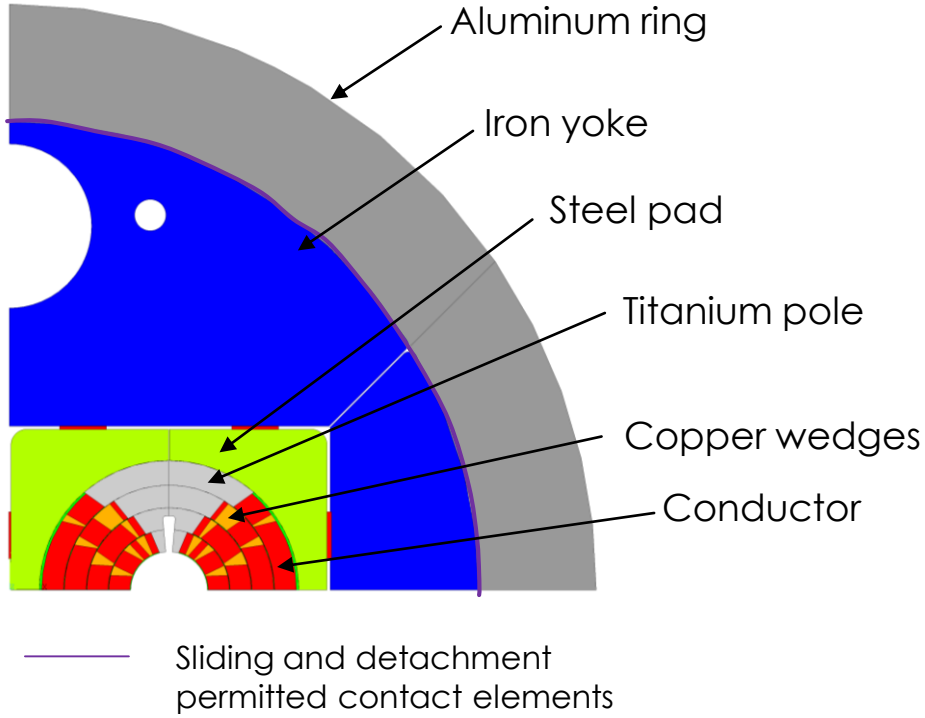
Mechanical analysis

ANSYS model



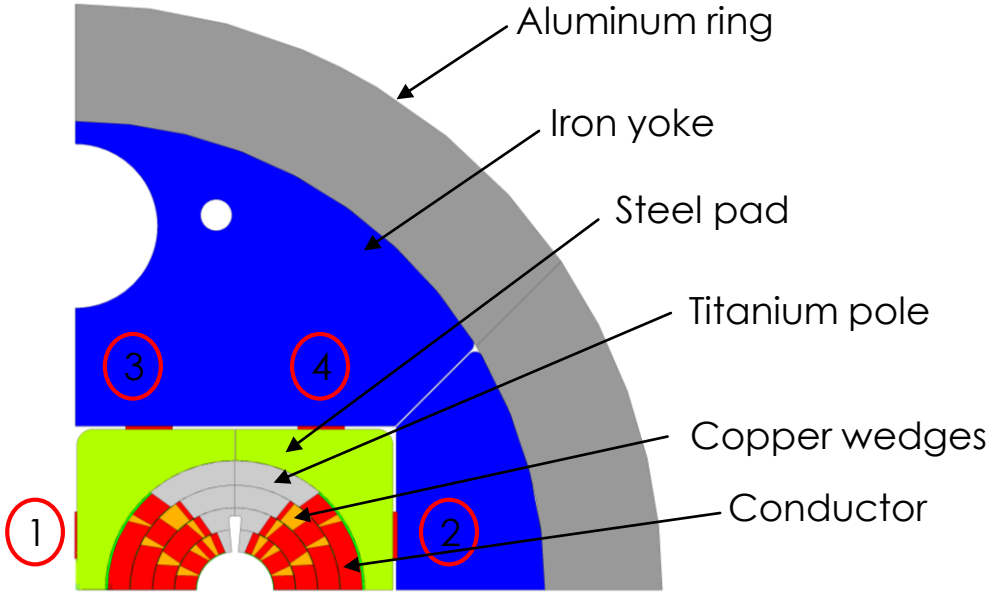
Mechanical analysis

ANSYS model



Mechanical analysis

