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ASYMMETRIC THERMO-CURRENTS DIMINISHING SRF CAVITY PERFORMANCE

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Abstract

Over the past years it became evident that the quality factor of a superconducting cavity is not only determined by its surface preparation procedure, but is also influenced by the way the cavity is cooled down. In this paper we will present results from numerical field calculations of magnetic fields produced by thermo-currents, driven by temperature gradients and material transitions. We will show how they can impact the quality factor of a cavity by producing a magnetic field at the RF surface of the cavity.

INTRODUCTION

The need to reduce the cost of the cryogenic infrastructure for future CW accelerators has driven the research on achieving high quality factor superconducting cavities. As a result, state of the art treated cavities display surface resistance approaches the theoretical limits. This allowed a deeper insight into the physics of parasitic effects, as they now become a prominent factor in limiting the performance of SRF cavities. One interesting finding, reproduced in different labs was that the quality factor of a cavity is impacted by the details of the cool-down procedure [1-3].

As of now, there seem to be two contributions resulting in the cool-down dependency of the cavity performance. One is flux pinning, the other is thermo-current.

Flux pinning describes the effect that a residual magnetic field is not fully expelled as the cavity becomes superconducting, resulting in an only partial Meissner effect. The trapped flux then concentrates in vortices which stay normal conducting and as a result, increases the losses of the cavity, denoted by a drop in the quality factor.

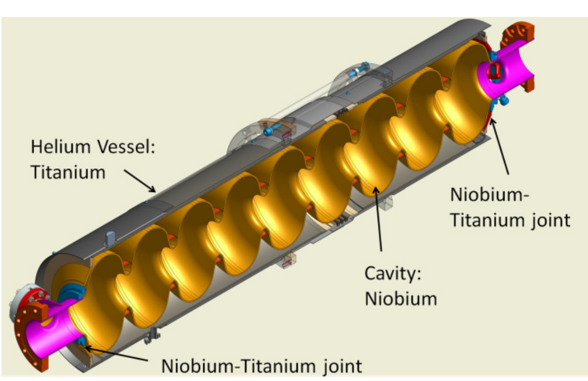

Figure 1: A superconducting cavity, welded into its helium vessel (dressed cavity).

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Thermo-currents on the other hand have no direct effect. They are a result of the Seebeck effect that exist if material joints are held at different temperatures. As shown in fig.1, a superconducting cavity, welded into its helium vessel, is essentially a Seebeck current loop. As of their nature, thermo-currents generate a magnetic field- which then may be pinned during cool-down. In the past, an analytical analysis argued that the axial symmetry of SRF cavities leads to no (or when considering the potential asymmetry from vessel or cavity port: negligible small) thermo-electric induced magnetic fields in the relevant RF penetration layer at the inner cavity surface [4]. The author concluded that thermo-electric currents are not a concern for the performance of SRF cavities. However, our findings indicated early-on [5] that thermo-electric currents may have a more severe impact on the SRF performance as so far predicted [6].

SEEBECK EFFECT

Thermo-currents are the result of the Seebeck-effect, which is well known in physics for more than a century: Discovered in 1826, Seebeck found that a current will flow in a closed circuit made of two dissimilar metals when the two junctions are maintained at different temperatures. The voltage is dependent on the material, leading to the definition of the Seebeck coefficient *S*:

$$\Delta U = S \cdot \Delta T \,. \tag{1}$$

Seebeck coefficients of metals can have either sign as they are defined relative to platinum. In a single metal arrangement, this voltage exists across the metal but does not result in a current flowing other than simply building up the charges, initially. If there is a material transition, where two different metals are joined, not only does a potential difference exist, there might also be a persistent current, driven by the temperature difference, if the loop is closed. As superconducting cavities are made out of niobium while the helium vessel enclosing them is typically titanium this effect is relevant for accelerator physics: During the cool-down of a dressed cavity (a cavity welded into its helium vessel) it is easy to imagine that both ends of the cavity (where the Nb-Ti transition is located) have different temperatures. Seebeck coefficients are temperature dependent, as given in tab. 1 for niobium and titanium. With the more general definition of the Seebeck coefficient, the thermo-voltage becomes

$$U_{th} = \int_{T_1}^{T_2} \left(S_{Nb}(T) - S_{Ti}(T) \right) dT \tag{2}$$

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Table 1: Thermoelectric Power (Seebeck Coefficient) for Niobium and Titanium, Taken from [7]. Values are Given in μV/K

