STUDY OF THERMAL EFFECTS IN SRF CAVITIES

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Abstract

Transient events occuring during the quench of superconducting RF cavities are analysed. An experiment was performed for the measurement of the time response of the commonly used surface thermometers to a heat pulse. The observed time response are much higher than the characteristic time of Qo decrease during cavity thermal breakdown. A method based on RF signal is proposed to evaluate the normal zone propagation velocity during a cavity quench. Numerical runs performed with a thermal code allow us to determine the normal propagation velocity as a function of the accelerating field. This result is used for numerical simulations of cavity behaviour during the quench for different quench fields.

Introduction

Thermal breakdown is still today one of the main limitation to reach high accelerating fields in SRF cavities. The understanding of the so-called quench phenomena improved with the development of surface thermometry which is very helpful to determine the location and nature of the defect responsible of the quench [1, 2]. Moreover, both analytical calculations and numerical simulations using thermal codes were used to study the influence of the most relevant parameters (thermal conductivity, defect size, kapitza resistance...) involved in the thermal behaviour of a cavity [3, 4].

At DESY, experiments performed with several cavities showed a systematic difference of the quench field between a cavity tested in the CW mode and the same cavity tested in the pulsed mode [5]. The increase of the quench field when the cavity is filled with a 1.3 ms pulsed RF power (TESLA specifications) as compared to the CW mode shows the importance of the transients: the time constants of thermal effects are of the same order of magnitude as the pulse duration. Such phenomenon should be investigated in order to reach cavities ultimate performances.

Experimental techniques available for studying the transients are surface thermometry and RF signals measurements. In the first section of this paper, the thermometer time response measurement is described and their ability to perform temperature measurements during fast transients are discussed. Then we propose a method based on RF signal analysis to measure the normal conducting surface expansion during a quench. Finally, we present the results of numerical calculations to simulate a cavity behaviour during a quench for different quench levels.

I. Determination of the thermometer time response

A quench occuring in an SRF cavity is a very fast phenomenon which typicaly lasts a few hundreds of microseconds. To study the transients during a quench with surface thermometry, we should previously determine whether or not the thermometers are fast enough to follow a sharp temperature increase. A simple experiment was performed to measure the thermometer time response.

The principle of the experiment is to press together two identical thermometers, using Apiezon N grease between their contact surfaces. Subjected to a pulsed power, the first thermometer plays the role of the heat source, and the temperature of the second one is measured as a function of time. Two different thermometer types were tested: the IPN design (Fig.1) and the Cornell design (Fig. 2), used at DESY.

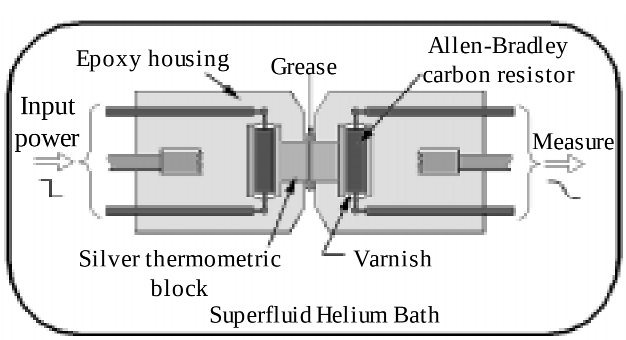

***Fig. 1**: Scheme of the experiment with the IPN thermometers.*

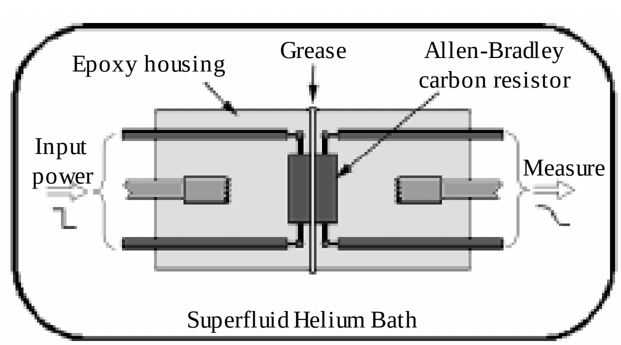

***Fig. 2**: Scheme of the experiment with the Cornell thermometers.*

Both thermometers are based on Allen-Bradley carbon resistor placed in an epoxy housing to insulate from the helium bath. In the IPN design, a silver block (high thermal conductivity) is added between the sensitive part of the thermometer and the cavity surface.

