THE QUEST FOR HIGH-GRADIENT SUPERCONDUCTING CAVITIES

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1 Introduction

Superconducting RF (SRF) cavities excel in applications requiring continuous-wave (CW) or long-pulse voltage. Since power losses in the walls of the cavity increase as the square of the accelerating voltage, copper cavities become uneconomical as the demand for high CW voltage grows with particle energy. Here the superconductivity comes to the rescue. The surface resistance of a superconducting cavity is five orders of magnitude less than that of copper. After accounting for the refrigerator power, a net gain of a factor of several hundred remains. The presence of RF structures also has a disruptive effect (impedance) on the beam, limiting the quality of the beam in aspects such as energy spread, beam halo, or even maximum current. Because of their capability to provide higher voltage, SRF systems can be shorter and impose less impedance. SRF cavities can also have large beam holes which drastically reduce impedance.

For these reasons, RF superconductivity has become an important technology for high energy and high luminosity accelerators. More than 2 GV have been installed in electron accelerators and operated at gradients between 4 and 10 MV/m. Beam currents up to 600 mA have been supported in continuous operation, and RF power up to 180 kW has been delivered to the beam through a single input coupler.

Many review articles [1-5] are now available covering the state of the art in RF superconductivity and its application to particle accelerators. There have been seven international workshops on RF superconductivity[6-12]. Their proceedings carry detailed information on the physics, technology, and applications of the field. A reference text [13] is now also available. The discussion here is an overall summary and review. The reader is encouraged to consult [13] for a more thorough discussion of the topics presented.

Many new applications of SRF are forthcoming, some demanding higher beam currents and higher input power, such as those for B-factories and intense
proton linacs for neutrons. Other applications demand higher accelerating gradients, such as those for linear colliders and muon colliders. The focus of this paper is on the challenges before us to reach high gradients to meet the needs of a superconducting linear collider.

The pioneer linear collider is the SLC at SLAC, delivering 100 GeV in the CM with a 3-km-long, 3-GHz copper linac. For the next linear collider, the beam energy needs to be increased by a factor of five over the SLC. But the bigger challenge is that the luminosity needs to be increased by a factor of $1 \times 10^8$ for useful physics in the TeV energy range. To meet this daunting requirement, SRF has many attractions, if the gradients can be improved to 25 MV/m at a $Q$-value of $5 \times 10^9$. In contrast to CW applications discussed above, the RF in a superconducting linear collider must be pulsed to keep the refrigerator size within limits. Nevertheless the duty factor (1%) is still much larger than in any normal conducting version (0.01%).

The long wavelength, SRF approach to TeV energy and high luminosities is a very attractive option as compared to the short wavelength, normal conducting route. Since the $Q$ of the superconducting cavity is very high, it is not necessary to fill the cavity very fast to avoid wasting energy, which means that modest peak powers (200 kW/m) can be used. Because the amount of energy that has to be delivered to the cavity is drastically lowered by the superconductivity, the SRF option permits a much lower RF frequency: 1.3 GHz instead of the 3–30 GHz for normal conducting versions. The low RF frequency has the pleasant consequence of drastically lowering the short- and long-range wakefields, fighting the main enemies of high luminosity. Yet another advantage stemming from the high $Q$ is that the pulse length can be made long enough to accelerate a thousand bunches separated by hundreds of meters. With these options, the desired luminosity can be achieved by higher collision frequency, rather than by squeezing the final spot size to the nanometer level. The relaxed spot size in turn eases the burden on the source and final focus systems.

The challenges for TESLA are to achieve high gradients reliably at high $Q$, and to produce high bunch charge, a large number of bunches, and intense positron beams. Refrigerators and cryogenic distribution systems will add complexity to the facility. However, the operating experience at CEBAF, LEP-II, HERA, RHIC, and the LHC should go a long way to providing an excellent experience base. The ultimate limit to the accelerating field of an SRF cavity is the RF critical magnetic field, which is the superheating field, about 0.23 Tesla. This surface field translates to a maximum accelerating field of 60 MV/m. The exact values depend on the detailed structure geometry. It is clear that such a fundamental limit pushes the superconducting approach to a long machine.

![Figure 1: Distribution of gradients and $Q_0$ at the onset of field emission for more than 300 CEBAF cavities. The average gradient is 8.7 MV/m.](image)

An international collaborative effort has been launched to build a TESLA Test Facility (TTF) at DESY. Its aims are to establish a technological base needed to build TESLA, to demonstrate progress toward the needed gradient and cost goals, to build and beam test a 500-MeV linac with high gradient SRF cavities.

