IMPROVING THE INTRINSIC QUALITY FACTOR OF SRF CAVITIES BY THERMAL CYCLING

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Abstract

We investigated the influence of the cooling gradients near the critical temperature T_c on the obtained intrinsic quality factor Q_0 of a TESLA cavity. Measurements were performed in the HoBiCaT test stand by briefly warming the cavity above T_c via He depletion inside the cryovessel and subsequent cooling. The temperature was measured at different points at the cavity and the cryo-tank. It turned out that there is a correlation between obtained Q_0 and the time lag between the first and the last transition of any sensor through T_c. This is interpreted as a spatial gradient. We have observed no correlation to the cooling speed, i.e. different temperature gradients in time. The findings could help explain the large fluctuations in measured Q_0 values in different test-stands. They could open up pathways to devising a cooling scheme to consistently obtain high residual Q_0 values.

INTRODUCTION

The RF-surface resistance of niobium is determined by two contributions: The BCS-resistance R_{BCS} [1] and the residual resistance R_{res}. The intrinsic quality factor Q_0 of a resonator made from this material is given by $Q_0 = G/(R_{BCS} + R_{res})$, with a material-independent geometry-factor G. While the BCS-resistance is pure physics, well defined and unavoidable, the residual resistance R_{res} is a matter of materials science and influenced by various material and operational parameters, like the RRR-value of the material, crystallinity and mosaicity, grain boundaries, lattice mismatch, inclusion of foreign atoms, like oxygen or hydrogen, surface smoothness, etc.

As a second effect, an ambient magnetic field that is present during the superconducting transition can be collimated at a region that remains normal conducting and continue to exist there at a local strength of above H_{c1}. Here, the Meissner-effect results in a remanent magnetisation by bunches of flux lines distributed over the cavity wall. Even after further cooling and reducing the external magnetic field these field lines can remain in place because the super-currents that maintain the flux cannot penetrate the normal conducting region (flux pinning). Hence, under realistic operating conditions, after cool-down vortices of flux are distributed over the cavity surface, although it would be energetically more favorable for it to be field-free. The movement of these vortices in the RF-field is a dissipative process that contributes to the residual resistance. Since the flux-pinning is assumed to be getting weaker towards higher temperatures, we have investigated if and how heating up the cavity near T_c can be utilized to get rid of frozen flux.

EXPERIMENTAL PROCEDURE

Experiments were carried out with a TESLA type cavity installed in the horizontal cavity testing facility HoBiCaT[2] at HZB. Cernox thermal resistors were placed at the Helium inlet of the titanium tank and the conical end pieces, the beampipes and the end flanges of both ends of the cavity as illustrated in Figure 1.

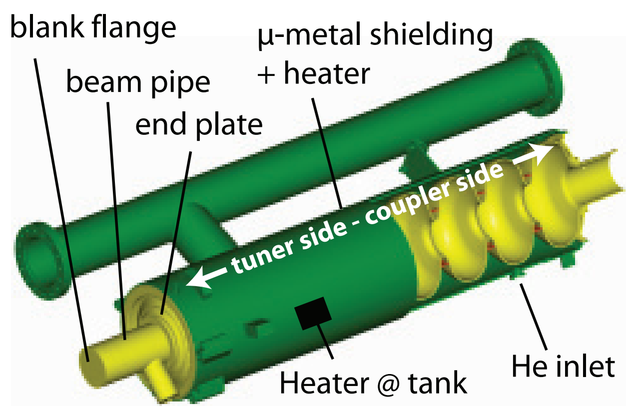

Figure 1: Placement of Cernox thermosensors and heater on the cavity tank.

All temperatures were monitored over time on a 1 second basis. Q_0 measurements were performed at critical or close-to-critical coupling.

The main objective of the measurements was to observe the influence of cool-down conditions on the achieved quality factor. For this, a thermal cycling was performed on the cavity, heating it slightly above T_c and cooling it down again in a controlled and reproducible manner. This was done by evaporating the liquid Helium from the cavity tank with a heater and closing the Joule-Thompson valve for the Helium supply. The Helium pumps were left running so Helium was slowly removed from the system. This procedure leads to a rapid temperature rise once all Helium is used up, which should be avoided, so the timing is rather critical. Depending on the duration of the cut in Helium supply and the used heater power, very different temperature profiles of the cavity could be established, some of which are exemplarily depicted in Figure 2. One entire cycle took approximately 4 hours before the cryosystem was once again stable enough to perform Q_0 measurements. Note that the cavity temperature always remained at temperatures below 80 Kelvin throughout the entire measurement. Also the RF-periphery and calibration remained identical (with slight adjustments of the input coupling via three-stub-tuner and antenna tip-position in order to stay at critical coupling throughout all measurements).

