HIGH GRADIENT SUPERCONDUCTING RF SYSTEMS

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Abstract

Superconducting Radio-Frequency (SRF) cavities are a promising technology for the next generation of electron positron colliders. In order to apply SRF technology in such machines, accelerating gradients must be improved, from the 5 to 10 MV/m level achieved in accelerators today, to the range of 20 to 30 MV/m. The state of the art in high gradient SRF technology will be discussed. Topics include achieved cavity performance, fabrication, preparation, handling, and processing techniques. Significant progress, e.g. multi-cell cavities with gradients > 25 MV/m and single-cell cavities with gradients > 40 MV/m, has been achieved over the past several years towards the goal of increased gradients. The major improvements have been in the areas of understanding and reducing cavity loading due to field emission and thermal quenches.

I. INTRODUCTION

Superconducting Radio-Frequency (SRF) technology has been an active field of research for accelerator cavities for the last 25 years. The SRF field has grown from the use of simple single-cell test cavities in a laboratory environment to reliable installation of hundreds of multi-cell structures in an operational accelerator. Hundreds of meters of SRF cavities are now used in accelerators around the world.

The SRF cavities used at such laboratories as KEK,[1] CERN,[2] Darmstadt,[3] Argonne,[4] and DESY[5] have retained their performance over time, showing SRF technology to be a reliable basis for continued construction of accelerators.

SRF cavities are presently being investigated as the basis for future electron positron colliders in the 0.5-2 TeV center of mass energy regime. Under the aegis of the TESLA[6] project, an international collaboration is operating towards this goal. SRF based accelerators present several advantages when compared with their normal conducting (NC) counterparts.[7]

Cryogenic considerations[8] have determined the choice of RF frequency for a high gradient cavity to be in the range of 1-3 GHz. Further consideration of thermal stability, wakefields, and availability of RF power sources has led the TESLA collaboration to the choice of a 9-cell 1.3 GHz cavity.

If SRF technology is to be used for construction of a TESLA machine, the accelerating gradients must be improved from the 5 to 10 MV/m level achieved in presently operated accelerators to 20 to 30 MV/m. In this presentation, I will review the efforts being made towards achieving this goal, showing the "state of the art" in obtaining high gradients, specifically as measured in multi-cell SRF cavities built for electron-positron machines.

It is useful to begin with a brief summary of the salient operational experience with SRF cavities in full accelerators. The observed limitations of these cavities will then be used as a launching point to discuss the current experimental efforts being pursued in order to overcome these limitations.

Finally, I will conclude with a discussion of future directions of SRF high gradient research.

II. OPERATIONAL EXPERIENCE

SRF cavities have proven themselves to be a viable and reliable basis for construction of accelerators. Cavities at DESY[9] and KEK[1] have to date logged many ten thousands of hours of operation with no significant degradation of cavity performance.

From the point of view of TESLA and other high gradient machines, it is most informative to investigate the experience to date of the SRF cavities of CEBAF. [10]

Figure 1 shows the achieved gradients in the CEBAF cavities, both in vertical testing and in horizontal commissioning in the accelerator. The cavities at CEBAF were constructed from niobium with RRR = 250. RRR (Residual Resistivity Ratio) is the ratio of bulk resistivity at room temperature to the NC resistivity at 4.2 K, and is used as a measure of the purity and thermal conductivity of the niobium.

The design parameters of the CEBAF cavities were an accelerating gradient of 5 MV/m, with an unloaded quality factor (Q_0) greater than 2.4 x 10^9 (operation at 2 K). In all, 338 cavities (in 169 pairs) have been installed in CEBAF, and have exceeded specifications. It is equally impressive that 70% of the cavities passed acceptance tests the first time that they were assembled and tested.

