Cold Spray Technology Applications for SRF Cavity Thermal and Mechanical Stabilization.

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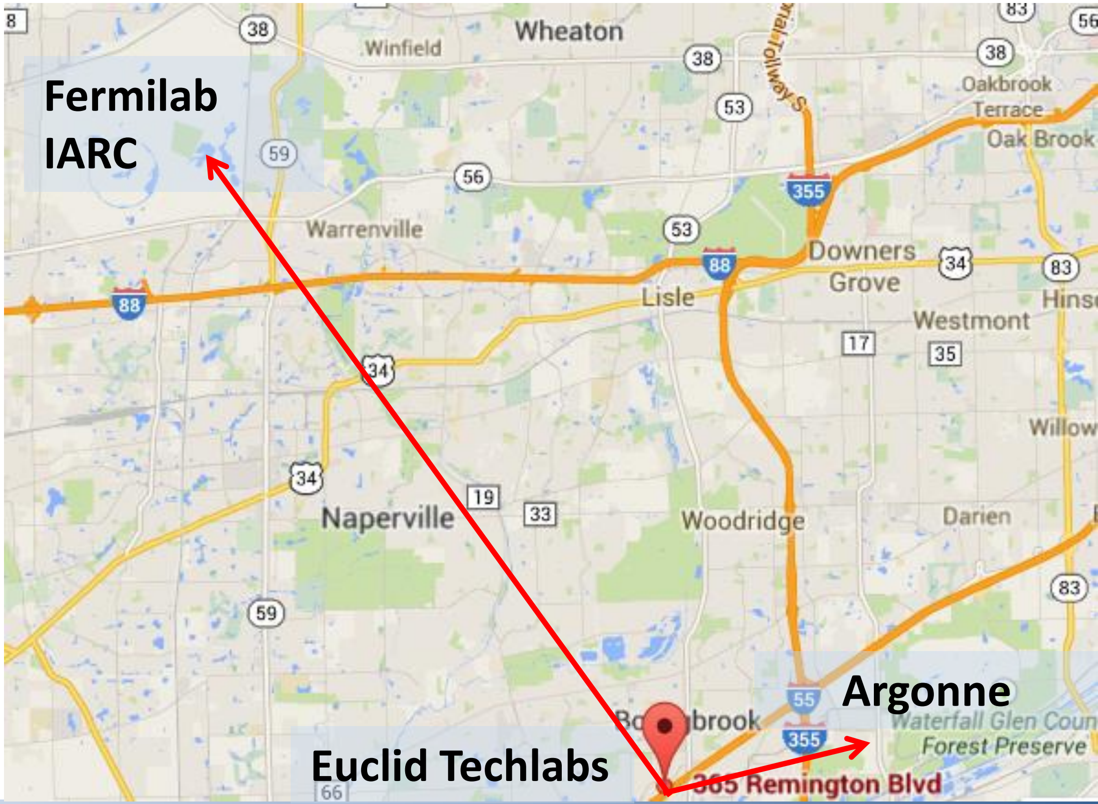
Euclid Techlabs

Euclid TechLabs LLC, founded in 2003 is a company specializing in the development of advanced materials and new designs for beam physics and high power/high frequency applications. Additional areas of expertise include dielectric structure based accelerators and "smart" materials technology and applications.

- 2 offices: Bolingbrook, IL (lab) and Beltsville, MD (lab and HQ)
- Tight collaborations with National Labs: ANL, BNL, FNAL, LANL, LBNL.
- Actively participate in Universities research programs: Caltech, Columbia, Duke, Penn State, UMD, IIT.



Lab Facility in Bolingbrook, IL

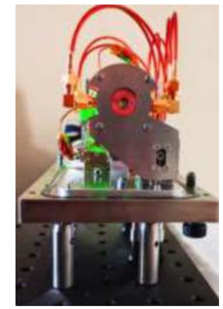
- Compact electron accelerator test facility (bunker)
- Time resolved TEM beamline
- Clean room/magnetron sputtering (TiN, copper, dielectrics)
- Field Emission cathode DC test stand
- Femtosecond laser
- RF/microwave/THz lab

Lab Facility in Beltsville, MD

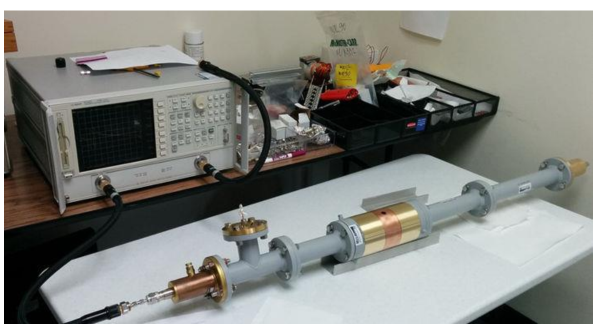
- Diamond growth lab
- HPHT and CVD reactors
- Photocathode lab

Key Euclid Technologies

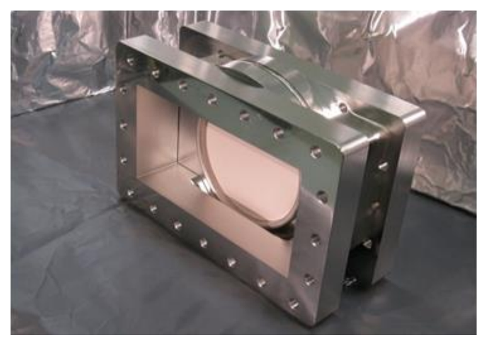
- Ultra-compact low energy accelerator (dielectric based)
- Stroboscopic pulser for Transmission Electron Microscope
- Electron guns for accelerators: Photo-, thermo-, field emission (FE)- and SRF guns
- Ferroelectric based fast tuner
- UNC Diamond based FE and photo cathodes
- Accelerator components (RF windows, couplers…)
- Other beam physics instrumentation



