

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

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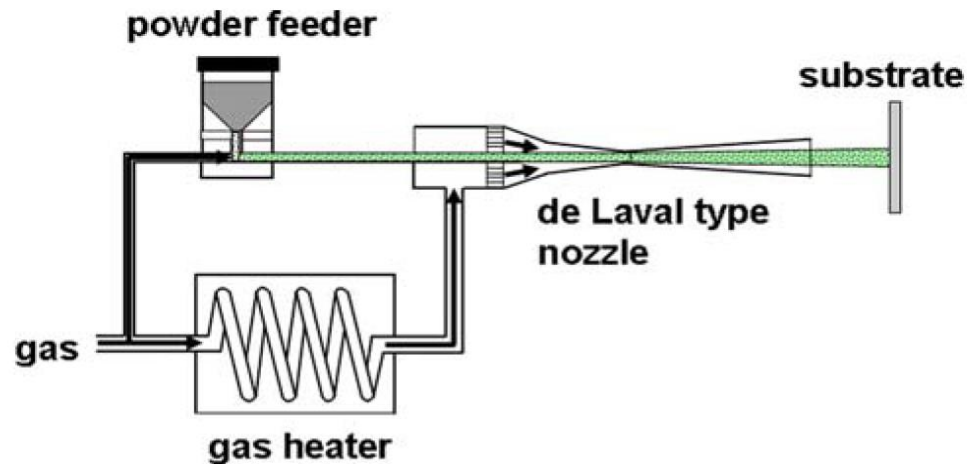
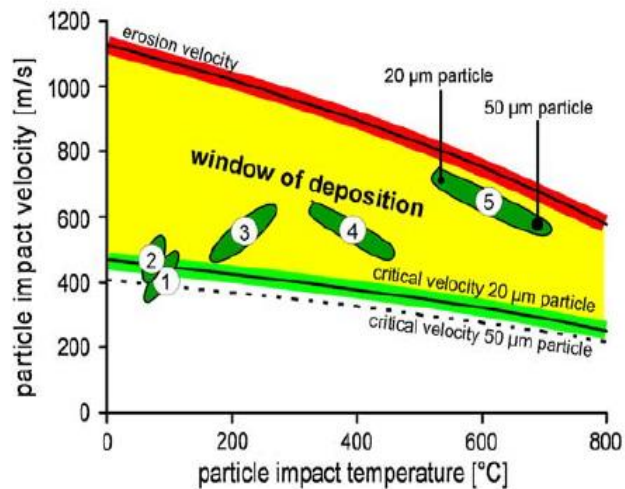
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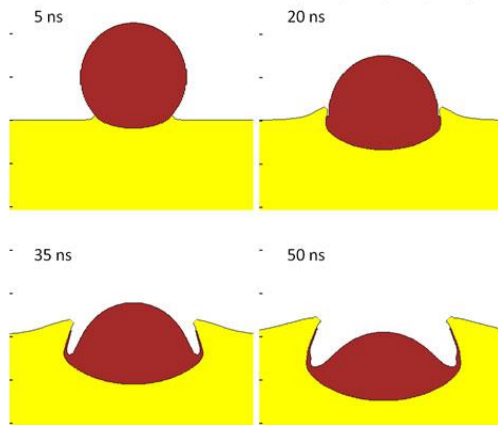
In collaboration with *Thomas Jefferson National Laboratory*

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Cold Spray Technology



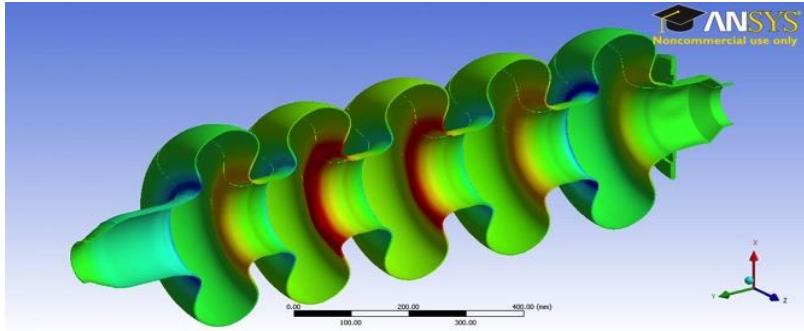
Window of deposition as function of particle temperature and velocity



