ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-WEPA52

DEMONSTRATION OF TWICE REDUCED LORENTZ FORCE DETUNING IN SRF CAVITY BY COPPER COLD SPRAYING*

R. Kostin†, C. Jing, A. Kanareykin, Euclid Techlabs LLC, Bolingbrook, IL 60440, USA
G. Ciovati, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
G. Brock, CTC, Inc., Johnstown, PA 15904, USA

Abstract

Superconducting RF (SRF) cavities usually are made of thin-wall high RRR Niobium that is susceptible to Lorentz Force Detuning (LFD) – cavity deformation phenomena caused by high magnitude RF fields. This type of deformation can be mitigated by using an additional copper layer deposited on the outer surface of the cavity. In this paper, we present both modeling results and experimental data of high gradient test of an SRF cavity at cryogenic temperatures. It was demonstrated that LFD can be significantly reduced (factor of two) by the copper cold spray reinforcement without sacrificing cavity flexibility for tuning. We also present a finite-element model that allows us to confirm our experimental results and optimize the cavity geometry for LFD reduction with incorporated coupled RF, structural and thermal modules.

INTRODUCTION

Cold-spray is a relatively new technique that allows spraying a metal powder on a substrate at very high speed in ambient conditions. As the metal particles hit the surface, they undergo a plastic deformation and bond to the surface. This approach was successfully used for conduction cooling of SRF cavity by a closed-cycle cryo-cooler. The cold-sprayed layer provided a robust bonding to the cavity and it was used as seed layer for electroplated copper [1].

Another application of this technology could be the stiffening of SRF cavities extending the barriers of current technological limitations. As of now, Lorentz Force Detuning (LFD) is minimized by Nb stiffening rings between cavity cells which are welded by electron beam. Cold-spray on the other hand provides a lot of flexibility. It is applied by a robotic arm manipulator with controlled thickness. The only limitation is that it is difficult to apply in the area close the the iris between the cells as the powder jet needs to be perpendicular to the surface for the deposited layer to have a good bonding to the substrate. The layer can be built-up about one inch higher from the iris. With this limitation in mind, Finite-Element-Analysis (FEA) was conducted using Comsol to investigate a possibility of LFD improvement. Copper was chosen as a material of deposition as the additional layer needs to have high thermal conductivity not to cause cavity overheating. The TESLA center-cell cavity shape was investigated [2]. The goal is to minimize LFD while keeping the cavity tunable. As long as the proposed approach will compete with standard stiffening technique such as stiffening rings, the stiffness of the Tesla cavity with rings was taken as the limit.

* Work supported by US DOE SBIR grant DE-SC0019589
† r.kostin@euclidtechlabs.com

MODEL STUDIES

Comsol Mechanical Studies

A 2D Comsol model of Tesla center-cell shape with no stiffening rings was created. The model was reduced down to a half-cell only with proper boundary conditions (BC) which resulted in stiffness of k=41.4 kN/mm. The results were compared with literature [3] and were in good agreement: for the 7-cell cavity stiffness will be around 3 kN/mm same as in [3]. Thus, the developed model provided reasonable results. At the next step, stiffness of the Tesla cell with stiffening rings at radius R=55 mm was found which equaled to 90 kN/mm for the half-cell geometry, thus this stiffness will be our limiting factor during cold-spray layer optimization. The results of the simulations can be found in Fig. 1, which demonstrates 11 um deformations under 1 kN of applied force to the cavity equator. The following mechanical properties were used: poison ratio k=0.38, Young's modulus at 2 K E=118 GPa.

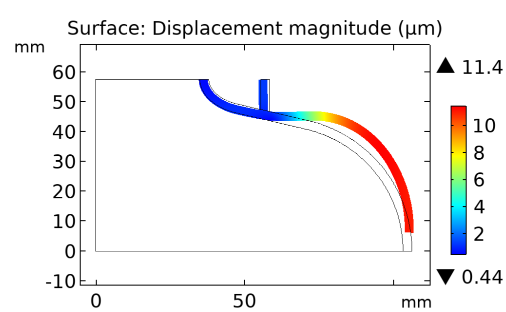

Figure 1: Tesla center half-cell deformation under 1 kN force.

