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RECENT PROGRESS IN RF SUPERCONDUCTIVITY

H. Piel
University of Wuppertal, Department of Physics
D-5600 Wuppertal, W.Germany

Summary

The wide spread activities to prepare major size superconducting accelerating systems mainly for the large storage rings presently under construction in Europe and Japan are based on the continuous progress in rf superconductivity achieved in the past years.

The thermal stability of s.c. cavities has been increased significantly by improving the thermal conductivity of niobium with different techniques. The promising attempts to sputter high purity niobium onto 500 MHz copper cavities have shown encouraging results. Multicell cavities at 3 GHz coated with Nb_3Sn achieved high Q values already at 4.2 K. Field emission studies using modern surface analytical tools are shedding more light on anomalous electric surface breakdown fields.

This report summarizes briefly the current activities in different laboratories and comments on recent achievements with superconducting cavities and in materials research. It concentrates on work performed prior to the preparation of accelerator experiments. These are discussed by R. Sundelin [1] and in other contributions to this conference.

Introduction

Research and development in radio frequency superconductivity progresses traditionally along two lines. It is for one the investigation of anomalous field limitations and power loss mechanisms in superconducting cavities. Final goal of this research is the achievement of the critical rf fields and the surface resistance predicted by theory which promises accelerating fields in niobium or Nb_3Sn resonators between 50 and 100 MV/m at rf losses of a few tens of Watts per meter of structure. The other line is characterized by the application of the momentary state of the art of this technology to accelerators for nuclear physics research, free electron lasers or as in recent times to the large electron positron storage rings in Europe, Japan and the United States. A comprehensive review of fundamentals and applications of rf superconductivity was attempted at the 2nd Workshop on RF Superconductivity at CERN last year [2]. The most recent tests of superconducting cavities in the storage rings CESR at CORNELL, TRISTAN at KEK and PETRA at DESY have been quite successful. Their essential results will be discussed in Ron Sundelins report at this conference [1].

The Superconducting Cavity Stabilized Oscillator[3] and the Single Atom Maser [4] are beautiful examples for the application of rf superconductivity in metrology. The true challenge to the field however always came from accelerator physics. Todays achievements allow the planning of accelerators using superconducting rf cavities with accelerating fields of 5 MV/m and Q values in the few times 10^9 regime. This is very adequate for the energy upgrading or energy saving programs for the large storage rings.

If one considers the use of superconducting cavities for the possible next generation of electron accelerators [5] - the linear colliders - then those design figures are not sufficient. It would be necessary to come much closer to the theoretical limits in a reproducible manner. Today we don't know of any fundamental phenomena which would prevent the operation of superconducting linear accelerators at accelerating fields of more than 20 MV/m and at Q values higher than $5 \cdot 10^{10}$. This report tries to describe the present status of the field and shall be considered as a continuation of previous reviews [6,7].

Superconducting cavities for electron accelerators

In order to evaluate the performance of s.c. cavities one has to compare resonators of similar shape. Today all resonators for electron accelerators are of the spherical or elliptical design. Cavities for heavy ion accelerators are quite different in geometry and their performance, although influenced by the same limiting mechanisms, is therefore discussed separately during this conference [8].

Table 1 summarizes important parameters and accomplishments in rf superconductivity applied to electron accelerators. The most ambitious program is underway at CERN. There one has started the prototype work for the production of eight four cell cavities of 352 MHz to be installed in the LEP storage ring in order to perform a large scale experiment [9]. If this will prove successful then the energy of LEP will be upgraded to about 100 GeV per beam using a s.c. accelerating system. The first prototype of such a four cell unit is shown in fig. 1.

