CM-P00061276

SUPERCONDUCTING NIOBIUM CAVITIES OF IMPROVED THERMAL CONDUCTIVITY

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The construction of large scale superconducting accelerators asks for reliable and economical manufacturing procedures for the superconducting cavities. The improvement of thermal conductivity of the niobium used can be of great benefit in that respect. We have built and tested single cell cavities at 500 MHz and 3 GHz from a newly available niobium sheet material of improved thermal conductivity. * At 500 MHz a maximum accelerating field of 13.0 MV/m at 4.2 K was achieved. At 3 GHz and 1.5 K as a best result 18.7 MV/m were obtained. A total of 15 cavity tests were carried out and the results clearly exceed field values obtained so far with standard reactor grade niobium at CERN and Wuppertal.

Measurements of the thermal conductivity of niobium at helium temperatures are discussed, the temperature dependence of the surface resistance of high purity niobium is given, the observed field and Q limitations and electron loading phenomena are outlined.

Introduction

Quenching caused by small area defects and electron loading are today the prime field limitations encountered in superconducting rf cavities for accelerator application. Improvements in the chemical cleaning procedures and in dust free working conditions as well as in diagnostic techniques have reduced the influence of these phenomena. Design accelerating fields of 5 MV/m for large scale s.c. accelerating systems like the one envisaged for LEP II can therefore be considered. Any cleaning procedure, however, will leave defects in the micron range, which produce thermal instabilities on the s.c. rf surface of the cavity. It was pointed out by H. Padamsee¹ that the threshold field for such an instability is increased if the thermal conductivity of niobium can be improved. For the same reason copper cavities sputter-coated with niobium films have been investigated.² In standard commercial reactor grade niobium the impurities O, N and C dominate the poor thermal conductivity of this material.³ These impurities can be controlled to a large extent during the electron beam melting of the raw niobium and the consecutive manufacturing steps of the sheet material. We have investigated niobium sheet of higher purity which is commercially available since December 1983 and performed rf measurements with 500 MHz and 3 GHz cavities fabricated from this material. The general goal of these investigations was to obtain higher accelerating fields than with standard niobium and to reach them reliably without applying elaborated guided repair methods to remove defect areas from the rf surface of the cavity. Similar work is carried out at Cornell.⁴

Thermal conductivity measurements

We have built up a computerized device to investigate the thermal conductivity λ of niobium in the temperature range from 1.5 to 10 K, which is described elsewhere.⁵ With this set up we measured λ of reactor grade niobium from different manufacturers. Typical temperature dependencies are given in Fig. 1.

* Manufactured by W.C.Heraeus, Hanau, W. Germany

Fig. 1: Thermal conductivity of reactor grade niobium (RRR=40) and niobium of higher purity (RRR=113)

The residual resistivity ratio (RRR) and the electronic thermal conductivity are both proportional to the mean free path of the conduction electrons. Improving the purity of niobium therefore increases both λ and RRR. Commercially available reactor grade niobium shows typical RRR values between 20 and 40⁶, corresponding to a thermal conductivity at 4.2 K between 5 and 10 W/mK. The theoretical RRR limit of about 30.000³ for ultra pure niobium indicates the possibility of improving λ for commercial niobium considerably. Influenced by these considerations and our measurements, W.C. Heraeus improved its production process of niobium sheet material. Its typical RRR of 113 and λ (4.2 K) of 28 W/mK exceed the best standard material by about a factor of 3 (see Fig. 1). The thermal conductivity of the new material depends in part on the vacuum conditions of the different furnaces used for the last fabrication step, which consists in an 1 h recrystallisation of the rolled sheet material at 850°C.

Very high temperature annealing (at 1800 to 2000°C) in UHV furnaces is used frequently to improve the residual quality factor of superconducting niobium cavities. It has, however, not been observed in any systematic way that the limiting fields in a cavity can be increased markedly by this treatment. The partial pressures of H₂O, O₂, N₂, CO and CO₂ within the hot zone of an UHV furnace are to a large extent unknown. If they are poor, O, N and C atoms will diffuse into the niobium, reduce its thermal conductivity and may thereby decrease the thermal stability of a s.c. cavity. We have heat treated a niobium sample with RRR=135 in the Wuppertal UHV furnace at 1900°C for 8 hours. A small