5 GHz kicker for TEM, BES/NIST

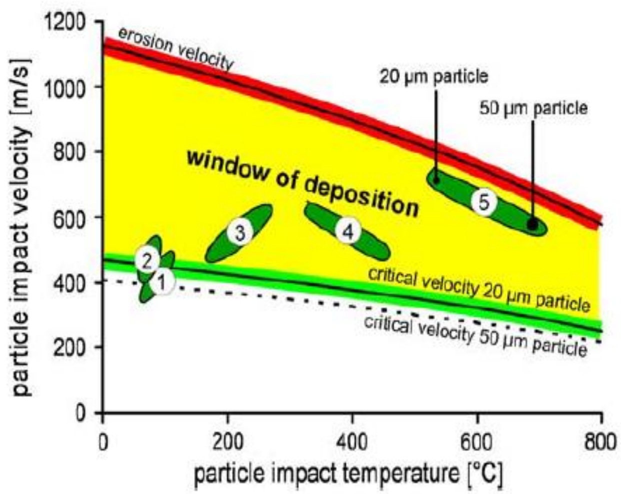


Fast ferroelectric 400 MHz tuner successfully tested at CERN

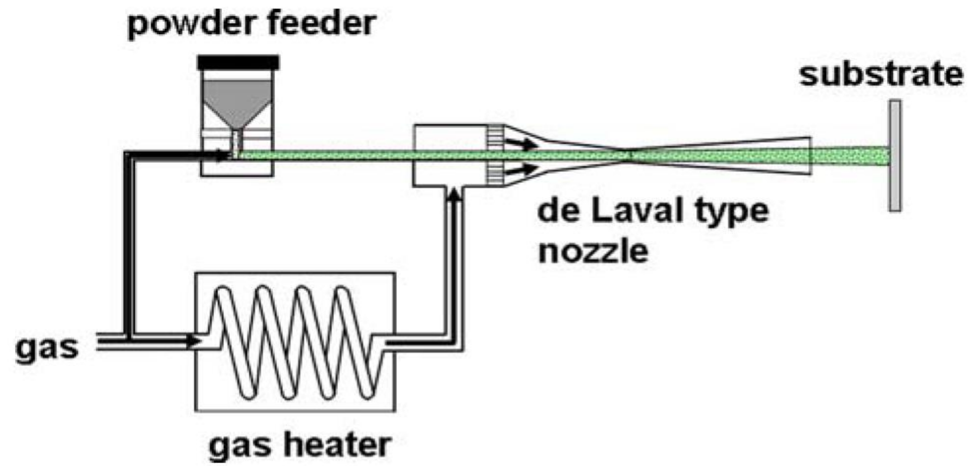


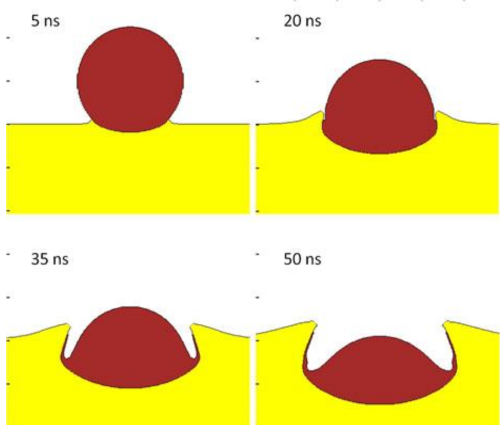
L-band RF window for AWA ANL

Cold Spray Technology



Window of deposition as function of particle temperature and velocity

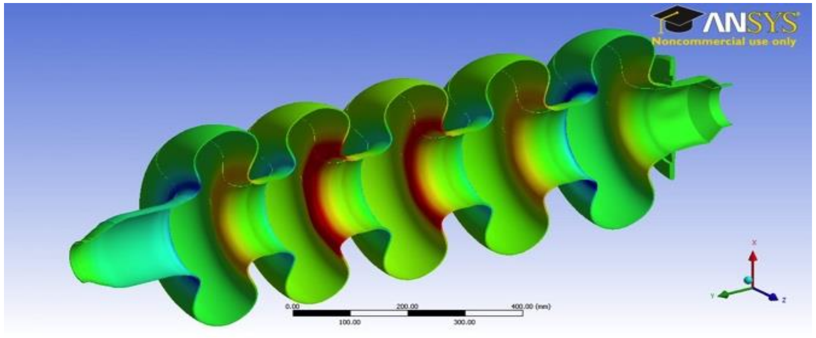


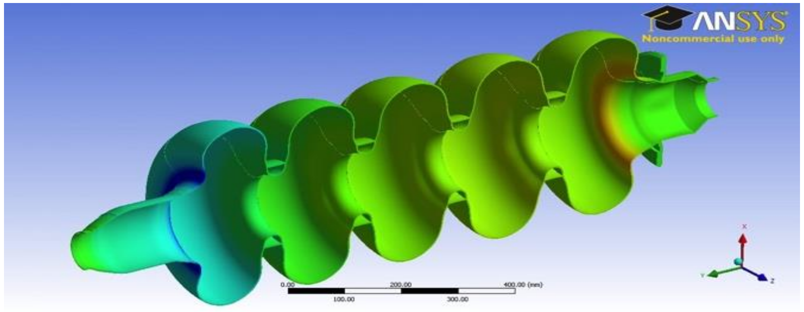


Deformation of a 20 micron copper sphere striking an aluminum surface

In the cold spray method, fine powder particles are propelled toward the substrate to be plastically deformed, which leads to flattening and bonding them to the underlying surface. Cold spray operating temperatures are very low compared with those of thermal and plasma spray. The low operating temperature with the use of inert gas prevents oxidation, phase transformation and grain growth in the coating during spray process.

Motivation



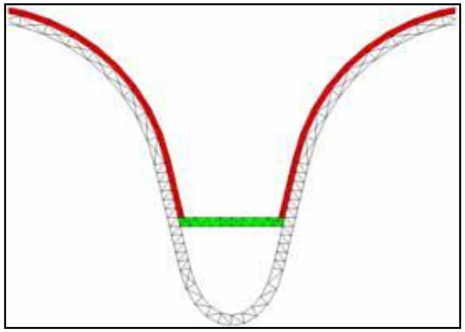


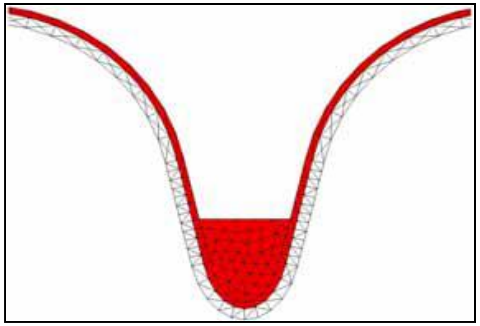
The most important source of frequency shifts in SRF cavities is due to the effect of microphonics and Lorentz forces. Additional stiffening is then needed to improve the cavity's mechanical stability and reduce the frequency shift.