The next step was to optimize the cold-sprayed Cu layer to reduce the Lorentz force detuning while keeping the cavity stiffness below 90 kN/mm for a half-cell model. A single center-cell Tesla Niobium cavity was available for cold-spray deposition and testing. The geometry of the cavity was built in Comsol for LFD optimization studies. The electric field in this model can be found in Fig. 2 below.

It is worth to mention, while the resonant frequency of the model with no beam pipes and with magnetic boundary condition at the iris was 1300 MHz (regular Tesla cell), single cell with beam pipes resonant frequency equaled to 1287.9 MHz. The field was scaled to 30 MV/m of accelerating gradient. The Cu layer was added at the equator region

5th North American Particle Accel. Conf. NAPAC2022, Albuquerque, NM, USA JACoW Publishing
ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-WEPA52

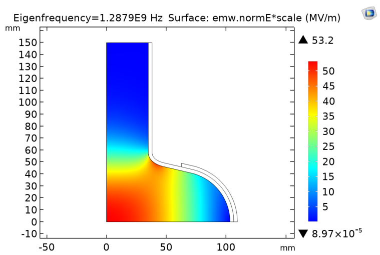

Figure 2: Electric field distribution in the single middle-cell Tesla cavity with Cu layer at equator region.

and was scanned from 0 to 8.5 mm thick. The results are presented in Fig. 3 below.

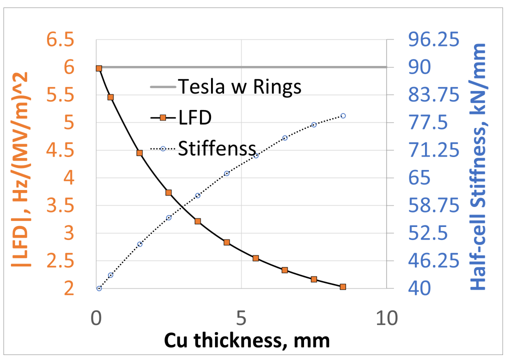

Figure 3: Comsol model simulation results.

As one can see from this plot, the stiffness of the cavity with Cu layer deposited at the equator is below the stiffness of Tesla cavity with rings even for 8 mm thick layer, while LFD is 3 times lower. The following mechanical properties of copper were used: poison ratio k=0.34, Young's modulus E=126 GPa. These are very encouraging results, however such a thick layer can reduce the cooling efficiency of the cavity and provoke quenching. Thermal studies were conducted to investigate this issue.

Thermal Studies

An analytical 1D model was created similar that of Ref. [4]. The following parameters were used: Kapitza resistance is 5000 W/m^2/K, cavity thickness is 3 mm, surface ohmic resistance is Rbcs+10 nΩ. Overheating magnetic field was investigated for different copper layer thickness and thermal conductivity. The results of the study can be found in Fig. 4.

Cold-sprayed copper RRR was measured to be around 10 but could be improved up to 130 by high temperature annealing as studies showed, which followed recipes from [5, 6]. This range in RRR corresponds to thermal conductivity variation from 10 W/m/K to 200 W/m/K at 2 K. As one can see from Fig. 4, magnetic overheating field is quite high in all cases. Overheating field for 3 mm thick cavity is 206 mT and is above the critical magnetic field of 190 mT for pure Niobium at 2 K. This corresponds to an accelerating gradient of ~45 MV/m which is rarely reachable due to local defects on the surface. Thus, this field can be treated as maximum reachable field and any additional copper layer will degrade

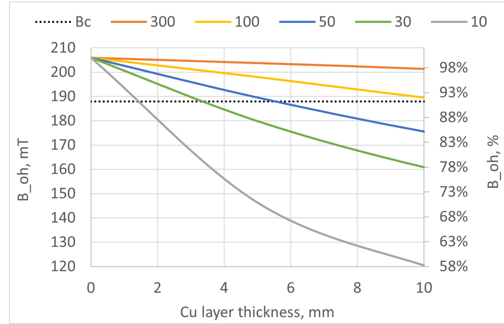

Figure 4: Overheating magnetic field as a function of Cu layer thickness for different thermal conductivity values shown in the legend in units of W/m/K.

the achievable gradient. In the case of k=10 W/m/K one can expect max reachable magnetic field of 130 mT which corresponds to 31 MV/m for an 8 mm thick Cu layer. However, the maximum reachable field can be completely recovered above critical field after annealing while reducing LFD by 3 times as was found earlier.

