Achievement of 35 MV/m in the Superconducting Nine-Cell Cavities for TESLA [1]

L. Lilje[2], D. Kostin, A. Matheisen, W.-D. Möller, D. Proch, D. Reschke, S. Simrock, K. Twarowski
DESY, Notkestrasse 85, D-22607 Hamburg, Germany

E. Kako, K. Saito
KEK, High Energy Accelerator Research Organization, 1-1, Oho, Tsukuba, Ibaraki, 305-0801, Japan

P. Schmüser
Universität Hamburg, Notkestrasse 85, D-22607 Hamburg, Germany

T. Suzuki
Nomura Plating Co., Ltd., 5, Satsuki, Kanuma, Tochigi, 322-0014, Japan

Abstract

The Tera Electronvolt Superconducting Linear Accelerator TESLA is the only linear electron-positron collider project based on superconductor technology for particle acceleration. In the first stage with 500 GeV center-of-mass energy an accelerating field of 23.4 MV/m is needed in the superconducting niobium cavities which are operated at a temperature of 2 K and a quality factor Q_0 of 10^{10}. This performance has been reliably achieved in the cavities of the TESLA Test Facility (TTF) accelerator. The upgrade of TESLA to 800 GeV requires accelerating gradients of 35 MV/m. Using an improved cavity treatment by electrolytic polishing it has been possible to raise the gradient to 35 - 43 MV/m in single cell resonators. Here we report on the successful transfer of the electropolishing technique to multi-cell cavities. Presently four nine-cell cavities have achieved 35 MV/m at $Q_0 \geq 5\times10^9$, and a fifth cavity could be excited to 39 MV/m. In two high-power tests it could be verified that EP-cavities preserve their excellent performance after welding into the helium cryostat and assembly of the high-power coupler. One cavity has been operated for 1100 hours at the TESLA-800 gradient of 35 MV/m and 57 hours at 36 MV/m without loss in performance.

Keywords: Superconducting RF cavities, Niobium, Surface superconductivity, Accelerating gradients, High-energy accelerators

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[2] Corresponding author: Lutz.Lilje@desy.de

1 Introduction

Electron-positron colliders have played a central role in the discovery of new quarks and leptons and the formulation and detailed verification of the Standard Model of elementary particle physics. Circular colliders beyond LEP are ruled out by the huge synchrotron radiation losses, increasing with the fourth power of energy. Hence a linear collider is the only viable approach to center-of-mass energies in the TeV regime. Such a linear lepton collider would be complementary to the Large Hadron Collider (LHC) and allow detailed studies of the properties of the Higgs particle(s). In the baseline design of the superconducting TESLA collider [1] the center-of-mass energy is 500 GeV (TESLA-500), well above the threshold for the production of the Standard-Model Higgs particle. The possibility for a later upgrade to 800 GeV (TESLA-800) is considered an essential feature to increase the research potential of the facility for the study of supersymmetry and physics beyond the Standard Model.

The design gradient of the TESLA-500 niobium cavities (23.4 MV/m) was chosen at a time when the typical accelerating fields in superconducting cavities were in the order of 3–5 MV/m. The factor of five increase presented an ambitious goal which, however, has been reached owing to the concentrated R&D efforts of the TESLA collaboration and of other institutions. A detailed description of the nine-cell cavities for the TESLA Test Facility (TTF) linac can be found in [2]. In the most recent series of 24 industrially produced TTF cavities the average gradient was measured to be 25 ± 2.6 MV/m at a quality factor $Q_0 = 10^{10}$. After the fabrication process these resonators were cleaned at DESY by chemical etching ("buffered chemical polishing BCP", see below) and subjected to a 1400°C heat treatment to enhance the low-temperature thermal conductivity of the niobium.

After many years of intensive R&D there exists now compelling evidence that the BCP process limits the attainable field in multi-cell niobium cavities to about 30 MV/m, significantly below the physical limit of about 45 MV/m which is given by the condition that the rf magnetic field has to stay below the critical field of the superconductor. For the type II superconductor niobium the maximum tolerable rf field appears to be close to the thermodynamic critical field (190 mT at 2 Kelvin).

Since a number of years, an improved preparation technique of the inner cavity surface by electrolytic polishing (or "electropolishing" for short) has opened the way to gradients of 35 - 43 MV/m in 1.3 GHz single-cell cavities [3, 4]. This development motivated a thorough R&D program on the electropolishing (EP) of single-cell test cavities. The results have been published recently [5]. In the present paper we report on the successful transfer of the EP technology to the nine-cell TESLA cavities.

2 Preparation of the inner cavity surface

2.1 Chemical etching and electrolytic polishing

Here we give a short outline of the chemical and electro-chemical methods which are applied to clean and prepare the inner cavity surface after the fabrication process. More details are found in [5]. Niobium metal has a natural Nb_2O_5 layer with a thickness of about 5 nm which is chemically rather inert and can be dissolved only with hydrofluoric acid (HF). The sheet rolling of niobium produces a damage layer of about 100 μm thickness that has to be removed in order to obtain a surface with excellent superconducting properties. One possibility is chemical etching which consists of two alternating processes: dissolution of the Nb_2O_5 layer by HF and re-oxidation of the niobium by a strongly oxidizing acid such as nitric acid (HNO_3) [6, 7]. To reduce the etching speed a buffer substance is added, for example phosphoric acid H_3PO_4 [8], and the mixture is cooled below 15°C. The standard procedure with a removal rate of about 1 μm per minute is called *buffered chemical polishing* (BCP) with an acid mixture containing 1 part HF (40%), 1 part HNO_3 (65%) and 2 parts H_3PO_4 (85%) in volume. At TTF, a closed-circuit chemistry system is used in which the acid is pumped from a storage tank through a cooling system and a filter into the cavity and then back to the storage.

