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FCC-ee Developments

Outline

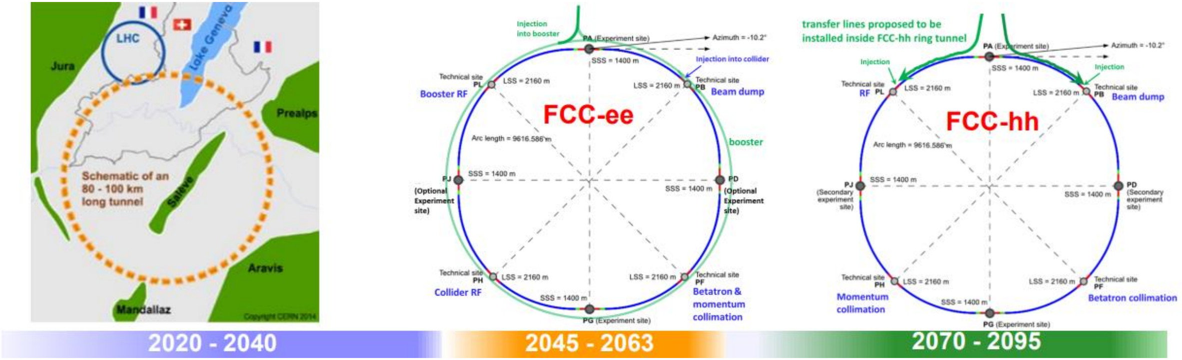
1. **FCC Week**
2. **Vacuum Chamber**
3. **Cold-Spray**
4. **Bake-out Track**
5. **Beam Position Monitor**
6. **Outgassing**
7. **Friction Stir Welding**
8. **Synchrotron Radiation Absorber**
9. **Conclusions and Future Outlook**

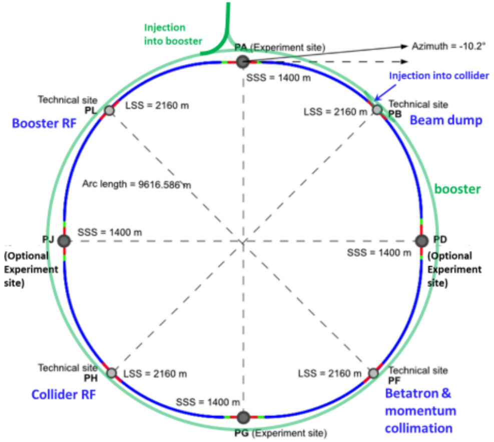
1: FCC Week

FCC Week 2023 (5-9 June 2023) · Indico (cern.ch)

FCC Week in London: Confirmed some decisions prior to upcoming mid-term review

Member states agreed that the FCC-ee then FCC-hh approach is best given the technological challenges





Ring placement has been finalised

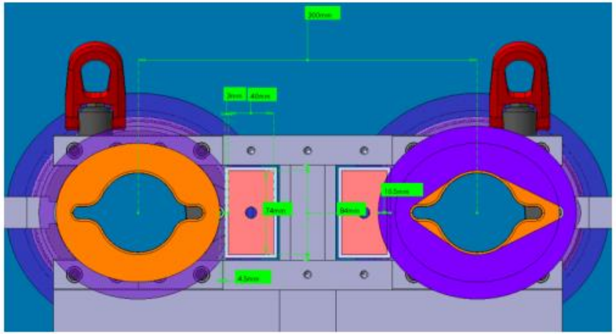
Changes from Conceptual Design Review (CDR) 2018:

- Surface points reduced from 12 to 8
- Circumference reduced from 97.8 km to 90.7 km
- New layout with 4-fold superperiodicity, FCC-ee will have 2 or 4 collision points
- Circumference matched to LHC and SPS tunnels for hadron beam injection

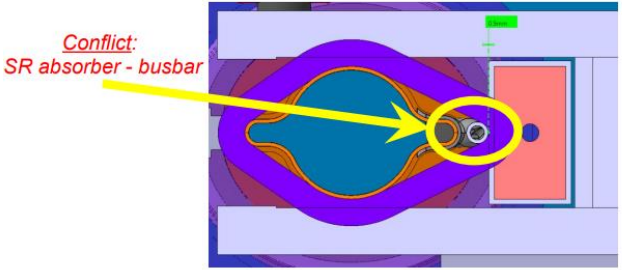
Parameter	unit	2018 CDR [1]	2023 Optimised
Total circumference	km	97.75	90.657
Total arc length	km	83.75	76.93
Arc bending radius	km	13.33	12.24
Arc lengths (and number)	km	8.869 (8), 3.2 (4)	9.617 (8)
Number of surface sites	—	12	8
Number of straights	—	8	8
Length (and number) of straights	km	1.4 (6), 2.8 (2)	1.4 (4), 2.031 (4)
superperiodicity	—	2	4

1: FCC Week

Inter-beam distance increased from 300 mm to 350 mm to accommodate Synchrotron Radiation Absorber (SRA) and electrical insulation to the busbar



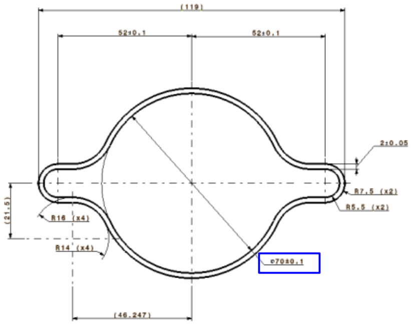
Dipole cross-section with Shape Memory Alloy (SMA) connectors



SRA integration to dipole

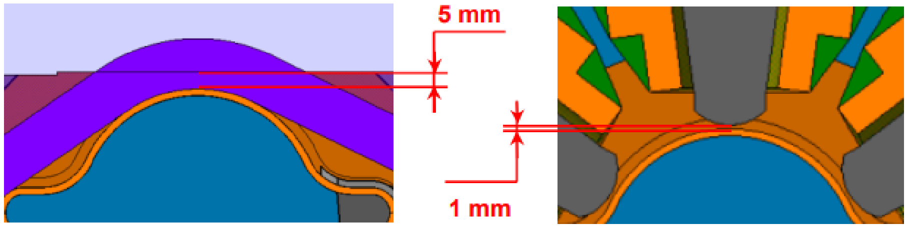
Aperture reduction: CDR proposed **70 mm** vacuum chamber internal diameter

