
CERN

FCC-hh beam screen design

3rd FCC week, Berlin

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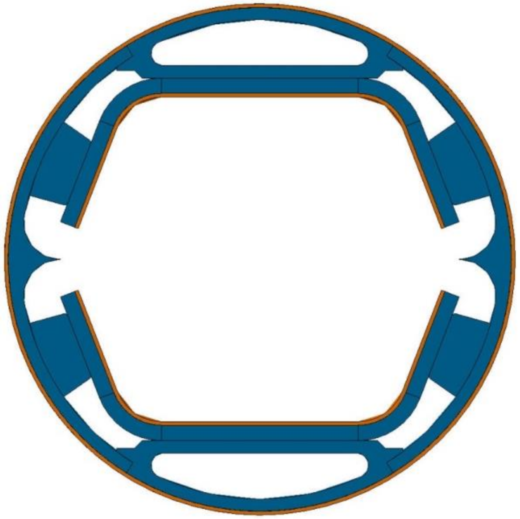
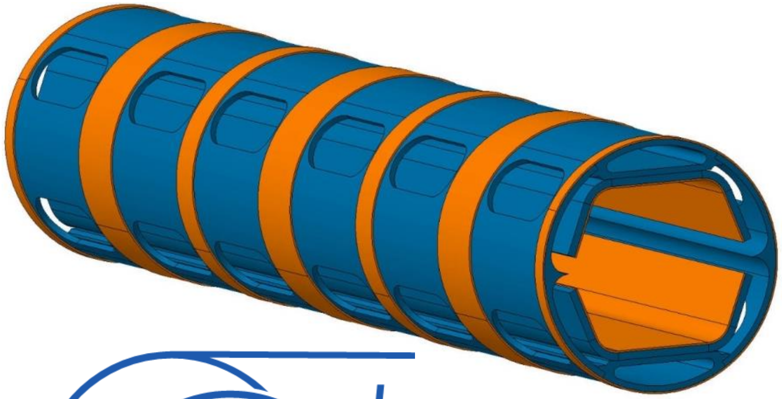
(1) CIEMAT, (2) CERN





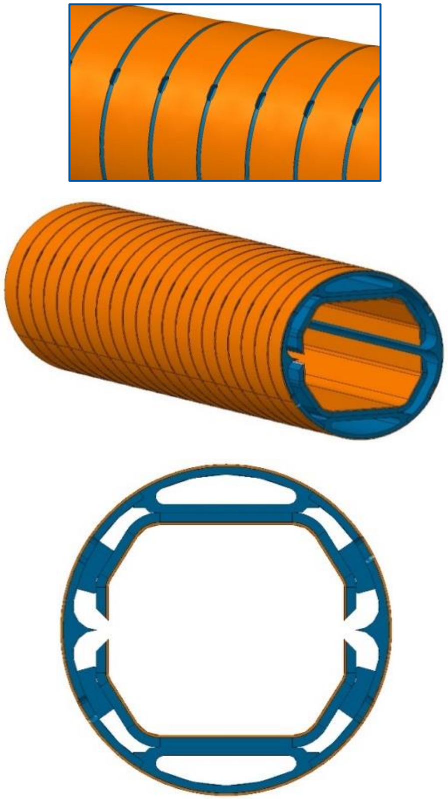
Outline

- BS design
  - Last geometry updates
  - Beam screen configuration
- Mechanical behaviour
  - Quench analysis
  - Mechanical effects of CLIQ system
- Thermal management
  - Temperature profile
  - Thermal stress
  - End dipole absorber
- Conclusions
- Next steps

Beam Screen Design

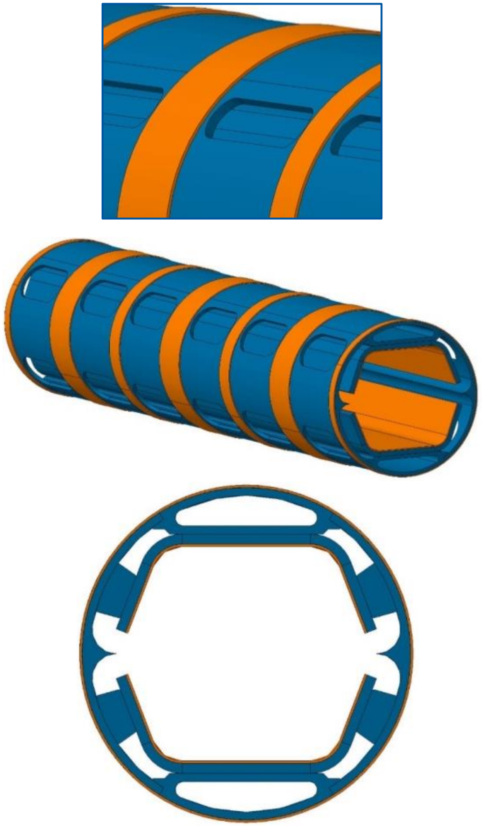
Beam screen evolution

FCC week Rome
04/2016

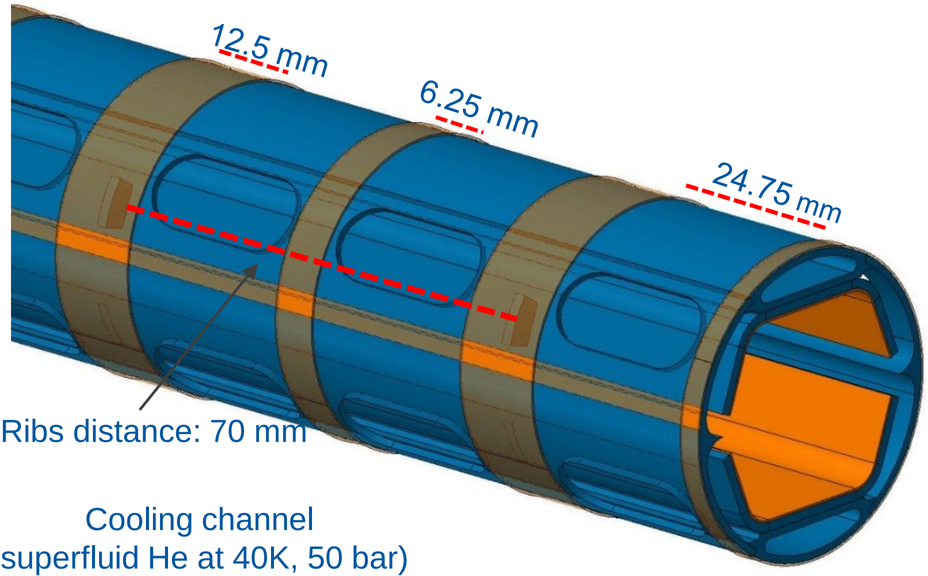


1. Bigger pumping holes in order to increase pumping capacity.
2. Copper strips optimized and adapted to the new pumping holes size.
3. Inner chamber geometry changed to achieve better mechanical and vacuum results.

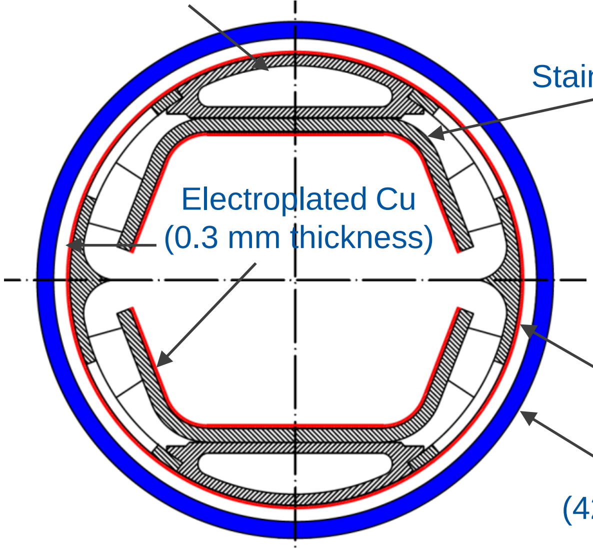
FCC week Berlin
06/2017



Geometry Design



Ribs distance: 70 mm



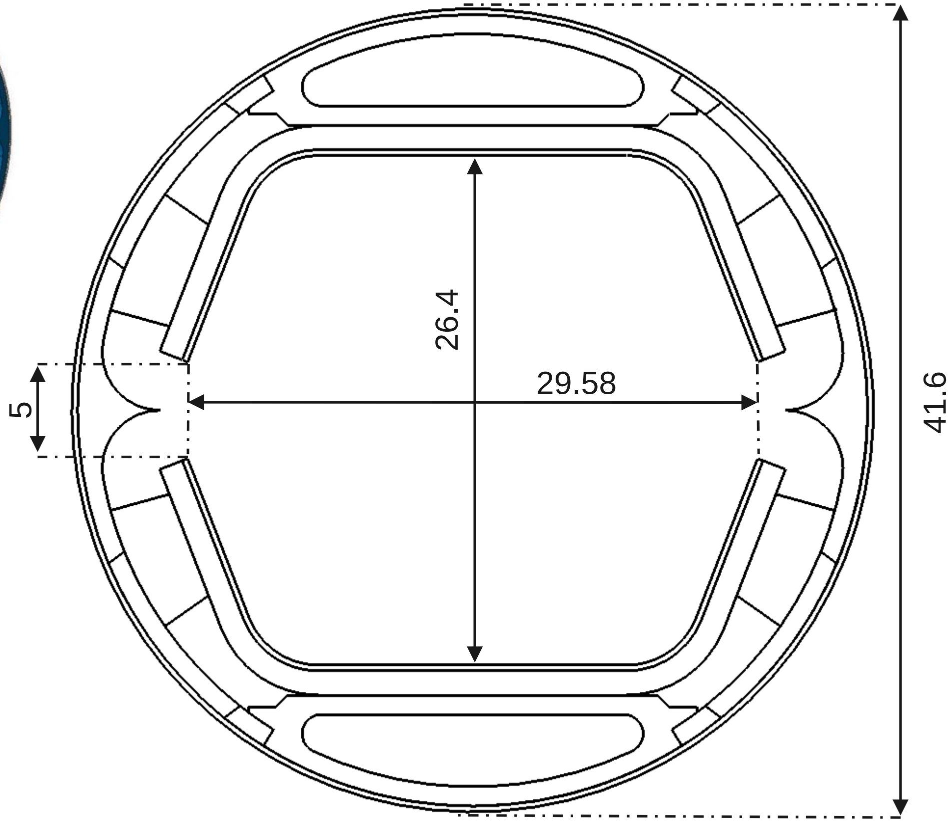
Cooling channel
(superfluid He at 40K, 50 bar)

Stainless steel P506

Electroplated Cu
(0.3 mm thickness)

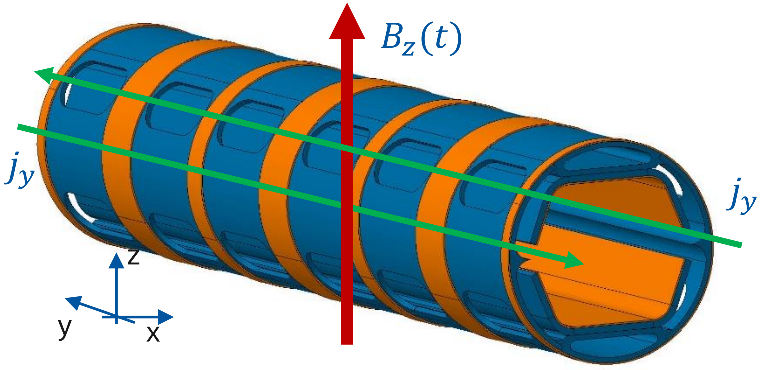
1.5 mm gap

Cold bore
(42.5 mm diameter)



Mechanical Design

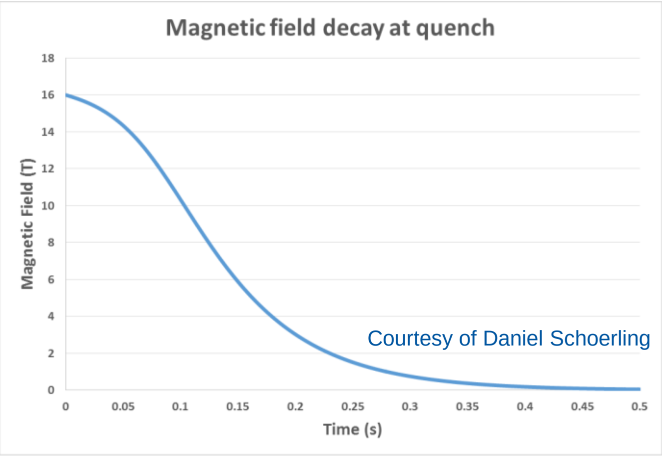
Magnet quench



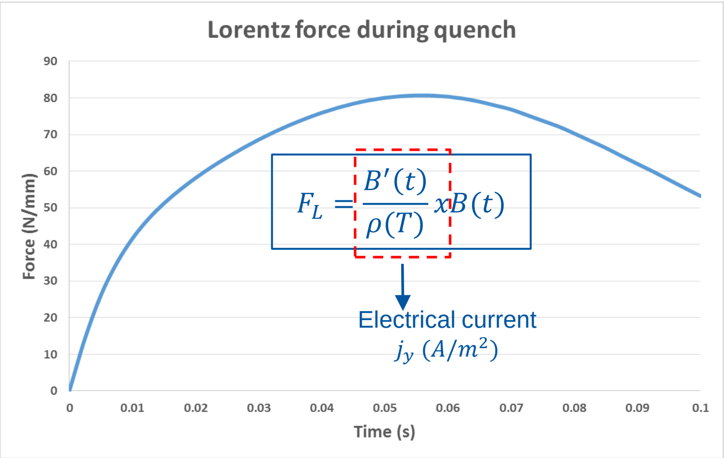
Variation of magnetic field at quench produces currents all along the beam screen.

