




FUTURE
CIRCULAR
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FCC-ee UPDATE ON VACUUM TECHNOLOGIES R&D

Outline

1. **Introduction**
2. **Vacuum Chamber**
3. **Cold-Spray**
4. **Bake-out Track**
5. **BPM Integration**
6. **UHV Validation**
7. **Friction Stir Welding**
8. **Synchrotron Radiation Absorber**
9. **Conclusions and Future Outlook**

1: FCC-ee Vacuum Introduction

We are undertaking research and development of vacuum system related requirements and technologies for implementation in FCC-ee

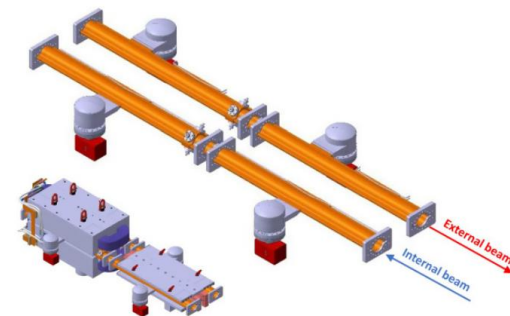
Concepts from **SuperKEKB**:

- Material choices
- 'Winglet' geometry
- Continuous cross section

The sheer scale of FCC requires an innovative approach to design philosophy by embracing new AM technologies that can be scaled for large series production

Areas we are studying:

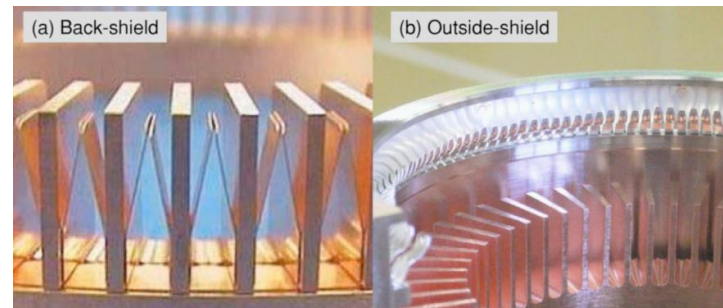
Vacuum Chamber, Interconnection / Bellows, Interconnection Flanges, Synchrotron Radiation (SR) Absorbers, utilisation of Additive Manufacturing (AM)



Conceptual design from CDR 2019

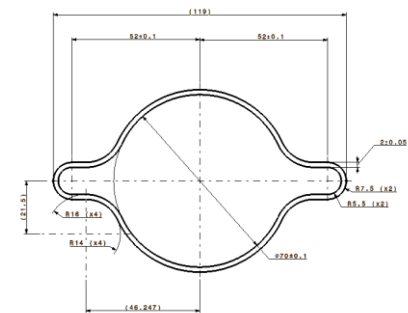
Interconnections presents challenges in its design:

- Thermal expansion of chambers
- Thermal management of components
- Mechanical misalignment and stability
- Contributions to beam stability



2: Vacuum Chamber Design

FCC-ee is a high-luminosity, low-emittance collider: *sensitive to beam degradations with regards to beam impedance*



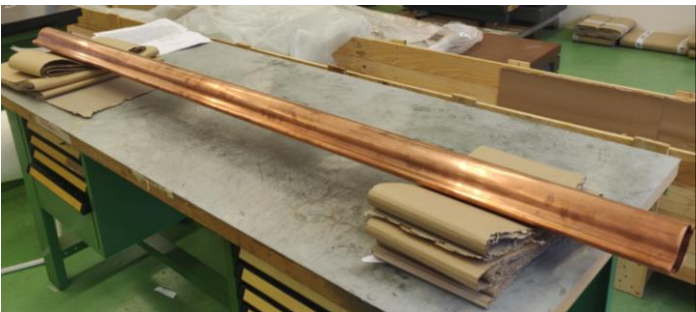
Project approach: Ease of manufacturing, cost-effectiveness and scalability (~182km of chamber required!)

Combine well-tested manufacturing methods with novel technologies →

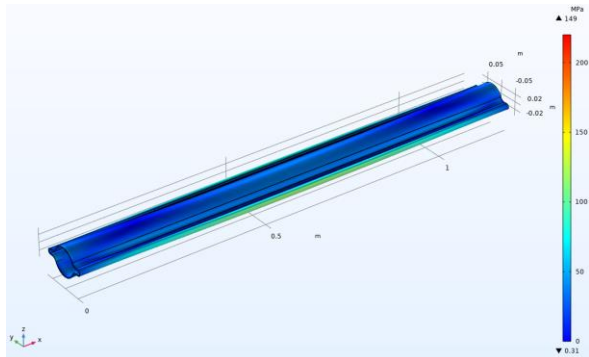
Cold-Extrusion to produce the chambers for prototypes. Up-to 12m long sections. Early studies show up to 12m is possible with this technique

Chamber is copper alloy for:

- Excellent thermal conductivity
- Low electrical resistivity
- Contributes to Synchrotron Radiation (SR) shielding



Cold-extruded prototype



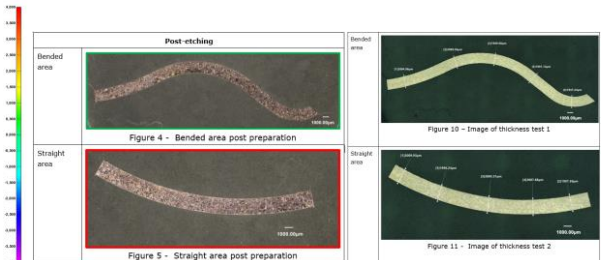
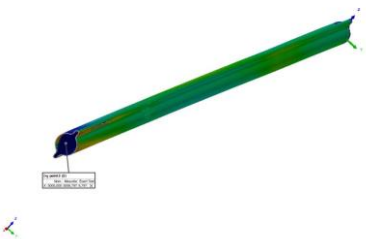
Mechanical integrity tested under vacuum & bake-out conditions (230 - 250°C (COMSOL)).

