EXPERIMENTAL RESULTS AND TECHNICAL RESEARCH AND DEVELOPMENT AT TTF

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Abstract

The effort of the international TESLA Collaboration at the TTF is focussed on the development of superconducting cavities to gradients of 25 MV/m and the operation of a linac with superconducting cavities as an integrated system test. Results on the performance of the nine cell superconducting cavities and on the R&D on single cells to gradients of 40 MV/m will be presented.

1 INTRODUCTION

Encouraged by the results from R&D work on superconducting cavities at CERN, Cornell, DESY, CEBAF, KEK, Saclay and Wuppertal [1,2,3], several institutions - the nucleus of the TESLA collaboration formally established in 1994 - decided in 1991 to set up a test facility for superconducting cavities at DESY [4].

The aim of the collaboration was to demonstrate the feasibility of superconducting cavity technology for a linear collider in the TeV range, which is considered to be the ideal choice for a collider with respect to the obtainable luminosity [5,6], due to the high conversion efficiency from mains to beam power and the small dilution of the beam emittance in the accelerating structures.

The major challenge to be mastered was the cost reduction from 40,000 $/MV at the time by about a factor of twenty, to become competitive with normalconducting concepts. This was considered possible by reducing the cost per meter by appropriate design and cost savings in large scale production and by increasing the cavity gradient from 5 MV/m at the time to 25 MV/m. 1.3 GHz was chosen for the operating frequency as a good compromise between requirements on shunt impedance, cost, maximum gradient, wakefield generation and availability of RF components.

From the competing requirements of getting a high filling factor and the avoiding of trapped modes, a cavity with 9 cells emerged, made from solid niobium as the only promising choice at the time to reach high gradients.

The collaboration also decided to construct a 500 MeV Linac as an integrated system test to demonstrate that a linear collider based on s.c. cavities can be built and operated reliably.

2 THE TESLA TEST FACILITY

The infrastructure (fig. 1) of the TTF [7] incorporated all the experience gained in the institutions mentioned above in a uncompromising way, supplying through all steps of cavity treatments a dust free environment, which had been found essential to obtain high gradients.

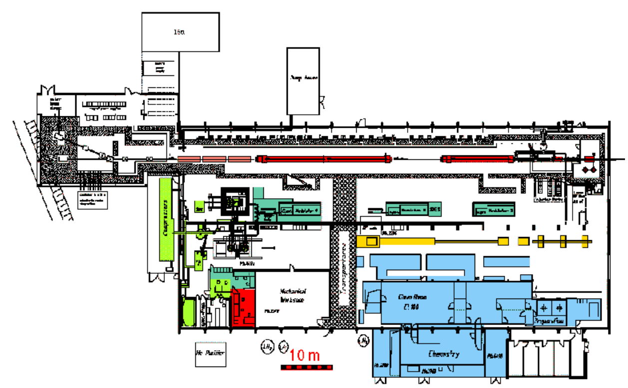

Figure 1: The TESLA Test Facility.

The large cleanroom area (from class 10000 down to class 10) houses the chemical treatment installations, a high pressure rinsing station using ultra-clean water, a UHV furnace for the purification of the niobium by titanisation at 1400°C and an assembly area allowing to assemble a string of 8 cavities and a superconducting quadrupole inside the cleanroom. Pumping and leak testing is performed inside the cleanroom with oilfree pumpstations located outside of the cleanroom area.

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All cavities are closed off in the class 10 cleanroom area by all metal sealed flanges or valves before leaving the cleanroom for further tests and installations. Also all components directly attached to the cavities like power input couplers, higher order mode couplers or pickup electrodes are carefully cleaned in the cleanroom area and are mounted to the cavities inside the class 10 area. For the venting of pumped cavities an ultra clean Argon gas system is used.

For RF-tests there are two vertical test dewars [8] and one horizontal test stand [9]. RF-power is either supplied by a 400 Watt cw generator or a 5 MW klystron plus modulator [10] for pulsed operation or peak power processing [11].

Relevant information on all cavities concerning treatment steps and test results are collected in an Oracle database [21]. A comprehensive description of the cavity treatment and the results can be found in [22].

