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Arc Vacuum Considerations and Beam Screen Design

Outline:

- Basic parameters of the synchrotron radiation for FCC-hh arcs
- Beam screen requirements and configuration
- LHC type beam screen
- Beam screen with absorber
- Roadmap
- Conclusion

The Synchrotron Radiation in the FCC-hh Arcs
Some Figures

FCC at nominal current and energy (0.5 A, 50 TeV), 16 T bending field:

- Critical energy: 4 keV,
- Photon flux: 10^{22} ph/s → $1.4.10^{17}$ ph/m/s
- Power: 2.2 MW → P' = 30 W/m

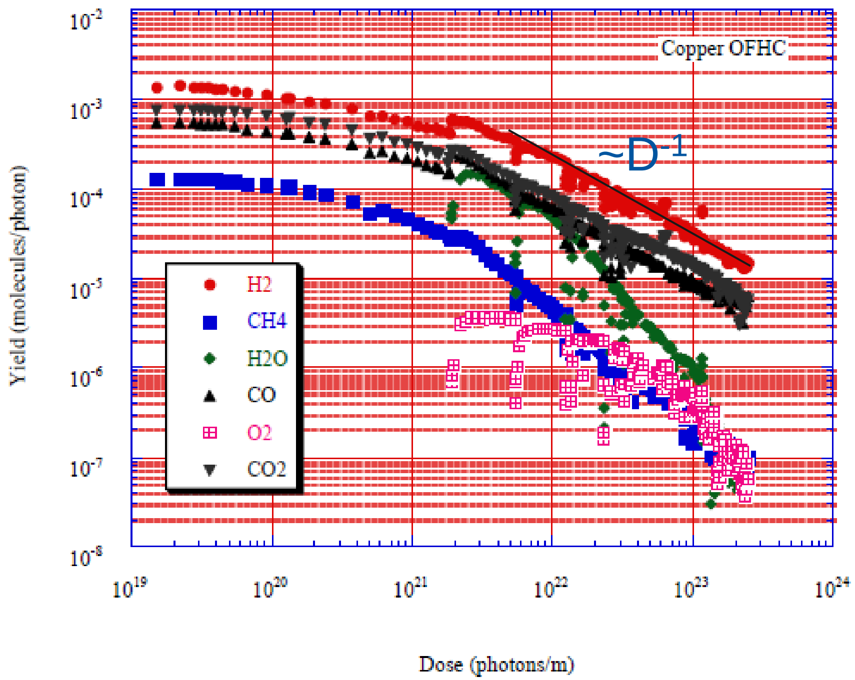
By comparison, LHC at nominal current and energy (0.5 A, 7 TeV), 8.33 T bending field (ρ=2804m):

- Critical energy: 43.8 eV,
- Photon flux: $7.4.10^{20}$ ph/s → $4.2.10^{16}$ ph/m/s
- Power: 3.3 kW → 200 mW/m

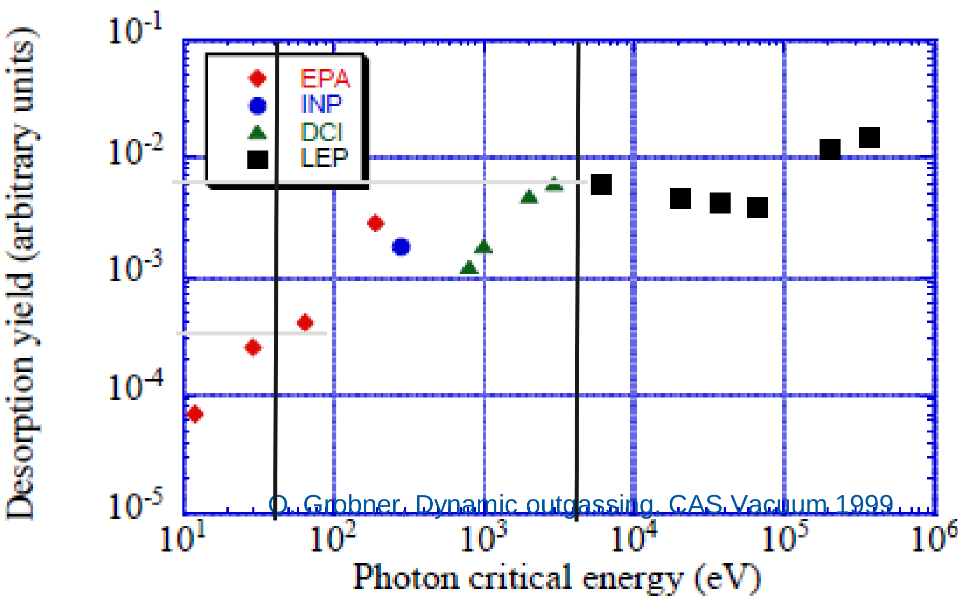
Photodesorption is important for the vacuum quality in FCC-hh.

The Synchroton Radiation in the FCC-hh Arcs Photodesorption

Typical photodesorption yield of OFHC copper, after bake out, at room temperature, ε_c=3.75 keV



Influence of the critical energy:



→ Photodesorption yield decreases as ~1/D, D being the photon dose.

→ Factor ~17 between 4keV (FCC-hh) and 43 eV (LHC).

The Synchroton Radiation in the FCC-hh Arcs
Photodesorption

Influence of the temperature:

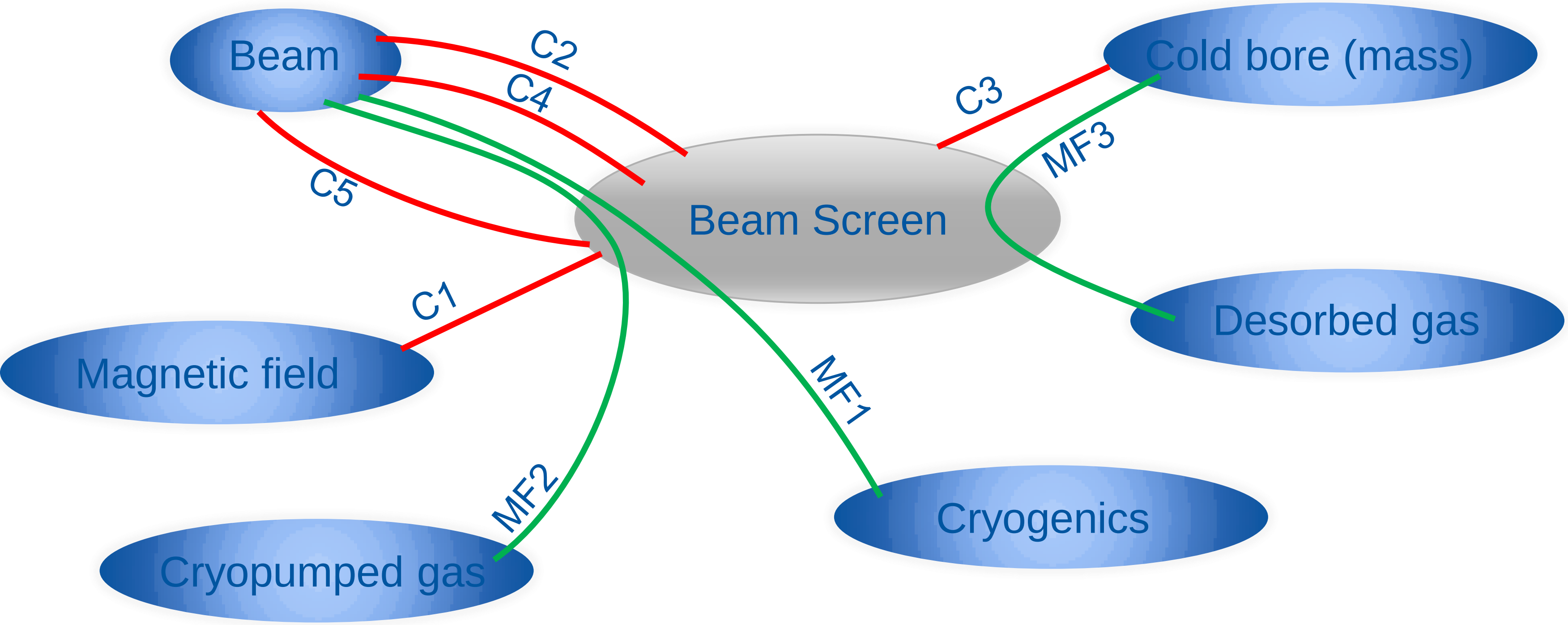
Photodesorption yields for OFE Copper, after 3.10^{22} ph/m dose, ε_c=194 eV

T[K]	H_2	CH_4	CO	CO_2
5	2.10^{-4}	-	-	-
78	4.10^{-4}	6.10^{-6}	2.10^{-5}	-
114	7.10^{-4}	2.10^{-5}	1.10^{-4}	4.10^{-5}
300	8.10^{-4}	2.10^{-5}	3.10^{-4}	2.10^{-4}

V. Baglin et al., THP1B03, EPAC 2000, Vienna, Austria

→ Factor ~1/2.5 at 50 K w.r.t room temperature.