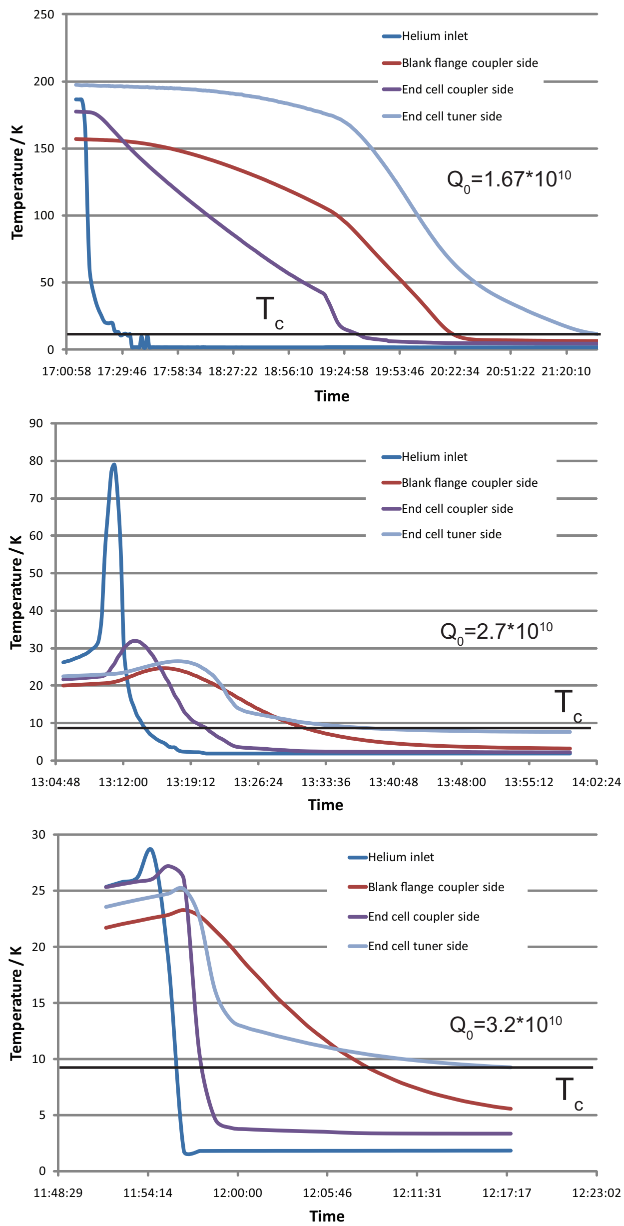

Figure 2: Time-series of the temperature profiles in Kelvin at various cavity during thermal cycling. Very different profiles could be obtained by only slightly changing the cycling parameters. Note that temperature and time axes vary in scale in the different plots. The cooling "duration" is defined by the time difference between the first and the last thermo sensor to drop below T_c.

RESULTS AND DISCUSSION

In the attempt to maximize Q_0 through thermal cycling the highest value was achieved by stopping the liquid Helium supply and heating the tank for 90 min at 30 W and then opening the JT-valve again. By doing this, the cavity experienced an almost 100% increase in Q_0 rising from an initial 1.67×10^{10} to 3.2×10^{10} at 1.8 K and 4 MV/m. It should be emphasized that measurements were performed in one cold run at the very same cavity with identical coupler settings, identical RF calibration, such that any deviation in Q_0 is necessarily a result of the cooling procedure itself. Both improvement and deterioration of Q0 could be demonstrated reproducibly.

