Vacuum System of the FCC-ee

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on High Luminosity Circular e+e- Colliders (eeFACT2022)
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Outline

- **Relevant machine and vacuum parameters**
- **Vacuum chamber cross section**
- **Synchrotron radiation spectrum, flux, power**
- **SR absorbers: yes or no?**
- **Pumping solutions**
- **Pressure profiles**
- **Prototyping, experiments, future work…**

Relevant machine and vacuum parameters

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THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Regular Article

FCC-ee: The Lepton Collider

Future Circular Collider Conceptual Design Report Volume 2

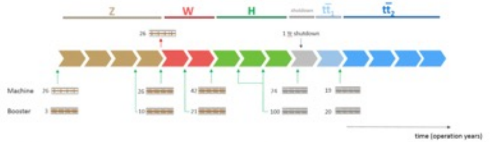


Fig. 4. FCC-ee operation time line. The bottom part indicates the number of cryomodules to be installed in the collider and booster, respectively, during the various winter shutdown periods; also see [22].

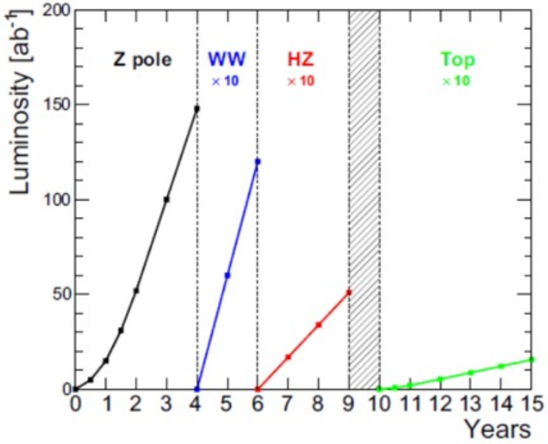


Fig. 1.2. Operation model for the FCC-ee, as a result of the five-year conceptual design study, showing the integrated luminosity at the Z pole (black), the WW threshold (blue), the Higgs factory (red), and the top-pair threshold (green) as a function of time. The hatched area indicates the shutdown time needed to prepare the collider for the highest energy runs.

Table 1. Machine parameters of the FCC-ee for different beam energies.

	Z	WW	ZH	$t\bar{t}$	
Circumference (km)			97.756		
Bending radius (km)			10.760		
Free length to IP l^* (m)			2.2		
Solenoid field at IP (T)			2.0		
Full crossing angle at IP θ (mrad)			30		
SR power/beam (MW)			50		
Beam energy (GeV)	45.6	80	120	175	182.5
Beam current (mA)	1390	147	29	6.4	5.4
Bunches/beam	16 640	2000	328	59	48

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

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

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

We aim at an average pressure giving a beam-gas scattering lifetime large enough not to be detrimental to the integrated luminosity, say in the low 10^{-9} mbar range or better, with a gas composition of 80~90% hydrogen, and no molecular masses above 44 (CO_2).

Typically, 80~90% H_2, 10~20% $CO+CO_2$, traces of CH_4

Vacuum chamber cross section

The choice of the vacuum chamber cross section is dictated by many different effects and requirements:

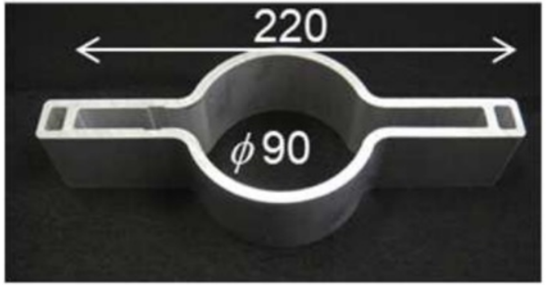
- **Minimize time to condition (to speed-up integrated luminosity at Z, most difficult case, vacuum wise)**
- **Minimize beam-gas scattering effects, i.e. minimize pressures and improve pumping efficiency**
- **Minimize e-cloud (e+) and ion-trapping (e-)**
- **Deal with large flux of Compton-scattered secondaries (at WZ, H, ttbar)**
- **Keep fabrication complexity to a minimum (2x 92 ~~98~~ km rings!);**
- **Satisfy impedance requirements (geometric and resistive-wall as well)**

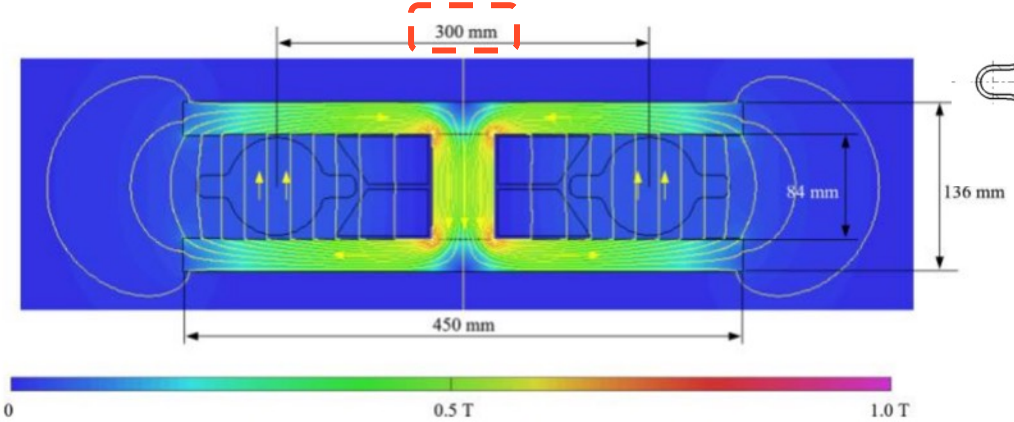
Vacuum chamber cross section

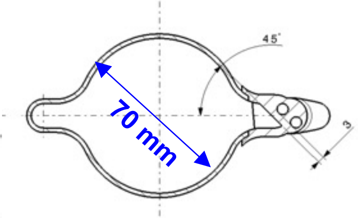
For this reasons we have proposed, in the CDR, to adopt a modification of the SuperKEKB vacuum chamber cross section (*), i.e. a circular chamber with two small symmetric "winglets" in the plane of the orbit

The diameter of the circular part is 70 mm (ID), vs 90 for SuperKEKB; vertical gap in our dipoles is 84 mm, same as the inscribed circle in the quadrupoles

The winglets we can accommodate taking into account the 300 mm horizontal beam-beam separation and the structure of the common-yoke dipoles and quadrupoles (**) are smaller than those of SuperKEKB. In our case the horizontal width is only 120 mm





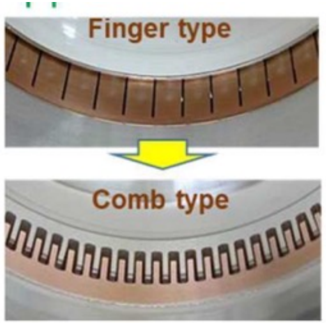


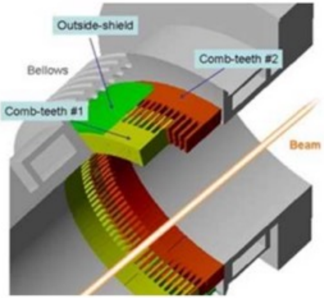
(*) Y. Suetsugu, KEK
(**) J. Bauche, CERN

Important issue with beam separation (300 mm) has been identified: difficulty to place SR absorbers, their cooling lines for internal beam (busbar); <u>make it bigger</u>?

