MANIPULATING THE INTRINSIC QUALITY FACTOR BY THERMAL CYCLING AND MAGNETIC FIELDS

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Abstract

For CW applications of superconducting cavities, obtaining a high quality factor is an important issue: Since the required cryogenic power drops inversely proportional to Q_0, a higher quality factor of the cavities implies lower investment- and operational costs of the cryo-plant. Q_0 is limited by BCS-losses and residual losses from impurities, grain boundaries and trapped magnetic flux. In TESLA 9-cell cavities typical values of $2{\cdot}10^{10}$ are being achieved at 1.8 K with sufficient magnetic shielding. We have observed a significant increase in the Q_0 value of up to 50% when subjecting the cavity to an additional cryogenic cooling cycle to intermediate temperatures above T_c. In a second set of experiment, the flux trapping was monitored by cooling the cavity down to 1.8 K at different ambient magnetic fields and results were compared with theoretical values.

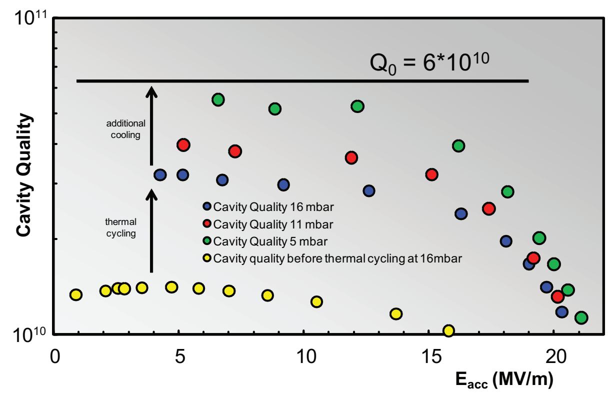

Figure 1: Q_0 values measured before (yellow) and after thermal cycling (blue). Further cooling increases Q_0 indicating that the cavity is still in the BCS limit.

THERMAL CYCLING: IMPACT ON ACHIEVED Q_0 VALUES

Q_0 measurements have been performed inside the HoBiCaT test facility on a horizontally positioned TESLA type cavity (BE-001) equipped with a TTF-III coupler. The BE-001 cavity had been cleaned with BCP and heat treated at 1400 °C. All measurements were performed at or very near to critical coupling which was achieved by adjusting the radial position of the antenna tip in the cavity and by including a three-stub-tuner in the waveguide between coupler and circulator. In contrast to the original TTF-III coupler for pulsed operation, a distance holder had been mounted between cavity and the coupler cold flange thereby shifting the coupler tip away from the cavity by an offset of 27 mm.
Electrodynamic Q_0 measurements have been crosschecked with thermodynamical values that were gained by measuring the 1.8 K helium consumption of the cryo-plant under equilibrium conditions. A direct comparison yielded an error margin of less than 20%.
Immediately after the first cool-down, Q_0 values of typically $2{\cdot}10^{10}$ are being achieved. We have observed that by heating the cavity briefly above T_c and cooling down to 1.8 K again, the quality factor can be reproducibly increased to $3{\cdot}10^{10}$, see Fig. 1.

Several hypotheses for the increase in Q_0 including thermocurrents due to temperature gradients were checked. However, attempts to artificially create thermocurrents with a heater attached to the tuner side of the cavity which imposes a temperature gradient over the cavity length during cool-down, failed: No Q_0 deviations were observed with this method. This proves, that **if** thermocurrents are involved, they are **not** acting on a macroscopic scale, but rather on a microscopic scale at the phase front of the superconducting transition. Unfortunately this was not accessible with our experimental methods. However, we favor a much simpler explanation as the most plausible one:
Mumetal shields are manufactured for a specific operating temperature range at which the used material exhibits the highest permeability. In HoBiCaT the outer shield at the inner cryostat wall is made for room temperature, while two different types of inner shields for the Helium vessel are available: One shield is optimized for 77 K the other one for 4 K. Characterization of the shields at room temperature shows a shielding efficiency of better than 99% (Fig. 2).

At small ambient magnetic fields up to 300 μT, 100% of the field is trapped inside the superconductor [1]. However, only the magnetic field at the exact instance of the superconducting transition is relevant for flux trapping. Once in the Meissner (Shubnikov) state, the superconductor rejects magnetic fields up to the critical flux H_{c1}. Since trapped flux leads to a degradation of the cavity performance, it is important to have the mumetal shield at the right temperature when the cavity reaches the transition temperature.
The regular cool-down scheme at HoBiCaT involves a fast cooling step in order to avoid hydrogen diffusion in the niobium which leads to Q-disease. The mumetal is not connected to the two-phase flow pipe of the cavity and cools down slower than the cavity. In the showcase example in

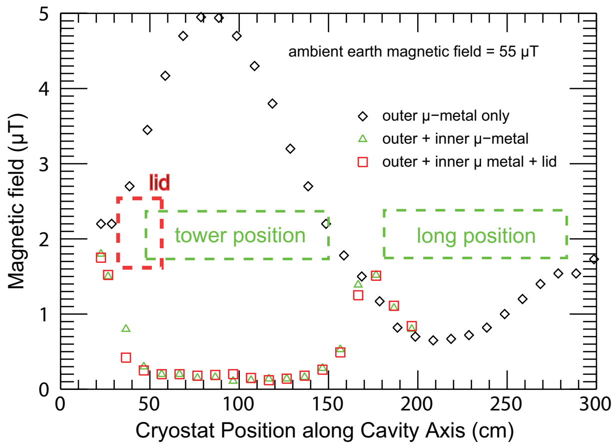

Figure 2: Magnetic shielding inside HoBiCaT measured at room temperature.

