# SRF Cavities for Future Applications

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*Abstract*

Superconducting cavities are under operation or construction for acceleration of electrons and heavy ions at several laboratories. At present gradients around 5 MV/m, beam current up to 10 mA and operating experience exceeding 10,000 h are typical values. The advantage of superconducting RF is the high cw accelerating gradient, the low operating cost to establish RF voltage and the favourable cavity shape for a low loss factor. Ongoing progress in improving Niobium material, simplifying design and fabrication, understanding of performance limitations and investing cures against field emission promise to increase the operating gradient at reduced investment costs. High beam current applications are investigated to take advantage of the small higher order mode impedance. The most challenging development is the use of superconducting cavities for a TeV Linear Collider (TESLA).

## I. INTRODUCTION

For more than ten years superconducting cavities are under use in accelerators. At several laboratories different types of low $\beta$ cavities operate under routine conditions to boost the energy of heavy ions. They produce cw gradients above the capability of normalconducting resonators and work reliable and cost efficient. This paper deals with cavities designed for $\beta = 1$ applications. A recent review of low $\beta$ superconducting cavities is given in [1].

Superconducting cavities are used to accelerate electrons in linacs (Darmstadt, Frascati, HEPL, JAERI, Saclay) and in storage rings (CERN, DESY, KEK). A recirculating linac with 160 m of superconducting cavities is under construction at CEBAF [2]. In total about 800 m of superconducting resonators are under operation or construction. Several $10^5$ cavity-hours of operating experience demonstrate the mature character of this technology. Detailes of the experience gained at different laboratories can be found in [3]. Improvements are expected in raising the operating gradient, lowering fabrication costs and in reliability of auxiliary equipment (input- and HOM couplers, windows, etc). In this paper recent developments and future projects are discussed.

## II. RECENT PROGRESS IN CAVITY TECHNOLOGY

### A. *Niobium material*

Superconducting cavities are produced from sheet material by electron beam welding. The mass production of Niobium has a high standard in respect to the purity of the bulk and the cleanliness of the surface. Considerable improvements have been gained in raising the thermal conductivity by further refinement during the melting processes. As measure of the (temperature dependent) thermal conductivity the value of RRR (Residual Resistance Ratio: $R_{300K}/R_{4.2K}$) is often quoted. Nb material with RRR = 300 is available in large quantities, an improvement by a factor of ten compared to that ten years ago. A high thermal conductivity stabilizes excessive heat flux, thus increasing the breakdown value of a quench.

A further increase of the thermal conductivity can be reached by Ti solid state gettering. The completed cavity is fired for several hours around 1400 $^0C$ together with some Ti material [4]. This purification process is especially valuable to heal mistakes during fabrication (e.g. bad vacuum in the $e^-$–welder). A maximum value of RRR 1000 at a cavity has been reported recently [5].

### B. *Cleaning procedures*

Field emission is the main effect in limiting the accelerating gradient in superconducting cavities. The low AC-loss of a superconductor makes the cavity sensitive to any additional loss mechanism. Another consequence of field emission is the dark current in linacs. Dust particles (metallic or dielectric) on the surface are the most likely source of field emission although other "irregularities" or intrinsic surface properties cannot be completely excluded. Cleaning of the surface by chemistry (BCP: Buffered Chemical Polish) and thorough rinsing is essential to suppress field emission. An automized chemical cleaning facility has been

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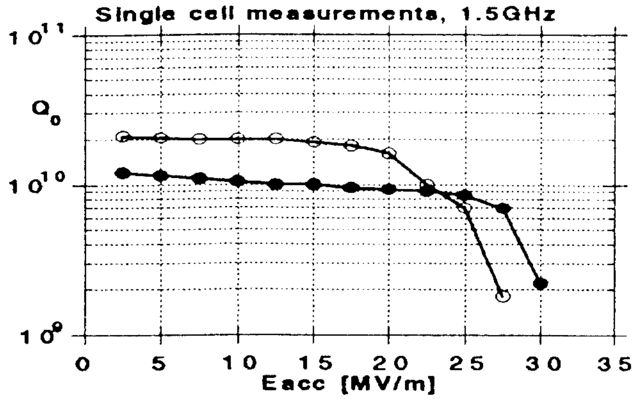


