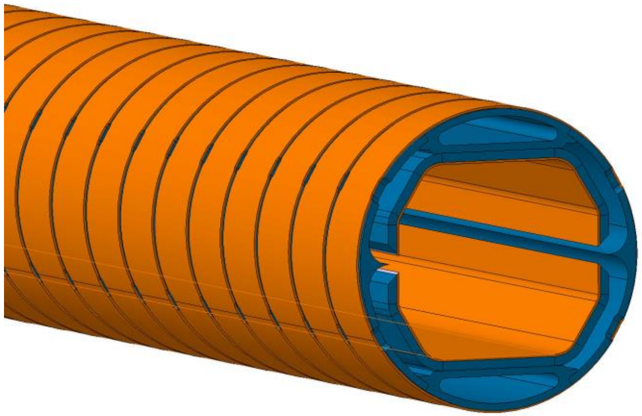
CERN

Research program on the cryogenic beam-vacuum of the FCC-hh

R. Kersevan (CERN-TE-VSC), on behalf of the EuroCircol collaboration

(with material from C. Garion, C. Kotnig, L. Tavian (CERN), and
Patrick Krkotić, Uwe Niedermayer, Oliver Boine-Frankenheim, Tech.Univ. Darmstadt)



Cross section and 3D model of the beam screen, and short prototypes

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Outline

- Beam screen functions and concept; why is it needed at all?
- Thermal study
- Cooling of the beam screen
- Vacuum performance
- Mechanical design
- Impedance issues
- Prototyping
- Tests at ANKA light source
- Summary

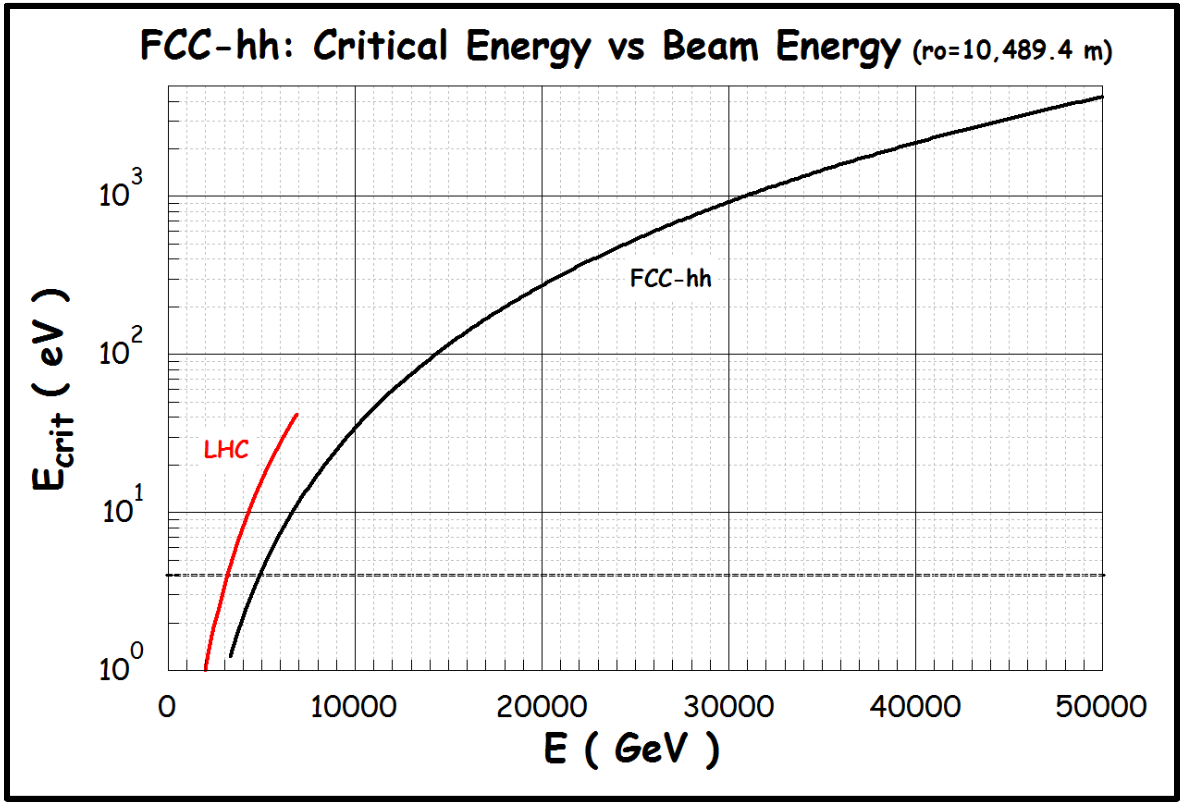
Why is a beam-screen (BS) needed at all?

- → **Without a BS there would be no vacuum stability** ← (known since SSC times)
- The synchrotron radiation (SR) flux and power generated along an FCC-hh dipole magnet is **much higher than that in the LHC:**

	LHC (7 TeV, 8.32 T)		FCC-hh (50 TeV, 15.9 T)	
Flux [ph/s/m]:	$4.3 \cdot 10^{16}$	→	$1.6 \cdot 10^{17}$	(3.7x)
Power [W/m]:	0.22	→	35.2	(160x)
Critical energy [eV]:	43.8	→	4270	(98x)

- **REQUIREMENT:** The allowable molecular density "seen" by the stored beams must stay below the **$2 \cdot 10^{14}$ H_2-equivalent/m^3**, a factor of **~5 lower** than in the LHC, to reduce the beam-gas scattering nuclear interaction and related **energy deposition in the cold mass** of the SC magnets (which could trigger a magnet quench);
- Without a BS the SR power would be absorbed at the cold-bore temperature (1.9 K): at 500 mA/beam, about **2.3 MW/beam** of SR would need to be handled by the cryogenic system at 1.9 K, driving its electric power requirement to the roof **exergy losses** to room-temperature… or **>1.1 GW total needed by the refrigerators**!);
- In the **LHC** the BS temperature is kept in the range **5-20 K**: for **FCC-hh** we aim at a range **40-60 K** (to be confirmed by vacuum/cryogenic tests which are underway).

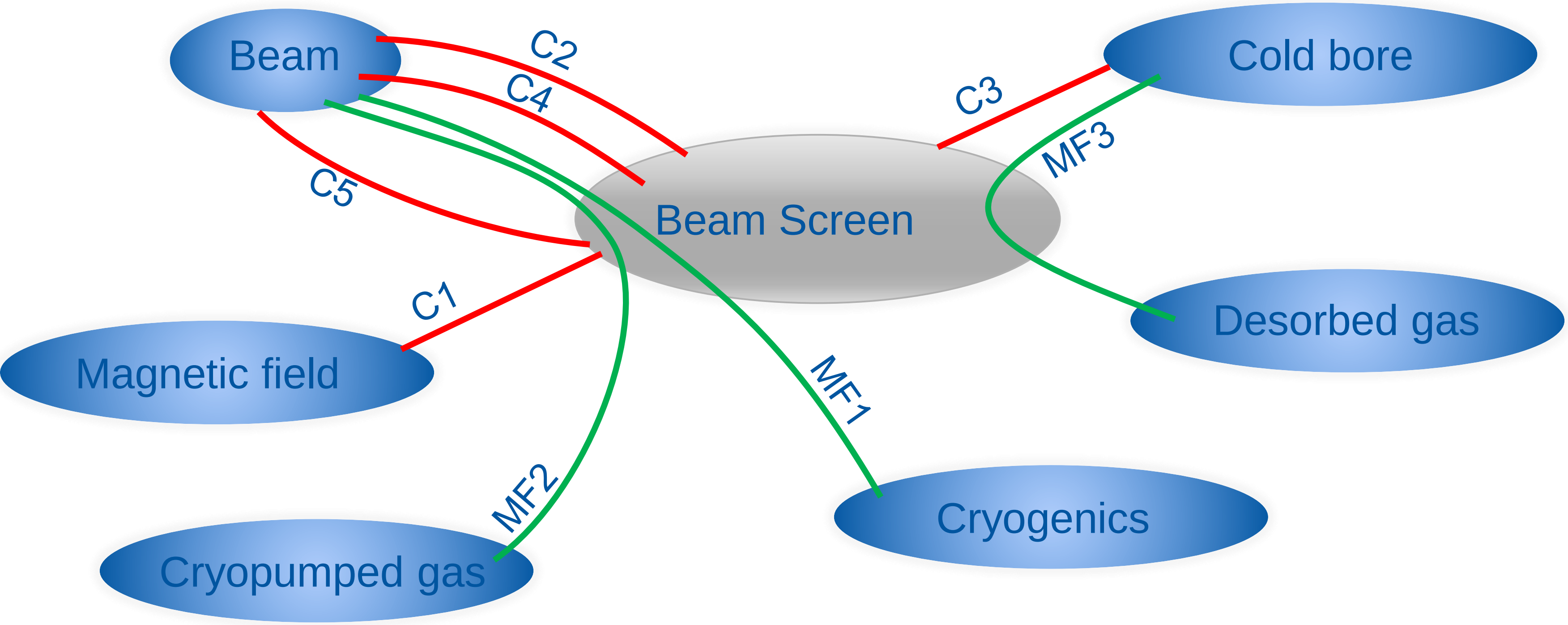
Critical energy E_{crit} of the SR photon spectrum for FCC-hh vs beam energy: it is shown that up to about 5 TeV E_{crit} stays below 4 eV (i.e. only edge-radiation may contribute to photodesorption, to be looked at separately)



E (TeV)	F (ph/s/m)	P (W/m)
3.3	5.6848e+13	0.0000
5	1.5818e+15	0.0018
7.5	7.2822e+15	0.0153
10	1.4609e+16	0.0535
15	3.0563e+16	0.2820
20	4.7361e+16	0.8979
25	6.3581e+16	2.1966
30	8.0213e+16	4.5582
40	1.1355e+17	14.4130
50	1.4693e+17	35.1923

LHC: Critical energy **E_{crit} = 43.8 eV** (@7 TeV);
Flux = 4.2e+16 ph/s/m (@500 mA)
Power = 0.183 W/m
“ “