Beam Screen functions



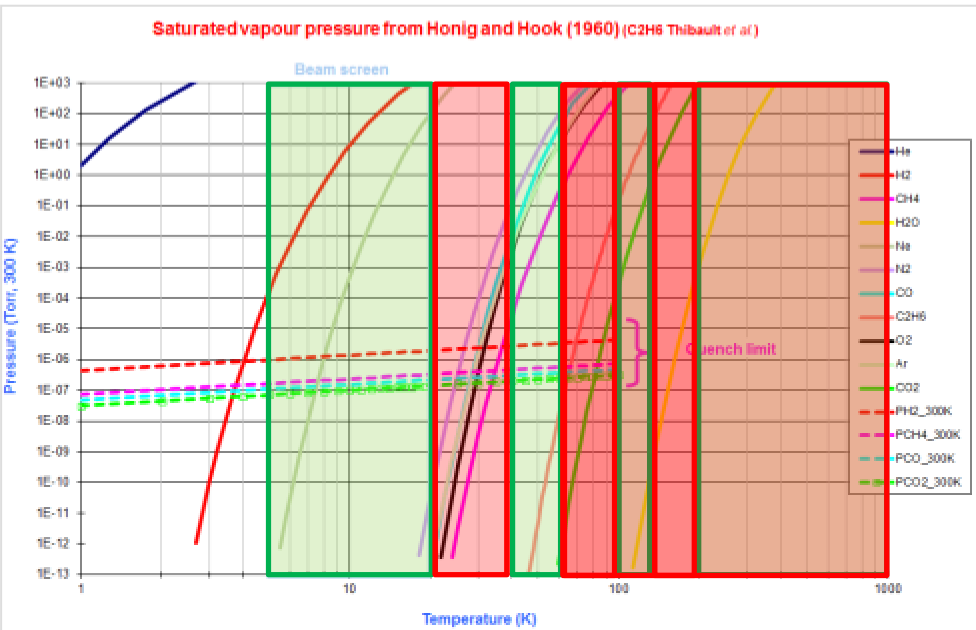
MF1 : Intercept beam induced synchrotron power and transfer it to cryogenic cooling fluid
MF2 : Hide the cryopumped gas from beam induced photon impingement
MF3 : Provide sufficient pumping speed of desorbed gas toward the cold bore
C1: Withstand the Lorentz's forces during a quench
C2: Fulfil impedance requirements
C3: Minimise the heat loads to the cold bore
C4: Mitigate electron cloud
C5: Maximize the beam aperture

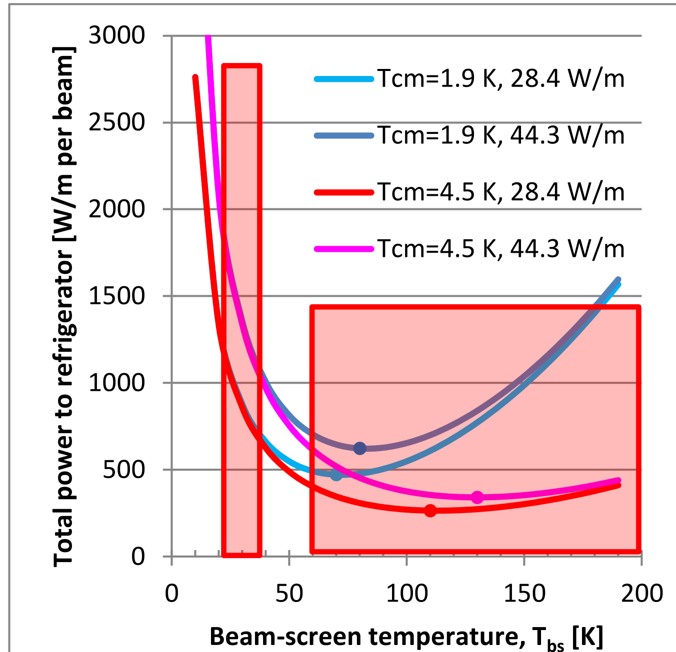
Beam Screen Boundary Conditions

Geometry:

- Coil inner diameter: 50 mm
- Helium radial gap: 1.5 mm (cooling of the coil and helium flow during quench)
- Cold bore thickness: 1.5 mm (stability under external pressure)

Temperature:





L. Tavian, FCC kick-off meeting, Geneva, 2014

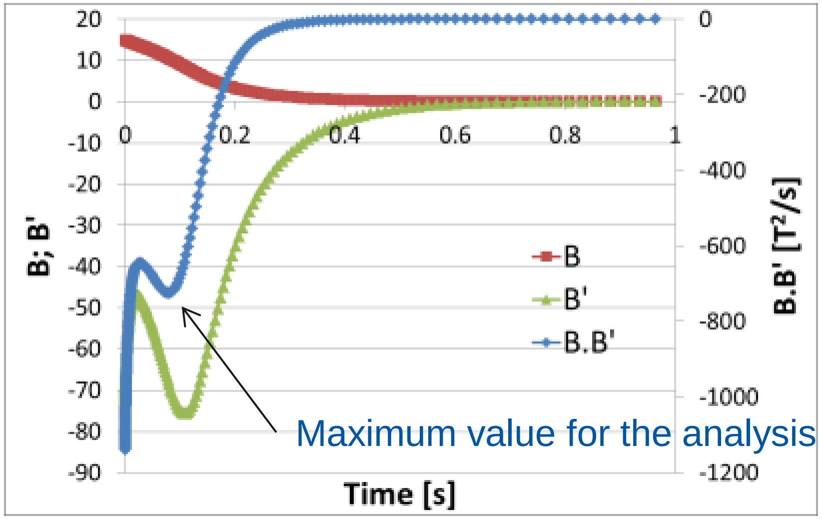
→ Beam screen temperature around 50 K.

Cold bore temperature is assumed to be **1.9 K**.

Beam Screen Boundary Conditions

Magnetic field:

- Magnetic field decay during a quench [E. Todesco]. BB'~725 $T^2.s^{-1}$



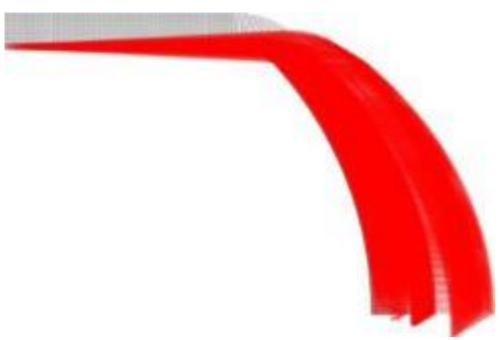
Lorentz forces during a quench are given by:

Magnetic field

Specific force

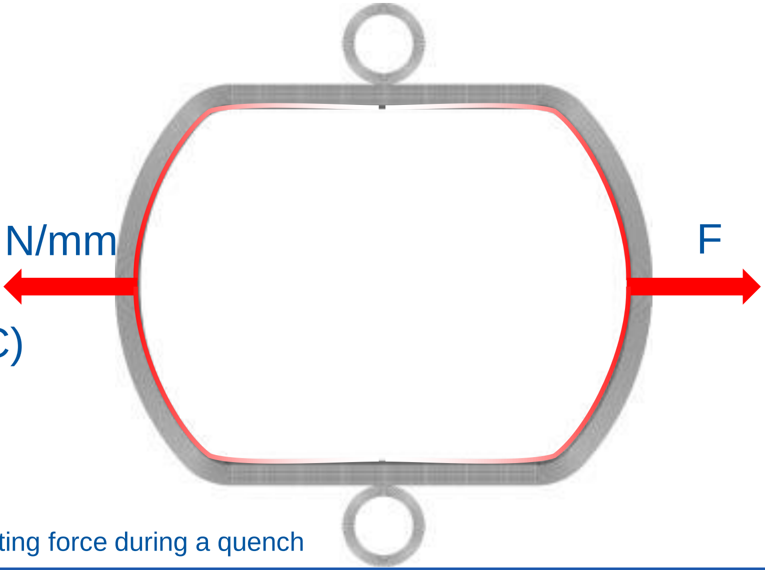
$$f = \frac{xB\dot{B}}{\rho}$$

Electrical resistivity



F ~ 140 N/mm

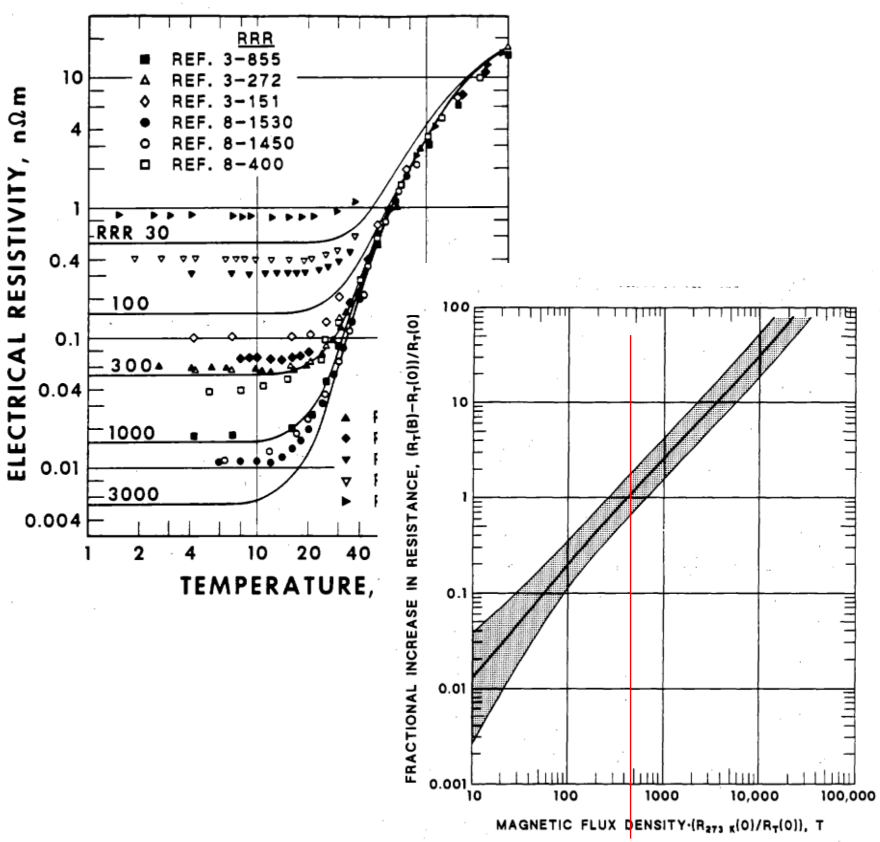
(* 7 LHC)

