ELECTRON LOADING IN L- AND S- BAND SUPERCONDUCTING NIOBIUM CAVITIES*

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Summary

Electron loading has been investigated in superconducting niobium L- and S- band TM_{010} mode single-cell cavities at high field by observing the x-radiation which electrons accelerated by the RF fields produce on collisison with a cavity wall. This x-radiation has been studied for various cavity lengths, cavity resonant frequencies, and vacuum and surface conditions. Also, electron loading has been found to produce regenerative excitation of higher modes in both L- and S-band cavities.

Introduction

Electron loading is the principal factor which limits the maximum fields achieved in superconducting accelerator type cavities with frequencies below about 2 GHz.[1,2,3,4] Most instances of electron loading at high fields are probably the result of field emitted electrons which are accelerated by the cavity RF fields and eventually collide with a cavity wall producing x-radiation and secondary electrons. This relationship of electron field emission to electron loading in superconducting cavities has been rather convincingly demonstrated by x-radiation data over a range of five decades which fits a Fowler-Nordheim equation modified to include the effects of electron dynamics in the RF fields, x-radiation production, and absorption of the x-radiation by the cavity walls.[5] The modified Fowler-Nordheim equation for the x-radiation intensity I is of the following form:

$$I = C\, E^{6.5} \exp\left[-6.83 \times 10^{3}\, \phi^{3/2}\, v(y)/\beta E\right] \quad , \qquad (1)$$

where ϕ is the work function of the metal in eV, $v(y)$ is a function given in reference 6, β is the electric field enhancement factor, and E is the surface electric field in MV/m. It has been found that ordinary electron-field-emission theory alone can not adequately account for all of the experimental data related to the x-radiation for superconducting niobium cavities; however, if one includes the possibility of resonant tunneling due to adsorbed gases the x-radiation data can be adequately explained and the x-radiation intensity still has the dependence on the electric field given in Eq. (1). Since electron loading is an important factor which limits the fields in superconducting cavities, electron loading was investigated by observation of x-radiation as a function of various cavity characteristics.

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Experimental Results and Discussions

Table I gives x-radiation data for a number of superconducting niobium TM_{010} mode single-cell L-band cavities with resonant frequencies of nominally 1.3 GHz. The first column gives the cavity identification and test number. The third column gives the x-radiation flux from the cavity at a distance of 1 m from the cavity and at the maximum surface electric field given in the second column. The enhancement factor β based on the x-radiation data and Eq. (1) is given in the fourth column. By calculating the average x-ray energy (from x-ray energy spectrum measurements) as a function of electric field, it was possible to show that β values should not be significantly different for x-radiation data based on photon counting rates measured with NaI(Tl) crystals and on ionization measured with ionization chambers. It has in fact been our experience that β values based on these two x-radiation measurement methods are in agreement. The fifth column in Table I gives the x-radiation flux at a maximum surface electric field of 15 MV/m based on an extrapolation using Eq. (1) and the other values in the table.

The conditions under which x-radiation measurements were made on the L-band cavities were varied with respect to the nature of the cavity vacuum, the condition of the cavity surface, and the cavity length (and thus the voltage across the cavity at a particular electric field level). There were two different techniques used to provide a vacuum for the cavities. The first method (continuously pumped) was to provide continuous pumping using ultra-high-vacuum techniques (sputter-ion pump and appropriate materials) through the coaxial line which provided variable RF coupling to the cavity. This continuously pumped method had two disadvantages: (1) the pumping speed through the coaxial line from the pump to the cavity was very low, and (2) some parts of the vacuum system remained at room temperature while the cavity was below 4 K. The second method (permanently evacuated) employed a low temperature microwave coaxial window to provide coupling to the cavity. With this coaxial window it was possible to attach the cavity to an ultra-high-vacuum pumping system and after evacuation to permanently seal the cavity vacuum by pinching off the copper tube connected to the ultra-high-vacuum system. Both vacuum methods achieved vacuums on the order of 10^{-8} torr. There is a general difference in the x-radiation characteristics of cavities prepared with the two vacuum methods as shown in Table I: for the continuously pumped method the β values lie between 412 and 508, and for the permanently evacuated method the β values are between 314 and 377. This difference for the two vacuum methods is still generally evident when one compares the x-radiation flux normalized to 15 MV/m, however, not as clearly (B-2 and B-3 can not be included in this comparison since the x-radiation flux given is after helium-ion sputter processing). Apparently rather small changes in vacuum conditions can influence the x-radiation characteristics of cavities. This result may be understood from another experimental observation that, even though the field level is kept very constant, the x-radiation level under some condi-

TABLE I

X-Radiation Data On Superconducting Niobium L-Band Cavities

Cavity and Test	Maximum Surface Electric Field, E_{max} (MV/m)	X-Radiation at E_{max} (mR/h at 1 m)	Enhancement Factor, β	X-Radiation E_{max} = 15 MV/m (mR/h at 1 m)	Comments
E-1	10.2	50	424	2000	continuously pumped
D-4	6.7	.2	438	2800	anodized, continuously pumped
B-2	18.4	200*	508 (197)	14	continuously pumped, sputter processed
B-3	15.5	65*	493 (338)	49	continuously pumped, sputter processed
FQ1-6	12.6	20	494	57	continuously pumped
G-1	15.4	250	430	205	continuously pumped
G-2	17.0	200	412	79	continuously pumped
G-5	21.5	730	377	53	permanently evacuated
D-5	11.3	1.5	331	43	permanently evacuated
K-1	10.9	0.05	314	3.0	permanently evacuated

* These radiation values measured after helium-ion sputter processing. The β values appropriate to these x-radiation values are shown in parenthesis in the β column after the value of β before processing.

tions can change by factors on the order of two in time both increasing and decreasing. This observation suggests that the addition or removal of just a few adsorbed atoms at a field emitting site may have a relatively large effect on the field emission current and hence the x-radiation.