2 A Review of the State of the Art

The state of the art in performance of sheet metal niobium cavities is best represented by the statistics of more than 300 5-cell, 1.5-GHz cavities built for CEBAF [14]. The CEBAF cavities were built by industry from nominal $\text{RRR} = 250$ niobium, and their performance was first measured in a vertical test dewar prior to installation in the accelerator. $\text{RRR}$ is a measure of the purity and the thermal conductivity of niobium. The formal definition of $\text{RRR}$ is

$$\text{RRR} = \frac{\text{resistivity at 300 K}}{\text{residual resistivity at low temperature (normal state)}}$$

Key aspects responsible for the outstanding performance of the CEBAF
cavities set are the antimultipactor, elliptical cell shape, good fabrication and welding techniques, high thermal conductivity niobium (RRR = 250), and clean surface preparation. The histogram of Figure 1 shows the distribution of fields at the onset of field emission. The accompanying scatter plot gives the $Q_0$ at the field emission onset field. On average, field emission starts at $E_{acc} = 8.7 \text{ MV/m}$, but there is a large spread, even though the cavities received nominally the same surface treatment and assembly procedures. In some cavities, field emission was detected as low as 3 MV/m, and in others it was found to be as high as 19 MV/m.

After the onset of field emission, the $Q_0$ of a niobium cavity typically starts to fall steeply because of exponentially increasing electron currents emerging from the surface. Figure 2 shows the typical field emission dominated $Q$ vs. $E$ behavior for CEBAF cavities [14].

In many cases, several minutes of CW processing (to be discussed below) with up to 100 W RF power, produced a 10–30% gain in performance for approximately 50% of the cavities. Of the total batch, 148 cavities exceeded 9 MV/m without significant field emission loading. As we will discuss, the reason for the large spread in the gradients is the large spread in emitter characteristics and the random occurrence of emitters on the RF surface.

Figure 2: Sample of vertical test results of CEBAF 5-cell, 1.5-GHz cavities that show field emission. Many cavities show the onset of field emission at $E_{pk} = 10–20 \text{ MV/m}$, but a few best cavities remain field emission free up to $E_{pk} = 30 \text{ MV/m}$. The $E_{pk}/E_{acc}$ ratio of these cavities is 2.6.

Figure 3: Distribution of quench fields for about 100 5-cell, 1.5-GHz CEBAF cavities. The $Q$-value shown is just below the quench field. $H_{pk}/E_{acc} = 47 \text{ Oe/MV/m}$.

A large number of CEBAF cavities were also limited by the phenomenon of thermal breakdown. Figure 3 shows the distribution of quench fields and the $Q_0$ values below quench for about 100 cavities. Here the average is 13.5 MV/m, and the best is 20 MV/m. The large spread in quench field reflects the spread in defect strengths and the statistical occurrence of defects.

Comparison of the field emission (Figure 1) onset and quench histograms (Figure 3) makes it clear that field emission is the predominant effect, but that quench limitation is only somewhat higher and may become dominant when emission is reduced to some extent.

3 The Physics of Thermal Breakdown

One important phenomenon that limits the achievable RF magnetic field is thermal breakdown of superconductivity, originating at sub-millimeter-size regions of high RF loss, called defects. When the temperature outside the defect exceeds the superconducting transition temperature, $T_c$, the losses increase, as large regions become normal conducting.

Experience shows that the quench field level does not change during a test
or after cycling to room temperature. Only the step of re-rinsing or re-etching a cavity has an effect on the quench field. This suggests that most defects are permanently lodged on, and strongly attached to, the superconducting surface.

It is possible to locate defects that lead to thermal breakdown by using the powerful temperature-mapping technique. After locating the hot site, the cavity can be cut cleanly and examined inside a scanning electron microscope (SEM). When we examine the vicinity of the predicted site, we find the defect and its associated contaminants. Chemical analysis can also be carried out, using an energy dispersive x-ray (EDX) system. Several examples of defects are given in Ref. [13]. Two different examples are given here. The first (Figure 4) [15] comes from a cluster of similar sites found near the thermal breakdown region in a single-cell S-band cavity that was limited by quench at 1035 Oe. Just below breakdown, the temperature rise near the defect at the outer wall of the cavity was nearly one degree K. EDX analysis revealed the particles to be copper.

Another defect [16] that showed thermal breakdown at 925 Oe (Figure 5) appears more like a sharp pit than a foreign material inclusion. Perhaps the inclusion was etched away leaving a sharp 100-μm-deep pit. Possibly there was substantial magnetic field enhancement at the edges of this pit which caused the breakdown.

Generally we do not have access to both (a) an SEM micrograph of a defect (to estimate its size) and (b) the thermometry data (to estimate its surface

Figure 4: SEM photograph of one among a cluster of copper particle fields.