ANSYS model



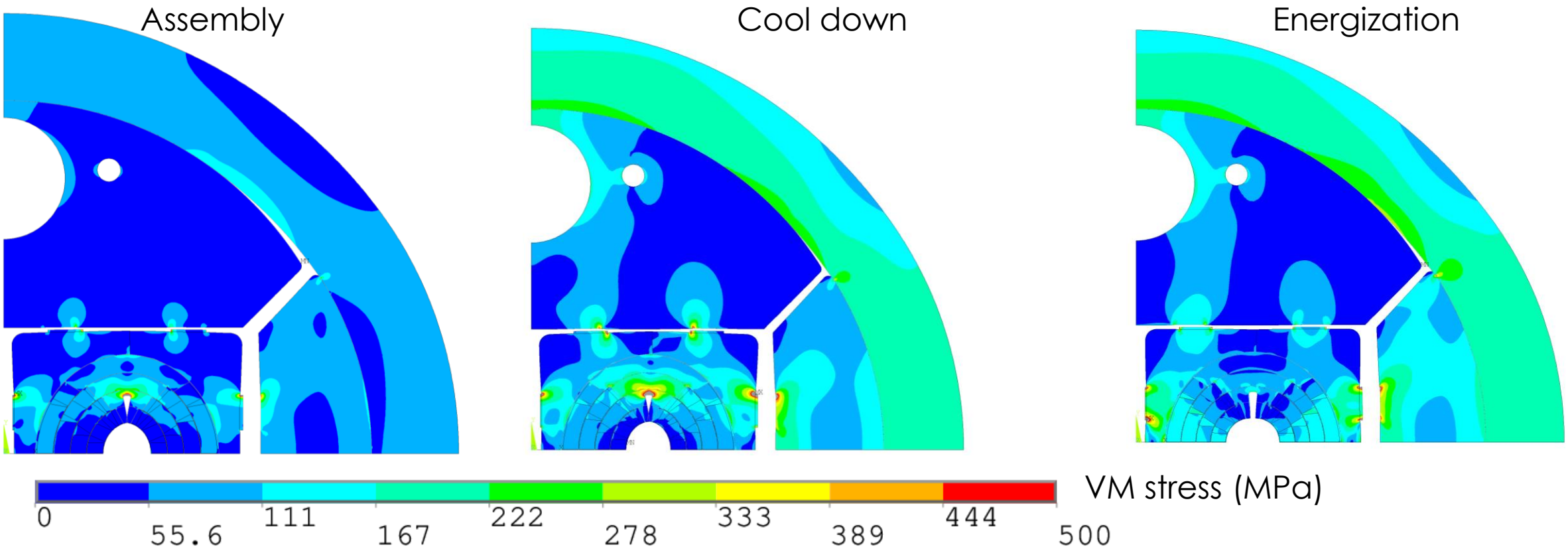
- Step 1: insertion of key 1
- Step 2: insertion of key 2 (60 Mpa applied)
- Step 3 insertion of keys 3 and 4 (30 Mpa applied)

