THERMAL BEHAVIOUR OF SRF CAVITIES AT HIGH GRADIENTS

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Abstract

At high gradients (Eacc > 15 MV/m), SRF cavities show anomalous RF losses resulting in a strong Qo decrease although no electrons activity or X-rays are detected. Tests performed on such cavities equipped with surface thermometers clearly show on broad areas non quadratic heatings with respect to the accelerating field. Numerical simulations using a thermal code allowed us to study the SRF cavity thermal behaviour in transient regime. Some results on the quench dynamic are confirmed by normal zone propagation velocity during thermal breakdown of different cavities.

1 INTRODUCTION

In several laboratories (C.E.A., K.E.K., D.E.S.Y...), a new phenomenon is sometimes observed on SRF cavities: at high gradients (above 15-20 MV/m), some cavities show a strong Qo degradation although neither electrons nor X-rays are detected (Fig. 1). At K.E.K., this cavity behaviour is sometimes observed, whereas it is systematic in the cavity experiments at Saclay [1]. Another remarkable fact is that the seamless spun cavities also showed such a behaviour [2]. In order to determine whether or not the extra power dissipated is due to anomalous RF losses, we have developped a surface thermometric system to measure the cavity wall heatings. Several tests on 1.3 GHz single-cell cavities equipped with this system were carried out in a close collaboration with the CE Saclay laboratory. For each test, the cavity performances were limited by a quench. A fast measurement of the instantaneous transmitted power during the quench allowed us to learn about the quench dynamics, such as the expansion velocity of the normal resistive zone and its size.

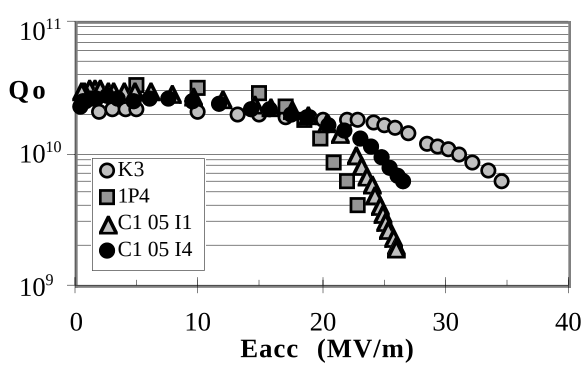

Figure 1: Qo degradation at high field without X-rays or electrons for different cavities: K3 (KEK), 1P4 (LNL spun cavity), C1-05 I1 and C1-05 I4 (Saclay).

[1] On leave from KEK

2 THERMOMETRIC MEASUREMENTS

Two cavities (C1-10 and C1-05) were equipped with surface thermometry and cold tested. Both showed the Qo degradation above 15 MV/m. The first interesting result is the linear dependency of the surface resistance Rs with the dissipated power Pcav in the cavity (Fig. 2). It seems to be a signature of this effect on bulk niobium cavities (EB welded or spun).

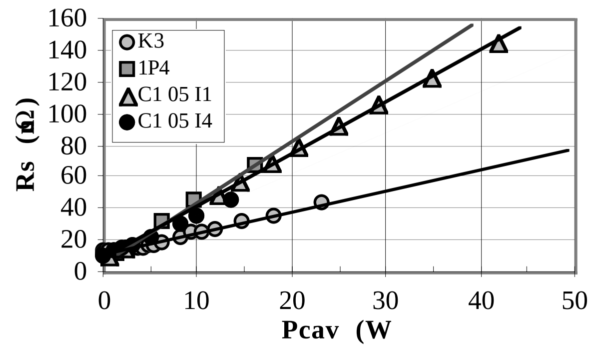

Figure 2: Variation of the surface resistance with the dissipated power in several cavities.

Two different assemblies were used for thermometric measurements. The first one was mostly dedicated to the study of the heatings on the equator. Surprisingly, only very low heatings (less than 10 mK) were measured on the equator, meaning that the weld is not responsible for the Qo degradation. This could be confirmed by the same observation of the Qo drop on seamless cavities (spun).

