



3rd PANDORA Progress Meeting
LNL 7-8 October 2024

Plasma chamber construction in AM

The DIAM (INFN Padova) activity on nuclear fusion plants, particle accelerators, and cooling systems

Adriano Pepato on behalf of the DIAM Group

INFN Sezione di Padova

DIAM – *Development and Innovation on Additive Manufacturing*



DIAM Workgroup

Technologists: Adriano Pepato (Manager of DIAM group);
Razvan Dima; Pietro Rebesan; Massimiliano Bonesso.

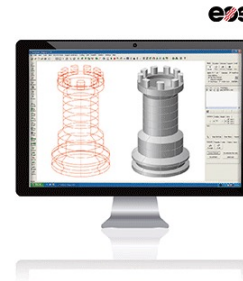


PhD Candidates and Research Fellow: Giacomo Favero;
Valentina Candela; Silvia Candela; Leonardo Salvò;
Francesca Valentini; Mehrdad Faraji; Davide Cester.

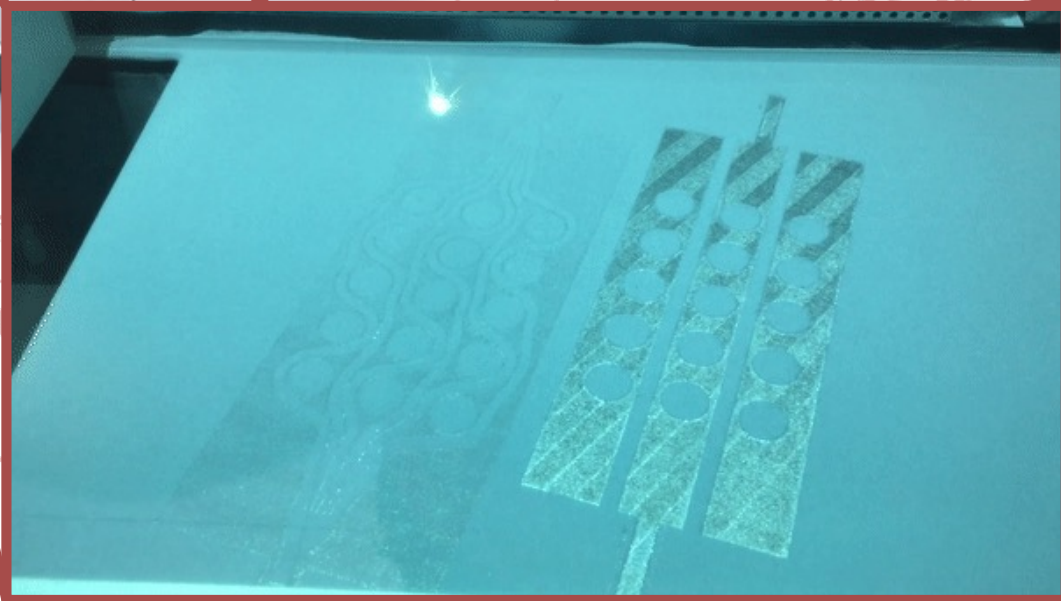


Laser Powder Bed Fusion Process

EOSint M280
Copper & Copper Alloys



EOS M100
Refractory Metals



DIAM Research Core

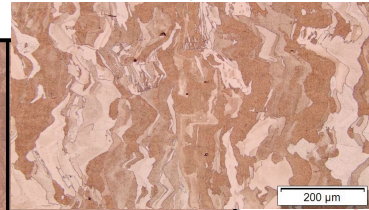
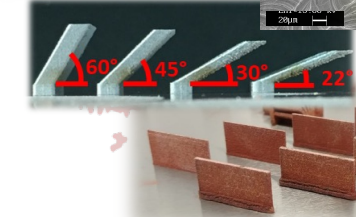
from MATERIAL to PRODUCT characterization

Production & Process parameters tuning

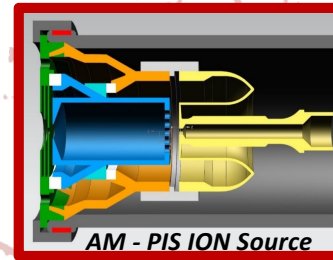
Microstructural & Geometrical Characterization

SA

- Bigger grains
- Recrystallized equiaxed grains
- Melt pools not observable



50 μm

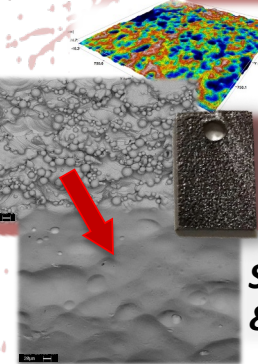
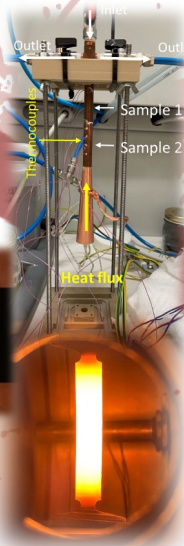
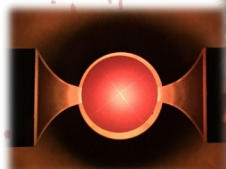
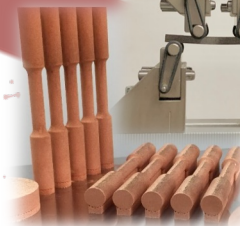


Design for Additive & Prototype Characterization



Mechanical Characterization

RT & HT Thermal Characterization



Surface analysis & finishing

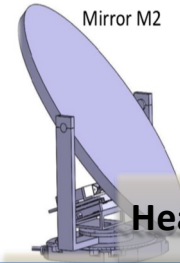
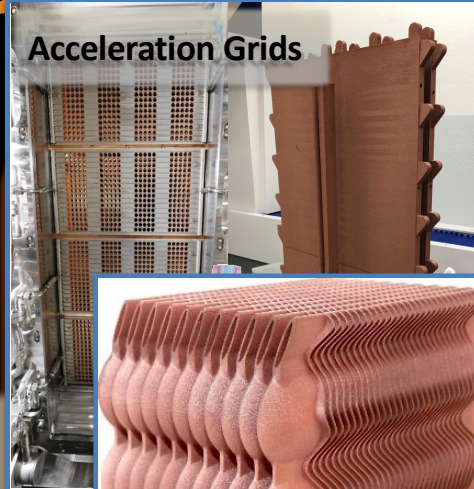
COPPER & COPPER ALLOYS

Nuclear Fusion

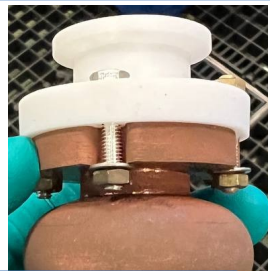
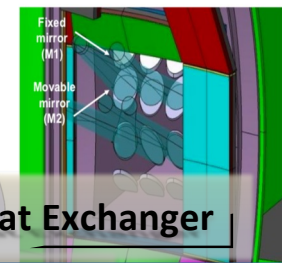
@ DIAM lab:

- ✓ Pure Copper
- ✓ CuCrZr

Acceleration Grids



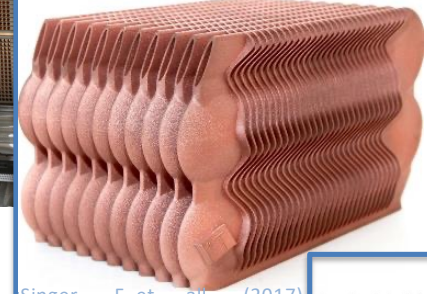
Heat Exchanger



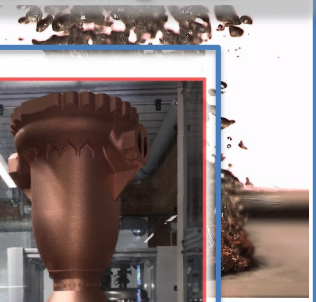
Fraunhofer IWS project enables green laser to melt pure copper

Physical and Chemical properties:

- Excellent thermal conductivity;
- Excellent electrical properties;
- Good mechanical properties (alloy);
- Good corrosion resistance;
- Anti bacterial performances.



Corals - boiling tests



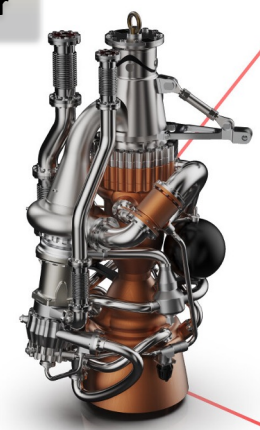
Singer, F., et al. (2017).
manufactured copper composite structures for management applications.

LAUNCHER CuCrZr
launcherspace.com

LAUNCHER E-2

THE WORLD'S **LARGEST 3D PRINTED** COMBUSTION CHAMBER ARRIVED AT LAUNCHER IN NOVEMBER 2019 FOR FULL-SCALE TESTING IN 2020.