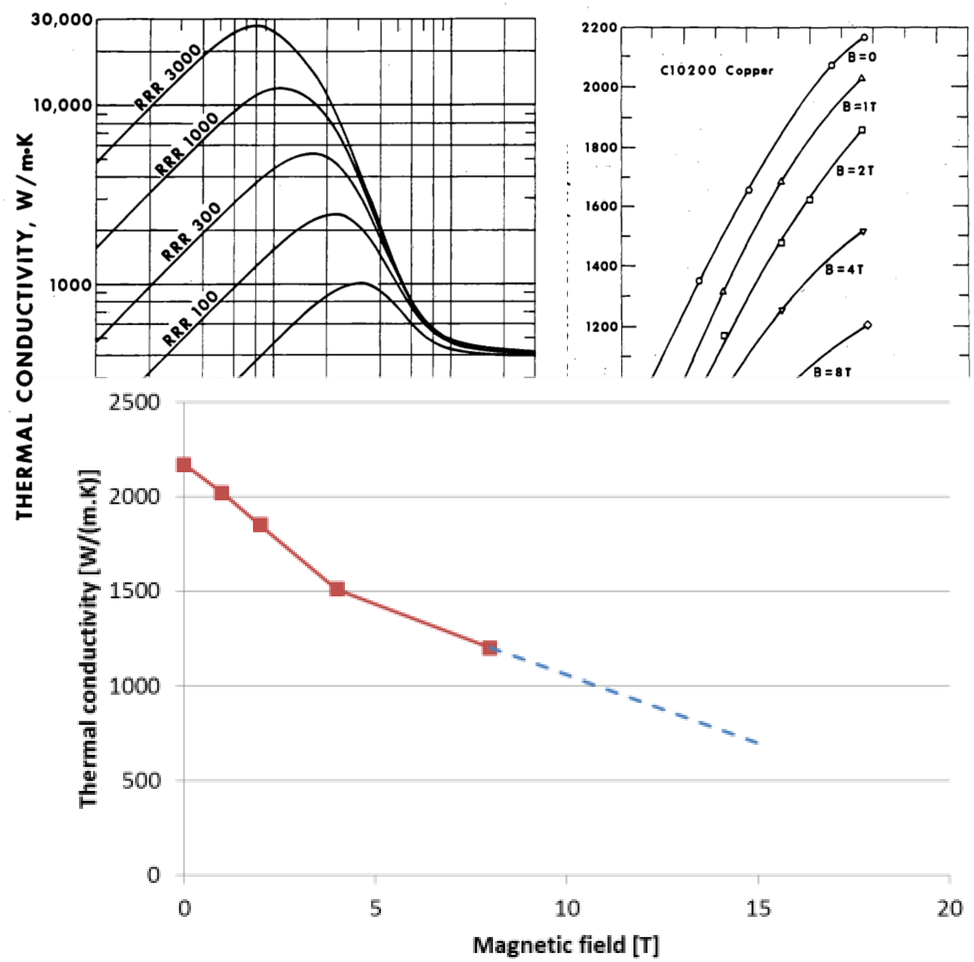


Nodal Lorentz force distribution and resulting force during a quench

Some properties of copper

[N.J. Simon, E. S. Drexler, R.P. Reed, Properties of Copper and Copper Alloy at Cryogenic Temperatures, 1992]





→ Electrical resistivity at 50 K under 16 T : 1 nΩ.m

→ Thermal conductivity at 50 K under 16 T : 700 W/(m.K)

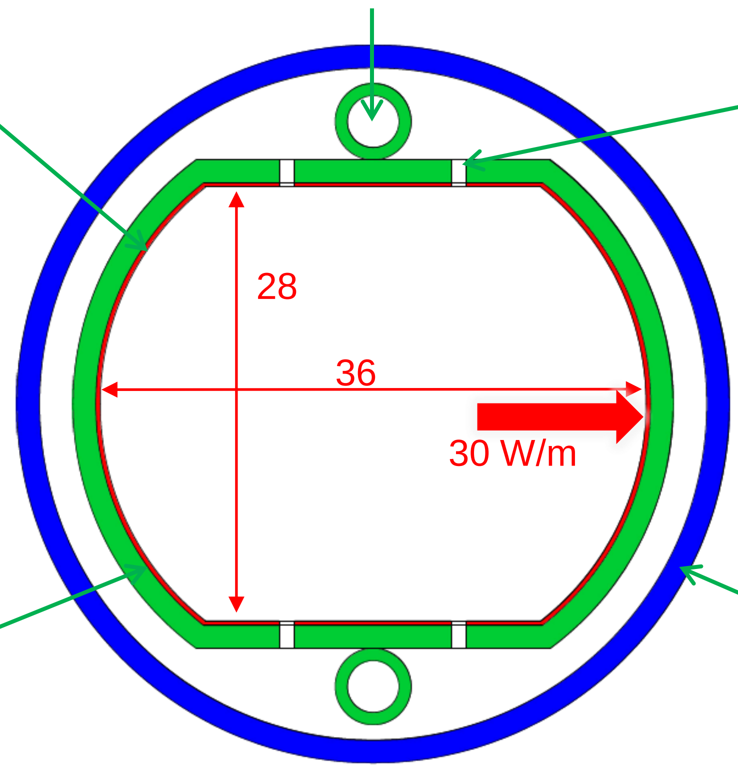
LHC-type Beam Screen

Configuration

<u>Cooling tube:</u>
- Heat transfer coefficient: 150 $W/(K.m^2)$
- Refrigerant temperature: 40 K

<u>Copper layer:</u>
- 0.3mm,
- k ~ 700 W/(m.K),
- σ_y = 70 MPa

<u>Pumping holes:</u>
- 5 %



<u>Stainless steel:</u>
- 1.5 mm,
- k ~ 6 W/(m.K),
- σ_y = 1200 Mpa,
- E: 240 GPa