Deformation of a 20 micron copper sphere striking an aluminum surface

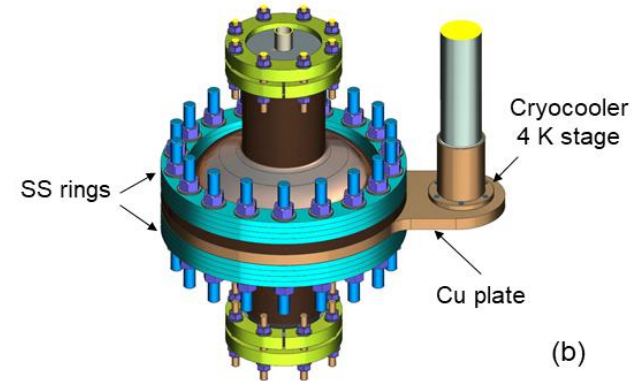
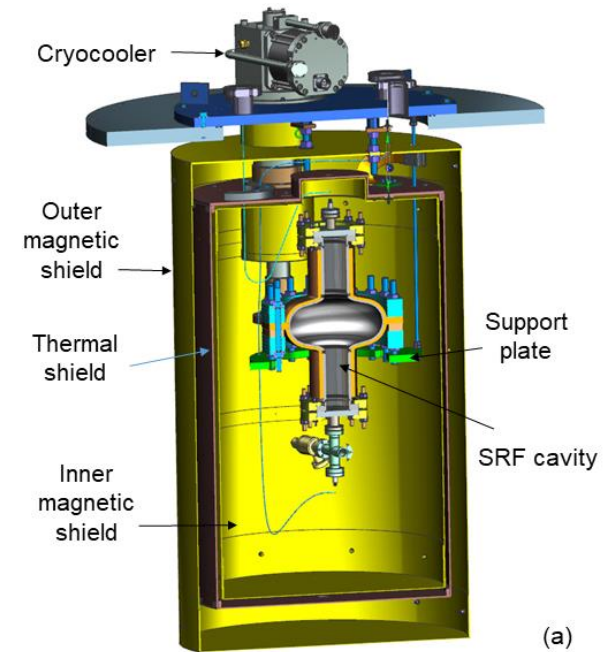
In the cold spray method, fine powder particles are propelled toward the substrate to be plastically deformed, which leads to flattening and bonding them to the underlying surface. Cold spray operating temperatures are very low compared with those of thermal and plasma spray. The low operating temperature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

Motivation



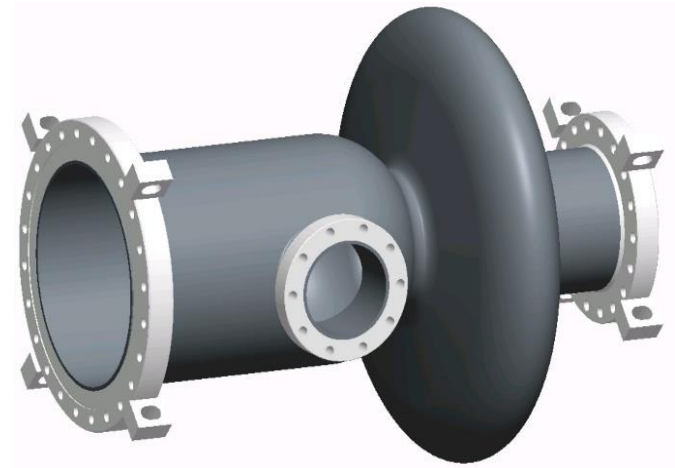
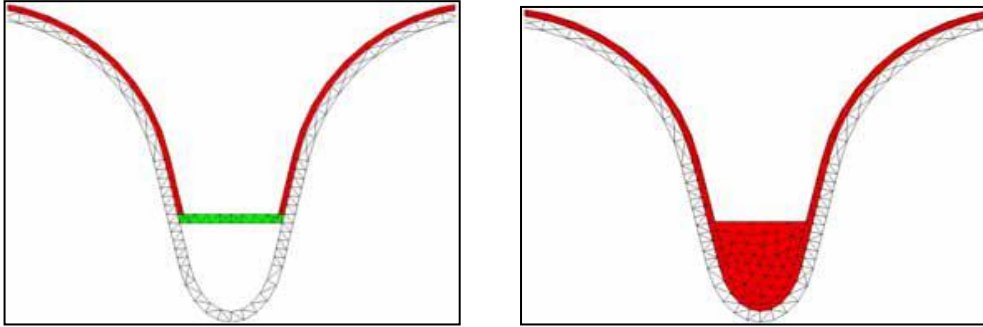
The most important source of frequency shifts in SRF cavities is due to the effect of microphonics and Lorentz forces. Additional stiffening is then needed to improve the cavity's mechanical stability and reduce the frequency shift.

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



arXiv:2001.10924v1
[physics.ins-det] 29 Jan 2020

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.