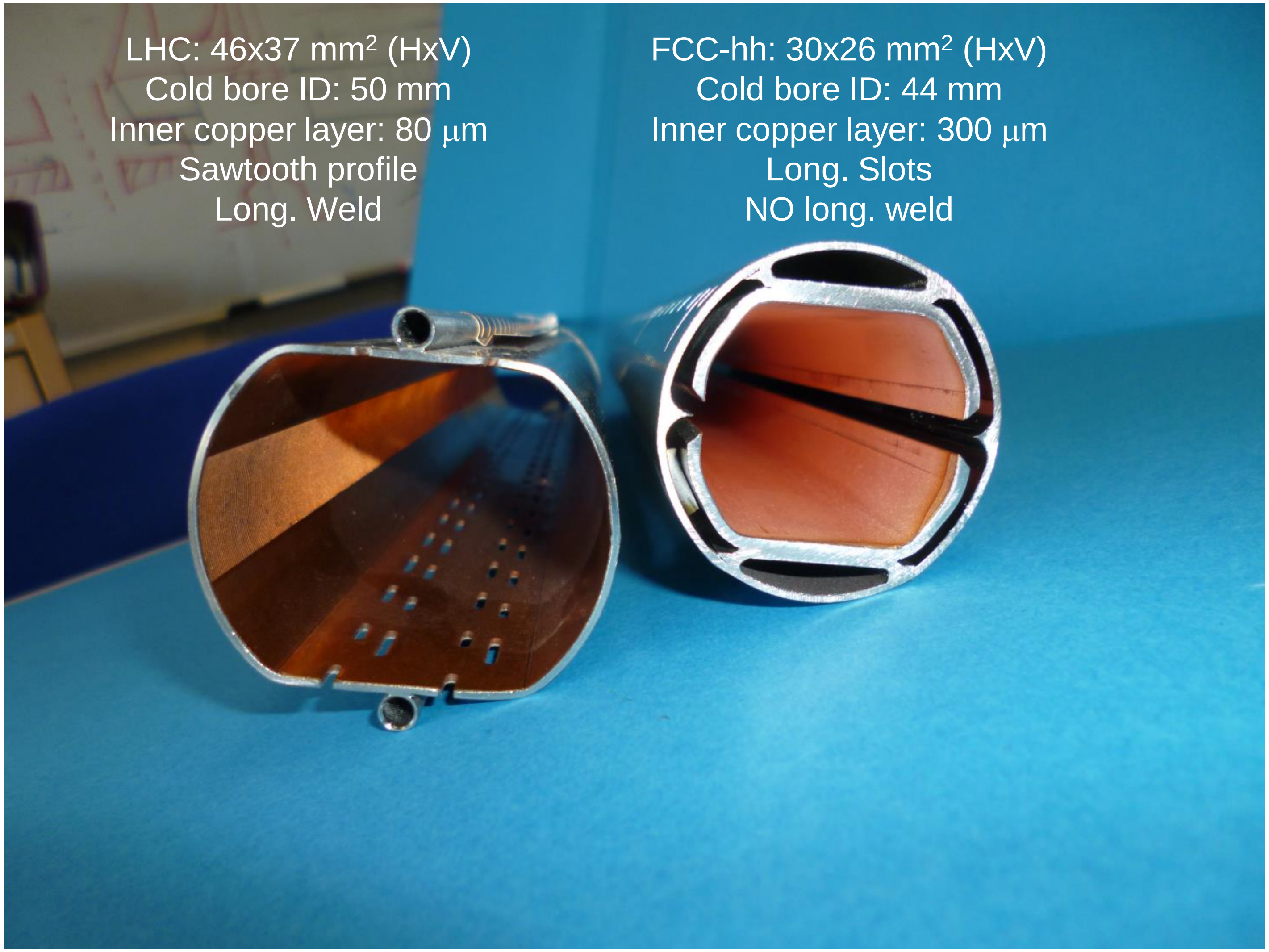
Beam Screen functions



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-stay-clear aperture

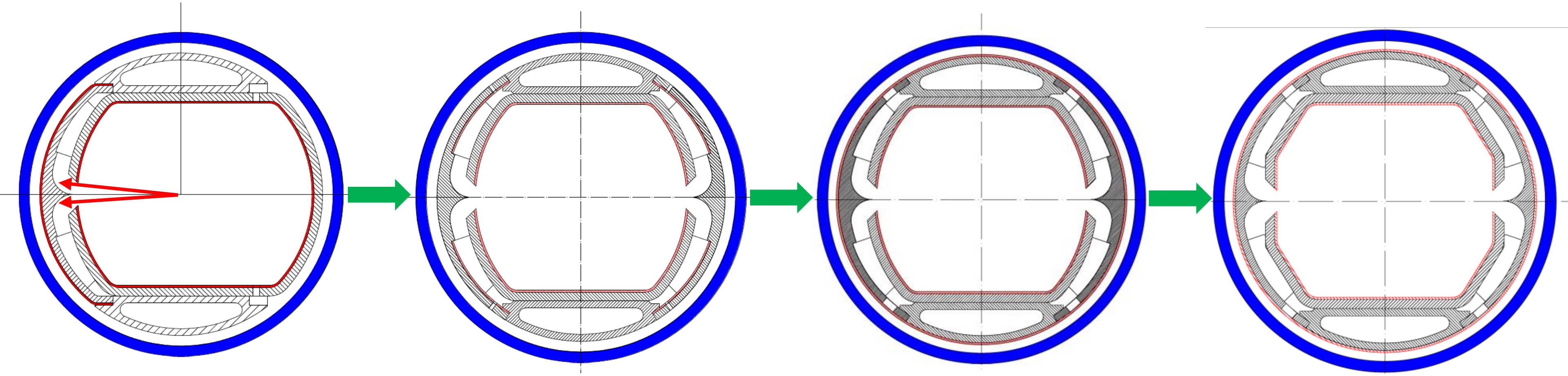
MF: Main Function;
C: Constraint

Beam screen: LHC vs FCC-hh



Design Updates

(Since FCC Kick-Off Meeting, Feb 2014, Univ. Geneva)

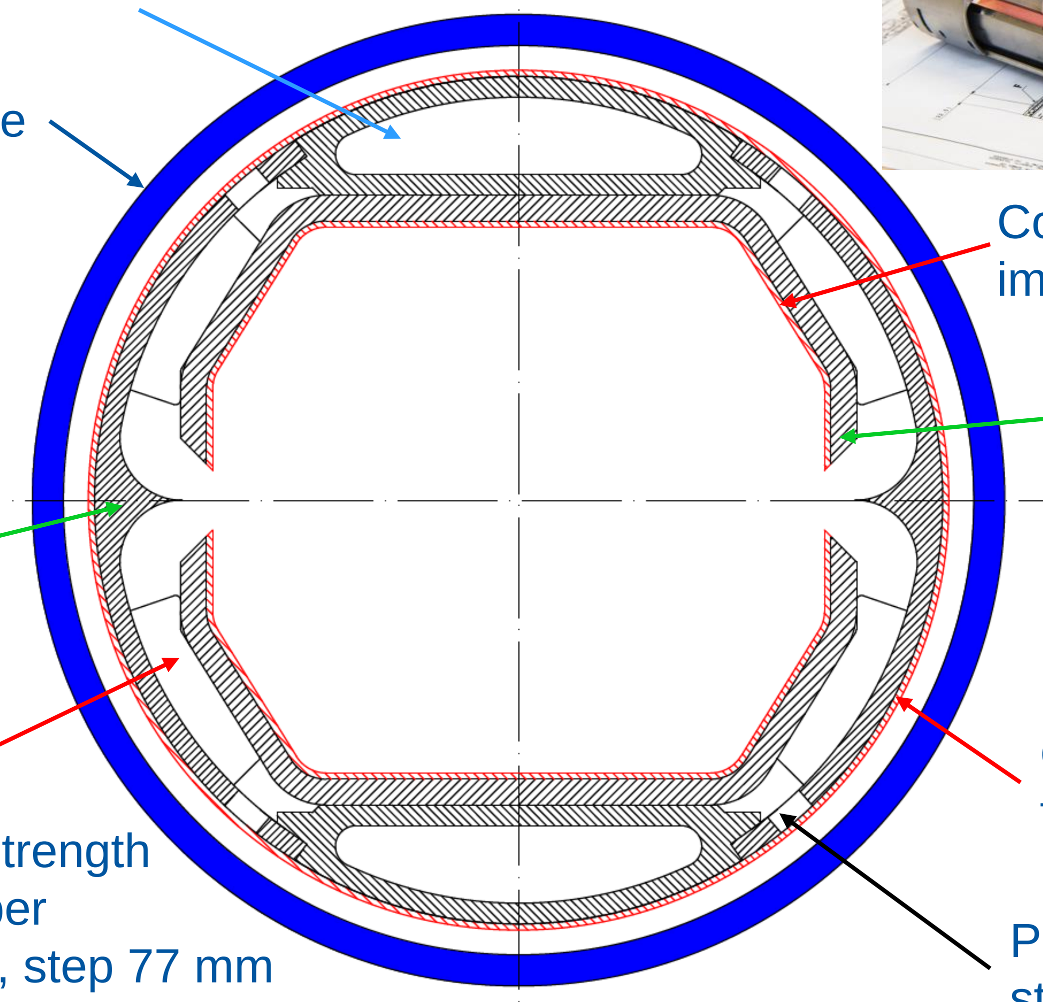


- Symmetrical design
  - → Better impedance (actually suggested by impedance people)
  - → Pumping holes hidden by the screen
- Thermal copper coating on the outer side
- Bigger pumping holes – no constraint for the distribution (to be confirmed)
- Polygonal shape of the screen (easier forming/machining/manufacturing)

Beam screen concept

Cooling channel (2x)

Magnet cold bore



Copper layer, 0.3 mm for impedance

Screen (2x ½)

Deflector (2x)

