Superconducting, hydroformed, niobium sputter coated copper cavities at 1.5 GHz

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Abstract

Results from RF tests of five-cell niobium sputter coated cavities are presented. Accelerating gradients of 13 MV/m at low field Q-values of 10^{10} have been obtained. Experimental data on the decrease of the Q-value with accelerating gradient are explained in a model, in which weak superconducting spots are driven normal by the RF field.

1. INTRODUCTION

Superconducting (sc) technology in the 1.3 to 1.5 GHz range may be attractive for future linear colliders in the TeV energy range (TESLA), provided larger accelerating gradients (about 25 MV/m) at high Q-values ($5 \cdot 10^9$) can be obtained at moderate costs. Copper cavities with a thin sc coating of sputtered niobium (NbCu cavities) may offer an alternative to niobium cavities made from sheet, both with respect to costs and to performance. They can be formed in a monolithic piece from a single tube by hydroforming (with intermediate annealing steps), they do not exhibit "quenching" thanks to the high thermal conductivity of copper at low temperature, and the material costs of copper are substantially lower than those of niobium.

However, the RF loss increases more than quadratically with the accelerating gradient (non quadratic loss, NQL), and the copper niobium interface has to be extremely clean to guarantee good adhesion and sufficient cooling of the sputtered film. If not so, minute (ø ≤ 1 mm) spots of niobium loosely connected to the copper can switch to the normal conducting (nc) state (Q-switch) and even heat up sufficiently that electrons are emitted. This kind of "electron loading" cannot be reduced by "processing".

In what follows we will report on a common effort of CERN and C.E./Saclay to develop 1.5 GHz sc NbCu cavities for large gradients and low RF losses. Previous results have been presented elsewhere [1 - 3].

In particular, two lines of research and development work will be described. Firstly, we will report on results on the feasibility of multi-cell cavities, and secondly on the physics of sputtered layers with the ultimate goal to understand and eliminate NQL.

2. EXPERIMENTAL RESULTS

2.1 Sputtering parameters and reproducibility of results

The sequence of production of the cavity proper, the chemical cleaning and the coating set-up are described elsewhere [3]. Here we will only give information on the sputtering parameters which determine the coating process: anode voltage V, discharge current I, argon gas pressure p, and temperature of the substrate T. All these parameters are intimately connected. Generally speaking, one reduces V to avoid neutral gas resputtering of the film from recoil neutral atoms bouncing off the cathode, which are known to induce constraints in the film. One reduces p to create a dense, non-columnar film. Increasing the power P = IV of the plasma discharge reduces the probability of contamination of the film by gas impurities. It is difficult to take account of all these constraints simultaneously.

Since the new sputtering set-up is available [3], five one-cell cavities and three five-cell cavities have been coated and tested. The coating parameters were not varied significantly, because the reproducibility of the result was to be checked. Prior to coating, the cavities were baked between 100°C and 170°C for 30 minutes. The current I was controlled to about 1.5 A and p between 6 and $7 \cdot 10^{-3}$ mbar. V stabilised around 380 to 410 V and T between 135 and 153°C. Thirty minutes of plasma discharge were needed per cell to produce a layer thickness of 1.6 to 1.8 μm (near the equator and iris of the cavity, respectively), or one hour for twice the thickness.

Four of the one-cell cavities had low field Q-values (at 1.8 K) of $(1.0 \pm 0.2) \cdot 10^{10}$; in three of them the maximum gradient at Q = $1 \cdot 10^9$ exceeded 10 MV/m.

When applying rinsing with ultra pure water at high pressure (high pressure water rinsing HPWR at 90 bar, 12 l/ min mass flow for 75 minutes), some parts of the coating washed off, indicating poor adhesion.

2.2 Feasibility of five-cell NbCu cavities

After hydroforming, the dispersion of the mechanical dimensions was ±0.4‰, and that of the π mode frequencies was ±0.3‰ [3]. The field flatness (defined as the ratio of maximum to minimum field amplitude) was 1.25. After five iterations of inelastic deformations a field flatness of 1.08 could be obtained. Plastic deformation of the cavity was achieved for a longitudinal deformation of individual cells (with the force applied to the irises) corresponding to a change of 500 kHz for the π mode frequency. The measured sensitivity to the helium bath pressure was -40 Hz/mbar.

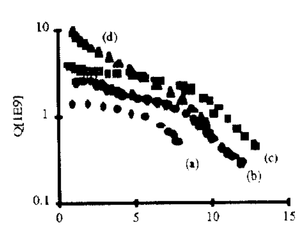

Fig. 1: Q-value vs. accelerating gradient in a five-cell cavity after various treatments: as received after coating (a), after rinsing with ultra pure water at low pressure (b) and high pressure (c, d).

