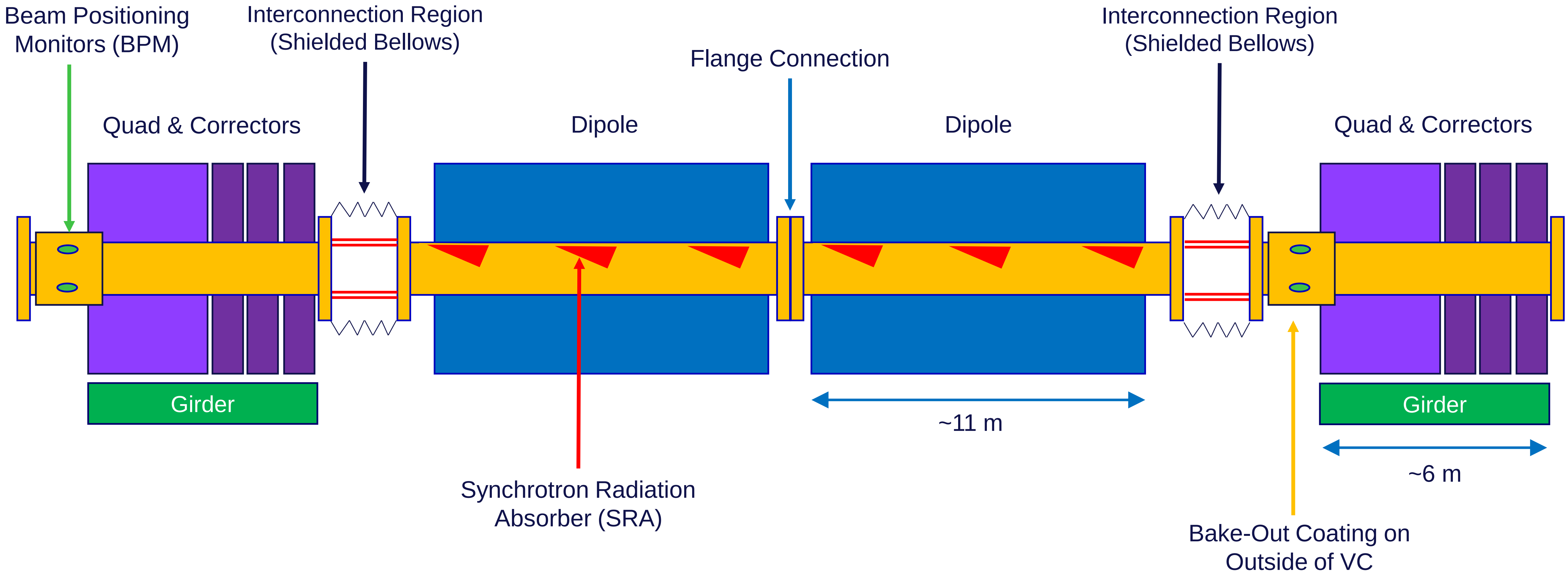
MATERIAL STUDY FOR THE FCC-EE ARC VACUUM SYSTEM

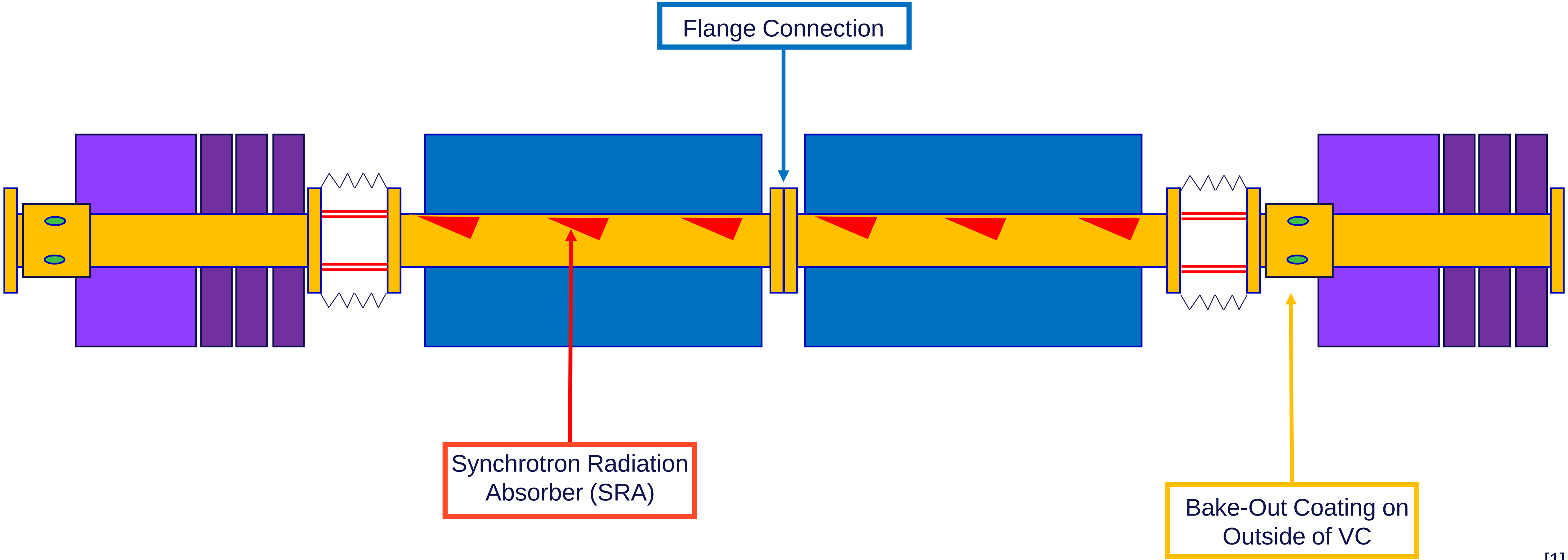
Martin Bammer
TE-VSC-DLM
TU Wien

FCC-ee Arc: Functional Layout



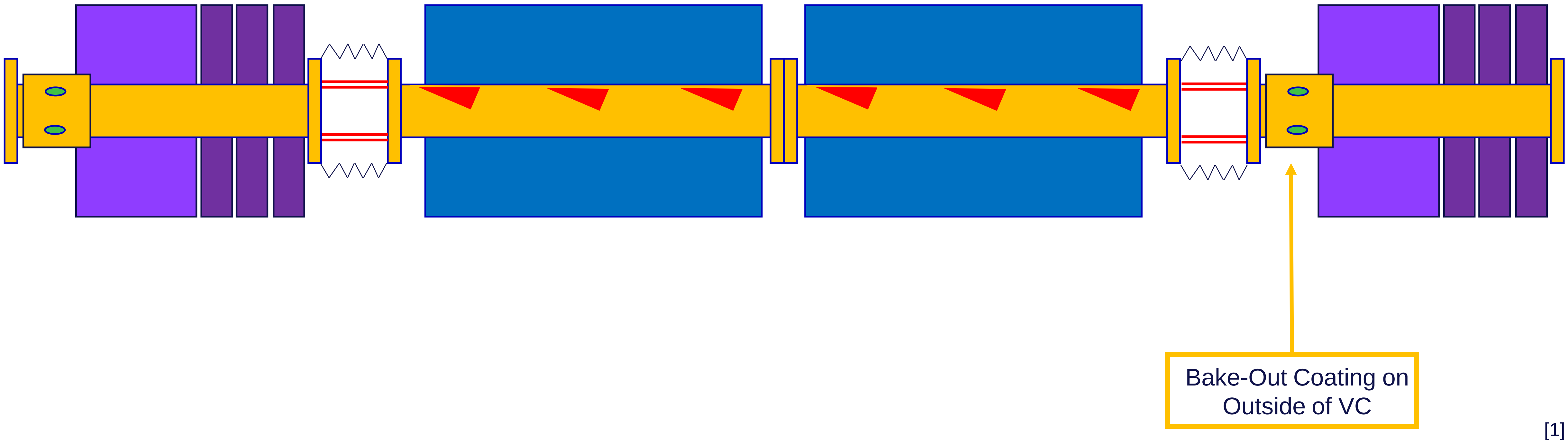
[1]

FCC-ee Arc: Functional Layout



[1]

FCC-ee: Ceramic/Metal Sandwich Study

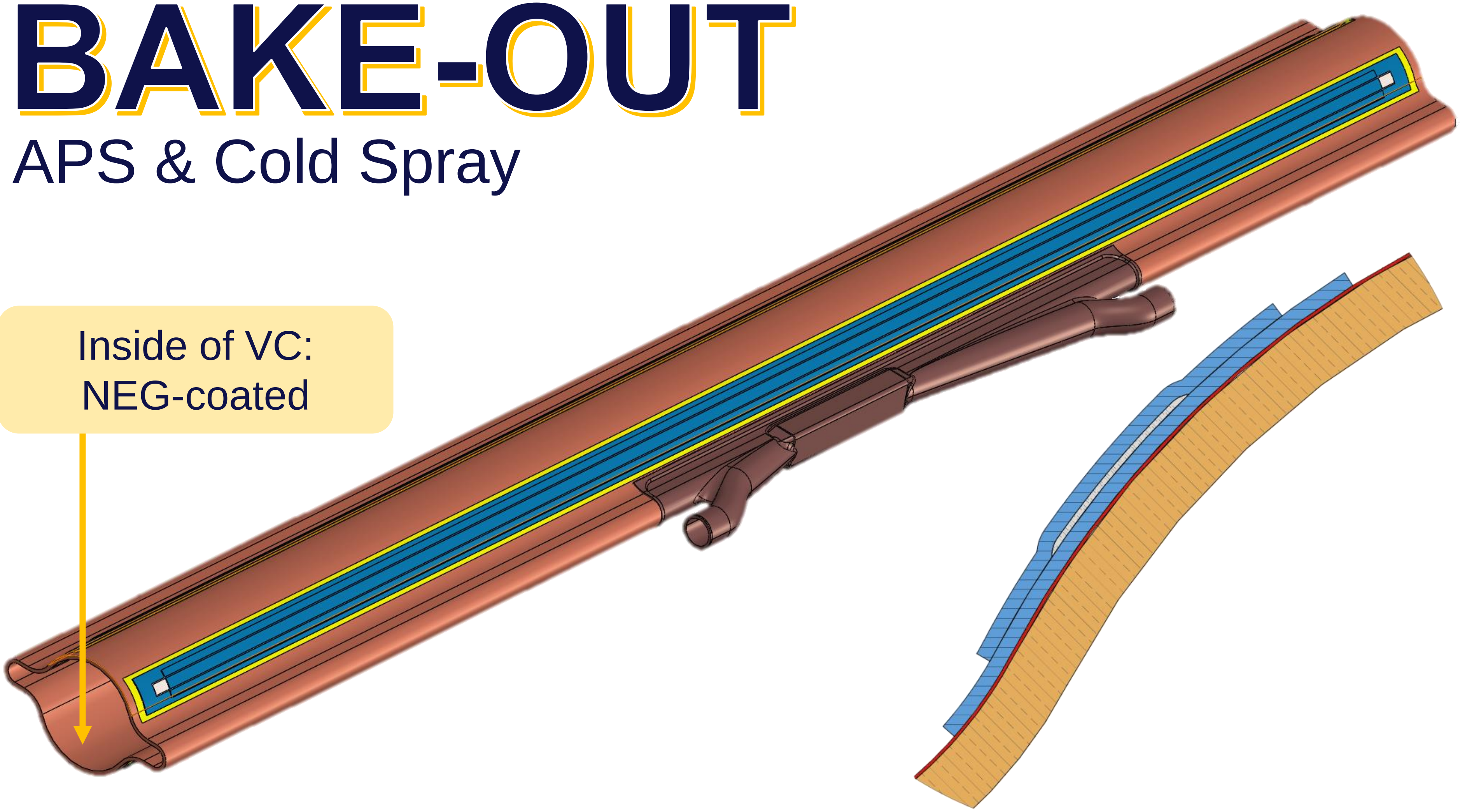


[1]