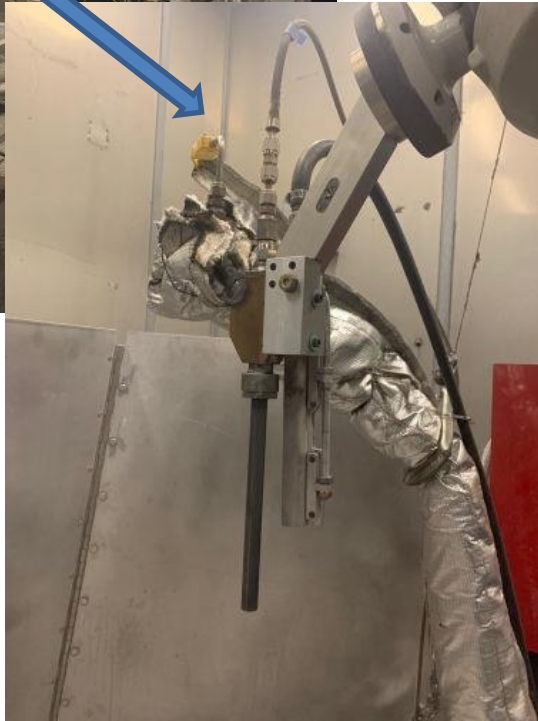
Phase I Accomplishments

- The cold-spray deposition of 99.9%-pure copper powder was performed using He and N₂ 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). Nb₃Sn 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, Nb₃Sn-coated inside and vacuum sealed.
- Task 6. VTS testing at JLAB of the SRF cavity coated on the inside with Nb₃Sn and copper cold sprayed on the outside.
- Task 7. Optimization of Euclid's conduction cooling cryomodule for the copper cold-sprayed SRF cavity test. Test in the cryomodule.
- Task 8. Final Report Preparation.
- Additional studies: LFD, powder degassing and Cold spray deformation studies.
-  - 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.

RRR Measurements



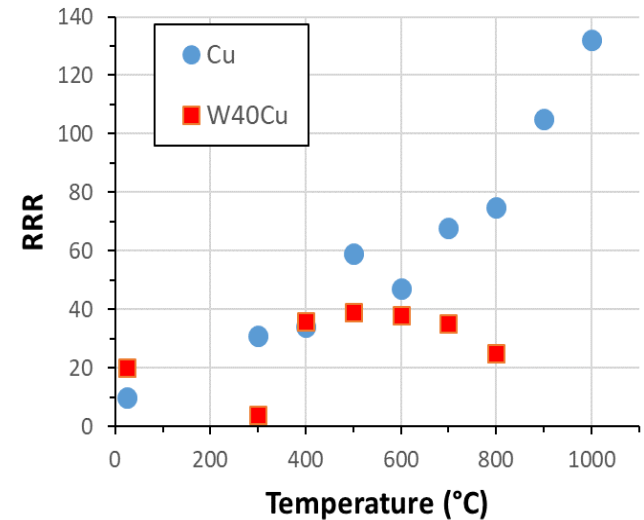
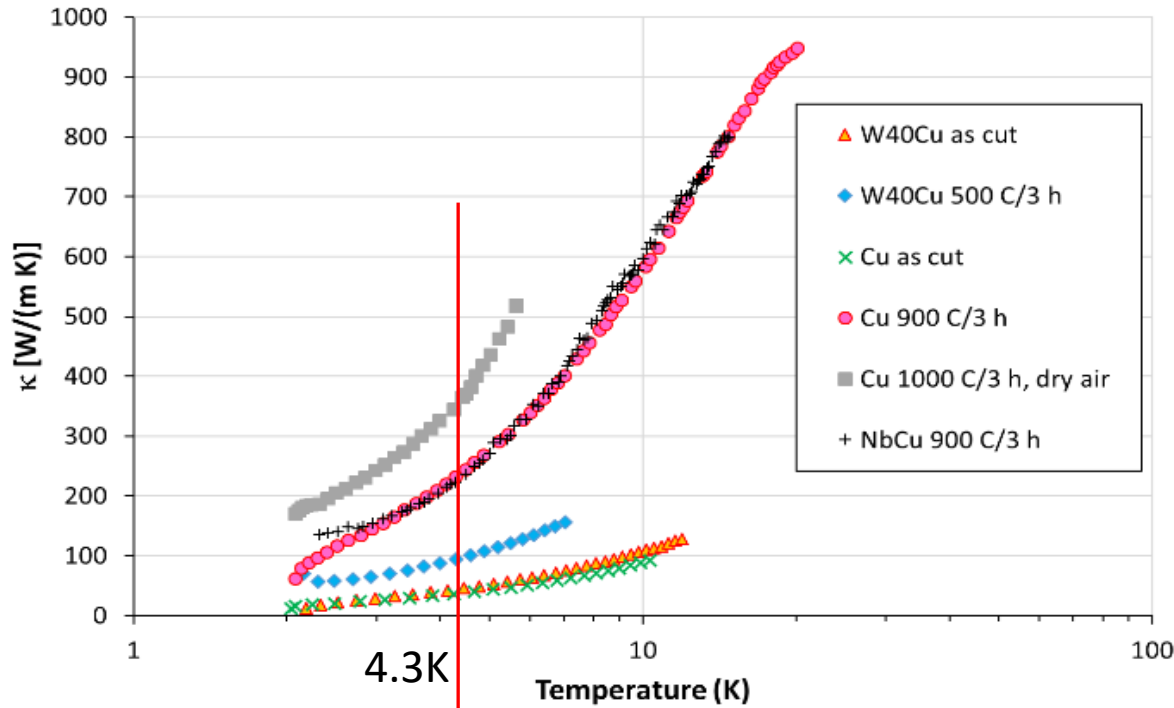
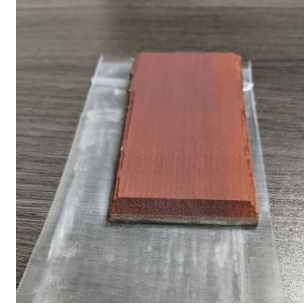
Sample	Temperature	Vacuum/Gas	RRR
Euclid Cu I	300C	vacuum	30.99
Euclid Cu II	400C	vacuum	34.02
Euclid Cu III	500C	vacuum	59.3
Euclid Cu IV	600C	vacuum	46.56
Euclid Cu V	700C	vacuum	67.79
Euclid Cu VI	800C	vacuum	74.58
Euclid Cu VII	900C	oxygen 10^{-4}	105.45
Euclid Cu VIII	1000C	oxygen 10^{-4}	131.65

