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CHARACTERIZATION OF SURFACE DEFECTS IN NIOBIUM MICROWAVE CAVITIES

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Superconducting microwave cavities usually break down at localized regions of enhanced losses¹. Several such regions have been located during low temperature cavity measurements using a temperature mapping system². The regions are then isolated by cutting the cavities and analyzed under a SEM to determine their size and composition. The breakdown field for such defects is calculated using a mesh program³ and compared with experiment. The composition of defects gives clues to the origin and suggestions for elimination of defects.

Introduction

At CERN a feasibility study on acceleration cavities for LEP is under way. Unloaded quality factors Q_0 well above 10^9 and acceleration fields E_{acc} above 6 MV/m have been achieved repeatedly in single 500 MHz single cell cavities at 4.2 K, providing an encouraging basis for application to LEP. Acceleration fields reached in the cavities of "spherical" shape are limited either by non resonant electron loading or by small isolated regions with increased r.f. losses causing a fast field breakdown (quench)¹. The progress achieved in surface treatments and the application of He-ion sputtering has enabled us to decrease electron loading to such an extent that the fields are now always limited by small lossy regions which cause fast breakdowns⁴. With the present standard treatment applied to 500 MHz cavities, there remain typically only 1 to 2 spots with strongly increased losses in one cell of $\sim 1 \text{ m}^2$ surface and up to fields of $\sim 7 \text{ MV/m}$. A precise knowledge of the nature and characteristic features of such regions is of great practical interest for the development of SC cavities.

Experimental approaches

The identification and localisation of dissipative spots is done by temperature mapping^{1,2,5}. The temperature mapping system allows to determine local temperature increases and thereby the local r.f.-losses^{2,6} with a resolution of about 2 cm^2 . The

r.f.-losses of a dissipative spot can be measured at different field-levels. This gives additional information on the spot as e.g. steep increases of r.f.-losses at definite field levels (switches) or associated electron activity. Measurement of the r.f. losses just below the quench field allows to determine the highest tolerable r.f.-losses of a given spot.

Two methods have been used to investigate the nature of these defects. In a first approach the cavity was inspected at room temperature by a specially designed Scanning Electron Microscope (SEM) which uses the cavity as its own vacuum chamber⁷. Its moving system can be operated from outside and allows a scan of the full cavity surface with a magnification variable between 5 and 500. It was always possible to detect in the region of a dissipative spot surface defects. However, the SEM had no possibility of elemental analysis. Such an analysis proved later in to be of crucial importance in order to discriminate dissipative spots from harmless surface irregularities which were detected in great number. Therefore another approach was chosen where a dissipative region localised by temperature mapping was carefully cut out of the cavity wall. As we did not want to destroy in this way our 500 MHz cavities, this procedure was applied to 3 GHz cavities. The area containing the defect was analyzed by a SEM allowing elemental analysis down to neon ($Z = 10$). In addition some information on elements with lower Z could be deduced from the bremsstrahlung spectrum. It was always possible to localise in the cut region the defect leading to the breakdown. This method will also allow investigations with other surface diagnostic methods like e.g. scanning Auger analysis.

Experimental results

In Table 1 all analyzed dissipative spots are presented. They are of a rather "unsophisticated" nature and are especially not related to the complex surface layers covering any Nb after a chemical treatment. We found so far 3 different kinds of defects:

TABLE 1. Summary of analyzed dissipative spots

Cavity No.	E_{acc}^{max} (MV/m)	H_{max} (Oe)	E_{max} (MV/m)	P_{diss} (mW)	r_D (μm)	Description
3000 MHz						
S3	2.9	100	4.0	-	1100	Central region with halo,
S4	3.4	140	0.9	280	220	Stain with many crystallites, K, Cl, (P) (fig. 1)
S5	6.8	235	9.5	310	40	Nb sphere with small contact region, switch (fig. 2)
S6	4.5	190	0	50	~ 180	W-inclusion at TIG weld (fig. 6)
S7	10.6	411	9.0	200	25	2 flat objects on the surface S, Ca (Cl, K)
					20	
S13	5.9	204	8.0	120	200	Stains with many crystallites K, Cl, biggest $r_D = 200 \mu$
S12	3.7	155	0.	30	~ 65	3 holes in a TIG weld with sharp edges (fig. 5)
500 MHz						
	2.7	92	1.66	320	760	Central region with halo Cu, Fe
	2.0	68	0.50	100	~ 12000	Burrs from scraping, Nb (fig. 4)

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- Drying stains.
- Surface irregularities (scratches, protrusions, holes).
- Inclusions of foreign material.