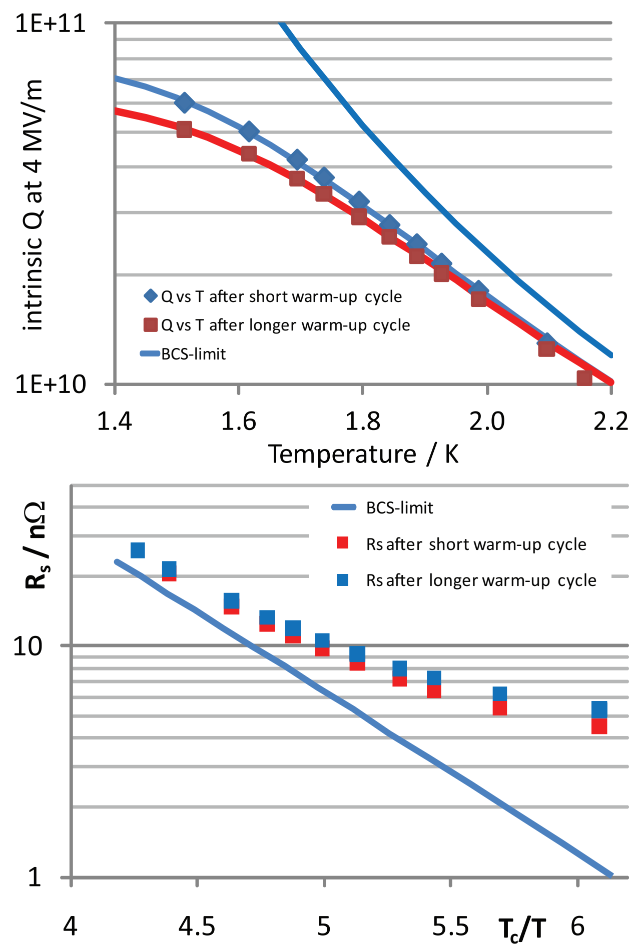

Figure 3: Measurement of Q_0 at several temperatures of the Helium bath gives information on the dominant limitations of Q_0. The curves give the temperature dependence of Q_0 values obtained at two different cycling routines. Accelerating gradient was always 4 MV/m. In the lower panel the same data is plotted as surface resistance versus inverse temperature. One can derive the residual resistance as $4.2n\Omega$ for the short cycle and $3.3n\Omega$ for the longer cycle. The mean free path is almost identical in both fits.

This effect becomes even more obvious when taking a Q_0 temperature series. Figure 3 shows the behavior of two different established Q_0 values upon varying the temperature of the Helium bath.

The residual surface resistance can be extracted from Q_0 by subtracting the calculated BCS-resistance as obtained from the measured temperature series, see Figure 3. The BCS-limit has been calculated with the empirical formula $R_{\mathrm{BCS}} = A\omega^2/T \exp[-1.8 \times T_c/T]$, where A is a parameter reflecting the RRR-value of the material or the mean free path, ω=1.3 GHz is the cavity resonant frequency, T_{c} = 9.2 K is the critical temperature. The residual resistance for the used TESLA cavity is then given by $R_{\mathrm{res}} = 270\Omega/Q_0 - R_{\mathrm{BCS}}$.

For the two curves in Figure 3 this yields residual resistance values 4.2 nΩ and 3.3 nΩ. The BCS-resistance is nearly identical in both fits which is evidence, that the RRR or mean free path has not changed due to the cycling procedure — at least not to an extent that would explain the differences in Q_0. Also, since the cavity was never above 80 K in either cycles, we don't expect any significant changes in the structure or motion of the hydrogen. Even more so, as it was possible to increase or decrease Q_0 which would involve hydrogen to diffuse to the surface and back into the bulk, because of the thermal cycling - all in a matter of minutes. Hence, the observed change in surface resistance is necessarily of magnetic nature rather than defects or RRR-issues.

There is a direct relation of the cycling parameters to the obtained Q_0, i.e. the same cooling parameters always yield the same Q_0 value. Thus Q_0 could not only be improved but also reduced with appropriate cooling parameters. In an attempt to find a correlation between temperature conditions at the cavity, the first guess was that the cooling speed (*temporal* gradient) was responsible for Q_0 variations. However, such a correlation could not be found. Instead, there is a correlation between Q_0 and the *spatial* gradient under which the cavity is cooled down. Figure 4 shows a plot of Q_0 versus the time difference between the first of all Cernox sensors to pass T_{c} and the last to pass T_{c}.

This cooling "duration" can be interpreted as the speed at which the interface between normal conducting and superconducting material is moving along the cavity. The smaller the cooling duration, the faster the velocity of this interface. Albeit not achieved in the measurements, zero cooling duration or total absence of a spatial temperature gradient should therefore yield the highest Q_0 values.