2023 we started to explore reducing the vacuum chamber diameter internal diameter to **60 mm** predominantly to reduce power consumption in Short Straight Sections (SSS) magnets and saturation in sextupole



HOWEVER:

This reduction is dependent on further impedance studies / simulations, and therefore beam stability



Dipole chamber integration

Sextupole chamber integration

Maintain same clearances as CDR

Courtesy: Jeremie Bauche

1: FCC Week

$$Z_{\parallel}(\omega) = C\frac{Z_0\omega}{4\pi cb}\left\{[sgn(\omega) - i]\delta_2 - 2i\Delta\left(1 - \frac{\sigma_1}{\sigma_2}\right)\right\}$$

$$Z_{\perp}(\omega) = C\frac{Z_0}{2\pi b^3}\left\{[sgn(\omega) - i]\delta_2 - 2i\Delta\left(1 - \frac{\sigma_1}{\sigma_2}\right)\right\}$$

Impedance

Resistive wall is the largest impedance source for FCC-ee studied currently

NEG coating is required to mitigate electron cloud build-up in the positron machine as well as for pumping reasons

Reducing the vacuum chamber internal diameter to 60mm results in a 60% increase to impedance

Transverse dipolar wake is proportional to $1/b^3$:

$$\frac{35^3}{30^3} = 1.6 = 60\%$$

Mitigation:

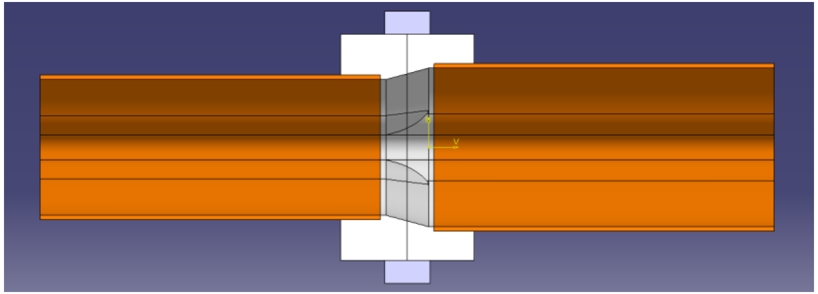
Reduce vacuum chamber internal diameter in SSS (Quadrupoles and Sextupoles) only

Therefore, only 10km of vacuum chamber with 60 mm diameter

Total impedance due to resistive wall increases by 6%

Work ongoing to propose an intermediatory taper from 70 mm to 60 mm

Taper required also from the interconnection (15° limit)



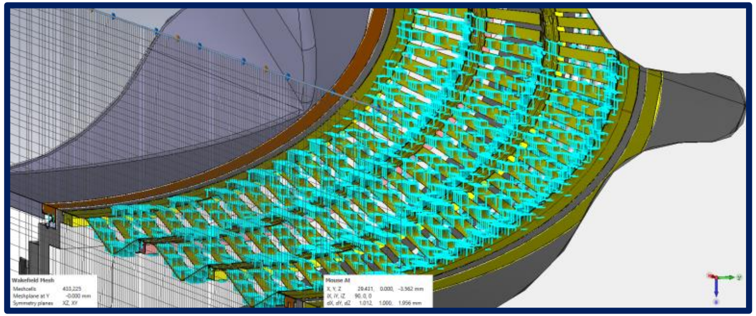
Courtesy: Mauro Migliorati

1: FCC Week

Impedance

Two interconnection types are being studied, ‘honey-comb’ (Option 1) and Deformable RF contact bridge

Approximately: 8700 interconnections: 2900 dipole arcs 24 m long with interconnections every 12 m plus a further 2900 quads / sexts arcs

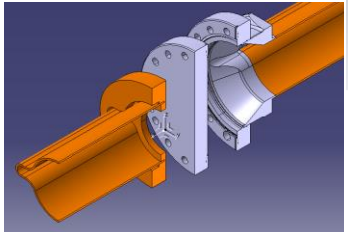


Some promising early results, simulations take considerable time and a lot of cross-checking with other teams required

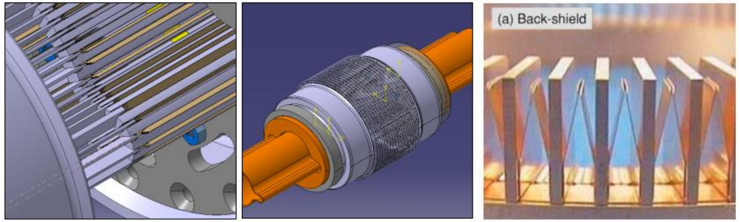
Design iterations ongoing to remove geometric impedance contributions

Smoother geometric transitions where possible (tapers)

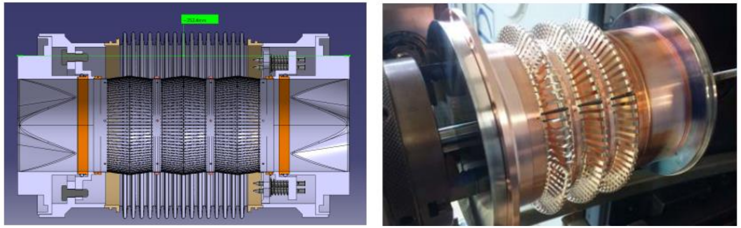
NEG coating tests to proceed (KARA)