Among the three five-cell cavities, two had poor results: the Q-value decreased steeply with accelerating gradient (due to Q-switches). The thickness of coating was 3.2 to 3.8 µm at the equator and the iris, respectively. The third cavity (thickness 1.6 to 1.8 µm at similar positions) had a Q-value at low field of $4 \cdot 10^9$ and a maximum accelerating gradient of 11 MV/m at $Q = 1 \cdot 10^9$ (Fig. 1), the field limitation being electron loading. No attempts have been made so far to decrease the electron activity, no thermal quench was observed. After a second HPWR the low field Q-value increased to more than 10^{10}, but the slope of the Q vs. E_a curve became somewhat steeper. A change of this slope after HPWR has already been observed before [1].

In conclusion, best RF results were similar to those of one-cell cavities, but the success rate (of producing a cavity without major surface flaw as for example a "Q-switch") was 33 %, compared 60 % for one-cell cavities.

2.3 Sample measurements

(a) Critical field B_{c2} and critical temperature T_c:

B_{c2} and T_c are measured inductively with a transformer consisting of two coplanar coils and the sample sheet in between [4]. A DC magnetic field (<3.5 T) parallel to the sample surface is superimposed. When the primary coil is driven AC in the kHz range, a significant voltage is induced in the secondary coil, when the sample is nc. This decreases substantially due to shielding when the sample becomes sc. The secondary voltage is measured vs. the temperature of the sample and vs. the DC magnetic field. A typical result (Fig. 2) shows smeared transitions, both in T_c and in B_{c2}, different from what was observed in bulk niobium. In addition, B_{c2} was significantly larger (3 T) than for bulk niobium (0.3 T). The RRR of the samples were between 10 to 20.

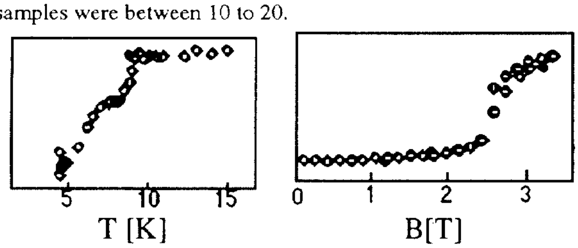

Fig. 2: Secondary coil voltage (arb. units) for measuring the critical temperature T_c (left) and the upper critical field B_{c2} (right) on a niobium layer sputter coated on a copper substrate. The RRR was 12 for this particular sample, and the temperature during coating was not controlled.

(b) Transmission electron microscope (TEM) analysis:

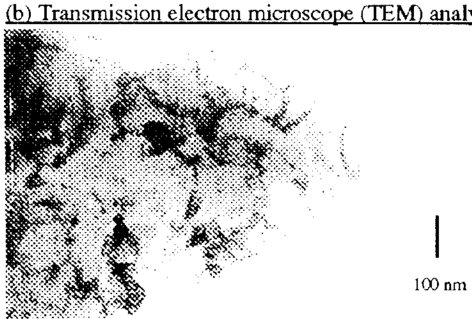

Fig. 3: Bright field TEM image of an ion beam thinned niobium sample, which was removed by high pressure water from a sputter coated one-cell cavity.

A sample which was removed from the cavity surface by a blast of HPWR was analysed in a TEM (Fig. 3).

Preliminary results are the following. A large number of grains per unit area are detected, of different size (5 to 200 nm). Within the grains, there are stacking faults and dislocations visible. In an analysis of elemental distribution neither oxygen nor sulphur contamination have been found. If the oxygen had been concentrated near the grain boundaries with a thickness of more than three monolayers, it would have been detected.

2.4 Measurements in conjunction with NQL:

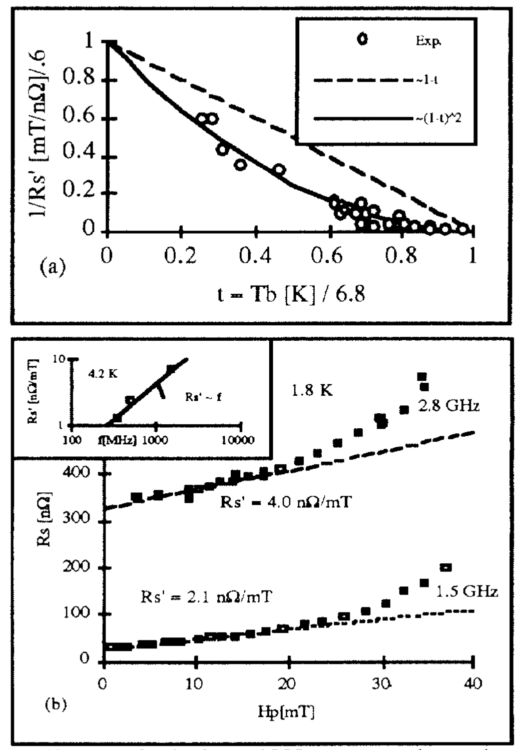

Fig. 4: Non quadratic loss (NQL) measured vs. the bath temperature T_b (a) and vs. the RF magnetic peak field amplitude H_p at 1.5 GHz and 2.8 GHz in the same cavity (b). The inset is explained in the text.

