HIGH ACCELERATING GRADIENTS IN 1.3 GHZ NIOBIUM CAVITIES

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Abstract

Very high accelerating gradients have been achieved in superconducting 1.3 GHz niobium cavities. The best continuous wave test results in multi-cell cavities have reached accelerating gradients of 32 MV/m, while the best one-cell cavities have exceeded 40 MV/m. This performance is reproducibly achieved with electrolytic polishing as a surface treatment. Various production techniques have shown very high gradients. The results from the TESLA Test Facility on nine-cell cavities will be reviewed to allow for a comparison of the standard niobium etching with the electropolishing.

1 HIGH ACCELERATING FIELDS IN MULTI-CELL CAVITIES

1.1 TESLA nine-cell cavities

The niobium cavities are fabricated from RRR 300 niobium sheets by deep drawing and by electron beam welding (Figure 1). Up to now 79 TESLA 9-cell cavities have been delivered by 4 European manufacturers: a first series of 28 in 1994, a second series of 27 in 1997, and 24 cavities of a third series have been delivered to DESY in 2001 [1].

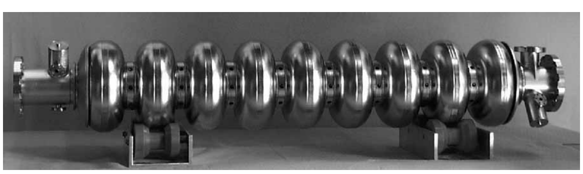

Figure 1: A TESLA niobium 9-cell cavity. The length of a cavity is about 1m.

1.2 Preparation sequence

The preparation of superconducting cavities for the cw acceptance test includes several steps [1]:

- removal of the damage layer by chemical etching
- 2 hours heat treatment at 800 C for the removal hydrogen and stress annealing
- 4 hours heat treatment at 1400 C with titanium getter for higher thermal conductivity to stabilize defects
- removal of the titanium layer by chemical etching
- field flatness tuning
- final 20 µm removal from the inner surface by etching
- high pressure rinsing (HPR) with ultra pure water
- drying by laminar flow in a class 10 clean room
- assembly of all flanges, leak-check
- 2 times HPR, drying by laminar flow and high Q input antenna assembly in a class 10 clean room

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1.3 Results

The cavities are specified with a Q_0 of 10^{10} at an accelerating gradient of 23.5 MV/m for TESLA-500. For TESLA-800 the specifications are a $Q_0=5\times10^9$ for the accelerating gradient of 35 MV/m. The acceptance test of the nine-cell cavities is done in a vertical cryostat, where the input coupler is adjustable to match the quality factor of the cavities. The cavities are excited in the continuous wave mode. Already in the first series the strict observance of clean treatment showed success by reaching gradients of 25 MV/m at Q values above $5\cdot10^9$ on several cavities. However, there were also a number of cavities that performed much worse. The reasons for this poorer performance were traced back to either improper preparation of the cavity dump bells before welding or to the inclusions of normal conducting material in the niobium.

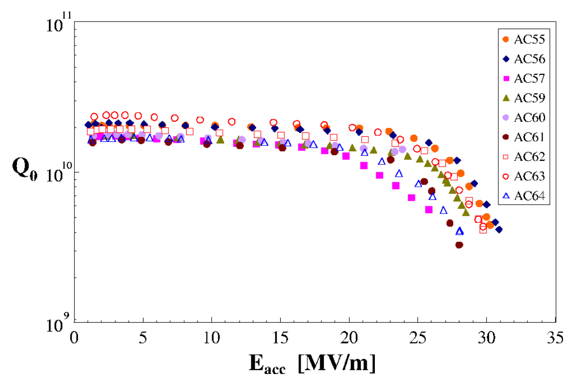

Figure 2: Excitation curves of 9-cell cavities from the last production [1].

For the second series, proper weld preparation was assured and all niobium sheets were scanned by an eddy current method to exclude sheets containing inclusions from cavity production. The success of these measures can be seen in figure 3 where the maximum measured gradient is shown for all 9-cell cavities measured up to now.

All 4 companies have demonstrated their capability of manufacturing cavities exceeding 25 MV/m at $Q=5\times10^9$. The progress in cavity production, treatment and handling is also manifested by the reduced scatter in cavity performance when looking at the three production series. For the first one the results range from 9 to 30 MV/m while the last series is located between 26 and 31 MV/m (Fig. 2).

