High gradients in superconducting RF cavities

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ABSTRACT

For a future superconducting e^+e^--Linear-Collider with a center of mass energy of 500 GeV to 2 TeV, accelerating gradients of 25 MV/m or higher have to be achieved in multicell structures. Although 40 MV/m in single-cell [1,2] and 29 MV/m in 9-cell 1.3 GHz cavities have already been reached, a safe way towards such high gradients is not yet established. The two main limitations are quench and field emission. We will focus our discussion on test results obtained from niobium 9-cell 1.3 GHz cavities produced by industry using conventional e-beam welding technique and from single-cell 1.3 GHz cavities produced at INFN Legnaro [3] by a spinning technique.

1. PRESENT STATUS

From the experience with single-cell cavities [1,2] there is no doubt that gradients of 40 MV/m can be achieved. Two 9-cell 1.3 GHz TESLA cavities have reached 29 MV/m at the TESLA test facility (TTF) [4]. In total 22 cavities were tested up to now in a vertical cryostat. The performance of the best nine cavities is shown in Fig. 1. It should be mentioned that the two best cavities (C21 and P1) and the cavities C25 and S28 were not limited by thermal breakdown but by field emission and the available RF-power. All cavities were heat-treated at 1400 °C except C25 and S28. Most cavities were made from niobium with residual resistivity ratio (RRR) 300 except C21, C25 and S28 which were produced from RRR 400 material.

2. MATERIAL PROPERTIES

The thermal conductivity of niobium improves with the RRR. Therefore higher RRR niobium should conduct better enhanced heating of defects. The heat transfer into the helium bath is also dependent on the Kapitza conductivity at the niobium-helium interface. Computer codes are available to study the influence of RRR and Kapitza conductance on the maximum reachable gradient for a given defect size [5,6]. In the past 20 years the RRR could be raised from 20 to 300 which is now industrial standard. In order to improve the RRR further, the cavities can be heat-treated at 1400 °C with titanium getter. Such a treatment normally doubles the RRR value. A heat-treatment at this high temperature leads to a considerable grain growth and the material gets soft which is a severe disadvantage as handling of the cavities may lead to plastic deformation. A better way might be to produce the cavities from RRR 600 material and avoid the treatment at 1400 °C. The results on S28 and C25 which were made from RRR 400 material and only heat-treated at 800 °C are very promising in this direction. For RRR 300 material the benefit of a heat-treatment at 1400 °C is evident from the test of cavities P1 and C21 shown in Fig. 2.

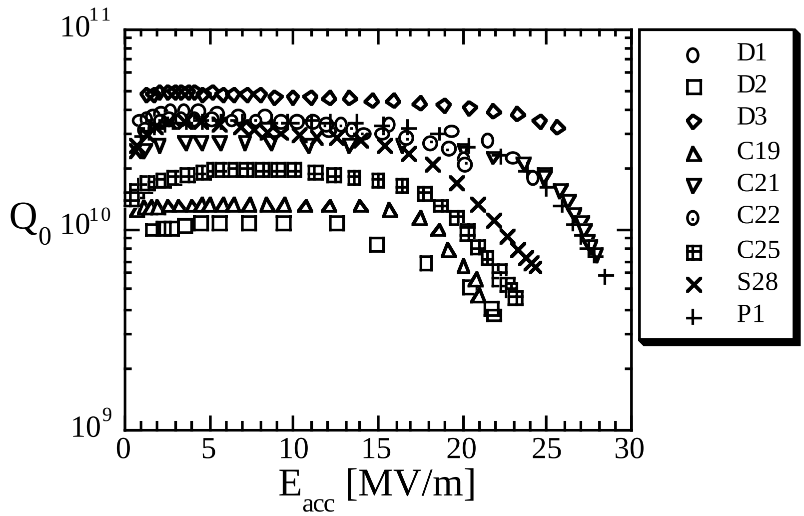


Fig. 1: Vertical test results on 9 cell cavities for the TESLA test facility linac. C21, C25, S28 and P1 are limited by field emission and available RF power. The other cavities are limited by quench.