Winglets:

- Continuous cross-section throughout
- Housing of SR (photon) Absorbers, pumps

Prototypes:

- 70mm diameter; 2m & 5m lengths manufactured
- 2mm uniform thickness, 11mm winglet height



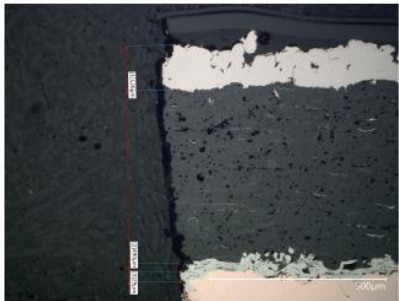
Validation campaign:

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

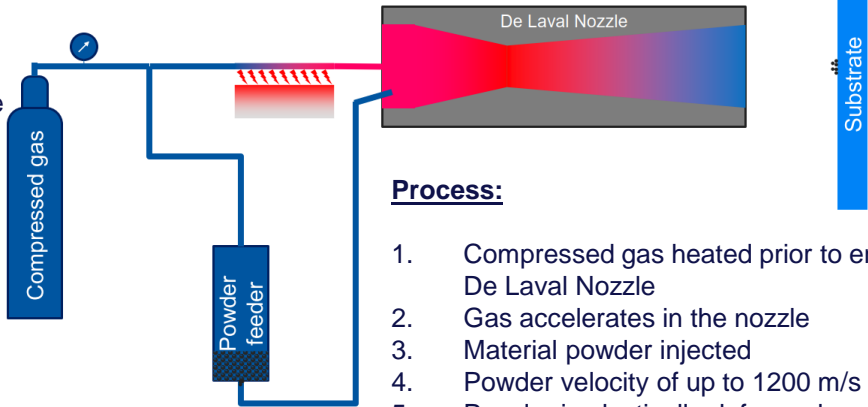
3: Cold-Spray

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

Courtesy: Adrien Didier



(b) $Al_2O_3 - 13TiO_2$



Process:

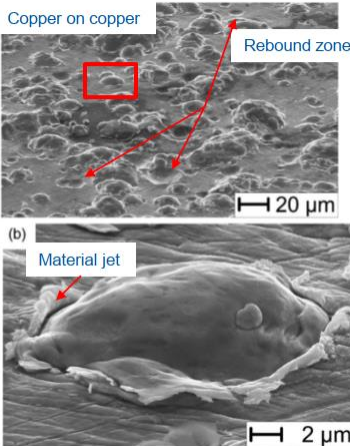
1. Compressed gas heated prior to entering De Laval Nozzle
2. Gas accelerates in the nozzle
3. Material powder injected
4. Powder velocity of up to 1200 m/s
5. Powder is plastically deformed and coating is built up.

Advantages: No powder melting, no significant impact on oxide content, powder mixtures possible, compressive residual stress, thick coatings possible (dependent on material), high-speed deposition rate.

Limitations: One of the materials must be ductile and accessibility to the surface must be well considered

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



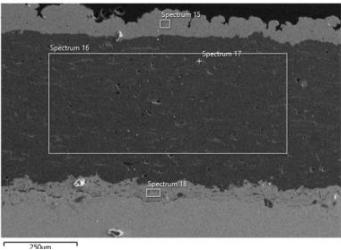
Assadi et al., Bonding mechanism in cold gas spraying, Acta Materialia, 51, 4379-4394, 2003

Table 1 Values of critical velocity for bonding assuming a particle size of 20 µm

Material	Melting point, °C	Critical velocity, m/s
Aluminium	660	620-660
Titanium	1670	700-890
Tin	232	160-180
Zinc	420	360-380
Stainless steel (316L)	1400	700-750
Copper	1084	460-500
Nickel	1455	610-680
Tantalum	2996	490-650

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



Layer configuration for bake-out application to vacuum chambers has been previously studied (*Further FCC-ee specific studies ongoing such as magnetic impact*) Thermal model developed to find baseline heat transfer coefficient (*h*)



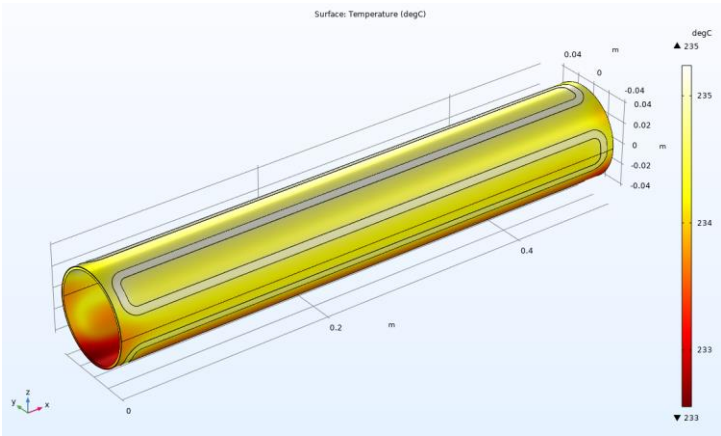
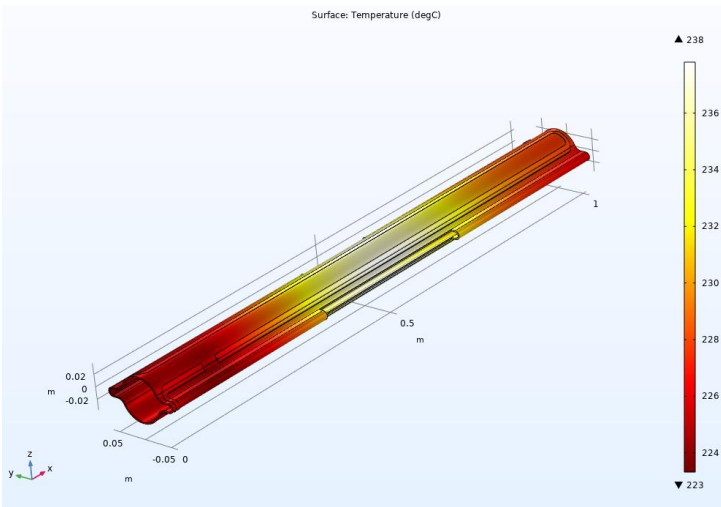
Temperature distribution across first model version of vacuum chamber (**S-Type track**)