Our partner



63.54

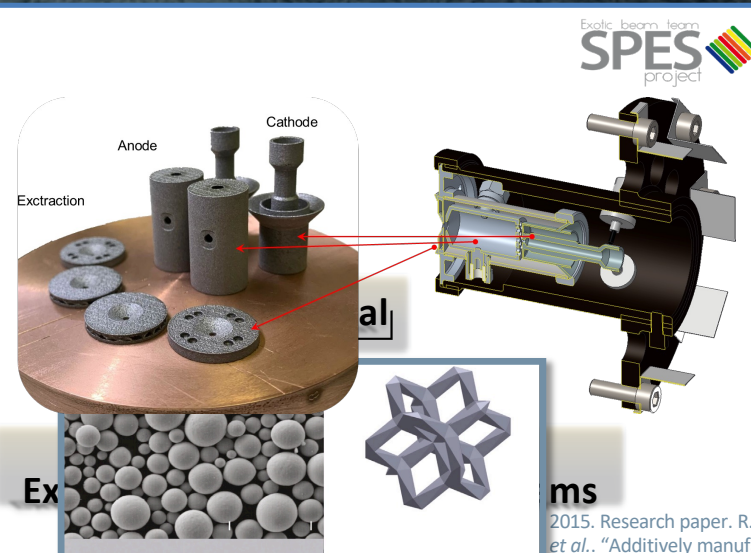
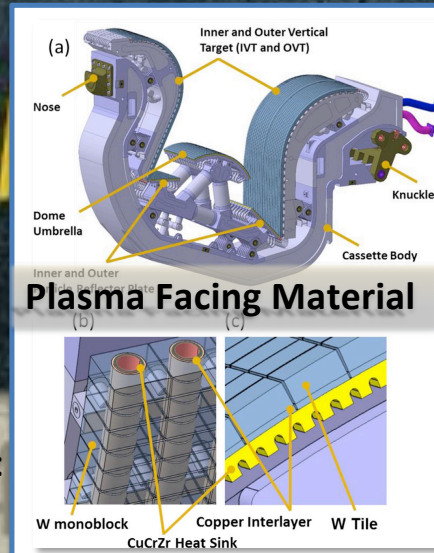
Nuclear Fusion & Nuclear Physics

@ DIAM lab:

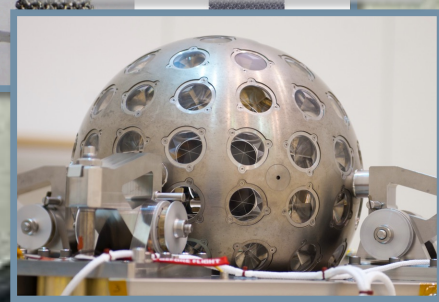
- ✓ Tungsten
- ✓ Molybdenum
- ✓ Tantalum
- ✓ Niobium

Physical and Chemical properties:

- Ultra-high melting point
- High density;
- Excellent corrosion resistance;
- Good thermal conductivity;
- Low thermal expansion;
- High strength and hardness.



Space and Aerospace



Nb
Niobium
92.90638

Ta
Tantalum
180.94788

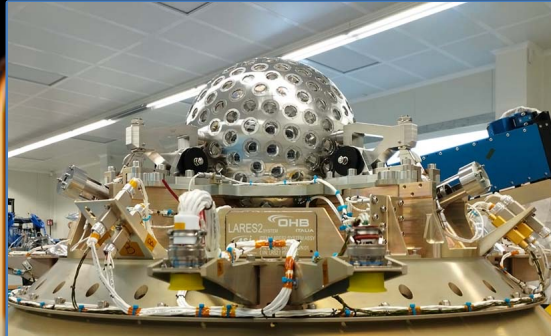
42

NICKEL SUPERALLOYS

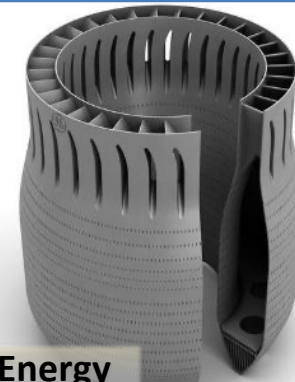
Aerospace

@ DIAM lab:

✓ Inconel 718



Satellite



Energy



Turbine Blades

Physical and Chemical properties:

- Exceptional strength;
- High heat resistance;
- Excellent corrosion protection;
- Good oxidation resistance;
- Excellent creep resistance;

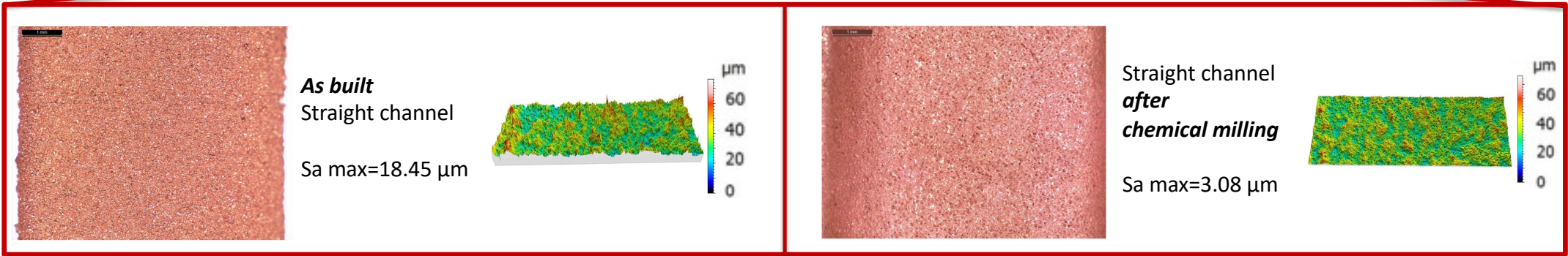
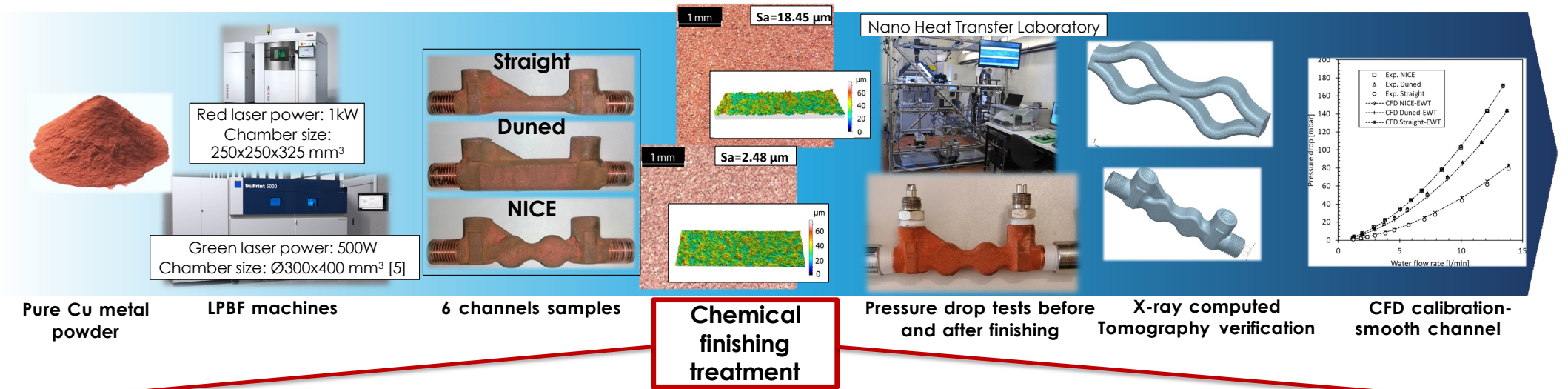