LABORATORY	CERN			KEK	DESY	CORNELL	DARMSTADT/WUPPERTAL	
ACCELERATOR	LEP			TRISTAN	PETRA/HERA	CESR	130 MEV RECYCLOTRON	
MATERIAL	Nb	Nb	Nb on Cu	Nb	Nb	Nb	Nb	Nb_3Sn
FREQUENCY IN MHz	350	500	500	500	1000	1500	3000	3000
OPERATING TEMPERATURE	4.2 K	4.2 K	4.2 K	4.2 K	4.2 K	1.8 K	1.8 K	4.2 K
SINGLE CELL CAVITIES E_a (MV/m) ** Q at E_a	10.8 $1.8 \cdot 10^9$	13.0* $0.7 \cdot 10^9$	10.8 $0.4 \cdot 10^9$	7.6* $0.6 \cdot 10^9$	5.5 $5 \cdot 10^8$	22.8* $2.5 \cdot 10^9$	18.7* $3 \cdot 10^9$	7.2 $1.1 \cdot 10^9$
MULTICELL RESULTS E_a (MV/m) ** Q at E_a	4-CELLS 6.0* $1.4 \cdot 10^9$	5-CELLS 5.0 $0.7 \cdot 10^9$	- - -	3-CELLS 5.8 $0.6 \cdot 10^9$	9-CELLS 5.5 $0.5 \cdot 10^9$	5-CELLS 15.3* $2.2 \cdot 10^9$	5/20 CELLS 5.7/4.4 $4/3 \cdot 10^9$	5-CELLS 4 $4.5 \cdot 10^9$

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

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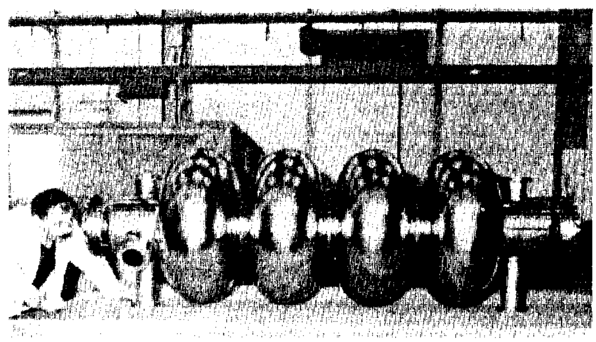

Fig. 1: Prototype of the four cell 352 MHz superconducting cavities foreseen for the energy upgrade of LEP.

It had its first test in April. The design field of 5 MV/m and the wanted Q of $3\cdot10^9$ were obtained at first attempt [10]. The research and development work at CERN concentrates at present onto the sputter coating of copper cavities with a niobium film [11].

In 1984 a 500 MHz three cell cavity was tested at KEK in Japan in the TRISTAN Accumulation Ring. This was done for the purpose of demonstrating the feasibility of the application of several tens of s.c. cavities to the TRISTAN Main Ring. With an accelerating field of 4.3 MV/m an electron current of 1mA was successfully accelerated to 5 GeV [12].

In March 1985 the most recent test of a s.c. system was carried out at DESY. A nine cell 1 GHz cavity operated at 4.5 K with an accelerating field of 2.5MV/m stored an electron beam of 2 mA at 7 GeV in PETRA [13]. This experiment is still going on and shall try to answer the important question on the long term behaviour of a s.c. resonator in a storage ring. In addition a development program has been started recently to design, build and test a 500 MHz superconducting rf modul for HERA. This is done to prepare a possible energy upgrade of the electron ring.

At CORNELL a 1.5 GHz s.c. cavity system was tested in CESR early this year. There the highest accelerating fields in multicell structures were achieved so far. The 15.3 MV/m of the laboratory test [14] of a fully equipped five cell cavity show the virtues of the new high thermal conductivity niobium and they come close to the parameters necessary for superconducting colliders [5]. The research and development program at CORNELL is aiming at this next step.

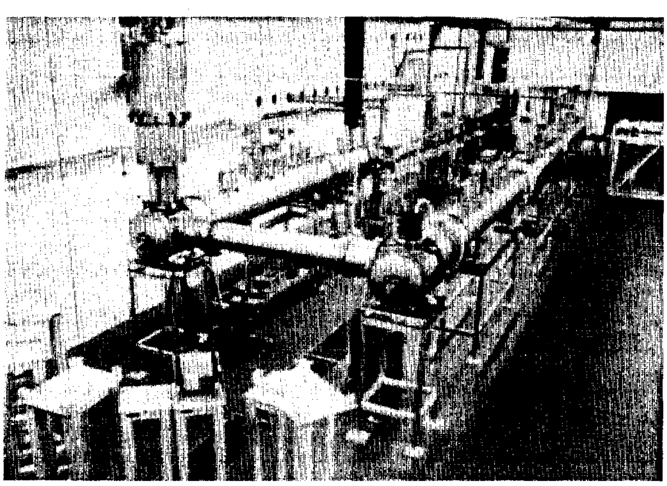

Fig. 2: Present status of the Superconducting 130 MeV Recyclotron for electrons at the Technische Hochschule Darmstadt. The cryostats for the superconducting injector (left) and the 40 MeV Linac (right) are seen.