After the cavities have passed the vertical acceptance test successfully, the helium vessel is welded to the head plates of the cavity. A 20 µm etching of the inner surface follows. In the last preparation step before the horizontal full systems test, the main power coupler is assembled to the high-pressure rinsed cavity. The external Q of the power coupler is typically 2×10^6.

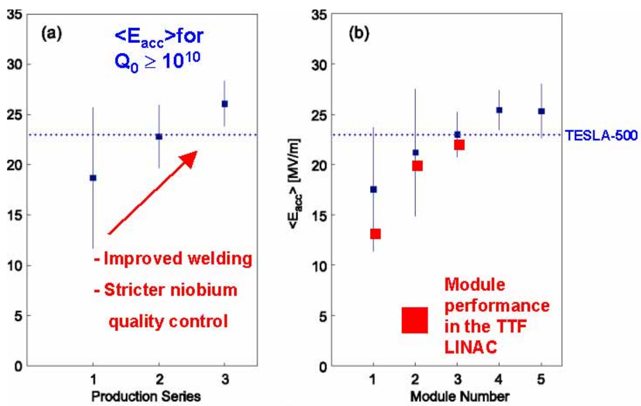

Figure 3: Average gradient, as measured in the acceptance test, of the 9-cell cavities of the three cavity productions (left). Average gradients of the cavities as they have been in the assembled accelerator modules. Red squares indicate the gradients obtained in the modules after installation into the LINAC [1].

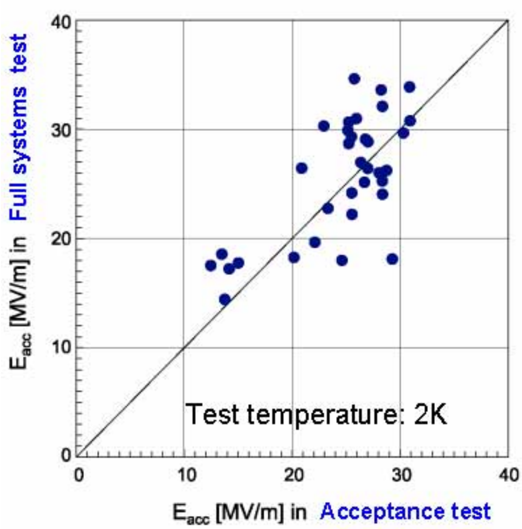

Figure 4: Comparison of results achieved in the acceptance test with the results in the full systems test [1].

More than 30 cavities have been tested in pulsed mode operation (see figure 4) in a full systems test in a horizontal cryostat or in the accelerator. The average gradient achieved in the vertical and the horizontal tests are quite similar as shown in Fig. 4. In a few cases the performance was reduced in the horizontal test due to field emission. In other cavities the maximum gradient was improved by the fact that the cavities are operated in pulsed mode instead of the cw operation in the vertical test. These results demonstrate that the good performance of a cavity can be preserved after the assembly of the helium vessel and the power coupler.

In figure 3 (right) the average gradients measured in the vertical test cryostat of the cavities, which were installed into the five accelerating modules is compared to the performance in the accelerator. Certainly, the presently achieved level of technology in cavity production will be adequate for the construction of a 500 GeV linear collider [6]. The achieved average gradient in one accelerating module is 22.5 MV/m and 20 MV/m in the other one. Two more modules, where all cavities have been successfully conditioned to gradients larger 25 MV/m, are ready for installation into the accelerator tunnel.

2 HIGH GRADIENTS IN SINGLE-CELL CAVITIES

2.1 Improved surface treatment: Electropolishing

Results from KEK [2,3] have shown significantly higher breakdown fields of over 160 mT corresponding to about 40 MV/m in several electropolished 1.3 GHz one-cell cavities. These results have been achieved with niobium material of moderate quality RRR = 200. Up to date only two chemically etched L-Band cavities have achieved these surface fields corresponding to 40 MV/m [4,12]. High magnetic fields were previously observed in electropolished X-band cavities in the 1970s [5]. A KEK-Saclay collaboration has convincingly demonstrated that EP raises the accelerating field by more than 7 MV/m with respect to BCP, while electropolished cavities suffer a clear degradation when they are subjected to a subsequent BCP [6]. Hence there is strong evidence that electropolishing is the superior surface treatment method.

