Update on the FCC-ee vacuum system development

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Outline

- **Vacuum system requirements and challenges in the FCC-ee arcs**
- **Pre-technical design and related technologies**
- **Ongoing activities**
- **Next activities**
- **Conclusions and future outlook**

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Context

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**

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

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

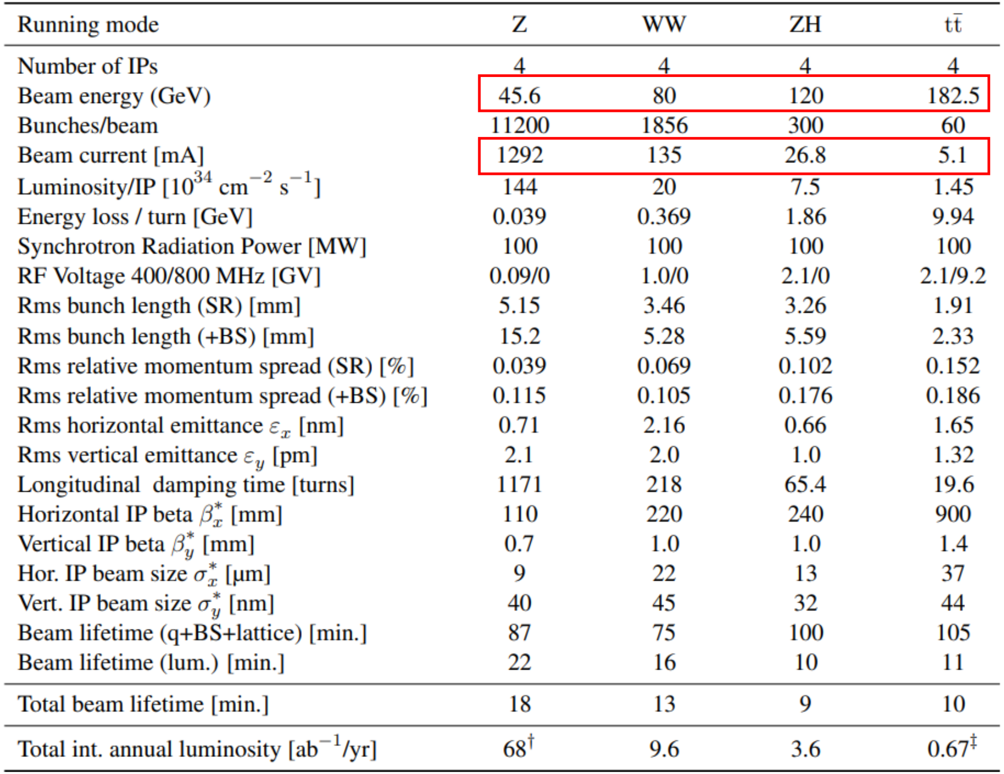
$$\varepsilon_c = 2218 \cdot E^3\,(GeV) / \rho(m)$$

For the vacuum system, the synchrotron radiation leads to:

- High local heat deposition: average ~740 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

To guarantee a quick decrease of the photon desorption yields and so a fast vacuum conditioning, it has been proposed to use localized Synchrotron Radiation Absorbers (SRA) along the vacuum chamber, spaced about 5-6 m apart.

The vacuum system shall consider impedance requirements.



Running mode	Z	WW	ZH	$t\bar{t}$
Number of IPs	4	4	4	4
Beam energy (GeV)	45.6	80	120	182.5
Bunches/beam	11200	1856	300	60
Beam current [mA]	1292	135	26.8	5.1
Luminosity/IP [10^{34} cm^{-2} s^{-1}]	144	20	7.5	1.45
Energy loss / turn [GeV]	0.039	0.369	1.86	9.94
Synchrotron Radiation Power [MW]	100	100	100	100
RF Voltage 400/800 MHz [GV]	0.09/0	1.0/0	2.1/0	2.1/9.2
Rms bunch length (SR) [mm]	5.15	3.46	3.26	1.91
Rms bunch length (+BS) [mm]	15.2	5.28	5.59	2.33
Rms relative momentum spread (SR) [%]	0.039	0.069	0.102	0.152
Rms relative momentum spread (+BS) [%]	0.115	0.105	0.176	0.186
Rms horizontal emittance ε_x [nm]	0.71	2.16	0.66	1.65
Rms vertical emittance ε_y [pm]	2.1	2.0	1.0	1.32
Longitudinal damping time [turns]	1171	218	65.4	19.6
Horizontal IP beta β_x^* [mm]	110	220	240	900
Vertical IP beta β_y^* [mm]	0.7	1.0	1.0	1.4
Hor. IP beam size σ_x^* [µm]	9	22	13	37
Vert. IP beam size σ_y^* [nm]	40	45	32	44
Beam lifetime (q+BS+lattice) [min.]	87	75	100	105
Beam lifetime (lum.) [min.]	22	16	10	11
Total beam lifetime [min.]	18	13	9	10
Total int. annual luminosity [ab^{-1}/yr]	68†	9.6	3.6	0.67‡

Synchrotron Radiation Spectra

- **Z-Pole: very high photon flux:**
  - **large outgassing load;**
  - **Quick commissioning.**
- **T-pole (182.5 GeV): 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))**

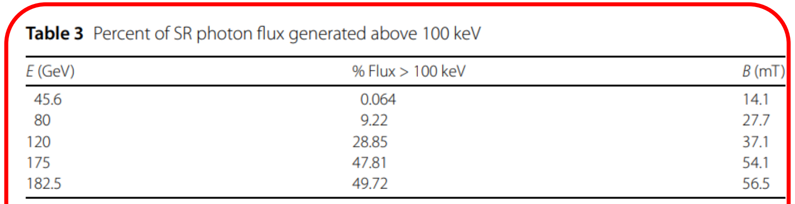


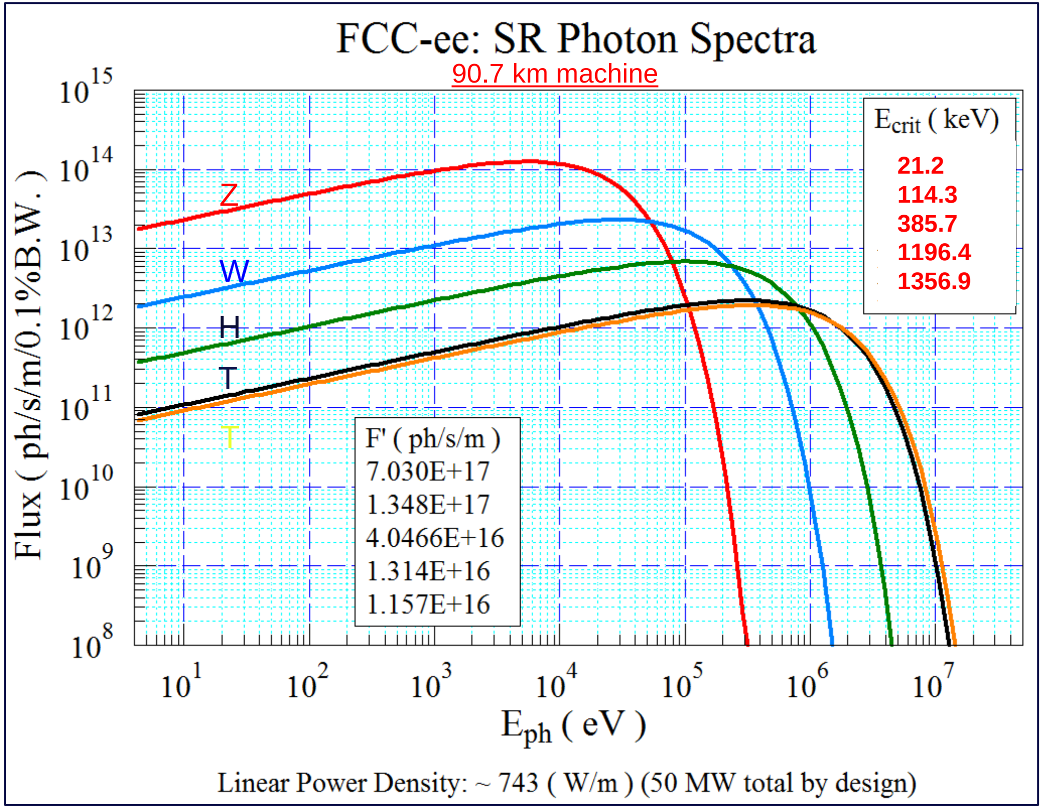
Table 3 Percent of SR photon flux generated above 100 keV