Molten salt steam g

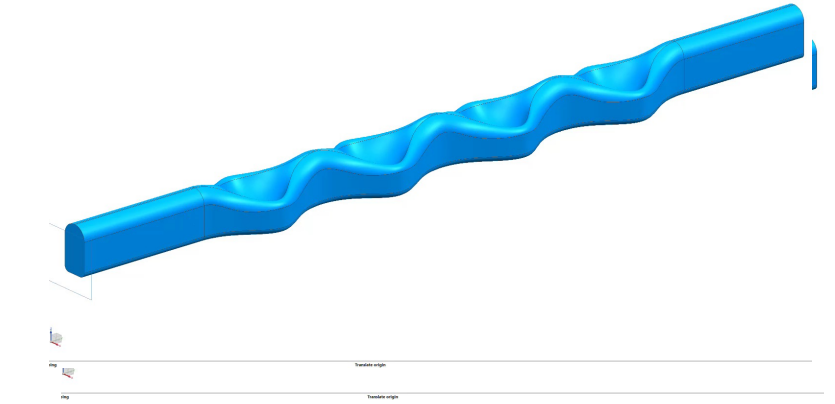
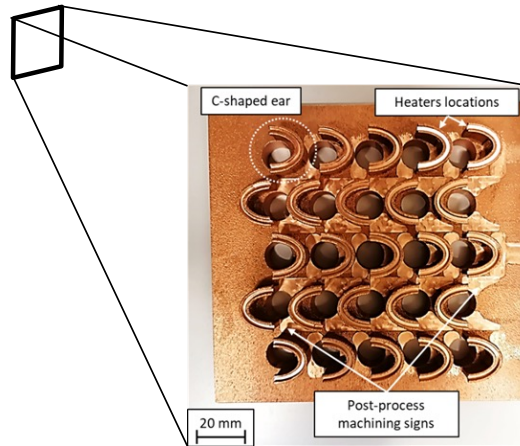
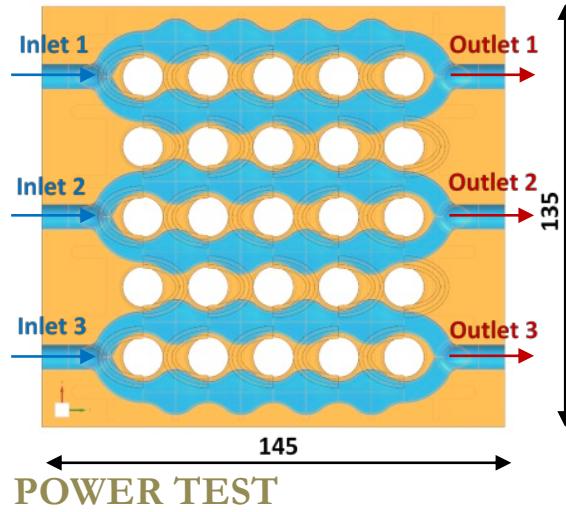
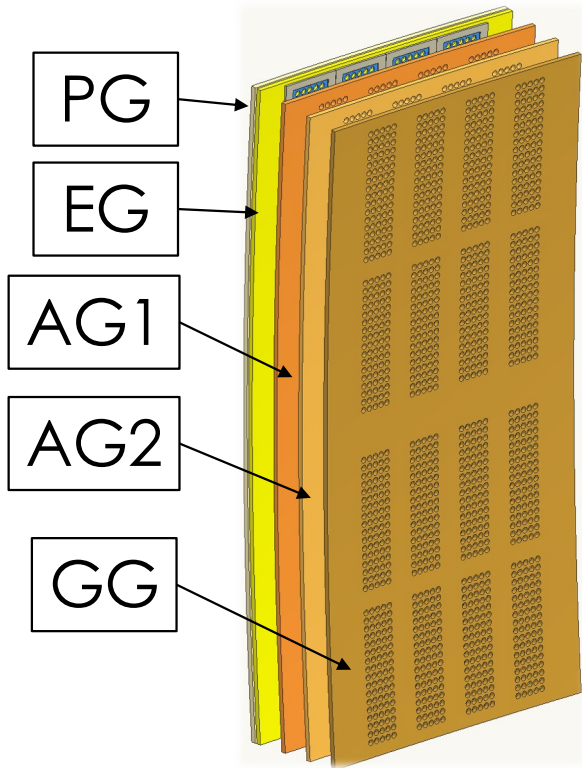
Oil and Gas



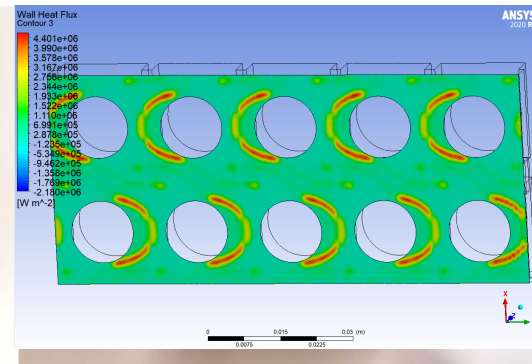
The integrated cooling system: performance optimization and pressure drop minimization



SISTEMA DI RAFFREDDAMENTO INTEGRATO GRIGLIE DTT NBI NAP

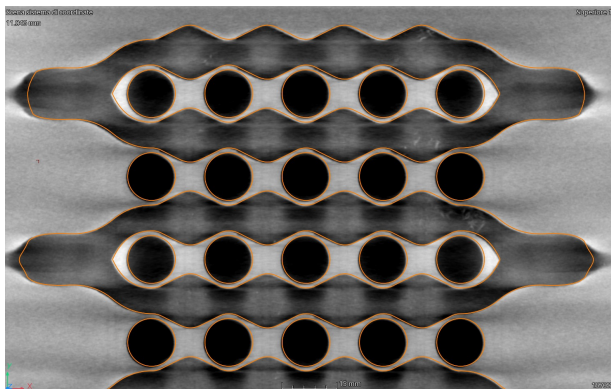


DUNED CHANNEL

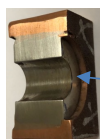
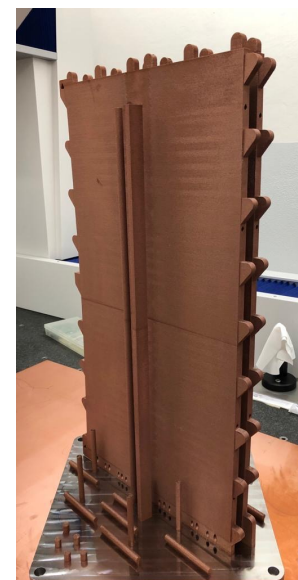


DTT AM applications for the NBI: Acceleration Grids

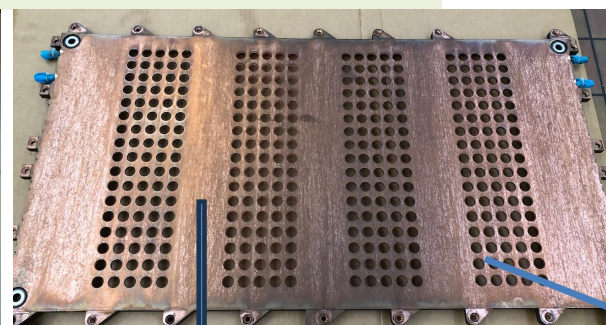
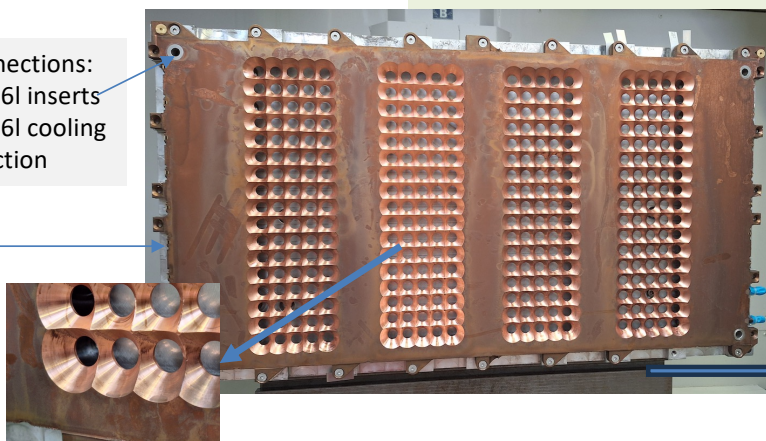
- First full-size prototypes
- Manufactured with AMCM M4K (Gmbh, EOS)
- Height 880mm; Width 450 mm
- Material CuCrZr
- Conformal cooling channels
- Spherical shape
- Heat treated with TAV S.p.A. furnace
- Quenched with GAr (argon gas)



Tomographic scan of an EG portion



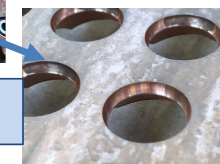
EBW connections:
- AISI 316l inserts
- AISI 316l cooling connection



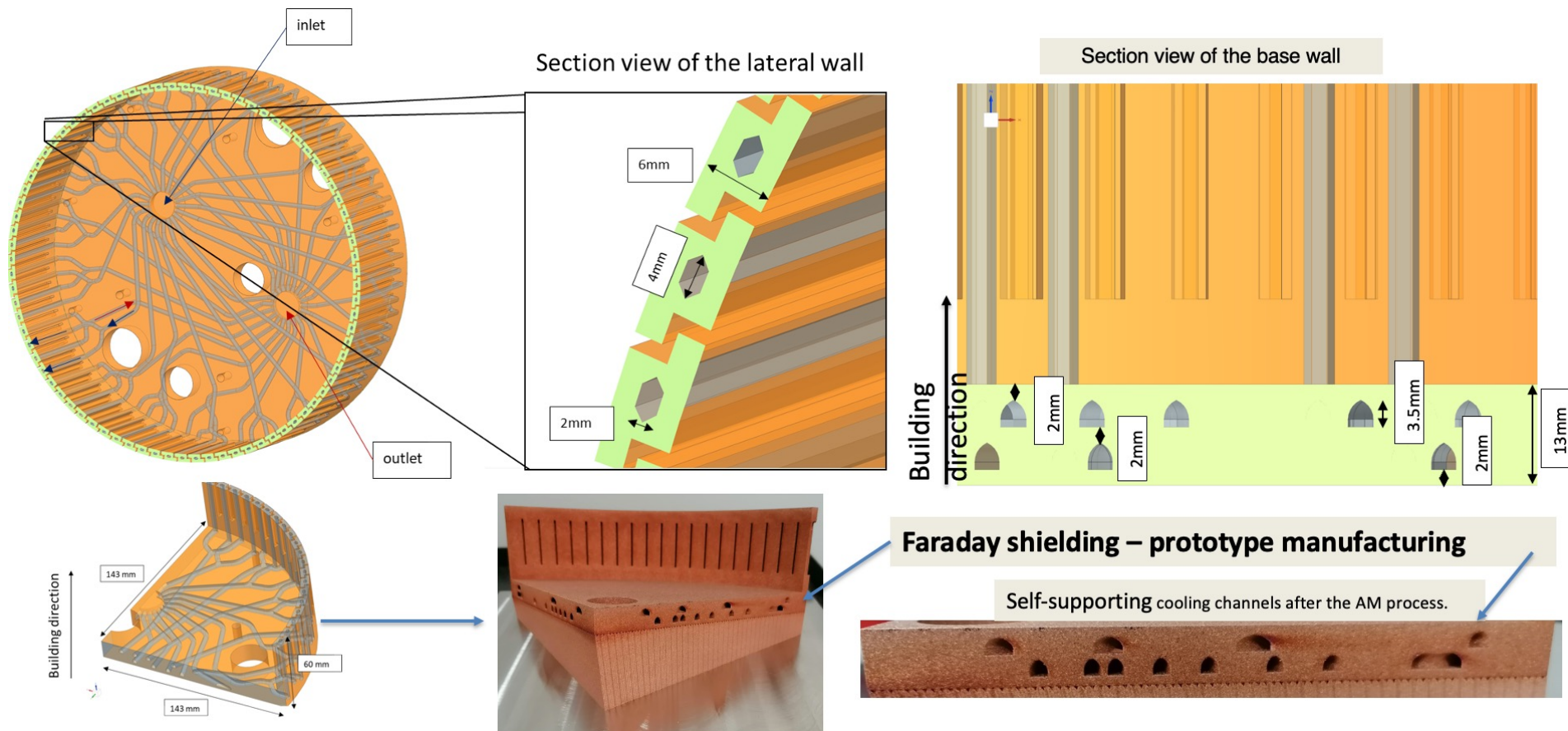
Plasma Grid finished and tested

Full-size printed Raw blanks:

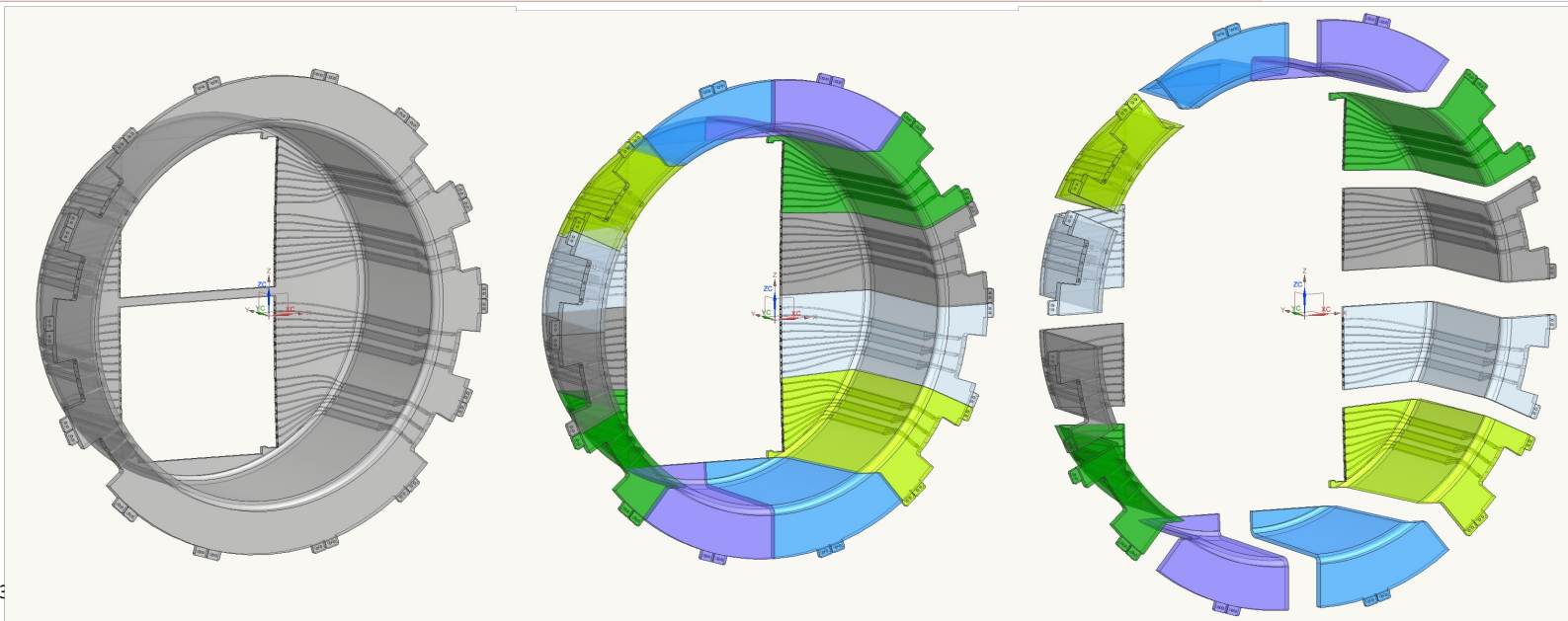
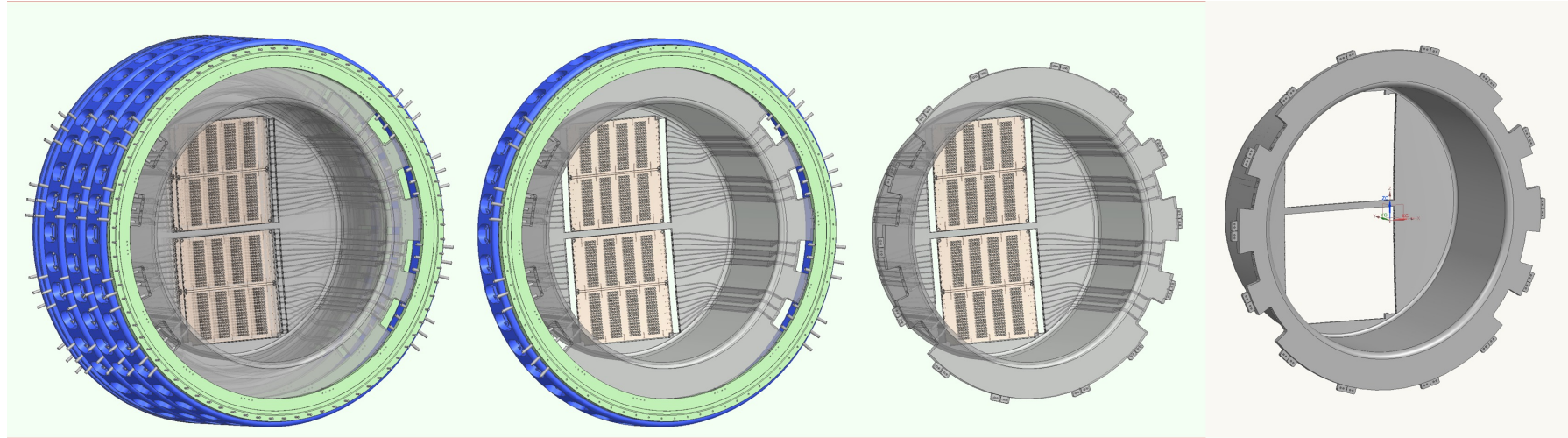
- Plasma Grid
- Extraction Grid
- Samples for fatigue lifetime study



DTT AM applications for the ION SOURCE: Faraday Shield



DTT NBI NAP: SUSPENSION SYSTEM (INCONEL 718) AND INSULATING RINGS

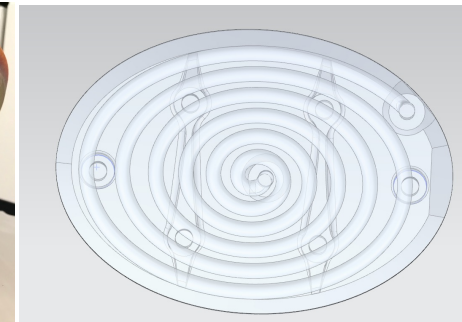


DTT AM applications for the ECRH



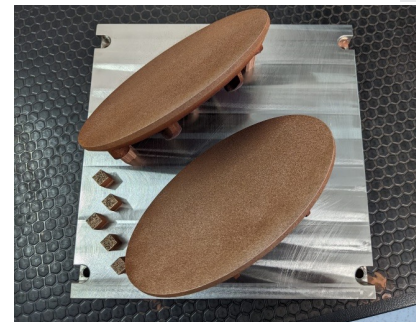
• M1 Mirror for the launcher

- First full-size prototypes
- Manufactured with EOSINT M280
- Material CuCrZr
- Spiral channel



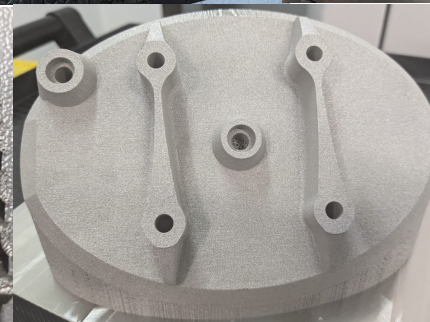
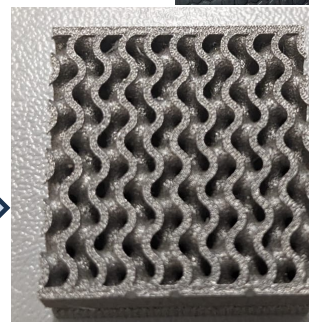
• Connection Line Mirrors

- First full-size prototypes
- Manufactured with EOSINT M280
- Material CuCrZr
- Spiral channel

