Cavity R&D for TESLA

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Abstract

The cavity research and development which was essential to achieve the performance goals of a Q_0 of 10^{10} at an accelerating gradient of 23,5 MV/m for TESLA-500 will be reviewed. Results from the 1,3 GHz nine-cell superconducting niobium cavities will be shown. For TESLA-800 the specifications are a $Q_0=5\times10^9$ for the accelerating gradient of 35 MV/m. It will be shown that this is achieved regularly in electropolished one-cell cavities. First promising results on nine-cell cavities are shown. For TESLA-800 it is necessary to increase the fill factor of the linac. This is achieved via the superstructure concept. The first succesful test with a piezoelectric tuner to compensate the frequency detuning during the rf pulse is shown.

CAVITY MANUFACTURING AND PREPARATION

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.

The preparation of superconducting cavities includes several steps:

- 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 ultrapure water
- drying by laminar flow in a class 10 cleanroom
- assembly of all flanges, leak-check
- 2 times HPR, drying by laminar flow and assembly
- of the input antenna with high external Q

A key element in the procedure is a large cleanroom area ranging from class 10000 down to class 10 to achieve a dust free environment for cavity preparation. The other important technique is called high pressure water rinsing where an ultra pure water jet removes particulate contaminations from the surface very efficiently.

The cleanroom area also houses facilities for chemical treatment, an UHV furnace for the heat treatment at 1400°C and an assembly area allowing to assemble a string of 8 cavities and a superconducting quadrupole under cotrolled conditions. Pumping and leak testing is performed inside the cleanroom with oilfree pumpstations located outside of the cleanroom area. The length of an accelerating module is 12.2 m.

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

ACCEPTANCE TEST RESULTS ON 9-CELL CAVITIES

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 was 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 normalconducting material in the niobium.

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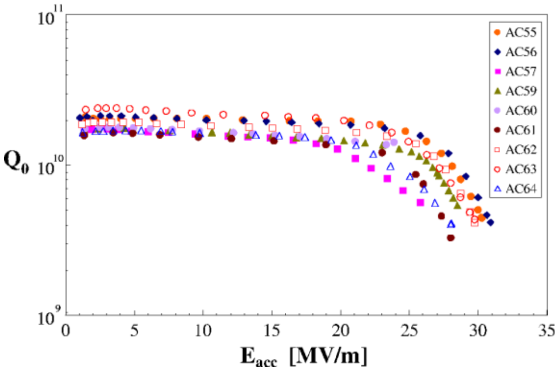

Figure 2: *Excitation curves of 9-cell cavities from the last production.*

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 [4]. 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).

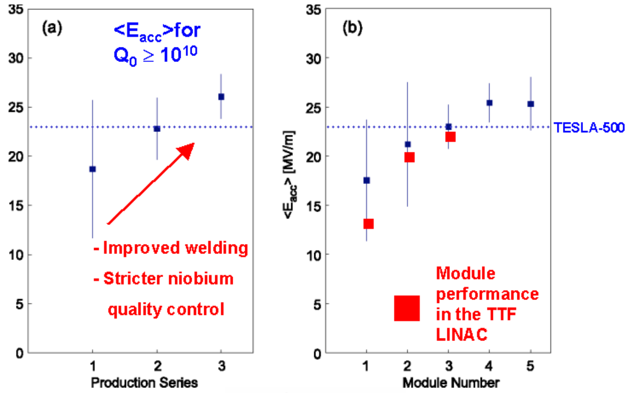

Figure 3: *Average gradient, as measured in the acceptance test, of the 9-cell cavities of the three cavity productions (left). Average gradients of the cavities as they have been in the assembled accelerator modules. Red squares indicate the gradients obtained in the modules after installation into the LINAC. The figure has been taken from [6].*

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.

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 cavites 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. A third module, where all cavities have been successfully conditioned to gradients larger 25 MV/m, is ready for installation into the accelerator tunnel.

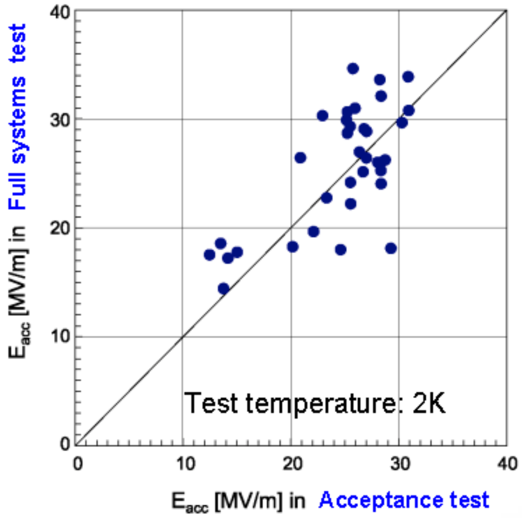

Figure 4: *Comparison of results achieved in the acceptance test with the results in the full systems test.*