The thermometer time constant τ_{th} could be determined from experimental data. The fall time (10%-90%) of the second themometer gives the overall time constant τ_{total} of the system. Assuming two identical thermometers, with the same time constant τ_{th}, we have the relation:

$$2\,\tau_{th}^2 = \tau_{total}^2 \quad \Rightarrow \quad \tau_{th} = \frac{\tau_{total}}{\sqrt{2}}$$

For the IPN thermometer, the measured time constant is τ_{th} = 9.5 ms at T=1.8K (Fig. 3). For the Cornell thermometers, we have measured τ_{th} = 6.5 ms at the same bath temperature (Fig. 4). The difference between the two types is mainly due to the heat capacity of the silver block.

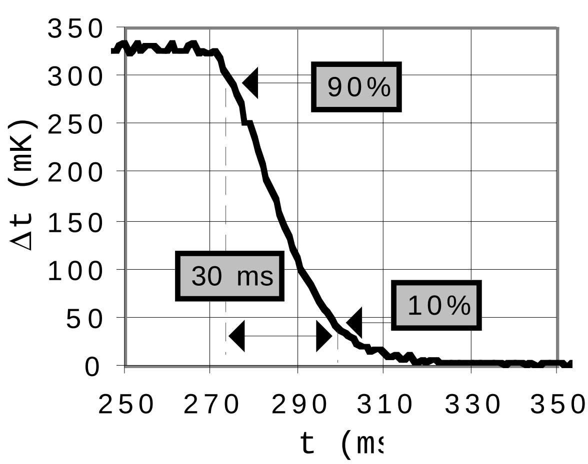

Fig. 3: *IPN thermometer response to a pulsed power at T=1.8 K.*

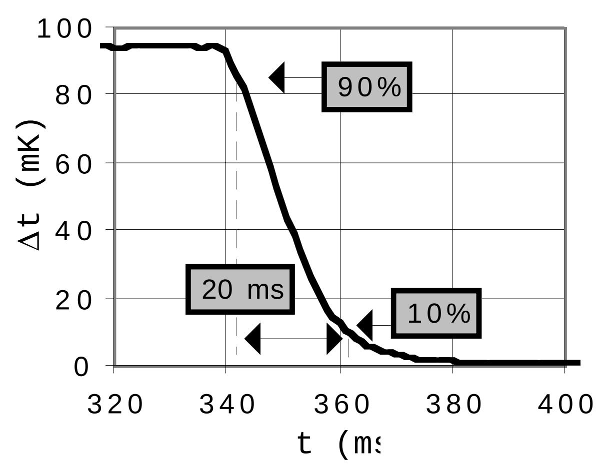

Fig.4: *Cornell thermometer response to a pulsed power at T=1.8 K*

One can find an equivalent electrical scheme (Fig. 5 - Fig. 6) to model this experiment, considering the heater as a current source and the different thermal resistances and heat capacities as electrical resistances and capacitors. Several parameters are involved in the determination of the time response: the thermal boundary resistance Rb, the silver thermal resistance

Rs, the contact resistance Rc, the silver heat capacity Cs and the carbon resistor heat capacity C.

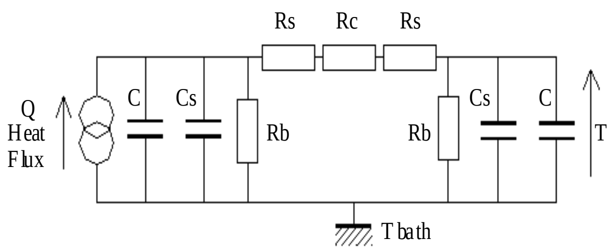

***Fig. 5**: Equivalent electrical scheme for the IPN thermometers.*

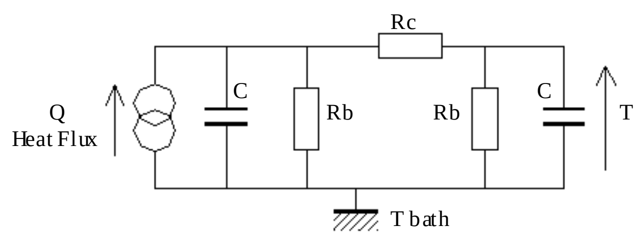

***Fig. 6**: Equivalent electrical scheme for the Cornell thermometers.*

According to the above model, the time constant could be estimated. The following values are used for the different parameters: grease thickness=0.5 mm, Rb=1000 K/W for IPN thermometer, Rb=1300 K/W for Cornell thermometer, $C_S \cong 6.9\ 10^{-6}$ J/K at T=2 K, $C \cong 7\ 10^{-6}$ J/K at T=1.8 K. Introducing these values in the model lead to time constants in good agreement with experimental data. Note that we observed a higher time constant at T=4.2 K, due to the strong temperature dependence of Rb, C, Cs.

