SUPERCONDUCTING ACCELERATING STRUCTURES FOR HIGH ENERGY ACCELERATORS

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Summary

Superconducting accelerating systems are presently under design, test or construction for large e^+-e^--storage rings and Linear Accelerators for Nuclear Physics research. Recent results from different laboratories and the progress in rf superconductivity of the past year is summarized briefly. New experiments with superconducting accelerating structures for velocity of light particles at frequencies between 350 MHz and 3 GHz show that an accelerating field of 5 MV/m is within reach today. The thermal stability of s.c. cavities has been increased significantly by improving the thermal conductivity of niobium with different techniques or by sputtering niobium onto copper cavities. Experiments with high thermal conductivity cavities at 500, 1500 and 3000 MHz and new developments in the design of superconducting structures are discussed.

Introduction

This year is the 20th anniversary of the first acceleration of electrons in a superconducting lead plated resonator at Stanford [1]. Between 1968 and 1970 very successful experiments with X-band-resonators fabricated from niobium [2] formed the basis for large scale systems built thereafter.

In the beginning of the 70's construction of the Stanford Superconducting Recyclotron [3], the Illinois Microtron using a superconducting accelerating section [4] and the CERN - Karlsruhe s.c. Particle Seperator [5] was started. In 1974 a superconducting resonator successfully accelerated a beam to 4 GeV in the CORNELL Synchrotron [6] and in 1976 the construction of the ARGONNE s.c. Heavy Ion Postaccelerator was begun [7]. Several of these devices have now been operated for many thousands of hours reliably and under routine conditions. It was shown that the drastic reduction of the rf surface resistance in s.c. cavities could be achieved even in complex resonators. The early expectations, however, to reach the very high electric accelerating or deflecting fields promised by the elementary theory of superconductors in radio frequency fields were not fulfilled. In analysing the performance of s.c. resonators it is necessary to consider their geometry. S.c. structures for proton and heavy ion accelerators therefore have to be discussed separate from accelerating structures for electrons. According to the title of my talk I want to focus on velocity of light structures.

The accelerating fields of 2 - 3 MV/m achieved in operating s.c. electron accelerators are about 10 to 15 times lower than promised by BCS - theory. This moderate achievement has lead to the impression that high duty factor electron accelerators should be based on classical technology and the cascaded microtron now under construction at Mainz is certainly an attractive alternative for energies below 1 GeV.

The early results at X-band frequencies and very encouraging and recent experiments at S and L-band, however, show that there are no additional fundamental limits and further research and development of s.c. rf technology should be rewarding. A new technology needs definite projects for its development and the 130 MeV s.c. recyclotron presently under construction at the Technische Hochschule in Darmstadt is a welcome opportunity.

The most ambitious continuous wave s.c. accelerating systems are planned today for the new high energy electron positron storage rings. It is recognised that for these accelerators superconducting accelerating systems are superior to normal conducting ones. Already energy gradients of 3 MeV/m result in significant power savings and the smaller number of cavities and their large iris diameter will increase threshold currents for beam instabilities and will therefore lead to higher luminosities. The experimental efforts and results connected with prototype experiments for electron positron storage rings have been summarized and discussed in last years conferences at Santa Fe [8] and Chicago [9,10]. I do not want to repeat the description of the successful storage ring experiments of the groups at CERN, CORNELL and KARLSRUHE, but try to give a brief summary of recent achievements.

Current Projects

Table 1 summarizes essential parameters and accomplishments of current projects in superconducting rf. Five projects span the frequency range from 350 MHz to 3 GHz. At CERN a five cell 500 MHz structure was developed during 1982 and used for a storage ring test at PETRA [10]. This five cell array has recently been tested and 5 MV/m were obtained after a proper surface treatment which was not possible prior to the test in PETRA. The experiments at CERN prepare the later use of s.c. accelerating units in LEP to upgrade its energy beyond 50 GeV. The present rf design for LEP asks for a frequency of 350 MHz. A single cell cavity was built for this frequency. This