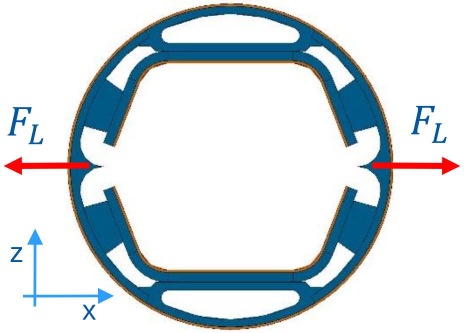
These currents produce Lorentz forces that have to be correctly withstand by the beam screen.

This 3D simulation has been carried out taking into account ‘Joule effect’ coupling magnetic field and temperatures ($\rho C_p \frac{\partial T}{\partial t} - \nabla(k\nabla T) = Q_e = JE$).



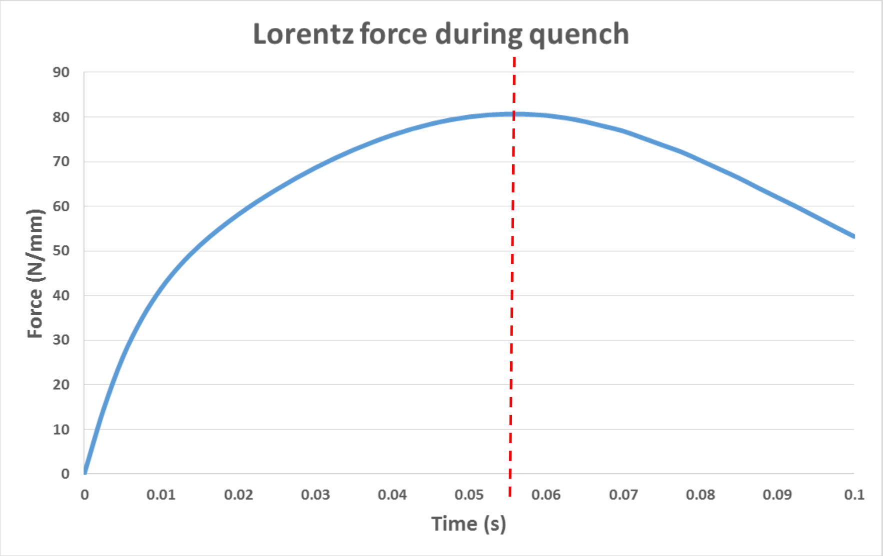
Courtesy of Daniel Schoerling

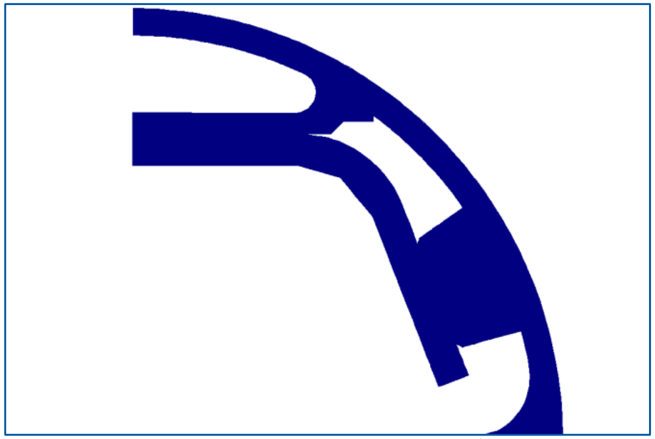




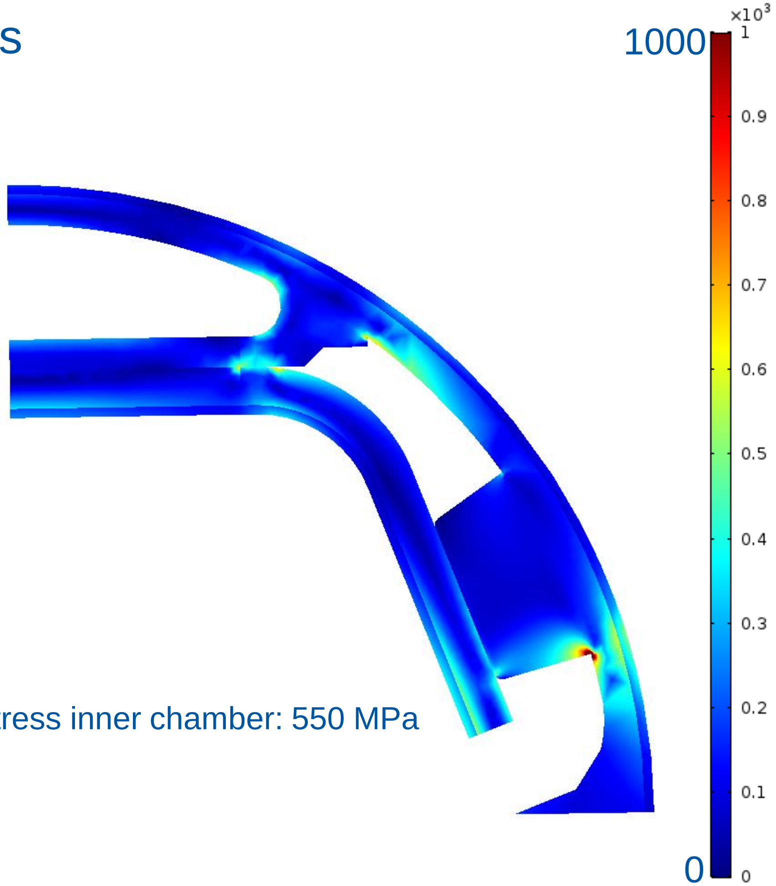
Mechanical Design

Stress analysis





Max displacement exterior beamscreen: 0.275 mm

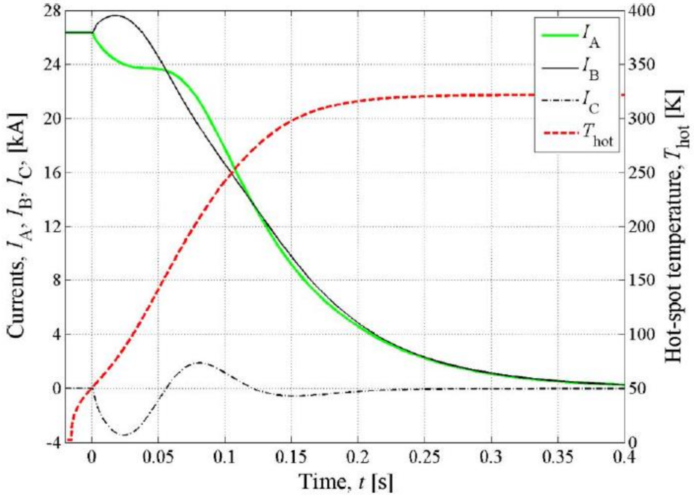


Max stress inner chamber: 550 MPa

Von Mises Stress (MPa)

Maximum stress reached at highest Lorentz force (0.055 secs): 550 MPa. No yield limit exceeded (1350 MPa at 50K).

CLIQ analysis



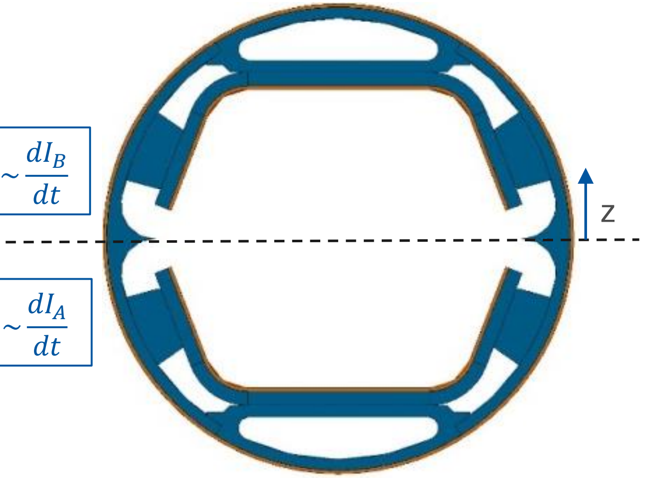
Different intensities on dipole coils (I_A, I_B) during quench. [1]

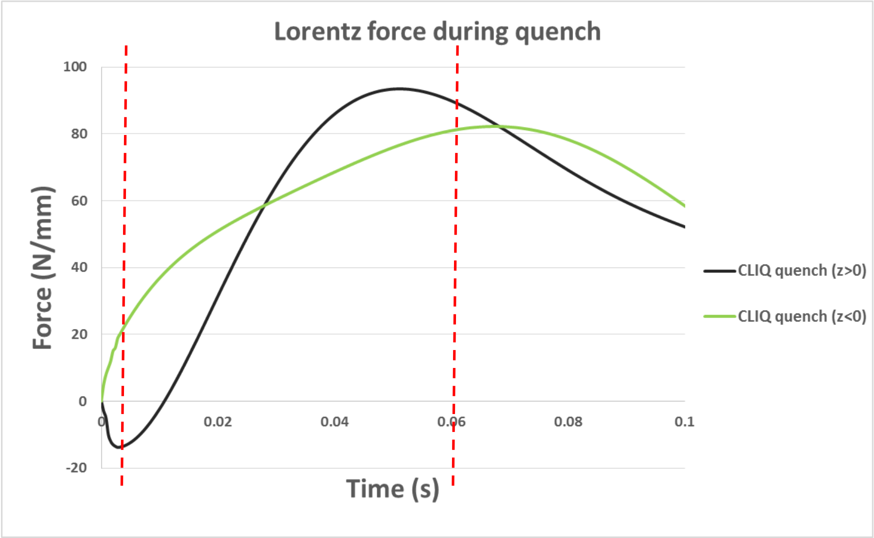
$$B'(t) \sim \frac{dI}{dt}$$

$$F \sim B'(t)$$

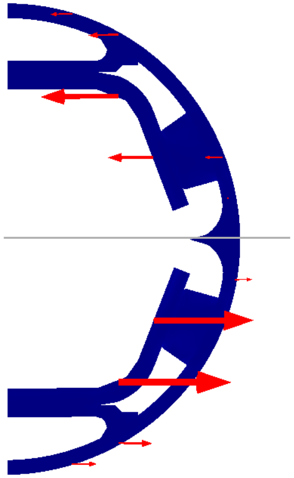
$$F_{z>0} \sim \frac{dI_B}{dt}$$

$$F_{z<0} \sim \frac{dI_A}{dt}$$

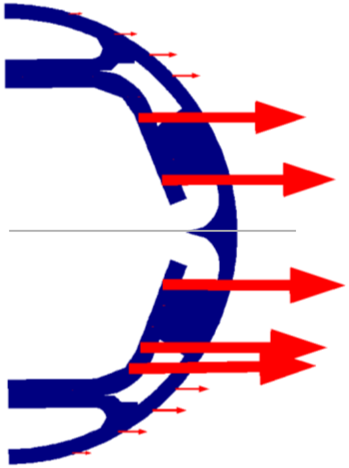




Inner copper layer force (~90% total force on beamscreen)