At SLAC tests are conducted with superconducting lead, niobium and Nb_3Sn cavities at 2.85 GHz which are driven by very short (~1 μs) rf pulses. The results obtained indicate that in this mode of operation fields close to the critical values can be consistently reached. The advantages and disadvantages of the pulsed method have been recently discussed in an excellent review [15].

At the Technische Hochschule Darmstadt a 130 MeV Superconducting Recyclotron for electrons is under construction by a Darmstadt-Wuppertal-Collaboration. The refrigeration system and the cryostat for the linear accelerator consisting of a 10 MeV injector and 40 MeV acceleration section is presently set up and shown in fig. 2. Five accelerating structures for this accelerator have been tested so far. Two of them reached more than 5 MV/m and in three cases the accelerating field was between 4 and 5 MV/m. The design Q of $3\cdot10^9$ was obtained in all cases. They were fabricated in 1984 from stock niobium with low thermal conductivity and a purity typical for niobium sheet material produced before 1984. Parallel to this program work in Wuppertal is concentrated onto the improvement of cavity performance, the development of Nb_3Sn resonators [24] and to metrology [4].

Progress in experimental techniques and materials

If one compares the summary of best results in table 1 with achievements at the time of the last Particle Accelerator Conference [7] one recognizes substantial improvements in the maximum accelerating fields and the fact that cavities fabricated from new materials like niobium sputtered onto copper and Nb_3Sn start to compete with resonators formed out of niobium sheet. The higher fields are for one due to the circumstances that the cavity fabrication (like electron beam welding in CORNELL) and the final chemical cleaning of the resonator is done increasingly careful and under clean room conditions [17]. The significant improvement of the purity of niobium is the other progress towards better and more reproducible results. Temperature mapping, a diagnostic tool now generally used, has shown that microscopic defects are responsible for anomalous field limitations and in part for the observed residual losses not explained by BCS theory. A defect is a microscopic surface area which is either geometrically disturbed (whiskers, cracks, etc.) or is composed out of another material (drying stains, large dust particles or inclusions)than the superconductor in question [18]. The trivial nature of the defects found so far supports the notion that there is nothing fundamental about the performance limits of todays superconducting cavities.

Niobium of high thermal conductivity: Electron field emission and defect induced thermal instabilities are the main mechanisms which limit the performance of s.c. cavities. A defect on a cavity's rf surface, for example a microscopic particle of normal conducting material, is heated in the rf field and the dissipated energy is transferred to the helium bath. The temperature gradient produced across the cavity wall may lift the temperature of the defect's environment above the critical temperature of the niobium and a sudden dissipation of the energy stored in the cavity will result. The threshold field of such a thermal instability can be increased if the thermal conductivity of niobium can be improved [19]. In standard commercial reactor grade niobium the interstitial impurities O, C and N determine the poor thermal conductivity [20]. These impurities can be controlled to a large extent during electron beam melting of the raw niobium and the consecutive manufacturing steps of the sheet material. The residual resistivity ratio (RRR) of niobium is proportional to its electronic thermal conductivity. Typical RRR values of standard niobium range between 20 and 40. Due to a refinement in production techniques requested by the needs of s.c. cavities niobium of RRR values between 80 and 160 is commercially available since the end of 1983. This advance was achieved mainly by improving the vacuum condition and the procedure during the multiple electron beam meltings of the niobium ingots [21]. The progress in cavity performance compared to the status of 1983 can be attributed mainly to this new material [22,23]. Not only the obtainable fields have increased, but also the reliability with which the present design fields of 5 MV/m can be reached.