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

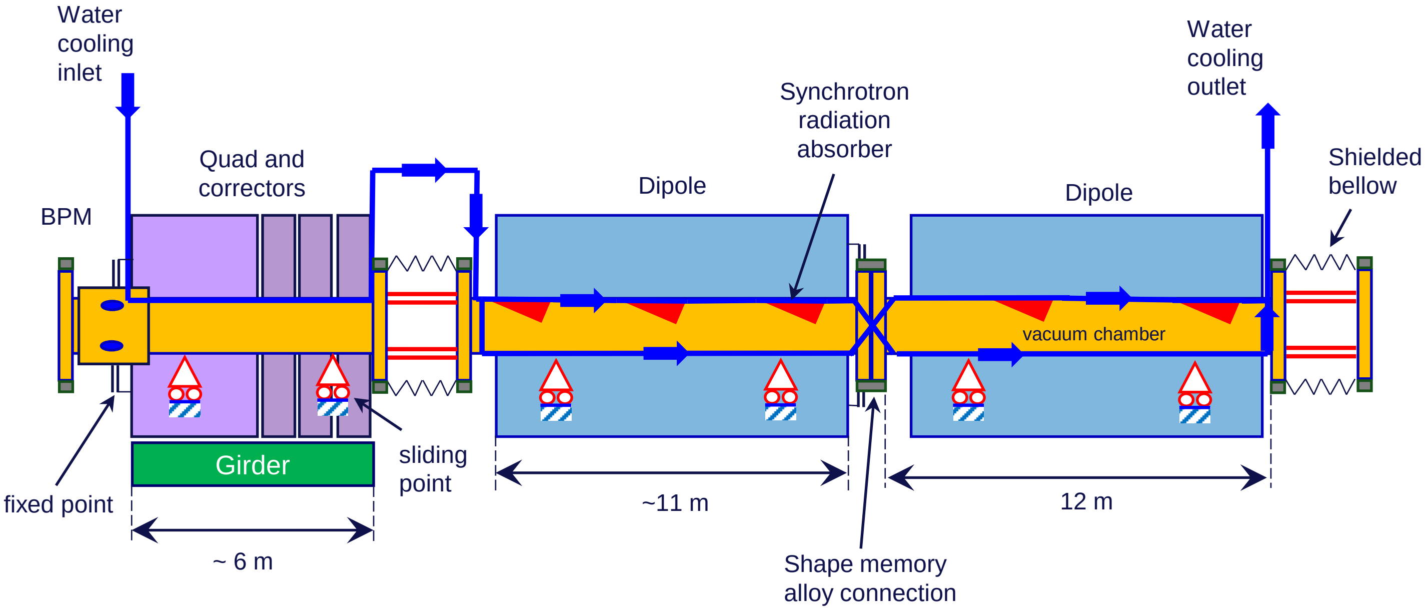
https://doi.org/10.1140/epjti/s40485-022-00087-w

See Marton Ady presentation for pressure levels.

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



Collider vacuum layout (functional, kinematic & cooling)



- Synchrotron radiation absorbers are installed in dipoles, shielding also the interconnections and quad/correctors.
- Longitudinal thermal expansion of the vacuum chamber during bake-out: 4 mm/m → 65 mm axial stroke for the shielded bellows.

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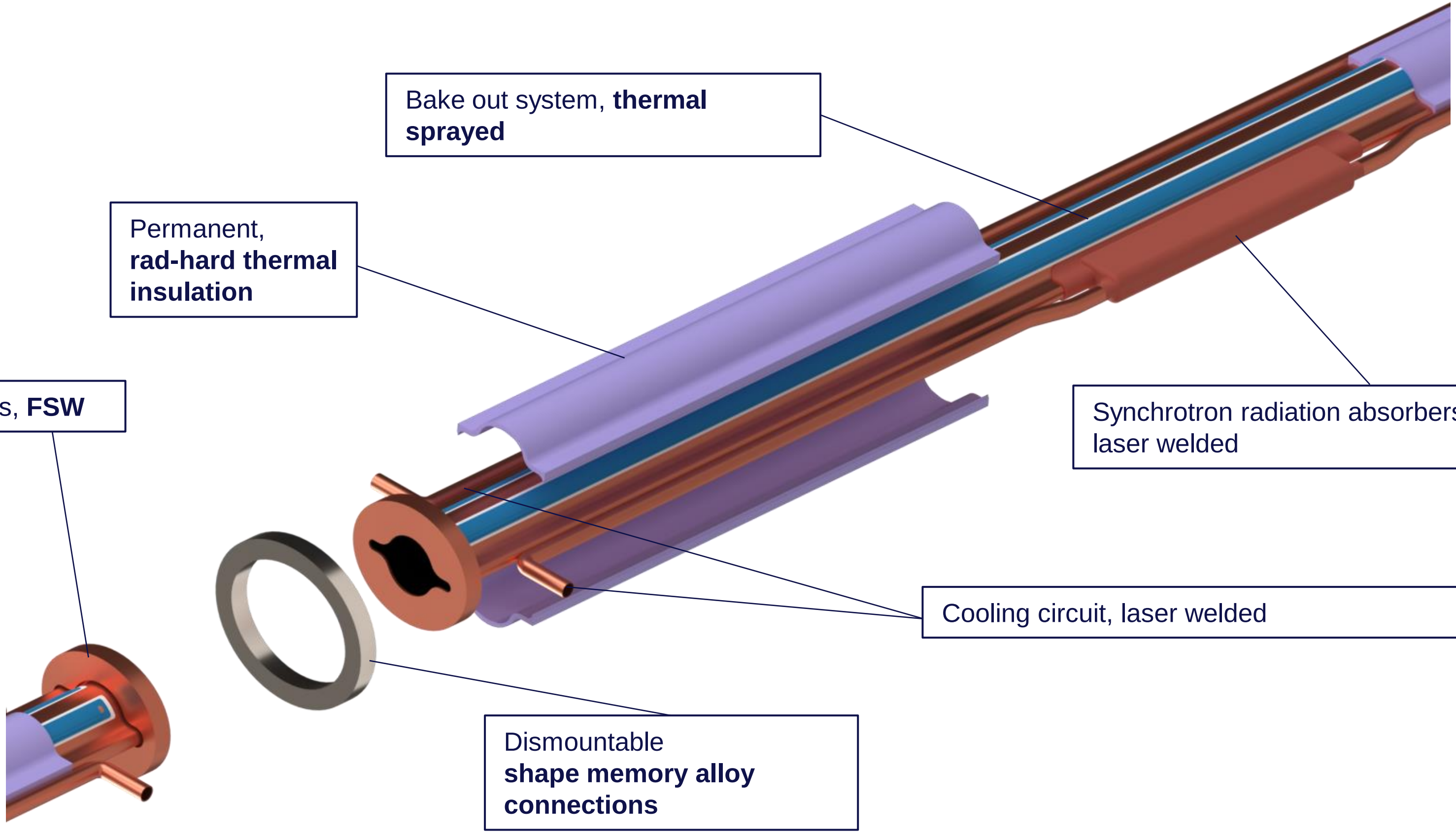
Collider vacuum chamber design