BAKE-OUT

APS & Cold Spray

Inside of VC:
NEG-coated

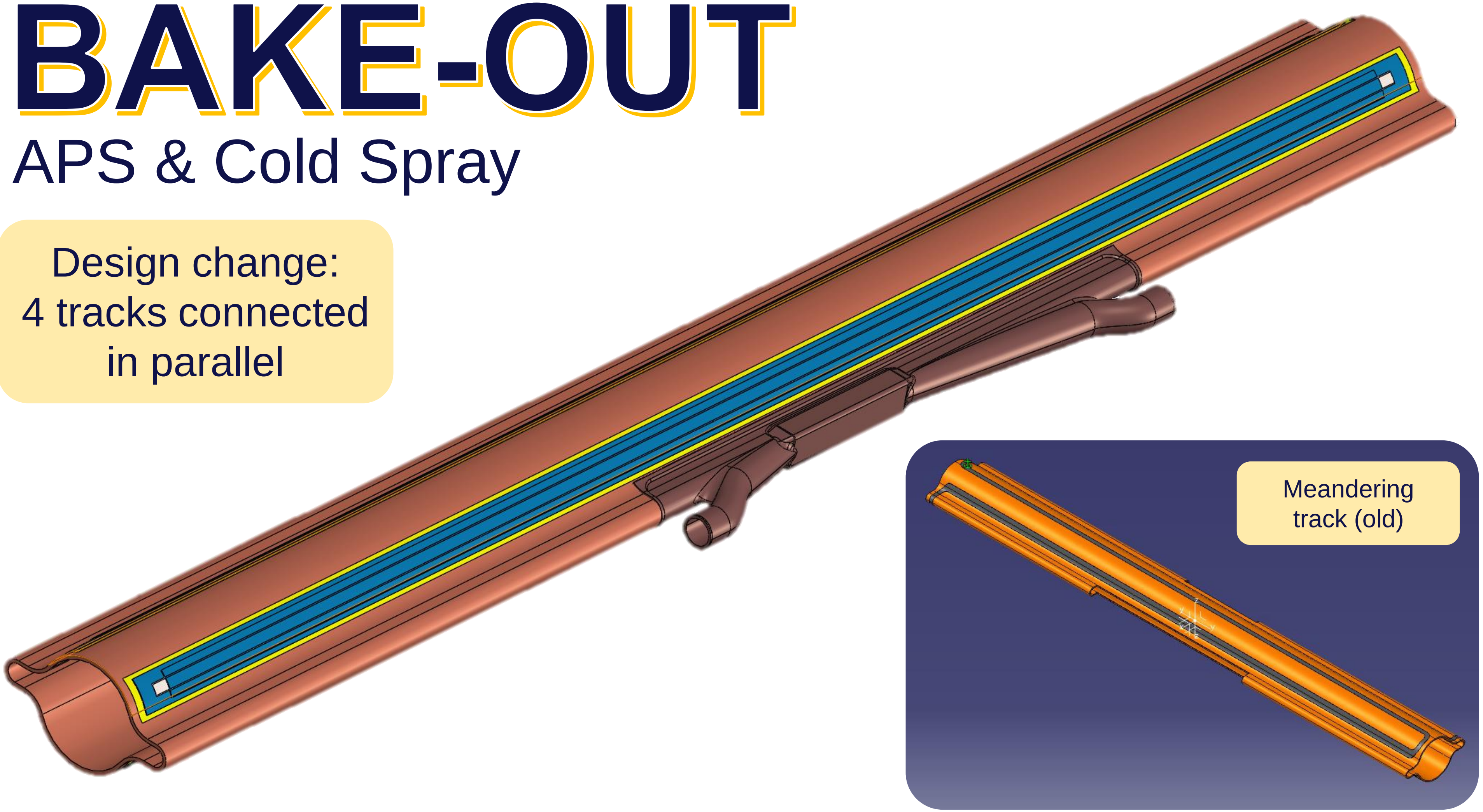


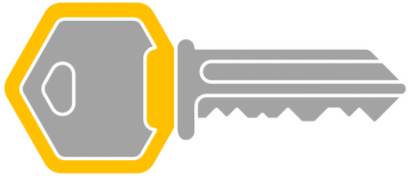
- T_B = 230 – 250°C
- Low porosity
- Insulator: High el. resistivity while th. cond. as high as possible
- Difference in th. exp. coeff. ↓
- As thin as possible
- Reduce cost

BAKE-OUT

APS & Cold Spray

Design change:
4 tracks connected in parallel





T_B = 230 – 250°C

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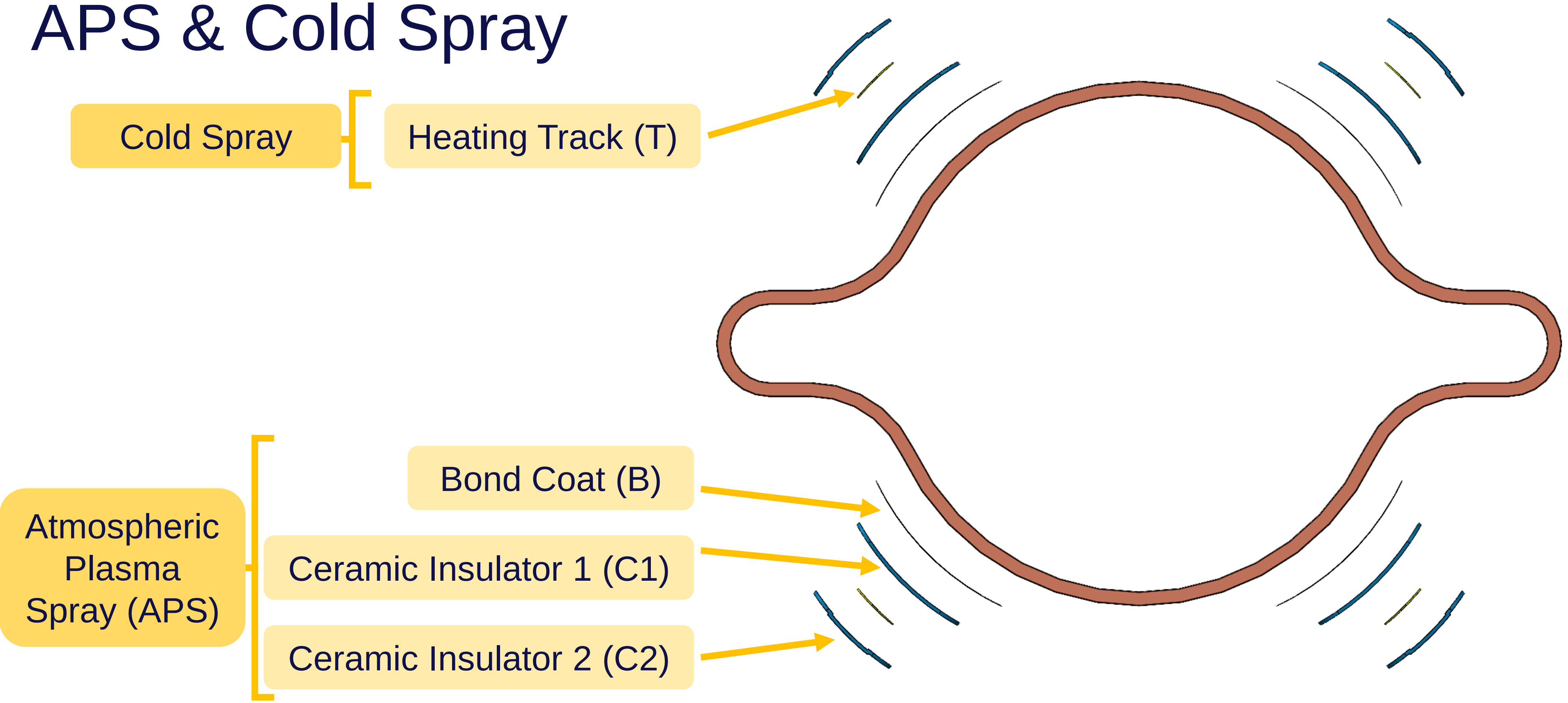


Vacuum Chamber: Cu-OFS

Bond Coat: NiCr20

Ceramic Insulator Choice 1: „Alumina-Titania“ Al_2O_3+TiO_2 87/13

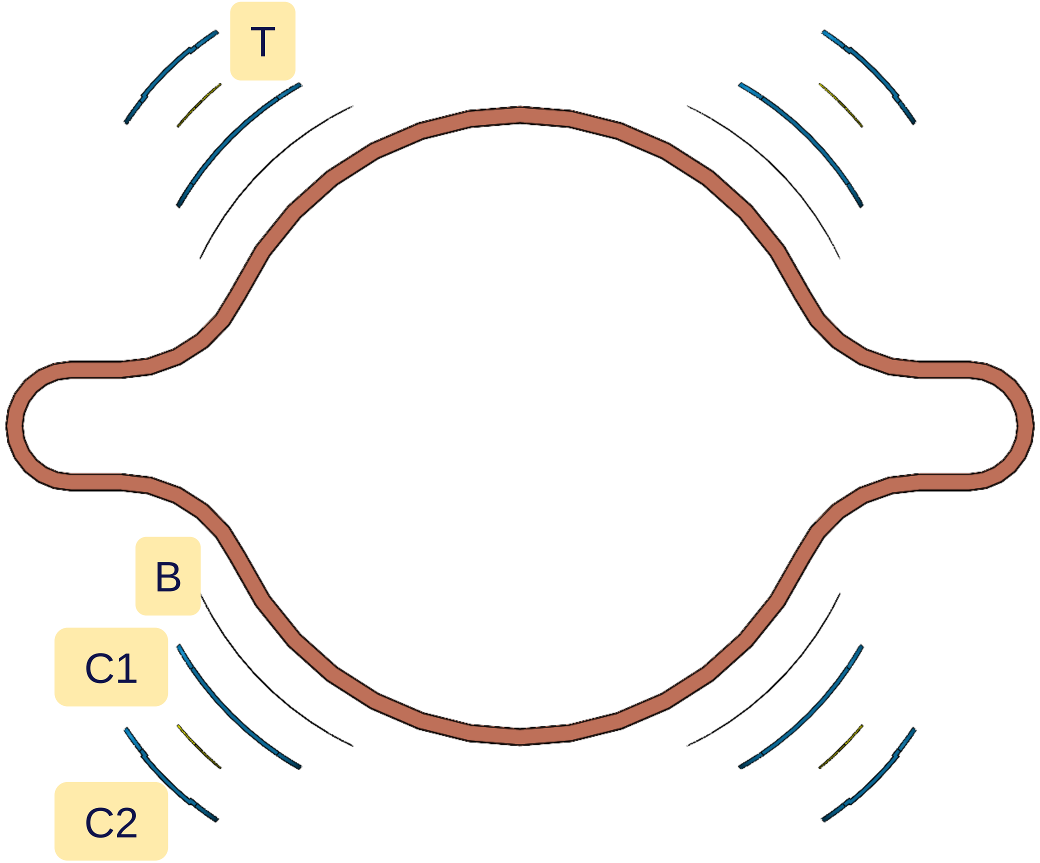
Ceramic Insulator Choice 2: “Spinel” Al_2O_3+MgO 72/28

Heating Track: Ti grade 4

BAKE-OUT

APS & Cold Spray

Layer	N. Thickness (µm)	
B	50	
C1	300	500
T	200	
C2	500	
Total ∑	1050	1250



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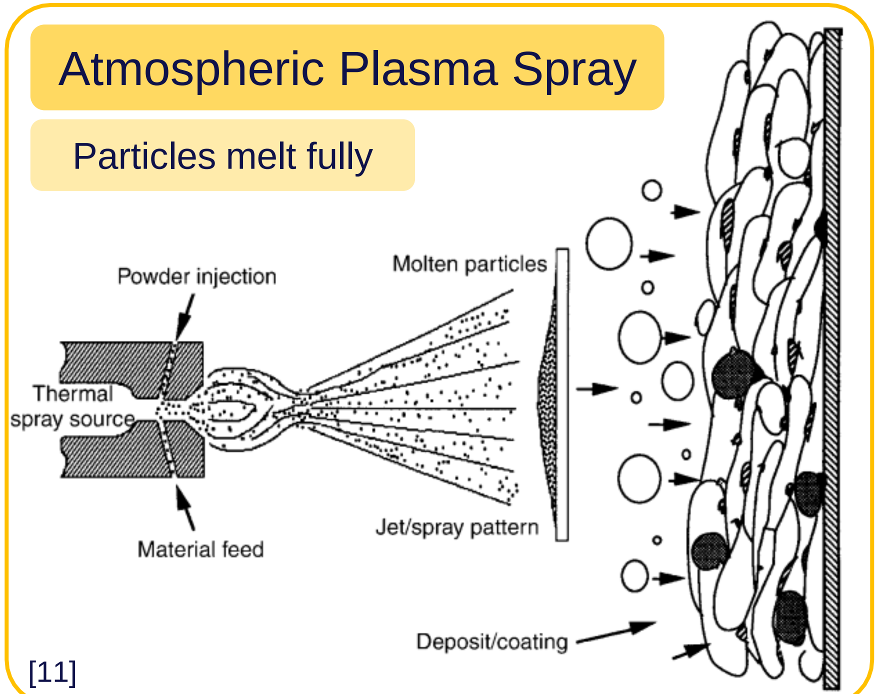
BAKE-OUT

APS & Cold Spray

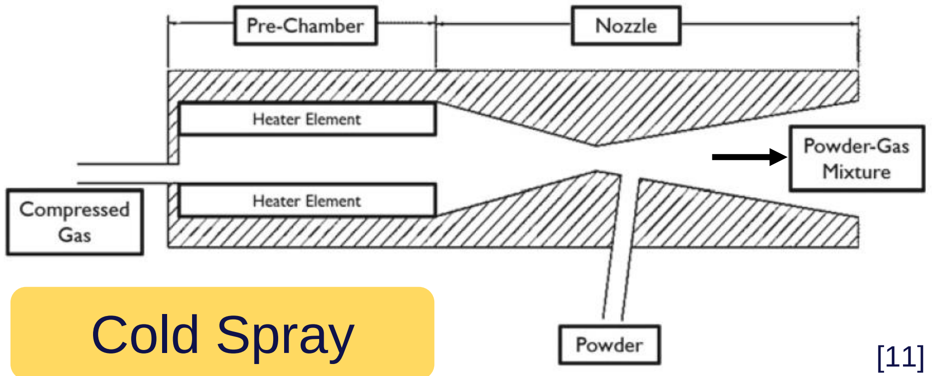
Atmospheric Plasma Spray

Particles melt fully



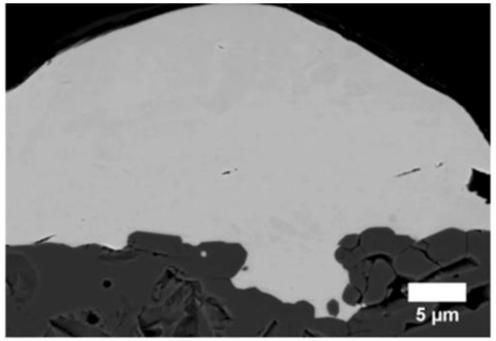
[11]

Particles are superplastically deformed



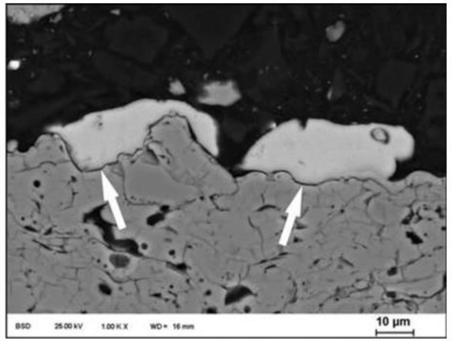
Cold Spray

[11]



[4]

CS: Ti on Al2O3



[4]

