# Activities on RF Superconductivity at the University of Wuppertal

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## Abstract

This report gives an overview over the work in rf superconductivity done during the last two years at the University of Wuppertal. The work was mainly focused on four topics: development and study of high-$T_c$ material, design, preparation and test of high gradient structures fabricated from high RRR niobium sheet material, study of enhanced field emission from broad area polycristalline niobium cathodes, and at least the design of a superconducting $H^-$- linear accelerator for spallation neutron sources. The latest results are presented either in this report or in two referenced posters and in a review talk all at this conference.

## Introduction

Research in rf superconductivity is established in Wuppertal since more than twenty years. [1] Many improvements on the way to obtain high accelerating fields have been developed. Today as gradients of 20 MV/m and even higher are reached routinely in laboratory tests the main obstacles to achieve higher fields are field emission and quenching. Though the cleaning and assembling techniques were essentially improved during the last years the residual resistance as well as threshold and magnitude of field emitted current are not predictable and differ from test to test significantly. Q-values at low field level are typically in the range of $5*10^9$ to $5*10^{10}$, the onset surface electric field for field emission is in most experiments $E_{peak}$ = 20 - 40 MV/m. For a better understanding we have investigated the residual resistance and its influence of thermal breakdown in a series of 12 experiments on four 3 GHz single-cell cavities. The physical properties of field emitters were studied with a field emission microscope.

An interesting application for superconducting cavities is given in the proposed European Spallation Neutron Source, ESS. Many types of accelerators are discussed for the creation of a pulsed 5 MW proton beam with an energy of about 1 to 2 GeV.[2] Superconducting cavities offer a high gradient, a large aperture, and a compact setup.[3]

The emphasis of research has changed to the study of high-$T_C$ materials and films due to a reduction of foundation for accelerator development. More than 80% of the total manpower of the group is involved in research on high-$T_C$ superconductors (HTS). Besides experiments to get a better and deeper physical understanding of HTS many possible applications are investigated. In this report we focus on RF superconductivity for accelerator applications.[4]

## High -$T_C$ Superconductivity

High frequency measurements are a very sensitive tool for the investigation of the electric and electronic properties of high-$T_C$ superconductors.[5] One important property is the surface impedance because it determines the quality factor of a cavity. In Fig. 1 we have summarized from different laboratories data of the surface resistance of Nb, $Nb_3Sn$, and single cristalline films of $YBa_2Cu_3O_7$ (YBCO) in the frequency range of 0.1 to 100 GHz. The Nb data are taken at 1.3 K, the $Nb_3Sn$ data at 4.2 K, and the YBCO at 77 K (full circles) and at 20 K (open circles). The lines indicate a quadratic dependence of the surface resistance with frequency which seems to be true also for YBCO films. For comparison the surface resistance of copper at 77 K is shown. The YBCO films are superior to copper surfaces - at least by more than two orders of magnitude in the frequency range used for accelerators - and therefore ready for application.