Bake-out requirement: 230 to 250 °C

Layer Reference (Order of application)	Layer Material	Layer Thickness (mm)
01 - Substrate	Cu OFE C10100	2
02 - Bond-coat	Nickel, Aluminium	0.05
03 - Underlayer	Ceramic Al(2)O(3) - 13T i0(2)	0.5
04 - Track	Titanium Grade 2	0.2
05 - Insulation	Ceramic Al(2)O(3) - 13T i0(2)	0.1 - 0.2

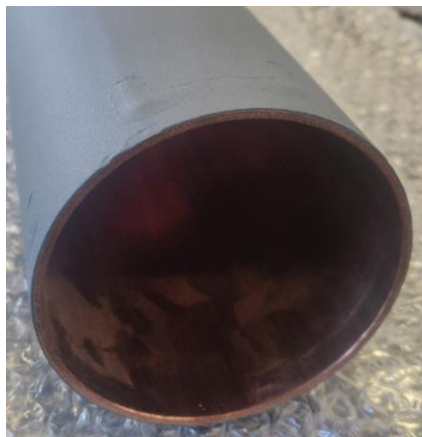
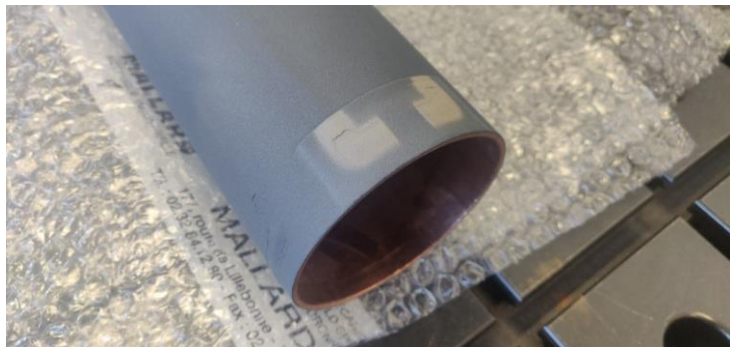
Order of plasma sprayed and cold-sprayed layers for the prototype bake-out track

First study we checked model on an off-the-shelf copper tube and moved to build a prototype



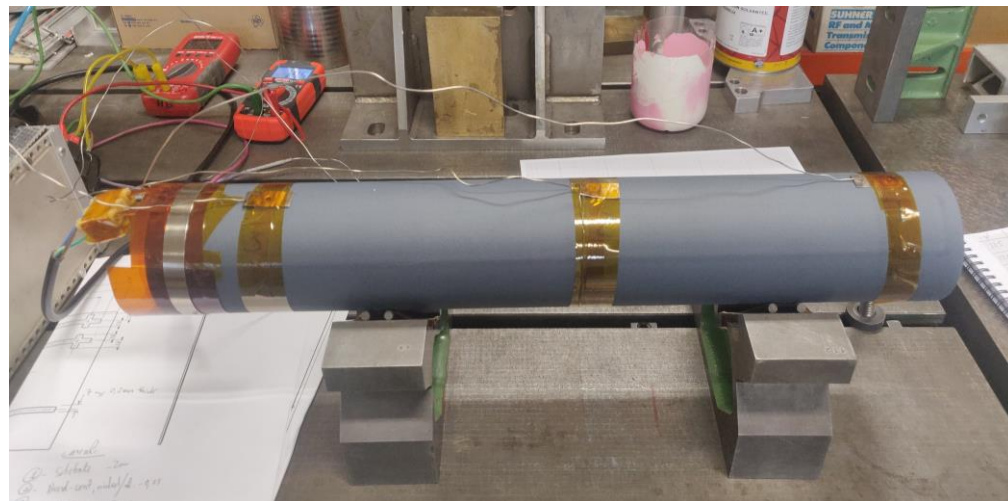
Model developed in COMSOL for a prototype tube for rapid testing. Round tube used

4: Bake-out Track



Prototype tube manufactured (80mm diameter x 500mm) to validate the model and test the cold-spray layer configuration

Some surface delamination defects and issues with spraying setup, particularly around radii

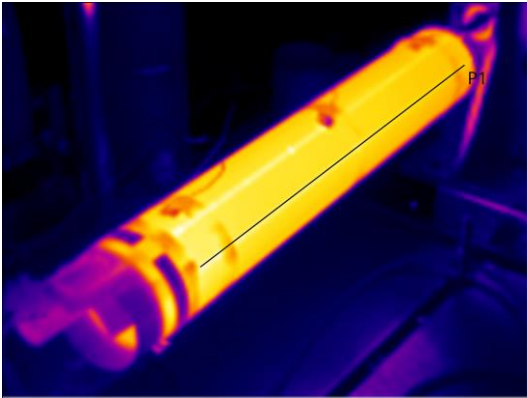


Prototype setup: glassy carbon supports to minimise heat loss, 3x thermo-couples across track to check temperature homogeneity

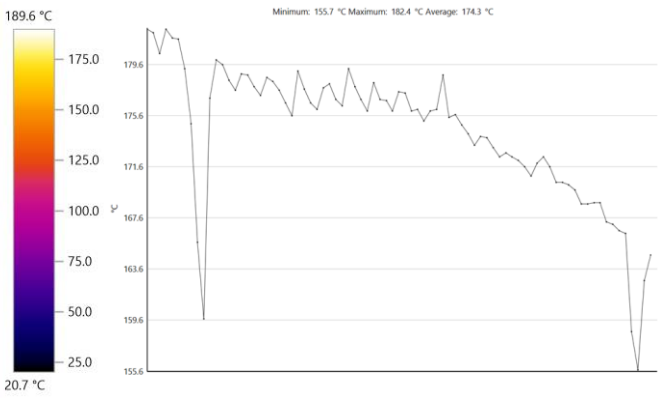


Electrical connectors across exposed titanium tracks

4: Bake-out Track



Bake-out test, thermal examination.
Higher temperatures correlate to areas of reduced titanium thickness.
Reasonably homogeneous temperature distribution.