The 1D model was compared to 2D Comsol simulation and was within 10% in agreement. Comsol results showed higher overheating magnetic field due to non-uniform magnetic field distribution along the surface which resulted in better cooling (Fig. 5).

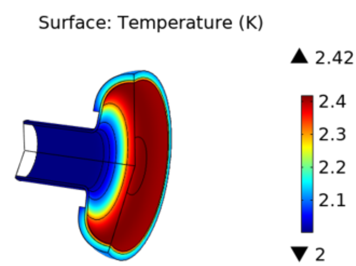

Figure 5: Temperature distribution in a single cell cavity at maximum reachable field of 196 mT with 8 mm thick Cu layer thermal conductivity of 50 W/m/K.

TEST RESULTS AT 2 K

An 8 mm thick copper layer was cold-sprayed onto the single cell Niobium cavity, shown in Fig. 6 below.

Figure 6: 1.3 GHz cavity with 8 mm thick Cu layer.

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-WEPA52

The cavity was tested in a vertical cryostat at JLab before and after the Cu layer deposition for a clear comparison of the cavity performance. One can find the "Q versus E" curve in Fig. 7 below.

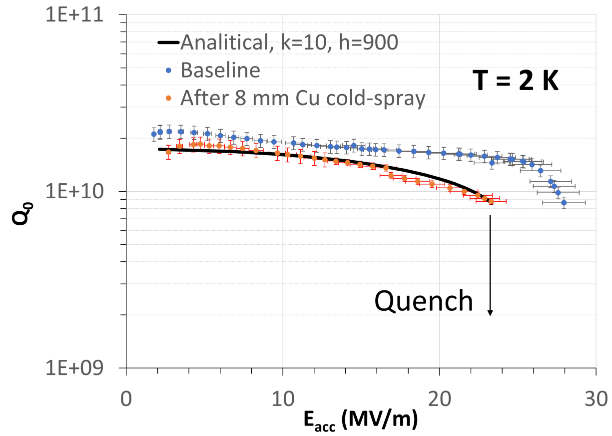

Figure 7: Q versus E_{acc} curve before and after Cu coating.

The bare cavity has reached 28 MV/m of accelerating gradient and it was limited by the high-field Q-slope, while the same cavity with 8 mm thick copper layer reached a bit lower gradient of ~24 MV/m (corresponds to 100 mT) which is 30% lower than previous analytical and Comsol estimations. The analytical model was investigated further to match the obtained experimental results. Literature search revealed Kapitza resistance change due to additional copper deposition [7]. The analytical model matched the results for thermal conductivity k=10 W/m/K and Kapitza conductance h=900 W/m^2/K. It is worth to note, that the annealed cavity would reach E_{acc}=31 MV/m limited by Kapitza resistance, thus it should be also improved if needed.

Sensitivity to external pressure (dF/dP) and Lorentz Force Detuning (LFD) were also measured and can be found in Fig. 8 and Fig. 9 correspondingly. The summary of the mechanical properties of the cavity with and without the Cu layer are summarised in Table 1.

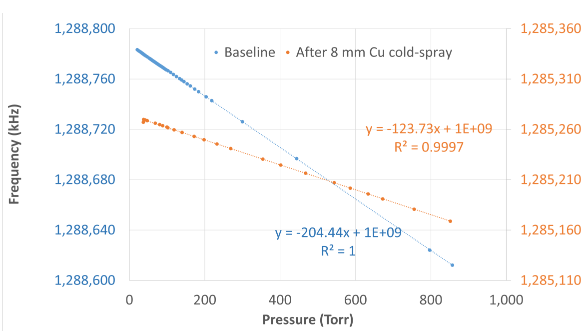

Figure 8: Sensitivity to external bath pressure before and after Cu coating.