} assembly

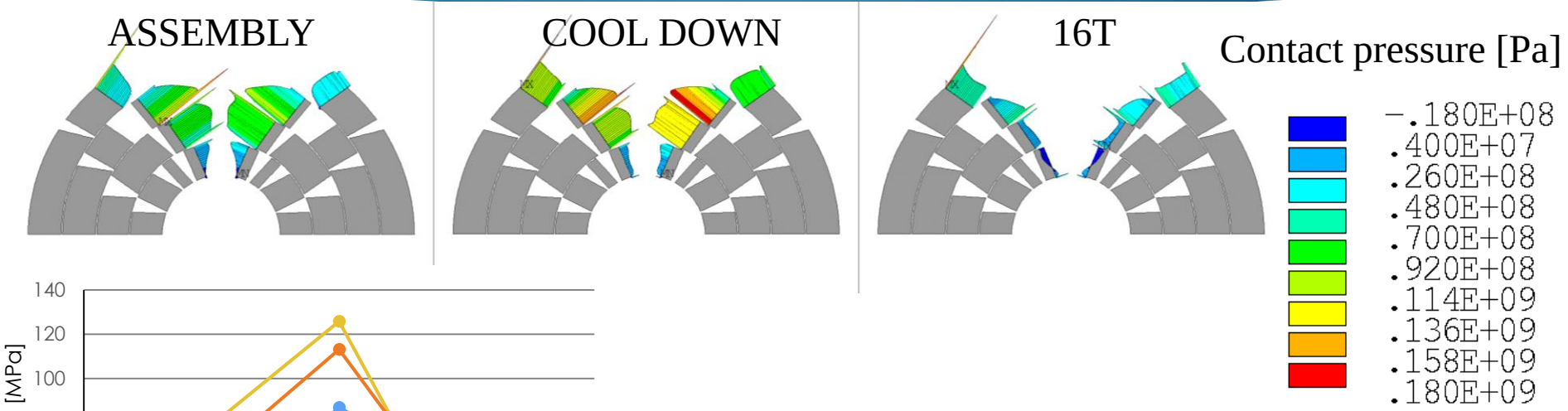
- Step 4: cooling down
- Step 5: energization to 16 T (application of Lorentz forces to the conductor elements)