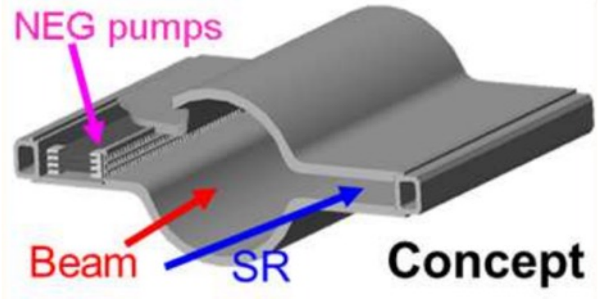
Vacuum chamber cross section

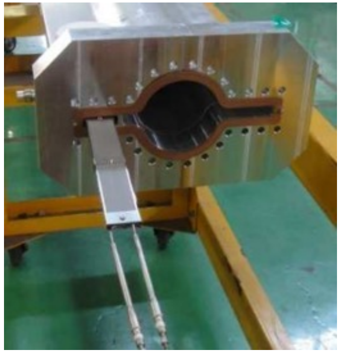
If we adopt the SuperKEKB vacuum chamber cross-section then it comes natural to try and adapt also the SuperKEKB concept for the MO-type flanges, bellows, and gate valves (*). This will probably help reduce the geometric impedance budget:





Unfortunately we can not adopt the distributed NEG strip pumping solution, since our winglets are not wide enough, only ~ 22.5 ~~25~~ mm

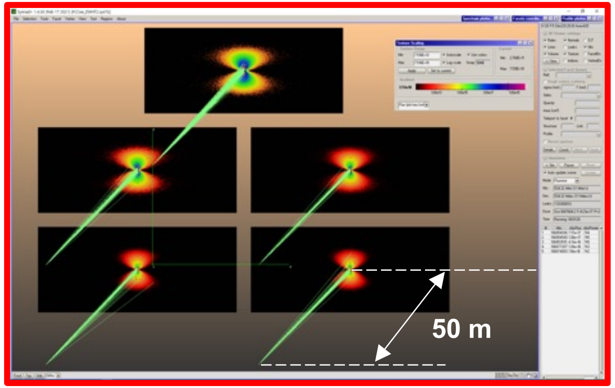


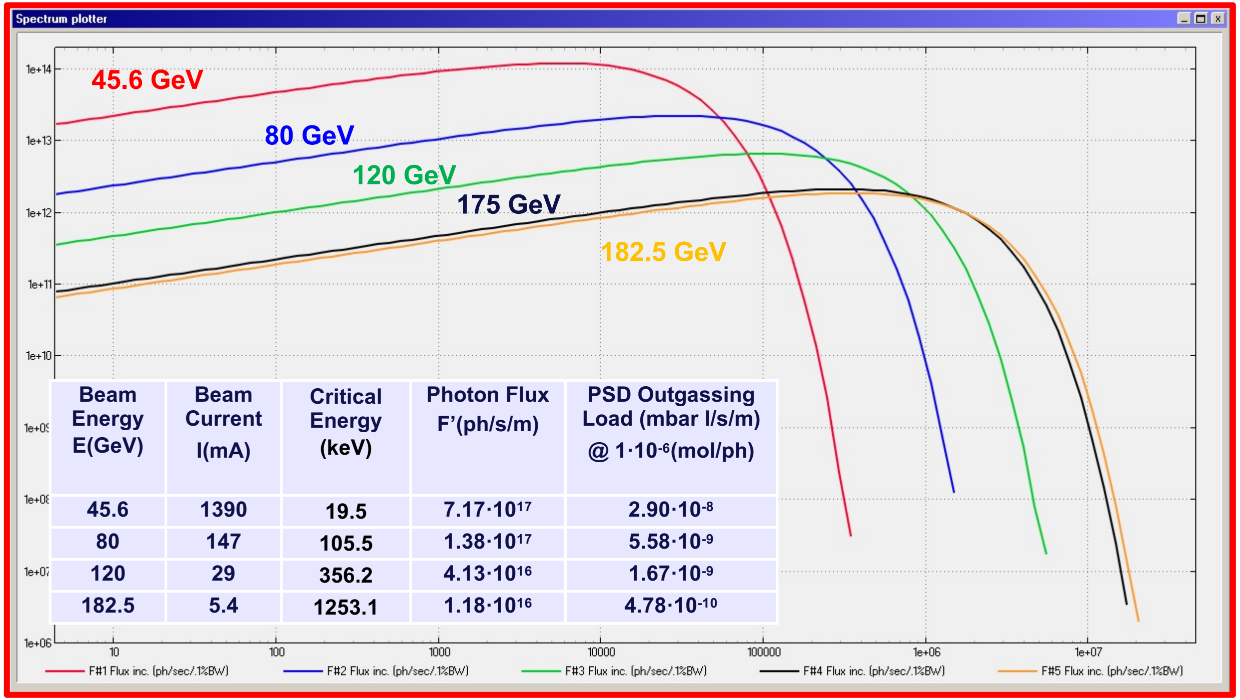


(*) Y. Suetsugu, KEK

Synchrotron radiation spectrum, flux, power

SR Spectra computed with SYNRAD+ (note: old 98 km lattice!)





Beam Energy E(GeV)	Beam Current I(mA)	Critical Energy (keV)	Photon Flux F'(ph/s/m)	PSD Outgassing Load (mbar l/s/m) @ $1\cdot10^{-6}$(mol/ph)
45.6	1390	19.5	$7.17\cdot10^{17}$	$2.90\cdot10^{-8}$
80	147	105.5	$1.38\cdot10^{17}$	$5.58\cdot10^{-9}$
120	29	356.2	$4.13\cdot10^{16}$	$1.67\cdot10^{-9}$
182.5	5.4	1253.1	$1.18\cdot10^{16}$	$4.78\cdot10^{-10}$

- **Radiation projected onto five 14x6 cm^2 screens;**
- **1 cm-long dipole arc trajectories;**
- **Flux distribution shown here,**
- **Logarithmic scale for textures, 6 orders of magnitude displayed;**

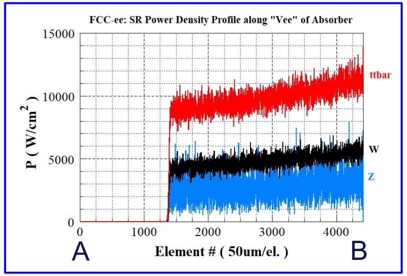
Units: Vertical: photons/s/(0.1% bandwidth)/m; Range [10^6 - $2\cdot10^{14}$]
Horizontal eV; Range [4 - $5\cdot10^6$]

SR absorbers: yes or no?

(note: the geometry of the absorber has been modified, see below)

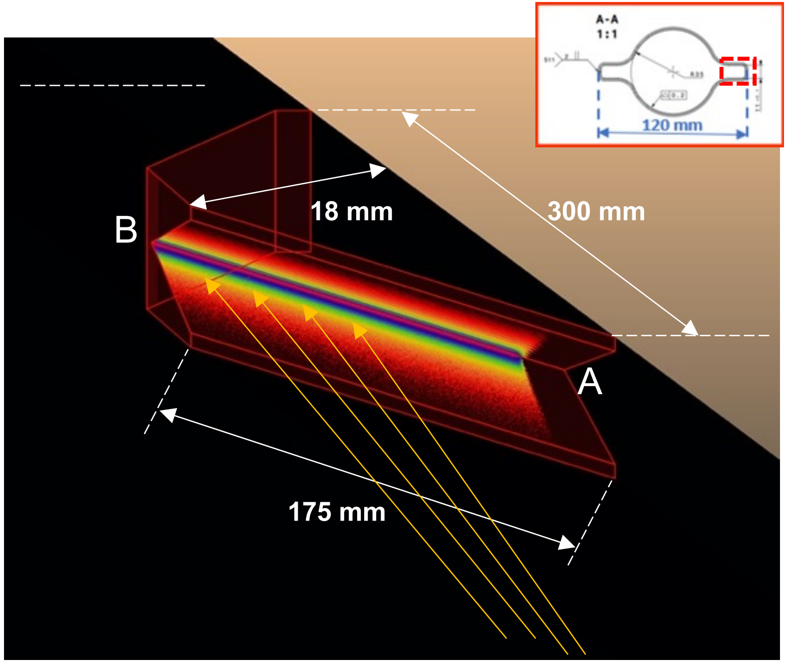
- **The high beam energy generates an extremely narrow fan of SR, swiping a strip along the external wall of the vacuum chambers**
- **If the SR is let impinge onto the vertical wall at the end of the winglet on the external side (60 mm from the beam axis), then the average photon travels ~38 m before hitting the wall**
- **If SR absorbers like in the figure are used, 1 every ~5.6 m, then the average distance is ~34.6 m**