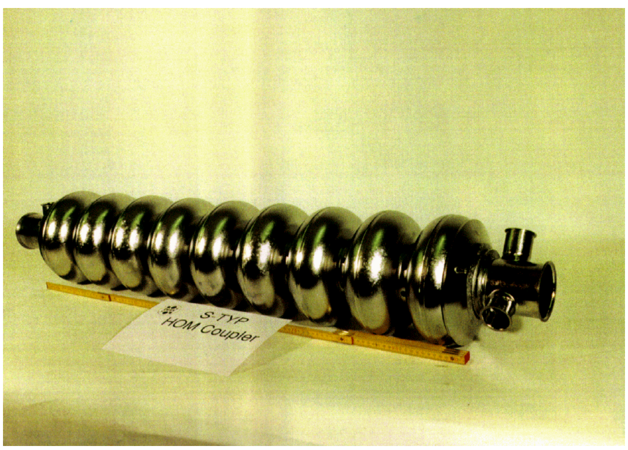

Figure 2: A 9-cell cavity.

3 RESULTS ON 9-CELL CAVITIES

The cavities (fig. 2) are fabricated from RRR 300 niobium sheets by deep drawing and by electron beam welding. Up to now 55 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.

Already in the first series the strict observance of clean treatment showed success by reaching gradients of 25 MV/m at Q values above $5 \cdot 10^9$ 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 unproper preparation of the cavity dump bells before welding or by inclusions of normalconducting grains in the niobium.

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 [12]. The success of these measures can be seen in fig. 3 where the average

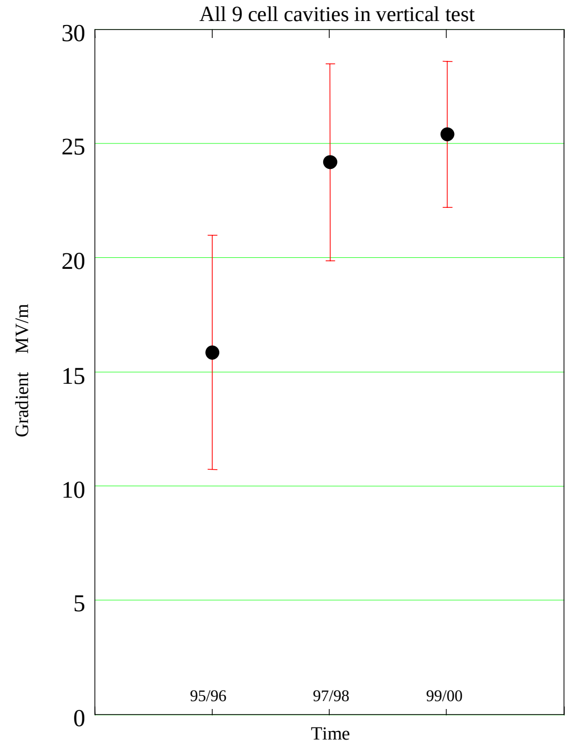

Figure 3: Average gradient of all 9-cell cavities measured in vertical tests during the past 5 years.