degradation of its electronic thermal conductivity by about 15% was observed, which dominates λ for temperatures above 4 K. Due to the reduction of crystal dislocations and because of strong increase of the grain size (from typical 50 μm to 2 mm) the phonon conductivity is increased to a peak value of 50 W/mK at about 2 K. This enhancement, however, does not improve significantly the thermal stability of a cavity even when operated at 1.8 K. This has been shown by thermal model calculations. The reduction of the electronic thermal conductivity has influenced us to perform the stress annealing of our cavities after the deep drawing only at 850°C. A similar reduction of the RRR can be expected for the welding zones of the cavity. We have measured samples of electron beam and TIG welds. In the electron beam weld λ (4.2 K) is reduced from 28 to 22 W/mK, in the TIG weld a reduction of λ (4.2 K) to 19 W/mK has been measured.

The surface resistance of high purity niobium

The rf surface resistance R_s of a superconducting cavity depends weakly on the mean free path ℓ of the conduction electrons. In niobium with an RRR value of 40 ℓ is about 1100 Å and increases to 3600 Å for an RRR of 135. Computing R_s according to the BCS theory shows that for this increase of ℓ the surface resistance at 3 GHz should be increased by about 25%.⁷ To confirm this prediction we have measured the temperature dependence of R_s in a 3 GHz cavity fabricated from niobium with an RRR value 135 and compared the result with the surface resistance of a cavity made from standard material (RRR=40). In Fig. 2 the expected difference of $R_s(T)$ for both materials can be clearly seen.

Fig. 2: Surface resistance $R_s(T)$ of two 3 GHz cavities, fabricated from niobium of different purity. $R_s(T)$ is the sum of the temperature dependent part R_{BCS} and the residual resistance R_{res} .

Cavity tests

To study the influence of the improved thermal conductivity on the cavity performance five cavities were built from material delivered by Heraeus in Hanau. Two cavities (C-500-1/2) at 500 MHz and one (C-3000-1) at 3 GHz were tested in CERN and two cavities (W-3000-1/2) were measured in Wuppertal. The CERN cavities⁸ were produced by spinning on a lathe, electron beam welding, chemical polishing, rinsing with dust free demineralized water and dust free drying as a last step before mounting to the test system. The Wuppertal cavities⁹ were deep drawn and electron beam welded by Interatom in Bensberg. The chemical treatment was done like in CERN but the water rinsing was followed sometimes by a methanol rinsing or by a high temperature treatment at 850°C in the Wuppertal UHV-furnace. A total of 15 tests were carried out, each one preceded by a new surface treatment of the cavity. The results obtained are summarized in table 1.

Discussion

The histograms of Fig. 3 compare the new results on high purity niobium with previous data on 500 MHz and 3 GHz cavities collected since the beginning of 1980. Included are only tests after a new chemical treatment of the cavity surface. The new cavities are treated according to the same preparational procedure as the one applied to the old cavities. At 500 MHz the average maximum field level of the old data is 18 mT and the new data are grouped around 38 mT. At 3 GHz the old average is about 25 mT and the new one is 55 mT. At both frequencies therefore an average improvement of the limiting fields by a factor of about two was achieved. The thermal conductivity of the standard niobium ranges from 5 to 10 W/mK compared to the niobium of higher purity where λ ranges between 20 and 35 W/mK and surpasses the old material by nearly a factor of four. If one adopts the most straight forward hypothesis that the distribution of surface defects included in the material or being produced during the fabrication and preparation of the cavities is the same for the old and the new material, one would expect the observed improvement just because of the increased thermal conductivity. Model calculations predict a dependence of the quench field level on the square root

Fig. 3: Histogram of test results for single cell cavities from niobium of different RRR
a) 500 and 350 MHz
b) 3 GHz (CERN and Wuppertal)

