Manipulating the Intrinsic Quality Factor by Thermal Cycling and Magnetic Fields

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Introduction

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. Q_0 is limited by BCS-losses and residual losses from impurities and trapped magnetic flux. With sufficient magnetic shielding for TESLA type cavities, typical values of $2{\cdot}10^{10}$ are being achieved at 1.8K. 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 (Fig 1). In a second experiment, the flux trapping was monitored by cooling the cavity at different ambient magnetic fields.

Thermal cycling – impact on achieved Q_0 values

Several hypotheses for the increase in Q_0 including thermocurrents due to temperature gradients were checked. The most plausible appears to be the following:

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 >99% (Fig 4).

At small fields up to 300 µT, all of the ambient magnetic field is trapped inside the superconductor[1]. However, only the magnetic field at the exact instance of the superconducting transition is relevant. Once in the Meissner state, the superconductor rejects magnetic fields up to the critical flux H_{c1}. Since the 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 passes the transition temperature.

In the regular cool-down scheme at HoBiCaT (Fig 2), the cavity reaches the superconducting transition temperature 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 (120 K) too warm which results in a significantly lowered permeability and performance.

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 3). 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. Here, no saturation of Q_0 was observed down to HoBiCaT's minimum achievable He pressures of 5 mbar (~1.5 Kelvin).

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 $R_s{=}4.6$ nΩ (Fig 1).