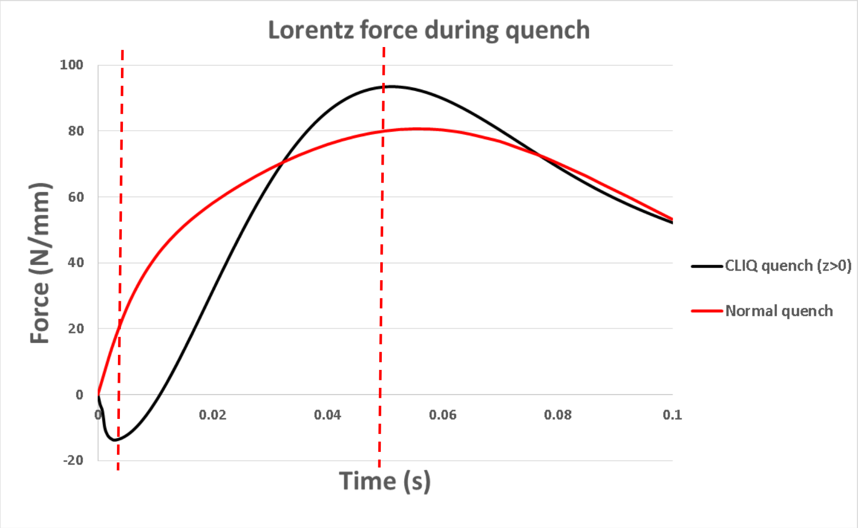
Lorentz Force 0.004 s

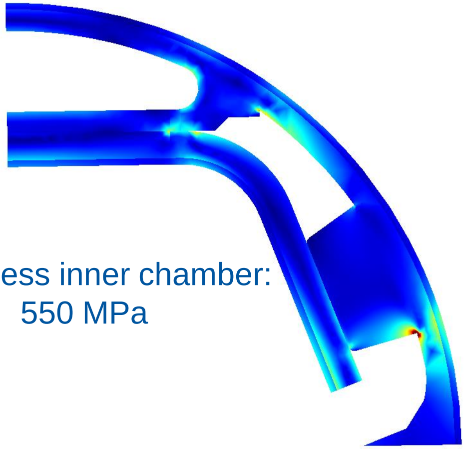


Lorentz Force 0.06 s (max total force)

[1] Design Study of a 16-T Block Dipole for FCC. IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 26, NO. 3, APRIL 2016

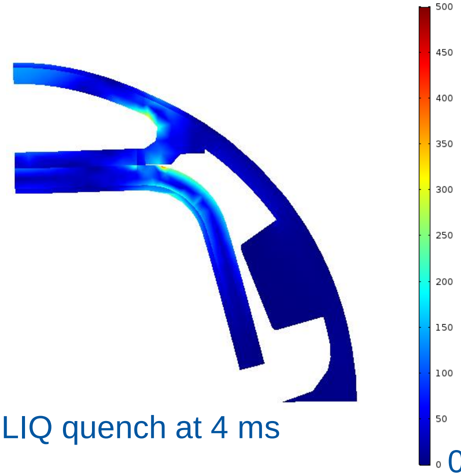
CLIQ comparative


Lorentz force during quench



Max stress inner chamber: 550 MPa

Normal quench at 50 ms

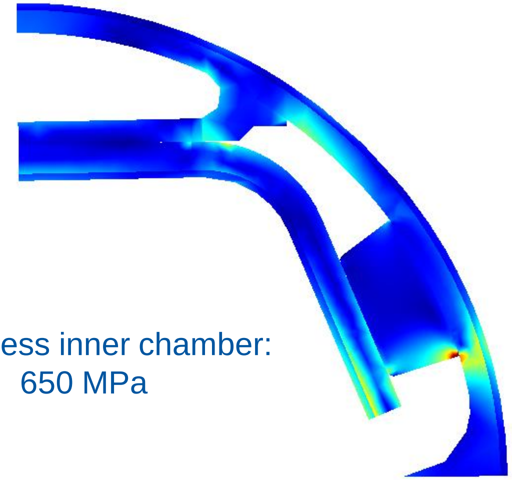


500

0

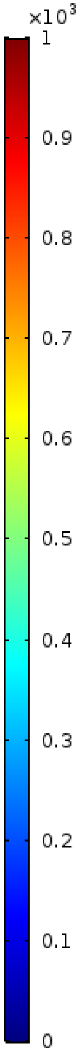
CLIQ quench at 4 ms

Von Mises Stress (MPa)



Max stress inner chamber: 650 MPa

CLIQ quench at 50 ms



1000

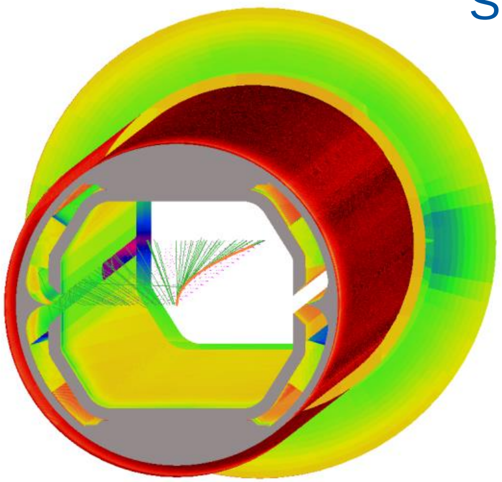
0

Von Mises Stress (MPa)

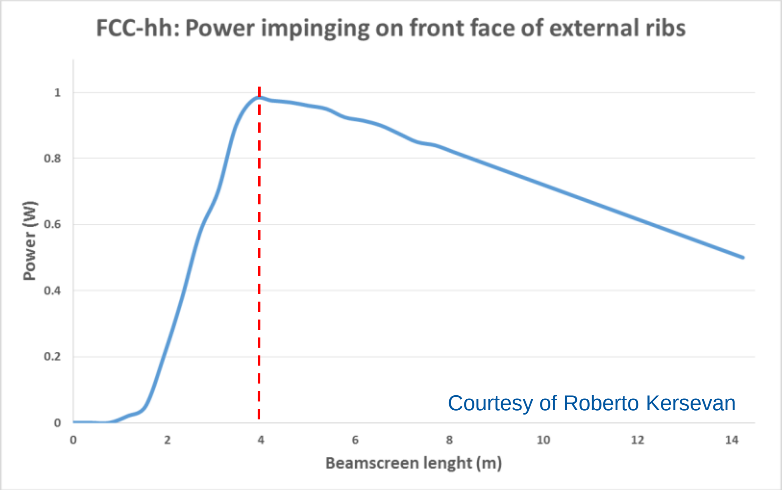
Besides with CLIQ, force distribution changes, mechanical behavior remains similar than in normal quench.

Thermal analysis

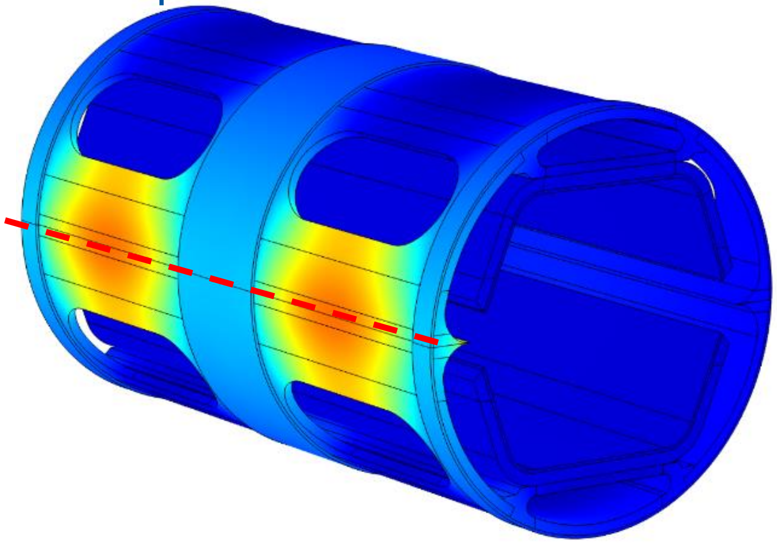
Synchrotron radiation impact



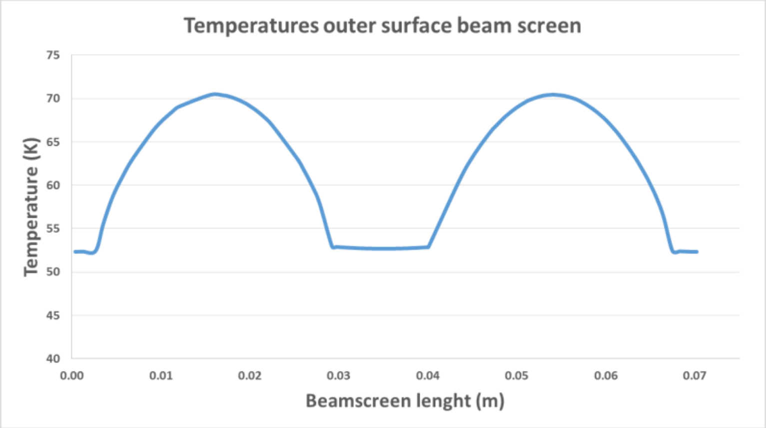
Synchrotron radiation power ~ 32 W/m
Beam intensity: 0.5 A, 50 TeV



Courtesy of Roberto Kersevan

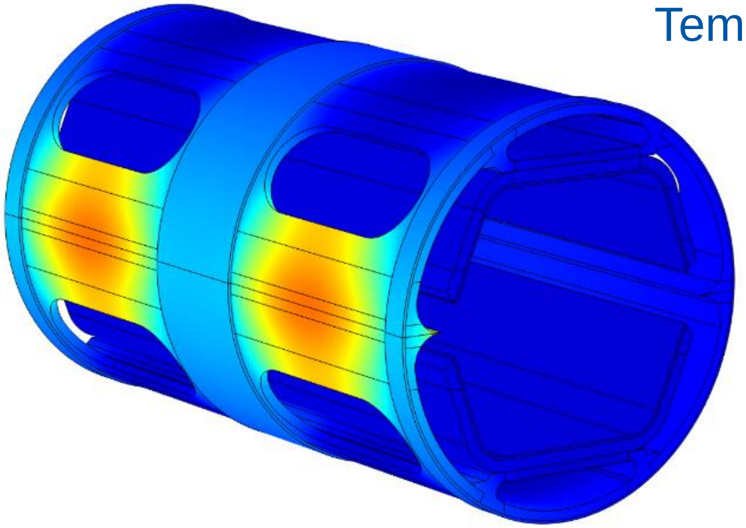


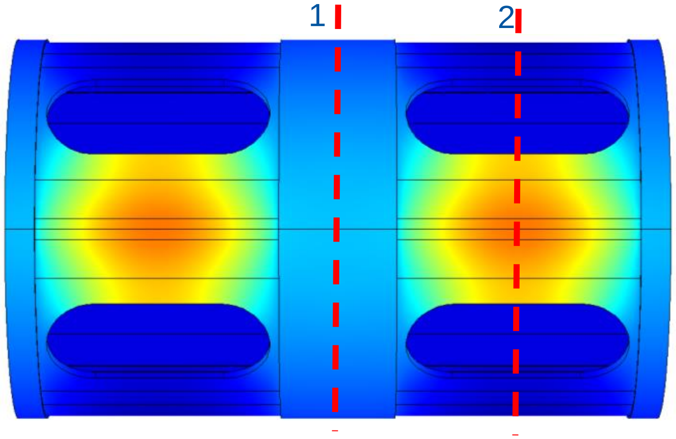
Temperature field produced by synchrotron radiation during beam nominal behaviour.