CS: Al on Al2O3

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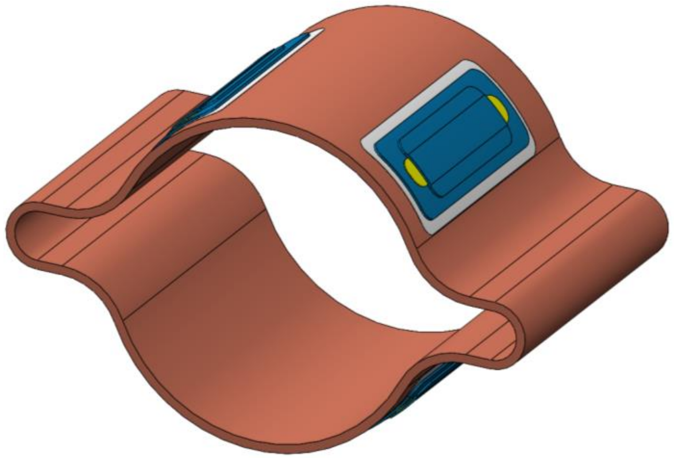
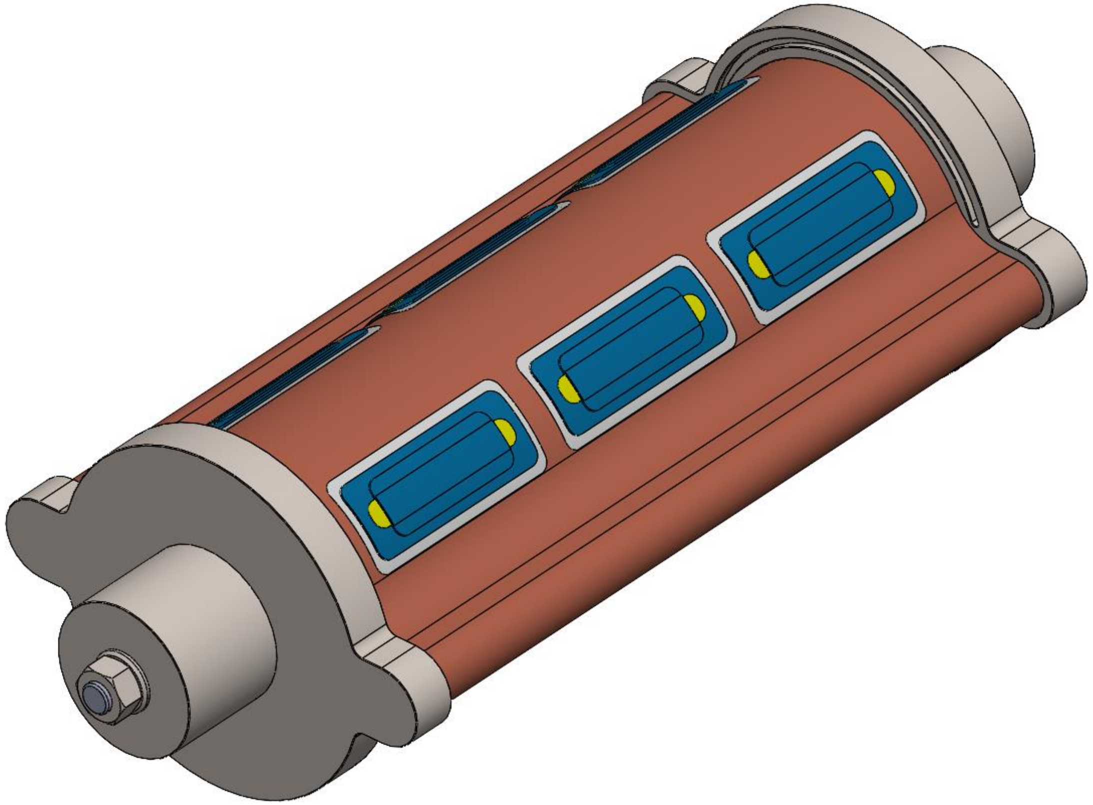
BAKE-OUT

Testing Samples





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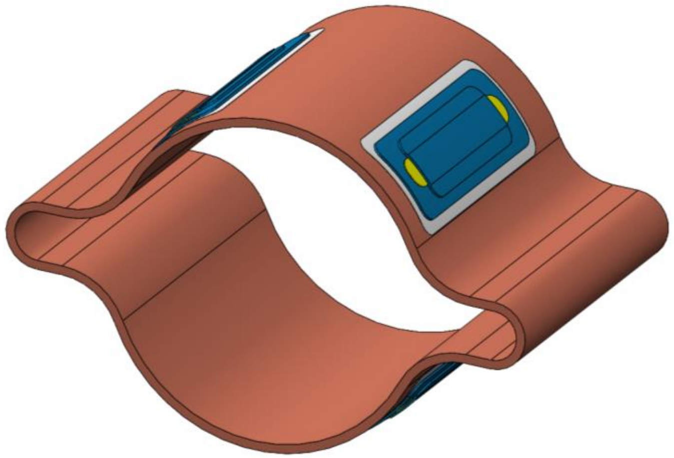

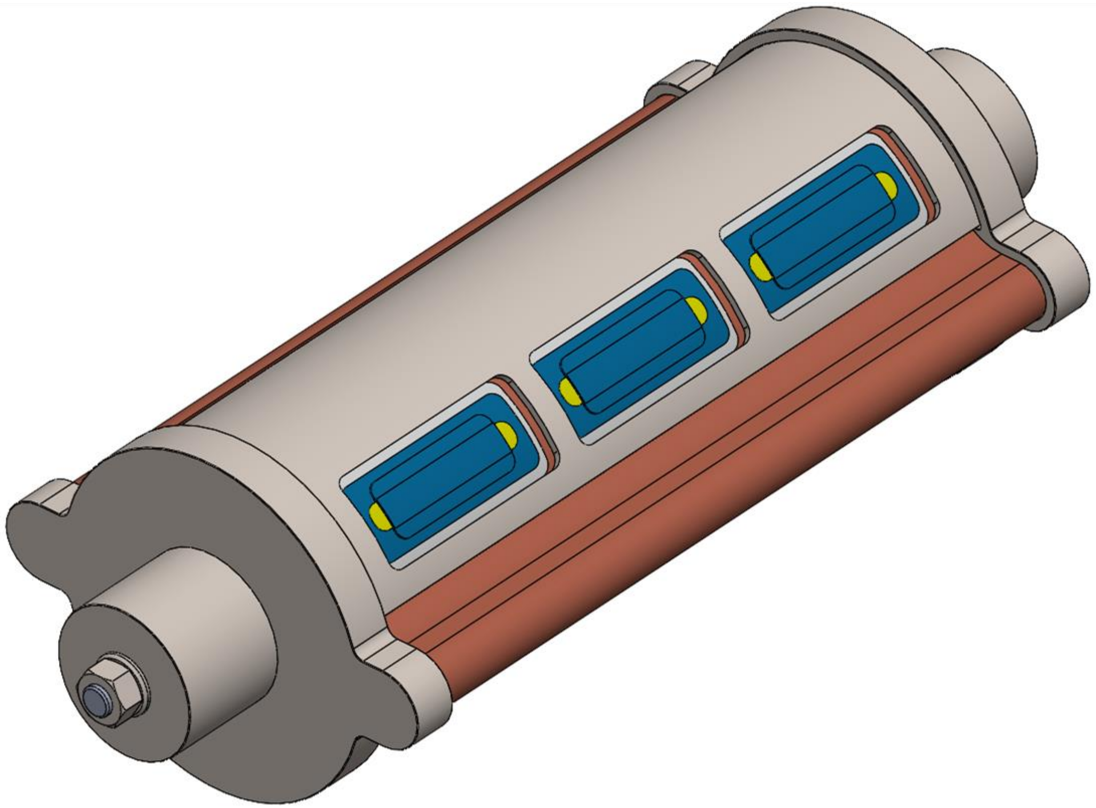

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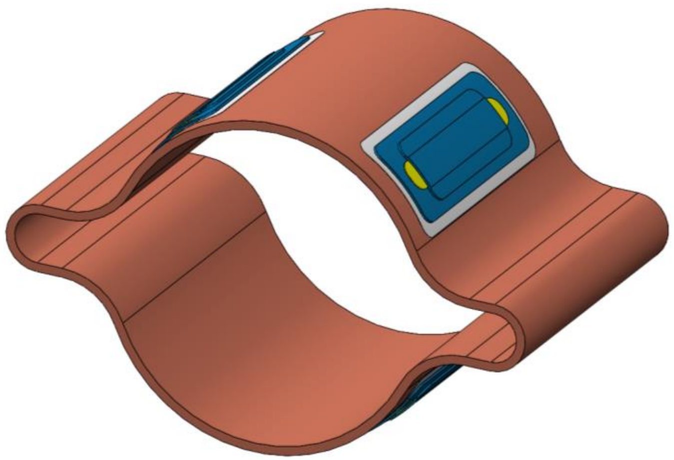

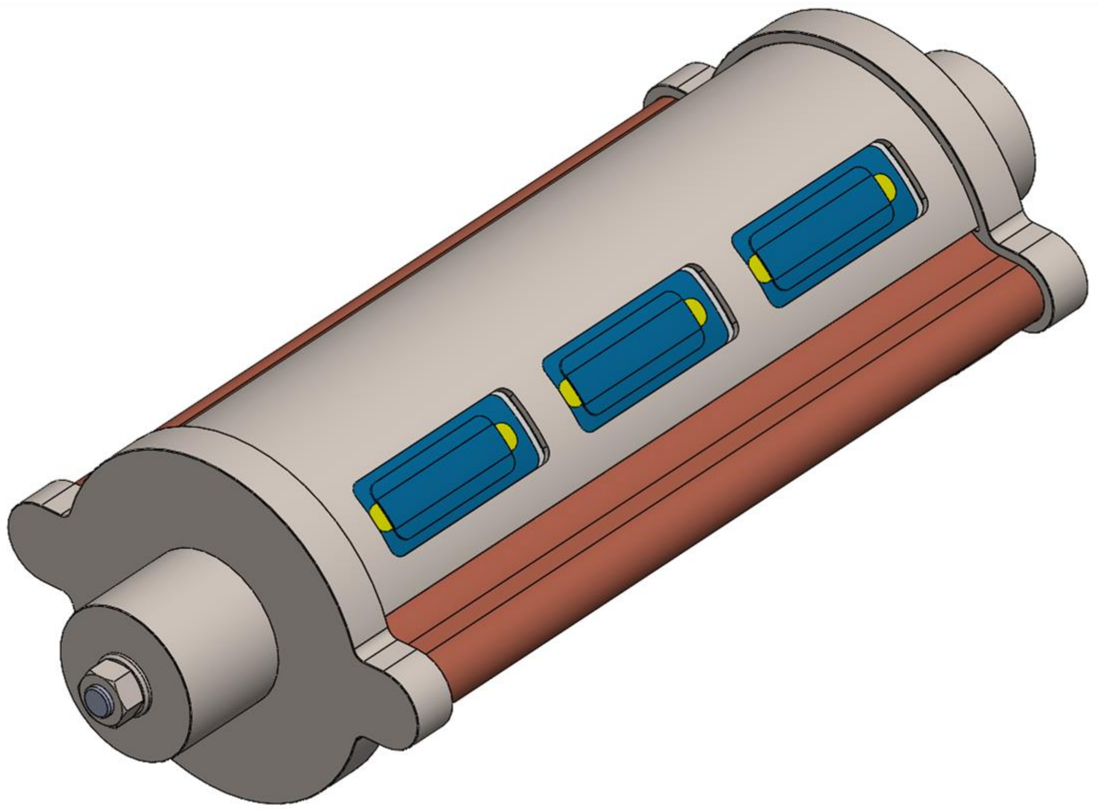

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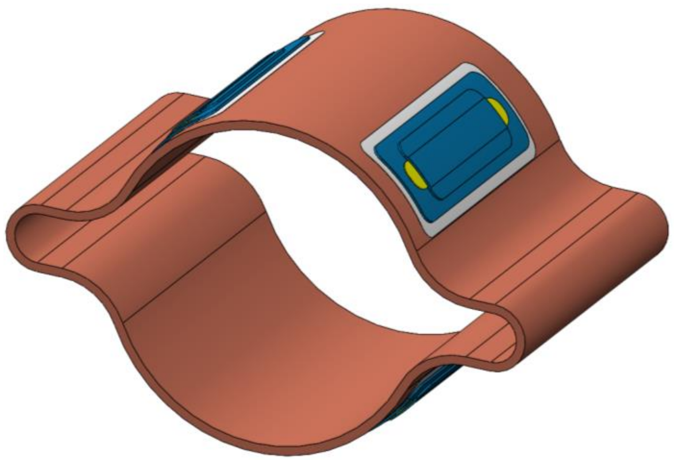

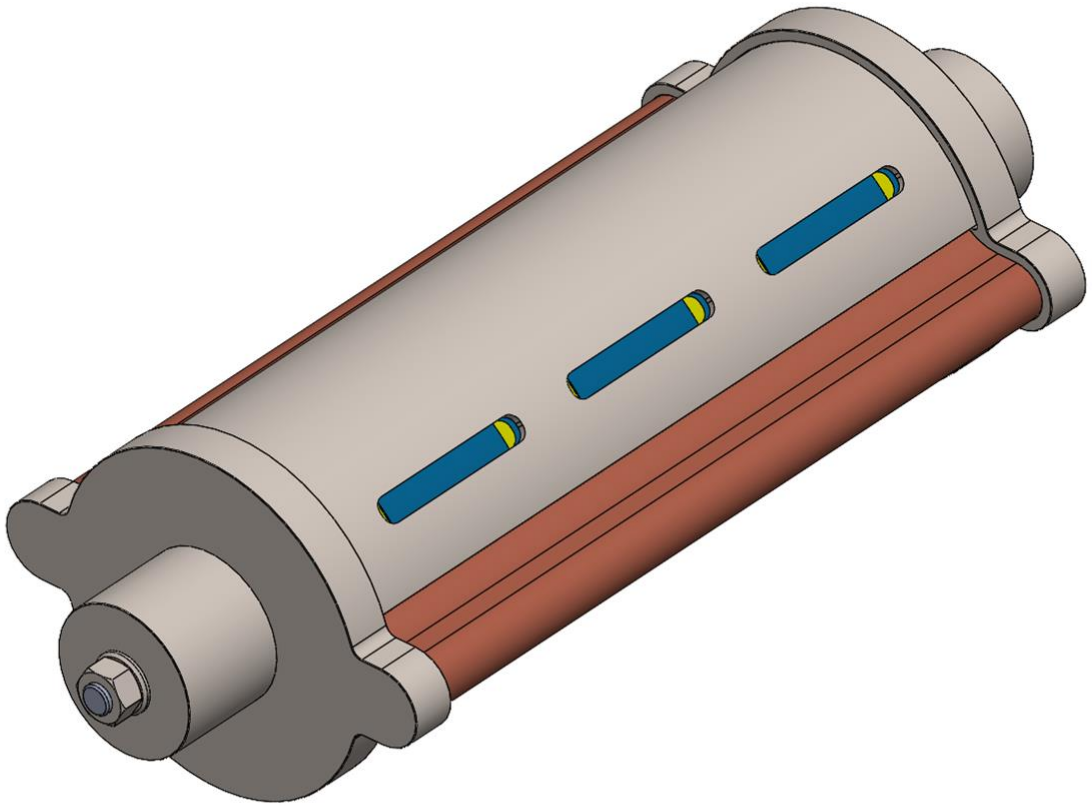

Vacuum Chamber:
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Heating Track:
Ti grade 4