	10 K	20 K	50 K	80 K	100 K
Nb	0.31	0.98	2.73	3.09	3.13
Ti	N/D	N/D	-3.00	-3.00	-2.60

THERMOCURRENT SIMULATION

In order to gain a better understanding, numerical simulations with CST® EM-Studio® were undertaken. We modelled a real size cavity with a simplified helium vessel (see fig. 3a). The Seebeck voltage was applied over an artificial gap on the right side of the helium vessel. For the simulation, realistic values for the expected thermo-voltage and the resistivity of the materials were used and the mesh was carefully adjusted to avoid numerical problems.

For the numerical simulation we assumed a Seebeck voltage of 150 μV, which corresponds to a temperature of 10 K on one side and 50-60 K on the other side (the calculation is based on experimental conditions as published in [8]. Below 50 K the thermoelectric power of titanium is unknown. Our extrapolation is a linear dependency of the coefficient with temperature between 10 K and the first data point at 50 K, as our measurements in [6] suggest a rather constant value at least below 10 K.

We also assumed constant resistivity for the niobium ($5\bullet10^{-10}$ Ωm) and the titanium ($2.5\bullet10^{-7}$ Ωm). The bellow of the titanium vessel was accounted for this simulation in terms of resistance but it was not modelled geometrically.

Symmetric Case

Even though the cavity/ helium-vessel may have non-uniform properties, symmetry exists if the properties are independent of the azimuth. In this scenario, a thermo-current is excited if a temperature gradient exists along the z-axis: The disparity of the temperatures at the material transitions results in a Seebeck voltage, driving this current.

However, due to the postulated symmetry, currents in the upper and the lower half are equal, resulting in a magnetic field that only exists between the outer cavity wall and the helium vessel. This is consistent with the analytical model in [4].

We calculated the current in the thermo- loop to be 4.8 A and the maximum magnetic field to be 25 μT . The results for the symmetric scenario are shown in fig. 3, where plot (a) gives the magnetic field configuration. The plots below give the magnetic field along a z-axis cut at the location of the equator (b) and the iris (c) near the centre of the cavity.

As expected, fields are symmetric and no field inside the cavity exists. As a consequence of the vanishing magnetic field at the RF surface of the cavity, thermo-currents in this symmetric case do not result in any contribution to the flux pinning at transition and thus do not influence the performance of the cavity.

