

PATHWAY TO A POST PROCESSING INCREASE IN Q_0 OF SRF CAVITIES

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Abstract

A significant improvement of the quality factor Q_0 from values of 1.5×10^{10} to values around 3×10^{10} at 1.8 K has been repeatedly achieved in a fully dressed and horizontally operated TESLA type SRF cavity by thermal cycling, i.e. heating the cavity briefly above the 9.2 K transition temperature of niobium and subsequent cooling. Conceivable explanations for this effect reach from (a) changes in shielding efficacy of the magnetic shielding to (b) thermal currents to (c) hydrogen diffusion. Our experiments suggest that neither (a) nor (c) are responsible for the changes in quality factor. It appears that the dynamics on frozen flux at the transition temperature is responsible for the observed effect. The pathway to this finding is presented and the application to SRF systems is elicited.

INTRODUCTION

In CW machines operated with superconducting cavities dynamic losses dominate the cryogenics budget. Hence, from a cost stand point the dynamic losses and hence the unloaded cavity quality factor Q_0 becomes more important than in pulsed machines. A reproducibly attained high value for Q_0 allows for the reduction of the cryogenic load and the operation with a smaller cryo plant.

Two terms contribute to the total surface resistance: The BCS resistance and residual losses. Residual losses are considered to originate to a great extent from trapped vortices inside the cavity wall that have a normal conducting core area which, albeit small in comparison to the total cavity surface, contributes to the total surface resistance in the same order of magnitude as the BCS resistance due to its hugely - by 6 orders of magnitude - increased local surface resistance.

Trapped flux is usually minimized by the installation of a magnetic shielding that reduces the earth magnetic field from 55 μT to less than 1 μT . It has been shown at disc shaped samples that 100% of a small ambient magnetic field is trapped in polycrystalline Nb material, as opposed to what one might expect from the Meissner effect [1,2].

THERMAL CYCLING

In an experiment reported earlier [3] thermal cycling, i.e. heating the cavity briefly above T_c was utilized to increase the Q_0 of a cavity. This experiment was repeated in much more detail with a different cavity taking Q_0 vs E_{acc} measurements at different helium temperatures in order to separate the BCS resistance and the residual losses. The cavity was tested in the HoBiCaT horizontal

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test facility setup [4] equipped with a TESLA cavity with TTF-III coupler very near critical coupling (β values between 1 and 2) and double (one cold, and one warm) magnetic shielding.

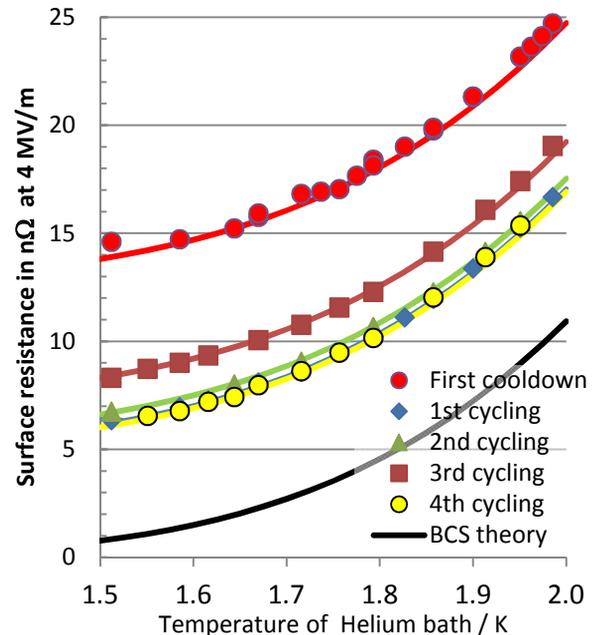


Figure 1: Surface resistance versus T curves at 4 MV/m gradient. Error bars are within the symbol size. The coloured lines represent the fit to the data points.

The temperature dependence of the surface resistance at 4 MV/m is presented in Figure 1. The uppermost curve shows R_s vs T after the initial cooling down (red dots). After subtraction of the BCS contribution, a largely temperature-independent value of 13.2 nΩ remains for the residual resistance. In a first cycling procedure the helium supply was turned off and the cavity was given just enough time to make the transition to normal conduction which was determined by monitoring the temperature of the outgoing helium gas. Then, helium supply and vacuum pumps were turned on again. The resulting residual resistance went down to 5.4 nΩ. In subsequent cycling runs it was attempted to increase the residual resistance again by turning off the cryo-plant for a longer time. The second run (green triangles) gave a small reduction which, however, was not significant (5.8 nΩ). Therefore, cycling was repeated - in this particular case 4 hours of cryo-downtime - and a significantly increased residual resistance of 7.4 nΩ could be demonstrated (dark red squares). Since monitored temperatures went beyond the 50 Kelvin limit, one might argue that the increase in resistance could have been caused by Q-disease. A fourth cycling procedure with an even shorter cryo-downtime

(yellow dots) was thus used to recover the low-surface-resistance state, with 5.3 n Ω even slightly undershooting the so far best value.