LABORATORY		CERN		KEK	DESY	CORNELL	DARMSTADT/ WUPPERTAL
PROJECT		PROTOTYP FOR LEP		PROTOTYP FOR TRISTAN	PROTOTYP FOR PETRA	PROTOTYP FOR CESR	RECYCLOTRON 130 MeV
TYPE OF STRUCTURE		SPHERICAL		SPHERICAL	ELLIPTICAL	ELLIPTICAL	SPHERICAL
FREQUENCY (MHz)		350	500	500	1000	1500	3000
OPERATING TEMPERATURE		4.2 K	4.2 K	4.2 K	4.2 K	1.8 K	1.8 K
BEST VALUES OF SINGLE CELL CAVITIES	E_a (MV/m)**	5.4	8.7*	6.5	5.5	11.8*	13.0*
	Q at high field	$3.5\cdot10^9$	$1\cdot10^9$	$4.1\cdot10^9$	$5\cdot10^8$	$1\cdot10^{10}$	$3\cdot10^9$
MULTICELL RESULTS		-	5-CELLS	3-CELLS	9-CELLS	5-CELLS	5/20-CELLS
	E_a (MV/m)**		5.0	5.8	5.5	5.4	5.7/4.2
	Q at high field		$0.7\cdot10^9$	$0.6\cdot10^9$	$5\cdot10^8$	$4.5\cdot10^9$	$4/3\cdot10^9$

Table 1: Essential parameters and achievements of current projects in superconducting rf, including all storage ring projects.
*) Cavities fabricated from high thermal conductivity niobium **) Under continuous wave operation

cavity was operated recently up to an accelerating field of 6 MV/m. This experiment shows that the choice of frequency is not primarily decisive for the obtained accelerating gradients. At KEK in Japan a 3 cell 500 MHz structure is scheduled for a beam test in the TRISTAN accumulation ring during the next months [11]. At DESY a project on superconducting rf was started with 1 GHz as operating frequency. There a twin module of two nine cell structures housed in one cryostat (fig. 1) is

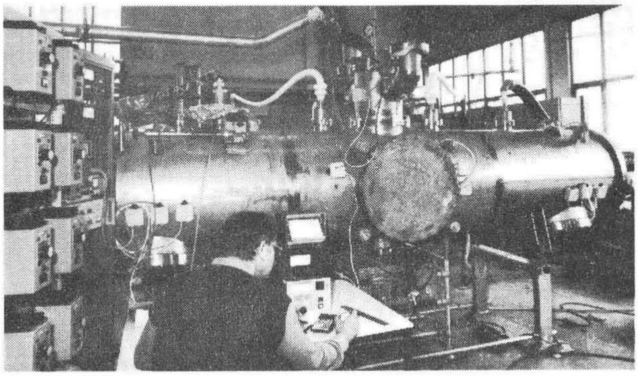

Fig. 1: DESY cryostat housing two nine cell (1 GHz) accelerating structures.

under construction and prepared for an experiment in PETRA during this summer [12]. At CORNELL a design of rotational symmetry is tested in order to compare its performance with the muffin tin structures already successfully operated in the CORNELL synchrotron and in CESR. Two five cell cavities (1.5 GHz) are presently prepared for a beam test in CESR [13]. The 5 and 20 cell 3 GHz structures (fig. 3) of table 1 are building blocks of a superconducting cw electron linac of 40 MeV which serves as the accelerating sections for the Darmstadt Recyclotron. This accelerator project is built in collaboration between the Universities of Darmstadt and Wuppertal. In a pilot experiment the 5 cell cavity was used to accelerate electrons during many experiments in the course of last year to an energy of approximately 1 MeV [14]. The accelerating field of the structure of 5.7 MV/m and the Q of $4 \cdot 10^9$ remained unchanged during this period.

The accelerating field of 5 MV/m which has been achieved in so many different laboratories at very different frequencies is one of the noticable achievements of the last year and one can be confident that 5 MV/m is today a good design value for velocity of light accelerating structures.