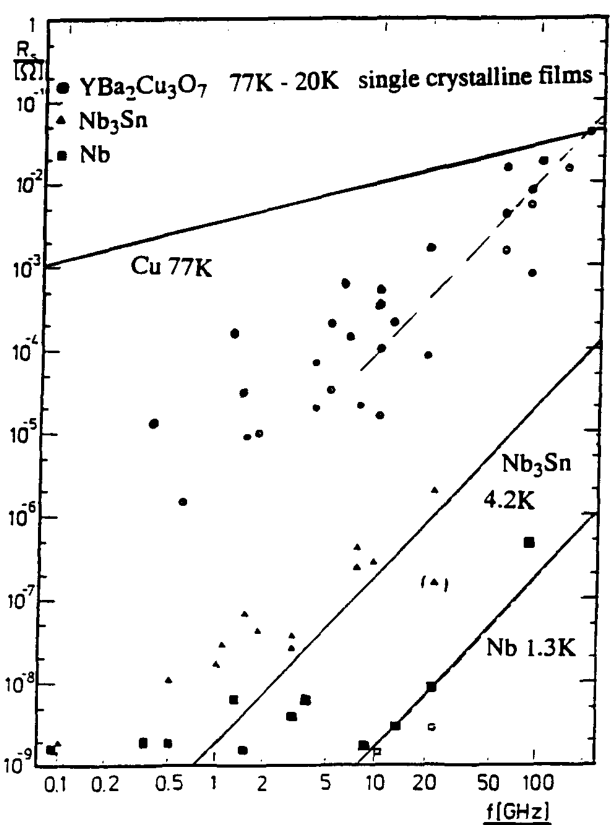


Fig.1 : Comparison of $R_s(\omega) + R_{res}$ for main superconductors and for copper

We have demonstrated that planar on-axis DC-sputtering from stoichiometric targets can be used to produce high-quality $YBa_2Cu_3O_{7-\delta}$ films. We have deposited high-quality YBCO films with a thickness between 200 and 500 nm and a size of 1 $cm^2$ on YSZ, MgO, and $NdGaO_3$ substrates. Shielding measurements have shown that critical temperatures between 89 and 93 K and transition widths between 0.7 and 0.2 K can be achieved reproducibly on all of these substrates. With an inductive contactless measurement technique a critical current density of up to $j_c = (5.1 \pm 0.5)$ MA/$cm^2$ at 77 K could be measured. For the best films, values of the surface resistance at 87 GHz and 77 K of $R_s = (16 \pm 3)$ mΩ have been derived. These films also show a significant reduction of the residual microwave losses at temperatures below 60 K, leading to $R_s$ values below 3 mΩ at 4.2 K. From such high-quality YBCO films on MgO, we have started to fabricate and optimize the design of microwave devices. [6,7]

We investigated the surface resistance of YBCO-crystal platelets, up to 5 x 10 $mm^2$ in size, and the microwave losses of the main flux compounds CuO and $BaCuO_{2 \pm x}$ at 3 GHz. $R_s$ of all crystals droped sharply at $T_c$ by about 3 orders of magnitude. The residual surface resistance $R_{res}$ of crystals grown by the self-flux method with flux residues on the surface is dominated by the microwave losses of $BaCuO_{2 \pm x}$. These losses are orders of magnitude higher than the losses of CuO and were found to increase below 40 K. From the accordingly corrected measurement results on large crystals, we can estimate an upper limit of the $R_{res}$ ~ 40 $\mu\Omega$. With nearly flux-free but small YBCO crystals we have achieved rf field independent $R_{res}$values close to the measurement limit up to 100 Oe. [8]

## Anomalous Loss Mechanisms

In a series of 12 experiments on four 3 GHz single cell niobium cavities we investigated the residual resistance and the thermal breakdown as limitations for the field gradients of superconducting accelerator cavities. In these cavities with an RRR=200-1000 surface peak fields above 50 MV/m and quality factors of $10^{10}$ and more were achieved routinely. The highest electric field level reached was 70 MV/m, the highest surface magnetic field was above 100mT. Field emission started beyond 30 MV/m. The influence of the residual gas composition in the vacuum system of the cavity was studied. It was found that hydrocarbons degradate the cavity performance very strongly whereas the exposure to $CO_2$ resulted in an unchanged Q-value.

The local distribution and the field dependence of the residual surface resistance were measured with two sets of thermometers. A set of scanning thermometers was used to detect local defects with good resolution. These defects were then analysed in with a second set of thermometers glued to the cavity wall in a further cryotest. The experiment showed that on defect free areas the temperature increase of the wall is proportional to the square of the surface magnetic field, $\Delta T \sim H^2$. On or close to the defect the increase of temperature was found to be exponential which can not be explained with simple thermal model calculations.

Very interesting especially for accelerator application is the following result: In postpurified niobium cavities and for frequencies below 3 GHz the maximum fields of about 25 MV/m and 100 mT can be achieved at 2 K, it is not necessary as it is often done in laboratory tests to cool down to say 1.3 K. A detailed discussion of these experiments is given in [9].