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

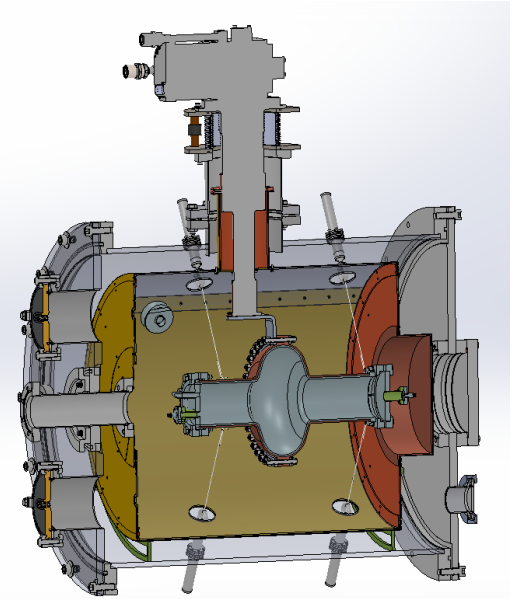
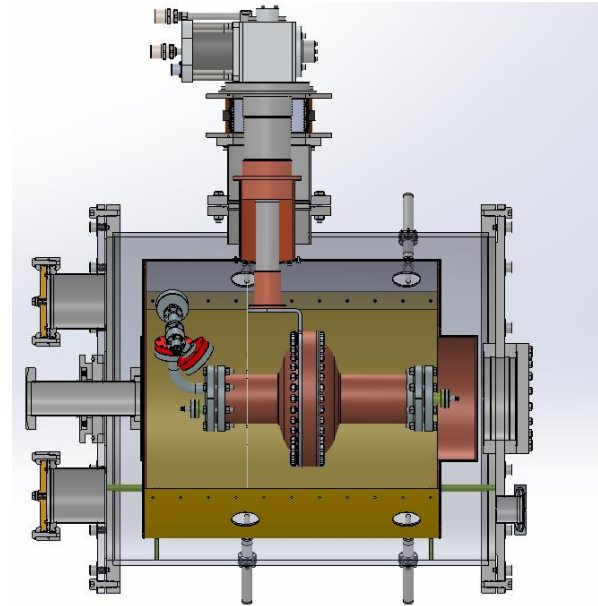
We also carried out cold-spray deposition with mixed tungsten and copper (W/Cu) on niobium coupons using cold-spray recipes for both He and N₂ gas deposition parameters.