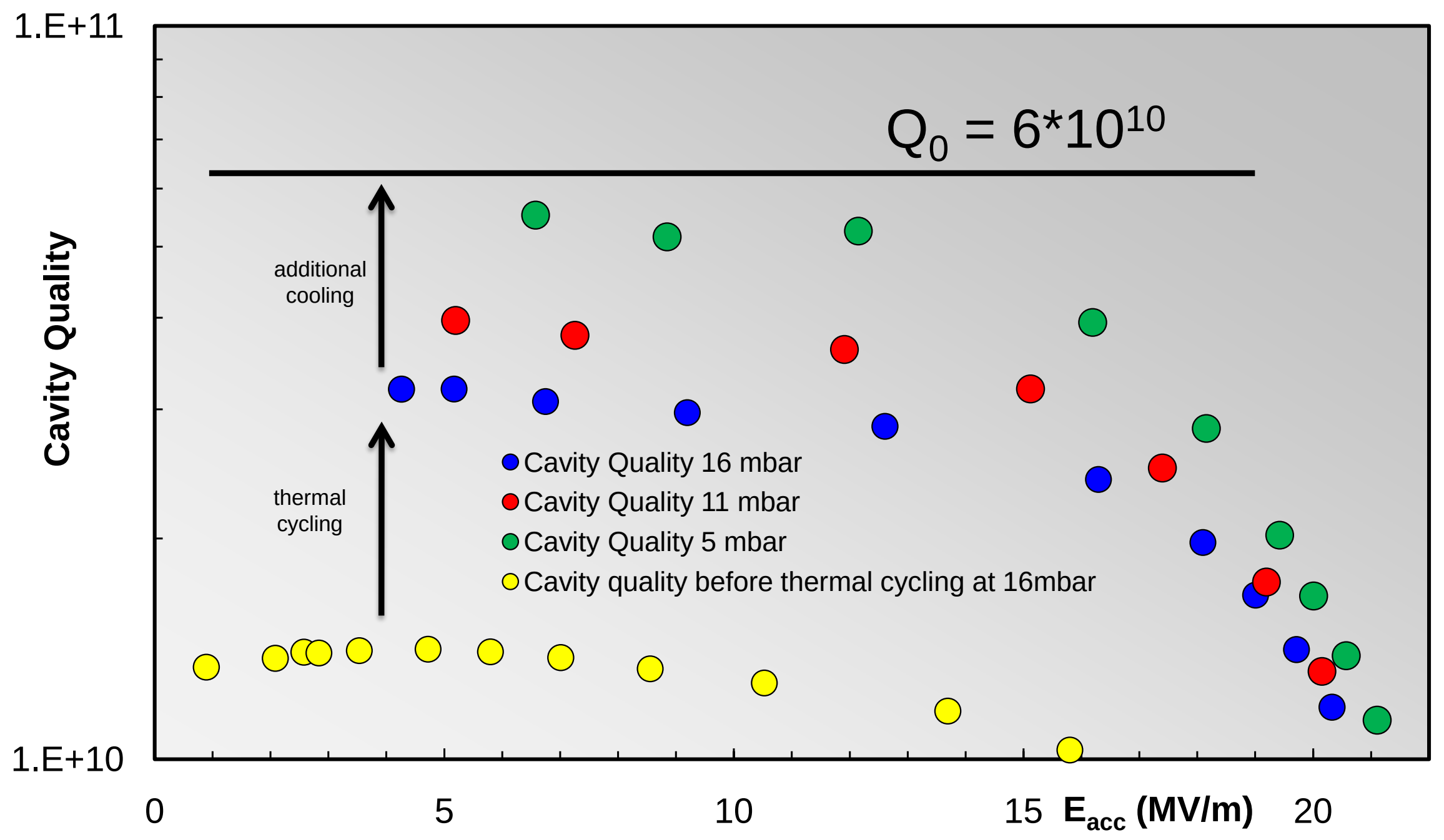

Fig. 1: Q_0 values measured before (yellow) and after thermal cycling (blue). Further cooling increases Q_0 indicating that the cavity is still in the BCS limit.

