ANALYSIS OF THE LOSSES OF SUPERCONDUCTING CAVITIES AS A FUNCTION OF FIELD AND TEMPERATURE

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Abstract

The ultimate achievable field in sputtered RF superconducting cavities (operated at 4.5 Kelvin) is limited both by the electron loading due to the non resonant field emission and by the Qo vs. E slope produced by a smooth increase of the RF surface resistance rising with the applied surface field.
The test of the 352 MHz cavities (developed for INFN at CERN) gave us the possibility of measuring the surface resistance of the superconductor in the whole range 1.8-4.5 Kelvin. The analysis of the Experimental results (below the onset of the electron loading) showed a variation of the Q (E) function with the temperature. The behaviour of the quality factor around 4.5 K is quadratic and smoothly changes to linear decreasing the operating temperature below the lambda point.
This effect suggests us that a crucial role is played by the Thermal properties of the Metal-Helium interface.
A Numerical method including this effect was developed and used to simulate the behaviour of the cavities on the full temperature range. A comparison between the Experimental and numerical data will be shown.

1 INTRODUCTION

One of the still open problems in the field of the RF superconductivity is the increase of the RF losses with the increase of the stored energy in the cavities.
This increase is quite smooth, and is more pronounced in S/C cavities operated in Boiling Helium I.
A typical example is the Qo versus field slope in the low frequency cavities used in the Storage Rings.
The phenomenon was first clearly seen in the LEP sputtered Niobium on Copper cavities [1], but it is also encountered in the Superconducting cavities (built using Bulk Niobium) of TRISTAN and BELLE at KEK. [2]
The same effect is observed in a minor extent in the cavities operating at frequency higher than one Gigahertz as the prototype Bulk Niobium TESLA Cavities. [3]
Recent development at the CEA-DAPNIA lab in Saclay [4] and at CERN [5] have shown that also good quality Niobium copper sputtered cavities exhibit a very low increase of the surface resistance with the field.
The still open question is if the field slope is something related to the material used to build the cavities, to the different surface treatments or is behaviour stated by some physical law.
We show in our work a possible explanation starting from some fine measurements taken at CERN on a prototype cavity built in a collaborative effort with INFN.
The aim was to build a reduced beta cavity for the a High Intensity proton linac (TRASCO project)
To have a better diagnostic of the cavity behaviour, we measured the Qo of the cavity on a wide range of temperature from 4.5 K down to 1.8 Kelvin, gathering a full set of coherent data as a function of temperature and surface fields.
The analysis of the experimental data suggested us a possible explanation for the "Qo slope" mechanism.

2 EXPERIMENTAL

2.1 RF measurements results

The Trasco cavities were built By the CERN SL/CT group following the standard procedure developed for the LEP S/C-cavities.
OFHC copper sheets were formed in half cups by Spinning, electro-polished 200 μm, to remove the strained copper, and assembled by EBW.

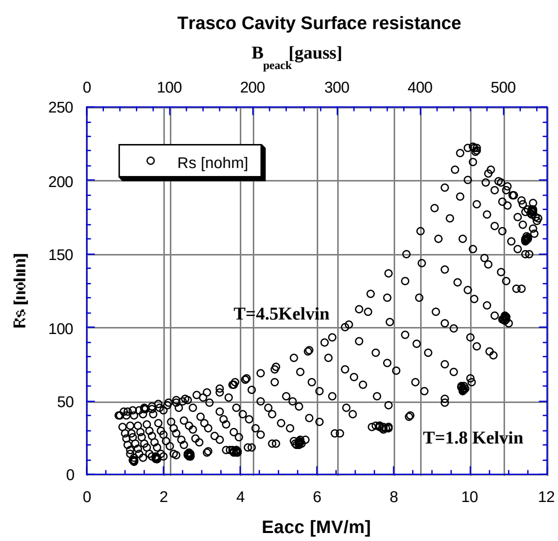

Figure 1; surface resistance versus fields as a function of the bath Temperature

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After the assembling the cavity was chemically polished (20 µm) and sputter coated with Niobium film 1.5 µm thick.

The full detail on the cavity construction is given in the companion paper WEP034, this conference. [6]

The Typical results of the RF measurements giving the Surface resistance of the superconductor as a function of the RF Fields and the temperature the are shown on figure.

