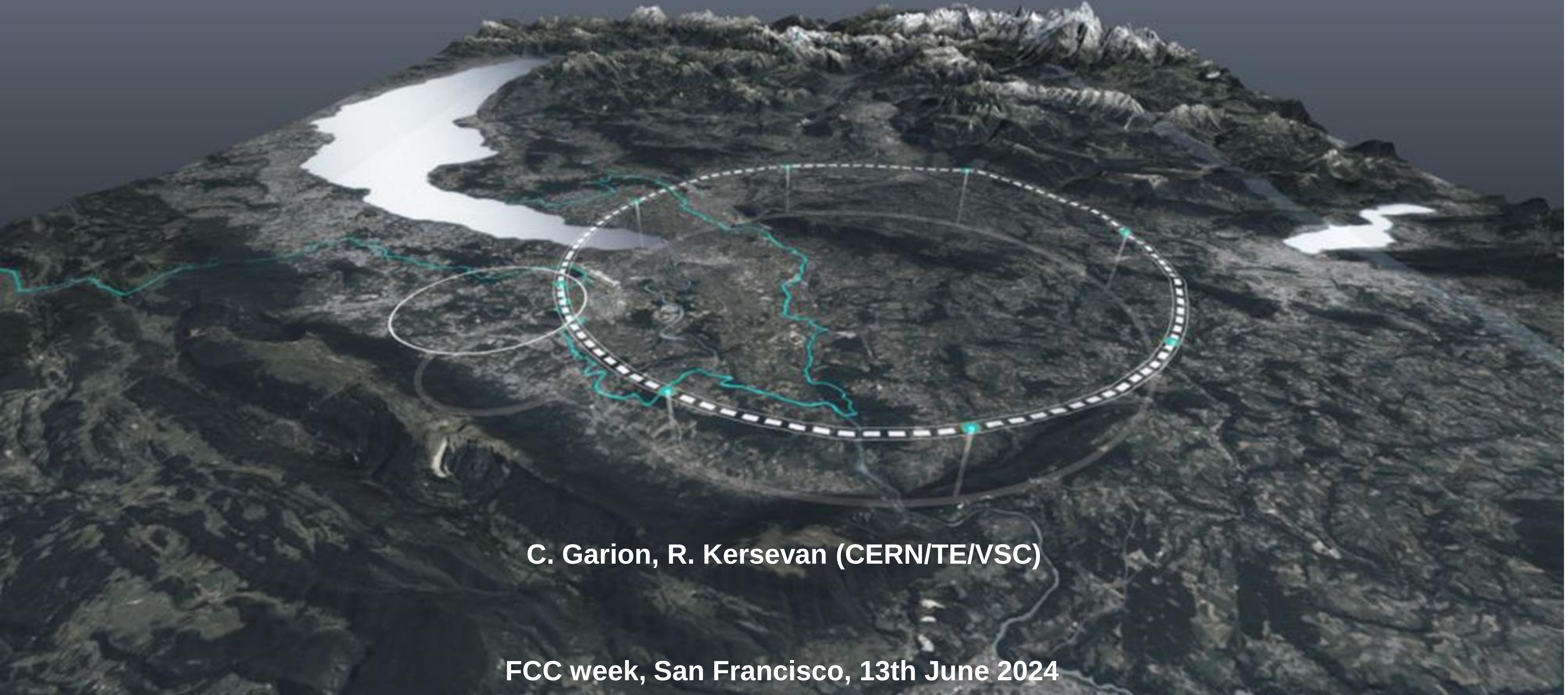
FCC-ee vacuum design status



C. Garion, R. Kersevan (CERN/TE/VSC)

FCC week, San Francisco, 13th June 2024

Outline

Vacuum system requirements, challenges and performance in the FCC-ee arcs.

Conceptual design and layouts.

Pre-technical design and related technologies.

Ongoing and next steps.

Conclusion.

Vacuum challenges in the FCC-ee arcs

The FCC-ee vacuum system has to cope with beam parameters from low-energy (45.6 GeV) high current (1270 mA) version to high-energy (182.5 GeV) low current (5.4 mA) configuration.

Big variation of nominal current vs beam energy, since all machine versions are **limited to 50 MW of synchrotron radiation losses per beam**

$$P\,(W) = 88.46 \cdot E^4(GeV) \cdot I(mA) / \rho(m)$$

$$F\,(ph/s) = 8.08 \cdot 10^{17} \cdot E(GeV) \cdot I(mA)$$

$$\varepsilon_c = 2218 \cdot E^3\,(GeV) / \rho(m)$$

For the vacuum system, the synchrotron radiation leads to:

- High local heat deposition: average ~650 W/m.
- High outgassing:
  - Pressure: low 10^{-9} mbar range
  - Reducing/eliminating the e-cloud and ion-trapping effects and related beam instabilities and losses

The vacuum system shall consider impedance requirements.

Parameters

FCC-ee collider parameters as of June 3, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	9.936			
Energy loss / turn	[GeV]	0.0394	0.374	1.89	10.42
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.9
Colliding bunches / beam		15880	1780	440	60
Colliding bunch population	[10^{11}]	1.51	1.45	1.15	1.55
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.4	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\text{lattice}}$	[pm]	0.75	1.25	0.85	0.9
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	1000 / 1.6
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.182
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.070 / 0.109	0.104 / 0.143	0.160 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	3.47 / 5.41	3.40 / 4.70	1.81 / 2.17
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.091
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	2.9
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP $\pm\theta_x$	[mrad]	±15			
Piwinski angle $(\theta_x \sigma_{z,\text{BS}})/\sigma^*_x$		21.7	3.7	5.4	0.82
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y [a]		0.0023 / 0.096	0.013 / 0.128	0.010 / 0.088	0.073 / 0.134
Lifetime (q + BS + lattice)	[sec]	15000	4000	6000	6000
Lifetime (lum) [b]	[sec]	1340	970	840	730
Luminosity / IP	[10^{34}/cm^{2}s]	140	20	5.0	1.25
Luminosity / IP (CDR, 2 IP)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

Synchrotron Radiation Spectra

- **Z-Pole: very high photon flux:**
  - ➢ **large outgassing load;**
  - ➢ **Quick commissioning.**
- **T-pole (182.5): extremely large and penetrating radiation, critical energy 1.36 MeV;**
- **T-pole (and also W and H): need design which minimizes activation of tunnel and machine components (→ FLUKA);**
- **W, H-pole: intermediate between Z and T; still E_{crit} > Compton edge (~100 keV (Al), ~200 keV (Cu))**

Critical energy: $\varepsilon_c = 2218 \cdot E^3$ (GeV) / ρ(m)