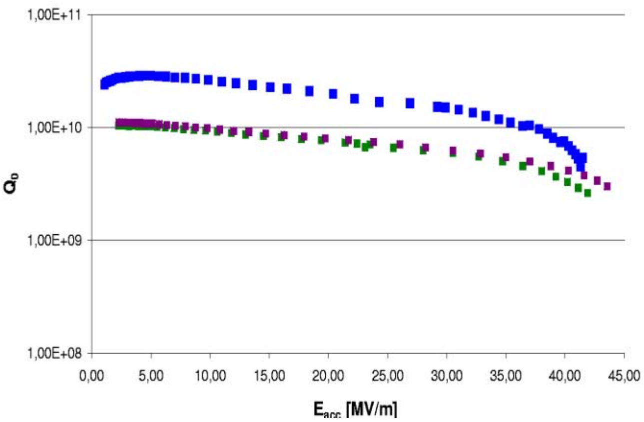

Figure 5a: *Results on electropolished single cell cavities from the CEA-CERN-DESY collaboration. Tests were done at 1,7 and 2 K. The figure is taken from reference [12].*

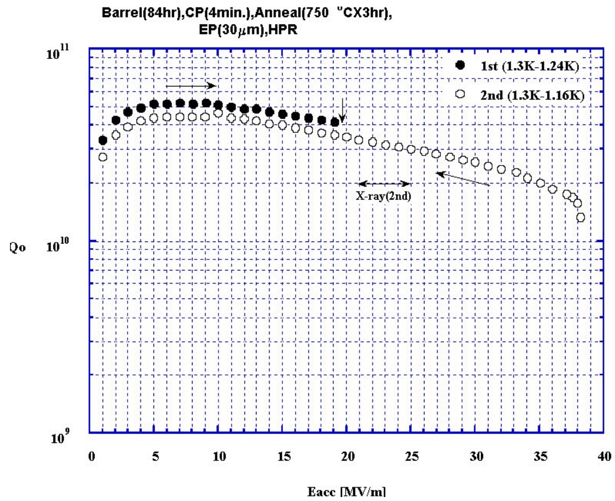

Figure 5b: *Results on a spun electropolished single cell cavity from a KEK-INFN collaboration. The figure is taken from reference [19].*

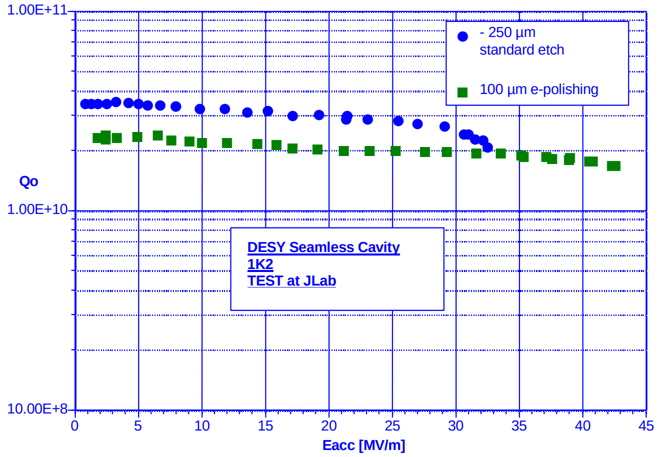

Figure 5c: *Results on a hydroformed electropolished single cell cavity. Test was done at a temperature of 2 K at TJANF. The figure is taken from reference [18].*

FURTHER R&D ON S.C. CAVITIES

Electropolishing of niobium cavities

There has been an R&D programme on single cell cavities in laboratories inside and outside of the TESLA collaboration with the goal to push the achievable gradients to 35 MV/m or above, which would allow for a substantial increase of the collision energy at the TESLA linear collider to 800 GeV.

For a number of years several remarkable results have been obtained at KEK [7] with electropolishing single cell niobium cavities, obtaining gradients close to 40 MV/m. These cavities were of comparatively low RRR=200-300 material, therefore opening the possibility to avoid the rather tedious and time-consuming high temperature heating at 1400°C. Of course, this is very desirable for cost reasons.