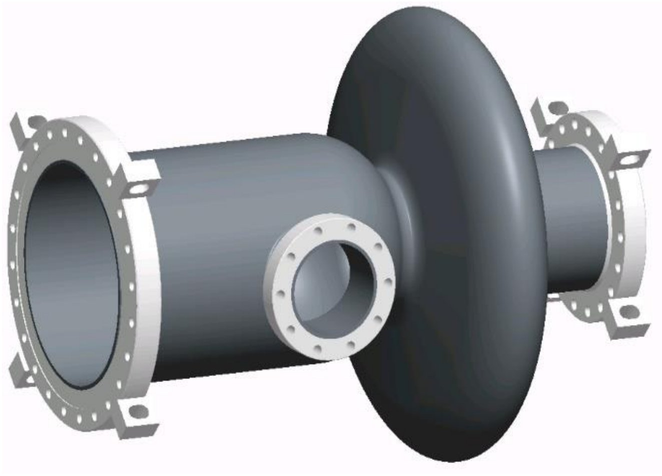
The use of Nb/Cu cold spray cladding material can provide mechanical stabilization, and thus stiffening rings may be avoided. A significant benefit of the proposed technology is also the addition of copper for thermal stability and conduction cooling.

The proposed ***cold spray technology*** will lead to a significant cost savings: the reduction in the Nb material thickness, the reduction in the number of manufacturing steps, and the improved thermal stabilization by the use of thin Nb/thick copper, allowing higher Q0 at higher gradient and lower losses. *One of the potential applications is the possible industrial use of SRF accelerators with conduction cooling.*

A Solution







The main innovation: the cold spray technology could be applied selectively to engineer stiffness locally, for example to reduce Lorentz force detuning. In addition, it could be applied to provide a first layer of copper on Nb for conduction cooling without the use of heat.

The challenging goal: develop a new robust technology for cold spray copper deposition on SRF niobium cavities providing required level of heat transfer through the copper-niobium interface. This type of technology, applicable for SRF cavity fabrication, is not currently available.

Phase I Accomplishments

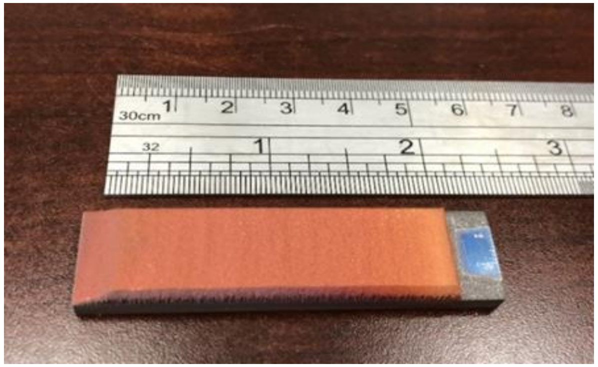
- The cold-spray deposition of 99.9%-pure copper powder was performed using He and N_2 propellant gases for various samples, and with technology optimizations.
- The thermal conductivity and residual resistivity ratio (RRR) of cold-sprayed test coupons were measured at JLAB while cooling the coupons down to 4.3 K from room temperature.
- The RRR of Cu was increased up to the range of RRR~50 at the 4.3 K temperature.
- The adhesion tests demonstrated that the cold-sprayed copper layers had very good mechanical bonding to the niobium substrate in all the samples examined.
- In general, the Phase I results demonstrated that the developed copper on niobium cold-spray technology can be implemented for the copper-niobium SRF cavity to provide increased mechanical and thermal stability, and could be used for conduction-cooled industrial SRF accelerator applications.

Phase II Tasks

- Task 1. Cold spraying of copper/tungsten on niobium coupons.
- Task 2. Microstructural analysis. Bonding strength measurements.
- Task 3. RRR measurements.
- Task 4. (In collaboration with JLAB). Nb_3Sn coating of the SRF cavity. Vertical Test Stand testing (VTS) testing of the Nb3Sn inside coated SRF cavity in JLAB facility.
- Task 5. Cold-spray deposition of Cu (or W/Cu) on a single-cell SRF cavity, Nb_3Sn-coated inside and vacuum sealed.
- Task 6. VTS testing at JLAB of the SRF cavity coated on the inside with Nb_3Sn and copper cold sprayed on the outside.
- Task 7. Optimization of Euclid's conduction cooling cryomodule for the copper cold-sprayed SRF cavity test. Conduction cooling testing of the cold sprayed cavity.
- Task 8. Final Report Preparation.