In pulsed operation of a cavity the stored energy W and any radiated power decrease exponentially with a time constant τ which represents the momentary loaded quality factor while the radiated power a measure of the momentary field is. So the complete $Q_0(E_{acc})$-curve can be calculated from one single measurement of the radiated power.[10]

# DC Field Emission

We study enhanced field emission from broad area polycrystalline niobium cathodes. A field emission scanning microscope is built in a UHV chamber and consists of a computer controlled sample micromanipulator and a rotatable high voltage anode holder The cathode is scanned by moving in a raster pattern while the field emission current is measured. When a field emitter is detected it can be in situ analysed with a scanning electron microscope. Moreover the sample can be heat treated up to $2000^{o}$ C without taking it out of the vacuum. Recently also an Auger analyser has been installed.

A first result is shown in Fig. 2.[11] A selection of field emission scans is shown after a series of successive heat treatments at temperatures of $800^{o}$ - $1400^{o}$ C and a pressure of $10^{-7}$ mbar for 30 min. The scans which have 13 mm diameter were carried out at different voltages with a 1 mm anode and a maximum current of 20 nA. If the field emitted current is higher a regulator reduces the voltage in order not to distroy the emitter by heating.

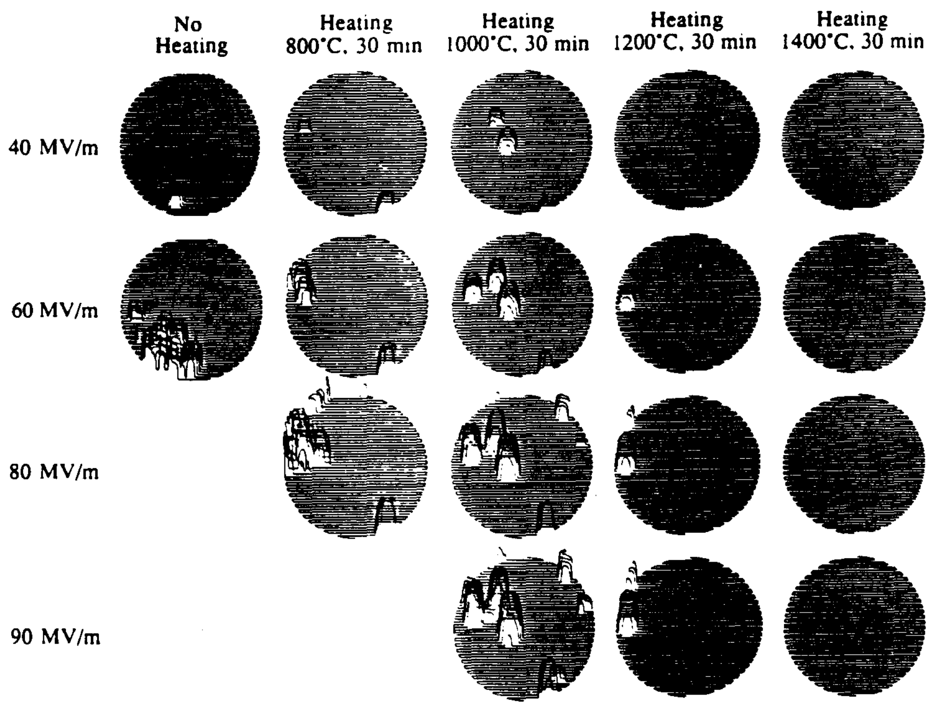


Fig.2: A selection of FE scans as a function of heat treatment on a chemically polished sample

It is recognized that the emission of unannealed surfaces generally was rather unstable for fields E > 50 MV/m. After heat treatment at $1200^{o}$ C only one emitter was active and after firing at $1400^{o}$ C no emission up to 90 MV/m could be seen. These results were reproducible. A detailed description of the experimental technique and further results on DC field emission are presented by E. Mahner at this workshop.[12]

# Design of a $H^-$ - Linac

We started to design of a $H^-$- linac for the proposed European Spallation Neutron Source - ESS. This source asks for a pulsed proton beam with about 1 $\mu s$ pulse width at 50 Hz repetitions rate and a beam power of 5 MW at the target. There are several types of accelerators which can deliver such a beam, one of them is a linac with one or more compressor rings. For an effective filling of the phase space of the accumulator ring the proton beam is generated by stripping of a $H^-$- beam during injection. The injection energy is 0.8 resp. 1.2 GeV depending on the number of rings, i.e. three resp. two. The linac $H^-$ - beam must have a pulse length of 2 resp. 1.3 msec and a peak current of 105 mA. The accelerator concept is shown in Fig. 3.