The collider vacuum chamber is a complex component designed with **new** and **innovative** technologies in the particle accelerator domain.



Bake out system, **thermal sprayed**

Permanent, **rad-hard thermal insulation**

Flanges, **FSW**

Synchrotron radiation absorbers, **3D printed**, laser welded

Cooling circuit, laser welded

Dismountable **shape memory alloy connections**

Extruded vacuum chamber (collider)

Geometry:

- Tube with two winglets up to 12 m long
- 2 mm thick, 60 mm ID (vacuum conductance 30 l.m/s)

Material: OFS Copper

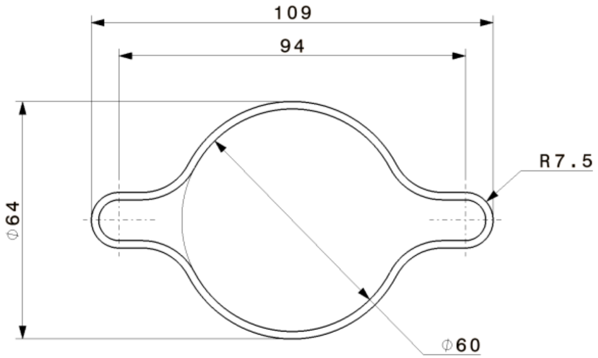
- Good thermal conductivity and low electrical resistivity
- Shielding for the X-Ray synchrotron radiation fan and minimizing the irradiation of machine and tunnel components

Surface treatment inside: thin (200 nm) NEG coating

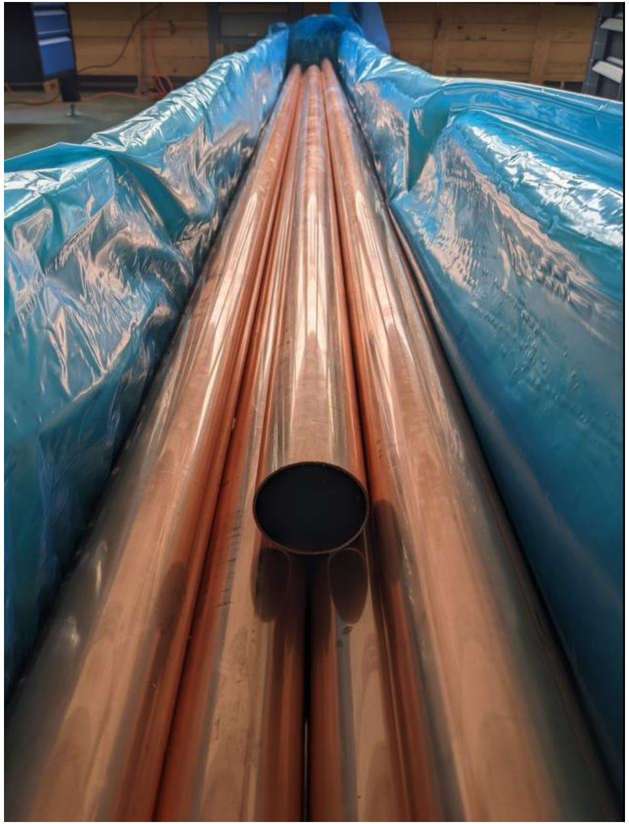
- Distributed pumping speed
- Low SEY
- Quick vacuum conditioning
- Long term performance of thin NEG coating to be assessed.

Surface treatment outside: thermal spray of bake-out system

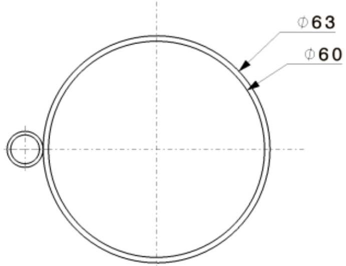
- Atmospheric Plasma Spraying (APS) for ceramic insulation
- Cold Spraying for heating elements
- Radiation hard
- Not ferromagnetic



Extruded vacuum chamber (booster)



Booster chamber prototype



Cross section of the booster vacuum chamber

Geometry:

- round seamless tube
- 1.5 mm thick, 60 mm ID

Material: OFE Copper

- Good thermal conductivity and low electrical resistivity

No NEG coating

A copper tube is spot welded on the chamber to ensure a water cooling whose size needs to be determined.

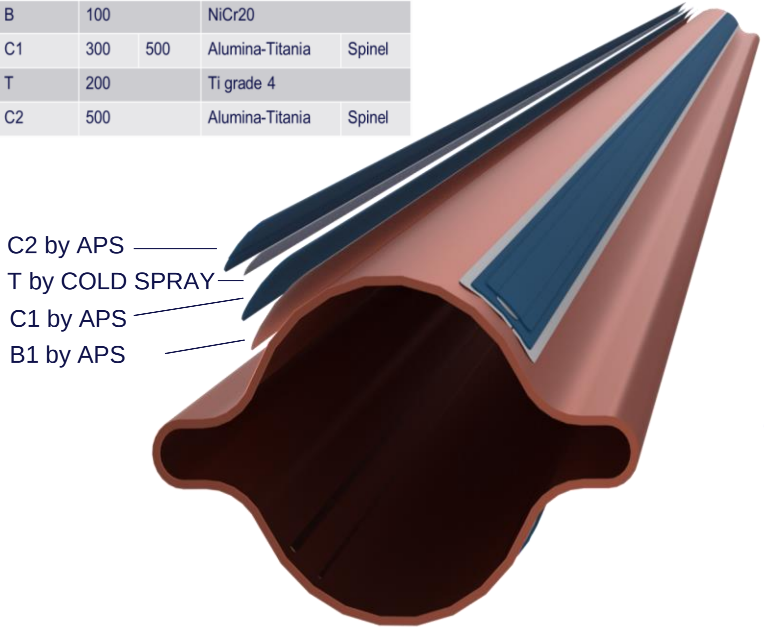
No lump photon absorbers are foreseen.