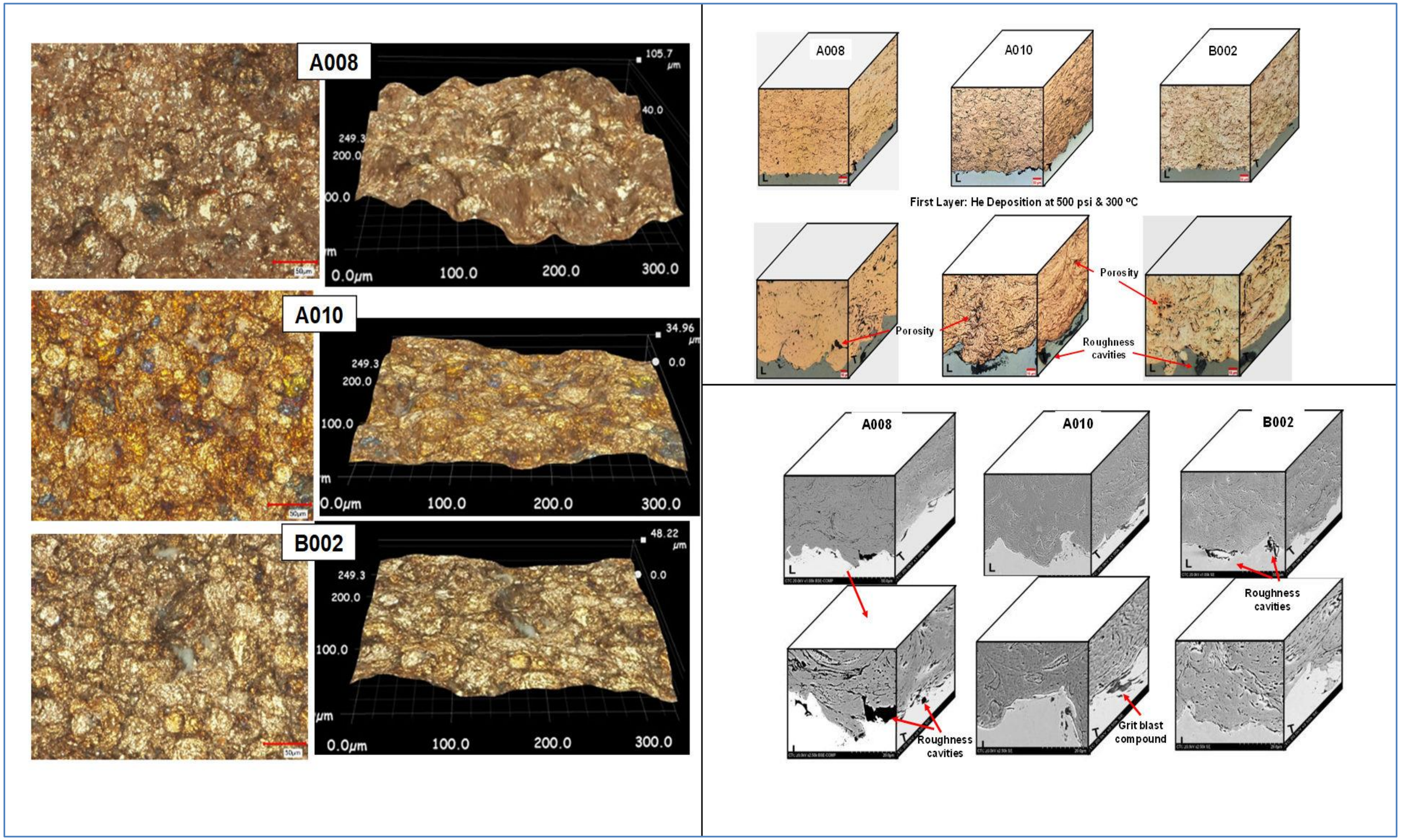
- ■ - done ■ - to be done ■ - in progress

Cold Spray Cu Deposition on Niobium



Rectangular 3x45x70mm (right) and disk 3x50mm (left) niobium coupons with 99.99% pure copper, 3mm thickness deposited by CTC, Inc.

Microhardness and Microstructure.



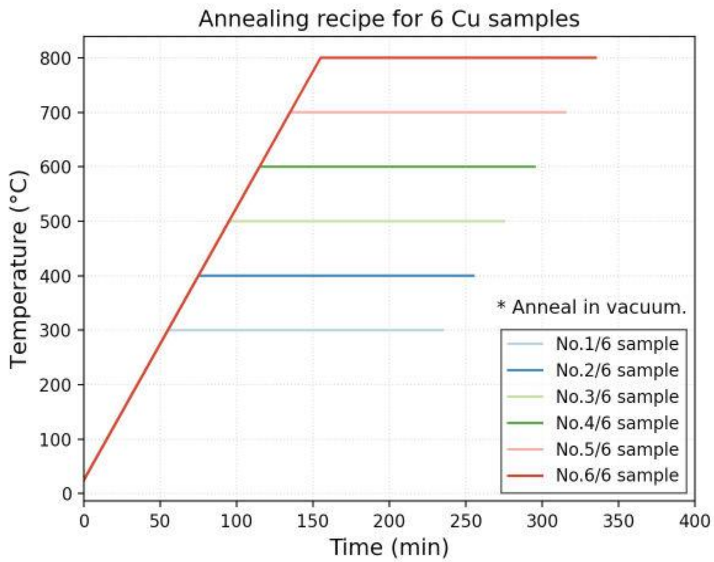
Surface appearance for the cold-spray coated Nb samples (top right) Light optical microstructure of copper cold-sprayed Nb substrate interface. (bottom left) SEM microstructure of copper cold sprayed on the Nb substrate, copper/Nb interface. (bottom right)

Adhesion Test

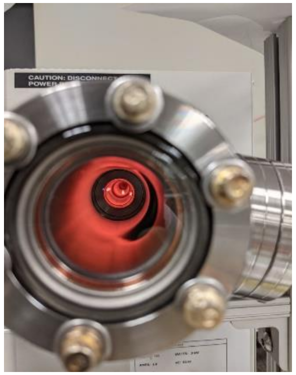
Sample ID	Max Burst Pressure (PSI)	Nature of Failure
A1 – Location 1	6,024	Adhesive
A1 – Location 2	6,124	Adhesive
B1 – Location 1	872	Adhesive
B1 – Location 2	792	Adhesive
A2 – Location 1	5,060	Adhesive
A2 – Location 2	5,556	Adhesive

PosiTest® Pull-Off adhesion tester used for copper cold-spray bonding strength. Measurement results of the pulling-off adhesion test of the copper niobium cold spray deposition of the coupons presented in the previous slide.

Annealing



Oxygen impact on thermal conductivity was considered with the annealing technology development. In order to determine the thermal conductivity of the Cu itself, the Nb/Cu strips $2 \times 2 \times 55$ mm^3 were cut by wire-EDM to separate the Cu from the Nb. Six samples were annealed at 300C -800C in vacuum 10^-8 Torr for 3 - 7 hours range, and two samples were annealed at 900C and 1000C for 12 hours at 10^-4 Torr oxygen.