The losses P generated per m^2 by a RF magnetic field of amplitude H can be split into magnetic and non-magnetic losses:

$$P = R_s H^2 / 2 + \text{others}, \qquad (1)$$

where R_s is the surface resistance and "others" comprise dielectric loss, electron impact, nc spots, etc.. R_s can be separated into several terms, the BCS and the residual one, which are more or less well known, and another one, named R_s', which takes into account NQL:

$$R_s = R_{BCS} + R_{res} + R_s' \cdot H + \ldots \qquad (2)$$

R_s' describes the physical mechanism which create the slope of the Q vs. E_a curve. In order to get more insight into the physics underneath, we have measured the temperature and frequency dependence of R_s' (Fig. 4).

The temperature of the cavity was determined by a calibrated germanium resistor (estimated precision < 0.1 K). The frequency dependence of NQL was measured by exciting not only the fundamental mode at 1.5 GHz, but also a higher (quadrupole) mode at 2.8 GHz.

The temperature dependence of NQL can be represented by

$$R_s' \propto 1 \Big/ \left(1 - T/T^*\right)^2, \qquad (3)$$

with T* = 6.8 K.

The frequency dependence was linear, contrary to what was indicated in a previous paper [3]. However, evidence now is confirmed by data from NbCu cavities at 4.2 K and 352, 500 and 1500 MHz (inset Fig. 4, b).

3. DISCUSSION

As we have already proposed in a previous papers [5], NQL may be explained by weak sc spots. At that time, we hypothesised oxygen as contaminant, in the form of spots of weak sc phases with depressed T_c. In the TEM analysis we did not find up till now any confirmation for this hypothesis. So we conclude that these weak spots must have a different origin: What we found was a large density of metallurgical defects within grains and a large scatter in grain size. These features are characteristic of granular superconductors, which are composed of (nearly perfect) grains and weak links in between [6].

For those granular superconductors, when lowering the temperature, the grains become sc at the transition temperature of the bulk material. The sample nevertheless is not yet in a phase coherent sc state. This will only happen when the temperature is still lowered and the Josephson "phase locking" temperature T_{cJ} is passed. Then the coupling energy between the grains becomes of the order of the thermal energy kT, such that energy fluctuations can no longer destroy the phase coherence over the whole sample. T_{cJ} can be substantially lower than T_c. It is also known, that the critical field B_{c2} increases with decreasing grain size [7]. These ideas would naturally explain the B_{c2} and T_c measurements on samples at DC.

As to the RF measurements, we define f as that fraction of the surface which the RF magnetic field H has driven nc. We define f_0 that fraction of the surface composed of weak links if H = 0. We assume the weak links when being nc contribute to the RF loss, and when being sc do not contribute at all. By increasing H by a differential amount dH, f will increase by a differential amount df, which in first approximation for small H is proportional to f_0. Hence the relation:

$$df/f_0 = dH/H_c(T), \qquad (4)$$

where the critical magnetic field H_c (T) was introduced for normalisation reasons ($f(H_c) = f_0$). The surface resistance being proportional to the nc fraction f of weak links, $\alpha \cdot f$ (proportionality factor α), we obtain

$$dR_s/dH = R_s' = \alpha f_0 / H_c(T). \qquad (5)$$

H_c (T) corresponds to the critical current j_c (T), by which the weak links are driven nc. Depending on their nature, $j_c(T) \sim T-T_c$ for weak links coupled by an insulator and $j_c(T) \sim (T-T_c)^2$ for weak links coupled by a metal [8]. The former temperature dependence has been published elsewhere [3], the latter has been found now (eq. 3). Hence we conclude,

$$R_s' = \alpha f_0 \Big/ \left[H_{c0}\left(1 - T/T^*\right)^2 \right]. \qquad (6)$$

It comes out naturally that T^* is identical with T_{cJ}.

As to the frequency dependence of R_s' it was suggested flux penetrates the intergranular medium in nanoseconds [9]. The energy needed to break the Cooper pairs is delivered by the electromagnetic field. This same energy can probably not coherently be delivered back to the electromagnetic field, when the nc electrons condense again into Cooper pairs. The RF loss is therefore proportional to the number of cycles per second, hence the RF frequency.

4. CONCLUSION

We have shown that a maximum accelerating gradient of 13 MV/m and a low field Q-value larger than 10^{10} can be obtained in five-cell NbCu cavities at 1.5 GHz. Thermal quenching was not observed, the limitation of the gradient was electron loading. These results are not significantly different from what has been obtained in one-cell cavities, despite the fact that in five-cell cavities the probability of having defects of poor adhesion is larger.

In the second part of the paper we have given an analysis of the decrease of the Q-value with the accelerating gradient in terms of weak links switching by the action of the RF field into the nc state and back into the sc one.

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