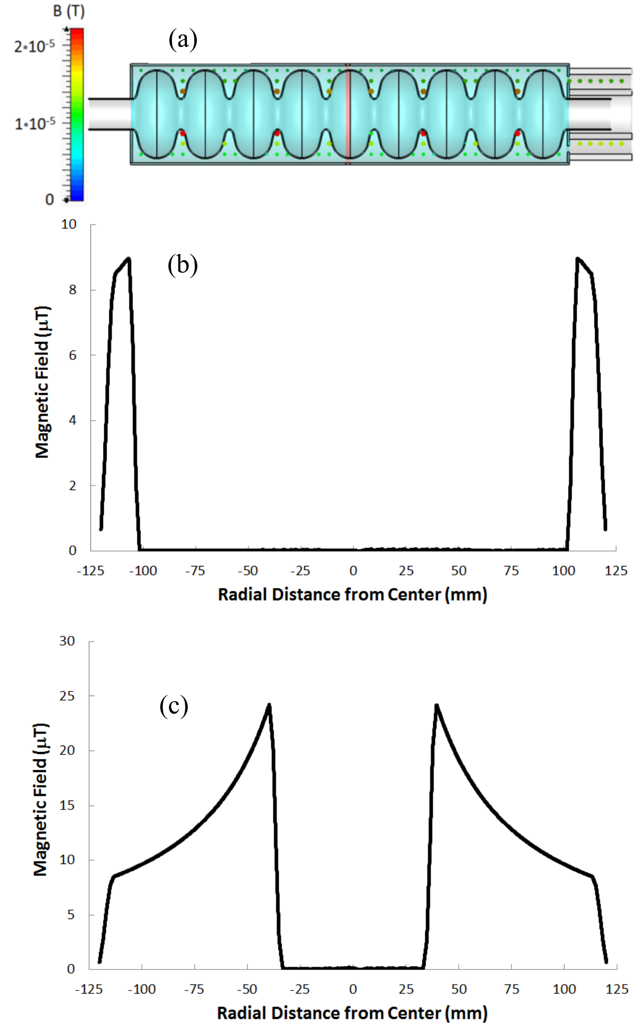

Figure 3: Results of the numerical field assuming azimuthal symmetry: 3-D field configuration (a), z-axis cuts along one equator (b) and at an iris (c), both locations where close to the cavity centre.

Asymmetric Case

To simulate the asymmetric scenario we applied the same conditions as described above except that we assumed the lower portion of the cavity to be a perfect conductor- representing its vanishing resistance in the superconducting state. The field configuration yielded is given in fig. 4 (a), the lower plots are z-cuts at the iris (b) and equator (c), respectively. As a result of the azimuthal asymmetry, magnetic fields are asymmetric and a reasonable large magnetic field exists inside the cavity which during transition of the upper half of the cavity through Tc could be trapped, causing an increase in the residual resistance and thus deterioration in the cavity Q.

Figure 4 also indicates that a measurable thermo-current induced magnetic field is generated outside the titanium vessel. This explains our initial findings referred in [5] which could not be explained so far. Given the field configuration has been simulated, this allows to index the field at the cavity surface without having to place a

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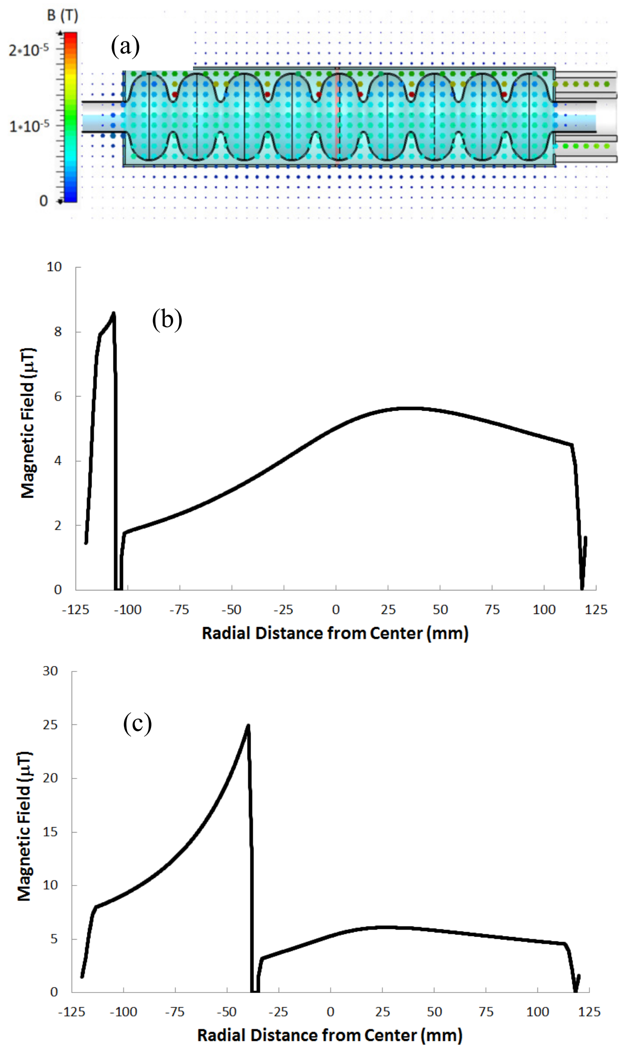

Figure 4: Results of the asymmetric calculation, where the lower portion of the cavity is assumed to be superconducting while the upper half remains normal conducting: 3-D field configuration (a), z-axis cuts along one equator (b) and at an iris (c).

magnetometer inside the cavity. Thus, a magnetic field reading outside the helium vessel permit a direct distinction between the thermo-electric magnetic fields which do not affect performance (symmetric, no field inside the cavity nor outside the helium vessel) and the fields which impact the performance (asymmetric with field inside the cavity and outside the helium vessel).