BAKE-OUT

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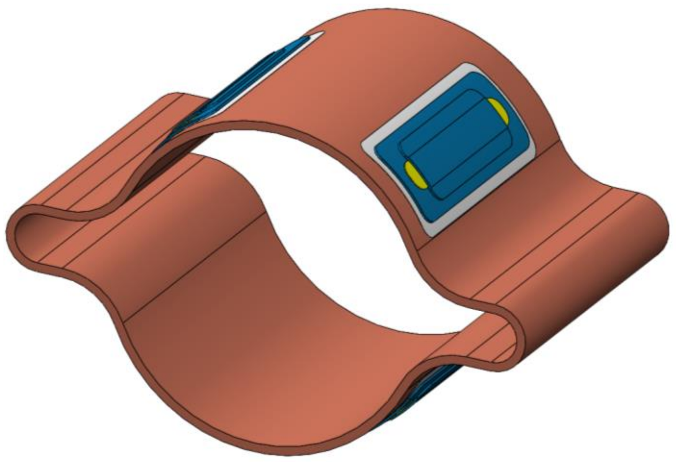

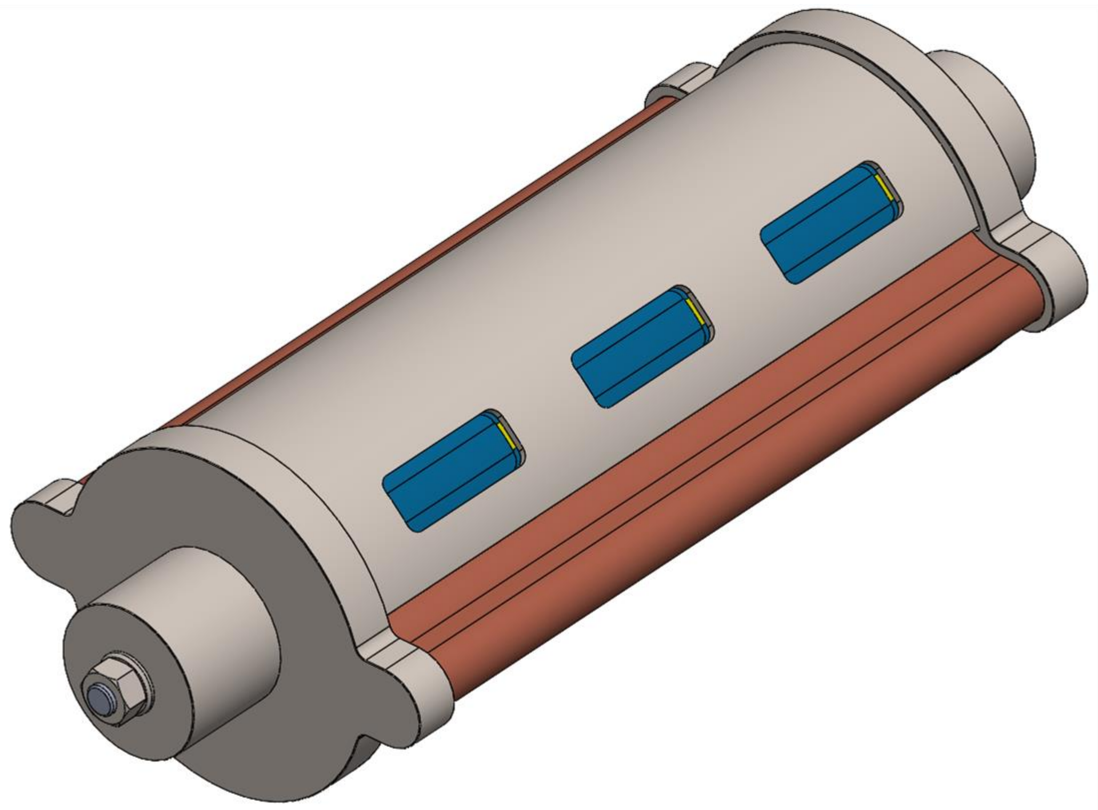

Vacuum Chamber: Cu-OFE

Ceramic Insulator Choice 1: „Alumina-Titania“ Al_2O_3+TiO_2 87/13

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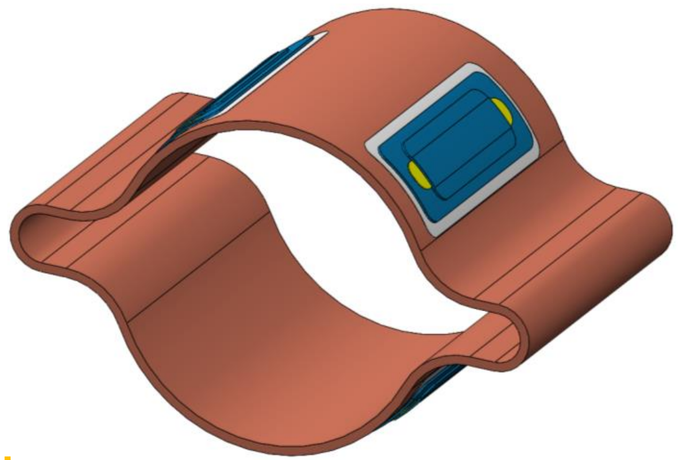
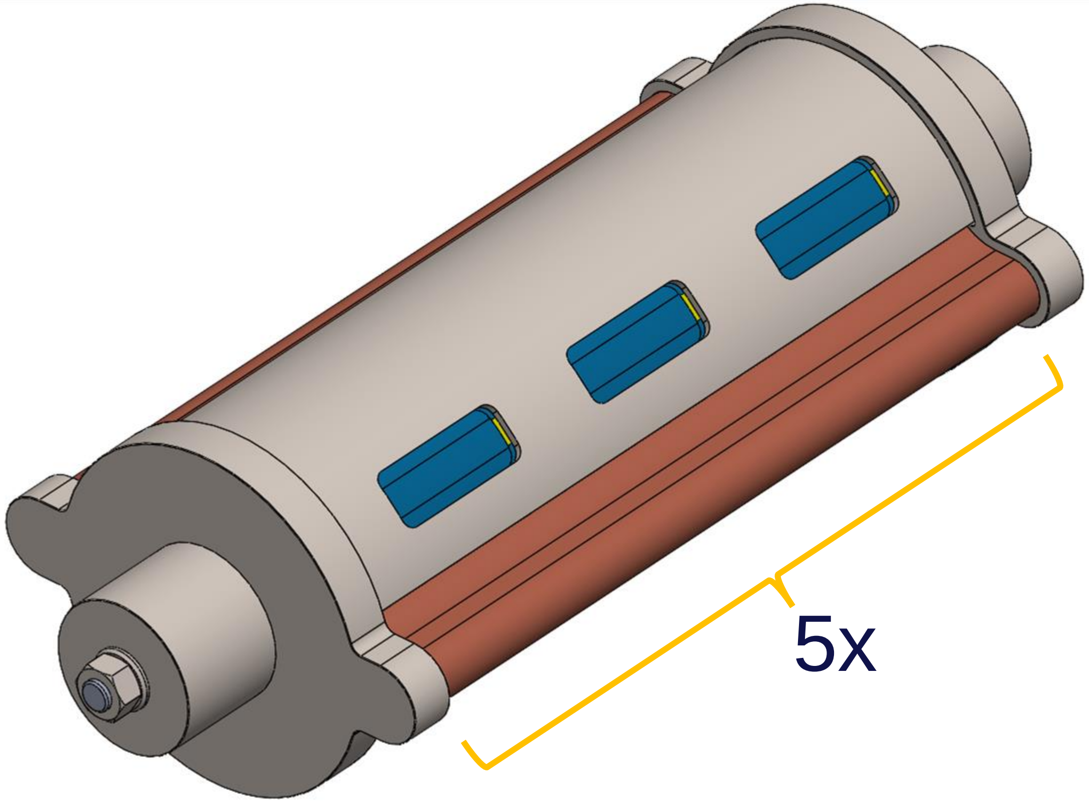
BAKE-OUT

Testing Samples



15x



5x

Vacuum Chamber:
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NiCr20

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Heating Track:
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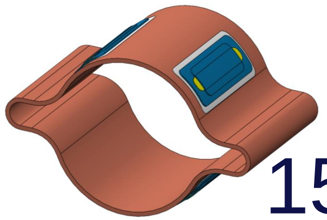
BAKE-OUT

APS & Cold Spray



15x each

Layer	Thickness µm	Material
B	50	NiCr20
C1	300	Alumina-Titania
T	200	Ti g4
C2	500	Alumina-Titania

Layer	Thickness µm	Material
B	50	NiCr20
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Layer	Thickness µm	Material
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Vacuum Chamber:
Cu-OFE

Bond Coat:
NiCr20

Ceramic Insulator
Choice 1:
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Al_2O_3+TiO_2 87/13

Ceramic Insulator
Choice 2:
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Al_2O_3+MgO 72/28

Heating Track:
Ti grade 4

BAKE-OUT

Outlook and Testing

Thermal Cycling Tests

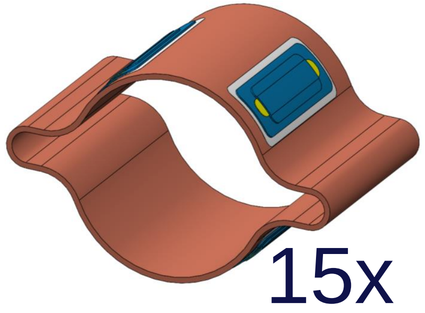
- Oven: RT – 250°C
- Multiple samples
- Extraction of 1 sample every 5 cycles
- GOAL: 50 cycles

Breakdown Voltage & Track Resistivity

- AC and DC sources
- Different humidity levels
- Monitoring resisivity after X cycles
- Heating tests by connecting the track

Microstructure Characterisation

- XRD
- LOM/SEM
- CT
- Hardness (Knoop or Indenter-Methods)