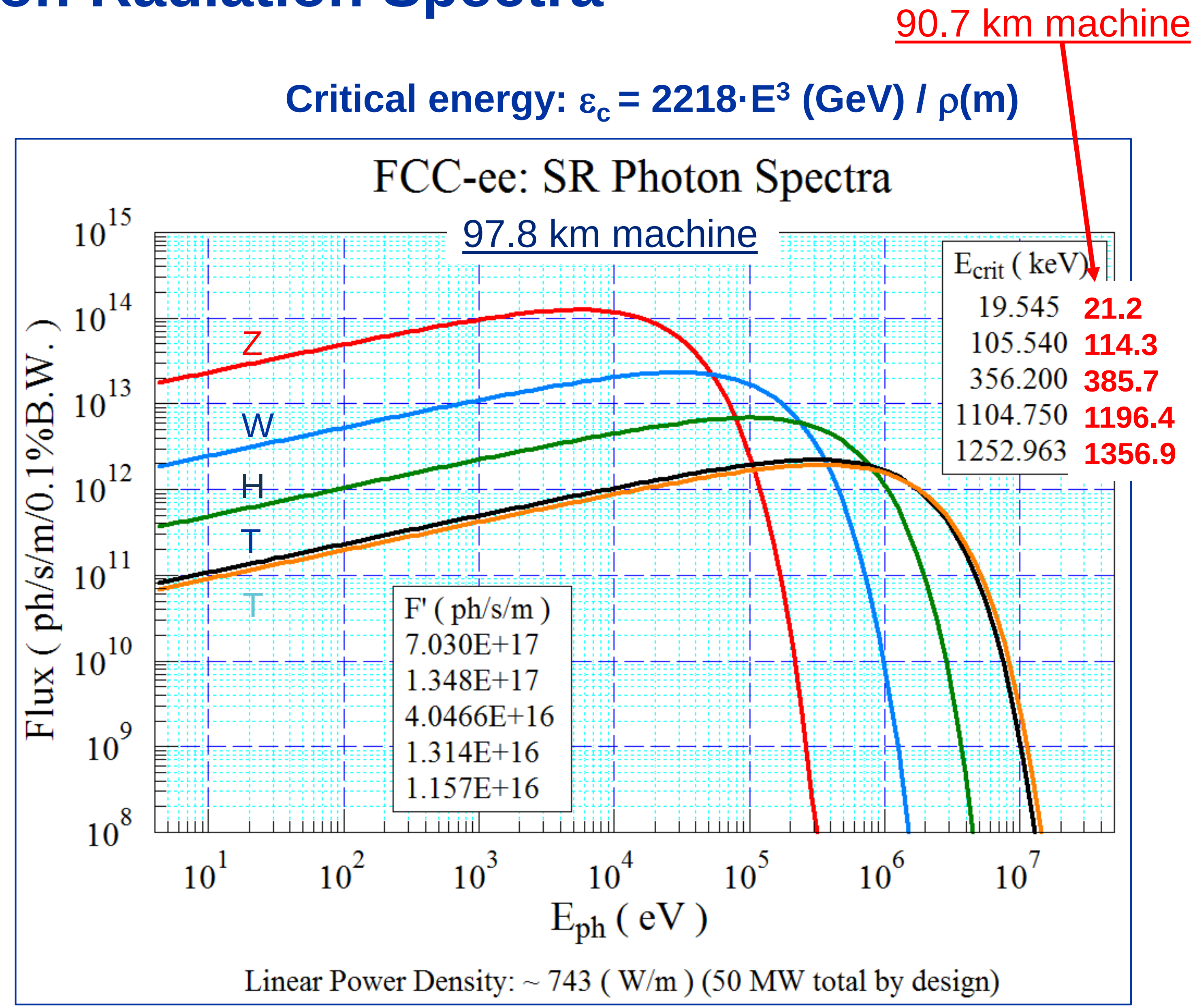


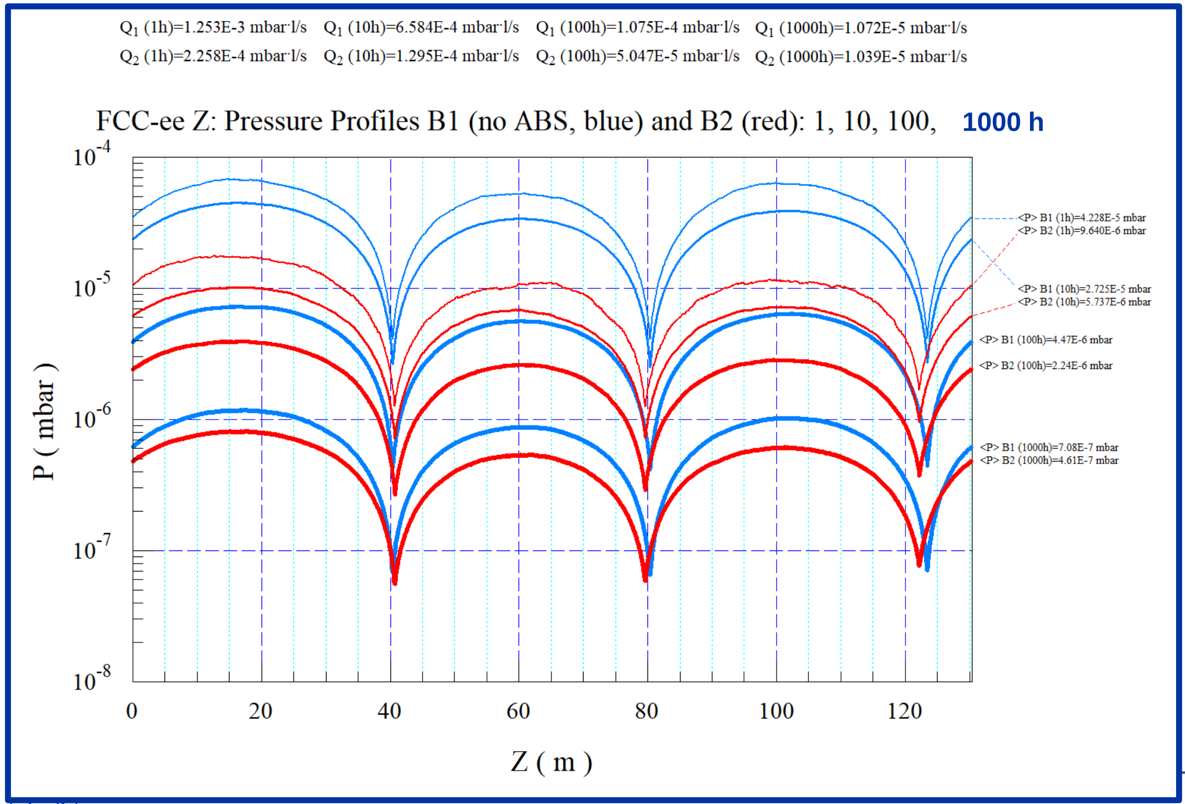
Table 3 Percent of SR photon flux generated above 100 keV

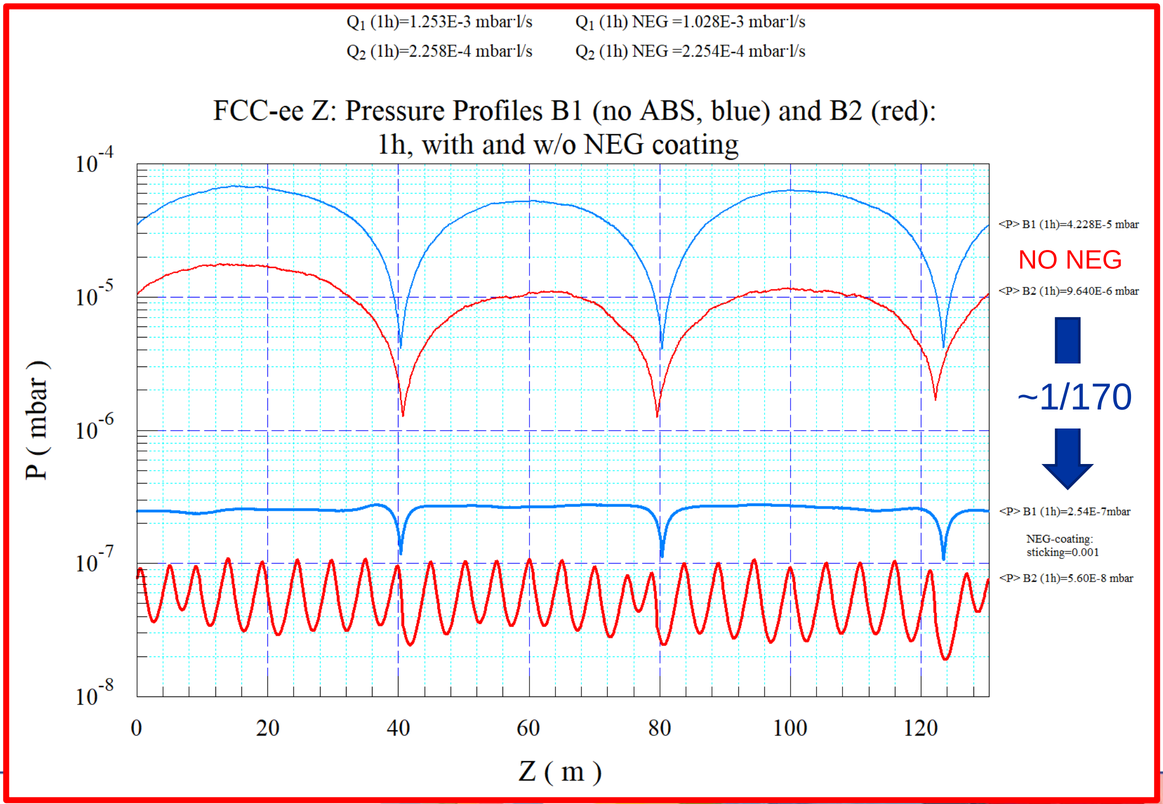
E (GeV)	% Flux > 100 keV	B (mT)
45.6	0.064	14.1
80	9.22	27.7
120	28.85	37.1
175	47.81	54.1
182.5	49.72	56.5

https://doi.org/10.1140/epjti/s40485-022-00087-w

Pressure profiles

- The PSD pressure profiles have been calculated for 4 different beam doses, corresponding to times of 1 h, 10 h, 100 h, 1000 h at nominal current (1270 mA); Simulated gas: CO
- On the left the case with 3x 100 (l/s) lumped pumps/beam, and <u>no NEG-coating</u>
- On the right, the case <u>with NEG-coating</u> with some residual sticking (*s*=0.001) for 1h case





FCC-ee vacuum chambers

Present design:

Geometry:

- Tube with two winglets
- 2 mm thick, 70 → 60 mm ID (vacuum conductance reduced from ~ 50 l.m/s to ~ 30 l.m/s, compared to the 100 l.m/s of the LEP chamber)

Material: OFS Copper

- Good thermal conductivity and low electrical resistivity
- Shielding for the X-Ray synchrotron radiation fan and minimizing the irradiation of machine and tunnel components

Surface treatment: thin (200 nm) NEG coating

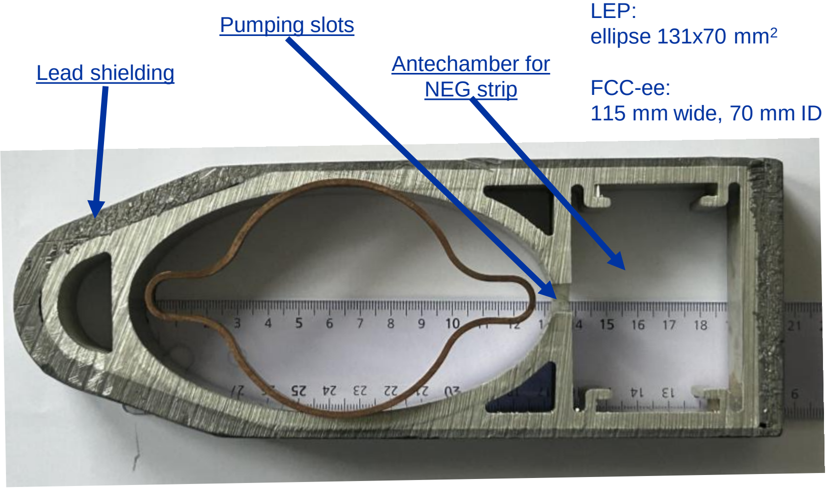
- Distributed pumping speed
- Low SEY
- Quick vacuum conditioning

Lumped SR photon absorbers:

- Distanced by about 5-6 m

Lumped pumps:

- no need for a systematic installation in vicinity of the absorbers →1 or 2 per cell



