ACHIEVEMENT OF 35 MV/M IN THE TESLA SUPERCONDUCTING CAVITIES USING ELECTROPOLISHING AS A SURFACE TREATMENT

Lutz Lilje[#], DESY, Notkestrasse 85, D-22607 Hamburg, Germany

For The TESLA Collaboration

Abstract

The Tera Electronvolt Superconducting Linear Accelerator TESLA [1] is the only linear electron-positron collider project based on superconductor technology for particle accelaration. In the first stage with 500 GeV center-of-mass energy an accelerating field of 23.4MV/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 $Q_0 = 5\times10^9$, and a fifth cavity could be excited to 39 MV/m. In three 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. Another cavity has been assembled into a TTF linac accelerator module and could accelerate electrons with a gradient of 35 MV/m.

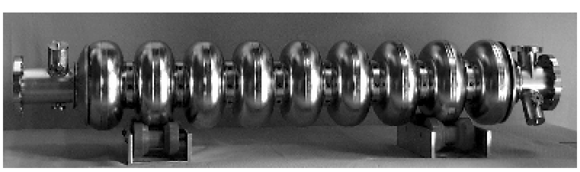

Figure 1: Superconducting 1.3 GHz 9-cell cavity for the TESLA Test Facility.

SURFACE TREATMENTS FOR THE CAVITIES FOR THE TTF LINAC

Etched Cavities

The 1.3 GHz nine-cell niobium cavities for the TTF linac (Fig.1) 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 [2]. 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.

In the most recent industrial production of 24 TTF cavities an average gradient 26.1+/-2.3 MV/m at a quality factor $Q0>1\times10^{10}$ was achieved. 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).

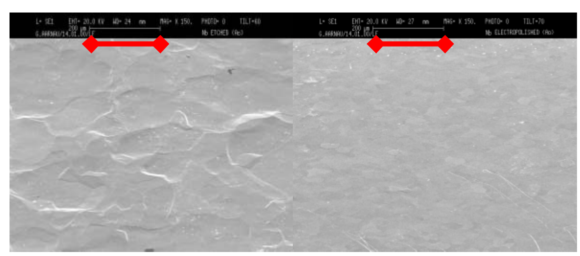

Figure 2: SEM surface picture of etched (BCP=Buffered Chemical Polish) and electropolished surface.

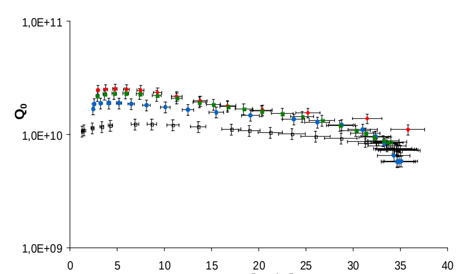

Figure 3: Excitation curves of four TESLA nine-cell cavities electropolished at KEK/Nomura Plating. Test temperature was 2 K.

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. This is an essential difference to the BCP process which tends to enhance the steps at grain boundaries (see micrographs in Fig. 2). Using electrolytic polishing, scientists at the KEK laboratory in Tsukuba (Japan) achieved gradients of up to 40 MV/m in single-cell cavities [7]. 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 confirming the KEK results on single-cell cavities [8].

The EP technique has been successfully transferred to nine-cell cavities within a joint KEK-DESY R&D program [9]. Cavities were sent to KEK/Nomura Plating after furnace treatment at DESY (5 cavities treated 800°C, 4 cavities at 1400°C) where electropolishing and first high pressure rinsing were carried out. Final assembly, final high pressure rinsing and bakeout at 120°C were carried out at DESY.

For an energy upgrade of TESLA to center-of-mass energy of 800 GeV (TESLA-800) a gradient of 35 MV/m at a Q_0 of 5×10^9 is needed. Out of the 9 cavities from the last production series of TTF cavities four cavities achieved this specification (The excitation curves are shown in figure 3) and six cavities more than 30 MV/m. Two cavities were strongly loaded with field emission. One of these cavities has been electropolished for the second time in the EP facility at DESY. The test results of this cavity at helium temperatures between 1.6 and 2.0 K are shown in figure 4. Accelerating fields of up to 40 MV/m have been reached which is a record for multi-cell niobium cavities.

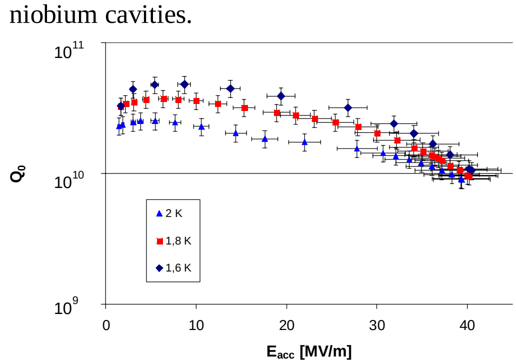

Figure 4: Performance of an initially field emission limited cavity after a second EP at DESY. A gradient of 40 MV/m was achieved in the low power contiuous wave measurement.