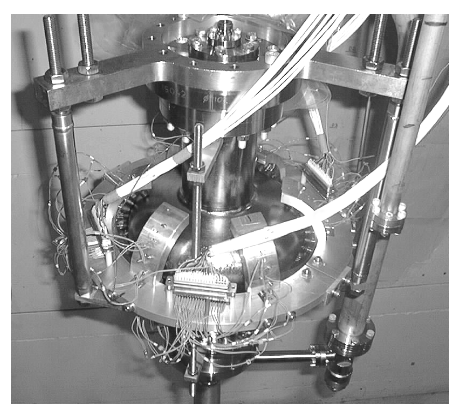

Figure 3: Thermometric apparatus mounted on the cavity.

Another assembly allows us to dispatch more thermometers out of the equator region. It consits of 60 surface thermometers dispatched on 6 arms around the cavity (see Fig. 3). All of them are placed in a region where the surface magnetic field is still at his maximum.

One important result is that the heatings measured are not quadratically dependent on the accelerating field (Fig. 4), meaning that the Qo drop is due to anomalous RF losses. Moreover, almost every thermometer has this characteristic, proving that broad areas are involved in this new loss mechanism. Nevertheless, the heatings do not exceed 80 mK (cavity C1-05), and this is not sufficient to explain the increase of the surface resistance by a temperature increase of the RF wall. A possible explanation for the Qo degradation is the existence of a damaged layer (mechanical or chemical) due to either High Pressure Rinsing or chemical polishing (CP) [3].

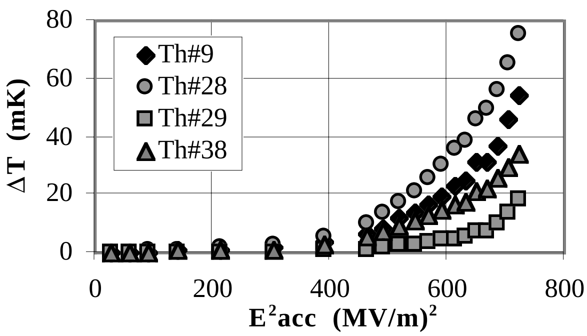

Figure 4: Heating measured on cavity C1-10 vs E^2_{acc}.

In order to verify the effect of an in-situ soft heating of the cavity at 110°C in the cryostat [4], we made temperature measurements before (C1-05 I1) and after (C1-05 I4) the treatment which strongly reduced the Qo drop (Fig.1). Between the two tests, the cavity was kept under pumping, but we had to dismount the thermometers. Despite the incertainty on the thermometer efficiency, one clear result is that for the same accelerating field, the heatings measured are much lower after the treatment (a factor 5 in average). The heatings did not exceed 7 mK at the maximum Eacc, but still some thermometers do not depend quadratically on Eacc. The quench occured at the same Eacc, at the same location, and the heatings reached are identical, confirming the independance of the quench from the Qo drop phenomenon.

3 QUENCH DYNAMICS STUDIES

Fast measurements of the transmitted power during a quench on the 1.3 Ghz cavities could give interesting informations on the quench dynamics with the use of an analysing method developped at the IPN [5].

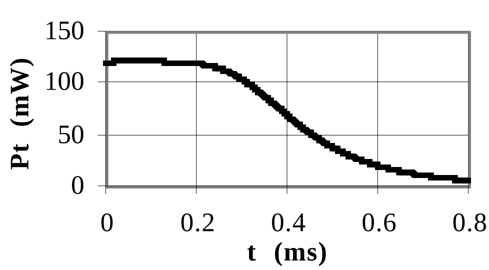

Figure 5: Transmitted power recorded during a quench in a 1.3 Ghz single-cell cavity (test C1-05 I1).