Vacuum chamber prototype cross-section, comparaison with LEP

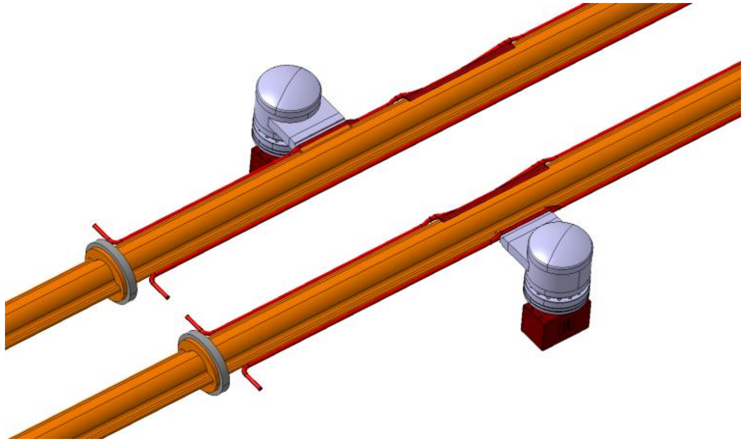
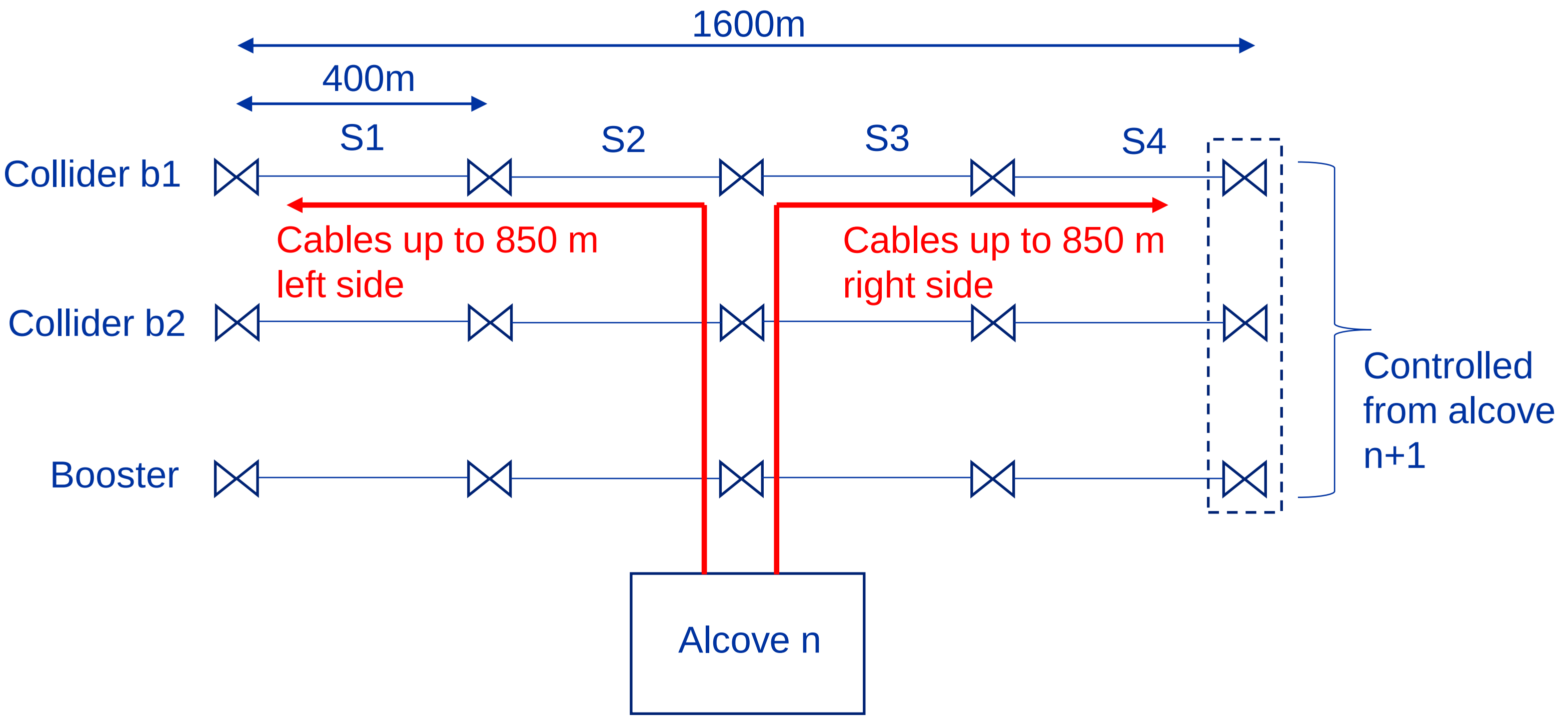


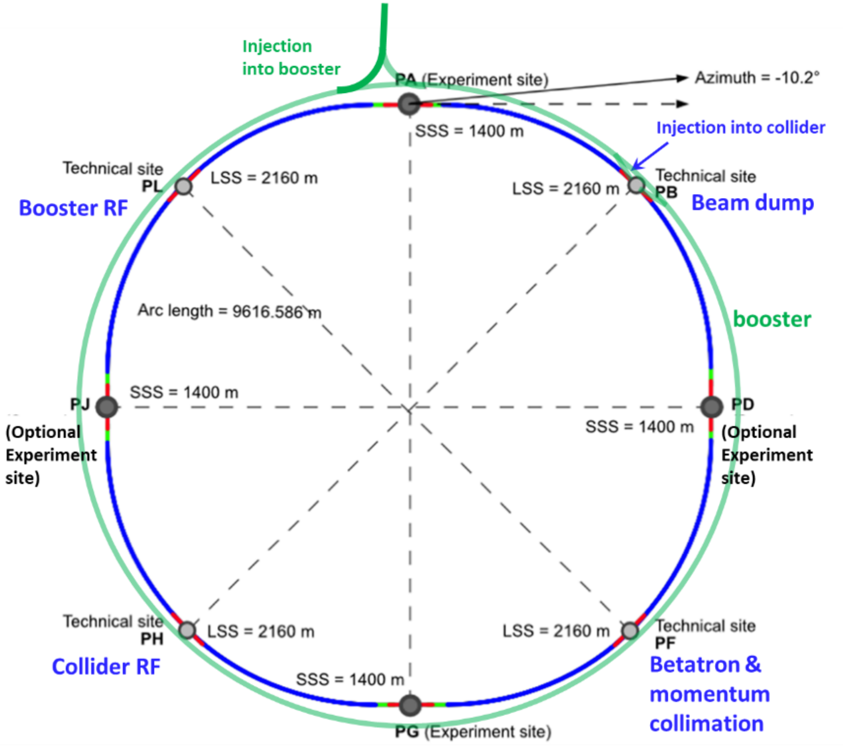
Illustration of vacuum chambers with absorbers and pumps

The whole vacuum system shall be designed with a cost-effective and sustainable approach.

Vacuum system layout

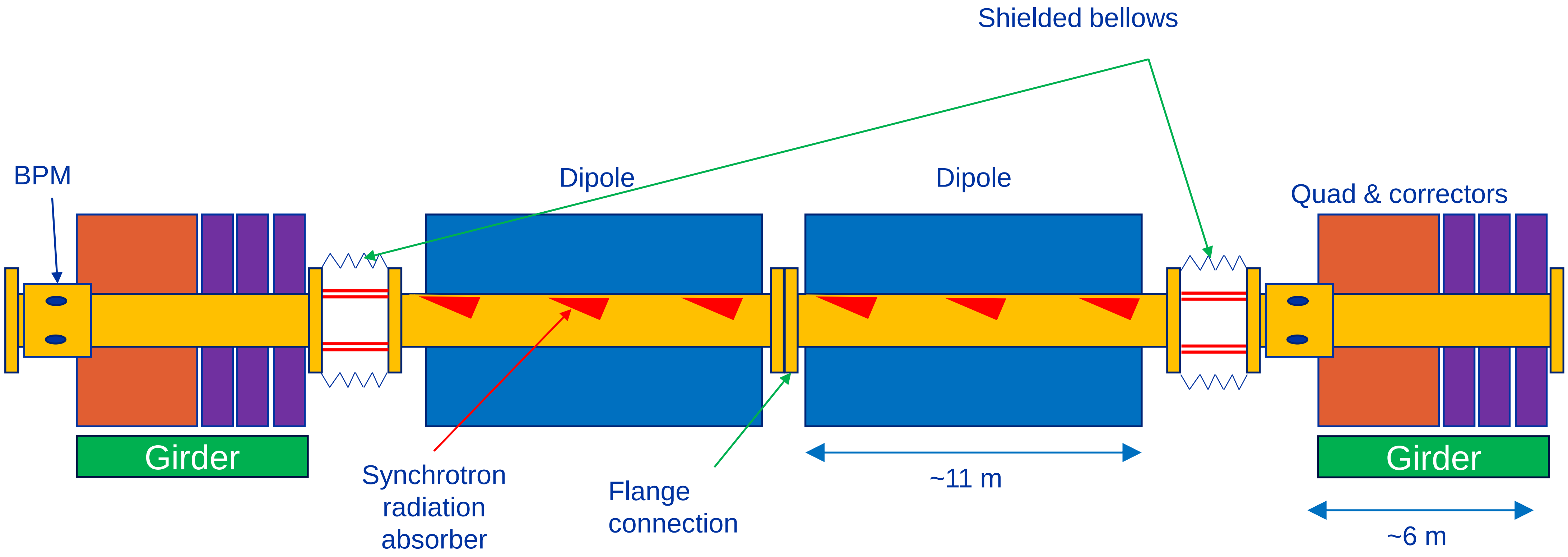
- Arc length = 9.6 km, 8 arcs, 6 alcoves per arc, distance between alcoves = 1600 m
- Vacuum sector length = 400 m for the collider and booster
  - Bakeout power 200W/m
    - 160kW for 2 vacuum sectors (collider b1/b2)
    - Heat extraction in the tunnel during bake-out
  - Sector commissioning/operation time
  - Reasonable number of gate valves (cost)