Electropolished Cavities High Power Tests

So far, three of the cavities (AC70, AC72, AC73) shown in figures 3 and 4 have been prepared for a high power test. The cavities were equipped with a liquid helium tank, a high power coupler and a tuning mechanism. The tests have been carried out in a horizontal cryostat at the TESLA Test Facility (CHECHIA) which effectively corresponds to 1/8[th] of an accelerator module. After being cooled to 2 K the dependence of the quality factor on the accelerating has been measured. Due to the strong coupling in the high power test $Q_{ext}=3\times10$ the quality factor of the cavity is calculated from the measured dynamic heat losses into the Helium bath.

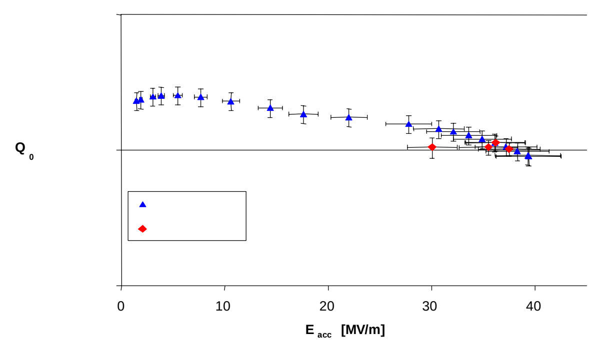

Figure 5: In the high power test the cavity AC70 achieved a gradient of more than 37 MV/m with $Q_0 > 10^{10}$, which is a factor of 2 above TESLA-800 specification. Test temperature was 2K. The repetition rate was 5 Hz.

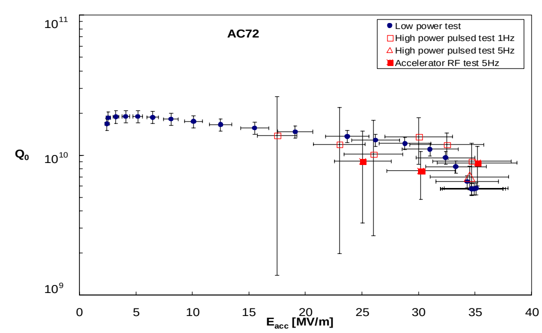

Figure 6: High power test of an electropolished TESLA nine-cell in the TTF linac. 35 MV/m were achieved with a quality factor of 9×10^9.

Several measurements at nominal pulse length (500 µs, filling time, 800µs flat-top) at a repetition rate of 1-10 Hz have been performed, all confirming the very good performance of the cavities in the vertical test (for two examples see figures 5 and 6). The quality factor of larger than 7×10^9 at a gradient of 35MV/m is larger than required for TESLA-800 in all cases. One cavity (AC70, Fig.7) achieved a gradient of 37 MV/m at a Q_0 of 1×10^{10}. Warm-ups of the cavity to 300 K and 150 K respectively did not change the cavity behaviour in any case.

The cavity AC73 has been operated for more than 1100 hours at 35 MV/m showing no sign of degradation. Neither the quality factor of the cavity nor the coupler performance degraded. Thermal breakdowns (quenches) of the cavity induced during the setup of the LLRF (Low-level RF system) were not influencing the quality factor either. This is a well-known behaviour for superconducting cavities. Breakdowns in the coupler also caused during setup of the Low Level RF system were not detrimental to the coupler performance.

The cavity AC72 was installed into an accelerator module for TTF after the high power test in CHECHIA. The final preparation and assembly (e.g. cavity-to-cavity connection) for the module did not change the performance of the cavity. At a gradient of 35 MV/m the cavity has been measured with a quality factor of 9×10^9 which is far above the specification for TESLA-800. The RF gradient calibration was crosschecked using an energy gain measurement of the electron beam.