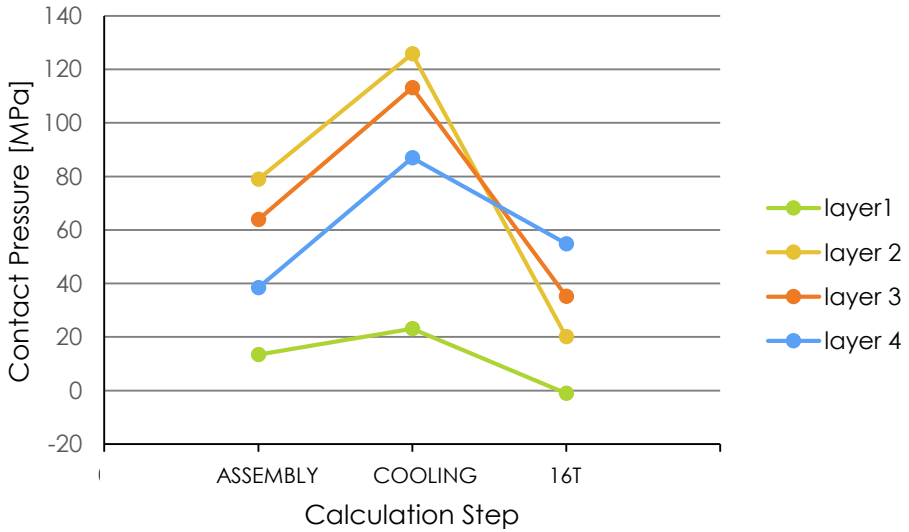
Mechanical analysis

Deformation x 20



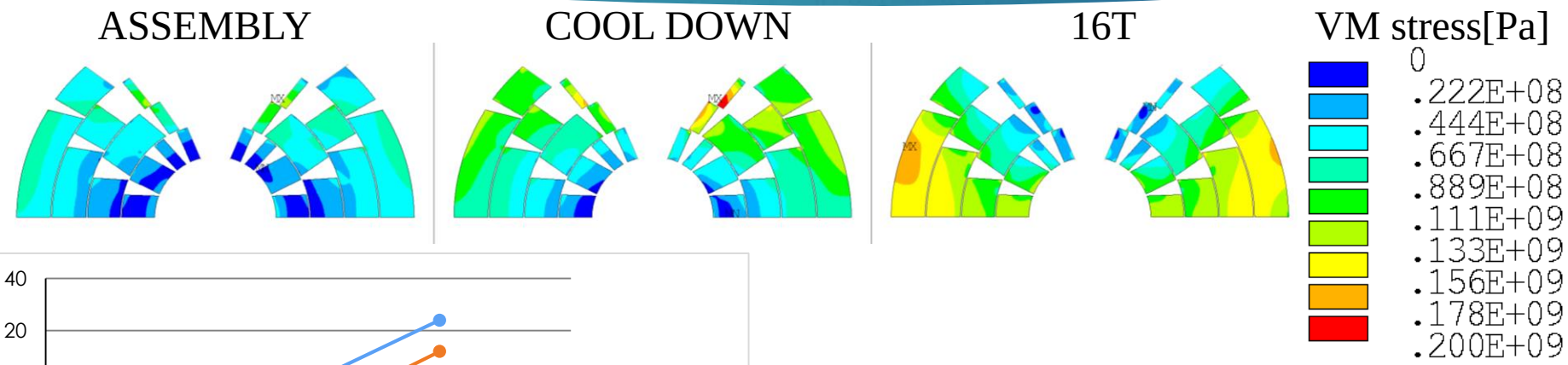
Mechanical analysis

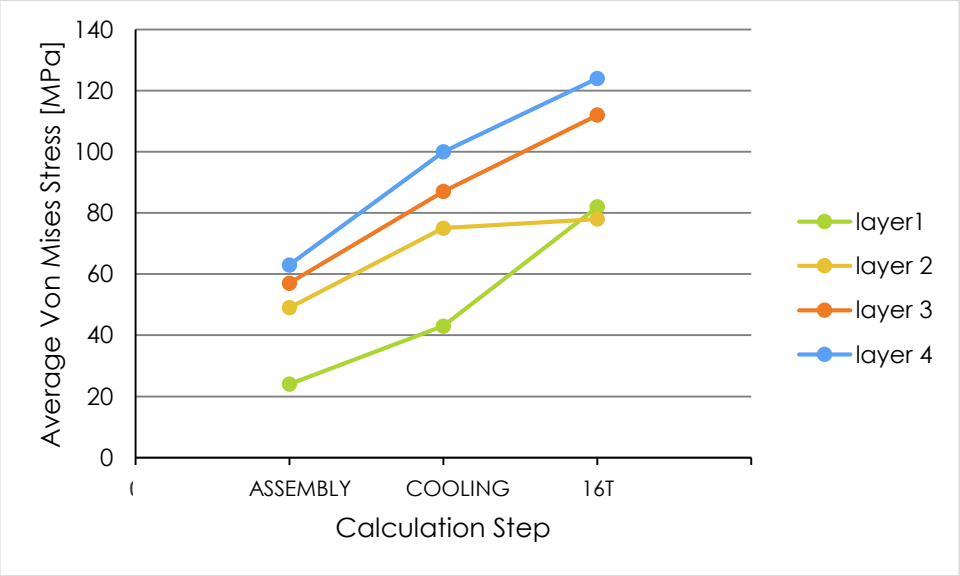




- Contact pressure increases after cool down (Al ring shrinking)
- No detachment even after energization at 16T