Temperature measurement taken across length of the track



Damage to radii at 50V on 5th test, new track design proposed (later slides)

Test conclusions:

- Reasonably homogenous temperature distribution
- Power usage needs to be lowered with insulation
- Track redesign required for ease of manufacturing and elimination of cold-spots

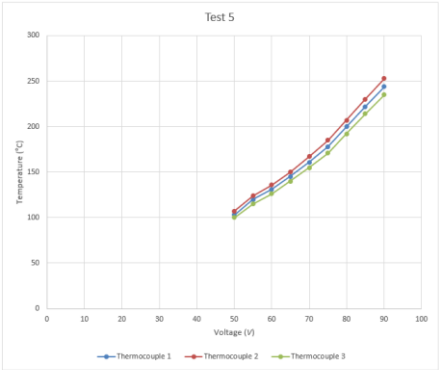


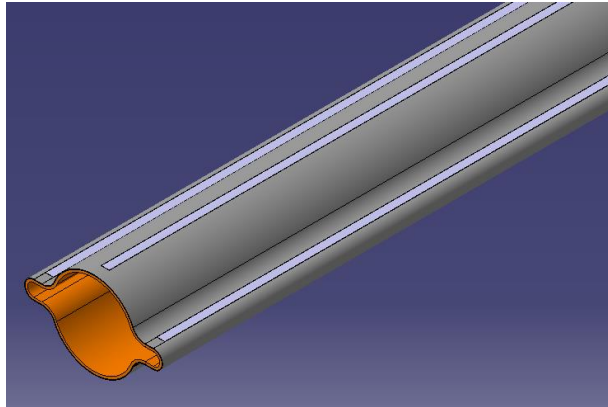
Figure 36 – Test 5 Results

Test 5 - Using glassy carbon on the Vee-blocks
Kapton and aluminium foil insulation addition

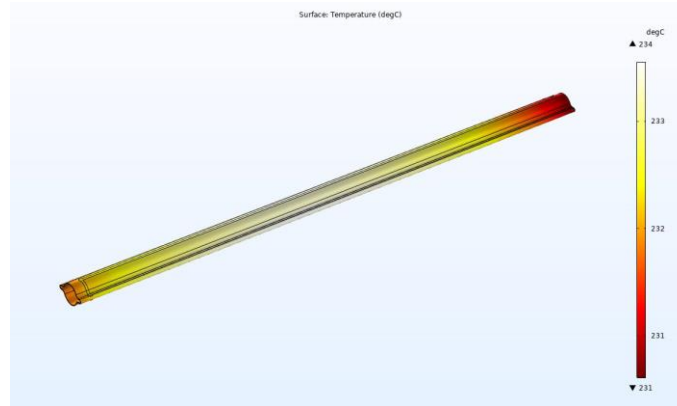
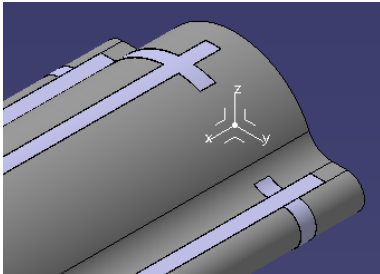
Voltage	Thermocouple 1	Thermocouple 2	Thermocouple 3	Current (Amps)	Power (Watts)	Resistance (Ohms)
50	103	107	100	2.44	122	20.49
55	120	124	115	2.59	142	21.24
60	131	136	126	2.81	169	21.35
65	145	150	140	3.01	196	21.59
70	161	167	155	3.26	228	21.47
75	178	185	171	3.46	260	21.68
80	200	207	192	3.64	291	21.98
85	222	230	214	3.86	328	22.02
90	244	253	235	4.06	365	22.17

4: Bake-out Track

To address the issues on the radius burning-out from a lack of material, a new design for the bake-out track has been proposed



The new design has two electrical connections points (one serving as a redundancy in case of failure) and a **lattice type track** to replace the S-type track:



Updated thermal model with new track design, indicates minimal change to min/max temperatures with same power input ($\sim 80\text{W/m}$).

Note: **Insulation study** underway to test various thin aerogel products and other OTS alternatives

Next steps in bake-out development:

- 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)

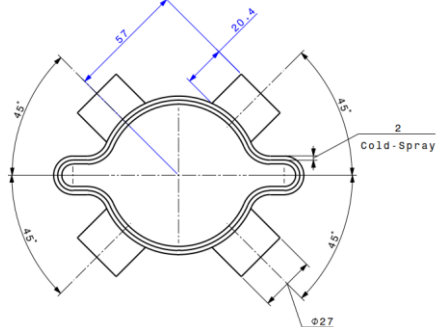
5: Beam Position Monitor - Integration

There are ~7000 BPMs in FCC-ee, with significant benefits to being directly integrated with the vacuum chamber for better spatial management. Interfaces are achieved by cold-spray additive manufacturing

First prototype has been achieved spraying pure copper to the FCC-ee chamber:

The scope of this prototyping is to:

- 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



Chamber: 2mm layer sprayed all around

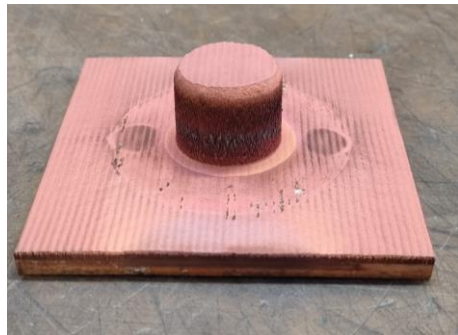


Chamber prototype with x4 bosses

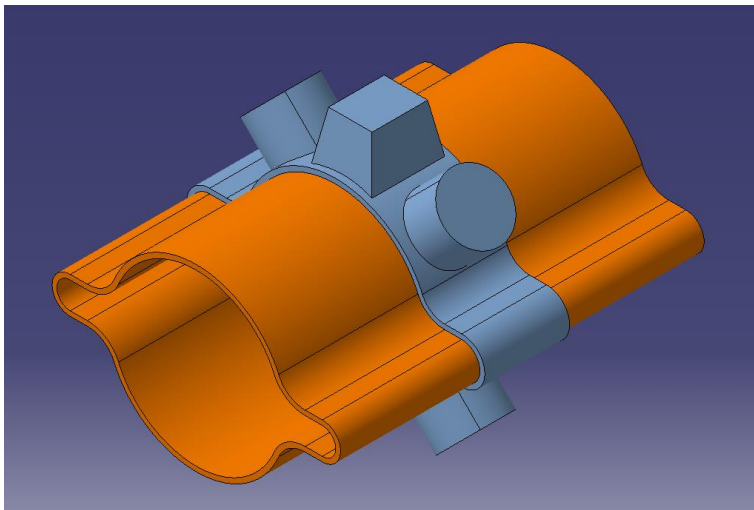
Further optimisation and study of the manufacturing process is required to enable this method for the scale required for FCC

For example, using robotic spray setup to avoid de-bonding issues on bosses

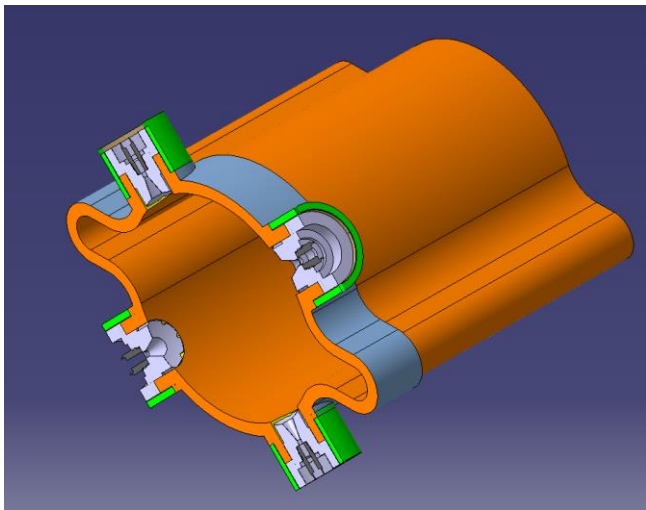
First tests will be performed on a sample cold-sprayed boss



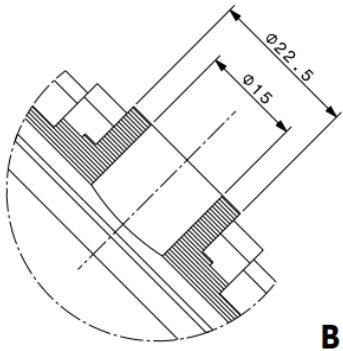
5: Beam Position Monitor - Integration



Option to manufacture additional features onto the substrate. For example, another boss is envisioned for chamber / BPM alignment to the machine



Components provided by BPM team early 2022, BPM team working on the component specifications



Localised machining to be tested on cold-spray

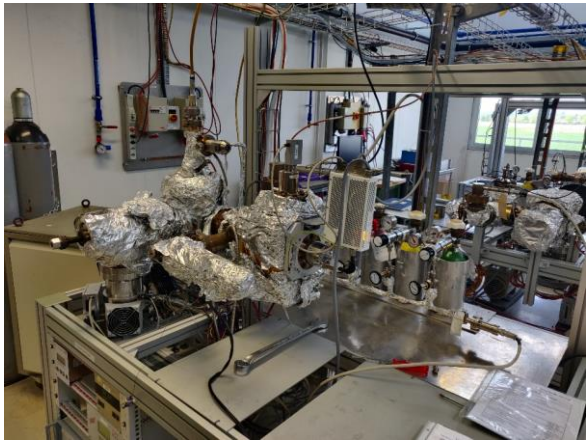
6: UHV Validation

Materials and manufacturing processes need to be validated for Ultra-High Vacuum (UHV) environments

Vacuum group place a particular priority on **outgassing** and **leak testing**

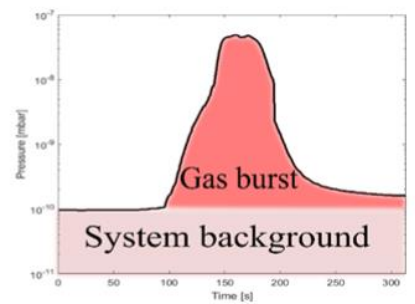
Outgassing: Thermal outgassing rate of a solid is characterized as the quantity of gas leaving the surface per unit of time exposed surface at a specified time after the start of the evacuation. The measured rate is the difference between the intrinsic outgassing rate and the rate of reabsorption on the surface in the test chamber

IE, outgassing measurement is based on **gas accumulation** across different time intervals

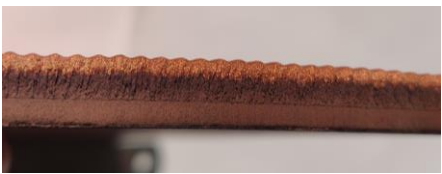


Pure copper and copper alloy cold-sprayed samples are undergoing testing

Samples are loaded into the accumulation chamber and after a bake-out at 250 °C, measurements are taken