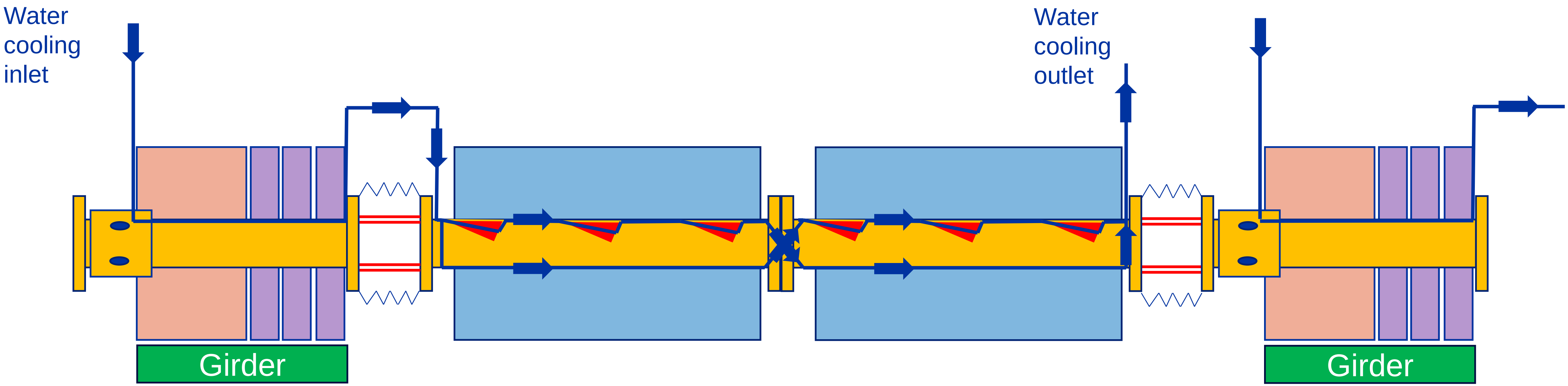
- 12 vacuum sectors controlled from one alcove
- Signal cables split into two for the left/right sides
- Signal transmission between alcoves using optical fibre

Functional layout



Synchrotron radiation absorbers are installed in dipoles, shielding also the interconnections and quad/correctors.

Vacuum chamber cooling layout

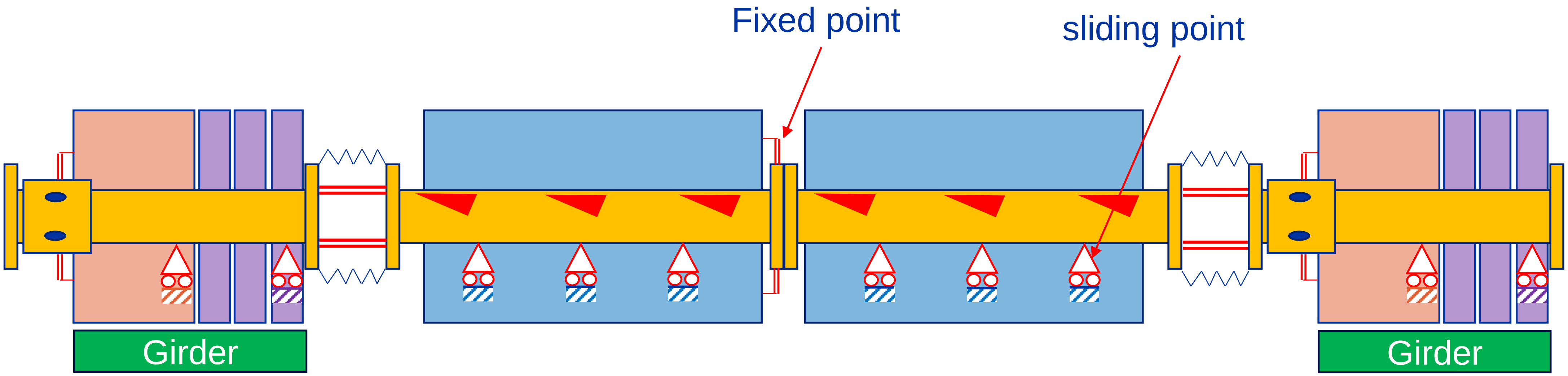


Heat deposition:

- Synchrotron radiations:
  - Absorbers: 9 kW/ dipole
  - Vacuum chamber: 1 kW / dipole
- Impedance (need to be reviewed):
  - Vacuum chamber: 80 W/m [E. Belli, CERN PhD thesis, 2018] → 25 W/m [M. Migliorati]
  - BPM: up to 400 W/BPM [CDR, p. 425], 375 W/BPM [E. Belli, CERN PhD thesis, 2018]
  - Interconnection: 225 W/bellows [E. Belli, CERN PhD thesis, 2018]

Vacuum chamber kinematic layout

Layout of the longitudinal supports



Bake out and NEG activation require a thermal cycle to 230 °C +/- 20 °C.
Longitudinal thermal expansion of the vacuum chamber: 4 mm/m → 65 mm axial stroke for the shielded bellows.

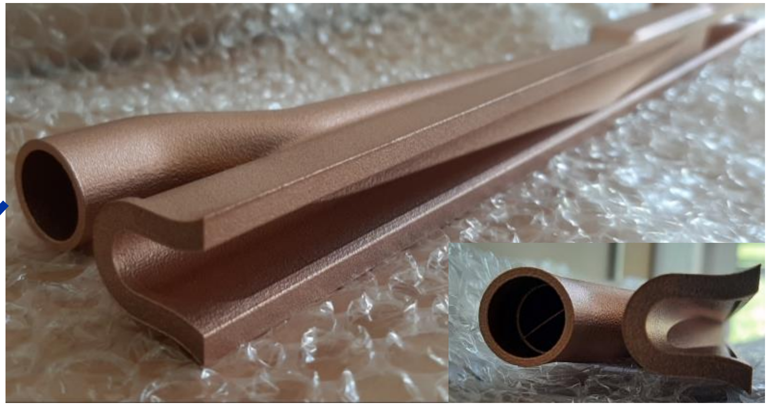
Pre-technical design and related technologies

The chamber design is based on an extruded profile equipped with:

- Synchrotron radiation absorbers, 3D printed, laser welded
- Cooling circuit, laser welded,
- Flanges, FSW welded,
- Bake out system, thermal sprayed
- Thermal insulation,
- Dismountable SMART connections
- Pumping dome, if any.

Vacuum chamber is NEG coated. Long term performance of thin NEG coating has to be assessed.

Additional shielding is integrated around the SRA.



3D printed synchrotron radiation absorber

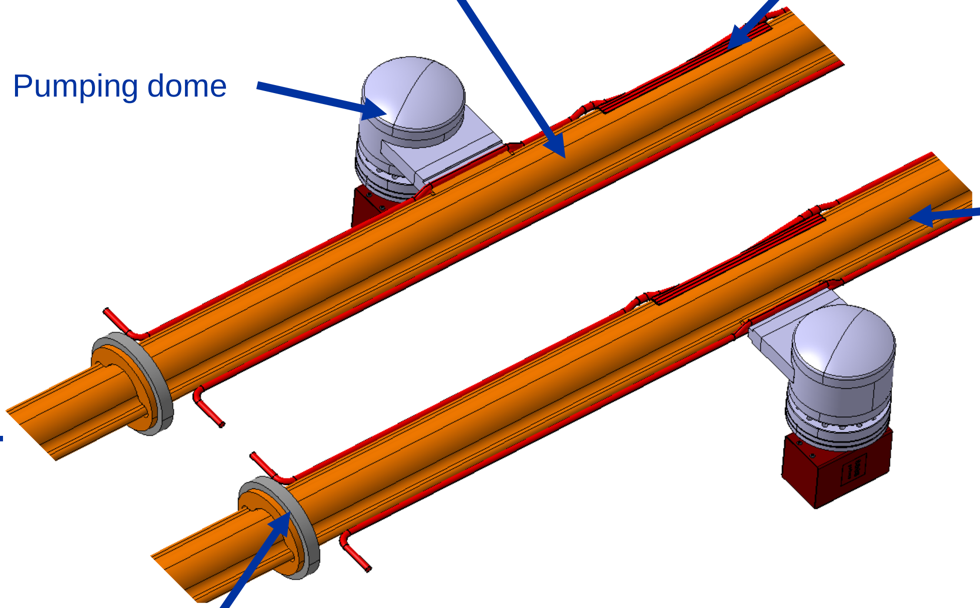
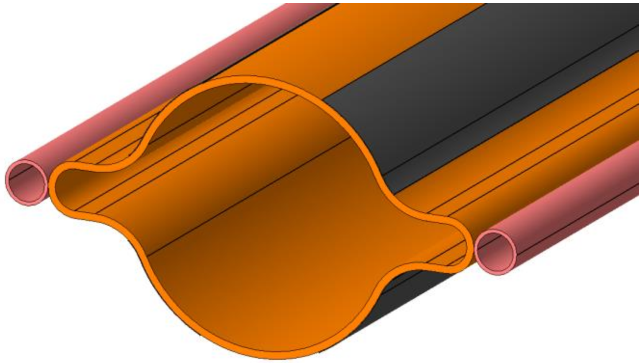
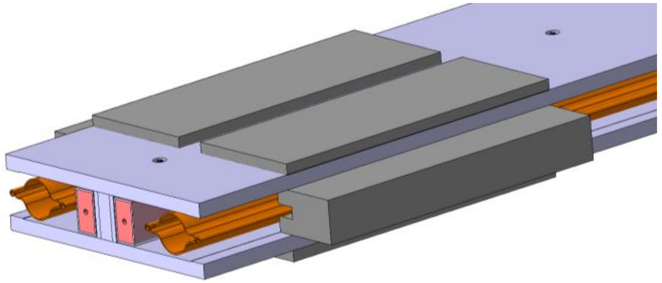