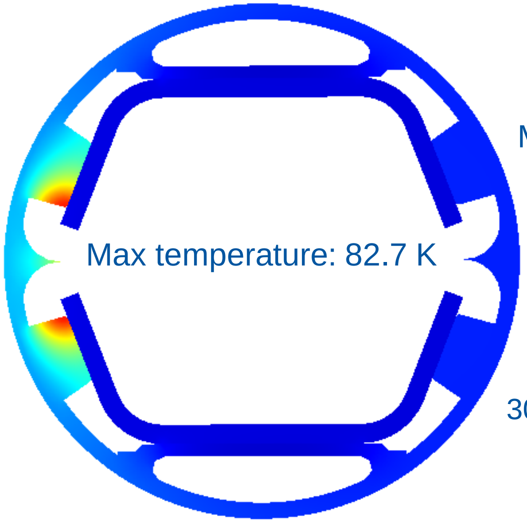
Thermal analysis

Temperature profile



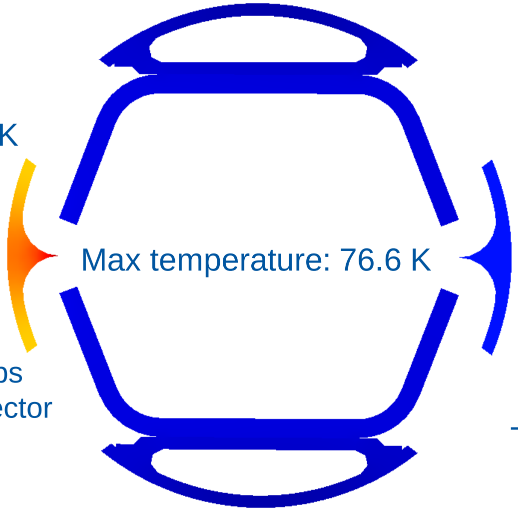


Section 1

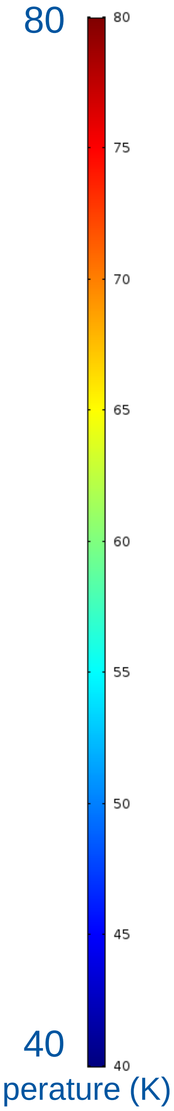


Max temp inner surface 43.7 K

Section 2



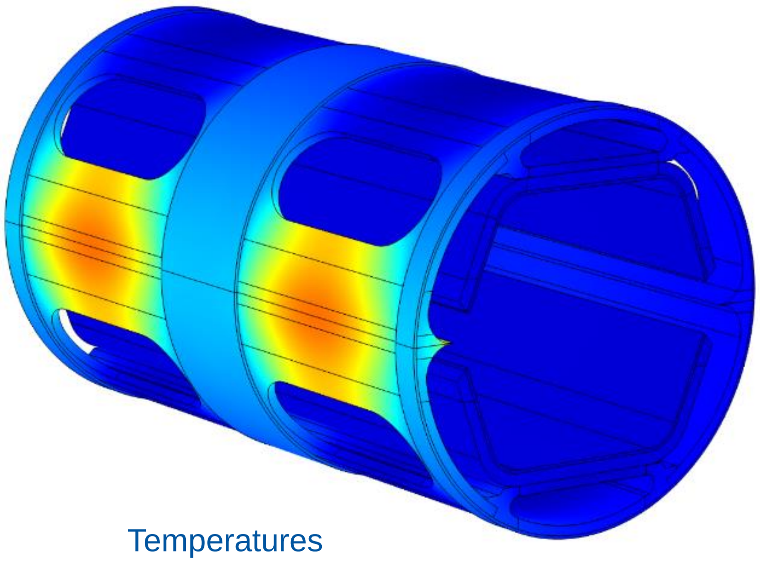
33% SR power absorbed by ribs
30% SR power absorbed by reflector



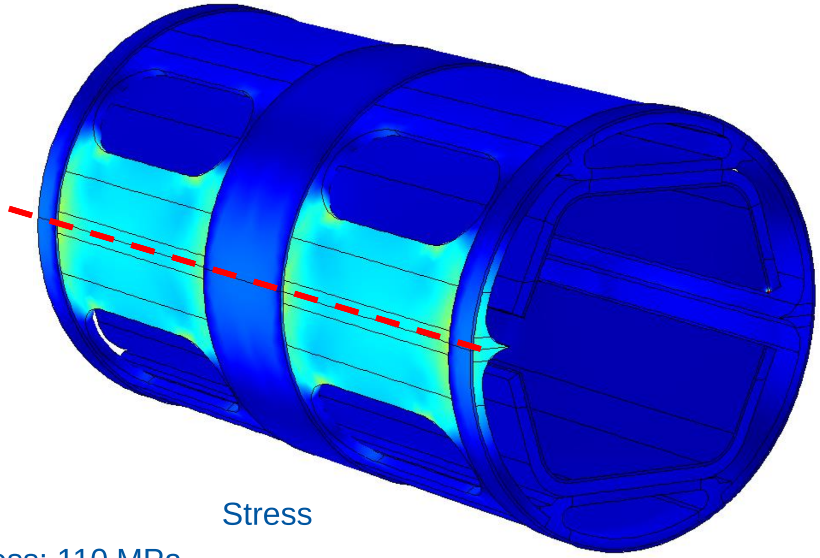
Inner beam screen temperature remains inside the temperature range allowed (between 40 K - 60 K).

Thermal analysis

Thermal stress



Temperatures

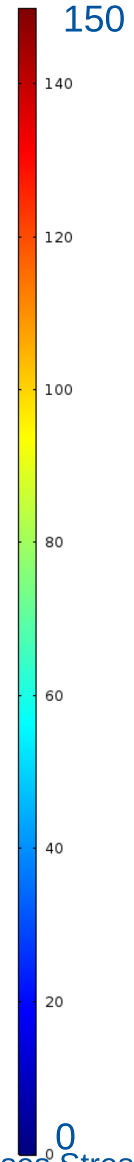


Stress

Max stress: 110 MPa

Max displacement: 0.01 mm

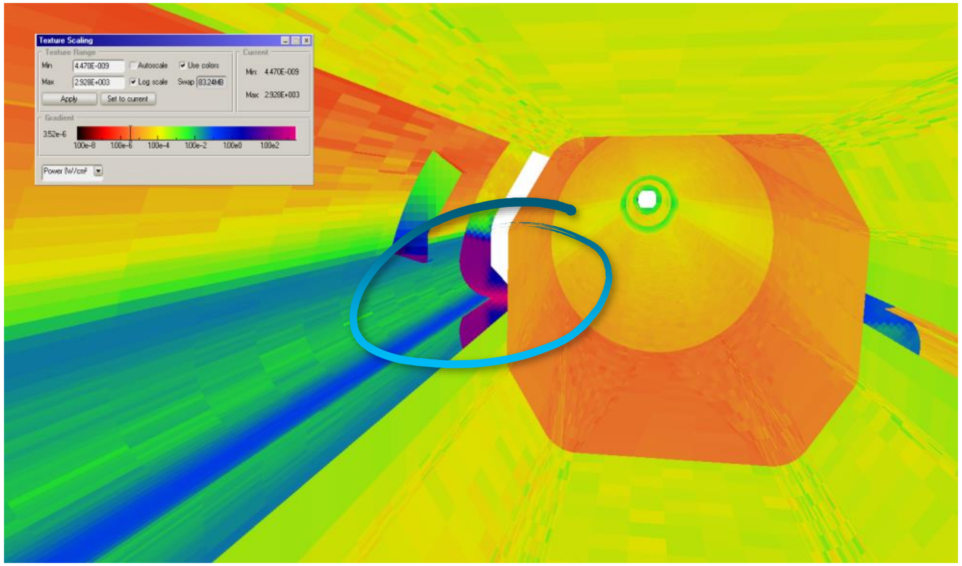
Similar thermal expansion coefficient for both stainless steel and copper avoid high stress values



Von Mises Stress (MPa)

Thermal analysis

End dipole absorber



Texture Scaling

Texture Range

Min 4.470E-009

Max 2.928E+003

☐ Autoscale

☑ Log scale

☑ Use colors

Swap 83.24MB

Current

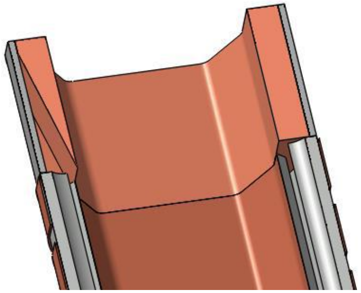
Min: 4.470E-009

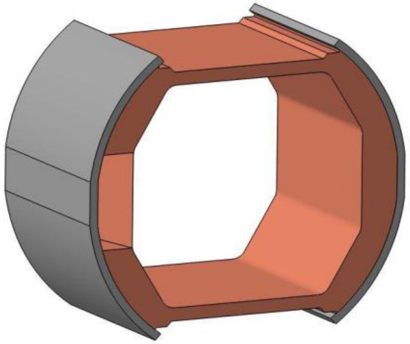
Max: 2.928E+003

Power [W/cm²]

*image by Ignasi Bellafont

61 W (18% of the absorbed power in the dipole)
Points with almost **3000 W/cm²**

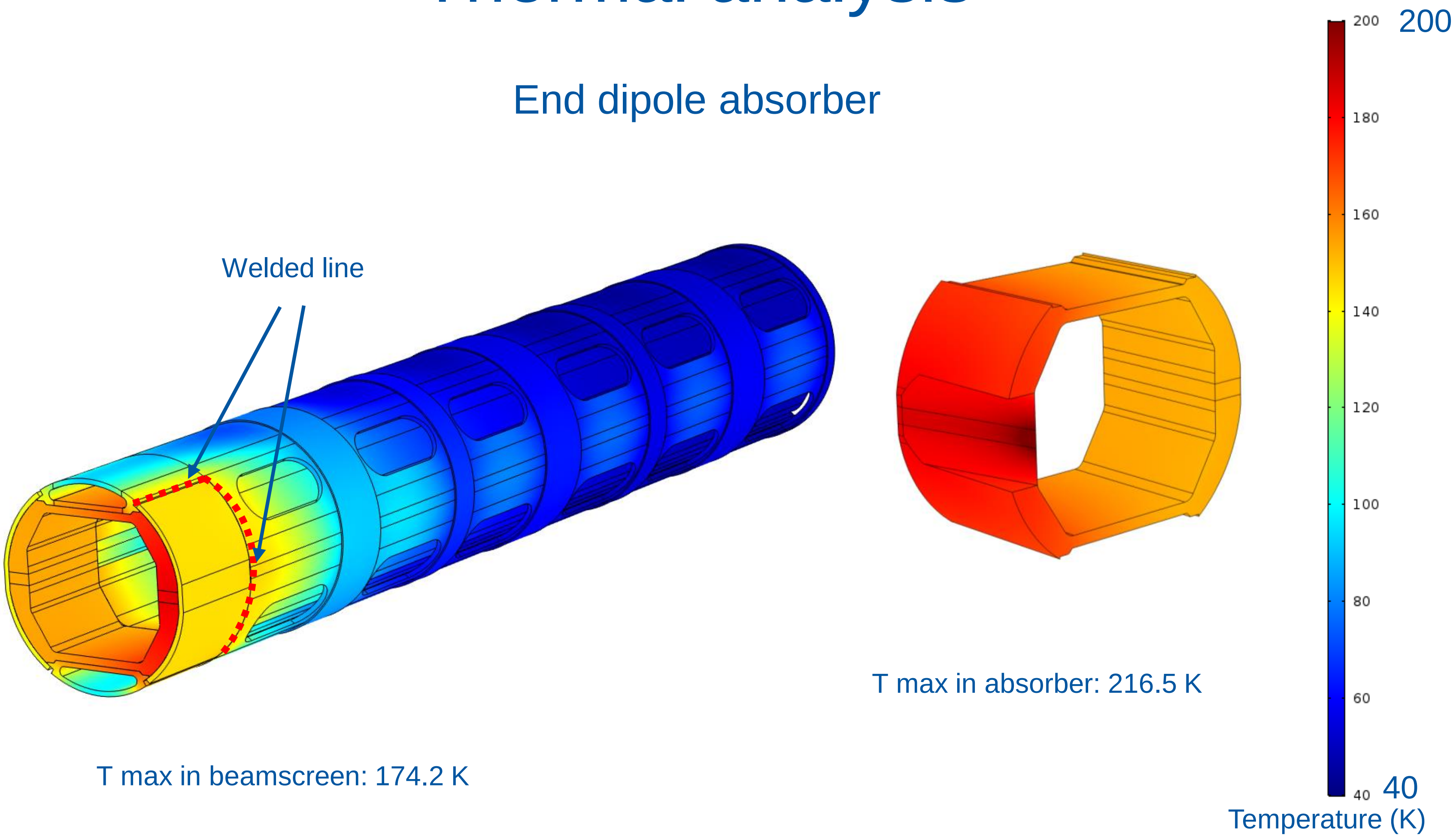




Due to the high SR density at the end of the dipole, an absorber has been designed in order to reduce as much as possible power density in this area.

Thermal analysis

End dipole absorber



Welded line

T max in absorber: 216.5 K

T max in beamscreen: 174.2 K

200

40

Temperature (K)

First simulations show that temperatures in the absorber reach very high values due to the SR stopped at the end of the dipole.

Conclusions

Mechanical design

- Simulations during a magnet quench have been done taking into account the Joule effect and using 3D massive finite element model. At quench conditions, beam screen mechanical behaviour remains under yield limit.

CLIQ analysis

- CLIQ discharge produces different Lorenz forces distribution on beam screen, nevertheless, beam screen mechanical behaviour remains similar than in normal quench.

Thermal analysis

- Taking into account synchrotron radiation impact during nominal behaviour, temperatures, as well as thermal stress in the new beam screen, remain on the range allowed (with similar results than in the previous model).

- Synchrotron radiation impact at end dipole absorber has been analyzed. High temperatures reached makes necessary to study in deep this area.