A gentler preparation method is provided by electrolytic polishing (EP). The material is removed in an acid mixture under the flow of an electric current. Sharp edges are smoothed out and a very glossy surface can be obtained. The electric field is high at protrusions so these will be dissolved readily while the field is low in the boundaries between grains and little material will be removed here. This is an essential difference to the BCP process which tends to enhance the steps at grain boundaries.

The electro-chemical processes are as follows [9, 10]:

$$\begin{aligned}
2Nb + 5SO_4^{--} + 5H_2O &\rightarrow Nb_2O_5 + 10H^+ + 5SO_4^{--} + 10e^- \\
Nb_2O_5 + 6HF &\rightarrow H_2NbOF_5 + NbOF_2 \cdot 0.5H_2O + 1.5H_2O \\
NbOF_2 \cdot 0.5H_2O + 4HF &\rightarrow H_2NbF_5 + 1.5H_2O
\end{aligned}$$

The roughness of electropolished niobium surfaces is less than 0.1 μm [11] while chemically etched surfaces are at least an order of magnitude rougher. The main advantage of EP is the far better smoothening of the ridges at grain boundaries. An electropolishing of at least 100 μm is needed both for surface smoothening and damage layer removal.

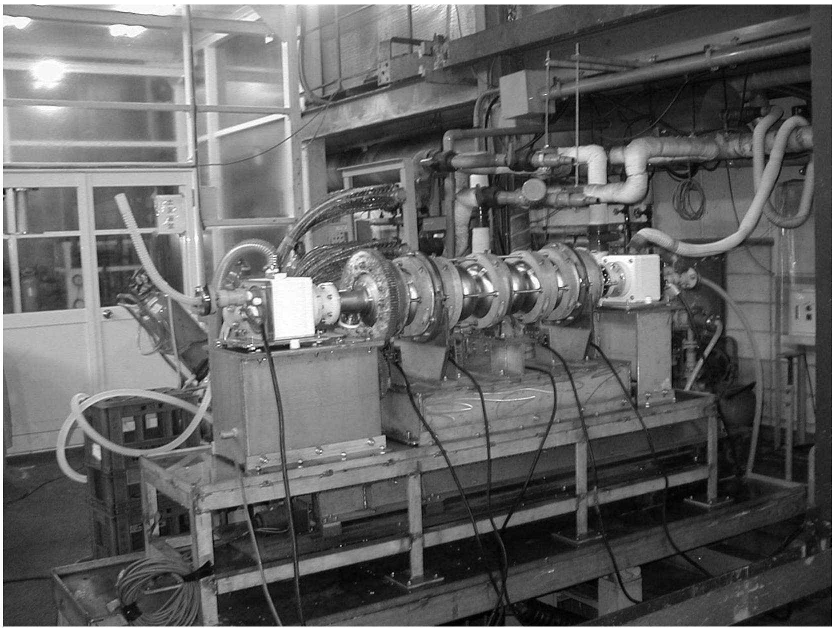


Figure 1: Setup for the electropolishing of multi-cell cavities at Nomura Plating (Japan).

2.2 Electropolishing of nine-cell cavities

At the KEK laboratory a long-term experience exists with the electropolishing of multi-cell cavities. The five-cell 508 MHz cavities of the TRISTAN electron-positron storage ring [12] were electropolished by an industrial company (Nomura Plating). Within a joint KEK-DESY program 9 TESLA nine-cell resonators of the most recent industrial production have been electropolished at Nomura Plating. The EP parameters are summarized in table 1.

The cavity is installed horizontally (see figure 1) together with the aluminum cathode. The lower half of the cavity is filled with the electrolyte which reacts with the the niobium surface only very slowly when no voltage is applied (etch rate less than 1 nm per hour). After the equilibrium filling level has been reached, the cavity is put into rotation and the voltage is applied between cavity and cathode while the current-voltage relationship is monitored. At a voltage of 15 - 20 V, the current through the electrolyte starts to oscillate indicating that the following two processes are taking place in alternating order: dissolution of the Nb_2O_5 by HF and re-oxidation of the Nb by H_2SO_4. The best polishing results are obtained for a current oscillation of 10 - 15% about the mean value. The temperature of the acid mixture

Acid mixture	10 % HF (40%) 90 % H_2SO_4 (96%)
Voltage	15 -20 V
Current density	0.5 -0.6 A/cm^2
Removal rate	30 μm/hour
Temperature of electrolyte	30 - 35 °C
Rotation	1 rpm
Acid flow	5 liters/s

Table 1: Parameters for the EP of nine-cell cavities.

is kept in the range 30 - 35°C. Temperatures above 40°C must be avoided as they result in etching pits on the surface. When the desired amount of material has been removed, the current is switched off. The rotation is stopped and the cavity is put into vertical position to drain the acid mixture. After rinsing with pure water the electrode is dismounted while keeping the cavity filled with water, thus avoiding drying stains from acid residues. The cavity is then transported into a clean room for high-pressure water rinsing.

