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

Supported by the DOE SBIR DE-SC0019589, Phase II

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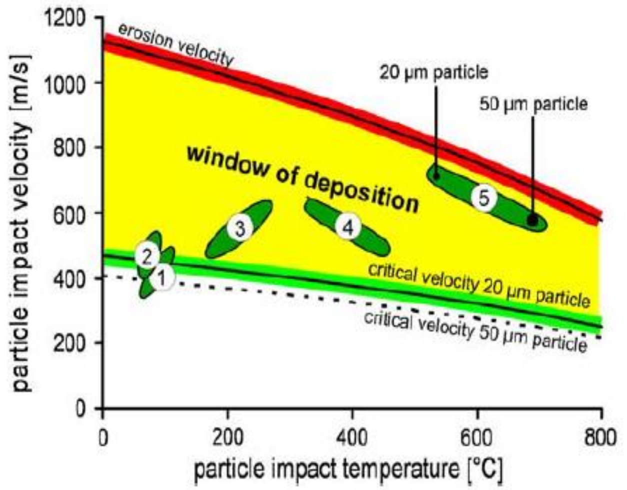
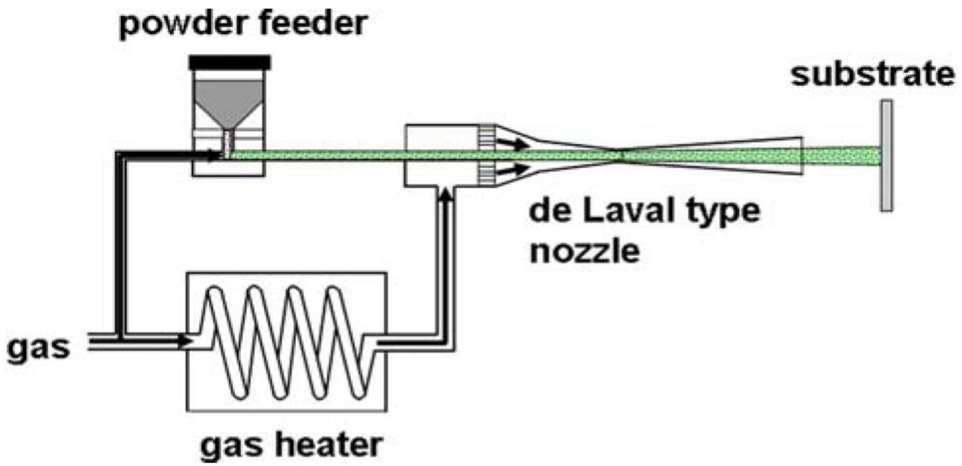
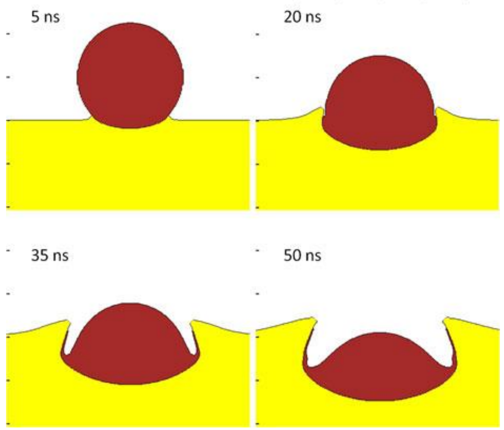
Department of Energy SBIR/STTR Exchange Meeting
August 15-17, 2023

