PROGRESS AND PLANS FOR R&D AND THE CONCEPTUAL DESIGN OF THE ILC HIGH GRADIENT STRUCTURES*

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Abstract

Gradients and Q□s in the dominant ILC candidate structure have shown steady improvement, reaching 35 — 40 MV/m over the last year using the best techniques of electropolishing, high pressure rinsing and 120… C baking for 48 hours. Progress and plans for these structures are reviewed. Above 40 MV/m, the surface magnetic field encroaches the range of the rf critical magnetic field, believed to fall between 1750 and 2000 Oe, depending on the theory. One way to circumvent the limit is to modify the cavity shape to reduce the ratio of peak magnetic to accelerating field.˚Two candidate shapes have evolved, the Re-entrant shape and the Low-Loss shape. Although field emission is aggravated by higher electric fields, it does not present a brick wall limit because high pressure rinsing at 100 bar eliminates microparticles which cause field emission. Results of single and multicell cavities will be presented. The record field in a single cell re-entrant cavity is now 46 MV/m corresponding to a surface magnetic field of 1750 Oe and a surface electric field of 101 MV/m.

REVIEW OF PROGRESS IN CAVITY & CRYOMODULE GRADIENTS

The superconducting linear collider collaboration has made significant advances during the past decade. More than a hundred 9-cell structures have been produced by industry. There has been a steady rise in 9-cell cavity performance at TTF due to material and process improvements. Chief among these have been high purity, (residual resistivity ratio, RRR ¯ 300) starting niobium sheet material, eddy current screening of niobium sheets to eliminate large (> 100 µm diameter) defects, careful electron beam welding procedures in a good vacuum (¯ 10^{-5} torr), controlled (< 15… C) buffered chemical polishing (BCP) in a mixture of acids (HF, HNO_3 and H_3PO_4) to remove 100 µm of surface damage layer, 1350… C titanium heat treatment to post purify the niobium to RRR values of 600 or higher, BCP of the inside and outside to remove the titanium deposits, high pressure rinsing with 100 bar water to remove micro-particle contaminants that cause field emission, followed by drying and assembly in a Class 10 clean room environment. Several cavities have reached the high level of performance with 800… C baking instead of the titanium post purification. Fig.1 traces the history of improving performance over nearly one decade.

As cavity gradients advanced, clean assembly techniques for cavity strings with input couplers and cryomodules continued to improve so that cryomodule performance has also been rising steadily. Fig.2 shows progress in cryomodule gradients over the last decade [1]. The difference between vertical test results and cryomodule results is decreasing as is the spread in gradients. Fig. 2b shows the *Q vs. E* curve for the average of eight cavities in module #5 when installed in TTF during 2004. Dark currents were far below acceptable values, the goal being < 70 nA at 25 MV/m per cavity, which would correspond to a 250 mW heat load. In module #4, the average was 15nA per cavity for 8 cavities, and in module 5, less than 25 nA per cavity for 7 cavities. One cavity showed dark current at the µA level due to a deviation in the assembly procedure of the input coupler.

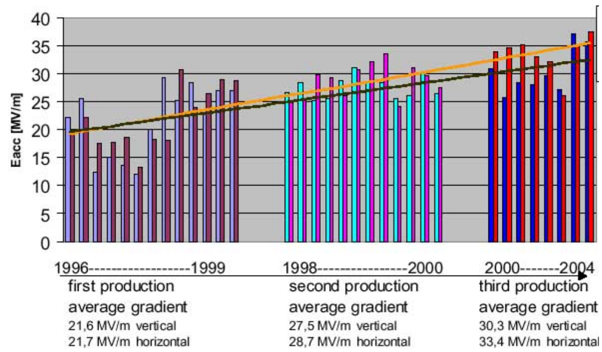

Figure 1: Progress in cavity gradients using standard BCP. Vertical and horizontal (fully equipped, high power) cavity test results are shown for each of three production batches. In each batch, the bar on the left is for the vertical test.