Mechanical analysis



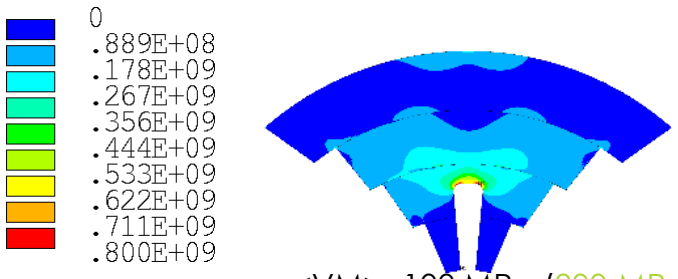


- VM stress far below current degradation limit (150 MPa @ RT -200 MPa @ 1.9K)
- Localized hot spot after cooling down (edge effect, negligible)

Mechanical analysis

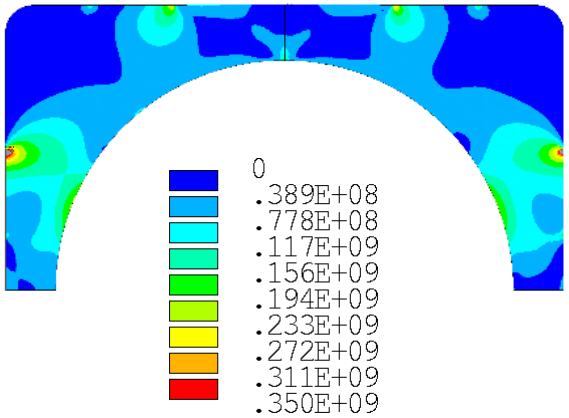
ASSEMBLY

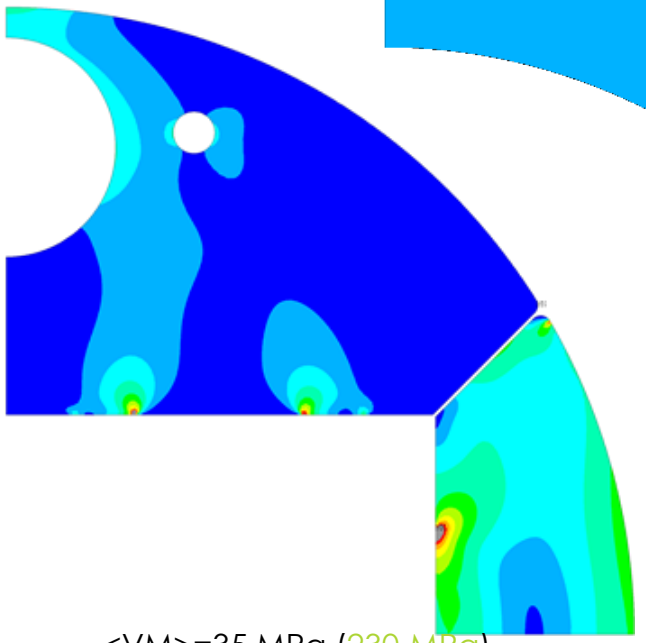
MATERIAL	Stress limit [MPa] RT	1.9 K
Austenitic steel (316LN)	350	1050
Al7075	480	690
Ferromagnetic iron	230	720
Ti6Al4V	800	1650



