2. Accelerating Structures for Future Linear Colliders

2.1. Superconducting Cavities of Ultimate Gradient for the TESLA Electron-Positron Collider

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2.1.1. 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 - 40 MV/m in single cell resonators and to more than 35 MV/m in nine-cell cavities.

2.1.2. 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. In the energy range beyond LEP, circular colliders 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 centre-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 centre-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 other physics beyond the Standard Model.

A detailed description of the superconducting TESLA cavities and their status as of February 2000 can be found in [2]. Here we report on the considerable increase in accelerating field that has been achieved in the past three years. This progress is largely due to an improved preparation technique of the inner cavity surface by electrolytic polishing instead of chemical etching. The chemical and electro-chemical preparation methods are therefore addressed in some detail. For a thorough discussion of superconducting radio frequency (rf) cavities and of microwave superconductivity we refer to the book *RF Superconductivity for Accelerators* by H. Padamsee, J.Knobloch and T. Hays [3] and to the review article *Superconductivity in High Energy Particle Accelerators* by P. Schmüser [4].

2.1.3. Cavity Preparation

2.1.3.1. Status and properties of the cavities for the TESLA Test Facility linac

The 1.3 GHz nine-cell niobium cavities for the TESLA Test Facility (TTF) linac (Fig.2) are made from 2.8 mm thick niobium sheets by deep drawing and electron beam welding. A damage layer of about 100 μm thickness is removed from the inner surface to obtain optimum performance in the superconducting state. For the TTF cavities this has been done so far by chemical etching. 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). Chemical etching of niobium 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) [5,6]. To reduce the etching speed a buffer substance is added, for example phosphoric acid H_3PO_4 (concentration of 85%) [7], 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, 1 part HNO_3 and 2 parts H_3PO_4 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.

In the most recent industrial production of 24 TTF cavities an average gradient 26.1± 2.3 MV/m at a quality factor $Q_0 \geq 1 \cdot 10^{10}$ was achieved. Typical excitation curves are shown in Fig. 1. The technology developed for TTF is hence adequate for TESLA-500 but considerable improvements are needed for an upgrade of the collider to 800 GeV. A detailed description of the present status of the nine-cell cavity layout, fabrication, preparation and tests can be found in [2].

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. This is 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 ($B_c \approx$190 mT at 2 Kelvin).

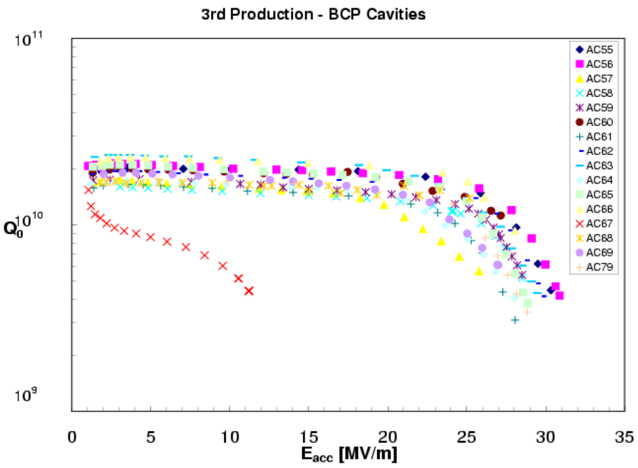


Figure 1: Excitation curves of several nine-cell TESLA cavities with surface preparation by chemical etching (BCP). The quality factor is plotted as a function of the accelerating field. The test temperature is 2 Kelvin. Cavity AC67, marked by crosses, developed a cold-leak during the test.

2.1.3.2. Electrolytic polishing

An alternative surface preparation method to etching is electrolytic polishing (EP). The material is removed in an acid mixture under the flow of an electric current. Sharp edges or tips 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. Using electrolytic polishing, scientists at the KEK laboratory in Tsukuba (Japan) achieved gradients of up to 40 MV/m in single-cell cavities [8]. This remarkable success motivated an R&D program on the electropolishing of single-cell cavities which was carried out in a collaboration between CERN, DESY and Saclay [9].