Results from the CERN-CEA-DESY collaboration confirm this (Figure 5). Several cavities have been manufactured and were treated with standard etching (BCP 1:1:2) and electropolishing. No postpurification at high temperatures was performed. For the cavities which were chemically etched an average gradient of 24 MV/m was achieved. The average of the electropolished cavities was significantly higher (35.7 MV/m).

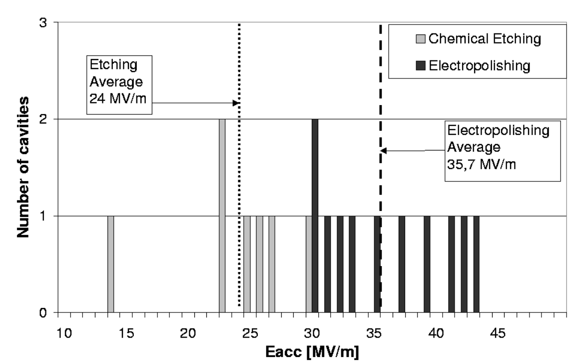

Figure 5: Distribution of the maximum accelerating gradients of etched and electropolished single-cell cavities. The average gradient for etched cavities is 24 MV/m. For the electropolished batch the average gradient is 35.7 MV/m [7].

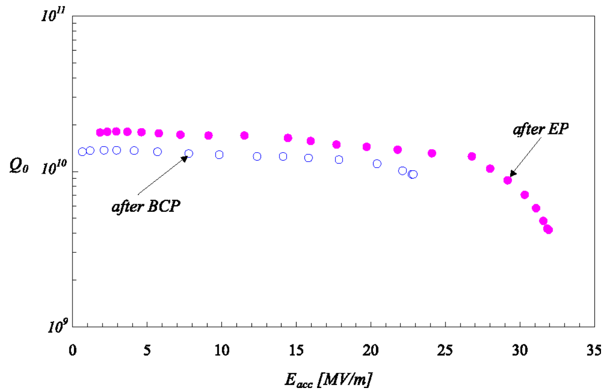

Figure 6: Performance of a nine-cell cavity after etching (BCP) and EP [1]. Electropolishing was done at Nomura Plating in collaboration with KEK.

Therefore the method of electropolishing was also applied to a nine-cell cavity in collaboration with KEK and the company Nomura Plating. After standard etching treatment the cavity yielded an acceleration gradient of about 22 MV/m. After the EP the maximum accelerating gradient improved to 32 MV/m in the continuous wave measurement [1].

2.2 Long-time air exposure

The long-term stability of superconducting cavities in particle accelerators is of course an important issue. A first measurement on exposing an electropolished to air at KEK indicated that a degradation of the maximum accelerating gradient might be possible [8]. At Saclay an electropolished cavity was baked out and achieved 36 MV/m at a Q_0 of 9×10^9. After this reference test the cavity was exposed to clean air for different time intervals. Before each measurement high pressure water rinsing was applied to avoid a particle contamination. Within the measurement errors no significant change in the cavity behaviour was observed even after exposure to air for 2 months (figure 6).

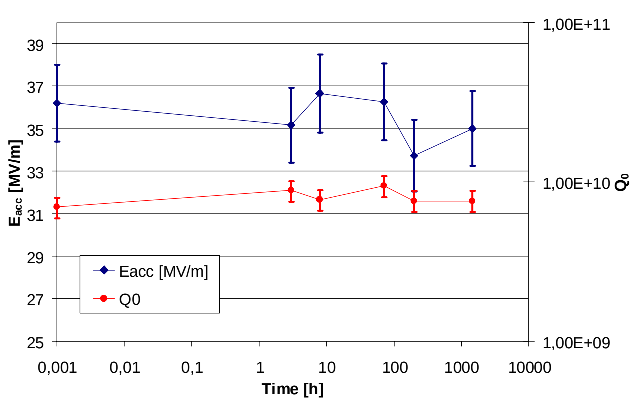

Figure 7: Top: Quality factor and accelerating gradient as a function of exposure time to clean air. High pressure water rinsing was applied before each test. Within the measurement errors no difference in the behaviour of the cavity was observed. Test temperature was 1.6 K [7].