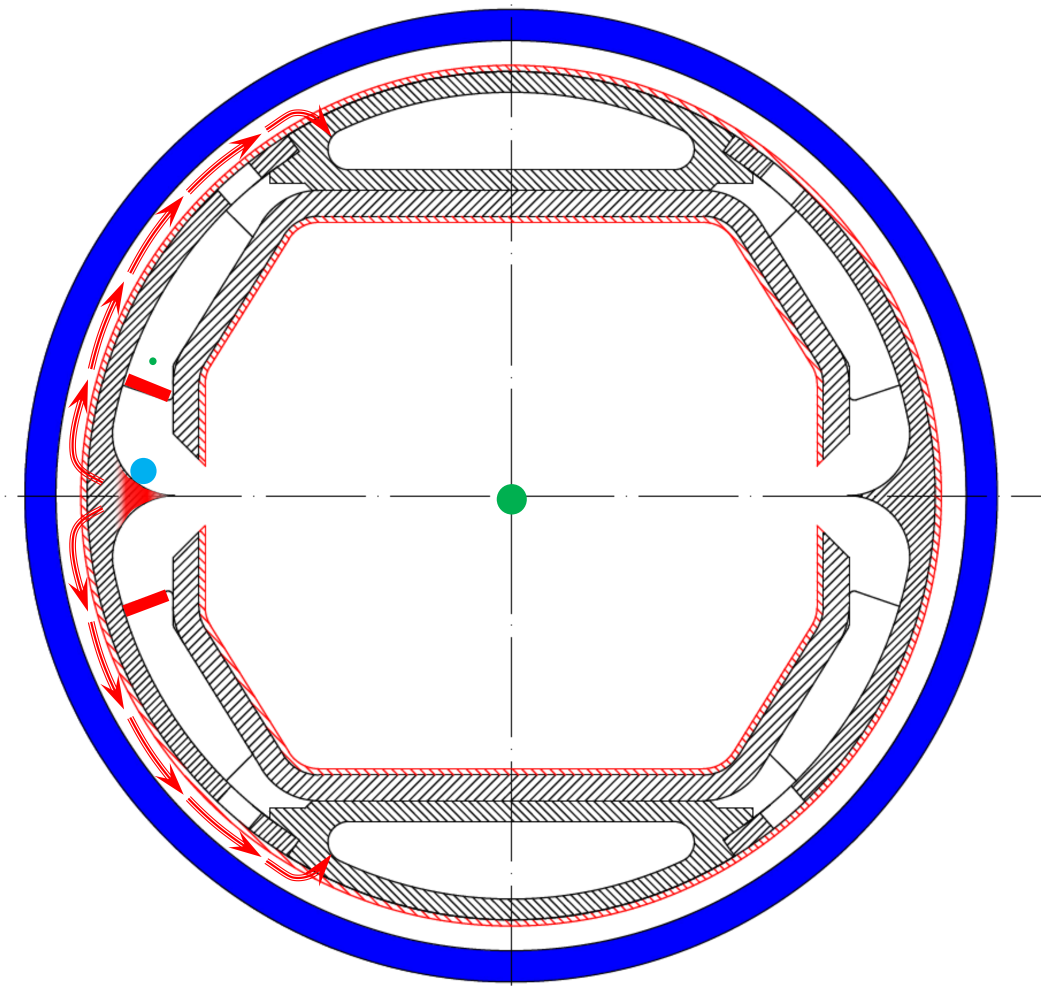
Copper strips for heat transfer

Ribs (4x):
- Mechanical strength
- Photon stopper
- 1.5 mm-thick, step 77 mm

Pumping hole (4x), step 11 mm

Beam screen concept – Working Principle

1. Photons are channelled in the antechamber and after one or more reflections are stopped by the ribs.
2. Photo-desorbed gas is channelled preferentially in the antechamber and pumped through pumping holes (some molecules wander around in the beam's path before being pumped)
3. Synchrotron radiation power is deposited mainly on the deflector tip and on the lower edge of the ribs (highlighted in red), and it is transferred to the cooling circuit mainly by the external copper.



Design – Main dimensions

(subject to change)

Cold bore diameter: 44/47 mm

Beam screen wall:

- 1.25 mm P506 (high-Mn high-N st. steel)
- 0.3 mm copper

Nominal aperture:

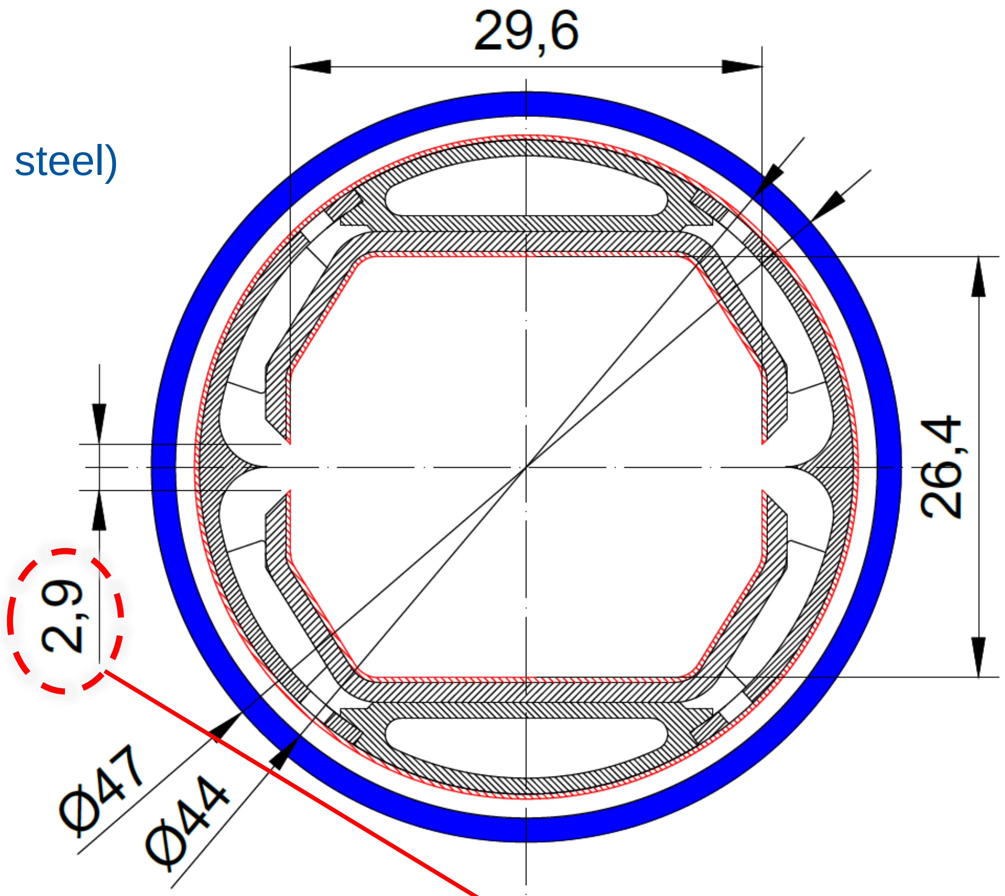
- H:~ 29.6 mm
- V:~26.4 mm

Slit height: ~ 2.9 mm

(→ 5 mm if validated by impedance experts)

Cooling channel:

- Thickness 1 mm
- Internal 53.58 mm^2
- Hydraulic diameter: 5.61 mm



Now 5 mm

(pending review of its effect on impedance)

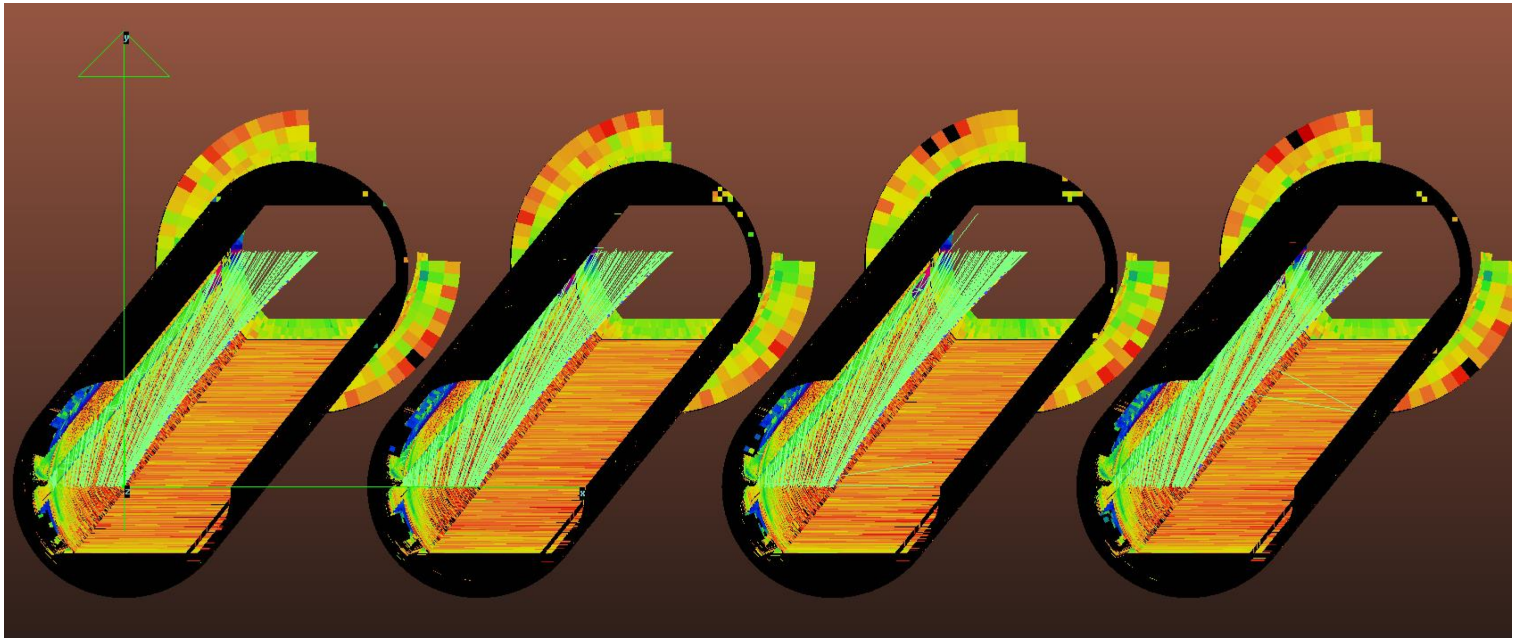
Copper for heat transfer: **0.3 mm thick**