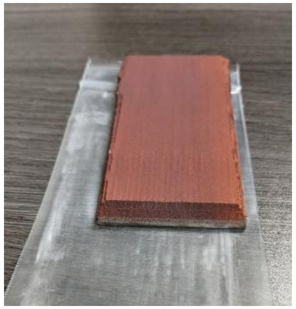
RRR Measurements

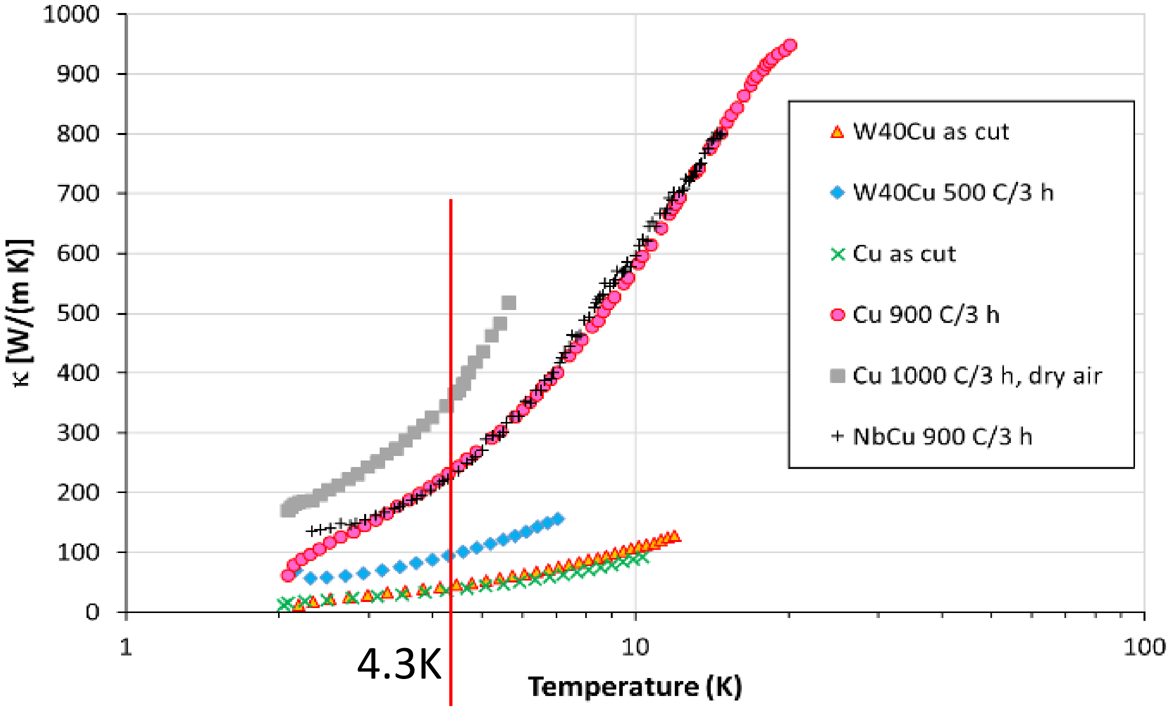
Sample	Temperature	Vacuum/Gas	RRR
Euclid Cu I	300C	vacuum	30.99
Euclid Cu II	400C	vacuum	34.02
Euclid Cu III	500C	vacuum	59.3
Euclid Cu IV	600C	vacuum	46.56
Euclid Cu V	700C	vacuum	67.79
Euclid Cu VI	800C	vacuum	74.58
Euclid Cu VII	900C	oxygen 10^-4	105.45
Euclid Cu VIII	**1000C**	**oxygen 10^-4**	**131.65**

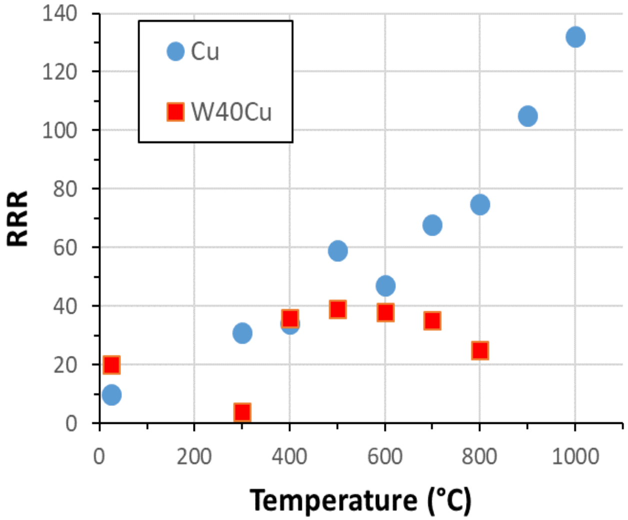
RRR measurement was performed, and the temperature dependence of the resistivity was measured at JLab with a standard 4-probe method while cooling down to 4.3 K from room temperature. The best result was demonstrated for the copper rod annealed at 1000C in Oxygen, **RRR=131.65.**

W/Cu vs. Cu Cold Spray on Nb

We also carried out cold-spray deposition with mixed tungsten and copper (W/Cu) on niobium coupons using cold-spray recipes for both He and N_2 gas deposition parameters.

