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High Gradient Superconducting Niobium Cavities A Review of the Present Status*

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Abstract—Superconducting niobium cavities used in particle accelerators are limited in their rf performance by two phenomena: quench field levels below the theoretical limit of the material caused by defects, and field emission loading resulting from artificial contamination of the superconducting surfaces during surface treatment and assembly procedures. In recent years the community involved in SRF technology developments has successfully improved cavity performances by applying advanced surface treatment methods such as chemical polishing, electropolishing, tumbling, high temperature heat treatment, high pressure rinsing, "in situ" high peak power processing and clean room assembly procedures. In addition, improvements in the material properties such as thermal conductivity by "solid state gettering" and very strict QA methods, both in material inspection and during cavity fabrication, have resulted in cavity performance levels of E_{acc} up to 40 MV/m in monocells and gradients in the vicinity of 30 MV/m in multicell structures at Q-values of ≈ 10^{10} at a temperature of 2K.

More recently the fabrication of "seamless" cavities by spinning is being pursued with encouraging results. This process eliminates electron beam welds, which sometimes are the causes of performance degradations.

I. INTRODUCTION

For more than three decades, superconducting cavities have been used in particle accelerator projects. This development started on the promise that superconducting cavities can be used under continuous wave operation with significantly lower power losses and higher accelerating gradients than normal conducting structures. Since the power losses in the walls of an accelerating RF cavity increase as the square of the accelerating voltage, normal conducting cavities become uneconomical as experimenters ask for higher beam energies, which in turn demand higher gradients. An accelerating cavity made from niobium dissipates 10^5 to 10^6 times less power at liquid helium temperature than a copper cavity at room temperature. After taking into account the low efficiency of the refrigeration system, which has to provide the low operating temperatures for the cavities, a net gain of several hundred over copper cavities remains. In addition, the low power consumption of superconducting cavities reduces the requirements for an optimized cavity design, which usually results in an as small as possible beam aperture with its negative effects on cavity-beam interaction. A superconducting cavity can be short because of its high gradients and permits a large beam hole, reducing disruptive and limiting effects such as energy spread, maximum currents and, for high current accelerators, even beam halos. Superconducting rf technology has come a long way since the first acceleration of electrons in a lead plated copper cavity at Stanford University [1]. After a period of disappointments and set backs in the early expectations and the struggle with unanticipated fundamental and technological problems, in recent years rf superconductivity has surged to become an important technology in the design and construction of new particle accelerators in nuclear physics, high energy physics, and free electron laser applications. Superconducting Radio Frequency (SRF) technology has been applied successfully in the last decade in several large scale particle accelerator projects all over the globe such as TRISTAN [2], HERA [3], LEP [4] and CEBAF [5] and is being pursued seriously for future applications such as B-factories—KEKB [6] and Cornell B [7]—, proton accelerators for spallation neutron sources [8] or for the production of tritium [9], linear colliders for electrons/positrons [10] or muons [11]. The renewed interest in the technology has only been possible as a result of significant progress in understanding and overcoming the limitations encountered in the 1970's. The systematic application of sophisticated diagnostic methods such as temperature mapping and radiation mapping at cryogenic temperatures, in conjunction with computer simulation calculations and surface analytical investigations, led to the elimination of the most severe performance limitations of superconducting cavities by resonant electron loading ("multipacting") and was instrumental in identifying the causes for field emission loading and thermal magnetic breakdowns in cavities. The promises of the technology dating back to the year 1970, when in a X-band cavity at the High Energy Physics Lab at Stanford University a record electric surface field of E_p = 70 MV/m [12] was measured, are only now materializing and cavity performances in larger structures comparable to this extraordinary result are achieved more frequently. These accomplishments have generated new applications for SRF technology: high beam currents are required in B-factories and intense proton machines, demanding the coupling of higher RF power to the cavities through coupling devices; for such machines the gradient requirements on the cavities are relatively modest. Other applications such as linear e^+e^- - colliders [TESLA] or muon colliders need quite high accelerating gradients up to 25 MV/m in a pulsed mode to be economically feasible. An upgrade of the CEBAF accelerator to a tripled end energy of 12 GeV is being proposed [13] with a 25 % addition of accelerating structure to the existing string of cavities and an increase of gradient by a factor of 2.5 to 3. Even though these requirements seem somewhat modest in comparison to the TESLA design, high Q-values in the neighborhood of 10^{10} and cw operation are needed at these gradients not to exceed the available cryogenic capacity. This boundary condition puts a large premium on the reproducibility of cavity performances and demands the development of "fool-proof" procedures for cavity treatment and assembly to achieve these values.