Beam Energy E(GeV)	Natural SR Vertical Angle, 1/γ (μrad)	Vertical Fan Height at 35 m, (mm)	Beam Current I(mA)	Linear Photon Power Density (*) P'(W/m)	Peak Surface Photon Power Density (*) P"(W/mm²)	Peak Surface Photon Power Density (**) P"(W/mm²)
45.6	11.2	0.40	1390	~ 620	~ 1.4	~ 32
80	6.4	0.22	147	"	~ 2.2	~ 56
120	4.3	0.15	29	"	~ 3.0	~ 85
182.5	2.8	0.10	5.4	"	~ 4.0	~115



*On external wall

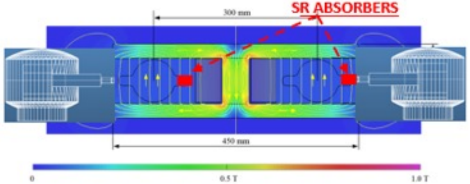
**On absorber

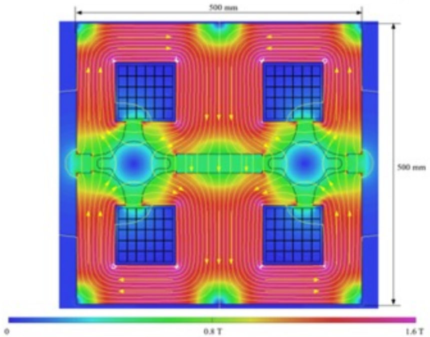


Pumping solutions

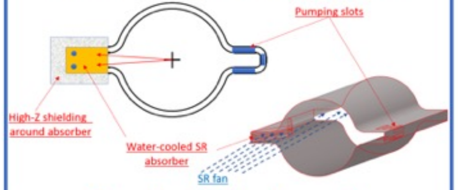
- **The 115 ~~120~~ mm horizontal width of the chamber with winglets does not let us install a practical linear NEG strip like SuperKEKB has done**
- **This leaves us with only two choices: use many lumped pumps, or use NEG-coating**
- **The specific conductance of the 70 mm ID chamber with winglets is ~47 l·m/s (ref. LEP ~ 100 l · m/s): This means that the system is rather conductance limited, and we would need to install un unreasonable number of lumped pumps in order to obtain a sufficient effective pumping speed**
- **We plan to use NEG-coating (as thin as 150 nm, to minimize the resistive-wall impedance contribution) in order to profit from its low photon-stimulated molecular desorption (PSD) and also a rather low photoelectron yield (PEY) and secondary electron yield (SEY) as well**
- **Low PEY and SEY are mandatory for the e+ ring, in order to avoid/minimize the electron cloud effect (ECE)**
- **Even a small residual sticking coefficient *s* for the NEG-coating gives a large distributed pumping speed, 11.8·*s* (l/s/cm^2, CO gas), with the coated wall surface of ~ 3120 (cm^2/m) or 36700·*s* (l/s/m)**

Pumping solutions



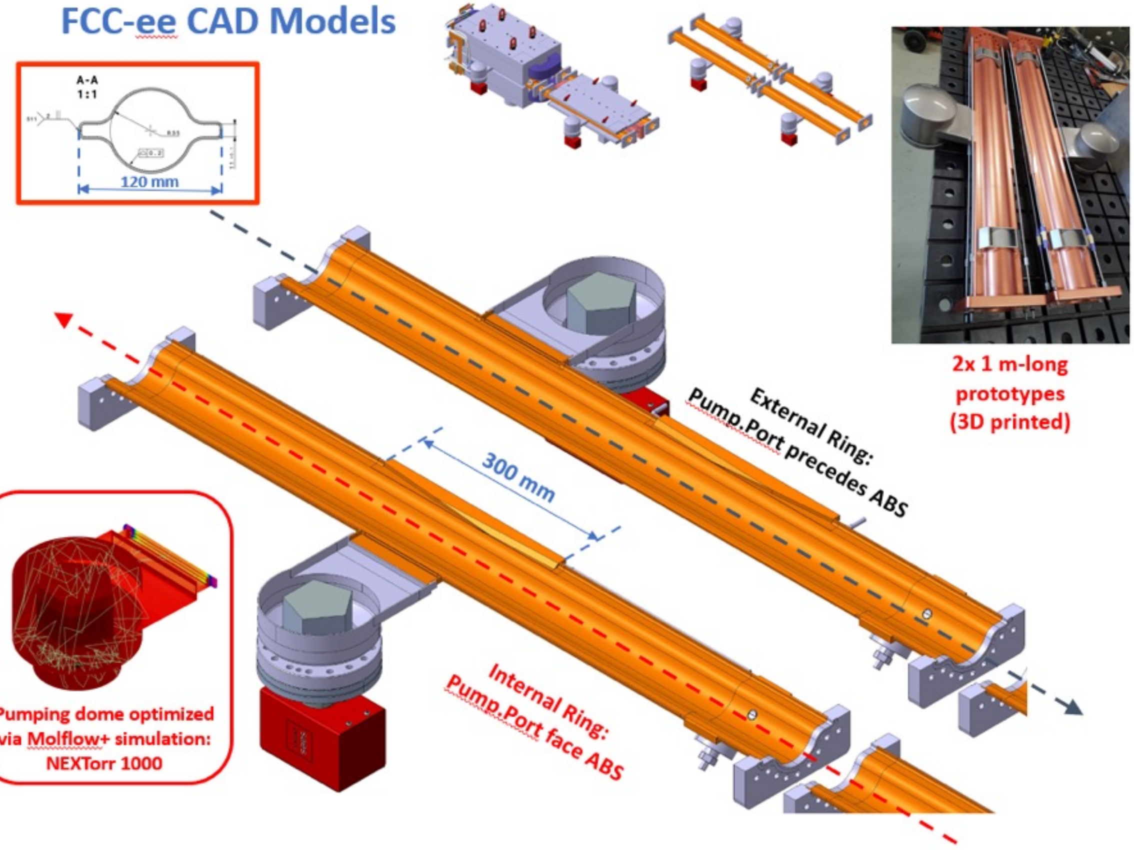


Material: OFC copper;
Specific Cond.: ~47 l·m/s (CO, 20 ºC)



Schematics of SR absorbers and pumping slots (internal beam)

FCC-ee CAD Models

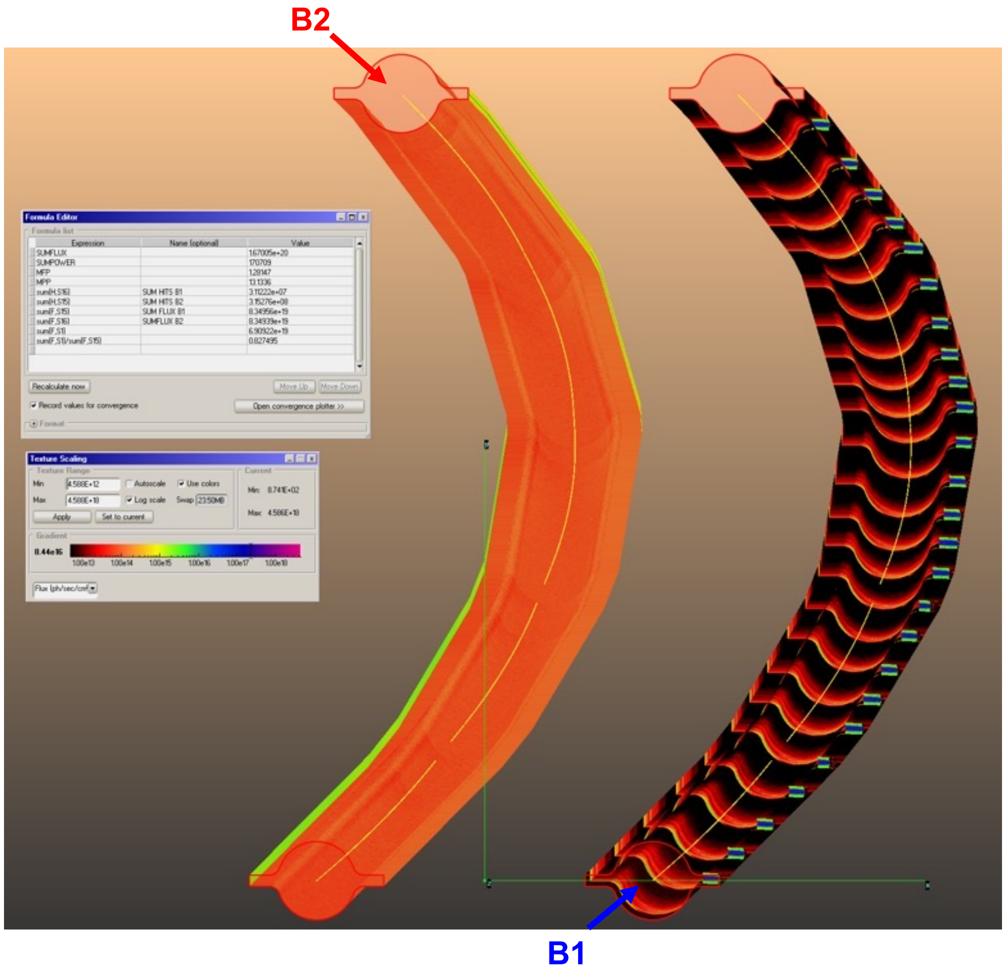


Pumping dome optimized via Molflow+ simulation: NEXTorr 1000

2x 1 m-long prototypes (3D printed)