The excellent performance of the CEBAF cavities is

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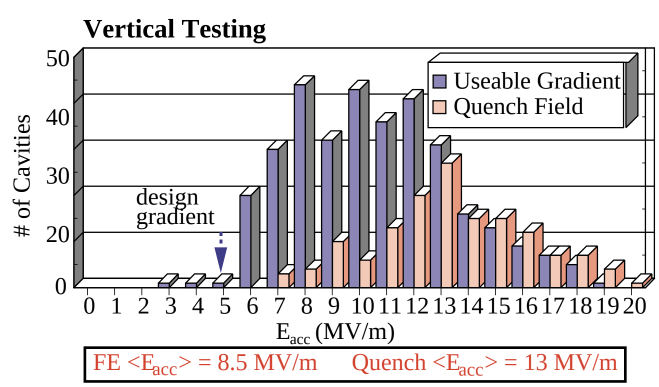
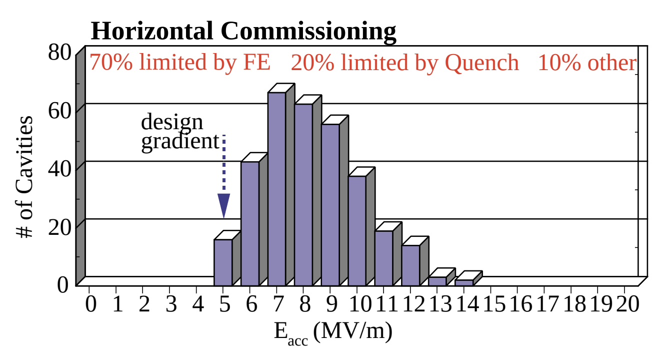


(a) Vertical tests of the cavities.



(b) Horizontal commissioning in the accelerator.

Figure 1. Results from CEBAF on 5-cell 1.5 GHz cavities.

nonetheless not adequate for the proposed TESLA machine. The two primary limiting phenomena for the CEBAF cavities are listed in Figure 1(a), quench (thermal breakdown) and field emission (FE). These are the same phenomena encountered in all other facilities with SRF cavities, and are thus the primary focus of nearly all SRF research groups. As is shown in Figure 1(b), 90% of the cavities installed in CEBAF had their final limitation due to one of these two phenomena.

It is worth noting that the achieved gradient and performance to date in CEBAF are significantly higher than that in previous facilities, largely due to the increased knowledge gained by the SRF research programs over the last 15 years.

III. STATE OF THE ART

For reasons of brevity, this discussion of the present state of the art of high gradients will be largely restricted to results obtained with multi-cell cavities, primarily because it is with multi-cell cavities that a TeV collider must be built. This approach will regrettably neglect excellent results obtained at many laboratories, including 1-cell test cavities,[11-13] and basic FE studies.[14,15] Interested readers are encouraged to consult the references for further information.

A. Quench

Quench, or thermal breakdown, is the phenomenon where as cavity fields are increased, a local heat source (defect) increases its dissipation until the heat dissipation overwhelms the local thermal conductivity, raising the local temperature of the RF surface above the critical temperature. The local hot spot will quickly grow to macroscopic size, eventually driving the entire cavity RF surface normal conducting, which then collapses the cavity fields.

