HIGH-GRADIENT SUPERCONDUCTING RADIOFREQUENCY CAVITIES FOR PARTICLE ACCELERATION

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Abstract

The development of radiofrequency (RF) superconductivity for particle acceleration has reached a level where many projects consider its use. One of the many attractive features of these accelerating structures is to achieve very high accelerating fields efficiently. The technology has been developed to a stage where accelerating gradients of more than 25 MV/m are being implemented in accelerator modules. In single-cell test resonators even higher gradients were already achieved. To operate cavities at these gradients efficiently their frequency needs to be kept stable to reduce the need for an overhead in radiofrequency power. Introducing active elements like piezoelectric actuators allows to achieve these goals.

INTRODUCTION

Superconducting accelerator modules offer high accelerating gradients combined with a high power conversion efficiency. The accelerator structures (also called cavities) have a surface resistance which is 6 orders magnitude smaller than that of copper in the frequency range of a few GHz. Therefore even with the costs of cooling included superconducting accelerator modules are an attractive option for particle accelerators.

The TeV-Energy Superconducting Linear Accelerator (TESLA) design for a linear collider was one of the driving forces to develop superconducting cavities with very high accelerating fields. The layout and design of the TESLA cavities which is also being used for the European X-ray Free-Electron-Laser (XFEL) has been discussed extensively in other publications [1, 2, 3]. The manufacturing and preparation processes are also described there. Papers discussing the more recent advances on surface preparation processes are also available [3, 4]. In the paper these advances will be briefly reviewed as well as the more recent developments concerning high gradient cavities for the International Linear Collider (ILC).

SURFACE PREPARATION FOR HIGH-GRADIENT CAVITIES

For superconducting cavities like the ones used in TESLA Test Facility (TTF) at very high electric and magnetic surface fields great care has to be taken during manufacturing and preparation for beam acceleration (Fig. 1). Normalconducting inclusions in the material and contaminations on the surface need to be avoided. For example, the niobium bulk material used for cavity fabrication needs to have good thermal conductivity as the heat produced on the inner side of the cavity needs to be conducted to the coolant (liquid helium) on the outside.

In addition, the preparation and assembly in clean rooms and ultra-pure water supplies for rinsing the surfaces are a must [3]. Electropolishing (EP) is the most promising surface preparation technique for superconducting cavities to remove the damage layer and to obtain the final surface finish. The niobium 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. It has been chosen to be the baseline cavity preparation for the XFEL as the time-consuming 1400°C furnace treatment for post-purification can be avoided.

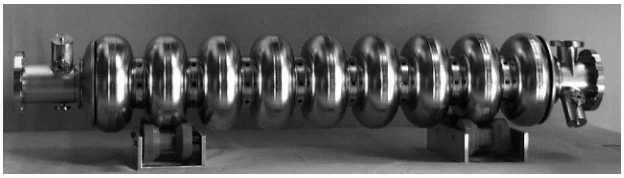

Figure 1: A TESLA niobium 9-cell cavity. The length of a cavity is about 1m.

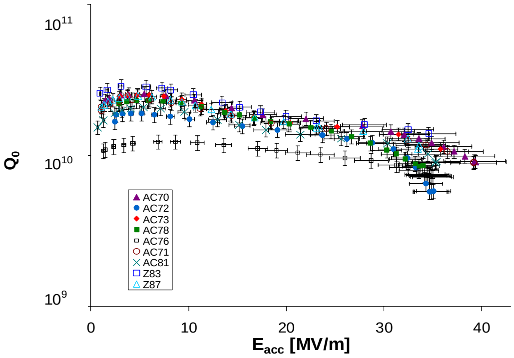

Figure 2: Several electropolished cavities yield gradients of more than 35 MV/m.

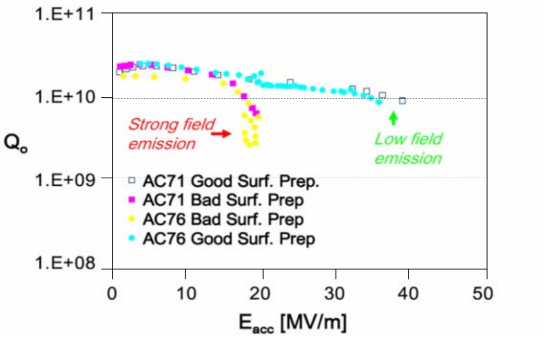

Figure 3: Examples for problems with field emission. Two cavities are shown which have been subjected to electropolishing twice. One of the tests shows strong field emission. The other tests show very good performance.