An electropolishing facility for nine-cell cavities has recently been commissioned at DESY. The electrolyte is circulated in a closed loop. The cathode is made from pure aluminum and is surrounded with a tube made from a porous PTFE[3] cloth to prevent the electrolytically produced hydrogen from reaching the niobium surface. Except for the cathode all components of the EP system are made from chemically inert plastic materials, e.g. Polyperfluoro Alkoxyethylene (PFA), Polyvinylidene Fluoride (PVDF) or PTFE. The acid mixture is stored in a Teflon-cladded container and water cooled via a Teflon-covered heat exchanger. The electrolyte is pumped with a membrane pump through a cooler and a filter with 1 μm pore size into the hollow cathode which has openings at the centers of the cavity cells. Inside the cavity the volume above the electrolyte is filled with dry nitrogen to prevent water vapour absorption by the strongly hygroscopic H_2SO_4. The exhaust gases are pumped through a neutralization system to avoid environmental hazards.

[3]Polytetrafluoroethylene, for example Teflon®

3 Performance measurements on electropolished nine-cell cavities

3.1 Low-power tests in the accelerating mode

All nine electropolished cavities were cleaned at DESY by rinsing with ultrapure water at high pressure. After the drying in a class-100 clean room, a low-power input coupler and a pickup antenna were mounted and the cavity was closed with UHV vacuum flanges. A first performance test was carried out in a vertical bath cryostat filled with superfluid helium at 2 Kelvin. In this cryostat, the rf power of a few 100 watts is transmitted into the cavity through a movable antenna in the beam pipe section of the cavity. The external quality factor Q_{ext} is adjusted to be close to the intrinsic quality factor $Q_0 \approx 10^{10}$. The time constant of the cavity is determined by the "loaded quality factor"

$$\tau = \frac{Q_L}{\omega_0} \quad \text{with} \quad Q_L = (\frac{1}{Q_0} + \frac{1}{Q_{ext}})^{-1} \approx \frac{Q_0}{2} \; .$$

A typical value is $\tau \approx 1$ s. When the cavity is operated in the pulsed mode the intrinsic quality factor can be easily computed from the time decay of the stored energy. The coupling strength of the pickup antenna to the electric field inside the cavity is determined by pulsed measurements at low gradient. Once this calibration is known the excitation curve $Q_0(E_{acc})$ can be measured in the continuous wave (cw) mode.

In the low-power test, two cavities showed strong field emission at 15-17 MV/m. These were sorted out for a second EP which is planned to take place in the recently commissioned EP facility at DESY (see below).

The remaining seven cavities without strong field emission, having passed the low-power test successfully, were then evacuated to a pressure of 10^{-7} mbar and subjected to a 48-hour bake-out at 120°C. According to the experience with the single-cell cavities [4, 5, 13, 14] this bakeout is an essential prerequiste for achieving high gradients in electropolished cavities. After the bakeout the performance tests in the vertical bath cryostat were repeated. The results of these second tests are discussed in the following.

The excitation curves of the four best cavities after EP at KEK are shown in figure 2. In November 2003 one of the field-emission loaded cavities has been repolished in the new EP facility at DESY. The test results of this cavity at helium temperatures between 1.6 and 2.0 K are shown in Fig. 3 . Accelerating fields of up to 40 MV/m have been reached which is a record for multicell niobium cavities. The maximum accelerating fields achieved in all

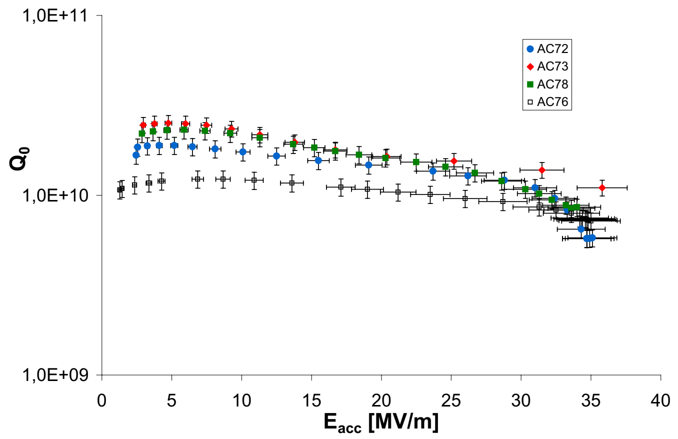


Figure 2: Excitation curves of the 4 best electropolished nine-cell cavities after the EP at Nomura Plating. Plotted is the quality factor Q_0 as a function of the accelerating field. The tests have been performed at 2 K.

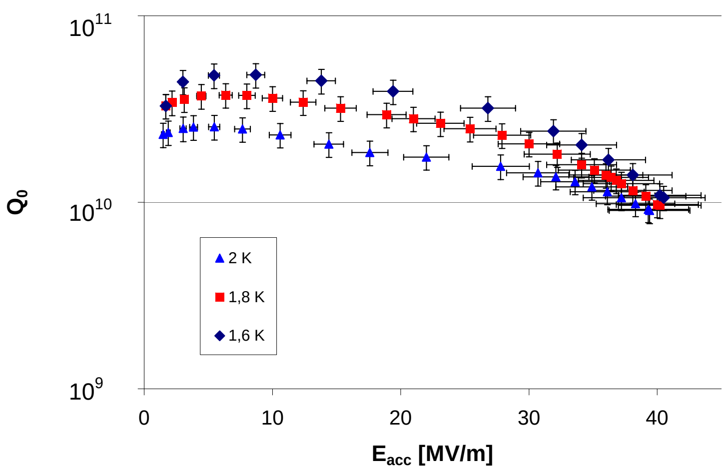


Figure 3: Performance of a cavity which received a second EP at DESY. This is one of the cavities suffering from field emission after the EP at Nomura Plating. An second EP of 40 μm removed the strong field emitter. A record gradient of 39 MV/m at 2 K and of 40 MV/m below 1.8 K was achieved.

eight TTF cavities after bakeout are shown in figure 4. These results prove that the TESLA-800 gradient of 35 MV/m is indeed within reach.