In contrast to the chemical etching applied to the cavities at TTF, which leads to a rather rough surface, electropolishing leads to a very smooth and shiny surface [8]. KEK and CEA Saclay have convincingly demonstrated that electropolishing raises the obtainable accelerating field substantially compared to the BCP treatment [9]. In a collaboration including KEK, CERN, DESY, CEA Saclay and TJNAF several single cell cavities have been electropolished and gradients around 40 MV/m were obtained in cavities produced by three different manufacturing techniques [10,11,18,19 – see figure 5]. It was discovered that baking the evacuated cavities at 75-150°C for 24 to 48 hours after the final high pressure water rinsing constitutes an essential step in reproducibly obtaining gradients around 40 MV/m at a high quality factor [17,11].

To transfer these findings to 9-cell cavities, work is going on at KEK and also at DESY. First results on a electropolished 9-cell cavities are very promising and have achieved an accelerating gradient of 32 MV/m (figure 6).

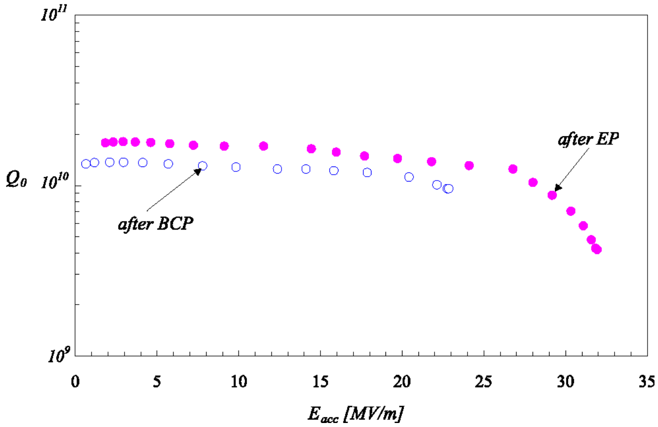

Figure 6: *Result on an electropolished nine-cell cavity. A clear improvement is seen as compared to its behaviour after etching (BCP). Test was done at 2K.*

Layout	E_{acc} [MV/m]	No of main coupler	No of HOMs couplers	No of tuners	Fill factor	P_{trans} [kW]
9-cell	23,4	2092	41184	20592	78,6	232
2x9 cell	22	10926	32778	21852	84,8	437

Table 1: Superstructure parameters. The number of main couplers is reduced by a factor of two, while the fill factor of the LINAC is increased by 6 %.

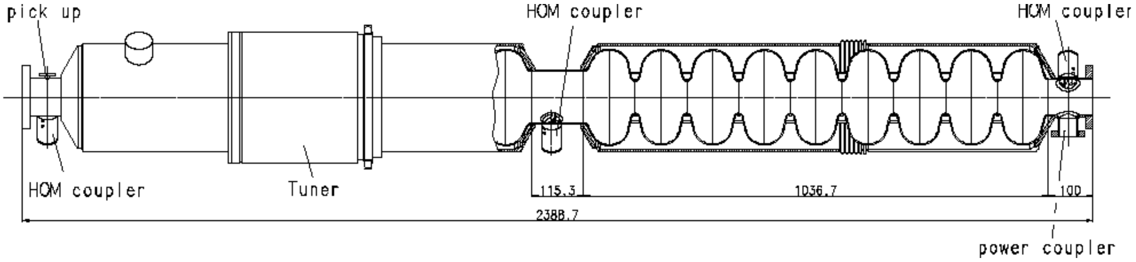

Figure 7*: Superstructure layout*

Superstructure concept

The limitations on the number of cells per cavity can be circumvented by joining two multicell cavities to form a so-called superstructure [20]. Short tubes of sufficient diameter enable power flow from one cavity to the next. The chain of cavities is powered by a single input coupler mounted at one end. HOM couplers are located at the interconnections and at the ends. The two cavities are equipped with their own frequency tuners.

The cell-to-cell coupling is k_{cc}=1,9%, while the coupling between two adjacent cavities is a superstructure is two orders of magnitude smaller at $k_{ss}3\times10^{-4}$ due to this comparatively weak inter-cavity coupling the issues of field homogeneity and HOM damping are much less of a problem than in a single long cavity with N=18 cells. The shape of the centre cells is identical to those in the 9-cell TTF structures while the end cells have been redesigned to accommodate the larger beam tube irisses.

Another advantage is that the number of main couplers could be reduced by a factor of two thus allowing for further cost savings.

Frequency stability of the cavities

The pulsed operation leads to a time-dependent frequency shift of the 9-cell cavities which is proportional to E_{acc}^2 (Figure 8). 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 (see figure 9) [21]. 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.