In past years, several review papers concerning the state of the art of SRF technology and its application to particle accelerators have been published, e.g. [14], [15]; more details of the technolgy and its developments over the years are available in the proceedings of eight international workshops and recently a reference text has been published [16], which discusses in detail the issues in SRF technology application in accelerators.

This contribution concentrates on the challenges encountered in extending the frontiers of SRF technology to higher gradients and reviews the progress made towards this goal in the last several years at the various laboratories working in this field.

II. BEHAVIOR OF A SUPERCONDUCTING CAVITY

A superconducting cavity as typically used in particle accelerator application is usually fabricated from niobium or niobium sputtered on copper. Its response to excitation by radio-frequency energy is described by two parameters, its Q-value and its achievable accelerating gradient.

The Q-value of a cavity is defined as the ratio of the stored energy (W) in the cavity to the power (P) lost in the cavity walls per RF cycle ($\omega = 2\pi f$)

$$Q_O = W / (P/\omega) \qquad (1)$$

The Q_O-value is inversely proportional to the surface resistance (R) of the material of the cavity walls. The proportionality constant is called the geometry factor (G) and depends only on the geometry and the electromagnetic field configuration in the cavity. It is typically of the order of 270 Ω for structures designed to accelerate velocity of light particles:

$$Q_O = G/R \qquad (2)$$

The surface resistance R is described by the microscopic theory of Bardeen-Cooper-Schrieffer (BCS): the electrical resistance of a superconductor decreases at high frequencies exponentially with decreasing temperature below the critical temperature T_c (T_c = 9.25K for niobium). For frequencies (f) small compared to the energy gap frequency ($\approx$ 700 GHz for niobium) and for temperatures $T < (T_c/2)$, the surface resistance is proportional to the number of normal electrons excited thermally across the gap Δ and can be expressed by [17]:

$$R_{BCS} \approx \omega^2 /T \exp -[(\Delta/kT_c)(T_c/T) \qquad (3)$$

In the superconducting, state an, external electromagnetic field penetrates only a distance λ (penetration depth) into a material. λ depends on frequency, temperature and purity of the material. For niobium, the material of choice for cavities used in accelerators, this depth is approximately 600 Å at a frequency of 1500 MHz and a temperature below 0.9 T_c . This means that all losses in a cavity take place in a very thin surface layer and that the quality of this layer is of utmost importance for excellent cavity performances.

The accelerating gradient E_{acc} is defined as the maximum energy a charged particle will gain in the time-varying RF fields by traversing an accelerating gap divided by the gap length. The accelerating gradient is proportional to the square root of the stored energy in the cavity.

$$E_{acc} \propto \sqrt{PQ_O} \qquad (4)$$

The accelerating gradient is related to the peak surface electric and magnetic fields in the cavity through Maxwell's equations. Since superconductors go from the superconducting state to the normal conducting state, if a critical magnetic field $H_{crit,sh}$ [sh=superheated] is exceeded, there are fundamental limitations to the achievable accelerating gradients in a superconducting RF cavity. In the case of niobium as the superconducting material, the fundamental magnetic field limit is app. 2400 Oe, which in a typical accelerating cavity corresponds to a gradient of $E_{acc} \approx 50$ MV/m. Such gradients are still beyond the present state of the art and are typically a factor of 3 to 6 higher than present achievements. However, there exist exceptions as shown below.