Structure Design

The high Q of s.c. accelerating structures is the main benefit of cryogenic accelerators. This feature relaxes the requirement to design structures for a maximum of relative shunt impedance r/Q, which is an essential figure of merit for normal conducting cavity arrays. Other design criteria can be considered, the most important of which are summarized in the following:

The individual cells of the array should be of spherical or elliptical shape to avoid one side electron multipacting. Chemical surface treatment and the subsequent rinsing procedures should be possible without an enhanced danger of residues (nose cones for example should therefore be avoided). All cells should be equal to avoid an unnecessary complexity of the higher order mode spectrum of the array. The band width of the most dangerous higher order modes should be as large as possible which leads to relatively large iris diameters. The tuning of the end cells should take into account the flatness of the field distribution of the critical higher modes [15]. This is specifically important if all rf couplers are to be located at the beam tube. Beam tube couplers avoid geometrical disturbances of the individual cavity cells and reduce the complexity of cryogenic engineering. They are therefore used in most of the recent designs.

Many of these conditions have influenced the design of present superconducting accelerating structures and have changed them compared to designs now in use. A very powerful computer code (URMEL) has been developed by T.Weiland [16]. It allows the computation of all higher order modes excited in resonators of rotational symmetry. The recent design of the s.c. accelerating structure for LEP [15] has made for the first time the attempt to take all design criteria listet above into account. The new LEP cavity is shown in fig. 2. The dimensions of the

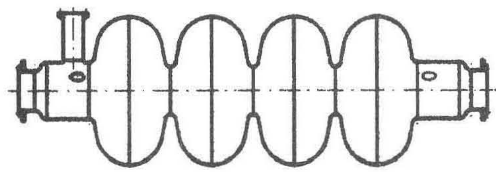

Fig. 2: Design of the new s.c. prototype resonator for LEP

wide portion of the beam tube are chosen to achieve a flat field distribution not only for the fundamental but also for the higher order modes (TM011 and TM012) which are most critical in the envisaged storage ring application. Figure 3 shows the accelerating structures of the Darmstadt Recyclotron. The beam tube diameter has been chosen for a free propagation of TM110 mode. The wide beam tube propagates all dipol modes excited inside the structure for frequencies above 3.5 GHz and all monopole modes (TM_{onp}) with the exception of the fundamental mode. Should the normal conducting and demountable coupling port not be sufficient to load critical modes, appropriate loading antennas can be added without disturbing the s.c. structure.

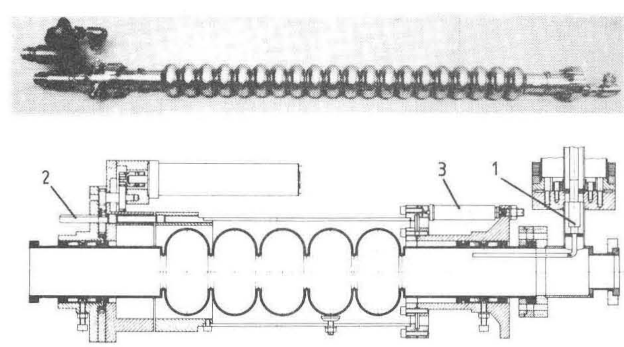

Fig. 3: 20 cell accelerating structure of the Darmstadt s.c. Recyclotron and schematic of a five cell structure including input coupler (1) and tuning system with motor driven course (2) and piecoelectrically driven (3) fine tuner.

Dynamic tuning is a necessity for s.c. structures. In present designs this is done by changing the length of the structure by motor driven, pneumatic or piecoelectric mechanisms (see fig. 3).

The proper choice of the operation frequency for s.c. accelerating cavities shall not be addressed in detail. The developments of the last years have shown, that in the frequency range from 350 to 3000 MHz a significant frequency dependence of the maximum obtainable accelerating field cannot be found for extended structures. For accelerating fields below 5 MV/m the correct choice of frequency is determined by accelerator physics requirements and economy. For storage ring frequencies in the range from 300 to 500 MHz at operating temperatures of 4.2 K appear as a good choice. For linacs where large apertures are not required 2 to 4 GHz at an operating temperature of around 2 K are very suitable.

