www.cern.ch

Status of the technology development for the FCC-ee vacuum system

C. Garion, CERN/TE/VSC

Content:

- Introduction to the FCC-ee vacuum system in the arcs
- UHV connections with Shape Memory Alloy couplers
- Additive manufacturing with gas dynamic cold spray coating
- Prototyping phase
- Summary

FCC-ee vacuum system in the arcs

The FCC-ee Vacuum system has to cope with beam parameters from low-energy (45.6 GeV) high current (1390 mA) version to high-energy (182.5 GeV) low current (5.4 mA) configuration.

Beam Energy E(GeV)	Beam Current I(mA)	Photon Flux F'(ph/s/m)	Dynamic Gas Load Q'(mbar·l/s/m)
45.6	1390	$7.17\cdot10^{17}$	$2.90\cdot10^{-8}$
80	147	$1.38\cdot10^{17}$	$5.58\cdot10^{-9}$
120	29	$4.13\cdot10^{16}$	$1.67\cdot10^{-9}$
182.5	5.4	$1.18\cdot10^{16}$	$4.78\cdot10^{-10}$

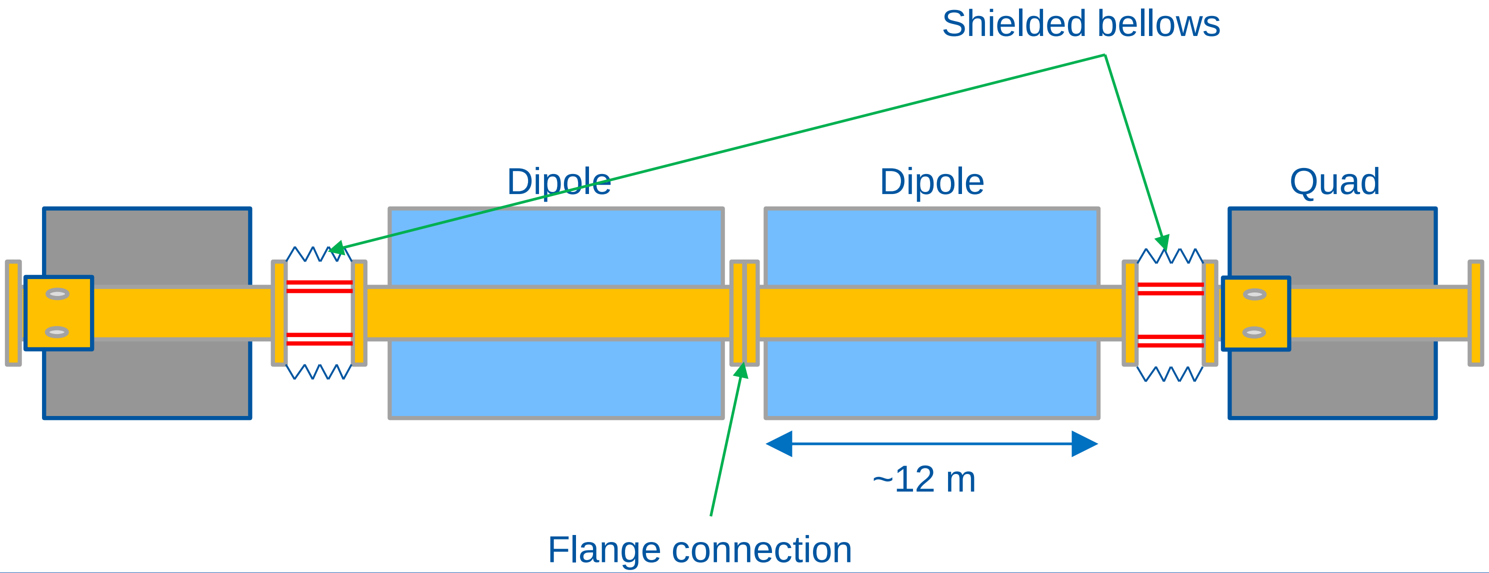
Relevant FCC-ee parameters for the vacuum system design

For the vacuum system, the synchrotron radiation leads to:

- High local heat deposition:
  - The limit is given by 50 MW/beam synchrotron radiation losses (~650 W/m).
- High outgassing:
  - Pressure: low 10^{-9} mbar range.

Layout:

- 2 rings of ~ 100 km.
- Cell length: ~55.9 m.



Vacuum, Surfaces & Coatings Group
Technology Department

FCC-ee vacuum chambers

Present design as presented in the CDR:

Geometry: Tube with two winglets
2 mm thick, 70 mm ID

Material: Copper

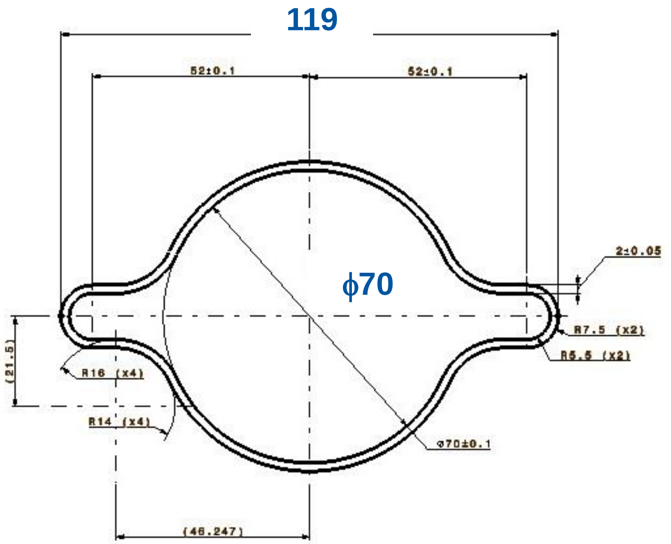
- Good thermal conductivity and low electrical resistivity
- Shielding for the X-Ray synchrotron radiation fan and minimizing the irradiation of machine and tunnel components

Surface treatment: NEG coating

- Distributed pumping speed
- Low SEY
- Quick vacuum conditioning

Lumped SR photon absorber:
Distanced by about 5.8 m

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



Vacuum chamber prototype cross-section

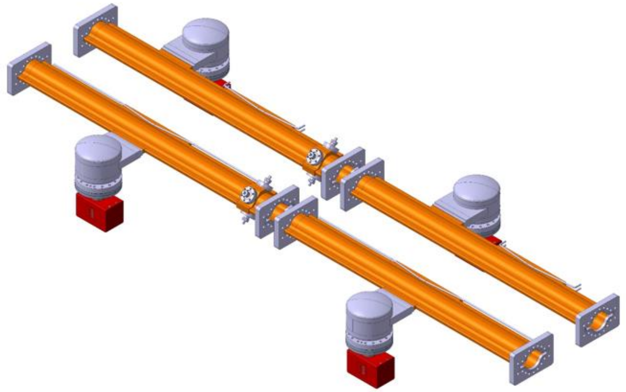


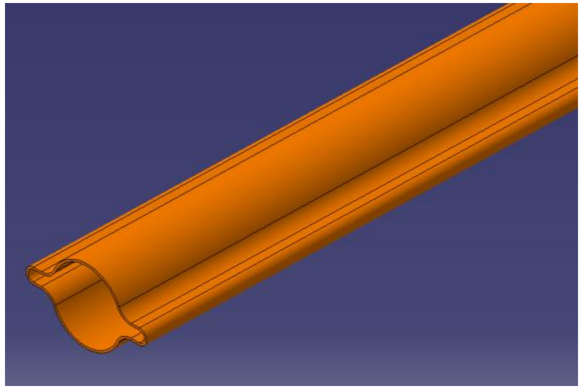
Illustration of vacuum chambers with absorbers and pumps

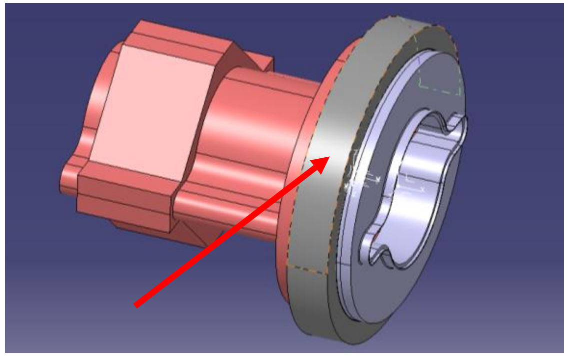
The whole vacuum system shall be designed with a cost-effective and sustainable approach.

New technologies in development for HEP and of interest for FCC-ee

Beyond the vacuum challenges related to the synchrotron radiation and dynamic vacuum, the vacuum system shall have an affordable cost.

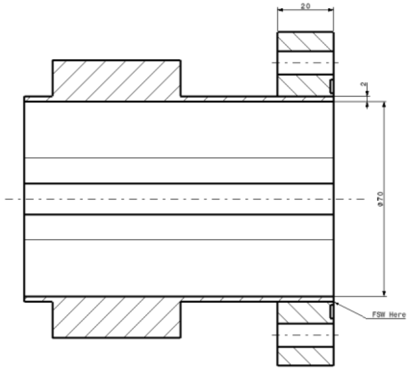
Technical solutions shall be defined to minimize the cost of the system. The production should be based on series industrial processes and with a minimum of interfaces.

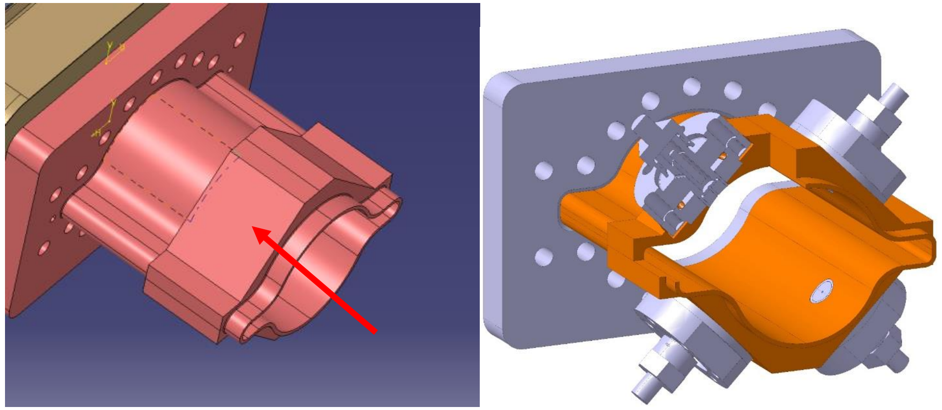

Copper extrusion


SMA connector

Some technologies are being developed and assessed for the main ring vacuum chambers:

- Shape Memory Alloy UHV connectors for:
  - Interconnection.
  - BPM pick-ups.
- Gas dynamic cold spray for:
  - Additive manufacturing of copper.
  - Permanent radiation hard bake out system.
- Weld of extruded chamber/flange.


Welding extrusion/flange


Cold sprayed copper for BPM integration

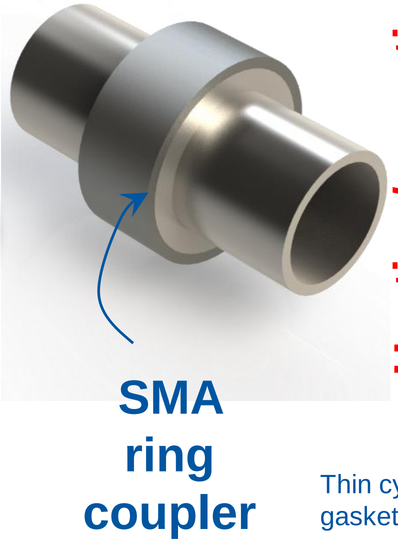
Concept of SMA connectors for UHV applications

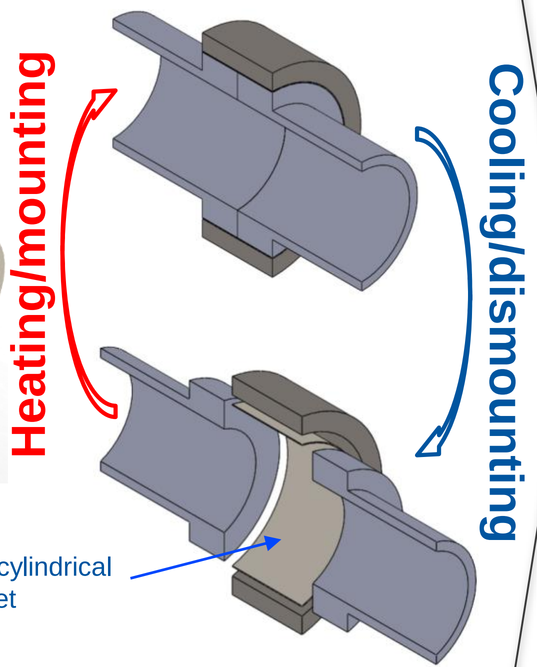
Standard vacuum coupling systems

Soft/hard materials +
mechanical force

Image source: web

Shape memory alloy couplers





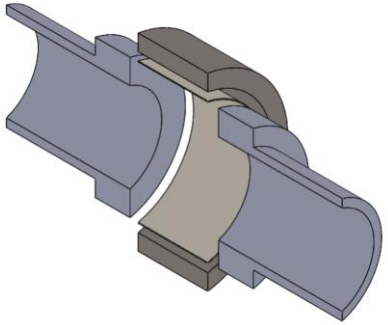
Soft/hard materials + temperature control

Concept of SMA connectors for UHV applications

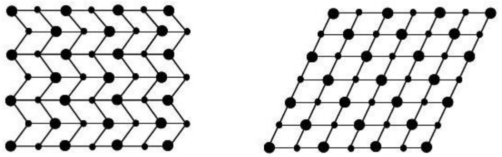
Heating/mounting

Martensite: stable at <u>low</u> temperature and <u>high</u> stress

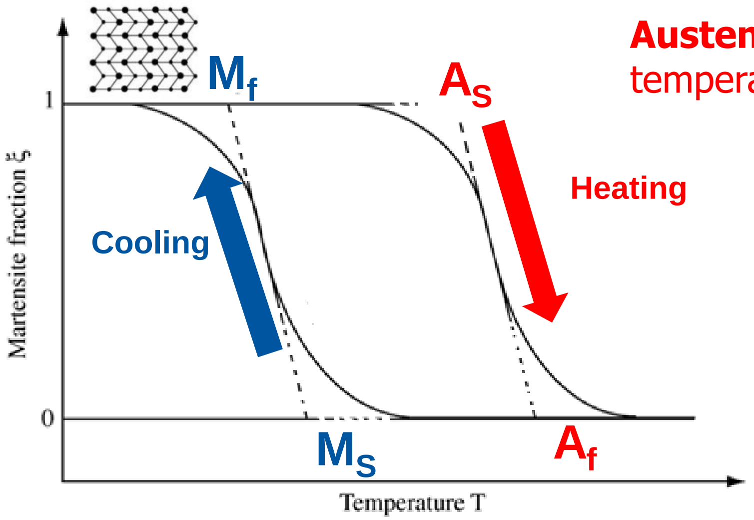
Austenite: stable at <u>high</u> temperature and <u>low</u> stress