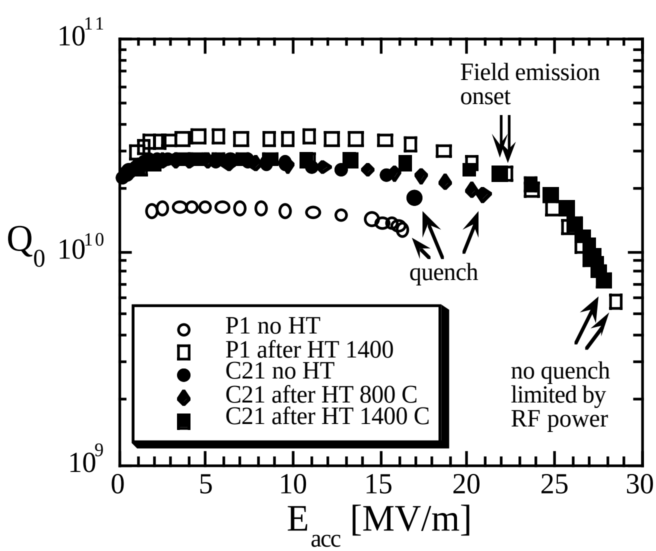


Fig. 2: Benefit of heat-treatment on cavities P1 and C21. After a heat-treatment of 1400 °C the maximum accelerating gradient in both cavities exceeded 28 MV/m. In the case of C21 it is shown that a 800 °C heat-treatment can also improve the RF performance, although the RRR does not change.

Several TTF-cavities suffered from foreign material inclusions in the material. In Fig. 3 the results of two cavities are shown where a large defect was found with temperature mapping 2-3 cm away from the equator weld. The performance is very poor although the cavities were heat-treated at 1400 °C. In one case, the defect was identified to be a tantalum inclusion [7]. In order to avoid such defects an eddy current scanning apparatus has been designed [7], capable of finding foreign material inclusions of at least 200 µm in diameter which may be below the RF surface as much as 500 µm. All niobium sheets for the new TTF cavity production have been scanned with this apparatus, the rejection rate being 5 %.

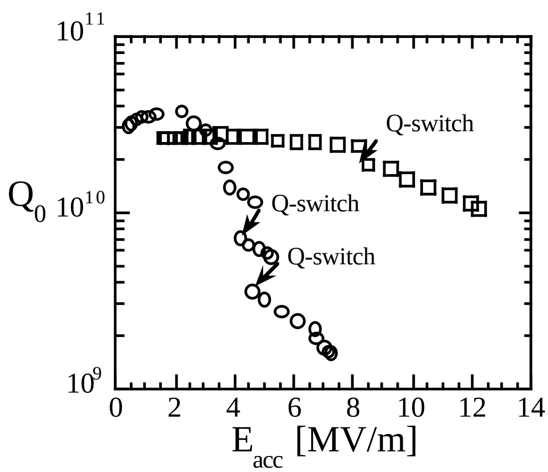


Fig. 3: Excitation curves of cavities with localized strong defects in the bulk material. So called "Q-switches", stepwise degradation of quality factor with increasing incident power, are observed.

3. WELD DEFECTS

The standard fabrication technique is based on electron beam welding of deep-drawn half cells. The iris weld is made from the inside to guarantee a smooth surface in the region of high electric field. Impurities in the weld are here not so critical, because the magnetic field at this location is very low. The highest magnetic fields are in the equator region. Hence impurities in the equator welds have to be strictly avoided. Careful precleaning of the weld area and a vacuum in the 10^{-5} mbar regime during welding are of importance. The equator welds are usually made from the outside.

The cavities S7 to S12 showed all a degraded RF performance: a continuous drop of quality factor with increasing accelerating field ("Q-slope", Fig. 4) and a quench at 10-15 MV/m. Using a dedicated temperature mapping system, the origin for both, the "Q-slope" and the early quench, were found to be defects in the equator weld [8]. With improved weld parameters and weld preparation a new cavity (S28) from the same manufacturer reached 24.5 MV/m without "Q-slope".