Vacuum Chamber: Cu-OFE

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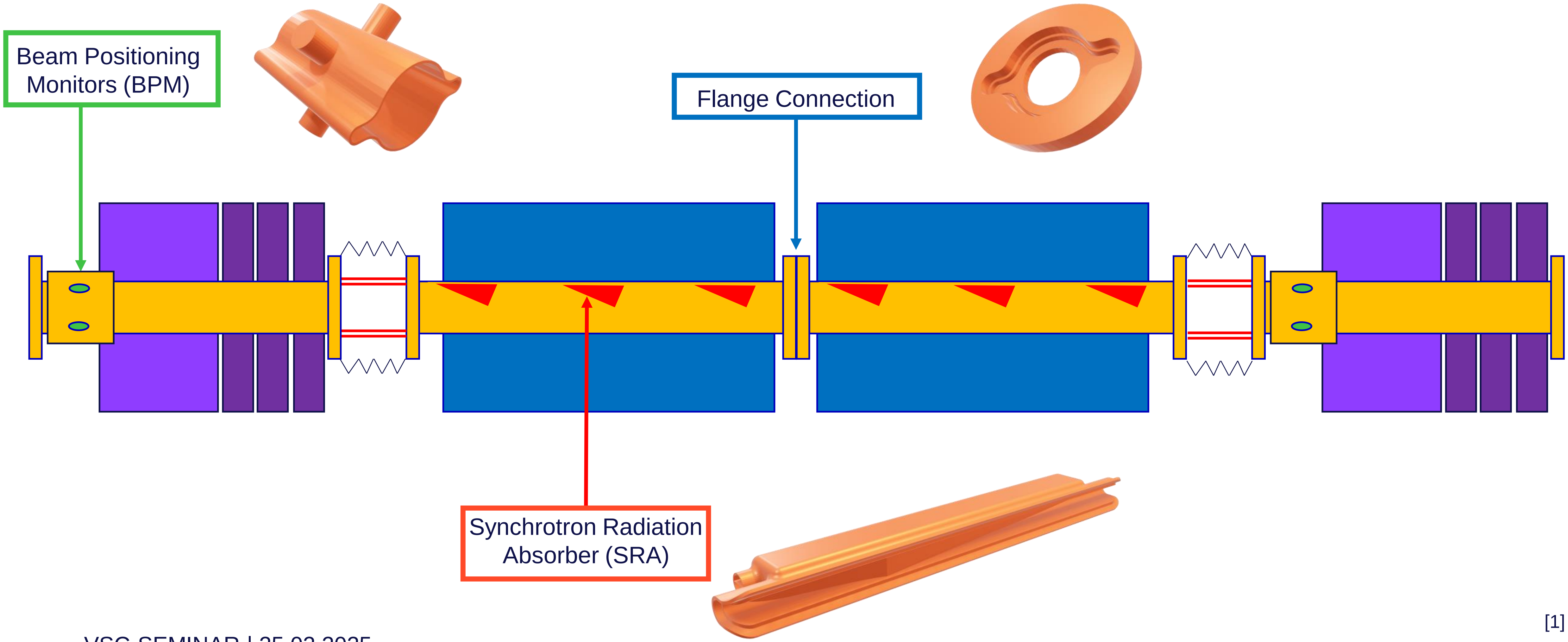
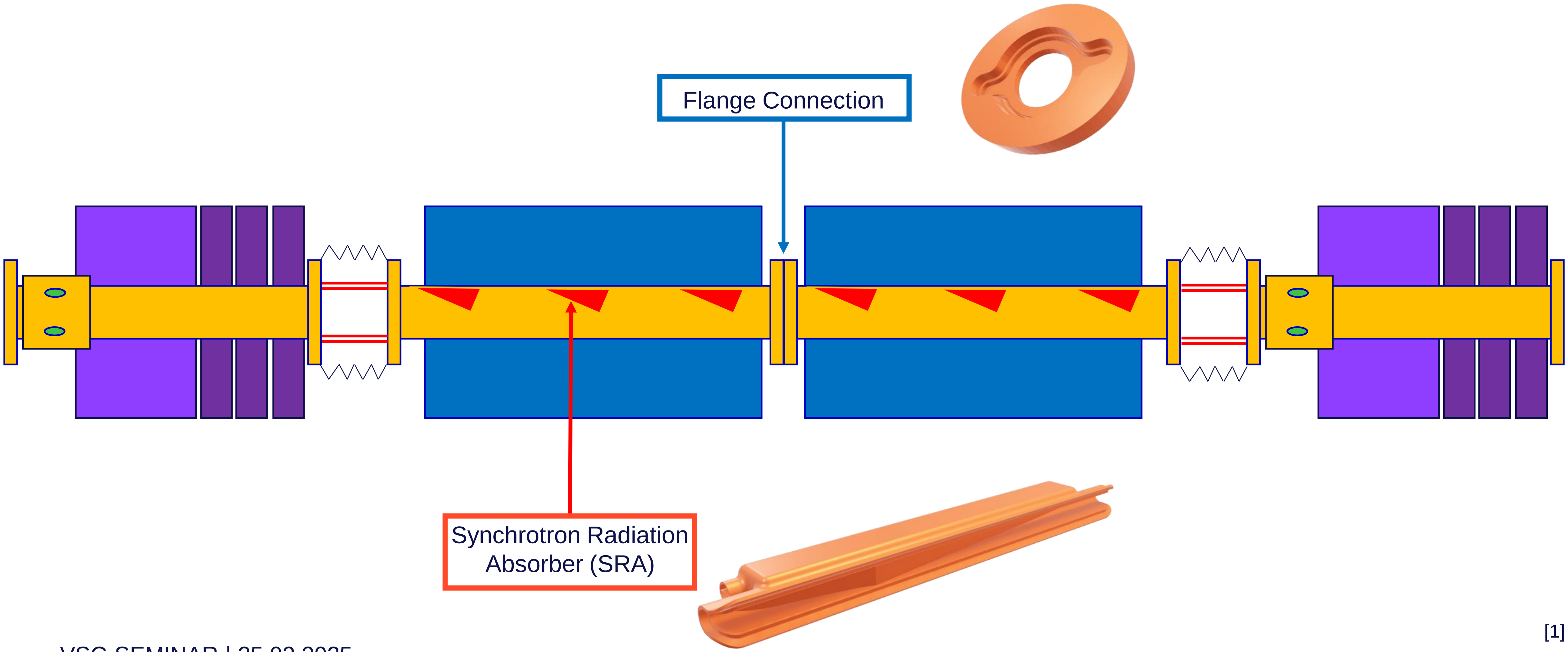
FCC-ee: Cu-Alloy Studies



[1]

FCC-ee: Cu-Alloy Studies

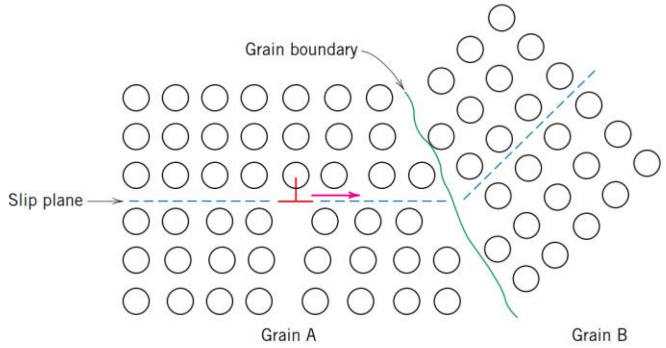


[1]

The 4 strengthening mechanisms of metals

Grain Size Reduction

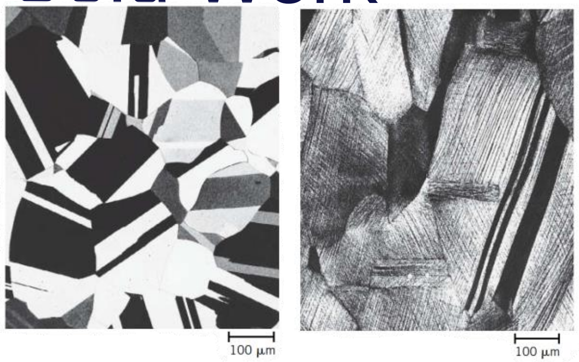
$$\sigma_y \propto \frac{1}{\sqrt{d}}$$

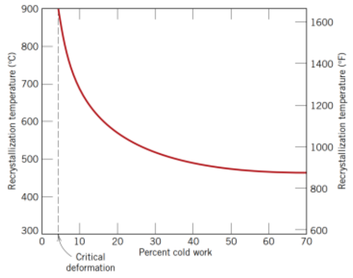


[2]

Cold Work

$$\sigma_y \propto \sqrt{\rho}$$

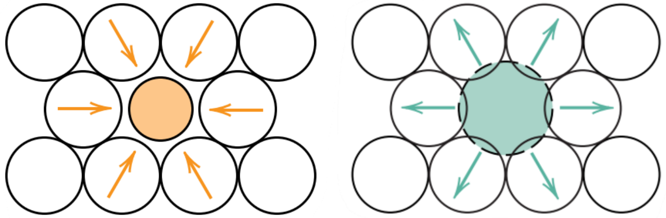




[2]

Solid Solution – Alloying

$$\sigma_y \propto \sqrt{c}$$

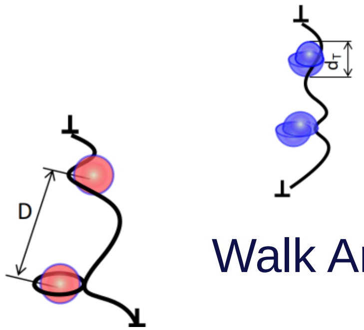


Interstitial

Substitutional

[2]

Precipitation Strengthening



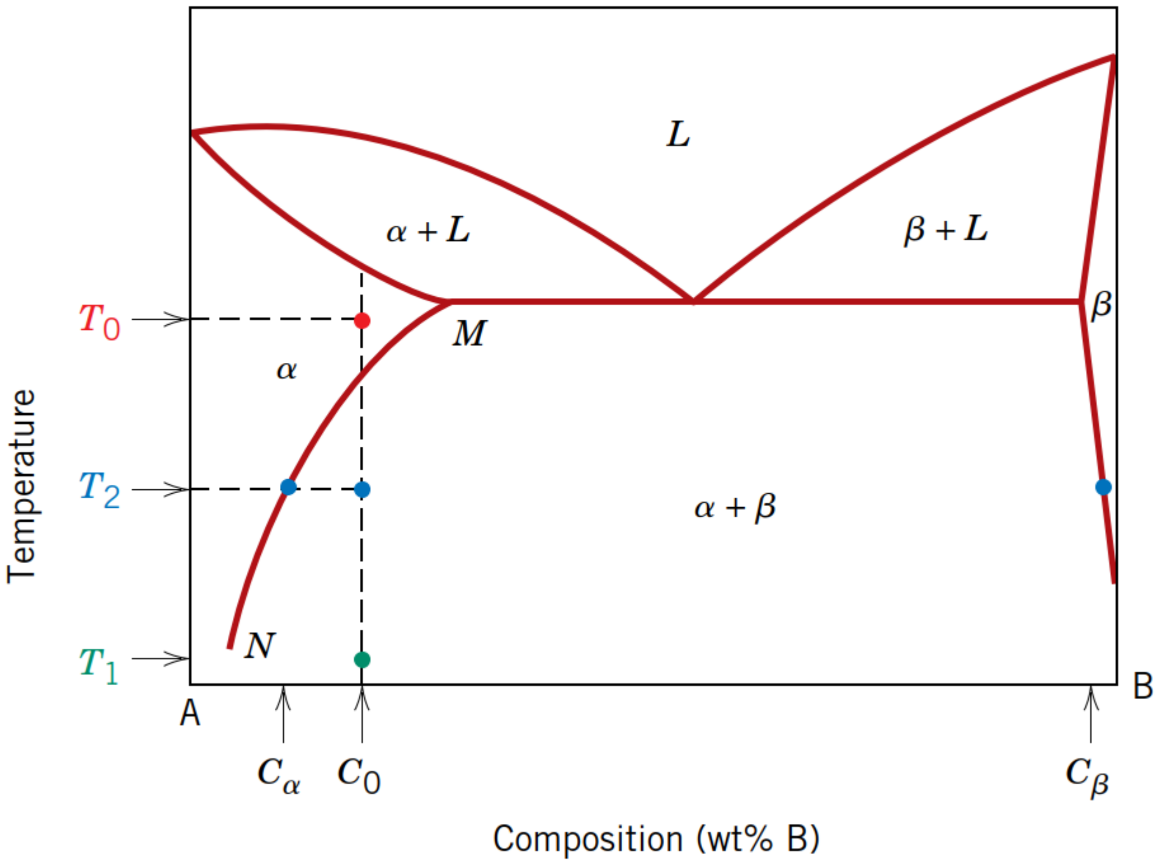
Cut $\sigma_y \propto \sqrt{r_P * f_P}$

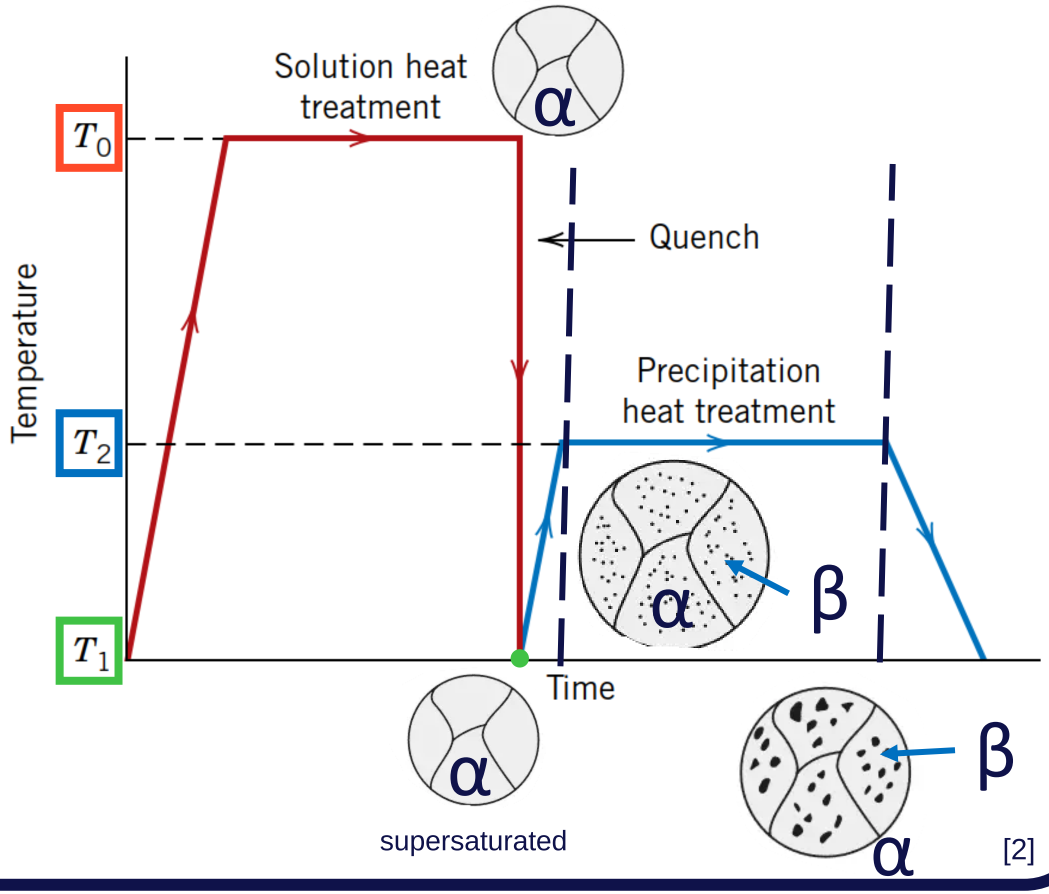
Walk Around $\sigma_y \propto \sqrt{f_P} * \frac{1}{r_P}$

[3]