Cold Spray Technology



Window of deposition as function of particle temperature and velocity

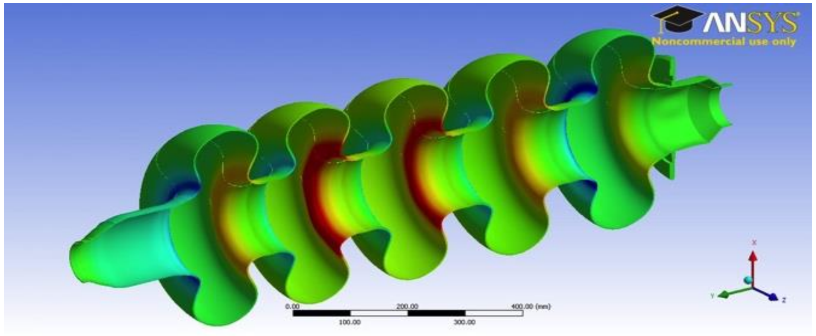




Deformation of a 20 micron copper sphere striking an aluminum surface

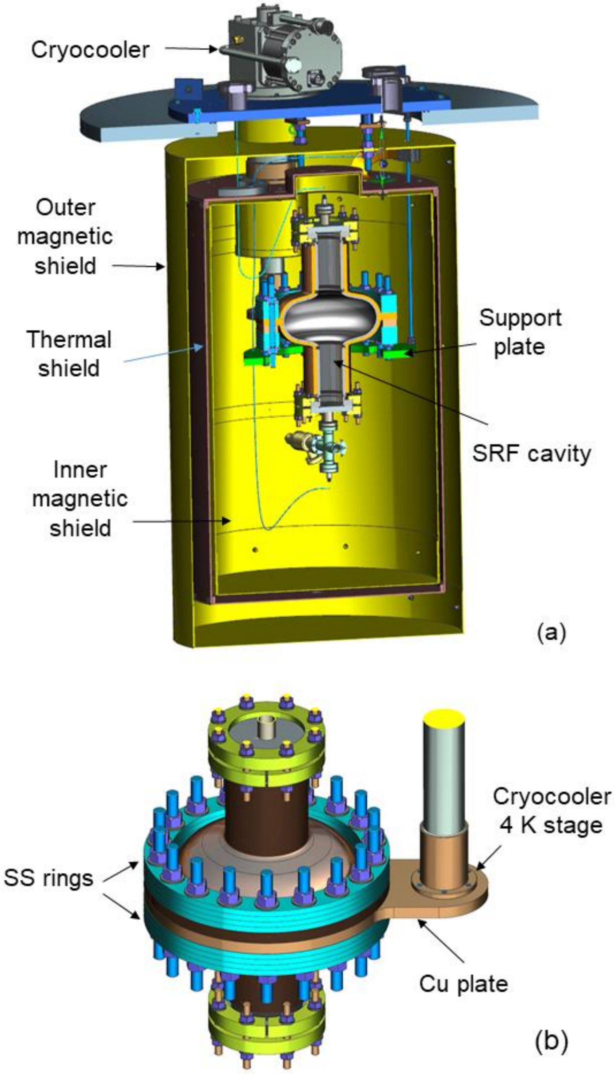
In the cold spray method, fine powder particles are propelled toward the substrate to be plastically deformed, which leads to flattening and bonding them to the underlying surface. Cold spray operating temperatures are very low compared with those of thermal and plasma spray. The low operating temperature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

Motivation



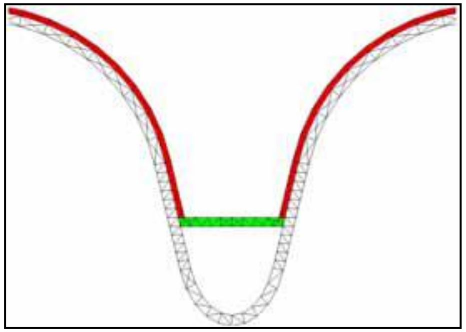
The most important source of frequency shifts in SRF cavities is due to the effect of microphonics and Lorentz forces. Additional stiffening is then needed to improve the cavity's mechanical stability and reduce the frequency shift.

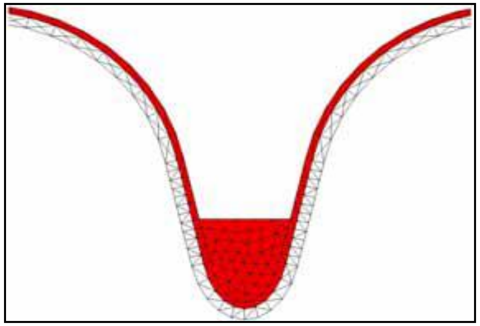
The use of Nb/Cu cold spray cladding material can provide mechanical stabilization, and thus stiffening rings may be avoided – manufacturing cost saving. *A significant benefit of the proposed technology is also the addition of copper for thermal stability and conduction cooling.*

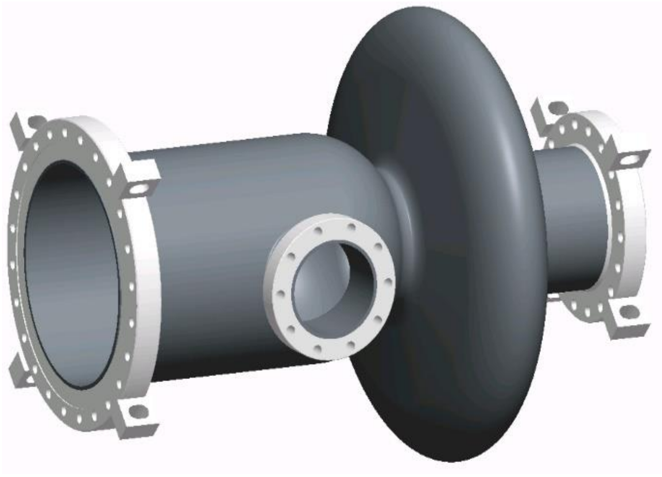


arXiv:2001.10924v1 [physics.ins-det] 29 Jan 2020

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.