Figure 5: SEM micrographs of a defect that caused thermal breakdown at $E_{pk} = 38$ MV/m, $H_{pk} = 925$ Oe. No foreign materials were detected by EDX. Depth profiling indicates that the defect is a depression at least 100 μm deep with steep walls. (a) Defect appears to be a large pit. (b) Same defect at a glancing incidence angle.
resistance). Typically, we know only the quench field level. For convenience, if we take a defect surface resistance of 10 mΩ, typical for normal conducting niobium, we can characterize the "strength" of a defect purely in terms of its size. In the future, for modelling purposes, we will refer to the strength of a defect only in terms of the size of a normal conducting defect, keeping in mind that defect size and resistance can span a broad range of values.

On rare occasions, when raising the RF power, there can be a small Q drop, called a "Q-switch" (Figure 6). In most cases, a Q-switch is caused by a region of niobium that is poorly attached to the surface, such as a poorly adhering, overlapped layer of niobium embedded during forming operations. Niobium balls from weld spatter also cause a Q-switch. At low fields, the niobium blistering or beads are superconducting and do not adversely affect the Q. At the switching field, the loosely attached region, which is thermally isolated, becomes normal conducting, dropping the Q. If the field is lowered, the Q does not recover since the detached region does not cool down until the RF field is lowered well below the switching field. A mm-sized tantalum-rich area of niobium was found at the Q-switch site suggesting that the defect was a superconducting alloy of niobium-tantalum [17].

A simple model and calculation that illustrates the essential features of thermal breakdown at a normal conducting defect predicts that the field reaches a maximum value

$$H_{\text{max}} = \sqrt{\frac{4\kappa(T_c - T_b)}{aR_n}}.$$  \hspace{1cm} (2)

Here a is the defect radius, $R_n$ is the defect resistance, $T_c$ is the bath temperature and $\kappa$ is the average thermal conductivity (e.g. at 4.2 K). For example, at a bath temperature of 2 K, a 50-μm-radius defect with $R_n = 10$ mΩ will break down at $H_{\text{max}} = 820$ Oe, if the RRR is 300, i.e. $\kappa$ is 75 W/mK.

This model is certainly oversimplified, because it ignores many physical aspects: the field enhancement due to the geometry of the defect, the temperature- and frequency-dependent BCS surface resistance of the surrounding superconductor, the residual resistance, the temperature dependence of the thermal conductivity, and the details of the heat flow between the niobium cavity wall and the helium bath. There now exist several computer codes based on iterative solutions of the heat flow equation to include such factors and to calculate the equilibrium temperature distribution at the RF surface and elsewhere. Remarkably, the salient conclusions reached by the simple model remain essentially true. For a given defect (a, $R_n$), $H_{\text{max}}$ increases as $\sqrt{\kappa}$. Apart from the defect parameters and the thermal conductivity, the other factors do not play as significant a role, because the heating at the defect dominates the power dissipation at the RF surface, and because the relatively low thermal conductivity of the niobium (for RRR = several hundred) essentially isolates the defect from the bath.

A representative result of the thermal model calculation (Figure 7) shows that the breakdown field for a 200-μm-radius defect increases roughly as $\sqrt{\text{RRR}}$, as expected from the simple model and Equation 2. We compare the results of the simulation with experiments in order to estimate the size of defects. Here we assume that thermal breakdown takes place near the equator, i.e. at the highest magnetic field region of the cavity. Experience shows that the typical breakdown field is 200 Oe for niobium of RRR = 40, which translates to 5 MV/m for a velocity-of-light structure. Simulations reveal that if the defect is a normal conducting region of 20 μm radius, it will break down at 5 MV/m.

4 The Physics of Field Emission

Reviews of this prolific subject can be found in Refs. [18–23]. Also, recent books cover a wide range of topics related to field emission [24, 25]. The temperature mapping diagnostic technique for superconducting cavities shows that emission always arises from particular spots, called "emitters" usu-
ally located in high electric field regions. The pattern of temperature rise as a function of position along a given meridian contains implicit information about the location and characteristics of the emission source. We can relate such symptoms to the trajectories of the electrons that emerge from the emitters, travel in the RF fields of the cavity, and impact the RF surface. The power deposited by the impacting electrons depends not only on the trajectory but also on the intrinsic properties of the emitter — i.e. on the field emission current. Fowler and Nordheim (FN) [26] showed that, in the presence of an electric field, electrons tunnel out of the metal into the vacuum because of their quantum-wave-like nature. However, comparison with the observed currents reveals that, at a given field, emission is substantially higher than the FN predictions. Traditionally, the excess has been attributed to a field enhancement factor $\beta_{FN}$ arising from hypothetical asperities on the surface that enhance the electric field. Associated with these hypothetical asperities there is also the traditional emissive area, $A_e$.

Much has been learned about the nature of emitters from superconducting RF cavity experiments equipped with temperature-mapping capabilities. The RF tests are followed by dissection of the cavity to examine the emitter with surface analytic instruments. Substantial advances in understanding the nature of field emission have also been made by DC high-voltage studies that locate emission sites with a needle-shaped electrode, followed by electron microscopy studies of the sites. By and large, both RF and DC studies reveal that emitters are micron- to sub-micron-size contaminant particles. The asperities originally envisioned were not usually found, except in isolated cases, e.g. when the surface was scratched to leave sharp protrusions at the edges of the scratch.