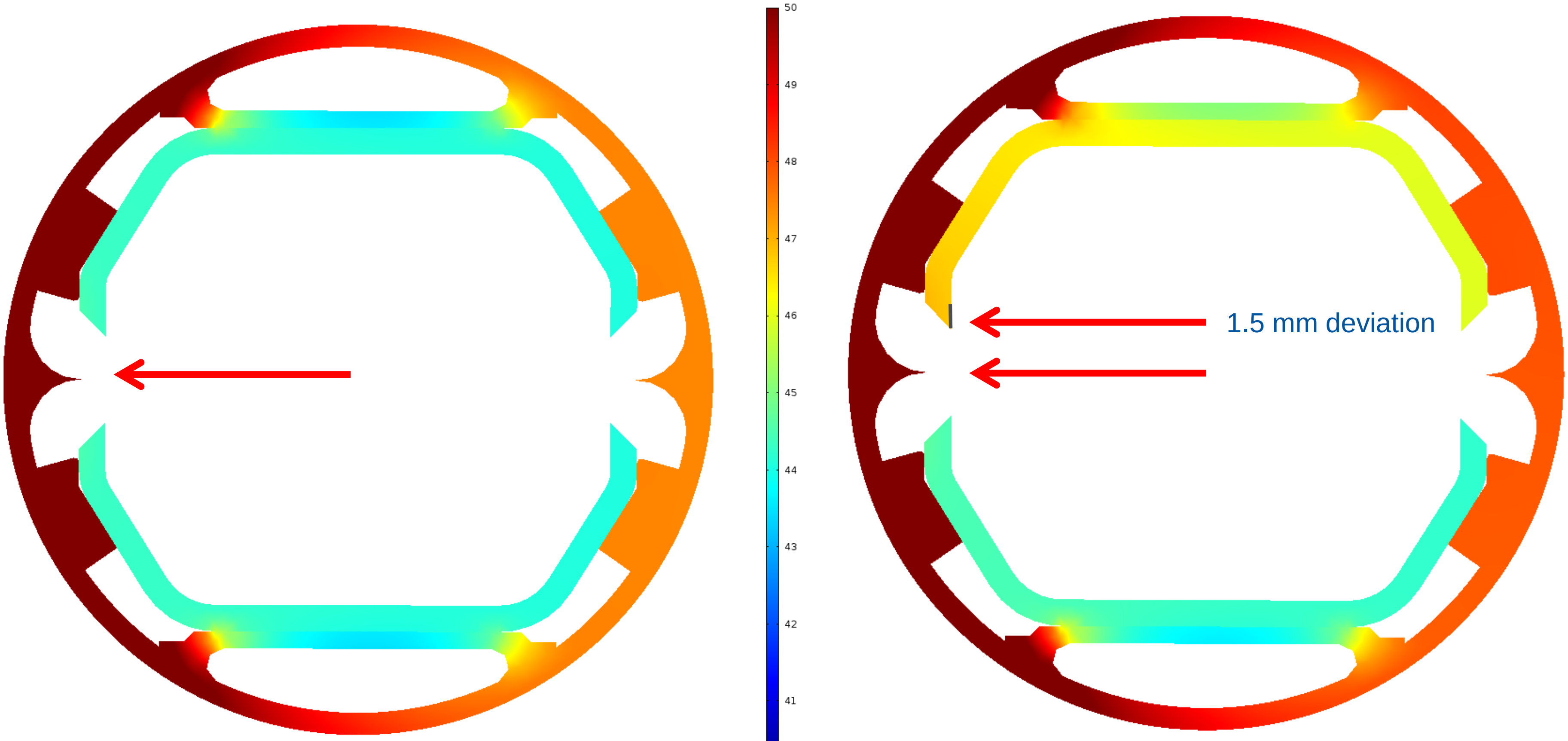
Next steps

- Check mechanical behaviour of beam screen on future geometry updates.
- Beam screen thermal analysis with future SynRad data.
- Study and reduce temperatures on dipole end cover.

THANK YOU FOR YOUR ATTENTION

Thermal analysis

Temperature profile

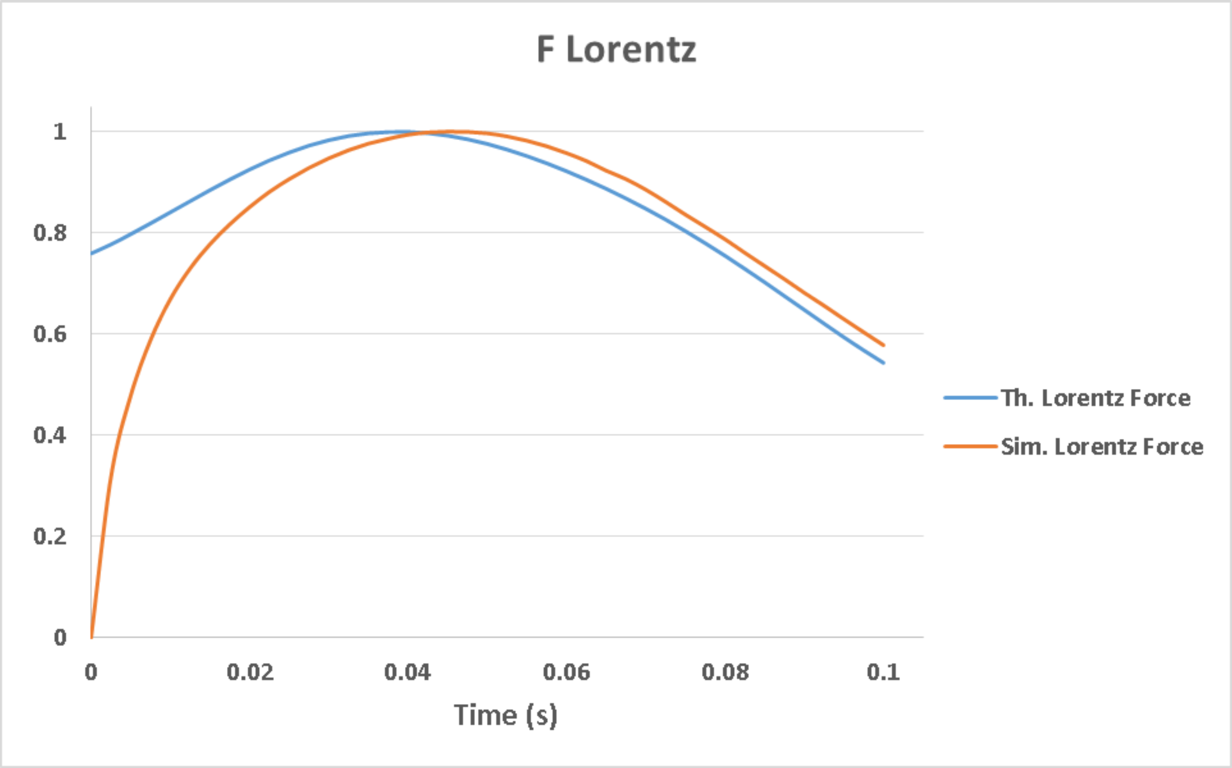


1.5 mm deviation

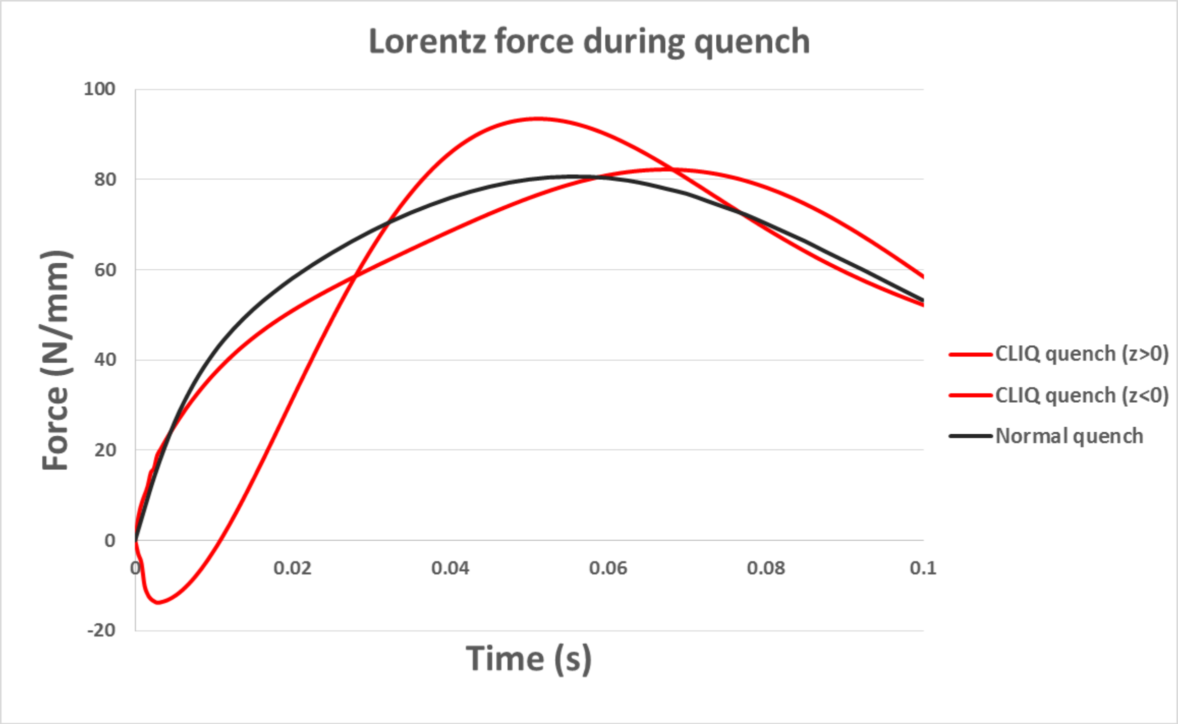
Max T inside beam screen: 44 K

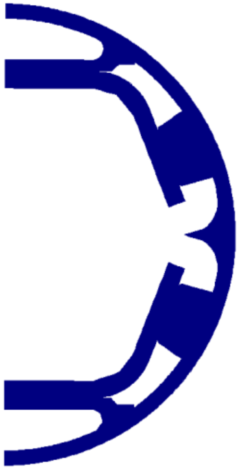
Max T inside beam screen: 46.8 K

Temperature (K)

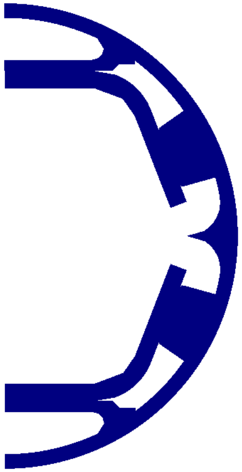

F Lorentz
1
0.8
0.6
0.4
0.2
0
0
0.02
0.04
0.06
0.08
0.1
Time (s)
Th. Lorentz Force
Sim. Lorentz Force

CLIQ comparative





Normal quench

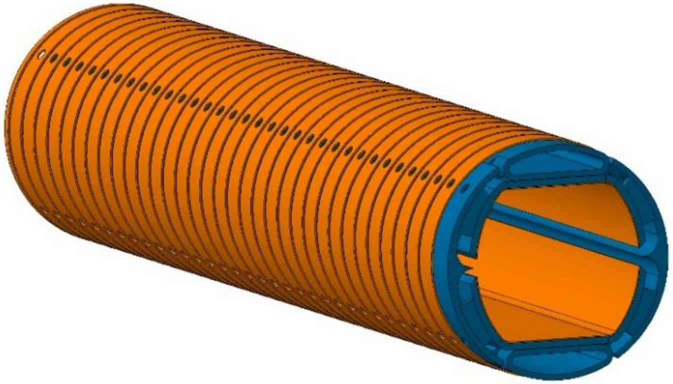


CLIQ quench

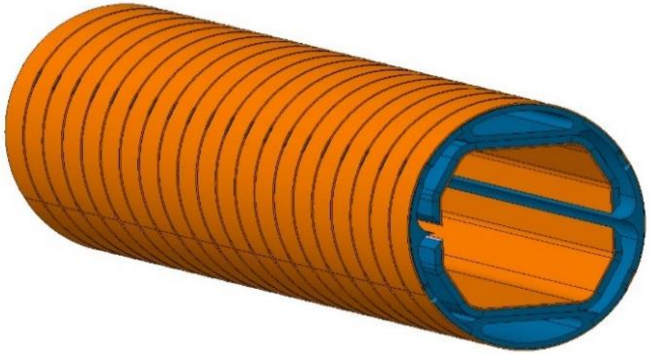
Beam Screen Design

Beam screen design updates

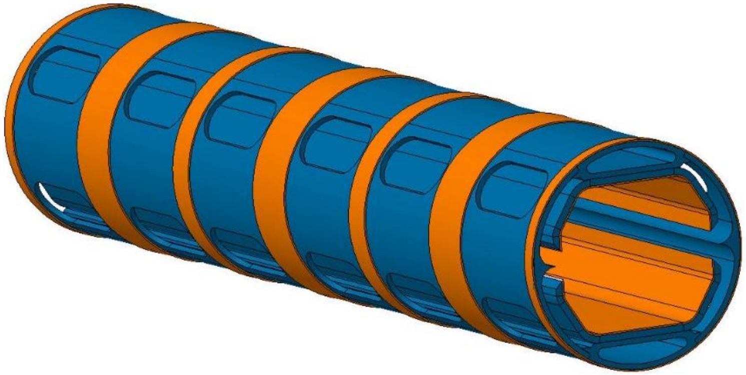
Orsay 09/2015
3th Eurocircol WP4 meeting