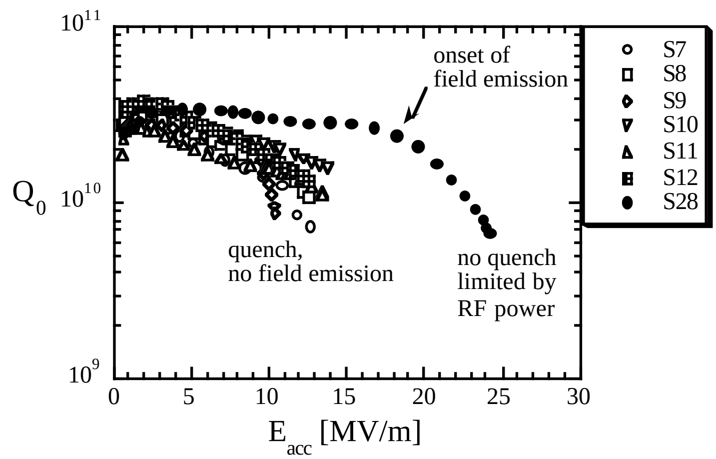
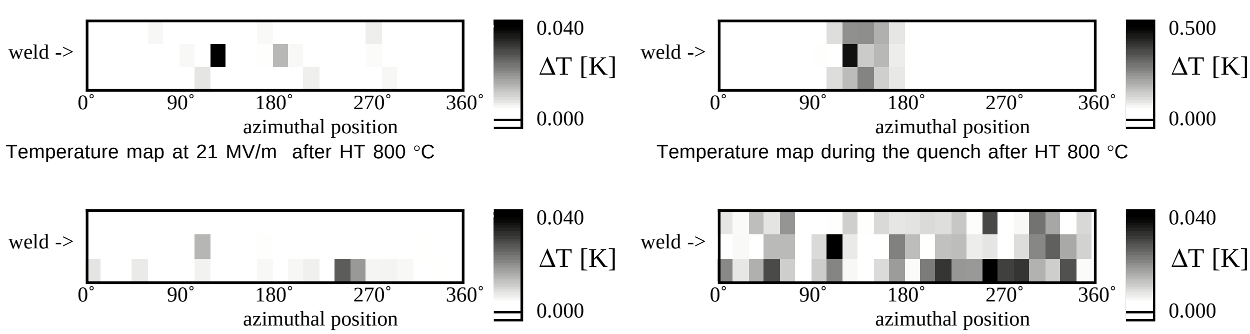


Fig. 4: RF-performance of cavities produced by one manufacturer with old (S7 to S12) and improved (S28) welding technique.

In several cavities exceeding 20 MV/m, equator welds were also found to be the limiting factor. The equator weld of cell 9 of cavity C21 had a defect which lead to a quench at 21 MV/m after the heat-treatment at 800 °C (see Fig. 2). The heating of the equator region of cell 9 just before the quench is shown in Fig. 5. Also shown is the heating during the self-pulsing quench. After the 1400 °C furnace-treatment the heating at this position was much less even at 28 MV/m. From this the conclusion can be drawn, that a heat-treatment of 1400 °C can cure some but certainly not all weld defects as is evident from the results on S7 to S11 shown in Fig. 4 which exhibit the same RF performance as cavity S12 which was only heat-treated at 800 °C.



Temperature map at 21 MV/m after HT 800 °C

Temperature map during the quench after HT 800 °C

Temperature map at 21 MV/m after HT 1400 °C

Temperature map at 28 MV/m after HT 1400 °C

Fig. 5: Temperature maps of equator region of cell 9 of cavity C21 at different field levels and after heat-treatment (HT) 800 °C as well as after HT 1400 °C. The distance between thermometers on the weld and below or above the weld is 1.2 cm, the azimuthal distance is 2.5 cm. Note the strong reduction of heating after the HT 1400 °C.

Another weld defect was found in cavity C25 which so far got only a heat-treatment of 800 °C. No quench was found in the π-mode up to 23.5 MV/m. By excitation in other coupled modes [9] quench locations were found in cell 5 at 26 MV/m and in cell 9 at 25 MV/m, both in the equator weld. This cavity will soon receive a heat-treatment at 1400 °C. As a last example we want to discuss the result of cavity C22. During welding a hole was burnt in the equator weld of cell 5 which was repaired by welding in a niobium plug. The cavity got a heat-treatment at 1400 °C and reached 20 MV/m with a quench in the repaired zone. From the examples above it is obvious that perfect welds are the prerequisite for gradients in the 30 to 40 MV/m regime

4. SEAMLESS CAVITIES

New cavity production schemes are investigated which avoid e-beam welding and have the possibility to reduce the costs. Hydroforming and spinning techniques are presently studied. The first 2 spun 1.3 GHz single-cell cavities (1P3 and 1P4) have recently been tested. These cavities were produced at INFN Legnaro in Italy [3] from RRR 300 material. The preliminary results are very promising and shown in Fig. 6.

The first cavity 1P3 has been tested twice so far after a total of 50 µm and 120 µm etching of the inner surface. The remarkable result is a strong "Q-slope" without field emission. The 50 µm removal is obviously not sufficient (Fig. 6). The cavity is now heat-treated at 800 °C and will be tested soon again.