The electro-chemical reactions in the EP process are as follows [10, 11]:

$$2\mathrm{Nb} + 5\mathrm{SO}_4^{--} + 5\mathrm{H_2O} \rightarrow \mathrm{Nb_2O_5} + 10\mathrm{H}^+ + 5\mathrm{SO}_4^{--} + 10\mathrm{e}^-$$

$$\mathrm{Nb_2O_5} + 6\mathrm{HF} \rightarrow \mathrm{H_2NbOF_5} + \mathrm{NbOF_2}\cdot 0.5\mathrm{H_2O} + 1.5\mathrm{H_2O}$$

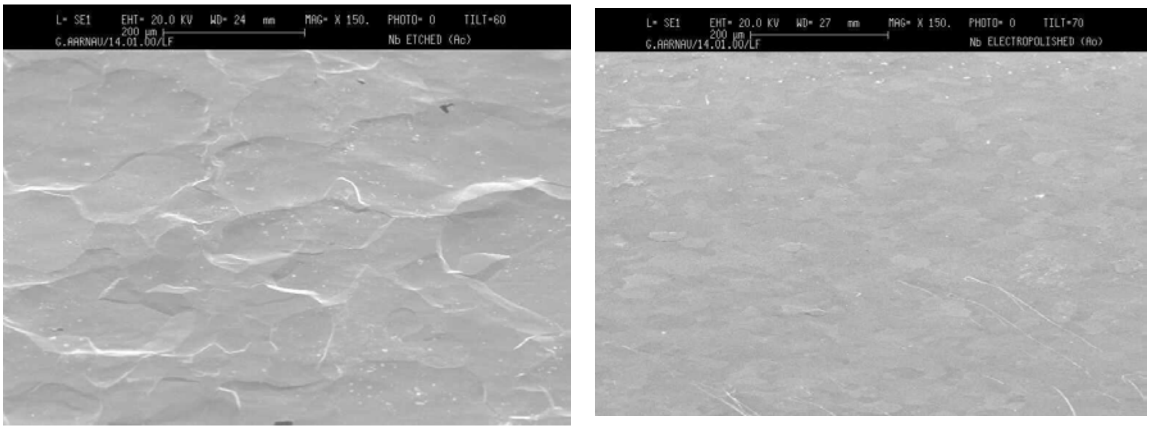
$$\mathrm{NbOF_2}\cdot 0.5\mathrm{H_2O} + 4\mathrm{HF} \rightarrow \mathrm{H_2NbF_5} + 1.5\mathrm{H_2O}$$

Recently, the EP technique has been successfully transferred to nine-cell cavities within a joint KEK-DESY R&D program [12]. The cavity is installed horizontally together with the cathode. The lower half is filled with the electrolyte which attacks the niobium 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 current-voltage characteristic is measured. At a voltage of 15 - 20 V the current starts an amplitude oscillation of 10 - 15% about the mean value which is an indication that two alternating processes are taking place: dissolution of Nb_2O_5 by HF and re-oxidation by H_2SO_4. The temperature of the acid is 30 - 35°C during the EP. When the desired amount of material has been removed, the current is switched off, the rotation is stopped and the cavity is turned into the 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 rinsing with ultrapure water at high pressure.

Figure 2: Superconducting 1.3 GHz 9-cell cavity for the TESLA Test Facility.

2.1.4. Comparison of etched and electropolished surfaces

Micrographs of BCP and EP treated niobium samples are compared in figure 3. One can see that EP smoothes out the grain boundaries far better than BCP. The average roughness of chemically etched niobium surfaces is in the order of 1 µm [13] while EP surfaces are at least an order of magnitude smoother. On etched surfaces the step height at grain boundaries can be a few µm. These steps may lead to a magnetic field enhancement and a premature breakdown of superconductivity [14].



a) 400 ×800 µm

b) 400 ×800 µm

Figure 3: Niobium surfaces after etching (left) and electropolishing (right). SEM micrographs are courtesy of G. Arnau, CERN.

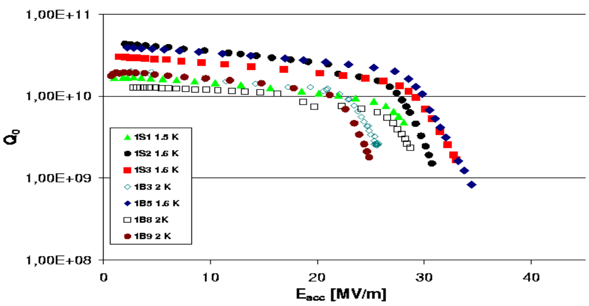


Figure 4: First tests of electropolished single-cell resonators. Note the strong degradation of the quality factor at accelerating fields $E_{acc} \geq 25$ - 30 MV/m.

2.1.5. Measurements on Electropolished Cavities

2.1.5.1. *Single-cell cavities*

A) First tests

In the first tests the electropolished cavities of the CERN-DESY-Saclay program faced an unexpected limitation: the excitation curves exhibited a strong degradation in quality factor at high field as can be seen in figure 4. Field emission of electrons could be excluded as an explanation for the performance degradation since neither X rays nor secondary electrons were observed.