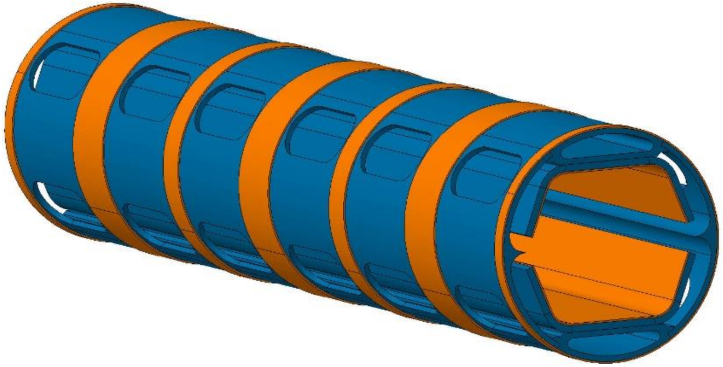
Rome 04/2016
FCC week

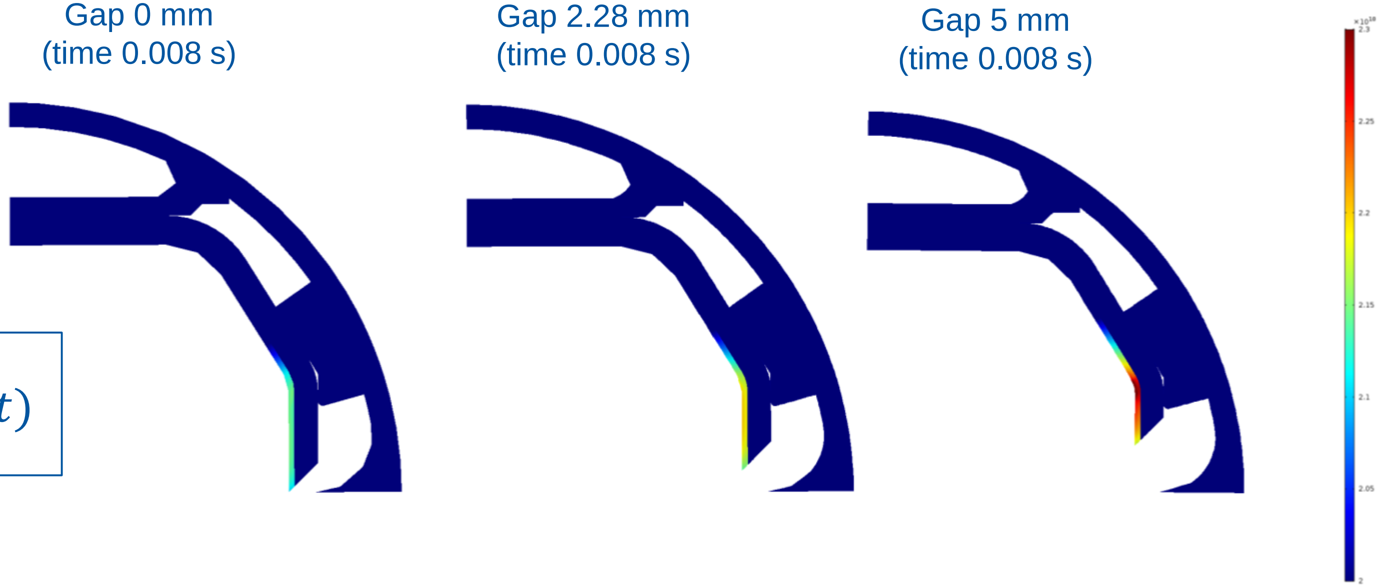


Barcelona 11/2016
5th Eurocircol WP4 meeting



Berlin 06/2017
FCC week




Gap 0 mm
(time 0.008 s)

Gap 2.28 mm
(time 0.008 s)

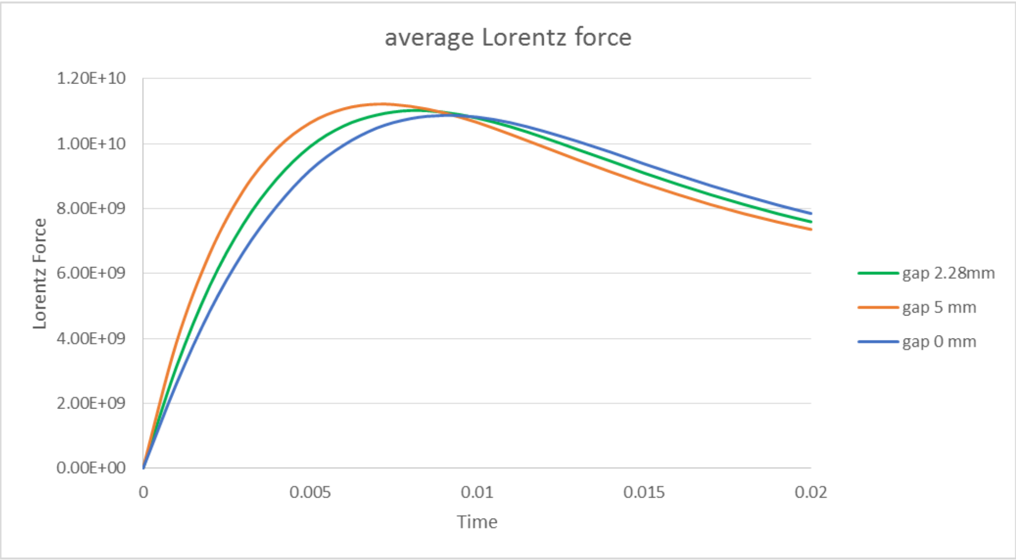
Gap 5 mm
(time 0.008 s)

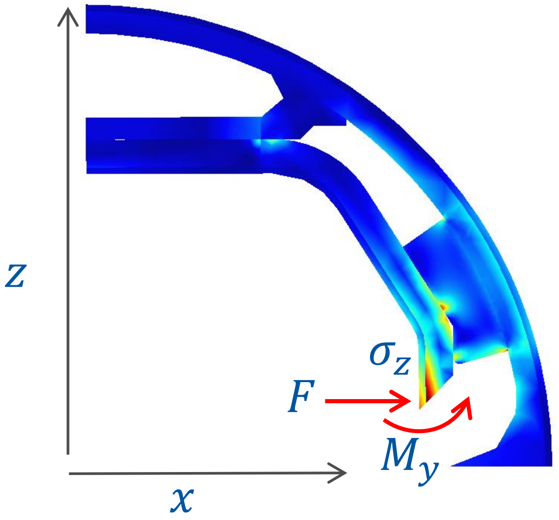
Lorentz force range:
2E10 – 2.3E10 N/m3

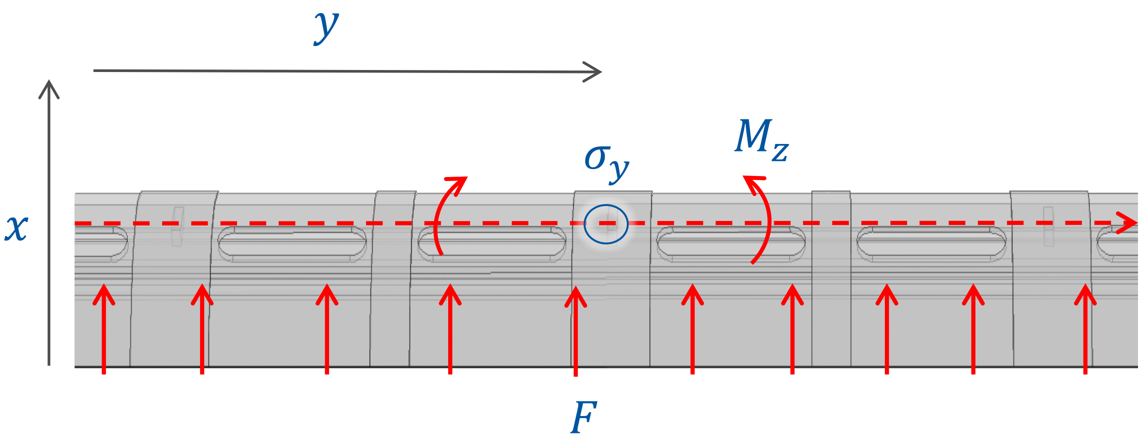
$$F_L = \frac{B'(t)}{\rho(T)} x B(t)$$

$$\begin{tikzcd}
B(t) \arrow[r] & B'(t) \arrow[r] & j \arrow[dl] \\
& b(t) \arrow[ul] & \\
& {} \arrow[u] &
\end{tikzcd}$$

Lenz law: The direction of current induced in a conductor by a changing magnetic field, due to Faraday’s law of induction, will be such that it will create a field that opposes the change that produced it.