Up to acceleration fields of about 5 MV/m no defects in electron beam weldings in the 3 GHz cavities were found. This confirms our observations in the 500 MHz cavities where - after standard treatment - no defect was found in about 25 m of weldings. More recently higher fields up to ~ 8 MV/m were achieved in 3 GHz and 500 MHz cavities⁴. At these fields for the first time breakdowns located at the welding regions were observed. The origin of these breakdowns have not yet been analyzed. Dust particles do not seem to have caused any defect giving rise to a breakdown up to the highest field levels achieved.

Drying stains

We call drying stains all residues which are most likely produced by the wet surface treatments (degreasing, chemical polishing, anodisation, rinsing). We remind that the final rinsing is always done by distilled dustfree water and that the cavity is afterwards dried in a laminar flow of dustfree air. Because of the presumed dielectric nature of drying stains we try to position the cavity in such a way that those stains are not produced in a region of large electric fields.

A typical drying mark with a radius of ~ 200 μm is shown in fig. 1. The object in the centre is thought to be a piece of fibre with a length of ~ 50 μm . In addition a large number of small cristallites are distributed all over the stain. The elemental analysis revealed for the fibre and the cristallites K, Cl and some P; from the bremsstrahlungs spectrum one concludes, that the elements in the fibre are embedded in an organic material.

Fig. 1 Drying mark from a 3 GHz cavity as seen by a SEM. The elements K, Cl and P were detected. The radius of the stain is ~ 200 μm .

Surface irregularities

This kind of dissipative spot does not contain any foreign material, but only niobium. However, the niobium parts may have a bad thermal contact to the bulk material and they heat up in the r.f. field much faster than the cavity walls, getting normal conducting at a certain field-level. An example is

shown in fig. 2, where a niobium-sphere with a radius of about 40 μm is attached to the cavity surface by a small contact area. The origin of this sphere is not clear since the cavity was chemically polished after welding and it was verified experimentally that this treatment should have changed the spherical shape. Nevertheless this sphere causing a breakdown gives further proof that welding beads have to be avoided or removed from the cavity surface. Fig. 3 shows the dissipated power P_{diss} in this area as function of the accelerating field E_{acc} . The dissipated power rises with approximately the square of the field up to a threshold at 2.5 MV/m. Here P_{diss} increases by an order of magnitude and above this threshold continues to rise up continuously to the quench at 6.8 MV/m. If one passes the threshold with decreasing field, there is no jump in P_{diss} . This confirms the hypothesis, that at 2.5 MV/m the sphere changes from the super- to the normal conducting state. At decreasing field, the sphere is already normal conducting and the increased r.f.-losses are sufficient to keep the temperature above T_c even at field-levels below threshold.

Fig. 2 Nb sphere detected with the SEM. The radius of the sphere is 40 μm .

Fig. 3 P_{diss} as a function of E_{acc} obtained by temperature scanning for the Nb sphere shown in fig. 2.

In the region shown in fig. 4 a lossy inclusion was taken off by a scraper, leaving some burring marks at the Nb surface, which later on were removed by grinding. These protrusions produced a breakdown at a field level of 68 G. After regrinding with no subsequent chemical polishing the field could be raised to 140 G and after a chemical polishing the treated region supported a field of 205 G without producing a quench.

Fig. 4 Effect of grinding with a tungsten carbide-tipped tool and the burrs (top right) from scraping as seen by the miniature SEM inside a 500 MHz cavity.

In some Nb sheet material used for fabricating cavities a large number of etching pits appeared after chemical polishing (about 100 pits/mm² of $\sim 1 \mu\text{m}$ diameter and with edges having a curvature radius of the order of $0.02 \mu\text{m}$). In some of these etching pits a contamination by aluminium (or aluminium oxide?) was detected by a SEM. Such etching pits seem not to produce quenches up to the highest surface field levels reached up to now ($\sim 270 \text{ G}$ and 16 MV/m). Another type of hole was localised in a TIG weld (fig. 5); holes have a diameter of $\sim 65 \mu\text{m}$ and an edge curvature radius $\ll 1 \mu\text{m}$. This type of hole produced a quench at 155 G. Holes of this kind were up to now never observed in electron beam welds.

