# HIGH FIELD SC-CAVITIES

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## *Abstract*

Two mechanisms limit high fields in superconducting cavities: thermal breakdown (quench) and loading by field emitted electrons. In the first case defects like normal conducting spots, bad weldings or thermal insulated particles on the surface might act as heating spots and should be avoided. Increased thermal conductivity of the cavity wall could also stabilise possible quench location. In the second case small micro sized particles have been identified as location of field emission. They must be avoided by appropriate cleaning techniques and ultra clean handling. Accelerating gradients around 20 MV/m could be achieved with multicell cavities, values from 30 - 43 MV/m were gained in single cell resonators. This can be compared with the thermodynamics limit of 50 MV/m equivalent to 200 mT surface field (Nb). These recent results are discussed in respect to the quality of Nb material and preparation techniques like high temperature firing, high pressure water cleaning and high RF power processing.


## 1 INTRODUCTION

There are major accelerating systems with superconducting cavities in operation or under construction: CEBAF with 338 cavities (5 cells, 1.3 GHz [1], CERN with 4 cavities in SPS and 272 cavities for LEP2 (4 cells, 352 MHz) [2], DESY with 16 cavities in HERA (4 cells, 500 MHz) [3], KEK with 32 cavities in TRISTAN (5 cells, 508 MHz; operation stopped after 6 years in 1995) [4]; some single cell cavities for high current applications at KEK [5] and Cornell [6]. At DESY a superconducting test linac (TTF, TESLA Test Facility [7]) is under constructin (9 cells, 1.3 GHz, 32 cavities). This effort is carried out by an international collaboration to explore the feasibility of a superconducting linear collider TESLA (TeV range Superconducting Linear Accelerator [8]). All these cavities are designed for phase velocity = 1, they are produced from Nb-sheet material or by sputtering Nb on Cu (CERN). The operating gradient Eacc ranges from 2.5 MV/m (high current application) to about 6 MV/m.

There are many applications with low ß superconducting cavities: for detailed information see ref. [9]. Solid Nb as well as sputtered Nb is used as fabrication method. For moderate performance also plated Pb on Cu is used.

Structures with ß = 1 have a typical pill box shape with a beam hole (iris) whereas ß < 1 cavities are loaded by capacitive gaps or inductive stubs. Comparing the performance of ß = 1 structures can be done straight forward by the number of achieved gradient because electric and magnetic surface fields scale similar. For structures with ß < 1 the local fields depend on details of the chosen design. Furthermore the number of test results with ß = 1 structures is about an order of magnitude larger than those with low ß cavities. Therefore this paper deals with the progress of ß = 1 structures. One expects that improvements in fabrication and treatment can be transferred to ß < 1 structures, too. All high gradient cavities are made from solid Nb. Therefore this paper deals with cavities made from solid Nb only.

## 2 IDEAL SUPERCONDUCTING CAVITY

In contrast to DC current, the RF field in a superconducting surface creates losses. The surface resistance is given for T < Tc/2 by

$$R_S = A \cdot \omega^2 \cdot \frac{1}{T} e^{-\frac{\Delta}{KT}} + R_{res} \qquad (1)$$

Rs: surface resistance
A: material parameter
ω: 2πf, frequency
T: temperature [K]
Δ: energy gap
K: Boltzman constant
Tc: critical temperature of superconductor
Rres: residual surface resistance

The first term describes the value according to BCS theory [10], the second term describes the difference between measured value and BCS value. Rres depends on surface conditions and cleanliness; typical values for a good cavity are below 5 nΩ. One should note that the surface resistance increases with frequency but decreases with temperature. Therefore cavities can be operated at the temperature of liquid Helium (T = 4.2 K) below 1 Ghz whereas at higher frequencies the operating temperature must be reduced. In most publications the quality factor Q

$$Q = \frac{\omega W}{P} \qquad (2)$$

Q = quality factor
W = stored energy
P = RF loss of the resonator.

is quoted rather than the surface resistance. The loss is proportional to the surface resistance so that

$$Q = \frac{G}{R_S} \qquad (3)$$

G = geometry factor of cavity shape, typical value 200 Ω

holds. For ideal conditions of a superconducting cavity the measured Q value should not depend on the field strength (but on temperature and frequency).

## 3 CRITICAL FIELD

Superconductivity breaks down above the critical temperature Tc and above the critical magnetic field Bc. This also holds for RF fields if the surface magnetic field exceeds Bc. The ratio of the maximum magnetic surface field and the accelerating electric field for a typical superconducting accelerator design is around 4.2 mT/MV/m. Therefore a maximum accelerating gradient of 50 MV/m can be expected for Nb at a critical magnetic field of Bc = 0.2 T.