2.3 Influence of the electron-beam welding on the cavity performance

The standard fabrication of the TESLA cavities is based on deep drawing of half-cells and electron-beam welding. The quality of the EB weld seam at the equator is crucial to the maximum performance achievable in the cavities and has been a problem in one batch of the first production of TESLA cavities.

Therefore the one-cell production was performed in two different EB welding machines. The idea here was to have one batch of 4 cavities with well established EB welding parameters performed by an industrial company with experience in the niobium welding (ACCEL Instruments, Bergisch-Gladbach).

In contrast, the second batch of 11 cavities was welded at CERN where the EB welding machine is equipped with a stainless steel vacuum chamber made according to ultra high vacuum standards. Whereas the vacuum in the standard production is of the order of a few times 10^{-5} mbar, the pressure in the CERN system could be lowered down to 3×10^{-7} mbar by using a cryopump and a longer time for pumping down.

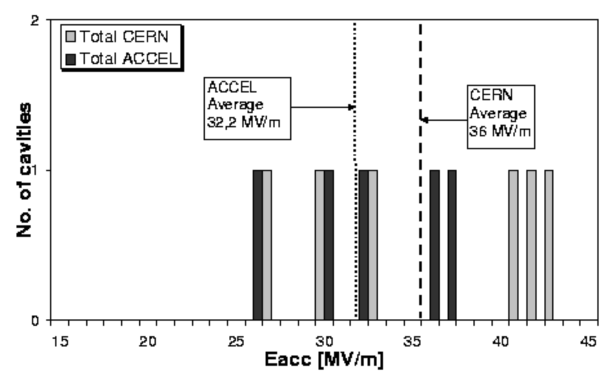

Figure 8: Comparison of accelerating gradients of cavities welded under ”normal” vacuum conditions (10^{-5} mbar) and under improved vacuum conditions (10^{-6} mbar) in the electron beam welding machine. The data for etched and electropolished cavities are shown. The best test on each cavity is taken [7].

2.4 Seamless resonators

Electropolishing was also tried on seamless resonators made by either hydroforming or spinning. For the hydroformed cavities a very good result was obtained at Jlab using a single-cell made at DESY [12]. A spun cavity made by INFN was electropolished and tested at CERN with a similar good result [13] confirming earlier results at KEK.

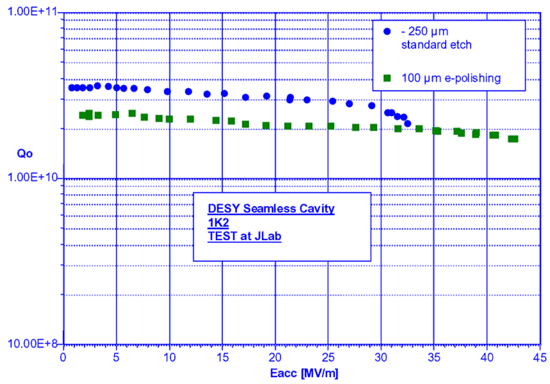

Figure 9: Excitation curve of a hydroformed single-cell cavity after etching and electropolishing [12].

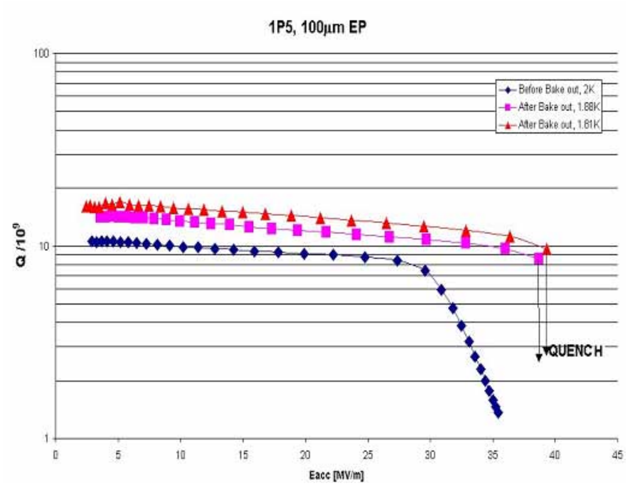

Figure 10: Excitation curve of an electropolished spun single-cell cavity before and after 'In-Situ' bakeout [13].