Fig. 3 the cavity becomes superconducting more than 12 hours before the mumetal is at its optimum temperature of 77 K (or 4 K). Thus, the shield is by 50 K (or 120 K) too warm which results in a significantly lowered permeability and performance (see inset in Fig. 4).

An easy solution to circumvent this problem is to let all components inside HoBiCaT reach equilibrium temperatures, then heat up the cavity slightly above 10 K by shutting off the Helium supply and evaporating Helium from the cavity with a heater (Fig. 4). This temporary return to normal conducting state removes frozen flux from the cavity walls. Due to the shield's high thermal inertia, which led to the discrepancy in the first place, it is not affected by this procedure. Utilizing this method we have been able to reproducibly increase measured quality factors by 50% - now typically reaching Q_0=$3{\cdot}10^{10}$ and well over $1{\cdot}10^{10}$ at 20 MV/m gradient.

However, even at such high Q_0 values the surface resistance is still BCS dominated: This was demonstrated by cooling down the cavity to even lower temperatures and measuring Q_0 again. The total surface resistance is composed of a temperature dependent part due to BCS-theory and a temperature independent residual part due to materials impurities, grain boundaries and frozen magnetic flux inside the material:

$$R_s = R_{BCS}(T) + R_{res} \quad (1)$$

The temperature dependence of the BCS part is due to the increase of the number of Cooper pairs upon temperature decrease. The residual losses are caused by normal conducting areas to which BCS theory does not apply and which are thus temperature independent (or at least they don't show a strong temperature dependence). A saturation of Q_0 towards lower temperatures would have indicated a predominant residual resistance. Yet, no saturation of Q_0 was observed down to HoBiCaT's minimum achievable He pressures of 5 mbar (corresponding to 1.5 K). Under these conditions, we have measured, to our knowledge, the maximum Q_0 value so far achieved in a horizontal test stand of Q_0=$6{\cdot}10^{10}$ or Rs=4.6 nΩ (Fig. 1). Thus, despite the better rf-performance of the cavity after the thermal cycling, there is still room for improvement of the Q_0 value, either by further improving the magnetic shielding, or by post manufacture-treatment of the niobium material itself (for example with a 120 °C bake).

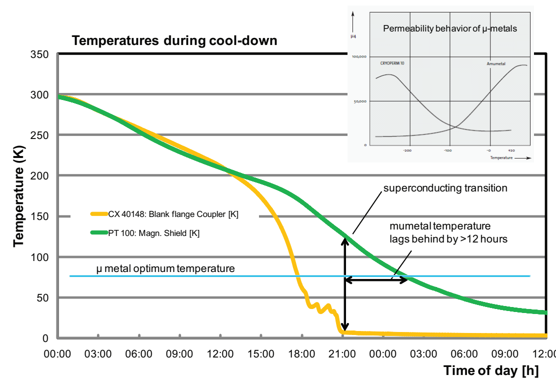

Figure 3: Temperature difference between mumetal and cavity upon primary cooling route. The cooling of the mumetal lags behind. In the instance of the superconducting transition of the cavity the mumetal is too warm, thus providing too little magnetic shielding [2]. Hence, the optimum Q_0 is not achieved.

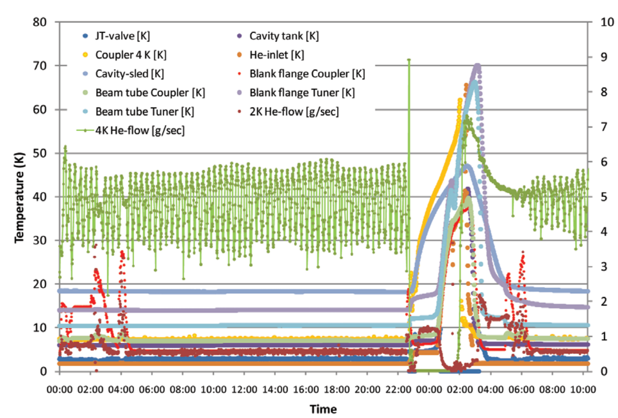

Figure 4: Thermal cycling routine: After closing the Joule-Thompson valve of the cryo-plant, liquid Helium is boiled off from the cavity tank with a 20 W heater. An entire cycle takes approximately five hours.