(on the inside of the BS for heat-transfer and resistive-wall impedance, and on the outside for heat-transfer)

Vacuum performance

Vacuum is driven by photo-desorption. The vacuum simulations are done in two steps:

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

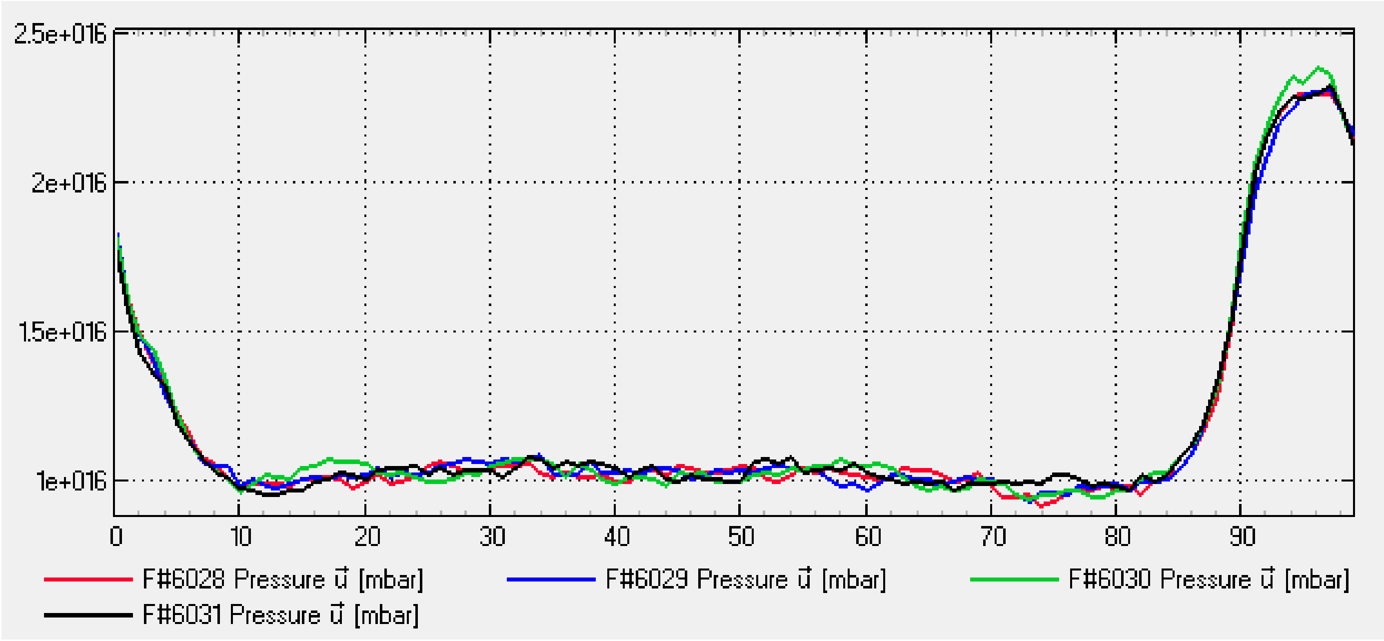


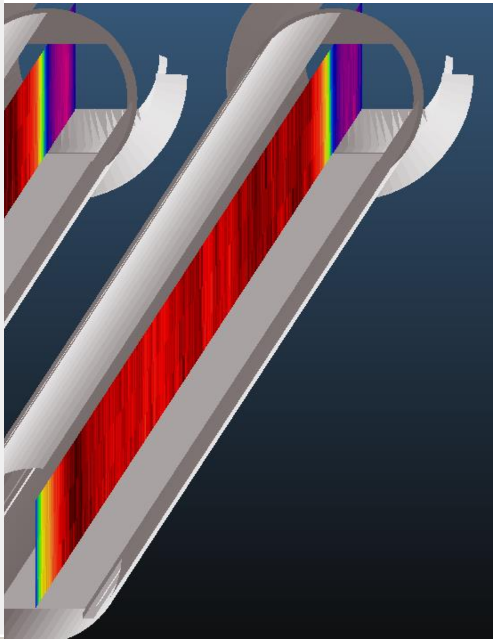
Synchrotron radiation (SR) ray-tracing model, showing 4x 14.3 m-long dipoles followed by a 1.65 m-long drift section (for interconnect, BPM block, etc..) on a bigger diameter, to minimize SR flux on it. The angle of incidence, photon energy, and surface roughness are taken into account during ray tracing.

Vacuum performance

Vacuum is driven by photodesorption. The vacuum simulations are done in two steps:

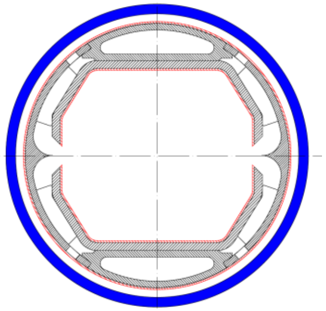
1. Simulation of the flux and power distribution of the synchrotron light (Synrad)
2. Simulation of the photon stimulated desorption and gas density (Molflow+)





Molflow+ calculation of the H_2 density profiles derived from the previous ray-tracing; The plot shows the 4 density profiles along each section after an integrated photon dose equivalent to 1h of beam at 50 TeV and 500 mA; The specification is < $2 \cdot 10^{14}$ H_2/m^3; The density bumps correspond to the drift sections, where no BS with pumping slots has been assumed; **Cold bore temperature is 1.9 K** (60 K for the beam screen); [R. Kersevan, I. Aichinger, Proc. FCC Week, Rome, 2016]

Vacuum performance



We have also started looking at different issues, such as:

- Effect of a BS misalignment (i.e. longitudinal slots not on the plane of the orbit)
- Effect of ramping the energy from 3.3 to 50 TeV on the SR spectrum and relate power loads and desorption: (**)
    - The injection energy for the FCC-hh baseline is presently 3.3 TeV, using the LHC as a high-energy injector
    - At 3.3 TeV the SR critical energy is below the threshold of 4 eV for photo-electron production, and photon-induced desorption as well;
    - During energy ramping the SR fan starts having photons above 4 eV at energies around 5 TeV. Between 5 and ~ 30 TeV the SR photon fan will hit a large part of the BS internal surface, contrary to higher energy cases.
- Instabilities/fluctuations in the temperature field along the BS, and their effect on the vacuum stability and residual gas density profiles (e.g. saturated vapour pressure of different gas species) → in progress
- First tests on a-Carbon coated chambers as e-cloud mitigation, at Photon Factory, KEK (***)
- So far no showstopper has been identified, but still **lots of work ahead of us**.

(*) R. Kersevan, https://indico.cern.ch/event/547790/

(**) R. Kersevan, Review of the FCC-hh Injection Energy, CERN, 2015, https://goo.gl/VAEoBz

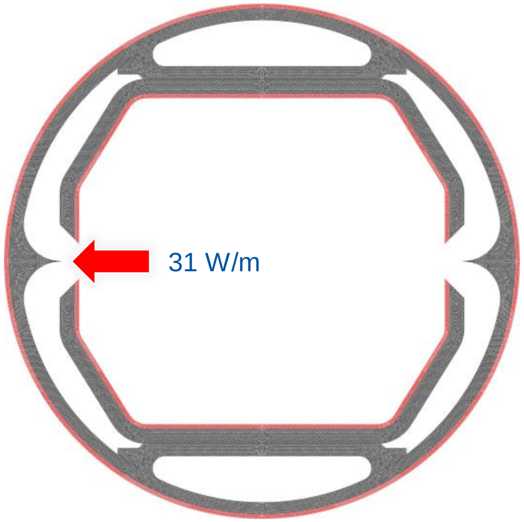
(***) Y. Tanimoto et al., FCC Week, Washingotn D.C., 2015 , http://goo.gl/eIYH4M

Thermal analysis

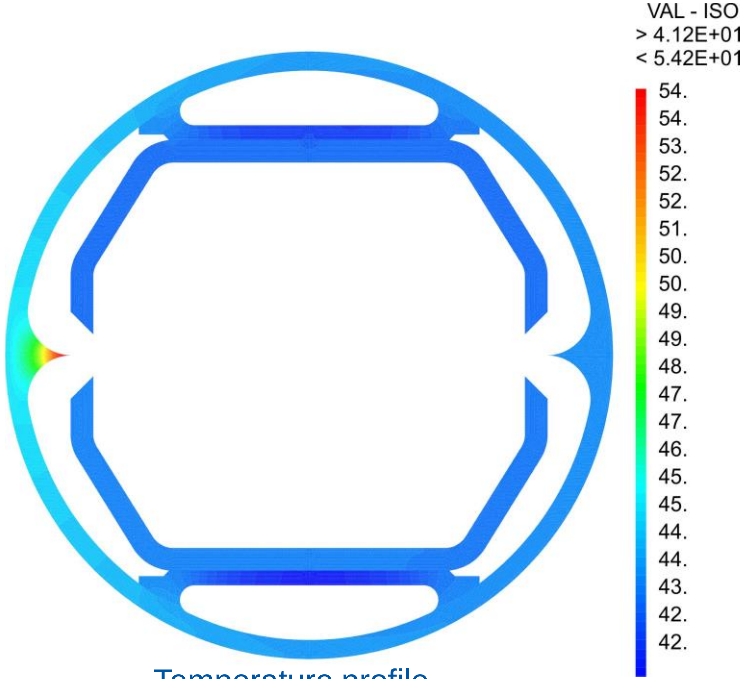
Nominal behaviour (SR fan centered with slot)

Model:

- 2D massive model
- Heat deposition of 31 W/m centered w.r.t. beam screen
- Heat deposition field based on SynRad+ simulation
- Thermal conductivity of copper estimated at 50 K and under 16T ~ 700 W.m^{-1}.K^{-1} (need to be measured)
- Thermal conductivity of stainless steel at 50 K ~ 6 W.m^{-1}.K^{-1}
- Convection coefficient of 150 W.K^{-1}.m^{-2}



Model



Temperature profile

Local temperature increase (reflector tip)

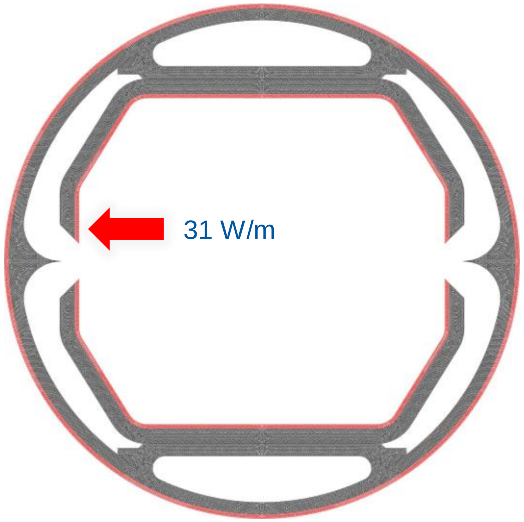
Screen temperature a few K (<3K) higher than the helium temperature

Thermal analysis

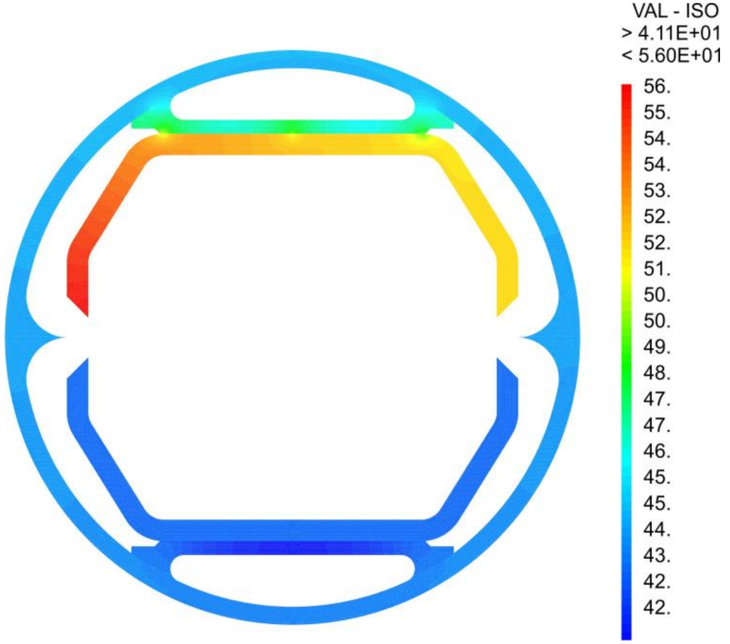
Off-plane beam behavior

Model:

- 2D massive model
- Heat deposition of 31 W/m on one beam screen edge
- Thermal conductivity of copper estimated at 50 K and under 16T ~ 700 $W.m^{-1}.K^{-1}$ (need to be measured)
- Thermal conductivity of stainless steel at 50 K ~ 6 $W.m^{-1}.K^{-1}$
- Convection coefficient of 150 $W.K^{-1}.m^{-2}$



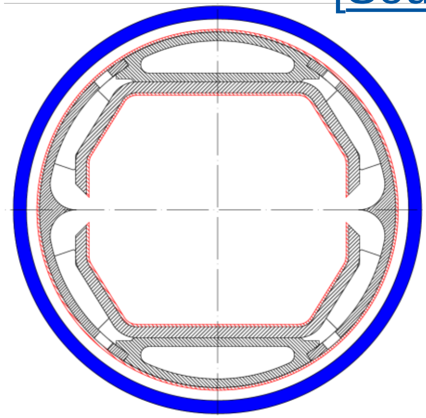
Model



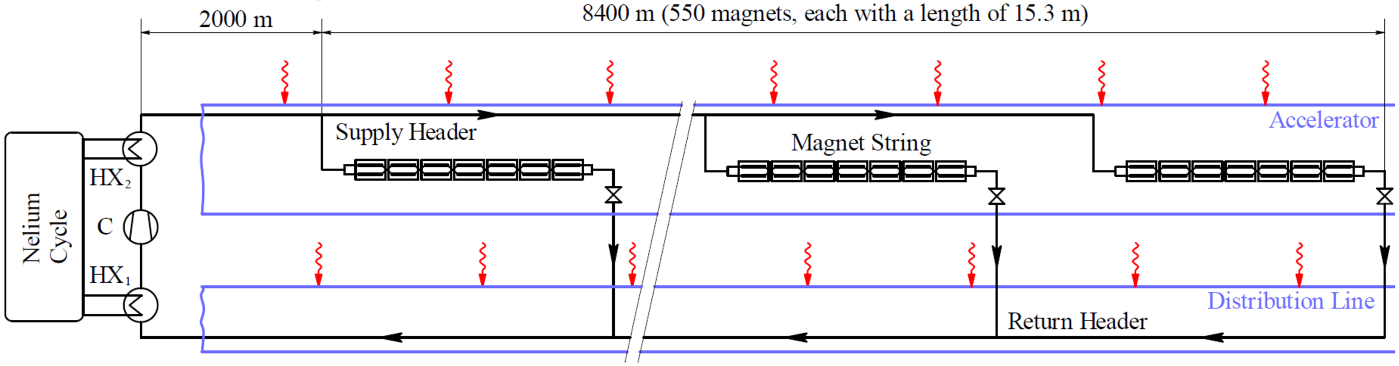
Temperature profile

Cooling of the beam screen

[Source: C. Kotnig, L. Tavian, poster 145, proc. FCC Week, Rome, 2016]



FCC cryogenic flow scheme for the beam screen circuit:



Hydraulic parameters:

$A_{cooling\ tube}$: 53.7 mm^2
A_{tot}: 107 mm^2
D_{hyd}: 5.6 mm

1. Control Valves → valves, but minimize necessary amount
2. Flow direction → counter flow scheme
3. Assembly scheme → assembly scheme HX1 - C – HX2 – MS - V
4. Supply pressure → supply pressure 50 bar

Cooling of the beam screen

[Source: C. Kotnig, L. Tavian, poster 145, proc. FCC Week, Rome, 2016]

Different scenarios and corresponding pressure losses in magnet strings (7 magnets)

Basic:

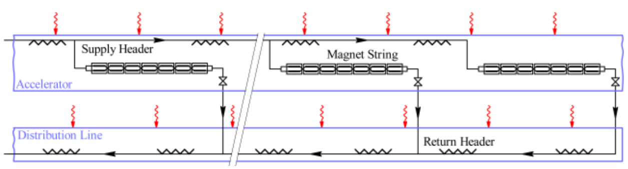
Supply header used to cool the thermal screen

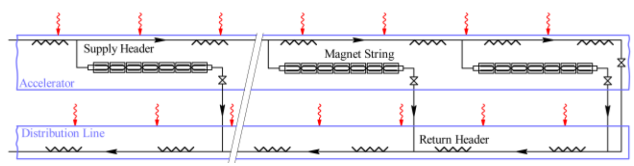
Bypass:

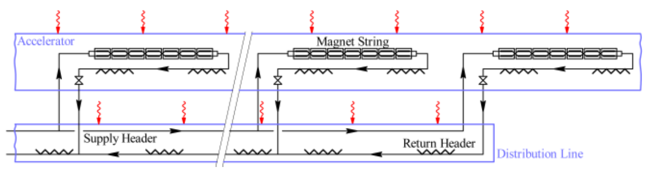
- Supply header used to cool the thermal screen
- Bypass valve at the extremity

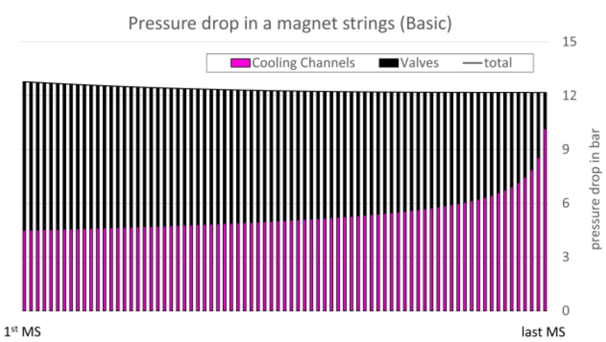
RH-Shield:

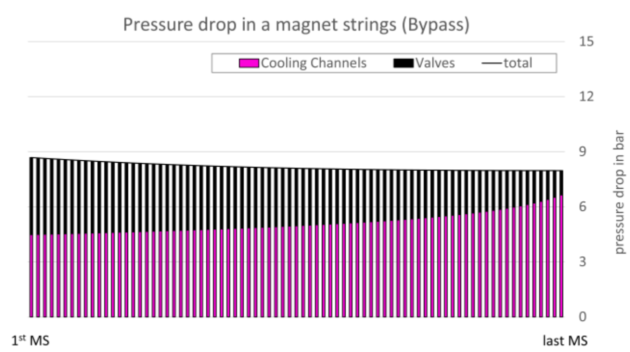
Return header used to cool the thermal screen