On the Fig. 7 is plotted the Eacc vs time curve (deduced from a measurement of the transmited power) as a function of time during a quench (occuring at 14.5 MV/m) on a 3 Ghz Nb cavity.

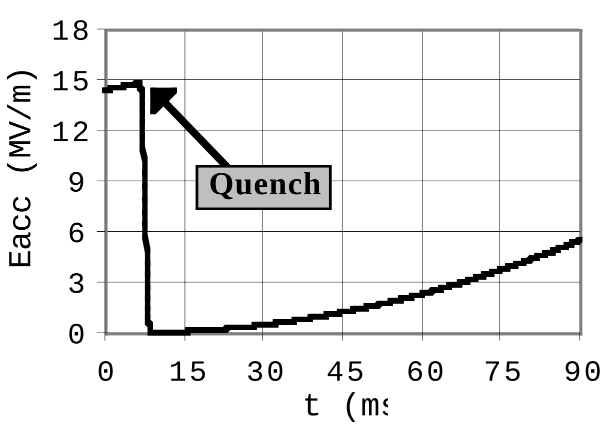

***Fig. 7**: Variation of Eacc during a quench in a 3 Ghz cavity.*

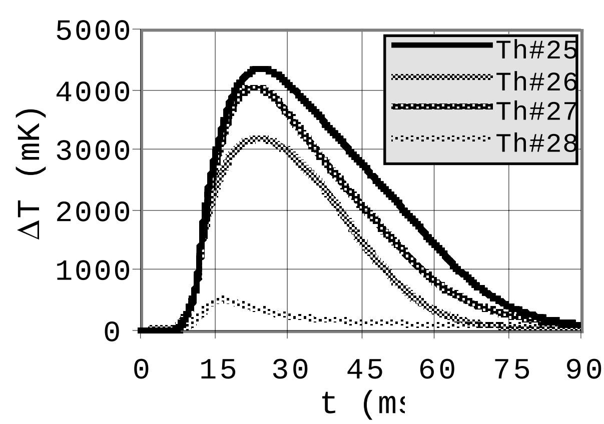

***Fig. 8**: Heatings measured on 4 thermometers during the quench.*

An array of 60 thermometers distributed all around the cavity near the equator region allowed us to measure heatings during the quench [6]. Eacc decreases in less than 1 ms but the corresponding heatings measured by the thermometers in the vicinity of the quench location seem to last much longer (Fig. 8): the measure is distorted by the thermometer time response.

The response time of both thermometer types are much longer than the time needed for the cavity temperature rise (Q_0 drop) during a quench so they are not suited for a reliable study of such transients.

II. The normal conducting surface growth

As the used thermometers are not fast enough to follow the sharp temperature increase during a quench, a method based on RF signal analysis is proposed to study the transients during a quench. The basics of the method is to determine the increase of the power dissipated in the cavity during a quench from the transmitted power signal measurement and to attribute it to a growth of a normal conducting region.

Without FE, the dissipated power P_{diss} is related to the magnetic field H, the cavity surface S_{cav} and the surface resistance R_s by the relation:

$$P_{diss}(t) = \frac{1}{2} \cdot \iint_{S_{cav}} H^2(t) \cdot R_S \cdot dS$$

During a quench, a normal resistive surface S_N (having a normal surface resistance R_S^N) grows. Then P_{diss} has two contributions: power dissipation in the superconducting area (= S_{cav} - S_N) and in the normal conducting region S_N.

$$P_{diss}(t) = \frac{1}{2} \cdot \iint_{S_{cav}-S_N} H^2(t) \cdot R_S \cdot dS + \frac{1}{2} \cdot \iint_{S_N} H^2(t) \cdot R_S^N \cdot dS \qquad \textbf{(1)}$$

