

## REVIEW ON HIGH- $\beta$ SUPERCONDUCTING CAVITIES

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### 2. Limitations in SRF Cavities

#### Abstract

Large superconducting RF systems are under installation (CERN), under commissioning (CEBAF) or under operation (DESY, KEK) in accelerators. A test facility with high gradient superconducting cavities for linear collider application is under construction in the framework of an international collaboration (TESLA). At present the performance of cavities from bulk Niobium is limited by quench (thermal instabilities) or by field emission. Accelerating gradients around 25 MV/m could be reached in multicell cavities repeatedly by applying advanced fabrication and preparation techniques. Multicell sputtered Nb cavities reach gradients around 10 MV/m and are limited by inter grain losses. Substantial effort is made to simplify fabrication, thus reducing investment costs.

#### 1 Introduction

For more than 20 years superconducting cavities have been developed for use in accelerators. Meanwhile several storage rings (TRISTAN, KEK [1]; HERA, DESY [2]; LEP & SPS, CERN [3]) are equipped (or will be upgraded) with superconducting RF (SRF) systems. Linear accelerators at CEBAF [4], Darmstadt [5], Frascati [6], HEPL [7] and Saclay [8] use SRF systems as the only accelerating units. B-factories are planned with SRF at CORNELL [9] and KEK [10]. All these cavities are designed for particles with velocity of light ( $\beta = 1$ ). Several heavy ion accelerators are in operation with low  $\beta$  superconducting cavities. This technique will be covered by another talk at this conference. In this paper  $\beta = 1$  resonators are described.

The basic advantage of superconducting vs. normal conducting cavities is the higher gradient at reduced operational costs for continuous wave (cw) applications. Furthermore the single passage higher mode impedance of a superconducting cavity is lower because the larger iris opening (the impedance is optimized via the high Q-value and not by the shape). For pulsed applications the ON-time can be considerably extended.

The accelerating gradient might be chosen as high as possible to get maximum voltage for a given free length. In case of a high beam current the maximum transferred RF-power per input coupler will set a limit to the accelerating gradient. In a large scale application the gradient has to be chosen to operate in the minimum of the total costs. This is roughly when the linear costs for cavities (including cryostat, LHe distribution system and auxiliaries) equal the effort for the cryogenic power. At continuous wave operation the optimum gradient is around 8 MV/m [11] (assuming present cavity production costs of 400 KDM per active meter). For pulsed operation the optimum gradient will increase.

#### 2.1 Magnetic field

One fundamental limit in superconducting cavities is the critical surface field  $H_c$ . If the critical field is reached, normal conducting areas are created and dissipate the stored energy. In the case of Niobium the critical value at low temperatures is 2000 Oe. The ratio of the maximum surface field to the accelerating field of a typical superconducting cavity design is  $H_p/E_{acc} = 40$  Oe/MV/m so that a theoretical value of 50 MV/m could be reached. So far other limiting effects stopped reaching this value.

#### 2.2 Global heating, defect free case

In contrast to the behavior under DC current, there is a non vanishing surface resistance under AC current. Its value decreases with lowering the operating temperature as well as lowering the operating frequency. The dissipated RF power establishes a temperature gradient across the cavity wall so that the temperature of the inner surface is higher than the cooling LHe. There is a critical value of the surface field: a further increase starts a thermal run-away by increased losses at increased surface temperatures. The threshold can be raised by improved thermal conductivity of the wall material. Recently this limitation has been observed with a 2 cell 3 GHz cavity at  $H_{peak} = 1430$  Oe [12]. For most SRF applications this effect is above the expected performance value of the accelerating gradient. For high gradient applications, however, this is an argument not to operate at too high frequencies (several GHz), especially when high fields are reached during processing the cavity with high power pulses (HPP). This was one reason why 1.3 GHz was chosen for TESLA instead of 3 GHz.