DISCUSSION

Various explanations for the Q_0 increase upon thermal cycling are conceivable. Since all measurements were performed at the very same cavity in the same measurement run, most properties with impact on Q_0 , like RRR, granularity, surface morphology, etc. remain unchanged, leaving changes in trapped flux as the most likely reason for changes in residual resistance.

Efficacy of the Magnetic Shielding

A first attempt at an explanation for the effect was a temperature dependence of the magnetic shielding efficiency. Being separated from the cavity by a superinsulation foil the inner magnetic shielding is cooled down slower than the cavity itself, cycling could lead to the cavity making the sc transition at different effective ambient magnetic field levels. However, as described in reference [5], permeability measurements of the utilized magnetic shielding materials vs temperature yielded no significant temperature dependence at the relevant temperatures. We even observed a small decrease of μ_r towards lower temperatures which should – if anything – lead to a smaller Q_0 after the first cycle instead of the observed enlargement. Also measurements of the shield temperature yielded no correlation to the obtained Q_0 .

Changes in Surface Chemistry after First Cycle

Another explanation is the removal of condensed contaminants from the cavity surface when allowing them to boil off or diffuse towards less harmful areas during the period of increased cavity temperature. This hypothesis cannot explain the fact that Q_0 can be decreased again by using sufficiently “bad” cooling conditions.

Also, Q -disease, i.e. hydrogen diffusion from the bulk to the cavity surface forming hydrides works in the other direction, and should lead to an increased surface resistance. It should not be reversible if the cavity is kept at low temperature (< 150 K).

Thermal Currents

The cooling down route of a cavity is optimized to avoid Q -disease by explicitly passing through the temperature range (150 K – 50 K) as fast as possible. This leads to a large thermal gradient during the initial cool-down that involves both ends of the cavity being at different temperatures during the superconducting transition.

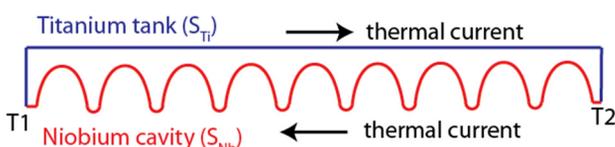


Figure 2: Thermo couple formed by tank and cavity.

The cavity-tank system can be considered as a conducting loop with toroidal symmetry, see Figure 2.

Since niobium and titanium have different charge carrier velocities, this loop acts as a thermo couple. When both ends of the cavity are at different temperatures a thermal voltage of $U = (S_{Nb} - S_{Ti}) \cdot (T_1 - T_2)$ arises, where S is the Seebeck coefficient of the respective materials, and $T_{1,2}$ the temperature of each contact point between tank and cavity. Since the loop is closed, this thermal voltage drives a thermal current in poloidal direction, i.e. along the cavity walls in axial direction and back through the titanium tank. The current gives rise to a magnetic field that cannot be screened by the magnetic shielding since it is originating from within. Due to the small Ohmic resistance and large cross sections of the involved materials, it is conceivable that magnetic fields can rise well up into the μ T range with realistic temperature differences along the length of the cavity. In the instance of the superconducting transition 100% of this flux may be trapped in the cavity walls [3]. Note that once the niobium is superconducting its contribution to the thermo power drops to zero, nevertheless the contribution of the titanium tank remains.

COMPARISON WITH MODEL SYSTEM

With a model experiment described in [5] we have measured these thermal currents, the thermo powers and the involved magnetic fields.

In this experiment, a 30 cm long niobium rod was anchored to a 4.2 K helium reservoir at both ends. With two separately operable heaters, also attached at both ends of the rod, temporal profiles and spatial temperature gradients could be imposed on the rod. The temperature distribution was monitored with seven CERNOX sensors attached along the rod axis. In order to simulate the conditions in a cavity-tank system both ends were interconnected with a grade 2 titanium wire forming a thermal circuit. Magnetic fields were measured by placing a 3D fluxgate magnetometer near the center of the rod.

With the setup we were able to resolve a number of issues: (I) *Thermal currents do exist in the system* and they create a magnetic field identical to electric currents. This was verified by opening the loop and attaching a current source and adjusting the electrical current until it resulted in the same magnetic field value as the thermal current. For this required electrical currents in the mA range were required. (II) *The magnetic fields associated with the thermo currents could be trapped* in the superconductor. This measurement is not trivial since the heaters produce their own magnetic field. In order to avoid that source of error, it had to be made sure that the heaters were turned off during the superconducting transition. Hence, all gradients had to be created by putting the system into a strong thermal disequilibrium and then turn off the heaters. The range of achievable gradients was diminished somewhat by this restriction, but nonetheless (III) a clear *correlation* could be seen *between temperature difference – or thermal current – and trapped magnetic field* as illustrated in Figure 3.