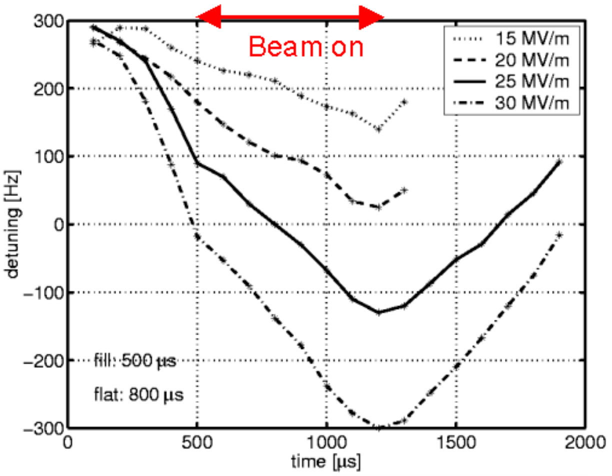

Figure 8: *Detuning of TESLA cavity during the RF pulse measured at different gradients.*

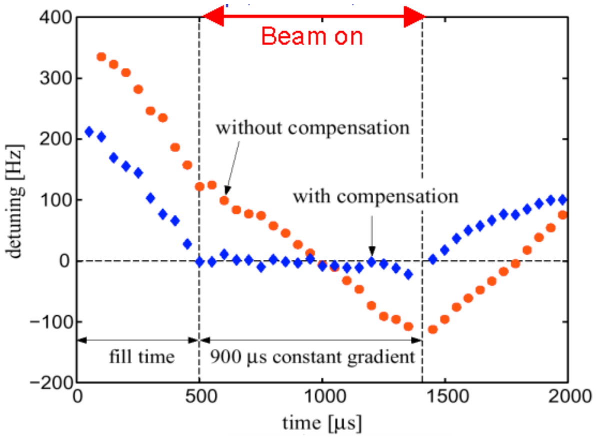

Figure 9: *Stabilisation of the frequency by means of piezoelectric element. In this test 200 Hz were compensated.*

SUMMARY

Average gradients well above 25 MV/m have been achieved for the TESLA 9-cell cavities from the latest production series. The results on the superconducting cavities are very reproducible. Procedures have been developed that allow to keep the performance of the cavities through all preparation steps for the installation in the accelerator. The cavity technology for TESLA-500 is therefore available. For electropolished one-cell cavities over 40 MV/m have been reached reproducibly. This allows to continue a focused R&D program towards TESLA-800 transferring the electropolishing technology to multi-cell cavities, where first promising results have been achieved already.

A scheme for increasing the fill factor of the linac has been developpped and will be tested soon. The stabilisation of the frequency during the radiofrequency pulse has been demonstrated with a piezoelectric element allowing efficient pulsed cavity operation at gradients of more than 35 MV/m.

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REFERENCES

[1] TTF-Proposal, DESY-TESLA-93-01

[2] J.-P. Carneiro, et al., *Proc. 1999 Part. Acc. Conf.*, New York 2027-2029 (1999)

[3] Y. M. Nikitina, J. Pflüger, *Nucl. Instr. and Methods* **A375** 325 (1996)

[4] W. Singer et al, 8th Workshop on RF Superconductivity, Abano Terme, Italy,1997

[5] J.G. Weisend II et al, 1999 Cryogenic Engineering Conference, Montreal, Canada, Advances in Cryogenic Eng., Vol. 45, Plenum Press, New York

[6] TESLA Technical Design Report

[7] K. Saito et al, 9th Workshop on RF Superconductivity, Santa Fe, 1999

[8] C.Z. Antoine et al, 9th Workshop on RF Superconductivity, Santa Fe, 1999

[9] E. Kako et al, 9th Workshop on RF Superconductivity, Santa Fe, 1999

[10] L. Lilje et al, 9th Workshop on RF Superconductivity, Santa Fe, 1999

[11] P. Kneisel, 9th Workshop on RF Superconductivity, Santa Fe, 1999, B. Visentin, ibd.

[12] L. Lilje, PhD Thesis, to be submittet to University of Hamburg in 2001

[13] G. Schmidt, et al., FEL 2000, Durham, USA

[14] H. Edwards, et al., *Proc. 1999 FEL Conf.*, Hamburg, II-75 (1999)

[15] J. Andruszkow, et al. , Phys. Rev. Lett., Vol.85, No 18,pp. 3825-3829(2000)

[16] J.Rossbach, Invited talk given at the FEL 2000, Durham, USA, and to be published in NIM A

[17] B. Visentin et al, 9th Workshop on RF Superconductivity, Santa Fe, 1999

[18] W. Singer et al, to be published , Electropolishing of a hydroformed niobium cavity, 2000

[19] E. Palmieri et al, to be published , Electropolishing of a spun niobium cavity, 2000

[20] J. Sekutowicz, M. Ferrario, C. Tang, Superconducting superstructure for the TESLA collider: A concept, Phys. Rev. ST Accelerators and Beams 2:062001, 1999.

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