In order to simplify the calculations, one can find an equivalent magnetic field distribution (constant $H=H_{pk}$ over a surface S) corresponding to the real field distribution H(s) for a surface S_{cav}. Then, assuming that the quench location is near the equator where $H = H_{pk}$ and with the assumption that R_S^N is constant, the equation **(1)** becomes:

$$P_{diss}(t) = \frac{1}{2} \cdot H_{pk}{}^2(t) \cdot \left[R_S \cdot S + (R_S^N - R_S) \cdot S_N(t) \right]$$

As $R_S^N >> R_S$, one gets: $P_{diss}(t) = \frac{1}{2} \cdot H_{pk}^{2}(t) \cdot \left[R_s \cdot S + R_S^N \cdot S_N(t) \right]$ **(2)**

Another assumption is to consider that the increase of the BCS dissipation due to the cavity heating near the quench location is small as compared to the dissipated power in the normal conducting area (namely, R_S is constant in the major part of the cavity). The relationship between P_{diss} and the unloaded quality factor Q_0 is (l is the accelerating lenght):

$$E_{acc}(t) = \frac{1}{l} \cdot \sqrt{\frac{r}{Q}} \cdot \sqrt{Q_0(t) \cdot P_{diss}(t)} \qquad \textbf{(3)}$$

Combining **(2)** and **(3)**, and using the relation that $E_{acc}(t) = \alpha \cdot H_{pk}(t)$ we obtain the following equation:

$$\frac{1}{Q_0(t)} = \frac{1}{2} \cdot \alpha^2 \cdot \frac{1}{l^2} \cdot \frac{r}{Q} \cdot \left[R_s \cdot S + R_S^N \cdot S_N(t) \right] \qquad \textbf{(4)}$$

Equation **(4)** shows that $S_N(t)$ could be deduced from an experimental measurement of $Q_O(t)$ during the quench. The equivalent surface S could be calculated with **(4)**, assuming S_N=0 and Q_0=G/R_s (G is the geometrical factor). From the transmitted power signal $P_t(t)$ (Fig. 9), the pulsation ω and the "external" Q_{ext}^t of the coupler, the stored energy U(t) is calculated (Fig. 10) using :

$$U(t) = \frac{Q_{ext}^t \cdot P_t(t)}{\omega}$$

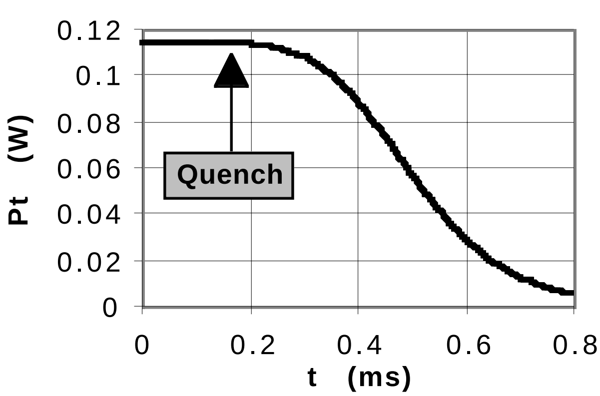

Fig. 9: *Typical transmitted power recorded during a 3 Ghz cavity quench.*

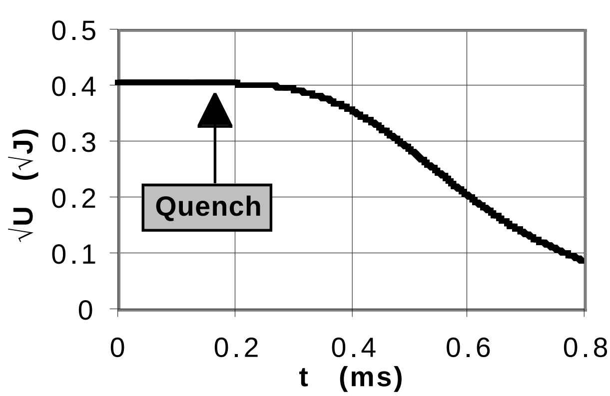

Fig. 10: *Square root of the stored energy during the quench.*

The next step is to use the technique of the Cornell group [7] to find the instantaneous $Q_0(t)$ (Fig. 11):

$$\frac{1}{Q_0(t)} = \frac{2\cdot\left(\sqrt{\frac{P_i(t)\cdot\omega}{Q_{ext}}} - \frac{d\sqrt{U(t)}}{dt}\right)}{\omega\cdot\sqrt{U(t)}} - \frac{1}{Q_{ext}} \qquad (5) \qquad \text{with } \frac{1}{Q_{ext}} = \frac{1}{Q_{ext}^{i}} + \frac{1}{Q_{ext}^{t}}$$

where P_i is the incident power (constant during the quench in our experiments) and Q_{ext}^{i} the incident external quality factor.