The experimentally observed behavior of a niobium cavity deviates from the theoretically expected behavior in four distinct features as shown schematically in the second curve in figure 1:

(a) The observed Q-value is significantly lower than predicted by the microscopic theory of superconductivity (BCS theory) due to the residual surface resistance caused by anomalous losses and defects in the material.

(b) At certain distinct fields the Q-value might drop to lower values caused by resonant electron loading ("multipacting")

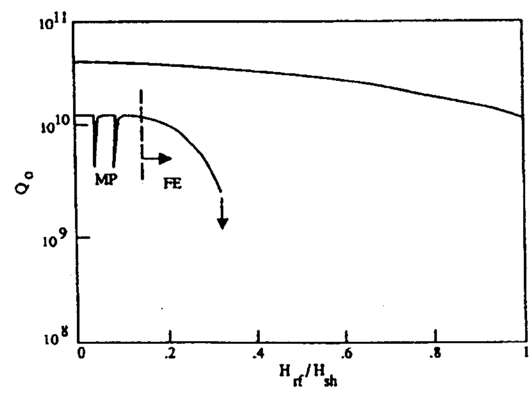

Fig. 1: Schematic behavior of a superconducting cavity under operation. FE indicates the onset of field emission loading; upper curve indicates the theoretical behavior.

(c) Above a certain field level in the cavity—typically 5 MV/m $\leq E_{acc} \leq$ 15 MV/m—the Q-value decreases exponentially due to non-resonant electron loading ("field emission")

(d) The experimentally observed field, at which the superconducting state disappears ("quench") is significantly lower than the theoretically predicted field as already mentioned above.

All the above listed deviations from the ideal behavior are to a large extent caused by the surface conditions of the superconducting material. Most knowledge has been gained through systematic application of diagnostic methods such as prominently temperature mapping or x-ray mapping in conjunction with scanning electron microscopy and elemental surface analysis as well as computer simulation calculations. Whereas the Q_O vs E_{ACC} behavior of a cavity gives a "global" picture of the cavity as a whole—some conclusions of phenomena such as multipacting, field emission or quenching can be deduced from the RF-signal response of the cavity—the application of diagnostics led to significant progress in understanding of localized phenomena in these cavities[18], [19].

III. LIMITATIONS AND CURES

A. Residual Surface Resistance

An example of an experimentally observed temperature dependence of the surface resistance of a niobium cavity at 1500 MHz is shown in fig. 2. As predicted by equation (2), an exponential decrease of R(T) is observed, but at lower temperatures R(T) is limited by the temperature-independent residual surface resistance R_{res}, which limits the achievable resistance experimentally usually to a few nΩ. Contributions to this residual resistance have been identified as normal conducting defects, dielectric losses by particulate surface contamination, adsorbates like hydrocarbons or residual gas condensation, macroscopic surface imperfections such as delaminations, cracks or crevices, chemical residue, frozen-in magnetic flux from insufficiently shielded ambient magnetic fields or precipitation of hydrogen in form of the ε-niobium-hydride phase ("Q-disease"). Many of these different contributions to the residual surface resistance can be avoided by proper treatment of the sensitive surfaces of a niobium cavity. Surface contamination from either chemical processing or particulate matter can have a significant impact on the achievable Q-values of cavities. With standard processing techniques such as buffered chemical etching in a solution of hydrofluoric, nitric, and phosphoric acids or electropolishing in a mixture of hydrofluoric and sulfuric acids, residual surface resistances of 10 - 20 nΩ are obtained routinely, provided that the assembly process of a cavity is done in a clean environment and particulate contamination is prevented. The contribution by externally frozen-in flux is ≈ 0.3 nΩ/ mGauss - therefore great care has to be taken to shield the earth magnetic field.

