BREAKDOWN FIELDS IN A SUPERCONDUCTING NIOBIUM CAVITY AT S-BAND

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Summary

The measurements of the RF breakdown and its localization in different modes of an S-band niobium cavity gave new insight about the thermal magnetic breakdown. Especially the TE_{011} mode, where the initial peak RF field of 810 Oe deteriorated to about 400 Oe after the cavity has been subject to the electron loading of TM modes causing surface damage. After damaging the surface by electron impact at He temperatures, the field level in all modes is limited to about 400 G. For TM modes this field level corresponds to a surface electric field of about 25 MV/m.

Introduction

In the past several years considerable progress has been made in the field of superconducting cavities.[1-8] For example, this is shown by the high breakdown fields H_{crit} at frequencies between 8 and 10 GHz up to 1600 Oe in a TE_{011} mode cavity and 1500 Oe in a TM_{010} mode cavity.[5] At lower frequencies, between 1-4 GHz, the breakdown fields have been considerably lower,[2-4] especially in TM mode cavities, with $H_{crit} \lesssim 600$ Oe. These low RF critical fields are not related to bulk properties but are due to weak or heated spots at the surface as discussed in [3,9]. These spots become normal at a field level below the bulk thermodynamic critical field ($H_c(0)$ = 1990 Oe). In this normal conducting region the RF dissipation is more than a factor of 10^5 higher than in the surrounding superconducting region which cause a thermal explosion,[9] i.e. the thermal magnetic breakdown.

Several causes for the nucleation of RF breakdown have been proposed[3,6,8-10] e.g. localized impurities, especially at welds, trapped flux or direct electron impact. The results on the multimode cavity - especially the reduction of the breakdown field and the motion of the breakdown spot - show that none of these proposed models can explain our results. Instead the measurements support a model of thermal magnetic breakdown initiated by surface damage and caused by electron impact in TM modes. This surface damage seems to be larger for wet oxidized or contaminated surfaces than surfaces prepared in a UHV furnace; and, seems to saturate for moderately clean surfaces. In similarly shaped cavities for one type of mode the electron loading strength[11] and the surface damage by those electron scales with f^{-1}. Hence, this surface damage can explain the reduced H_{crit} in low frequency cavities.[2]

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Measurements and results

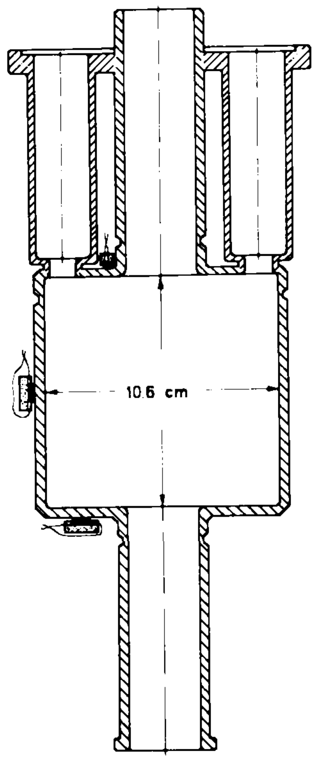

Fig. 1: Schematic drawing of S-band cavity with beam tubes. The cavity is constructed out of several niobium parts that have been electron beam welded together. The welds are shown as thinned walls in the drawing. Carbon resistors used to detect heat pulses are indicated schematically.

The measurements discussed here were made on a beam hole cavity (see Fig.1) in which a number of modes can be excited between 2 and 5 GHz. The addition of beam holes to the cavity allows better chemical surface treatments because it gives better access to the interior surfaces. The various parts of the cavity were electropolished before final electron-beam welding. The surface treatments after welding have included cold chemical polishing, oxipolishing, and high temperature annealing in a UHV furnace. A more detailed description of the surface treatments is given in Ref.4. The best results in terms of H_{crit} and R_{res} were attained after an high temperature anneal at 1750°C for 20 hours. During the cool-down cycle N_2 at one atmosphere was introduced at 400°C which increases the cooling rate at low temperatures by about a factor of 10. The cavity is tested in a vertical position as indicated in Fig. 1. The microwave coupling is provided by two coaxial lines which are pumped by a sputter-ion pump located on top of the dewar. It is possible that gases from the warm portion of the vacuum system condense on the cold cavity walls when the cavity is at helium temperature.