2.5 'In-Situ' Bakeout

The excitation curves of the electropolished cavities exhibit a strong degradation in quality factor at high field as can be seen in figures 10 and 11. No signs of X-rays were detected and also the electron pick-up antennas did not show signals. Therefore field emission of electrons seemed to be excluded as a field-dependent loss mechanism. With temperature mapping a global heating was found in the area of high magnetic fields around the equator [14].

At Saclay a similar strong degradation was observed for chemically etched cavities [9, 10, 11]. As noted by Visentin [11, 15] it is possible to improve the behaviour of cavities at high gradients by a simple 'in-situ' bakeout. This heating is applied after the last high-pressure water rinsing with the cavity being under vacuum at temperatures around 100 - 170°C for 48 - 70 hours. The cavity is usually kept in the cryostat under helium atmosphere. The baking was intended to improve vacuum conditions. Building on the experience the electropolished cavities have been baked at temperatures of around 100°C with remarkable success (figure 10 and 11).

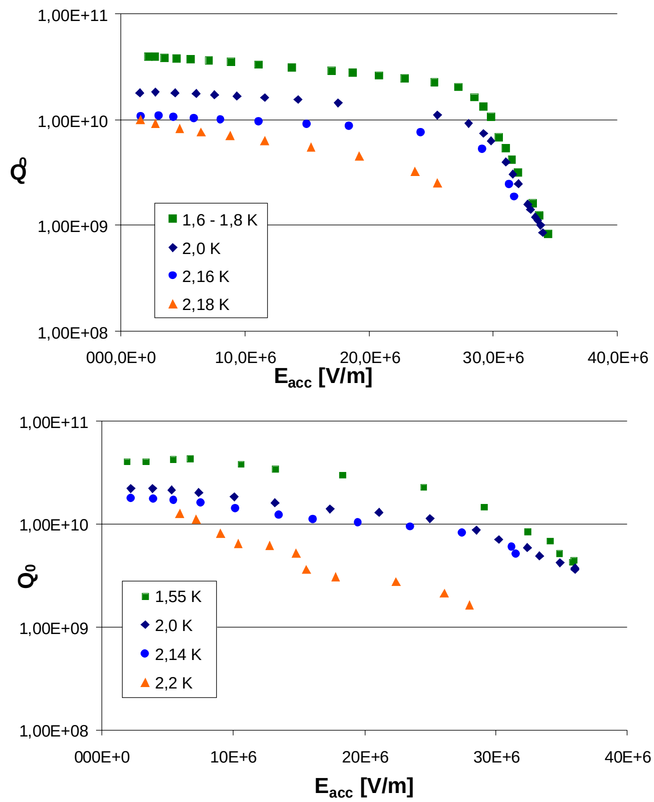

Figure 11: Excitation curve of an electropolished single-cell cavity before and after 'In-Situ' bakeout measured at different helium temperatures [13].

Tests at several temperatures in the range between 1.5 K and 2.2 K have been performed on an electropolished cavity before and after 'in-situ' bakeout (see figure 11). At low field the quality factor is reduced as expected from BCS theory before and after bakeout. At high field, the degradation of the quality factor before bakeout has always the same behaviour, if the helium temperature T>2K. The degradation starts at 30 MV/m.

The maximum breakdown field is also not changed when the temperature is below or equal to 2 K. This is also true for the case in which the cavity is 'in-situ' baked (see figure 11 bottom). These results are consistent with thermal model calculations [17,18]. For a bath temperature of either 1.8 K or 2 K there is no difference in the maximum breakdown field. Only when the temperature is close to the Lambda-point (2.17 K) the breakdown field is reduced. This can be understood since the heating will cause a superfluid to normalfluid transition with the consequence that the heat cannot be conducted away fast enough and will cause the niobium to heat up further, so that the breakdown of the cavity will happen at a lower field. This applies for unbaked and baked cavities. If one increases the temperature above the lambda-point, a degradation of the quality factor due to the insufficient cooling can already be seen at very low field. The breakdown field of the cavity is reduced further to values below 30 MV/m.

3 CONCLUSION

Several 'In-Situ' baked, electropolished bulk niobium single-cell resonators at 1.3 GHz have achieved accelerating fields of more than 35 MV/m. Most of these resonators have been electron-beam welded, but by now there exist also cavities that have been either hydroformed or spun.

First results on electropolished nine-cell resonators show that the process is technically feasible and 32 MV/m have been measured in a cw test already.

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