## 4 FIELD LIMITATION

### *4.1 Global Heating*

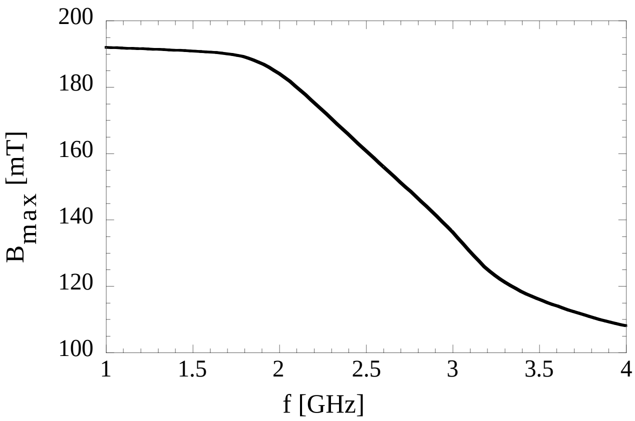


Fig. 1: Model calculation of thermal instability due to global heating by the surface magnetic field as function of frequency (Nb wall thickness 1.5 mm, $\lambda_{4.2K}$ of Nb is 60 W/mK, T = 1.8 K) [11]. The strong frequency dependency is expected because of the quadratic frequency term in the BCS surface resistance (see equ. 1).

The surface current in a superconducting cavity will produce heat due to the surface resistance. Therefore the heat flux q through the Nb and the Kapitza resistance at the Nb to liquid Helium interface establish a temperature increase of the inner cavity surface

$$\Delta T = q \cdot \frac{1}{\lambda} + q \cdot R_K \qquad (4)$$

$\Delta$T = temperature increase of inner cavity surface to liquid Helium

q: heat flux due to RF losses

$\lambda$: thermal conductivity of wall material

$R_K$: Kapitza resistance

The surface resistance will increase because of its exponential dependency on temperature (see equ. 1). There is a critical heat flux (or critical surface magnetic field) in the sense that a runaway situation occurs and the cavity becomes normal conducting. The corresponding critical accelerating field was calculated in [11] (see Fig. 1). The critical field can be raised by increasing the thermal conductivity of Nb. But finally the Kapitza resistance will determine the maximum value. It should be noted that lower frequencies are favoured because of the quadratic frequency term in the surface resistance (see equ. 1 and Fig. 1).

### *4.2 Local Heating*

A small normal conducting spot on the RF surface of the cavity can initiate a similar thermal run away at even lower surface magnetic fields. At a typical wall thickness of 3 mm Nb and f = 1.3 GHz, 1.8 K, $\lambda_{4,2K}$ = 60 W/mK (TESLA cavity) a normal conducting defect with a diameter of 20 µm will limit the maximum field to around 25 MV/m. As in the case of global heating here the Kapitza resistance will finally determine the maximum fields, too. Here it should be noted that there is an optimum wall thickness: the transverse heat flux is suppressed by a too thin wall. The sudden transition of a cavity to the normal conducting state is named a quench (as for magnets) but the dissipated stored energy is small (several tens of Joules).

### *4.3 Limitation by Field Emission*

In many cavity experiments the following observation is made:

- the quality factor Q drops with increasing slope for increasing field levels,
- $\gamma$ radiation is observed outside the cryostat,
- finally the maximum field is limited by too high RF power absorption (low Q); sometimes also a quench occurs.

This phenomenon is explained by field emission of electrons from surfaces with high electric fields. The electrons are accelerated by the RF field and finally dissipate the kinetic energy by impacting the cavity wall. There is evidence that dust particles on the surface play a dominant role as emitting site for field emission [12].

## 5 OPTIMUM OPERATING GRADIENT

For a given accelerating voltage the length of a linac scales inverse with the accelerating gradient whereas the RF loss power increases linear with the gradient. There is a minimum of total cost (investment + operation) when linear and cryogenic costs are about equal. The RF loss depends on frequency and temperature whereas the refrigerator efficiency depends on temperature (and absolute cooling power also). For a typical storage ring installation (f ~ 500 MHz, Q ~ 5 x $10^9$, cw operation) the optimum gradient is not higher than 10 MV/m. If the cavity field is pulsed the cryogenic load is reduced and higher gradients are favourable. In the case of TESLA (f = 1.3 GHz, T = 1.8 K, beam pulse 800 µsec, rep. rate 10 Hz) the optimum gradient is around 50 MV/m.