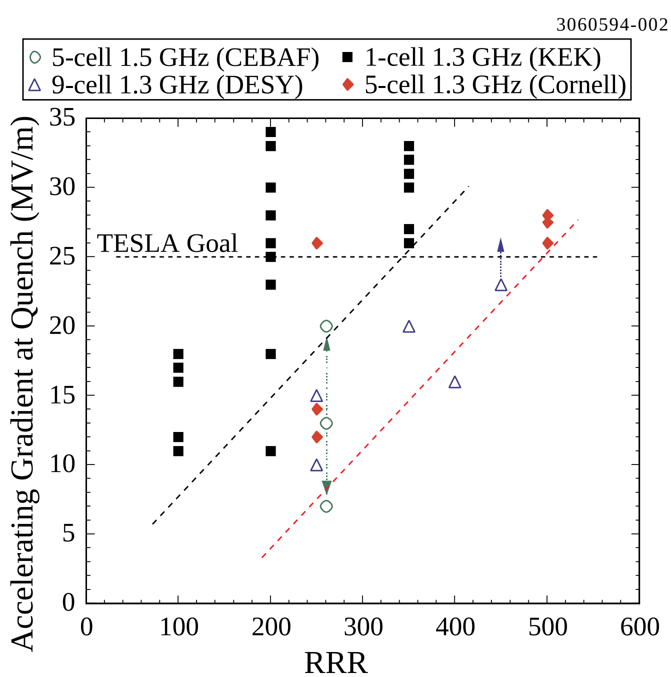


Figure 2. Achieved accelerating gradient plotted as a function of RRR (residual resistivity ratio) of the niobium in the cavities. A more complete description of this plot is provided in the text.

The most natural solution to the problem of quench is increased thermal conductivity, in order that the dissipated heat can be conducted away before the critical temperature is surpassed. The most common method for obtaining higher thermal conductivity has been to improve the purity of the bulk niobium used in cavity fabrication. Figure 2 displays measured quench fields at several different laboratories plotted as a function of cavity RRR. The data from CEBAF in Figure 1(a) is shown in the form of its average and range. The two diagonal lines are meant to show an approximate value of RRR necessary to insure a quench field above a given value. The upper line is for 1-cell cavities, while the lower line bounds the 5-cell and 9-cell cavities.

The purity of bulk niobium as delivered by industry has increased from RRR = 40 in the early 1980s to in excess of 500 today. Through solid state gettering,[16] the RRR can be further increased by up to a factor of 2, making RRR ≥ 1000 now a possibility. Extrapolation of the plots in Figure 2 show that RRR ≥ 500 is necessary for multi-cell cavities with quench fields consistently above E_{acc} = 25 MV/m.

One more possibility for increased thermal conductivity is the possibility of niobium-copper sputtered cavities,[17] where the increased thermal conductivity of the copper substrate would be used to conduct the heat. This technology is not yet feasible, however, due to an exponential decrease in Q_0 with increasing fields from granular superconductivity effects.

B. Field Emission

Field emission has been the dominant limitation on SRF cavities for the last ten years (since niobium with RRR greater than 100 became widely available). FE is tunneling of electrons out of the niobium surface in the presence of high surface electric fields. Many comprehensive reviews of the subject and its relationship to SRF cavity behavior are available.[18-21] FE related dissipation grows exponentially with increasing fields, quickly consuming all power available in a low power SRF setup. Furthermore, the impact of emitted electrons on the cavity surface causes heating, further degrading the RF performance of the cavity.

The most important information that has come from field emission studies, in both DC[14,22] and RF[15,23] conditions, is that FE is directly related to micron sized surface contaminations, in particular metallic particles. Table 1 shows a listing of the various contaminants found in emission studies at several different laboratories. Most of the elements detected can be traced to either actions or materials related to the processing or assembly of the cavities and their test apparati.

Recent results indicate the further possibility that RF surface contamination could lead to a thermal quenches.[26]

TABLE 1. Contaminants found in FE sites.

Geneva DC	Saclay DC	Wuppertal DC	Cornell RF
Ag,Al,C,Ca,	Ag,Al,C,Ca,	Al,Cs,Ca,Cu,	C,Ca,Cr,Cu
Cr,Cu,Mn,O,	Ci,Cr,F,Fe,	Mn,O,S,Si	F,Fe,In,Mn
S,Si,W	K,Mg,N,Na	Ti,W	Ni,O,Si,Ti
	Ni, O, Si, Ti, Zn		

Given the effect of surface preparation on FE performance, the thrust of many of the investigations into SRF cavities has been in the area of producing a cleaner RF surface. It is likely that the most important gains in performance have come through use of clean rooms and protocols for assembly of cavity testing systems. Past studies on ultra high vacuum baking of the cavity[24,25] produced the first major breakthroughs to the 20 to 30 MV/m range that we seek. However furnace treatment is an expensive procedure, in time and resources, thus the effort to find alternative methods of obtaining clean, and therefore emission free, surfaces has been continued.