TABLE II

X-Radiation Data At S-Band

Cavity and Test	Max. Surface Electric Field, E_{max} (MV/m)	X-Radiation at E_{max} (mR/h at 1 m)	Enhancement Factor, β
7-3	30	2	115
7-6	20.6	.8	381
7-7	30	< .05	77
5-5	35.3	200	210
5-7	12.5	.4	247
8-3	19	1	252

Table II gives x-radiation data for a number of superconducting niobium TM_{010} mode single-cell S-band cavities with resonant frequencies of about 2.8 GHz. It is interesting to compare these S-band x-radiation data with those for L-band in Table I. The maximum surface electric fields for S-band are on the average about 1.7 times those for L-band. At these maximum electric fields, the β values and x-radiation flux values for S-band are considerably below those for L-band. The dynamics of the electrons in the cavity RF fields are not likely to influence the comparison of S-band to L-band data since the maximum fields scale approximately proportional to the frequency. Two possible explanations for the difference in the x-radiation from S-band and L-band cavities are (1) a statistical model for field emitting projections with high β (based on high electric field area) and (2) a frequency dependent field emission theory. All of the S-band cavity tests used low temperature microwave coaxial windows (permanently evacuated), and thus one should compare the data in Table II only with the last three entries in Table I. In as much as one out of six S-band cavity tests had a β similar to those for the three L-band tests and the area of an S-band cavity is about 1/5 the area of an L-band cavity, the x-radiation data supports a statistical model for field emitting projections of high β, although they by no means necessitate such a model. Although ordinary electron field emission is not likely to have any frequency dependence until well above the 1-10 GHz region, it may nonetheless be possible that resonant tunneling of electrons through the surface potential barrier (due to adsorbed gas) may have a frequency dependence in the 1-10 GHz region.

The cavities for all of the tests indicated in Table I were fired in ultra-high-vacuum at about 1800°C. This firing was the final processing step just before assembly and testing of the cavity, except for cavity test D-4 which was anodized to a depth of about 400 Å as a final processing step. As seen in the table, there is no obvious difference in the x-radiation characteristics between the anodized cavity and the fired cavities. The surface of two of the cavities (in tests B-2 and B-3) were subjected to helium-ion sputter processing while the cavities were at about 2K. This helium-ion sputter processing had a very dramatic effect on the β value and the x-radiation level. For example, in test B-2 the β value decreased from 508 to 197 along with a decrease by a factor of 0.01 in the x-radiation at 15 MV/m. The helium-ion sputter processing is discussed in detail elsewhere.[5]

The three last entries in Table I are cavities of different lengths which were permanently evacuated: cavity D is 10.0 cm long, cavity G is 7.8 cm long and

TABLE III

Regenerative Excitation of Higher Frequency Modes

Cavity and Test	Frequency of TM_{010} Mode (GHz)	Regeneratively Excited Mode and Frequency	E_{max} Required for Excitation (MV/m)	X-Radiation at E_{max} (mR/h at 1 m)
G-1	1.326	TM_{110}-2.017	15.4	200
G-2	1.326	TM_{110}-2.017	15.0	60
G-5	1.326	TM_{020}-2.937	21.5	65
7-6	2.847	TM_{110}-4.216	18.0	.8

cavity K is 5.9 cm long. It would appear from the Table that there may be some length dependence of the x-radiation characteristics, particularly in the x-radiation flux normalized to 15 MV/m; however, more measurements must be made to make any conclusion.

Regenerative excitation of higher modes by field emitted current accelerated by the RF field of the TM_{010} mode has been observed in both S- and L-band cavity tests. Table III gives the results for several cavity tests in which a higher frequency mode was excited. As can be seen from the table the higher frequency modes were only found along with a large x-radiation level and hence electron loading. Regenerative excitation of higher modes has been observed in both the TM_{110} and TM_{020} modes. This regenerative excitation of higher modes appears to be very similar to regenerative beam breakup in accelerators except that the electron current originates from electron field emission rather than from an accelerator beam. Measurements have been made which show that increasing the RF coupling and hence decreasing the loaded Q of the regeneratively excited mode increases the time required for build up of this mode. Also, there is a starting x-radiation level (or field level) for regenerative excitation of the higher mode. As the x-radiation level is increased above the starting level, the build up time for regenerative excitation decreases. Field emission currents calculated from the Fowler-Nordheim equation, x-radiation data, and typical field emission areas are on the same order as starting currents calculated for regenerative beam breakup based on the loaded Q and shunt impedance of the regeneratively excited mode.

Conclusions

Electron loading in superconducting niobium cavities at high fields has been investigated by observing x-radiation as a function of various cavity characteristics. It appears that the electric field enhancement factor β for electron field emission and the consequent x-radiation level depend on the cavity vacuum: β values and x-radiation levels were generally less for permanently evacuated cavities than for continuously pumped cavities which had parts of the vacuum system at room temperature. Also the x-radiation data support a statistical model for field emitting projections of high β based on the high electric field area, although they by no means necessitate such a model. It has been found that higher modes are often excited when large x-radiation levels are present. The excitation of these modes may be accounted for by regenerative excitation involving the field emitted current and the properties of the higher mode.

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