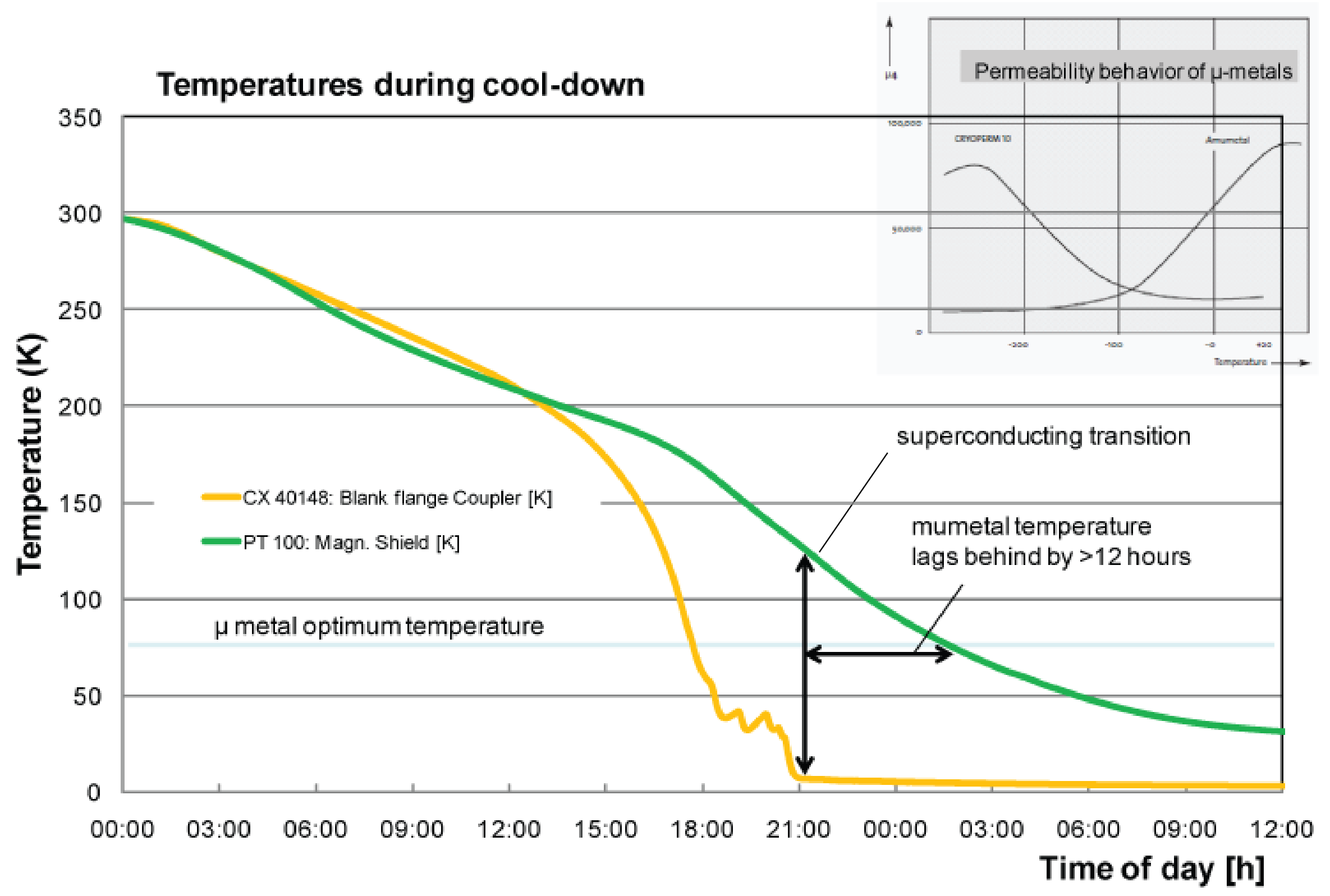

Fig. 2: Temperature difference between mumetal and cavity upon primary cooling route. The mumetal lags behind and is off its optimum temperature at the superconducting transition.