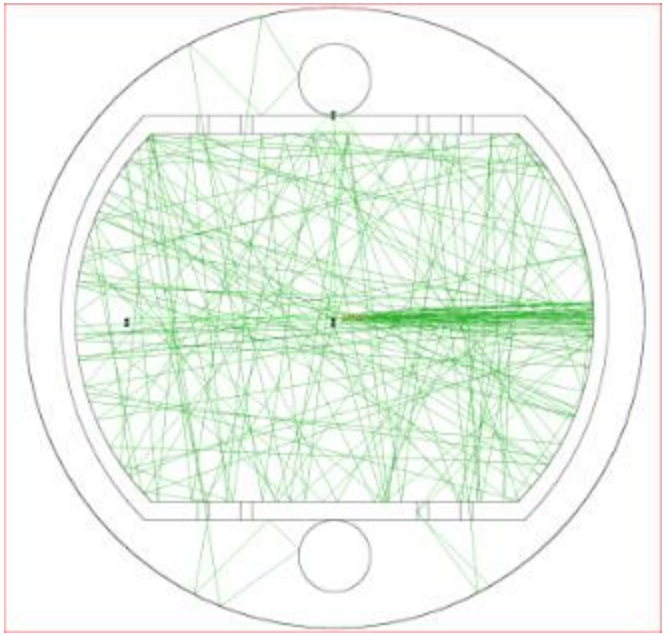
Cold Bore: 1.9 K

LHC-like BS solution

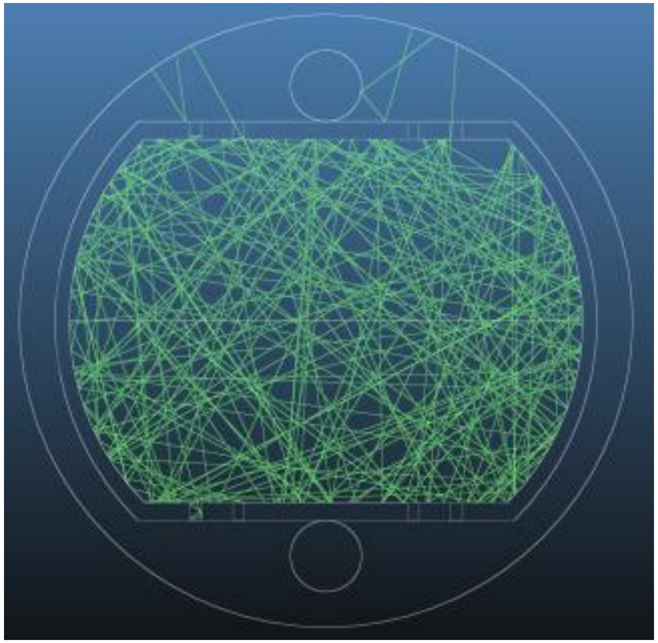
LHC-type Beam Screen

Vacuum study

1. Simulation of the flux and power distribution of the synchrotron light (Synrad+)



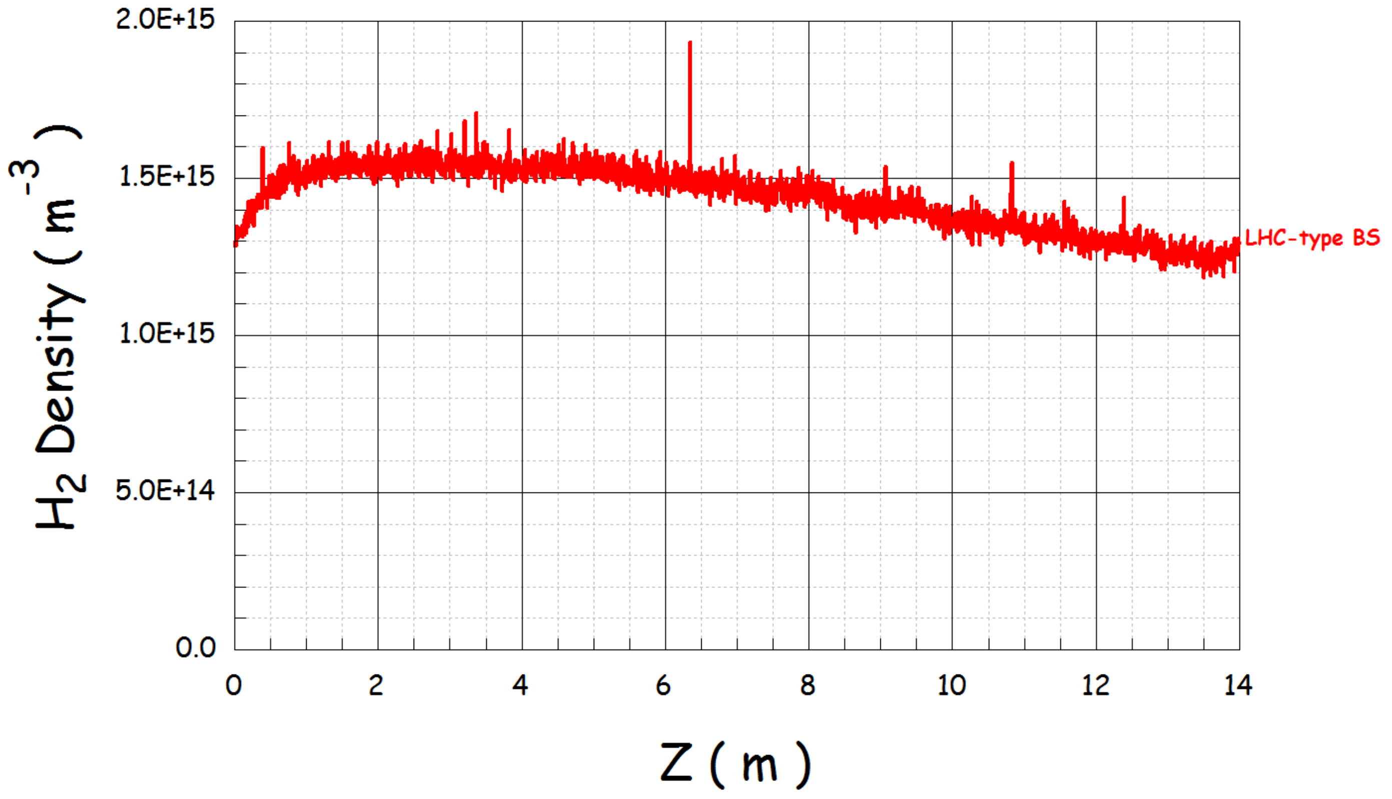
2. Simulation of the photon stimulated desorption and gas density (Molflow+)



All SR-induced gas load may interact with the beam.

LHC-type Beam Screen

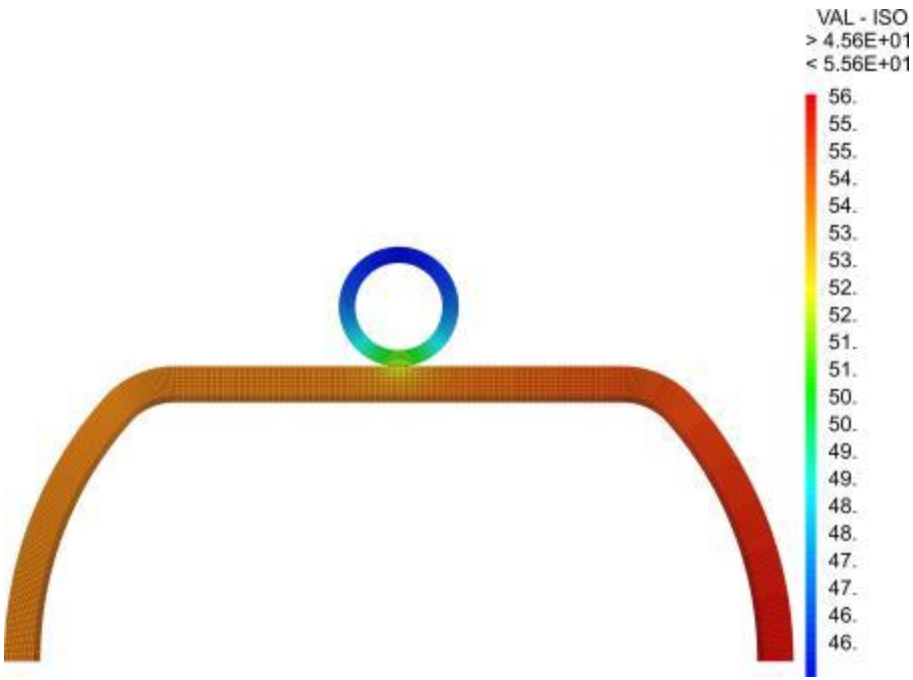
Vacuum study



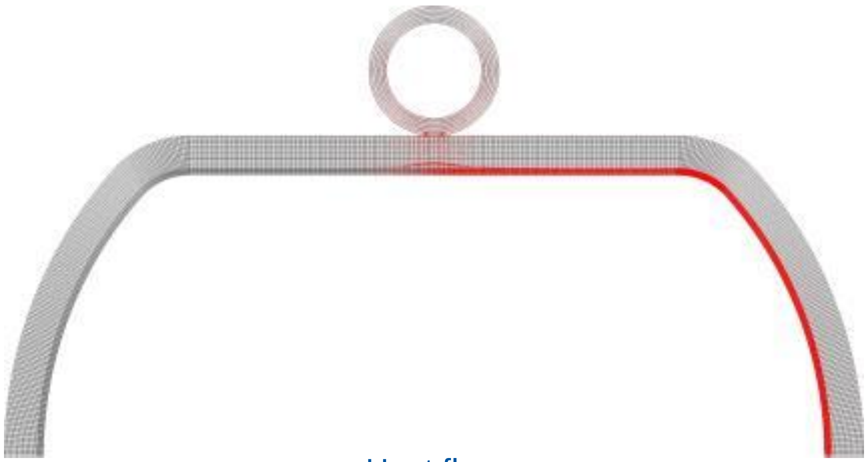
A gas density, slightly higher than 10^{15} molecules/m^3, is expected after 1 day at nominal current and energy.

LHC-type Beam Screen

Thermal study



Temperature profile

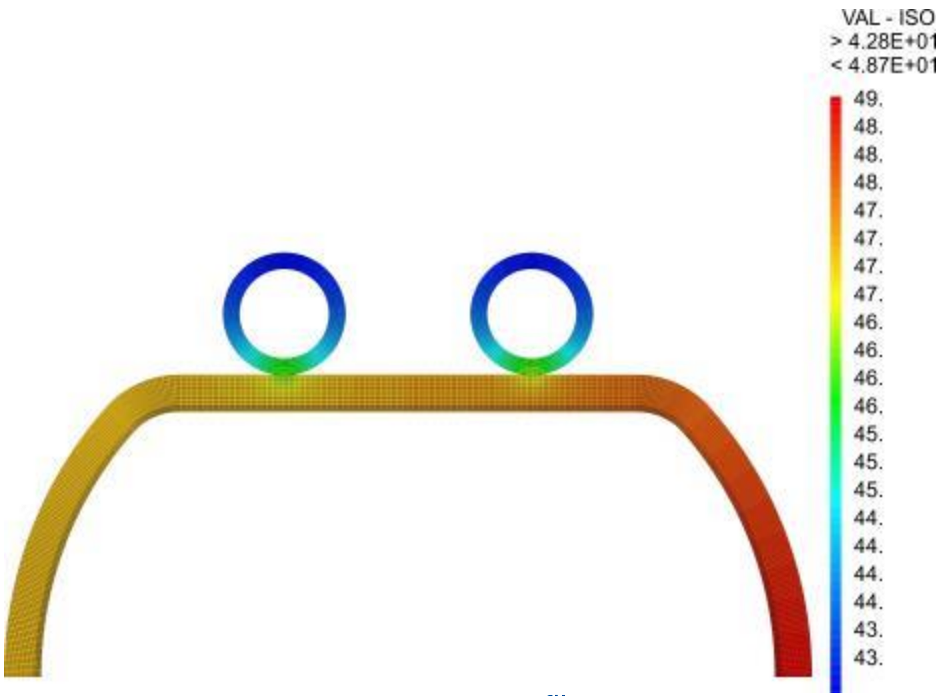


Heat flow

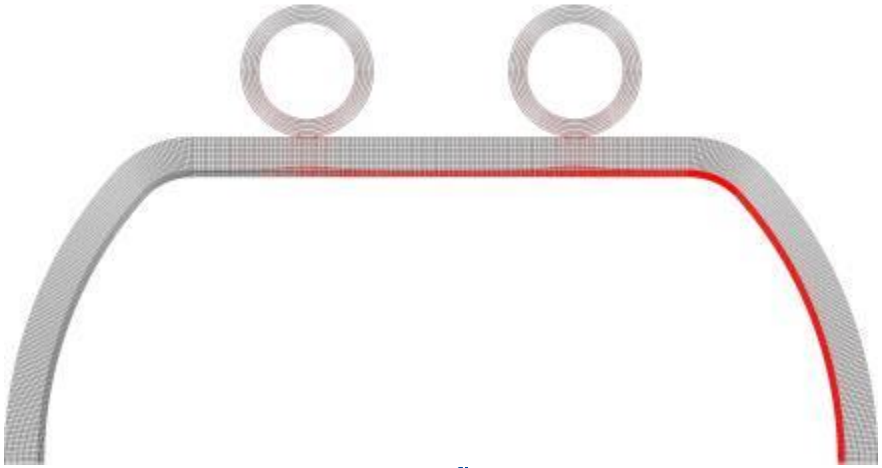
→ Temperature difference between refrigerant and beam screen: ~ 16 K.
→ Temperature gradient along the copper layer: ~ 2 K.
→ Heat carried by the copper layer.