#### 2.3 Defect heating, quench

This is a limitation by thermal run-away initiated by a spot of enhanced losses. The critical value is determined by size and nature of the local defect and also by the thermal conductivity of the wall material. Therefore this limitation might occur even at low gradients of some MV/m. Defects in welds, loosely bound particles or heavy scratches have been identified as reasons for a quench. But not in all cases a "bad spot" or any irregularity could be detected during inspection a quench location, which had been localized by thermometry. Improvements in material and fabrication procedures, clean chemistry and assembly pushed limitations by quench to values above 10MV/m. A general cure is to increase the thermal conductivity of the wall material to values as high as possible. Because of the simpler measurement here the number of RRR (residual resistance ratio, resistivity at 300 K/resistivity at 4 K) is quoted rather than the thermal conductivity. In the case of Niobium RRR equals (roughly) 4

times the  $\lambda$  value at 4.2 K. Niobium of quality RRR 300 is available in large quantities (as compared to RRR 50 ten years ago). Further improvement of RRR by a factor 2 to 3 can be reached by a post purification process [13]: the complete cavity is fired inside a Ti (or Yt) foil at 1400 °C for 4 h. Gaseous impurities (N, C, H) in the bulk Nb are getterd by the thin Ti film on the Nb surface (created by evaporated Ti). Unfortunately the RF surface of the Nb has to be cleaned from Ti by chemistry (about 50  $\mu\text{m}$ ) afterwards. It seems obvious, that this procedure should be applied at an early stage of production when chemical cleaning of the Nb surface is necessary anyhow (typically 100  $\mu\text{m}$  to remove the damaged surface layer). But the afterwards deterioration of the RRR observed in the welding zone is an unsolved problem.

#### 2.4 Multipacting

Multipacting in superconducting cavities was a nuisance some time ago. Meanwhile this phenomenon was identified as a species of one point trajectories in the magnetic field region. It could be cured by shaping the cavity contour (spherical or elliptical) to minimize the stable phase area [14]. In couplers (input and higher order mode), however, multipacting is observed and might limit the performance of the superconducting cavity. Recently simulations in coaxial lines predicted stable one side trajectories in the electric field region [15]. Multipacting in wave guides (two side in electric field region) are well investigated in components for space craft applications [16]. In both cases a thin coating with a material of low secondary electron yield helps to suppress multipacting.

#### 2.5 Field emission

Field emitted electrons will be accelerated by the RF field and transfer the kinetic energy to the cryogenic system after impinging the cavity wall. The cavity Q-value will be decreased because of the withdrawn RF energy or by enhanced losses due to heating the RF surface. At large accelerating gradients the electrons might be captured and be transported downstream the linac ("dark current"). The capture threshold scales with operating frequency and has a value of about 7.5 MV/m at 1.3 GHz (TESLA frequency) [17].

Field emission is the dominant limitation at high accelerating gradients. Nevertheless this effect happens at moderate gradients, too.

"Dust particles" on the RF surface will field emit electrons so that cleanliness is essential in reaching high gradients. It has been observed, however, that field emitters can be activated or de-activated after heat treatment or warm-up and cool down cycles. Surface chemistry and absorbed gases are important parameters and their role is not completely understood.

#### 2.6 Q-limit by hydrogen

Some years ago additional RF losses were experienced which depend on material (especially observed at high RRR Niobium), cool down rate (enhanced at slow cool down rate) and on conditions of chemical treatment (enhanced for chemical treatment above 25 °C) [18]. It is known, that dissolved Hydrogen in Niobium undergoes a phase transition around 100 K and forms a  $\text{Nb}_x\text{H}_y$  compound below this

temperature. These normal conducting  $\text{Nb}_x\text{H}_y$  precipitations on the RF-surface produce additional losses.

Degassing the Nb at 800 °C is the only known reliable remedy. If a temperature treatment cannot be applied, a fast cool down in the dangerous transition regime helps to suppress the additional losses. A detailed understanding of how the Hydrogen is injected during chemistry or why the effect depends on history of mechanical forming the Niobium needs more investigation.

#### 2.7 Q limit by magnetic field

The normal conducting core of captured magnetic flux gives raise for RF losses. For bulk Niobium the magnetic field at the cavity has to be reduced to less than 30 mOe (one tenth of the earth magnetic field) in order to reach Q-values above  $10^{10}$ . Passive or active (energized coils) shielding can be used but needs some effort especially in linac type arrangements. Sputtered Niobium films are much less sensitive and need no shielding against the ambient earth field because of their enhanced critical field  $H_c$  and thus smaller normal conducting surface area [19].

### 3. Recent R&D Work with Superconducting Cavities

R&D activities with superconducting cavities are carried out at different laboratories. In most cases single cell accelerating cavities or specially designed test resonators are used in order to have a fast turnaround. In a second step positive results will be transferred to large scale production techniques.