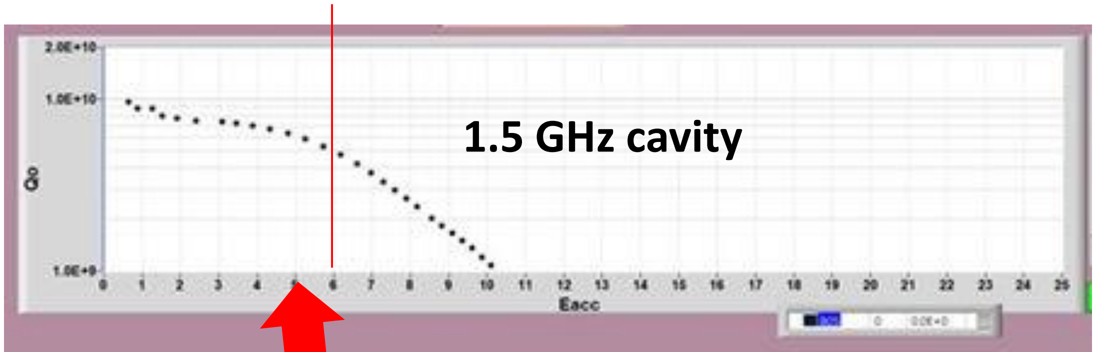


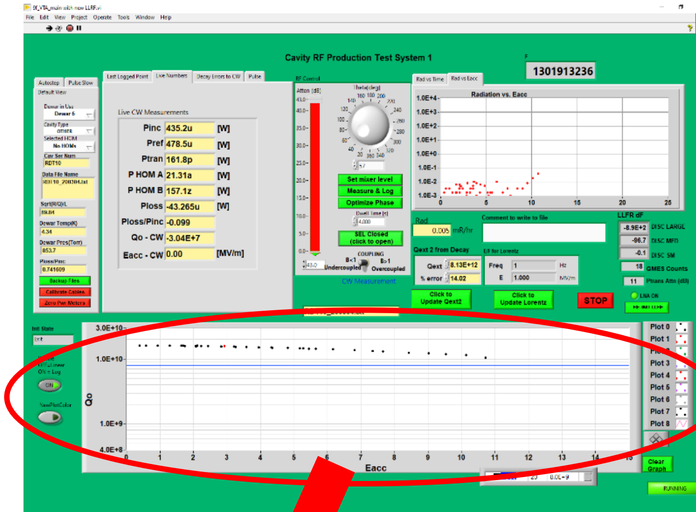


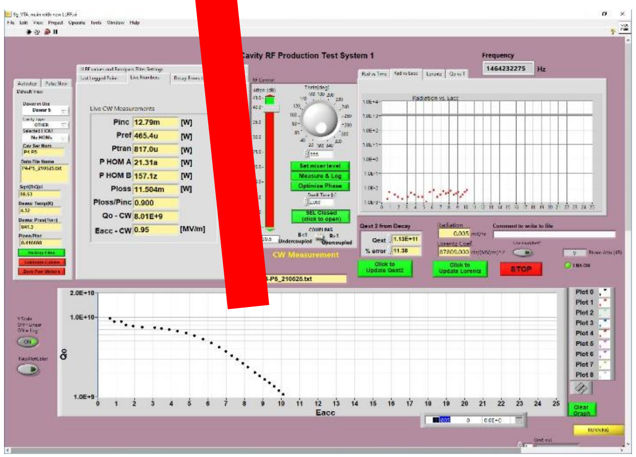


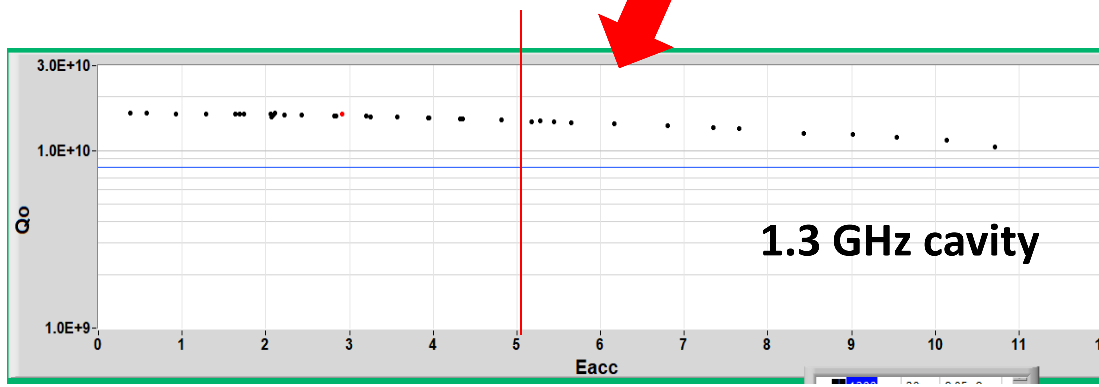
A powder mix with 90 wt.% W and 10 wt.% Cu was used providing 60.1 wt.% W and 39.7 wt.% Cu of Cu/W. Samples 2 × 2 were subjected to vacuum annealing in the temperature range 300 °C – 800 °C for 3 h. The residual resistivity ratio (RRR) was measured on W40Cu samples, It was found that maximal **RRR value of CuW cold sprayed layer did not exceed ~40**, while **RRR of Cu layer was > 130**,

1.5/1.3 GHz Nb3Sn Cavity Testing





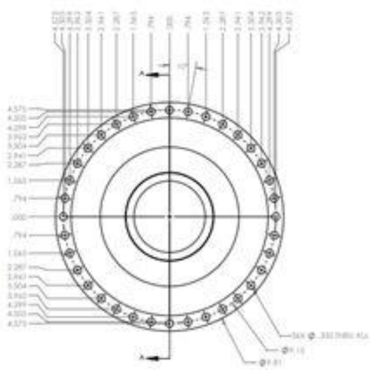


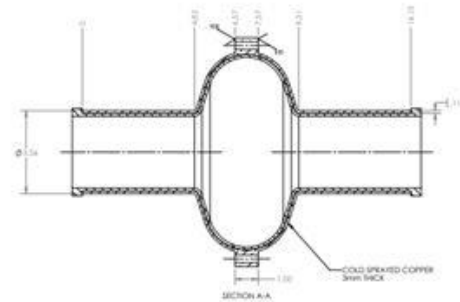


The test results of P4-P5 1.5GHz after a new coating: strong Q-slope above E_{acc}~5 MV/m.

