HIGH ELECTROMAGNETIC FIELDS AT LOW RF LOSSES IN SUPERCONDUCTING S-BAND ACCELERATOR CAVITIES

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Abstract

Field emission loading and thermal instabilities are the main obstacles limiting the performance of superconducting accelerator cavities today. The prevention of surface contaminations as well as the homogenization and purification of the niobium raw material suppress both phenomena. High-temperature annealing at 1300°C under exposure to titanium vapor provides sufficient diffusion and gettering of the interstitial impurities like oxygen. We have applied this treatment to single-cell 3 GHz cavities fabricated from reactor grade and medium purity Nb resulting in accelerating fields E_{acc} above 20 MV/m reproducibly. In the postpurified reactor grade cavity E_{acc}= 25 MV/m at a Q_0(1.5 K) value of 10^{10} was achieved. In contrast to previous experiments no field emission was observed up to a surface electric field of 63.8 MV/m. A thermal instability occured close to the cavity equator at a peak magnetic field of 104.6 mT. The scaling of this result to lower frequencies will be considered.

Introduction

The threshold accelerating gradient for a TeV superconducting linac to be competitive with proton storage rings like SSC and LHC at the high energy physics frontier is about 30 MV/m [1]. At such high fields Q_0 values above 10^{10} would reduce the refrigeration costs or increase the affordable luminosity significantly. At present niobium cavities are one of the most advanced technologies to satisfy these challenges. Their ultimate performance will be given by the superheating magnetic field and the BCS surface resistance, which are about 200 mT and 10 nΩ at 3 GHz and 1.8 K [2]. For the usual π-mode standing wave structures these values correspond to accelerating gradients E_{acc} of 45 MV/m at a Q_0 of $2.5 \cdot 10^{10}$.

During the past eight years major improvements have been made on the understanding of anomalous field limitations in superconducting cavities. At first temperature mapping of the outer cavity surface in subcooled helium uncovered the location of large normal conducting defects and enabled a subsequent guided repair [3]. As predicted by thermal model calculations [4], quenching caused by the remaining defects was shifted reliably to magnetic surface fields above 50 mT by using niobium of high thermal conductivity [5,6]. Therefore field emission loading has become the dominant performance limitation of superconducting Nb cavities [7]. Dc-field emission studies on Nb samples have shown that the enhanced electron emission does usually not originate from surface protrusions but from micron-size particles or foreign material inclusions, and that emission free Nb surfaces up to 200 MV/m can be obtained by high temperature firing above 1400°C [8].

According to the scaling law for the threshold field of local thermal breakdown [4], large defects must be either avoided or thermally stabilized to prevent quenching. While the first alternative is rather laborious the second seems to be much more elegant especially for multicell structures. On the other hand any defect leads to residual losses, i.e. limits the achievable Q_0. Furthermore it is not clear, to what extent defects contribute to the enhanced rf field emission. Because of these reasons the purification as well as the homogenization are important to improve the performance of superconducting niobium cavities [2]. In this paper we report about measurements on single-cell S-band cavities in which different techniques were tried to suppress both quenching and field emission loading.

Experimental Techniques

The spherically shaped cavities were fabricated by deep-drawing and electron beam welding from Nb sheets (2 mm) of different purity grade. S3 is an old reactor grade cavity which has been tested, locally repaired and annealed in an UHV-furnace at 1850°C several times resulting in quench field levels up to 7.3 MV/m and residual Q_0 values up to $7 \cdot 10^{10}$ [6]. Than it was coated successfully with Nb_3Sn by Sn vapor diffusion at about 1100°C [9]. SW1 and SW2 were originally built from medium purity material (RRR = 90 and 135) providing in four tests each maximum E_{acc} of 12 MV/m and 18.7 MV/m at Q_0 values around 10^{10}, limited by quenching again [6]. Only moderate heat treatments at 850°C had been applied to these cavities to maintain their purity grade. Several attempts to coat SW2 with Nb_3Sn failed, despite of the reduction of its purity in the coating furnace to RRR ≈ 60.