Recent, promising results have been obtained at several laboratories using a high pressure water rinse (HPR) as the final step prior to assembly to the vacuum apparatus. In HPR, a jet of ultra pure water (pressure ≥ 80 bar), is used to dislodge surface contaminants which are believed to be resistant to more conventional rinsing procedures.

An example of an HPR results on a 5-cell cavity at CEBAF is shown in Figure 3. On first measurement, the cavity was limited as shown to E_{acc} = 9 MV/m, with severe FE loading. The cavity was disassembled, rinsed with HPR, and then reassembled. Upon re-testing, the open circled curve was measured, limited only by a quench at 14 MV/m.

1-cell cavities have had even more impressive results, with many different labs[11,12,27] reporting multiple measurements of accelerating gradients in excess of 30-35 MV/m following HPR treatment. Indeed, the highest gradient reported to date is E_{acc} = 43 MV/m in a 1-cell cavity tested at CEBAF following HPR.[28]

Despite this promising work, however, consistently emission free surfaces continue to elude us, especially in the case of multi-cell cavities, where the larger surface area brings a proportionally larger probability of a contamination. One emitter is sufficient to limit the performance of an SRF cavity to unacceptable levels. This concern is especially daunting when one considers that with the proposed gradient, a 0.5 TeV collider would require 20,000 cavities.

The best results in reducing or eliminating FE after the cavity has been assembled have been obtained through High Power Processing (HPP).[29] HPP is an extension of the successful practice of conditioning an RF cavity, where the emission in a cavity is reduced to acceptable levels through gradual raising of the incident power. Thermometry has shown that processing occurs through a local reduction in FE,[29] as evidenced by reduced electron impact heating. Microscopic investigation of RF surfaces following processing[23,29] has determined that processing occurs when the FE current is raised high enough to cause melting and/or vaporization of micron sized regions of the RF surface, presumably the emitter.

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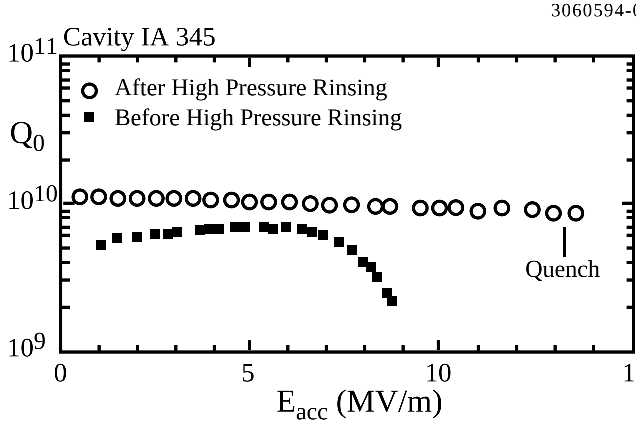

Figure 3. Q_0 vs. E_{acc} plots showing high pressure rinsing results on a 5-cell 1.5 GHz cavity at CEBAF.

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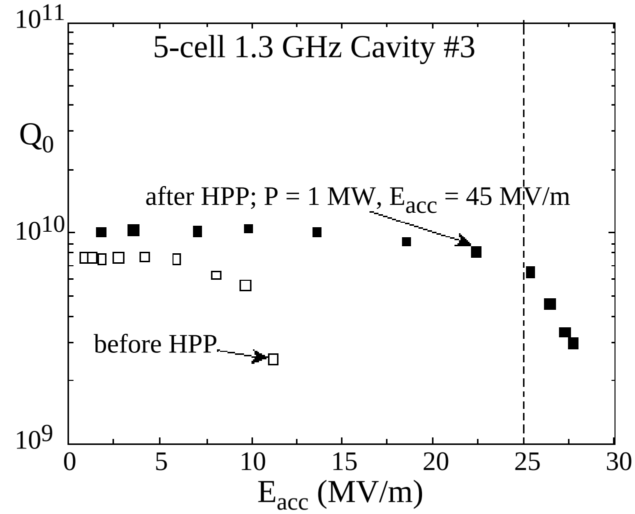

Figure 4. Q_0 vs. E_{acc} plots showing high power processing (HPP) results on a 5-cell 1.3 GHz cavity at Cornell.