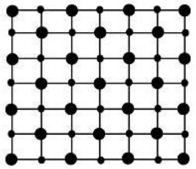


Martensitic enlarged cold-shape

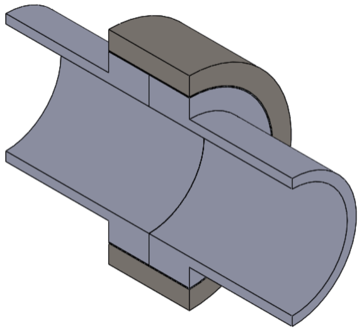


Twinned (low stress) or detwinned (high stress) martensite





Austenite



Austenitic contracted hot-shape

Cooling/dismounting

Reversible phase transformation: displacive transformation without diffusion process

- **A_s**: Austenite start temperature
- **A_f**: Austenite finish temperature
- **M_s**: Martensite start temperature
- **M_f**: Martensite finish temperature

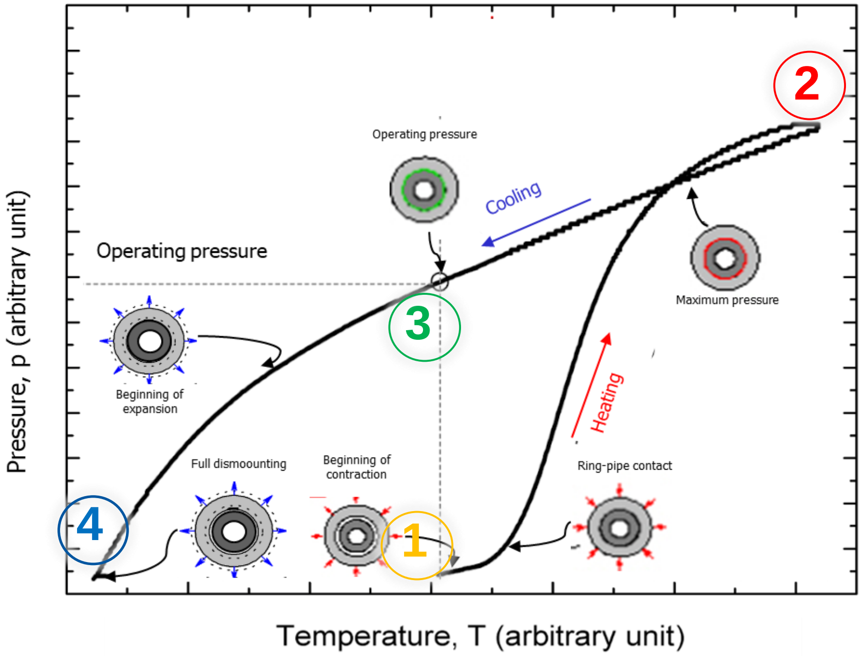
Transformation Temperatures (TTs) depend on:

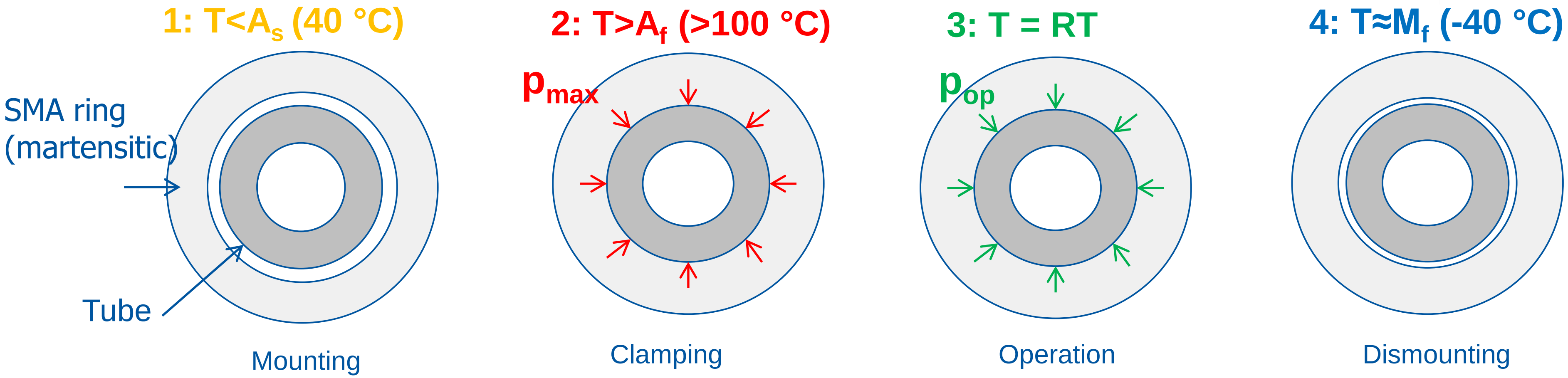
- Chemical composition
- Internal stress/strain field (dislocation arrays/precipitates)
- Thermo-mechanical cycling

Operation principle

- A_s: Austenite start temperature (Ring contraction starts)
- A_f: Austenite finish temperature (Ring contraction ends)
- M_s: Martensite start temperature (Ring expansion starts)
- M_f: Martensite finish temperature (Ring expansion ends)

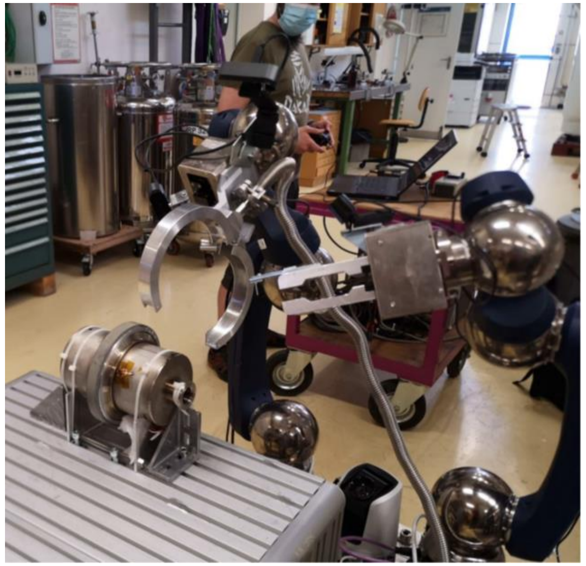
1. Mounting at room temperature
2. Tightening by heating above 100 °C
3. Leak Rate < 10^{-10} mbar·l·s^{-1} at room temperature
4. Dismounting by cooling down to -40°C





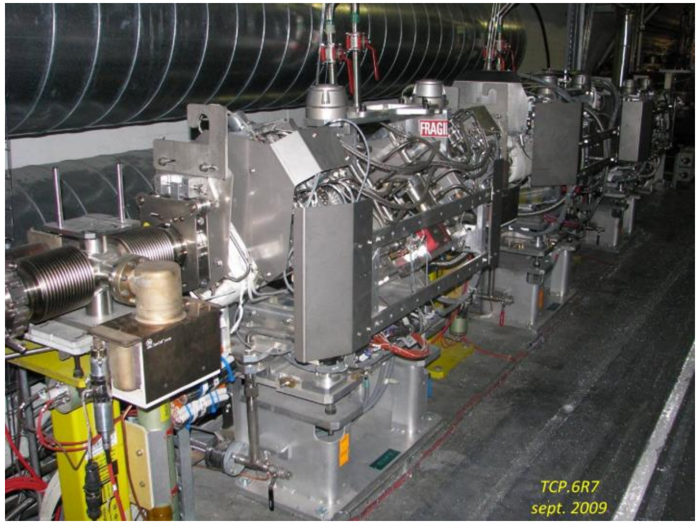
Advantages and potential applications

- A compact, leak tight and easily mountable\dismountable connection system, compatible with accelerator environment:
  - Magnetic permeability < 1.002
  - Thermal outgassing < 10^{-13} mbar.l^{-1}.s^{-1}.cm^{-2}
  - Radiation hard (up to 4 MGy at least)
- Possibility of remote controlling\activation
- Possibility to connect dissimilar materials
- Possibility to use in high demanding areas (e.g. collimator areas, machine/detector interface)

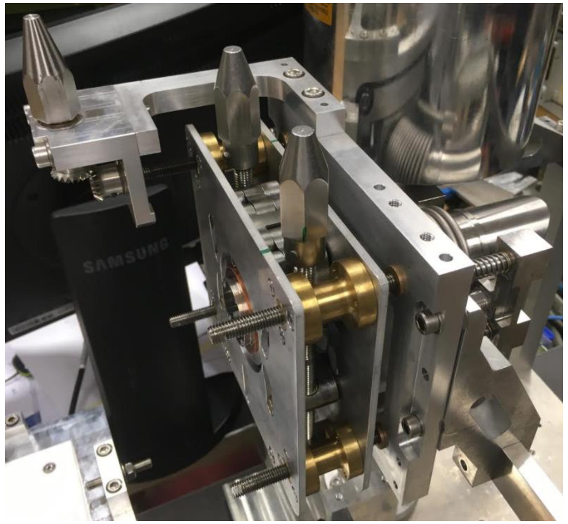


Declamping with a robot

LHC dump windows



LHC collimators



Vacuum module for the MDI area

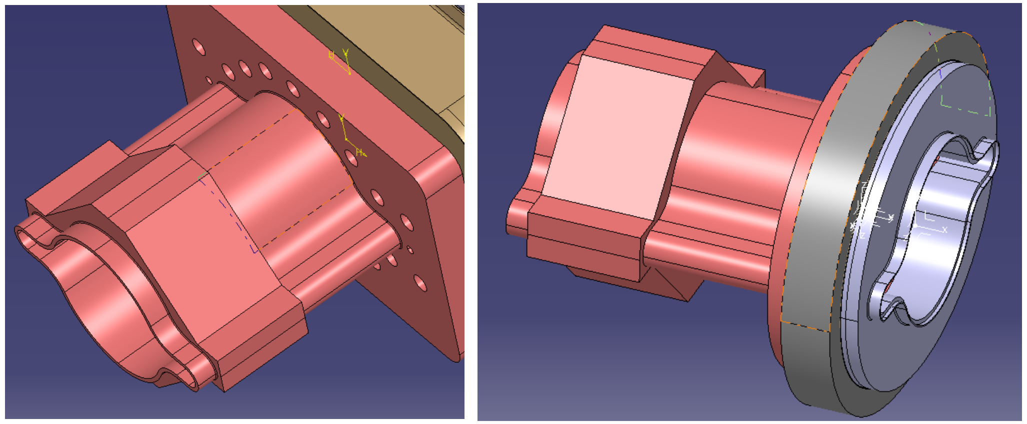
SMA-based UHV prototype joints validated

Examples of different validated SMA connectors

- Compatibility with various pipe geometries (DN16, DN25, DN50, DN100) and metals (steel, aluminum, copper, etc.)
- Bimetallic joints (St/Ti,St/Alu)
- Zero - longitudinal gap connection

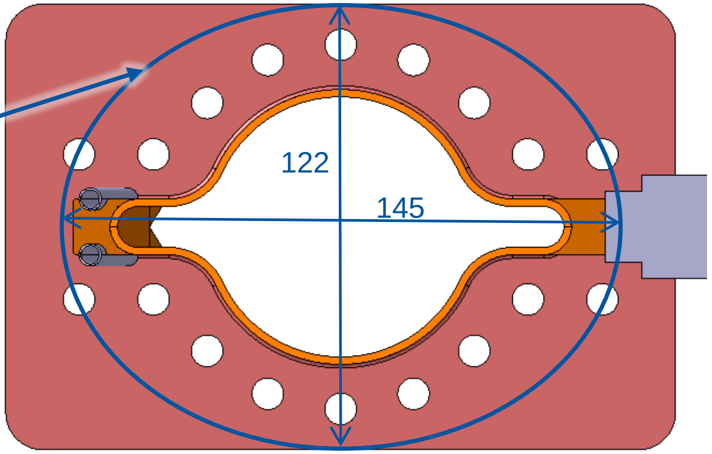
Oval-shaped connectors for FCC-ee chamber interconnections

Preliminary analytical calculations and FE simulations



Replacement of bolted flanges by SMA connectors

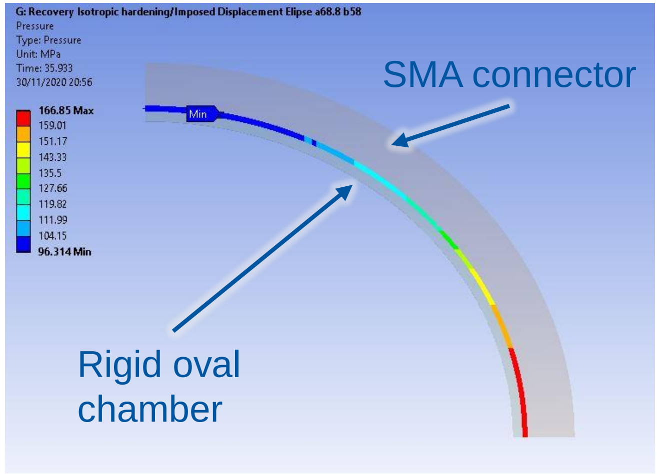
Preliminary elliptic profile for SMA connector compatibility based on existing DN100 QCF.