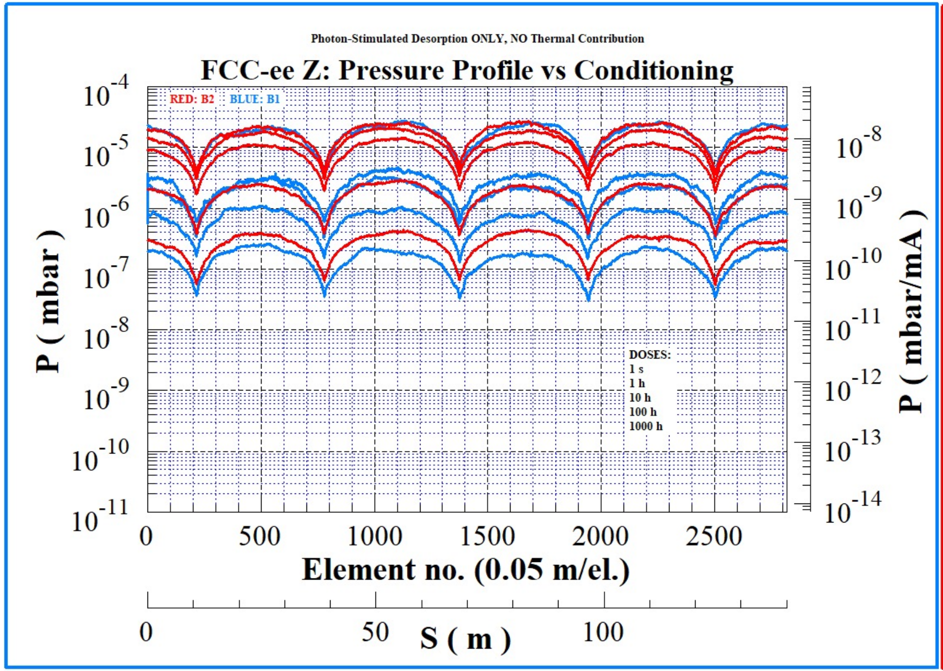
Pressure profiles

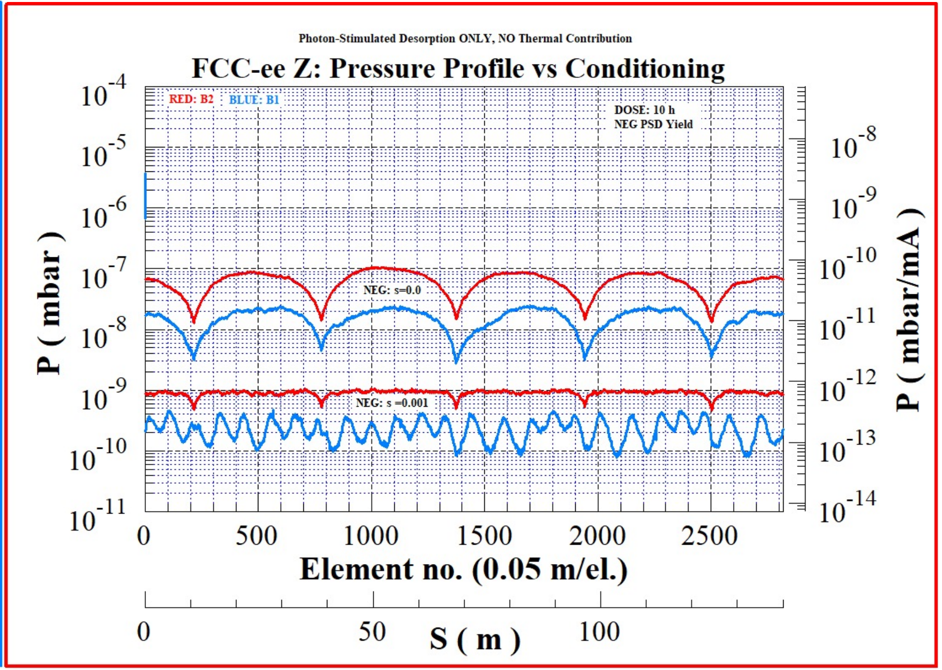
- **We have used Molflow+ to calculate the PSD pressure rise at different beam doses, using the photon irradiation maps calculated by SYNRAD+**
- **A sample 140.7 m-long section of an arc has been considered, with the two beams side by side**
- **The orbits along 5 dipoles interleaved with 5 quadrupoles are simulated, importing the lattice files from MADX into SYNRAD+**
- **The 3D model for B1 has 25 absorbers placed at ~ 5.6 m average spacing (avoiding quadrupoles and sextupoles which have tight coils), while B2 has no absorbers, and the SR fan is let impinge onto the bottom of the external winglet** **(see also B. Humann, this conf.)**



Pressure profiles

- **We have calculated the PSD pressure profiles for 5 different beam doses, corresponding to times of 1 s, 1 h, 10 h, 100 h, 1000 h. Simulated gas: CO**
- **On the left the case with 5x 100 (l/s) lumped pumps/beam, and no NEG-coating**
- **On the right, the case with NEG-coating, saturated (i.e s=0) and with some residual sticking (*s*=0.001)**





One comment on vacuum conditioning (slide added last minute)

From yesterday talk of M. Sullivan: *IR Design Issues for High Luminosity and Low Backgrounds*, slides 7-8

High Current Issues

- SR critical energy values for the main bend magnets of various machines
- The PEP-II B-factory HER had a bend magnet critical energy of 9.8 keV
- SuperKEKB bend magnet critical energy for the HER is 2.6 keV
- FCCee and CEPC bend magnet critical energy for the Z running is about 20 keV
- The EIC bend magnet critical energy for the 10 GeV beam is about 6.2 keV and 36 keV at 18 GeV
- The new machines (FCCee, CEPC and EIC) will need to go through significant beam pipe "scrubbing" time before being able to achieve their design high current values
  - The superKEKB has been scrubbing the beam pipe (especially in the new LER beampipe) for more than 2 years. They now are reaching beam currents above 1 A.