Illustration of vacuum chambers with absorbers and pumps





3D printed synchrotron radiation absorber

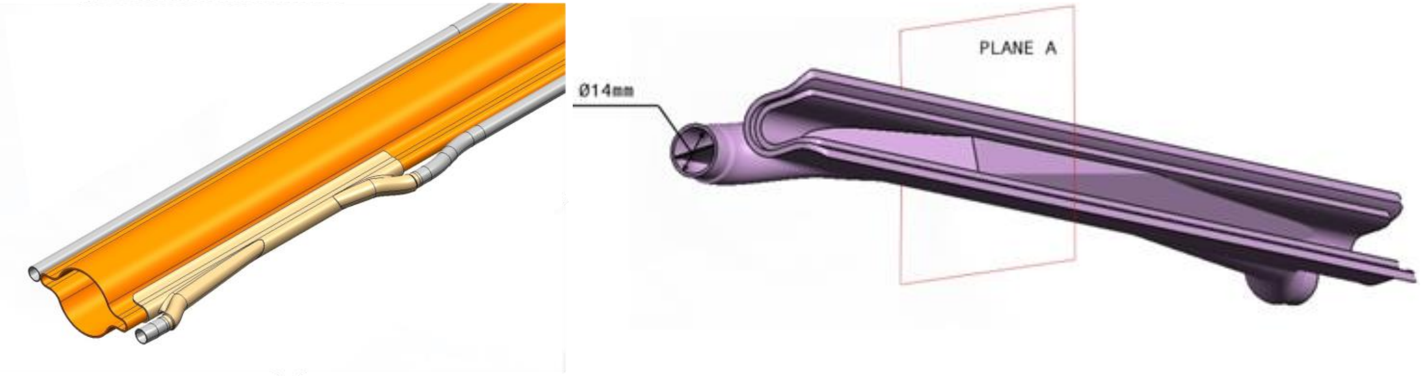
Additive manufacturing

3D printing of Synchrotron radiation absorber

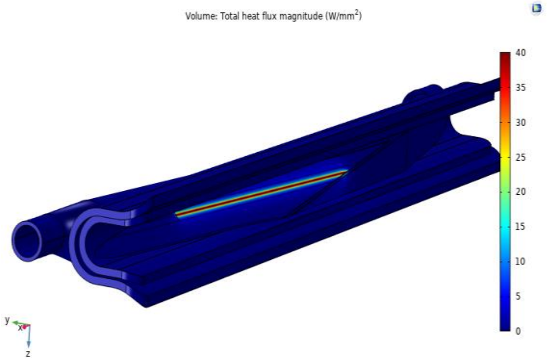
High local heat deposition (~ 3kW) in confined space (20 cm long, 8 mm high)

→ high heat transfer required

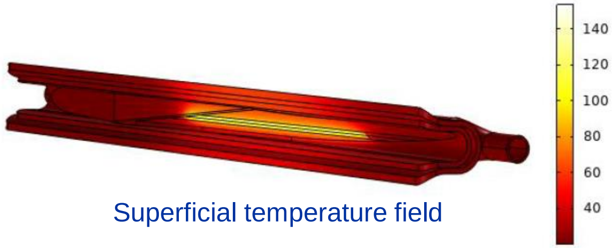
→**Complex geometrical shape** required and obtained by **3D printing** of copper alloy



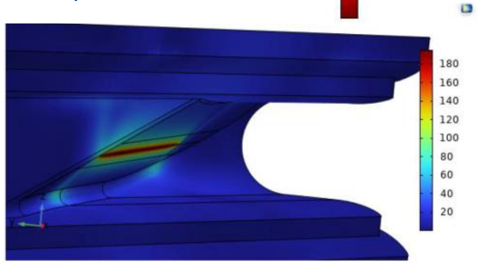
Twisted-tape design of the synchrotron radiation absorber.



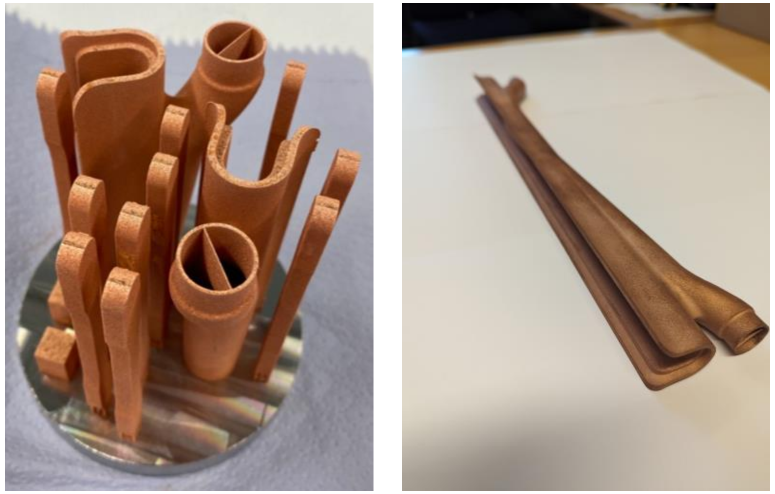
Synchrotron radiation heat distribution with 60 W/mm^2 peak density and amounting to 2.5 kW/absorber.



Superficial temperature field



Von Mises stress field



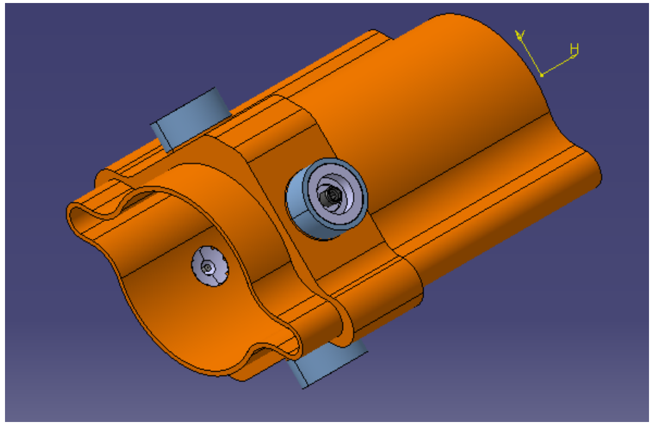
3D printed prototype and samples

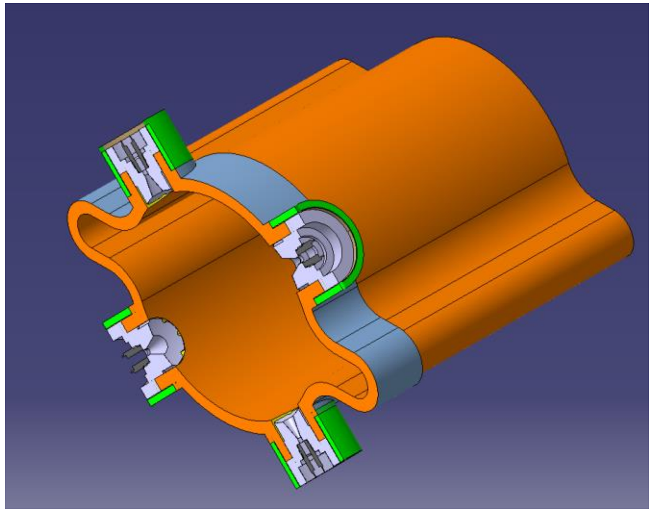
See Marco Morrone’s presentation.

Additive manufacturing

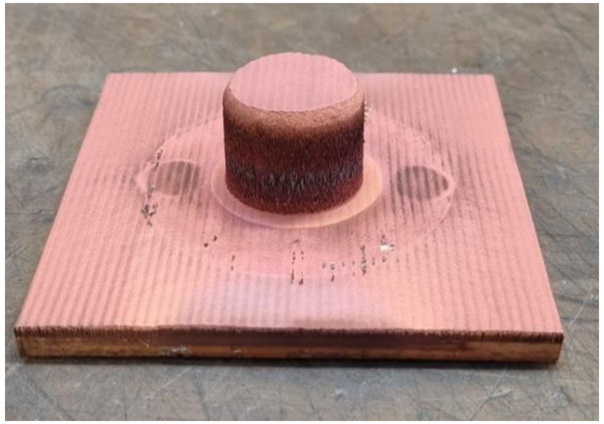
Cold spray of BPM interfaces

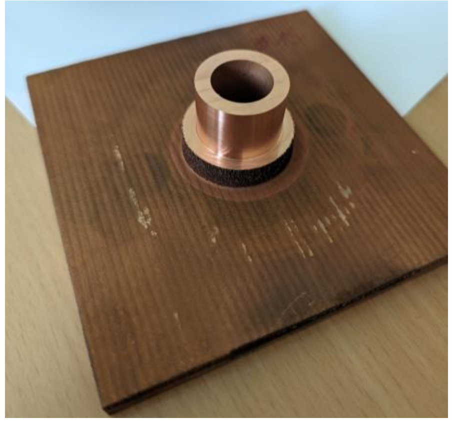
Integrated BPM with interfaces obtained by copper cold spray on copper cold drawn chamber.