#### 3.1 High pressure water rinse.

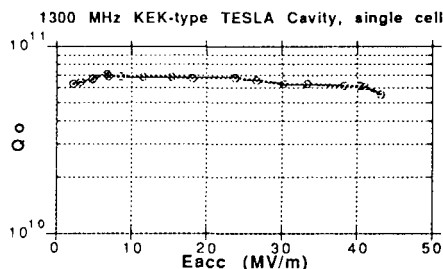


Fig. 1: High gradient cavity after cleaning by high pressure water rinse (treatment: 15 min. chemical polish, high pressure ultra pure water rinse, 3x methanol rinse in cleanroom) [20].

A high pressure water rinse is a well known cleaning technique in the semiconductor industry. Dust particles are removed from the surface and will be washed away by a laminar water stream. In order to clean the inner surface of a cavity a rod with one or several spray nosels is inserted into the cavity. The rod is moved along the cavity axis under slight rotation to reach all surface areas. Infrastructure for high pressure water rinse has been installed at several laboratories. An outstanding example of the benefit of high pressure water rinse is shown in fig. 1. A single cell cavity of the TESLA-KEK shape reached a gradient of 43 MV/m with no sign of field emission.

### 3.2 High power processing

High power processing (HPP) of sc-cavities has been developed at Cornell [21]. A heavily overcoupled cavity is filled by a short (several 100  $\mu$ sec) pulse of high power (about 1 MW). High fields are reached shorter than the thermal equilibrium of a heated spot. Therefore field emitting spots heat up to their melting point and explode. Many "star bursts" have been detected as trace of such an event. Early experiments have been carried out at 3 GHz because of availability of a klystron. Meanwhile a 1.3G Hz klystron has been installed so that HPP experiments could be carried out with TESLA cavities. Fig. 2 shows the behavior of a TESLA shape 5-cell cavity before and after HPP. This cleaning technique can be applied in situ so that cavities in the linac could be cured against field emission after a dust accident.

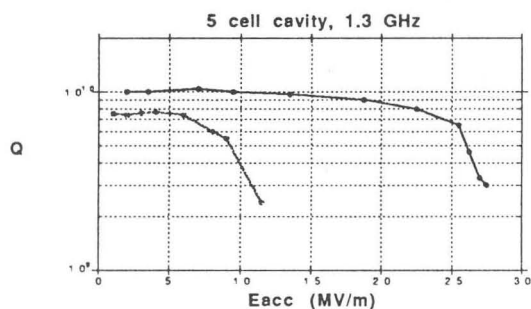


Fig. 2: Measurements of a five cell TESLA cavity before (lower curve) and after high power processing (HPP) [21].

### 3.3 Sputtered films

Further work on niobium sputter coated Cu-cavities is carried out in a CERN/Saclay collaboration. Five-cell cavities (1.5 GHz) are fabricated by hydroforming Cu tubes. Sputter parameters are varied and different cleaning techniques, including high water pressure rinse are applied. Accelerating gradients of 13 MV/m and low field Q-values of 10<sup>10</sup> could be reached [22]. No quench was observed and the maximum gradient was limited by field emission. The strong decrease of the Q value with gradient is explained by metallurgical defects within grains.

NbTiN coatings for cavities are investigated at Saclay [23]. This material presents a lower BCS surface resistance at 4.2 K than Nb due to its higher critical temperature. The bottom plate of a TE011 cavity is coated by magnetron sputtering. A lowest value of 40 n $\Omega$  for the residual resistance was measured at small RF fields (4 GHz). So far coating of a single cell failed because of blistering due to internal stress in the NbTiN films.

### 4. DC Field Emission Studies

DC-field emission from small surfaces has been studied in two different ways: clean surfaces were scanned after different

cleaning or heat treatments (Wuppertal [24]) or the field emission of a surface being sprayed with small particles was studied (Saclay [25]). In the first case it could be proven that fired Nb (1400 °C) emits much less than a wet treated surface. This is in agreement with the reduced RF field emission of fired cavities. A surprising result is the enhanced field emission of a former "clean" surface after a moderate heat treatment around 500 °C (some ten minutes). The reason for this behavior is not understood.



Fig. 3 SEM picture of iron particles on the surface of a RF tip. After applying RF fields the particles line up and are "glued" to the surface by small molten areas [25].

The investigation with artificial dust particles concluded that

- a) particles with a conducting surface emit stronger than those with non conducting surface,
- b) irregular shaped particles emit stronger than equivalent small spheres,
- c) the observed high field enhancement values (above 100) can be explained by a double tip model (a very small particle sits on top of another small particle),
- d) field emitting particles tend to melt at the interface particle to substrate.