CONCLUSION

Our simulations have shown that conditions can exist under which thermos-currents can contribute to the cavity performance: If an azimuthal asymmetry exists, thermo-currents can generate magnetic field at the RF layer of the cavity that is subject to flux trapping. A reason for this asymmetry can be found in the cool-down, if a transversal temperature gradient in the dressed cavity exists. This is usually the case in a horizontal test, where the cavity is cooled through a stream of cold helium entering through a cool-down port at the lower portion of the helium vessel, while the exhaust is located on the top. This results in a lower temperature of the lower portion of the cavity with decreased resistance and increased current in that region. As the resistivity of the titanium is almost constant below 50 K [9], the change of resistance has to be caused by the niobium with the most drastic change to happen as the niobium becomes superconducting.

The thermo-current effect has less influence in vertical tests for two reasons. Usually, only bare cavities are tested, but a closed current loop might exist over the cavity support frame. Longitudinal temperature gradients might be huge resulting in large thermo-current induced magnetic fields. However, due to the mostly preserved azimuthal symmetry as a result of the only z-dependant temperature distribution, fields are symmetric eventually generating no flux at the RF layer of the cavity.

REFERENCES

[1] J.-M. Vogt, O. Kugeler, and J. Knobloch "Impact of cool-down conditions at Tc on the superconducting rf cavity quality factor", Phys. Rev. Sp. Top. – Acc. and Beams 16 (2013)102002.

[2] N. Valles, R. Eichhorn, F. Furuta, G.M. Ge, D. Gonnella, Y. He, V. Ho, G. Hoffstaetter, M. Liepe, T. O'Connell, S. Posen, P. Quigley, J. Sears, V. Veshcherevich,"Cornell ERL Main Linac 7-Cell Cavity Performance in Horizontal Test Cryomodule Qualification", Proc. of the 2013 Int. Conf. on Part Acc., Shanghai, China (2013) 2459.

[3] A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, "Dependence of the residual surface resistance of SRF cavities on the cooling rate through Tc", arXiv:1401.7747

[4] A. C. Crawford, "A Study of Thermocurrent Induced Magnetic Fields in ILC Cavities." arXiv, (1403.7996), 2014

[5] R. Eichhorn, et al., "High Q Cavities for the Cornell ERL Main Linac", Proceedings of SRF2013, Paris, France (2013) 844.

[6] R.Eichhorn, C. Daly, F. Furuta, A. Ganshyn, "Investigation of thermocurrents limiting the performance of superconducting cavities", Proceedings of IPAC2014, Dresden, Germany (2014) 2621.

[7] F. J. Blatt, P.A. Schroeder, C.L. Foiles, D. Greig, "Thermoelectric Power of Metals", Plenum Press, 1976.

[8] D. Gonnella, R. Eichhorn, F. Furuta, M. Ge, D. Hall, V. Ho, G. Hoffstaetter, M. Liepe, T. O'Connell, S. Posen, P. Quigley, J. Sears, V. Veshcherevich, A. Grassellino, A. Romanenko, D. Sergatskov, "Nitrogen-Doped 9-Cell Cavity Performance in a Test Cryomodule for LCLS-II", J. Appl. Phys. 117, 023908 (2015).

[9] W.R.G.Kemp, P.G. Klemens, G.K. White, "Thermal and electrical conductivities of iron, nickel, titanium and zirconium at low temperatures", Austr. Jorn. Of Phys. 9 (1956) 180.