An effective procedure to clean niobium from the most critical oxygen is the evaporation of yttrium onto the niobium surface developed at CORNELL [23]. During this process the surfaces of a niobium cavity are brought into proximity to an yttrium foil at a pressure of about 10^{-5} Torr at 1250°C for several hours. A vapor deposited film of several μm thickness traps oxygen diffusing rapidly from the bulk to the surface. The oxygen enriched surface layer of yttrium is then dissolved chemically. Starting from standard material (RRR≈30) the RRR value and thereby the thermal conductivity can be improved by about a factor of three (depending on the initial oxygen content). Starting from high purity commercial niobium RRR values of up to about 500 were obtained at CORNELL. The same technique has been tried experimentally at CORNELL [25] and KEK [26] using much cheaper titanium foils at slightly higher temperatures with similar success. The KEK results on a single cell 500 MHz cavity contained in table I were obtained that way.

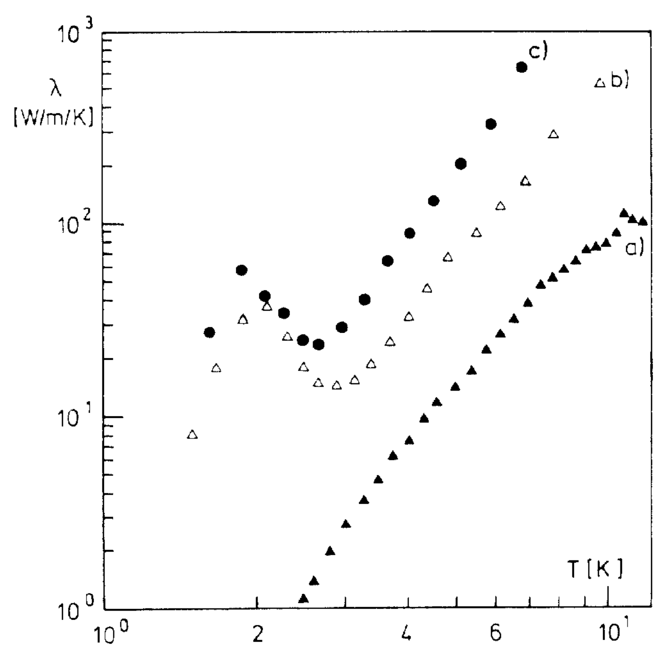

Fig. 3: The temperature dependence of the thermal conductivity of niobium samples of different purity characterized by its residual resistivity ratio RRR.
a) RRR = 36, b) RRR = 152, c) RRR = 360.

Figure 3 shows the measured temperature dependence [27] of niobium samples of different purity. Curve a) represents the status of 1983 and curve b) shows the quality of niobium which is now commercially available. Figure 3 c) gives the thermal conductivity of a niobium sample which was yttrium treated at CORNELL. One can see that the thermal conductivity of niobium could be raised from about 10 W/(mK) at 4.2 K to about 100 W/(mK).

<u>Copper cavities sputter-coated with a niobium film:</u> The London penetration depth of the rf field into the niobium is only about 50 nm. Therefore, it would be very desirable to have a reliable technique by which a film of pure niobium of a few μm could be deposited onto a copper cavity. This would not only improve the thermal stability at high fields but also give the possibility to produce a niobium layer virtually free of foreign material inclusions. A feasibility study towards this goal was started at CERN in 1980. A method was developed to coat a 500 MHz cavity made of OFHC copper with a thin niobium film by DC bias sputtering [11] Fig. 4 shows a schematic view of the sputtering arrangement.