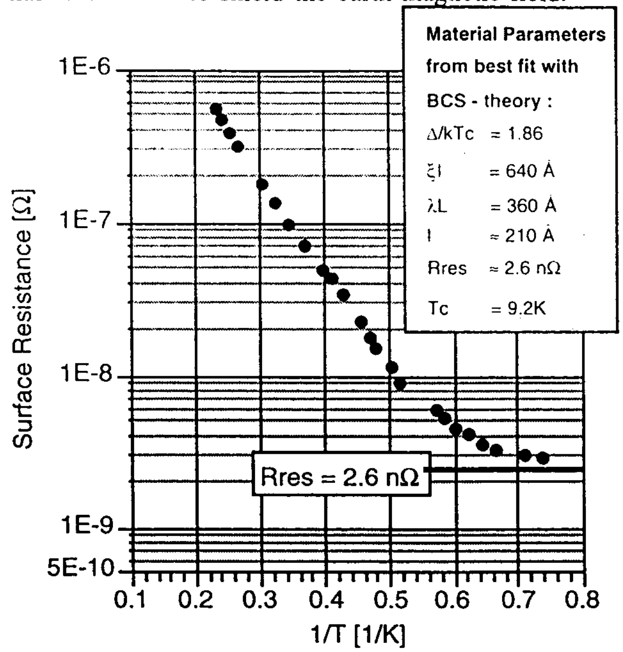

Fig. 2: Example of R(T) of a Niobium cavity at 1500 MHz

Hydrogen, which is either present in the material from the manufacturing process or is interstitially dissolved in the material during the chemical processing, can contribute, in high purity niobium of a residual resistivity ratio (RRR) ≥ 200, orders of magnitude to the residual resistance. This "Q-disease" can be avoided by a fast cooldown of the cavities through the dangerous temperature region of 70 K $\leq T \leq$130 K or by totally hydrogen degassing the material at T > 1400 C for a few hours in ultrahigh vacuum. Such a heat treatment also homogenizes material inhomogeneities such as oxygen clusters and stress relieves the material. After heat treatment, residual resistance values below 5 nΩ are not uncommon. Removal of the residual impurities in the niobium gives a lower residual resistance and values below 1 nΩ have been reported [20].

B. Resonant Electron Loading ("Multipacting")

Multipacting is a high vacuum resonant avalanche effect, which can occur in RF cavities, when secondary electrons are emitted , accelerated and redirected back to the cavity walls by the RF fields in response to impinging primary electrons. More secondary electrons are generated, if the secondary electron emission coefficient of the surface material is larger than 1 for the impact energies of the impinging electrons. The build-up of an electron cloud results, if certain resonant conditions are met by the RF fields. A multipacting "barrier" is established, which shows up as a strong decrease in Q-value at a constant field level: all additional RF power fed to the cavity is used to increase the multipacting currents rather than for the build-up of RF fields. Computer simulation calculations of electron trajectories were successfully used to modify the cavity shapes and therefore the field configurations in such a way that the resonant conditions for multipacting were eliminated or at least strongly reduced. Multipacting in SRF cavities is nowadays no longer an issue in cavities for velocity-of-light (ß=1) cavity shapes; occasionally it shows up in the modified cavity geometries of spherical or elliptical cross sections [21], [22], especially, if the secondary electron emission coefficient of the surfaces has been enhanced by contamination. More recently, with the advent of several proton accelerator projects, which have to use structures with narrow accelerating gaps for lower particle velocities (ß < 1), concerns of multipacting have reappeared. However, with advanced surface cleaning techniques, such as electropolishing followed by high pressure ultrapure water rinsing [HPR], no difficulties with multipacting were encountered. Fig. 3 shows the performance of a scaled JAERI $\beta = 0.48$ cavity [23].