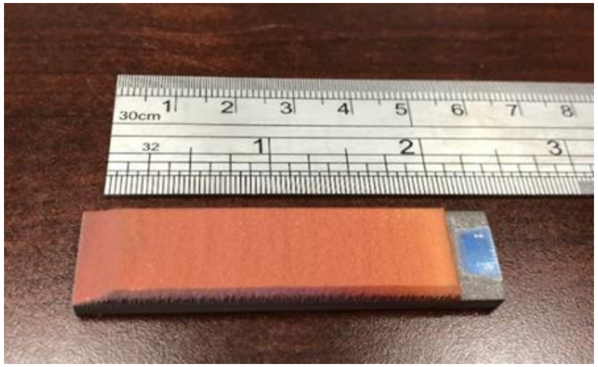
Phase I Accomplishments

- The cold-spray deposition of 99.9%-pure copper powder was performed using He and 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

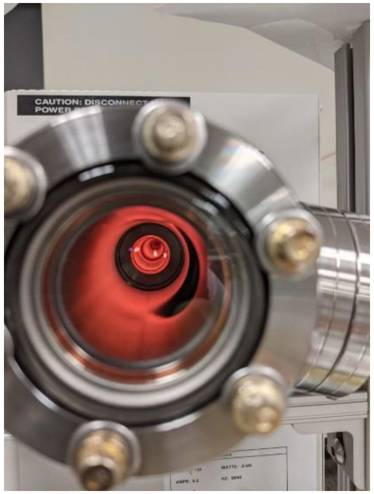
- **Task 1. Cold spraying of copper/tungsten on niobium coupons.**
- **Task 2. Microstructural analysis. Bonding strength measurements.**
- **Task 3. RRR measurements.**
- **Task 4. (In collaboration with JLAB). Nb_3Sn coating of the SRF cavity. Vertical Test Stand testing (VTS) testing of the Nb3Sn 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. 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.

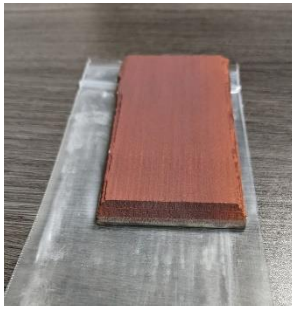
RRR Measurements



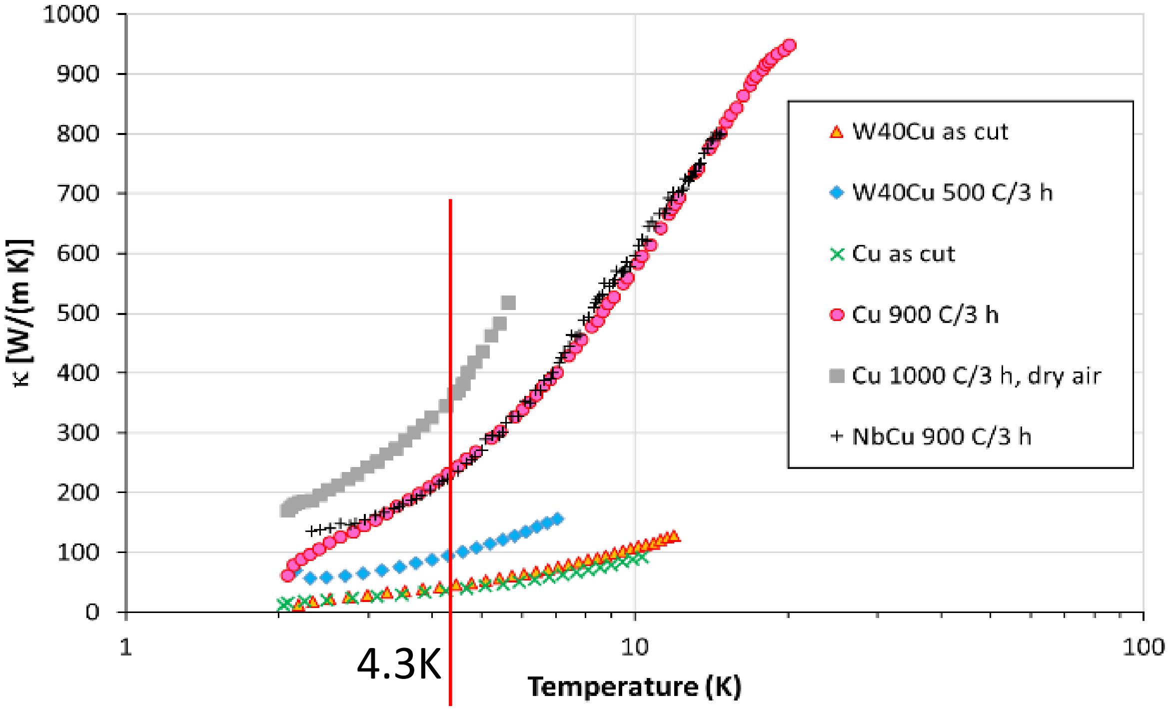
Sample	Temperature	Vacuum/Gas	RRR
Euclid Cu I	300C	vacuum	30.99
Euclid Cu II	400C	vacuum	34.02
Euclid Cu III	500C	vacuum	59.3
Euclid Cu IV	600C	vacuum	46.56
Euclid Cu V	700C	vacuum	67.79
Euclid Cu VI	800C	vacuum	74.58
Euclid Cu VII	900C	oxygen 10^-4	105.45
Euclid Cu VIII	**1000C**	**oxygen 10^-4**	**131.65**