These cavities were postpurified by solid state gettering [5] to improve their thermal stability against quenching. The thermal conductivity of commercially available bulk niobium is determined by the interstitial impurities O, N and C [10]. The mean diffusion lengths of these impurities in Nb reach some mm already after a few hours at temperatures around 1300°C (Fig. 1). Using metals with a higher affinity to O, N

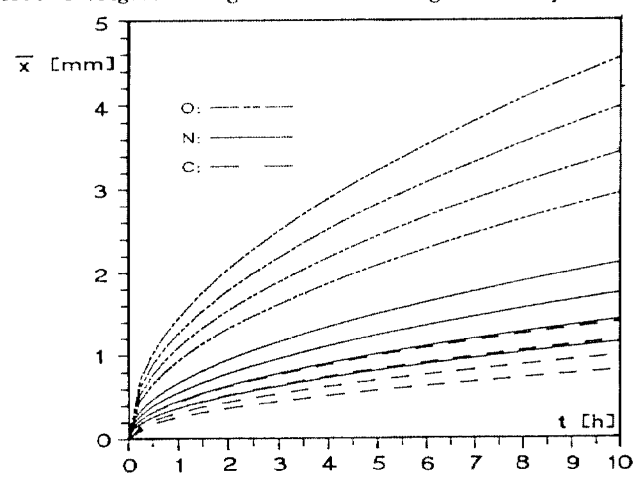

Fig. 1: Diffusion lengths of the main interstitial impurities O, N and C in Nb as a function of annealing time. Each set of four lines correspond to temperatures between 1200°C and 1350°C in 50°C steps, respectively.

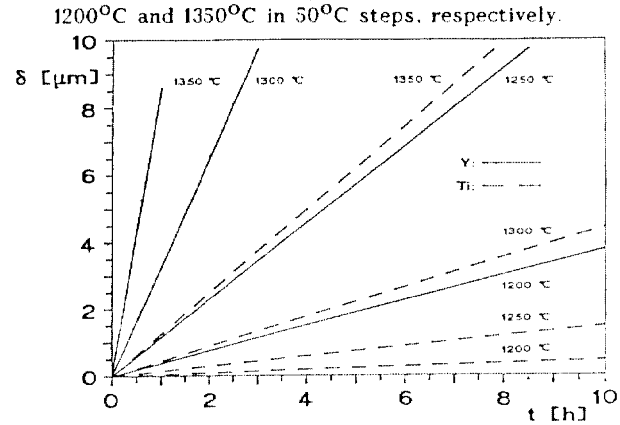

Fig. 2: Growth of yttrium and titanium layer thicknesses as calculated from the velocity of evaporation for equal size of desorbing and adsorbing surface.

and C like yttrium or titanium [11] which have sufficient evaporation rates at the same temperatures (Fig. 2), these impurites can be removed from Nb by solid state gettering. Considering the dominant oxygen content of typically 500 at.-ppm for reactor grade Nb and a maximum solubility of O in Y and Ti of about 15 at.-% and 25 at.-% [12], yttrification for 4 h at 1250°C or titanification for 10 h at 1300°C are at least necessary to remove oxygen from Nb completely. These parameters have been chosen for the postpurification of the cavities, resulting in RRR values of about 400 for SW1 (Y), 430 for SW2 (Ti) and 160 for S3 (Ti) found by thermal conductivity measurements on samples.

After these treatments the getter material was removed in a 1:1:1 solution of 48% HF:65% HNO_3:85% H_3PO_4. Because of the enhanced diffusion of Ti along the grain boundaries, extended chemical polishing of at least 50 μm Nb was found to be necessary to avoid a Q_0 degradation by residual Ti contamination. The final surface preparation consisted of a extensive rinsing in demineralized, filtered water. Only SW2 was rinsed afterwards in methanol. The cavities were assembled under laminar air flow conditions to the cryogenic test system. For SW2 and S3 a particle counter (≥ 0.2 μm) was used to minimize dust contamination.