C. Non-resonant Electron Loading ("Field Emission")

Beyond a certain field level in a superconducting cavity electrons are drawn out of the surfaces by the RF-electric fields, are accelerated in the RF fields and gain sufficient energy to produce heat and bremsstrahlung when impinging on opposing surfaces, resulting in an exponential decrease of the Q-value with increasing field level in the cavity. This loading is presently in many cases limiting the performance of superconducting cavities and great efforts are exercised by many laboratories involved in SRF technology developments to understand the causes for this phenomenon and to find techniques to shift the onset fields to higher values. The use of diagnostic techniques—prominently temperature mapping and radiation mapping—coupled with surface analytical techniques and computer simulation calculations has led to an understanding of the sources of field emission and established the basis for techniques to shift the limitations towards higher values: Field emission originates from point-like, localized sources. They are frequently "artificial" contamination of micron-size particles of foreign elements—"dust"—loosely attached to the surfaces. The emission currents can be described by a modified Fowler-Nordheim correlation, with "emitting area" and "field enhancement factor" as parameters. These parameters can vary over a wide range depending strongly on the processing and handling of the surfaces. Adsorbates in addition to particulates can greatly enhance field emission loading, however RF-processing and helium processing have been used as effective techniques to reduce electron loading. A very successful method is High Peak Power Processing (HPPP) [24] as an "in-situ" method to attack and destroy field emission sites : in this technique short pulses of high power RF are used to "process" emitters, which eventually will disappear after an explosive evaporation. An example of the improvements in cavity performance gained by this technique is shown in fig. 4 [25].

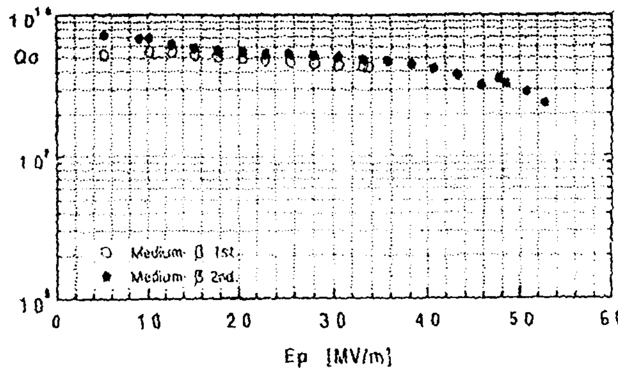

Fig. 3: Results of a scaled JAERI cavity of $\beta = 0.43$ (f = 1300 MHz) in development for a Proton Linac

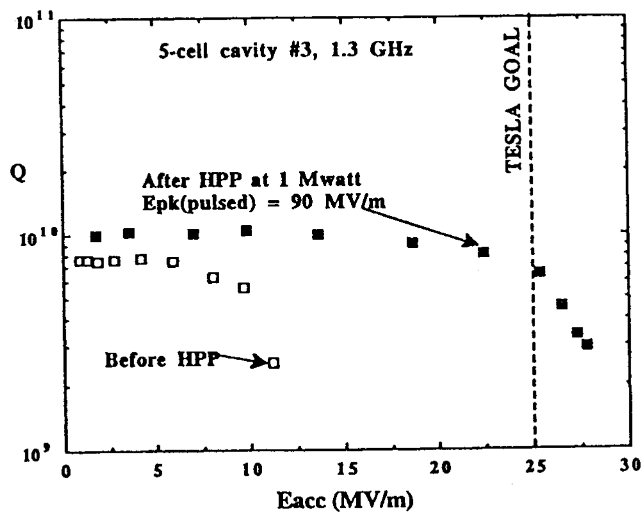

Fig. 4: Test Results on a 5-cell, 1.3 Ghz cavity before and after High Peak Power Processing [25]

A quite successful technique also is high pressure ultrapure water rinsing [HPR], which aimes at removing emission sites rather than destroying them. Nevertheless, field emission is still the dominant limitation nowadays in superconducting cavities; the limitation is not of fundamental nature, since in special cavities surface fields up to $E_p = 210$ MV/m have been measured [26], but are closely connected to efficient contamination control measures. More details about FE can be found in ref.[16].