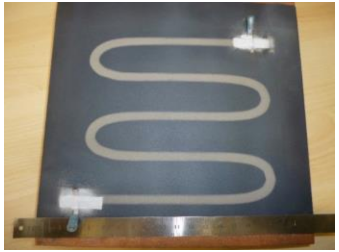
At the moment, no bakeout is envisaged and, therefore, non-shielded bellows are only used to compensate for mechanical and alignment tolerances.

Bake out system

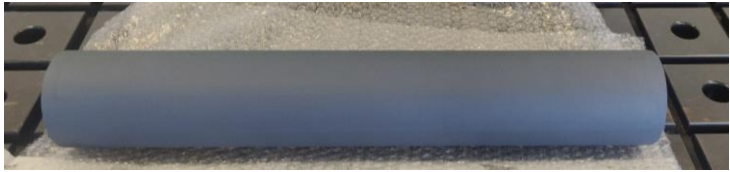
Thin (up to 1.3 mm) and permanent rad-hard heating element is required to heat the collider vacuum chamber to 230 °C +/- 20 °C for NEG activation.

Layer	Thickness µm		Material	
B	100		NiCr20	
C1	300	500	Alumina-Titania	Spinel
T	200		Ti grade 4	
C2	500		Alumina-Titania	Spinel



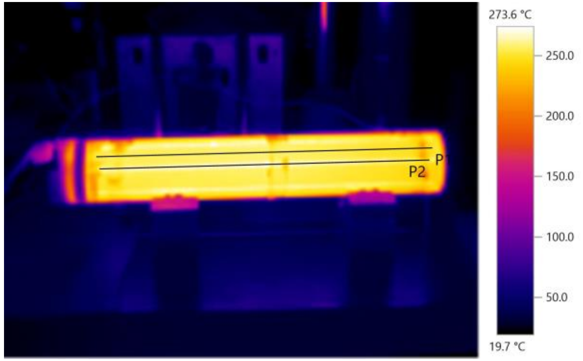


Copper plate with plasma sprayed ceramic and 0.2 mm thick cold sprayed titanium heating track



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

Cross section of the OFE copper tube

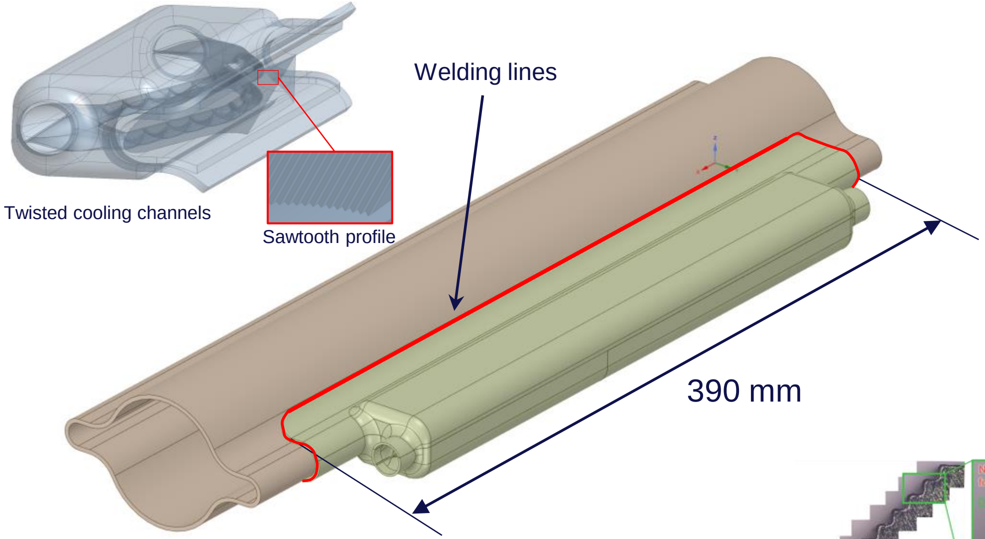


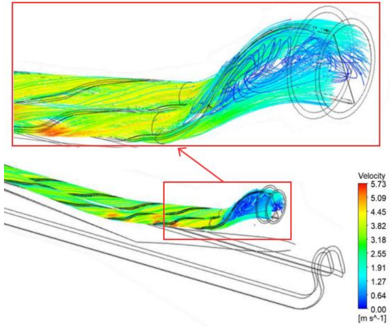
Temperature field

- A first prototype of a copper tube with a permanent bake out system was successful justifying exploring this technology further:
  - Temperature more than 250 °C with good temperature homogeneity of +/- 10 °C.
- Collaboration with industrial and academic partners ongoing to optimize the cost and ensure long term reliability.

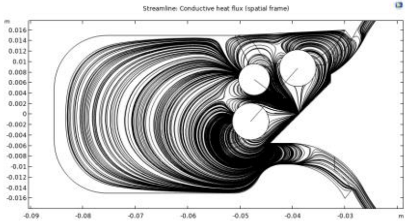
See Martin Bammer presentation.

The Synchrotron Radiation Absorber

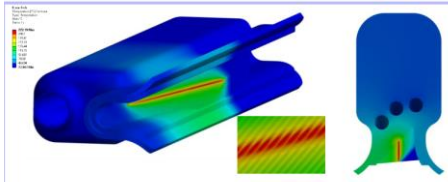




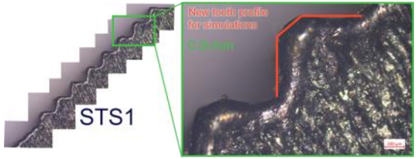
CFD to assess the water flow



Heat flux streamlines to optimise positions of the cooling channels

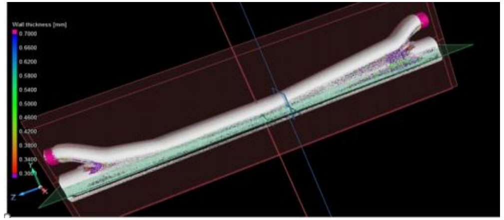


Temperature distribution



Sawtooth profile 3D printed

3D printed prototype and samples



Tomography analysis to assess the internal structure

- High local heat deposition (~ 3.5 kW on average and 4.5 kW max) to be absorbed by each absorber → an efficient cooling system is needed.
- A high heat transfer can be achieved by twisted tape cooling channels (to increase turbulence) thanks to 3D printing .
- 5 absorber per half arc cell distanced 5-6 m are considered. A study to use 4 absorbers with a regular pattern is ongoing.
- Sawtooth profile is being assessed to reduce photon reflection and photoelectron generation.

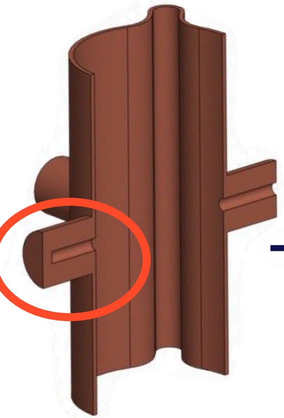
See Stefania Grozavu and Marton Ady presentations.