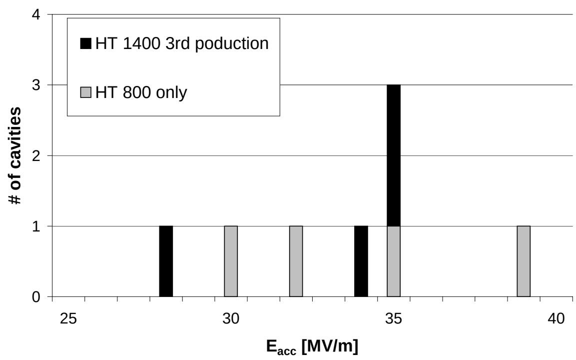


Figure 4: Maximum accelerating field achieved in electropolished nine-cell cavities. Gray bars: cavities with 800°C annealing, black bars: cavities with 800°C and 1400°C annealings in sequence. This is an indication that the annealing at 1400°C can be avoided for EP cavities, see sect. 3.4.2.

3.2 Performance of single cells in the nine-cell cavities

In an N-cell cavity, each single-cell eigenmode splits up into N coupled modes which are characterized by an rf phase advance of $m \cdot \pi/N$ between neighbouring cells ($m = 1, \ldots N$). For a perfectly tuned cavity the normalized amplitudes ($A_{m,j}$) in the individual cells are

$$A_{m,j} = \sqrt{\frac{2 - \delta_{mN}}{N}} \sin\left(\frac{m\pi}{2N}(2j-1)\right) \tag{1}$$

where m is the mode index, j the cell number and δ_{mN} is the Kronecker symbol ($\delta_{mN} = 1$ for $m = N$ and 0 otherwise). Only in the π mode with $m = N$ (the accelerating mode) the electric field has the same magnitude in each cell. By measuring the excitation curves for all coupled modes it is possible to determine the maximum attainable field in each cell, apart from a left-right ambiguity: in a nine-cell structure the cells 1 and 9, 2 and 8, 3 and 7, 4 and 6 are indistuinguishable in this analysis. The mode analysis is therefore a useful tool to identify cells of lower performance and to enhance the statistical basis for comparing the relative benefits of various chemical or electro-chemical treatments. It should be noted, though, that the electric field amplitudes in the cells depend critically on slight frequency detunings from cell to cell. Therefore the accelerating gradients derived from the mode analysis have a larger systematic uncertainty (≈ 15 %) than the gradient in the accelerating π mode which is determined with an accuracy of 8%.

The single-cell performance of etched and electropolished cavities is compared in figure 5. In the BCP-treated nine-cell TTF cavities of the third production series, the average maximum gradient amounts to 28.9 MV/m.

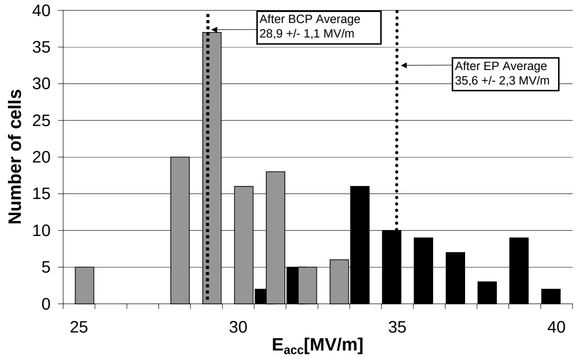
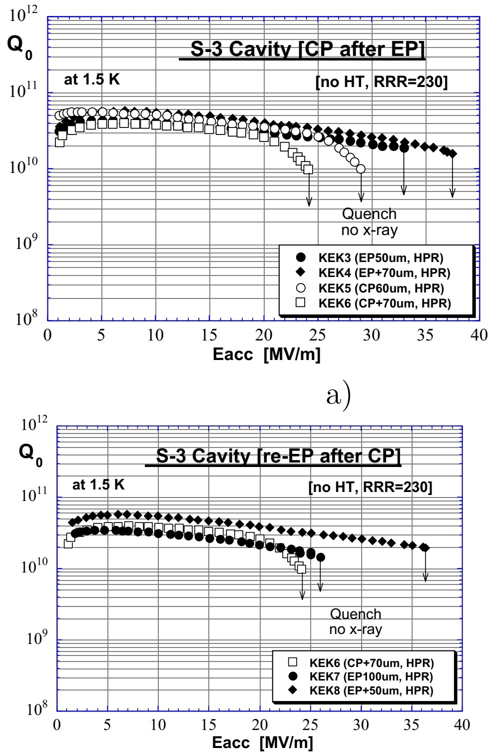


Figure 5: Distribution of accelerating gradients in individual cells. The single cell statistics derived from the coupled mode measurements are compared for chemically etched (gray) and electropolished (black) nine-cell cavities. The average maximum gradient is 28.9 MV/m for BCP-treated cavities and 35.6 MV/m for EP-treated cavities.

The electrolytically polished cavities, on the other hand, achieve an average single-cell gradient of 35.6 MV/m. (As mentioned above, one cavity with heavy field-emission loading has been left out). This is clear evidence that electropolishing is far superior to chemical etching in the preparation of the rf surface of the cavities.