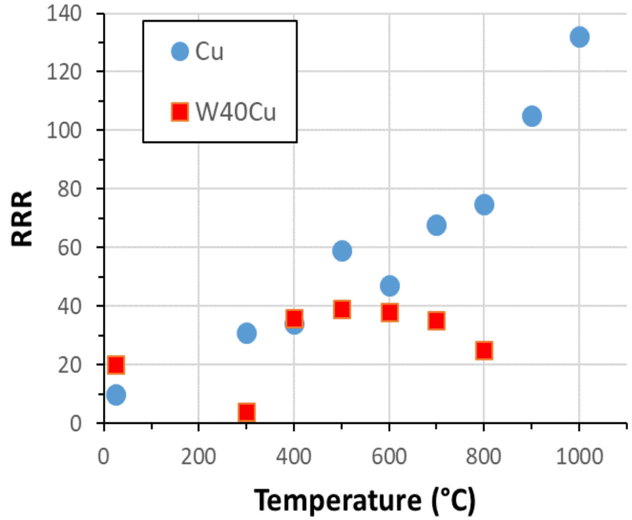
RRR measurement was performed, and the temperature dependence of the resistivity was measured at JLab with a standard 4-probe method while cooling down to 4.3 K from room temperature. The best result was demonstrated for the copper rod annealed at 1000C in Oxygen**, RRR=131.65.**

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 N_2 gas deposition parameters.



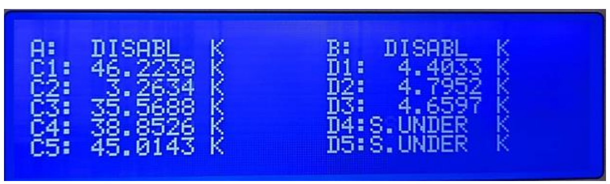


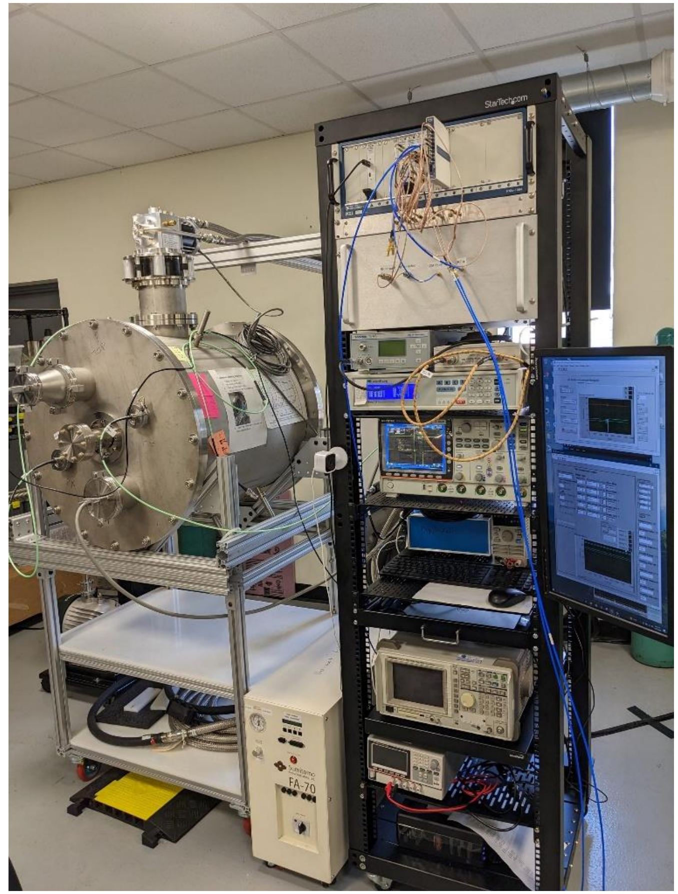
It was found that maximal **RRR value of CuW cold sprayed layer did not exceed ~40**, while **RRR of Cu layer was > 130**,

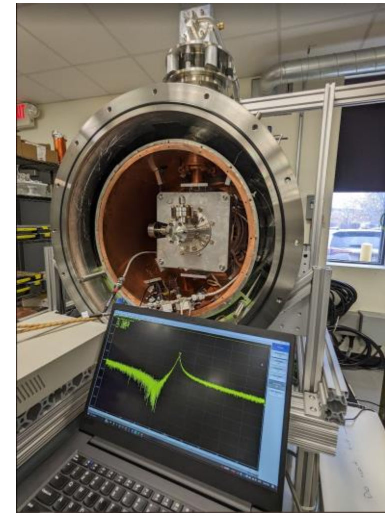
Conduction Cooling Cryomodule

- Euclid has developed conduction cooling cryomodule to host an SRF/Nb3Sn cavity for industrial SRF accelerators