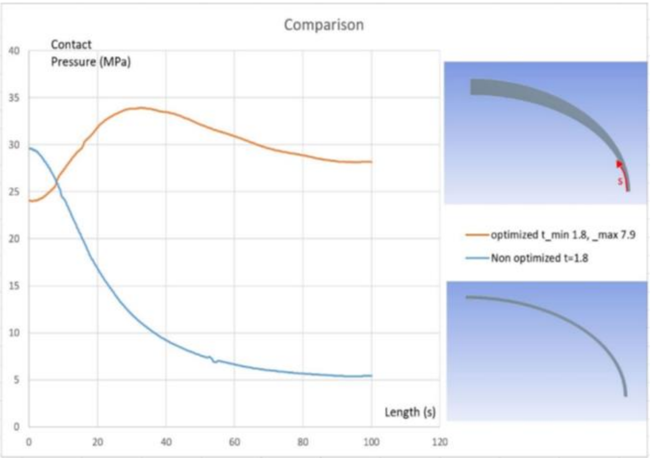


Typical expected space in the interconnection

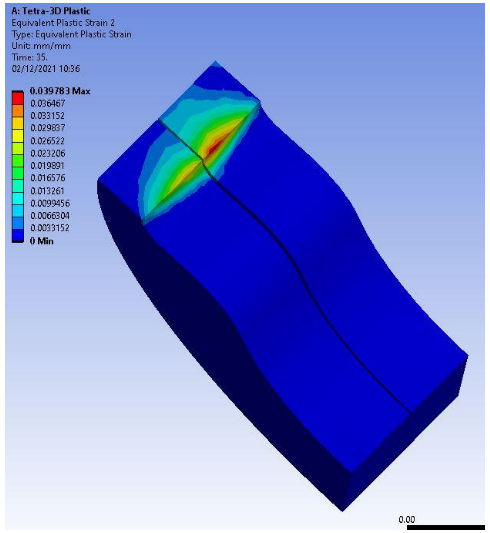
Challenges:

- **Non Uniform contact pressure**
- **Training of Oval SMA rings**





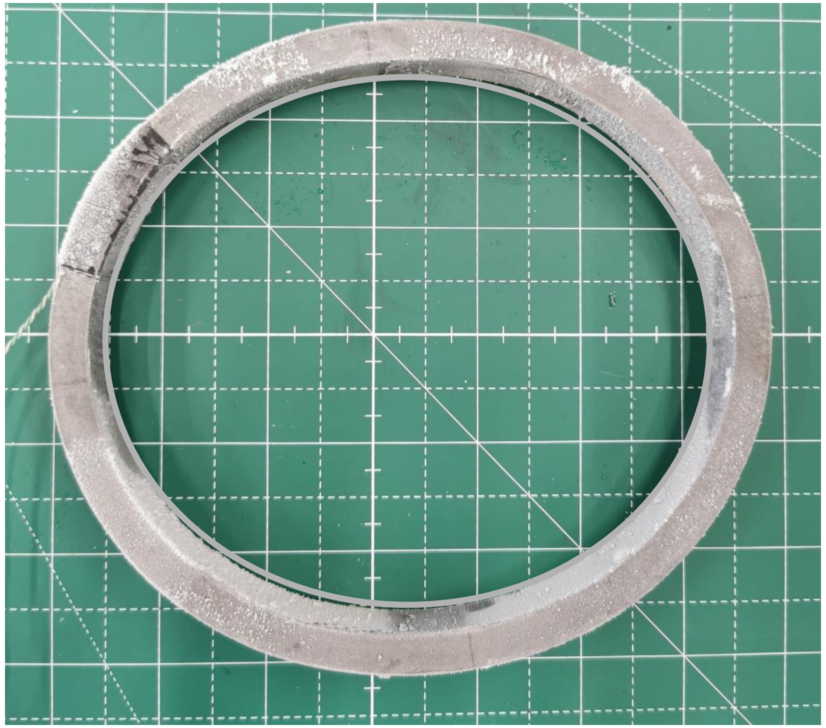
Simulations of contact pressure

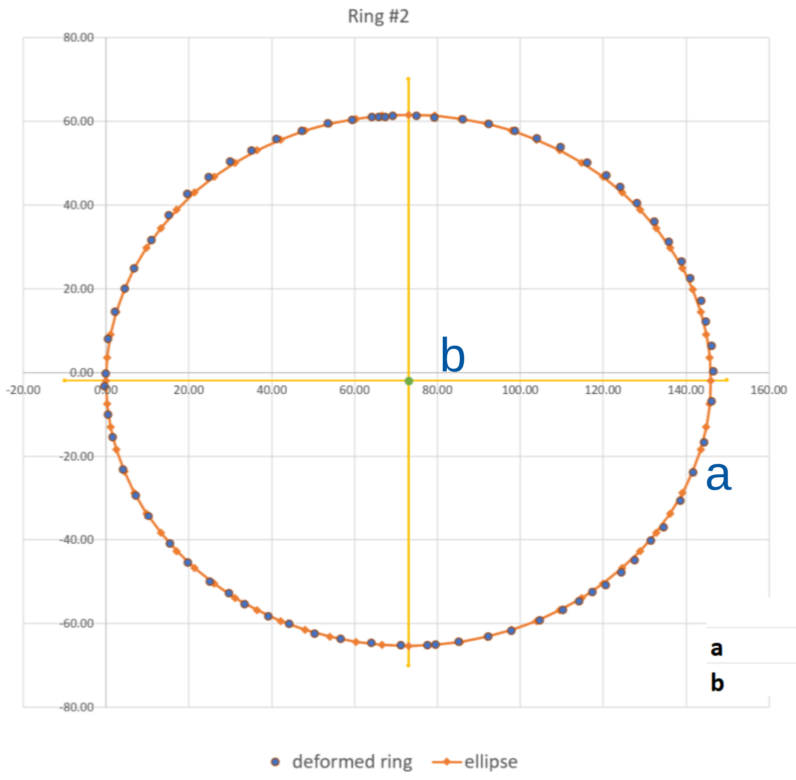


Plastic strain in the flange

Training setup for oval-shaped connectors

Design, Simulations and Manufacturing





	[mm]
a	73
b	63.455

Trained ring after ovalisation

Next steps:

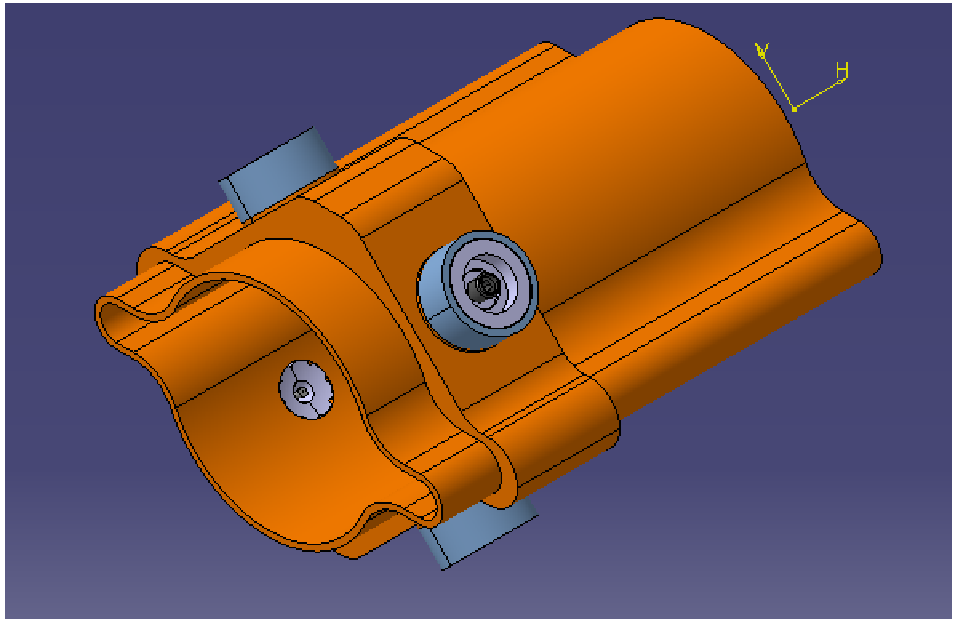
- Future tests
    - Recovery stress test (contact pressure measurement)
    - Repeatability of training
- Optimisation of the ring/flange and training

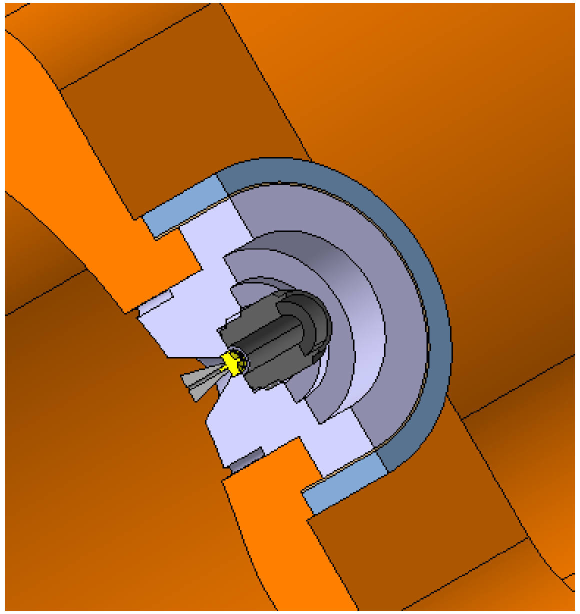
Circular connectors for FCC-ee chamber/BPM button

Preliminary considerations

SMA connectors could be advantageously used to integrate the BPM pickup to the vacuum chamber :

1. More compact than DN16 CF flange.
2. Easier to assemble.
3. Transition with copper (no brazing) → cheaper.

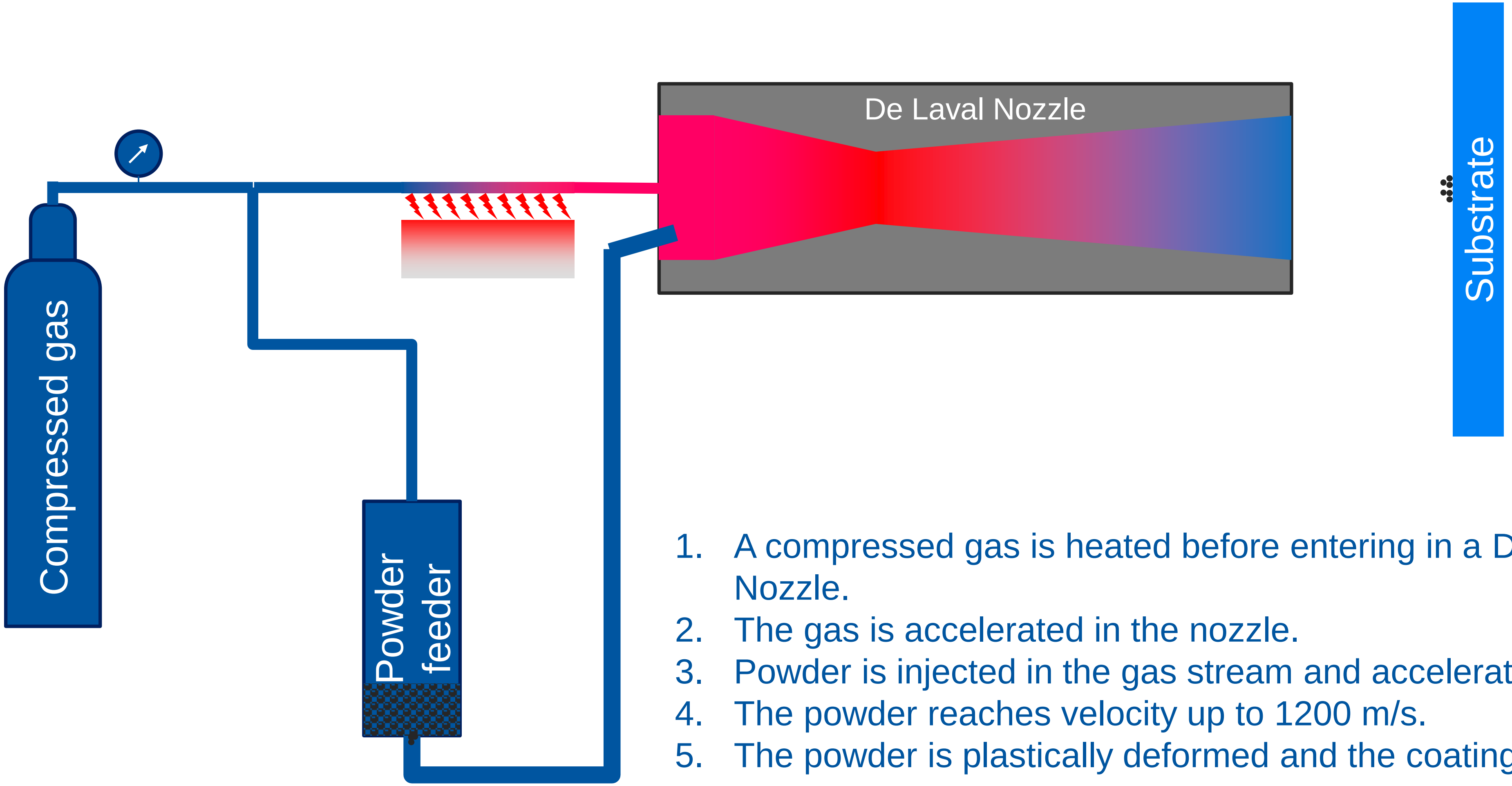




Design update of the FCC-ee BPM block on the vacuum chamber, incorporating the proposed equipment (BPM design given CERN/SY/BI for illustration)

Principle of Cold Spray

The gas dynamic cold spray coating is based on the projection of solid powder at high velocity.



1. A compressed gas is heated before entering in a DeLaval Nozzle.
2. The gas is accelerated in the nozzle.
3. Powder is injected in the gas stream and accelerated as well.
4. The powder reaches velocity up to 1200 m/s.
5. The powder is plastically deformed and the coating is building up.

Cold Spray Advantages and Limitations

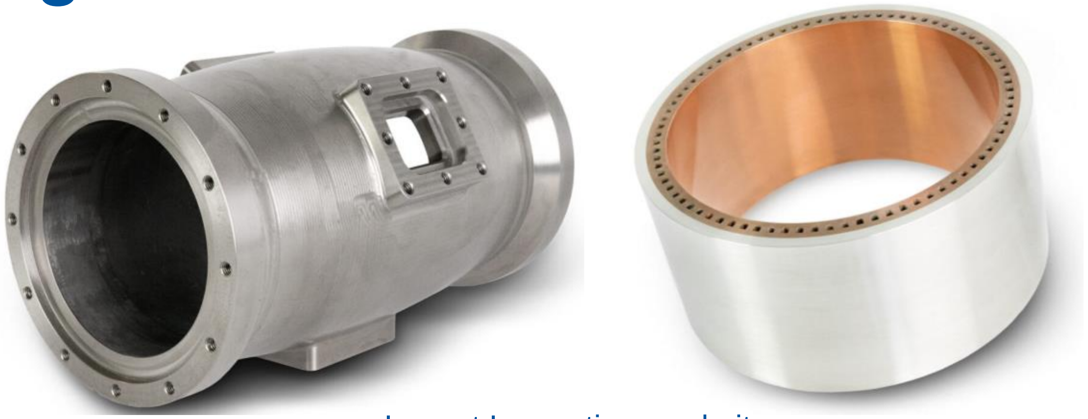
Advantages:
- No powder melting.
  - → No phase change.
  - → No grain growth.
  - → Low heating of the substrate.
- No significant impact on the oxide content w.r.t. initial material.
- Powder mixture possible.
- Compressive residual stress (fatigue life increase).
- Nozzle geometry can be tuned for a given jet size.
- Thick coating.
- High deposition rate.