High Temp. stable

Precipitation Heat Treatment





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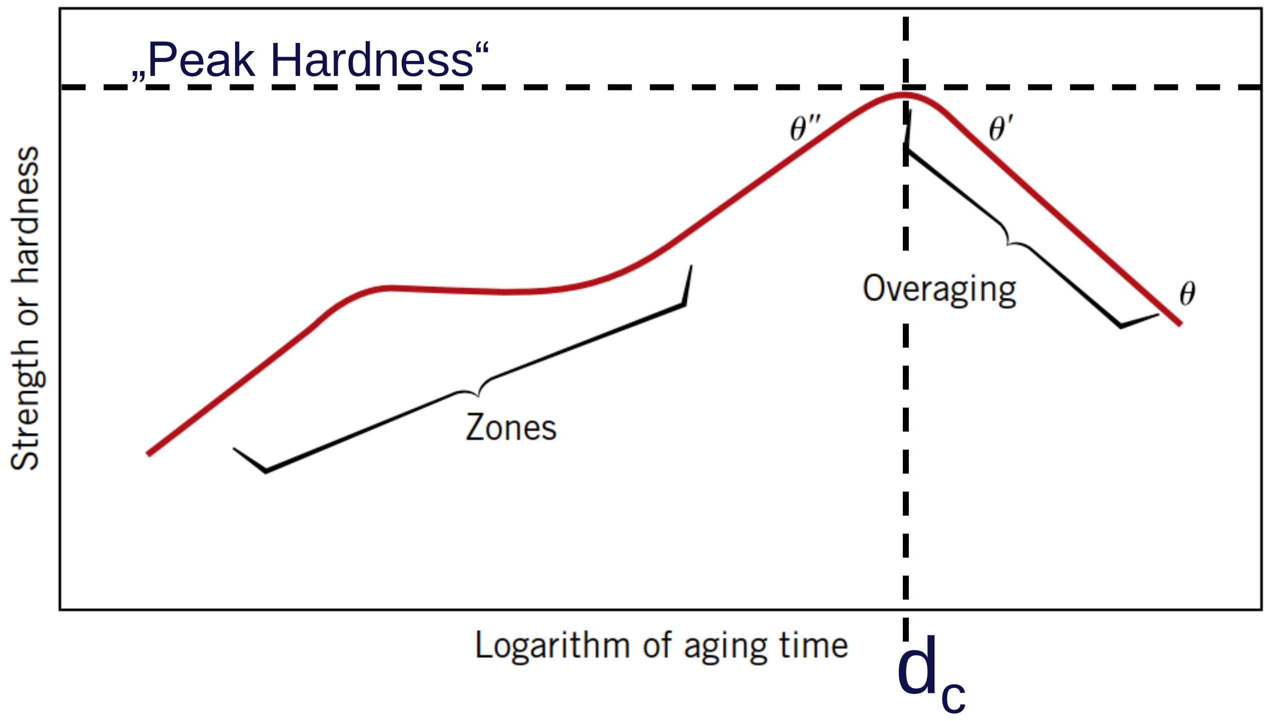
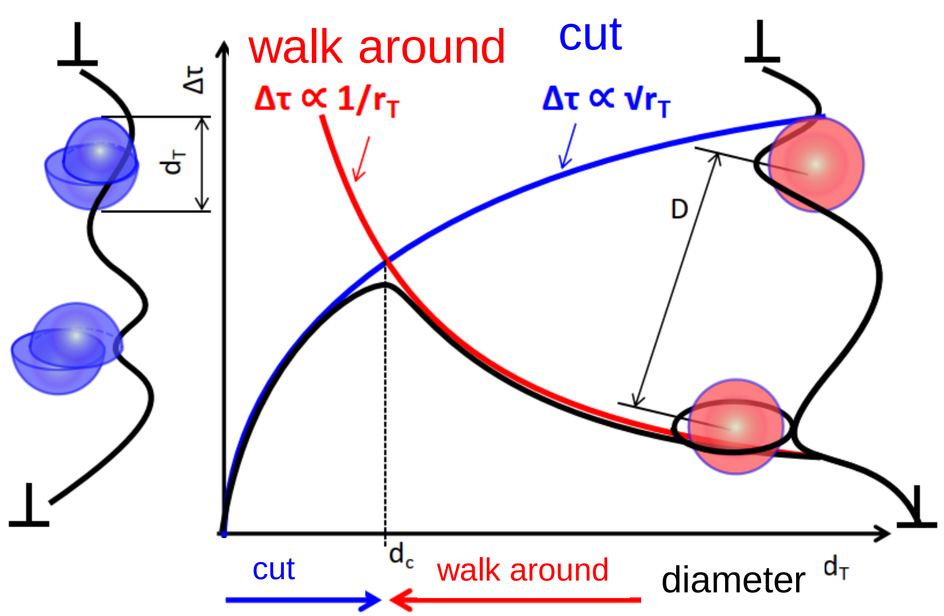


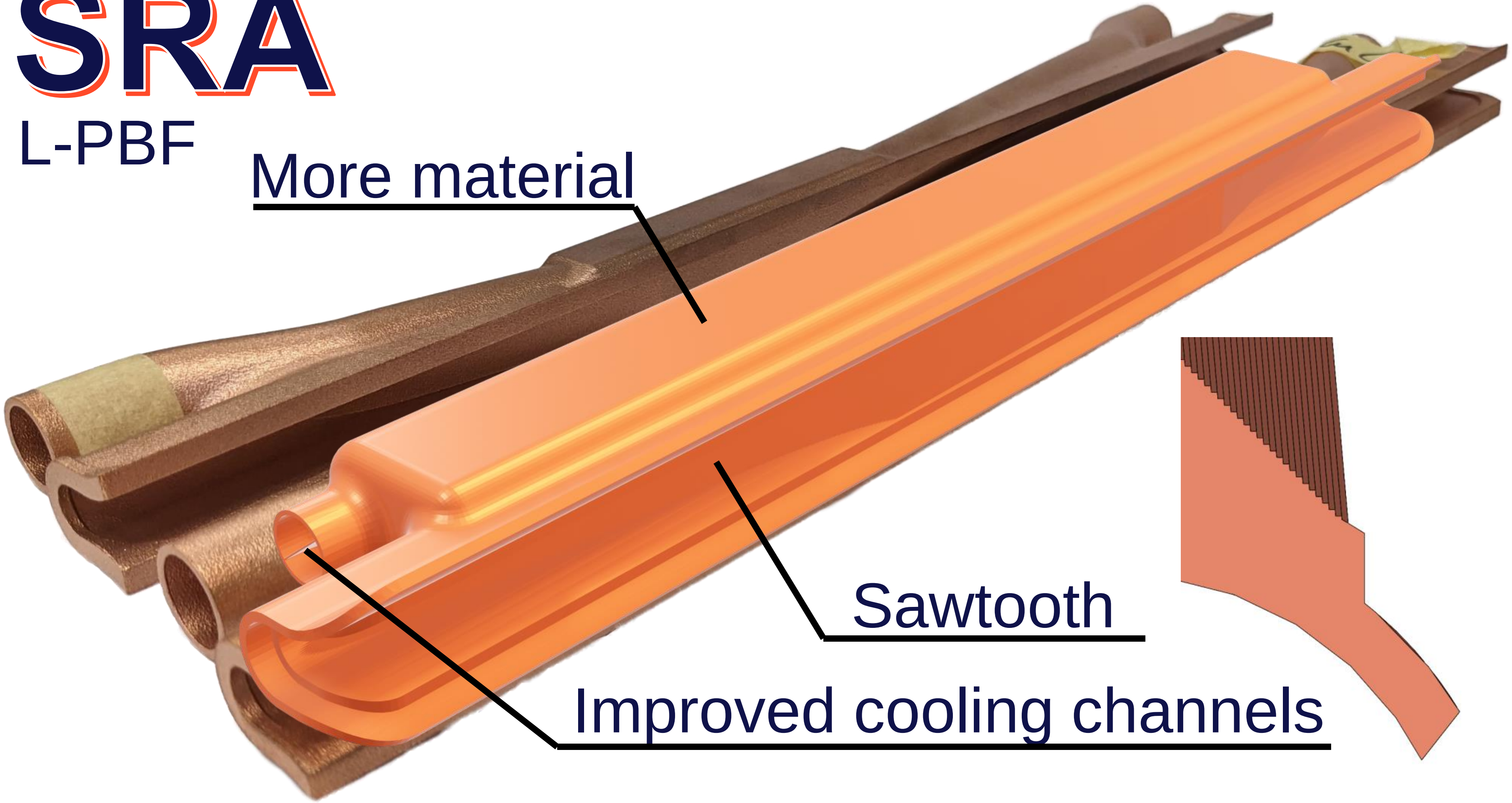


Incongruent particles are always walked around by dislocations, regardless of size!

[2], [3]

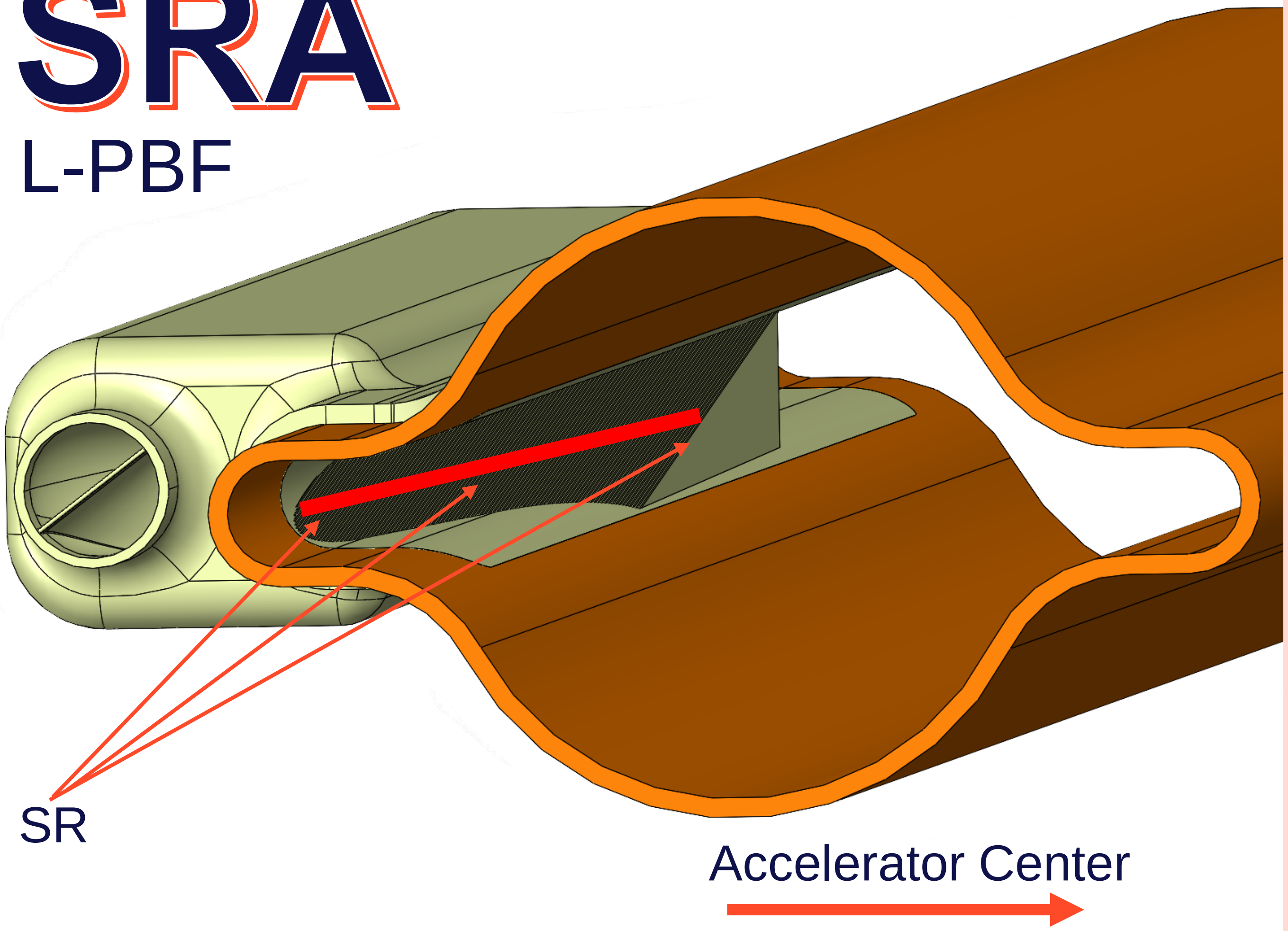
SRA

L-PBF



- High th. & el. cond.
- Non-ferromagnetic
- Fatigue & corrosion lifetime
- Weldable to vacuum chamber
- Density as high as possible
- Temperature stability
- High elastic limit

SRA
L-PBF



Current simulation results:

4.5kW heat load applied on sawtooth

Equivalent von Mises stress:
max. 500 MPa

Equivalent elastic strain:
max. $3.5*10^{-3}$

Temperature:
max. 250°C

Thank you Fabrice, Marco & Stefania!

- High th. & el. cond.
- Non-ferromagnetic
- Fatigue & corrosion lifetime
- Weldable to vacuum chamber
- Density as high as possible
- Temperature stability
- High elastic limit

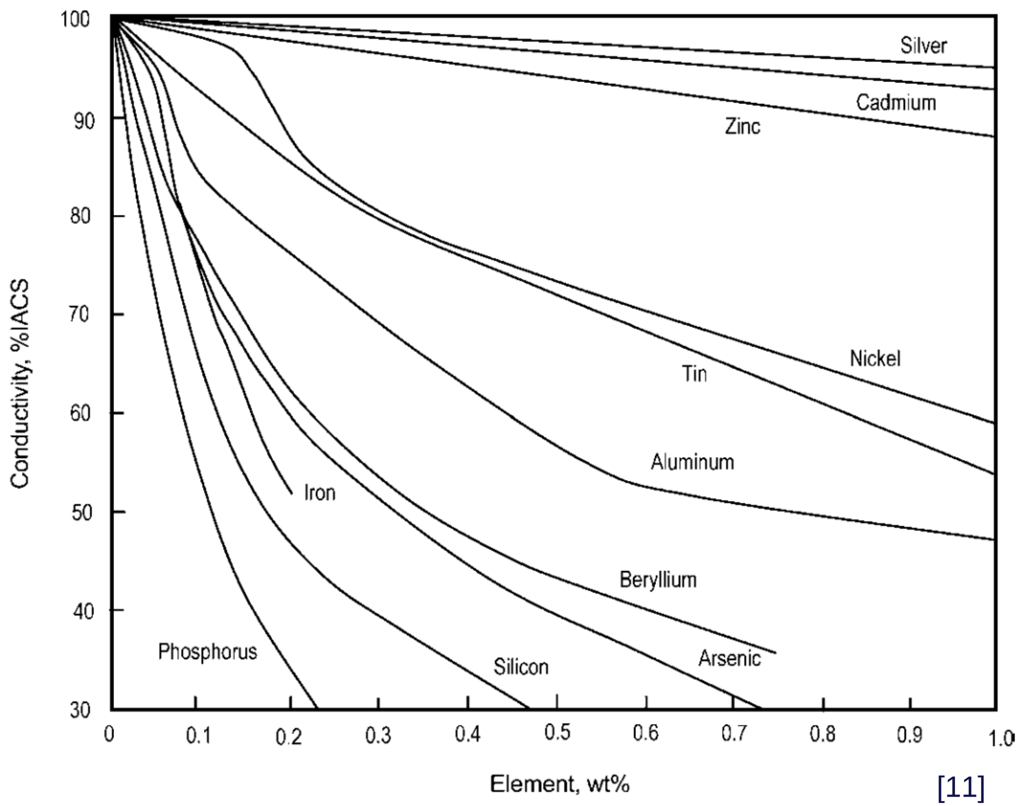
SRA

L-PBF

Only „Coppers“ and „High-Copper“ Alloys are considered

Coppers: > 99wt% Cu
UNS: C10100 – C15815 [5]

High-Copper Alloys: ≤ 5wt% alloying elements
UNS: C16200 – C19900 [5]



[11]

Th. & el. cond. limit alloying wt%

High th. & el. cond.