Finally, by combinig the equations **(4)** and **(5)**, the normal conducting surface is deduced:

$$S_N(t) = \frac{\frac{2\cdot\left(\sqrt{\frac{P_i\cdot\omega}{Q_{ext}}} - \frac{d\sqrt{U(t)}}{dt}\right)}{\omega\cdot\sqrt{U(t)}} - \frac{1}{Q_{ext}}}{\frac{1}{2}\cdot\alpha^2\cdot\left(\frac{1}{l}\sqrt{\frac{r}{Q}}\right)^2\cdot R_S^N} - \frac{R_S\cdot S}{R_S^N} \qquad \mathbf{(6)}$$

Assuming a circular shape for the expanding normal region $S_N = \pi . R_{NC}^2$, we have an immediatly measurement of the normal conducting surface radius $R_{NC}(t)$ (Fig. 12).

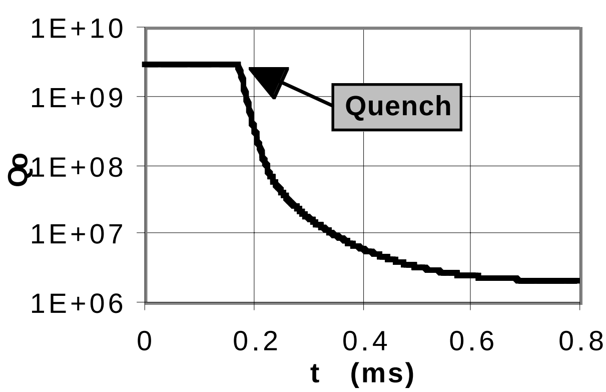

***Fig. 11**: Unloaded quality factor during the cavity quench.*

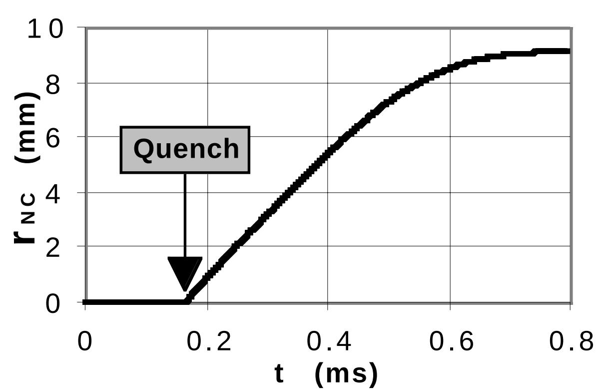

***Fig. 12**: Increase of the radius of the normal conducting area.*

From r_{NC} (t), we calculate easily the expansion velocity $V_{NC}(t)$ (Fig. 13). From E_{acc} (t) and V_{NC} (t) curves we can deduce the $V_{NC} = f\ (E_{acc})$ curve (Fig. 14).