Several examples of emitters can be found in Ref. [13]. Three different examples are shown here. The first (Figure 8) [15] is a particle containing titanium, carbon, oxygen, sodium, indium, aluminum, and silicon. This appears as a very jagged particle. The second (Figure 9) [16] appears as a relatively smooth particle which contains carbon, oxygen, iron, chromium, and nickel. Finally Figure 10 shows a particle of silica located on the RF cavity surface and characterized with SEM/EDX before the cavity was subjected to high electric field in the RF cold test [27]. Later we will show what happened to this site after application of an RF electric field of about 75 MV/m.

A remarkable finding from the DC studies on emitters is that not all microparticles turn out to be field emitters. Besides the presence of the microparticle, additional physical aspects appear to play important roles in determining

Figure 7: Thermal model predictions for the breakdown field of various normal conducting defects. For comparison, the quench field calculated from Equation 2 is shown by * . Note that the full simulations show a higher field value because they include the temperature-dependent thermal conductivity, the average of which is higher than the thermal conductivity at 4.2 K. For these cavities $H_{pk}/E_{acc} = 47$ Oe/MV/m.

Figure 8: SEM photograph of a field-emitting particle located by temperature mapping and dissection of a single-cell 3000-MHz cavity. EDX analysis showed the particle to contain titanium, carbon, oxygen, sodium, indium, aluminum and silicon.
whether a particle is, or is not, a field emitter: the detailed geometry, the condensed gas adsorbrates, and possibly the interaction between the particle and the insulating layer on the surface. Rather than delve into these factors here we refer the reader to references cited at the beginning of this section.

Sensitized by the results about the microparticulate nature of emitters, new approaches have been adopted to strive for a higher level of cleanliness in cavity surface preparation, leading to fewer emission sites and better cavity performance.

KEK studies [28] with high-pressure (≈ 100 bar) water rinsing (HPR) show a factor of a hundred reduction in particle count on silicon wafers. DC field emission studies at Wuppertal [29] on ≈ cm² samples also show that the density of emitters is reduced by HPR.

5 The Physics of Emitter Processing

When raising the RF electric field in a superconducting cavity for the first time (i.e. with a freshly prepared surface), the field emission often decreases abruptly; the cavity is said to process or condition. Temperature maps show that individual emitters extinguish during such processing events. Much progress has been made in subsequently characterizing the processed emitters at a microscopic level using surface analysis techniques such as SEM, EDX, Auger, and AFM. Many examples are given in the literature. Here we give two different examples from 6-GHz mushroom-cavity tests. In the first example (Figure 11), we show a processed emitter site with a 200-µm starburst feature and a single central 5-µm molten crater (expanded SEM picture) around which are several submicron-size molten copper particles. Presumably these are residues of the original (larger) copper emitting particle.

As mentioned above, before carrying out one of the mushroom-cavity tests, we located and characterized a silica particle (Figure 10). Figure 12 shows the result of applying high RF electric fields (maximum 75 MV/m) to the silica site. To the best of our knowledge, this is the first time a field-emitting particle has been characterized both before and after its explosion. The 100-µm site has a multiple “starburst” shape with a 10-µm molten crater-like core region in the expanded version. EDX could detect no foreign elements at this site. This is not unusual for sparked sites. However, in such cases Auger analysis will usually show the central molten crater to be covered by a thin layer of foreign elements, presumably from the original field emission particle. The explosive processes in the spark are sufficiently intense to vaporize the original field-emitting particle, occasionally leaving smaller molten particles (Figure 11) and most often a thin
film that can be detected only by Auger [30].

The results of emitter and processed emitter studies have considerably improved our understanding of both field emission and conditioning. There are a large number of particles on the RF surface, typically 100 particles per cm² with sizes between 0.3 μm and 20 μm. These particles are lodged on the surface during preparation, exposed from the bulk during chemical etching, or introduced at the cavity assembly or pump-out stages.

Only some (∼10%) of these particles turn out to be field emitters between 20 and 100 MV/m. The metallic ones (i.e., the conducting particles) are most likely to emit. Particles generally have a very irregular shape, and the microprotrusions enhance the field emission characteristics. Other important factors are the nature and quantity of condensed matter on the particle and possibly the interface between the particle and the substrate. Because of these many factors it is not surprising to find a large distribution in $\beta_{FN}$ and $A_e$ values. Some particles that are not field emitters may become emitters later if gas adsorbs. Emission may also activate abruptly in an emission-free cavity if a particle arrives at a high field region.