It was discovered by Visentin et al. [15] that the performance of etched cavities could be considerably improved by applying a moderate thermal treatment to the finished cavity. This will be called *bakeout* in the following. The procedure at Saclay was as follows. After the last high-pressure water rinsing the cavities were evacuated and then heated up to 170°C for 70 hours. The remarkable observation was that this low-temperature baking improved the quality factor at maximum field by a nearly factor of 3.

B) Application of low-temperature bakeout to EP cavities

Building on the experience with BCP cavities at Saclay and with EP cavities at KEK (where a bakeout at 85-100°C had been part of the standard preparation) a 48 hour bakeout at 120°C was applied to the EP cavities of the CERN-DESY-Saclay collaboration. Figure 5 shows that a dramatic improvement is achieved: several single cell cavities reach now accelerating gradients of up to 40 MV/m with quality factors above $5{\cdot}10^9$. This behaviour is very similar to the observations made at KEK.

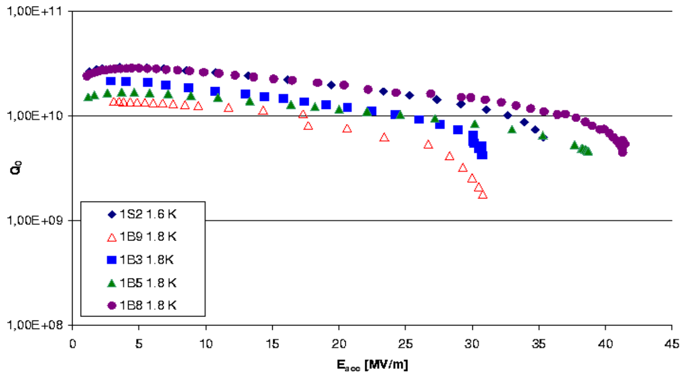


Figure 5: Excitation curves of electropolished one-cell cavities after the low-temperature bakeout. The tests have been performed at slightly different temperatures (1.8-2 K).

The high-temperature treatment of niobium cavities is a well-known method to improve the performance, see below. The surprising observation made with the bakeout effect is that a thermal treatment at 120-140°C, where the diffusion of gases dissolved in the niobium lattice is extremely slow, has a profound influence on the high-gradient performance. It it obvious that the bulk niobium cannot be affected by the bakeout but only a thin surface layer which, however, is essential for the microwave superconductivity.

C) “Q-disease” and 800°C annealing

Electrolytic polishing generates hydrogen which can easily penetrate into the niobium lattice. The danger exists that niobium hydride compounds are formed if the material is exposed to temperatures around 100 K for an extended period. These Nb-H compounds have very high microwave losses and may reduce the quality factor by one or two orders of magnitude. This unfortunate effect has been named *Q-disease*. The hydride formation depends on the dwell time the cavity spends in the dangerous region around 100 K. With a fast cooldown from room temperature within 1 hour, the hydride formation is reduced to an acceptable level.

A dedicated experiment was carried out to this end, the results are shown in figure 6. An electropolished cavity with excellent performance after a fast cooldown was then exposed to a temperature of 100 K for 2 days. In the new test the quality factor was very low. Then the cavity was heated to 800°C in a UHV furnace to remove the hydrogen from the bulk material. The exposure of the cavity to the dangerous temperature of 100 K for 2 days was repeated. This time no Q degradation was observed, indicating that the “Q-disease” was completely cured by the furnace treatment.

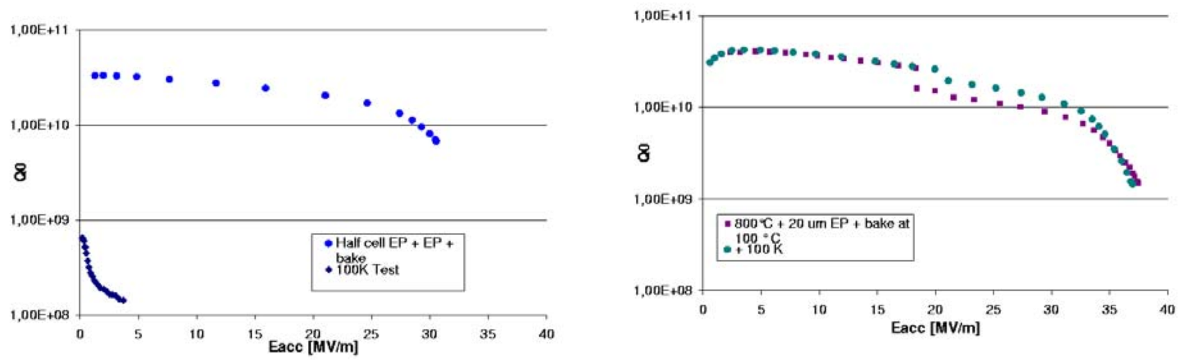


Figure 6: Demonstration of the “Q disease”. Left: The excitation curve of an electropolished and baked cavity before and after a two-day exposure to a temperature of 100 K.
Right: The same cavity after an 800°C furnace treatment and a short EP of 20 μm. The “Q disease” is completely cured and does not reappear when the cavity is exposed to 100 K. Test temperature 1.6 K.