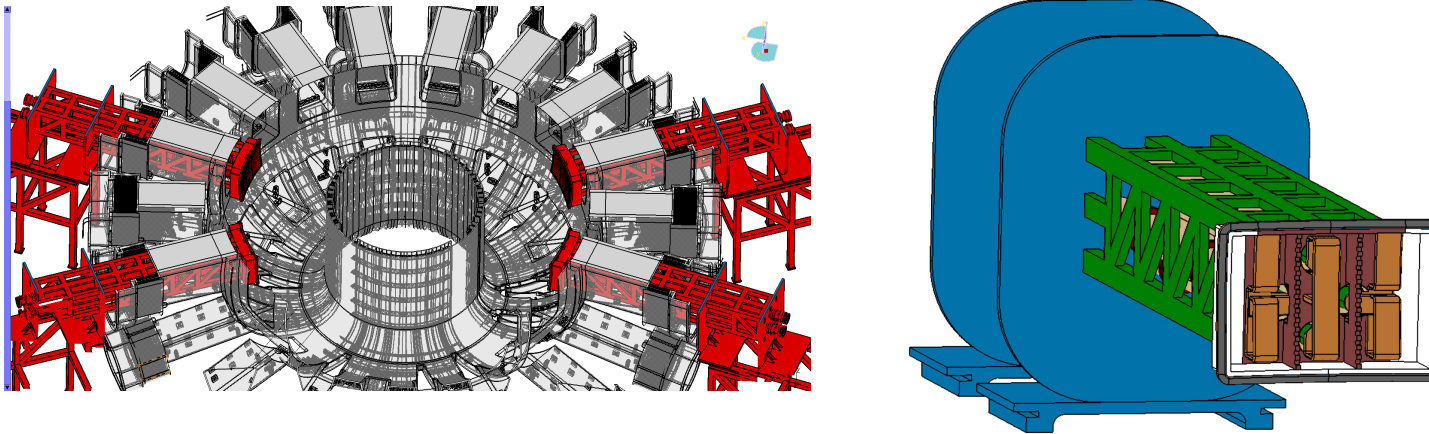


• M2 Mirror for the Launcher

- First prototype WIP
- Manufactured with EOSINT M280
- Material AISI316L
- Triply periodic minimal surface (TPMS)



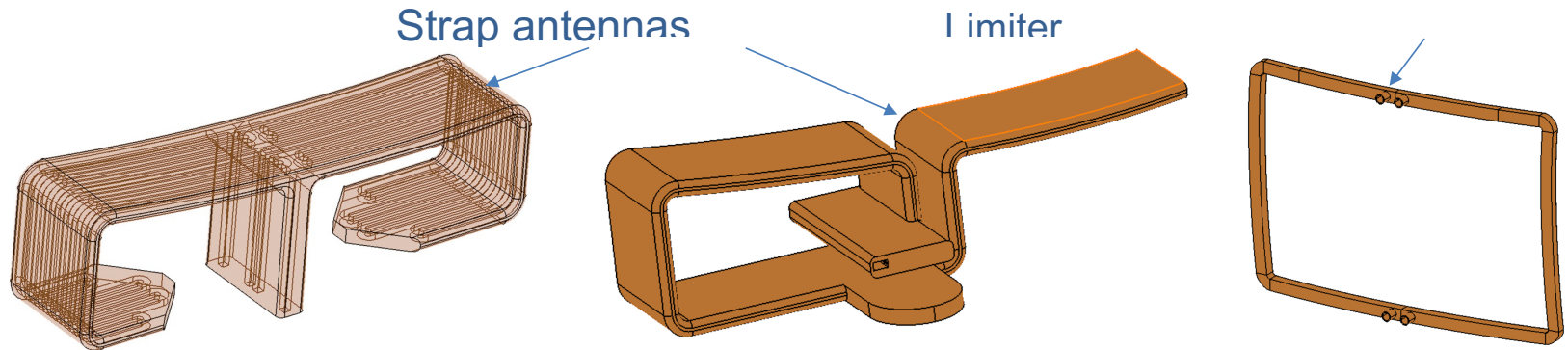
ICRH System AM components: Strap antennas and Limiters



Poster Session:

- *VP-4 Progress in the development of the ICRF system of DTT; S. Ceccuzzi et al.*

Strap antennas and limiters could be easily manufactured with AM large machines. The reference material being CuCrZr alloy.



WP 1 main results

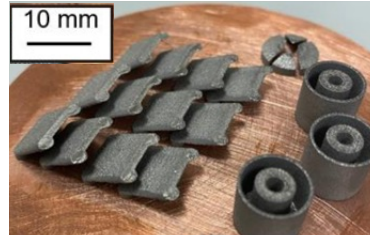
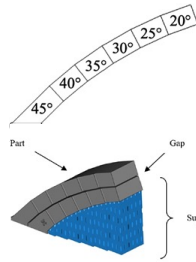
Characterization of pure refractory metals

AMIS

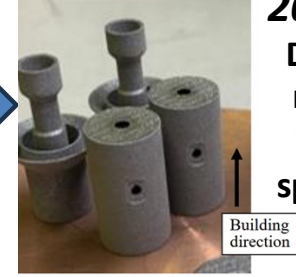
Mechanical characterization of pure Ta samples

Mechanical Prop.	E [GPa]	UTS [MPa]	A [%]
Vertical AM	193.7 ± 3.2	512.2 ± 4.3	17.0 ± 1.0
Horizontal AM	181.6 ± 0.5	459.4 ± 1.2	23.8 ± 1.2
Standard	180.2 ± 2.6	337.6 ± 2.3	27.5 ± 0.6

Geometrical characterization of pure Ta samples



In order to be able to produce the final parts with pure Ta

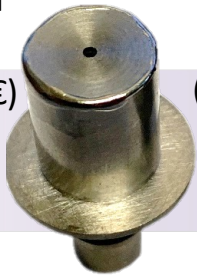


2024 Focus on: Development of new Refractory Metals Alloys specifically DfAM

WP 2 main results

Development of a New ION source DfAM

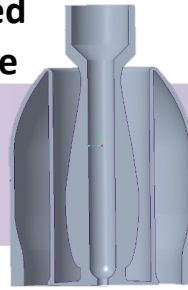
0. Standard cathode (Cost ~ 1100 €)



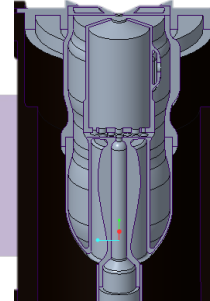
1. first AM cathode (Cost ~ 400 €)



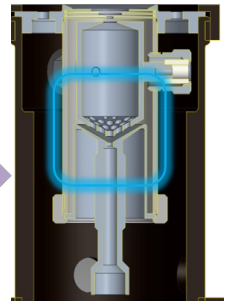
2. enhanced AM cathode



3. Fully AM FEBIAD ion source

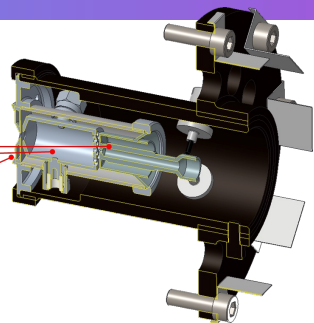
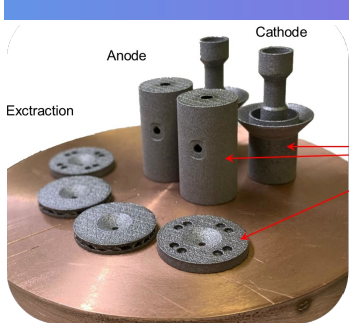


4. AM FEBIAD ion source with conical interface

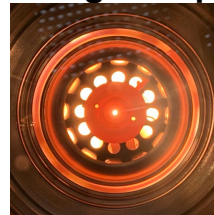


WP 3 main results

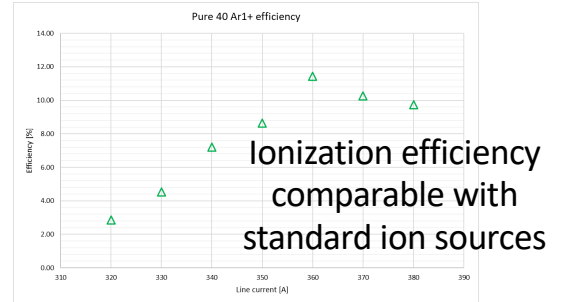
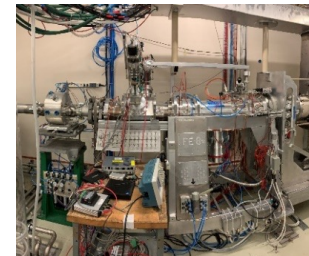
Off-line/On-line test of New ION sources