### 5. Results from Large Scale Production

At CEBAF 340 cavities (5 cells, 1.5 GHz) have been produced. They are fabricated from presently available high purity Niobium of RRR  $\geq$  250. Preparation included standard cleaning and assembling techniques but not a heat treatment nor high pressure water rinse. Cavity pairs were tested in vertical arrangement and sealed for cryostat assembly if accepted. The test results can be summarized as follows [26]:

- The maximum gradient was limited either by quench or by field emission to about equal amount.
- The average usable gradient (less than 1 W field emission loading, some distance from quench) is 9.4 MV/m at  $Q = 7 \times 10^9$ .
- There is a large spread in performance. Best and worse values for gradient are 8 to 18 MV/m for quench limitation and 4 to 18 MV/m for onset of field emission. These data indicate, that for high gradient application in future accelerators:
  - the RRR of the Nb material has to be increased,
  - the cleaning technique needs essential improvement,
  - quality control of material and procedures is needed to reduce spread of performance.

At CERN 168 sputtered NbCu cavities (4 cells, 350 MHz) are under production at three different companies. Meanwhile 105 cavities have been accepted (gradient of 6 MV/m at a Q value of  $4 \times 10^9$ ) in vertical tests and 19 accelerating modules (each containing 4 cavities) were assembled by industry and shipped to CERN [27]. On average a second Nb coating was needed to get the specified Q value. Meanwhile the temperature control during coating was improved and resulted in an increased success rate after the first coating.

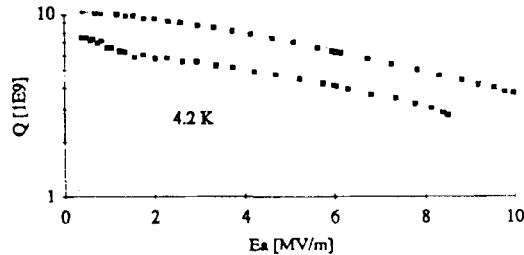


Fig. 4 Performance of best (upper curve) and worst cavity of 105 accepted NbCu cavities at CERN (design values: 6 MV/m at  $4 \times 10^9$ , 4.2 K).

## 6. Performance in Accelerators

### 6.1 KEK

The TRISTAN main ring is equipped with 32 superconducting cavities (5-cells, 508 MHz). Since 1988 a total of 29600 hours of operation were accumulated. Typical operating conditions in 1994 are: accelerating gradient 3.2-3.8 MV/m, beam current of 14 mA (18 mA) during physics runs (injection), input coupler power of 50 kW, HOM power of 200 W per coupler [1]. The operating gradient is limited by a fast decay of the stored energy. The time constant is much shorter than that of a typical quench (thermal runaway). The enhanced trip rate of the end placed cavities of the SRF system and the fact, that realignment of Q- and SX-pole magnets reduced the trip rate indicates, that synchrotron radiation might trigger the fast breakdown. On the other hand the trip rate is also reduced after a moderate warm up to 50 K to desorb Hydrogen from the surface. A possible explanation for the fast breakdown is a synchrotron light induced desorption of Hydrogen. The succeeding RF discharge could absorb RF energy in a short time.

### 6.2 DESY

In HERA 16 sc cavities (4-cells, 500 MHz) are installed in HERA in addition to the 84 nc resonators. Since 1990 a total of 17000 operating hours were accumulated. In 1994 typical operating conditions are [2]: accelerating gradient 3 MV/m, beam current of 30 mA during physics runs, input power of 60 kW and HOM power of 50 W per HOM coupler. The gradient is limited by enhanced RF-losses (Q-disease). The trip rate is dominated by multipacting in the main coupler. Nevertheless the operation is very reliable (see fig. 5).

Hera runs Sept. 93

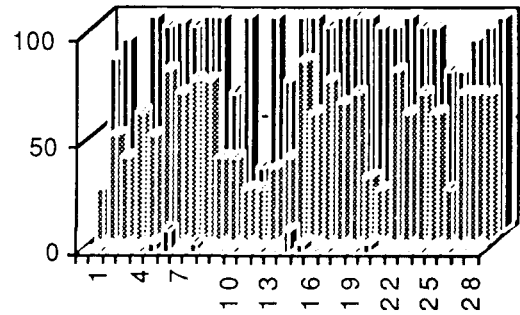


Fig. 5 Statistics of beam loss due to sc-system trips (Sept. 93). Bars show (back to front): sc-system active time, beam on time, beam off time due to sc-system trips (in %) [2].