2.1.5.2.Nine-cell cavities

Within the KEK-DESY program 9 nine-cell cavities of the last production series were electropolished at the Japanese company Nomura Plating and sent back to DESY for the performance tests. Two cavities with strong field emission at 15-17 MV/m were sorted out for a second EP. The remaining seven cavities were evacuated to a pressure of 10^{-7} mbar and subjected to a 48-hour bakeout at 120°C. The excitation curves of the four best cavities are shown in figure 7. These results prove that the TESLA-800 gradient of 35 MV/m is indeed within reach.

Very recently, one of the field-emission loaded cavities has been electropolished for the second time 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 figure 8. 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 eight TTF cavities are also shown in figure 7.

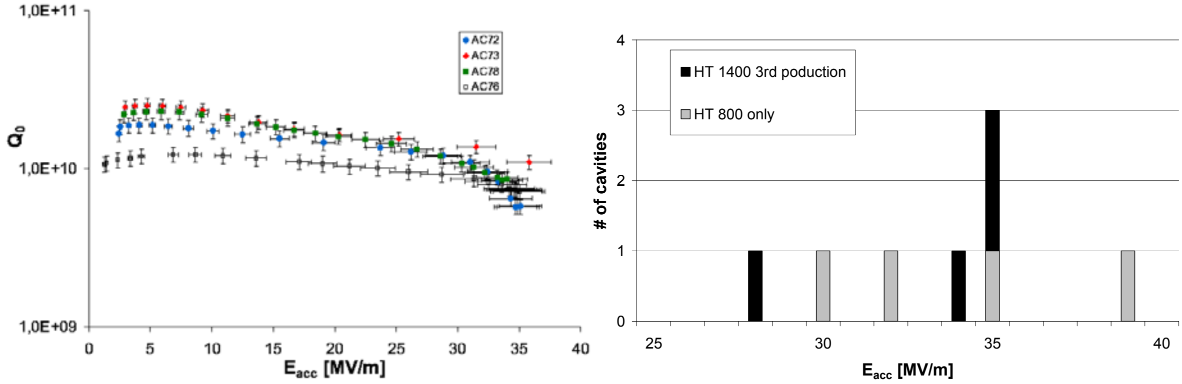


Figure 7: Left: Excitation curves of four excellent electropolished nine-cell cavities after EP at KEK. The tests have been performed at 2 K. Right: Maximum accelerating field achieved in eight electropolished nine-cell cavities. Gray bars: cavities with 800°C annealing, black bars: cavities with both 800°C and 1400°C annealings.

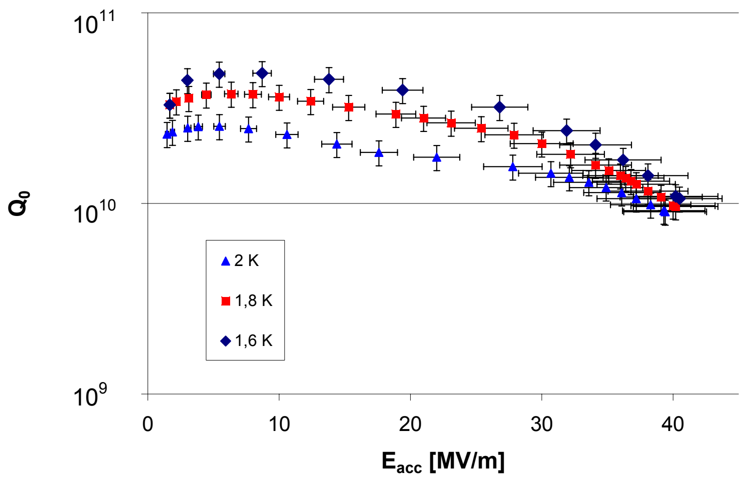


Figure 8: Performance of an initially field emission limited cavity after a second EP at DESY.

2.1.6. Microwave Surface Resistance

Superconducting magnets operated with direct current are free of energy dissipation, however, this is not the case in microwave cavities. The “normal” electrons, which are not bound in Cooper pairs, carry out forced oscillations in the time-varying magnetic field and dissipate power in the material. Although the resulting heat deposition is many orders of magnitude smaller than in copper cavities it still constitutes a significant heat load on the refrigeration system. As a rule of thumb, 1 W of heat deposited at 2 K requires almost 1 kW of primary ac power in the refrigerator. There is now a worldwide consensus that the overall efficiency for converting primary electric power into beam power is about a factor two higher for a superconducting than for a normal-conducting linear collider with optimized parameters in either case [22]. Another definite advantage of a superconducting collider is the low resonance frequency of the cavities that can be chosen (1.3 GHz in TESLA). The longitudinal (transverse) wake fields generated by the ultrashort electron bunches upon passing the cavities scale with the second (third) power of the frequency and are hence much smaller in TESLA than in the "Next Linear Collider NLC" (f = 11 GHz). The wake fields may have a negative impact on the beam emittance.