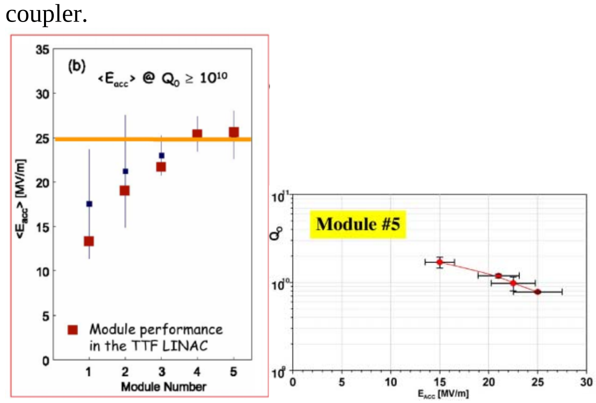

Figure 2: (a: left) Progress in cryomodule gradients and spread. Cryomdule test results come in agreement with vertical test results. (b: right) Q vs E curve for module#5.

35 MV/M BY ELECTROPOLISHING & MILD BAKING

Over the last three years, the use of electropolishing combined with mild baking (100… — 120… C) has yielded CW gradients between 35 - 40 MV/m to meet the one

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TeV upgrade requirement for the ILC. Fig. 3 shows the performance of six best 9-cell cavities at TTF[1] as tested in a vertical dewar.

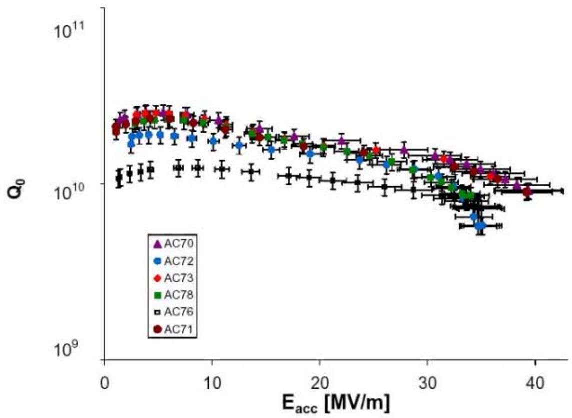

Figure 3: Vertical test results for six 9-cell cavities after electropolishing and baking.

For a niobium surface prepared by BCP the Q starts to drop steeply above accelerating fields of 20 MV/m, and eventually a quench occurs. The Q-drop occurs even when there is no field emission, as judged by the absence of x-rays. For want of a better term, the phenomenon carries the label “high-field Q-slope.” Temperature maps show that losses take place in high magnetic field regions of the cavity [2]. There are usually many patches of losses which increase rapidly with field, suggesting the existence of weak superconducting regions, but not the entire surface. The cause of the weakness is yet not well understood (although models exist). The good news is that 100 — 120… C baking for 50 hours ameliorates the weakness and reduces the Q-slope. However, baking does not usually raise the quench field for most cavities prepared by BCP. Cavities with electropolished surfaces also show similar high field Q-slopes, but baking is much more effective in flattening the Q-slope, and inhibiting the quench so that significantly higher fields can be reached.

Roughness plays a role in Q-slope and quench. BCP yields a rough surface because each grain etches at different rate depending on crystal orientation. As shown in the SEM photographs of Fig. 4 the typical step height between grains can be a few µm. Electrolytic etching or electropolishing (EP) yields a much smoother surface [3]

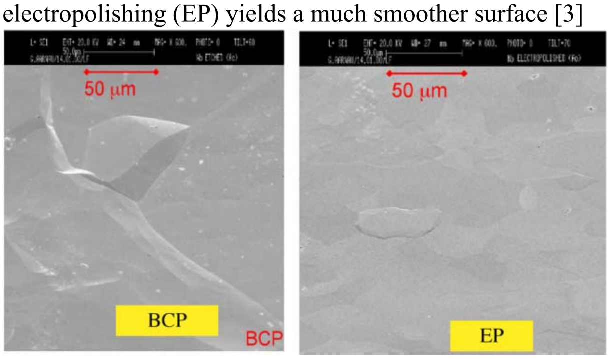

Figure 4: SEM pictures of niobium surfaces prepared by BCP (left) and EP (right).

with ¯ 100 nm roughness. Grain boundary steps can give rise to magnetic field enhancements of about 100% aggravating the Q-slope mechanism, and leading to quench. It is suspected that baking heals the weak region by redistributing oxygen from the oxide or oxide-metal interface. More R&D is needed to fully understand the Q-slope and the baking benefit.

Among the electropolished and baked cavities, several 9-cell units equipped with input couplers, higher order mode (HOM) couplers and tuners have been operated at TTF inside a single-cavity test cryomodule (called CHECHIA) with a high power klystron to reach gradients between 35 - 38 MV/m. Fig. 5 shows the best case [1].