When the field increases and the emission current density exceeds $10^{11}$ A/m² the temperature at the emission region becomes high enough to melt a small region of the particle. A microprotuberance of the emitting particle may melt and cease to emit, but the overall emission from the particle will continue at some baseline level. When the cavity fields are raised for the first time and individual microemitters melt, the emission current is unstable until the susceptible regions are all melted.

Atoms evaporate from the melted regions. Ohmic heating from the FN current also degasses surface adsorbed atoms. The presence of gases plays a paramount role in emitter processing. A study in progress [16] is using the program MASK [31] to simulate ionization of the gas by field-emitted current and the attendant consequences. At 30 MV/m, emitted electrons will gain 30 eV within a micron of the rf surface, sufficient energy to ionize the gas. A chain of events then takes place on a very short time scale (nanoseconds) with the presence of gas playing a central role. As the field emission current ionizes the evaporated and/or desorbed gas, the ions are accelerated by the field toward the emission site. The ion current produces secondary ions and electrons, and heats the site further by bombardment, so that more gas is produced. A plasma is formed extending out to several hundred microns. Electron and ion bombardment from the plasma cloud cleans up the surface, leaving a physical pattern on niobium that is devoid of surface residues such as flourine. The plasma fingerprint has the shape of a starburst.

Figure 11: SEM micrographs of a processed emission site. (a) Large starburst with single central molten crater. (b) The expanded molten crater region shows sub-micron-size melted copper particles, presumably from the original copper emitting site.
MASK simulations show that, since the ions move slowly, a significant number can accumulate near the emitter, leading to substantial electric field enhancement. The amount of field enhancement depends on the total current from the emitter. Estimates based on available processed emitter data suggest that when the total current approaches the level of a milliampere the emitter will process; i.e. there are enough ions to initiate a discharge, which is the avalanche breakdown of the gas surrounding the site. At the core of the arc, the intense current can melt niobium, produce molten craters, vaporize the entire emitting particle, and leave a deposited film of the original contaminant on the crater. In many cases the discharge event leaves behind molten debris. Plasma pressure during the discharge excavates the molten zone and ejects droplets. There may be multiple arcs between the ion cloud and the niobium, resulting in multiple craters from a single original emission site. The crater and other melted particles do not emit because they are smooth particles.

The model suggests that, for a site with particular values of $\beta_{PN}$ and $A_c$, the field $E$ must be increased to reach a $\beta_{PN}E$ value corresponding to an emission current density $> 10^{11}$ A/m$^2$ to approach heating and melting at the site so that a sufficient gas density is created. But to process a site the total current must reach a threshold value near one mA. To reach the necessary field level, high RF power is required. Short pulses are sufficient, because the emitter explosion takes place very fast (nanoseconds) when conditions are ripe.

6 How To Avoid Thermal Breakdown

An obvious approach is to prepare the niobium material with great care to keep it free of defects. Along the same lines, gains are foreseen from searching the starting niobium sheet for defects by a method such as eddy-current scanning [32].

The most effective way to prevent thermal breakdown from small defects is to raise the thermal conductivity of the niobium to increase $H_{\text{max}}$, as suggested by Equation 2. Then defects will be able to tolerate more power before driving the neighboring superconductor into the normal state. The most effective approach to increasing the thermal conductivity of niobium is to remove the interstitial impurities by improving the electron beam melting technique used for refining the ingot. Niobium is now available with $\text{RRR} = 250$ to 300 from U.S. and European suppliers who use the techniques of multiple and slow melting. New Russian niobium is available with $\text{RRR} = 500$ to 700 [33].

Yet another technique for improving niobium purity is solid-state gettering. It was first applied [34] to raise the RRR of niobium cavities by using yttrium

Figure 12: SEM micrographs of a processed emission site. (a) SEM picture of the silica particle after the RF test. (b) Expanded SEM picture of the sparked silica particle. Here we see the molten crater region in more detail.
to coat the niobium surface. Yttrium has a higher affinity for oxygen than does Nb [35–37]. The coated niobium is heated to a temperature, e.g., 1200 °C, such that oxygen diffuses rapidly. The mobile interstitial impurity atoms sink into the foreign metal layer when they arrive at the surface of the niobium. The coating and purification operations can be combined into one step because the vapor pressure of yttrium is large enough to form an evaporated layer at the diffusion temperature. With solid-state gettering for 4 hours, a factor of 2 to 3 improvement in RRR is possible for commercially available niobium, corresponding to nearly complete removal of the oxygen, which is the dominant impurity. After the purification stage, the getter material and the underlying compound layer are chemically etched away. Commercial niobium of RRR = 30 can thus be improved to RRR = 90, and commercially prepared niobium of RRR = 250 to 300 has been improved to RRR = 500. Russian niobium now available with starting RRR = 500 to 700 has been improved to RRR = 1000 to 1400. The post-purification must be done after the half-cell forming stage or later, because grain growth at high temperature will destroy the mechanical workability of niobium.