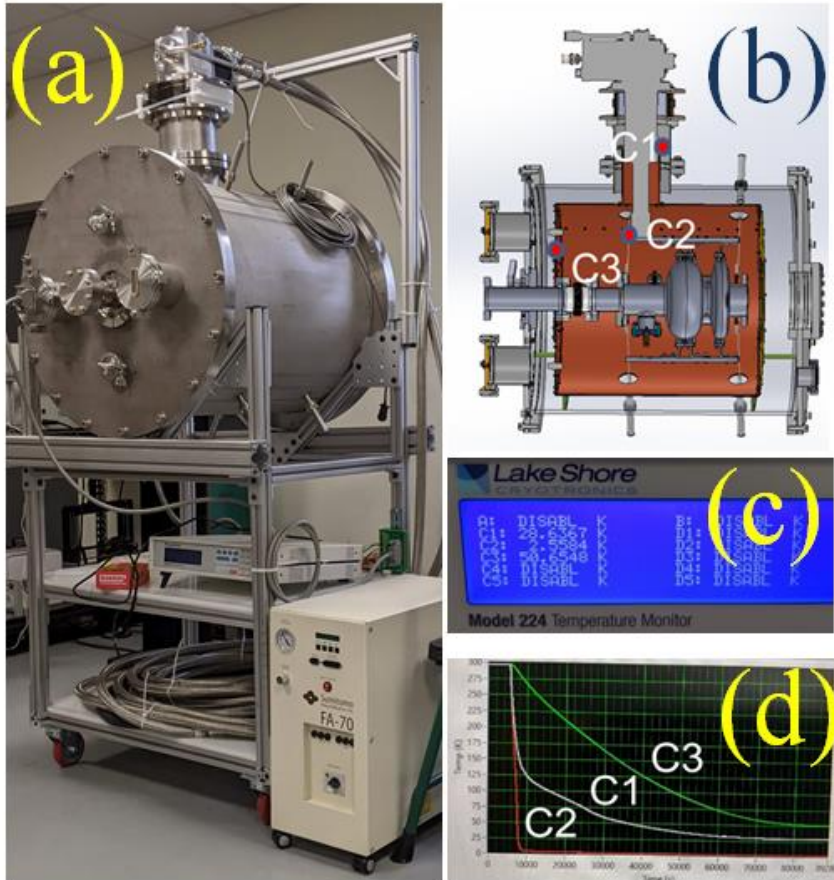
A powder mix with 90 wt.% W and 10 wt.% Cu was used providing 60.1 wt.% W and 39.7 wt.% Cu of Cu/W. Samples 2 × 2 were subjected to vacuum annealing in the temperature range 300 °C – 800 °C for 3 h. The residual resistivity ratio (RRR) was measured on W40Cu samples, It was found that maximal **RRR value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

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 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.

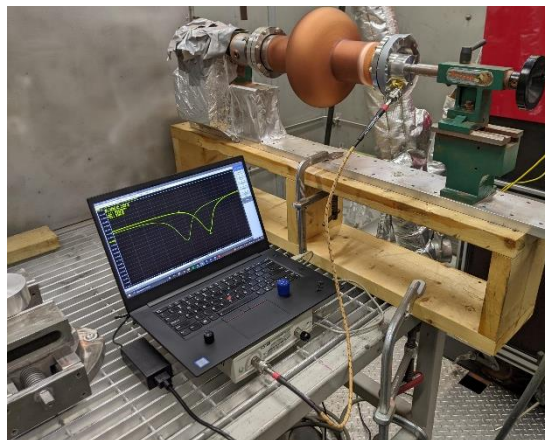
(a) The full assembled cryo-module; (b) 3D cut-away view to show the location of three temperature sensors; (c) cryo-temperature reader; (d) cooldown process indicated by three sensors.

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

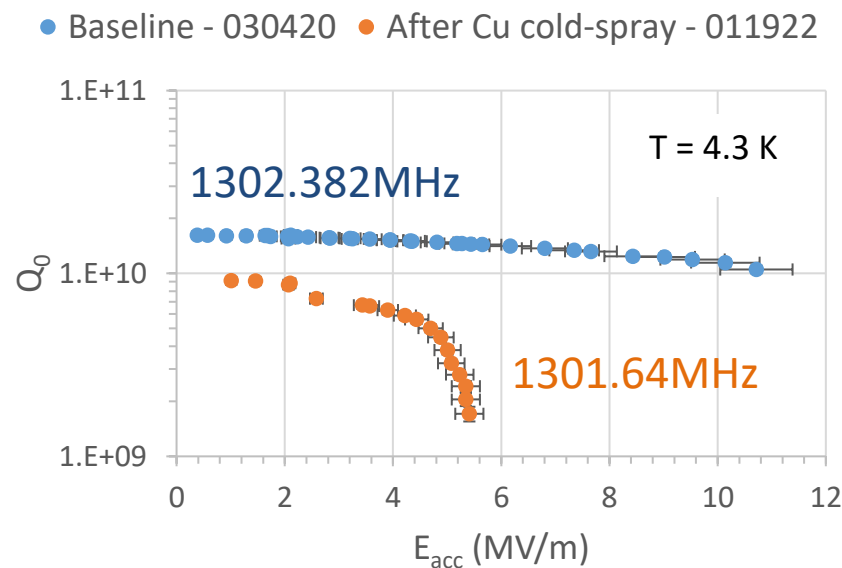
	Radiation	Beam pipe	Suspension	RF cables	Total
30K zone	2 W	17 W	NA	0.8 W	20 W
4K zone	0.01 W	0.03 W	0.05 W	0.05 W	0.14 W