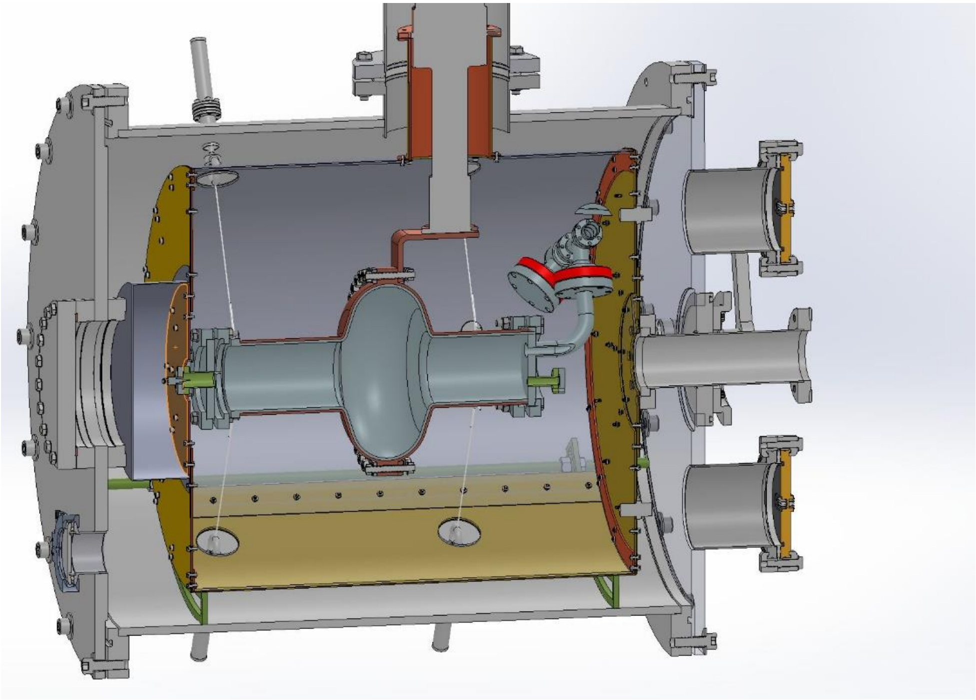
1.3 GHz single-cell cavity was coated with Nb3Sn last year. The cavity was tested at 4 K. The quality factor was above 10^{10} up to 11 MV/m.

Copper Cold Spray for 1.3GHz Cavity



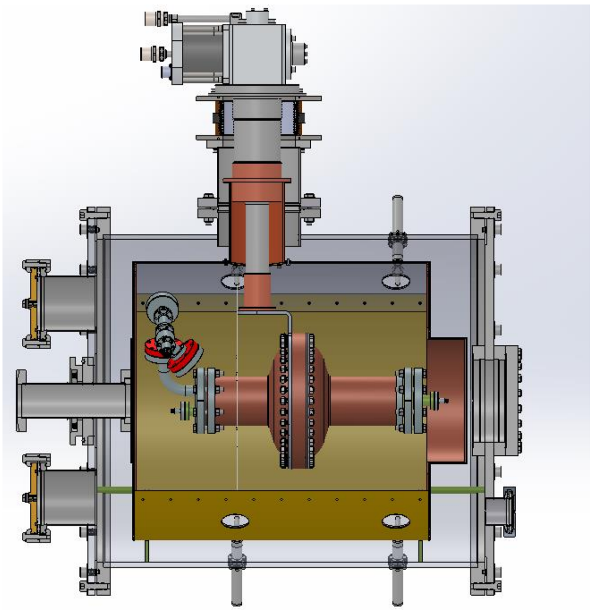


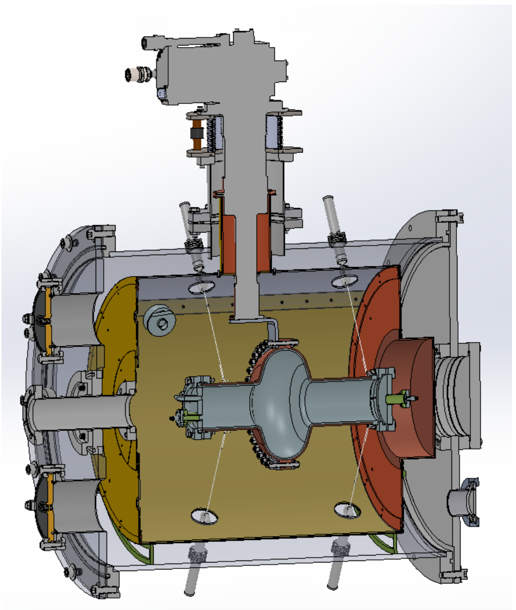
- The Cu layer will be cold sprayed onto the cavity outside surface with additional thick area at the equator region
- CU flange will be machined at the equator to connect the cavity to the cryocooler for cooling.
- The drawings is ready and is under revision by CTC, Inc.



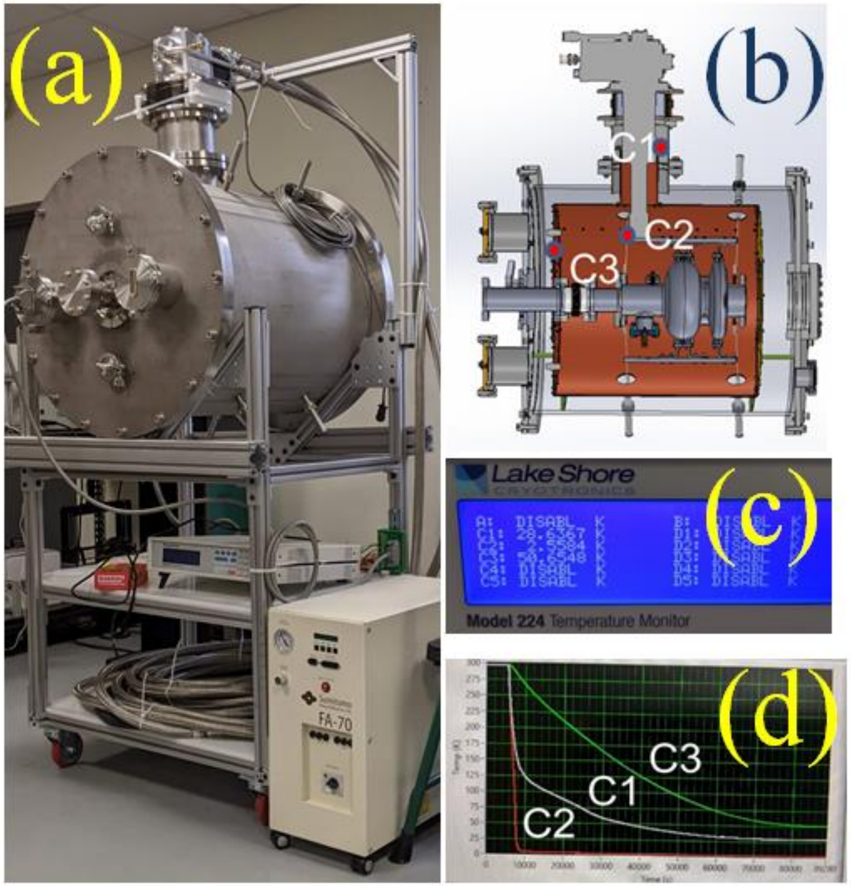
Cold spray cavity fits inside Euclid's cryomodule

- 1.3GHz cavity will be Cu cold sprayed and tested in Euclid's cryomodule after a vertical test in liquid Helium at Jlab.
- The cavity will arrive sealed with burst valve assembly. The cryomodule reconfiguration is required to fit the cavity inside.
- The design of the internal radiation screen has been modified (side extender added) and is due for manufacturing now.
- The cavity will be cooled through high purity Al bus and secured to the cavity by SS keeper rings. All the required components have been designed.