Fig. 5 Hole detected by a SEM in a TIG weld. Radius $\sim 65 \mu\text{m}$.

Inclusions of foreign materials

We call inclusions all foreign materials in good thermal contact with the niobium surface. Inclusions can exist already in the Nb sheets from which the cavities are produced, or they can be produced during spinning or welding. We try to detect them by visual inspection of Nb sheets and half-cells, by a simple rust-test in water (for Fe inclusion) or by inspection after anodisation. If such inclusions are localised they are removed by grinding with a hard-metal tool.

In fig. 6 an example of an inclusion in a weld is given. During the TIG welding a tungsten tip of the welding torch was imprisoned inside the weld. This tip survived the following chemical cleaning and produced a quench at 190 G. The field dependence of r.f. losses shows no kinks or switches and the SEM analysis revealed only W for the tip.

Fig. 6 W inclusion in a TIG weld as seen by a SEM. Mean radius estimated to $\sim 180 \mu\text{m}$.

Comparison with a model of thermal breakdown

It has been shown that lossy regions can produce fast breakdowns by a thermal instability for surface magnetic fields up to $\sim 400 \text{ G}$. This hypothesis is supported by a few experimental facts amongst which we note heating¹ of defects well below the breakdown field H_{max} or E_{max} and mode mixing experiments⁸.

A computer program³ has been written to model the thermal breakdown behaviour which incorporates all the heat production and heat transport factors, i.e. defect radius r_D , defect resistance R_D , surface resistance of SC niobium $R_s(T)$, wall thickness, thermal conductivity of niobium $K(T)$ and cooling-conditions of the He-bath. This effort was necessary since the complexity of the problem does not lend itself to an analytical solution. However, an inspection of table 1 shows that all defects belong to the case of defects producing breakdowns at field levels below $\sim 400 \text{ Gauss}$. For this kind of defect the power input into the defect is much larger than into the neighbouring superconductor and the program gives two predictions:

- The maximum dissipated power is proportional to the defect radius.

- The maximum local H-field scales with the square-root of the thermal conductivity K.

With the relation

$$P_{\text{diss}} = 1/2 R_s H^2 \cdot \pi r_D^2 \quad (1)$$

and by using the numerical results of the computer programme applied to our conditions one gets

$$P_{\text{diss}}^{\text{max}} = 36.4^\circ\text{K} \cdot \langle K \rangle \cdot r_D \quad (2)$$

and

$$H_{\text{local}}^{\text{max}} = \sqrt{\frac{23.2^\circ\text{K} \cdot \langle K \rangle}{R_s \cdot r_D}} \quad (3)$$

where $\langle K \rangle$ is the effective thermal conductivity between $\sim 4^\circ\text{K}$ and 9.2°K .

With formula (1) the resistance of the lossy spot can be computed if P_{diss} , r_D and H are known. Similar formula can be established for regions with dielectric losses.

For a comparison with the computer model one should keep in mind that it is not always possible to determine the effective size of a lossy region or the thermal conductivity of the underlying niobium which may be influenced by the lossy object. In addition the thermal contact between the defect and the Nb may be poor. Considering these uncertainties we find that the computer model gives the correct order of magnitude for the maximum tolerable dissipated power.

Conclusions

Temperature mapping was used for localising in 500 MHz and 3 GHz Nb cavities a number of small regions with increased r.f.-losses causing at some definite field level a thermal breakdown. It was always possible to identify by a SEM a surface defect at the origin of the increased r.f.-losses. Three types of defects were found up to now:

- Drying stains.
- Surface irregularities (scratches, protrusions, holes)
- Inclusions of foreign material.

These objects have typical dimensions between 20-1000 μm and for metallic defects the surface

resistances observed lie in the region around 5 mOhm corresponding to the value of normal conducting metals. Quench field levels correspond to local magnetic surface fields between 60 and 400 G and to electric fields of 0.9-9 MV/m. A comparison with a computer model for thermal breakdown gave a satisfying agreement between the measured and calculated dissipated power at the breakdown field. The result of these investigations lead us to improved care and cleanliness of all fabrication steps and surface treatments. In addition we were forced to a much more systematic optical inspection of cavity parts during and after fabrication. By using an optical telescope we were able to detect potential quench candidates and eliminate them by grinding before the final chemical polishing. In a series of 4 single 500 MHz cavities we reached acceleration fields above 6 MV/m at the first cooldown.

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