Additive manufacturing

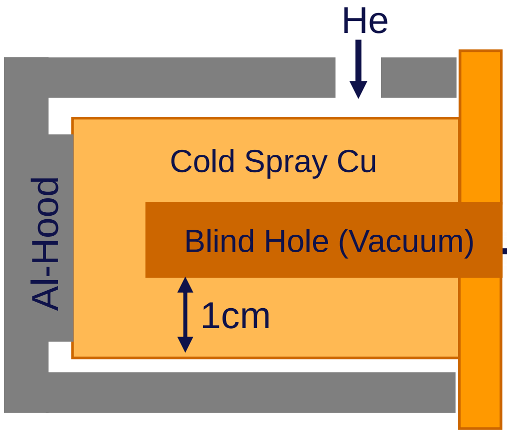
Cold spray of BPM interfaces

See Martin Bammer presentation.

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

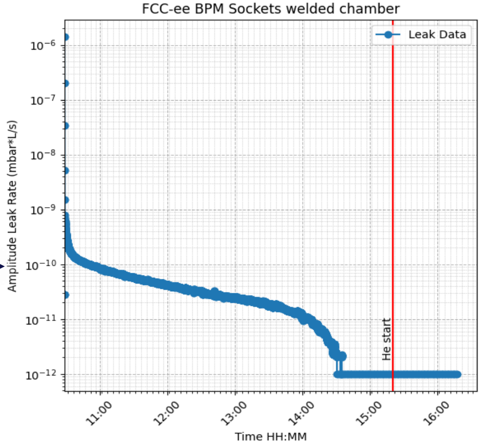


Blind hole diametre: 6mm

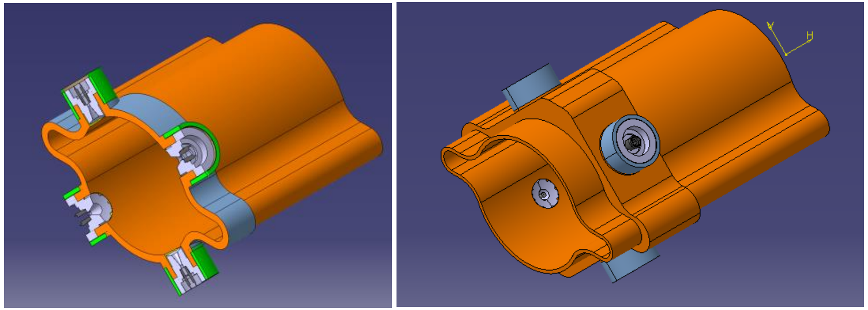


He-injection Setup

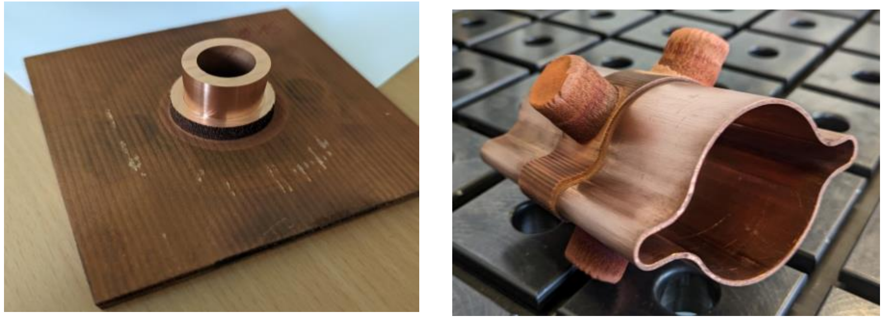
Photo of test setup



No helium leak signal observed during the test



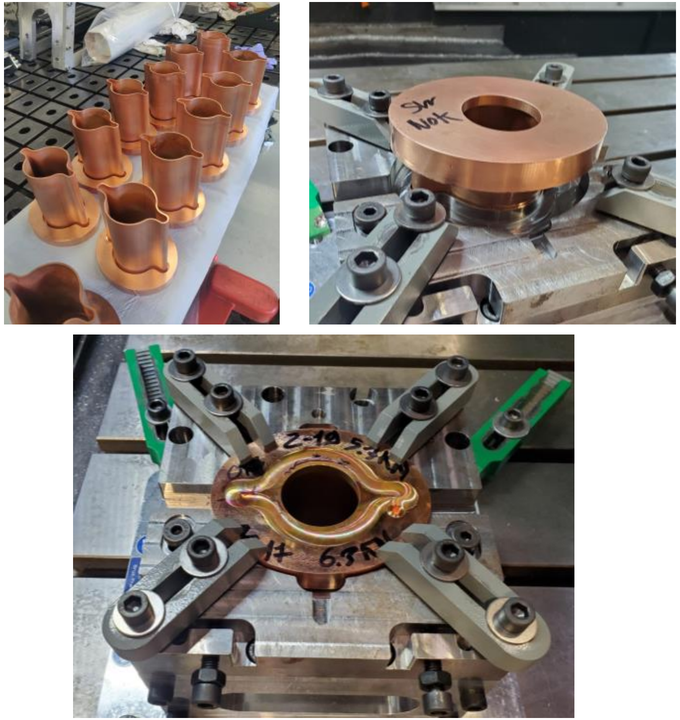
Design of BPM interfaces



Test of cold sprayed bosses on a plate and 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

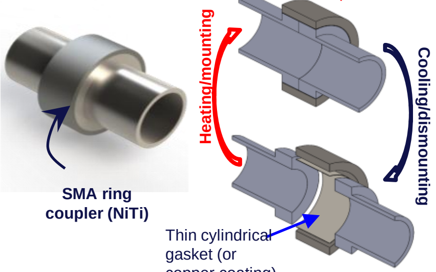
Stir welded flange after local remachining

Leak testing carried out on completed assemblies

Welding test on a 2m long chamber in horizontal configuration in preparation at CERN.

Shape Memory Alloy connectors

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


Austenitic contracted hot shape

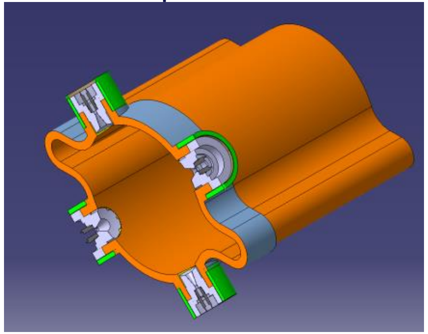
Heating/mounting

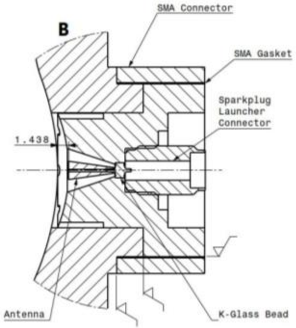
Cooling/dismounting

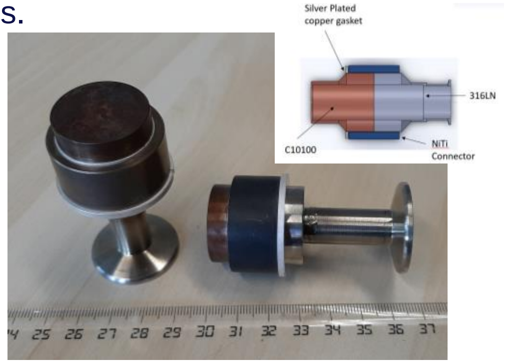
SMA ring coupler (NiTi)

Thin cylindrical gasket (or copper coating)