Continuous wave (CW) low power (≤ 100 W) RF processing of SRF cavities is severely limited by the exponential growth of the power dissipation under FE conditions. All available power is consumed before the fields, and therefore the FE current, can be raised high enough to initiate processing. With HPP, the incident power is raised to the order of hundreds of kilowatts to a megawatt, allowing fields to be increased high enough for processing to occur. Figure 4 shows the Q_0 vs. E_{acc} plot of a 5-cell 1.3 GHz cavity tested at Cornell. The pattern of measurement shown is typical: a cavity is severely limited by FE, which is impervious to conventional, low power, RF processing. HPP is applied with high power (in this case up to 1 megawatt), following which the attainable CW fields are greatly improved, sometimes by more than 100%. Three different 5-cell 1.3 GHz cavities reached gradients higher than 25 MV/m with this procedure.[30]

Studies of HPP on multi-cell cavities at both 1.3 GHz and 3 GHz have shown that success in processing is directly related to the magnitude of the fields reached during the HPP procedure. Put more succinctly, as long as the fields continue to increase in HPP, the CW performance will similarly improve. Empirically, it has been found in 5-cell 1.3 GHz that FE loading will be essentially eliminated in fields up to 50 % of the level reached during HPP.[30]

Finally, HPP also provides the possibility for *in situ* treatment of cavities which have been degraded by vacuum accidents. Normally a vacuum accident would require complete disassembly and re-cleaning of an affected cavity. With HPP,

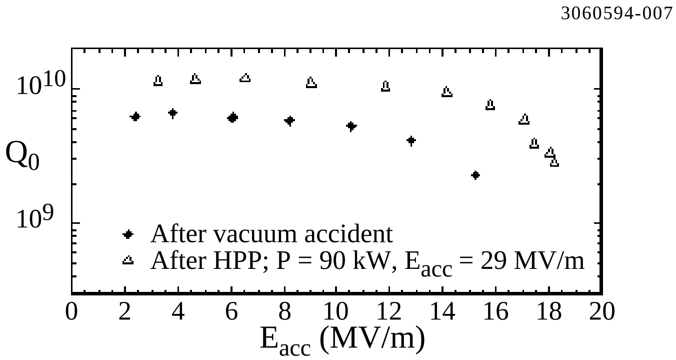

Figure 5. Q_0 vs. E_{acc} plots showing recovery of cavity performance with HPP following a vacuum accident.

the principle has been established that the cavity could regain all or most of its pre-accident performance without disassembly. Three separate 9-cell 3 GHz cavities were tested following vacuum accidents,[29,31] and, in each case, at least 80% of the cavity's previous performance was regained through HPP. The Q_0 vs. E_{acc} plots for one of these accidents are shown in Figure 5.

C. Putting It All to Work: The TESLA Test Facility

In order to further demonstrate the feasibility of the TESLA approach to a TeV collider, the TESLA Collaboration has begun work on the TESLA Test Facility (TTF), a 50 meter, SRF based linac, to be constructed with SRF technology at DESY. Current status of the TTF was discussed in another presentation at this conference.[32,33]

In setting up the TTF, the TESLA Collaboration has taken advantage of the latest information from the SRF community regarding the best methods of preparing cavities for RF performance. The TTF has a state of the art chemical and clean room facility, which includes a high pressure rinse system capable of delivering rinse water at up to 100 Bar, and a UHV furnace for surface preparation and/or RRR improvement. Figure 6 shows the Q_0 vs. E_{acc} plots from measurement of the capture cavity, which was procured by Saclay, then prepared and tested at DESY. As can be seen, the cavity