LHC-type Beam Screen

Thermal study



Temperature profile

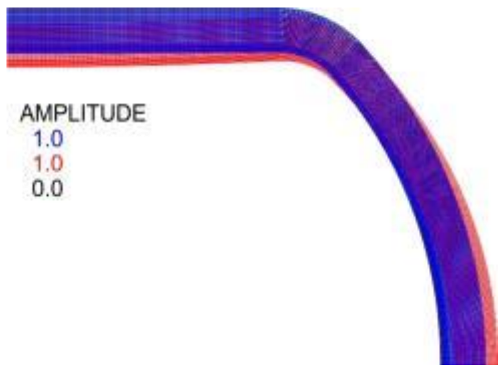


Heat flow

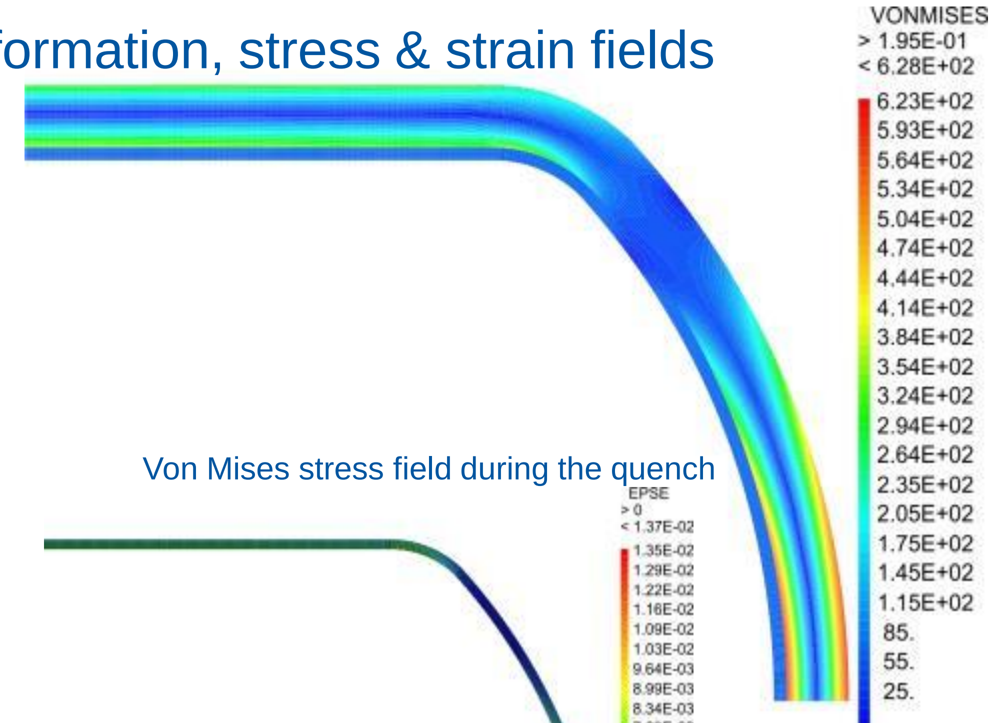
→ Temperature difference between refrigerant and beam screen: ~ 9 K.
→ Temperature gradient along the copper layer: ~ 1.6 K.
→ Heat carried by the copper layer.

LHC-type Beam Screen

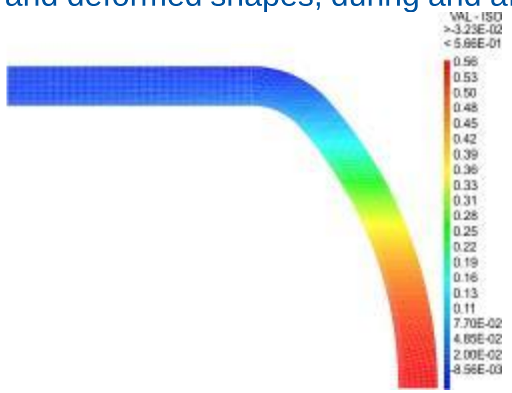
Mechanical study – Deformation, stress & strain fields



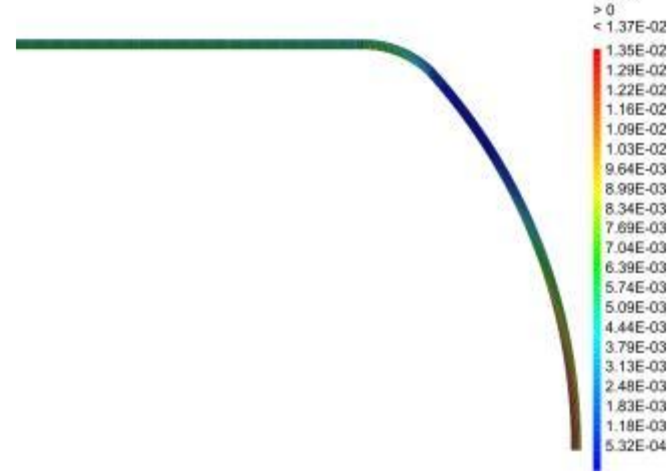
Initial and deformed shapes, during and after a quench



Von Mises stress field during the quench



Horizontal displacement during the quench



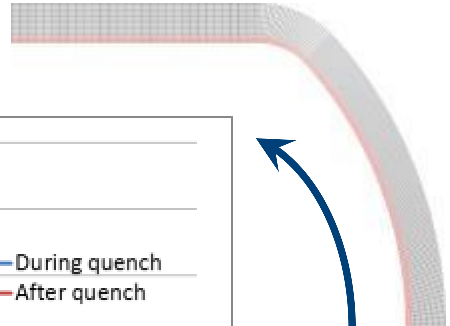
Plastic strain in the copper after the quench

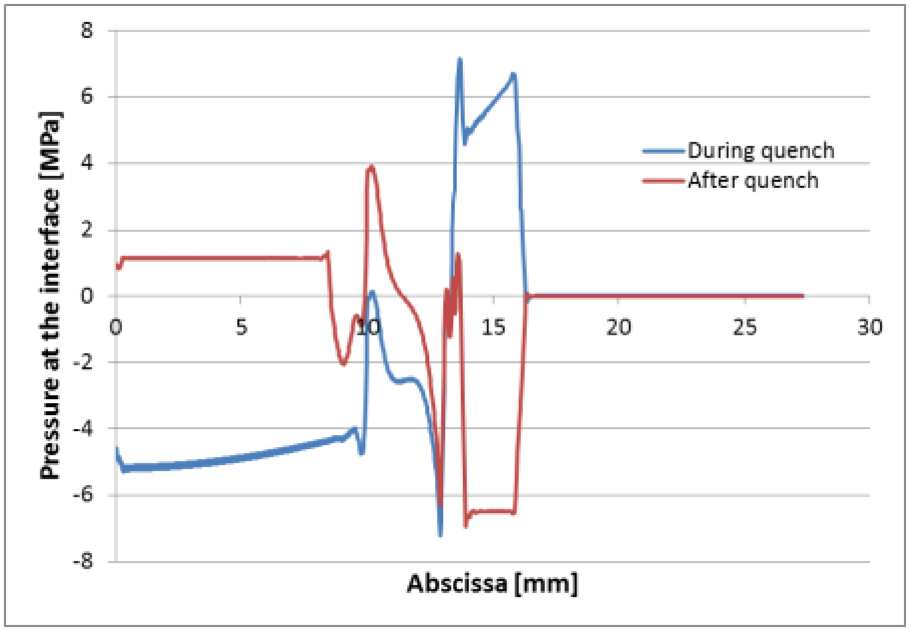
→ No significant overall plastic deformation of the beam screen