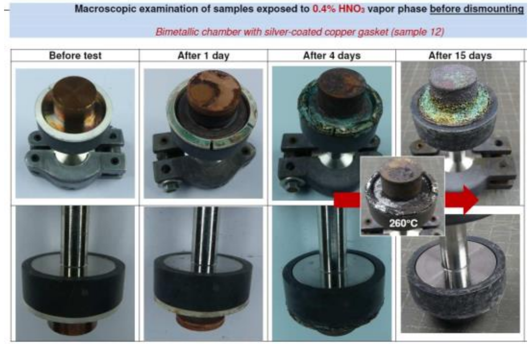
Martensitic enlarged cold shape







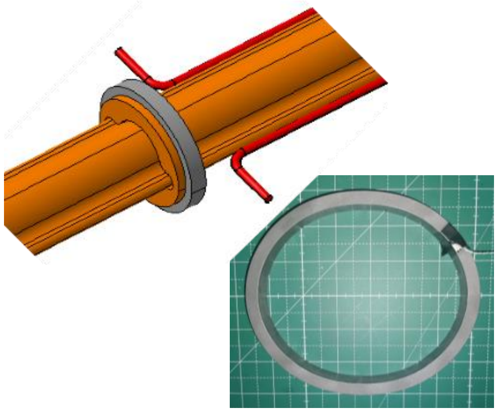
Compact bi-metallic (Cu/St. St.) connection of the BPM pick-up


Macroscopic examination of samples exposed to 0.4% HNO_3 vapor phase before dismounting

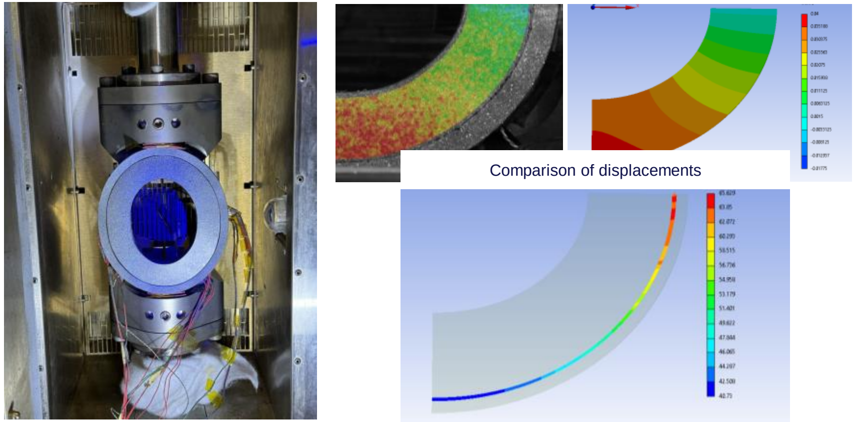
Bimetallic chamber with silver-coated copper gasket (sample 12)

Before test	After 1 day	After 4 days	After 15 days

Accelerated corrosion tests in harsch environment



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


Comparison of displacements

Assessment of the contact pressure

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

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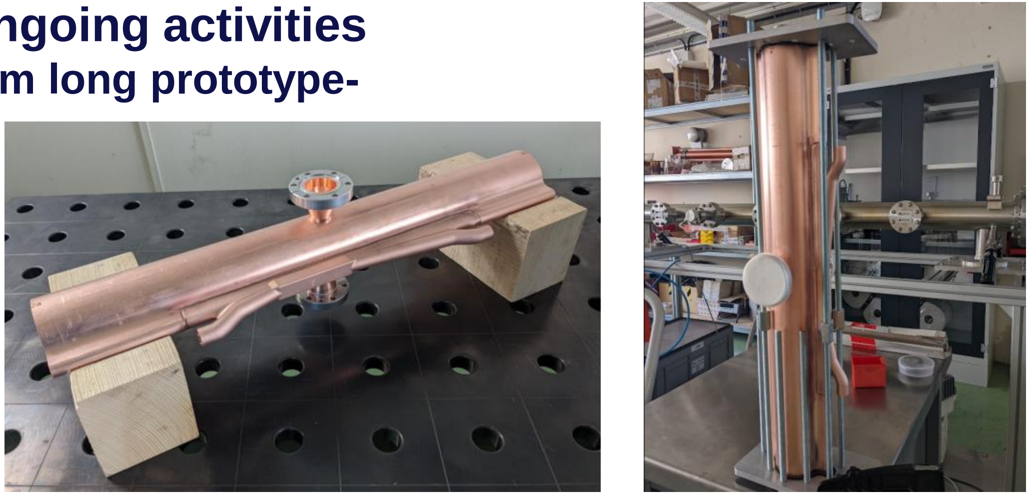
Ongoing activities
-2m long prototype-

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

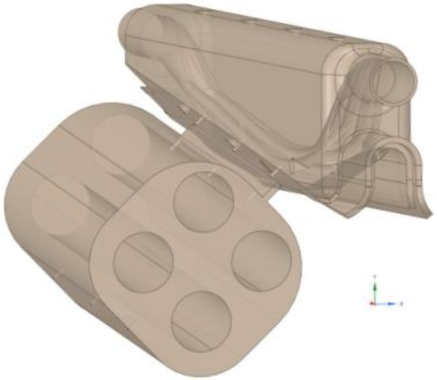


FCC-ee vacuum chamber prototype and leak test preparation

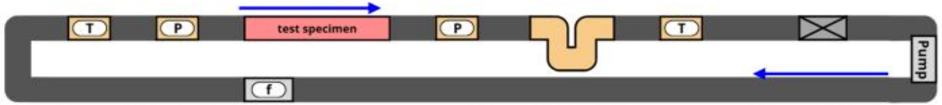
Machining and adjustment for electron beam welding tests