Conduction Cooling Cryomodule



Euclid has developed conduction cooling cryomodule was to host an SRF/Nb3Sn cavity with cold sprayed copper for industrial SRF accelerators

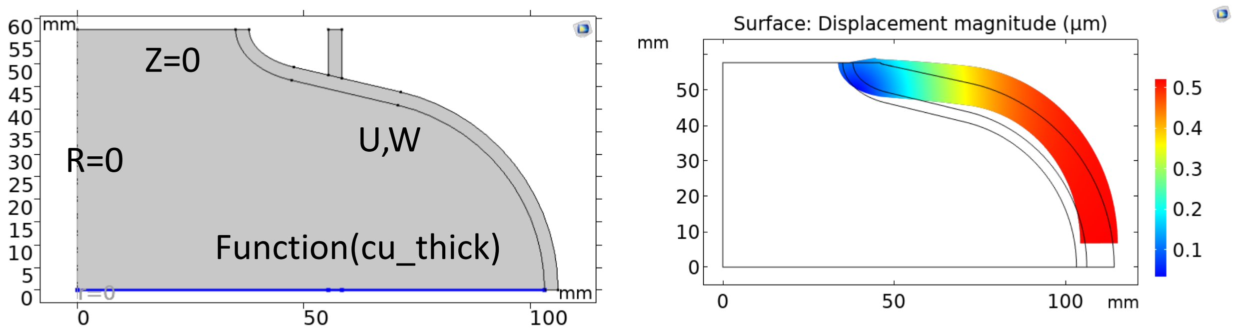
The cryomodule was assembled and successfully cooled down. Temperature of the 1st stage reached 28K in 24hrs while the 2nd stage **cooled down to 2.5K** and are within the expected values.

(a) The full assembled cryo-module; (b) 3D cut-away view to show the location of three tempe-rature sensors; (c) cryo-tempe-rature reader; (d) cooldown process indicated by three sensors.

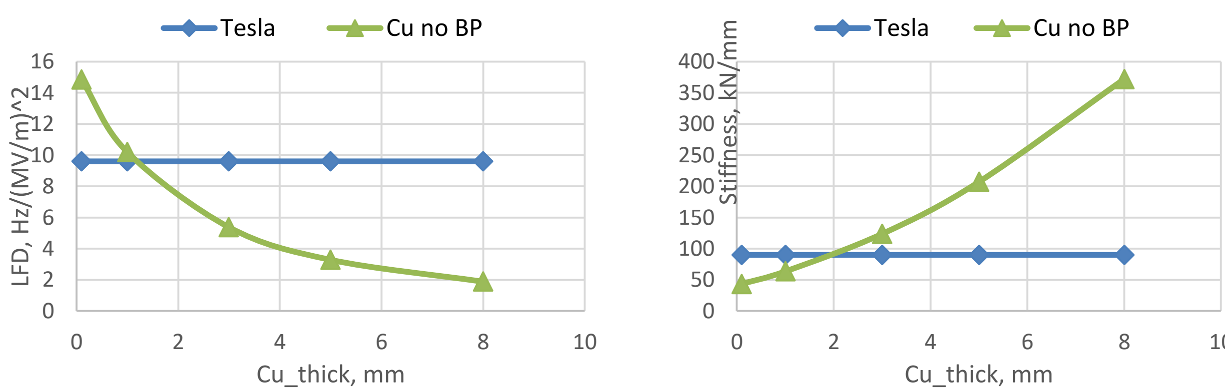
Table 1. Static heat load to 30K and 4K zones in UEM cryomodule.

	Radiation	Beam pipe	Suspension	RF cables	Total
30K zone	2 W	17 W	NA	0.8 W	20 W
4K zone	0.01 W	0.03 W	0.05 W	0.05 W	0.14 W

LFD Modeling for Cold Spray Cu on the 1.3 GHz SRF Cavity



(a) Boundary conditions for moving mesh (b) LFD displacement magnitude for 30MV/m E field for Cu=8mm thick.



(a) LFD, $H_{z/}(MV/m)^2$ vs. copper thickness, (b) Stiffness, kN/mm vs. copper thickness.

Even for 2 mm thick cold spray copper layer **LFD is reduce by 30%**, ~7.5 $H_{z/}(MV/m)^2$ in comparison with 9.6 $H_{z/}(MV/m)^2$ for the original Tesla cavity.

Summary

- We completed the cold spray deposition of 3 mm Cu and W/Cu layers on Nb coupons using recipes for both He and N_2 gas deposition parameters.
- Nb/Cu were annealed at 300C -1000C. The RRR measurement was performed, the best result was demonstrated for the copper rod annealed at 1,000C in oxygen, RRR=131.65, *K*~350W/m*K. Adhesion test demonstrated ~5,000 PSI bonding strength.
- Initially planned Nb3Sn coating for the 1.5GHz Jlab's cavity was found with quality factor Q_0 degradation at ~ 5 MV/m accelerating field. It was decided to use 1.3GHz cavity with Nb3Sn coating. To fit the 1.3 GHz cavity, modification of the Euclid's cryomodule has been done.
- Cold-spray deposition of Cu on a single-cell SRF cavity with Nb_3Sn-coated is currently being carried out.
- Lorentz Force Detuning (LFD) modeling for cold spray Cu deposited on the SRF cavity demonstrated that for 2 mm thick copper layer the LFD value is reduce by 30%.

Acknowledgements

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  - Michelle Shinn, Manouchehr Farkhondeh
  - Brenda May, Kerri Fomby

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  - CTC, Inc. Brock Galesich