Figure 1: Measured results after application of thorough cleaning technique: (o) single cell (1.5 GHz) treated by automized chemistry [6], (•) single cell (1.5 GHz) treated by high pressure water rinsing [5]

established at Saclay [6]. The cavity undergoes a degreasing, BCP, rinsing and drying process under sealed off conditions. Several single cell cavities have been tested so far. Figure 1 shows a typical result: The cavity stays at a high Q value of $10^{10}$ and no field emission is seen until 20 MV/m. It has to be demonstrated that these exceptional properties can be gained at multicell cavities, too. A similar equipment is under construction at DESY to process 9 cell 1.3 GHz cavities [7].

Rinsing with high pressure water is another cleaning technique. First encouraging results on 350 MHz sputtered single cell cavities have been reported from CERN [8]. Recently single cell 1.5 GHz cavities have been treated several times at CEBAF [5]. Figure 1 shows a typical result: high gradients without field emission up to $E_{acc}$ = 25 MV/m could be measured reproducibly.

## C. *High power processing (HPP)*

In many experiments the onset of field emission is raised to some degree by operating the cavity at high field level (cw or pulsed). The time constant of a superconducting cavity and lack of RF power does not allow to reach higher fields under pulsed conditions in order to do more processing. At Cornell cavities have been HPP treated [10], similar test stands are under construction for 1.3 GHz 5 and 9 cell cavities at Cornell, FNAL, DESY. RF pulsed power (300 kW to 1 MW, 100 $\mu$s to 1 ms) and adjustable input coupler allow to reach high fields before thermal runaway occurs. Figure 2 shows the properties of 9 cell cavities before and after HPP. Further processing was limited by the available RF power. Thermometry and surface studies on these cavities and special demountable single cell resonators (mushroom cavity) [11] have been carried out in parallel. It is concluded that dust particles as possible field emitters are heated during the RF pulse to such an extent that they evaporate in a short time. One attractive feature of HPP is the possibility to apply in situ processing in the linac (to do processing after a dust accident, e.g.).

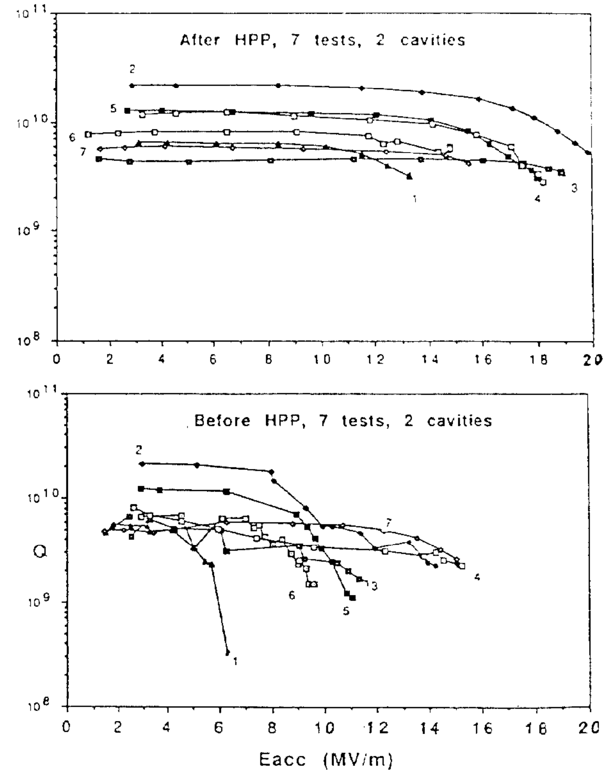


Figure 2: Measured results of 9 cell cavities (3 GHz) before and after HPP [10]

## D. *Nb sputter technology*

At CERN the technology of Nb sputtering for cavities has been developed [12] and was transferred to industry. In total 150 4 cell cavities (350 MHz) are being produced at three companies [13]. The advantages of a sputtered cavity are

- cost saving of Nb material; this is especially true for large cavities at low frequencies,
- reduced surface resistance as compared to bulk Niobium and thus savings in operation costs,
- no need for a magnetic shielding against ambient field,
- stabilization of quench areas by the high thermal conductivity of Cu.

