Study of Thermocurrents in SCRF cavities via measurements of the Seebeck Effect in niobium, titanium, and stainless steel thermocouples

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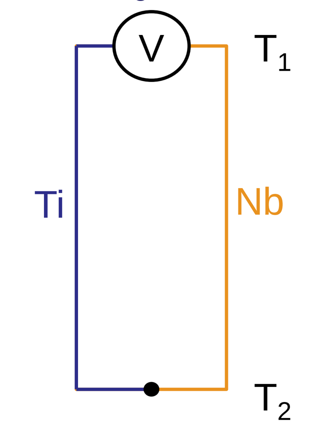
Introduction: Why study thermocouples?

Magnetic field lines around the inner surface of Superconducting Radio-Frequency (SCRF) cavities dissipate energy and lower the quality factor of the cavity. Magnetic shielding around the cavities is successful at blocking external magnetic fields from interfering. It does not protect against internal magnetic fields caused by thermo-electric effects during the cooling process. A current of 1 A flowing around the 10 cm radius of a cavity-helium vessel circuit can produce 10 µT flux density, a level that is of concern if allowed to penetrate inside the cavity.

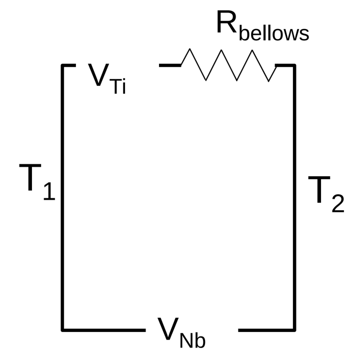
Nb cavities become superconducting at 9.2 K. The Seebeck Effect gives rise to electrical current when two dissimilar metals are joined and subjected to a thermal gradient. This thermal gradient is created when the cavity is cooled rapidly.

The Seebeck Effect in Nb thermocouples is largely unstudied. Couples with Ti and SS are possible in cavity-helium vessel designs. To simulate the cavity-helium vessel system, we use Nb+Ti and Nb+SS wire thermocouples immersed partially in LHe to explore the voltages and currents possible in the cavity-vessel systems.

Nb+Ti thermocouple diagram



Equivalent cavity-He vessel circuit



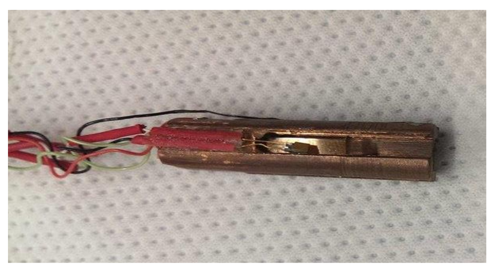
Experimental Procedure

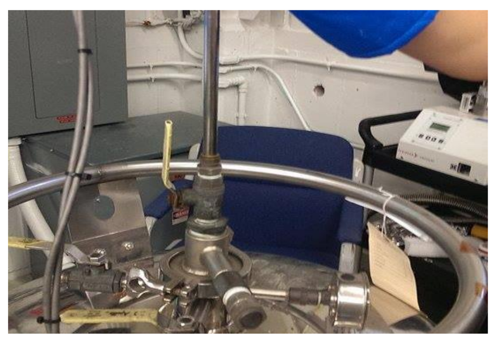
Thermocouple Fabrication
- Ti, Nb, and SS wires of high purity are joined by spot welds and insulated with shrink tubing

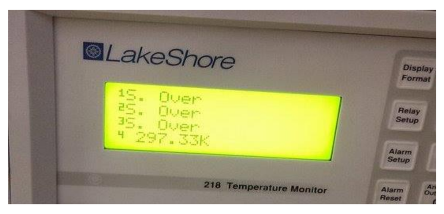
Support rod and RTD assembly
- Calibrated RTD secured to Cu mount and inserted into support rod
- Leads secured near RTD with Kapton tape

Insertion into Dewar
- Neck of Dewar modified
- Support rod and thermocouple lowered into LHe
- Junction immersed initially

Data Acquisition
- Support rod raised
- For each height, a temperature and a voltage are recorded manually

