MEASUREMENTS ON SUPERCONDUCTING HELICES FOR THE FIRST SECTION OF THE SUPERCONDUCTING PROTON ACCELERATOR AT KARLSRUHE

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Abstract

Measurements on a superconducting helically loaded resonator are described. Peak electric fields up to 30 MV/m and magnetic fields up to 1000 G at high field Q's in the order of 10^8 were obtained in CW operation. Peak fields in the fundamental mode were limited by electron field emission and in the first harmonic mode by thermal breakdown. No drastic changes in Q and peak fields were observed due to cycling the resonator between He and room temperatures.

1. Introduction

The application of RF superconductivity to an accelerator requires an energy gradient of at least 1 MeV/m for economic feasibility. However, a given field on the axis corresponds to a much higher surface field in any practical accelerator structure. Surface fields can be limited either at a critical magnetic field, or by electron field emission or by surface losses which cause thermal breakdown. The obtainable energy gradient will then also be limited by one of these factors. For a helically loaded resonator, the field enhancement factor, i.e. the ratio of electric and magnetic surface fields to the accelerating field are both high compared to TE or TM cavities. The higher peak field to accelerating field ratio, the low frequency and the different fabrication technique make it difficult to compare the measurements of helically loaded resonators to cavity measurements.

We have previously reported measurements at 90 MHz for helically loaded resonators[1]. The helices used in these measurements were fabricated from 1/4 in. OD Nb tube, while the outer cylinder was made of lead plated copper. The essential result was that surface fields of 17 MV/m and 450 G could be obtained in steady state operation at high field Q's in the order of 10^8. The fields were limited by RF-surface losses often enhanced by field emission producing a thermal breakdown. The first section of a superconducting helix accelerator[2] is now under construction using this fabrication technique, i.e. niobium helices contained within a lead plated outer conductor.

In order to study another possibly more economic design of the helix accelerator, a smaller helically loaded resonator fabricated fully from Nb has been investigated. Different tests were performed to study the features of an all niobium technique in conjunction with an electropolishing and anodizing treatment. Special interest was paid to changes in Q's and peak fields due to aging and temperature cycling. The latter is of particular importance to the operation of a real accelerator.

2. Fabrication and surface treatments

The geometry of the helix resonator (fig. 1) was changed in comparison to the earlier measurements[1]. A smaller b/a and a smaller helix radius were used (table I).

Tables I

Parameters of the helically loaded resonator.

helix radius	a =	3.2 cm
radius of outer conductor	b =	6.4 cm
pitch	s =	1.0 cm
number of turns	n =	13
OD of tube	d =	0.63 cm
ID of tube	d_i =	0.48 cm
resonant frequencies	f_o =	80 MHz 139.5 MHz
geometry factors	G =	4.3 Ω, 5.1 Ω
helix parameter	x =	0.88
phase velocity	β =	0.06

The Nb tube was mechanically polished and wound on a mandrel. The outer conductor was rolled from a 3 mm Nb sheet and electron beam welded to form a cylinder. The Nb surface was further refined by electropolishing ($\sim$40µ)[3], after which the helix was outgassed for 1 1/2 h at 1000^0 C at a vacuum of 6 x 10^{-6} Torr to remove hydrogen.

Four different test runs were performed with this resonator. For test 1, the surface was cleaned by chemical polishing (10µ in 60 % HNO_3 and 40 % HF at -10^0 C). Before test 2 the resonator was cleaned with HF, chemically polished again and then anodized in a 12,5 % NH_3 solution (U = 12 V

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→ 240 Å of Nb_2O_5)[4) 5)]. Test 2,3 and 4 were then performed without subsequent chemical treatment of the surface. After test 2, the resonator was warmed to room temperature for a period of 2 days and then cooled for test 3. After test 3, it was warmed to room temperature for 10 days and cooled for test 4. During this time, the resonator was kept continuously under a vacuum of about 5×10^{-8} Torr. During these tests, "processing" with high RF power took place and surface changes may have occured.

3. Experimental procedure

RF coupling was accomplished with two variable probes in the top plate of the resonator (fig. 1).