Possible applications:
- Additive manufacturing
- Coating (surface or local coating, metallization of polymer)
- Metallization of
- New materials (composite material)

Limitations:
- One constituent has to be ductile.
- Accessibility to the surface to be coated.

New Manufacturing Process

Additive manufacturing for:
- Manufacturing of components of potentially dissimilar materials
- Joining of dissimilar materials
- New feature
- Repair
- Local reinforcement of thin walled structure



Impact Innovations website

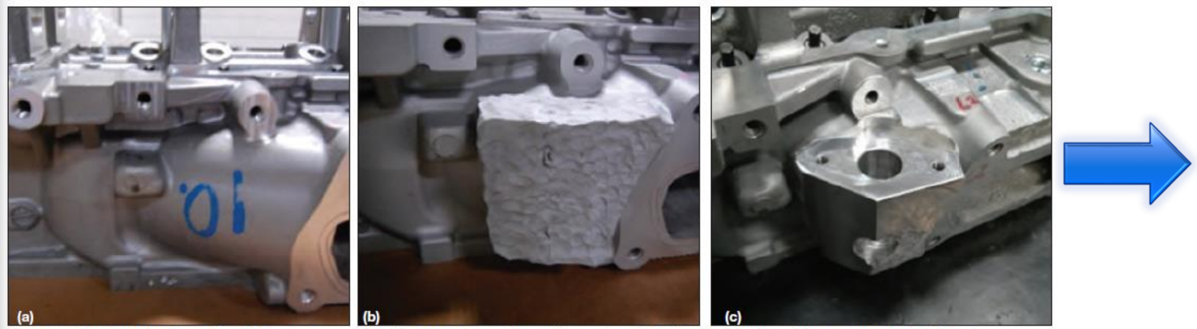
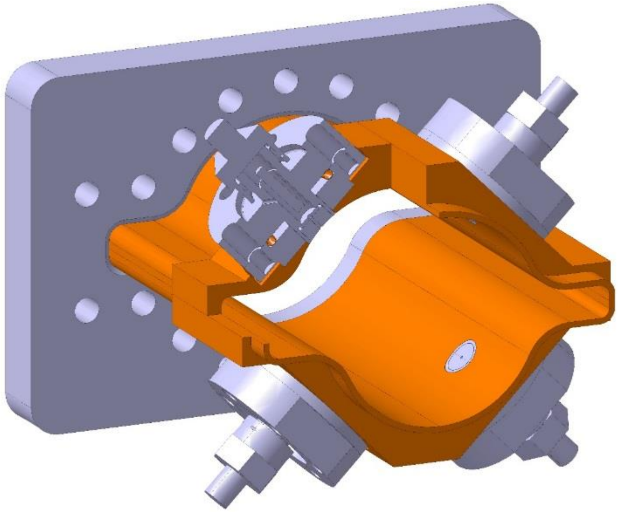


Fig. 3 — *Freeform feature added to a prototype machine component by cold spraying. (a) Prior to spraying, (b) as sprayed, (c) finished.*

J. Villafuerte, ADVANCED MATERIALS & PROCESSES, 2014



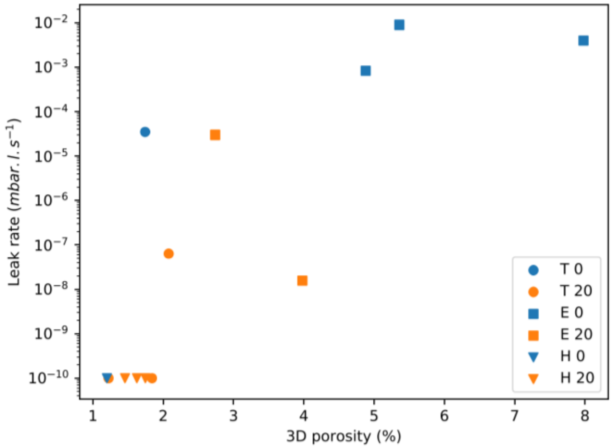
FCC-ee quadrupole chamber with BPM

Suitability of cold spray additive manufacturing for UHV applications?

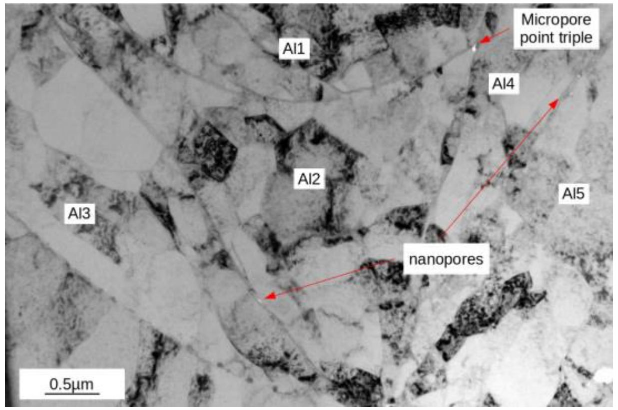
Leak tightness of cold sprayed additive materials:

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 the process.
3. The influence of powder morphology on the porosity formation.



Influence of porosity on leak tightness for different powders and process parameters [1]

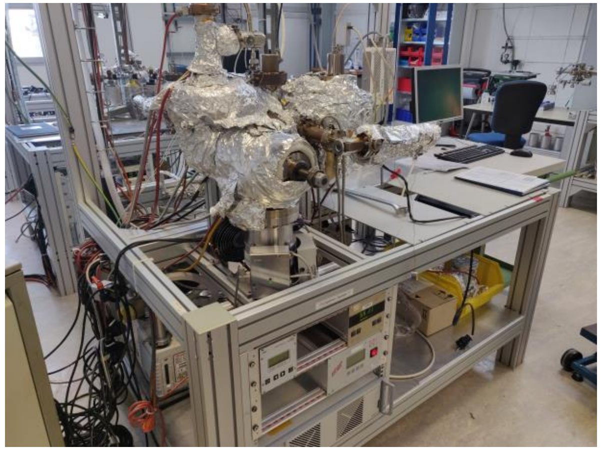


Porosity formation in cold sprayed aluminium [1]

Preliminary tests on copper are in preparation:

- Copper-to-Copper Cold-Spray samples manufactured
- Test bench for thermal outgassing fully refurbished
- Tooling for leak tightness test available

Samples for leak tightness and thermal outgassing tests



Test bench for thermal outgassing measurement by accumulation of baked samples

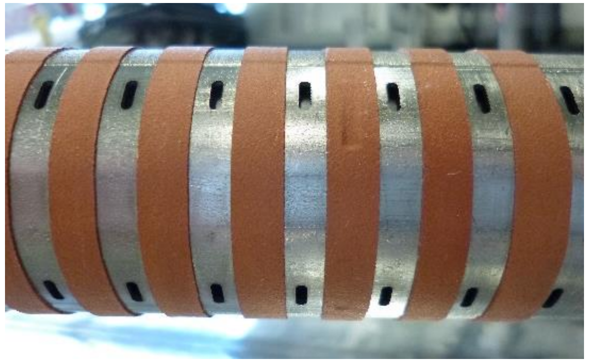
[1] Etude de la relation entre porosité et étanchéité à l'ultra-vide de dépôts à base d'aluminium obtenus par projection dynamique par gaz froid ("cold spray"), Sébastien Weiller: http://www.theses.fr/2021UPSLM004

A technology successfully applied in Accelerators

Local coating:

Heat transfer:

Copper trips on FCC-hh beam screen prototype.



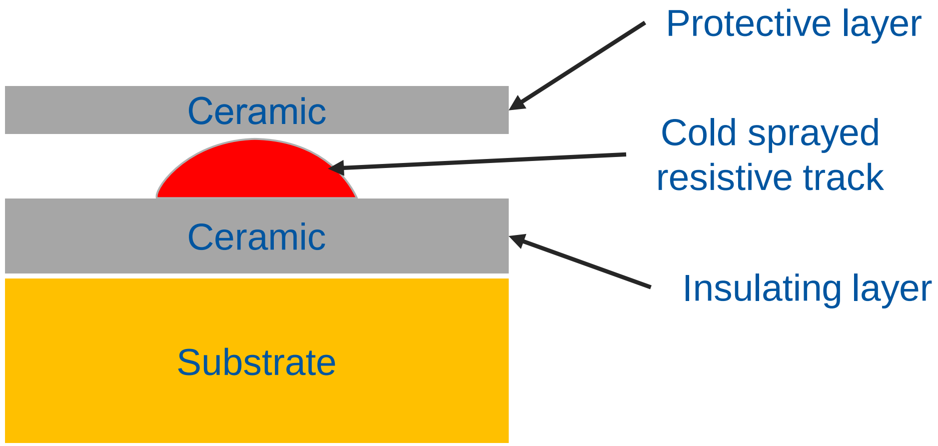
Electrode:

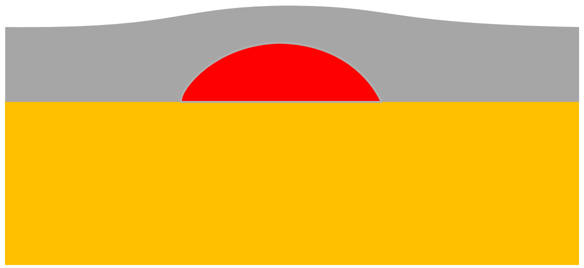
- Measurement of electrons for the FCC-hh beam screen prototype experiment at ANKA.
- Clearing electrode (optimisation of ceramic layer required for non-baked system).

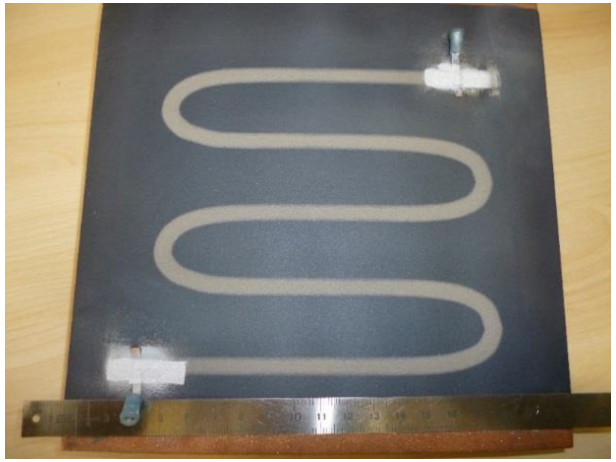
Copper and aluminium cold spray coating on ceramic insulated copper coated stainless steel sheet

Possible Applications in Accelerators

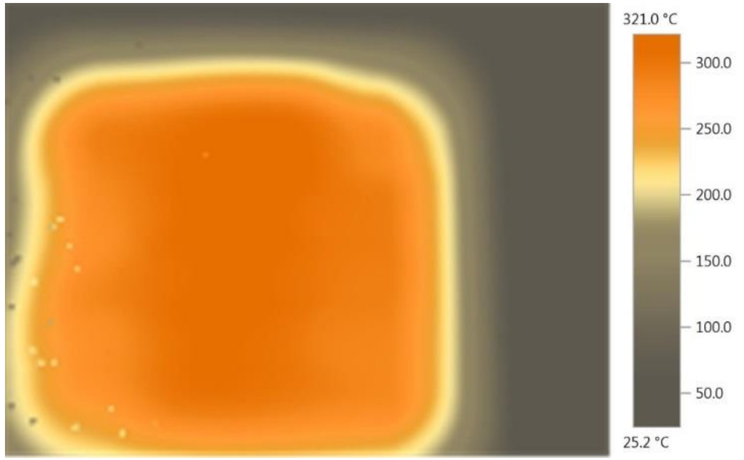
Local coating: Permanent radiation hard heating element for bake out (in or outside vacuum)







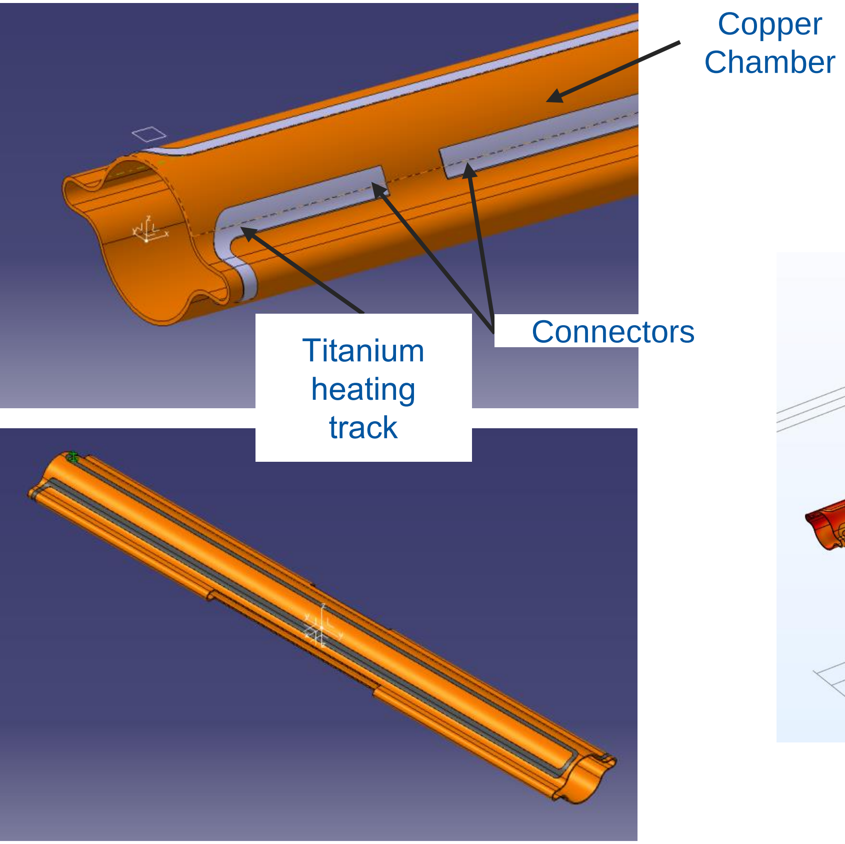
Copper plate with plasma sprayed ceramic and 0.2 mm thick cold sprayed titanium heating track