Tab. 1: Summary of cavity tests

Cavity	$\lambda(4.2\text{K})$ (W/m)	Test No.	room temp. treatment	low temp. processing	$Q_0/10^9$		maximum surf. fields		E_{acc}^* (MV/m)	field limitations and remarks
					low field	high field	H_p (mT)	E_p (HV/m)		
C-500-1	28	1	CP20, H ₂ O, DD	9 h He	1.3	1.0	33.8	17.5	9.0	MP at equator
		2	Anod. H ₂ O, DD	2 h He	1.3	0.7	48.9	25.2	13	Quench near lower iris, MP at $8 < E_{acc} < 9$ MV/m
		3	HF, H ₂ O, DD	7 h He	1.3	0.5	45.1	23.3	12	Quench near lower iris due to NREL
		4	local EP, H ₂ O, DD	3 h He	1.3	0.6	34.2	17.7	9.1	MP at eq.
		5	depos. Ph, H ₂ O, DD	0.7 h He	1.2	0.8	31.6	16.3	8.4	MP at eq.
C-500-2	28	1	CP20, H ₂ O, DD	2 h He	2.4	1.0	35.7	18.4	9.5	MP at eq.
C-3000-1	28	1	CP24, H ₂ O, DD	1 h rf 2 h He	2.7	1.8	47.9	28.5	11.4	Quench ~ 20 mm below eq.
W-3000-1	22	1	HCl, CP15, H ₂ O, Meth	-	2.1	1.0	29.4	17.5	7.0	Quench, Al particle
		2	HCl, CP15, H ₂ O, Meth	1 min He	4.0	3.0	50.4	30.0	12.0	Quench near lower iris
		3	HCl, CP15, H ₂ O, Meth 1 h 850°C	1 h He	12.0	3.0	49.6	29.5	11.8	Quench near lower iris
		4	HCl, CP15, (H ₂ O), Meth 1 h 850°C	15 min rf	3.9	1.5	43.3	26	10.3	NREL starts at $E_{acc} < 1$ MV/m Quench near lower iris
W-3000-2	35	1	HCl, CP15, H ₂ O, Meth	1 h He	8.6	1.0	56.7	34	13.5	no Quench, rf power limited due to NREL
		2	HCl, CP15, (H ₂ O), Meth 1 h 850°C	10 min rf 20 min He	10.0	0.5	68.0	40.5	16.2	no Quench, rf power limited due to NREL
		3	HCl, CP15, H ₂ O, Meth 1 h 850°C	10 min rf 1 h He	10.0	0.4	67.6	40	16.1	no Quench, rf power limited due to NREL
		4	HF, HCl, CP15, H ₂ O, Meth 1 h 850°C	10 min rf	6.3	2.4	78.5	46.5	18.7	Quench ~ 15 mm below eq.

Abbreviations: CP20: 20 μ m chemical polishing in a 1:1:1 solution of HF:HNO₃:H₃PO₄; H₂O: rinsing in demineralized dust free water; (H₂O): rinsing in tap water; Meth: rinsing in dust free methanol; Anod: Anodization (100V) in NH₄OH; HF(HCl): dissolution of oxides (contaminations); DD: dust free drying; local EP (depos.Ph): intentional treatments to remove (deposit) regions of enhanced losses ¹⁰; 1 h 850°C: 1 h bake out at 850°C in an UHV furnace; MP: electron loading due to multipacting; NREL: non-resonant electron loading

* E_{acc} is defined as the computed voltage gain of a relativistic particle passing a single cell cavity with cutoff tubes devided by the length of the cell ($L = \lambda/2$)

of λ .¹ This simple argument may, however, not cover the whole truth. About 50% of all measurements displayed in table 1 show a limitation by resonant or non-resonant electron loading. An elimination of electron loading may well lead to an even higher average limiting field for the new material. Therefore, it cannot be excluded that there is also a smaller density of material inherent defects contributing to the improved results of the new material.

For a large scale application of s.c. cavities with accelerating fields above 5 MV/m the reduction of rf induced cryogenic losses becomes of growing importance. Therefore, the observed Q_0 values shall be discussed. The results given in table 1 are measured at 4.2 K (500 MHz) and 1.5 K (3 GHz). The low $Q_0 = 1.3 \cdot 10^9$ of C-500-1 is limited by losses due to the short cutoff tubes of this cavity. In general Q_0 values between 2 and $3 \cdot 10^9$ are observed for the CERN 500 MHz cavities, essentially limited by RBCS at 4.2 K. The measured residual Q_0 of the 3 GHz cavities range from $4 \cdot 10^9$ to 10^{10} . Comparing the test results of W-3000-1/2 before and after bake out at 850°C it seems that even such a moderate heat treatment improves the residual Q_0 . This

treatment could well be applied to multicell accelerating units.