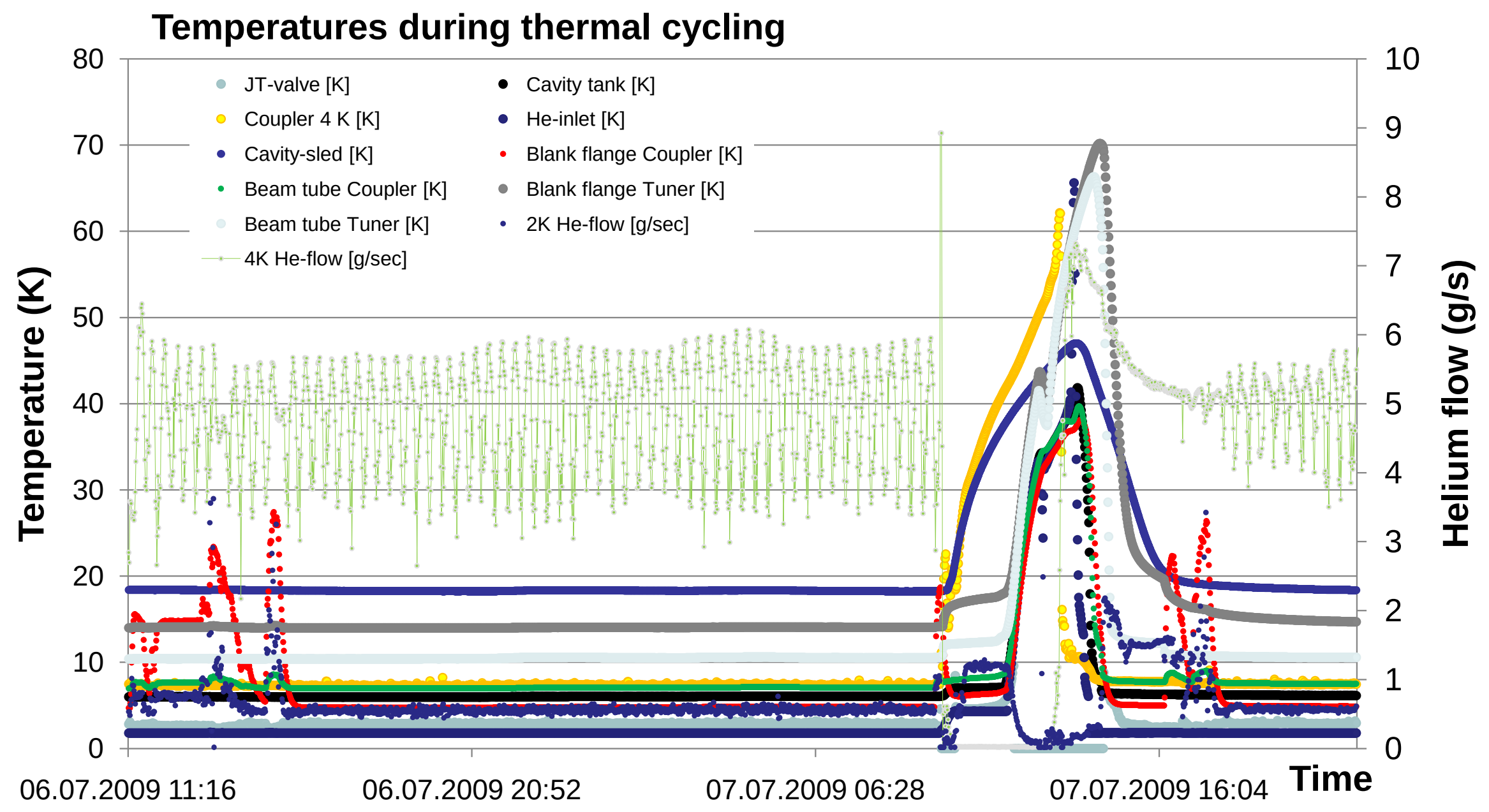

Fig. 3: Thermal cycling routine

Magnetic dependence of the surface resistance

We have measured the influence of a magnetic field on the surface resistance by cooling the cavity down in an ambient magnetic field. Two different setups were used: A solenoid wrapped around the tuner side of the beam pipe and a solenoid mounted underneath the inner µ-metal shield along the entire length of the cavity (Fig 5). The resulting fields on the cavity surface were calculated with Radia[2], a package for Mathematica taking into account the influence of mumetal, cavity and titanium tank.

From the resulting field a spatially resolved surface resistance was calculated according to[3]

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

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

$$\overline{R_s} = \int_S R_{mag}(\vec{r})\,|\mathbf{H}(\vec{r})|^2 ds \Big/ \int_S |\mathbf{H}(\vec{r})|^2 ds$$

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

$$Q_0 = \frac{G}{R_{BCS} + \overline{R_S}(H)}$$

Q_0 curves have been recorded with different magnetic fields applied during the superconducting transition (Fig. 6). These values have been compared to the theoretically predicted values. It turns out that our measured Q_0 values were 2 (1.5) times higher (Fig 7). A possible solution is to modify the empirical factor that relates magnetic field to surface resistance. The data fits best if we use 0.23 instead of 0.3. This correction would diminish the effect of a magnetic field on the Q_0 of a cavity.