Field Limitations and Thermal Stability

The origin of field limitations far below theoretical promise is since long one of the main subjectives for research on s.c. cavities. In 1979 the technique of temperature mapping was developed at CERN and it was demonstrated that well localized defects were one of the prime causes for quenching [17]. This was assumed since long, but this diagnostic method allowed the localisation, investigation and the guided removal of these defects and helped to improve the reliability with which accelerating fields of around 5 MV/m could be obtained also in multicell cavities. The observed defects are of a large variety. Chemical residues (drying stains), metal inclusion (iron, tantalum, tungsten), cracks in welds, welding splutter or voids were found to be responsible for excessive local losses, which can lead to a quench of the cavity field. The detection of the quench location allows its removal for example by grinding. After each grinding procedure a short chemical cleaning is necessary which always includes the danger of new defects (i.e. chemical residues or dust). Fig. 4 shows as an example the temperature map of the first 20 cell structure for the Darmstadt Recyclotron with clearly visible defects and a quench field of 3.7 MV/m. After grinding in several locations of enhanced losses the accelerating field was improved to 4.2 MV/m, but a new defect was introduced as can be seen from fig. 4.

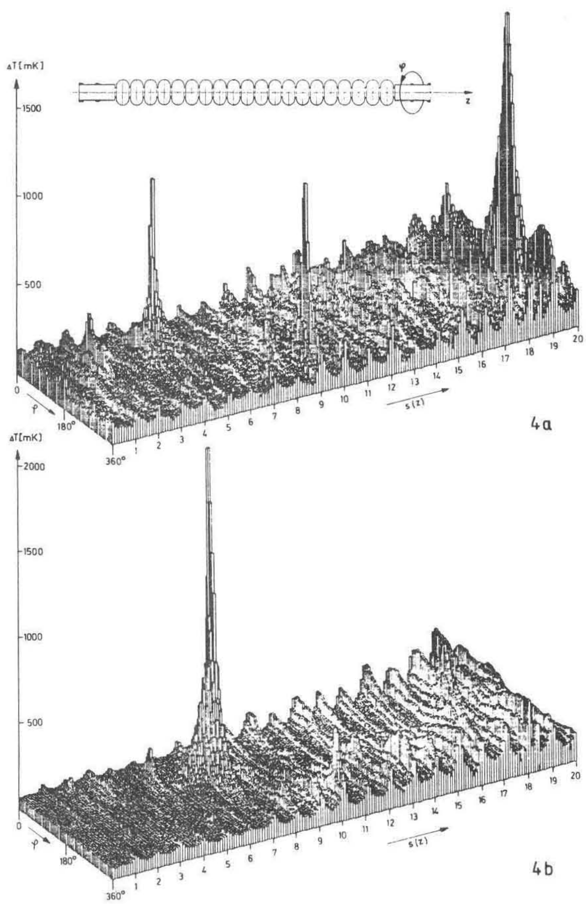

Fig. 4: Temperature map of the 20 cell accelerating unit of the Darmstadt Recyclotron after first test (fig. 4a, quench field 3.7 MV/m) and after grinding (fig. 4b, quench field 4.2 MV/m, showing the creation of a new defect during the repair cycle. The coordinate S(Z) measures the surface distance along the axial direction Z of the structure. The temperature elevation (ΔT) in the iris regions is due to the reduced cooling of these zones in the subcooled helium bath.

For a long time it was in the center of interest to avoid or to remove such defects and little interest was paid to the question of the thermal stability of s.c. cavities. It was pointed out by H. Padamsee [18] that the threshold field for thermal instabilities can be increased substantially if the thermal conductivity of the cavity wall is improved. To achieve this two alternative approaches have been followed recently. In one attempt one tries to increase the conductivity of the niobium itself. Another possibility is to deposit a very thin layer of niobium onto a high conductivity material like copper. At CERN the thermal conductivity of niobium from different manufacturers has been measured [19]. A typical temperature dependence of λ is given in fig. 5. The