→ Plastic deformation of the copper layer

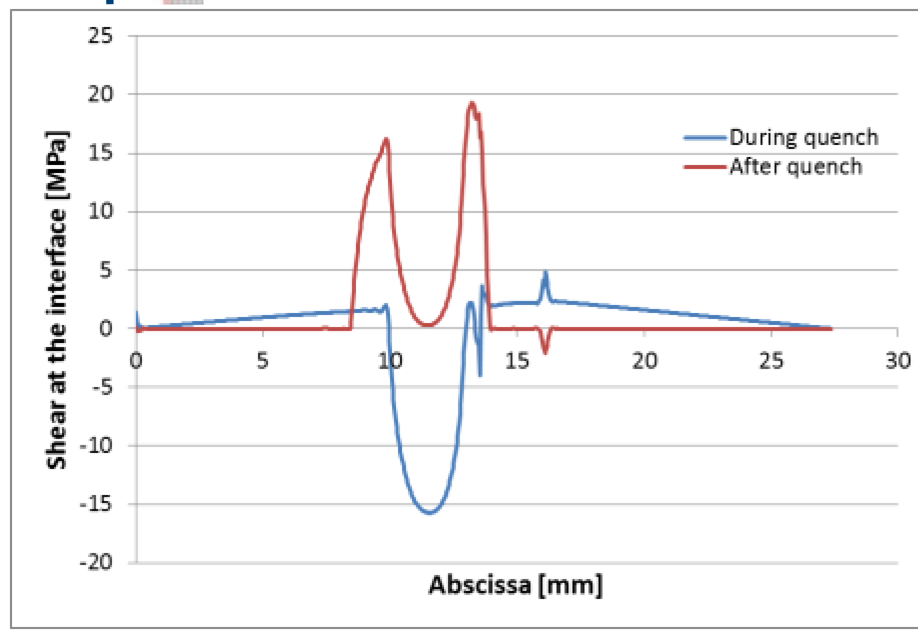
LHC-type Beam Screen

Mechanical study – Interface copper/stainless steel





Normal stress at the interface stainless steel/ copper



Shear stress at the interface stainless steel/ copper

→ Delamination tensile and shear stress around 6 and 20 MPa, respectively

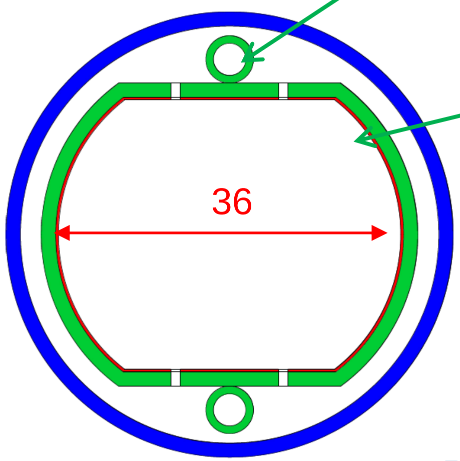
Beam Screen with absorber

Configuration

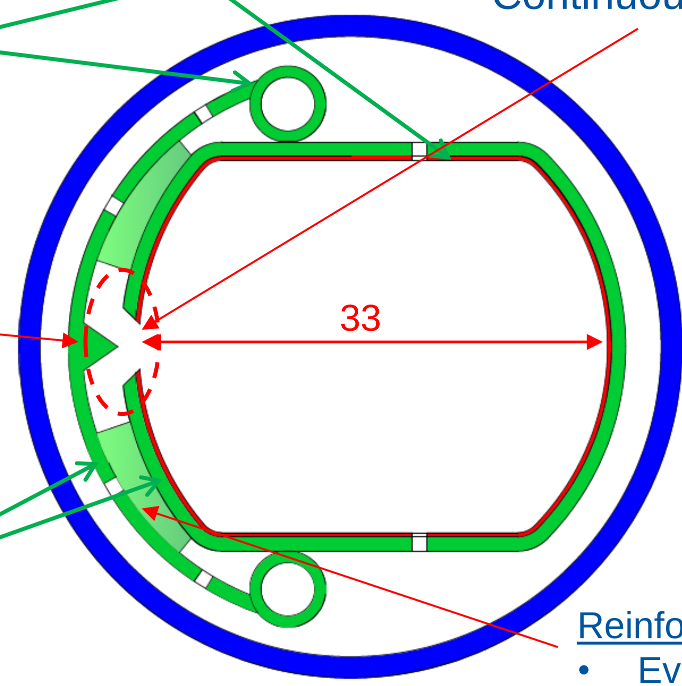
A combined BS, made up of a LHC-like BS with a continuous slot and an “external” SR power absorber is proposed.

Copper layer:
- 0.3mm,
- k ~ 700 W/(m.K),
- σ_y = 70 MPa

Cooling tube:
- Heat transfer coefficient: 150 W/(K.m^2)
- Refrigerant temperature: 40 K



LHC-like BS solution



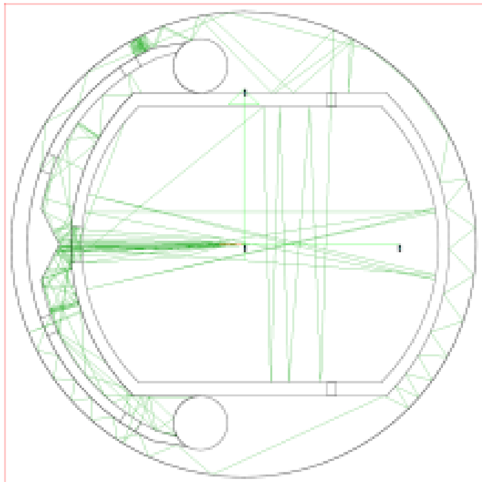
Slotted BS solution asymmetric

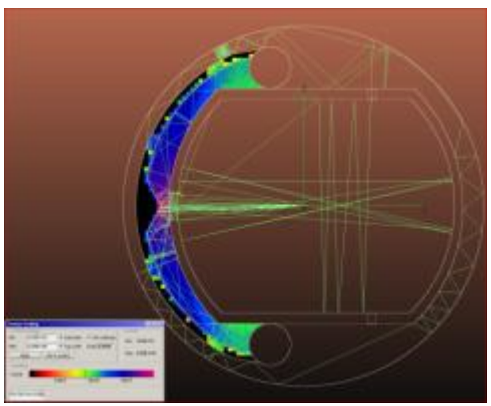
P506:
- 1 mm,
- k ~ 6 W/(m.K),
- σ_y = 1200 Mpa,
- E: 240 GPa

Reinforcement ribs:
- Every 200mm

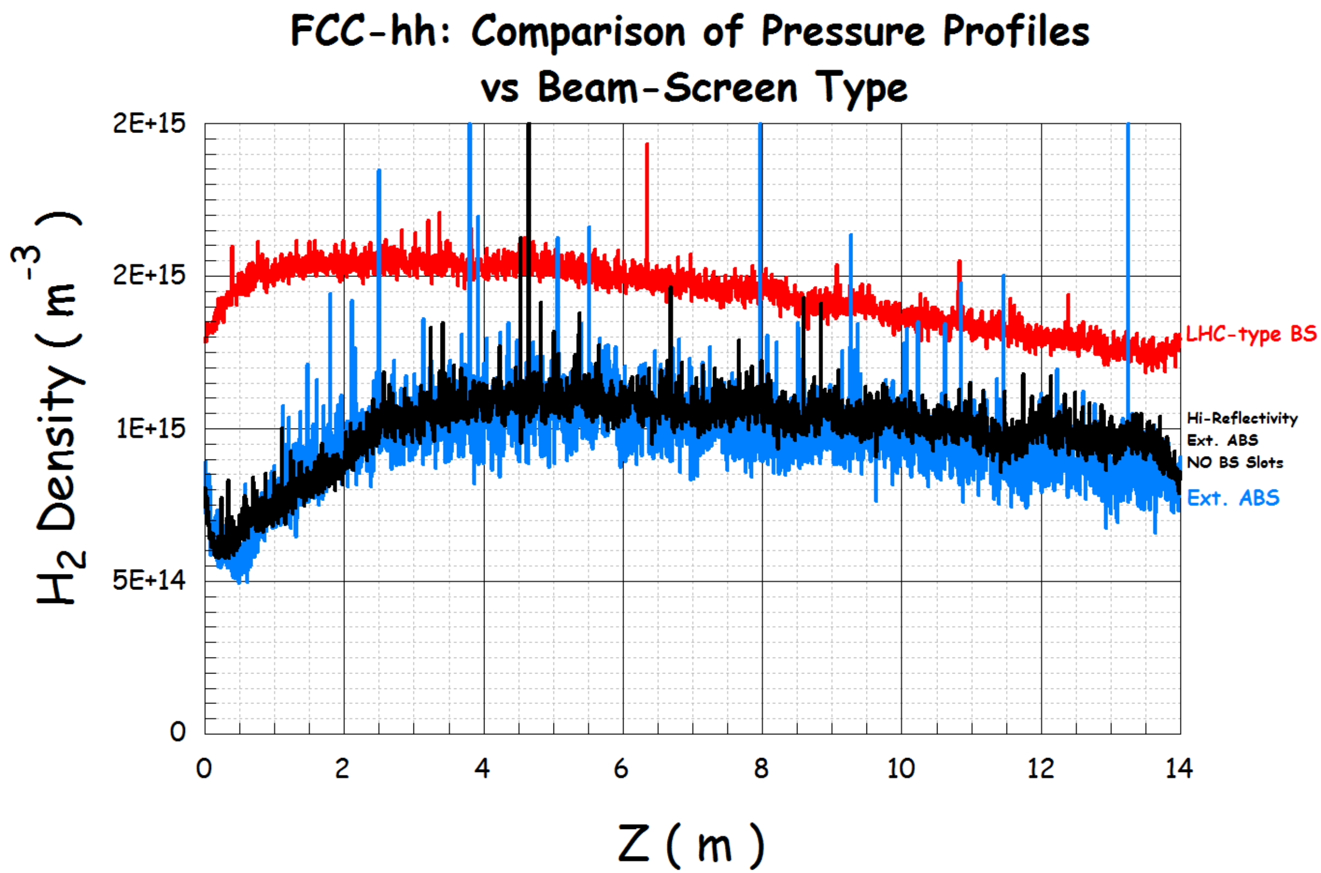
Beam Screen with absorber

Vacuum study





Monte Carlo simulations of photon distribution



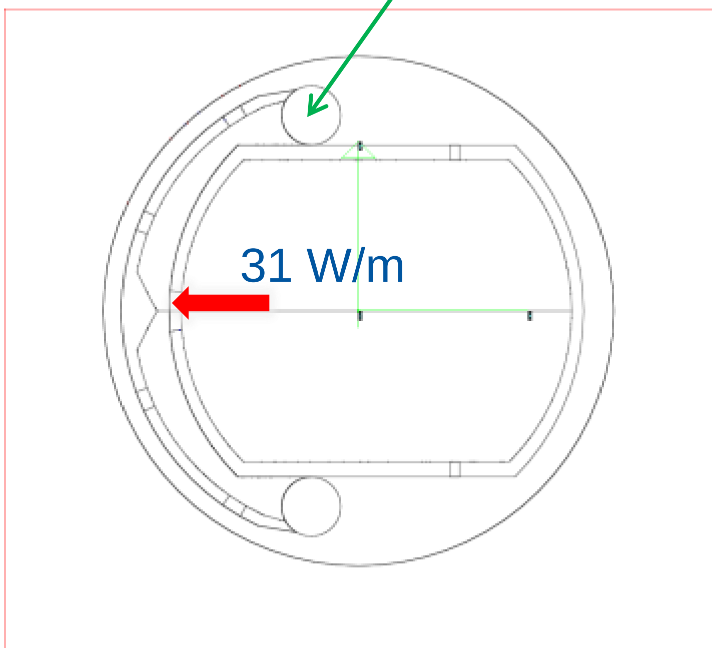
A gas density of around 10^{15} molecules/m^3 is expected after 1 day at nominal current and energy.