Soon after the application of solid-state gettering by yttrium to niobium cavities, it was found that titanium is also an effective solid-state getter [38]. However, since the vapor pressure of titanium is lower than that of yttrium, higher temperatures or longer times are needed. For example, to remove oxygen in a few hours, titanium must be used at 1350 to 1400 °C. Since titanium diffuses into niobium to a substantial depth (∼100 μm) along the grain boundaries [39], heavy chemical etching becomes necessary after the post-purification step. The outside surface of a cavity must also be etched about 50 μm to reestablish good Kapitza conductance [40]. Titanium does have the intrinsic capability to remove nitrogen and carbon by solid-state gettering because of its appreciable affinity for these impurities. Affinities are compared in [41]. But since the diffusion rates of nitrogen and carbon are much lower than that of oxygen, very long gettering times are necessary. Using titanium for more than 50 hours, RRR values >1000 have been achieved in samples of starting RRR = 200 [42].

High RRR niobium has some important negative side effects [13]. Since the BCS surface resistance increases with the electron mean free path, high RRR cavities have a lower BCS $Q_0$. This effect is not important at operating temperatures below 2 K when the BCS component is negligible, and residual losses dominate the $Q$. High RRR niobium cavities are more sensitive to $Q$ degradation from hydrides [13], because they lack the interstitial impurities that serve to trap diffusing hydrogen and prevent the formation of lossy hydride clusters on the RF surface. Precautions are therefore necessary during the chemical etching stage of high-RRR niobium to avoid hydrogen contamination. Solid-state gettering lowers the yield strength of the material. Appropriate measures must be taken to avoid collapsing a thin-wall cavity whose yield strength has been lowered by purification.

Coupled with the efforts to overcome field emission, RRR ≈ 500 has already allowed niobium cavities to reach accelerating gradients between 20 and 28 MV/m in the case of 5-cell, 1500 MHz cavities. But to reach high accelerating fields reliably, also in large-area accelerating structures (e.g., the 9-cell, 1.3-GHz cavities), RRR > 500 is very much desired.

7 How to Avoid Field Emission

Field-emitter studies discussed above show that increased vigilance in cleanliness during final surface preparation and assembly procedures is important to keep particulate contamination and associated emission under control. Figure 13 shows the care and cleanliness necessary during chemical etching and rinsing. Figure 14 shows the cavities being assembled in a clean room at the TTF.

A technique to further improve cleanliness is high-pressure water rinsing (HPR). The technique was originally applied at CERN [43] but the full potential of the method was best demonstrated at CEBAF [44], KEK [28], and DESY. A jet of ultrapure water is used to dislodge surface contaminants resistant to conventional rinsing procedures. Figure 15 shows a Cornell 500-MHz single-cell cavity for CESR under preparation for HPR. The benefits of HPR in reducing field emission are well demonstrated in tests on 5-cell cavities at CEBAF and at DESY.

After the RRR of several 5-cell cavities at CEBAF was improved to RRR = 500 by titanium solid-state gettering HPR was applied. It was possible to overcome both the field emission and quench limitation, to give the excellent results shown in Figure 16 [45].

Similarly good results are forthcoming from the 9-cell, 1.3-GHz structures for TTF, as shown in Figure 17. In a spectacular best result, the $Q_0$ remained near $4 \times 10^{10}$ from low fields all the way up to $E_{acc} = 25$ MV/m. The low-field $Q_0$ values for the TTF cavities are higher because of better shielding against the earth's DC magnetic field. Most cavities appear field emission free up to $E_{acc} = 15$ MV/m. From the quench limitation of most of these cavities it is clear that still higher RRR is needed. At the same time, we see from the drop in $Q_0$ above $E_{acc} = 20$ MV/m that HPR is not able to eliminate field emission in every cavity or every test.
Figure 13: Chemistry and rinsing facility at the TTF.

Figure 14: Clean room assembly at the TTF.

8 High-Power Pulsed RF Processing

The supercleanliness approach of HPR has demonstrated a potential to reduce field emission, but temperature maps have shown that a single field-emission site can degrade the $Q_0$ of a superconducting cavity if the emitter will not process away at the maximum RF power available. In large-area structures there is always a significant probability that a few emitters will find their way onto the cavity surface. There is also the danger of dust falling into the cavity during installation of power-coupling devices. We have already mentioned these reasons for the large spread observed in cavity performance. The contamination threat is especially clear in the light of the experience at all laboratories of a 20% decrease in performance between acceptance tests and in-accelerator tests. Another factor that makes the threat of dust contamination especially clear is the "area effect". The dependence of achievable field on cavity area has been examined on several occasions over the years ([22, 34, 46, 47]) as SRF technology continued to evolve. If we define an envelope from the maximum field reached at any stage in the technology development, we find the empirical rule that the maximum field decreases as (cavity area)$^{-1/4}$. Innovations such as high purity niobium, high power processing or high pressure rinsing keep pushing the envelope to higher fields. Nevertheless, at any stage in the evolution of cavity treatment technology, the maximum achieved fields decrease with cavity area.