Non-ferromagnetic

Fatigue & corrosion lifetime

Weldable to vacuum chamber

Density as high as possible

Temperature stability

High elastic limit

SRA

L-PBF

Only „Coppers“ and „High-Copper“ alloys are considered

Selected Heat Treatments

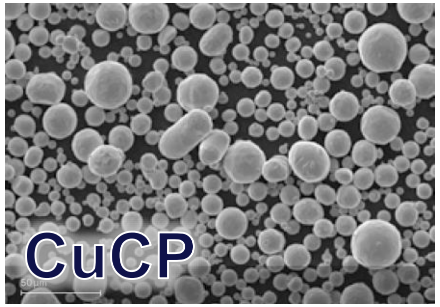
CuCP → As-Printed

CuCrZr:

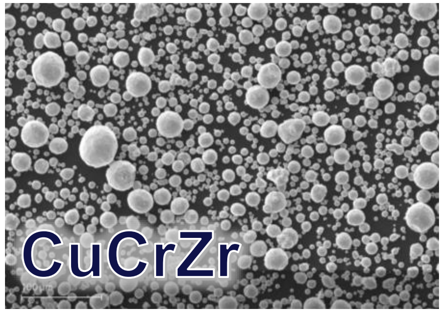
Cu_5Zr
$Cu_{14}Zr_{51}$
Cr
} Main Precipitates [8]

→ DAH: 490°C 1h in Vacuum

→ As-Printed



Cu: min 99.95 wt%
15 – 53 µm [7]



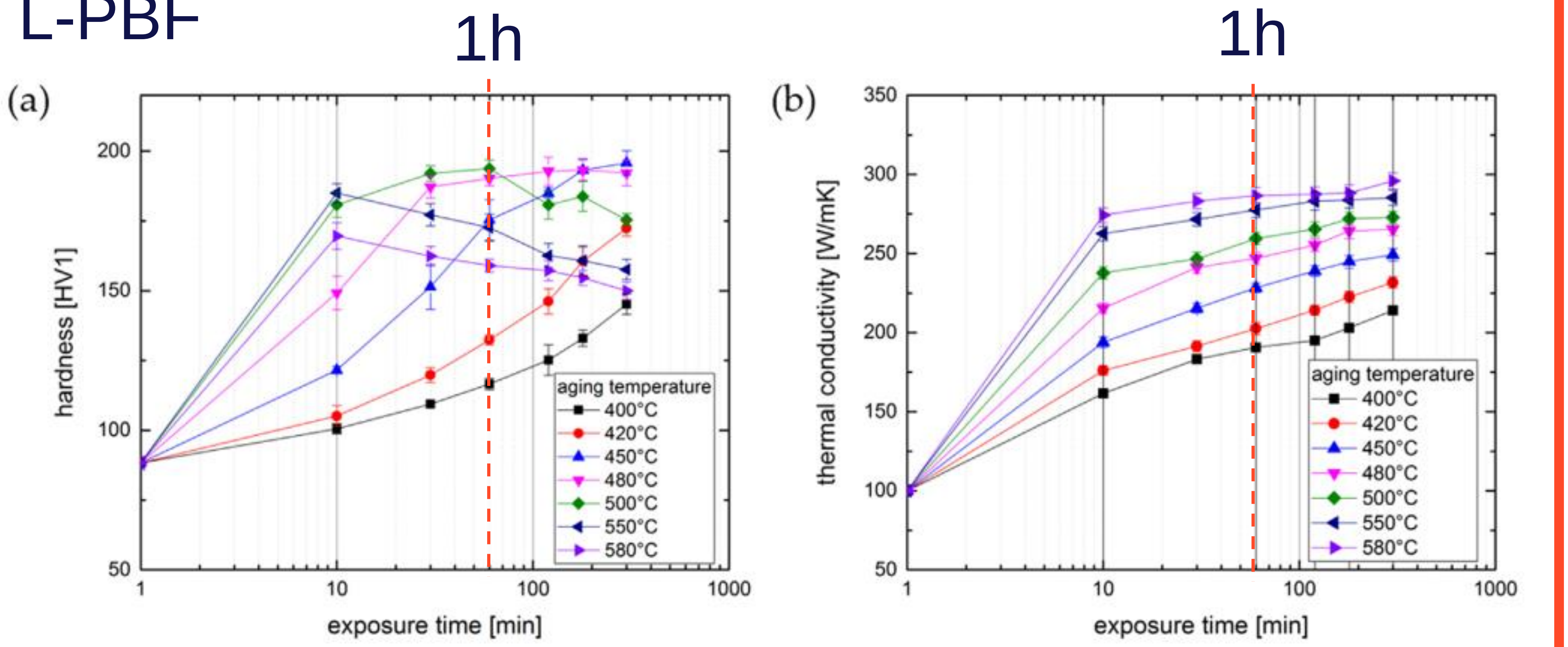
Cu: bal.
Cr: max. 1.15wt%
Zr: max. 0.25wt%
15 – 75µm [6]

SRA

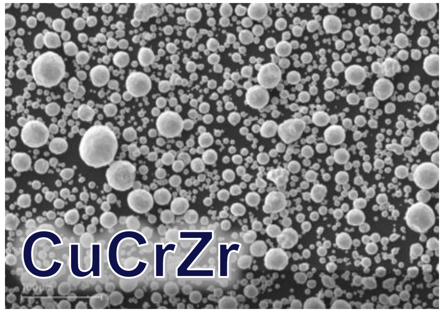
L-PBF

L-PBF CuCrZr DAH-Heat treatment literature

Hardness (Strength) / Conductivity trade-off



[8]



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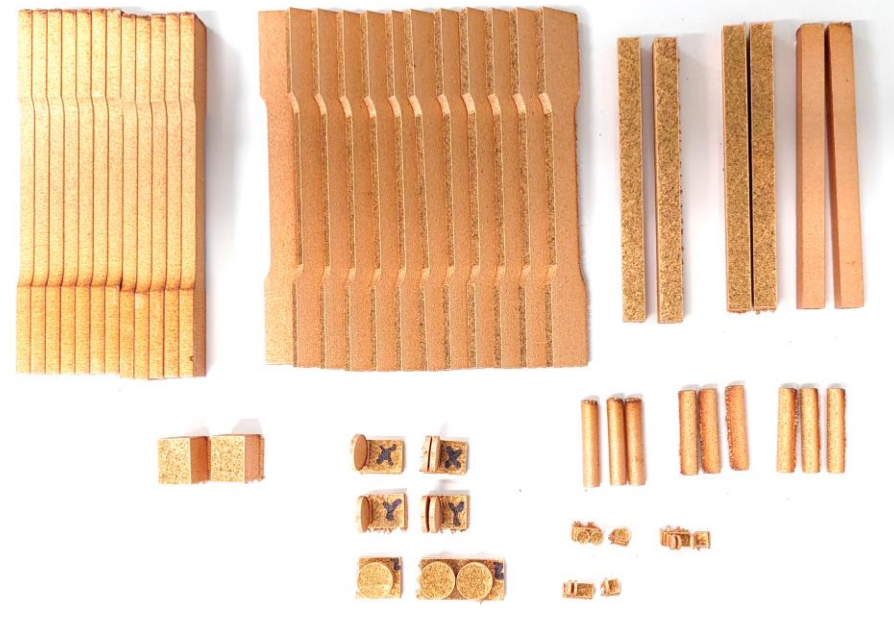
SRA

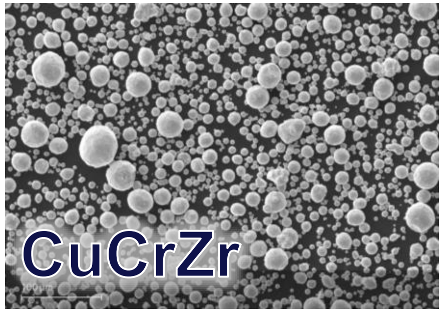
L-PBF



CuCP – As-Printed

CuCrZr - DAH

CuCrZr – As-Printed



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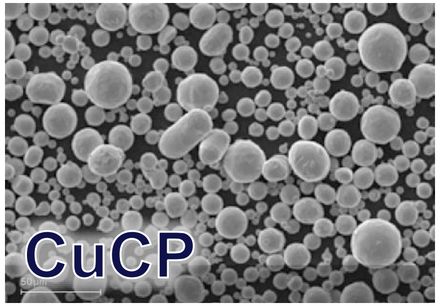

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SRA

L-PBF

Phase 1 – Base Parameters

- Tensile tests (horizontal and vertical)
  - DIN 50125-E 5 x 10 x 40
  - Including measurement of lateral contraction for Poisson's ratio
- Dilatometry (x, y, z)
  - Cylinders DM5 x 25 mm
- DSC (specific heat)
  - Disc DM4 x 1mm
- LFA (thermal diffusivity)
  - Disc DM12.7 x 1.2
- Density
  - Archimedes Principle
- Thermal conductivity (x, y, z)
  - Bar 8 x 8 x 100mm
  - At cryogenic temperatures

With MME

„done“

If necessary

Phase 2 – Fatigue and Fracture

- New Prototypes with Sawtooth
- Elasto-plastic fracture toughness (horizontal and vertical)
  - ASTM CT Specimen B=10mm
- Fatigue crack growth (horizontal and vertical)
  - ASTM CT Specimen B=10mm
- Fatigue/Wöhler Tests
  - with Univ. of Calabria
- Microstructure Analysis
  - LOM, REM, TEM, XRD
- Hardness Testing

Order in March 2025

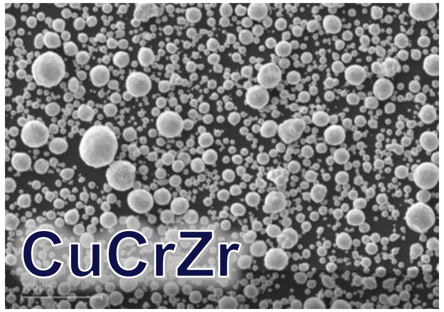
With MME

Phase 3 – Integration

- Welding tests with vacuum chamber (laser)
- Laser/Electron Beam irradiation tests of absorber
- Corrosion and Heat-Exchange Measurements with fluid

End of the Year

Merci Christian!



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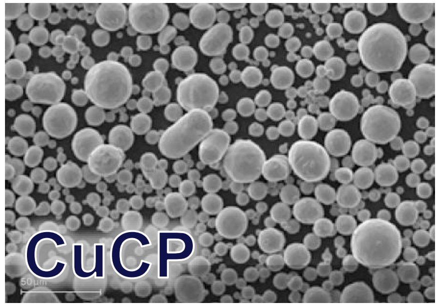
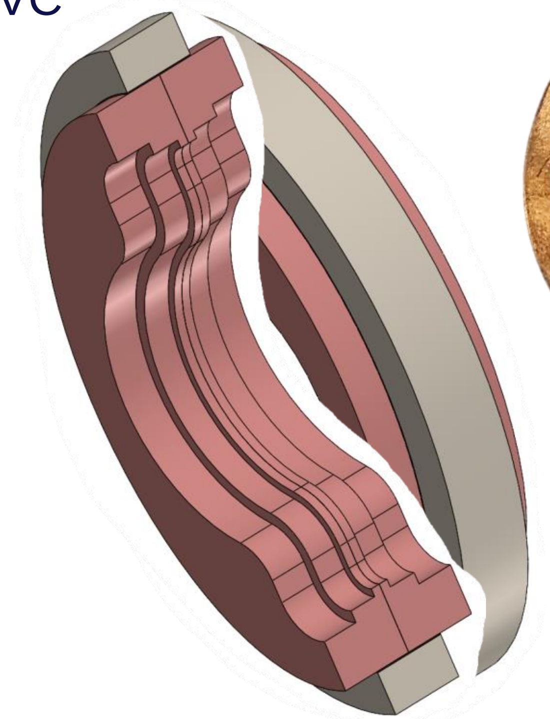


Cu: min 99.95 wt%
15 – 53 µm [7]