The superiority of electropolishing was convincingly demonstrated in an earlier experiment at KEK, see figure 6 [3]. A single-cell (S-3) cavity reached 38 MV/m after an EP 120 μm. A subsequent chemical etching of 60 resp. 130 μm reduced the gradient to 29 resp. 24 MV/m. A new electropolishing (150 μm) recovered the initial high performance. Studies at DESY on electropolished single-cell and multi-cell cavities confirmed the performance degradation due to a subsequent etching, see figure 7. An etching of just 20 μm reduced the maximum accelerating gradient by 5 MV/m.



a)

b)

Figure 6: Test series on a single-cell niobium cavity (S-3) at KEK: (a) Excitation curve of the cavity after EP (50 resp. 120 μm) and degradation due to chemical polishing (CP) after the EP. (b) Recovery of high gradient performance due to a 150 μm EP of the etched cavity. HPR stands for High Pressure Rinsing with ultrapure water.

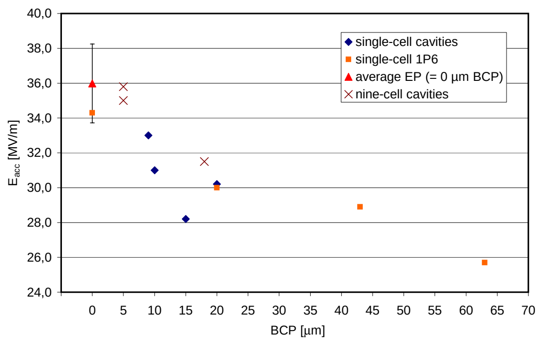


Figure 7: Performance degradation of electropolished niobium cavities due to subsequent etching with a removal of 5 to 65 μm.

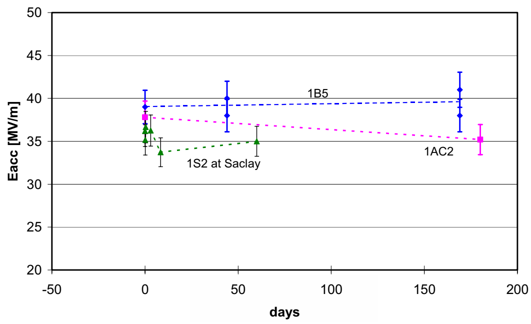


Figure 8: Accelerating gradient as a function of exposure time to clean air. Within the measurement errors no difference in the behaviour of the cavities was observed.

3.3 Long-term stability of the electropolished surface

The remarkable improvement of niobium cavities gained by electropolishing will of course only be useful for the accelerator if the EP surface preserves its good properties over a long time period. In a first endurance test at Saclay an EP-treated 1-cell cavity was exposed to clean air for 2 months without a significant change in performance. This was verified in experiments at DESY (see figure 8) for a period of 6 months. One single-cell cavity was filled with nitrogen and kept for more than 18 months. In this case a reduction of the initial, very high gradient was observed but the usable gradient was still above 35 MV/m, see Fig. 9.

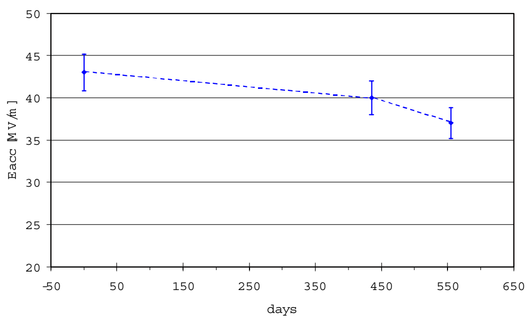


Figure 9: Accelerating gradient as a function of exposure time to clean nitrogen. The observed reduction is still within the experimental errors. A second experiment is under way. Test temperature was 1.8 K.

3.4 High temperature heat treatments

3.4.1 Heat treatments of chemically etched cavities

The TTF cavities are made from niobium sheets by deep drawing and electron-beam welding. Two high-temperature heat treatments are applied. The first step is a two-hour annealing at 800°C in an Ultra High Vacuum (UHV) furnace which serves two purposes: removal of dissolved hydrogen from the bulk niobium and mechanical stress release from the deep drawn and welded multicell structure. The second step is a four-hour treatment at very high temperature (1400°C) such that oxygen, nitrogen and carbon can diffuse out of the niobium. A titanium layer is evaporated onto the niobium surface to getter the foreign atoms and to protect the niobium against oxidation by the residual gas in the UHV furnace. The residual resistivity ratio RRR and the low-temperature heat conductivity of the bulk niobium increase by a factor of two, and the average gradient in BCP-treated cavities grows by about 5 MV/m. The experience at TTF has shown that the 1400°C heat treatment is an indispensible prerequiste for achieving gradients above 25 MV/m with a surface preparation by chemical etching (BCP).

It must be noted, however, that the 1400°C annealing is accompanied with a number of undesirable effects: large grain growth, softening of the material, necessity of an additional etching to remove the titanium getter layer. To obtain good deep drawing properties the grain size of the niobium sheets is in the order of 50 μm. There is little grain growth at 800°C but during the 1400°C annealing the grain size grows up to several millimeters. The resulting tensile strength is very low, about 5 MPa, hence the cavities are quite vulnerable to plastic deformation and frequency detuning after the high-temperature treatment. Another problem are the boundaries between the large grains. The titanium getter penetrates deep into these boundaries, a depth of 60 μm has been measured in samples. The titanium must be completely removed since otherwise a drastically reduced performance is observed, see Fig. 10. For this reason the TTF cavities are subjected to an 80 μm BCP after the 1400°C annealing.