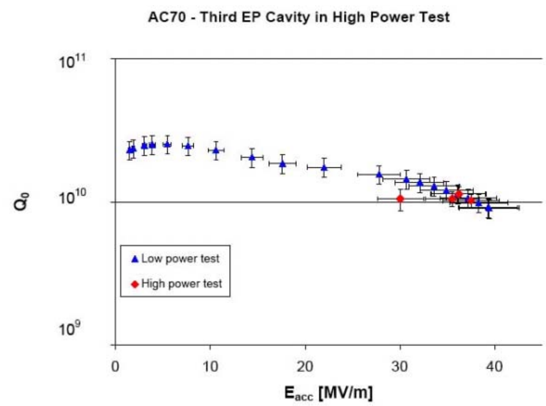

Figure 5: Horizontal test result of a fully equipped cavity after EP and bake.

One of the three CHECHIA tests on EP/baked cavities was a long-term test. The cavity operated stably for more than 1100 hours at 35 MV/m at a Q value of $7x10^{9}$. Operation was without quench or trips originating from the cavity-coupler system. There was very little field emission below 35 MV/m as judged from the low x-radiation level. Another fully equipped cavity was installed in a complete TTF cryomodule after its CHECHIA test. It operated at 35 MV/m at a Q of $6x10^{9}$. The low level rf system with piezo tuner successfully compensated for the Lorentz force detuning at the high gradient [1].

CONCEPTUAL DESIGNS FOR HIGHER GRADIENT STRUCTURES

Several laboratories are pursuing gradients above 35 MV/m with multiple goals: larger operating margin, lower cost, smaller site, or higher final energy for the ILC upgrade. Cost studies [4] show that gradients higher than 35 MV/m have little benefit on the total (capital + operating) cost of the 500 GeV linac, unless the Q is maintained at 10^{10}.

The best single-cell cavities at many laboratories reach 40—42 MV/m. Above these gradients, the magnetic field at the surface approaches the fundamental limit where superconductivity breaks down. One way to circumvent this limit is to modify the shape of the cavity to reduce the ratio between the peak magnetic field and the accelerating field. Two shapes have emerged, as shown in Fig. 6, the Low Loss (LL) shape [5] and the Re-entrant (RE) shape [6]. Table 1 compares the apertures, peak surface electric and peak surface magnetic fields of the new shapes with the TTF shape.

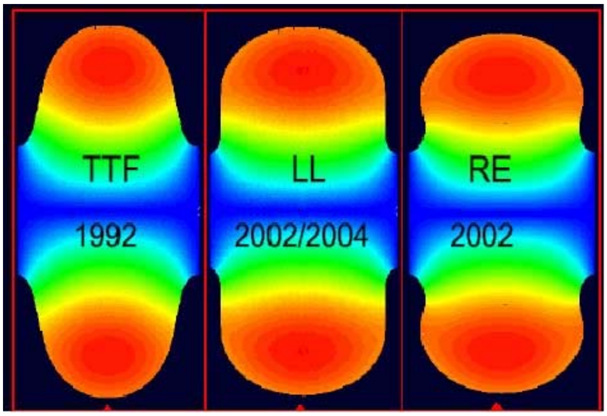

Figure 6: Comparison of the TTF shape (left) with the LL (middle) and re-entrant shape (right).

Table 1 : Comparision of aperture, and surface fields for three shapes.

Design Aperture	TTF 70 mm	LL 60 mm	RE 70 mm
Epk/Eacc	2.0	2.36	2.2
Hpk/Eacc	4.2	3.61	3.76

Simulations show that the re-entrant shape is free from one side multipacting and that two-side multipacting is weak as for the TTF shape. The downside of the new shapes is the higher accompanying surface electric field, which enhances field emission of electrons from the regions of high electric field. For example, to reach Eacc = 45 MV/m, the peak surface electric field would approach 100 MV/m. Field emission does not present a brick-wall limit, however, because techniques such as high-pressure water rinsing at pressures of about 100 bar eliminate the microparticle contaminants that cause field emission. Another important aspect of cavity shape is beam aperture. Smaller apertures produce stronger wakefields. For example the LL shape has 18% higher longitudinal and 65% higher transverse wakefields[5]. The re-entrant shape has the same aperture as the TESLA shape. Nevertheless, reducing the aperture, say from 70 to 60 mm, would yield higher accelerating gradients because it would allow a surface magnetic field 16% lower. Further studies are in progress to evaluate the trade-off between higher wakefields and higher potential accelerating gradients. The Lorentz force detuning coefficient of the new shapes is slightly higher than for the TTF shape [7].