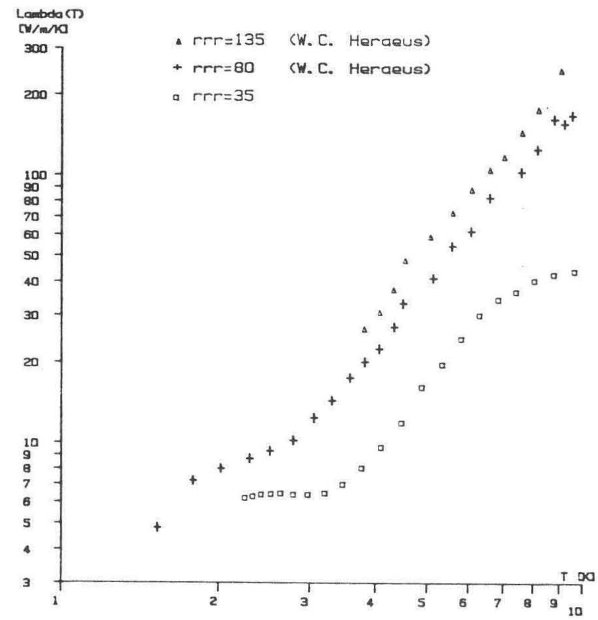

Fig. 5: Temperature dependence of the thermal conductivity of niobium sheet material of different Residual Resistivity Ratios (RRR).

residual resistivity ratio (RRR) of niobium is to a good approximation proportional to its thermal conductivity at 4.2 K. The material used so far shows rrr-values between 20 and 40, whereas the theoretical limit is as high as 35000 [20]. This large difference indicates that there is ample room for improvement. In standard reactor grade niobium the interstitial impurities O, N, C and H [20] dominate the poor conductivity of this material. These impurities can be controlled to a large extend during the electron beam melting of the raw niobium and the consecutive forging, rolling and annealing steps. Influenced by the above considerations, W.C. Heraeus (Hanau, W. Germany) refined its production process and sheet material with RRR values of 80 and 135 could be produced (fig. 5). The difference between the two kinds of material is explained by the different vacua during the final annealing. For the very large sheet material necessary for the 500 MHz cavities at CERN a standard vacuum furnace with diffusion pumps has to be used. The material with RRR = 135 was annealed in the UHV-furnace in Wuppertal. One 500 MHz and one 3 GHz cavity was fabricated from RRR = 80-material and tested. At 500 MHz E = 8.7 MV/m was obtained [21] at first test (high field Q_o of $1 \cdot 10^9$ at 4.2 K). At 3 GHz in four experiments, each time after a new surface treatment, quench fields between E_a = 7.5 and 12 MV/m were reached. Both experiments (at 500 MHz and 3 GHz) exceeded all previous results at CERN or at Wuppertal. Another 3 GHz cavity was built from RRR = 135 niobium and tested. In two experiments (with a new surface treatment each time) 13.6 MV and 16.3 MV/m were obtained. These values were limited by large field emission currents and the available rf power. In fig. 6 the recent results from CERN, DESY and WUPPERTAL are plotted against the RRR value of the

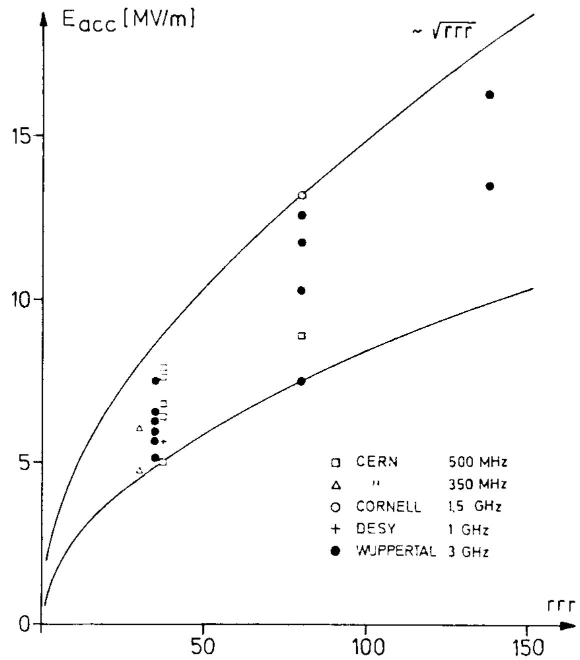

Fig. 6: Dependence of the quench field of different single cell cavities and their thermal conductivity.