$$\sigma_y = \frac{M_z \cdot y}{I_y}$$

$$\sigma_z = \frac{M_y \cdot z}{I_z}$$

High Lorentz force

Gap deflector change

$$\sigma_y = \frac{\uparrow M_z \cdot y}{I_y}$$

$$\sigma_z = \frac{M_y \cdot z \downarrow}{I_z \downarrow}$$

$$\sigma_{y2.28} > \sigma_{y5}$$

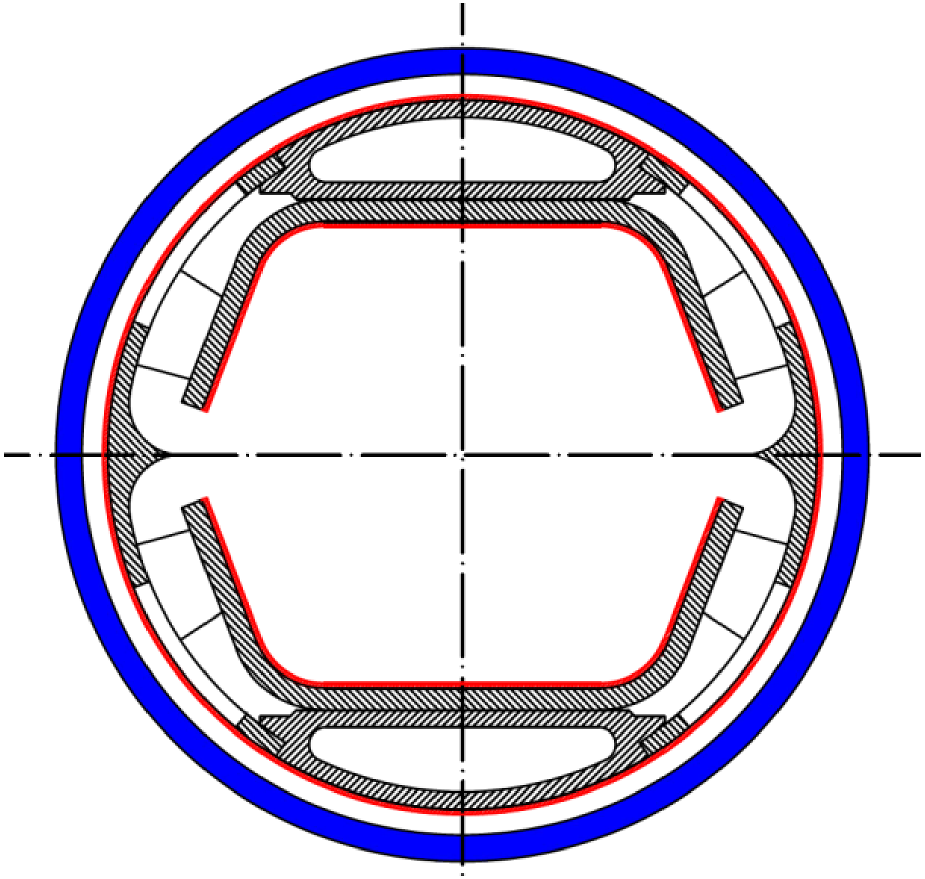
$$\sigma_{z2.28} > \sigma_{z5}$$

$$\sigma_x \approx 0$$

$$\sigma_{VM} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$$

$$\sigma_{VM2.28} > \sigma_{VM5}$$

Thermal load to cold bore



1 • Nuclear scattering: 191 mW/m

2 • Synchrotron radiation: 2.4 mW/m

3 • Thermal radiation: 2.33 mW/m

4 • Beam screen supports: 25 mW/m

5 • ~~Image currents~~

6 • ~~Electron cloud effect~~

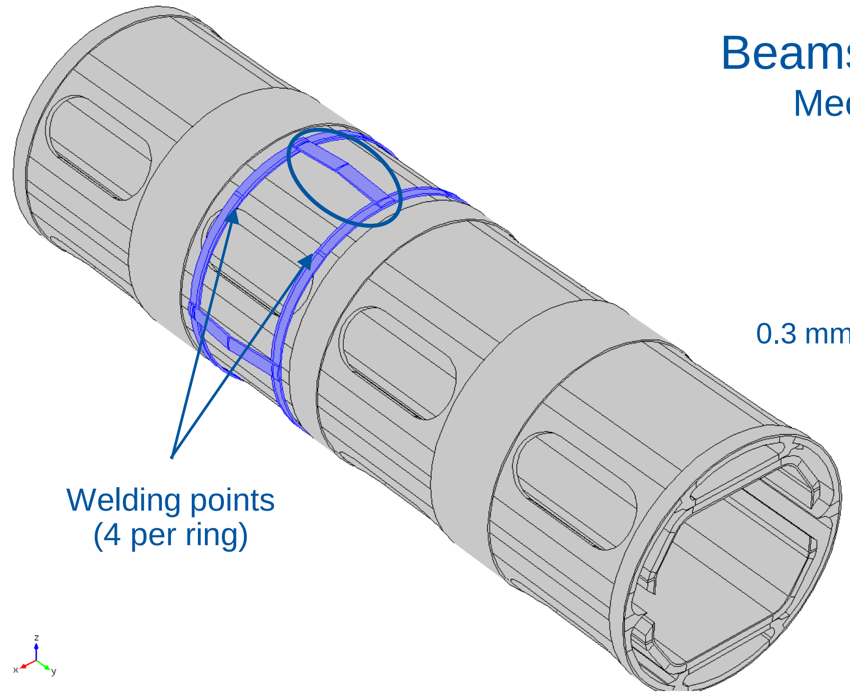
Max power allowed: 300 mW/m

Total thermal load transferred to cold bore: 220.7 mW/m

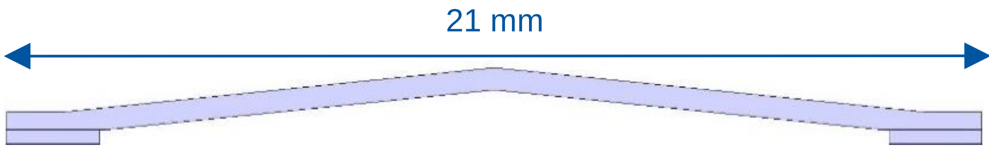
Thermal load to cold bore

Beamscreen supports.

Mechanical analysis



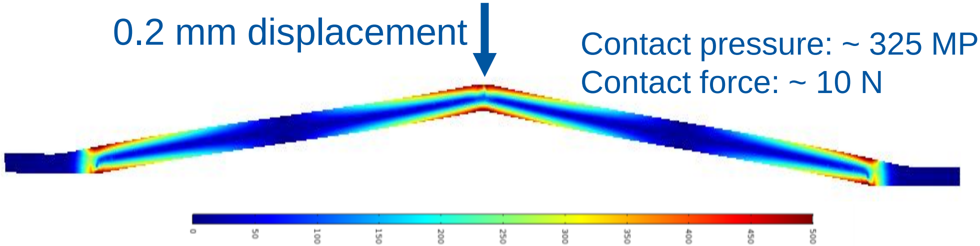
Welding points
(4 per ring)



1.7 mm height
(→ pre-stress 0.2 mm)

0.2 mm displacement

Contact pressure: ~ 325 MPa
Contact force: ~ 10 N



Von Mises stress

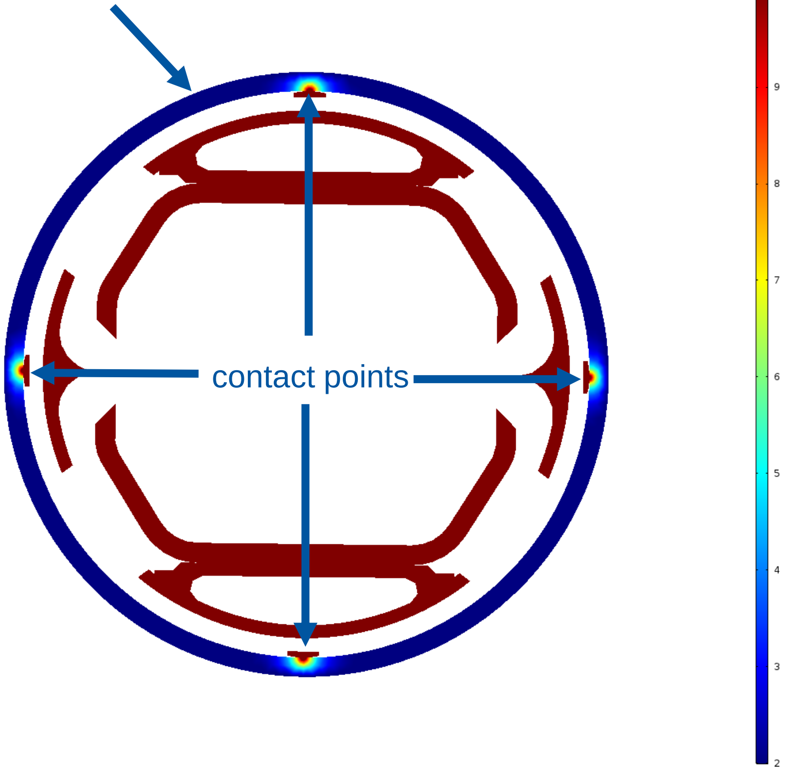
Mechanical behaviour acceptable

Thermal load to cold bore

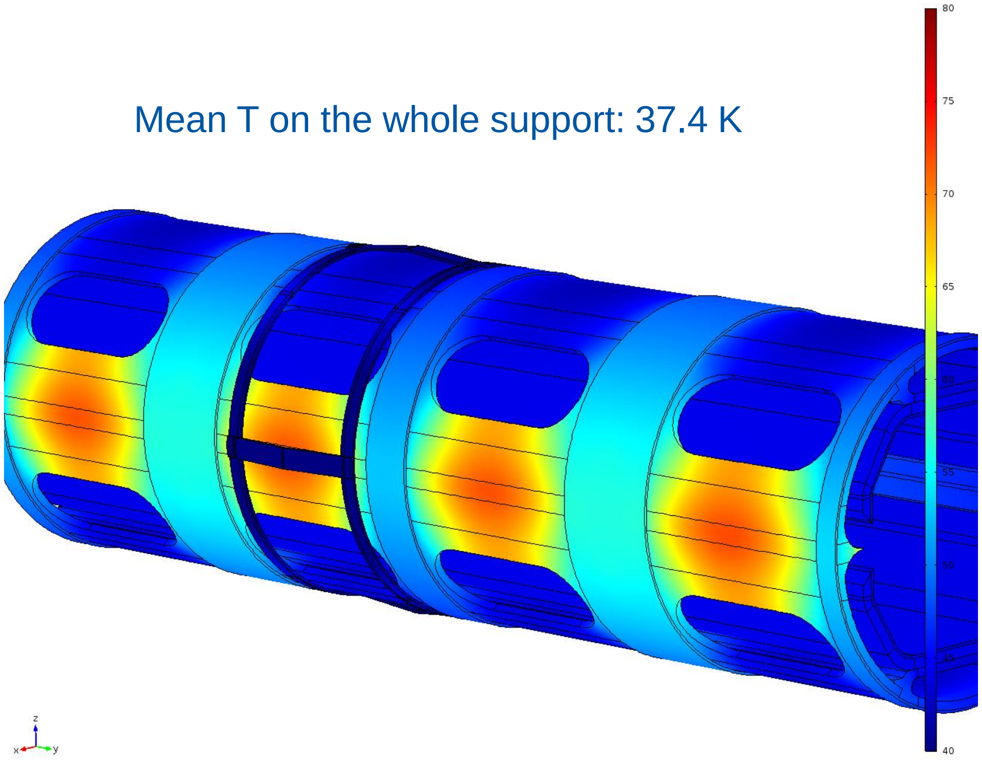
Beamscreen supports.

Thermal analysis

Cold bore: 1.9 K



contact points



Mean T on the whole support: 37.4 K

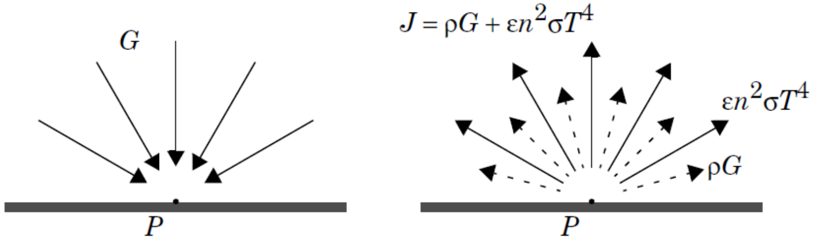
Total heat load transferred: 25 mW/set

Assuming one set per meter: 25 mW/m

(beam screen alignment study in process)

Thermal load to cold bore

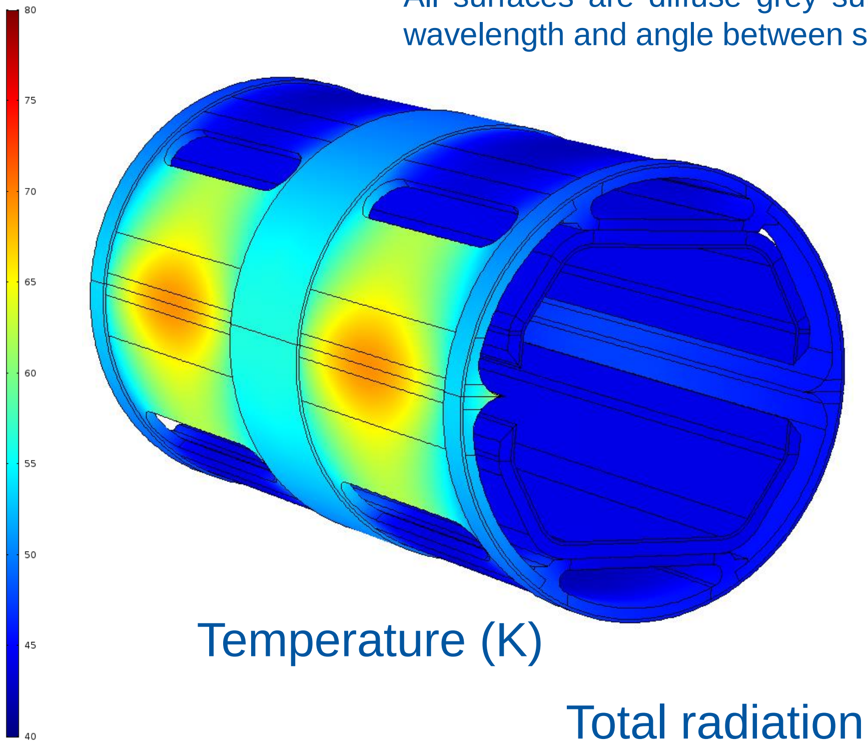
Radiation



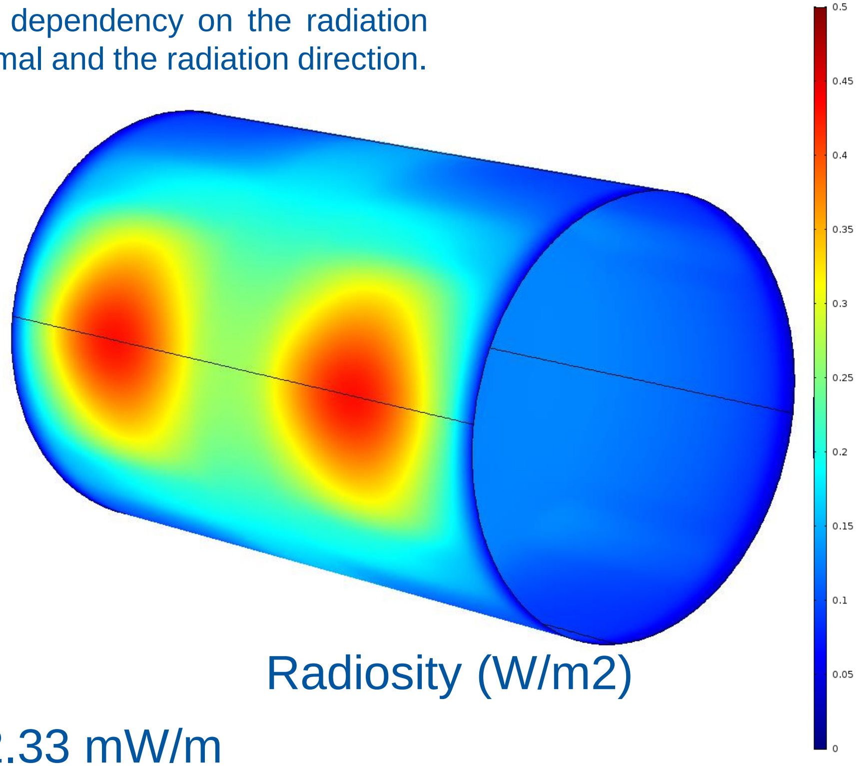
$$q = \varepsilon(G - n^2 \sigma T^4)$$

$\varepsilon_{cu} = 0.02$
$\varepsilon_{ss} = 0.07$
$n = 1$
$\sigma = 5.670373 \cdot 10^{-8}\ W m^{-2} K^{-4}$

All surfaces are diffuse grey surfaces: No dependency on the radiation wavelength and angle between surface normal and the radiation direction.