MAGNETIC DEPENDENCE OF THE SURFACE RESISTANCE

In order to better understand and quantify the effect of an ambient magnetic field on the cavity performance during superconducting transition, we have measured the intrinsic quality factor Q_0 after cooling the cavity under an external magnetic field. For generating this field, a long copper wire was wound around the Helium tank along the entire length of the cavity, forming a solenoid underneath the inner mumetal shield (Fig. 5). This solenoid could be supplied with currents up to 8 A before ohmic heating kicked in. The resulting field on the cavity surface was calcu-

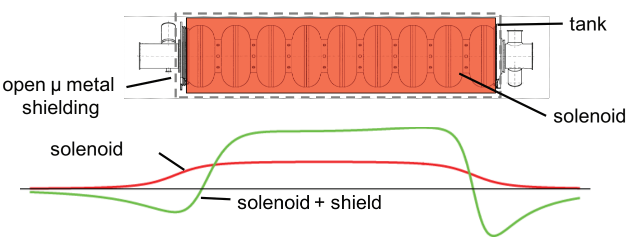

Figure 5: Setup for generating ambient magnetic fields inside the cavity: A solenoid is placed underneath the mumetal shield which acts as a yoke and increases the effect of the solenoid alone. This non-linearity has been taken into account in the field calculations.

lated with the Mathematica package Radia[3] taking into account the influence of the mumetal. The influences of cavity and titanium tank on the field could be safely neglected due to their paramagnetic nature above T_c. Prior to the superconducting transition, magnetic field lines are penetrating the cavity at all conceivable angles. For the frozen flux, we have used the absolute values of the calculated field vectors with the simple reasoning, that in the case of flux penetration in a type II superconductor, the exact opposite of the Meissner transition is happening to a magnetic field line: namely an orientation perpendicular to the cavity surface instead of parallel. From the resulting field distribution, a spatially resolved surface resistance was calculated according to [4]

$$R_{mag}(\vec{r}) = 0.3[\mathrm{n}\Omega] H_{ext}(\vec{r})[\mathrm{mOe}]\sqrt{f[\mathrm{GHz}]} \qquad (2)$$

where the factor 0.3 is an empirical value for Nb with RRR=300. In combination with the H field distribution at the cavity walls, integration over the cavity surface yields an average contribution of the field to the surface resistance according to

$$\overline{R_{mag}} = \frac{\int_S R_{mag}(\vec{r})|H(\vec{r})|^2 ds}{\int_S |H(\vec{r})|^2 ds} \qquad (3)$$

BCS losses can be obtained from the measured Q_0 at zero magnetic field. They add up to the total quality factor under an external field according to

$$Q_0 = \frac{G}{R_{BCS} + \overline{R_{mag}}} \qquad (4)$$

Q_0 curves have been recorded with different magnetic fields applied during the superconducting transition (Fig. 6). These values have been compared to the calculated values. In Fig. 7 the solenoid current that was used in the cool-down cycle is plotted against the obtained Q_0 value. For illustration purposes, a second vertical axis containing the maximum magnetic field obtained anywhere on

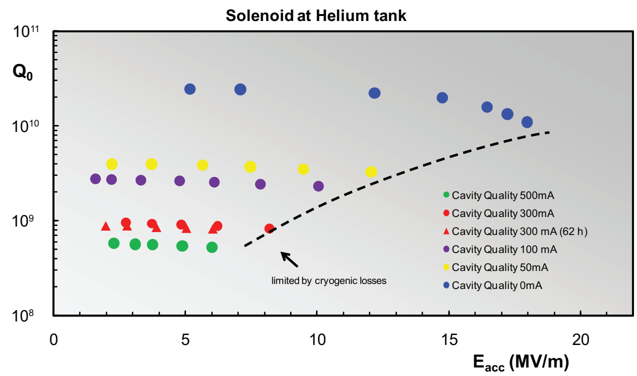

Figure 6: Q_0 values measured under different ambient magnetic fields generated by solenoid currents.

the cavity surface has been plotted. It turns out that our measured Q_0 values were twice as high as the theoretically expected. A possible resolve to this contradiction is

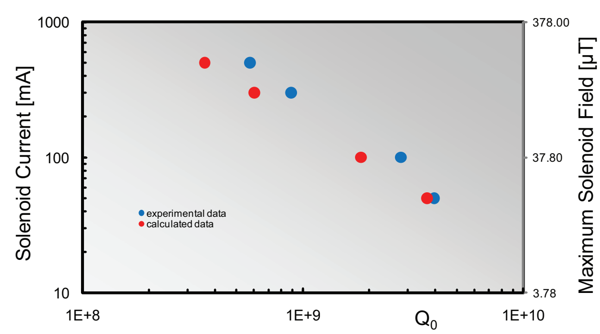

Figure 7: Comparison between experimental (blue) and theoretical (red) Q_0 values due to an external magnetic field during cool-down of the cavity. Experiment yields higher Q_0 values for a given field than predicted by theory.

to postulate a modification of the empirical factor that relates magnetic field to surface resistance in Equation 2. The data fits best if **0.23** instead of 0.3 is used. This correction would imply, that the effect of a frozen magnetic field on the Q_0 degradation of a cavity is smaller than anticipated.

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