More on High Currents

- The higher SR critical energies for the FCCee and CEPC at the Z pole running could mean that the beampipe scrubbing time may be longer
- The higher energy photons can penetrate more deeply into the beam pipe wall thereby dislodging more gas molecules located farther inside the material
- As more current is stored in the ring more gas molecules are dug out of the wall and the dynamic gas pressure increases which shortens the beam lifetime
- The beam develops non-gaussian tail distributions in X and in Y from scattering off of gas molecules and collimator settings or actual beam pipe apertures or the dynamic aperture of the ring will cause beam particles in these tails to be lost
- If the perturbations generated by the gas pressure is often enough then the size of the core of the beam can increase lowering the expected luminosity

- New FCC-ee **92 km lattice** has slightly **higher critical energy**, and **higher linear power and flux densities**
- A fraction of 91% of the SR flux is generated at energies below the critical energy, so the effect of a higher critical energy should not be that important; the difference in fraction between 20 keV and 5 keV is **~32%**
- New SR absorber design has **large angle of incidence** for the X-ray fan; **we want** photons to go as deep as possible into the bulk of the absorber, so as to reduce the number of **photoelectrons** capable to go into the beam chamber and, more importantly, cause **photon-stimulated desorption** (**PSD**); <u>good for W, H, ttbar too (Compton scattering)</u>

Prototyping, experiments, as per FCC Week 2021 PRESENT STATUS/PLANS

1. Design prototype vacuum chambers with and without SR absorber (~ 2 m-long) and test them at light source (KARA/KIT?) UNDERWAY

2. Test behavior of thin NEG-coating at light source SCHEDULED EXPERIMENTS TO TEST REFLECTIVITY AT "BEAR" BEAMLINE, ELETTRA LIGHT SOURCE, TRIESTE, Sept-Oct 2022

3. Define deposition technique for dipolar ~ 12 m-long vacuum chambers (horizontal sputtering with mole?, other techniques?) DESIGN OF 12 m-LONG COATING BENCHES UNDERWAY

4. In-situ measurement of photoelectron yield at light source CONCURRENTLY WITH No.2

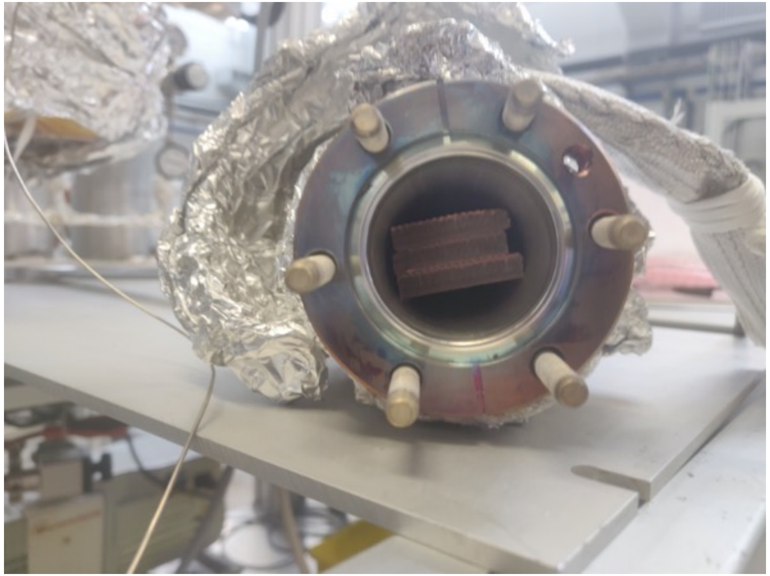
5. Test other thin-films with potential application to FCC-ee: amorphous carbon (a-C), hydrophobic silicon films (to reduce pump down time without bakeout); test surface texturing techniques (e.g. LASE) WILL PRODUCE SEVERAL 2m-LONG PROTOTYPES FOR KARA's "BESTEX" TEST STAND OR OTHER FACILITY

6. Determine material and fabrication technology of SR absorbers and bonding technique to the vacuum chamber (surface power density above 100 W/mm^2 at the ttbar energy) UNDER DESIGN & THERMAL ANALYSIS, SEE NEXT SLIDES

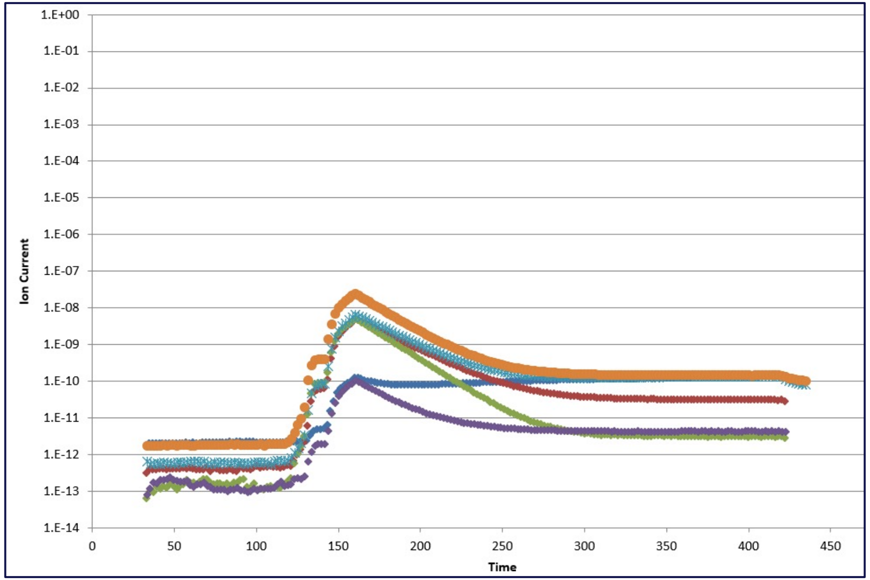
7. Design, fabricate, and test bellows with RF fingers, under elongation and misalignment conditions similar to those expected for FCC-ee, BPM blocks SEVERAL DESIGN OPTIONS UNDER ANALYSIS, SEE NEXT SLIDES

8. Continue collaboration with FLUKA team (see B. Humann/F. Cerutti), magnet group, tunnel integration working group, and machine optics group (plus MDI) TO BE RESUMED, IMPLEMENTING NEW 92 km LATTICES

Cold-Sprayed additive manufacturing: validation of vacuum compatibility



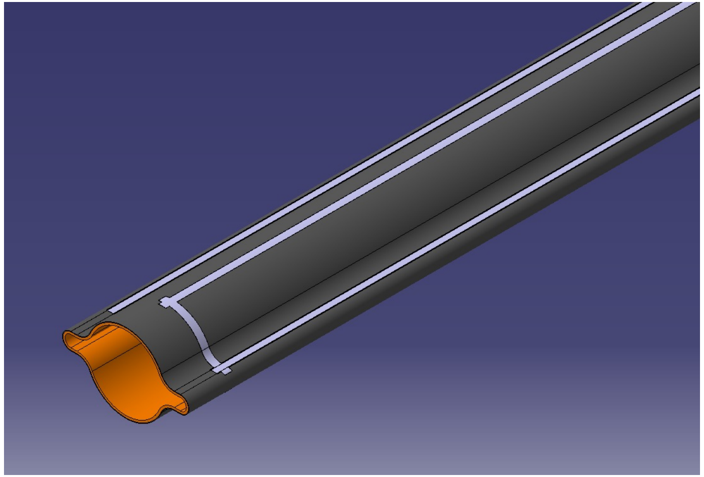
Cold-Spray Samples for outgassing measurements