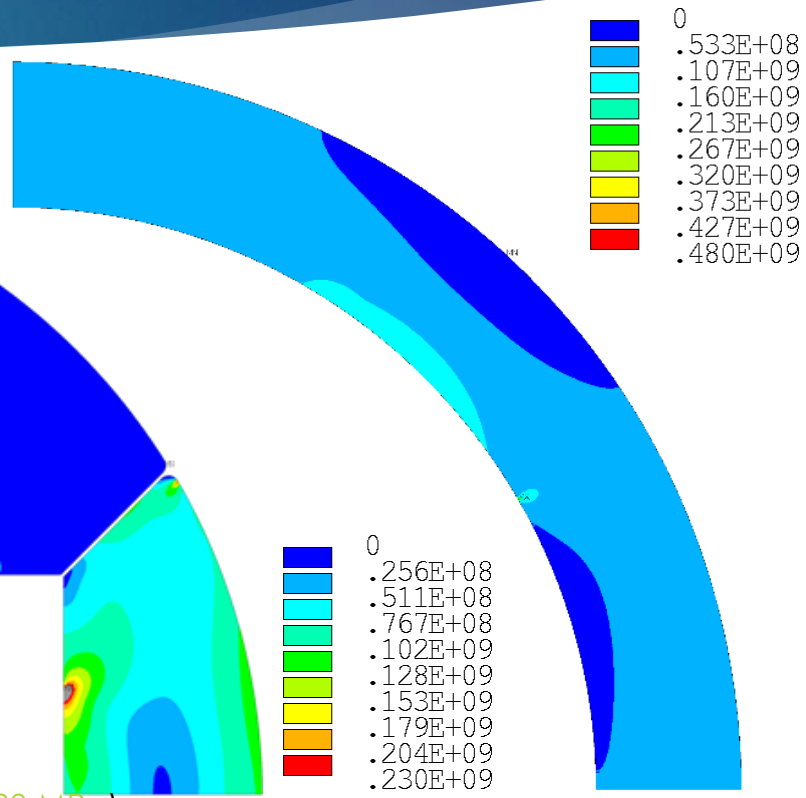
<VM>=100 MPa (800 MPa)

<VM>=55 MPa (350 MPa)





<VM>=35 MPa (230 MPa)

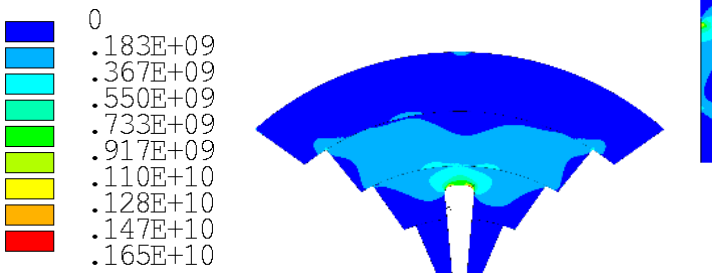


<VM>=70 MPa (480 MPa)

Mechanical analysis

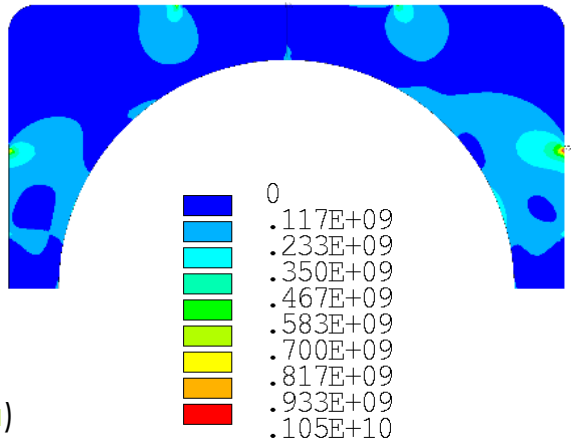
COOL DOWN

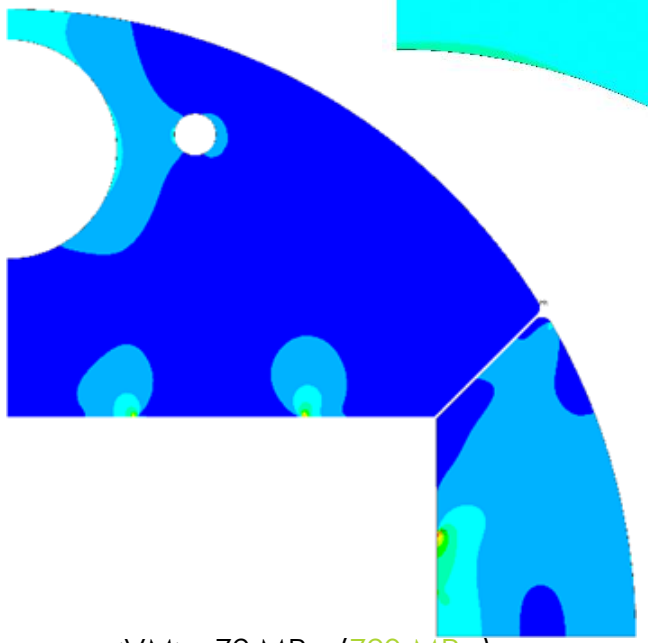
MATERIAL	Stress limit [MPa] RT	1.9 K
Austenitic steel (316LN)	350	1050
Al7075	480	690
Ferromagnetic iron	230	720
Ti6Al4V	800	1650