The EP technique has been successfully transferred to nine-cell cavities within a joint KEK-DESY R&D program [4]. Since then DESY built a system for the electropolishing of nine-cell cavities. With this setup now a lot of operational experience has been accumulated. Several cavities have achieved accelerating gradients of more than 35 MV/m in vertical tests (see Fig. 2). One of these cavities could be tested inside an accelerator module and kept its excellent performance. Recently, there have been problems with enhanced field emission (Fig. 3). There are hints of a contamination of the EP setup with sulphur. Several rinsing methods are under study to remove this contamination efficiently.

The experience gained with the setup will be used to start a study together with industry. So far, the costing of the cavity preparation for TESLA was based on etching and 1400°C post-purification. Although the EP process is more complicated than etching, some cost reduction is expected due to the avoidance of the furnace treatment.

CAVITY DESIGN

With the accelerating gradient approaching the theoretical limit in the current cavity design several proposals are dealing with the improvement of the shape of the resonators to lower the ratio between peak magnetic surface field B_{peak} and accelerating gradient E_{acc}. The TESLA shape has a favourable low E_{peak}/E_{acc}, acceptable cell-to-cell coupling and wakefield loss factors. It has lower risk of field emission and dark current.

Two new shapes, the re-entrant shape (Cornell University) and the low-loss shape (originally designed for CEBAF), are being developed [5, 6]. Both new shapes have a lower B_{peak}/E_{acc} and a higher G x R/Q. They have a higher gradient reach since B_{peak} is considered to be the fundamental limit, and lower cryogenic losses. Both shapes have higher risk of field emission since E_{peak}/E_{acc} is 20% higher than in the TESLA shape. The iris aperture is another geometrical difference between the two new shapes. The low-loss shape has a smaller iris aperture by about 15%, whereas the Cornell re-entrant shape has the same aperture as that of the TESLA shape.

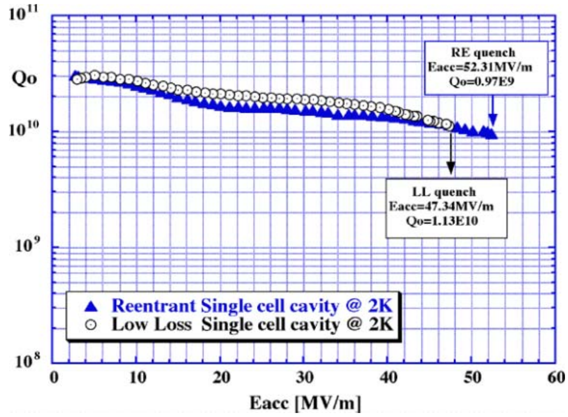

Figure 4: Test results of single cell cavities with a smaller B_{peak}/E_{acc}. Tests performed after surface treatment at KEK.

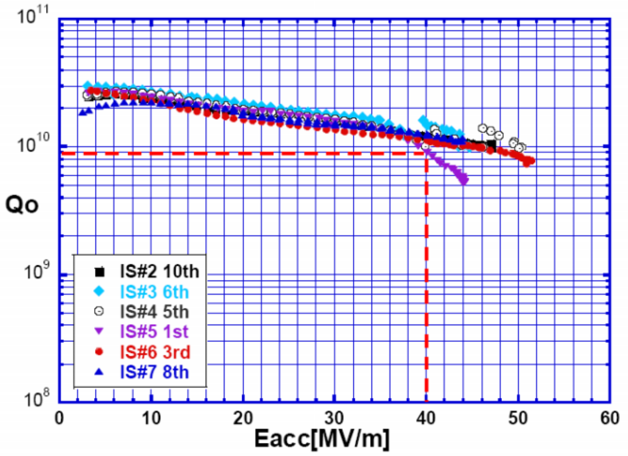

Figure 5: Tests of several single-cell cavities of the low-loss shape which are called Ichiro Shape (IS) in Japan.

The first tests of single-cell cavities after surface treatment at KEK are very promising (see Fig.4 and Fig.5). Very high gradients between 45 up to more than 50 MV/m have been obtained in several cavities. Currently, the first multi-cell cavities are under test.

PULSED OPERATION OF HIGH-GRADIENT CAVITIES

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. 6. The RF control system changes the klystron frequency and phase dynamically to compensate 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. 7. 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 ILC gradient of 31.5 MV/m. In addition, the piezoelectric actuator may be used to cancel microphonic noise between the RF pulses. Therefore, the fast active detuning will be used also in the XFEL.