It was pointed out recently ¹¹ that the temperature mapping technique carried out on superconducting cavities immersed in subcooled helium at 2.3 to 2.5 K is limited to peak surface magnetic fields of about 24 mT for niobium cavities of 3 GHz. This limit is inverse proportional to the cavities frequency. Therefore, temperature maps of the loss distribution of the 3 GHz cavities reported here cannot be given. At 500 MHz this technique can still be applied as can be seen from Fig. 4. Three small area defects and a broad loss distribution can be observed. The latter is due to frozen in magnetic flux as the cavity was cooled down in an ambient magnetic field of 0.13 Gauss. The comparison of other temperature maps with line like losses caused by field emitted electrons for both materials has shown that the full width half maximum of the temperature signals at the outer cavity wall (thickness 3 mm) are broadened from typically 20 mm for the old material to 36 mm for the new material due to the increased thermal conductivity as expected from model calculations.

Fig. 4: Temperature map of a 500 MHz cavity at $E_{acc} = 12.5$ MV/m. The temperature increase ΔT of the outer cavity surface is plotted against the surface coordinates $s(z)$ and $s(\phi)$ (z =length in arbitrary units along a meridian, ϕ = azimuthal location)

Electron loading

From table 1 one recognizes that in almost all experiments the final performance of a cavity could only be reached after some low temperature processing (rf processing and He-ion sputtering). This indicates the fact that all cavities showed electron loading which general starts at peak electric surface fields of about 12 to 15 MV/m both at 500 MHz and 3 GHz. Sometimes free electron currents, measured by pick-up probes located in the cutoff tubes are already observed at surface fields as low as 2 MV/m. This low field electron loading can be overcome easily by rf processing.

At an accelerating field of about 8.5 MV/m, which was not accessible so far with cavities of 500 MHz made from standard niobium, a resonant electron loading was discovered and analysed.¹² It is a two point multipacting of electrons around the zero crossing of the electric surface field at the cavities equator. This resonant barrier could be passed by electron impact processing twice and accelerating fields of 12 and 13 MV/m were reached at 500 MHz.

In the 3 GHz cavity fabricated from niobium with the best thermal conductivity available to us field emission was strong and hard to overcome. Four consecutive tests were carried out and the coupling of the cavity to the rf drive system was increased in steps, so that even under strong electron loading enough power could be coupled into the resonator. In the last test when the external Q of the cavity was reduced to $5 \cdot 10^8$ enough power for a successful rf processing was available. At 18.7 MV/m a thermal instability limited the accelerating field. The change of the cavity Q_0 with field at 500 MHz and 3 GHz measured with the two best cavities are shown in Fig. 5. Up to about 80% of the maximum field a small reduction of Q_0 with increasing field can be recognized. Above this field level a stronger decrease occurs which is caused by electron field emission. As a best result, a peak surface electric field of 46.5 MV/m at $Q_0(1.5 K) = 2.4 \cdot 10^9$ has been reached at 3 GHz.

Conclusions

The performance of single cell rf cavities at 500 MHz and 3 GHz fabricated from niobium sheet of improved purity has been tested. The thermal conductivity of this new material was measured and found to be between 22 and 35 W/mK at 4.2 K. It superceeds standard reactor grade niobium in this respect by a factor of about four. The average of the limiting accelerating fields measured in 15 cavity experiments is improved by a factor of about

Fig. 5: Dependence of the cavity Q_0 on the accelerating field E_{acc} for a 500 MHz and a 3 GHz cavity.

two in comparison to the average of the results obtained in cavities fabricated from standard niobium. In any one of the described tests the design accelerating field of 5 MV/m suggested for the superconducting accelerating stations of LEP was surpassed significantly without any guided repair.

In the 500 MHz cavities for the first time accelerating fields higher than 8 MV/m could be obtained. Around 8.5 MV/m a special kind of two point multipacting at the equator of the spherical cavity was found. Above 10 MV/m the performance of the cavities suffered from field emission induced electron loading. Rf processing and helium ion sputtering proved to be effective methods to reach accelerating fields as high as 13 MV/m at 500 MHz and 18.7 MV/m at 3 GHz in continuous wave mode operation. The maximum fields obtained were limited by local thermal instabilities on the rf surface. A further and still possible improvement of the purity and thereby the thermal conductivity of niobium is therefore certainly worthwhile. The experiments reported here indicate that design accelerating fields of 5 MV/m should be safe for large superconducting accelerating systems and guided repair may not be necessary on cavities produced from presently available high purity niobium.

Acknowledgements

We would like to thank Ph. Bernard for his encouraging support of this experimental work. We have appreciated very much the help of the technicians of the CERN/EF/RF group and of the members of the SB workshop. The support of the cryogenics group of the CERN EF division is gratefully acknowledged.

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