According to the BCS (Bardeen-Cooper-Schrieffer) theory of superconductivity the microwave surface resistance of a superconductor is given by

$$R_{BCS}(T,f) = A\frac{f^2}{T}\exp\left(-\frac{\Delta}{k_B T}\right)$$

Here 2Δ is the energy gap of the superconductor and f the radio frequency. The most important prediction is the exponential temperature dependence which is experimentally verified (Fig. 9). The factor A depends on material parameters like the coherence length ξ, the electron mean free path l, the Fermi velocity v_F and the London penetration depth λ_L. The BCS resistance of niobium at 1.3 GHz is about 600 nΩ at 4.2 K and drops to 10 nΩ at 2 K. For this reason cooling with superfluid helium at 2 K is essential for ultimate cavity performance. Moreover, the quadratic frequency dependence favours low-frequency cavities, e.g. f = 1.3 GHz at TESLA. A refined expression for R_{BCS}, derived from the two-fluid model of superconductors, is [16]:

$$R_{BCS}(T,f) \propto \sigma_{nc}\cdot\lambda_{eff}^3\frac{f^2}{T}\exp\left(-\frac{\Delta}{k_B T}\right) \qquad \lambda_{eff} = \lambda_L\sqrt{1+\xi/\ell}$$

Here σ_n is the conductivity due to the normal-conducting component. As a consequence, the BCS resistance is does not assume its minimum if the niobium is extremely pure ($l >> \xi$) but only moderately pure, $l \approx \xi$. The surface resistance contains in addition a term called *residual resistance* which is caused mainly by impurities and amounts to a few nano-ohms for an excellent niobium surface.

The low-temperature bakeout has an interesting effect on the surface resistance: the residual resistance increases by a factor of about 1.5 whereas the BCS resistance decreases by the same factor, see Fig. 9. Both observations can be understood if one assumes that the baking creates a somewhat "dirty" surface layer with shorter mean free path l than in the bulk niobium. One conceivable explanation is a partial disintegration of the Nb_5O_5 oxide layer and the formation of niobium suboxides. For a detailed discussion we refer to the review talk by B. Visentin at the 2003 SRF workshop [17].

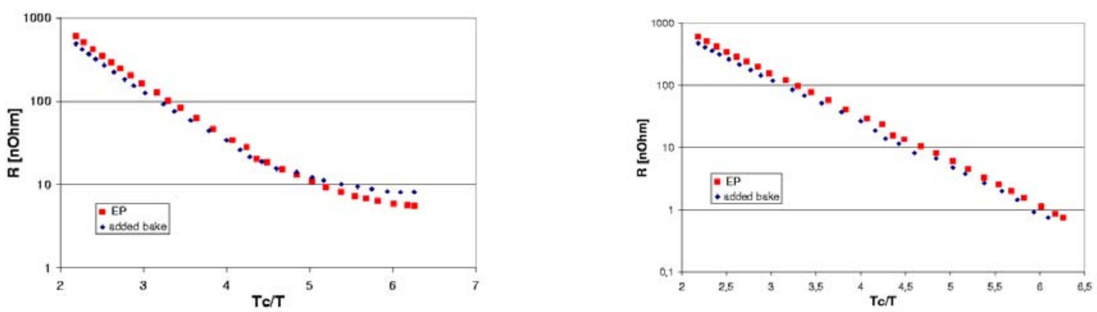


Figure 9: Left: Temperature dependence of the surface resistance before and after bakeout of an EP cavity. Right: The BCS surface resistance. The residual resistances of 4.7 nΩ for the unbaked cavity and of 7.4 nΩ for the baked cavity have been subtracted.

It should be noted that these surface resistance data are derived from measurements of the cavity quality factor at a few MV/m. The peculiar high-field behaviour of unbaked EP-cavities, namely the strong Q degradation, cannot be explained in terms of the surface resistance since this quantity is independent of the magnitude of the electromagnetic field in the cavity. On the contrary, a strongly field-dependent resistance would be needed to account for the rapid decrease of Q_0 towards large gradients. This effect is not yet understood.