The above remarks make it clear that a technique for eliminating emitters
Figure 15: High-pressure rinsing set-up for a single-cell cavity at Cornell.

Figure 16: Field emission and quench-free performance of four 5-cell CEBAF cavities after improving RRR to 500 by solid-state gettering with titanium and by HPR. The maximum field in these tests was limited by the available RF power.

Figure 17: Performance of a dozen 9-cell TTF cavities after improving RRR by solid-state gettering with titanium, and then cleaning by HPR.
in situ is highly desirable for successful application of superconducting cavities to accelerators. Such a technique has been developed. Called high pulse power processing (HPP), it has been successfully applied to 3-GHz, 9-cell cavities [48], to 1.3-GHz 5-cell cavities [49] and to 1.3-GHz 9-cell cavities [17]. One example of “before-and-after” HPP from each of these multi-cell test series is shown in Figure 18, Figure 19 and Figure 20. Figure 21 shows the HPP apparatus installed at the DESY TTF.

The essential idea of high power RF processing of an emission site is to raise the surface electric field at the emitter as high as possible, even if for a very short time (\( \ll \mu \text{sec} \)). As the field rises, the emission current rises exponentially to the level at which melting, evaporation, gas evolution, plasma formation, and ultimately a microdischarge (RF spark) take place. The ensuing explosive event destroys the emitter. We have discussed in detail the evidence for this model and the probable chain of events involved. Emitters have been processed away, and the field levels raised substantially. This is not to say that, with HPP, the need for cleanliness is eliminated. We reemphasize that to reach the highest possible field in a reproducible manner, one must continue to be ever vigilant in the fight to avoid field emitters.

Figure 18: Improvement of a 9-cell cavity by HPP processing. The solid symbols show \( Q_0 \) vs. \( E_{\text{acc}} \) before HPP. The open symbols show the results of the measurement following HPP processing with incident power up to 100 kW when the maximum pulsed surface electric field reached was 88 MV/m. The RRR of this cavity had been improved to about 500 by solid-state gettering with yttrium. The cavity did not reach thermal breakdown up to the maximum CW field of the test.

Figure 19: Before HPP the 5-cell, 1.3-GHz cavity was limited by heavy field emission to \( E_{\text{acc}} = 12 \) MV/m. After applying 1 MW of power and reaching 90 MV/m in the pulsed mode with pulse length 250 \( \mu \)sec, the field emission was processed away and \( E_{\text{acc}} = 28 \) MV/m was possible. The RRR of this cavity had been improved by solid-state gettering with titanium to about 500.

Figure 20: Improvement in gradient of a 9-cell cavity by HPP. The \( Q_0 \) drop could be recovered by warming up to room temperature.
The key to effective HPP processing is to force the peak fields during processing to the highest possible value. The klystron power, pulse length, and coupling need to be arranged accordingly. The overriding factor determining the success of HPP is the peak electric field reached during the pulsed RF stage. If this field is not raised, no benefits are observed for the CW low-power performance. It was found that conditioning for longer times at the same field level, or with longer pulses at the same field level, did not help to reduce field emission or to reach higher fields. This experience is consistent with the finding that emitter processing takes place only when the emitter current density and the total current exceed certain threshold values as discussed earlier. Both emission current density and total current depend on $E_{pk}$.

To obtain field emission free behavior at a certain operating field level it is necessary to condition cavities to even higher values — i.e. to approximately twice the operating field,

$$E_{pk} \text{ (CW)} = 0.5 \times E_{pk} \text{ (pulsed)}. \quad (3)$$

An important benefit of HPP is that it can be applied to recover cavities that may have been accidentally contaminated, e.g. in a vacuum mishap. This has been demonstrated using 9-cell structures at 3 GHz [48].

There are some limits to the maximum achievable field during HPP. One is the rapidly falling $Q_0$ with increasing $E_{pk}$. An even more severe $Q_0$ decline occurs if thermal breakdown is reached during the RF pulse. After this stage is reached, further gains in $E_{pk}$ can come only with very large increases in pulsed power, because the growing normal conducting region absorbs the available RF power very rapidly. However, it has been experimentally shown that the quench field may be exceeded for short periods. Even when thermal breakdown starts, $E_{pk}$ can be pushed up by increasing the incident power, and decreasing $Q_0$, so that the cavity fills more rapidly. Under these conditions, the electric field continues to increase in the time it takes for the quench to propagate. Thus it is possible to extend processing beyond the thermal breakdown limit, at the expense of higher power. Therefore high thermal conductivity for niobium also proves beneficial to processing emission by HPP. By raising the thermal conductivity and avoiding thermal breakdown, it is possible to reach higher fields and thus to process more emitters. Moreover, high thermal conductivity cavities will better tolerate the heat deposited by the higher emission currents that will arise when the HPP field is raised. It is important to recognize that efforts to avoid quench by preparing defect-free cavities will not eliminate the need for high thermal conductivity for effective field emission processing.