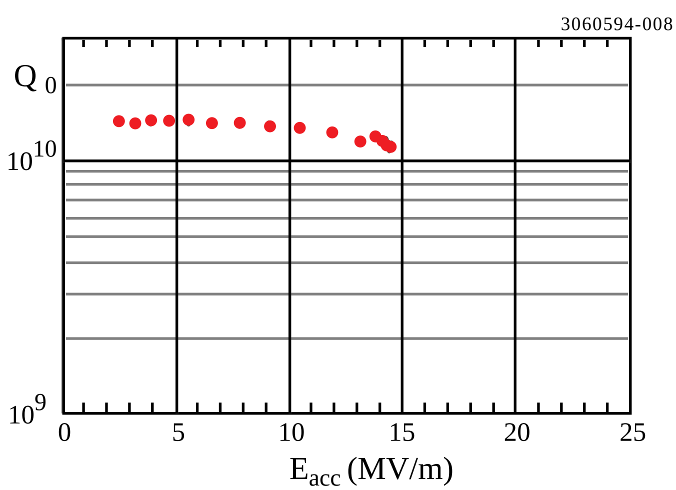

Figure 6. Q_0 vs. E_{acc} plot showing the performance of the TTF capture cavity (9-cell, 1.3 GHz, RRR = 250), tested at DESY.

was essentially emission free up to 14.5 MV/m, where a quench was encountered. This cavity has RRR of only 250, as it is designed for operation at only 12 MV/m.

The TTF also has an HPP setup capable of delivering up to 1 Megawatt pulses of up to 2 msec. The HPP procedure has been successfully used on several cavities to date, the most successful being the vertical test of cavity # 2, a production cavity with HOM couplers.

Figure 7 shows the CW measurements; through HPP processing, the cavity reached a CW accelerating gradient of 22 MV/m. More significantly, during HPP, the cavity was operated in the conditions prescribed for TESLA- input coupling Q_{ext} = 3 x 10^6, RF pulse length = 1.3 msec, incident power of 250 kW. Figure 8 shows oscilloscope traces of the power transmitted to a monitor probe (upper trace), and the incident power delivered to the cavity (lower trace). As can be seen in Figure 8, the cavity reached an accelerating gradient of

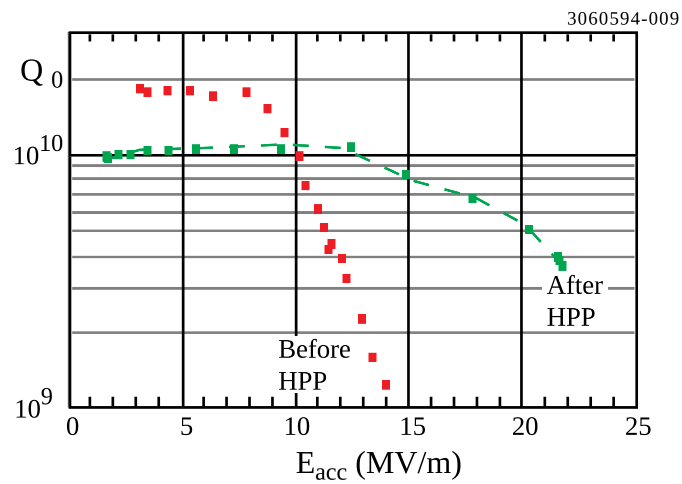

Figure 7. CW Q_0 vs. E_{acc} plots of TTF cavity #2, (9-cell, 1.3 GHz, RRR = 350), before and after HPP ($P \leq 400$ kW, $E \leq$ 32 MV/m).