## 6 RECENT EXPERIMENTAL RESULTS

The present fabrication methods to produce high gradient cavities are as follows:

a Start with high conductivity niobium sheet material.

b After e- beam welding the cavity is heat treated at 1400 °C for about 4 h together with Ti material placed inside and outside the Nb structure. Afterwards about 100 µm of surface layer is removed by chemical or electrochemical methods to remove the Ti layer and to produce a clean Nb surface.

c High pressure water is used to clean the Nb-surface from contaminations.

d At cryogenic temperature the cavity is processed with high RF power pulse (HPP).

It is necessary to do all assembly work in a clean room (class 10 to class 100) to prevent dust contamination of the RF surface. The benefit of the individual steps can be demonstrated by the following examples.

### *6.1 High Pressure Water Rinse*

At TTF a 9-cell cavity was measured after heat treatment and chemical etching but without high pressure water treatment and no HPP. After measurement the cavity was warmed up, cleaned by a high pressure water treatment and measured again. The first measurement shows the typical degradation of the Q-value at higher values of Eacc and γ radiation is observed in this state (see Fig. 2). The maximum gradient is limited at 7.5 MV/m by too high power absorption. After cleaning with high pressure water the field emission loading is reduced and the cavity quenches at 15 MV/m.

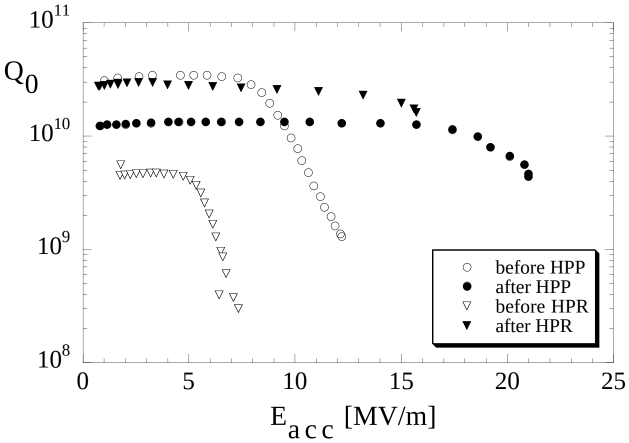


Fig. 2: Benefit of HPP (high RF power processing) and HPR (high pressure water rinse). Two different TTF cavities have been measured before (open points) and after (closed points) treatment by HPP and HPR, respectively.

### *6.2 High Temperature Treatment*

At Saclay several single cell cavities quenched around 6 MV/m. A temperature mapping system at the outer cavity surface localised the quench at the equatorial weld. After heat treatment the cavity field could be raised to 19 MV/m, limited by a quench (see Fig.3).

In another example five 5-cell cavities have been heat treated at CEBAF and all reached quench fields of Eacc around 20 MV/m. This must be compared with the average value of quench limit of 13 MV/m for the series production of 338 CEBAF cavities (no heat treatment).

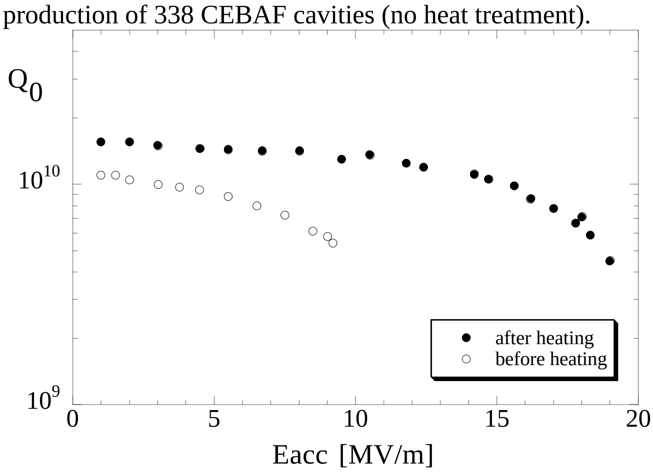


Fig. 3: Improvement of a single cell cavity after heat treatment with Ti at 1400 °C for 4 h (Saclay [13]). Several single cell cavities were limited by a quench at the equatorial weld. After heat treatment all cavities showed improved performance. There is evidence, that due to imperfect weld preparation enhanced contamination was collected at the weld and initiated excessive heating. During heat treatment the contamination was probably diluted and thus the bulk Nb was homogenised.

### *6.3 High RF Power Processing*

The field emission loading can be reduced by high power processing. This technique was developed at Cornell and successfully applied to 5-cell cavities [17].