Results and Discussion

Tab. 1: Best results on residual Q_0 and maximum field levels of three different single-cell S-band cavities at 1.5 K.

Cavity	Q_0 (max.)	Q_0 (0.95 H_p)	H_p [mT]	E_p [MV/m]	E_{acc} [MV/m]	limit
SW1	$8 \cdot 10^9$	$1.5 \cdot 10^9$	96	59	23	FE
SW2	$6 \cdot 10^9$	$2.2 \cdot 10^9$	102	62.8	24.5	FE, Q
S 3	$3 \cdot 10^{10}$	$1.0 \cdot 10^{10}$	105	63.8	25	Q

In Tab. 1 the best performance data of the high purity Nb cavities are summarized. They have been achieved in the first test after postpurification for SW1 and S3 and in the second for SW2. This underlines the reliability of getting E_{acc} levels well above 20 MV/m due to the thermal stabilization of defects. Nevertheless two of three cavities are still limited by quenching at magnetic surface fields H_p around 100 mT close to the equator weld as detected by carbon resistors. In addition to higher thermal conductivity guided repair especially in the weld regions must be considered for further improvements. In SW1 and SW2 strong field emission loading was observed the onset field level of which increased as usual after short processing (Fig. 3). A more detailed investigation

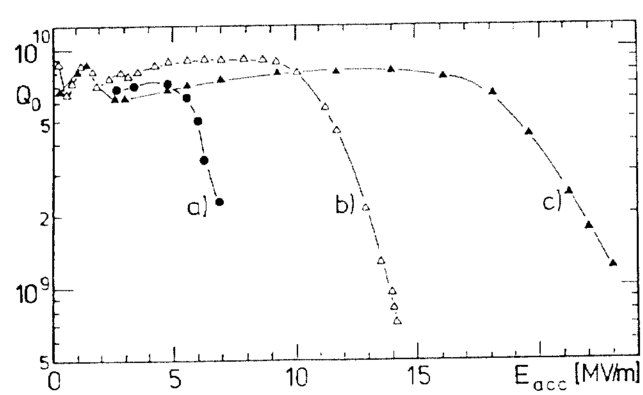

Fig. 3: $Q_0(E_a)$ dependence measured for SW1 at 1.6 K initially (a) and after 30 min rf- (b) and 45 min He-processing (c).

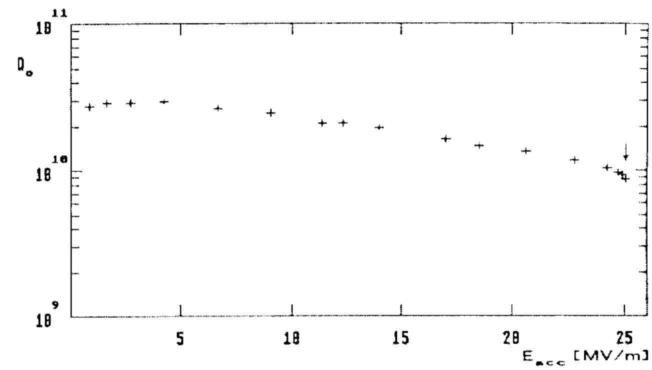

Fig. 4: $Q_0(E_a)$ dependence measured on S3 at 1.4 K. The arrow marks the field limitation by quenching

of field emission in our cavities based on the measured Q_0 degradation, probe current and X-ray distribution will be reported elsewhere [12]. Here we will focus on the most interesting test result for S3, where no field emission was found up to the maximum accelerating field of 25 MV/m (Fig. 4) which corresponds to a peak electric surface field E_p of 63.8 MV/m. Moreover this cavity provided much higher Q_0 values at low field levels than the other both, staying above 10^{10} up to the maximum field strength nearly. Keeping in mind that S3 has a significantly lower purity grade RRR, this result is a strong hint for the beneficial effect of the homogenization by high temperature annealing at 1850°C on the reduction of possibly both field emission and quenching.