A possible explanation opens up when we consider experiments conducted with niobium samples that are also presented at this conference [4]. This work suggests the existence of electrical currents driven by a spatial thermal gradient. These currents have a magnetic field around them that may be frozen into the material - all the more so, since the thermal currents should be highest right at the instance of the transition due to the jump in specific heat capacitance that goes along with the superconducting transition.

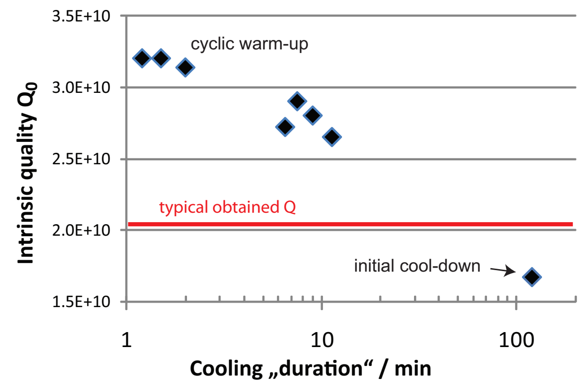

Figure 4: Correlation between Q_0 and cooling "duration". A significant increase in Q_0 can be achieved by heating the cavity above and cooling below the transition temperature after the initial cool-down.

In an earlier attempt to explain the increase in Q_0 it was suggested that the temperature dependence of the permeabilities of the magnetic shielding materials — as supplied by the vendors — yielded a different effective static magnetic field at the cavity in each cycle and was thus responsible for the different Q-values [3]. We could falsify this hypothesis by performing identical cycles at different temperatures of the magnetic shielding which was realized with a heater attached to the shield. The Q_0 value was not affected by the shield's temperature.

In order to verify this result the effciency of three typical shielding materials also used in HoBiCat have been measured directly: Mu metal, Cryoperm 10 heat-treated for 4 K operation and Cryoperm 10 for 70 K operation. Ring shaped sheets of 2 mm thickness, 30 mm outer diameter and 10 mm inner diameter were prepared by the Sekels company and measured inside HoBiCat parasitically during a cool down procedure. The discs were attached to a holder frame at the 4 K table inside HoBiCat and held in place with a copper holder bar with screws made from mumetal, in order to avoid thermal stress. During cool-down standard hysteresis measurements were performed with primary and secondary windings wrapped around the ring, bringing the material into saturation. The measured permeability values are presented in Figure 5. The measurement shows that the Cryoperm material does not improve its performance below 130 K, μ_r is even slightly dropping. The absolute values of these samples are fairly high - significantly higher than values given for actual shields formed from them. However, we don't expect the temperature dependence to change when going from a near perfect sample to a shielding. Therefore the temperature of the magnetic shielding in the instance of the superconducting transition cannot be responsible for a change in frozen flux and thus in Q_0.

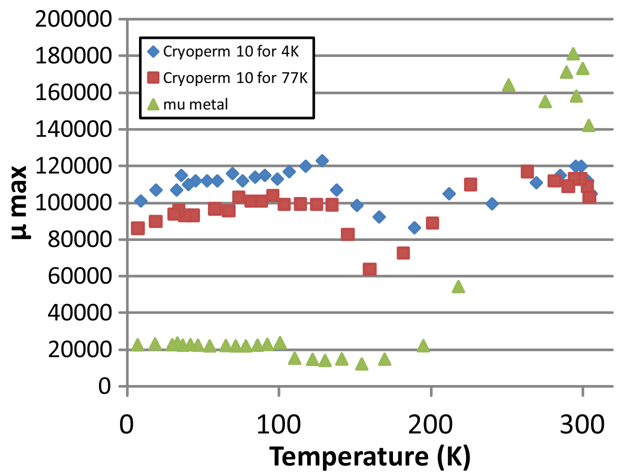

Figure 5: Measured permeabilities of different magnetic shielding materials: Mumetal, Cryoperm 10 sintered for 4 K operation and Cryoperm 10 sintered for 70 K operation.

OUTLOOK

In future experiments the cavity will be equipped with more thermo-sensors and heaters in order to further explore the parameter space of temperature gradients. Trapped flux is intended to be measured directly with a magnetometer underneath the shielding close to the cavity wall. Also, in parallel the studies of the effect of temperature gradients on samples will be continued.

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