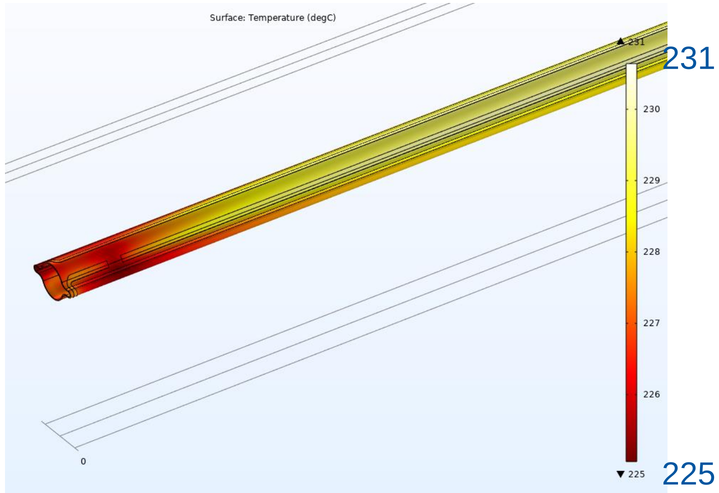


Measurement of the temperature field

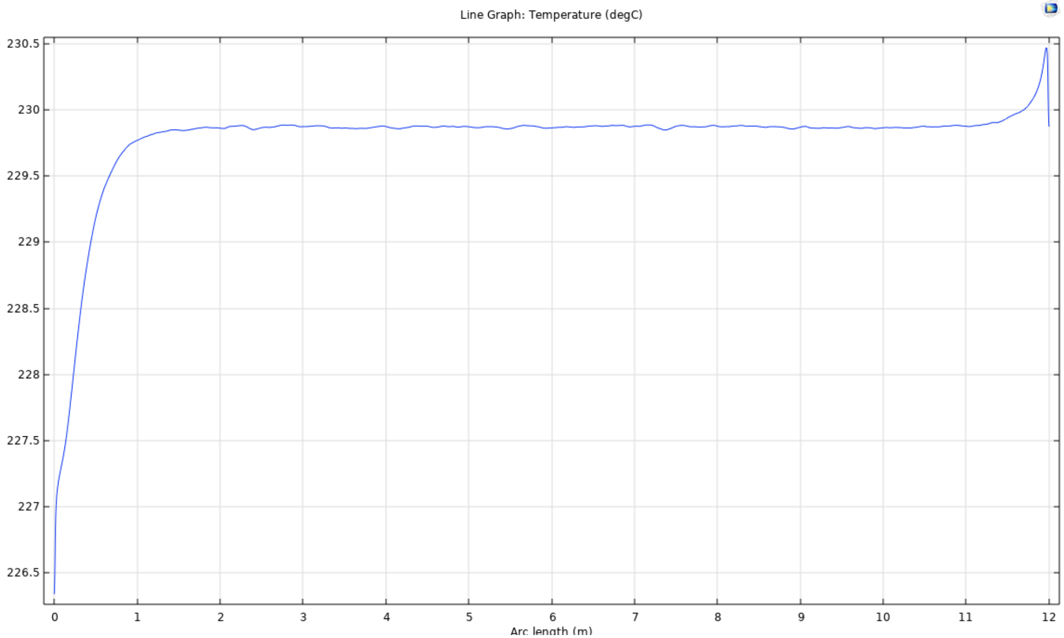
Possible Applications in Accelerators

Local coating: Permanent radiation hard heating element for bake out (in or outside vacuum)





Expected temperature field along the vacuum chamber

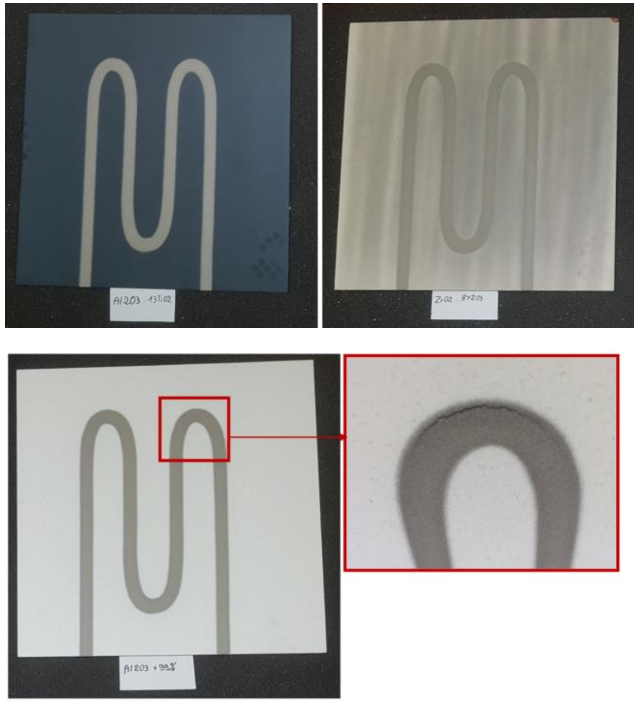


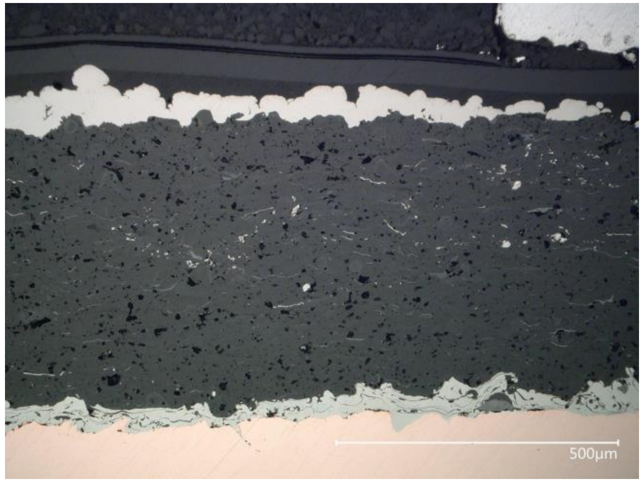
Expected temperature profile along the vacuum chamber

Study of the ceramic layer

Samples with different ceramics, ~ 0.5 mm thick, plasma sprayed on copper plates, have been manufactured:

- Al_2O_3 99%
- Al_2O_3 – 13 TiO_2
- Cr_2O_3 – 4 SiO_2 – 3 TiO_2
- ZrO_2 – 8Y_2O_3



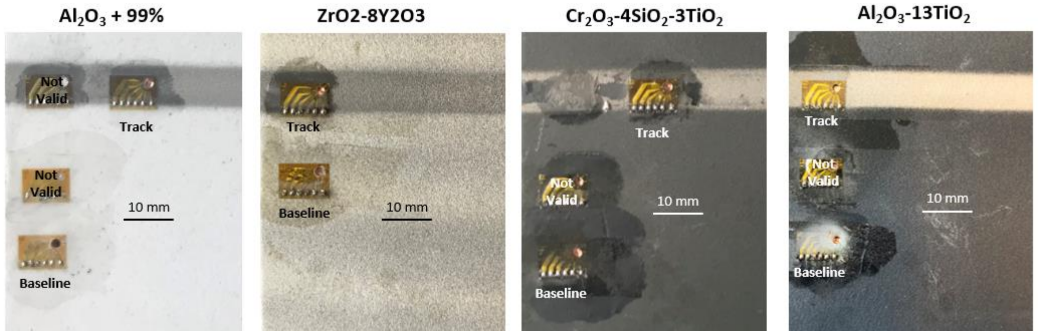


Al2O3+13TiO2

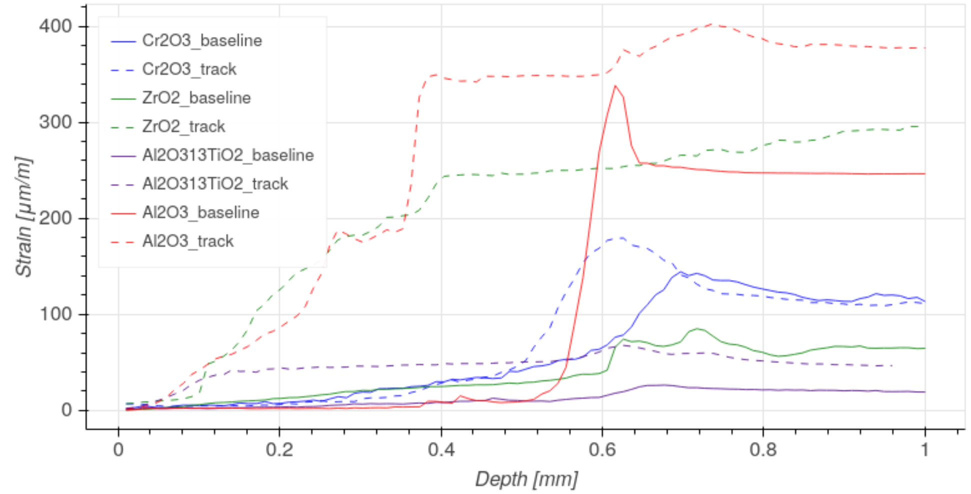
The different ceramic layer revealed different adhesion quality of the Ti track.

Residual stresses

Residual stresses have been assessed by hole drilling method, on the ceramic and on the track.

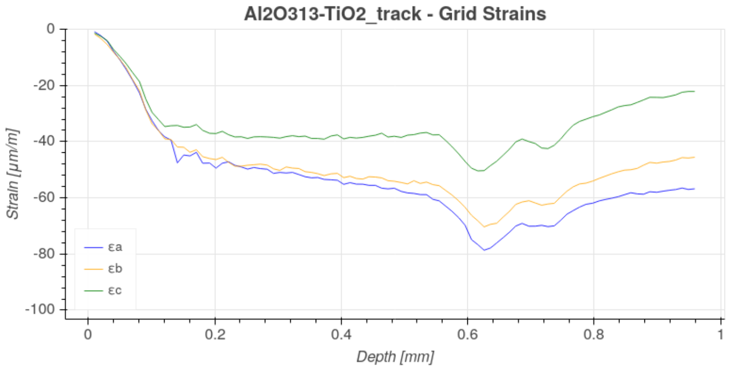


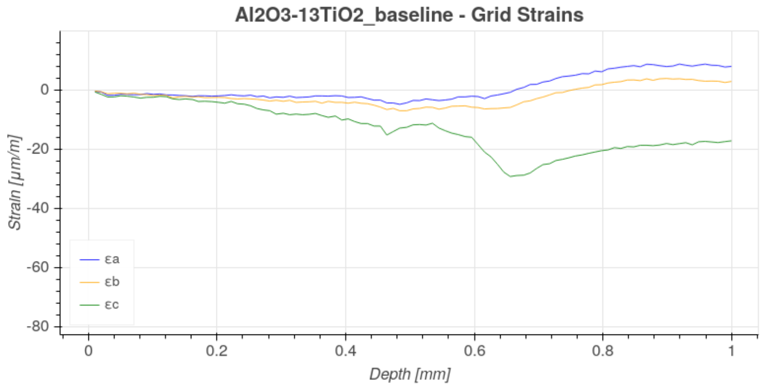
$$\epsilon_{vm} = \frac{1}{\sqrt{2}}\sqrt{(\epsilon_1-\epsilon_2)^2+(\epsilon_2-\epsilon_3)^2+(\epsilon_3-\epsilon_1)^2}$$



Comparative strain measurements

Significant difference is observed between the different ceramics. Al_2O_3-$13TiO_2$ exhibits the lowest residual stress, in the 10 MPa range.





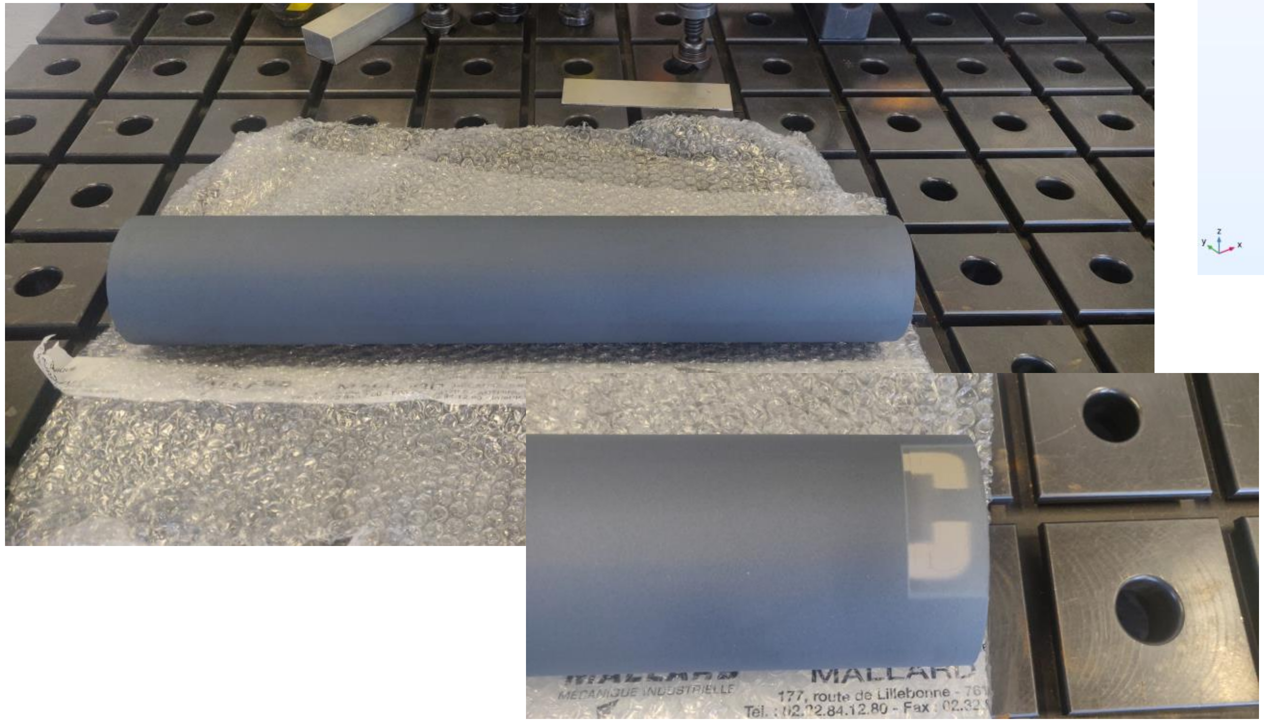
Strain measurements for Al_2O_3-$13TiO_2$ ceramic layer

Functional tests have been successfully carried out on the Al_2O_3-$13TiO_2$ plate, including 50 thermal cycles to 250 °C.