Figure 3 shows performance data of solid Nb and sputtered Nb cavities. It can be seen that sputtered cavities show enhanced Q values. The maximum fields $E_{acc}$ reached are comparable.

## E. *Field emission*

Ongoing experiments at Saclay [15] and Wuppertal [14] investigate the nature of field emission from Nb surfaces by scanning the surface with a needle under high DC voltage. At Saclay dust particles are produced on purpose and their field emission is characterized. An analysis of the large amount of data leads to the following conclusions [15]:

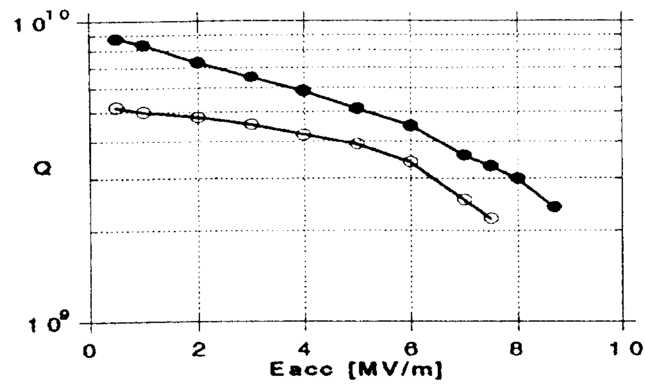


Figure 3: Measured result of 4 cell cavities (350 MHz) at acceptance test [13]: (∘) average of 19 cavities made from solid Nb, (•) average of 14 cavities made by sputtered Nb on Cu

- field emitting sites could always be identified with dust particles,
- metallic dust particles emit at lower values of surface field than dielectric dust,
- there is no big influence of the underlying $Nb_xO_y$ layer.

At Wuppertal clean Nb surfaces are investigated. Conclusions are [14]:

- most field emitting sites could not be identified with dust particles,
- very often the field emitting site is near to irregularities of the surface topology (etching pits?, etc.),
- after 1400$^0$C UHV bake out suface fields up to 100 MV/m could be achieved reproducibly without field emission,
- field emitters seem to reappear after heating at $600 - 800^0C$.

It is not prooven, however, that field emission under DC voltage or RF fields is determined by the same processes. RF heating of a loose particle on the surface might initiate a thermal field emission. The benefit of HPP and the obvious evaporation of earlier field emitters indicate that for surface fields in the range of 20 to 50 MV/m dust particles might play a dominant role.

# III. NEW DEVELOPMENTS

## A. *RF power saving*

Saving of RF installation and operating cost by use of superconducting cavities is not a new argument. In the past this issue was often underestimated. Doubts about the reliability of superconducting RF accelerating systems prevailed. Operating experience at CERN, DESY and

| | U(MV) | $P_{klys.}$ (MW) | $P_{ac}$ (MW) |
|---|---|---|---|
| NC | 81.3 | 3.4 | 5.66 |
| SC | 55.7 | 0.25 | 0.42 |
| Cryogenic | | (500 W at 4.2 K) | 0.15 |
| **Tot.** | **137.0** | | **6.23** |
| NC | 137.0 | 9.65 | 16.05 |
| SC | - | - | - |
| **Tot.** | **137.0** | **9.65** | **16.05** |
| **Energy saving:** | | | 16.05<br>- 6.23<br>**9.82** |
| **saving:** 4000 h × 9820 KW × 0.15 DM/KWh = **5.9 MDM** | | | |

Table 1: Operating conditions of the RF system in HERA $e^-$ in 1992 (upper part). The part below shows the corresponding expenditures without superconducting RF and gives with the resulting energy savings (NC: Normalconducting, SC: Superconducting)

KEK demonstrates, however, that superconducting cavities work stable and reliable after overcoming difficulties with auxiliary equipment (HOM couplers, cables and connectors, proper synchrotron radiation shielding etc.) which, of course, need adequate attention. It is difficult to give a formula of investment and operating cost saving which covers any case of application. It also varies in case of new or supplementary installation. The operating conditions of the HERA normal- and superconducting RF system is given as example. The upper part of table 1 shows the operational data during the 1992 run. The lower part gives calculated data for the same circumferential voltage but without superconducting cavities.