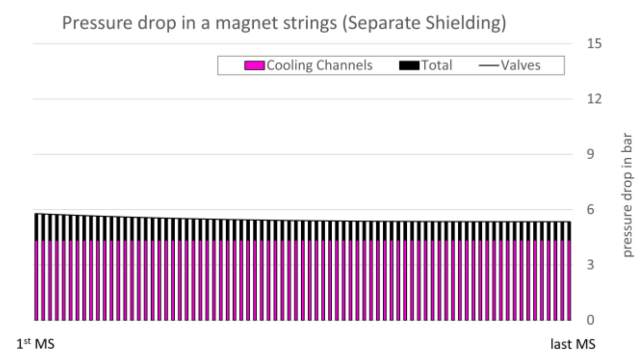












$\Delta p_0 \approx 13$ bar

$\Delta p_0 \approx 9$ bar

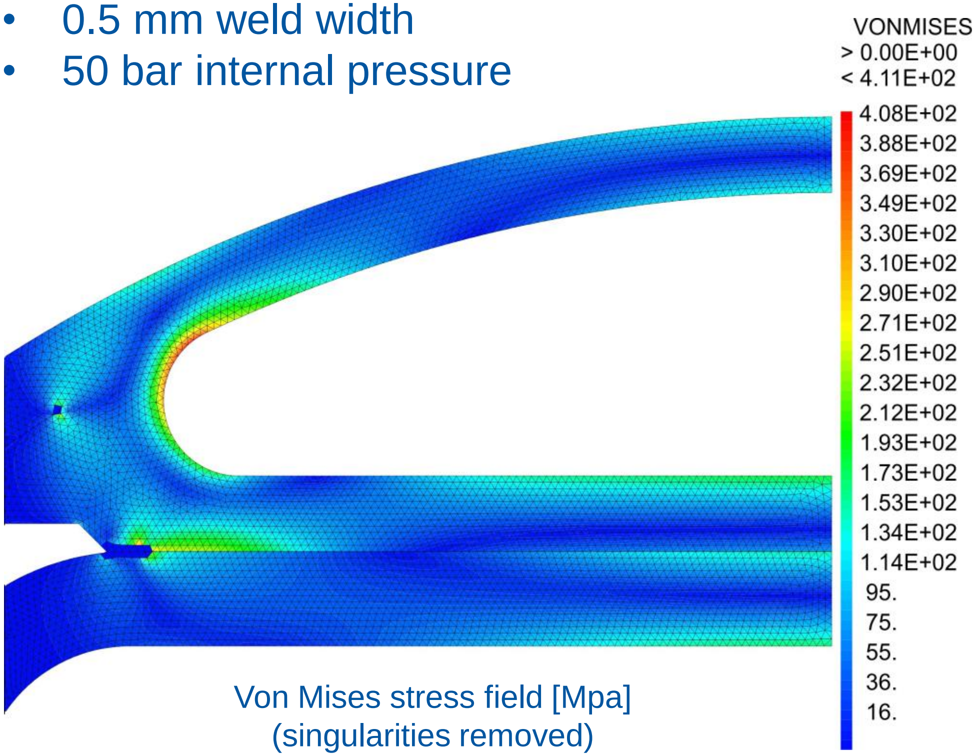
$\Delta p_0 \approx 6$ bar

The separate shielding scheme is the preferable choice to minimize the pressure drop and therefore the necessary power consumption for cooling magnet strings of reasonable lengths.

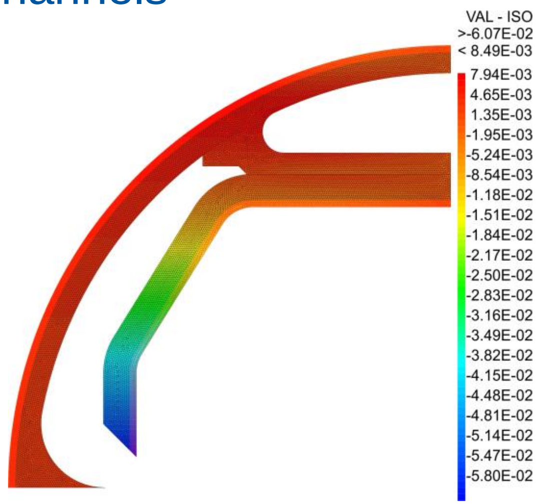
Mechanical analysis

Internal pressure in the cooling channels

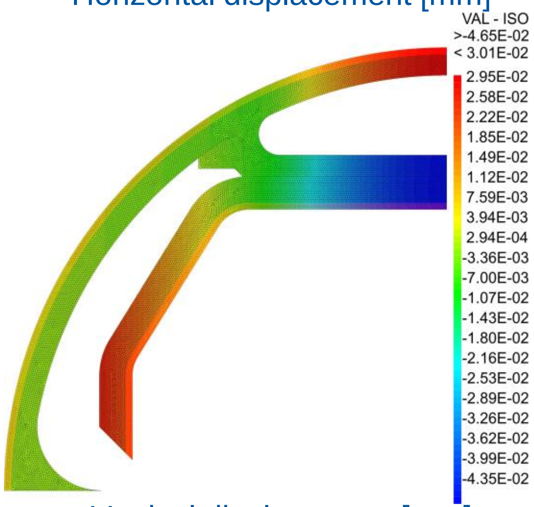
- Cooling channel thickness: 1 mm
- 0.5 mm weld width
- 50 bar internal pressure



Von Mises stress field [Mpa]
(singularities removed)



Horizontal displacement [mm]



Vertical displacement [mm]

→ OK for nominal operation.
→ Pressure test: checked.

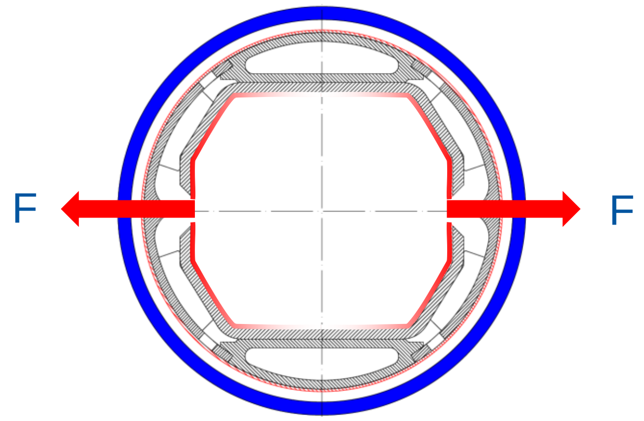
Mechanical analysis

During magnet quench

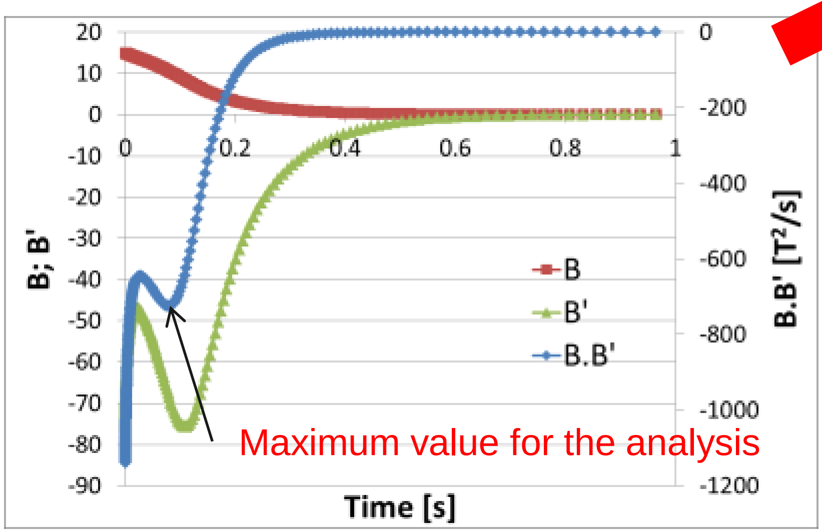
F ~ 140 N/mm ← !!

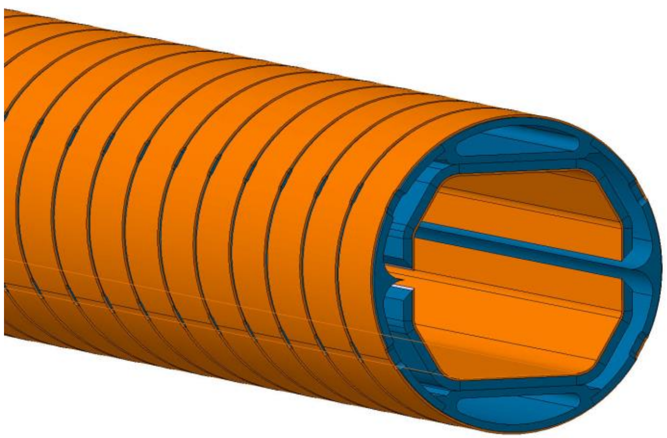
Model:

- Quarter of beam screen, solid elements
- Electrical conductivity of copper estimated at 50 K and under 16T
- Heat dissipation by Joule effect taken into account
- Eddy currents in the reflector
- Static analysis
- **Lorentz force driven by the parameter B·B' ~ -725 $T^2.s^{-1}$**