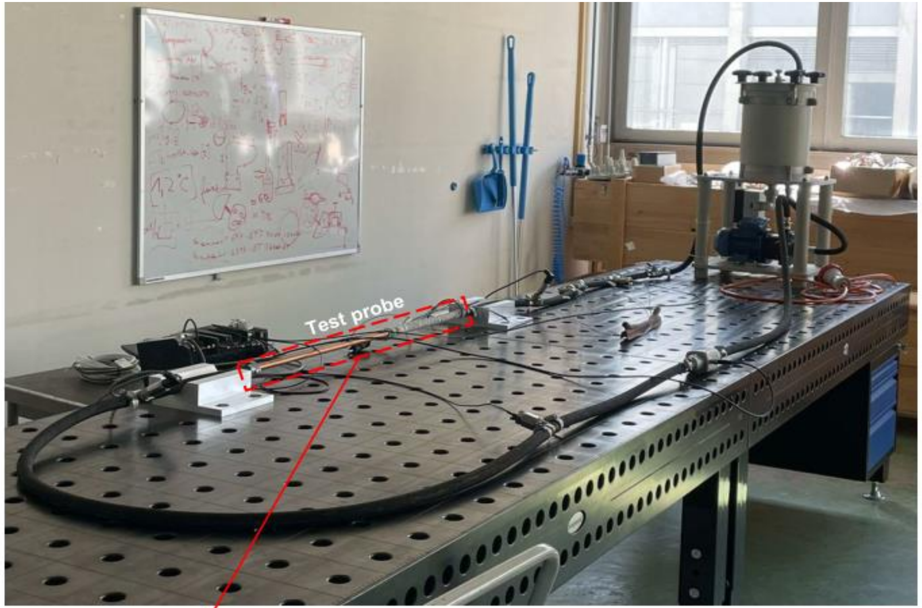
Ongoing activities

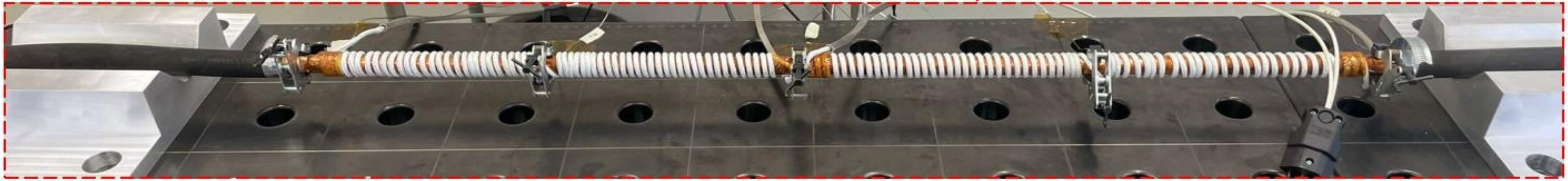
-Experimental validation of CFD analyses-



SRA sample designed for the test



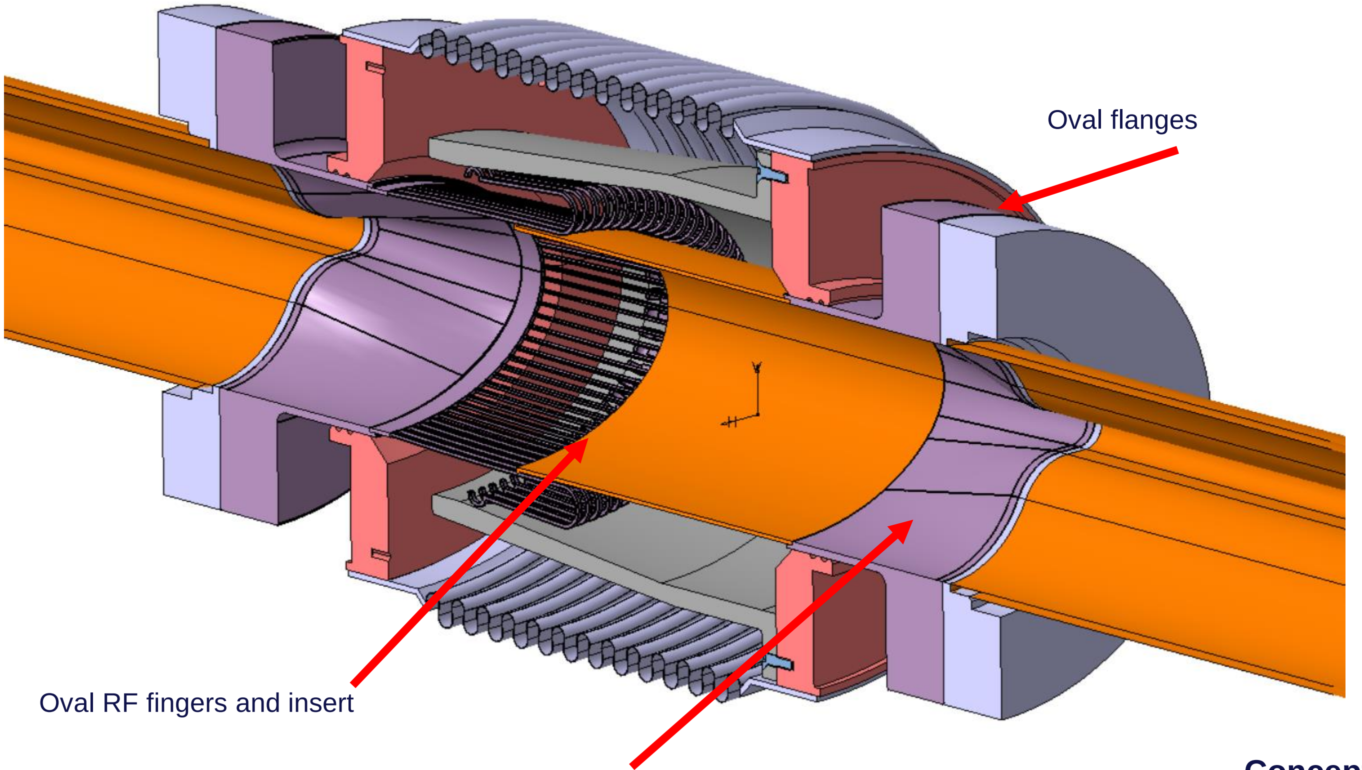




Test bench to assess thermal transfer capabilities of SRA

Ongoing activities

-FCCee vacuum chamber connections-



Oval flanges

Oval RF fingers and insert

Copper transition Oval – Circular+ winglet

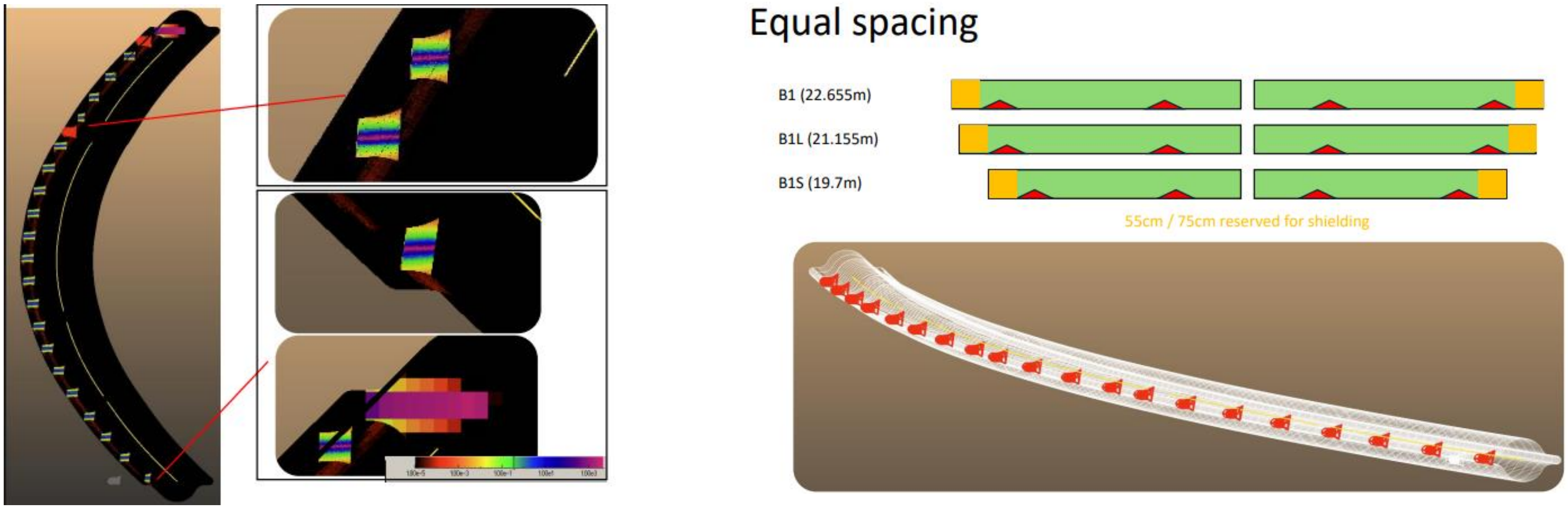
Connections:

- Baseline design: Shape Memory Alloy connector
- Alternative design: CF like, knife edge oval flange

Conceptual design for illustration only.