Outgassing campaign ongoing, promising results

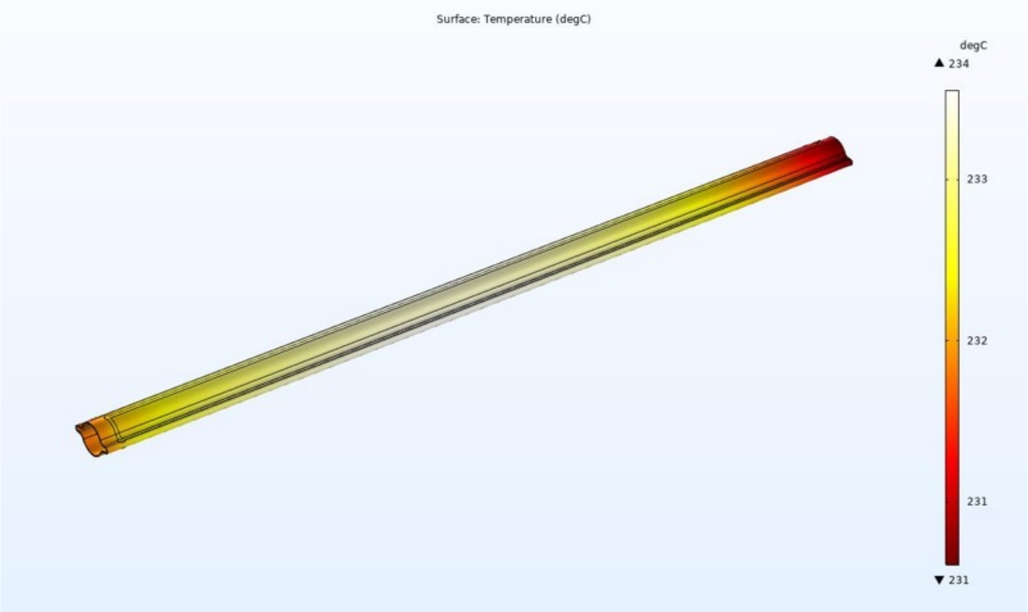
Courtesy S. Rorison, CERN

Development of cold-sprayed titanium tracks for ~250 °C bake-out



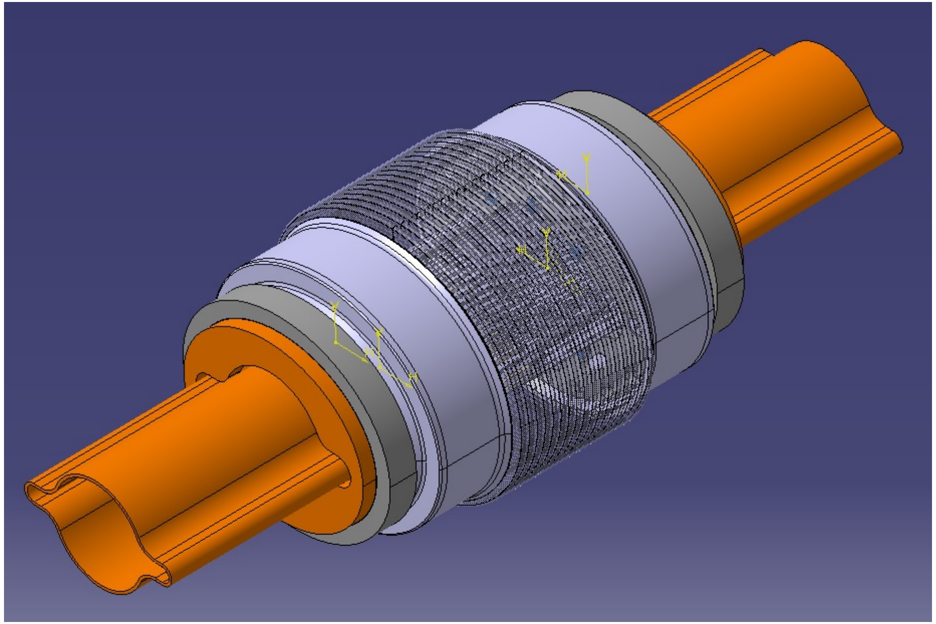
Development of cold-spray titanium tracks for FCC-ee vacuum chamber

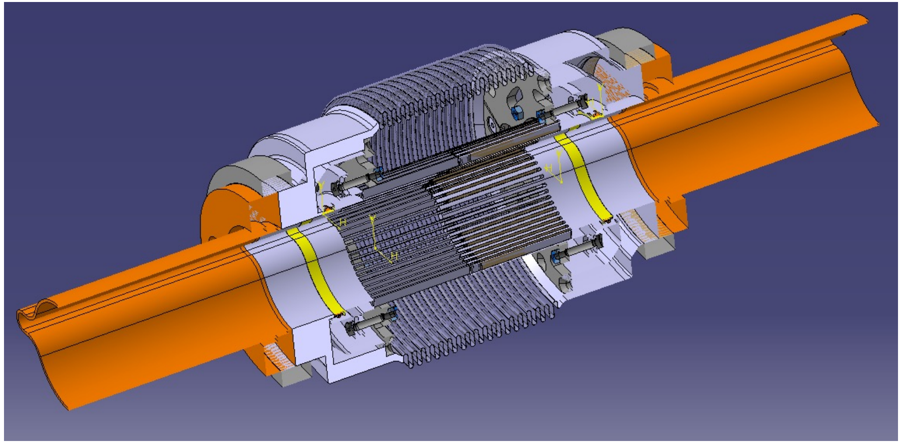
Courtesy S. Rorison, CERN



Thermal testing of design suitable for prototyping; Rather uniform temperature profile

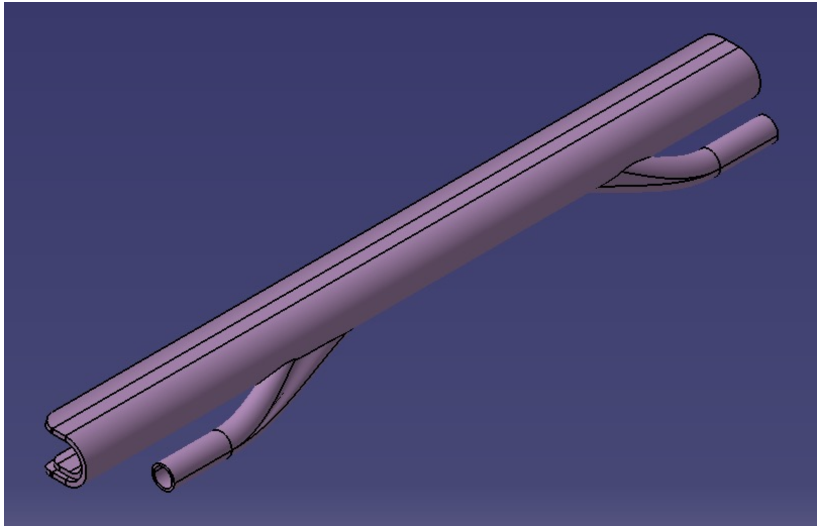
Development of RF contact fingers and bellows

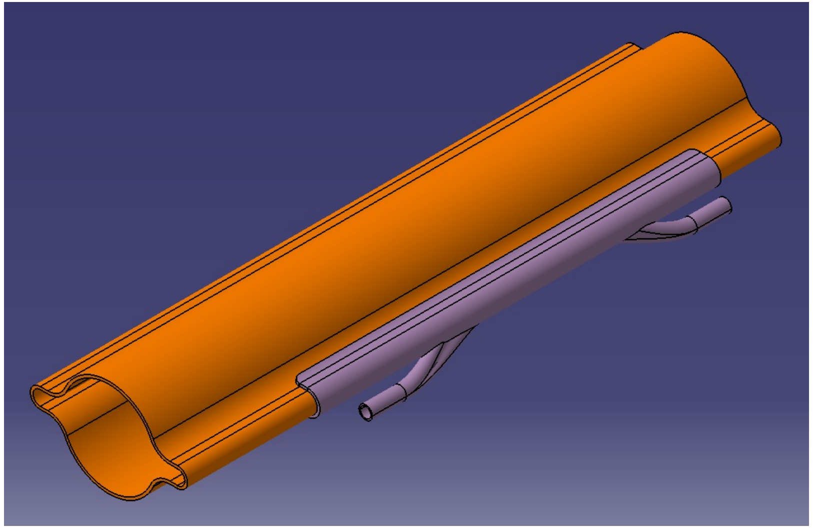




Courtesy S. Rorison, CERN

Design of inclined SR absorber: additive manufacturing (3D laser printing)





Courtesy S. Rorison, CERN

Design of BPM blocks: additive manufacturing (cold spray technol.)

Technology

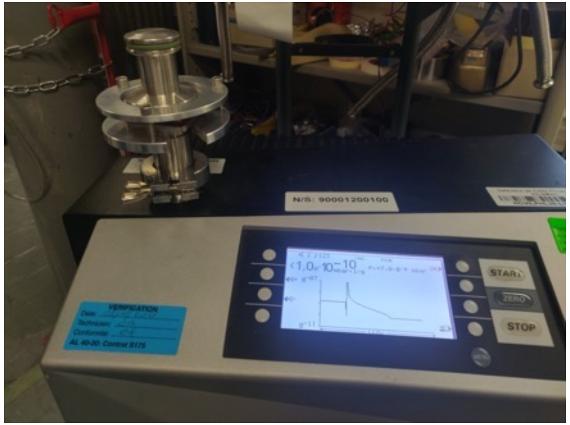
SMA couplers

Cold spray:

- Composite metallization with aluminium coating
- Copper additive manufacturing
- Track

Leak detection tooling

Remote handling systems



Helium Leak Test tool

Suitability of cold spray additive

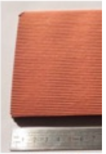
Leak tightness of cold sprayed additive materials:

A previous study on aluminium coating has shown [1]:

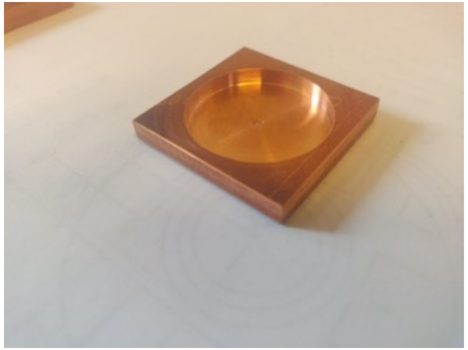
1. Helium leak tight coatings are achievable.
2. The presence and the role of microporosities formed during th process.
3. The influence of powder morphology on the porosity formation

Tests done on copper samples have successfully demonstrated the tightness of the materials.