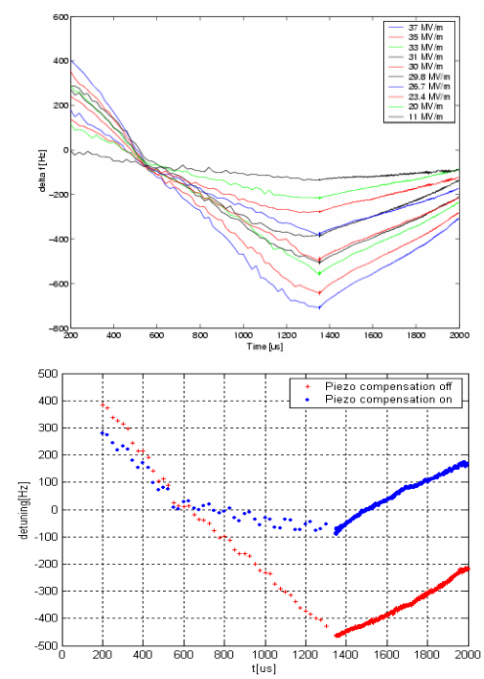

Figure 7: Top: Frequency detuning during one RF pulse measured at various gradients. Bottom: Compensation of Lorentz-forces using piezoelectric tuners.

LORENTZ-FORCE DETUNING COMPENSATION

In addition during the high power test, the compensation of the Lorentz force detuning could be demonstrated. The pulsed operation leads to a time-dependent frequency shift of the 9-cell cavities which is proportional to E_{acc}^2 (Fig.7). The stiffening rings joining neighbouring cells are adequate to keep this Lorentz-force detuning within tolerable limits up to the nominal TESLA-500 gradient of 23.4 MV/m.

To allow for higher gradients the stiffening must be improved, or alternatively, the cavity deformation must be compensated. The latter approach has been successfully demonstrated using a piezoelectric tuner at 23.4 MV/m in a previous test reducing the Lorentz-force detuning by about 200 Hz [10]. Meanwhile, while operating at 35 MV/m a compensation of more than 500 Hz over the full pulse length was achieved (see figure 7). The result indicates that the present stiffening rings augmented by a piezoelectric tuning system will permit efficient cavity operation at the TESLA-800 gradient of 35 MV/m.

CONCLUSION AND OUTLOOK

35 MV/m have been achieved in several nine-cell cavities. High power tests could confirm the good performance after full assembly of the coupler and the tuner. With the assembly of such a high gradient cavity into the TTF machine without loss in performance it has been shown that the preparation and assembly methods are principally at hand. This proofs that the gradient goal for TESLA-800 is in reach.

ACKNOWLEDGEMENT

The author wants to express his gratitude to E. Kako and K. Saito from KEK whose work on electropolishing L-Band niobium cavities was an essential element for exploration of highest gradients in TESLA cavities.

The work and support of the people in the TESLA collaboration is gratefully acknowledged.

REFERENCES

[1] R. Brinkmann, et al. (editors), *TESLA - Technical Design Report*, volume II. DESY, March 2001. ECFA 2001-209, TESLA Report 2001-23.

[2] B. Aune et al. The Superconducting TESLA Cavities. *Phys. Rev. ST-AB*, 3(9), September 2000. 092001.

[3] H. Padamsee and J. Knobloch and T. Hays, RF Superconductivity for Accelerators, John Wiley & Sons, 1998

[4] B. Hillenbrand, N. Krause, K. Schmitzke, and Y. Uzel. Abschlussbericht - Supraleitende Resonatoren. Technical Report NT 2024 7, Siemens AG, Dezember 1982. BMBF Forschungsbericht.

[5] Gmelin, *Handbuch der anorganischen Chemie*, volume 49 (Nb). Springer Verlag Berlin, 1970.

[6] J. Guerin, *Etude du bain de polissage chimique de niobium*, Technical Report TE/LC/157/89, CERN, October 1989.

[7] K. Saito et al. Superiority of Electropolishing over Chemical Polishing on High Gradients. In V. Palmieri, editor, *Proceedings of the 8th Workshop on RF Superconductivity*, volume I+II, pages 759 - 813, Abano terme, October 1997. INFN.

[8] L. Lilje, D. Reschke, D. Proch, A. Matheisen, P. Schmüser, D. Trines, C. Benvenuti, D. Bloess, H. Preis, L. Ferreira, H. Wenninger, E. Chiaveri, R. Losito, C. Antoine, J.-P. Charrier, and H. Safa. Improved surface treatment of the superconducting TESLA cavities. 2003. Nucl. Inst. Meth. A 516 (2-3); 2004; pp. 213-227.

[9] L. Lilje, Peter Schmüser et al., Achievement of 35 MV/m in the Superconducting Nine-Cell Cavities for TESLA. Nucl. Inst. Meth. A 524 (1-3); 2004; pp. 1-12.

[10] M. Liepe, W.D. Moeller, S.N. Simrock, Dynamic Lorentz Force Compensation with a Fast Piezoelectric Tuner, DESY TESLA-01-03, 2001