D. Quenches

Quench field levels in niobium cavities are - with a few exceptions- on the average still significantly lower than the fundamental limit given by the critical magnetic field. The reasons for this inferior performance have been found in thermal instabilities occuring at localized areas ("defects") of enhanced losses. Such defects can be surface contamination like chemical residue, debris, dust, areas of weak superconductivity, or surface imperfections like holes, scratches, crevices, delaminations, weld splatter from electron beam welding, or foreign material inclusions. As a result of these observations, very thorough inspections of the raw material either visually or by eddy current and squid scanning [35] are used. Each handling step during the manufacturing process has to be carefully monitored ; defect-free electron beam welds are essential: chemical treatment procedures with very pure chemicals in clean room environments and prolonged rinsing procedures with ultrapure, particulate-free water, which is used either in form of high pressure water jets or is "spiked" with ozon [41] are applied; cavity assemblies in clean rooms down to class 10 are essential to effectively reduce contamination. Thermal model calculations resulted in the recognition that thermal instability threshold fields are proportional to the square root of the thermal conductivity of the cavity wall material and are inversely proportional to the square root of the defect radius and defect resistance [27], [28]. This was a major break-through in improving cavity performances, because the thermal conductivity of commercially available niobium could be increased by a factor of ≥ 5 through multiple electron beam melting under improved vacuum conditions. Further improvements have been made by solid state gettering, a process during which niobium is heat treated at temperatures above 1200° C in a high vacuum in the presence of a material with higher affinity to interstitial impurities (hydrogen, oxygen, nitrogen, carbon) and lower vapor pressure than niobium, preferably titanium.

IV. RECENT EXPERIMENTAL RESULTS

A. Solid Niobium Cavities

At the 8th Workshop on RF Superconductivity in Abano Terme, Italy, one year ago K. Saito of KEK provoked the SRF community by claiming the superiority of electropolishing over chemical polishing as a final surface treatment [29]. These claims—even though backed up by a variety of experimental data—were met with some skepticism. Meanwhile there is more evidence of the benefits of electropolishing: in fig. 5 are data from a 1300 MHz mono cell cavity shown, which after electropolishing of 60 μm significantly improved [30]; however it should be mentioned that this cavity once exhibited a gradient above 40 MV/m after chemical polishing (CP) of app. 150 μm, but after additional material removal by CP deteriorated to the shown performance. It is speculated that enhanced grain boundary etching by large amounts of CP could cause inferior performance, which can be recovered by the smoothening effect of electropolishing.

Also at KEK work is continuing on the KEKB factory project. Both excellent cavity performances have been achieved on 500 MHz B-factory cavities [31] and the "Crab" cavity, which reached peak surface fields of 40 MV/m [32]. One of the best results of a full scale B-factory cavity of large surface area is shown in fig. 6.

After the successful beam test of a full cryo-module equipped with eight 9-cell cavities in the spring of 1997, the TESLA Test Facility (TTF) project is gearing up to implementing further cryo-modules into the existing machine. After refinements of the QA procedures—eddy current scanning of the niobium sheets used for cavity fabrication and improved electron beam welding procedures—and applying post purification heat treatments, deeper material removal, high pressure rinsing and class 10 clean room assembly the last nine cavities used for TTF had an unprecedented average gradient of $E_{acc} \approx 24$ MV/m, close to the design value of $E_{acc} \approx 25$ MV/m. In a test in a horizontal cryostat a record gradient of $E_{acc} \approx 33$ MV/m was measured in a pulsed mode (fig. 7) [33].

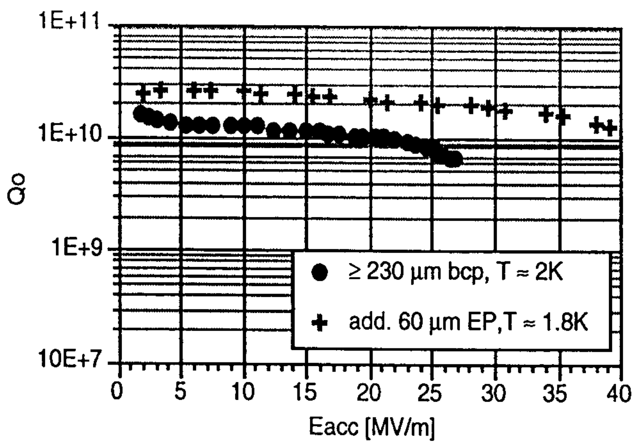

Fig. 5: Results from Cavity JL-1 after 230 μm of buffered chemical polishing and subsequent electropolishing of 60 μm