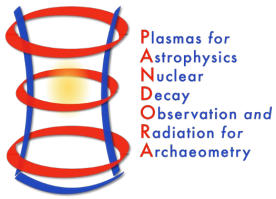


High temperature test

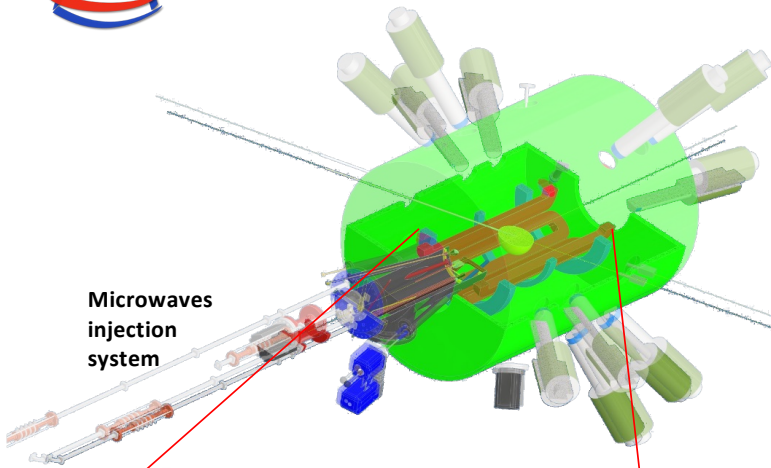


Successfully operated at HT (2000 °C) for 3 weeks

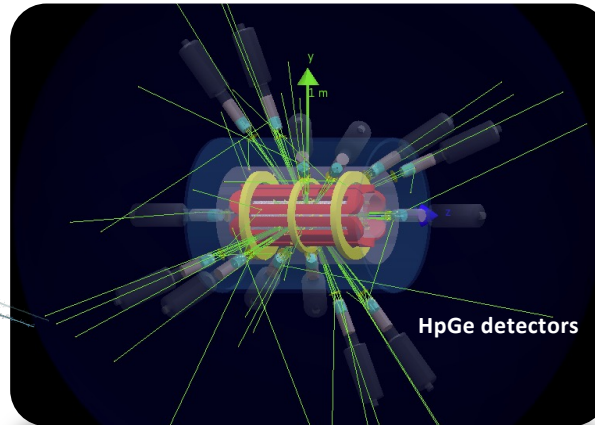




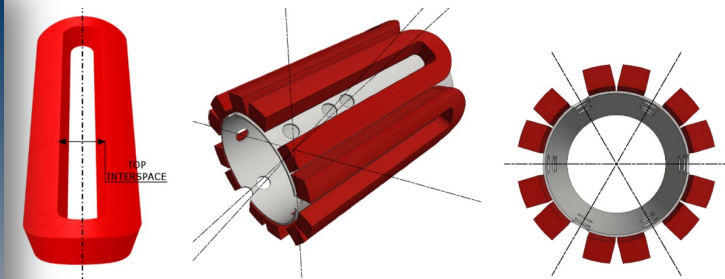
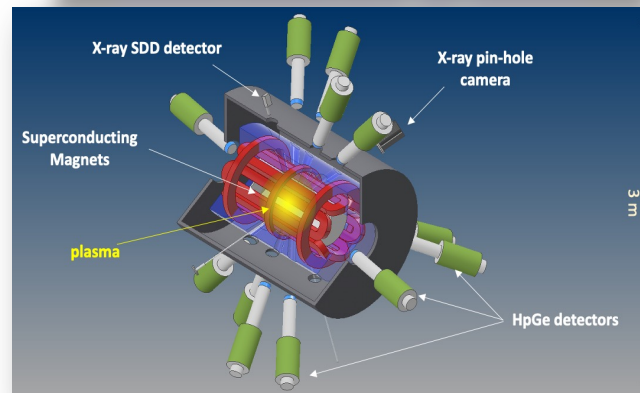
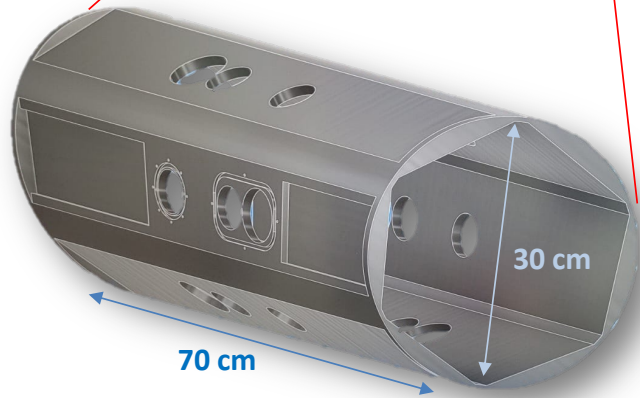
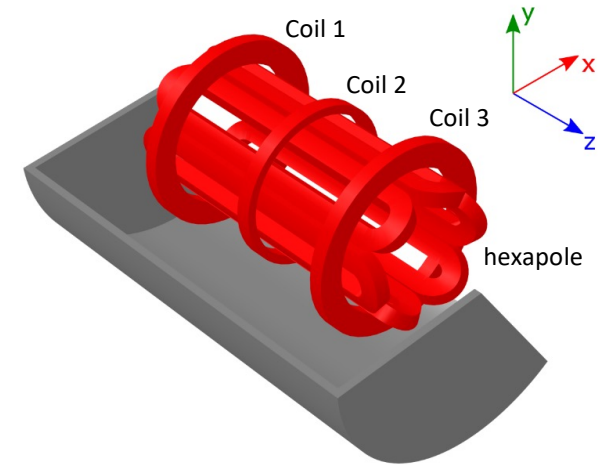
The **New ECRIT – ECR Ion Trap** (the largest never built...) is made of fully superconducting magnets, allowing radial position of HpGe detectors



Microwaves injection system



HpGe detectors

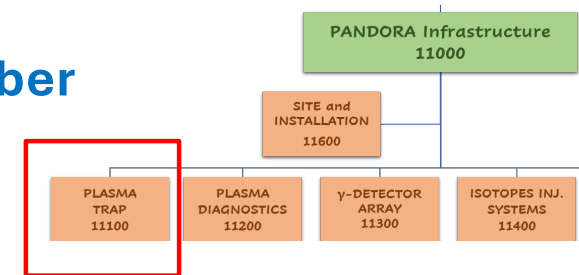


PANDORA superconducting magnetic system

An advanced (Stain. Steel) plasma chamber design is needed to operate at 10^{-8} mbar supporting a 10 kW plasma power and radial "holes" for measuring γ -ray emission

MAIN SUBSYSTEMS UPDATES: plasma chamber

(LNS + PD ACTIVITY)



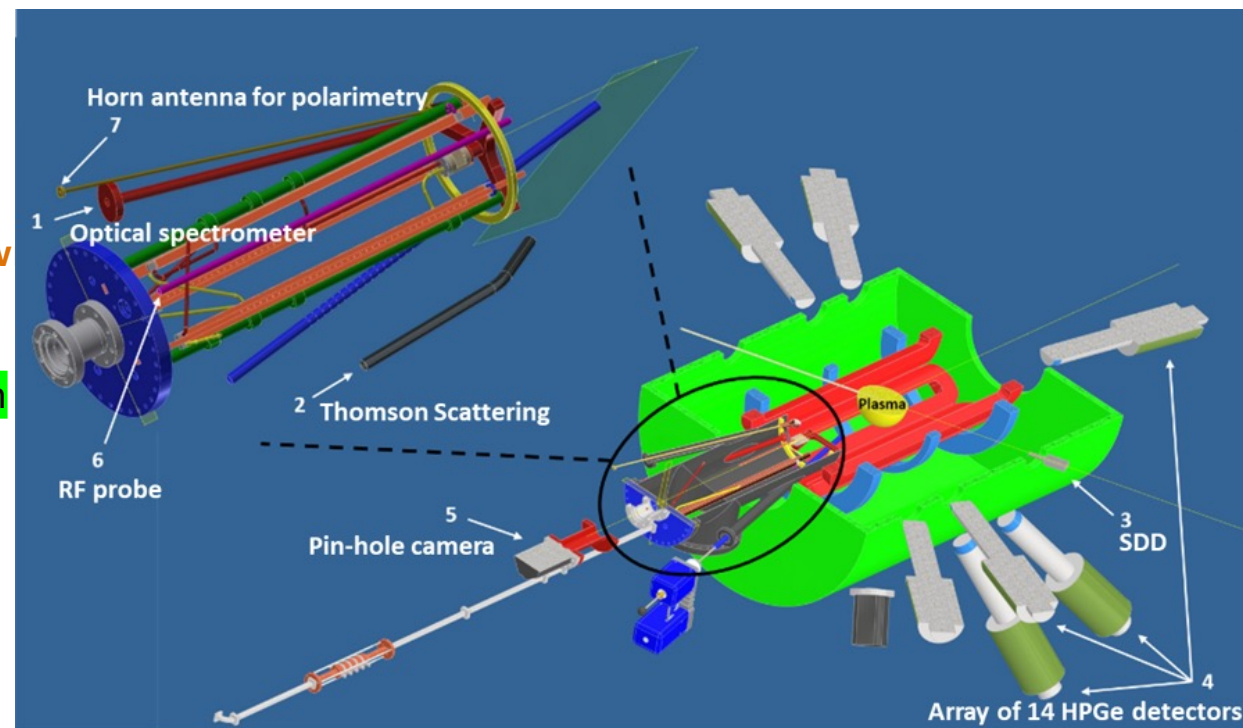
The design of the main plasma chamber is ongoing

The end caps, through several flanges and feedthroughs, allow to connect the vacuum pipe, the RF injection waveguides, the gas inlet, the oven, and several diagnostic devices.