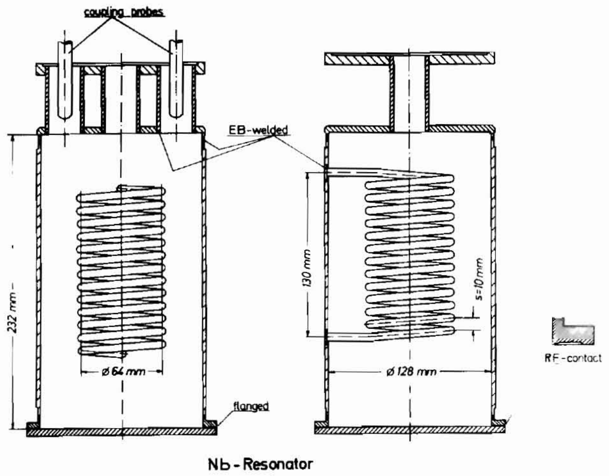

Fig. 1: Experimental layout of the full Nb helix

The associated coaxial lines were closed at the bottom end by "cold" ceramic windows, to separate the line vacuum from the cavity vacuum. The pumping connection to the resonator was closed by a piston just above the resonator after cooling down to lN_2-temperature to protect the sensitive superconducting surfaces against room temperature gaseous sources. The resonator pumped on itself by cryosorption.

The earth's magnetic field was shielded to about 5 mG. The electrical set up was identical with the one previously described[1)]. An RF generator (maximum power 8W) was tuned to the resonator frequency by phase sensitive feedback. The RF power reflected from and transmitted through the resonator was measured in the usual way. To avoid excitation of mechanical vibrations of the helix the RF input power was operated continuously. The adjustable input probes were fabricated of copper. The coupling losses in these probes were carefully determined and taken into account.

Field strengths have been determined by measuring the static frequency shift Δf_{stat}, due to radiation pressure,

$$\Delta f_{stat} \propto P_c Q'_o \propto \omega E^2 .$$

In the 80 MHz mode the relevant calibration measurements gave $P_c Q'_o\{W\} = 4.7 \times 10^5 \; \Delta f_{stat} \; \{kHz\}$. Perturbation measurements were performed at Frankfurt on a room temperature model of the same geometry to obtain the relation between $P_c Q'_o$ and field strength. Due to end effects, the field distribution in a short λ/2-helix is very difficult to calculate, whereas for a long helix (several λ/2) the theoretical values are in fairly good agreement with perturbation measurements[6) 7)]. The field enhancement between surface fields and axial fields is higher for the λ/2-helix than for the long helix, i.e. for given surface fields the axial field in a long helix is higher. For application in a superconducting helix accelerator one uses long helices (several λ/2-helices strongly coupled electrically). This effect has been taken into account using corrections described in ref. 1. In tables II and III, maximum surface fields are given along with axial fields, E_{OTW}, which would be present in a long helix. This would correspond to the obtainable energy gradient of a section of the superconducting accelerator.

4. Results and discussion

At the beginning of each test, unloaded Q's were measured at very low power levels (low field Q) for several modes. The best 4.2°K Q is lower than the theoretical value[8)] by a factor of about 5. Still we observed an improvement factor of about 4 to the temperature of the residual resistance. In the 80 MHz-mode, the best $Q_o = 11.2 \times 10^8$ at 1.8°K corresponds to a residual surface resistance of 3.8×10^{-9} Ω.

The low field Q's showed no systematic trends or significant degradation due to thermal cycling. In test 2, Q_o was probably degraded by frozen impurities on the surface, since after thermal cycling, Q rose by a factor of 3.

After the "processing" operation described below, Q was measured at successively higher field levels. There is evidence that Q degrades with long time processing at least for a given test run. However, when the resonator was warmed to room temperature the low field Q's were nearly reproduced. In tables II and III, the low field Q's and the Q's after processing (in brakets) are summarized for the fundamental mode at 80 MHz and the first harmonic mode at 139 MHz.