The microwave measurements made on the multimode cavity include the measurement of H_{crit} and R_{res} in the TE_{011}, TE_{012}, TE_{111}, TM_{010}, TM_{011}, TM_{012}, TM_{013}, TM_{110} and TM_{111} modes. The effect of electron impact was studied by measuring the electron free TE_{011} mode before and after electron loading was produced by exciting TM modes. Measurements have also been made to study the location of the thermal magnetic breakdown as a function of mode and electron surface damage. The position of breakdown was found by detecting the heat pulse produced by breakdown with carbon resistors as described previously by one of the authors.[2]

Table I:

The minimum RF surface resistance, the surface resistance at the limiting fields and the limiting fields in the TE_{011} mode. In each test the values are given for the initial measurement and for the measurement after electron damage was produced by excitation of the TM modes. The surface preparations prior to each measurement were:

a) chemically polished, anodized, rinsed, and assembled while wet with CH_3OH
b) chemically cleaned, annealed at 1750°C in UHV furnace. During cool down N_2 at 1 atm. was introduced at 400°C to increase the cooling rate.
c) chemically polished, rinsed in NH_3OH, H_2O and CH_3OH and assembled while wet with CH_3OH.

Test	TE_{011} Initial values		
	Min. R_{res} (nΩ)	R_{res} at H_{crit} (nΩ)	H_{crit} (Oe)
a	6.9	9.8	650
b	6.6	8.8	810
c	10.5	10.5	780
	TE_{011} values after γ's		
a	40	40	430
b	17	19	510
c	73	78	330

In Table I data are shown illustrating the effect of surface damage on R_{res} and H_{crit} in the TE_{011} mode. The basic test procedure was first to measure the surface resistance as a function of RF field level in the electron free TE_{011} mode up to H_{crit}. Then various TM modes were excited and both electron multipacting and electron field emission were observed. The TE_{011} mode was remeasured after γ-radiation was produced in one of the TM modes. The reduction of H_{crit} in the TE_{011} mode shown in Table I cannot be explained by a model where electron impacts directly cause thermal magnetic breakdown by localized heating or the breaking of Cooper pairs because the TE_{011} mode has no surface electric fields.

A systematic study of the sensitivity of the niobium surface to electron damage as a function of surface treatment has not been made. However, anodized and wet prepared surfaces seem to be more sensitive to electron impact than surfaces for which heat treatment is the final step in the cavity's preparation. As discussed below, the lower end plate of the cavity had a lower H_{crit} than the upper end plate as has also been reported in sealed TM_{010} mode cavities.[2] This indicates that contamination or absorbed gas may play a role in the surface damage mechanism.

Table II:

Summary of the best results in terms of field level in various modes. The values are taken from several different tests on the cavity. Only the results of the TE_{011} mode change significantly with test.

Mode	Frequency [GHz]	H_{crit} [Oe]	E_{max} [MV/m]
TE_{011}	3.7	810	-
TM_{010}	2.1	380	29
TM_{011}	2.6	400	26
TM_{012}	3.6	415	20
TM_{110}	3.4	410	22

In Table II a summary of the highest fields achieved in various modes is given. The difference between H_{crit} in the TE_{011} mode and H_{crit} for the TM modes is very clear. However, if one compares the values of H_{crit} in the TE_{011} mode after γ's (see Table I) with H_{crit} for the TM mode the differences are smaller. In run c the values of H_{crit} in the TE_{011} and TM modes were all comparable after significant γ's had been produced. This indicates that the field levels reached in TM mode are influenced by self-induced electron damage to the surface.