The basics of the method is to determine the increase of the power dissipated in the cavity during a quench from the transmitted power (P_t) signal measurement (Fig.5) and to attribute it to a growth of a normal conducting surface. The first step is to use the technique of the Cornell group [6] to find (Fig. 6) the instantaneous Qo:

$$\frac{1}{Q_0(t)} = \frac{2 \cdot \left(\sqrt{P_i(t)/Q_{ext}} - \frac{1}{\omega} \cdot d\sqrt{Q^t_{ext} \cdot P_t(t)}/dt \right)}{\sqrt{Q^t_{ext} \cdot P_t(t)}} - \frac{1}{Q_{ext}}$$

$$\text{with} \quad 1/Q_{ext} = 1/Q^i_{ext} + 1/Q^t_{ext}$$

where Pi is the incident power (constant during the quench in our experiments), Q_{ext} the external quality factor and ω the angular frequency.

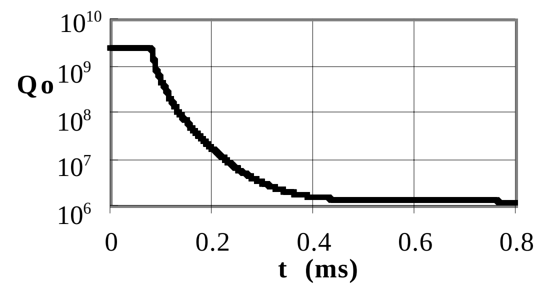

Figure 6: Quality factor decay during the cavity quench.

Without FE activity, the dissipated power is related to the magnetic field peak H_{pk}, the equivalent cavity surface S, the normal surface S_N, the surface resistance R_s and the normal surface resistance R^N_S by the relation :

$$P_{diss}(t) = \frac{1}{2} \cdot H_{pk}{}^2(t) \cdot \left[R_s \cdot S + R^N_S \cdot S_N(t) \right] \qquad (1)$$

The relationship between P_{diss} and the unloaded quality factor Qo is (l is the accelerating length):

$$E_{acc}(t) = \frac{1}{l} \cdot \sqrt{\frac{r}{Q}} \cdot \sqrt{Q_O(t) \cdot P_{diss}(t)} \qquad (2)$$

Combining (1) and (2), and using the relation $E_{acc}(t) = \alpha \cdot H_{pk}(t)$, we obtain the following equation:

$$S_N(t) = \frac{1}{Q_0(t) \cdot \frac{1}{2} \cdot \alpha^2 \cdot \left(\frac{1}{l} \sqrt{\frac{r}{Q}} \right)^2 \cdot R^N_S} - \frac{R_S \cdot S}{R^N_S}$$

Note the strong influence of R^N_S as $S_N \propto 1/R^N_S$ (we have used $R^N_S = 2.2 \ \text{m}\Omega$).

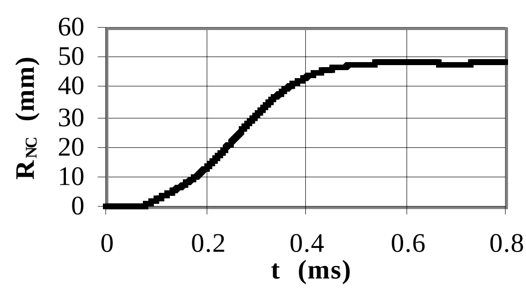

Figure 7: Radius of the normal conducting area.

Assuming a circular shape for the expanding normal region $S_N = \pi \cdot R_{NC}^2$, we have an immediate measurement of the normal conducting surface radius R_{NC} (Fig.7). For this cavity, the radius of the normal zone was 48mm at the end of the quench, corresponding to 10% of the cavity surface. From $R_{NC}(t)$, we can easily calculate the expansion velocity $V_{NC}(t)$ and from the Eacc(t) and $V_{NC}(t)$ curves we deduce the experimental V_{NC} = f (Eacc) curve (Fig.8).