At low fields (below 40 G), two field saturation levels were observed in the 80 MHz-mode. These were explained as multipactoring. Multipactoring levels were also

Table II: Results of the 80 MHz-mode

Test nr.	$(Q_o)_{T<1.8^oK}$ low field	$(Q_o)_{T<1.8^oK}$ high field	E_{OTW} axis MV/m	E_{SW}^{max} MV/m	B_{SW}^{max} G	limitation
<1>	5×10^8	-	-	-	-	-
<2> anodized	3×10^8 (1.9×10^8)	0.75×10^8	3.0	23	950	insufficient generator power
<3> warmed up for 2 days	11.2×10^8	1.7×10^8	3.1 3.4*	24 26*	1000 1080*	field emission
<4> warmed up for 10 days	8.8×10^8 (6.5×10^8)	0.85×10^8	2.7	21	870	field emission

E_{OTW} is calculated for a long helix; Q's given in brakets are after processing. * values are short term operation.

Table III: Results of the 139 MHz-mode

Test nr.	$(Q_o)_{T<1.8^oK}$ low field	$(Q_o)_{T<1.8^oK}$ high field	E_{OTW} axis MV/m	E_{SW}^{max} MV/m	B_{SW}^{max} G	limitation
<1>	3.5×10^8	-	-	-	-	-
<2> anodized	2.9×10^8 (2.2×10^8)	0.8×10^8	2.5	29	800	insufficient generator power
<3> warmed up for 2 days	9.5×10^8	1.3×10^8	2.5	30	820	surface losses
<4> warmed up for 10 days	10×10^8 (5.6×10^8)	1.1×10^8	2.0	23	650	surface losses

E_{OTW} is calculated for a long helix; Q's given in brakets are after processing.

observed in the higher mode at 139 MHz. These barriers were overcome by "processing", i. e. applying high RF power to the resonator for several hours[1]. If a multipactoring barrier had vanished due to processing, it did not return at lower fields as long as the resonator was at helium temperature. Warming to room temperature and cooling down again brought back the same multipactoring barriers.

After processing, higher fields in the resonator were reached and x-rays were observed from the cavity. The maximum obtainable fields were limited in test 2 by the available generator power and in tests3 and 4 by field emission.

Electron field emission always started at peak surface fields of about 14 MV/m in the 80 MHz-mode and at 23 MV/m in the 139 MHz-mode. Fowler-Nordheim plots indicated enhancement factors for electron field emission of about 200. A radiation level of 500 mrem/h outside the dewar was observed at a field of E_{max} = 20 MV/m. An intensity maximum of the x-radiation was found at 120 keV.

High field Q's, just at the beginning of x-ray detection due to field emission, are also given in tables II and III. Q decreased considerably with field for example by a factor of 8 at a field of 14 MV/m in test 4.Results are given in figs. 2 and 3.

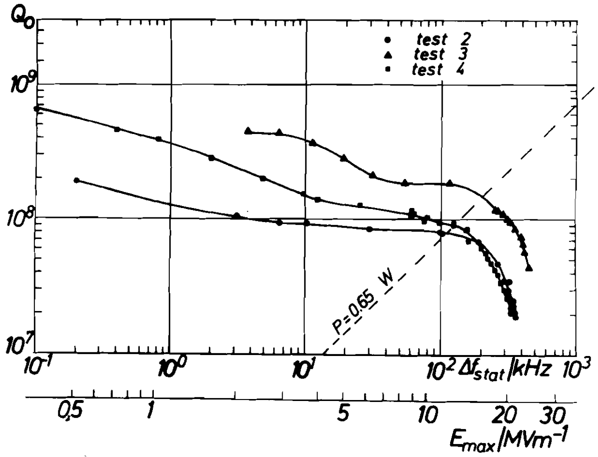

Fig. 2: Q as a function of peak electric field for the 80 MHz-mode.

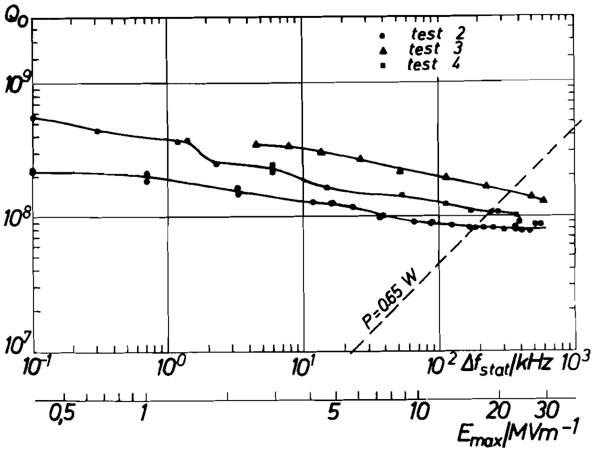

Fig. 3: Q as a function of peak electric field for the 139 MHz-mode.