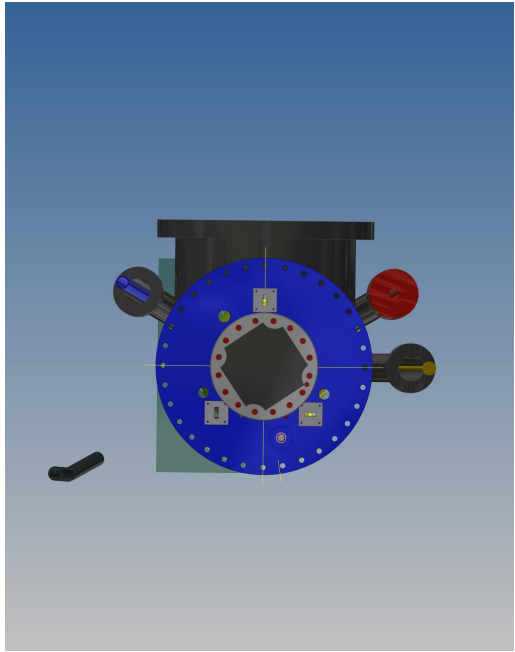
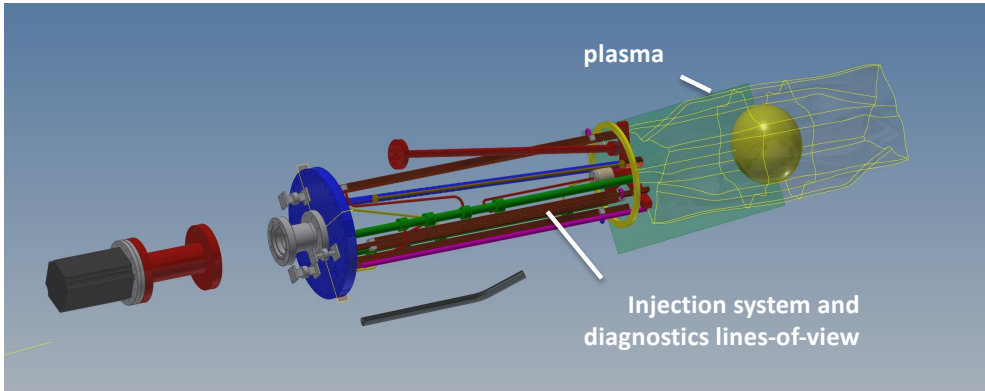
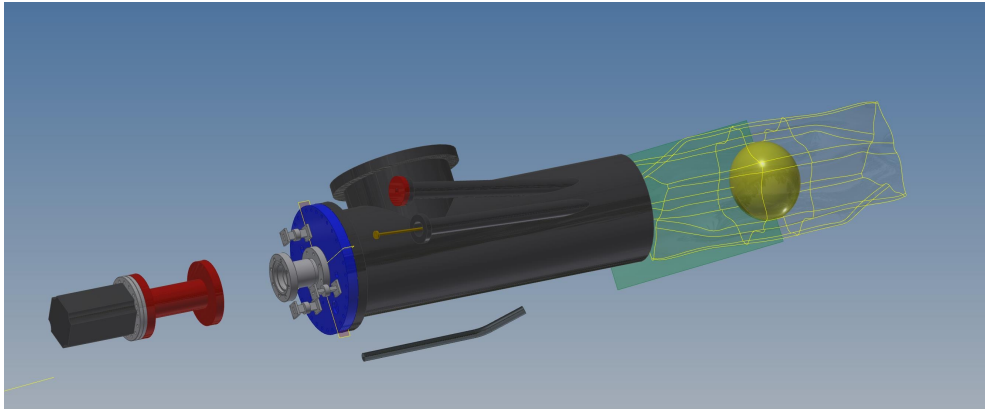
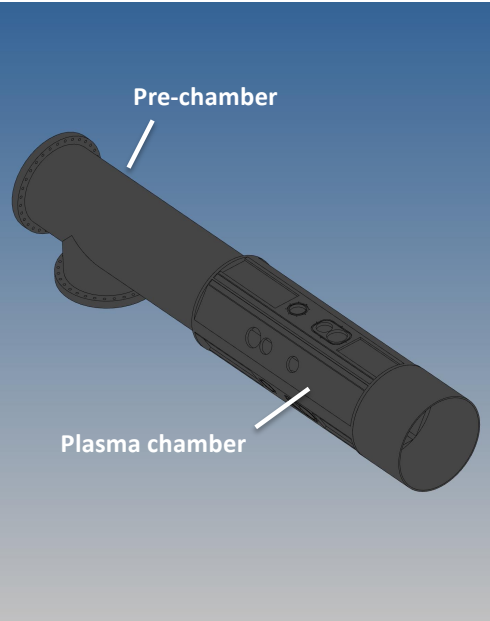
Many aspects concerning the positioning of different diagnostic tools on the injection side of the chamber were defined but still work needs to be done to complete the design.

The completion of the design will be possible only when the technical specifications (dimensions) of the magnetic trap will be known

With INFN-PD we have already ordered 120 kg of Inconel (Nickel alloy) for the chamber fabrication by Additive Manufacturing - Dec. 2023
Delivery at INFN-PD in April 2024



Plasma chamber and pre-chamber



Vacuum: 10^{-8} - 10^{-7} mbar
Total RF power: 10 kW



INFN
GRAZIE

Thank you for your attention



CuCrZr – EOS M280 30 μm

- Thermomechanical characterization with different heat treatments

6 GHz SRF cavities and surface smoothing

CuCrZr – AMCM EOS M290 1kW

- 80 μm and 60 μm process were investigated
- Parameters optimization for the infill, contour and downskin
- Heat treatments: both DAH and SA treatments
- Tests: OM, SEM, TEM, Hardness, Eddy currents, Tensile properties, Thermal conductivity, Surface roughness, CTE (as-built conditions)



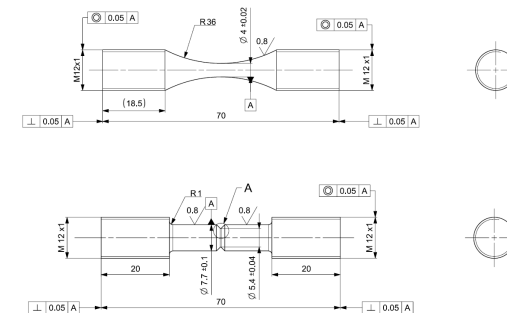
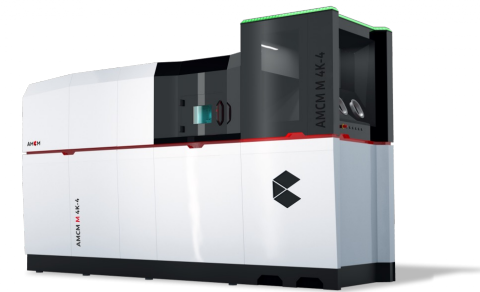


Characterization of AMCM 4K CuCrZr 80 μm

- Relative density
- Microstructural characterization
- Tensile tests
- **Fatigue life (hourglass and notched)**

Low and high cycle fatigue life at RT and 300 $^{\circ}\text{C}$ of the following materials:

- EOS CuCP EOS M290 1KW
- EOS CUCRZR 60 μm EOS M290 1KW
- EOS CUCRZR 80 μm AMCM 4K (optimized parameters)
- CuCrZr EOS M280





PhD project - Corrosion of components made by additive manufacturing for extreme applications

Corrosion/erosion performance with the same water chemistry condition found in ITER NBTF systems and at same high velocity required (up to 12 m/s) and temperature (150 °C)

- CuCrZr
- Inconel 718

Corrosion behavior in molten salts at the high temperature (550 °C)

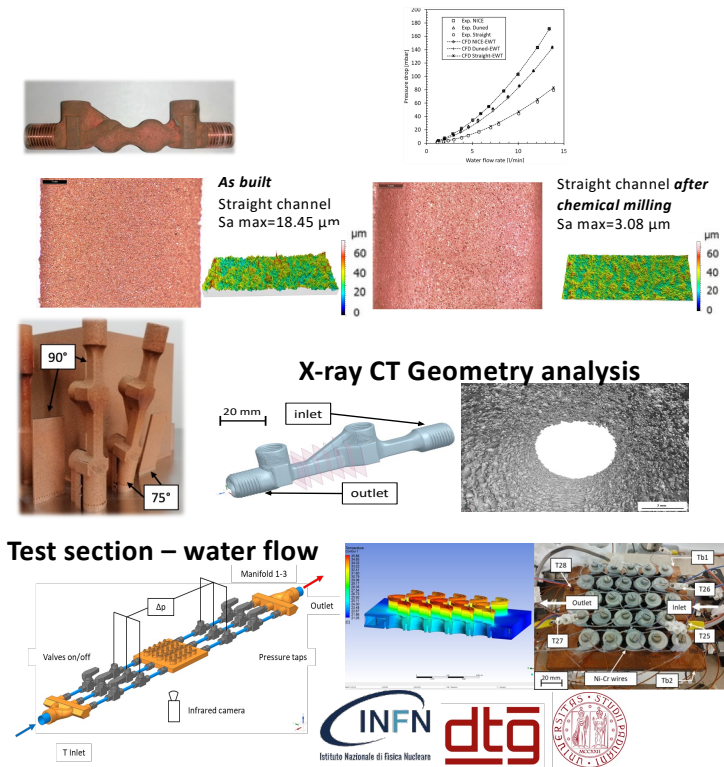


AM for thermal management application: numerical modelling and experimental tests.

Fluid flow inside additively manufactured and smoothed cooling channels.

Influence of the building orientation on the hydraulic performance of additively manufactured cooling channels.