Experiments were done to study the location of the thermal magnetic breakdown as a function of mode and electron damage. Measurements in a TM_{010} mode S-band niobium cavity have been previously made by one of the authors,[2] but the measurements in the multimode cavity have yielded new clues about the mechanism causing thermal magnetic breakdown. The thermal magnetic breakdown in a particular mode will occur at the point where the magnetic field first exceeds some local H_{crit} at the surface. The location of the maximum magnetic field is dependent on mode. Therefore different areas of the cavity can be sampled by measuring more than one mode. If the surface RF properties are inhomogeneous then the breakdown will not necessarily occur in the region of maximum field. The surface inhomogeneities can be precipitates of NbO, carbides or surface damage due to electron impact.

A series of measurements on the cavity have demonstrated that the location of breakdown in the TE_{011} mode can be altered by exciting TM modes between measurements of the TE_{011}mode. The fields in the TE_{011} mode are not dependent on the azimuthal angle and the points of the maximum H-field lie on a circle around the middle of the cylinder wall. The ratio of maximum H-field on the cylinder wall to the maximum H-field on the endplates is 1.6 for the TE_{011} mode. Before the excitation of the TM modes the TE_{011} mode breakdown was in the middle of the cylinder wall. After measurements on the TM_{111} mode during which electron multipacting was observed, the TE_{011} breakdown was found in a new location on the cylinder wall. The TM_{110} mode was excited and γ-radiation caused by the impact of field emitted electrons with the cavity walls was observed. Before further γ's were produced the location of breakdown was checked and found unchanged from the previous measurement. Then the cavity was operated for 15 min in the TM_{110} mode at $H_{max} \sim 400$ Oe and $E_{max} \sim 20$ MV/m with the production of γ's. After this the breakdown in the TE_{011} mode was found in a 3rd location in the middle of the cylinder wall. The mechanism involved in the relocation of breakdown appears to be the creation of a new weak spot in the surface of the superconducting niobium rather than an improvement in the properties at the former location of breakdown. This follows from the observation that each change in location was accompanied by a decrease in the H_{crit} in the TE_{011} mode. In this set of measurements the value of H_{crit} in the TM mode did not decrease significantly during the measurements.

The results of the measurements on breakdown as a function of mode show different breakdown locations for different modes. For example the TE_{011} breakdown occurred on the cylinder wall as described above, while the TE_{012} breakdown occurred on the lower endplate in the region of maximum H-field. The breakdowns in the TM_{012} and TM_{013} mode were located on the lower endplate also in the region of highest fields but in a slightly different location than for the TE_{012} mode.

Discussion

In this paper we reported on RF breakdown and their location. As witnessed by the deterioration of TE_{011} mode results due to electron loading in TM modes, electron impact damages Nb surfaces. This surface damage should be differentiated from bulk radiation damage, which for slow electrons consists in point defects[12] and cannot explain the observed deterioration of R_{res} and H_{crit}. This was already discussed in [13] where a model for surface damage was proposed consisting in the formation of (normal) conducting precipitates of some niobium oxides. This damage of the superconductor oxide interface saturates after some hours electron impact depending, e.g., on the thickness of the dielectric oxide. Hence, anodized and wet oxidized Nb, which is covered at least by 50 Å Nb_2O_5,[14] show more surface damage, than sealed cavity surfaces oxidized during cooling in a UHV furnace, where Nb_2O_5 is thinner ($\lesssim$ 20 Å).[15] But there are indications[16] that Nb covered only with a thin oxide layer ($\lesssim$ 20 Å)[15] becomes fairly reactive by electron impact at He temperatures and deteriorates if contaminents or gases are present. The bottom of the cavity is more easily contaminated than the top endplate and this could explain the observation, that the breakdowns occur preferentially at the bottom endplate. In the multimode cavity after electron loading for several hours, the breakdown spot was localized in the region of maximum magnetic field for each mode. This indicates, that the surface damage is quite homogeneous and that inhomogeneities present from the beginning play no significant role. It should be mentioned, that near the welds no breakdown was observed, in contrast to [6].

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