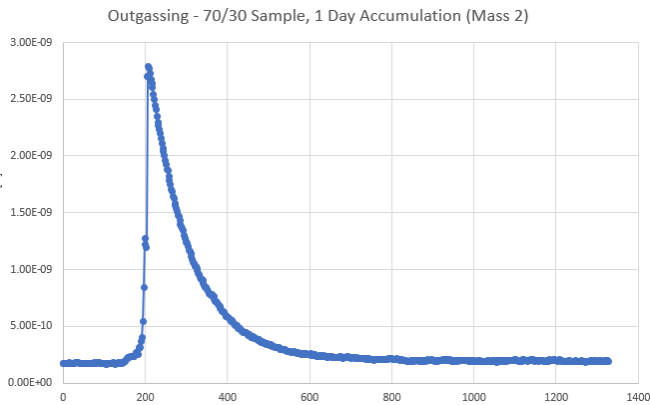


Outgassing setup at CERN and principle of operation

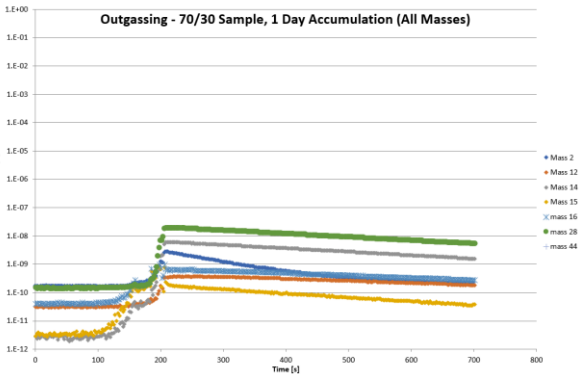


6: UHV Validation

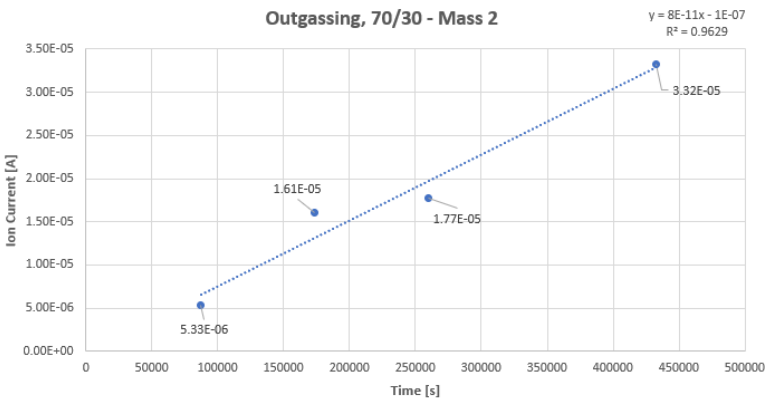
Example of results



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

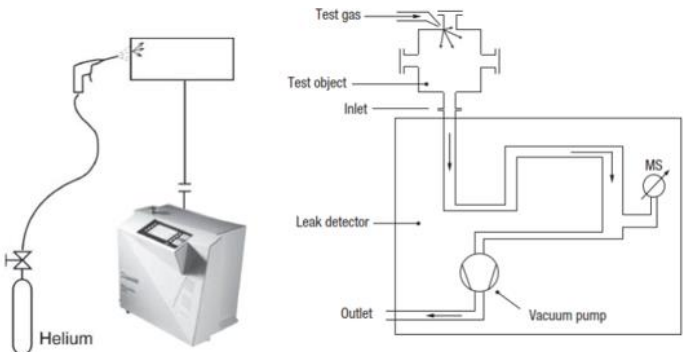
Nitrogen is being monitored as this is the gas medium for cold-spray

Linear progression of gas accumulation over time

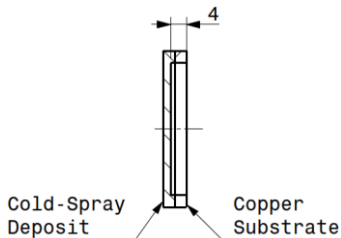
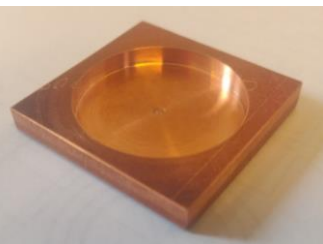
6: UHV Validation

Cold-Spray has demonstrated its **versatility of use**, particularly for permitting construction of coatings with powder and substrate combinations of heterogeneous materials. Cold-Spray must therefore be able to fulfil the need for a material thin enough to not compromise the transparency to secondary radiation, provide sufficient thermo-mechanical strength and ensure **gas tightness in UHV conditions**.

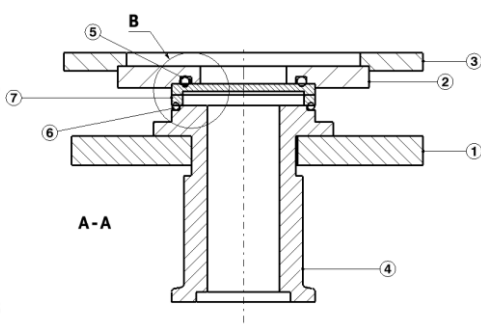
Leak rate qualifying result: $10^{-10} \text{ mbar} \cdot \text{l} \cdot \text{s}^{-1}$



Operating principle of a vacuum leak test



Tools have been developed for a standardised test for materials, in this case cold-spray:



This particular tool tests the interaction layer between the substrate and deposit

40 x 40mm samples constructed for leak tightness using helium

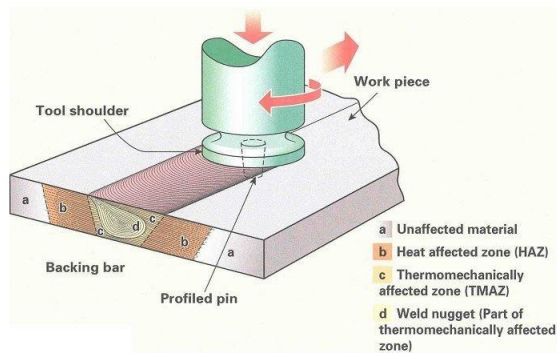


All samples have passed leak tightness tests down to 1.4mm thickness of the deposit layer. This process is now being used to test LPBF 3D printed samples