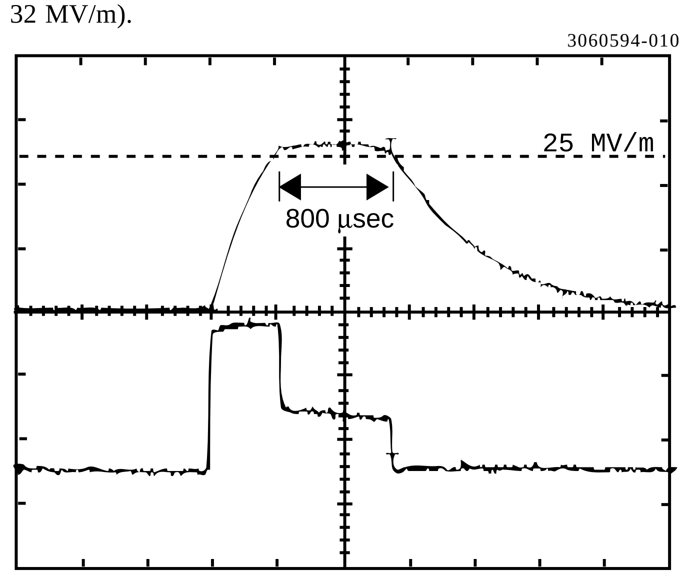

Figure 8. Oscilloscope traces captured during operation of TTF Cavity #2 operated under pulsed conditions at an accelerating gradient of approximately 26 MV/m. A description of this figure be found in the text.

26 MV/m after filling for 500 μsec. At this point, the forward power was stepped down to 100 kW, in order to simulate the effect of beam load on cavity fields. The cavity maintained E_{acc} = 26 MV/m for the entire 800 μsec designed for TESLA operation, and then decayed away naturally when the incident power was turned off.

Horizontal testing, followed by installation in the TTF, of this and subsequent cavities will proceed beginning this summer.

IV. FUTURE DIRECTIONS AND REMARKS

The prospect for further gains in high gradient superconducting RF accelerators is very bright. The concerted research effort undertaken in the last fifteen years to extend the attainable gradients has paid off with significant gains. The progress in achieved gradients (CW testing) is shown clearly in Figure 9. The maximum achieved gradients at the time of compilations in 1980 and 1989 are included as line plots for reference to show the gains made over time. Nearly all research in extending gradients today is being performed with 1-3 GHz cavities, with surface area between 0.05 and 0.8 square meters, hence the lack of gains in other regions.

The two primary limiting phenomena, field emission and quench are well understood. Improved purity of niobium has increased quench limits significantly. A clean RF surface is the most important determining factor in reducing FE. HPR and clean assembly procedures are helping provide such a surface. HPP is effective in reducing field emission in cavities which exhibit FE in spite of clean assembly procedures.

The design gradient for TESLA has been met in vertical testing of the TTF cavity at DESY. Repetition of this measurement in a horizontal cryostat, followed by installation in the TTF are scheduled for later this summer. By the 1997 PAC, we expect to show how the TTF project has further demonstrated the feasibility of TESLA.

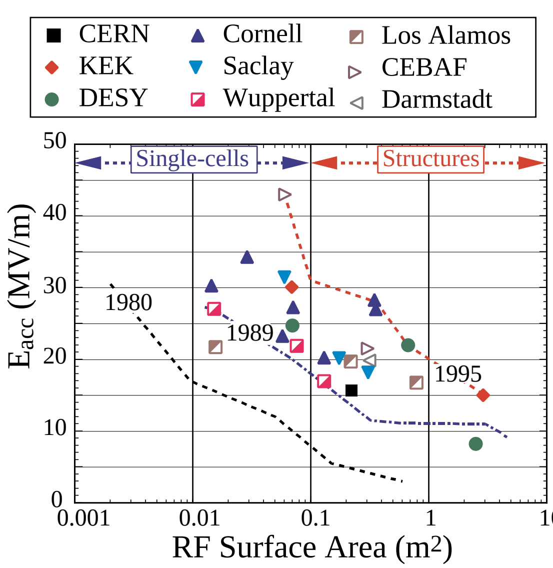

Figure 11. Historical progress in the attainable accelerating gradients, plotted as a function of RF surface area per cavity. High gradient studies are now performed primarily for cavities with area between 0.05 and 0.8 square meters.

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