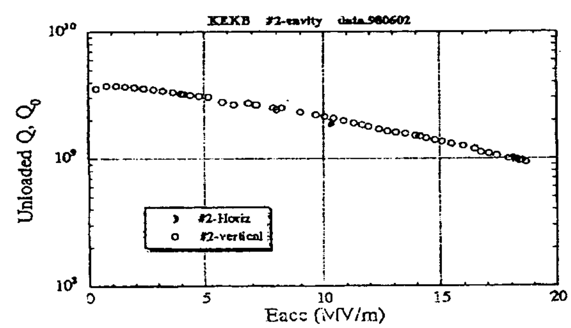

Fig. 6: Best performance of a KEK-B factory cavity tested in a vertical position

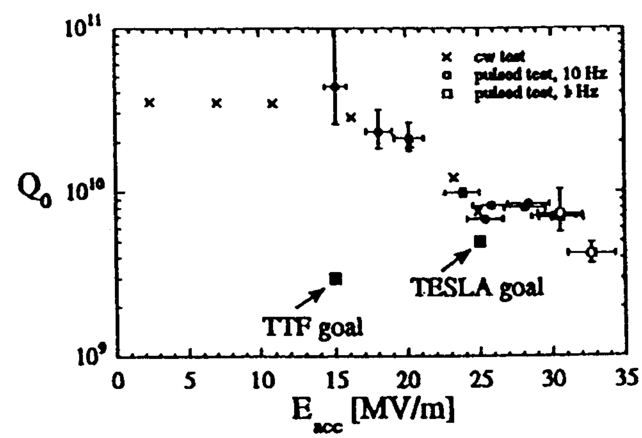

Fig. 7: Horizontal test result of cavity C23 compared to vertical test

At Saclay, cavity performances in mono cells around $E_{acc} \approx 25$ MV/m are routinely achieved after post purification heat treatment. Recently it was reported that after a moderate heat treatment at 170 C under vacuum for 70 hours improvements in the Q value at high gradients and increases in the quench field level have been measured (fig. 8) [34]. At LANL a single cell cavity of β = 0.64 developed for a future high intensity proton linac such as APT reached an accelerating gradient of E_{acc} = 10.7 MV/m. corresponding to a peak surface field of E_p = 38 MV/m [40]. Efforts are going on at DESY and INFN Legnaro to fabricate "seamless" cavities by hydroforming [35] or spinning [36], eliminating electron beam welds, which on occasion are the reason for inferior performance. If feasible, such a technique would significantly reduce cavity costs because of reduced labor in fabrication and QA and would permit the mass production of cavities on a shortened time table. In collaboration with INFN, several mono cell cavities have been chemically treated and tested at Jlab after a series of subsequent surface treatments. All cavities reached gradients $E_{acc} > 25$ MV/m, however above $\approx$ 18 - 20 MV/m a strong decrease in Q-value was observed even without the presence of field emission. An example is shown in fig. 9. This Q-degradation at high gradients has also been seen occasionally in other laboratories. It is until now not understood.

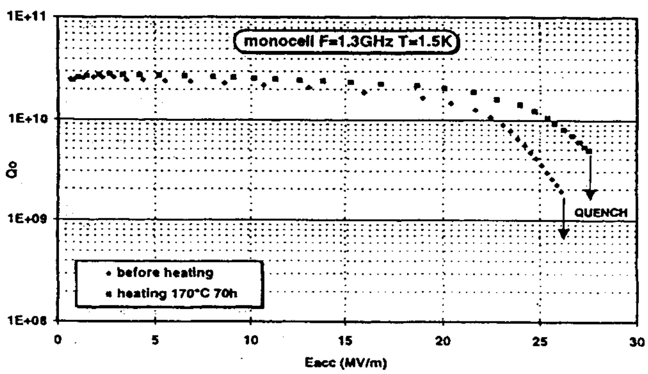

Fig. 8: Improvement of cavity performance after moderate heat treatment at 170 C [34]