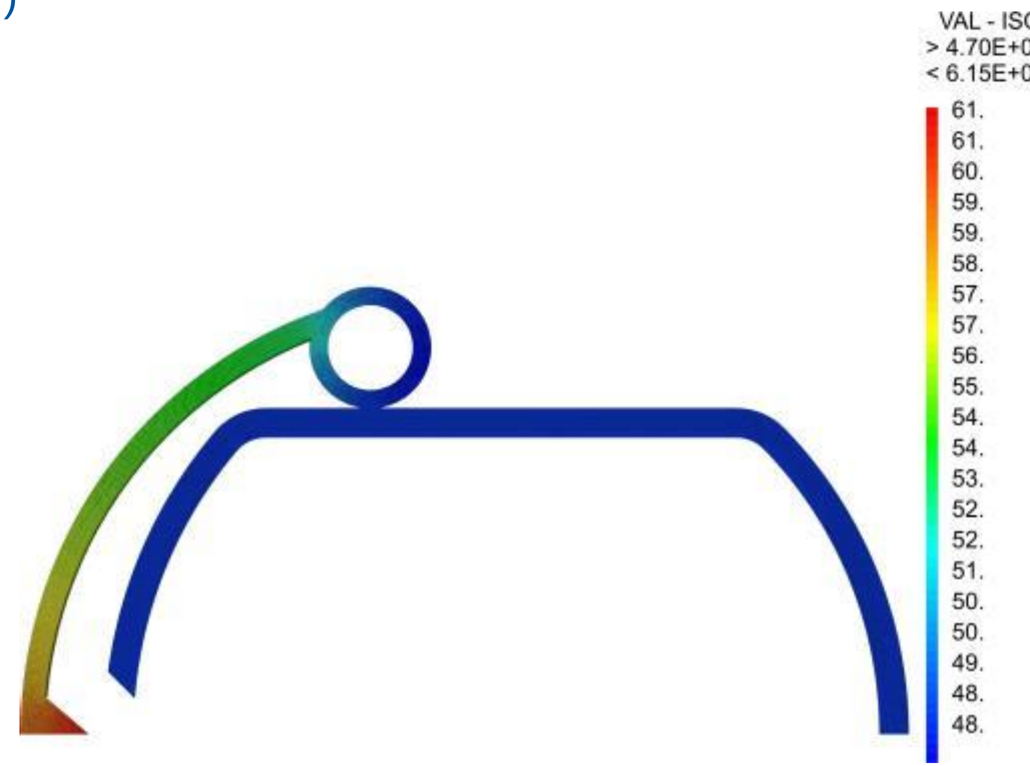
Beam Screen with absorber

Thermal study

Cooling tube:

- Heat transfer coefficient: 150 W/(K.m^2)
- Refrigerant temperature: 40 K



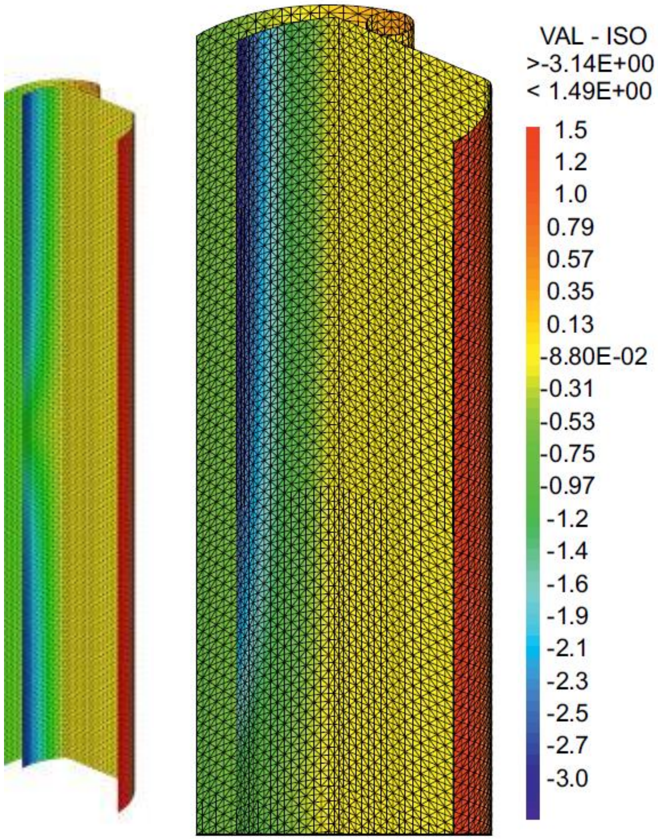


Temperature profile with 0.1 mm copper layer on the absorber

Heat carried by the low thermal conductivity absorber → high temperature : ~ 100 K
Thermal conductive layer required.

Beam Screen with absorber

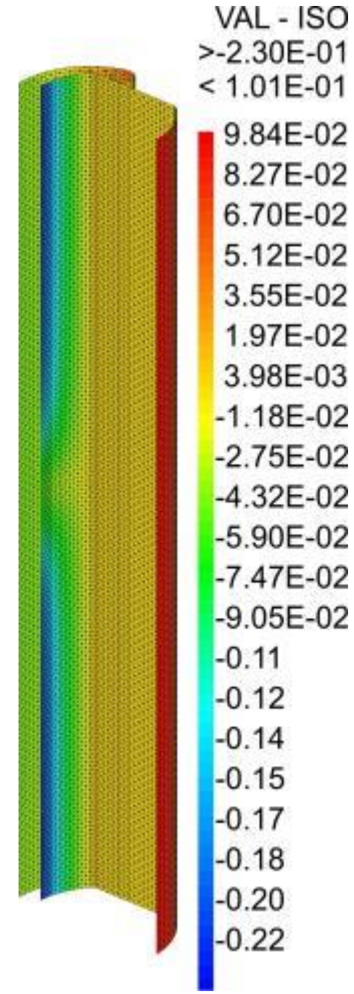
Mechanical study - Displacements



Horizontal displacement during a quench

→ Ribs are mandatory to avoid large deformations

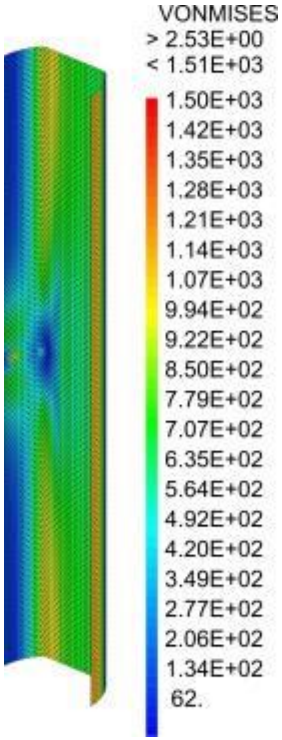
→ Residual deformation after the quench



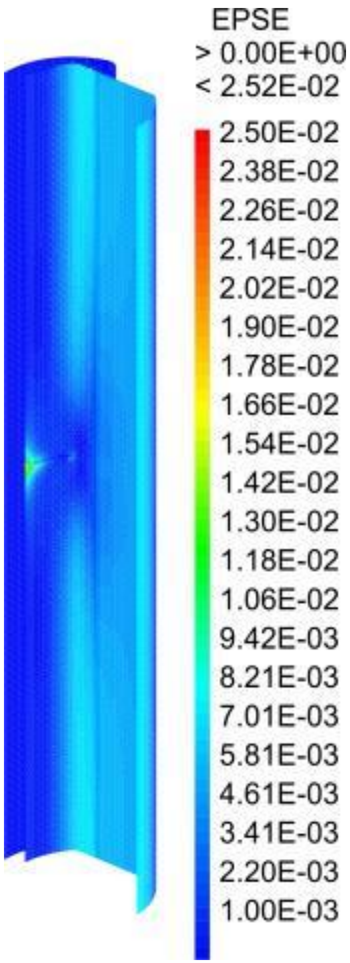
Residual horizontal displacement after a quench