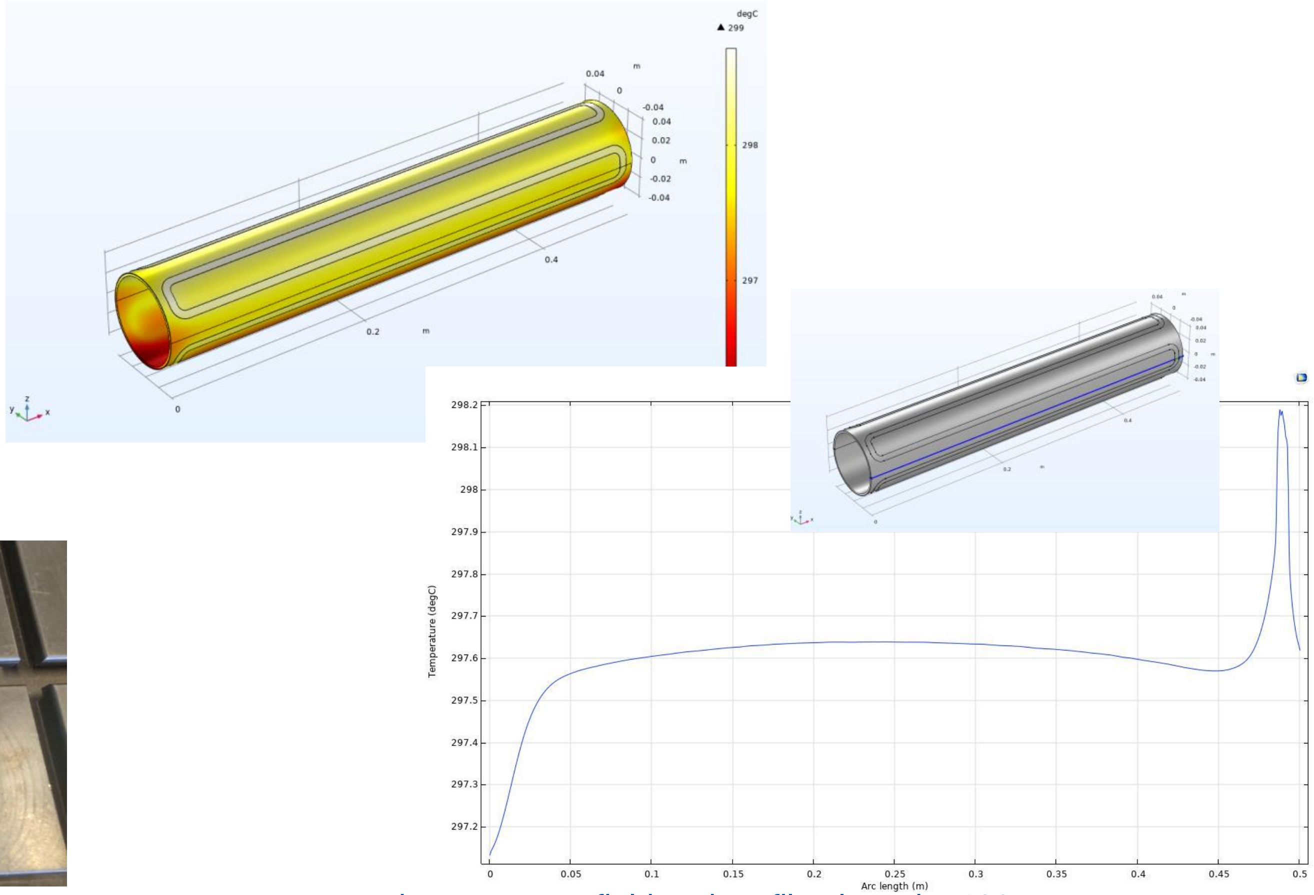
Prototype – Proof of concept

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

- OFE copper tube, 84 mm * 2 mm, 500 mm long
- Al_2O_3-TiO_2 ceramic layer
- Track in titanium, ~ 110 μm thick, 8 mm width
- Distance between the tracks: ~30 mm



Interfaces for the electrical connections

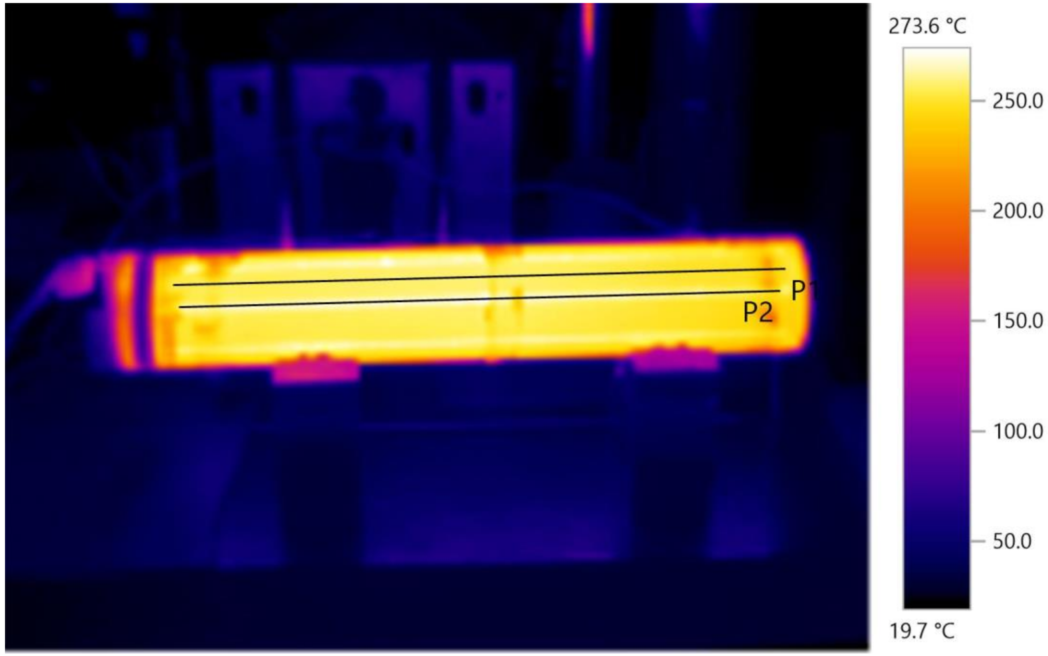


Expected temperature field and profile along the ϕ80 mm vacuum chamber prototype

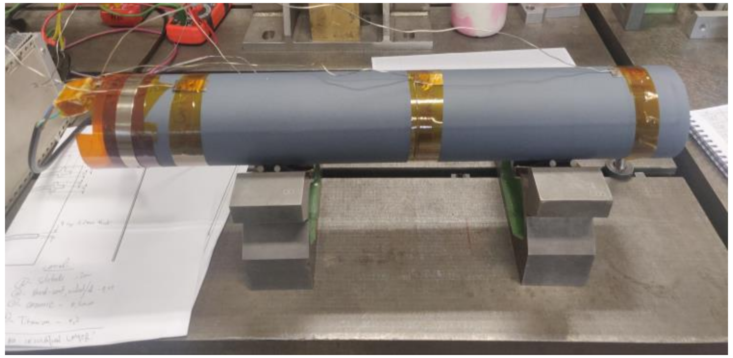
Prototype – Proof of concept

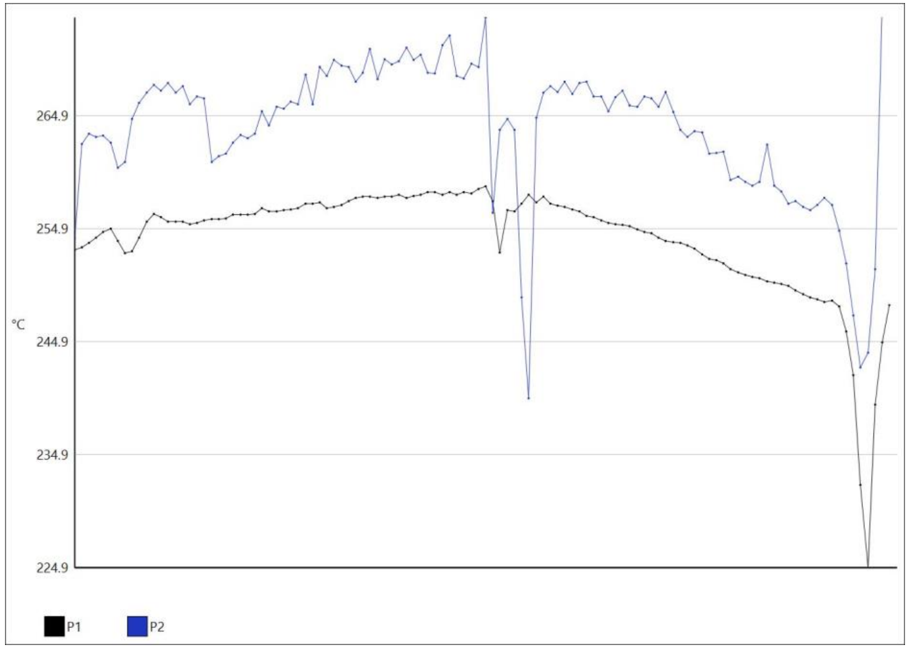
Thermal tests:

- Low thermal conductance supports
- DC current power supply
- Electrical connections clamped on the tube



Temperature field





Longitudinal temperature profile

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

Prototype – Proof of concept

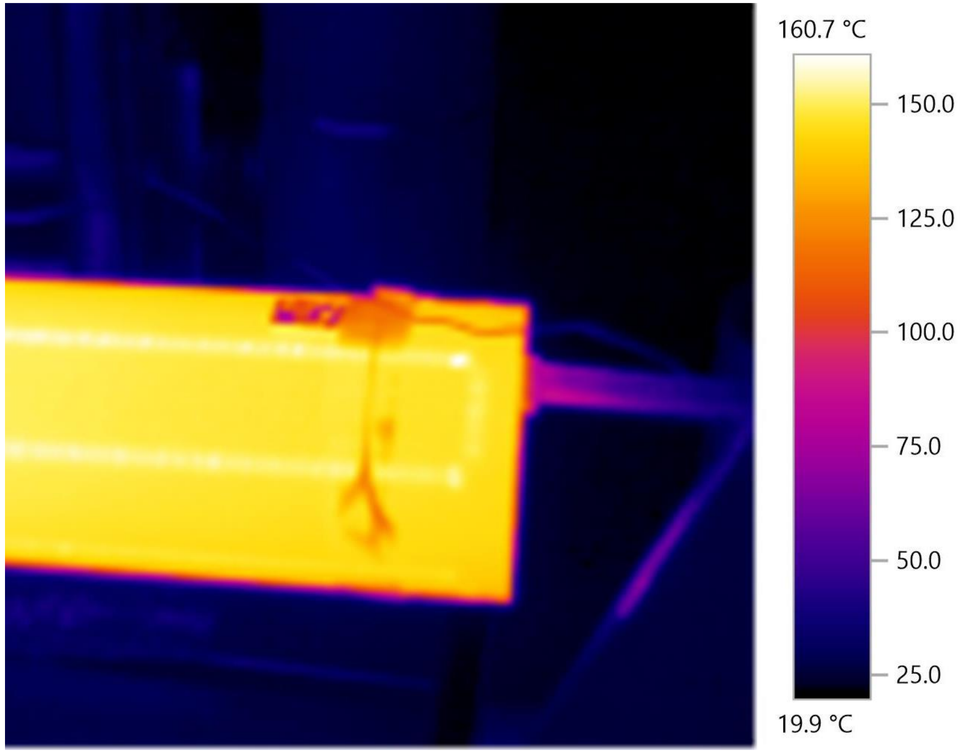
Some further developments are required:

1. Thickness irregularities have been observed in the corners of the track (different speed of the gun) → cold spots (thicker) and hot spots (thinner).

→ Better management of the robot displacement required.

→ Tests of different track U turn paths.

Thickness irregularities



Hot/cold spots induced by thickness irregularities

2. Measurements of the electrical resistance is not in agreement with expected value → measurement of resistivity of cold sprayed material ongoing.
3. Electrical connections to be defined for a safe operation.

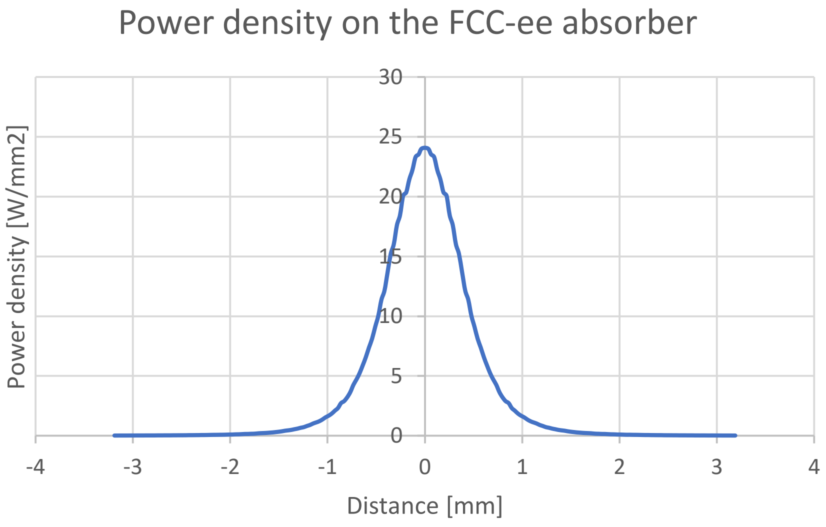
Prototyping phase

Different technologies are being assessed, on small samples, independently and in parallel:

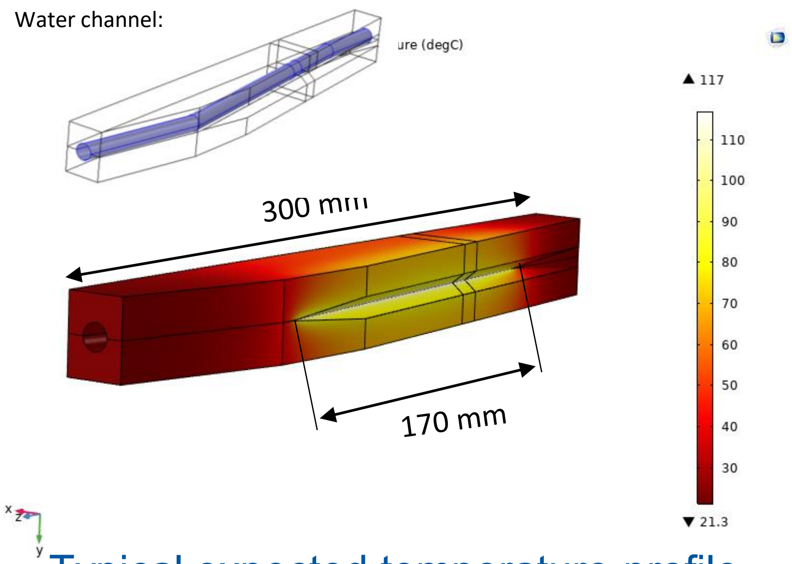
- SMA connectors
- Copper cold spray additive manufacturing
- Radiation hard permanent bake out system
- Friction stir welding

In parallel:

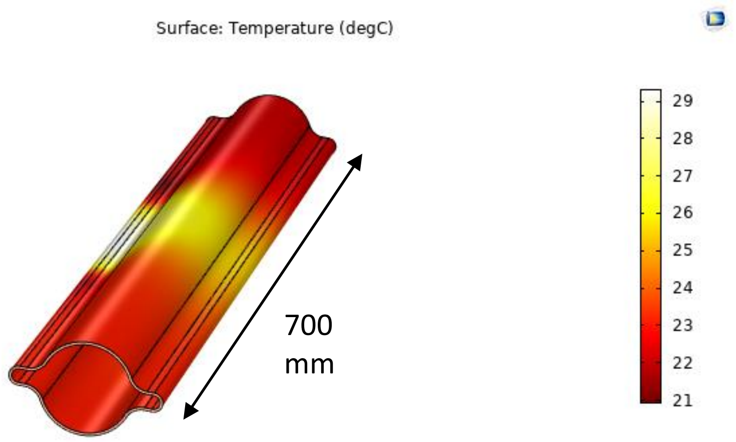
1. Design of lump absorbers: thermal mechanical study, water cooling, assembly to the vacuum chamber.