Lorentz forces

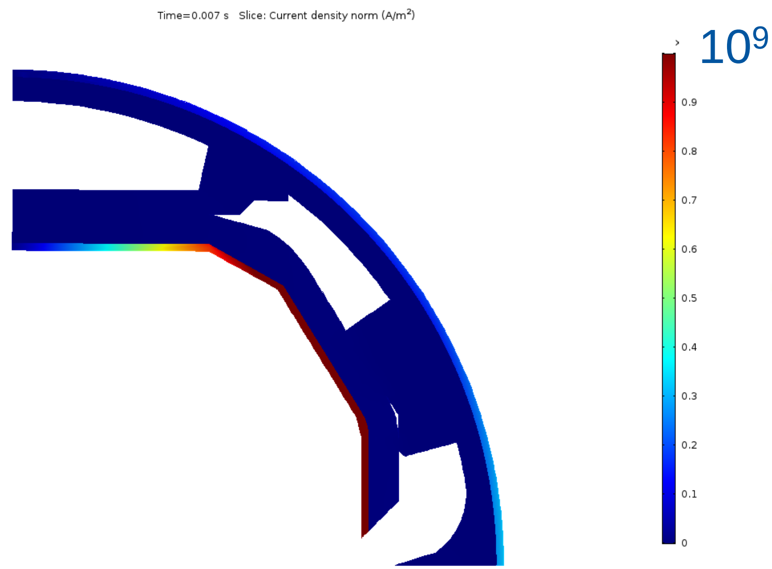




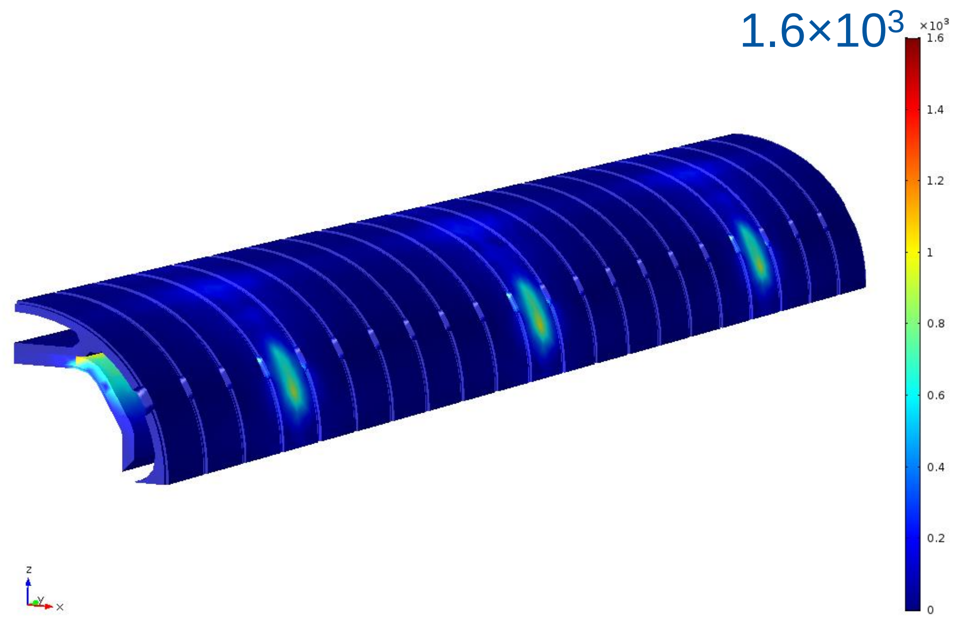
Discontinuous Cu layer on the outside, to reduce the Foucault currents

Mechanical analysis

<u>During magnet quench</u>



Current density [A/m²]



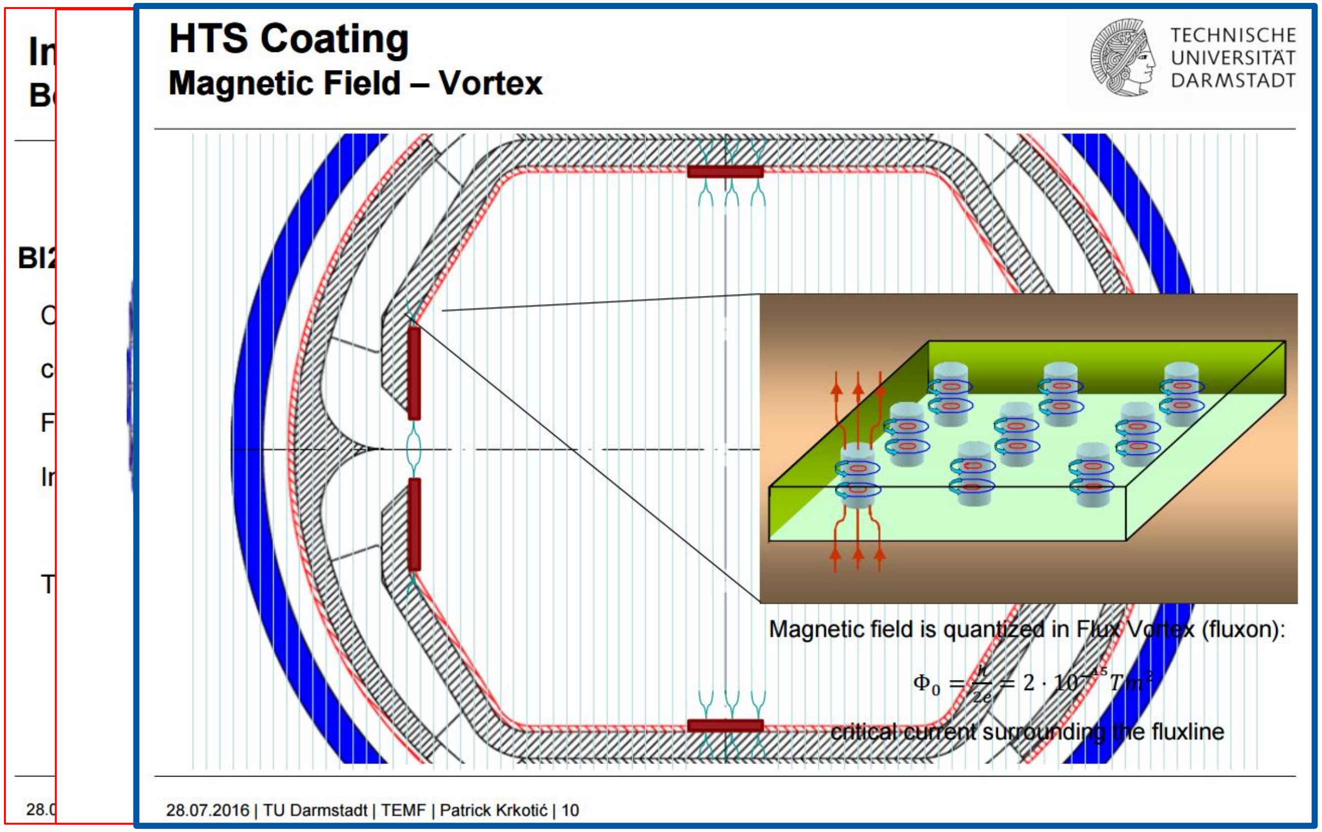
Von Mises stress in the beam screen [MPa]

Current density in the external copper much lower than on the inside.

Even if the model has to be refined, results of the beam screen behaviour during a quench are promising. Space between the ribs has to be optimized.

Impedance issues

- Preliminary 2D calculations performed already (see O. Boine-Frankenheim and co-workers)
- They have driven the 1 slot → 2 slot change
- Detailed 3D analysis to be performed (needs lots of computing power!)
- Alternative solutions are being looked at (like high-temperature superconducting coatings see for instance https://indico.cern.ch/event/558844/ , and S. Calatroni, CERN)



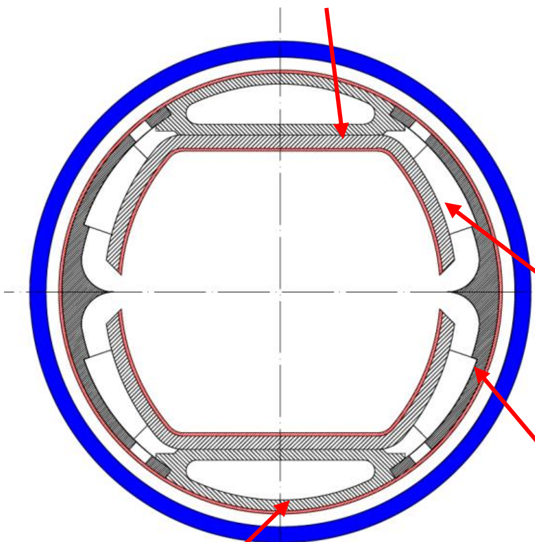
Prototypes

Series vs first prototypes

Sub-component manufacturing:

Series

Beam screen wall:
- P506, 1.25 mm
- copper colamination, 0.3 mm



Reinforcement:
- P506
- punching

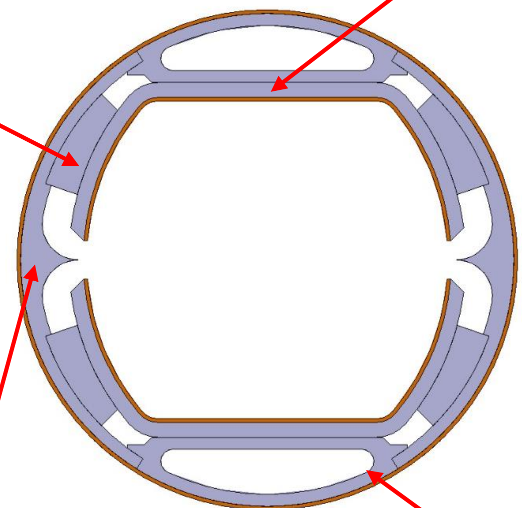
Cooling channel:
- P506 stainless steel
- Extruded

Reflector:
- P506 stainless steel
- Extruded + finishing

1st prototype

Beam screen wall:
- 304L, 1. 5 mm
- copper electrodeposition, 0.05 mm

Reinforcement:
- 304L
- Laser cutting

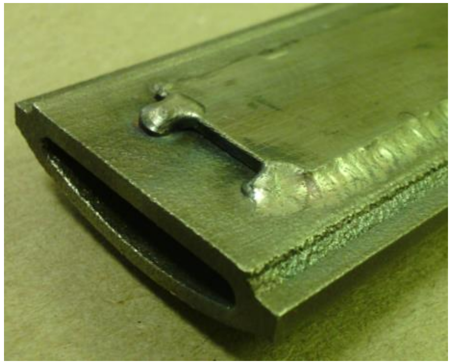


Reflector:
- 304,
- Machined + forming + finishing

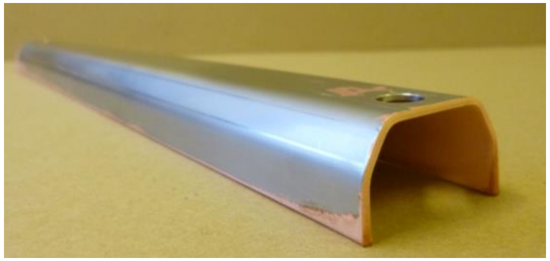
Cooling channel:
- 316L,
- 3D printed + machined