The quality of the film was perfectly the same in al the cavities (either single or multicell). For this reason we can assume that the measured Surface resistance values are representatives for the surface resistance of the sputtered niobium.

2.2 Data Analysis

The analysis of the data showed, as usual for low frequency cavities, a very strong contribution from the Field emitted electrons accelerated by the fields of the cavity.

This contribution start to be dominant for accelerating fields higher than 4MV/m.; the losses follow the Fowler-Nordheim law [7] growing exponentially with a field enhancement factor β=100.

The low field (below 4 MV/m) losses are temperature sensitive.

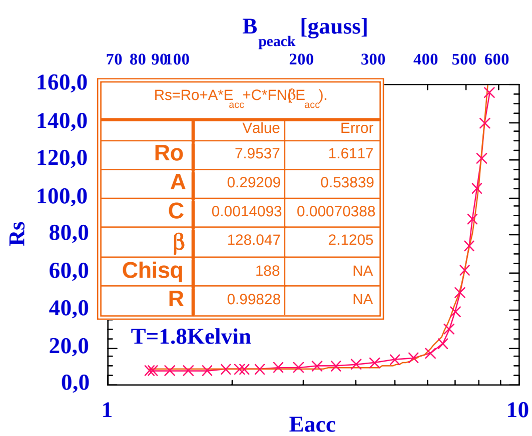

Figure 2, best fit of the losses of the cavity at 1.8K, at Low field Q(E)~Ro+A*Eacc

Trying to fit with the surface resistance in that range with a simple polynomial function of the accelerating field we obtain a linear fit for the data taken at 1.8 Kelvin (figure 2) and a parabolic fit for the 4.5K data. (Figure 3)

These first results suggested us that the temperature plays a quite important role on the "Q versus field Slope"

Numerical Simulation

To check the correctness of our feeling we extensively used an In House developed computer code used for the prediction of the maximum achievable fields in superconducting cavities [8]

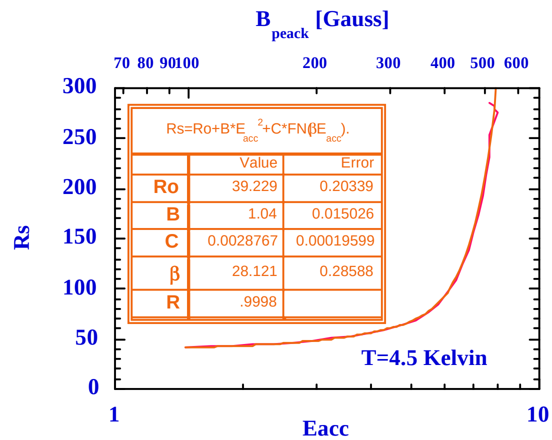

Figure 3, best fit of the losses of the cavity at 4.5K, at Low field Q(E)~Ro+B*E_{acc}^{2}

2.3 The Numerical Model

The Computer codes solves the Thermal Problem of the heat transport from the inner surface of a Superconducting Cavity Taking into account:

1. The RF Surface resistance of the superconductor using an approximation coming from the Perry Wilson's Formula. [9] plus a Constant Residual Surface resistance set to 10 nanohoms
2. The thermal Conductivity of the cavity wall using a database of data coming from the former NBS [10] and from the available Low temperature data for Niobium and Copper.
3. The thermal resistance at the cavity_wall-helium interface. We use the Kapitza resistance Formula [11] measured in the early seventies by Mittag at Karlsruhe, for boiling Helium II below 2.17 Kelvin and the Johannes [12] experimental curve for the nucleate bouiling Helium I over the λ–point temperature.
4. The critical heat Flow for the Onset of the film boiling in Helium. (About 1Watt/cm^2).
5. The heat at the cavity surface is generated as the sum of the RF Losses plus the heat generated by the Fowler-Nordheim Electrons at the impact with the cavity wall.

The Typical output plot of the code is shown on figure 4

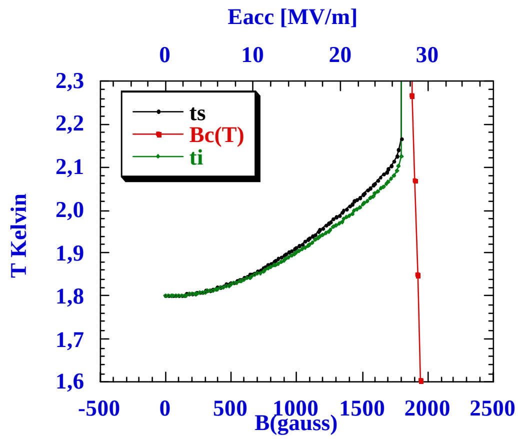

Figure 4, Surface Ts and Interface Ti temperatures for a Trasco cavity at 1.8K (no electron loading).