Heat deposition of ~4kW per absorber



Typical expected temperature profile



3.8 W power transmitted in the air (over 700 mm)

Prototyping phase

In parallel:

2. Alternative designs and manufacturing processes will be explored to take into account, in particular, the design and integration of the synchrotron radiation absorbers.

3. Discussions about the vacuum system integration, in particular in the magnets, just started. Significant changes, i.e. interbeam distance, length of interconnections with shielded bellows, might be required.

In a second step, the technologies will be applied for the manufacturing of a representative short vacuum chamber prototype:

- ~ 2 m
- Based on copper extrusion and lump absorber
- Early 2023

Conclusion

In a desire to propose cost-effective technical solutions for the FCC-ee vacuum system, the CERN vacuum group has undertaken a series of developments in UHV technologies:

- SMA connectors is a mature technology for UHV applications. Implementation study to FCC-ee has been initiated as well as the verification of its suitability to respond to the FCC-ee particularities.

- Radiation hard permanent bake out system is under development. Good progress has been done so far: proof of concept test has been successfully carried out.

- Additive manufacturing of copper by cold spray is in a first exploratory phase.

Further activities are initiated and will be reinforced in the near future:

1. Lumped absorber: thermal mechanical design, integration study and prototyping.

2. Interconnection: Some conceptual designs available. Technical design to be done.

3. Vacuum chamber prototype manufacturing.

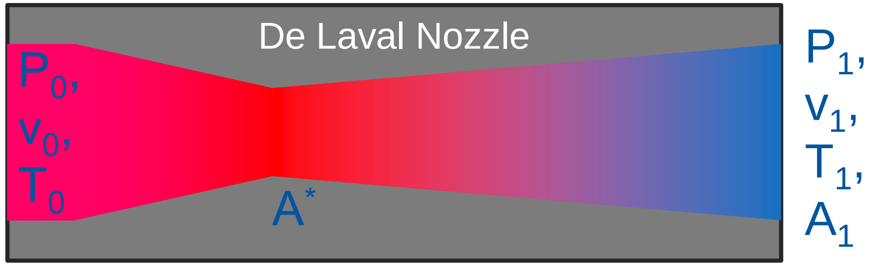
The development of the FCC-ee vacuum system and the related technologies started but requires significant efforts.

Thanks for your attention.

Thanks to the vacuum team, in particular Christian Duclos, Roberto Kersevan, Hendrik Kos, Marco Morrone, Fabrizio Niccoli and last but not least Samuel Rorison.

Principle of Cold Spray

1D isentropic flow equations:



$$\frac{P_0}{P_1} = \left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{\frac{\gamma}{\gamma - 1}}$$

$$\frac{T_0}{T_1} = 1 + \frac{\gamma - 1}{2} M_1^2$$

$$M_1 = \frac{v_1}{c_1} = \frac{v_1}{\sqrt{\gamma R_s T_1}}$$

$$\frac{A_1}{A^*} = \frac{1}{M_1}\left[\frac{2}{\gamma + 1}\left(1 + \frac{\gamma - 1}{2} M_1^2\right)\right]^{\frac{\gamma + 1}{2(\gamma - 1)}}$$

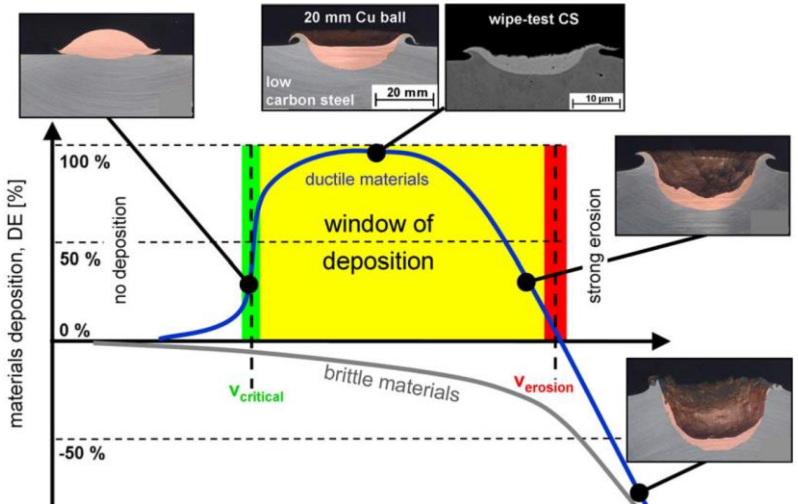
$$\gamma = \frac{c_p}{c_v}$$

γ=5/3 (1.67) for monoatomic perfect gas
γ=7/5 (1.4) for diatomic perfect gas and
γ=1,33 for polyatomic perfect gas

R_s is the specific gas constant given by R/M_{molar}

Nitrogen is commonly used. Helium is used to reach higher velocity.

Bounding mechanism

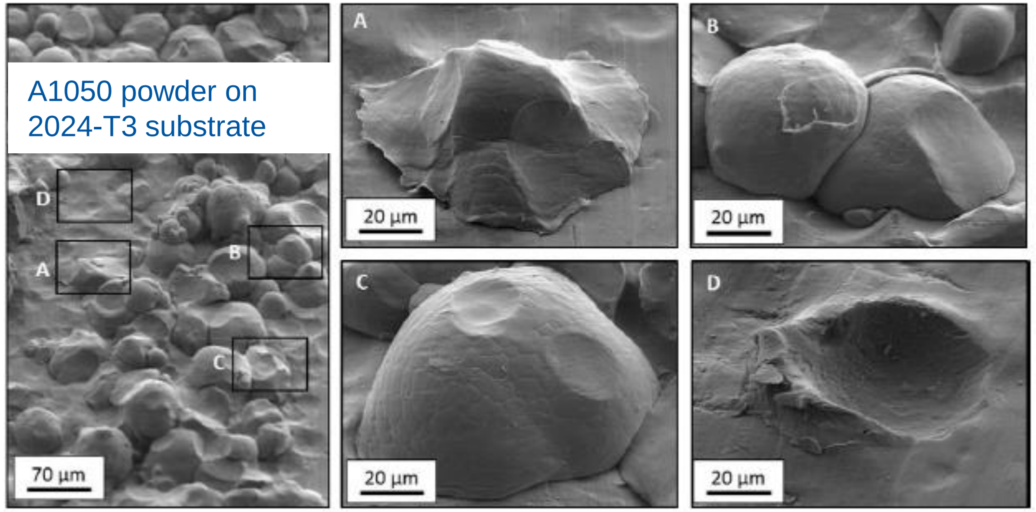


T. Schmidt et al., From Particle Acceleration to Impact and Bonding in Cold Spraying, Journal of Thermal Spray Technology, 18, 5-6, 794-808, 2009

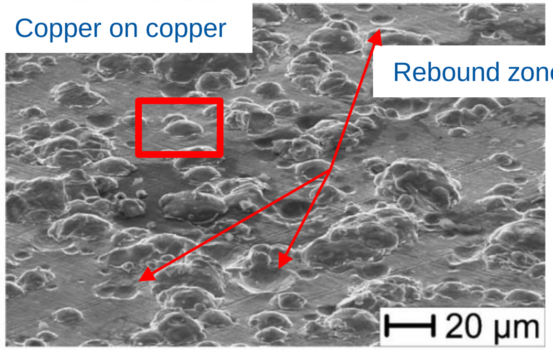
Table 1 Values of critical velocity for bonding assuming a particle size of 20 µm

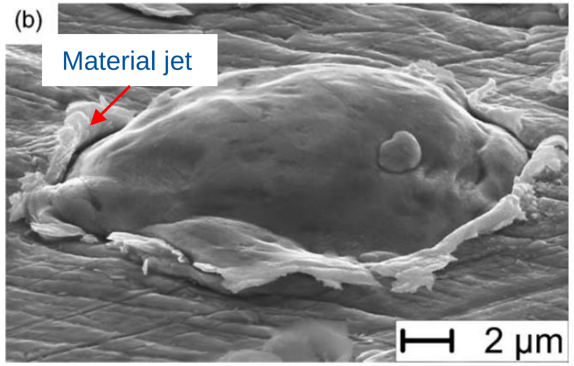
Material	Melting point, °C	Critical velocity, m/s
Aluminium	660	620-660
Titanium	1670	700-890
Tin	232	160-180
Zinc	420	360-380
Stainless steel (316L)	1400	700-750
Copper	1084	460-500
Nickel	1455	610-680
Tantalum	2996	490-650

Typical surface around the critical velocity



Q. Blochet, Influence of substrate surface roughness on cold-sprayed coating-substrate bond strength in aluminum-based systems, PhD Thesis, Mines ParisTech, 2015





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

Some properties: example of copper

Electrical conductivity

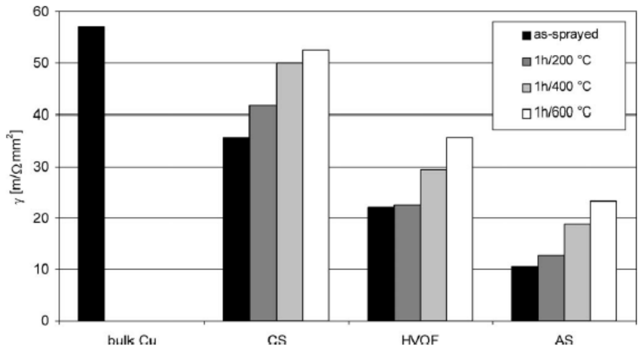


Fig. 9. Conductivity of Cu-coatings processed by cold spraying, HVOF spraying and arc spraying in the as-sprayed state and after different annealing conditions. Annealed bulk Cu serves as reference material.

T. Stoltenhoff et al., Microstructures and key properties of cold-prayed and thermally sprayed copper coatings, Surface & coatings Technology, 200, 2006

Bounding strength

With helium

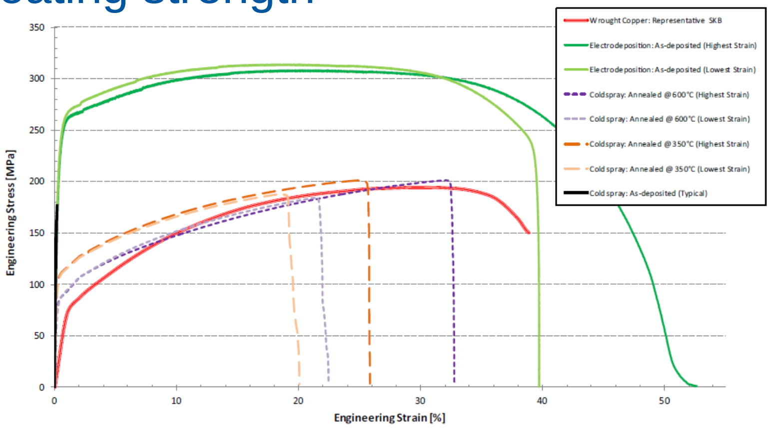
Coating material	Substrate material	Substrate preparation	Bond strength		Reference
Cu	Aluminum	Grit blasting	30–35	ASTM C-633	Taylor et al. (2006)
Cu	Copper, AA5052, AA6063		> 150	Modified tensile test	Huang and Fukanuma (2012)

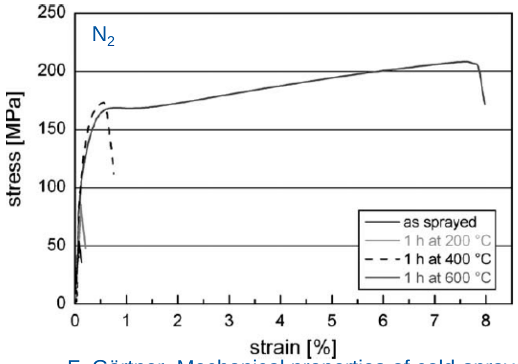
With nitrogen

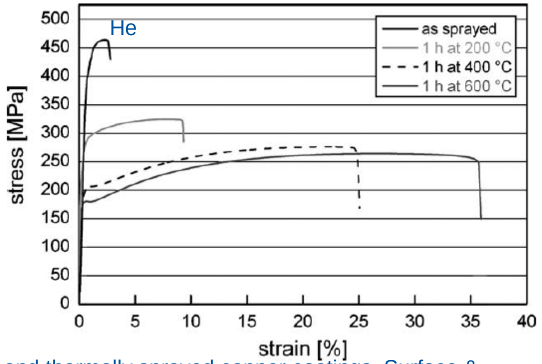
Cu	Copper	Grit blasting	17	JIS H 8664	Fukanuma and Ohno (2004)
Cu	Aluminum	Grit blasting	24	JIS H 8664	Fukanuma and Ohno (2004)
Cu	Aluminum	Grit blasting	> 40	ASTM C-633	Gärtner et al. (2006)
Cu	Steel	Grit blasting	10–20	ASTM C-633	Gärtner et al. (2006)
Cu	Aluminum, Copper	Grit blasting	40	EN 582	Stoltenhoff et al. (2006)
Cu	Steel	Grit blasting	10	EN 582	Stoltenhoff et al. (2006)
Cu	Copper, AA5052, AA6063		> 100	Modified tensile test	Huang and Fukanuma (2012)
$Cu+Al_2O_3$	Copper, steel	Grit blasting	20–23	EN582	Koivuluoto et al. (2008a, b)