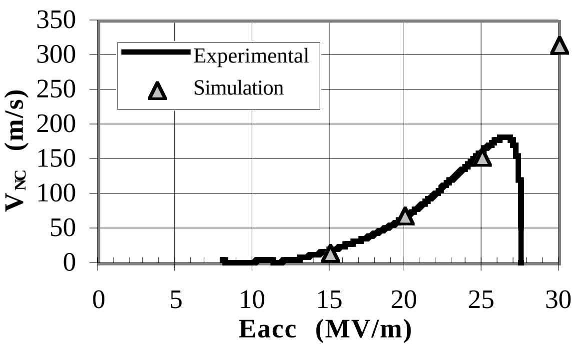

Figure 8: Experimental and simulated normal zone propagation velocity as a function of the accelerating field.

In order to study the influence of the niobium thermal properties on the quench dynamic, we have used the transient thermal code "Fondue" [7] to calculate the curve V_{NC}=f(Eacc). This code simulates the heating of a Niobium plate (2mm thick) subjected to a heat flux (function of Eacc) on one side and cooled by He II (kapitza resistance) on the other side. V_{NC} is calculated from the radial temperature profile on the RF side as a function of time, giving the instant when each cell of the mesh reaches the critical temperature $T_c(H_S)$. Knowing the thermal conductivity of the niobium (RRR=570), we were able to simulate V_{NC}=f(Eacc) (using R_S^N=2.2mΩ), which fit quite well with the experimental data (Fig.8).

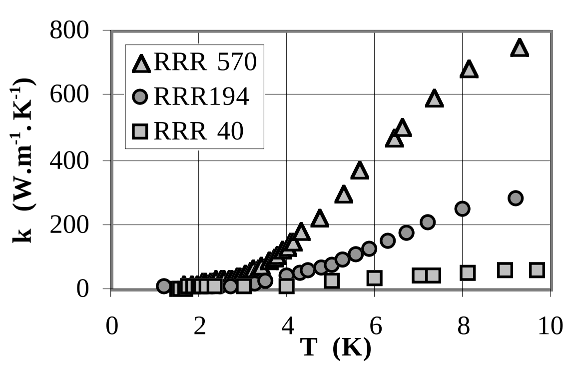

Figure 9: Thermal conductivity for numerical simulations.

The influence of various parameters on the normal zone expansion velocity is then studied [8]. Note first that V_{NC} does not depend on the defect size in the studied range 50µm - 1000µm. Then runs were performed with different thermal conductivities (Fig.9). As shown in figure 10, the higher the thermal conductivity, the faster is the normal zone growth rate. The transients are also strongly affected by the normal resistance of the niobium. On the contrary, an important variation of the residual surface resistance or the kapitza resistance does not affect the quench dynamics.

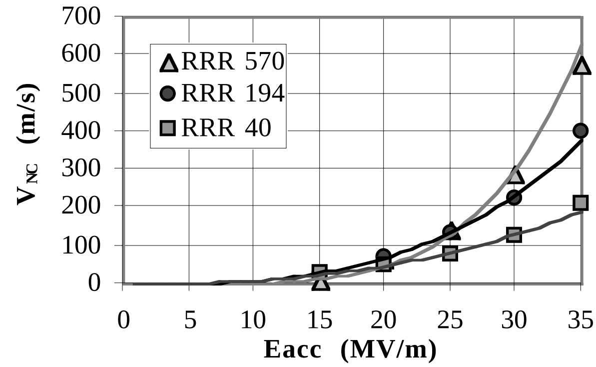

Figure 10: Calculated normal zone expansion velocity as a function of E_{acc} for different RRR (R_S^N = 2 mΩ).

4 CONCLUSION

Surface thermometry was used to prove that the Qo degradation at high fields was due to anomalous RF losses, which seem to be characterized by a linear dependency of the surface resistance with the dissipated power in the cavity. These RF losses are due to bad broad areas which could be originated by a damaged or a weak superconducting layer on the RF side of the cavity wall.

Two complementary methods have been developped (experimental and simulational), giving the tools to study and understand the mechanism of the quench propagation in SRF cavities.

The authors would like to thanks A.Caruette, B.Coadou, B.Daillant, N.Hammoudi, K.Wosinski and J.F.Yaniche for their technical assistance.

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