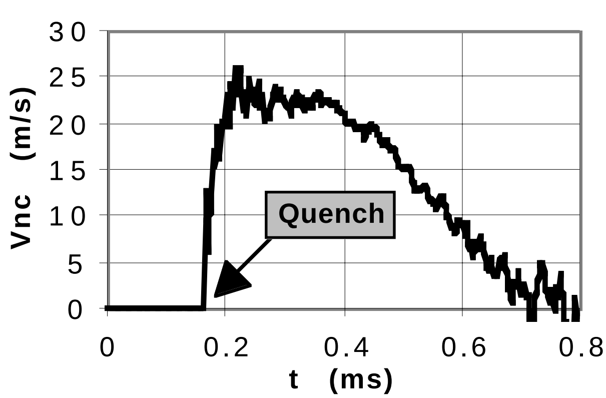

Fig. 13*: Expansion velocity of the normal conducting area.*

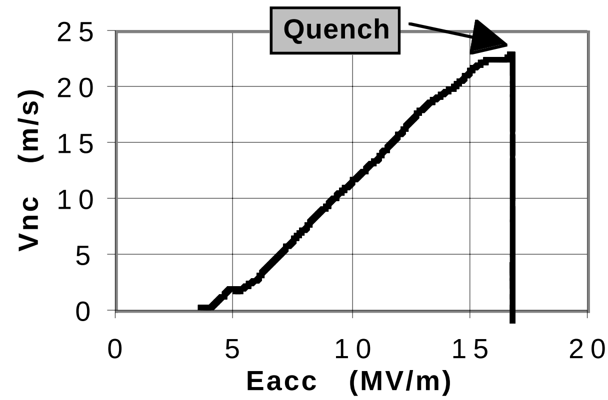

Fig. 14*: Expansion velocity as a function of the accelerating field.*

All the curves presented above are calculated from the transmitted power recorded during a 3 Ghz cavity quench (initial RRR=40, heat-treated at 1200°C, quench at 16.5 MV/m at T=1.8 K). Note that as S_N is proportionnal to $1/R_S^N$, the normal surface resistance R_S^N is an important parameter of the model (we used R_S^N=3 mΩ at 3 GHz).

The single measurement of the transmitted and incident power is sufficient to determine the normal conducting region growth, providing that the Q_0 value before the quench is known.

III. Numerical simulations

In order to determine the cavity behaviour during a quench, we have performed numerical simulations to calculate the expending velocity as a function of the accelerating field. For this purpose, we have used a transient thermal code (Fondue) [8] which simulate the heating of a Niobium plate submitted to a heat flux (proportional to Eacc) on one side and cooled by He II (kapitza resistance) on the other side. The following input parameters were used: 2mm thick Nb plate, f= 3 Ghz, RRR=40 (giving the Niobium thermal conductivity), a surface resistance of 100 nΩ and a normal surface resistance R_S^N of 3 mΩ. For Eacc > Equench , 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 Tc. The calculated V_{NC} =f(Eacc) curve is plotted on Fig. 15.

One important result is that V_{NC} does not depend on the defect radius R_d (or very slighty) in the studied range 50 μm-1000 μm.

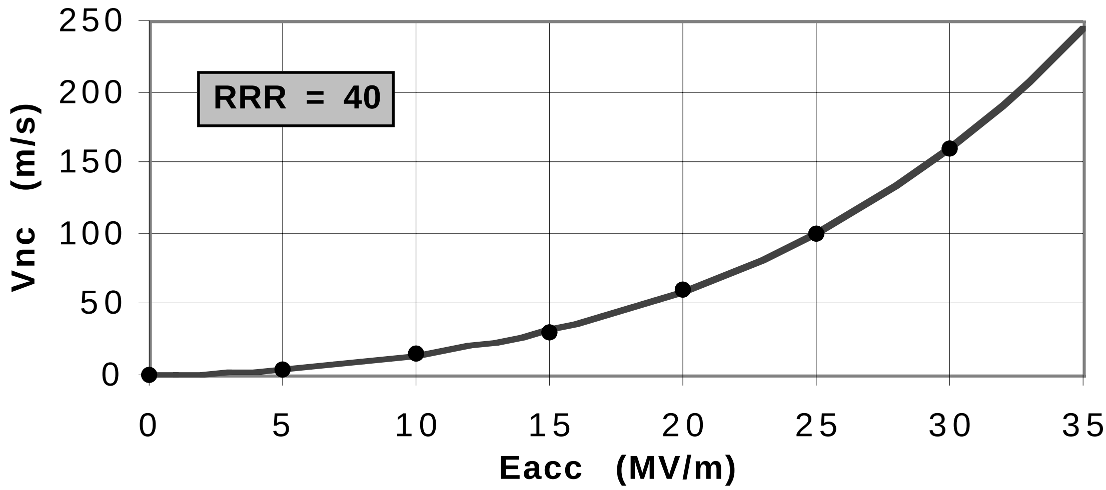

Fig. 15: *Calculated expansion velocity as a function of Eacc.*

The main conclusion is that for a given cavity, i.e. for given thermal properties, V_{NC} depends only on Eacc. This result could be used to simulate the cavity behaviour during a quench, for different quench fields. We only need to know the Qo at low field, the external coupling, the normal resistance of the Niobium and the calculated V_{NC} =f(Eacc) curve. However, the calculation requires a mathematical program, for resolving the second order differential equations involved. Results on the simulated normal surface radius is plotted in the figure 16.