- The cryomodule was commissioned and already cooled a Nb3Sn cavity







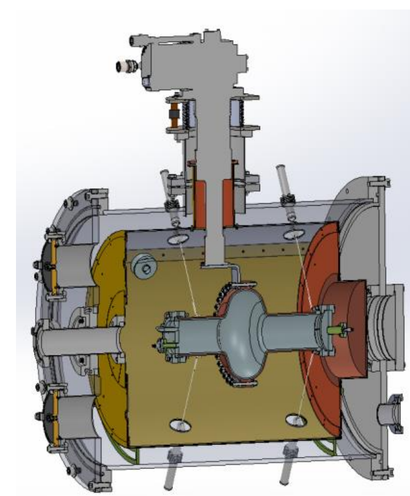
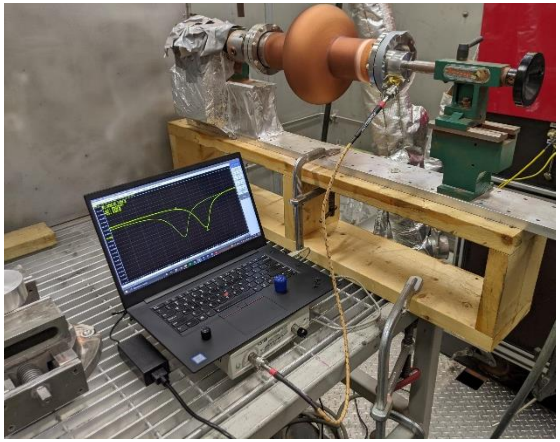


Table 1. Static heat load to 30K and 4K zones in UEM cryomodule.

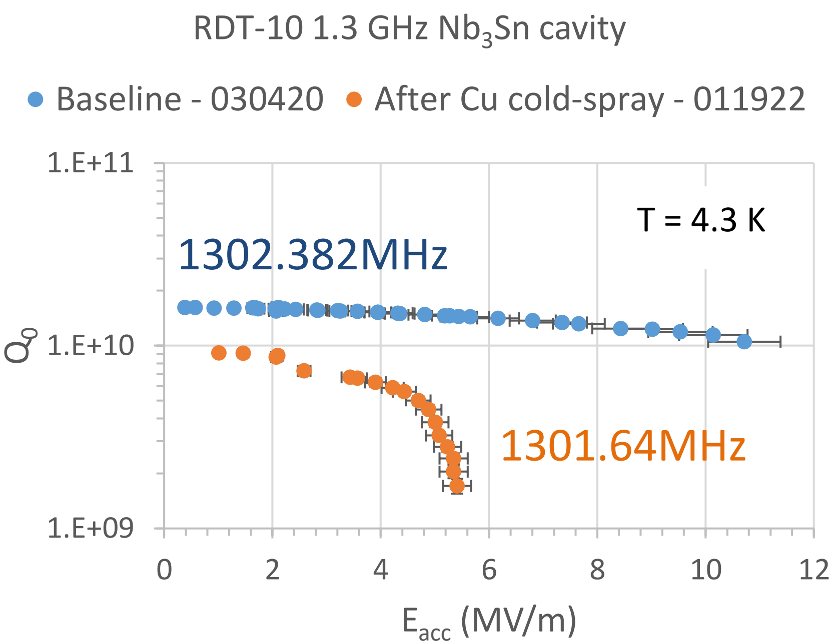
	Radiation	Beam pipe	Suspension	RF cables	Total
30K zone	2 W	17 W	NA	0.8 W	20 W
4K zone	0.01 W	0.03 W	0.05 W	0.05 W	0.14 W

250um of cold-sprayed copper on a Nb_3Sn 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 – Nb_3Sn cracked.
- Frequency difference of 749 kHz (additional 186 kHz from cold spray) w/wo CU layer at 4K was observed – results of deformations while preparing for the cold spray deposition.



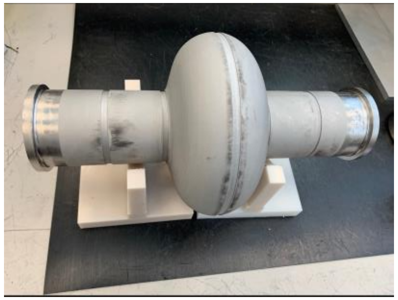
- Cavity had gaps which were filled with CU by cold spray followed by lathe machining.