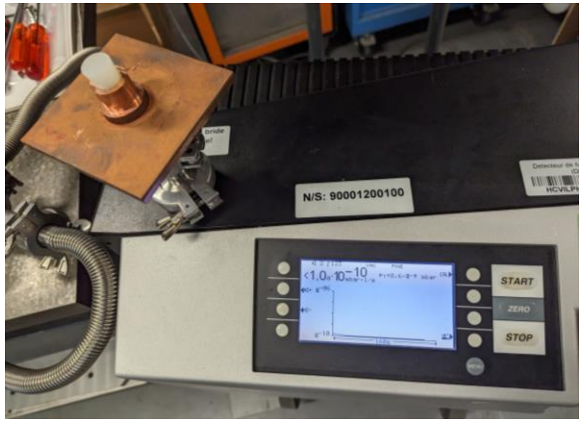




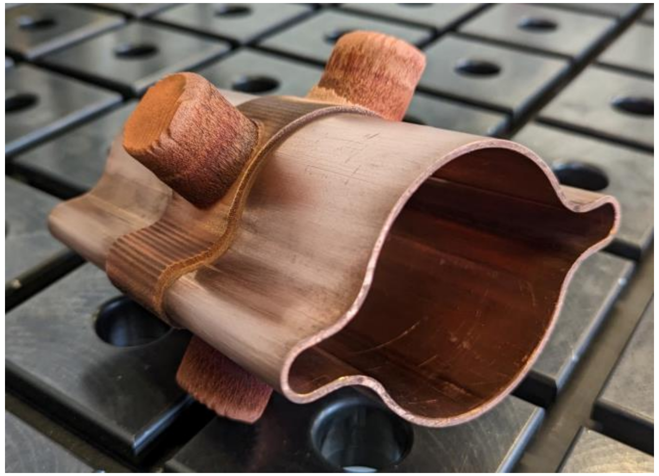
Design of BPM interfaces

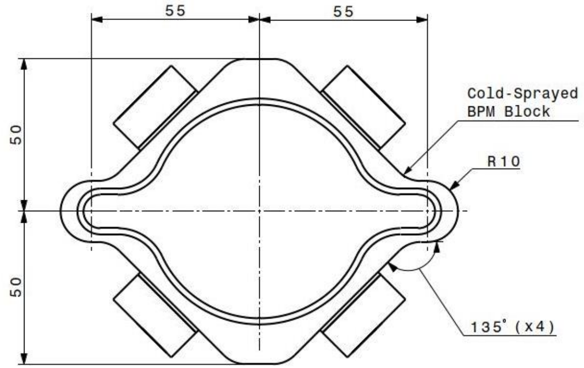






Machining and leak testing of cold-sprayed boss

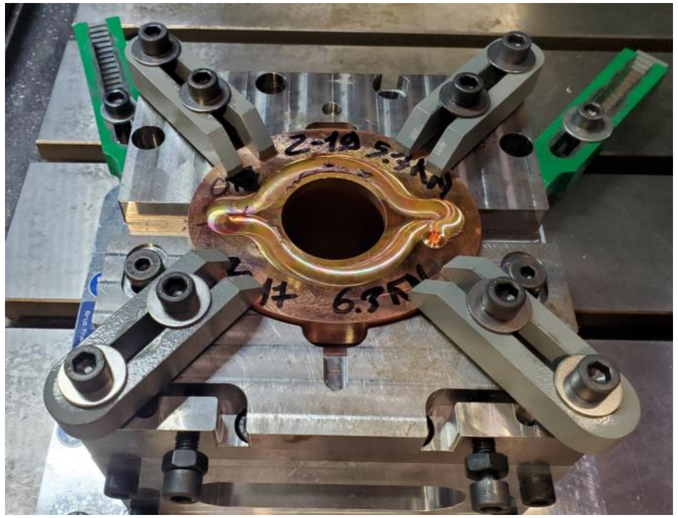




Test of cold sprayed bosses on a chamber prototype

Friction stir welding

FSW is a **fast and robust** industrial process, suitable for copper, which allows final precise machining of the interfaces on the same machine.



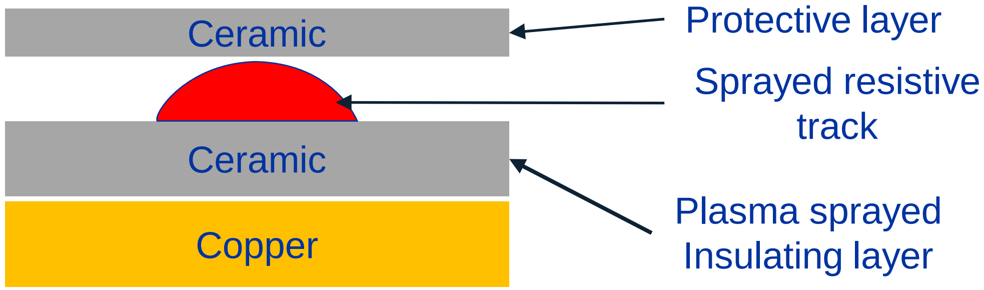
Weld parameters determined

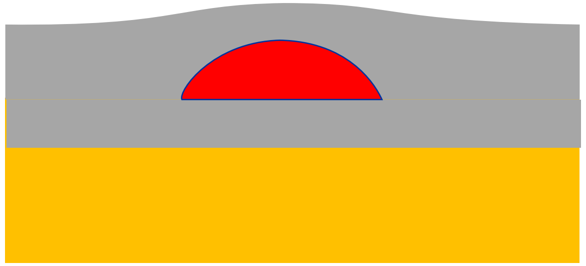
Stir welded flange after local remachining

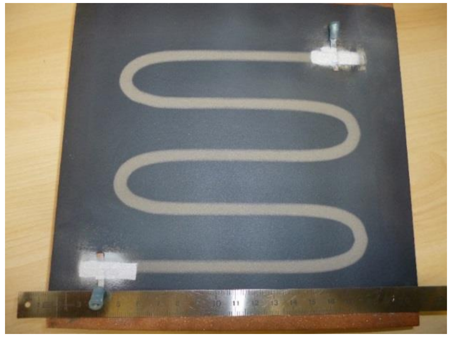
Leak testing carried out on completed assemblies

Bake out system

Thin and permanent radiation hard heating element is required to heat the vacuum chamber to 230 °C +/- 20 °C.



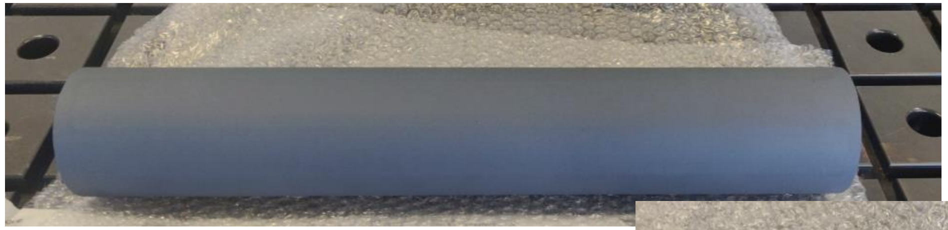


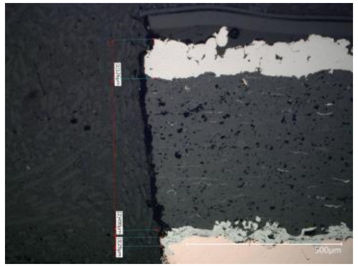


Copper plate with plasma sprayed ceramic and 0.2 mm thick cold sprayed titanium heating track

A first prototype of a copper tube with a permanent radiation tolerant bake out system has been produced:

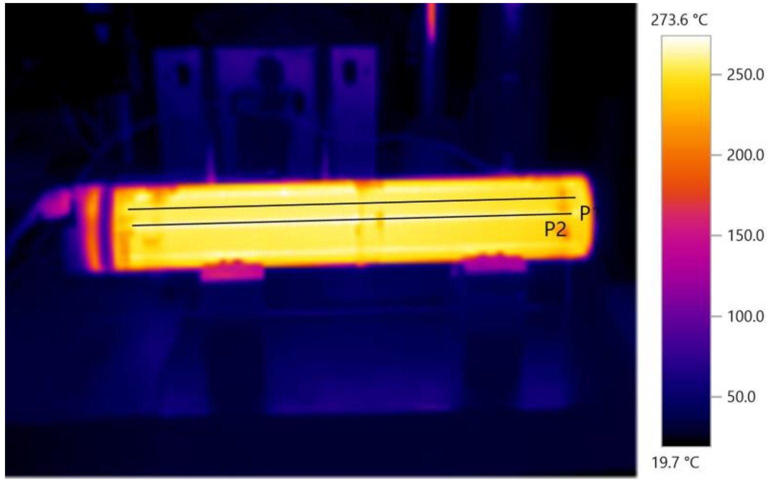
- OFE copper tube, 84 mm * 2 mm, 500 mm long
- Al_2O_3-TiO_2 ceramic layer; track in cold sprayed titanium, ~ 110 μm thick, 8 mm width, 30 mm distance





Cross-section

Interfaces for the electrical connections



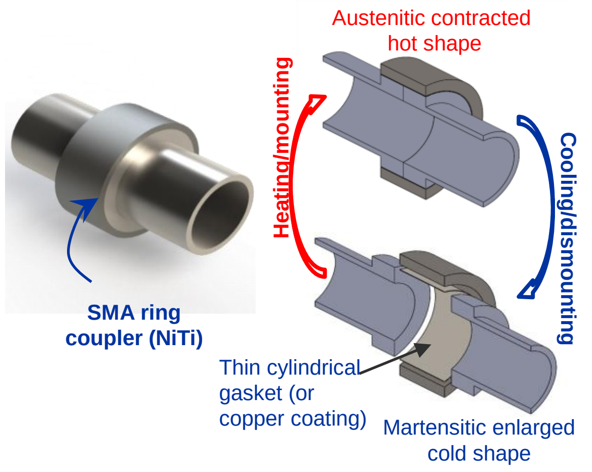
Temperature field

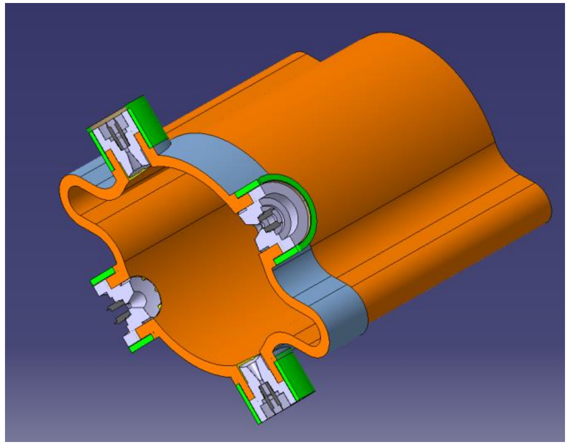
- ➢ Successful heating to more than 250 °C.
- ➢ Good temperature homogeneity: +/- 10 °C.