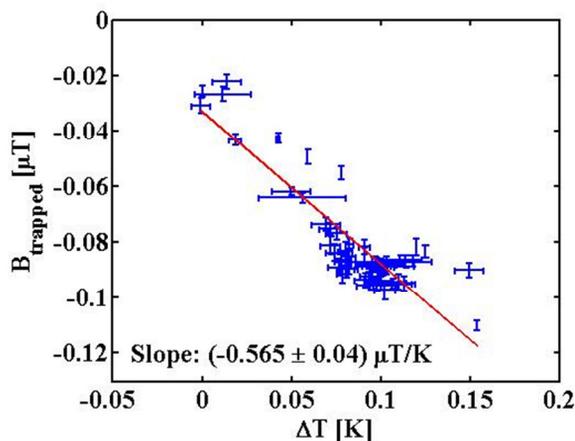


Figure 3: Trapped flux resulting from thermo currents from different spatial temperature gradients along niobium rod during sc transition.

A value of $\sim 0.6 \mu\text{T/K}$ was obtained for the dependence of trapped flux from the temperature difference. This value must be assumed to be strongly influenced by the geometry of the setup and can thus not be directly applied to the cavity-tank system. However, it should be sufficient for an estimation of the order of magnitude: In the model system a temperature difference of 1.7 K would be sufficient to create 1 μT additional trapped flux which corresponds to an increase of the surface resistance by $2\text{n}\Omega$, see for instance [6], and which is in the order of the changes measured at the cavity. Note that external magnetic fields were screened to less than 1 nT at the location of the probe. The extrapolation of the curve yields 30 nT which can be regarded as an upper limit for the bias due to expulsion of background magnetic fields.

(IV) An additional effect could be observed upon isothermal cooling of the rod, i.e. zero temperature gradient which could be achieved by applying identical power values to both heaters (or, alternatively by interrupting the electrical circuit at the titanium wires). It was observed that the *expulsion of an ambient magnetic field due to the Meissner effect is becoming less effective with increased cooling rates*. In Figure 4 the absolute amount of expelled flux measured with the fluxgate magnetometer is plotted against the logarithmic cooling rate. The slower the rod is being cooled down, the more flux is expelled, the less flux remains in the rod. These findings are in agreement with earlier published results for a disc-shaped geometry of the sample [1]. A possible reason for this behaviour is that flux expulsion via Meissner effect (with the Meissner state being energetically more favourable than a state with frozen flux) seems to be more effective when remaining a few millikelvin below T_c for longer periods of time [7]. Again, the application to a real cavity can only be made qualitatively, since the demagnetization factor influences the driving force of flux expulsion and differs from for the systems is different for cavity and rod.

Both, thermal and spatial gradients work in the same direction: the larger they are, the more flux is trapped in the superconductor.

In order to incorporate these findings into an accelerator layout, the cryo-plant would have to be designed such that it enables smooth temperature control around T_c .

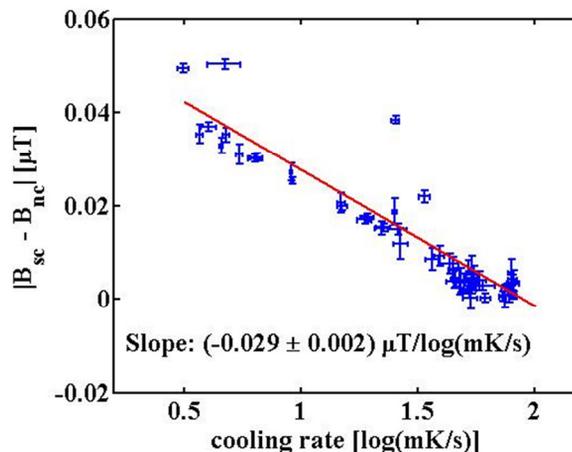


Figure 4: Expelled field vs logarithmic cooling rate in the model system.

CONCLUSION

A temperature gradient along a cavity weld into a tank leads to thermal currents that cause magnetic fields which are trapped in the superconductor material during the superconducting transition. Thermal cycling diminishes this effect by reducing the effective temperature gradients. Based on these findings we propose to add a step to the standard cavity cooling procedure: The fast cool down to avoid Q -disease should be terminated before the cavity undergoes the superconducting transition, somewhere between 10 K and 50 K, and the system should be given time to thermally settle. After achieving a sufficient uniform temperature distribution, cooling can proceed.

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