Short prototype manufacturing

3D printed cooling channel



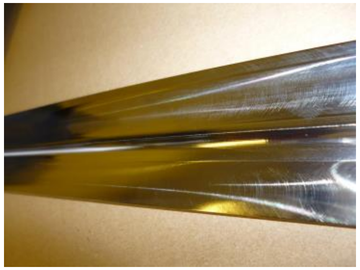
Copper coated screen



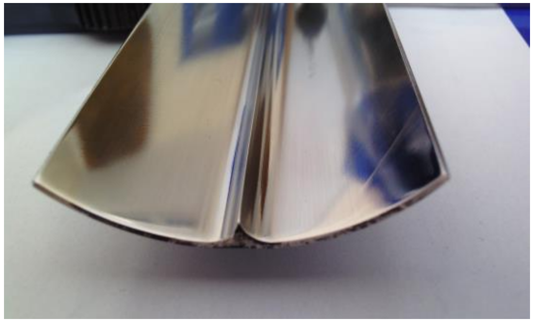
Machining

Welding and machining

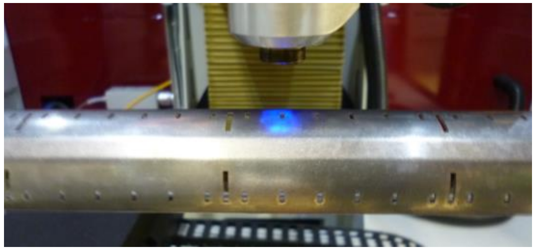
Deflector manufacturing



Milling



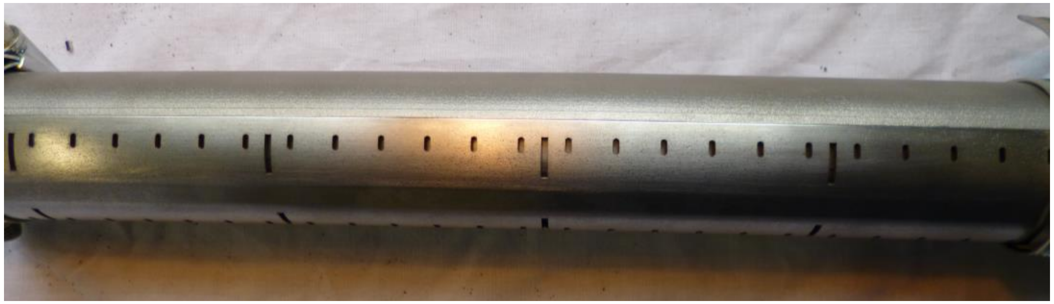
Forming



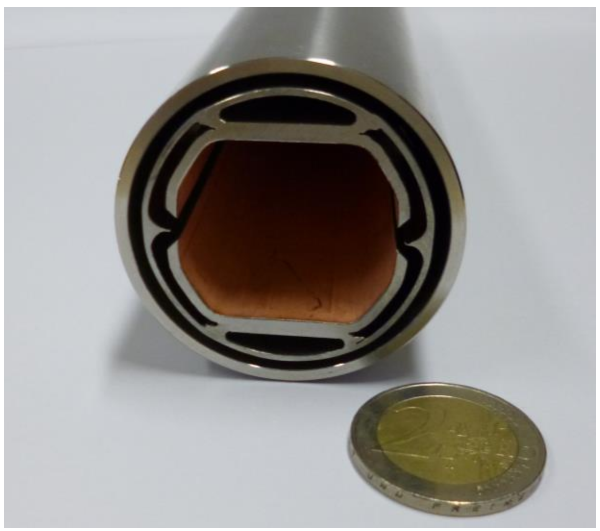
Laser cutting

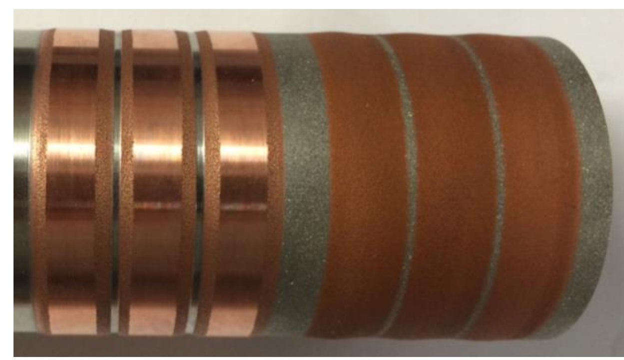
Polishing

Short prototype manufacturing



Assembly and welding

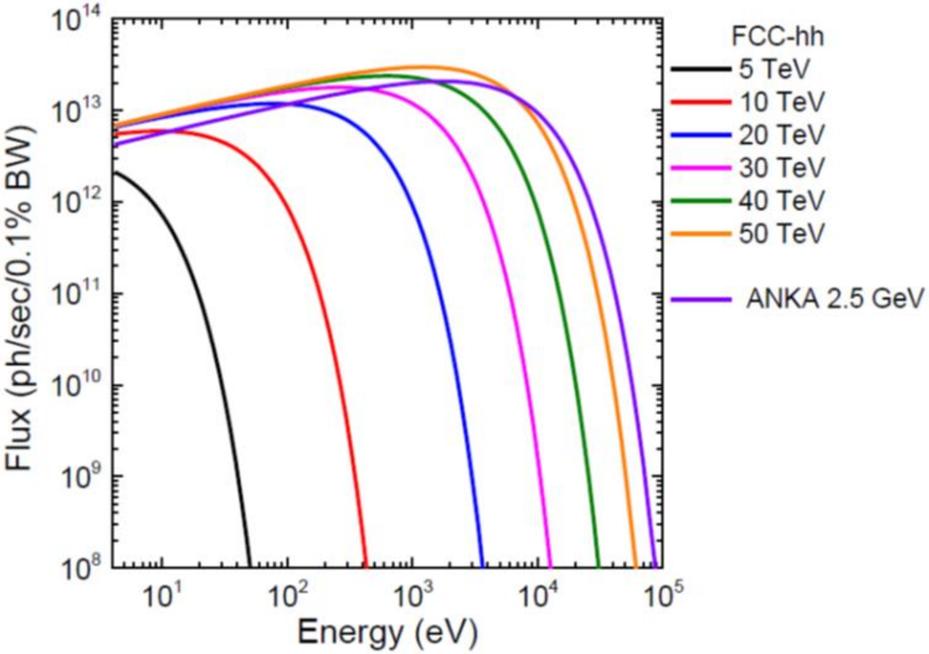


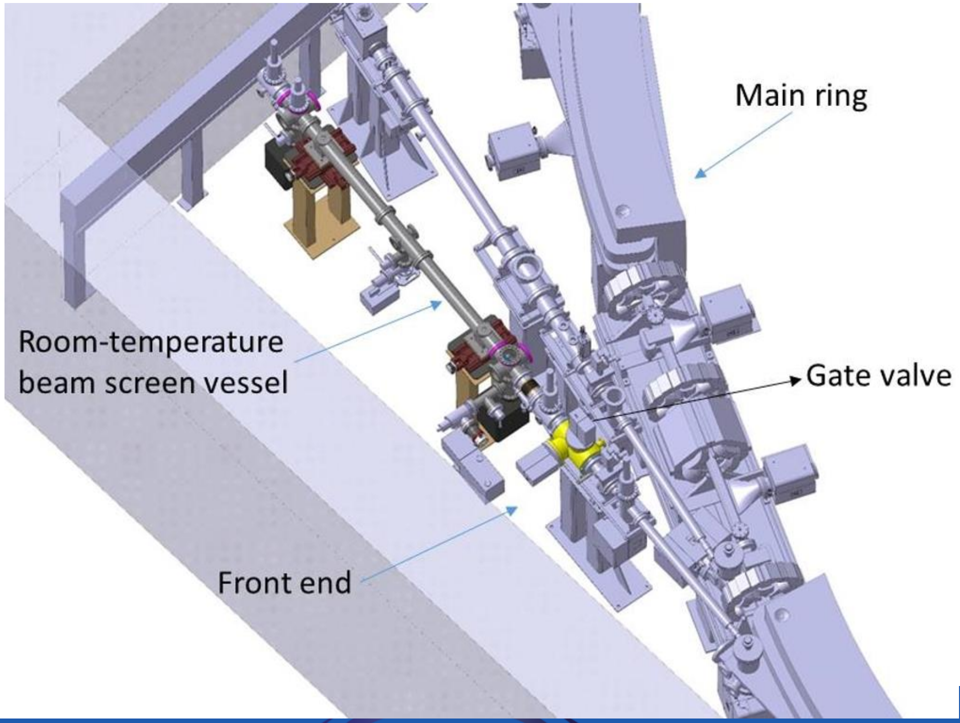


Copper coating
(plasma sprayed)

Long prototype to be installed at ANKA (Karlsruhe)

- ANKA light src.: E=2.5 GeV, e_{crit}=6.2 keV
- At 2.2 GeV e_{crit}= 4.3 keV (same as FCC)
- Bending magnet beamline available
- **EuroCirCol collaboration is preparing a test on a 2m-long BS prototype**





Conclusion and next steps: (see also **bonus slides** at the end)

- **A novel beam screen design has been proposed**. It relies on an antechamber to channel the synchrotron radiation and localize the photo-desorption, while allowing the interception of the copious amount of SR at a higher temperature
- **Thermal, mechanical and cryogenic aspects have been studied**. No showstopper has been identified so far, although a lot of work is still ahead
- A **more detailed analysis** (3D model, singularities, Joule heating) is underway
- An **optimization of the slit and deflector** lip geometries is underway.
- **First short prototypes**, ~ 30 cm long, have been manufactured. Main manufacturing techniques have been validated and will be used for the production of a 2 m long prototype
- **2 m long prototype**, to be installed and tested at ANKA light source, will be manufactured by the end 2016 (installation Q1-Q2 2017, **see EuroCircol collaboration** pages), and tested. Performance simulations done (**I. Bellafont**)
- The **vacuum performance simulated** for the arcs of the 50+50 TeV collider is found to be satisfactory in terms of residual gas density after a **proper conditioning SR photon dose** is accumulated (same as for SR light sources)
- **The electron cloud issue** is, for the baseline design, expected to be handled via **thin-film coatings** (e.g. **amorphous carbon**), **surface texturing** (e.g. **laser ablation**), see EuroCirCol collab., or other suitable technique (should be tested on a positive-charge beam machine, **CESR**? **DaΦne**? Other?)

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