Several designs for a fast detuning compensation are currently under development. Besides the improvements aiming at the integration into the mechanical motorized slow frequency tuners and lower cost [7, 8], alternatives to piezo-electric elements are considered. An alternative are magnetostrictive elements.

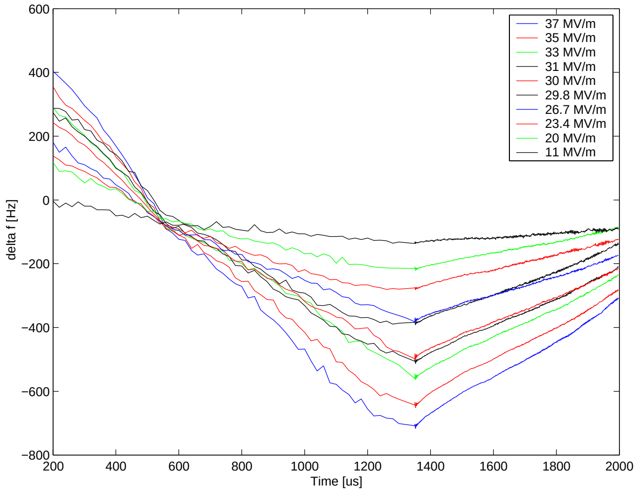

Figure 6: Lorentz-force detuning in pulsed mode operation at gradients from 11 to 37 MV/m.

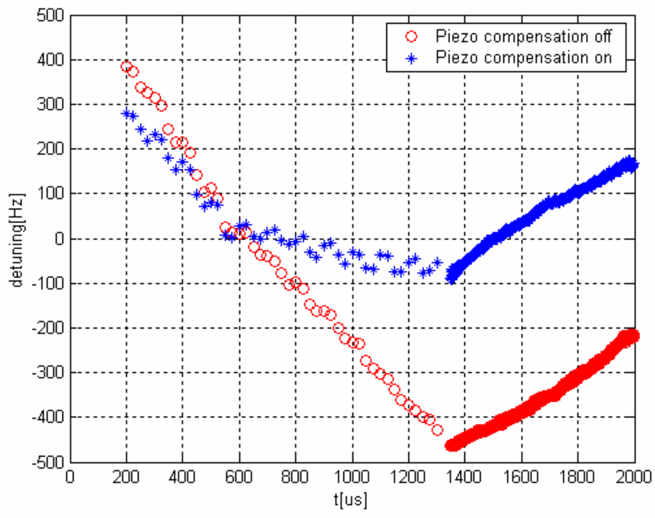

Figure 7: High-power pulsed test at 35 MV/m of an electropolished nine-cell cavity. Frequency detuning during cavity filling and "flat top" at 35 MV/m with and without piezo-electric compensation.

CONCLUSION

The development of high-gradient superconducting radiofrequency cavities has resulted in cavities approaching the fundamental limit in several cases. This is due to significant improvements in both the material properties of the superconductors as well as in the surface preparations. For the latter, more R&D is underway to improve the quality control of the applied processes. This of mutual interest for both large-scale projects: XFEL and ILC.

With the well-developed TESLA cavity shape being used for the European XFEL reaching the fundamental magnetic field limit, new cavity shapes have been successfully tested in single-cell resonators. The enhanced E_{peak}/E_{acc} ratio makes the cavities more vulnerable to field emission. Tests on multi-cell cavities with the new shapes are underway to demonstrate the feasibility of these concepts.

A proof-of principle experiment demonstrating fast-detuning compensation within an RF pulse has been successfully performed. Improved designs are under development and test.

ACKNOWLEDGMENTS

The author would like to thank the colleagues from the TESLA collaboration for their ongoing support and the many fruitful discussions. A very special acknowledgement is given to Peter Schmüser (University of Hamburg) who supported the work on the high-gradient accelerating structures in many important ways.

Several people are acknowledged for providing data and viewgraphs for this paper and the conference talk: J. Sekutowicz, K. Saito, E. Kako, A. Matheisen, H. Weise, D. Kostin, R. Lange, P. Sekalski, M. Liepe, M. Kelly, K. Shepard, H. Padamsee

The support of the EC Research Infrastructure Activity under the FP6 "Structuring the European Research Area" program (CARE, contract number RII3-CT-2003-506395) for parts of this work is acknowledged.

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