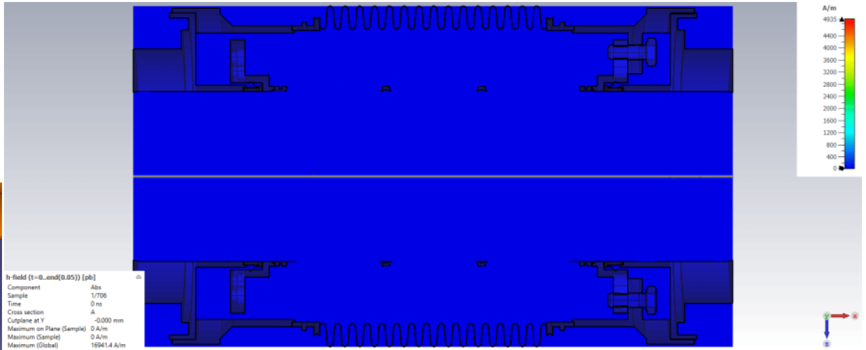


Option 1



Option 2



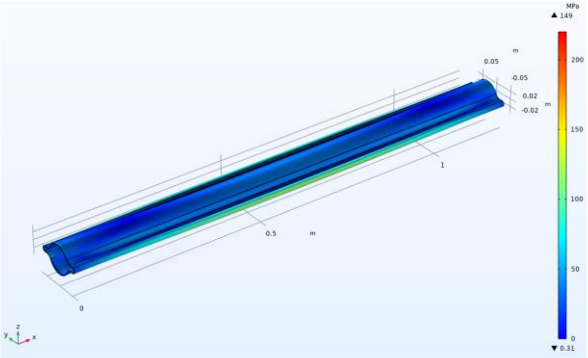


Courtesy: Patrick Krkotic

2: Vacuum Chamber Design

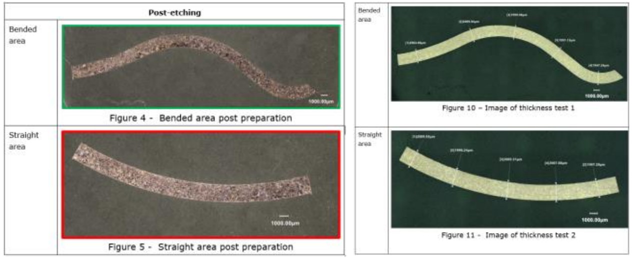
Project approach: Ease of manufacturing, cost-effectiveness and scalability (~182km of chamber required!) → Combine well-tested manufacturing methods with novel technologies → **Cold-Extrusion** to produce the chambers for prototypes. *Up-to 12m long sections.* Early studies show up to 12m is possible with this technique

Since the last presentation: November 2022



Cold-extruded prototypes have been delivered

2m and 5m variants



Mechanical integrity tested under vacuum & bake-out conditions (230 - 250°C (COMSOL).

Validation campaign:

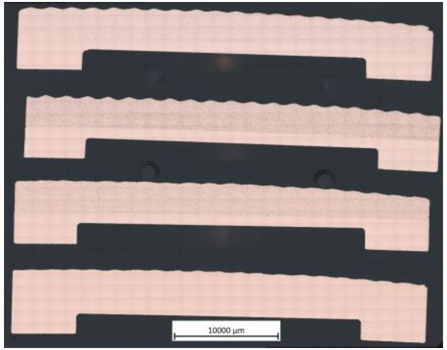
- Hardness
- Grain definition / size
- Uniformity of thickness
- Geometric deformation (3D scanning)
- Tensile testing

Overall **good** results so far, further tests to do and consideration such as post-processing

3: Cold-Spray

Additive manufacturing technique for rapid application of powdered materials to ductile surface

Metallography: Optical (LOM) and electron microscopy (SEM) inspections

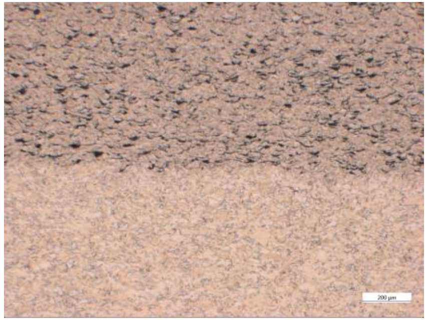


Microstructure appears fine and homogeneous for all CS samples. Alumina addition is homogeneously spread throughout the microstructure

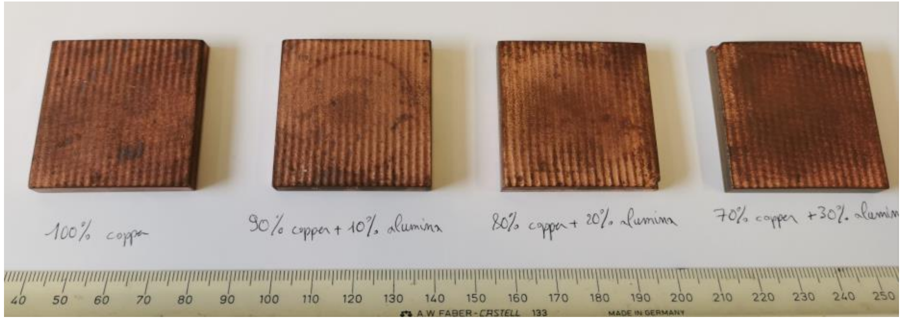
Interfaces are free from imperfections (Cavities, cracks, lack of adhesion). This is confirmed with SEM-EDS inspections

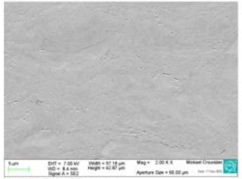
Hardness of cold-spray layer is ~140 HV1 for all samples

Results will be used as a reference state for future applications of studied systems

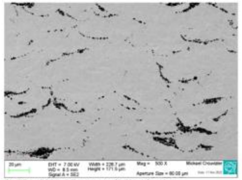


Interface, etched (70/30)