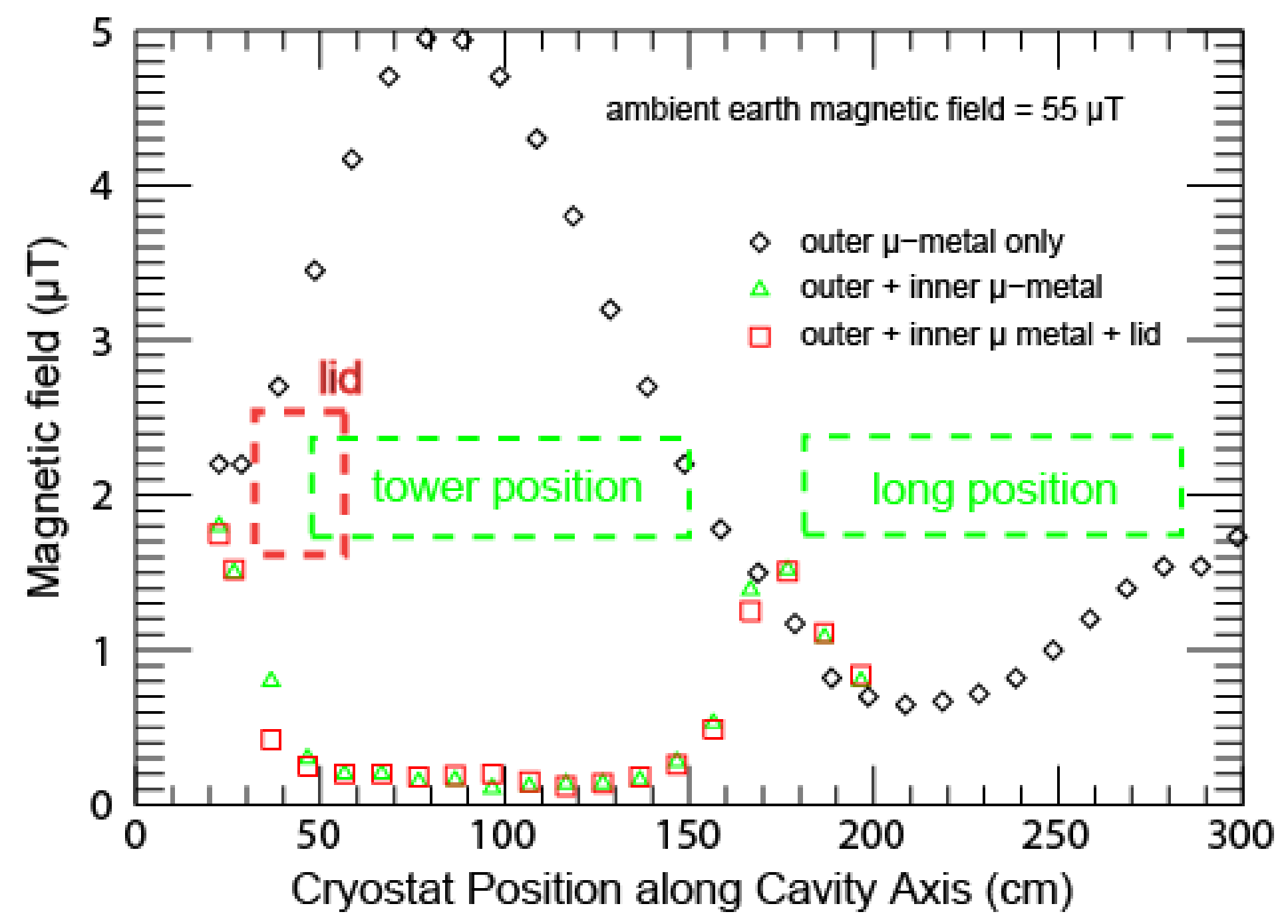

Fig. 4: Characterization of the efficiency of the magnetic shielding layers at room temerpature.

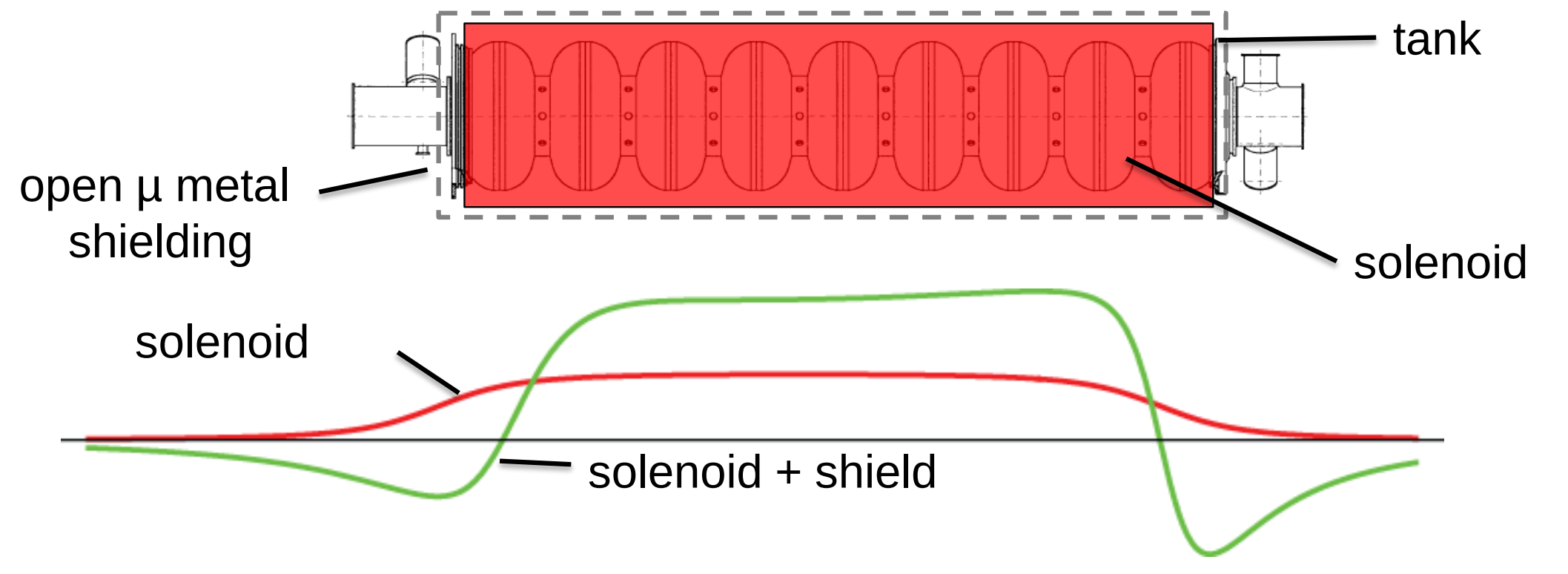

Fig. 5: Experimental arrangement: The solenoid is situated underneath the mumetal which partly acts as a yoke. The lower plot shows the resulting fields calculated with RADIA.