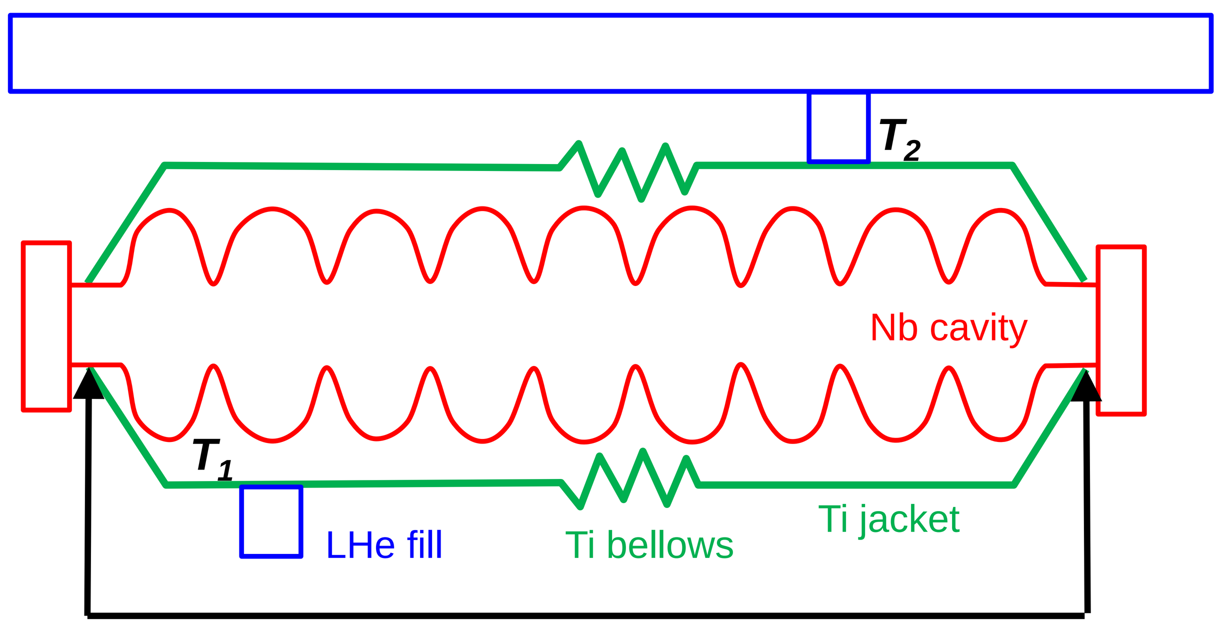






Technician's variation: Thermocouple secured inside brass can; thermocouple weld secured near RTD with leads leading out of dewar; support rod lowered into dewar; junction immersed finally

Possible Effects of Thermo-currents in SRF Cavities



$$V_{Ti\text{-}Nb} = (S_{Ti} - S_{Nb})(T_2 - T_1)$$

Are thermo-currents strong enough to introduce flux lines during cool down? [1,2]

Does the presence of current assist the sweeping of flux from the cavity? [3]

Experiments

Experiment 1 was performed to establish a base-line potential across a maximum thermal gradient.

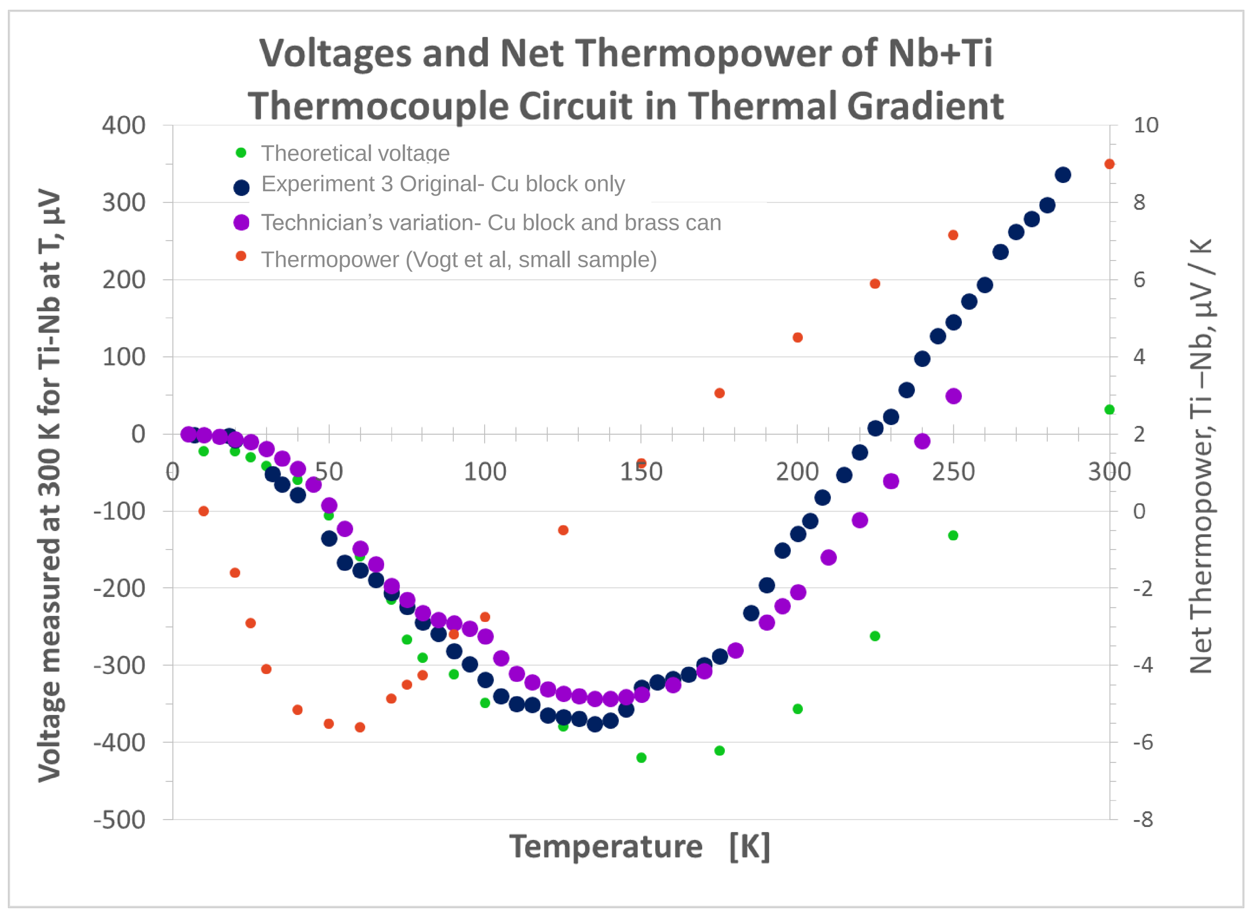
Experiment 2 was performed to test potentials with reference to Cu, explore low voltage measurement techniques and confirm the results of Experiment 1.