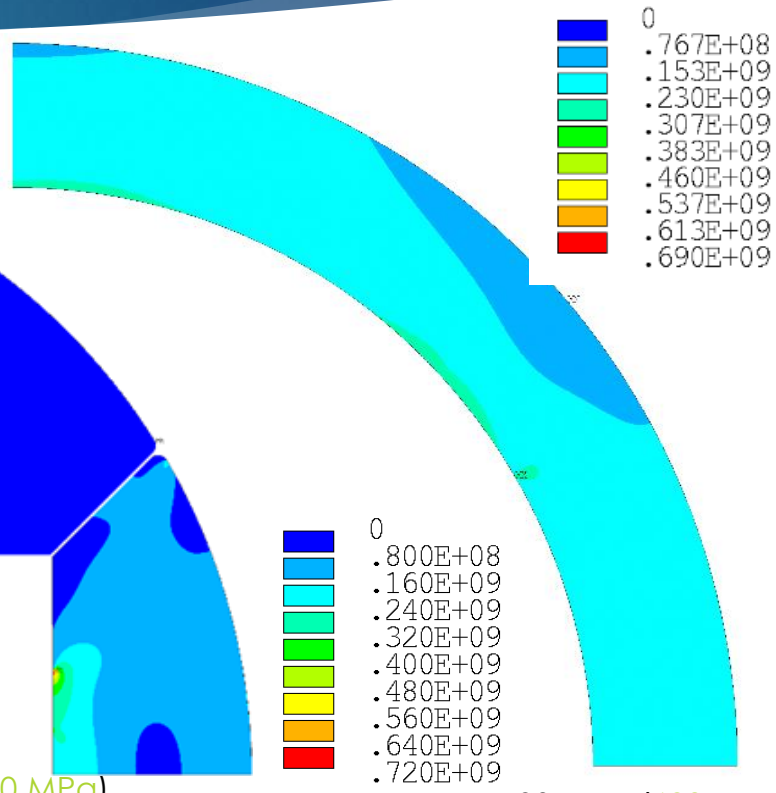
<VM>=165 MPa (1650 MPa)

<VM>=98 MPa (1050 MPa)





<VM>=72 MPa (720 MPa)

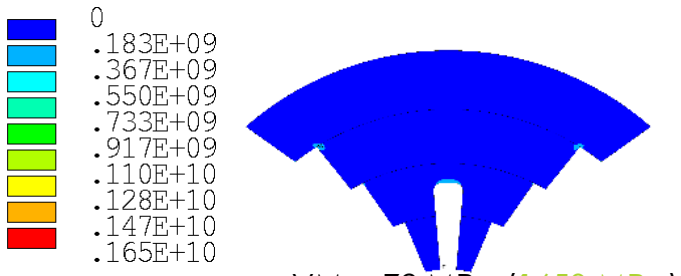


<VM>=180 MPa (690 MPa)