Vacuum group collaborate closely with partners to validate materials and methods for UHV applications

7: Friction Stir Welding

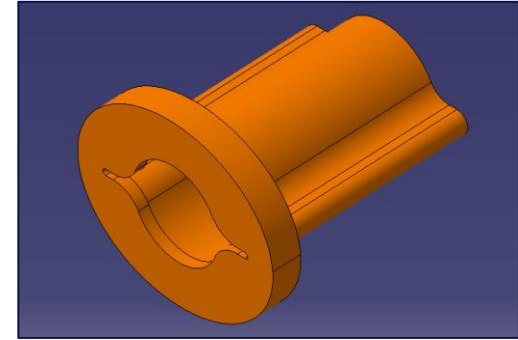
Friction Stir Welding (FSW) is an innovative solid-state technique that joins metals without melting by utilizing a rotating tool to generate controlled friction and heat. With exceptional weld quality, increased strength, minimized defects, and improved efficiency, FSW is a compelling solution for diverse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

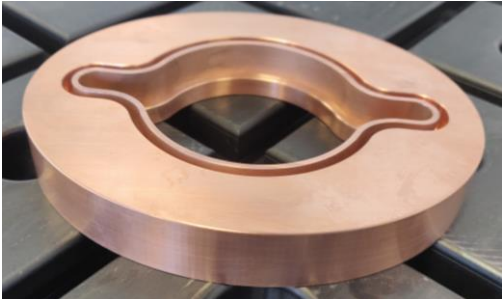
Considerations:

- 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 involves design of the clamp, destructive testing of ‘short’ components and ISO standard weld report of the results:

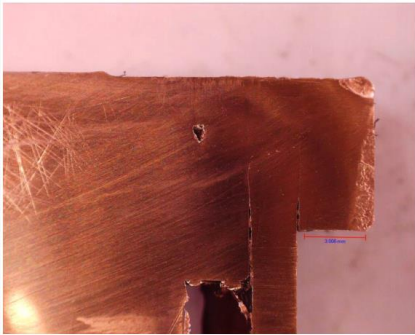


6 Flanges + short chamber (17.5mm) to determine optimal weld parameters using a destructive testing approach.

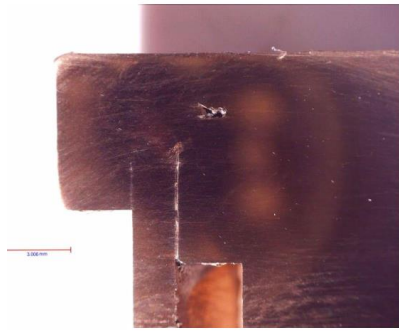


Macroscopic inspection

- 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



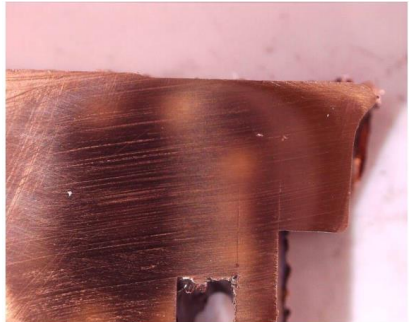
Cross-section 1



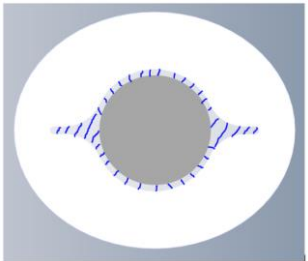
Cross-section 2

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



Cross-section 3

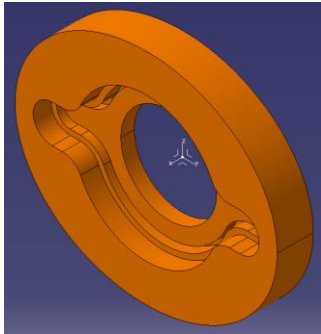


New design for Flange (pre-weld)

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



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



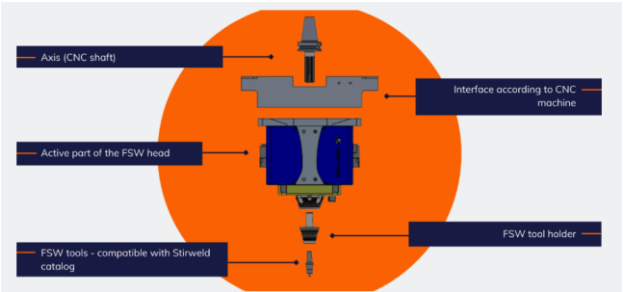
Series completed units for further R&D efforts at CERN

Future outlook:

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

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

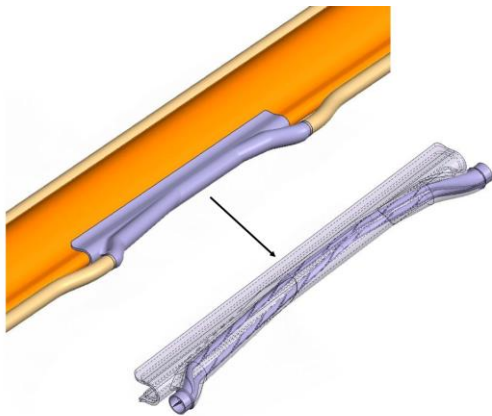
Leak testing to UHV conditions will now take place at CERN and any necessary mechanical characterisations required