At DESY 9-cell cavities for TTF have been processed by HPP and the improvement can be seen in Fig. 2.

### *6.4 Combined Treatment*

A combination of high temperature firing, high pressure water cleaning and high power processing is expected to assure best cavity performance. At DESY several 9-cell TTF cavities have been processed this way and the result is plotted in Fig. 4.

At CEBAF several single cell resonators were treated by firing and high pressure water cleaning. Accelerating gradients around Eacc =30 MV/m and a maximum of 43 MV/m were reached [16].

## 7 DISCUSSION

### *7.1 Cleaning with High Pressure Water*

The final cleaning of a cavity by high pressure water turned out to be a very reproducible and effective means to get rid of small "dust" particles from the cavity surface. After this treatment cavities show a dramatic improvement in respect to the onset of field emission. This has been demonstrated by many single cell and multicell structures and is considered to be an essential part of the standard cavity treatment.

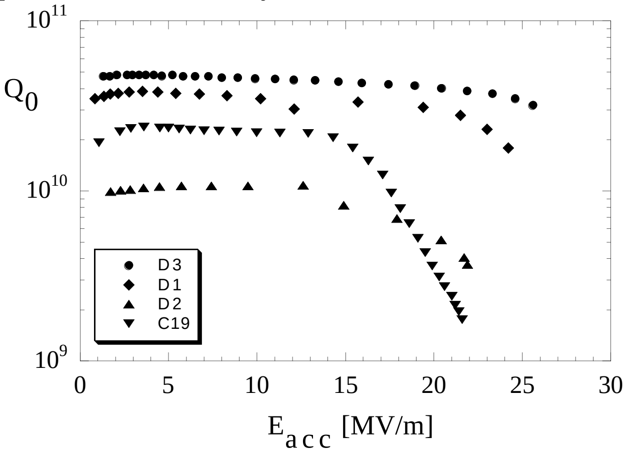


Fig. 4: Vertical test result of 9-cell cavities which have been accepted for TTF. The cavities have been manufactured by two different companies. It should be noted, that cavity D3 was measured without any high RF power processing. Cavity C19 was welded into its He tank afterwards and was measured in the horizontal test cryostat with high power input coupler and HOM coupler assembled to it. It was operated up to 18 MV/m under pulsed condition (TESLA pulse 800 µsec flat top, rep. rate 10 Hz).

## *7.2 High Power RF Processing*

High RF power processing is a means to clean a surface in situ. Many pictures of blown off field emitting particles ("star burst" signature of the surface) demonstrate the mechanism of cleaning [17]: the fast raise of the cavity field overheats a field emitting particle so that it explodes. The left over of such an event is less active in field emission.

The benefit of high RF power processing is that it can be applied in situ. Therefore a cavity can be cleaned without disassembly. It is an effective method to restore good cavity performance after some dust contamination due to a vacuum accident, for example. In some occasions, however, the quality factor dropped slightly after high RF power processing. After warm up this enhanced loss disappeared. The nature of this loss is not understood.

## *7.3 Heat Treatment of Nb*

A high thermal conductivity of the Nb is needed to keep the temperature increase small at a defect (normal conducting spot) on the RF surface. Nb for cavity production with a thermal conductivity $\lambda_{4.2K}$ of 90 W/m/K is presently available. By heating with Ti at 1400 °C the Nb is purified by solid state gettering and then the conductivity is increased by about a factor of 2. Further improvement could be reached by more effort but the Kapitza resistance will limit the gain. In Fig. 5 single cell data are plotted vs thermal conductivity. It can be seen that the expected increase of cavity performance with the square root of $\lambda$ [17] holds below $\lambda \sim$ 100 W/m/K. Above this value the data scatter more but indicate a saturation effect.

It has been demonstrated by RF [18] and DC [19] measurements that heat treatment at 1400 °C reduces the probability of field emission. Furthermore the material is homogenised as measured by the value $H_{c2}$ [20]. The beneficial effect of heat treatment for a weld defect (see Fig. 3) is most likely due to this homogenisation. In conclusion, a heat treatment of a Nb cavity at 1400 °C seems to be beneficial but the increase of thermal conductivity above $\lambda \sim$ 100 W/m/K is no longer the dominant effect.