250um of cold-sprayed copper on a Nb₃Sn cavity.

- 250um thick layer of OFE copper was deposited. Further deposition was interrupted by too high frequency shift of +186 kHz.
- The cavity was tested at Jlab vertical cryostat, performance degradation was noticed – Nb₃Sn cracked.
- Frequency difference of 749 kHz (additional 186 kHz from cold spray) w/w/o CU layer at 4K was observed – results of deformations while preparing for the cold spray deposition.
- Cavity had gaps which were filled with CU by cold spray followed by lathe machining.



RDT-10 1.3 GHz Nb₃Sn cavity

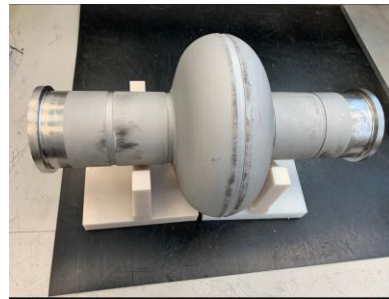


Stress build-up investigation

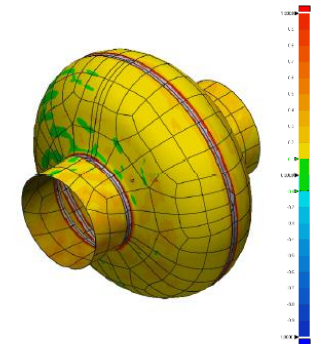
- Cu layer etched away: +23.8 kHz, +133um cavity length.
- Cold spray copper is not responsible for Nb₃Sn cracking - confirmed.
- 3D scanning technique is used to accurately monitor the SRF cavity shape
- The average shape deviation was measured to be (210 ± 100) um.
- In combination of 3D stress simulation, we hope to have a deep understanding of the mechanic impact of cold spray on the cavity wall, thus find out a patterned or non-uniform cold spray process to minimize its effect on the cavity frequency.
- A new baseline 3D laser scan of the shape of the outer surface was measured and the cavity has been shipped to CTC for the deposition of a 1 mm thick Cu layer.



Cavity w CU layer

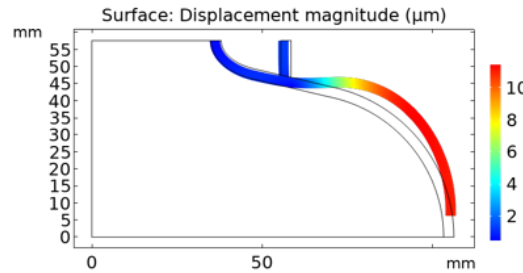
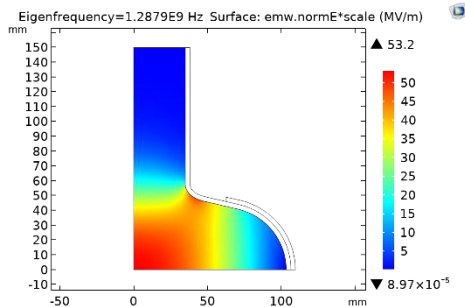