New ideas are usually proved in single-cell cavities before the technical challenges of multi-cell accelerating units are addressed. A LL single cell cavity at Jlab [8] reached Eacc = 40 MV/m at a Q value of $6x10^9$after EP and bake. The first 70 mm-aperture re-entrant single-cell cavity fabricated at Cornell reached a world record accelerating field of 46 MV/m at a Q value of 10^{10}, and 47 MV/m in the pulsed mode. Fig. 7 [9] compares the re-entrant single cell with a TTF shape cavity, and Fig.8 shows the canonical *Q vs E*.

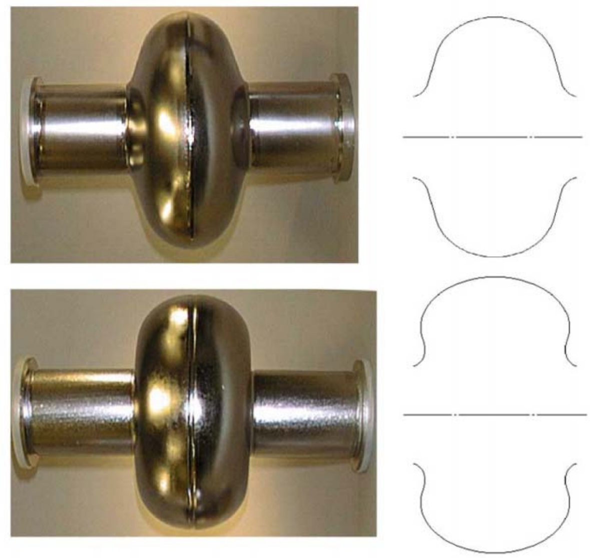

Figure 7: (Upper) TTF shape niobium cavity. (Lower) Rentrant shape cavity.

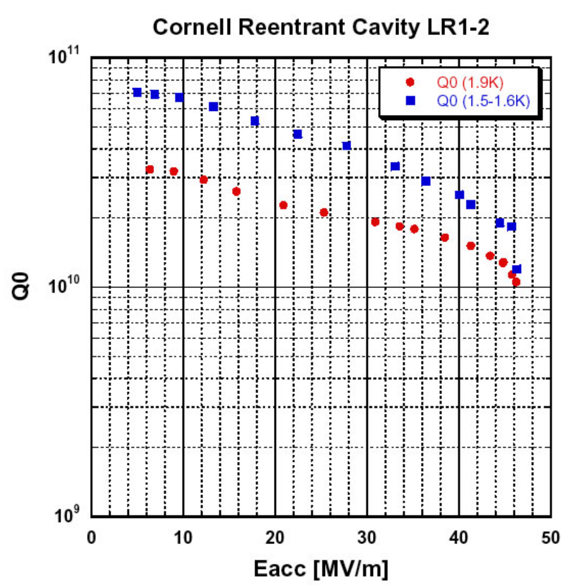

Figure 8: Record performance of the re-entrant cavity.

To reach record performance levels, the cavity was made from high-purity niobium (with RRR = 300), post purified to RRR > 600 with yttrium at 1200º C to avoid premature thermal breakdown of the superconductivity. Electropolishing provided a smooth surface. High-

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pressure rinsing at 100 bar scrubbed the surface free of the microparticles that cause field emission. In addition, baking at 100 °C for 50 hours promoted a redistribution of the oxygen in the radio-frequency (RF) layer.

PROMISING NEW MATERIAL

Another approach to higher gradients is to improve the material. Jefferson Lab [10] has started investigation of very large grain and single crystal niobium sheets cut by electro discharge machining (EDM) directly from the melted ingot (Fig.9a). The large grain material shows that the Q-slope starts at a higher magnetic field, and at an even higher field for the single crystal cavity. A single cell cavity (2.2 GHz) of the LL shape fabricated from single crystal reached Eacc = 45 MV/m at Q of 7×10^9 after BCP and bake (Fig. 9b). With the absence of grain boundaries, even BCP treatment provides a surface smoothness of the order of 20 nm in the single grain material. It is remarkable that the single crystal was not destroyed by deep drawing the cups from the sheet or by electron beam welding the two cavity halves together. No grain boundaries were found in the weld seam. Large grain material does have grains in the weld seam. The presence of the Q-slope before baking shows that grain boundaries and surface roughness are not the only causes of the Q-slope.