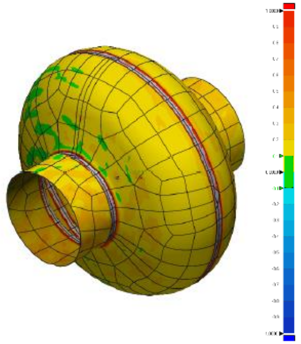
Stress build-up investigation

- 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

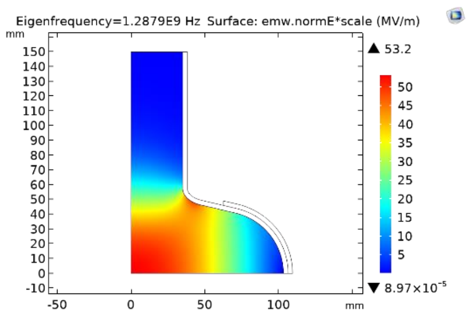


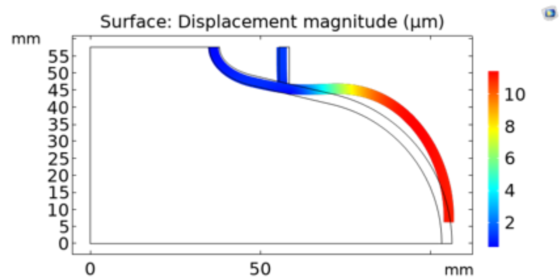
Cavity w CU layer etched



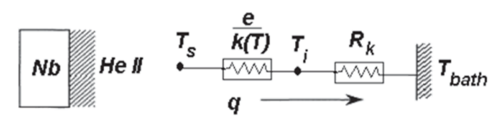
3D map difference

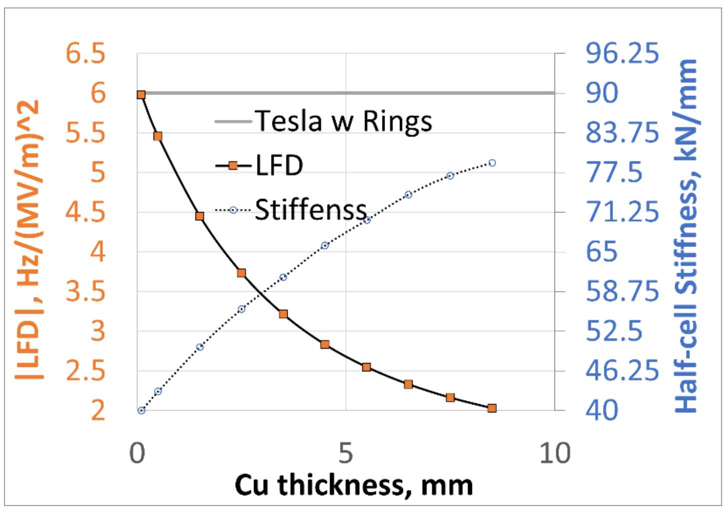
LFD Modeling for Cold Spray Cu on the 1.3 GHz SRF Cavity

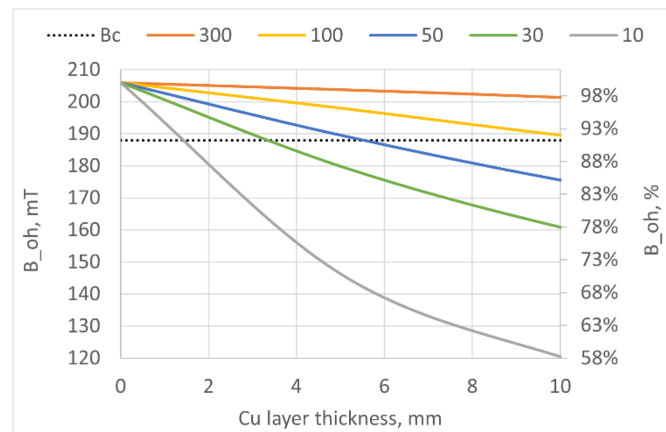




$$B_0(T_s) = \mu_0 \sqrt{\frac{(T_{bath} - T_s)}{0.5 \cdot R_s(T_s)} \cdot \left(\frac{k \cdot h_k}{e \cdot h_k + k}\right)}$$