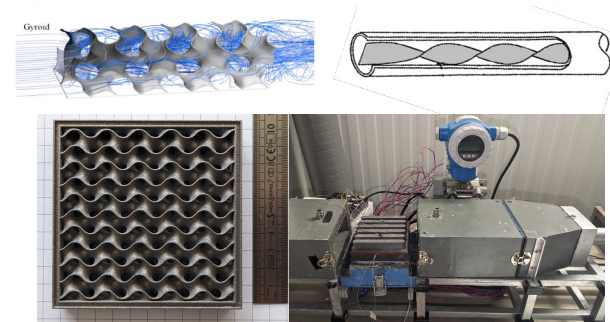
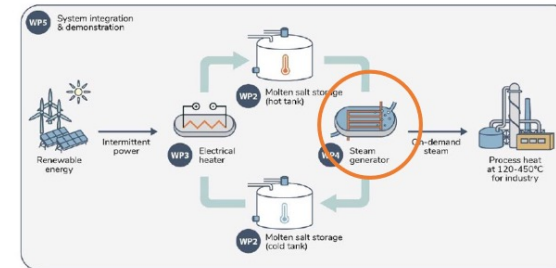
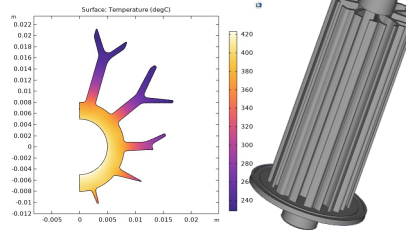
Experimental tests and CFD simulations of additively manufactured extraction grid prototypes for the DTT neutral beam injector.





LoCoMoSa: additive manufacturing of a steam generator for thermal storage.
Topology optimization

- Comsol
- Ntopology



Experimental investigation of topology optimized geometries for the improvement of power energy density for latent energy storage systems (PCM)

PhD Program of National Interest in Technologies for fundamental research in Physics and Astrophysics

- ➔ **SCHOLARSHIP N.2** **Materials - Metallurgy**
 HOSTING UNIVERSITY/RESEARCH CENTRE: Università degli Studi di Padova
 CURRICULUM: Mechanics
 TOPIC: Development and Characterization of Innovative Additively Manufactured Metal Alloys for High and Ultra-High Temperature Applications
- ➔ **SCHOLARSHIP N.3** **Design for Additive Manufacturing - Mechanical**
 HOSTING UNIVERSITY/RESEARCH CENTRE: Università degli Studi di Padova
 CURRICULUM: Mechanics
 TOPIC: Advanced Design for Additive Manufacturing (DfAM) approaches for cutting-edge applications in Physics and Engineering
- ➔ **SCHOLARSHIP N.8** **Chemistry**
 HOSTING UNIVERSITY/RESEARCH CENTRE: Università degli Studi di Padova
 CURRICULUM: Mechanics
 TOPIC: Sustainable Surface Finishing of Additively Manufactured Metal Components for High-Precision Applications
- ➔ **SCHOLARSHIP N.29** **Mechanical - SPES**
 HOSTING UNIVERSITY/RESEARCH CENTRE: INFN - Laboratori Nazionali di Legnaro
 CURRICULUM: Mechanics
 TOPIC: Development, design and testing of metallic components for high-temperature nuclear physics applications produced using additive manufacturing technologies

DM 629 P.A.

Periods abroad	Periods in companies/institutions
Mandatory	Mandatory in companies, research centres or public administrations

DM 630

Periods abroad	Periods in companies/institutions
Mandatory	Mandatory in the company

INFN-LNL & Weal3T System

INFN

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- Cu**
- M. Bonesso, P. Rebesan, S. Mancin, C. Gennari, I. Calliari, R. Dima, A. Pepato, **Effect of Particle Size Distribution on Laser Powder Bed Fusion Manufacturability of Copper**, *Berg Huettenmaenn Monatsh - BHM Berg* (2021), DOI: [10.1007/s00501-021-01107-0](https://doi.org/10.1007/s00501-021-01107-0)
 - V. Candela, M. Pozzi, E. Chyhyrynets, *et al.* **Smoothing of the down-skin regions of copper components produced via Laser Powder Bed Fusion technology**, *Int J Adv Manuf Technol* (2022), DOI: [10.1007/s00170-022-10408-8](https://doi.org/10.1007/s00170-022-10408-8)
- W**
- P. Rebesan, M. Bonesso, C. Gennari, R. Dima, A. Pepato, M. Vedani, **Tungsten Fabricated By Laser Powder Bed Fusion**, *Berg Huettenmaenn Monatsh - BHM Berg* (2021), DOI: [10.1007/s00501-021-01109-y](https://doi.org/10.1007/s00501-021-01109-y)
- Mo**
- P. Rebesan, C. Gennari, F. Zorzi, M. Bonesso, I. Calliari, R. Dima, A. Pepato, M. Vedani, **Interface analysis of additively manufactured pure molybdenum and AISI 304 stainless steel building-plate**, *Materials Letters* (2021), DOI: [10.1016/j.matlet.2021.130763](https://doi.org/10.1016/j.matlet.2021.130763)
 - P. Rebesan, M. Ballan, M. Bonesso, A. Campagnolo, S. Corradetti, R. Dima, C. Gennari, G.A. Longo, S. Mancin, M. Manzolaro, G. Meneghetti, A. Pepato, E. Visconti, M. Vedani, **Pure molybdenum manufactured by Laser Powder Bed Fusion: thermal and mechanical characterization at room and high temperature**, *Additive Manufacturing* (2021), DOI: [10.1016/j.addma.2021.102277](https://doi.org/10.1016/j.addma.2021.102277)
- Nb and Ta**
- P. Rebesan, **Laser powder bed fusion of refractory metals: A new way to produce components and devices for nuclear physics**, *Nuovo Cim. Della Soc. Ital. Di Fis. C. 46* (2023) DOI: [10.1393/ncc/i2023-23074-1](https://doi.org/10.1393/ncc/i2023-23074-1)
 - S. Candela, P. Rebesan, D. De Bertoli, S. Carmignato, F. Zanini, V. Candela, R. Dima, A. Pepato, M. Weinmann, P. Bettini **Pure niobium manufactured by Laser-Based Powder Bed Fusion: influence of process parameters and supports on as-built surface quality**, *The International Journal of Advanced Manufacturing Technology* (2024) DOI: [10.1007/s00170-024-13249-9](https://doi.org/10.1007/s00170-024-13249-9)

Publications

Simulations

G. Favero, M. Bonesso, P. Rebesan, R. Dima, A. Pepato, S. Mancin, **Additive Manufacturing for Thermal Management applications: from experimental results to numerical modelling**, *International Journal of Thermofluids* (2021), DOI: [10.1016/j.ijft.2021.100091](https://doi.org/10.1016/j.ijft.2021.100091)

G. Favero, G. Berti, M. Bonesso, D. Morrone, S. Oriolo, P. Rebesan, R. Dima, P. Gregori, A. Pepato, A. Scanavini, S. Mancin, **Experimental and numerical analyses of fluid flow inside additively manufactured and smoothed cooling channel**, *International Communications in Heat and Mass Transfer* (2022), DOI: [10.1016/j.icheatmasstransfer.2022.106128](https://doi.org/10.1016/j.icheatmasstransfer.2022.106128)

Fusion

V. Candela, C. Cavallini, C. Gasparri, L. Armelao, V. Candeloro, M. Dalla Palma, M. Fadone, D. Marcuzzi, M. Pavei, A. Pepato, *et al.* **Investigations on Caesium Dispersion and Molybdenum Coating on SPIDER Components**. *Materials* (2023), DOI: [10.3390/ma16010206](https://doi.org/10.3390/ma16010206)

Design

A. Giroto, M. Ballan, P. Rebesan, R. Dima, A. Monetti, I. Bodini, D. Paderno, V. Villa, A. Pepato, M. Manzolaro, **Additively manufactured tantalum cathode for FEBIAD type ion sources: production, geometric measurements, and high temperature test**, *Journal of Physics: Conference Series*. DOI: [2687.082047](https://doi.org/2687.082047). [10.1088/1742-6596/2687/8/082047](https://doi.org/10.1088/1742-6596/2687/8/082047)

IPAC Proceedings

1. A. Pepato, *et al.* **Implementation of the Additive Manufacturing for metals approach: the production of the acceleration grids for DTT NBI project**, 14th International Particle Accelerator Conference, Venezia (2023)
2. V. Candela, *et al.* **Additive Manufacturing of 6 GHz seamless SRF copper cavities: printing, surface treatments and performance investigations**, 14th International Particle Accelerator Conference, Venezia (2023)
3. M. Ballan, *et al.* **Additively manufactured tantalum cathode for FEBIAD type ion sources: production, geometric measurements, and high temperature test**, 14th International Particle Accelerator Conference, Venezia (2023)
4. M. Bonesso, *et al.* **Laser powder bed fusion of CuCrZr for nuclear fusion acceleration components**, 14th International Particle Accelerator Conference, Venezia (2023)
5. S. Candela, *et al.* **Laser powder bed fusion of pure niobium for particle accelerator applications**, 14th International Particle Accelerator Conference, Venezia (2023)
6. G. Favero, *et al.* **Predictive capabilities in CFD simulations of additively manufactured extraction grid cooling channels for the DTT NBI system**, 14th International Particle Accelerator Conference, Venezia (2023)