The second cavity 1P4 has been tested 3 times until now: after a 130 µm etching of the inner surface, after heat-treatment at 800 °C plus additional 100 µm etching and after additional etching of 60 µm. The cavity improved from 20 MV/m to 23 MV/m to 25 MV/m (Fig. 6). The next step in the test program will be the heat-treatment at 1400 °C. Also the cavity 1P4 shows a Q-degradation at high fields without field emission loading.

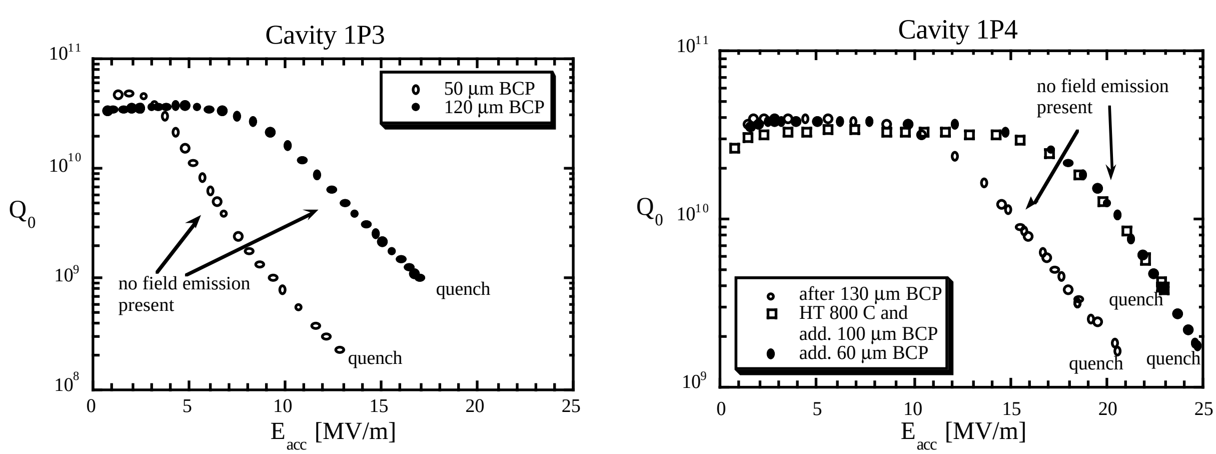


Fig. 6: RF performance of the first 1.3 GHz single-cell cavities made by spinning.

Temperature mapping was used to study the loss mechanisms and the origin of the slope. The temperature map of cavity 1P3 reveals strong heating at the lower iris region at almost all azimuthal positions. There the magnetic fields are negligible. During the spinning process, this iris was made at the end. Cavity 1P4 shows heating inside 2 bands close to the equator, but less heating directly on the equator and no heating at the iris regions. The cavities 1P3 and 1P4 have been made in slightly different ways in terms of deforming the grains during the production [10]. The observed Q-degradation may be related to the spinning process. Optimal spinning parameters as well as optimized preparation of the niobium sheet prior to the spinning have still to be found.

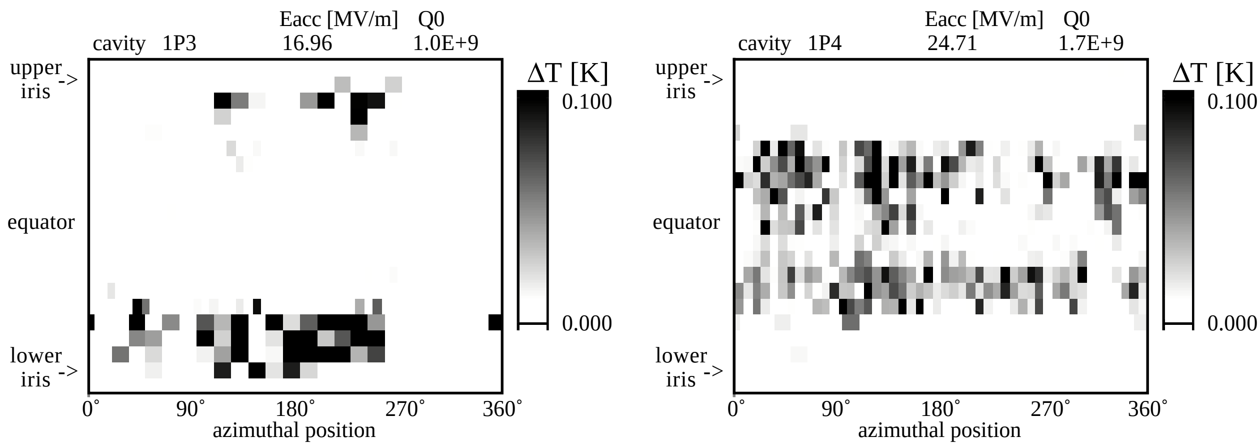


Fig. 7: Temperature maps of the single-cell cavities 1P3 and 1P4 at fields just below the quench. The maximum temperature rise was 400 mK in both cases. The temperature scale is set to 100 mK in order to display also areas with lower heating. The heating areas are causing the Q-drop at high gradients (see. Fig. 6).