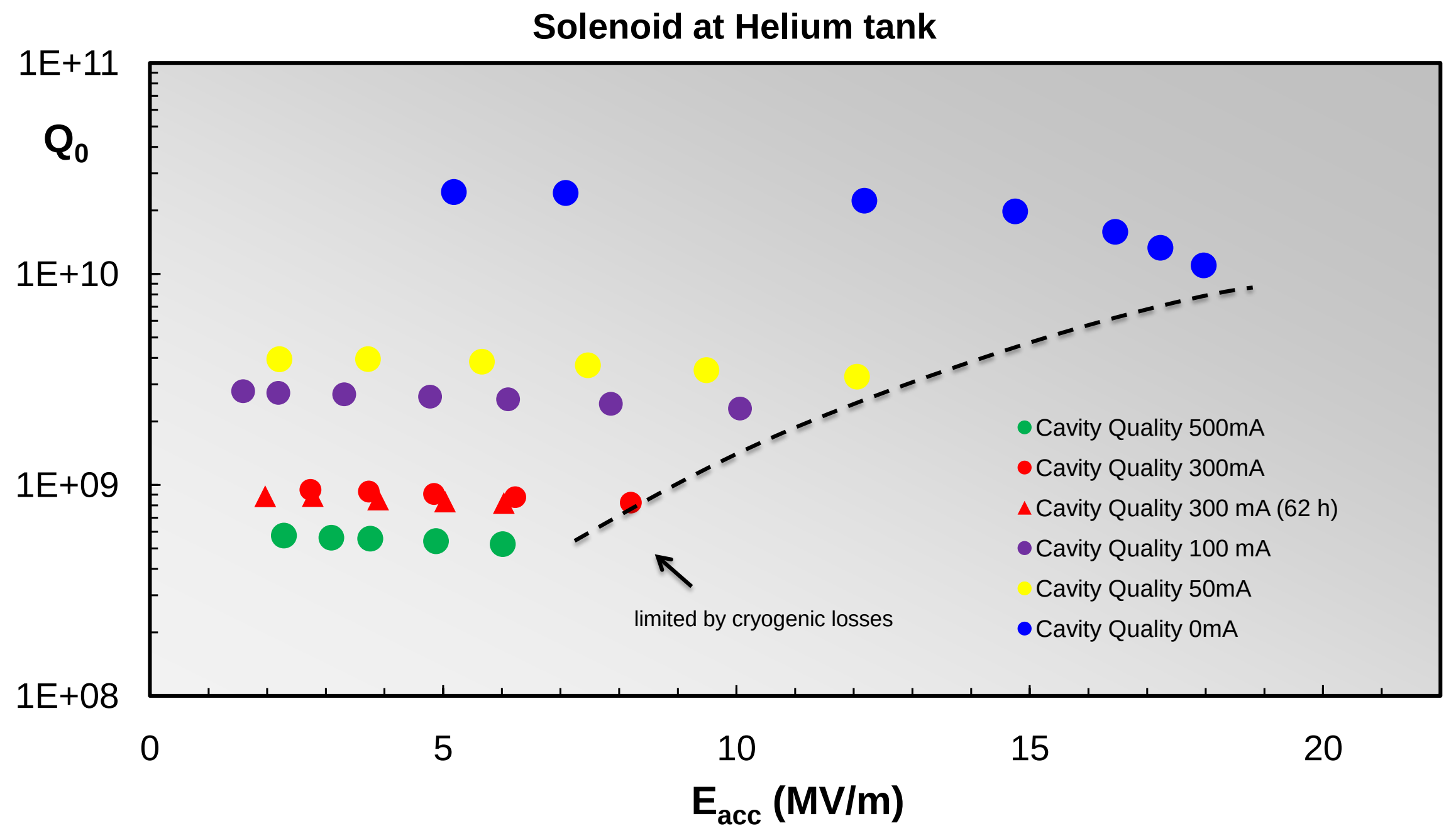

Fig. 6: Q_0 values measured under different ambient magnetic fields generated by solenoid currents.