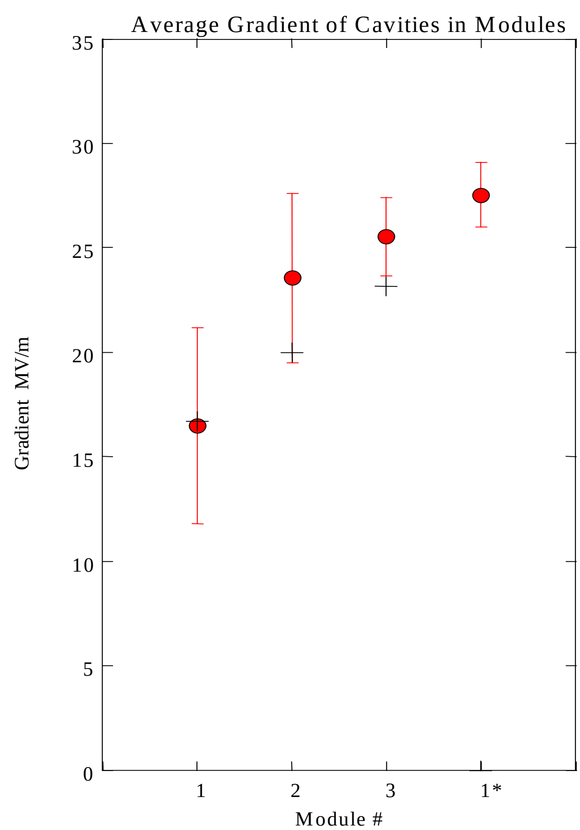

Figure 4: Average gradient, as measured in vertical tests, of the 9-cell cavities assembled into accelerator modules. Crosses indicate the gradients obtained in the module.

measured gradient and the standard deviation is shown for all 9-cell cavities measured up to now. Part of the increase in gradient can certainly also be contributed to the growing experience of the crew handling the cavities at TTF. All 4 companies have demonstrated their capability of manufacturing cavities exceeding 25 MV/m at $Q=5\cdot10^9$. However, part of the scatter in fig. 3 is due to the different level of experience at the companies.

The progress in cavity production, treatment and handling can also be seen in fig. 4, which shows the average gradient measured in the vertical test cryostat of the cavities, which were installed into the three accelerating modules up to now. Module # 1 has been disassembled in the meantime and been equipped with new cavities after a modification [13] of the cryostat (module # 1*).

After successful vertical test the cavities are welded into a titanium helium vessel. The performance of the fully equipped cavity - input coupler, HOM coupler, pickup probe mounted inside the cleanroom - can be tested in the horizontal test cryostat. There the cavities are tested with the nominal RF puls (500 µsec filling time and 800 µsec flat top). Fig. 5 shows the achieved gradients in the horizontal test vs. the gradient in the vertical test for all measured cavities of the second production series. No systematic deterioration of the achieved gradients is observed.

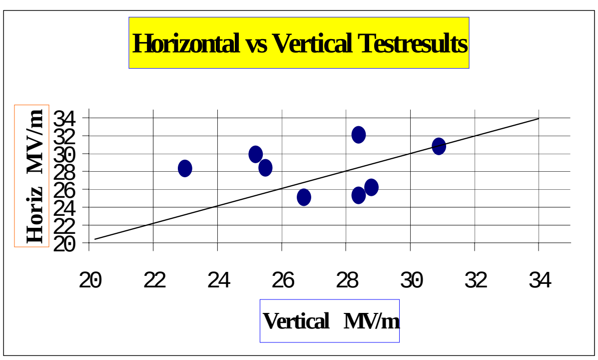

Figure 5: Horizontal vs vertical testresults for cavities of the second production.

Fig. 4 shows also the average gradients obtained in the accelerating modules in the linac. Module # 1 was operated with an RF pulse of only 100 µsec flat top, whereas module # 2 and # 3 were operated with the maximal flat top of 800 µsec. The achievable average gradient in module # 2 was limited by discharges in the input couplers, as not enough time had been spent on conditioning. In module # 3 it was found that the gradient of the cavity next to the superconducting quadrupole was reduced by about 7 MV/m as compared to the vertical test, which may be due to inadequate magnetic shielding. This question will be answered when module # 1* will be tested, which at present is exhibited at DESY in an outstation of the EXPO 2000. It must be said that up to now rather than trying to obtain record gradients, emphasis has been given to commission the linac, the diagnostics and the controls, to measure beam properties and to bring the FEL into operation [20].

It appears that with the presently used treatment procedures and the existing infrastructure a further substantial increase in the cavity gradients is not to be expected. However, the production and treatment procedures are obviously consolidating, increasing the number of cavities performing to specification on the first test. Certainly the presently achieved level of technology in cavity production will be adequate for the construction of a 500 GeV linear collider.

4 FURTHER R&D ON S.C. CAVITIES

4.1 Single Cell R&D

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 40 MV/m or above, which would allow for a substantial increase of the collision energy at the TESLA linear collider.