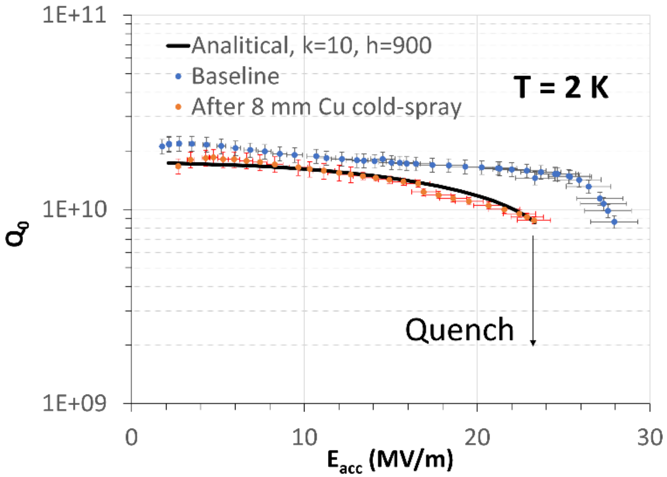




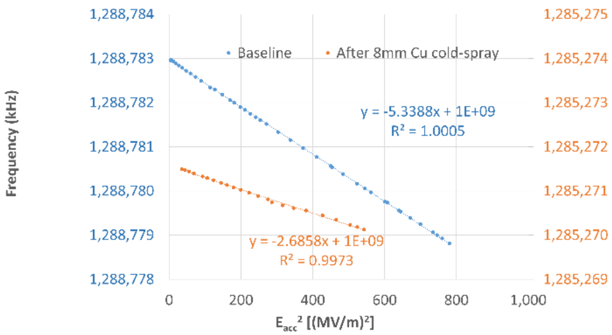
Overheating magnetic field as a function of Cu layer thickness for different thermal conductivity values shown in the legend in units of W/m/K.

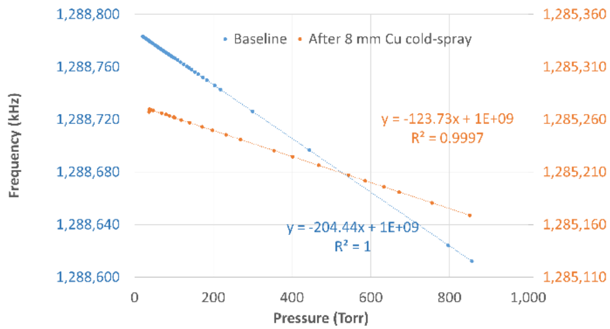
See also: R.Kostin et al., "Demonstration of Twice Reduced Lorentz Force Detuning in SRF Cavity by Copper Cold Spraying", in Proc. NAPAC'22, Albuquerque, NM, USA, 2022. WEPA52.

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.



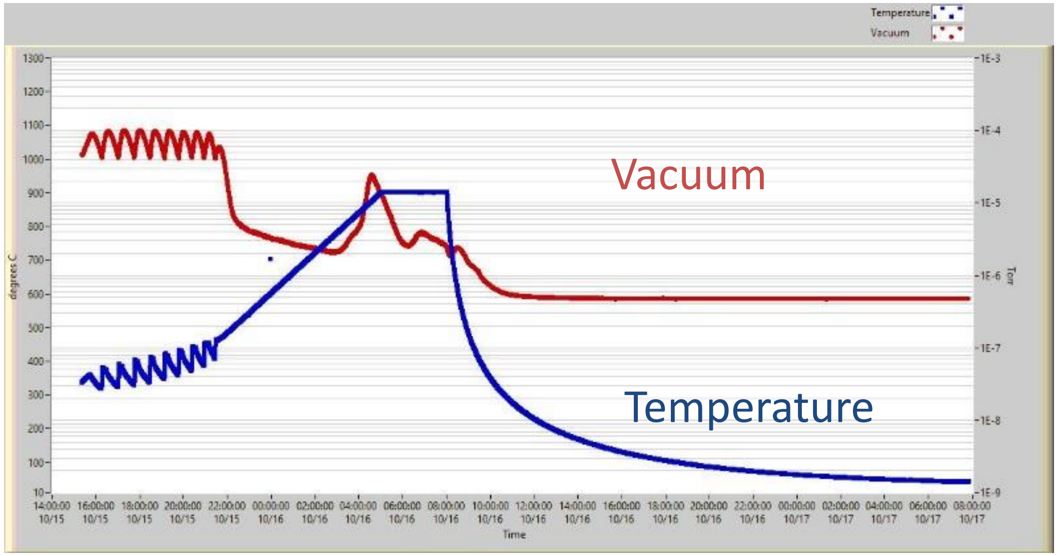


Parameter	Before	After
Max Eacc, [MV/m]	28.0	23.5
dF/dP, [Hz/torr]	204.0	124.0
LFD, [Hz/(MV/m)2]	5.3	2.7
Resonant Frequency change, [MHz]	--	-3.5

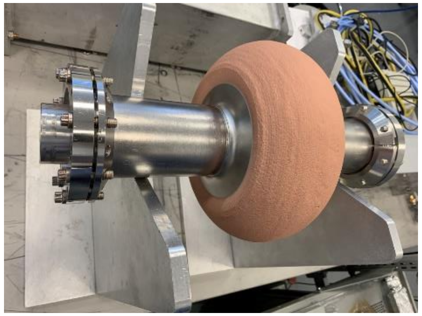
On the left: Frequency sensitivity of the cavity to the external pressure; On the right: Frequency sensitivity to the accelerating gradient in the second power, i.e. LFD, for the regular cavity (blue curve) and the cavity with 8 mm layer (orange).

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 were initiated with Penn State University.