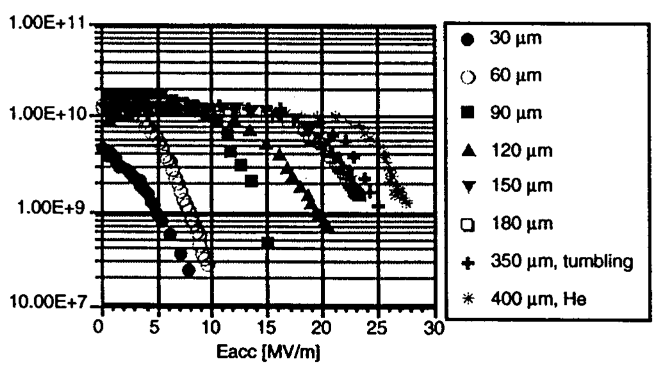

Fig. 9: Results from a "seamless" mono cell cavity; the gradient improved with successive material removal by buffered chemical polishing as indicated. [He=Helium processing]

B. Composite Nb/Cu Cavities

For the LEP II project niobium sputtered copper cavities have been successfully developed over several years and are now installed and operated in the accelerator. In this process a thin film of niobium is sputtered by magnetron sputtering onto the copper substrate taking advantage of its high thermal conductivity in thermally stabilizing the cavity against thermal breakdown. In addition, the LEP II cavities are of large size (350 MHz) and there are significant cost savings in niobium material costs realized by using only a thin niobium layer instead of solid material. These cavities with sputtered niobium layers show a characteristic slope in Q_o vs E_{acc}. Intensive studies at CERN have been conducted in the last several years to understand this effect and to find sputtering conditions, under which the Q - degradation is absent [37], [43]. The condition of the Cu/Nb interface, its state of oxidation and the migration of impurities at the boundary and within the niobium layer can strongly influence the RF properties of the deposited films. Films, which lack the above mentioned slope in Q_0 vs E_{acc} have been successfully produced.

Another approach of reducing niobium material costs, take advantage of the high thermal conductivity of copper and additionally mechanically stabilize the cavities against microphonics and radiation pressure effects at high gradients is being taken by the Saclay group. A copper layer is sprayed by plasma spraying onto a thin niobium cavity. First cavities made by this method showed encouraging results [38].

In a collaboration between KEK and INFN the fabrication of seamless cavities made from composite Nb/Cu sheet formed by explosion bonding is being pursued as a possible cost reducing fabrication technique for high gradient cavities needed for Linear Collider application. First cavities have been formed; even though the spinning process seems to be without obvious problems with respect to formability, more developement is needed to avoid cracks in the niobium at places of largest deformation [39].

V. SUMMARY

In the last several years significant progress has been made in understanding and eliminating limitations to cavity performances by " inventing" and applying new or improved techniques in cavity handling as listed in Table I. Many of the excellent results reported by the SRF community are for well controlled laboratory tests in vertical test dewars. What counts eventually is the performance in the accelerator environment. Understanding and avoiding the sources of contamination and more so of recontamination during assembly steps seems most important. Many steps are being taken in this direction by stringent control of processes and procedures, by consciously reducing particulates on equipment, tooling and hardware, use of high purity, low particulate processing chemicals and ultrapure water rinsing. In this respect, the TTF as the presently most ambitious project in this technology is showing the way.

TABLE I
SUMMARY OF IMPROVED CAVITY TREATMENT TECHNIQUES USED TO OVERCOME LIMITATIONS

Limitation	Action
Suppression/Elimination of multipacting	Modification of cavity shape to spherical or elliptical cross sections Very clean surfaces to suppress δ
Suppression/Elimination of defects	Improved inspection procedures (eddy current scanning of defects) Improved electron beam welding Improved chemical surface treatment ("internal chemistry" in clean room, filtered acids, electropolishing) Improved rinsing techniques (HPR, ozonized water) Deeper material removal, tumbling[42] Class 10 clean room assembly
Stabilization of defects	Purer material: RRR > 200 Post Purification
Field Emission	High Pressure Rinsing Ozonized water rinsing Electropolishing Vacuum baking High Peak Power Processing Class 10 clean room assembly Improved contamination control

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