Cavity w CU layer etched

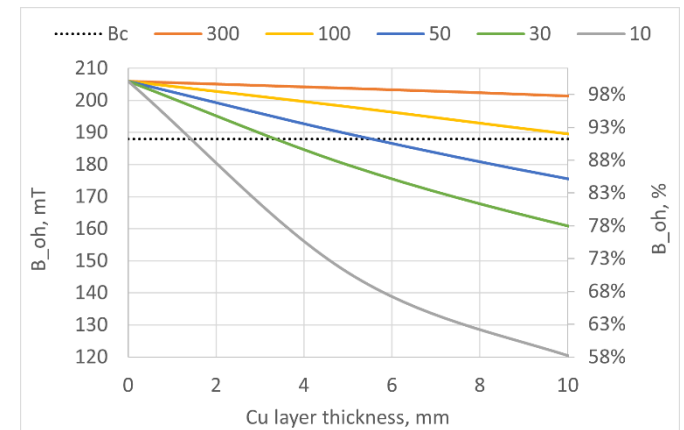
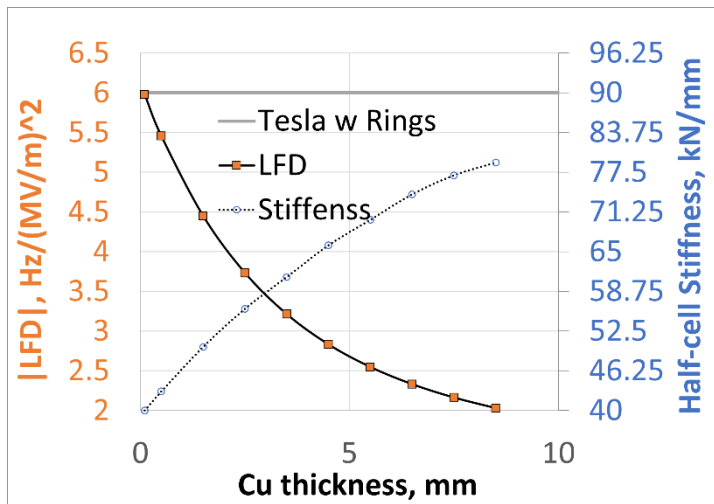
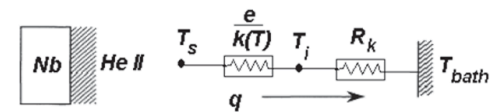


3D map difference

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



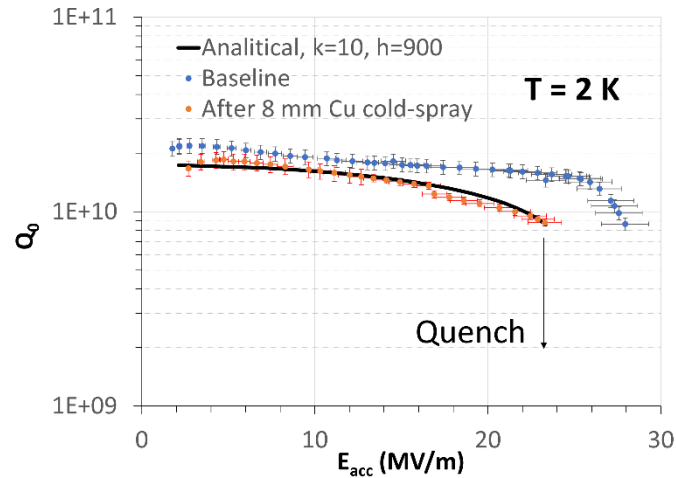
$$B_0(T_s) = \mu_0 \sqrt{\frac{(T_{bath} - T_s)}{0.5 \cdot R_s(T_s)} \cdot \left(\frac{k \cdot h_k}{e \cdot h_k + k} \right)}$$



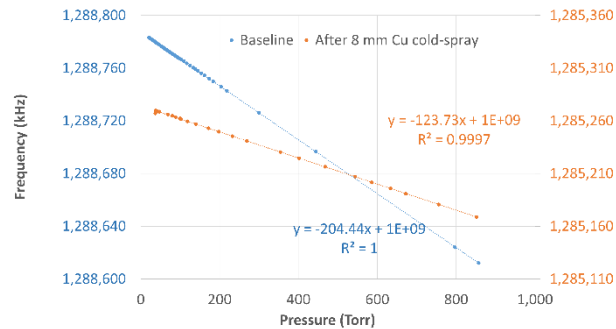
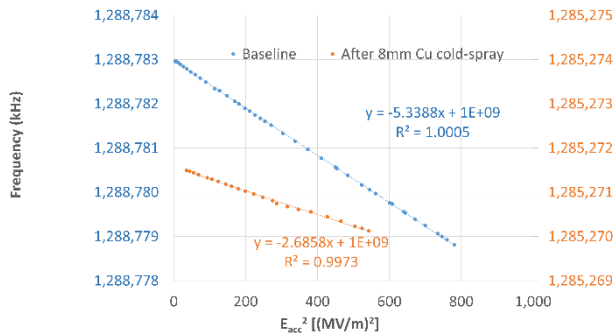
Overheating magnetic field as a function of Cu layer thickness for different thermal conductivity values shown in the legend in units of W/m/K.