The code compute recursively the temperature of the cavity surface, exposed to fixed value the RF Field, till a stable solution (if any) for the heat transport to the helium bath is found.

The RF field is then increased by a prefixed amount and a stable thermal solution for the new field is found.

The computation is continued till either the surface temperature exceeds the critical temperature at the given mag-field or the heat flow exceeds the film boiling critical heat flux.

The plot for the Trasco cavity (without electron loading) operating at 4.5 Kelvin is shown on figure 5

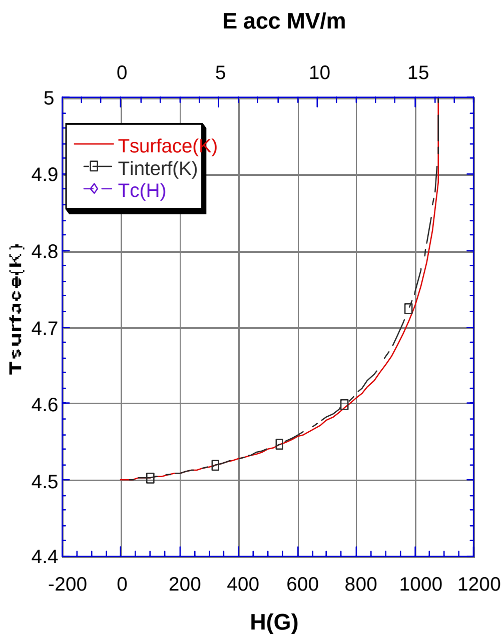

Figure 5, Surface Ts and Interface Ti temperatures for a Trasco cavity at 4.5K. (No electron loading)

From the comparison of the two plots it appears that at the two temperatures the thermal limitations are quite different.

The only common feature is that in both cases at the given heat Flux the temperature drop across the cavity wall (difference between T surface and T interface in the figure) is negligible compared to the temperature drop on the wall-bath interface.

This temperature drop is higher in LHeI than in LHeII, and produces an early breakdown for LHeI refrigerated cavities.

Typical temperature Drops on the interface are ~ 0.2K for HeII and 0.5 K for HeI

This temperature variation does not seem so big to produce large effects.

2.4 Simulations results

Let now look at the Q_0 versus bag field plot computed using the Surface resistance values computed by our Code. The two situations are reported in figures 6 and 7.

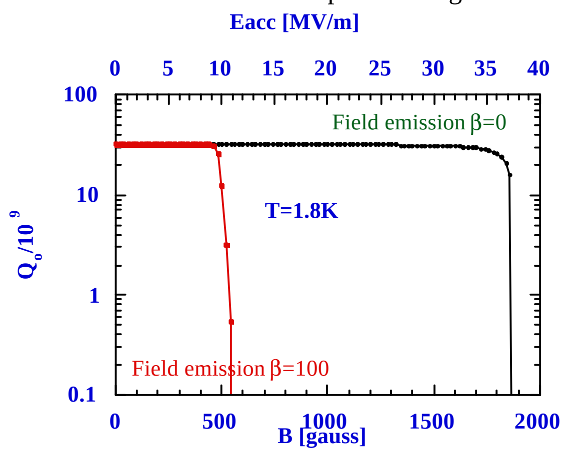

Figure 6 Qo versus Field plots for the Trasco cavity at 1.8 K, two different Heat generation scenarios; β=100 Field emitted electrons heating; β=0 no lectrons.