FLANGES

CNC-Machining & Friction Stir Welding

Groove for VC

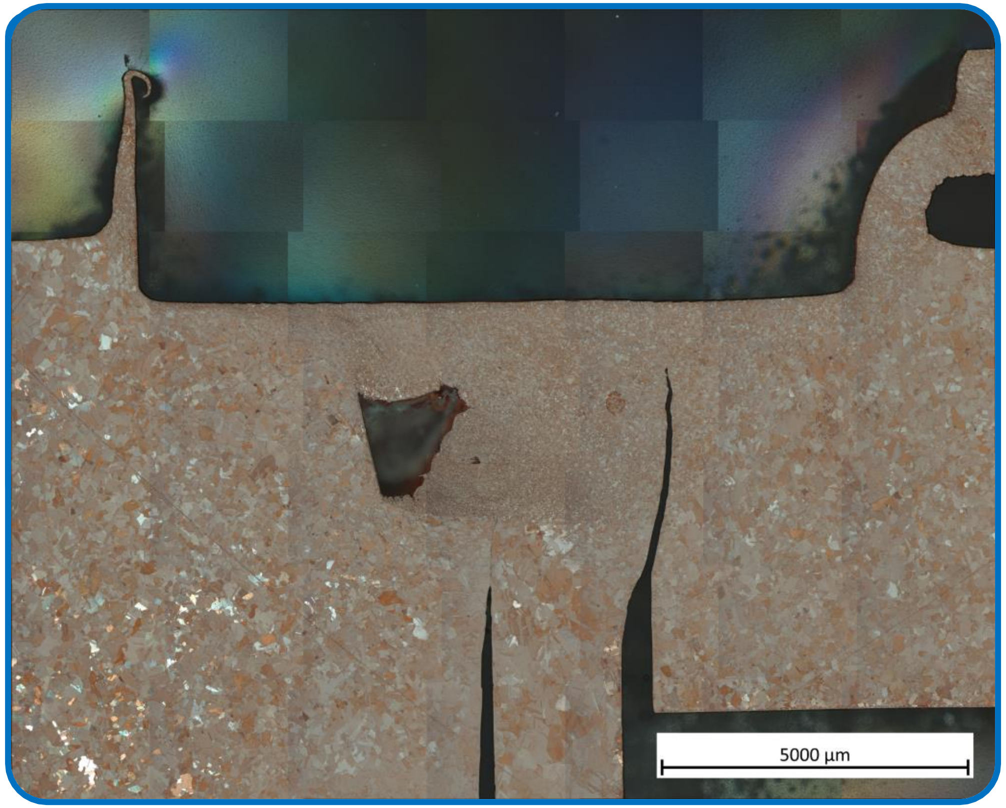


After Welding

- Low impact on beam impedance
- Min. hardness SMA contact pressure: max. ~70 MPa
- Non-ferromagnetic
- Weldable to VC
- Pressfit with VC thorugh groove in flange

FLANGES

Friction Stir Welding Tests of 2024



[12]

[12]

Company: Stirweld

Takeover from Samuel Rorison

Cu-OFE flange on Cu-OFE VC

Issues with Tolerances → Heat transfer from flange to VC not sufficient

Redesign of flange groove

FLANGES

Outlook

Production of new Flange Geometry

- Preparation for next round of FSW-manufacturing
- Milling of flanges at CERN (Cental Workshop, March/April 2025)

Heat Treatment Study in Collaboration with TU Wien for bulk CuCrZr

- Peak hardness treatment
- additional HT at Bake-Out temp. afterwards (12h, 1d, 2d, 4d, 8d)
- Precipitation characterization, hardness and compression testing
- Phase simulations with MatCalc

Assess compatibiliy with knife-edge technology as alternative design

CuCrZr

Cu: bal.
Cr: 0.8wt%
Zr: 0.08wt% [9]

CuNi2SiCr

Cu: bal.
Ni: 2.4wt%
Si: 0.7wt%
Cr: 0.5wt% [10]

Min. hardness SMA contact pressure: max. ~70 MPa

Honorable mention: CuBe2

Outlook

Continuation of materials selection studies

- SRA
- BPM
- Flanges
- Bake-Out

Integration and manufacturing of prototype-chambers

- 2m chambers
- Intermediate length chambers
- 12m chambers
- Assemblies with cooling circuits, magnets, etc.

Thank you!

Literature

#	Reference
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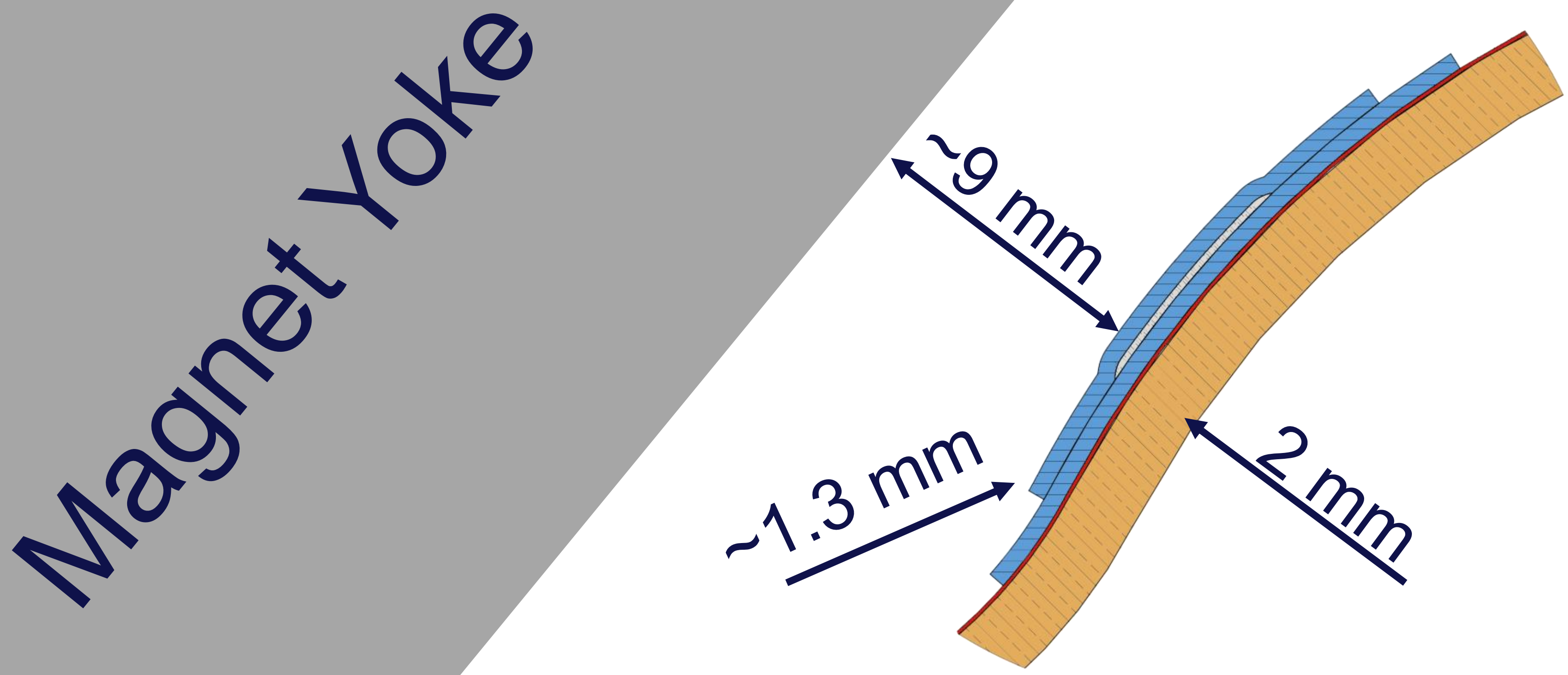
[4]	Imbriglio2021 – https://doi.org/10.1007/s11666-021-01229-4
[5]	Totten2016 – ASM Handbook Vol. 4E, Heat Treating of Nonferrous Alloys – DOI: 10.31399/asm.hb.v04e.a0006276
[6]	EOS GmbH – EOS Copper Alloy CuCrZr – https://www.eos.info/en-us/metal-solutions/metal-materials/copper#eos-copperalloy-cucrzr – last access: 06.06.2024[online]
[7]	EOS GmbH – EOS Copper Alloy CuCP – https://www.eos.info/metal-solutions/metal-materials/copper#eos-copper-cu – last access: 06.06.2024[online]
[8]	Wallis2019 - https://doi.org/10.1016/j.msea.2018.12.017

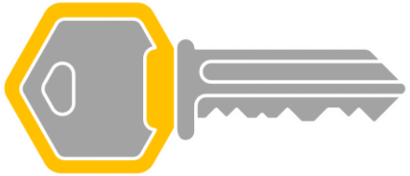
Literature

#	Reference
[9]	Wieland GmbH – Elmedur X – https://www.wieland.com/en/resources/downloads?resource-category=1186 – last access: 19.02.2025[online]
[10]	Wieland GmbH – Elmedur NCS – https://www.wieland.com/en/resources/downloads?resource-category=1186 – last access: 19.02.2025[online]
[11]	Tucker2013 – ASM Handbook Vol. 5A, Thermal Spray Technology – DOI: 10.31399/asm.hb.v05a.a0005714
[12]	Duclos2024 – EDMS 3164263

BAKE-OUT

APS & Cold Spray

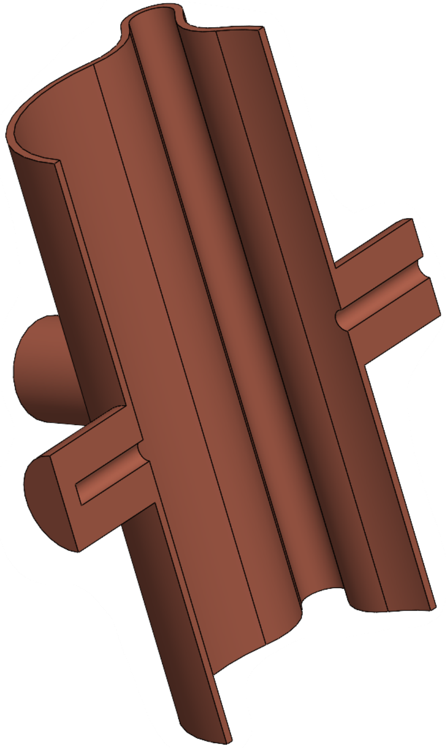


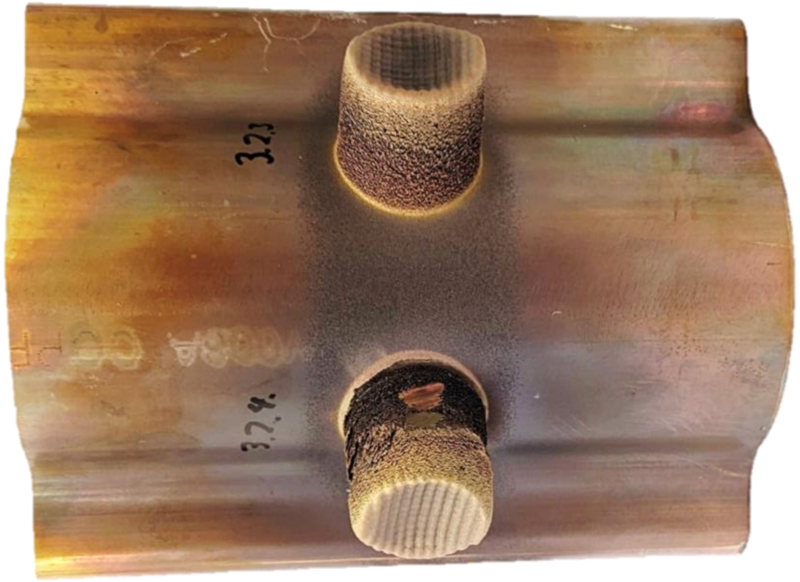


- T_B = 230 – 250°C
- Low porosity
- Insulator: High el. resistivity while th. cond. as high as possible
- Difference in th. exp. coeff. ↓
- As thin as possible
- Reduce cost

BPM

Cold Spray Additive Manufacturing

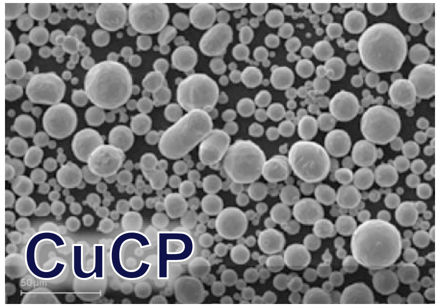




Low Porosity → Leak Tightness

Min. Hardness: SMA contact pressure: max. 150MPa

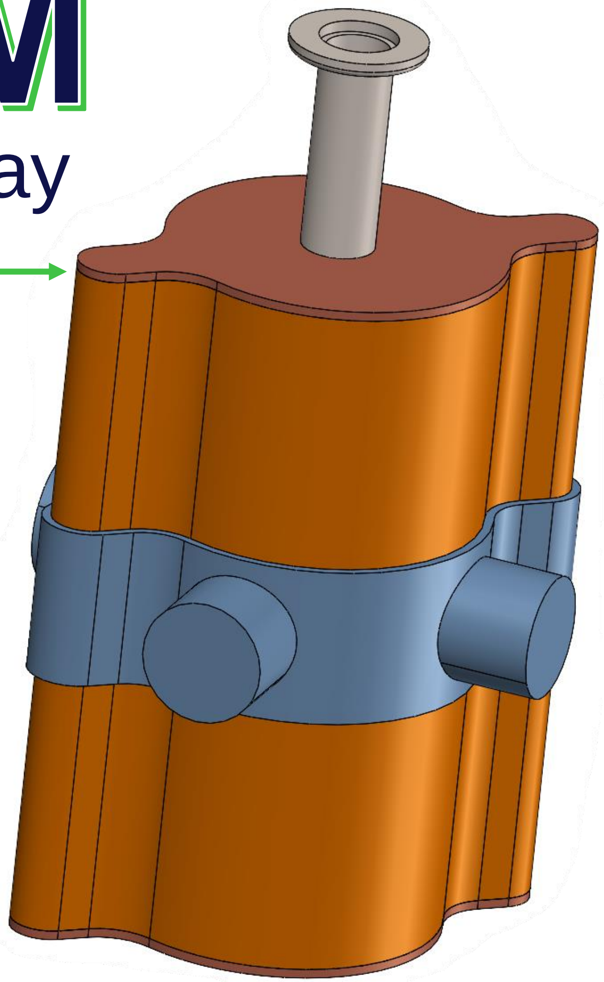
Non-Ferromagnetic



BPM

Cold Spray

TIG-Welding



TIG-Welding

Post Heat Treatment
12h at 250°C in air

Low Porosity → Leak Tightness

Min. Hardness: SMA contact pressure: max. 150MPa

Non-Ferromagnetic