Figure 21: HPP test setup at DESY TTF.
A possible concern about the HPP method is the degree to which $Q_0$ may be degraded by the presence of a large number of destroyed emitters. Another concern is whether the crystals may become defects that cause thermal breakdown. Some of the $Q_0$ vs. $E$ curves after HPP presented above do indeed show $Q_0$ degradation due to HPP. Generally, however, $Q_0$ is not degraded below $10^{10}$. A single-cell 3-GHz cavity, which was processed by HPP to $E_{pk}$ $\approx$ 70 MV/m, still showed $Q_0 = 10^{10}$ at $E_{pk} = 40$ MV/m CW. Furthermore, on dissection, more than 40 starburst-crater areas were found in this cavity. Therefore the large numbers of processed sites do not seriously degrade $Q_0$ or create a thermal breakdown problem. This is not surprising, since the molten regions are generally $< 10 \mu m$ in size so that even a large number of craters do not pose a serious threat. One may, of course, wonder whether processing at higher fields could prove more dangerous. Experience to date shows that even after processing at 130 MV/m, $Q_0$ remains $> 10^{10}$ at $E_{acc} = 20$ MV/m.

It is important to keep in mind that cavities with RRR = 250 - 300 will not exceed $E_{acc} = 15$ MV/m, on average. This conclusion is well borne out by CEBAF quench statistics (Figure 3). Several groups have shown that the quench field of an individual cavity that shows thermal breakdown below 15 MV/m can be improved by post-purification to above 25 MV/m. Figure 22 shows one example from the Cornell experience with 5-cell cavities and Figure 23 shows another from DESY TTF cavities. In such cases, it is also necessary to avoid field emission limitations, either by successful HPR or by HPP to destroy remaining emitters. As a rule, therefore both high RRR as well as HPP/HPR are essential to ensure the highest possible gradients.

9 Closing Remarks

Producing high gradients and high $Q_0$ in superconducting cavities demands excellent control of material properties and surface cleanliness. The spread in gradients that arises from the random occurrence of defects and emitters must be reduced. It will be important to improve installation procedures to preserve the excellent gradients now obtained in laboratory tests in vertical cryostats.

In the case of defects, eddy-current scanning methods are proving useful in eliminating defective starting material. In order to reach the highest accelerating fields, the highest thermal conductivity niobium is essential to avoid thermal breakdown both from defects and from intense field emission current that must be sustained for effective processing of emitters. High-pressure rinsing and high-power processing are essential to avoid field emission and to destroy remaining emitters. Figure 24 summarizes the quest for high gradients in multicell ac-

![Figure 22: Improvement in performance of cavity due to post-purification and HPP. Note that the abscissa is $E_{pk}$. Upper: Before post-purification, RRR = 250, thermal breakdown limited the maximum field to $E_{acc} = 13.5$ MV/m. Lower: After RRR improvement (at least a factor of two), the field could be raised to $E_{acc} = 21$ MV/m, but in the presence of heavy field emission. This was successfully processed by using HPP. During the processing stage, 1 MW of power applied raised $E_{pk}$ to 90 MV/m in the pulsed mode with pulse length 250 $\mu$s. After processing, the CW field reached $E_{acc} = 27$ MV/m.](image-url)
Figure 23: Improvement in performance of a 9-cell cavity due to post-purification and HPR. Before post-purification, RRR = 400, thermal breakdown limited the maximum field to $E_{acc} < 20$ MV/m. After RRR improvement and HPR, the field could be raised to $E_{acc} = 28$ MV/m, but in the presence of heavy field emission.

Figure 24: A summary of the results on multicell cavities showing the importance of high RRR coupled with emission reduction techniques such as HPP and HPR. The dashed line shows the $\sqrt{RRR}$ dependence expected from the simple theory of thermal breakdown.

Figure 25: Improvement in performance of multicell cavities due to post-purification and HPR or HPP.

The new techniques for bulk niobium cavities have demonstrated that gradients can be improved to between 20 and 30 MV/m in multicell structures. In Figure 25 we compare the recent data for about 25 structures prepared by the most advanced techniques with the results of more than 300 structures prepared without using HPR or HPP. A log scale is being used here because the total number of structures prepared by the new techniques is still small relative to the existing technology base. But the progress to date is indeed encouraging. If gradients of 20–30 MV/m can be reliably achieved, exciting new applications are on the horizon, such as for a TeV linear collider or a multi-TeV muon collider.

References