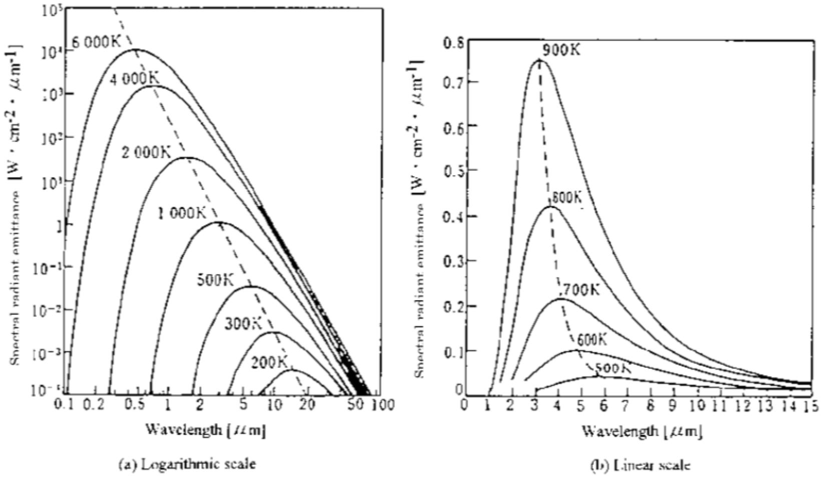


Temperature (K)



Radiosity (W/m2)

Total radiation heat: 2.33 mW/m

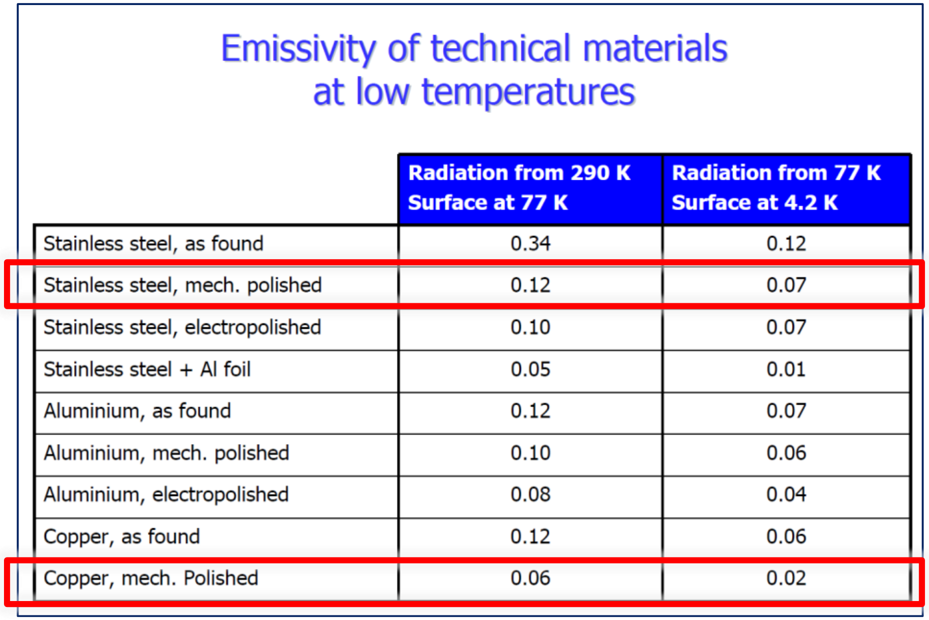


(a) Logarithmic scale

(b) Linear scale

Fig. 6.2 Spectral radiant emittance of a blackbody

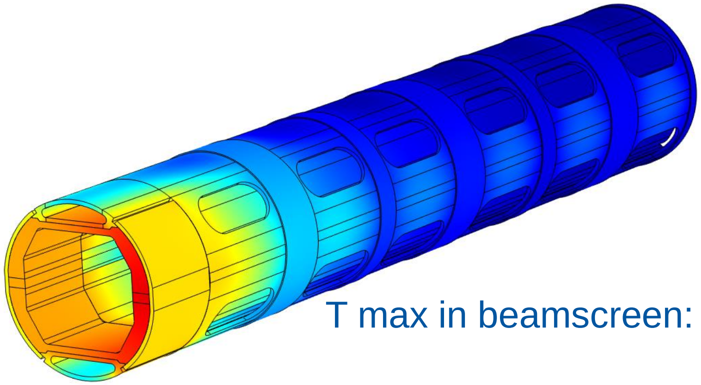
$$W_\lambda = \frac{c_1}{\lambda^5\left\{\exp\left(\frac{c_2}{\lambda T}\right)-1\right\}}$$



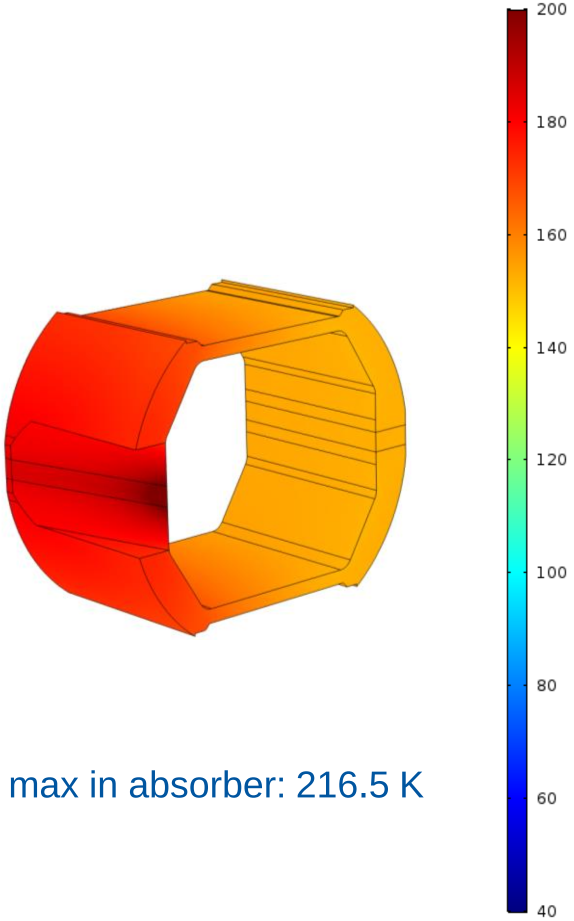
Emissivity of technical materials at low temperatures

	Radiation from 290 K Surface at 77 K	**Radiation from 77 K Surface at 4.2 K**
Stainless steel, as found	0.34	0.12
Stainless steel, mech. polished	0.12	0.07
Stainless steel, electropolished	0.10	0.07
Stainless steel + Al foil	0.05	0.01
Aluminium, as found	0.12	0.07
Aluminium, mech. polished	0.10	0.06
Aluminium, electropolished	0.08	0.04
Copper, as found	0.12	0.06
Copper, mech. Polished	0.06	0.02

End dipole absorber

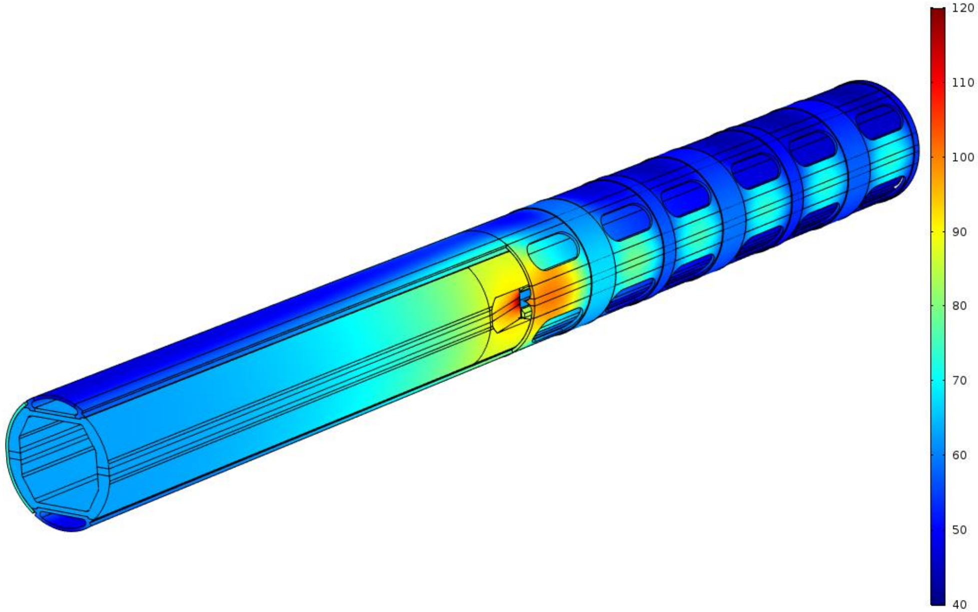


T max in beamscreen: 174.2 K



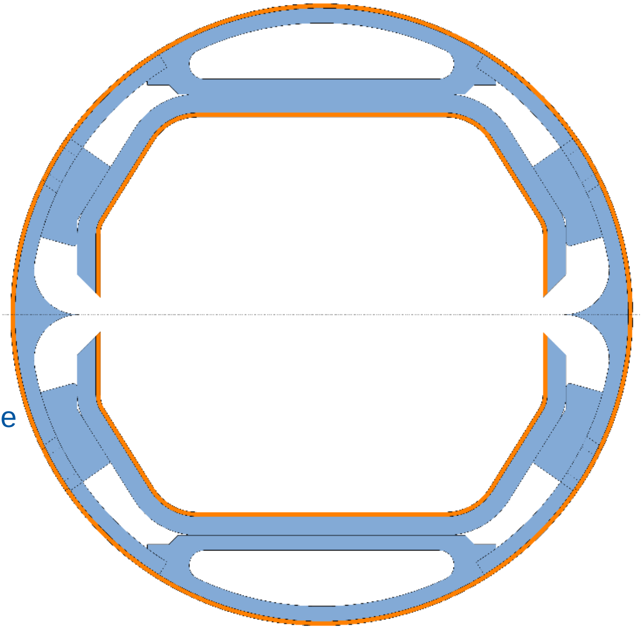
T max in absorber: 216.5 K

Temperature (K)



Mechanical Design

Material properties



Copper

Mechanical properties

- Density, ρ = 8700 (Kg/m^3)
- Young's modulus, E = 110 (GPa)
- Poisson's ratio, v = 0.35

Magnetic properties

- Relative permittivity, ε = 1
- Relative permeability, μ = 1
- Resistivity changes with temperature

Thermal properties

- Thermal conductivity, k = 700 (W/(m·K))
- Heat capacity changes with temperature
- Coefficient thermal expansion, α = 17E-6 (1/K)

P506 (high-Mn high-N austenitic stainless steel)

Mechanical properties

- Density, ρ = 7850 (Kg/m^3)
- Young's modulus, E = 205 (GPa)
- Poisson's ratio, v = 0.28

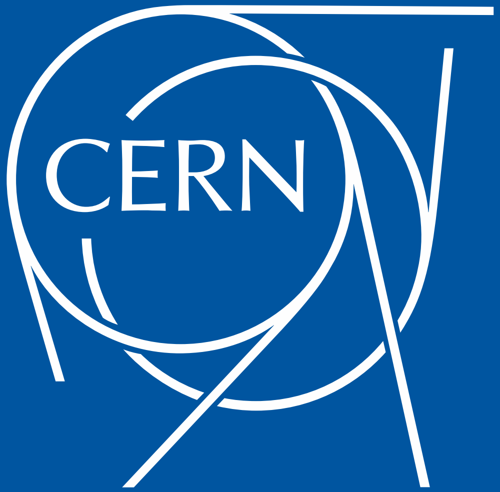
Magnetic properties

- Relative permittivity, ε = 1
- Relative permeability, μ = 1
- Resistivity, ρ = 5E-7 (Ω·m)*

Thermal properties

- Thermal conductivity, k = 5 (W/(m·K))
- Heat capacity changes with temperature
- Coefficient thermal expansion, α = 12.3E-6 (1/K)

* Due to the high value of stainless steel resistivity, and its small variation with temperature, it has been considered constant with temperature.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