The high field Q was always in the order of 10^8 for both modes. The highest surface fields were obtained in test 3, which had the largest high field Q. This may indicate a limitation in maximum fields by the cooling capacity. The helix tolerates a certain loss which is only dependant on the tube diameter. Recent measurements on the heat flow of superfluid helium gave for this particular tube diameter a critical heat flow of 1.7 W/cm^2 [9]. As a consequence, the helix tolerates a loss of 0.65 W. In addition, heat losses on the outer conductor will occur, which can be determined from our measurements by assuming a constant surface resistance in the field emission range. Then, the additional losses due to field emission can be substracted from the total losses. The heat losses on the outer conductor are determined with the further assumption that the helix itself will have a thermal breakdown at 0.65 W (line P=0.65 W in figs. 2 and 3).Thus heat losses on the outer conductor are in the order of 1 W (0.6 W at 24 MV/m in test 3 and 1.2 W at 21 MV/m in test 4). Additional losses caused by field emission were in the order of 5 W in the fundamental mode. Therefore, field emission was called the dominant mechanism of breakdown for this mode, whereas in the first harmonic mode at 139 MHz surface losses caused breakdown. Losses due to field emission were very small in the higher mode, since field emission did not start until 23 MV/m.

5. Conclusions

The present results and the previously ones reported from this laboratory [1] are the first results on anodized niobium helices. Anodizing of niobium together with electrochemical polishing has recently proven to be a successful method in S-band cavities [5]. We have transferred this method to the helix and did not look into other possible methods of surface treatment. In an electrochemical polished and anodized niobium helix we obtained surface fields as high as 24 MV/m and 1000 G in the 80 MHz mode and 30 MV/m and 820 G in the 139 MHz mode.

With respect to the first section of a superconducting proton accelerator the present results may be summarized as follows:

- the full Nb technique gave the same Q's and higher peak fields than the mixed Pb/Nb-technique in a larger geometry.
- no significant degradation of Q and field was found with time and thermal cycling.
- the obtainable energy gradient in the first section of a superconducting helix accelerator should be at least 2.5 MeV/m.
- if one operates at an energy gradient of about 2 MeV/m, only little x-radiation due to field emission should be present.

However, our results are also rather surprising. The Q's of the helix are relatively moderate but the observed surface fields are high and only comparable with results obtained on very small X-band cavities (10 GHz) [10] [11]. One therefore is tempted to look for the common properties between helically loaded resonators and X-band cavities.

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References

(1) J.L. Fricke, B. Piosczyk, J.E. Vetter and H. Klein, Kernforschung Karlsruhe, to be published in Part. Acc.
(2) A. Citron, Kernforschung Karlsruhe, Proc. 1970 Proton Lin. Acc. Conf. NAL Batavia, Vol. I, 239 (1970)
(3) H. Diepers, O. Schmidt, H. Martens, R.K. Sun, Phys. Lett. (1971) to be published
(4) H. Martens, H. Diepers, R.K. Sun, Phys. Lett. 34A, 439 (1971)
(5) P. Kneisel, O.Stoltz, J. Halbritter, H. Diepers, H. Martens, R.K. Sun, this conference
(6) O. Siart, Dissertation Uni Frankfurt (1970) to be published in Part. Acc.
(7) A.J. Sierk, C.J. Hamer and T.A. Tombrello, Part. Acc. 2, 149 (1971)
(8) J. Halbritter, Z. Phys. 238, 466 (1970)
(9) G. Krafft, Kernforschung Karlsruhe, to be published
(10) J.P. Turneaure and Nguyen Tuong Viet, Appl. Phys. Lett. 16, 333 (1970)
(11) M.A. Allen, Z.D. Farkas, H.A. Hogg, E.W. Hoyt and P.B. Wilson, IEEE Trans. Nucl. Sci., NS 18, No. 3, 168 (1971)