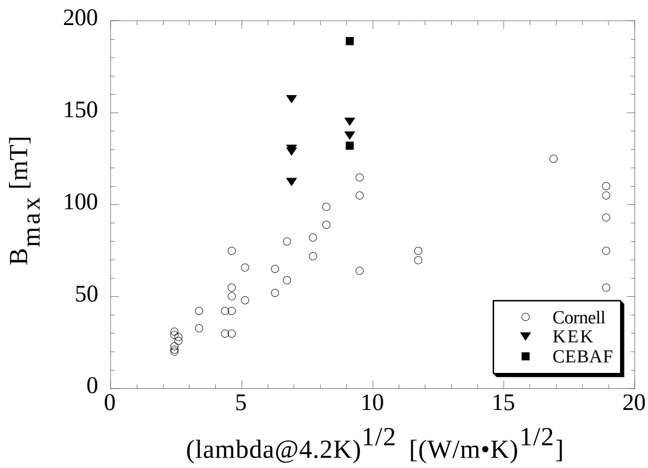


Fig. 5: Comparison of maximum magnetic surface fields measured with single cell cavities of different Nb material: Cornell at 8 GHz [14], KEK at 1.3 GHz [15], CEBAF at 1.5 GHz [16]. Model calculations predict a scaling of Bmax with the square root of the thermal conductivity [17]. This is in agreement with the Cornell data for $\lambda <$ 100 W/mK. Above this value the Kapitza resistance at the Nb to LHe interface seems to dominate the cooling conditions. The data from KEK and CEBAF (dark symbols) are recent measurements and might reflect the progress in fabrication and cleaning since 1985 (Cornell data).

## *7.4 Material Defects*

The application of high pressure water cleaning, progress in dust free assembly and processing by high RF power shifted the onset of field emission to higher cavity gradients. Therefore usually a quench determines the performance of a high gradient cavity. Single cell cavities reach gradients above 30 MV/m (best value 43 MV/m) whereas multicell structures are limited around 20 MV/m (best value 27 MV/m). Defects on the surface (enhanced loss) or in the bulk (reduced thermal conductivity) are considered as reason for the quench limit. Only in a few cases defects could be identified. At TTF a quench location was investigated by means of some non destructive methods: eddy current and $\gamma$ ray absorption. Although the exact nature of the defect is unknown, there is evidence that defects in the bulk niobium are responsible for the quench.

There is the suspicion that the high temperature treatment with Ti at 1400 °C might have an inherent danger of defect production: Ti can diffuse into the bulk Nb along grain boundaries to such a depth which usually is not removed by standard chemical etching. The remaining Ti at the grain boundary could explain the peculiar slope and jump of the quality factor when raising the field and will finally initiate a quench (see Fig. 6). The diffusion rate of Ti depends on material parameters (grain size) and details of the firing cycle which are not under control or are not optimised. Therefore modification of the heat treatment (temperature profile, only outer Ti coverage) are investigated to reduce the spread of performance of high temperature treated cavities.

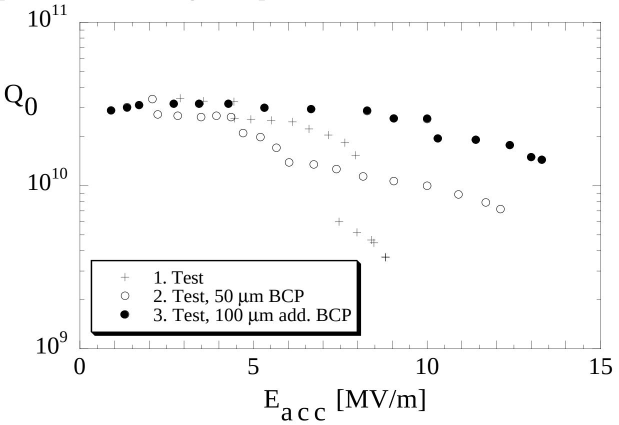


Fig. 6: Behaviour of a "bad" cavity (9-cell, TTF) with two additional surface treatments by BCP (buffered chemical polish). The signature is a jump in Q (Q-switch) and a decrease of Q when raising the field. This behaviour is most likely due to a defect in the bulk Nb because the cavity performance improved somewhat after surface removal (50 µm, 100 µm)

## 8 CONCLUSION

Progress has been made in fabrication and treatment of superconducting cavities:

- improvement of the quality of Nb by high temperature treatment together with Ti solid state diffusion cleaning,
- final cleaning of the cavity surface by high pressure water,
- consequent application of clean room technology during assembly,
- in situ processing with high RF power to remove field emitting particles.

Accelerating gradients above 30 MV/m (above 20 MV/m) can be reached with single cell cavities (multicell structures). At this level a quench of the cavity is the dominant limiting effect. To further raise the field and to reduce the spread of performance new ways of quality control of the bulk niobium are needed.

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