See also: R.Kostin et al., "Demonstration of Twice Reduced Lorentz Force Detuning in SRF Cavity by Copper Cold Spraying", in Proc. NAPAC'22, Albuquerque, NM, USA, 2022. WEPA52.

High Power Test of 1.3 GHz SRF Cavity with 8 mm Cold Sprayed Copper.



See also: R.Kostin et al., "Demonstration of Twice Reduced Lorentz Force Detuning in SRF Cavity by Copper Cold Spraying", in Proc. NAPAC'22, Albuquerque, NM, USA, 2022. WEPA52.

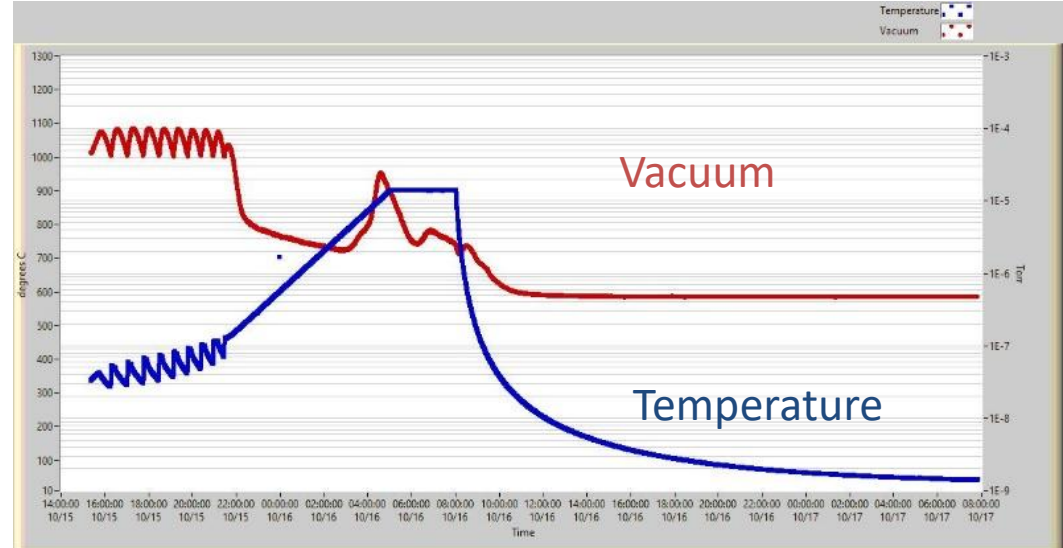


Parameter	Before	After
Max Eacc, [MV/m]	28.0	23.5
dF/dP, [Hz/torr]	204.0	124.0
LFD, [Hz/(MV/m) ²]	5.3	2.7
Resonant Frequency change, [MHz]	--	-3.5

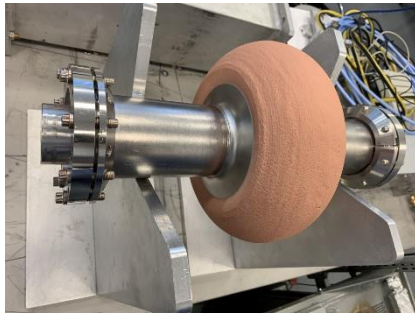
On the left: Frequency sensitivity of the cavity to the external pressure; On the right: Frequency sensitivity to the accelerating gradient in the second power, i.e. LFD, for the regular cavity (blue curve) and the cavity with 8 mm layer (orange).

1.3 GHz SRF Cavity with 8mm Cold Sprayed Copper annealing for higher RRR

- The cavity was annealed at 900C for 3 hrs
- Vacuum level fluctuations was observed due to degassing
- That lead to cracking of the copper layer
- Powder degassing studies are initiated with Penn State University.



Cold sprayed Cu layer cracked



Cavity before the Annealing



Cold sprayed Cu layer cracked

Summary

- We completed the cold spray deposition of 3 mm Cu and W/Cu layers on Nb coupons using recipes for both He and N₂ 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, $K \sim 350 \text{ W/m}^2 \cdot \text{K}$. Adhesion test demonstrated $\sim 5,000$ PSI bonding strength.
- Nb₃Sn cavity was coated with cold sprayed copper and tested at 4K. Performance degradation was observed due to the damage of the Nb₃Sn layer during pre-processing at CTC. Frequency shift observed and investigation studies were initiated. Cavity is shipped to CTC for a new layer deposition and 3D mapping.
- Lorentz Force Detuning (LFD) modeling for cold spray Cu deposited on the SRF cavity demonstrated 2 times LFD reduction. Cavity was covered with 8mm thick Cu layer and tested confirming the results. Outgassing issues were observed and investigation studies were initiated in collaboration with Penn State University.

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