The conceptual setup of the linac consists of two ion sources with about 50 keV, two times two RFQs which accelerate the beam to about 5 MeV. Chopping can be done easily behind the first RFQ, after the second the beams are funneled. Then the beam accelerated further in a superconducting low beta linac with spoke resonators to around 150 MeV. In a high beta linac with spherical structures of increasing length the beam is accelerated to its final energy.

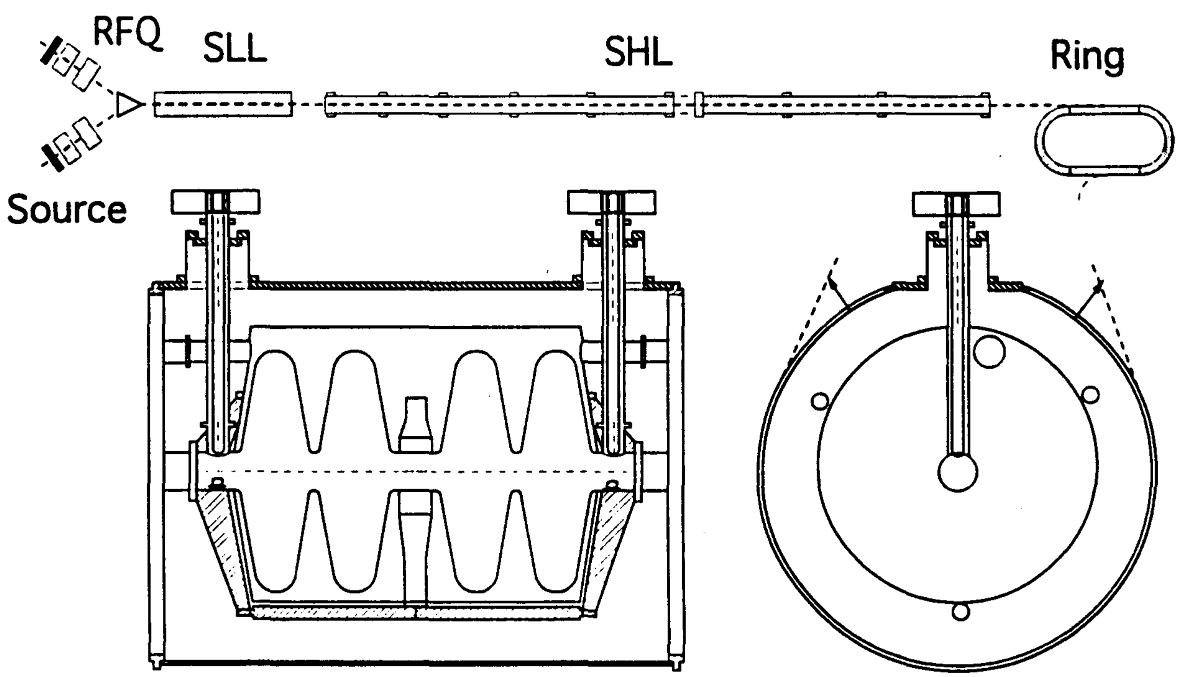


Fig. 3: General layout of the accelerator and a cryomodule with two-cell structure

We focus our attention on this high beta linac. The design frequency is 350 MHz so an operating temperature of 4.2 K can be chosen. The RFQs operate at 175 MHz. To keep the ratio of the length of the cavities to the total length of the accelerator (filling factor) high multicell structures should be used. As the maximum power which can be coupled into a cavity is today typically limited by electron discharge in the input coupler to about 200 KW, and as the required peak current is quite high only short structures can be used. We propose two-cell structures. Then the accelerating field is limited by the input power to 3 to 4 MeV/m depending on the length, i.e. the $\beta$, of the structure. For a gradient of 9 to 10 MeV/m which can be achieved in the structures an input power of 600 KW is necessary. In an experiment when high peak power processing (HPP) was applied to a cavity it has been shown at Cornell that 955 KW can be transported on an input line.[13] So it seems that the limitation by the available input power is not very severe. For a better filling factor two two-cell structures are connected by a cutoff tube, i.e. the total length is shorter by one cutoff tube plus one bellow. The total length of the high-$\beta$ linac can be reduced to 150 resp. 230 m which is important for cost reduction.