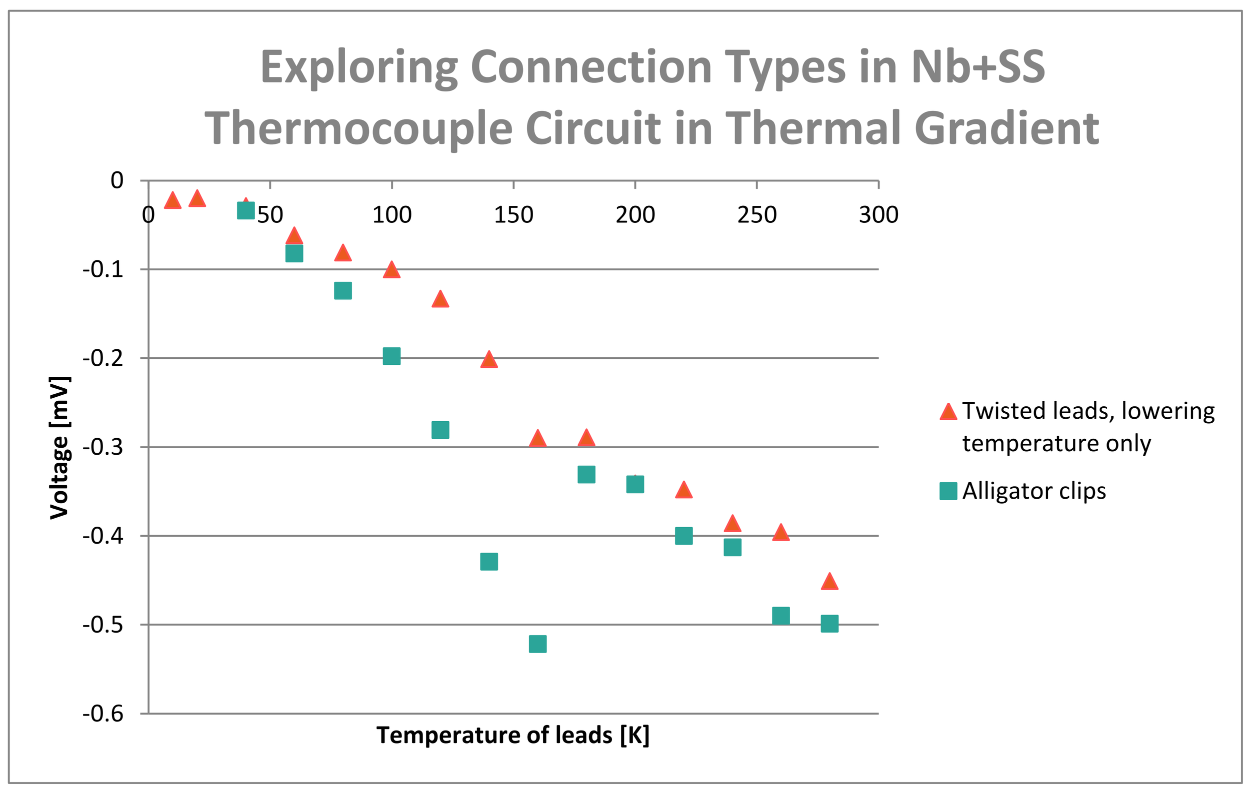
Experiment 3 was performed to measure the Seebeck Effect over a range of thermal differentials. A similar experiment was performed by a technician (see above), who obtained very similar data.