2.1.7. High-Power Pulsed Operation of Electropolished Cavities

2.1.7.1.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 field in the cavity has a filling time of 500 μs and a „flat-top" time of 800 μs during which the bunched beam is accelerated. The nominal pulse repetition rate is 5 Hz.
At an accelerating field of 23.4 MV/m and an average beam current of 9 mA (for TESLA-500) an rf power of 210 kW per nine-cell cavity is transmitted through a coaxial power coupler. Almost all of this power is transferred to the beam. The external quality factor amounts to $Q_{ext} = 2.5\ 10^6$.

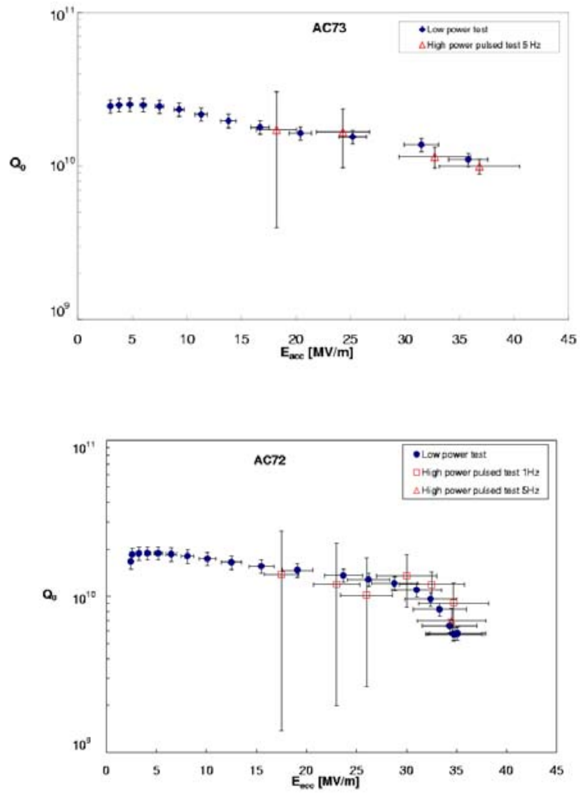


Figure 10: High power test of two electropolished nine-cell cavities: (a) Cavity AC73, this cavity was operated for more than 1100 hours at 35 MV/m. (b) Cavity AC72. The excitation curves obtained in the low power test in the vertical bath cryostat are shown for comparison and prove that the excellent performance is preserved after assembly of helium tank and high power coupler.

So far, two electropolished cavities (AC72, AC73) have been welded into a liquid helium tank and equipped with a high-power coupler and a frequency tuning mechanism. High power tests without beam have been carried out in a horizontal cryostat at the TESLA Test Facility. Figure 10 shows the 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 maximum gradient for more than 1100 hours without any degradation.

2.1.7.2. 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 the square of the magnetic field. In the pulsed operation of the 9-cell cavities this leads to 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. 11. The rf control system changes the klystron frequency and phase dynamically to accomodate for the cavity detuning. This method works properly up to the nominal TESLA-500 gradient of 23.4 MV/m.

To allow for higher gradients the cavity detuning must be compensated. This can be done with a piezoelectric tuner, see Fig. 12. The piezo-actuator changes the cavity length dynamically by a few µm and stabilizes the resonance frequency to better than 100 Hz during the beam acceleration time. The piezoelectric tuning system will permit cavity operation at fixed 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.