With the today available klystrons which deliver a peak power of 4,5 MW in 10 msec pulses eight cavities can be driven with one such klystron. In total 16 resp. 24 klystrons are needed.

The design capacity of the refrigerator including a contingency of 150 % is 1.8 KW resp. 2.3 KW. A Q-value of $4*10^9$ at a field level of 9.5 MV/m is assumed.

## References

[1] H. Piel and Wuppertal Group, "Superconducting Cavities and their Applications - Recent Work at the University of Wuppertal", Proc. of the 4th Workshop on RF Superconductivity, KEK, Japan (1989) pp. 109-138

[2] S. Martin and C.W. Planner, "Accelerator Design Parameters for a European Pulsed Spallation Neutron Source.", Proc. of the Third European Particle Accelerator Conference, Berlin, (1992) pp. 435-437

[3] H. Lengeler, "Superconducting Cavities for Neutron Spallation Sources and Other High Intensity Proton Accelerators", Proc. of the 6th Workshop on RF Superconductivity, CEBAF, Newport News, (1993), to be published

[4] H. Piel, "High $T_C$ Superconductivity For Accelerator Cavities", Nucl. Instr. Meth. A287 (1990), pp. 294-305

[5] H. Piel and G. Müller, "The Microwave Surface Impedance of High-$T_C$ Superconductors", IEEE Trans. Mag. 27,2 (1991), pp. 854-862

[6] M. Lenkens, B. Aschermann, S. Hensen, M. Jeck, S. Orbach, H. Schlick, H. Chaloupka, G. Müller, H. Piel, "Preparation and non-destructive characterization of $YBa_2Cu_3O_{7-\delta}$ films for microwave applications", Journal of Alloys and Compounds, 195 (1993), pp. 559-562

[7] S. Orbach, S. Hensen, G. Müller, H. Piel, M. Lippert, G. Saemann-Ischenko, S.A. Wolf, "Effect of oxygen deficiency and disorder on microwave losses of epitaxially grown $YBa_2Cu_3O_{7-\delta}$ films", ibid. [6] pp.555-558

[8] D. Wehler, J. Dreibholz, M. Meyer, G. Müller, H. Piel and Th. Wolf, "Surface resistance of large $YBa_2Cu_3O_{7-x}$ crystals at 3GHz with residual losses caused by flux compounds", ibid. [6] pp. 575-578

[9] D. Reschke, W. Görlich, G. Müller, H. Piel, J. Pouryamout, R.W. Röth, "Detailed Studies of Anomalous Loss Mechanisms in S.C. 3 GHz Single -cell Cavities at $E_{peak}$ up to 70 MV/m and $Q_o$ up to $7*10^{10}$", ibid. [3]

[10] D.W. Reschke and R.W. Röth, "Fundamentally Fastest Method Measuring $Q_o(E_{acc})$-Performance of S.C. Cavities", ibid. [3]

[11] E. Mahner, N. Minatti, H. Piel and N. Pupeter, "Experiments on enhanced field emission of niobium cathodes", Applied Surface Science 67 (1993) pp. 23-28

[12] E. Mahner, "Understanding and Suppressing Field Emission using DC", ibid. [3]

[13] J. Kirchgessner and the Cornell Group, "Superconducting RF Activities at Cornell University", ibid. [3]

[14] H. Heinrichs, "Design of High-β Linac and Cost Comparison", Proc. of the International Workshop on High Intensity Proton Linear Accelerators for Future Spallation Neutron Sources", Witten (1993), to be published