3.4.2 Heat treatments of electropolished cavities

The moderate annealing at around 800°C is an important cavity preparation step which should be retained to avoid the danger of niobium hydride formation ("Q-disease"), see [5]. On the other hand, the experience gained at KEK and DESY with the single-cell program justifies the expectation that the 1400°C annealing can be safely discarded for electropolished cavities. The Japanese 1-cell cavities [15] were heat treated at $T = 760$°C only, and in spite of a comparatively low residual resistivity ratio of $RRR \leq 300$,

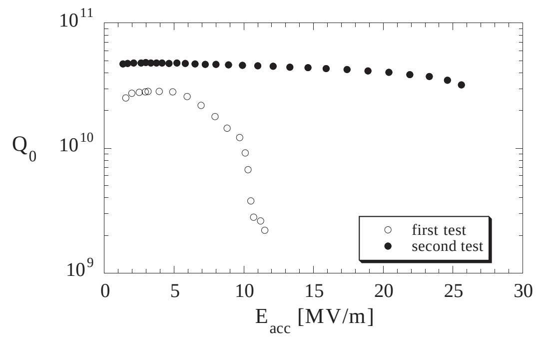


Figure 10: Degradation of cavity performance by remainders of the titanium getter layer and improvement after complete removal of this layer.

achieved gradients of 35 to 40 MV/m. In the CEA-CERN-DESY single-cell program [5] seven cavities were tested after the 800°C annealing with an average gradient of 35.4±5.3 MV/m and three cavities were heat-treated at 1400°C yielding 34.7±2.5 MV/m (see table 2).

The nine multicell TTF cavities sent to Japan for electrolytic polishing had previously undergone the standard BCP treatment at TTF. Five cavities had been annealed at 800°C while four cavities were had been subjected to an additional 1400°C annealing. The field-emission loaded cavity which was sorted out belonged to the first category. The maximum gradients achieved in the eight remaining 9-cell resonators have already been shown in Fig. 4, the average value is $< E_{acc} >= 34.0 \pm 3.9$ MV/m for the 800°C-annealed cavities and $< E_{acc} >= 33.0 \pm 3.3$ MV/m for the 1400°C-annealed cavities. Two 800°C-annealed cavities belongs to the five excellent nine-cell cavities shown in figures 2 and 3. From the single-cell analysis of the eight cavities the following numbers are obtained: $< E_{acc} >= 35.6 \pm 2.8$ MV/m for 800°C-annealing and $< E_{acc} >= 35.6 \pm 1.7$ MV/m for 1400°C-annealing (see table 2). These results, combined with with the data from the single-cell R&D programs, provide convincing evidence that the 800°C annealing alone is sufficient to achieve excellent performance in electropolished nine-cell cavities.

In early 2004 a new series of nine-cell cavities will be delivered to DESY. It is foreseen to prepare these cavities by electropolishing and test them after the 800°C annealing. If the same promising results should be obtained than found here, the 1400°C annealing can certainly be avoided for the cavities of the proposed X ray Free Electron Laser at DESY since this machine requires only moderate acceleration fields. Further investigations will be needed to decide whether the 1400°C annealing would provide a larger safety margin for the 800 GeV option of the TESLA collider.

Batch of cavities	800°C	1400°C
single-cells	35.4±5.3	34.7±2.5
nine-cells	34.0±3.9	33.0±3.3
single cell analysis of nine-cell cavities	35.6±2.8	35.6±1.7

Table 2: Overview on accelerating gradients measured on electropolished cavities with different high temperature annealings.

3.5 High-power pulsed operation of electropolished cavities

3.5.1 Excitation curves

In the TESLA collider the cavities have to be operated in the pulsed mode to keep the heat load on the superfluid helium system within acceptable limits. The rf power of about 210 kW per nine-cell cavity (for TESLA-500) is transmitted through a coaxial power coupler. The external quality factor amounts to $Q_{ext} = 2.5 \cdot 10^6$ at an accelerating field of 23.4 MV/m and an average beam current of 9 mA (during the rf pulse). The cavity has a filling time of 500 μs and a "flat-top" duration of 800 μs during which the bunched beam is accelerated. The nominal pulse repetition rate is 5 Hz. The time constant of the cavity equipped with a high-power coupler is dominated by the external quality factor and practically insensitive to the intrinsic quality factor Q_0 since

$$Q_L = (1/Q_0 + 1/Q_{ext})^{-1} \approx Q_{ext} \quad \text{for} \quad Q_{ext} \ll Q_0 \ .$$

Therefore, Q_0 cannot be derived from the time decay of the stored energy but instead has to be calculated from the heat transfer to the helium bath which can be measured only with large errors at low fields.

So far, two cavities (AC72, AC73) were prepared for a high power test without electron beam. The cavities were welded into a liquid helium tank and equipped with a high power coupler and a frequency tuning mechanism. The tests have been carried out in a horizontal cryostat at the TESLA Test Facility. Figure 11 shows the test results at a repetition rate of 5 Hz for AC73 and of 1 Hz for AC72 in comparison with the excitation curves measured in the low-power tests. It is very encouraging that both cavities achieve the same maximum gradient as in the low-power test. Within the large errors also the quality factors are in agreement. Another very important result is that cavity AC73 could be operated at 35 MV/m for more than 1100 hours and at 36 MV/m for 57 hours without any degradation.