Despite of the small size of a single-cell 3 GHz cavity, the absence of any field emission up to very high field levels provides important information about the density of emitters. For this purpose in Fig. 5 the calculated correlation between the relative size of the inner cavity surface and the normalized electric surface field distribution is shown. The local field at which significant field emission will be observed is well defined due to the exponential Fowler-Nordheim dependence: from the existing data 4000 MV/m can be accepted as the threshold field $E_{th} = \beta \cdot E_p$ [13]. Using this number, for each part of the cavity surface A_i with local field E_i a corresponding β_i can be determined from the given E_p = 63.8 MV/m in our test. As the most pessimistic assumption, the first emitter would occur just above the quench field. Therefore we get an upper limit for the density of emitters per area $N(\beta_i)$ in this test by taking the inverse sum of all A_i at which the local field E is less than or equal to E_i (Fig. 6). In this statistical model our result can be scaled now to single-cell cavities at lower frequencies, for which the A_i increase quadratically. As an

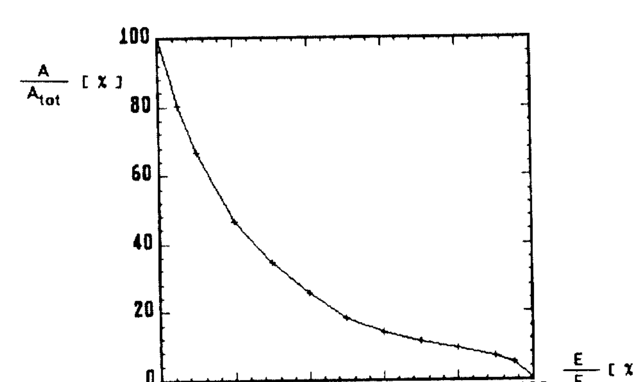

Fig. 5: Relative surface area A/A_{tot} of the sperically shaped single-cell cavities at which the normalized electric surface field is greater than E/E_p. For 3GHz A_{tot} is about 218 cm^2.

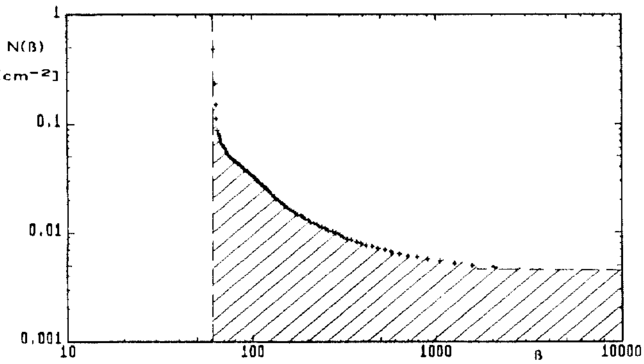

Fig. 6: Upper limit for the density of electron emitters in a 3 GHz single-cell cavity as a function of the anomalous field enhancement factor $\beta = E_{th}/$ 63.8 MV/m. The shaded region represents the best performance achieved in cavity S3.

example we have got less than one emitter per 10 cm^2 within 96 % of the the peak field, i.e. for fields above 61.2 MV/m or β above 65. Vice versa for an area of 100 cm^2 no field emission occured up to electric surface fields of 15 MV/m.

Conclusions

Increasing the thermal stability of niobium by postpurification methods, we have reproducibly achieved accelerating gradients above 20 MV/m in three different single-cell 3 GHz cavities. In the best homogenized cavity no field emission occured up to peak electric surface fields of 63.8 MV/m, corresponding to an accelerating field of 25 MV/m at a Q_0 of about 10^{10}. Further improvements on the field and Q_0 levels will request the avoidance of defects as well as their thermal stabilization.

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