Ongoing activities

-Position of the absorbers with relative tolerance study and impedance calculations-



Equal spacing study for the SRA (see Marton Ady’s presentation).

Impedance (values to be reassessed):

- 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]
- Impact of the absorber moving towards the beam axis

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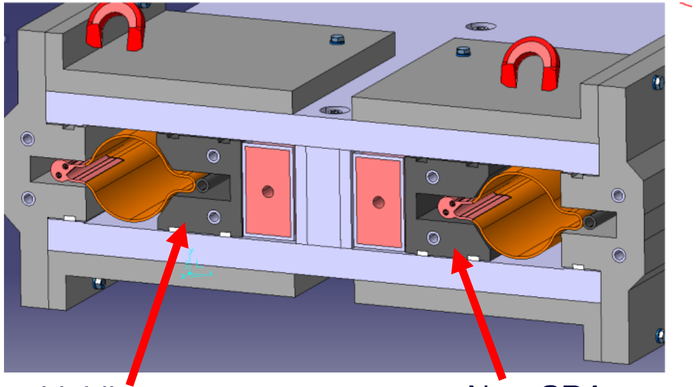
Next activities
-Optimisation of the internal shielding integration-

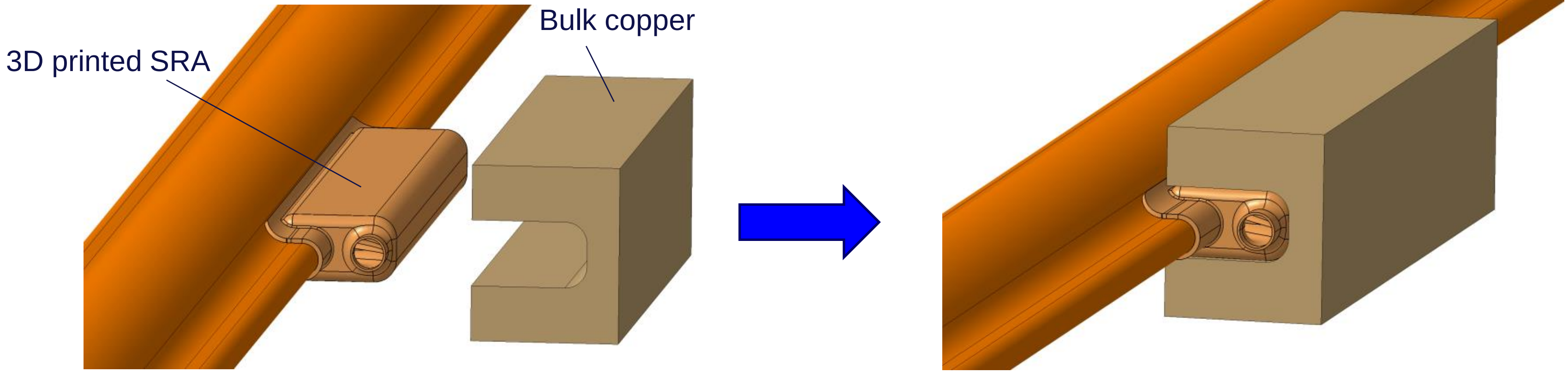
Thermal insulation and low thermal conductance support

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

Optimisation of the shielding around the internal absorber by adopting a bulkier SRA. The implications are being studied (see also A. Lechner, B. Humann presentation).

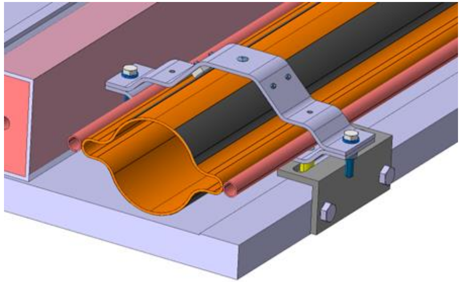


New SRA concept



Bulky component connected to the 3D printed SRA (by brazing or fastening) to optimize integration

Next activities
-Integration-

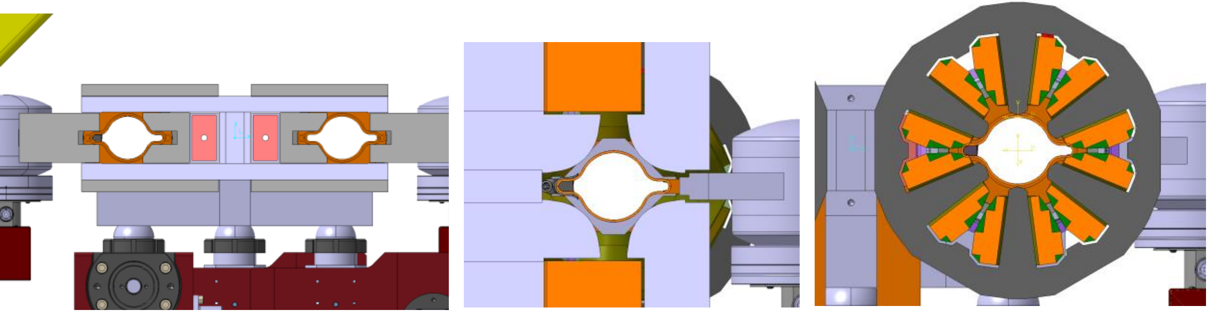


Proposal of a chamber support

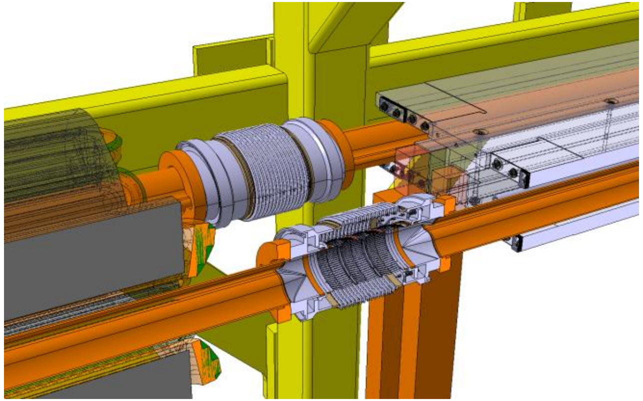
Integration of the different technologies to FCC-ee vacuum system and assessment of their robustness (tolerances, reliability, ageing,…).

Integration of the vacuum system in the FCC-ee in close synergy with STI and MSC

- 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 magnets



Interconnection zone with cooling circuit

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Conclusions and Future Outlook

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 to fulfil FCC-ee requirements and/or to reduce costs is on **full swing for pre-TDR phase.**

The **main challenge** is to minimize costs by making these technologies **scalable**, **industrially viable**, and capable of operating with low maintenance and operational costs.

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Thank you for your attention