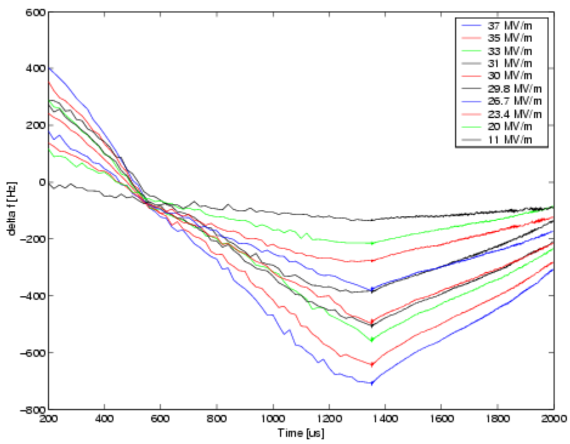
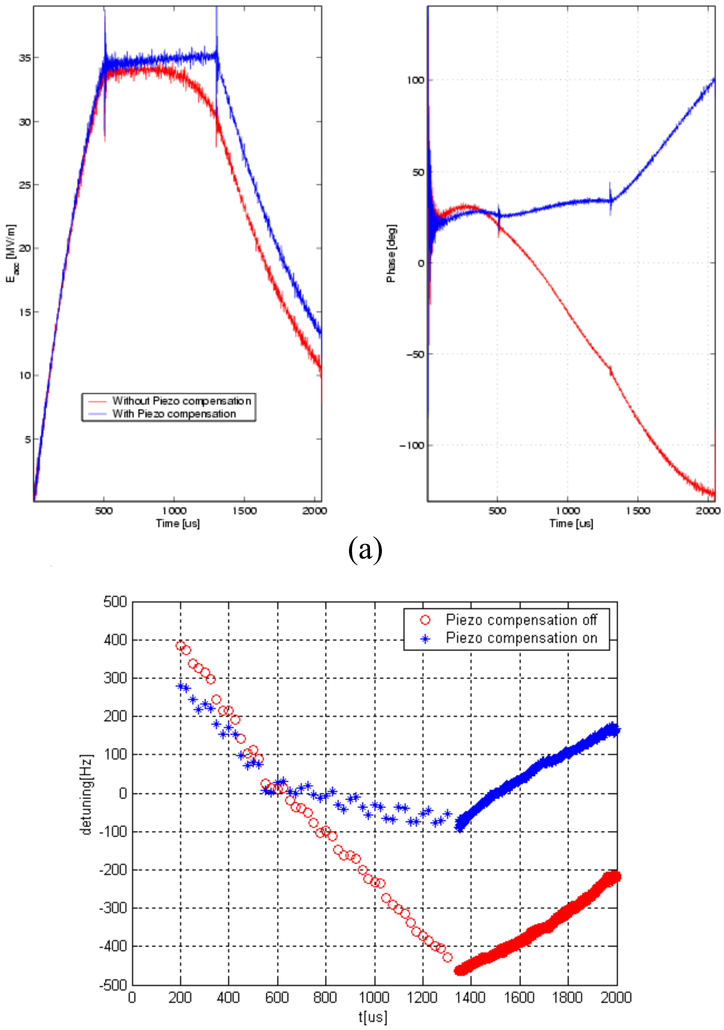


Figure 11: Lorentz-force detuning in pulsed mode operation at gradients from 11 to 37 MV/m.



(a)

(b)

Figure 12: High-power pulsed test at 35 MV/m of an electropolished nine-cell cavity.
(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 nearly constant accelerating field and phase.
(b) The measured detuning during cavity filling and "flat top" at 35 MV/m with and without piezo-electric compensation.

2.1.8. The Superstructure Concept

In striving for highest collider energies not only the gradient in the cavities but also the active acceleration length have to be maximized. There are, however, two effects which limit the number of cells N_c per resonator. With increasing N_c it becomes more and more difficult to tune the resonator for equal field amplitude in every cell: the sensitivity of the field homogeneity to small perturbations grows with N_c^2. Secondly, in a very long multicell cavity 'trapped modes' may be excited by the short particle bunches. These are coupled oscillations at high frequency which are confined to the inner cells and have such a low amplitude in the beam pipe sections that they cannot be extracted by the higher-order mode (HOM) couplers mounted the beam pipe. Trapped modes may have a detrimental influence on the beam emittance and must be avoided. The number $N_c = 9$ chosen for TESLA appears a reasonable upper limit.

The limitation in the number of cells can be overcome by the *superstructure* concept proposed by J. Sekutowicz [23]. Several multicell cavities are joined by beam tubes of length $\lambda/2$ (λ = 230 mm is the wavelength of the accelerating mode). Within each cavity there is an rf phase advance of π from cell to cell, while the phase advance between adjacent multicell units is zero. This ensures that the particles experience the same accelerating field in all cells of the superstructure. The superstructure is supplied with rf power by a single input coupler at one end. The interconnecting pipes have a sufficiently large diameter to permit the flow of rf power from one cavity to the next.
For the TESLA electron and positron linacs a superstructure consisting of two 9-cell cavities is envisaged [1], see figure 13. Compared to the layout with separated 9-cell cavities, this superstructure improves the filling factor by 6 % and saves a factor of two in input couplers and waveguide components.

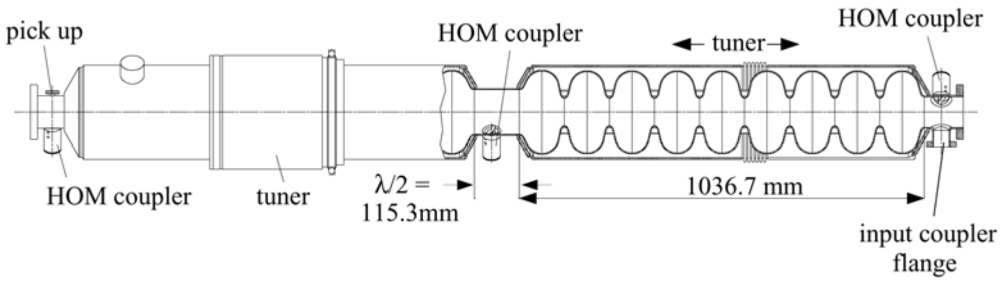


Figure 13: Layout of the 2x9-cell superstructure for TESLA-800 (the right 9-cell subunit is shown in cutaway view). One input coupler supplies the rf power for 18 cells.