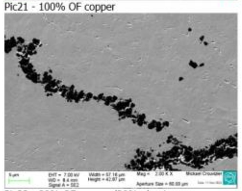




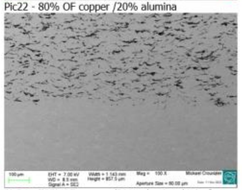
Pic21 - 100% OF copper



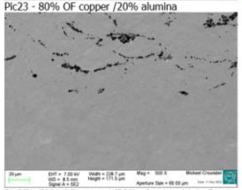
Pic22 - 80% OF copper /20% alumina



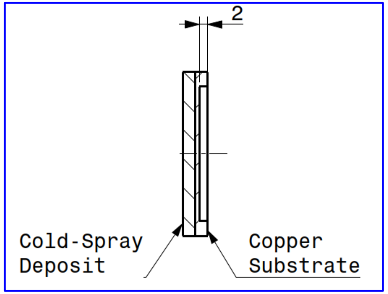
Pic23 - 80% OF copper /20% alumina



Pic24 - 70% OF copper /30% alumina / interface



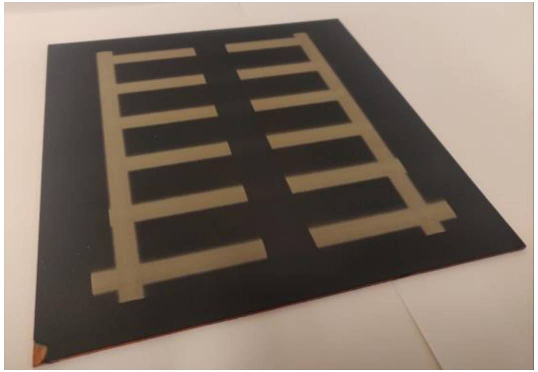
Pic25 - 70% OF copper /30% alumina / interface



Cold-spray samples

4: Bake-out Track

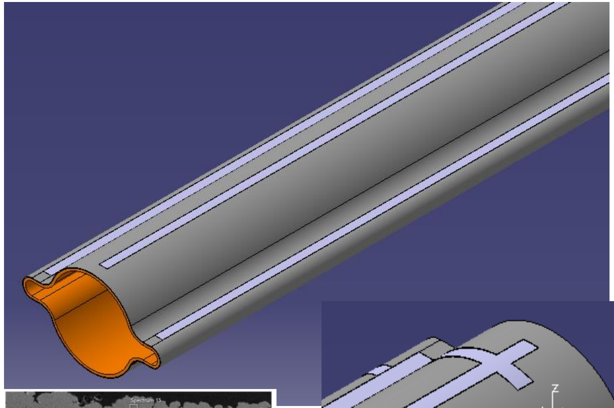
A permanent radiation resistant bake-out system is required due to intense and hard SR photon spectrum and related radiation deposition

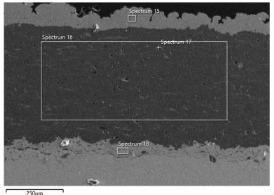


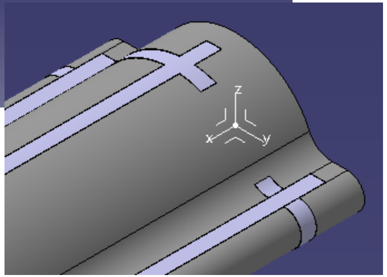
Summary of cold-spray study:

- Analysis (microscopic) of Cold-Sprayed layers
- Build on previous studies to create practical uses for FCC-ee
- Further studies on-going to determine effects to beam, magnetic properties etc

Lattice-track design with two separate heating tracks



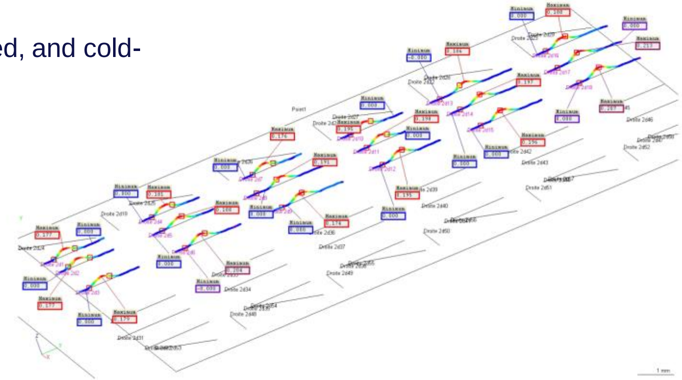




Design of lattice track

Different spray configurations tested to check for de-lamination

Profile of each track was checked, and cold-spray specification updated



Next:

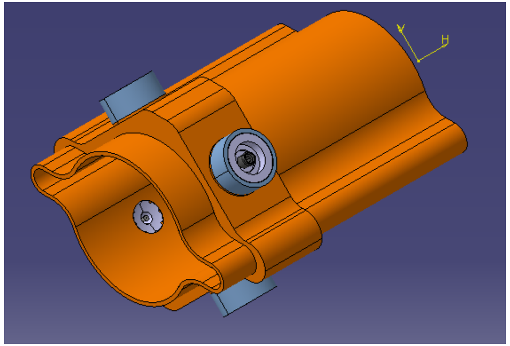
- Cost-estimation for large series production (Further refinements needed)
- Tests to determine any interference with magnetic fields
- Prototype procurement of new lattice type track on FCC-ee profile (2m)
- Bake-out tests with insulation options (Thin Aerogel, 5mm)

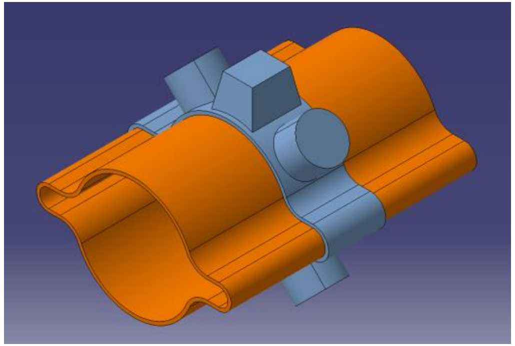
5: Beam Position Monitor

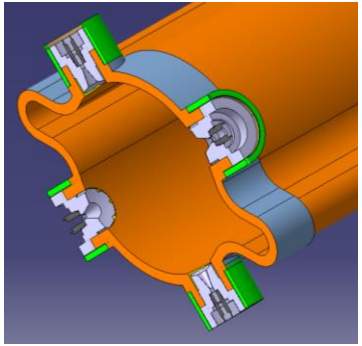
There are ~8000 BPMs in FCC-ee, with significant benefits to being directly integrated with the vacuum chamber for better spatial management. Interfaces with the vacuum chamber are achieved by cold-spray additive manufacturing