## B. *High current applications*

There is an increasing demand for superconducting cavities in future accelerators with high beam currents:

- reduced cavity-beam interaction by the intrinsic low value of the HOM loss factor of a typical superconducting cavity shape (no nose cones, large iris hole, low operating frequency),
- high gradient, thus reducing the number of cells needed (benefit for length and HOM impedance),
- saving of RF installation and operating costs.

One example of a high current design is the single cell cavity (500 MHz) developed at Cornell for use in a B-factory (CESR B) [16]. The principle layout is presented in Figure 4. The challenge of this design is the HOM damping scheme and the power rating of the input coupler. The higher order modes are damped by a lossy plating at the outer end of the beam pipe. This broad band damping

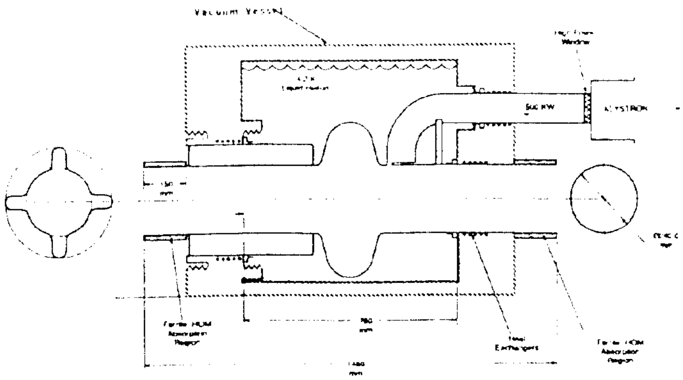

Figure 4: Principle layout of the single cell cavity (500 MHz) for use in a B-factory [17]

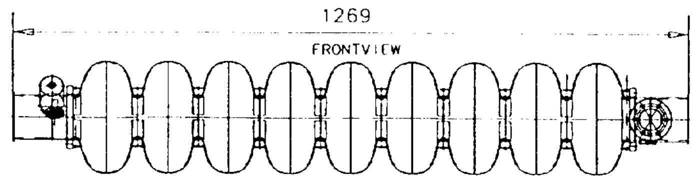


Figure 5: Cross section view of the TESLA 9 cell cavity (1.3 GHz) [7]

scheme is supplemented by a type of riged waveguide to transfer HOM energy below the cut off frequency of the beam pipe, too. High damping with equivalent Q values of around 100 could be measured with Cu models [17]. The input coupler consists of a rectangular waveguide with a coupling slot towards the cavity. First cold measurements demonstrated $E_{acc} = 10$ MV/m at Q value of $2 \times 10^9$ [18].

### C. *High gradient applications*

Superconducting cavities have been proposed for linear colliders since some time [19]. An international collaboration has been formed to work on the design of TESLA [20] (TeV Superconducting Linear Accelerator) and to build a test facility [7]. Superconducting cavities allow storage of RF energy in a very efficient way. As consequence long RF pulses can be established at low frequencies (large cavities). The benefits for a linear collider are:

- low cavity loss factor, thus very relaxed alignment and vibration tolerances,
- long bunch to bunch distance,
- moderate RF peak power demand.

In order to reduce the total costs of TESLA substantial improvements are needed as compared to the state of the art of today:

- the investment costs of about 400 kDM/1 active m (HERA SRF), have to be reduced by a factor of about four,
- the operating gradient has to be raised above 20 MV/m.

In the following paragraphs ongoing and planned R & D effort is described.

1) *Cavity:* The shape of the cavity has to be optimized in respect to

- low value of $E_{peak}/E_{acc}$ to suppress field emission,
- low loss factors $K_{\parallel}, K_{\perp}$ to reduce wake fields,
- high shunt impedance to reduce the refrigerator load,
- high cell to cell coupling to reduce tolerance sensitivity,
- low $H_{peak}/E_{acc}$ values to suppress local heating,
- appropriate shaping to avoid trapped modes (with fields only in the middle cells thus having no damping by end cell couplers).