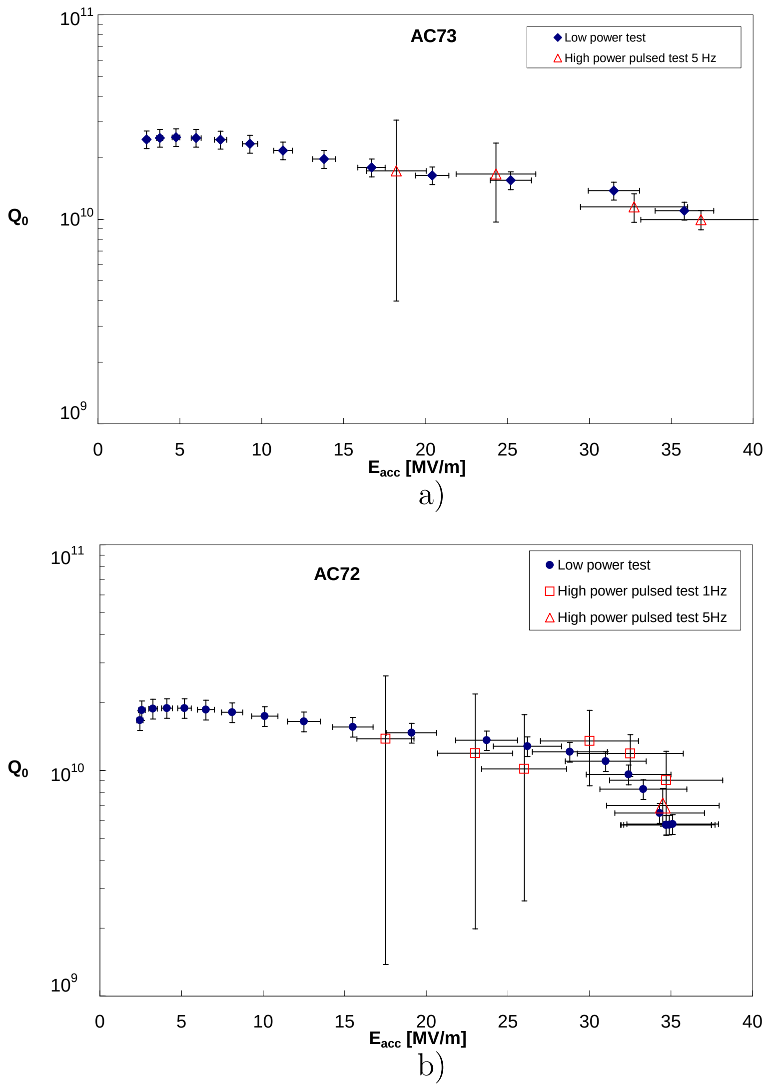


Figure 11: High power test of two electropolished nine-cell cavities: (a) Cavity AC73, this cavity was operated for more than 1100 hours at 35 MV/m. (b) Cavity AC72. The excitation curves obtained in the low power test in the vertical bath cryostat are shown for comparison and prove that the excellent performance is preserved after welding of the helium tank and assembly of the high power coupler.

Cavity AC73 was tested three times at a repetition rate of 10 Hz. Between the first two tests the cavity was warmed up to room temperature, between tests 2 and 3 it was kept for several hours at 150 K to check for a possible Q degradation through the formation of niobium hydrides. No indication of the "Q-disease" was seen. In all three 10 Hz tests the same high performance as at 5 Hz was achieved. In cavity AC72 a lower quality factor was seen at repetition frequencies above 1 Hz. This could be traced back to excessive heating at a damaged cable connector of a higher-order mode coupler.

3.5.2 Frequency stabilization in pulsed operation

The Lorentz force between the rf magnetic field and the induced currents in a thin surface layer causes a slight deformation of the cells in the order of micrometers and a shift in resonance frequency which is proportional to E_{acc}^2. In the pulsed operation of the 9-cell cavities this results in a time dependent frequency shift during the rf pulse. The TESLA cavities are reinforced by stiffening rings which are welded between neighbouring cells and reduce the detuning by a factor of two. Experimental data on the detuning are shown in Fig. 12. The "Lorentz force detuning" can be handled adequately by the rf system up to the nominal TESLA-500 gradient of 23.4 MV/m.