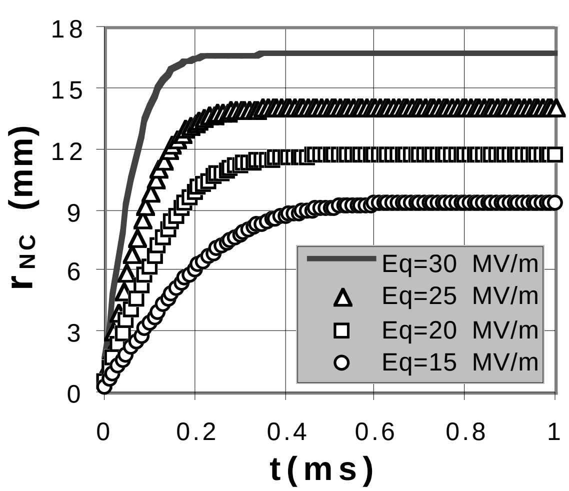

Fig. 16: *Calculated normal region radius for several quench fields.*

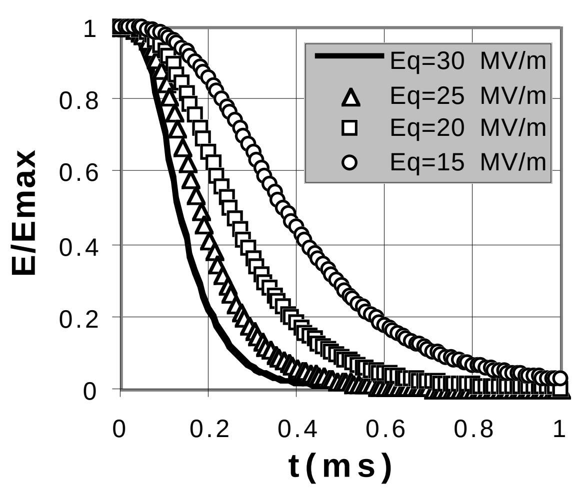

Fig. 17: *Eacc decrease during a quench for different quench fields.*

The higher the quench field is, the bigger is the normal conducting region radius. We see also on both Fig. 16 and 17 that a higher quench field induces a faster growing rate of the non superconducting area.

We have plotted on the Fig. 18 the time constant τ_q (defined as the time needed for the accelerating field to decay to the half of its value xhen a quench occurs) versus the quench field.

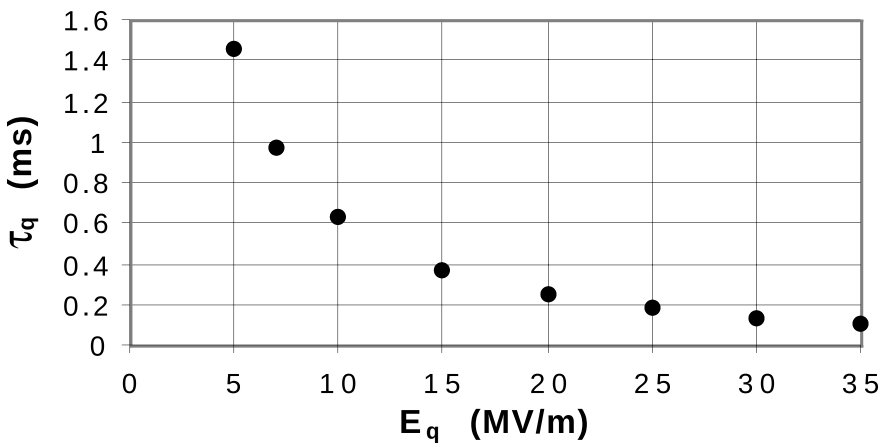

Fig. 18: *Time constant τ_q as a function of the quench field.*

The shape of the simulated curve is in good agreement with experimental results at K.E.K. [9] (only the shape could be compared because the conditions of the simulation are not the same as the experimental conditions).

Conclusion

From measurements of the thermometer time response and comparisons with RF signals, we showed that actual commonly surface thermometers are not suited for transient temperature measurements during thermal breakdown. But informations on the quench dynamic could be drawn from analysis of RF signals during a quench: the dynamic of the normal zone propagation could be determined from the transmitted power signal. The difficulty lies in the data acquisition: a fast oscilloscope is needed in order to have enough data points during the quench to insure an accurate analysis. On the other hand, simulations were performed to find the dependence of the normal conducting region growth rate on the quench field. The result was used to simulate the cavity behaviour during a quench, for different quench fields. This analysis method will be used in the near future to study the influence of the material thermal properties on the quench dynamic.

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