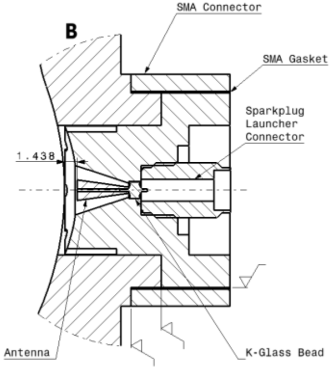
<u>Scope of prototyping:</u>

- Prove feasibility of cold-spraying a complex geometry;
- Test machining / post-processing options of cold-sprayed copper;
- Conduct UHV related tests (Leak testing);
- Mechanical characterisations of copper cold-spray;
- Test Shape Memory Alloy (SMA) connectors



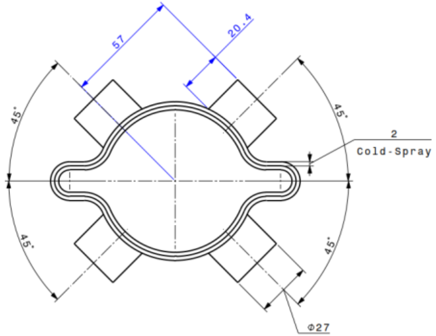






<u>Design update:</u> Includes possibility for additional boss for alignment

SMA connector dimensions remain unchanged, specific BPM components under investigation by Beams Instrumentation team

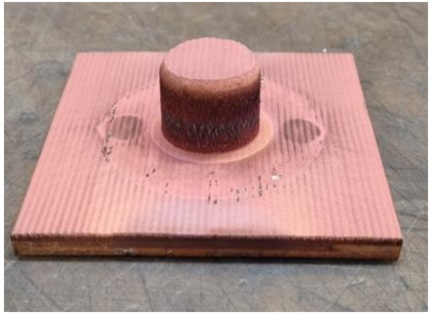


5: Beam Position Monitor

First cold-spray BPM prototypes successfully manufactured with pure copper

2mm base-layer:

4x bosses sprayed:



Test plate sprayed with same parameters, including boss dimensions. Machined to dimensions on previous slide. No issues reported with machining

Further optimisation and study of the manufacturing process is required to enable this method for the scale required for FCC:

For example, using robotic spray setup to reduce application time

Next:

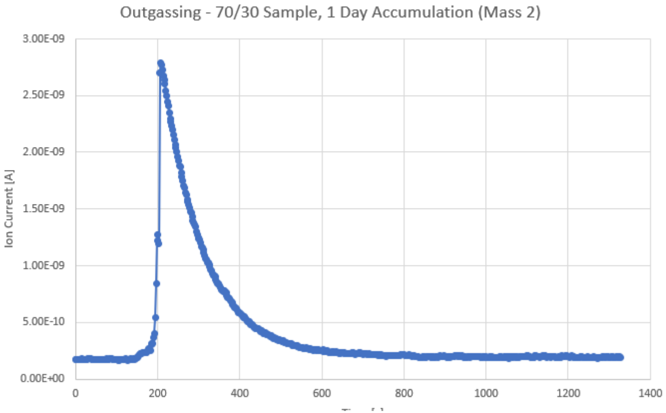
Simulate SMA connection on test plate and leak test

Machine BPM prototype bosses

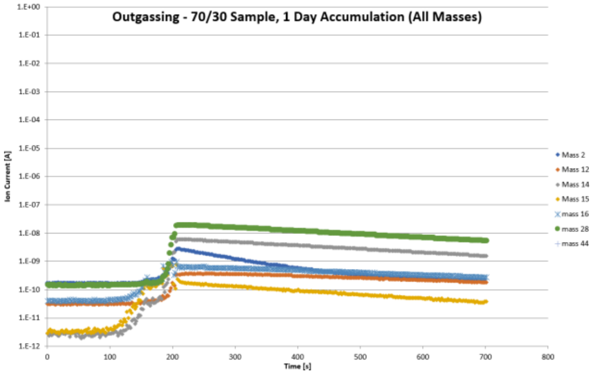
Build SMA connectors and leak test BPM prototype

6: Outgassing

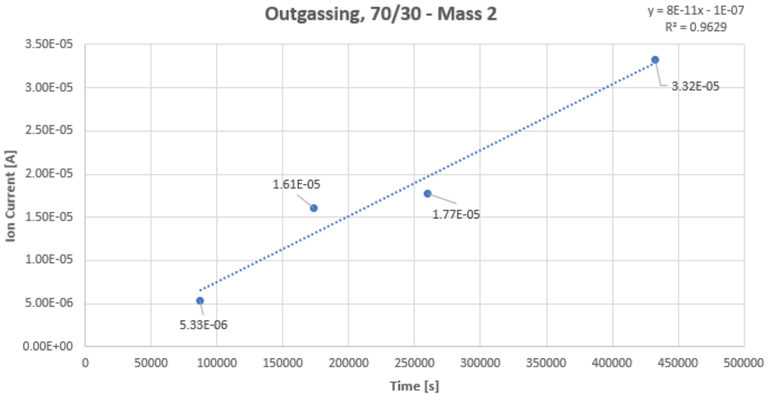
Example of results



Copper alloy (70% copper, 30% alumina) outgassing over 1 day accumulation for Mass 2 above and all masses below



Mass 2		
Accumulation time (days)	[s]	Quantity [mBar l]
1	87300	5.33E-06
2	173700	1.61E-05
3	260100	1.77E-05
5	432900	3.32E-05



Specific Outgassing Rate [mBar l/cm2 s]	7.71E-14

Results so far:

Background gases established

First results (70/30) are within acceptable limits for outgassing

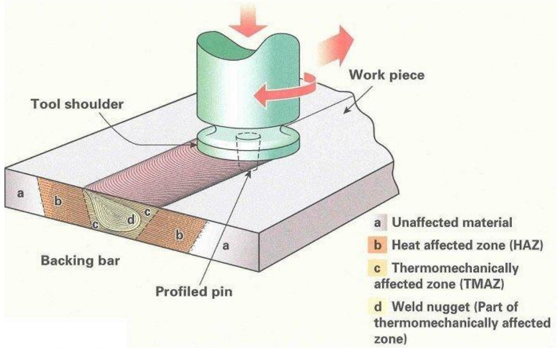
Nitrogen is being monitored as this is the gas medium for cold-spray

Linear progression of gas accumulation over time

Pure copper cold-spray samples currently being tested

7: Friction Stir Welding

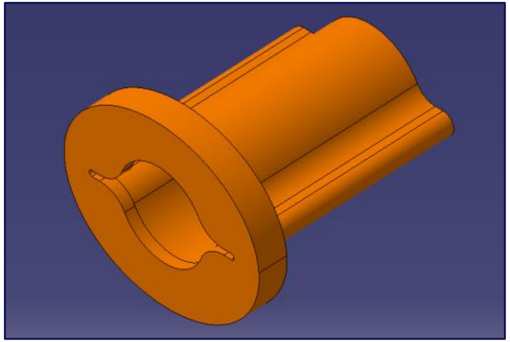
Friction Stir Welding (FSW) is an innovative solid-state technique that joins metals without melting by utilizing a rotating tool to generate controlled friction and heat. With exceptional weld quality, increased strength, minimized defects, and improved efficiency, FSW is a compelling solution for diverse research and development needs and future manufacturing options for FCC



For FCC-ee interconnections, we are testing FSW to join the flanges to the vacuum chamber in a cost-efficient and scalable method instead of standard welding techniques (MIG, TIG, e-beam etc)

Ease of manufacturing:

Automated, repeatable, no edge preparation & post-processing on same machine. Cheaper than MIG / TIG and energy efficient



Advantages:

- Solid-state; defects associated with melting/solidification during fusion welding such as pores and solidification cracks are avoided
- Lower peak temperatures: reduction in distortion and shrinkage
- No filler metals, flux, shielding gas, hence, no fumes or spatter are generated
- Can be highly automated, fast welding: 0.5mm/sec
- Energy efficient

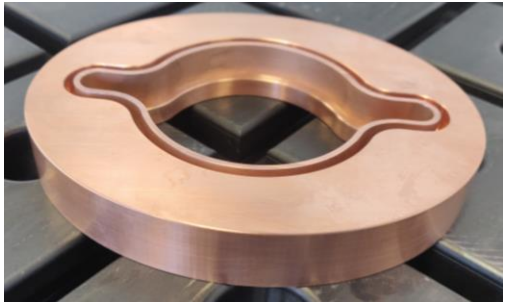
Considerations:

- Exit hole after welding tool is removed, several mitigation options.
- Heavy duty clamping required
- HAZ needs to be assessed depending on material thickness
- Leak tightness to be confirmed
- Mechanical deformities (geometric) must not interfere with plans for implementing SMA

7: Friction Stir Welding

The first challenge with FSW is to find optimal weld parameters unique to this design

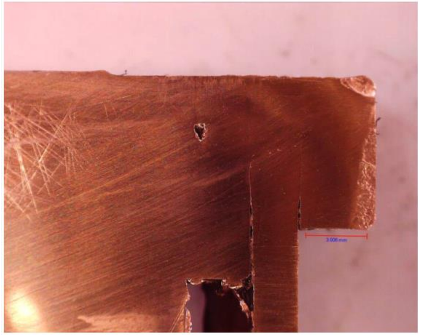
Phase 1 involved design of the clamp, destructive testing of ‘short’ components and ISO standard weld report of the results:



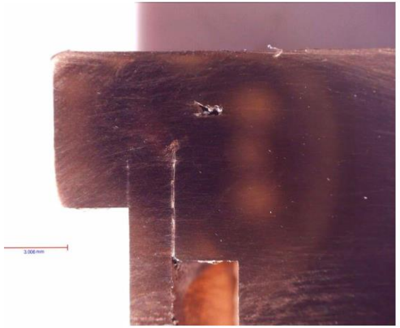
6 Flanges + short chamber (17.5mm) to determine optimal weld parameters using a destructive testing approach.

Macroscopic inspection

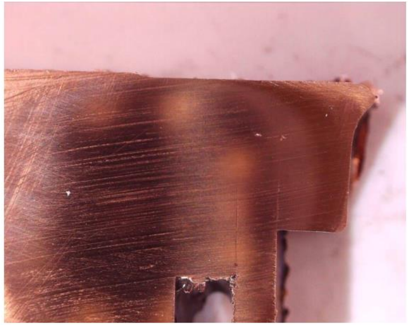
- Good shoulder print on part surface
- No visible porosity in surface
- Excessive infiltration in the end of the weld (tool collapse, too hot)
- The flange is modified to the new design for pre-welding



Cross-section 1



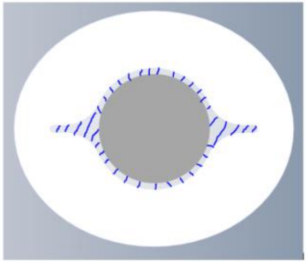
Cross-section 2



Cross-section 3

Results from Phase 1 of Friction Stir Weld (FSW) Tests:

- Good shoulder print on part surface
- Small porosities into some locations, no expected effect on vacuum sealing, as they are internal porosities.
- Porosity maximum size = 0,9 mm
- No residual bond between flange and chamber
- On cross section 3, we see copper pushed away on the internal side of the flange