materials used. The scatter of the data at a fixed RRR value is due to different defects. For a given defect the quench field should increase with the square root of the RRR value. Although the number of experimental results for high RRR cavities is still low fig. 6 indicates the tendency of a quench field increasing with thermal conductivity. At CORNELL two methods have been used to improve the thermal conductivity of commercial niobium [13]. The starting materials were standard reactor grade niobium (500 - 1000 ppm Ta) and electrodeposited niobium with a low tantalum content. X-band cavities were outgased between 1950 and 2200° C at 10^{-8} to 10^{-10} Torr in an induction furnace with cold walls. Maximum RRR values of 550 (for standard niobium) and 1400 (for the Ta-free material) were obtained. In 40 tests magnetic surface fields between 250 and 1250 G were measured. (This corresponds to accelerating fields of about 6 MV/m to 30 MV/m). Although the Ta-free niobium is expensive and the very high temperature outgassing is hardly conceivable for large cavity arrays, these experiments show the expected correlation $E_a \sim \sqrt{RRR}$ as indicated also in the data displayed in fig. 6. Another much more suitable procedure to clean standard niobium from the most critical oxygen is the evaporation of Yttrium onto the niobium surface, developed at CORNELL. During high temperature treatment of several hours at 1200°C the interstitial oxygen migrates into the Yttrium layer which has a higher affinity to oxygen than niobium. This oxygen enriched layer is then chemically dissolved. Starting with a material of RRR = 25 an RRR of 100 could be obtained. A cavity was welded together after its cups had been treated according to this procedure. A surface magnetic field of 600 G. (E_a approx. 13 MV/m) was obtained at a low field Q of $5 \cdot 10^{10}$. Heavy field emission was encountered at this field level.

At CERN a quite different approach is persued to increase the thermal stability of s.c. cavities [22]. A single cell 500 MHz cavity was built from OHFC and a niobium layer of a thickness ranging from 1.5 to 5 µm was deposited by sputtering. The cavity was rf tested and a very encouraging accelerating field of 8.6 MV/m was obtained. The low field Q of $2 \cdot 10^9$ (4.2 K) degraded to $3 \cdot 10^8$ at the maximum field. Due to its very high conductivity the cavity remained stable and only the available rf power (190 W) determined the maximum field. The Q deterioration is due to defects which have most likely been introduced during the sputter process and appear to be avoidable.

If one considers these new results one is lead to conclude that the high field limits set by the BCS theory can be reached if one only continues along the discussed line. This, unfortunately, is not true. At peak electric surface fields of 20 to 30 MV/m (corresponding to accelerating fields of about 7 to 10 MV/m electron field emission from the cavity walls becomes the dominating limitation. Field emission currents grow exponentially with the electric field and cannot be compensated by even the highest thermal conductivity (t.c.) which is technically feasible. The high t.c. cavities at CERN, CORNELL and WUPPERTAL are already limited in their performance by heavy electron loading. The quench of the CERN cavity at 8.7 MV/m is caused by field emitted electrons which is clearly seen in the two temperature maps shown in fig. 7. The reduction of field emission

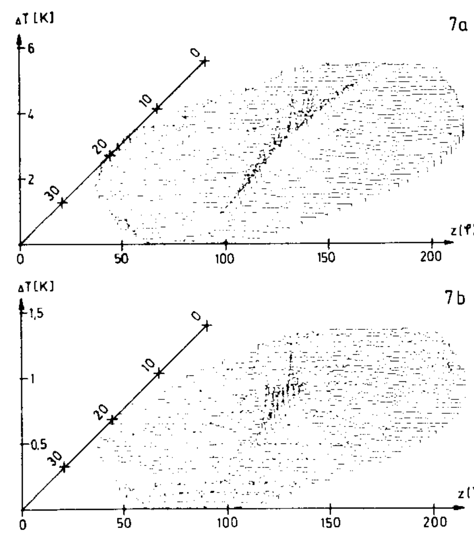

Fig. 7: Two temperature maps of the CERN 500 MHz cavity. Fig. 7a shows the temperature increase induced by electrons emitted from single source. Fig. 7b shows the cavity during quenching initiated by field emission. The temperature increase ΔT of the outer surface of the cavity is plotted against the surface coordinates s(Z) and S(ϕ). S(Z) is the length (in arbitrary units) measured along the meridian of the cavity surface and S(ϕ) gives the azimuthal location.