Thermal outgassing measurements are ongoing.



Samples for lea

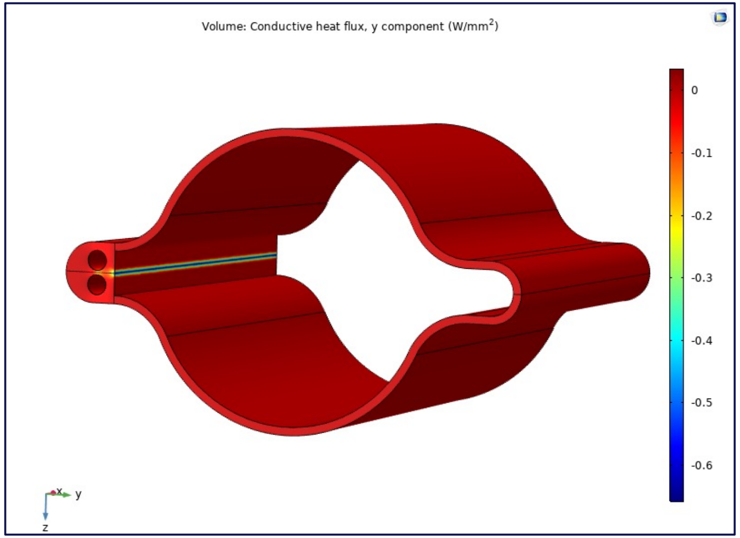


Shape-Memory Alloy (SMA) collars tested for flanges (reduced machining, no holes for screws)

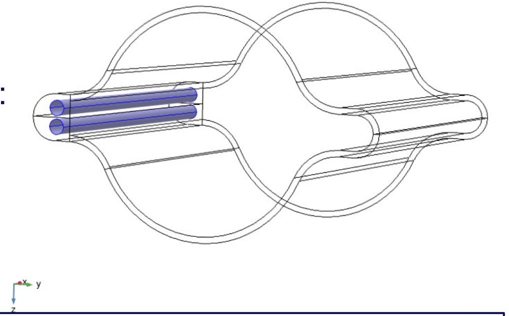
Cold-sprayed samples of pure copper and various alloys for leak testing

Courtesy S. Rorison, CERN

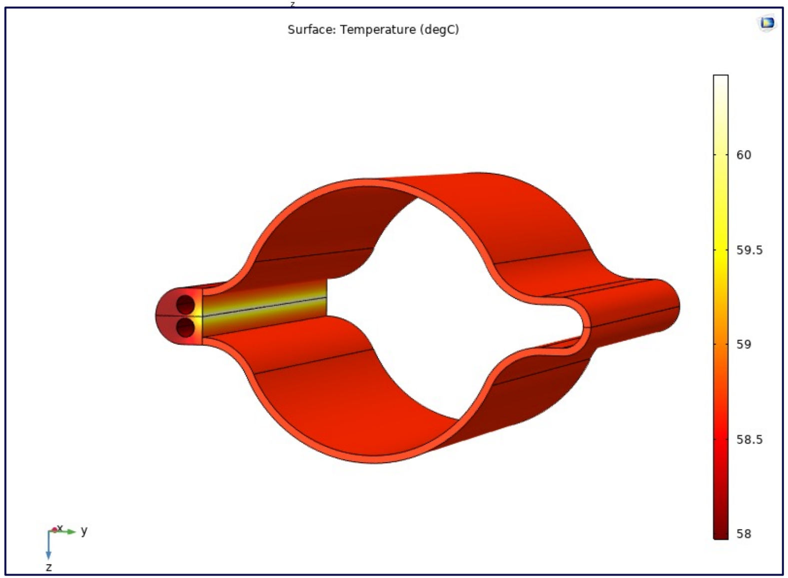
Thermomechanical analysis SR absorbers (courtesy M. Morrone, CERN)



Water channels:
2 x Ø 5 mm



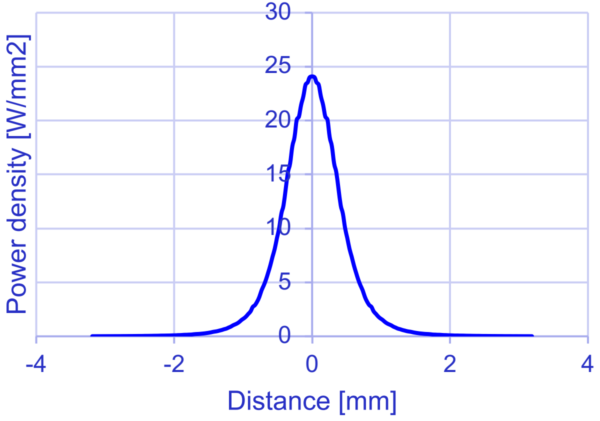
η= 523 W/m²/K
(**Laminar flow**)



Thermal power: 600 W/m
Gaussian distribution vertically

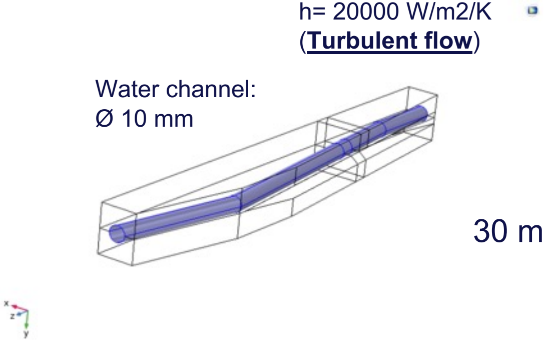
Thermomechanical analysis SR absorbers (courtesy M. Morrone, CERN)