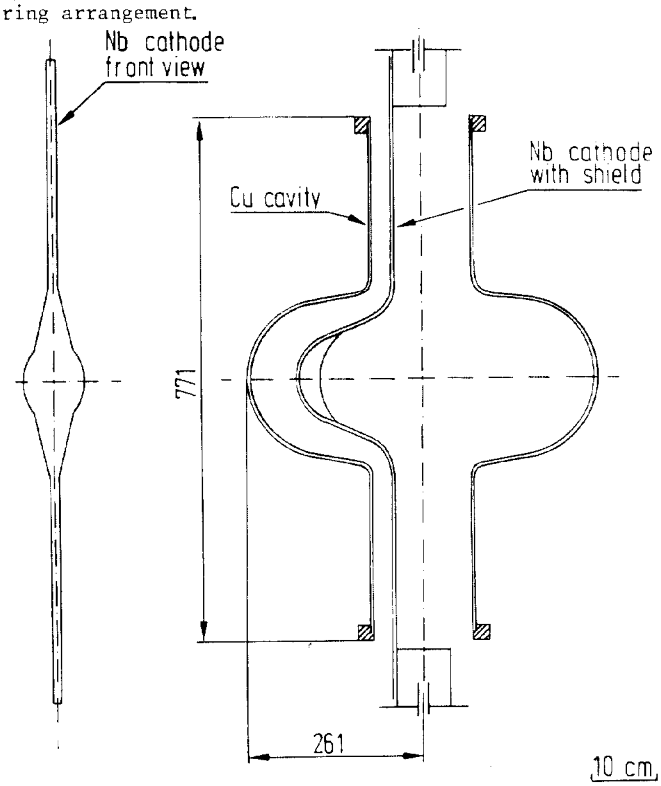

Fig. 4: Schematic view of the arrangement to sputter niobium onto a 500 MHz cavity at CERN.

Three properly shaped niobium cathodes are rotated inside the copper cavity, at a potential of −1400 V and an argon pressure of $5\cdot10^{-2}$ Torr. In order to confine the sputtering discharge to the front of the cathodes, the latter are surrounded on the back and laterally by a shield in 4 mm distance. This shield is biased at + 80 V with reference to the cavity wall which is at ground potential. During 24 h a sputtered film between 1.1 μm (equator) and 3.7 μm (iris) is grown. The results obtained in first experiments with 500 MHz cavities in 1984 were quite encouraging [11]. A maximum accelerating field of 8.6 MV/m was reached which is comparable to the best results from niobium cavities. The observed reduction of the cavity Q with increasing field however asked for a further improvement of the experimental procedure to produce a niobium layer free of defects. In very recent experiments [16] an accelerating field of more than 10 MV/m (table I) was achieved in one case and in another case a low field Q of $3.7\cdot10^9$ was obtained which reduced to $2\cdot10^9$ at the design field for the superconducting LEP cavities of 5 MV/m. It should be noted that the sputter-coated copper cavities never showed a thermal instability. On the basis of these results the coating of a four cell 352 MHz copper cavity is planned at CERN as a next step.

<u>Progress in field emission studies:</u> Resonant and non-resonant electron loading are loss mechanisms in superconducting cavities under c.w. operation [28]. Resonant electron loading has been virtually eliminated in velocity of light accelerating cavities by the proper choice of a spherical or elliptical shape. The impro-

ving ability to avoid lossy defects on niobium surfaces and the progress in thermal stability of s.c. cavities have allowed surface electric fields of more than 25 MV/m at all frequencies suitable for accelerating structures. At such surface fields field emission induced electron loading is observed and constitutes an important field limitation. The measured emission currents from the point like sources seen in s.c. resonators do not correspond to predictions by the Fowler-Nordheim Theory applied to an ideal niobium surface. The origin of this anomaly is still unknown but it can be assumed that the field emission in rf cavities is related to the DC field emission from broad area cathodes. At the University of Geneva experiments are underway to study the field emission properties of niobium samples prepared similarly to cavity surfaces [29]. The measurements are carried out in a commercial Vacuum Generators "ESCALAB" UHV System including a scanning electron gun producing a beam of 0.5 μm in diameter, a 157° spherical sector electron analyser, a secondary emission detector and an argon gun. Niobium samples of 1.4 cm diameter can be fixed to a purpose built manipulator capable of a cathode x-y-z-movement, necessary for the field emission scans. The anode holder can take up several anodes for example a 1 mm diameter flat anode and a pointed tungsten anode which has been electrolytically etched to a micron size tip radius (fig.5).

Fig. 5: Tungsten tip of the pointed anode of the "field emission scanning microscope" set up at the University of Geneva together with an emitting particle on a niobium surface.