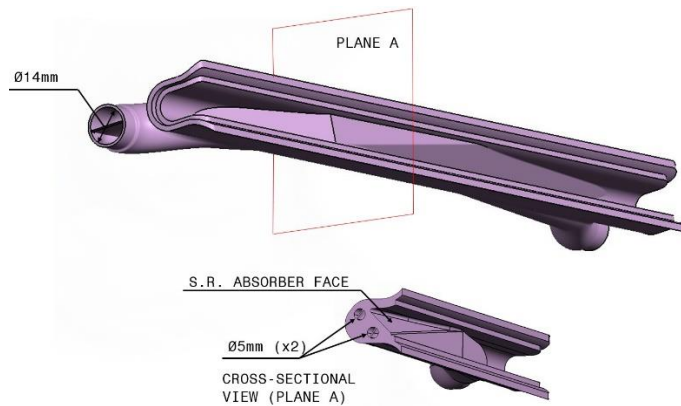
8: Synchrotron Radiation Absorber

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

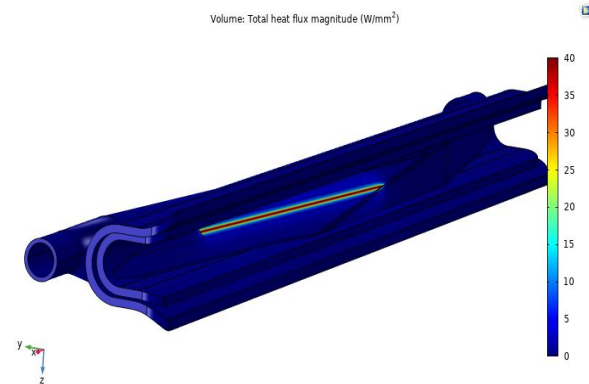
The absorbers are designed to withstand demanding temperature and thermal stresses induced by the resulting heat load. Simulations show max temperature of 150° C, with cooling wall channel reaching 65° C.



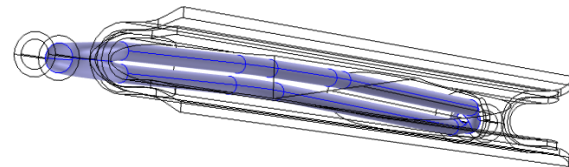
Chamber with view of the absorber



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

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'

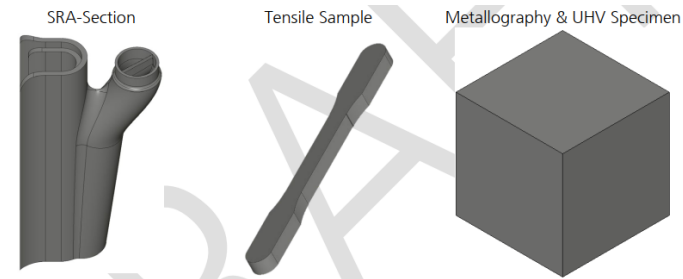
The complex internal geometry of the SRAs calls for the use of additive manufacturing technology, the water cooling channels include a twisted-tape 'insert', the turbulence generated by the tape improve heat transfer capabilities

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.

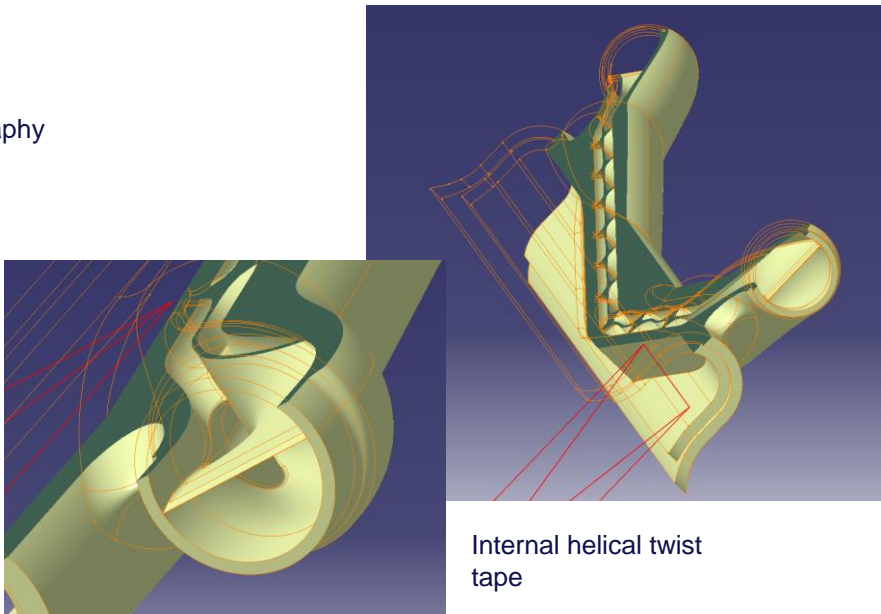
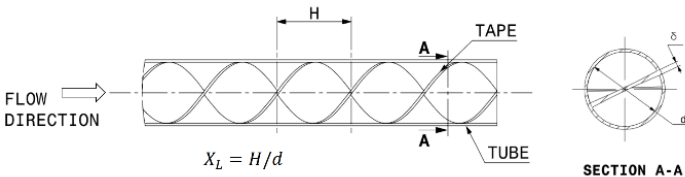
This project is in collaboration with **I-FAST** at CERN and **Fraunhofer Institute**

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, pressurised water cooling and validation of thermo-mechanical models



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



8: Synchrotron Radiation Absorber



First samples of the SRA and pieces for mechanical characterisation successfully printed (This week!!)

9: Conclusions and Future Outlook

- We have demonstrated that we are exploring the use of interesting manufacturing technologies that can 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
- BPM integration design offers a compact solution, first proof-of-concept has been manufactured, testing and improvements will take place
- Possibility to use SMA technology (Already being implemented in LHC and HL-LHC) in BPMs and interconnections
- 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, further work will focus on proving horizontal manufacturing
- Synchrotron Radiation Absorber 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

Further details available at the poster session later today, including the interconnection design between the chambers



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
 - Poster session details Interconnection designs being tested
- **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