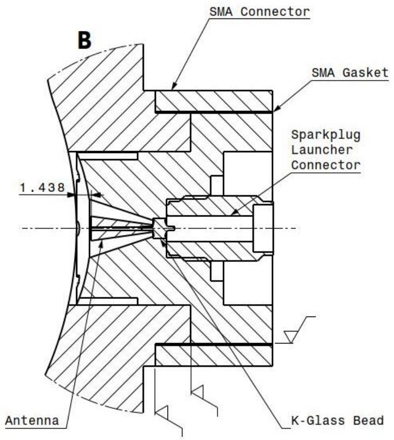
Further studies and development are required to ensure long term reliability and to optimize the cost.

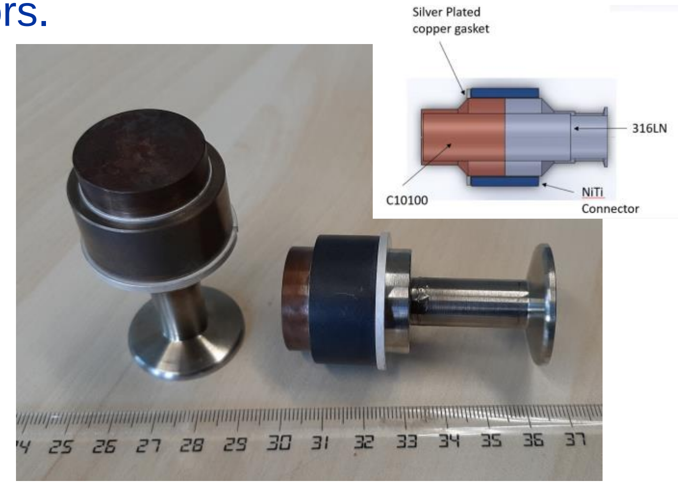
Shape Memory Alloy connectors

Compact and bi-material UHV connections are required and are done by SMART connectors.

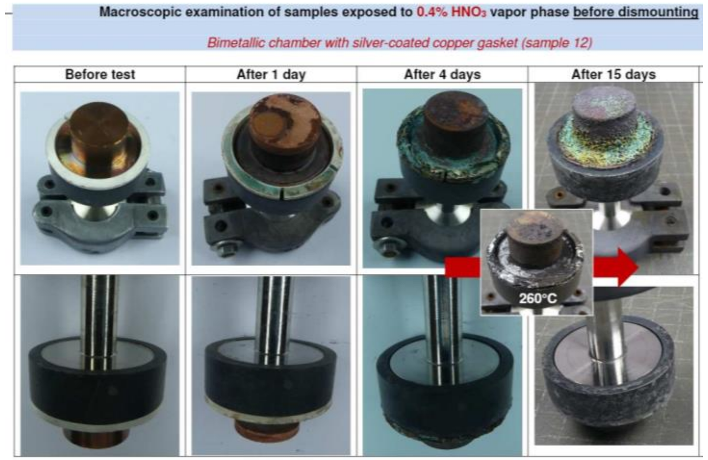




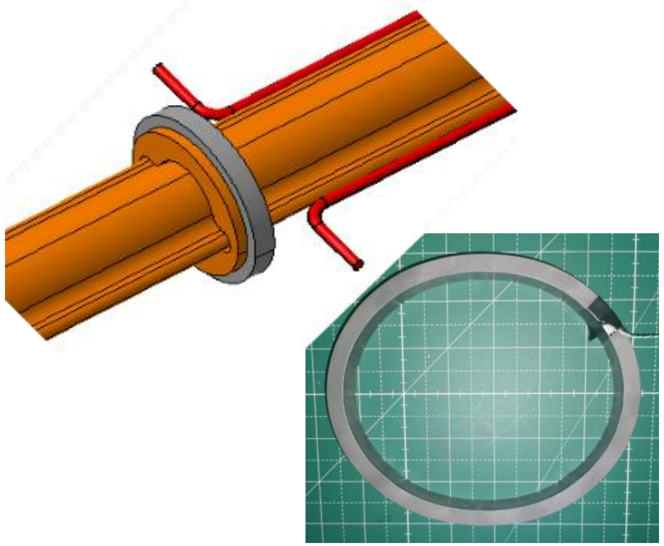




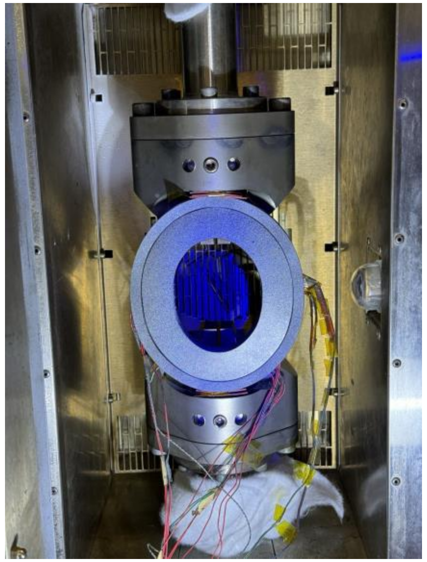
Compact bi-metallic (Cu/St. St.) connection of the BPM pick-up

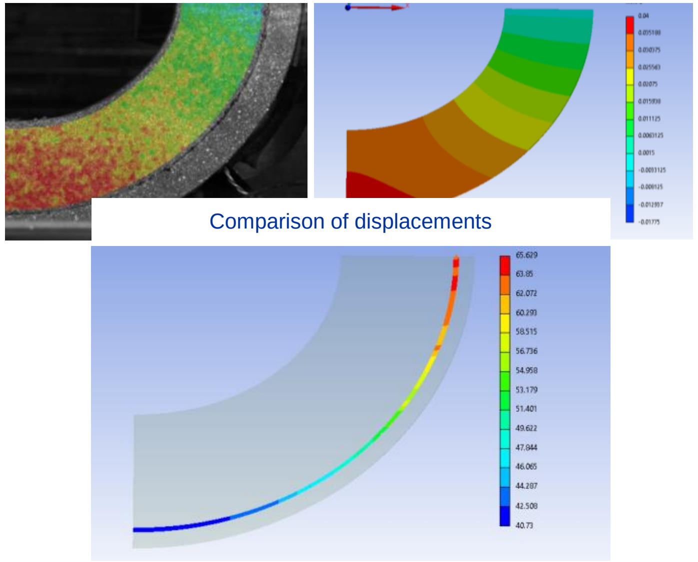


Accelerated corrosion tests in harsch environment



Oval rings for chamber connections (Cu/Cu & Cu/St. St.)





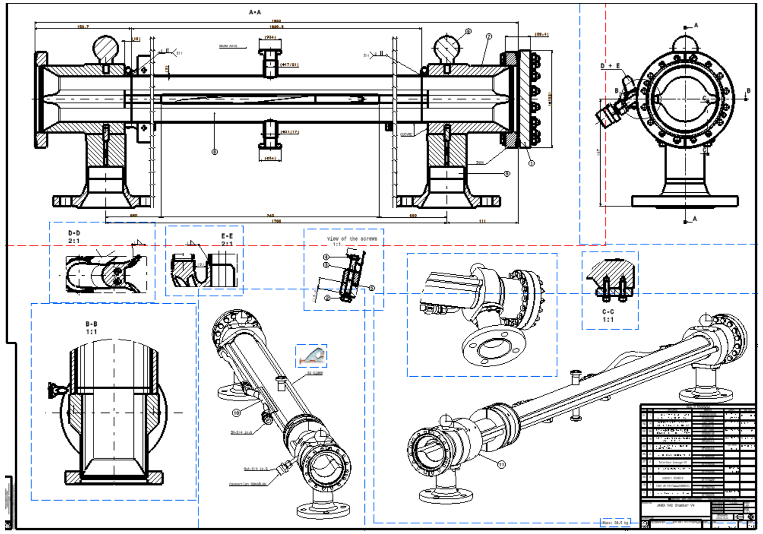
Assessment of the contact pressure

Further studies and development are required to ensure feasibility and reliability of oval connectors.

2m long prototype

FCC-ee vacuum chamber prototype

Design of chamber prototoype for tests at KARA synchrotron radiation light source



Copper extrusion

Machining and adjustment for electron beam welding tests

Ongoing and next steps

Thermal insulation and low thermal conductance support

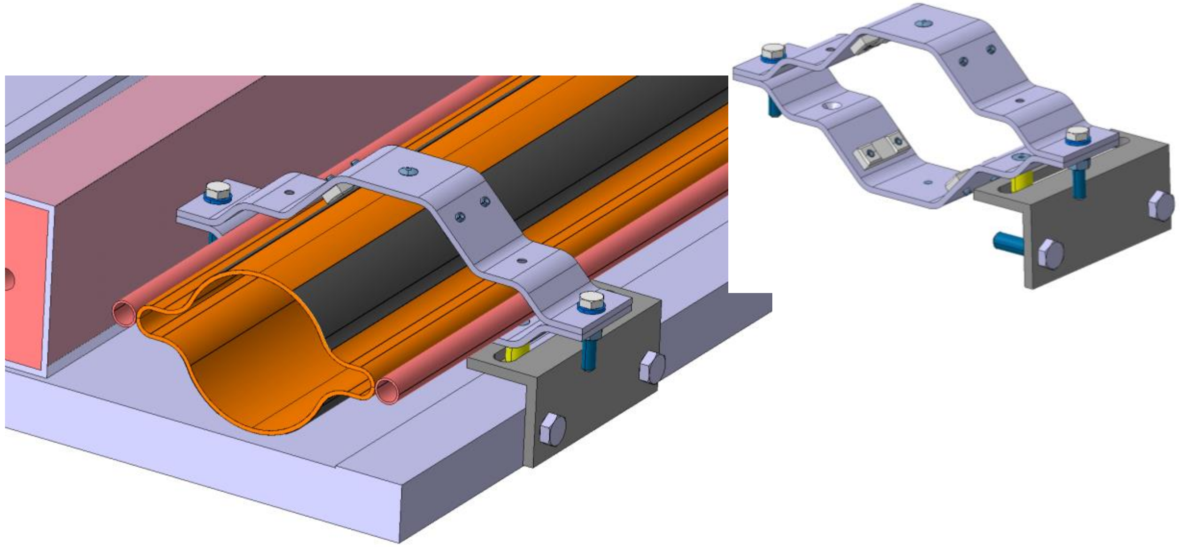
- Thin (5 mm) permanent radiation hard insulation
- Targeted contribution of the supports : < 10 %