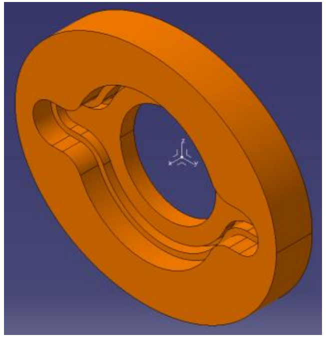


New design for Flange (pre-weld)

7: Friction Stir Welding

Phase 2 produced a series of flanges + chambers at 150mm length for practical demonstration and prototyping

This will also prove that the process is repeatable and can potentially be scaled up for large series production



Flange is redesigned as per Phase 1 results

Less machining required initially; winglets are now solid to prevent tool collapse during welding

Series of assembled units prepared for welding

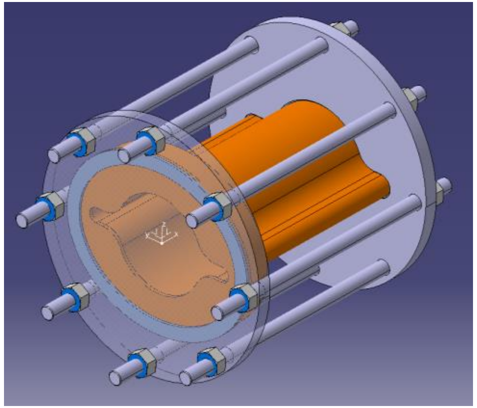
Series completed units for further R&D efforts at CERN

Next:

We will study implementing this welding process into a horizontal machining centre so that multiple processes associated with the chambers can be undertaken to minimise the steps involved: In collaboration with EN colleagues

Example: A typical machining centre can be adapted to include a FSW tool as well as a cutting tools

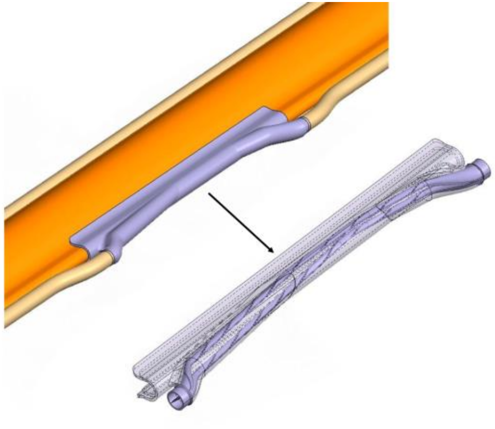
Leak testing to UHV conditions will now take place and any necessary mechanical characterisations required



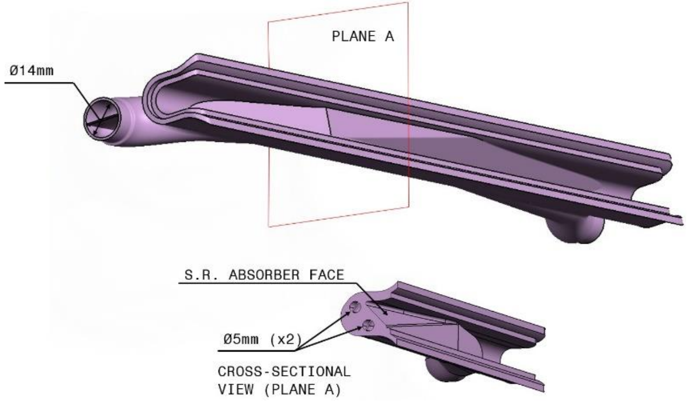
8: Synchrotron Radiation Absorber

Copious amounts of Synchrotron Radiation (SR) power and flux are generated in FCC-ee. Local absorbers approximately every 5m will be used to guarantee a rapid decrease of photon desorption yields and fast vacuum conditioning. This helps to contain the high-energy Compton-scattered secondaries once the beam energy is increased up to 182.5 GeV

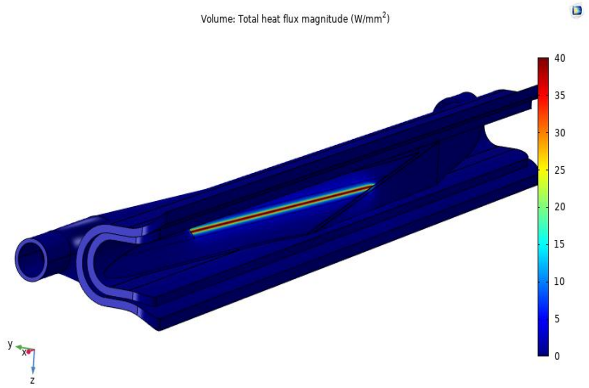
The absorbers are designed to withstand demanding temperature and thermal stresses induced by the resulting heat load. Simulations show max temperature of 150° C, with cooling wall channel reaching 65° C.



Chamber with view of the absorber

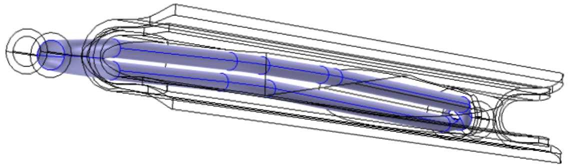


Cross-section through the absorber



SR fan is absorbed on a narrow strip on the absorber

The absorber is a ~350mm long copper insert that will be welded to the chamber on a cut aperture in the winglet

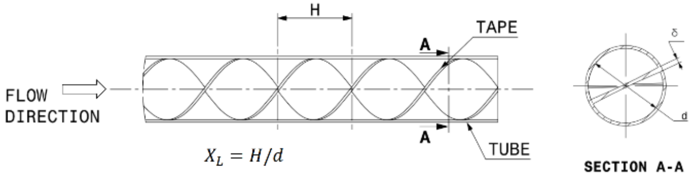


Courtesy: Marco Morrone, Fabrice Santangelo

8: Synchrotron Radiation Absorber

The complex internal geometry of the SRAs calls for the use of additive manufacturing technology, the water-cooling channels include a twisted-tape ‘insert’

The complex internal geometry of the SRAs calls for the use of additive manufacturing technology, the water-cooling channels include a twisted-tape ‘insert’, the turbulence generated by the tape improve heat transfer capabilities

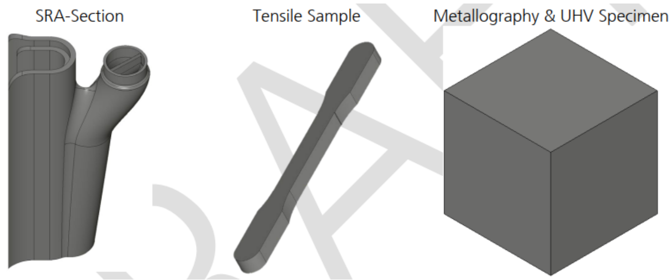


Laser Powder Bed Fusion (LPBF) has been selected as the method for the first prototype. As far as we know, this is the first copper 3D printed synchrotron radiation absorber.