8 mm thick copper layer deposited on the cavity helped to reduced Lorentz force detuning by 2 times, while the dF/dP was reduced by 1.65 times. The real geometry of the sprayed copper layer (end edge is tangential to the cavity

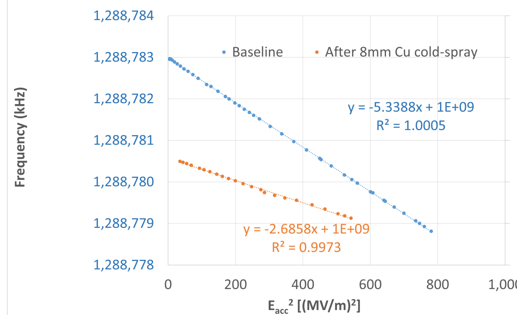

Figure 9: LFD before and after Cu coating.

surface unlike perpendicular) was simulated in Comsol and LFD reduction by 2 times (not 3) was confirmed. It was noticed that the cavity frequency was reduced by -3.5 MHz after the copper deposition. The cavity was vacuum annealed to release mechanical stresses in the copper layer potentially incorporated during the deposition process and to improve the thermal conductivity however the copper cracked with significant trapped gas spikes observed. Copper powder degassing studies are currently being carried out.

Table 1: Parameters Change Due to 8 mm Thick Cu Layer

Parameter	Before	After
Maximum E_{acc}, MV/m	28	23.5
dF/dP, Hz/torr	204	124
LFD, Hz/(MV/m)^2	5.3	**2.7**
Resonant Frequency change, MHz	–	-3.5

CONCLUSION

Copper Cold-spray technology was investigated as a low-cost method to improve the mechanical properties of Nb SRF cavities. Comsol model was developed to investigate potential benefits which showed that LFD can be reduced up to 3 times. A thermal analytical model showed no significant performance degradation. An 8 mm thick copper layer was deposited on the equator region of the cavity. The cavity was high power tested in liquid helium bath before and after the copper layer deposition for comparison. The technology showed a significant LFD improvement which was reduced by 2 times however the maximum accelerating gradient was limited to ~24 MV/m. A significant frequency change after Cu cold-spraying was observed, likely related to mechanical stresses built-up during the coating process.Trapped gases within the Cu powder caused the coating to crack during vacuum annealing to improve the thermal conductivity of the cold-sprayed Cu. Future focus of the work will be concentrated solving these issues.

ACKNOWLEDGMENTS

We would like to thank the technical staff at JLab's SRF Institute for the cavity preparation and Dr. P. Dhakal for the baseline RF test of the cavity.

ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-WEPA52

REFERENCES

[1] G. Ciovati *et al.*, "A Multi-layered SRF Cavity for Conduction Cooling Applications", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 538–542. doi:10.18429/JACoW-SRF2019-TUP050

[2] B. Aune *et al*., "The Superconducting TESLA Cavities", *Phys. Rev. ST Accel. Beams*, vol. 3, p. 092001, 2000. doi:10.1103/PhysRevSTAB.3.092001

[3] S. Posen and M. Liepe, "Mechanical optimization of superconducting cavities in continuous wave operation", *Phys. Rev. ST Accel. Beams*, vol. 15, p. 022002, 2012. doi:10.1103/PhysRevSTAB.15.022002

[4] A. Aizaz *et al.*, "Thermal design studies in Superconducting RF cavities: Phonon peak and Kapitza conductance", *Phys. Rev. ST Accel. Beams*, vol. 13, p. 093503, 2010. doi:10.1103/PhysRevSTAB.13.093503

[5] F. R. Fickett, "Oxygen-Free Copper at 4 K: Resistance and Magnetoresistance", *IEEE Transactions On Magnetics*, vol. 19, no. 3, 1983. doi:10.1109/TMAG.1983.1062352

[6] S.S. Rosenblum, W.A. Steyert, and F.R. Fickett. "A simple method for producing high conductivity copper for low temperature applications", *Cryogenics*, vol. 17, p. 645, 1977. doi:10.1016/0011-2275(77)90123-0

[7] S.Bousson *et al.*, "Kapitza Conductance and Thermal Conductivity of Materials used for SRF Cavities Fabrication", in *Proc. SRF'99*, Santa Fe, NM, USA, Nov. 1999, paper TUP028, pp. 263–266.