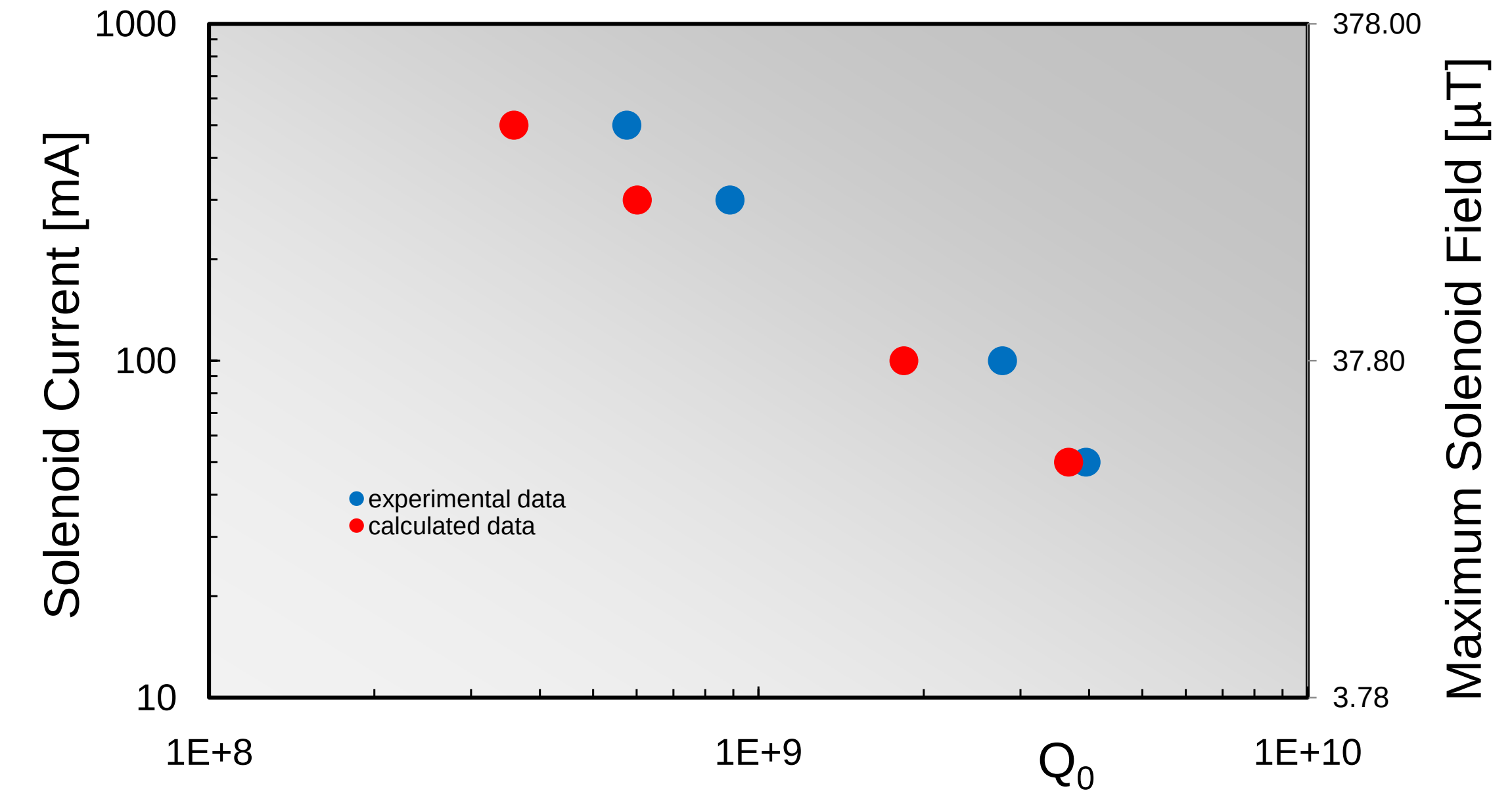

Fig. 7: Comparison between experimental and theoretical values. Experiment yields higher Q_0 values for a given field.

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