currents is one main problem to be solved. A very useful tool is the reduction of the emissivity of field emitting sites by He ion sputtering [23]. During this process a s.c. cavity is operated at high electric field under a partial He-pressure of about 10^{-5} Torr and the ions produced by the emission current are accelerated back onto the emitting site. The effectivity of this sputter process increases with the obtainable electric surface field. Cavities not limited by defect induced quenches allow a more effective use of this technique. In the 3 GHz cavity RRR = 135, tested in WUPPERTAL, the field emission current was reduced after only 20 minutes of the ion sputtering by many orders of magnitude. The apparent Fowler Nordheim field enhancement factor β was reduced from 570 to 135 and the cavity could be operated at about twice the field. This can be seen from fig. 8 where the Q value of this cavity is plotted against the accelerating field before and after the ion sputtering. Experiments on artificial emitters (graphite particles are

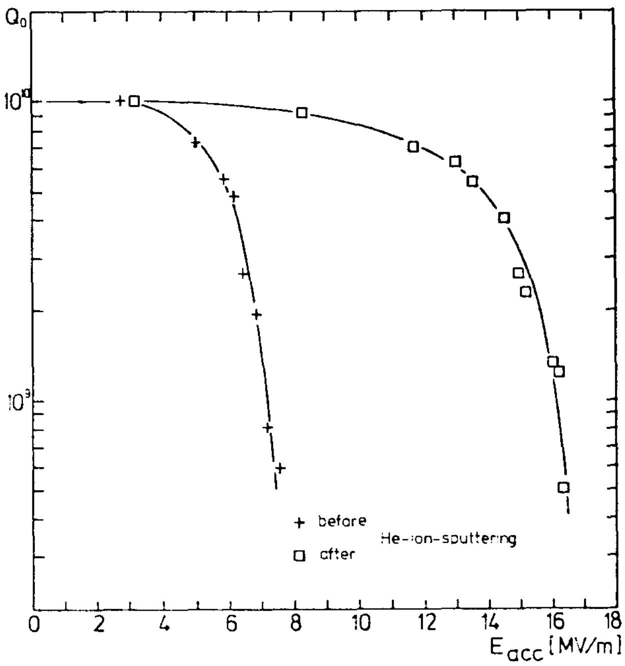

Fig. 8: Dependence of the cavity Q on the accelerating field before and after He-ion sputtering. (T = 1.5 K)

interesting candidates) introduced into s.c. cavities are underway at CERN, to gain more insight into the nature of rf field emitters and to learn more about the physical process responsible for the observed reduction of emission currents by He ion sputtering. D.C. field emission experiments on broad area niobium electrodes using modern surface analytical tools (i.e. scanning electron microscopy and scanning Auger spectroscopy) have been started at the University of Geneva. They will hopefully give more insight into the nature of the field emitting sites on cavity surfaces. The rôle of secondaries emitted by the impact of field emitted electrons in rf cavities needs experimental and computational analysis. Work in this direction is going on at CERN and CORNELL.

A careful discussion of our present knowledge of field emission goes beyond the scope of this report but it is clear that the work in this field has to be continued in order to improve the performance of s.c. cavities further.

Conclusion

In the past year accelerating fields of 5 MV/m have been obtained with manufacturing procedures, suitable for large scale production of extended accelerating structure in the frequency range from 350 MHz to 3000 MHz. Large storage ring projects are planned on this basis. Recent work has improved the design of s.c. cavities.