Cold sprayed Cu layer cracked

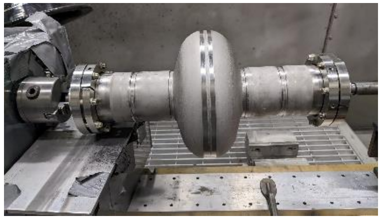


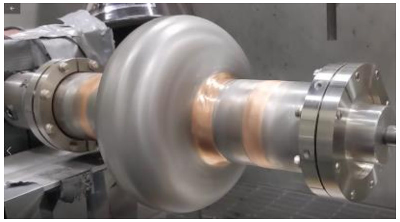
Cavity before the Annealing

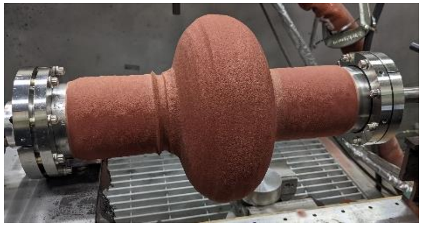
Cold sprayed Cu layer cracked

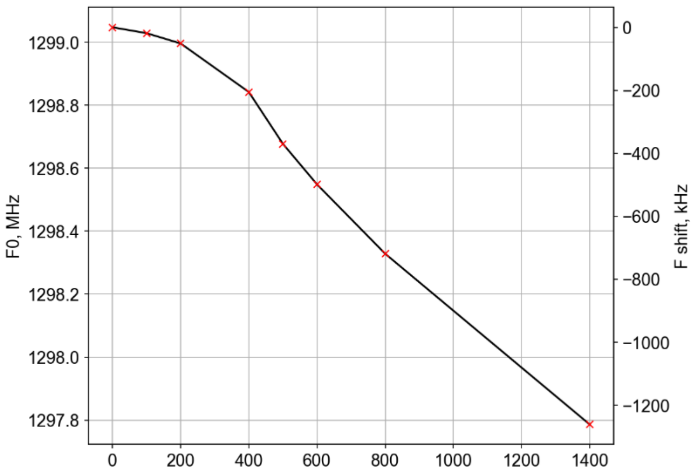
Powder degassing and deposition

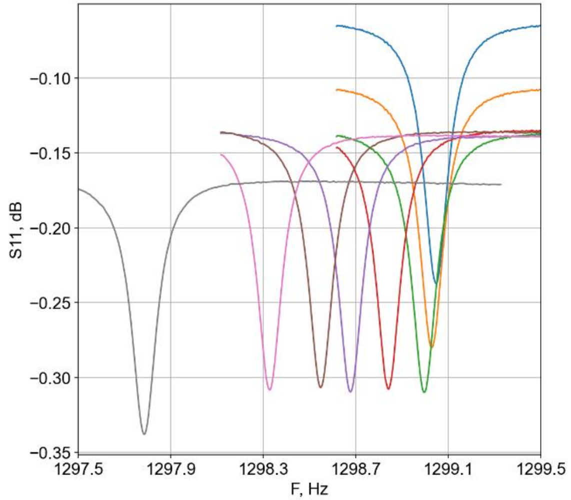
- F shift is linear and does not depend on the thickness of the deposition

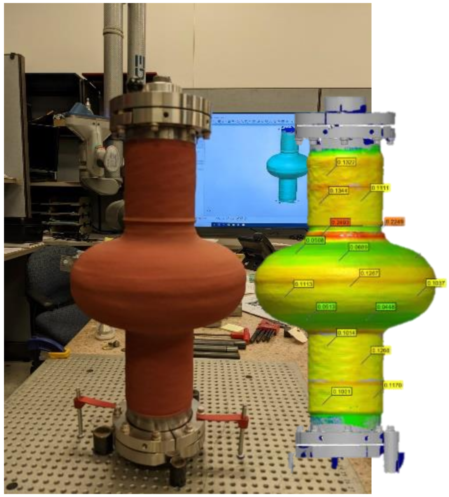












Summary

- Cu and W/Cu 3mm thick layers on Nb coupons were deposited.
- Annealing recipe was found to increase RRR from 10 to 130 (RRR=131.65, *K*~350W/m*K). Coupons RRR were measured at 4K.
- New recipe of deposition was developed substituted prohibitively expensive He gas deposition to N_2 deposition: ~5,000 PSI bonding strength achieved.
- Nb3Sn cavity was cold sprayed with copper and tested at 4K. Frequency shift was discovered. Low Field Q0 as high as 1E10 was demonstrated however mid-filed degradation was observed due to the cracked Nb3Sn layer.
- Cold spray technology demonstrated the possibility of stiffening the cavities by two times reduced LFD on Nb cavity with 8 [mm] thick Cu layer tested at 2K, however, an outgassing issue was observed during high temperature baking.
- Powder degassing process was established in collaboration with Penn State University. Degassed powder was deposited on the cavity while monitoring frequency shift and cavity shape deformations (under investigation).

Acknowledgements

- DOE, Office of Science Nuclear Physics
  - Michelle Shinn, Manouchehr Farkhondeh
  - Brenda May, Kerri Fomby
- Our collaborators
  - JLab: Robert Rimmer, Gigi Ciovati
  - CTC, Inc: Brock Golesich
  - Penn State: Tim Eden.