Mechanical analysis

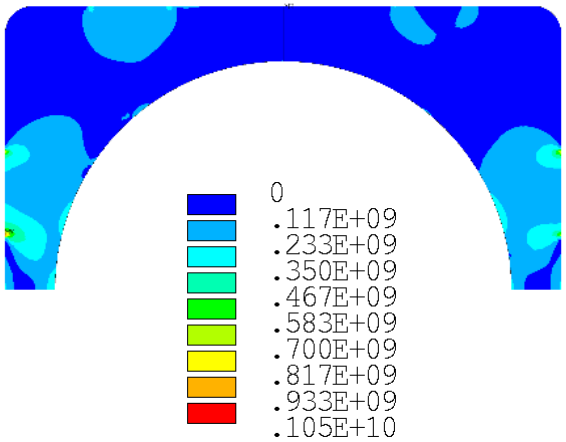
ENERGIZATION

MATERIAL	Stress limit [MPa] RT	1.9 K
Austenitic steel (316LN)	350	1050
Al7075	480	690
Ferromagnetic iron	230	720
Ti6Al4V	800	1650

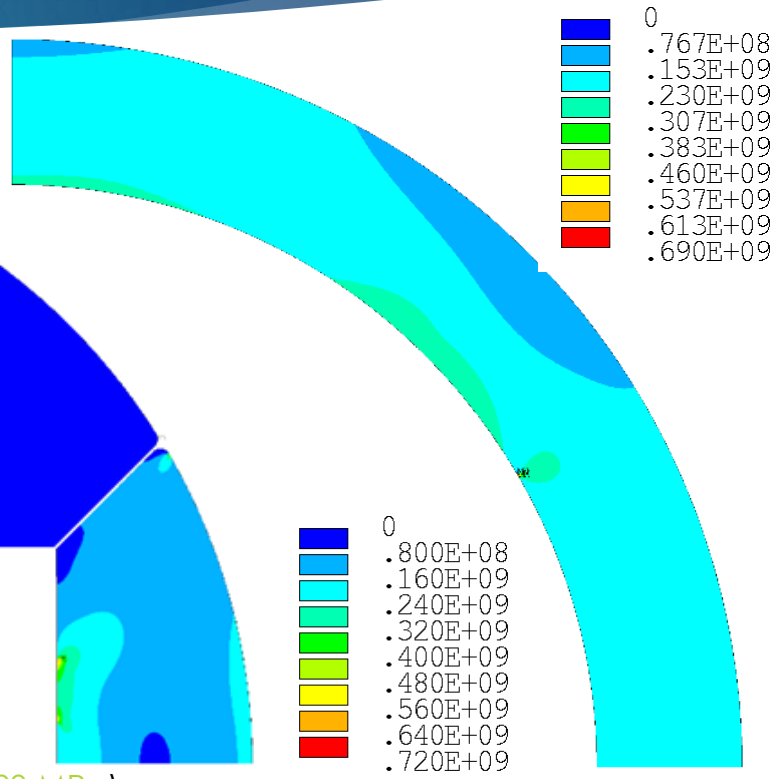


<VM>=72 MPa (1650 MPa)

<VM>=103 MPa (1050 MPa)



<VM>=75 MPa (720 MPa)



<VM>=187 MPa (690 MPa)

Conclusions

- In the framework of the EuroCirCol project, 16 T dipoles for FCC are being studied. INFN is in charge of the cosθ coil configuration, presented in this contribution in its double aperture (LHC-like) version.
- Extensive mechanical and magnetic analysis leads to a promising configuration, composed by two 4 layers graded coils, inserted in a layered structure (coils < rectangular steel pad < magnetic yoke < aluminum ring). The required pre-stress is given by the «bladder and keys» technique
- Our model, assuming realistic condition on the cable used :
  - fullfils all the mechanical constrains, both the stress level in the conductore and in the support structure and the contact pressure between the coil and the poles;
  - fulfils requirments on margin and peak field and exhibits acceptable quality field
- Considering the maturity of the analysis, INFN in collaboration with CERN is evaluating the possibility to build a demonstrative short model (2 m long).

Thank you

Back-up slides

Cable assumption:
1500 A/mm2 @1.9 K @ 16 T
RRR=100
d_{strand}^{MAX}=1.2 mm
Cu/non CU_{MIN}=0.8:1
Margin 14 %