For a number of years remarkable results have been obtained at KEK [14] with electropolishing single cell niobium cavities, obtaining gradients close to 40 MV/m. In contrast to the chemical etching (Buffered Chemical Polishing) applied for the cavities at TTF, which leads to a rather rough surface, electropolishing leads to a very smooth and shiny surface [24].

About a year ago a collaboration between KEK and Saclay has convincingly demonstrated that electropolishing raises the obtainable accelerating field substantially compared to the BCP treatment [15].

In a collaboration including KEK, CERN, DESY, Saclay and Jefferson Lab. several single cell cavities have been electropolished and gradients around 40 MV/m were obtained [16]. It was discovered that baking the evacuated cavities at 75-150°C for 24 to 48 h 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]. Very recently 42.5 MV/m at $Q=1.5\cdot10^{10}$ were obtained on an electropolished single cell cavity produced by hydroforming in a collaboration between DESY, KEK, INFN, Jefferson Lab. and INR Troitsk [18], see fig. 6.

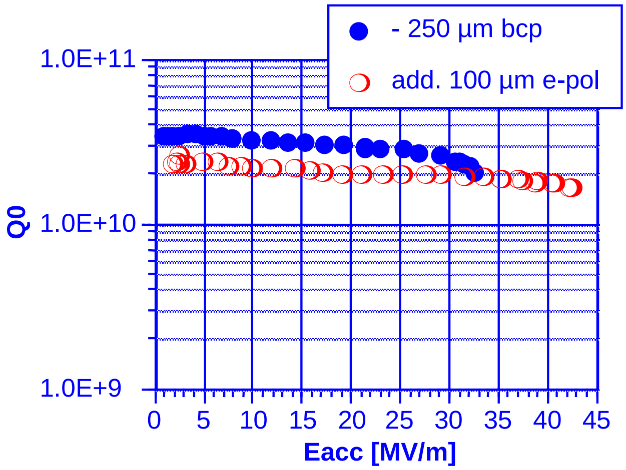

Figure 6: Q vs Eacc for cavity 1K2 after bcp and ep surface treatment.

To transfer these findings to 9-cell cavities, the development of proper tooling to electropolish 9-cell cavities is underway at DESY, FZ Juelich and CERN.

4.1 Cavity Stiffening

To make proper use of gradients in the order of 40 MV/m the detuning of the cavity by the electromagnetic fields has to be reduced by further stiffening. With the present wall thickness and the stiffening rings, welded to adjacent cells, the Lorentz detuning would exceed the resonance width of about ± 300 Hz. This would require additional power overhead for the regulation of the RF power source, thus reducing the mains to beam power conversion efficiency.

A very interesting technique has been investigated at Orsay [19] by spraying copper onto the niobium cavities. Very promising results have been obtained but the heat conductivity of the copper seems not to be sufficient up to now to allow high gradient operation with the stiffened cavities. Stiffening the niobium structure by tightly fit perforated titanium shells is being investigated at DESY. There are several other ideas like spraying porous layers of titanium or niobium which are waiting to be explored.

In this context the recently resumed R&D programme at CERN on Nb sputtered copper cavities is of great interest.

4.2 Increasing the filling factor

In the accelerating module at TTF the distance between adjacent cavities is rather large with 0.35 m compared to the active cavity length of 1.038 m. To improve the filling factor of the linac, the ratio of active to total length, the concept of the superstructure was proposed [23]. The structure consist of 4 cavities of 7 cells each, spaced only 0.115 m apart corresponding to $\lambda_{RF}/2$. Only one input coupler supplies the power to 4 cavites. 7 cells per cavity instead of 9 were chosen to ease the control of the field flatness over the whole structure. For the technical design report of TESLA, which is presently in preparation, an accelerating module containing 4 superstructures is under design. Keeping the length of the linear collider unchanged, this layout requires a gradient of only 22.5 MV/m for 500 GeV cm energy. The reduced number of couplers and the simplification of the RF distribution system in the superstructure concept compared to the present layout of the TTF linac may lead to a cost reduction of the project. However, as in total more cavities are required and the RF components like circulators or input couplers have to cope with about a factor of four higher power levels, a careful cost analysis will be performed. One prototype of the superstructure is being manufactured and a test with beam is planned in the TTF linac for the beginning of 2001, to validate the concept.