Using this anode a high electric field can be produced on a very small area of the niobium sample. Peak surface fields of 500 MV/m have been measured locally. By moving the cathode the anode is scanned automatically across the sample with a 1 μm setting precision. Fig. 6 shows a scanning image of 1 cm^2 of a niobium surface at different scanning fields and after different treatments of the sample. The scan along each line of one image is carried out at a constant field. When a field emission site is encountered the electric field is electronically reduced to hold the emission current below a fixed limit. These field reductions result in vertical deflections on the plotted lines. After localizing an emitting site it is investigated with the built in scanning electron microscope (fig. 5) and analysed regarding its chemical composition by an Auger analysis. So far the most important results of Ø.Fischer's group at the University of Geneva are as follows:

In general one can say that broad area cathodes seem to show the same kind of anomalous field emission as observed in s.c. cavities. In detail the following statements seem to be valid: The emission are most certainly not coming from metallic protrusions with a static electric field enhancement. The emission sites are to their majority associated with micron-size particles sitting probably rather loosely on the surface. The elemental composition of these particles is not unique. In a minority of cases no particle was seen down to a resolution of 0.5 μm. The emission from micron-size particles underline the importance of the clean room techniques applied to the final cavity treatments before assembly. A very recent result of the Geneva group is shown in fig. 6.

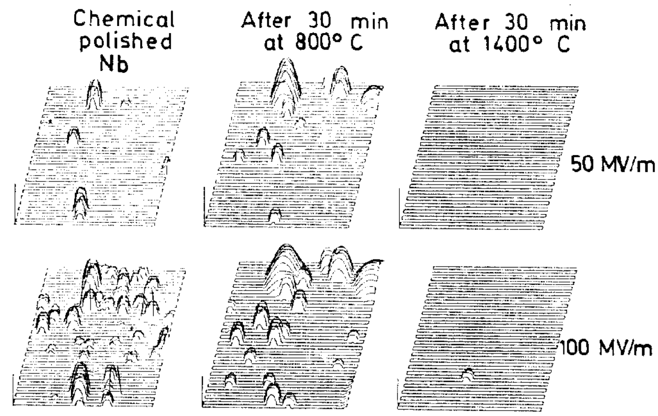

Fig. 6: Field emitting sites on a niobium surface and their sensitivity to bakeouts.
Upper row: Scanning field 50 MV/m. Lower row: Scanning field 100 MV/m. From left to right:No bakeout, 800°C, 1400°C (30 mins each). All scans are performed with an anode of 1 mm diameter.

In the ESCALAB System the samples (cathodes) can be moved under UHV conditions to a station where they can be baked out at temperatures up to 2000°C. Fig. 6 shows a series of field emission scans of one and the same sample which prior to each scan was baked out for 30 minutes at a given temperature [30]. The number of emitting sites is reduced considerably after a bakeout at a temperature of more than 800°C. This interesting observation certainly asks for more studies but it may already be seen as a hint to apply high temperature firing under UHV and clean room conditions to s.c. cavities to surmount the field emission barrier. In a recent experiment carried out at CERN and Wuppertal [22] with a 3 GHz single cell cavity of high thermal conductivity it was in fact observed that the field emission loading after a bakeout of several hours at 850°C was strongly reduced compared to the loading seen in the same cavity after a standard chemical treatment under clean room conditions but without a final UHV firing.

Nb_3Sn cavities: The Q and thereby the shunt impedance of a s.c. accelerating structure increases exponentially with the critical temperature T_c of the superconducting material. Therefore niobium, the element with the highest T_c (9.2 K) is the material most frequently used for s.c. cavities. Among the A15 materials, characterized by high critical temperatures and critical thermodynamic magnetic fields (B_c), Nb_3Sn has gained early attention [31,32]. Its T_c of 18.2 K and its B_c of 500 mT make it a promising material for s.c. cavities. The brittleness of this compound is of no disadvantage in this application. A Nb_3Sn layer of typical 5 μm is formed on a niobium cavity by the vapor diffusion process [33]. The cavity is processed in a vacuum furnace around 1100°C and in contact to a tin atmosphere with a partial pressure of a few 10^{-3} Torr.

In recent time work with Nb_3Sn resonators has been resumed at Wuppertal. For the first time the temperature mapping technique was applied to single and multicell cavities to learn more about the seemingly high residual resistance of Nb_3Sn and its significant field dependence and about field limitations specific to Nb_3Sn [24]. One component of the residual resistance was found to be dependent on the cool down cycle.