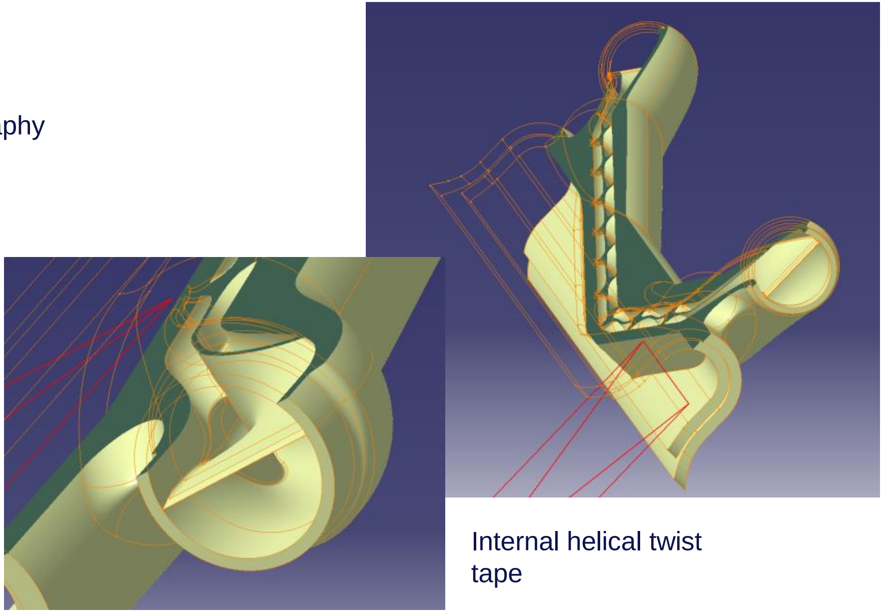
This project is in collaboration with **I-FAST** at CERN and **Fraunhofer Institute**

Phase 1: 95mm (1:1) part for proof-of-manufacturing, tensile samples and metallography samples for initial studies. Concentrated studies over the summer will take place

Phase 2: Full size SRA to contribute towards mock-up assembly, welding tests, outgassing, pressurised water cooling and validation of thermo-mechanical models



See: “Preliminary design of the FCC-ee vacuum chamber absorbers”



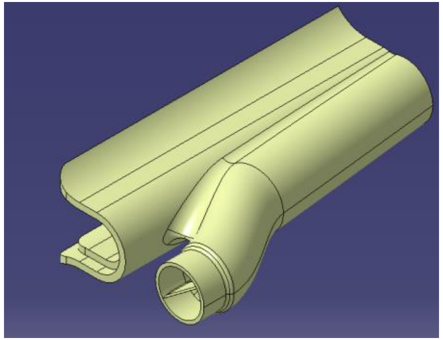
Internal helical twist tape

8: Synchrotron Radiation Absorber

First samples of the SRA and pieces for mechanical characterisation successfully printed at Fraunhofer using Trumpf 1000 green laser 515 nm wavelength machine

Next

- Mechanical characterisations starting
- Full size (350 mm)
- Cost estimation



9: Conclusions and Future Outlook

- We have demonstrated that we are exploring the use of interesting manufacturing technologies that could be scaled up to meet the challenges of FCC-ee
- The chamber benefits from the winglet design by incorporating the absorbers and pump inlet/outlets
- First bake-out tests are very encouraging and prove cold-spray is feasible for this, we continue to make improvements to the design to bring down the cost (localised undercoat spraying for example)
- BPM integration design offers a compact solution, first proof-of-concept has been manufactured, testing and improvements are taking place
- Possibility to use SMA technology in BPMs, Interconnections and transitions from 70 mm to 60 mm diameter
- Outgassing and leak testing has been successful so far, further testing ongoing for pure copper LPBF and cold-spray parts
- FSW parameters have been established and first series of parts for UHV testing are completed, future work will focus on proving horizontal manufacturing option
- SRA prototyping is progressing, a detailed initial design has been presented. First samples have been printed, and a testing campaign to validate this process for FCC-ee is underway

Next milestone: FCC mid-term cost review, October 2023

Thank you for your attention.

Additional Information

- **Impedance**:
    - Two designs are being tested, ‘honey-comb’ (Like SuperKEKB) and the DRF
    - Refer to detailed updates from Mauro’s talk on Tuesday
    - Resistive wall, winglets, bellows are the biggest contributors to transversal impedance
- **NEG**:
    - NEG-coating has been chosen as the main pumping mechanism, mainly because it guarantees low PSD yield and low secondary electron yield (SEY) as well.
    - 12m seems feasible for NEG coating deposition
- **Reduction of chamber diameter to 60mm**:
    - Reduction to 60mm diameter leads to increase in impedance by 60%
    - For vacuum simulations in SYNRAD and Molflow, provided the coating does not change there is little difference. Pumping speed is reduced by approx. 15% due to surface area reduction
    - The NEG coating proposed has already been reduced to 200nm, so far there is little room to reduce any further
- **Cooling**
    - Dependent on effective bunch length at collision (Lots of variables right now!), shorter the bunch length = higher dissipated power
    - Vacuum group are studying uniform heating across system of 200 W/m