Motivated by the concern about the higher power levels in the RF power couplers a second concept is being elaborated, called the compressed TTF structure. In this layout 12 cavities of 9 cells are assembled into one cryostat of about 16 m length. The distance between adjacent cavities is reduced from 35 cm to about 25 cm, yielding a filling factor which is only 3 % smaller than for the superstructure concept. Each 9-cell cavity will have its own input coupler.

Common to both schemes is the necessity for a different tuning mechanism from the one used for the TTF cavities at present. The level system of the present tuning system [25] is located in the space between cavities and does not allow a substantial reduction of the cavity distance (see fig. 7). A new tuning system has been designed which is attached to the helium container of the cavity [26]. The new tuning mechanism will be part of the prototype test of the superstructure next year.

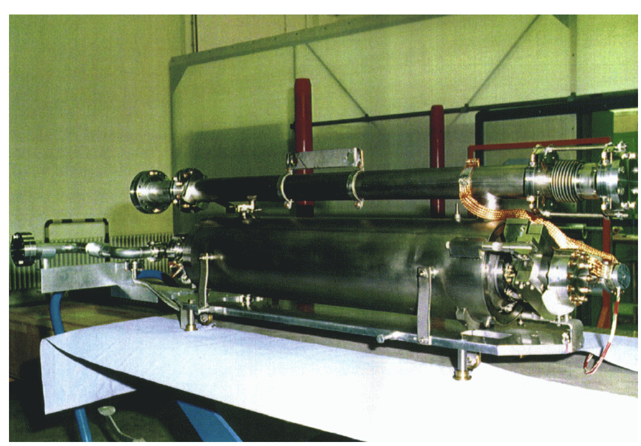

Figure 7: 9-cell cavity with tuning system.

5 CONCLUSION

It has been demonstrated that the present level of technology - for industrial cavity production and for the treatment and handling steps applied at TTF - is certainly adequate for the construction of a 500 GeV linear collider. The ongoing R&D programme gives convincing evidence that with a cavity treatment based on electropolishing properly applied to multicell cavities, gradients of 40 MV/m at quality factors exceeding $5 \cdot 10^9$ can be achieved.

Gradients in this range and the successful completion of the ongoing developments to stiffen the cavities mechnically and to increase the filling factor in the accelerating modules will allow for the operation of TESLA at cm energies of 800 GeV.

REFERENCES

[1] 4th Workshop on RF Superconductivity, Tsukuba 1989, KEK Report 89-21, Ed. Y. Kojima

[2] 1st International TESLA Workshop, Cornell 1990, CLNS 90-1029

[3] 5th Workshop on RF Superconductivity, Hamburg 1991, DESY M-92-01

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

[5] R. Brinkmann, DESY M-95-10 (1995)

[6] R. Brinkmann, EPAC98, Stockholm

[7] A. Matheisen, 46th International Symposium of the American Vacuum Society, Seattle, 1999

[8] T.H. Nicol et al, IEEE Proceedings PAC93, Vol. 2

[9] P. Clay et al, ICEC95, Columbus, Ohio

[10] H. Pfeffer et al, EPAC94, London

[11] J. Graber, Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip. 350, 572 (1994)

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

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

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

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

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

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

[18] I. Gonin et al, contribution to this conference

[19] S. Bousson et al, 9th Workshop on RF Superconductivity, Santa Fe, 1999

[20] J. Rossbach, contribution to this conference

[21] P.D. Gall et al, 9th Workshop on RF Superconductivity, Santa Fe, 1999

[22] B. Aune et al, DESY-Report DESY 00-031

[23] J. Sekutowicz et al, 9th Workshop on RF Superconductivity, Santa Fe, 1999

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

[25] P. Leconte et al, TESLA 93-29

[26] H. Kaiser, TUP043, 9th Workshop on RF Superconductivity, Santa Fe, 1999