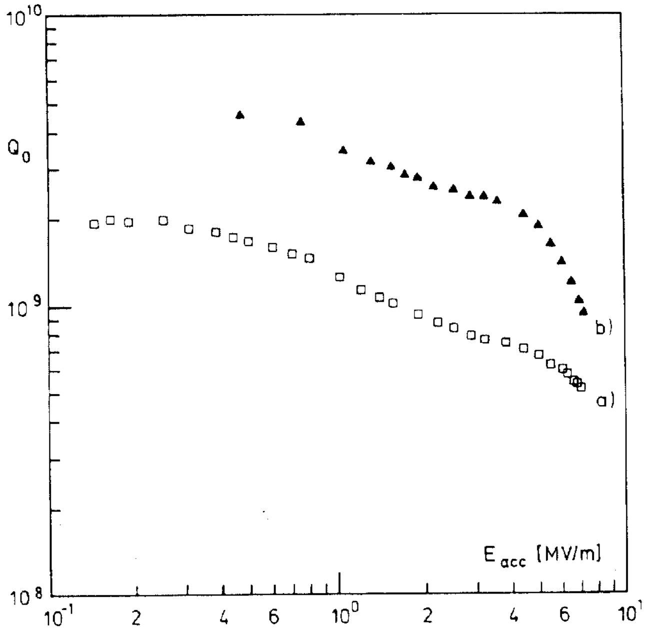

Fig. 7: Dependence of the cavity Q on the accelerating field and on the cool down procedure.
a) two sets of data after fast cool down;
b) after slow cool down.

Fig. 7 shows a Q versus E_a (accelerating field) curve which clearly shows the significant difference between the residual losses after a fast and a slow cool down of the cavity. A careful study of the temperature maps taken in both cases indicate that even the residual losses after a slow cool down are at least in part caused by the same mechanism. The origin of these losses is unclear. At present it is assumed that frozen in magnetic flux produced by thermoelectric currents and excited at the Nb_3Sn-Nb-interface is responsible. Measurements at 20 GHz, 8 GHz and 3 GHz performed at Wuppertal show that the minimum residual resistances scale with the square root of the frequency. The lowest residual resistance found so far was measured in a five cell 3 GHz structure to 27 nΩ. Scaling this to 1 GHz would result in a cavity Q of about $2 \cdot 10^{10}$ at 4.2 K. It is certainly worthwhile to continue to study the origin of the residual losses in Nb_3Sn cavities. 1 GHz would be a handsome frequency for a superconducting linear collider. At 4.2 K at theoretical Q of about $2 \cdot 10^{11}$ is expected for Nb_3Sn accelerating resonators at this frequency. The accelerating fields obtained in Nb_3Sn cavities are comparable to results from cavities fabricated from low purity niobium. Temperature maps taken on a five cell Nb_3Sn 3 GHz cavity at different field levels [24] show the existence of microscopic regions of weak superconductivity. Already at low surface fields (10 mT) these regions switch to a high loss state and lead to thermal instabilities. At present one can only speculate about the nature of these switching defects. Impurity inclusions in the niobium base material which disturb the uniform Nb_3Sn layer and which become weak superconducters by the proximity effect are one explanation. The use of the new high purity niobium for the production of Nb_3Sn cavity is therefore a next experimental step. This and experiments with 1 GHz cavities, covered with Nb_3Sn, are planned in a cooperation between DESY and the University of Wuppertal.

Conclusions

The past year is marked by successful storage ring experiments at CORNELL, DESY and KEK. Accelerating fields attained in single and multicell cavities have passed the 15 MV/m line. This achievement is brought about mainly by the improvement of the thermal conductivity of niobium by refined industrial production procedures and by new purification techniques. The increasing care in cavity fabrication, surface treatment and mounting under clean room conditions has certainly contributed to this progress. Copper cavities sputter-coated with a niobium layer and resonators with a Nb_3Sn surface start to compete with pure niobium. The operation of the first stage of the Superconducting Recyclotron at Darmstadt is expected this year. The successful test of a four cell 352 MHz prototype cavity at CERN lets one look optimistic to the large scale experiments with superconducting cavities in storage rings.

Acknowledgements

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