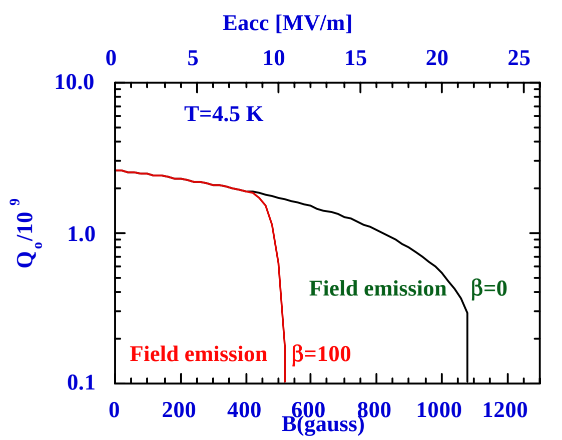

Figure 7, Qo versus Field plots for the Trasco cavity at 4.5 K, two different Heat generation scenarios; β=100 Field emitted electrons heating; β=0 no electrons.

It is apparent at the glance that the behaviour of the cavity at the two different temperatures is quite different in the case of no electron loading.
In LHeII the Qo is fairly constant over the whole range of mag-field. The quench happens close to the Critical Field of the niobium; The surface resistance just before the quench Is decreased by a factor two.
In LHeII at 4.5K the surface resistance smoothly decreases by a factor roughly ten from low field value to value at the quench field.
If the case of electron loading the exponentially growing FN characteristic of the emitted current dominate the Qo drop at High field, limiting the cavity at roughly the same value of accelerating field (10 MV/m or 500Gauss in the given case.)

2.5 Comparison with the Experimental results

The result of our simulations (figure 8) are in good agreement with the measurement taken the Trasco Cavities (both single-cell or multicell) shown in figure 9

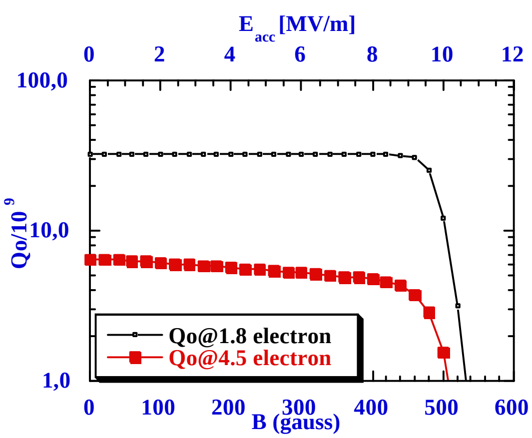

Figure 8, Qo Versus field for the Trasco cavity at1.8K and 4.5K (computed)

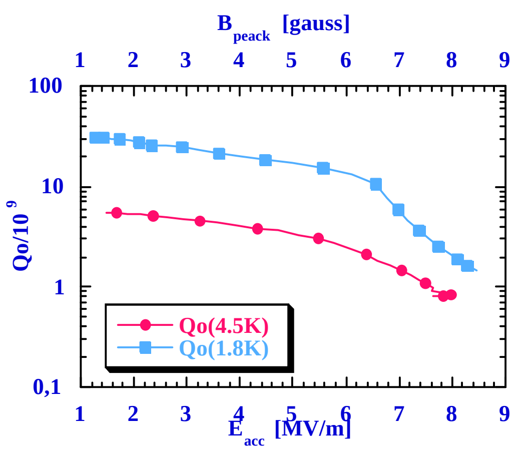

Figure 9, Qo versus field For the Trasco cavity at 1.8K and 4.5K (experimental data)

In both cases the non-resonant electron loading gives the Ultimate limitation on the field; the computed value agree with the measured one.
The Qo versus field slope is steeper at 4.5 K and reproduces the slope measured on the cavities.
Our simulations does not account for the evident slope on the 1.8 K measurement, but in our assumption the value of residual surface resistance is a constant not depending upon the field nor the temperature.

3 CONCLUSIONS

The simulation of the thermal behaviour of a 352 MHz Niobium on copper cavity gives us some Hints about one (at least) of the mechanisms producing the reduction of the Qo with the increasing field experienced in The LEP cavities.
Part of this effect is produced by the effect of the temperature step at the LHe bath–cavity wall Interface.
This temperature step increases at high Field the operating temperature of the cavity surface producing an increase of the BCS surface resistance.
This effect is lower at operating temperatures in LHeII at least due to the following reasons:

1. Below the helium λ point In superfluid the Kapitza conductance is Quite lower than the Interface thermal resistance in nucleate boiling helium
2. Below 2 K the RF surface resistance at this frequency is dominated by the residual resistance (in not depending (the present Knowledge) from the temperature and having a small (if not negligible)) dependence from the surface field. for good quality films

4 REFERENCES

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