Progress also can be stated in achieving a better thermal stability of s.c. cavities either by sputtering niobium onto copper or by significantly increasing the thermal conductivity of commercial niobium. This development contributes a safety margin to design accelerating fields of 5 MV/m and relaxes the conditions for the surface preparation of s.c. cavities. At the same time these experiments have opened a new possibility to come closer to the theoretical limits promised by the BCS theory. Field emission is the next hard barrier to be overcome.

The construction of the 130 MeV s.c. Recyclotron in Darmstadt offers a welcome opportunity to push the technology of rf superconductivity. The results of the oncoming storage ring experiments in CORNELL, DESY and KEK offer new tests of accelerating units with accelerating fields in the 5 MV/m region. The plans to go beyond 50 GeV in the LEP storage ring have a good foundation with the present achievements and a large scale application of this kind will have an unprecedented impact on rf superconductivity and its rôle in the design of new high energy accelerators.

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References

1. J.M.Pierce, H.A.Schwettman, W.M.Fairbank, P.B.Wilson, Proc. of the 9th International Conf. on Low Temperature Physics,Part A(Plenum Press,N.Y.1965),p.396
2. J.P.Turneaure and Ira Weissman, J.Appl.Phys. 39(1968), p.4417
3. C.M.Lyneis, M.S.McAshan, R.E.Rand, H.A.Schwettman, T.I.Smith and J.P.Turneaure, IEEE Trans.Nucl.Sci. NS-28(1981),p.3445
4. P.Axel, L.S.Cardman, H.-D.Gräf, A.O.Hanson, R.A. Hoffswell, D.Jamnik, D.C.Sutton, R.H.Taylor and L.M. Young, IEEE Trans.Nucl.Sci. NS-26(1979),p.3143
5. A.Citron, G.Dammertz, M.Grundner, L.Husson, R.Lehm and H.Lengeler, Nucl.Instr.Meth. 164(1979), p.31
6. R.M.Sundelin et al., Proc. of the 9th International Conf. on High Energy Accelerator (1974), p. 128
7. L.M.Bollinger, Proc. National Accelerator Conf.(1983) IEEE Trans.Nucl.Sci NS-30(1983), p.2065
8. M.Tigner, Proc. of the 1983 Particle Conf.,Santa Fe, IEEE Trans.Nucl.Sci. NS-30(1983), p.3309
For a recent review see M.Tigner, H.Padamsee CLNS-82/ 553, Cornell 1982 AIP Conf. Proc. (USA) No.105,801 (1983)(U.S. Summer School on High Energy Particle Accelerators, Stanford, CA, USA 2.-13. Aug.1982
9. H.Piel, Proc. of the 12th International Conf. on High Energy Accelerators, Fermilab 1983, p.571
10. Ph.Bernard et al., Proc. of the 12th International Conf. on High Energy Acc., Fermilab 1983, p.244.
11. Y.Kojima, private communication
12. W.Ebeling et al., Proceedings of the 1983 Accelerator Conf., Santa Fe, IEEE Trans.Nucl.Sci. NS-30 (1983), p. 3357
13. H.Padamsee, private communication
14. H.Heinrichs et al., Proc. of the Conf. on Nuclear Physics with Electromagnetic Interactions (1979) Lecture Notes in Physics 108, p.176 and T.Grundey et al., to be published in Nucl. Instr. Meth.
15. E.Haebel, P.Marchand, J.Tückmantel, CERN/EF/RF 84-2 (1984)
16. T.Weiland, DESY 82-015 and DESY M-82-24.
17. Ph.Bernard et al., Proc. of the 11th International Conf. on High Energy Accelerators,Geneva(1980),p.878
18. H.Padamsee, IEEE Trans.Magn. Vol. MAG-19 (1983), p. 1322
19. A.Schopper and W.Weingarten, CERN/EF/EF 83-7
20. K.Schulze, Journal of Metals, Vol. 33, No. 5(1981), p. 33
21. W.Weingarten, private communication
22. Ch.Benvenuti, private communication
23. H.A.Schwettman, J.P.Turneaure and R.F.Waites, Journ. Appl.Phys. 45 (1974), p. 914