Beam Screen with absorber

Mechanical study – stress, strain fields



Von Mises stress field in the beam screen wall



Plastic strain field in the copper after a quench

→ High stress level in the beam screen

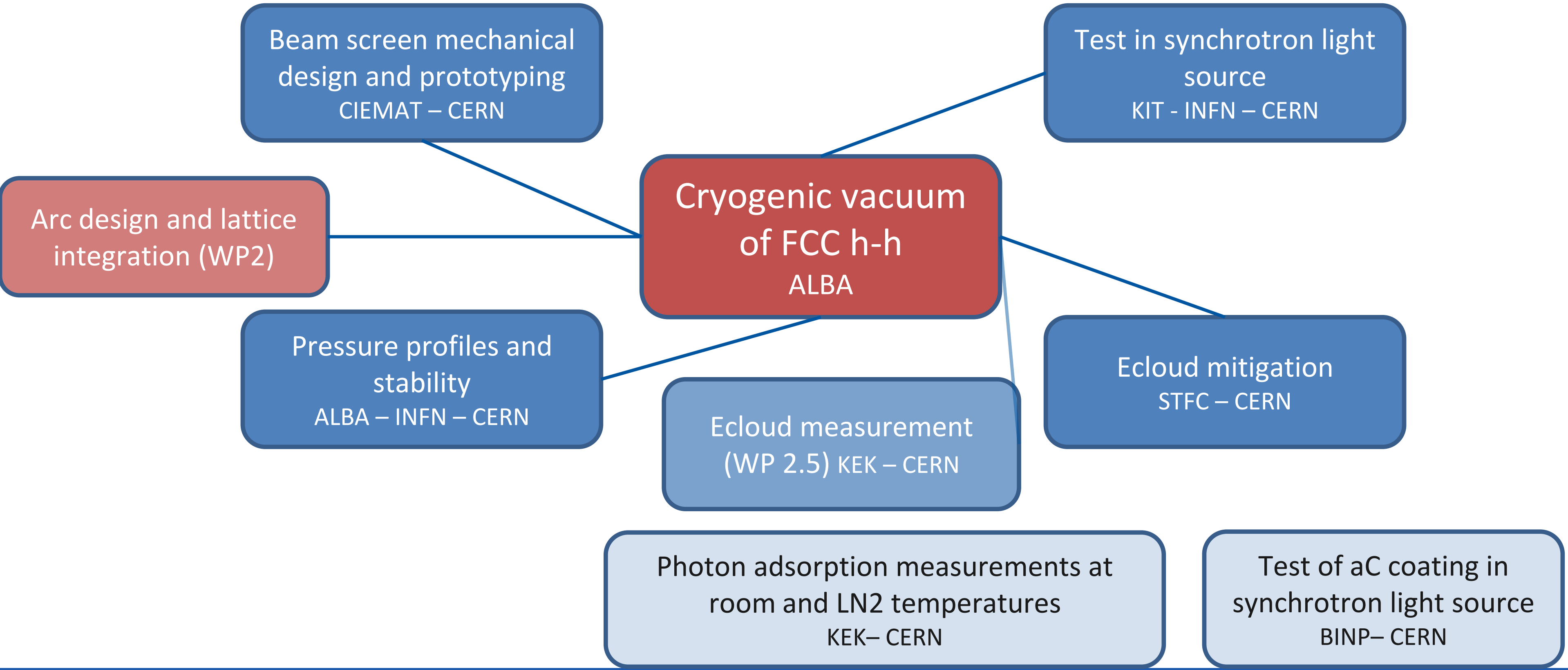
→ Plastic deformation of the copper layer

⇒Increase the thickness and/or higher strength material (titanium alloy)

Roadmap

The technical design concept for the FCC-hh beam-pipe is covered by the cryogenic beam vacuum system work package (WP4) of the European Circular Energy-Frontier Collider Study (EuroCirCol).

Several participants are involved:



Roadmap

Deliverables:

1.	Analysis of vacuum stability at crogenic temperature	Oct-16
2.	Preliminary beam screen and beam pipe engineering design	May-17
3.	Measurements of vacuum chamber at light source	Sep-17
4.	Analysis of beam-induced vacuum effects	Nov-17
5.	Preliminary cryogenic-beam-vacuum system design	Sep-18

Milestones:

1.	WP group established and hiring complete	May-15
2.	Beam screen model heat load and photo-electrons density analysis	Dec-15
3.	Measurement setup at light source operational	Mar-16
4.	Proposal of coatings to mitigate electron-cloud effects	Jun- 16
5.	Report on recommended follow-up R&D	Dec-18

Conclusions

Preliminary concepts of the FCC-hh beam screen are under study. Vacuum, thermal and mechanical aspects have to be integrated.

The design of the FCC-hh cryogenic vacuum system is very challenging:

- From a technical point of view:
  - Dynamic vacuum
  - Heat transfer of the synchrotron radiation power
  - Mechanical stability, in particular during a quench
  - Material properties at cryogenic temperature under high magnetic field

- From an organizational point of view:
  - Several collaborators
  - Different expertise
  - New setups

Both are very exciting.

Thanks for your attention

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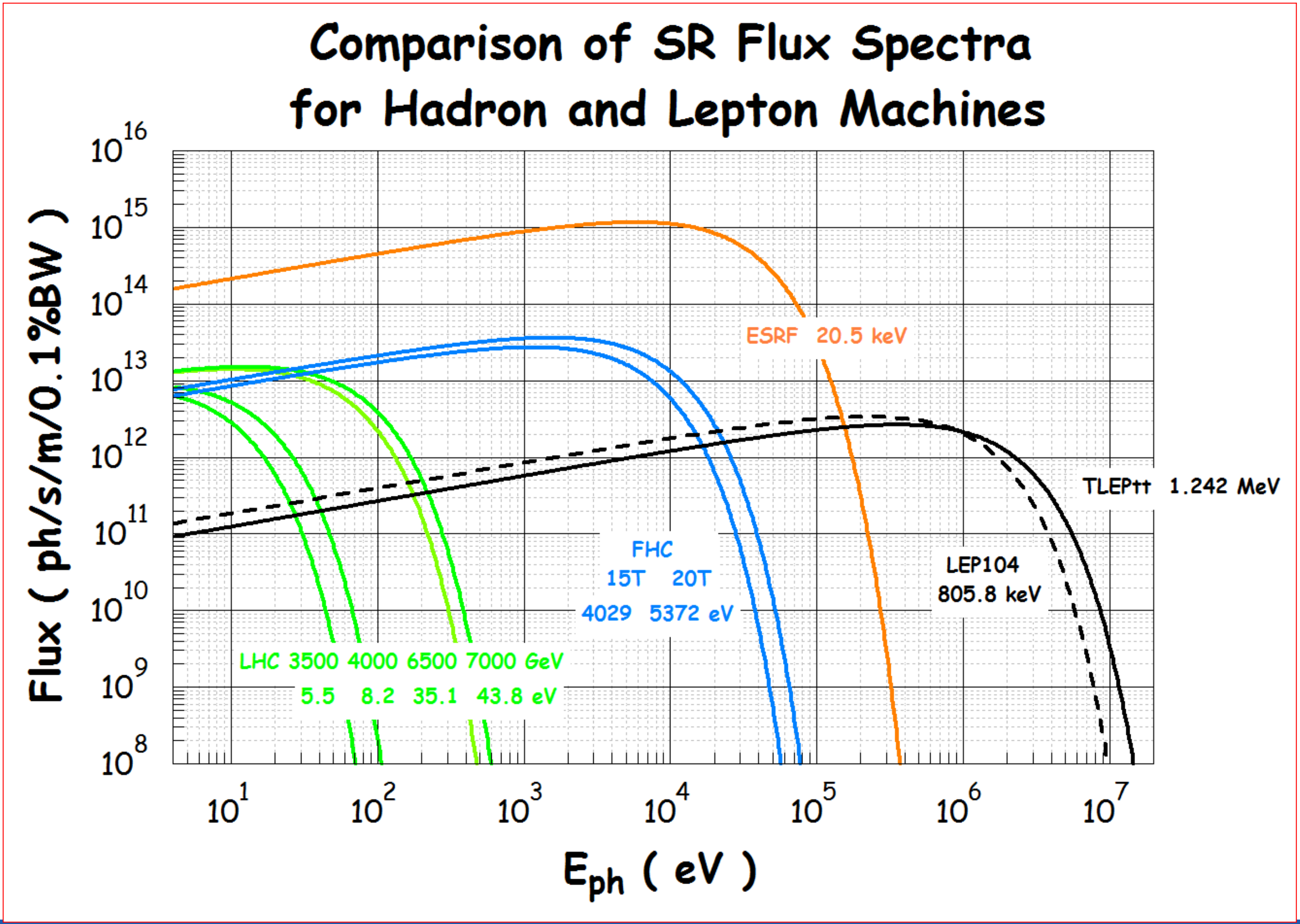
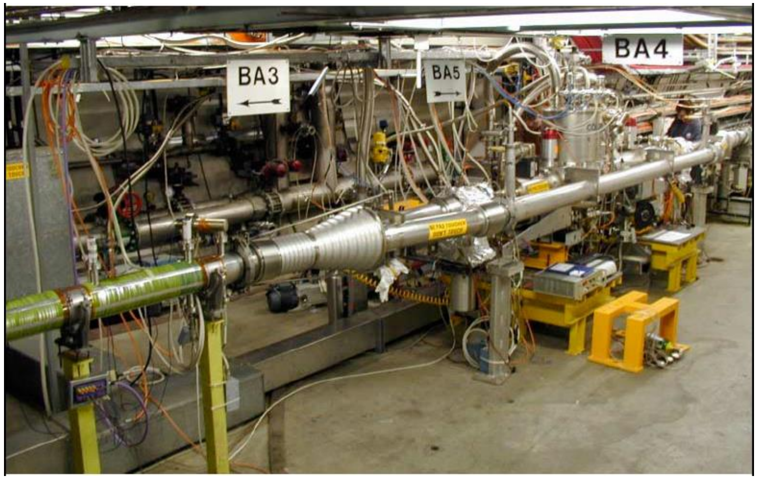
The Synchroton Radiation in the FCC-hh Arcs
SR spectra

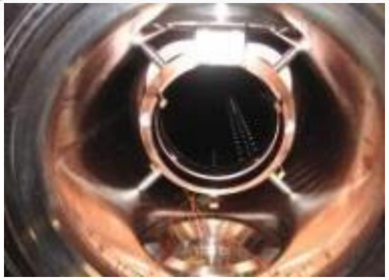


Electron cloud mitigation:
anti-multipacting coating or surface treatment

Coating:

- Amorphous carbon coating
- Operating temperature at 40-60 K
- Tests ongoing in ColdEx (SPS beam)





Surface treatment:

- Laser induced surface texture []
- Operating temperature at 40-60 K