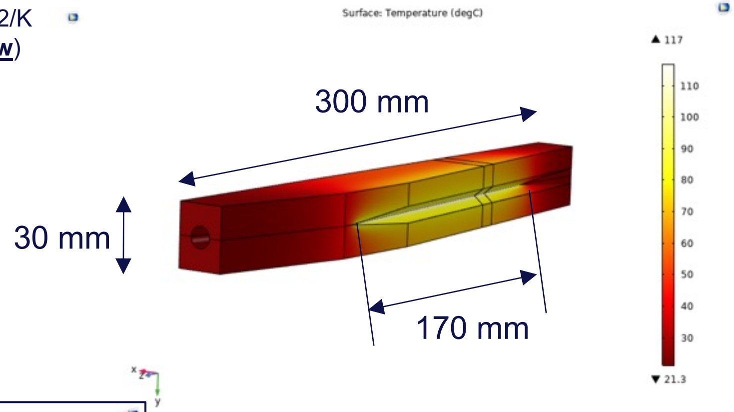
Power density on the FCC-ee absorber

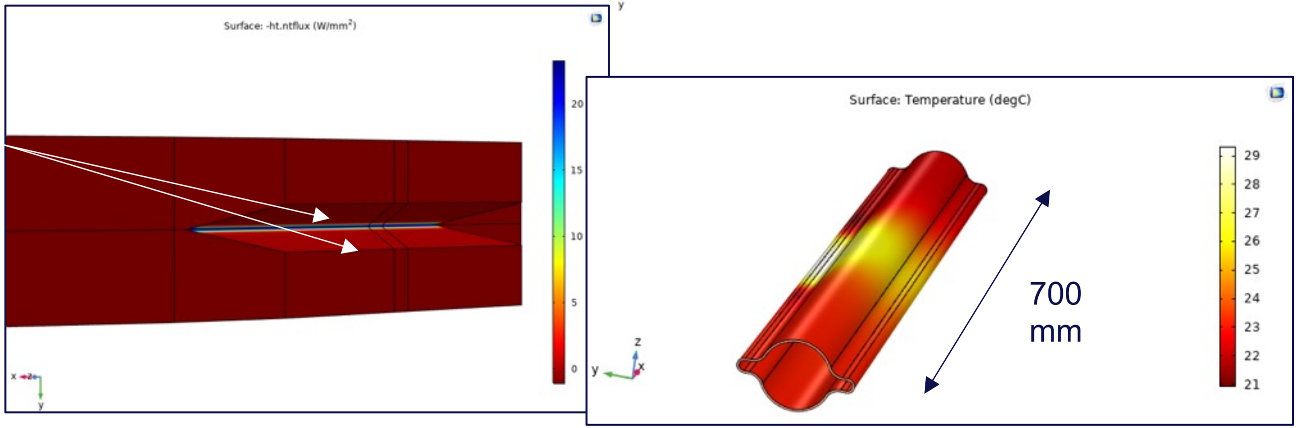


Half Gaussian applied on each slanted side of the absorber (170 mm long)

Lumped absorber_V1
(V-groove)



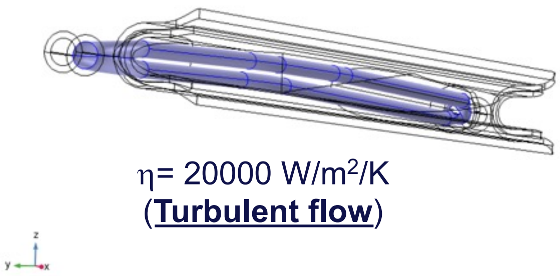




Thermomechanical analysis SR absorbers (courtesy M. Morrone, CERN)

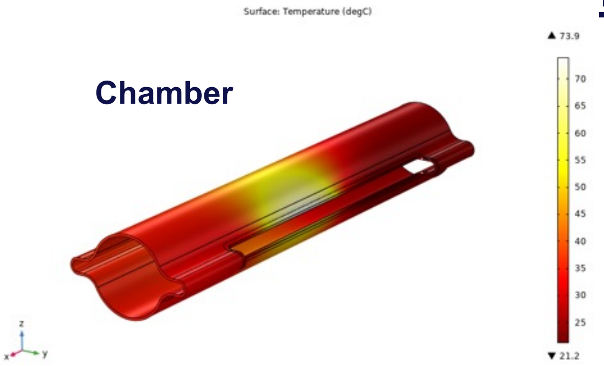
Local absorber V5_gaussian

2 x water channel:
Ø 5 mm (INLET Ø 8 mm)

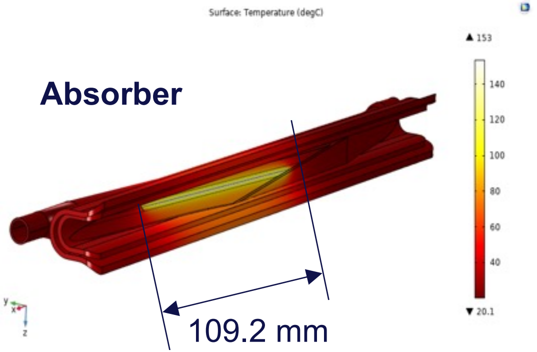


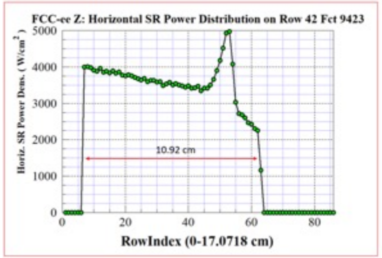
η= 20000 W/m^2/K
(**Turbulent flow**)

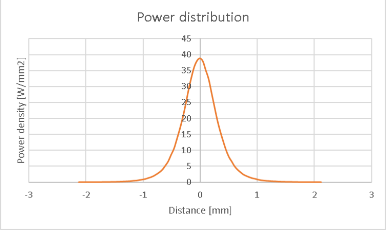
Chamber

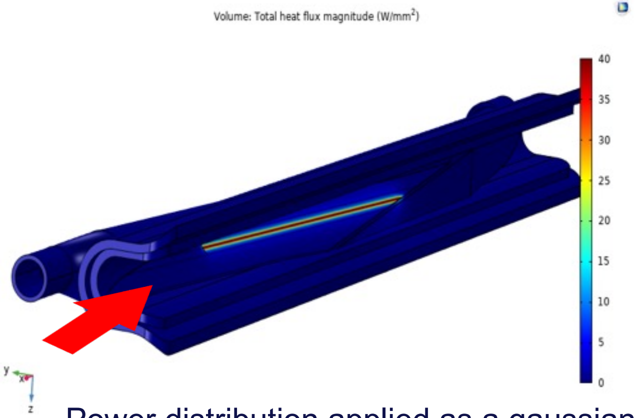


Absorber

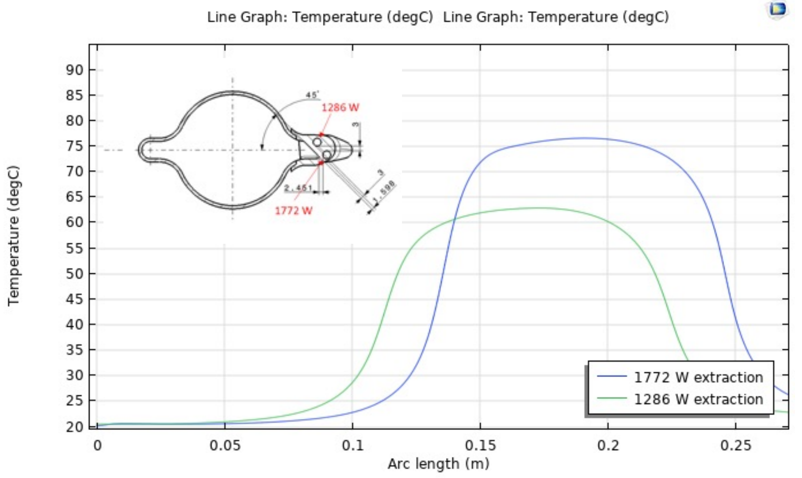








Power distribution applied as a gaussian fit.
Integrated power is ~ 3.1 kW over 110 mm



Conclusions

1. The vacuum system for the FCC-ee arc sections has been under study since many years; we look with interest the progress on **SUPEKEKB vacuum commissioning** and troubleshooting, and **CEPC design** as well
2. We have come to the conclusion that the aggressive experimental program with large integrated luminosity values within a rather short amount of time (4 yrs for the Z-pole starting from an unconditioned machine) require two things:
   i. **NEG-coating of the chamber**
   ii. **Localized ("lumped") SR absorbers**
3. We have generated several pumping configuration scenarios, changing the number of additional pumps and the partial saturation of the NEG-coating
4. A series of prototypes are under advanced design and prototyping; we have ordered a circular copper extrusion for the chamber which is weld-free and would allow forming of the chamber with winglets; **<u>we have put ease of fabrication at industrial scale and cost-saving at the forefront of our design</u>**
5. Tests on various welding techniques for connecting flanges (e.g. **stir-friction weld**.) and also of **additive manufacturing techniques** (e.g. **3D laser** and **cold-spray**) are being pursued for the flanges, BPM blocks, and SR absorbers
6. 2m-long prototype is going to be designed and will be possibly tested with **SR irradiation** at a SR light source (BESTEX test bench at KARA/KIT?); tests will be also carried out on potential **e-cloud mitigation** techniques and **impedance** issues
7. Design of **NEG-coating horizontal benches** capable to deposit the required thin-film along ~12m-long chambers is pursued (capitalizing on technology developed for HL-LHC); **Tunnel integration** under study as well (dedicated working group)
8. Still, **lots of work to do** on the vacuum system for the **full-energy booster**, the **special chambers for wigglers**, the **MDI region**; Also, more work on **modeling the new lattice**, and **passing the new geometry data to the FLUKA team**.

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Thank you for your attention!
Questions?

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