Notable features of the experiments

- Fluctuations in temperature were reduced by anchoring test junctions and thermometer to a copper block. Later, the block was enclosed inside of a brass can.
- Temperature control was obtained by raising height of the probe above the level of liquid He in a dewar.
- After reducing sources of noise, agreement between Nb-Ti direct couples and Nb+Cu to Ti+Cu was obtained to 17% uncertainty.
- Twisted and welded junctions appeared to behave similarly; twisted and clamped lead connections also behaved similarly

Results





Results

Significant thermal voltages were recorded, up to 350 µV for a temperature gradient of 135 K.

Discussion of Results

- The experimental data differ from an integration of $\Delta S(T)dT$ over the observed temperature interval above 150 K (gradients above 145 K)
  - Data for $S(T)$ for Ti and for Nb were taken from the thermopower measurements reported in [1]
  - There is good agreement below 120 K (gradients of 115 K).
- The presence of the brass can improved thermal stability somewhat; differences between our experiment and the theoretical data may be due to disagreement between RTD temperature and thermocouple temperature
- New data explores the thermopower for Nb-SS couples, should stainless steel helium jackets ever be used.
- Voltage difference between t and 4.2 K can be estimated from the measured difference between 300 K and t.
- $V(4.2\ to\ 300K) = \int_{4.2K}^{300K} S(T)dT = \int_{4.2\ K}^{t} S(T)d + \int_{t}^{300K} S(T)dT < 10\mu V$
- Therefore, $V(4.2K\ to\ t) = 10\mu - V(t\ to\ 300K) = 10\mu V - \int_{t}^{300K} S(T)dT$
- See next column for implications for SRF cavities →

Voltage and Current* as Functions of Thermal Gradient

T_2 (K) T_1 = 9 K	Approx. Thermo- Electric Potential (µV)	Current in cavity-helium vessel circuit (A)
20	15	0.50
30	20	0.67
40	45	1.5
50	92	3.0
60	150	5.0
70	200	6.7

* Circuit resistance = 30 µΩ. Calculated resistance based on RRR = 300 for Nb, dimensions of pieces, and resistivity of bellows sample [4]. Note – Cold worked Ti, and grade 5 Ti, may be superconducting at 4.5 K when in the body-centered-cubic phase.

Conclusion

We successfully measured and verified the magnitude of potentials possible by the Seebeck Effect along Nb+Ti and Nb+SS thermocouples subjected to a thermal gradient. The Seebeck voltages obtained followed theoretical trends, but with offsets above ~120 K. Substantial voltages were reproduced by multiple measuring techniques. We determined a 20 K differential, i.e. the warm end of the cavity is at 30 K when the cold end passes through 9.2 K, can produce ~1 A current in the cavity-vessel system. This may have important implications for flux nucleation and removal. Stainless steel cryostats have high resistivity and would reduce this effect.

Flux nucleated due to gradient

We consider a worst case, where thermo-electric current of maximum amplitude flows in a loop that contains the cavity interior. The enclosed area is approximately 1 meter x 10 cm = 0.1 m^2. Using the smaller dimension in the Biot-Savart equation, $\mu_0 H = I / R$, an estimate of 1 A / 0.1 m = 10 A/m can be made, or a flux density of approximately 10^{-5} T (= 0.1 Gauss). Using the flux quantum $\phi_0 = 2 \times 10^{-15}$ T-m^2, this equates to 10^9 flux lines across the cavity. While the actual number of flux lines nucleated should be much less, the number could still be substantial since vertical test stands are shielded from external sources to well below this level.

[1] Vogt, J-M., O. Kugeler, and J. Knobloch. "Impact of cool-down conditions at T c on the superconducting rf cavity quality factor." *Physical Review Special Topics-Accelerators and Beams* 16, no. 10 (2013): 102002.
[2] Gonnella, Dan, and Matthias Liepe. "Cool down and flux trapping studies on SRF cavities." In *Proceedings of LINAC*. 2014.
[3] Romanenko, A., A. Grassellino, O. Melnychuk, and D. A. Sergatskov. "Dependence of the residual surface resistance of superconducting radio frequency cavities on the cooling dynamics around Tc." *Journal of Applied Physics* 115, no. 18 (2014): 184903.
[4] Anthony C. Crawford. "A Study of Thermocurrent Induced Magnetic Fields in ILC Cavities" Mar 31, 2014. 23 pp. FERMILAB-FN-0980-TD