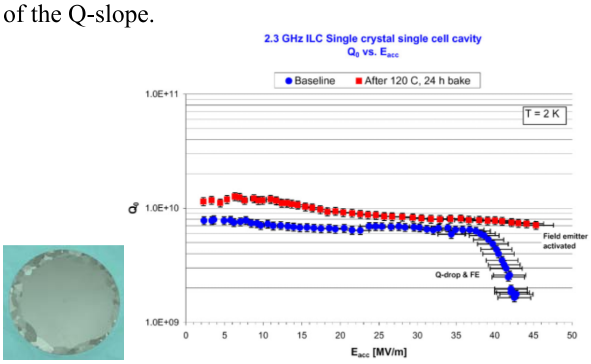

Figure 9: (a:left) Disk sliced from ingot, the center region is single crystal. (b: right) Q vs E before and after baking for BCP treated 2.2 GHz single cell cavity.

There are many advantages to using ingot slices of large and single grains over standard sheet material. Skipping the many steps (forging, grinding, rolling and annealing) between ingot and polycrystal sheet reduces cost and maintains the purity and RRR of the ingot. The simpler (and less expensive) BCP procedure can be used to obtain a smooth surface. In fact the BCP smoothness was better (27nm) than the EP smoothness on a fine grained polycrystal material (250 nm).

R&D PLANS AT EXISTING AND NEW TEST FACILITIES

TTF plans to continue R&D and tests for higher gradients in cryomodules and with beam. Eight EP 9-cells capable of 35 MV/m will be installed in Cryomodule #6 and tested by early 2006 in a new module test stand under preparation[1]. This module will subsequently be installed for high gradient beam tests in TTF by mid-2006. The European X-FEL project will be important for ILC. Industrialization activities are starting for the X-FEL which will require about 1000 cavities and 100 cryomodules. A new cavity and module test facility under preparation for the X-FEL production is expected to be complete by 2008.

A new Superconducting Module and Test Facility (SMTF) is coming together as a world-wide collaboration under the leadership of Fermilab. 21 laboratories, universities and institutes have joined the international collaboration. The goals are : to get up to speed on ILC technology in US, master procedures to reach reliable ILC performance, acquire cavities and cryomodules (including next generation versions), carry out long term beam tests and iterate as necessary to answer many of the items listed as R1, R2, R3 and R4 and detailed in the TRC Greg Loew Report [11]. Among these, it will be important to determine trip rates, recovery times, dark current, amplitude & phase control, alignment, vibration, input coupler performance, and HOM damping. It is anticipated that adequate coverage of the many items will need significant testing capability and time beyond those to become available in TTF-II at DESY. Another goal of SMTF is to engage US industries and to participate in launching large-scale industrialization for ILC in the US.

Among the near term activities under way are twelve 9-cell cavities from four different sources: AES (a US industry), ACCEL (in Germany) and four LL cavities from KEK. Chemical treatment, EP and vertical tests will be conducted at the partner facilities of Jlab, Cornell, LANL, MSU and ANL. Horizontal tests on fully equipped caviteis will be conducted at Fermilab. A Horizontal Test Dewar (HTD) similar to CHECHIA at TTF is under construction at FNAL. The first cavity string and cryomodule will be constructed from eight best cavities using new facilities to be set up at FNAL.

KEK is setting up a new Superconducting Test Facility (STF) to address all stages of cavity, cryomodule and RF development [12]. The near term goals are to fabricate and test 9-cell cavities of the LL shape, named ICHIRO cavities, after a superstar Japanese baseball player. Fig.10 shows the first completed cavity, soon to be tested. The ambition is to reach 45 MV/m gradient before the TDR for ILC. A cryomodule design for four ICHIRO cavities is underway.

SUMMARY

The technology of 25 MV/m at Q values near 10^{10} is established. Procedures exist for 35 MV/m, and there is an existence proof of 35 MV/m cavity inside a complete module. There is a strong need to establish repeatable performance at the 35 MV/m level and to demonstrate 35 MV/m in a full cryomodule. Past those milestones, plans are underway to carry out long-term beam tests and get on the long road to industrialization. Intense activities underway for the X-FEL in Europe will be important for many aspects of the ILC. SRF technology efforts are expanding rapidly world-wide to meet ILC goals and requirements. New cavity shapes and new materials for high gradients are on the horizon for reaching higher energies for the ILC upgrade. Single cell cavities are now reaching 45 — 47 MV/m.

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