The elements of the cavity shape (iris ∅, curvature of equator and iris boundary) have different or even contradictory consequences to the above mentioned properties. There is no unique cavity design with the exception of a rounded (circular or elliptical) equator region to avoid multipacting. Figure 5 shows the shape of the TESLA cavity. A number of 9 cells per cavity has been choosen. More cells are desirable for economy reasons and might be possible. But sufficient HOM damping and avoiding trapped modes do not recommend an increase of this number without further detailed and time consuming studies. The low value of $E_{peak}/E_{acc} = 2$ is important to succeed in suppression of field emission.

The existence of trapped modes can be explained by a field flatness problem due to heavily detuned end cells (which are compensated for the fundamental mode). One way to overcome this problem is to detune the end cells even more but in an asymmetric way. Detuning one end cell sufficiently more than the other one results in a tilted field profile. As consequence one of the HOM couplers at each end of the cavity damps very effectively. Measurements on three 9 cell Cu cavities with these asymmetric end cells confirmed this idea [21]. It could be demonstrated, too, that the fundamental mode field pattern is undistorted by proper compensation.

At gradients of some 20 MV/m the cavity contour will be deformed and the resonant frequency is shifted by a noticeable value. This is due to the Lorentz force action of the electromagnetic fields to the surface currents. The iris region is bent inwards, the equator region is bent outwards, both result in a lower resonant frequency. Experimental values of 4 Hz per $(MV/m)^2$ have been reported [18].

FEM analysis of the 1.3 GHz TESLA cavity (wall thickness 2.8 mm) predicts about 1000 Hz shift at 25 MV/m [22]. This value has to be compared to the loaded bandwidth of 330 Hz. The proposed stiffening ring at the iris (see Figure 5) reduces the effect to 300 Hz, further reduction requires expensive stiffening schemes at the equator. Modulation of frequency and phase of the RF drive during filling the cavity has been proposed to reduce amplitude and phase variation during the beam pulse to an acceptable value [23].

A naive interpretation of the Brillouin diagram concludes that the slope and thus the group velocity of the $\pi$–mode is zero. It was investigated whether the energy withdrawn by one bunch can be restored within the 1 $\mu$s bunchdistance in the 9 cell standing wave cavity. The transient behaviour of a coupled resonator model was investigated by applying the Laplace transformation [21]. The result is that the field can be reestablished in each cell but that there are amplitude oscillations at the $10^{-3}$ level. This can be understood as beating patterns of the non-$\pi$ mode excitations. The distortion of the energy resolution of the beam by this statistic effect needs more investigation.

2) *Cryostat:* Most savings in the linac costs can be gained by substantial improvements of the cryostat design. The present layout shows warm–cold transitions every few cavities, expensive distribution boxes and separate transfer lines. In the TESLA design a cavity string of 1700 m is cooled by one 10 kW, 1.8 K refrigerator. A 300 mm ∅ suction line pumps the whole string to 1.8 K and is the mechanical support of the cavities at the same time. One integrated valve box every 144 m supplies LHe to the cavities. The smallest assembly unit is 12 m long, containing 8 cavities and one superconducting quadrupole. Figure 6 shows a cross section of the present layout. Each cavity is surrounded by its own He–tank; couplers and flanges are placed outside the LHe. Slow tuning is done by a motor and gear box at cold temperatures. A coaxial input coupler penetrates the vacuum vessel every 1.3 m. The power rating of the coupler is 200 kW beam power (1.5 ms) and up to 1 MW, 500 $\mu$s for in situ HPP.

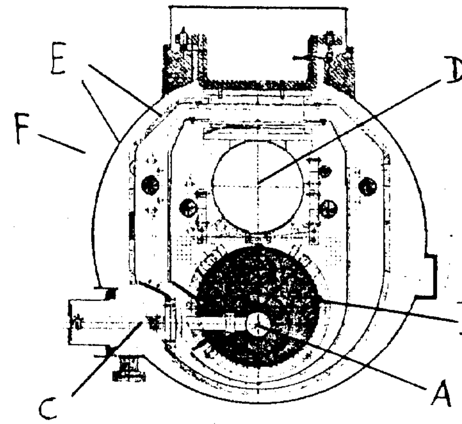


Figure 6: Cross section of the TESLA crystat: A: cavity, B:LHe vessel, C: input coupler, D: suction line, E:radiation shields, F: vacuum vessel.

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