### 6.3 Darmstadt

At the University of Darmstadt a recirculating linac is in operation since 1991. The linac consists of  $10 \times 20$ -cell cavities (3 GHz), typical operation for nuclear physics studies is 84 MeV at beam current up to 10  $\mu$ A. The cw gradient of 3.2 MV/m is limited by available cryopower.

### 6.4 Saclay

At Saclay MACSE is used as an experimental device for accelerator physics investigations. It consists of  $5 \times 5$ -cell cavities (1.5 GHz) and operates at an average gradient of 12 MV/m and beam currents up to 100  $\mu$ A.

### 6.5 CEBAF

In CEBAF 338 5-cell cavities (1500 MHz) are installed, commissioning started in early 1994 [4]. In July 1994 a total of 286 cavities were operational. The energy gain of the injector, north linac and south linac is 45, 355 and 408 MeV, respectively [28]. The corresponding gradients are 5.00, 5.22 and 6.18 MV/m. They are limited by RF forward power or by cavity performance (quench, field emission).

## 7. TESLA

TESLA (TeV Energy Superconducting Linear Accelerator) is a design for linear collider based on superconducting cavity technology. RF energy can be stored efficiently by superconducting resonators. Therefore low frequency cavities (large volume) at long RF pulse can be used in the linac. The large iris opening reduces transverse impedance and thus alignment is relaxed. The long pulse allows many bunches at large distance. A detailed discussion of the TESLA parameters can be found in [29].

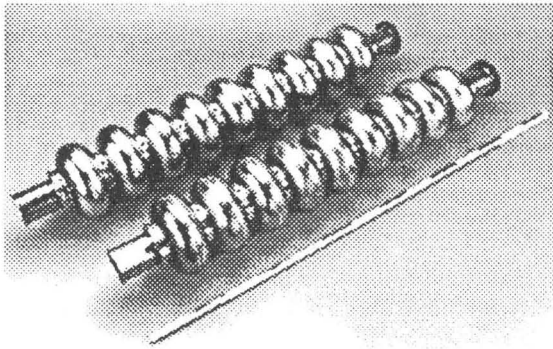


Fig. 6 First Nb cavities for TTF ( $f_0 = 1.3$  GHz, 9 cells,  $E_{\text{peak}}/E_{\text{acc}} = 2.0$ )

A high gradient of 25 MV/m is necessary to keep the length and thus the investments costs of the linac small. Furthermore a considerable reduction of the construction costs for cavities and cryostat is required. Within the frame of an international collaboration a TESLA Test Facility (TTF) is constructed at DESY to develop the necessary technology and demonstrate the feasibility of the design [30]. In August 1994 the infrastructure (automized chemistry, high pressure water rinse, high temperature furnace, cleanrooms class 10 to 10000, high power RF processing, vertical and horizontal test stands) is being commissioned and first tests of two nine cell cavities started. Another 18 cavities are under fabrication and will be delivered before end of 1994. The linac will consist of 32 cavities and operate at nominal 500 MeV.

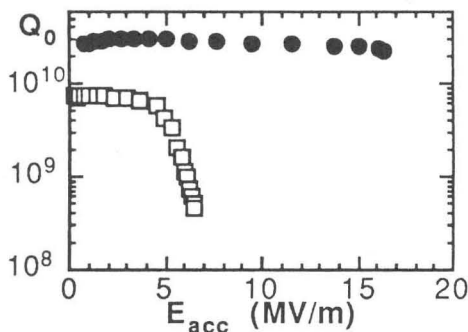


Fig. 7 Measured performance of the first TTF cavity (9 cells, 1.3 GHz): lower curve before, upper curve after high pressure water rinse (100 bar) [31].

### Conclusion

Superconducting cavities are under operation since several years in storage rings and two major systems are under commissioning or installation with operating gradients around 5 MV/m. Progress has been made in understanding present limitations by field emission and quenching. Applying new processing techniques gradients up to 43 MV/m at Q-values above  $10^{10}$  at single cell and 25 MV/m at 5 cell cavities were reached. A unique infrastructure is under commissioning for the TESLA Test Facility to apply those techniques to 9

cell cavities and to demonstrate the cavity performance of 25MV/m under beam conditions.

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