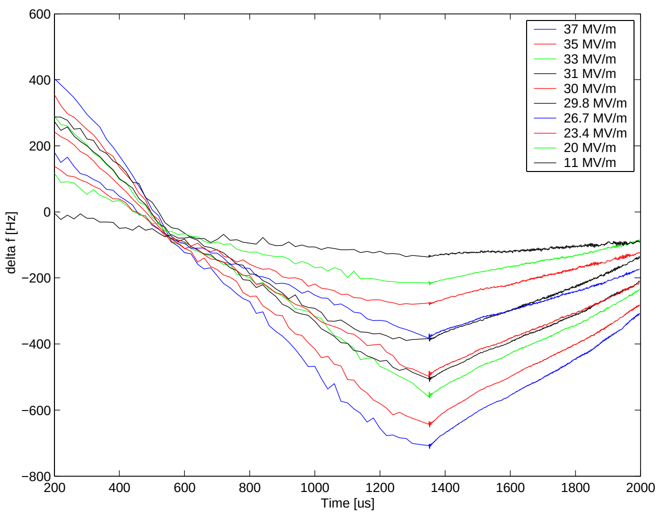
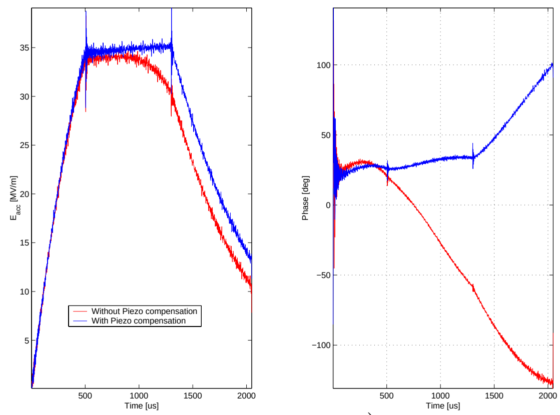
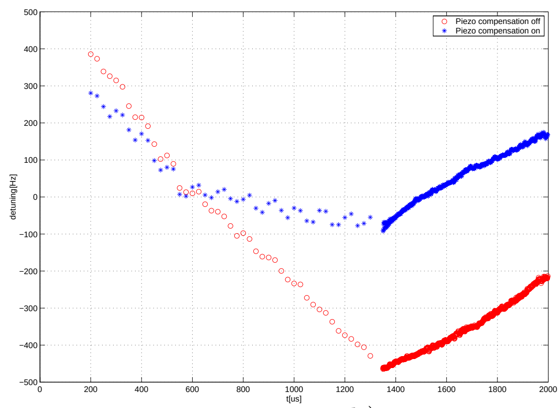


Figure 12: Lorentz-force detuning in pulsed mode operation at gradients between 11 and 37 MV/m. The resonance frequency shift Δf is plotted as a function of time. Filling time of cavity between 0 and 500 μs, "flat top" between 500 and 1300 μs, decay of cavity field for $t > 1300$ μs.

To allow for higher gradients the stiffening must be improved, or alternatively, the cavity detuning must be compensated. The latter approach has been successfully demonstrated using a piezoelectric tuner, see Fig. 13. The piezo-actuator changes the cavity length dynamically by a few μm and stabilizes the resonance frequency to better than 100 Hz during the flat-top time. The data in Fig. 13 prove that the stiffening rings augmented by a piezoelectric tuning system will permit to operate the electropolished cavities at fixed resonance frequency up to the TESLA-800 gradient of 35 MV/m. In addition, the piezoelectric actuator may be used to cancel microphonic noise between the rf pulses.



a)



b)

Figure 13: High-power pulsed test of an EP cavity at 35 MV/m. (a) Lorentz-force detuning causes a mismatch between klystron and cavity, associated with a time-dependent reduction of the accelerating field and a strong variation of the cavity phase with respect to the rf frequency. The compensation of the cavity detuning by a piezoelectric actuator leads to a constant accelerating field and a reduced drift in the relative phase. (b) The measured detuning at 35 MV/m with and without piezo-electric compensation.

4 Discussion of the results and conclusions

A comprehensive understanding why electropolishing is so much superior to chemical etching is still missing, however a few explanations exist. The sharp ridges at the grain boundaries of an etched niobium surface may lead to local enhancements of the rf magnetic field and thereby cause a premature breakdown of superconductivity at these localized spots. A model based on this idea was developed by Knobloch et al. [16] and can account for the reduction of the quality factor Q_0 at high field. Magnetic field enhancements will be much smaller on the smooth EP surface. Another advantage of a mirror-like surface is that a surface barrier of the Bean-Livingston type [17] may exist. The surface barrier prevents the penetration of magnetic flux into the bulk niobium in a certain range beyond the lower critical field B_{c1} ($\approx$ 160 mT for niobium at 2 K). The "penetrating field" B_{pen} exceeds B_{c1} considerably for a perfectly smooth surface. Magnetic fluxoids will enter and leave the material only above this penetrating field, hence the power dissipation associated with fluxoid motion will start only at $B_{rf} > B_{pen}$. The delayed flux penetration was experimentally verified in electropolished samples of the type II superconductors Pb-Tl and $Nb_{0.993}O_{0.007}$ [18, 19]. The experiments showed also that roughening of the surface by scratching and chemical etching destroyed the barrier and reduced the penetrating field to $B_{pen} = B_{c1}$. From these results we may conclude that an EP-treated superconducting cavity is likely to remain in the Meissner phase up to an rf magnetic field exceeding B_{c1} by a significant amount whereas a BCP-treated cavity will go into the mixed phase at B_{c1} and then suffer from enhanced power dissipation.

The two arguments for the superiority of electropolished cavities refer to the topological structure of the surface: it is smooth for EP and rough for BCP. However, the positive influence of the 120°C bakeout on the high-field performance of EP-cavities cannot be explained that way because the surface topology will not be changed by the bakeout. For a discussion of conceivable physico-chemical processes occuring during the bakeout we refer to the review talk by B. Visentin at the recent SRF2003 workshop [20].

In summary we can say that electropolished bulk niobium cavities offer the high accelerating gradients which are required for the upgrade of the TESLA collider to 800 GeV. For the first time, accelerating fields of 35 MV/m have been achieved in nine-cell cavities. One cavity could be excited to 39 MV/m even without the 1400°C heat treatment, which is an indispensible prerequisite for the BCP-treated TTF cavities to reach 25 MV/m. In two high-power tests it could be verified that EP-cavities preserve their excellent performance after welding into the helium cryostat and assembly of the high-power coupler. One cavity has been operated for 1100 hours at the TESLA-800 gradient of 35 MV/m and 57 hours at 36 MV/m without loss in performance.

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