The coupling between two adjacent cavities in a superstructure is about two orders of magnitude smaller than the cell-to-cell coupling within each subunit. To demonstrate that this small coupling is compatible with the requirement of a low beam energy spread a proof-of-principle experiment of two 2x7-cell superstructures was carried out at the TTF linac [23]. The rf power flow through the interconnecting pipe was found to be sufficient to replenish the stored energy in each cell between successive electron bunches. The measured bunch-to-bunch energy fluctuation was within the TESLA specification of $\sigma_E/E \leq 5 \cdot 10^{-4}$, see figure 14. Besides this, it was confirmed that a field homogeneity of better than 90% could be achieved in the superstructure. The excitation of beam-induced higher-order-modes was thoroughly studied and sufficient damping was verified.

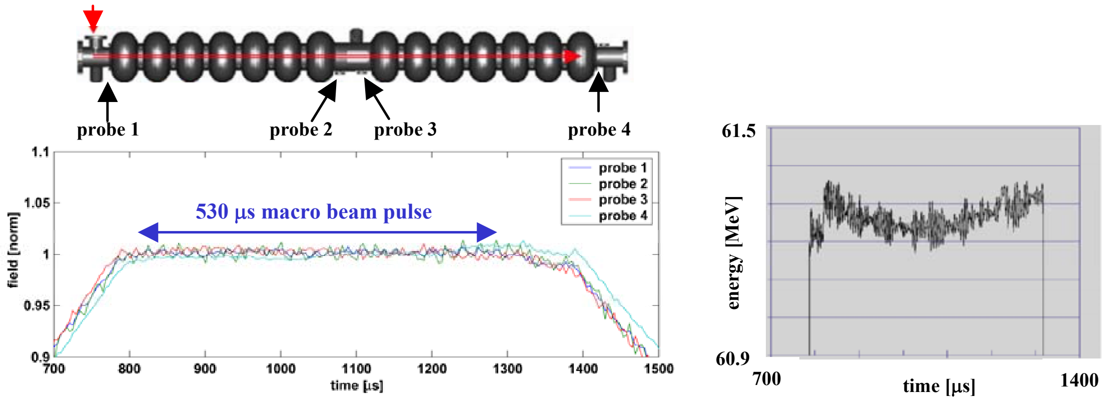


Figure 14: Energy gain along a 530 μs macro beam pulse (4 nC bunch charge, 1 μs bunch separation). Left: Measured signals of field probes near the end-cells of a 2x7-cell superstructure. Right: Measured beam energy at the end of the TTF linac. The energy fluctuations are within the specified limits of $\sigma_E/E \leq 5 \cdot 10^{-4}$. (Courtesy J. Sekutowicz.)

2.1.9. 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 cause a premature breakdown of superconductivity at these localized spots. A model based on this idea was developed by Knobloch et al. [14] and is able to explain the reduction of the quality factor Q_0 at high field. Magnetic field enhancements will not occur on the smooth EP surface. Another advantage of a mirror-like surface is that a surface barrier of the Bean-Livingston type [18] may exist. The surface barrier prevents the penetration of magnetic flux into the bulk niobium in a certain range above the lower critical field B_{c1} ($\approx$ 160 mT for niobium at 2 K). The "penetrating field" B_{pen} may exceed the lower critical field B_{c1} by a significant amount for a perfectly smooth surface. Only above this penetrating field magnetic fluxoids will enter and leave the material in a periodically varying field and cause power losses. 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 or 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. On the other hand, a BCP-treated cavity with rough surface will allow magnetic flux penetration at $B_{rf} \geq B_{c1}$ and then suffer from enhanced power dissipation.

In summary we can say that electropolished bulk niobium cavities offer the very high accelerating gradients which are required for the upgrade of the TESLA collider to 800 GeV. For the first time, accelerating fields of up to 39 MV/m have been achieved in nine-cell cavities. In high-power tests it could be verified that EP-cavities keep their excellent performance after assembly of the helium cryostat and the high power coupler [12]. One cavity was operated at the TESLA-800 gradient of 35 MV/m for 1100 hours without any degradation.

2.1.10. Acknowledgements

The results shown in this publication represent the work of many people. We want to thank all members of the TESLA collaboration for many interesting discussions. Special thanks go to Jacek Sekutowicz for discussions on the superstructure and to Kenji Saito and Eiji Kako from KEK for carrying out the electropolishing of nine-cell cavities together with Nomura Plating.

2.1.11. References

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