After Jeandin et al., Coating properties in Modern cold spray, Ed. J. Villafuerte, Springer, 2015

Coating strength







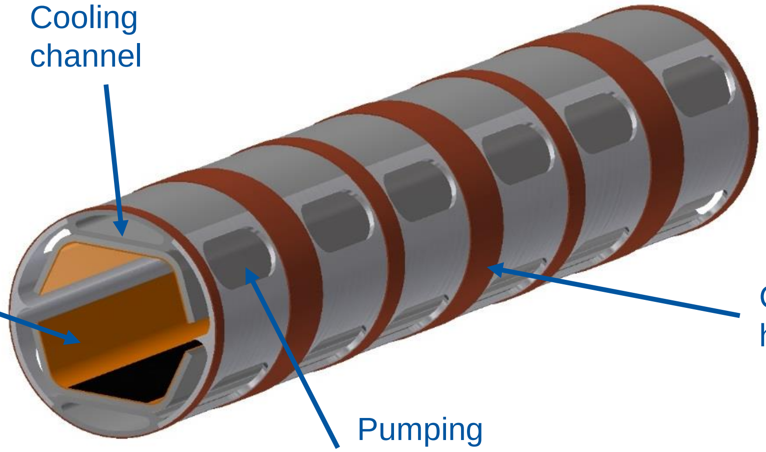
C.H. Boyle, Mechanical performance of integrally bounded copper coatings for the long term disposal of used nuclear fuel, Nuclear Engineering and design, 293, 2015

F. Gärtner, Mechanical properties of cold-sprayed and thermally sprayed copper coatings, Surface & Coatings Technology 200, 2006

→ Material properties are affected by the cold spray process but they can significantly be recovered by dedicated post treatment.

Application to FCC

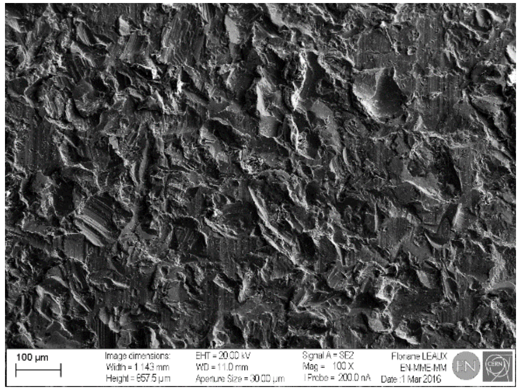
FCC-hh beam screen



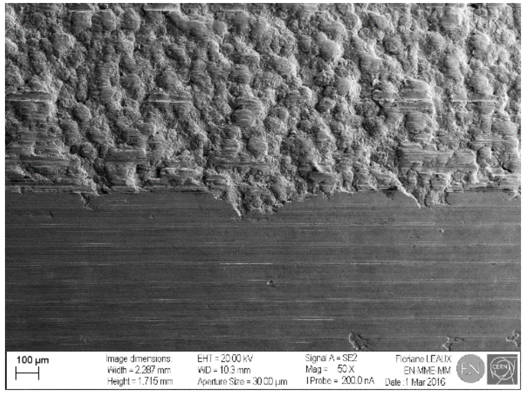
Requirements:

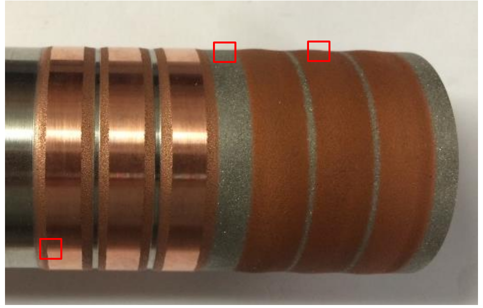
- Copper material (thermal conductivity)
- Stainless steel substrate
- Discountinuous (longitudinally → reduced Lorentz forces during a magnet quench)
- Continuous as close as possible to the cooling channel (better cooling and temperature control)
- Done after beam screen assembly (welds)
- No spray or coating contamination inside the beam screen
- Industrial process

Application to FCC beam screen

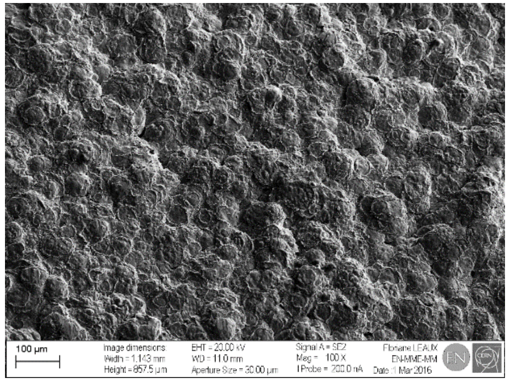


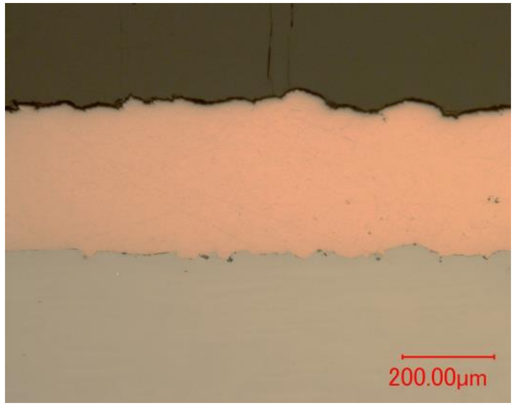
Surface preparation by blasting (Al_2O_3)





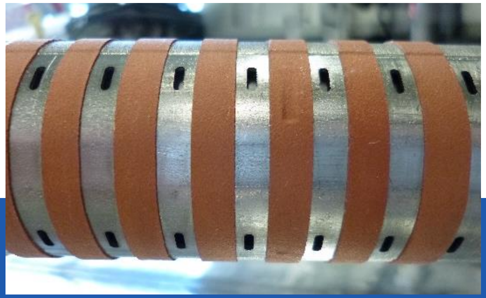
Cold sprayed copper on austenitic stainless steel.



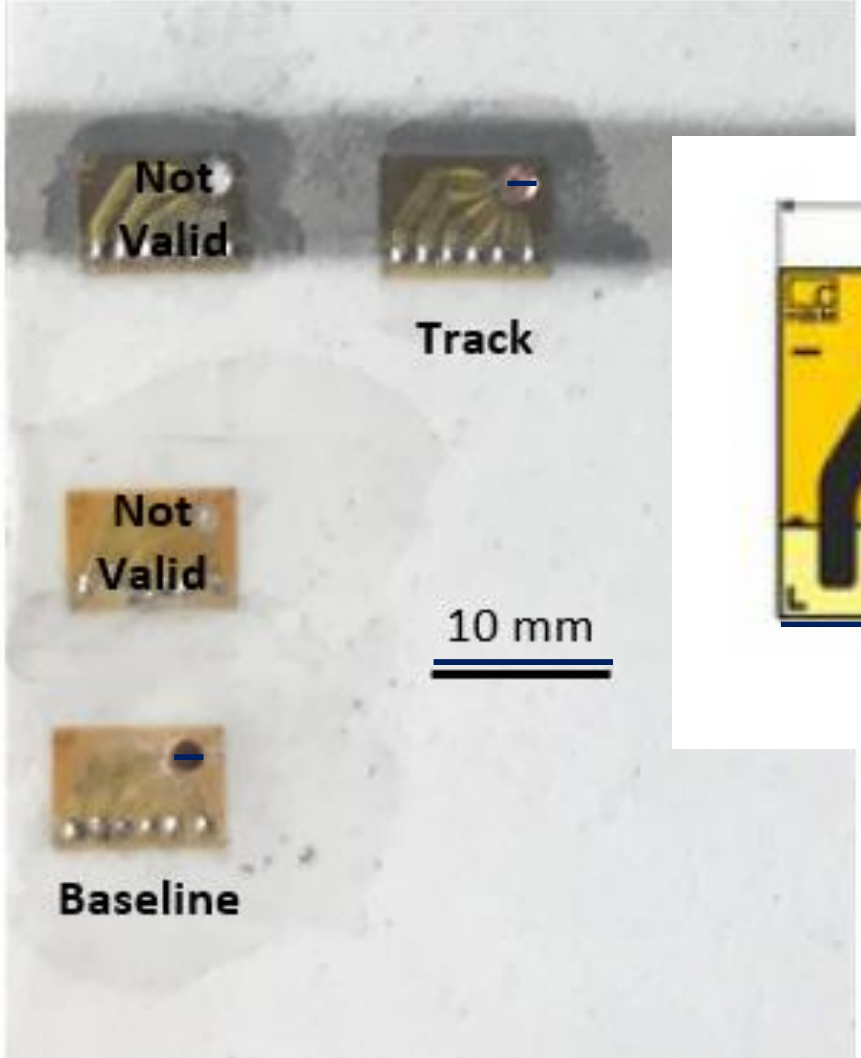


Possible improvements:

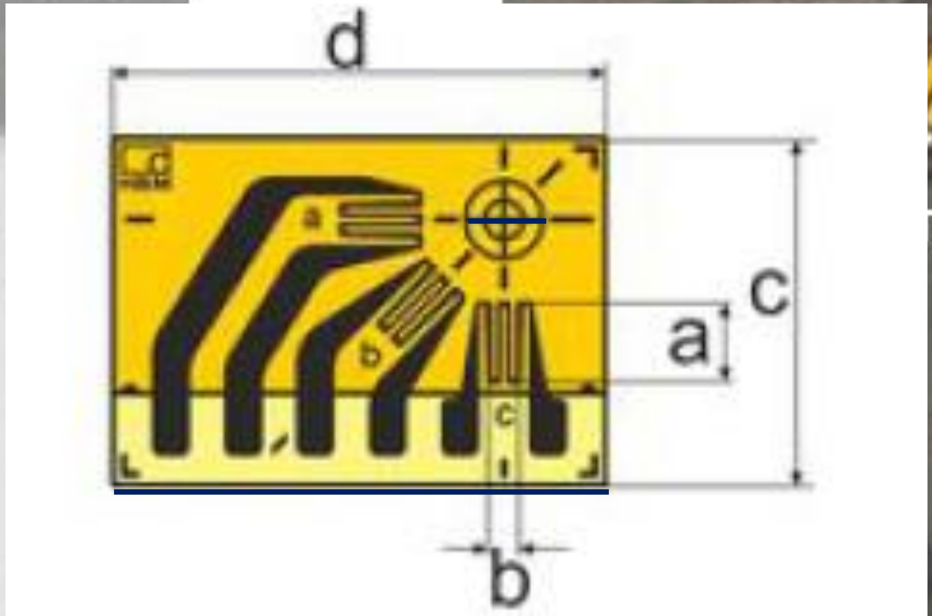
- Surface preparation: laser treatment
- Nozzle geometry: correct width
- Process parameters

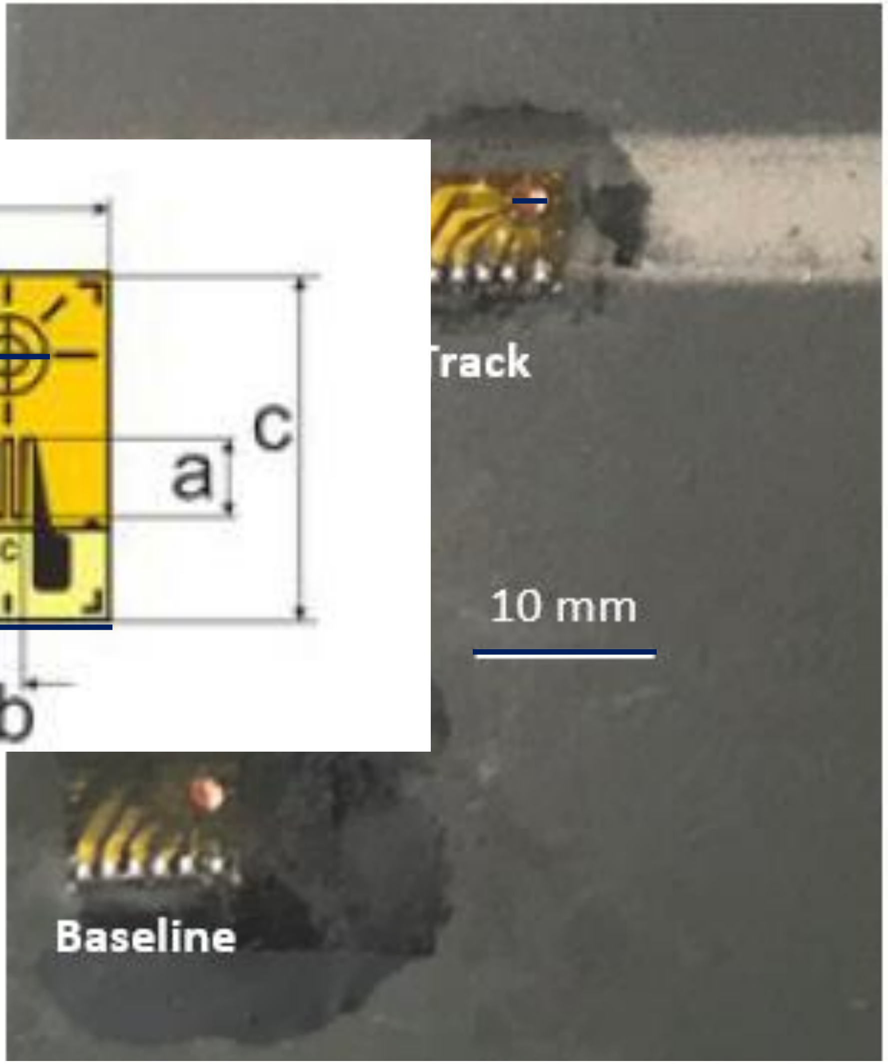


Al_2O_3 + 99%



Cr_2O_3-$4SiO_2$-$3TiO_2$





35