External shielding integration [B. Humann, A. Lechner]

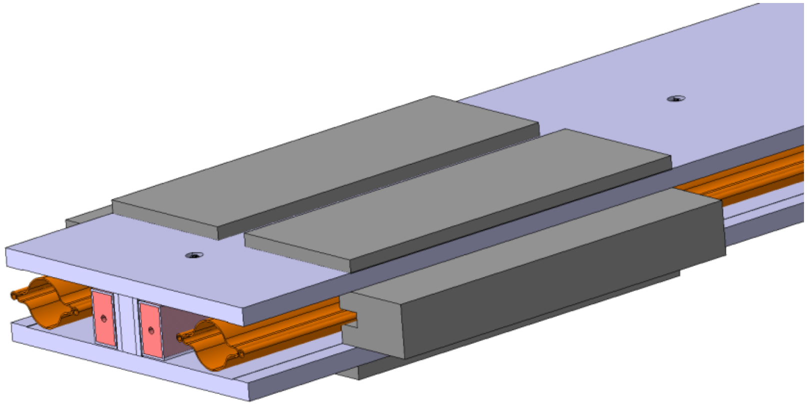
- O(150-200kg)/SRA
- O(1-1.2kW)/SRA

Interconnection (RF bridge)

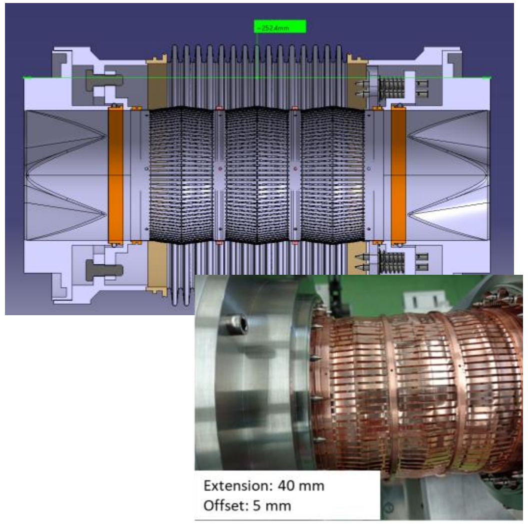
- High strokes (axial: 65 mm; transversal: 3 mm)
- High heat deposition O(100W)/IC



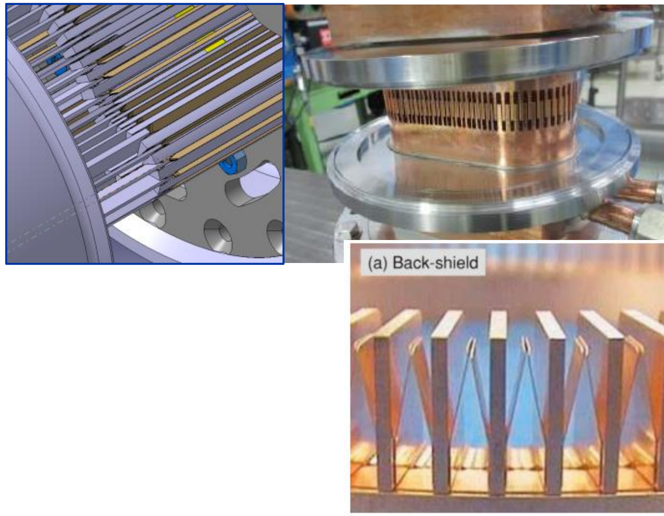
Proposal for the chamber support



External shielding



DRF bridge based on HL-LHC design



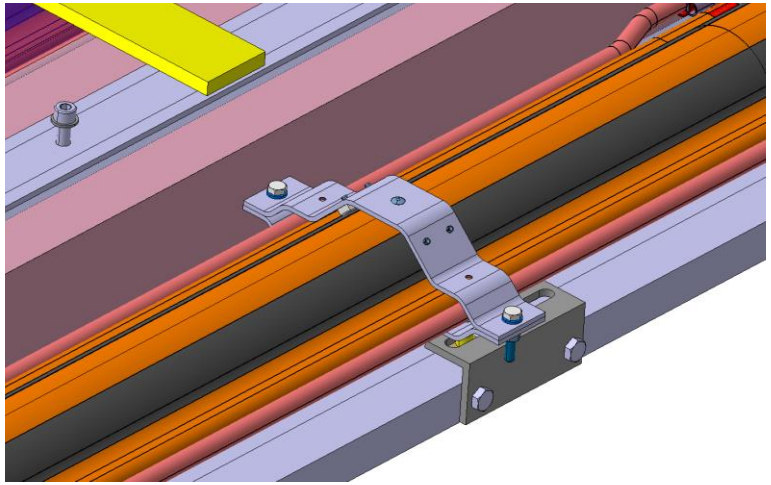
Comb RF bridge based on superKEKb design

Ongoing and next steps

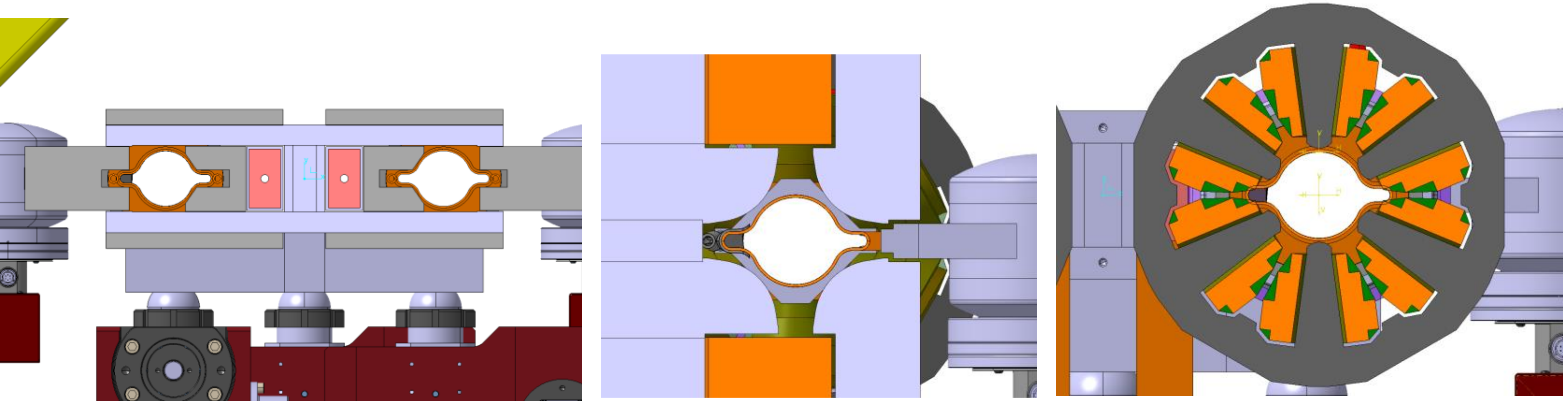
Integration of the different technologies to FCC-ee vacuum system and assessment of their robustness (tolerances, reliability, ageing,…).

Integration of the vacuum system in the FCC-ee:

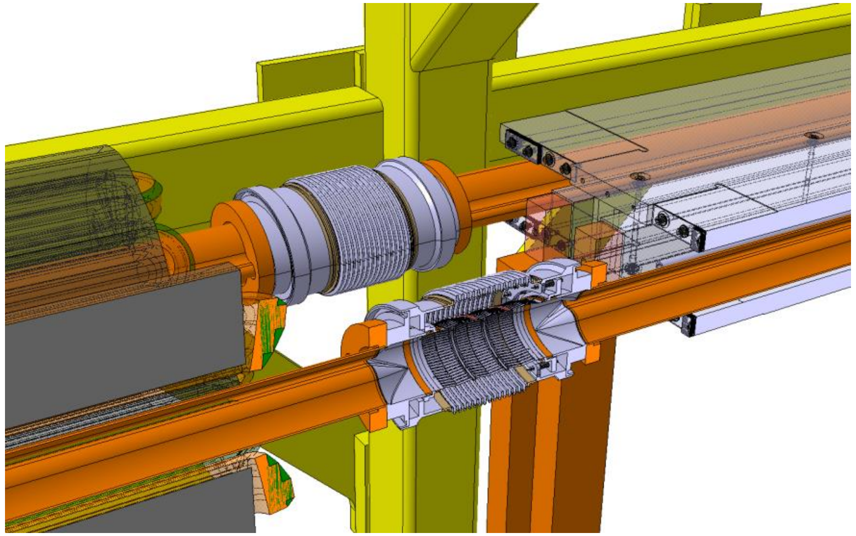
- Interfaces with magnets and beam instrumentations and assembly strategies.
- Layout: vacuum sector, sector valves, radiation tolerant instrumentation, radiation tolerant cables.



Integration of the vacuum chamber in the dipole



Integration of the vacuum chamber in the magnets



Interconnection zone with cooling circuit

Conclusion

The FCC-ee arc vacuum system rises several challenges:

- High beam induced effects.
- Robust and radiation hard vacuum system.

The vacuum system performance relies on distributed NEG pumping with fast conditioning of localized synchrotron radiation absorbers.

The R&D of several critical technologies have been initiated to fulfil FCC-ee requirements and/or to reduce costs. The R&D phase is still ongoing for these technologies that have then to be implemented to the FCC-ee system.

Several critical points are being tackled:

- Design of the interconnections and thermal-mechanical studies based on updated beam parameters (impedance).
- Assessment of the transient behaviour and long-term reliability.

home.cern