5. INFRASTRUCTURE

Class 10 cleanrooms and high pressure rinsing (HPR) [11] with ultraclean water are key elements to reach high gradients in superconducting cavities without field emission. Although HPR has been found to be very effective, it is difficult to get field emission free cavities at gradients above 20 MV/m.

A technique to reduce field emission in assembled cavities is high power processing (HPP) [12]. The cavities in the TTF linac are equipped with a high power coupler. Because of the complicated mounting conditions higher field-emission loading might be expected. A comparison of the vertical test results with the performance of the cavities after installation in the linac is shown in Fig. 8. The majority of the nine cavities did not change from the vertical test to operation in the linac. 2 cavities D3 and C19 are showing some degradation caused by higher field emission loading. There is still hope to improve this cavities with more HPP. One cavity, D2, shows a much better result in the linac. It is sometimes observed, that a cavity can reach higher gradients under pulsed conditions (800 µs constant gradient time) than under cw operation. It appears that insitu HPP is the best insurance in order to maintain the vertical performance in the linac operation.

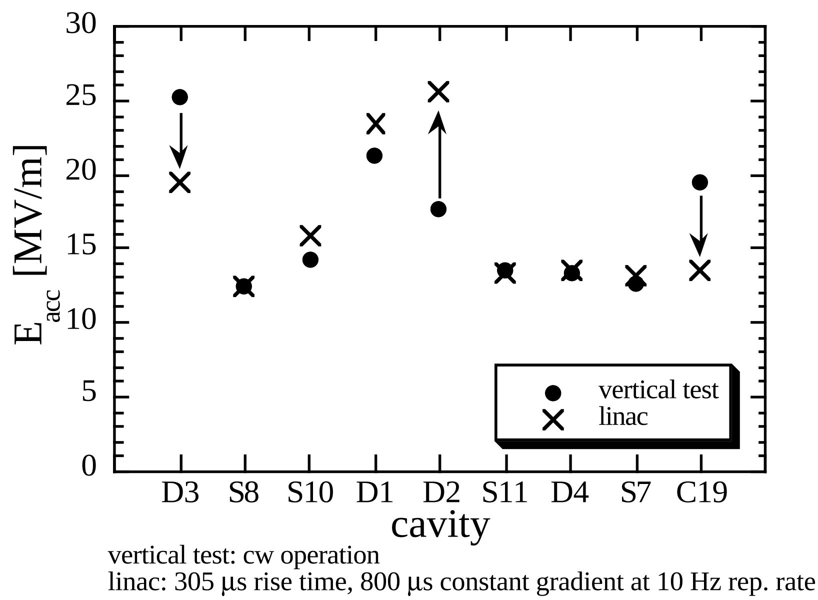


Fig. 8: Comparison of vertical test results to the performance of the cavities after installation in the linac. 2 cavities degraded caused by higher field emission loading, one cavity improved.

6. CONCLUSIONS

There is now doubt anymore that cavities made from pure niobium can reach 40 MV/m at 1.3 GHz. Eddy-current scanned material, the present fabrication techniques and preparation steps are sufficient for a gradient of 25 MV/m. In order to reach 30-40 MV/m, significant improvement in material, welds and cavity handling are needed. The use of high RRR material is desirable but the 1400 °C heat-treatment may still turn out to be necessary. New fabrication methods like spinning have the potential of reducing the cost and avoid the delicate welds. First test results on spun cavities are promising. By approaching 40 MV/m one certainly comes close to the limit of niobium and parameters like grain size, roughness of the superconducting surface and the Kapitza conductance can play a role.

ACKNOWLEDGMENTS

The author wants to thank all members of the TESLA collaboration for many helpful discussions. Severe thanks especially to the colleagues involved in the preparation and testing of the cavities and to V. Palmieri for the possibility of testing the seamless cavities.

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