EXPERIENCE WITH SUPERCONDUCTING CAVITY OPERATION IN THE TESLA TEST FACILITY

M. Pekeler for the TESLA Collaboration*
Deutsches Elektronen-Synchrotron DESY, D–22603 Hamburg, Germany

Abstract

A description of the TESLA Test Facility, which has been set up at DESY by the TESLA Collaboration, will be given. Measurements of the superconducting 9-cell cavities in vertical and horizontal test cryostats will be presented, as well as the experience with the first two accelerator modules in the TTF linac. Future cavity R&D efforts will be described.

1 INTRODUCTION

A linear e^+e^- collider with a center-of-mass energy of $\geq$ 500 GeV would be an ideal machine to search for further fundamental constituents of matter and their interactions and to address the problem of mass generation in the Standard Model. Among the different designs (NLC, JLC, VLEPP, CLIC & TESLA), TESLA is the only one using superconducting cavities and a low radio frequency of 1.3 GHz. The high conversion efficiency from primary to beam power and the small emittance dilution makes the superconducting version an ideal choice for high luminosity operation [1]. The TESLA 500 GeV collider design is based on nine-cell cavities with a gradient of 25 MV/m at a quality factor Q of more than $5 \cdot 10^9$ [2]. An important feature is the integrated X ray Free Electron Laser (FEL) working on the Self-Amplified Spontaneous Emission (SASE) principle. This FEL will produce a photon beam at Angstrom wavelengths with peak brilliance exceeding that of third generation synchrotron radiation sources by 10 orders of magnitude.

2 THE TESLA TEST FACILITY

In 1992 the TESLA Collaboration decided to set up the TESLA Test Facility (TTF) [3] at DESY comprising the complete infrastructure for the treatment, assembly and test of 9-cell superconducting cavities and a superconducting linac for a fully integrated systems test with beam. The aim was to achieve gradients of 15 MV/m in a first step and to gradually approach the 25 MV/m design gradient of the linear collider.

2.1 The TTF linac

The original proposal was to built a 500 MeV superconducting linac as a test bed for the cavities and RF systems foreseen for TESLA, but during the last years the design of the TTF Linac was extended to include from the beginning the important option of a Free Electron Laser in the Vacuum Ultraviolet regime [4]. Two injectors have been in use, a 250 keV thermionic gun [5] producing an average current of 8 mA at low bunch charge, and a 4 MeV laser-driven RF photoinjector [6] with the same average current, but a high bunch charge of 8 nC corresponding to the TESLA specifications. The electrons are captured by a superconducting nine-cell cavity (see figure 1) providing an energy gain of 13 MeV. In 1997 the first stage of the linac was successfully commissioned with the thermionic injector and one cryomodule containing eight 9-cell cavities with an average gradient of 15 MV/m [7]. The second cryomodule was installed in summer 1998. All cavities exceeded a gradient of 20 MV/m in the vertical test, four reached even the TESLA goal of 25 MV/m. The cavities of the third module which is presently being assembled will all operate at 25 MV/m.

Together with the installation of module 2, the thermionic gun was replaced by the photoinjector and a bunch compressor was installed between the two modules. The undulator magnet together with module 3 will be mounted this summer. The proof-of-principle experiment for the SASE type FEL is planned for the fall. In Phase II the TTF linac will be equipped with 5 more cryomodules, a second bunch compressor and a three times longer undulator. The completion of a VUV FEL user facility is planned for the fall of 2001.

2.2 The TTF infrastructure

The TTF infrastructure for cavity preparation and test [8] was completed in 1995 and is composed of a complex of clean rooms (from class 10 000 to class 10), a chemical etching facility and an ultra-clean water supply. A UHV furnace is available to improve the thermal conductivity of the cavity via heat-treatment at 1400 °C in the presence of titanium gettering. The last step of cavity preparation is a high pressure (100 bar) rinsing with ultra pure water.

* TESLA Collaboration: **Armenia:** Yerevan Pysics Institute, **P.R. China:** IHEP Beijing, Tsinghua Univ. Beijing, **Finland:** Inst. of Physics Helsinki, **France:** CEA/DSM Saclay, IN2P3 Orsay, **Germany:** Max-Born-Inst. Berlin, DESY Hamburg and Zeuthen, Univ. Wuppertal, Univ. Hamburg, Univ. Frankfurt, GKSS Geesthacht, FZ Karlsruhe, TU Darmstadt, TU Berlin, TU Dresden, RWTH Aachen, Univ. Rostock, **Italy:** INFN Frascati, INFN Legnaro, INFN Milano, INFN Roma, Univ. Roma II, **Poland:** Polish Acad. of Sciences, Univ. Warsaw, INP Cracow, Univ. of Mining & Metallurgy, Polish Atomic Energy Agency, Soltan Inst. for Nuclear Studies, **Russia:** JINR Dubna, IHEP Protvino, INP Novosibirsk, INR Troitsk, **USA:** Argonne National Lab., Cornell Univ., FNAL, UCLA

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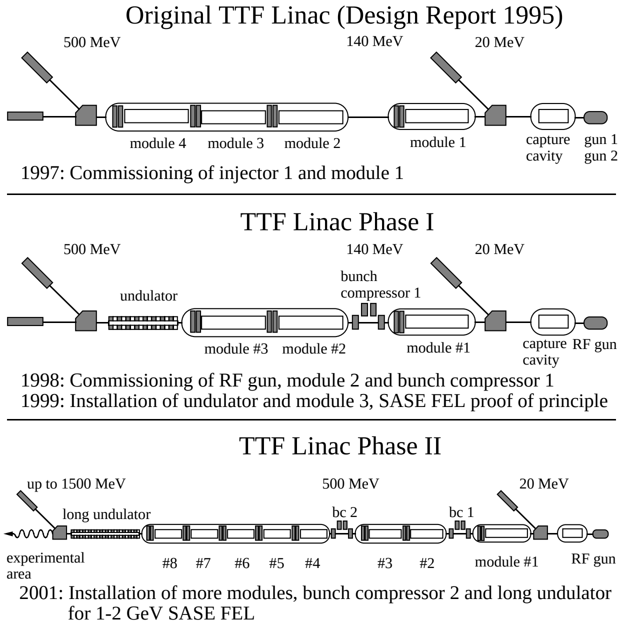


Figure 1: Development stages of the TTF linac design.

All cavities are tested in superfluid helium of 2 K in a vertical bath cryostat. The possibility exists to apply high peak power processing [9] as well as temperature mapping of the outer cavity surface [10]. Cavities having passed the vertical test are welded into their helium tank. The fully assembled cavity can be tested in a horizontal cryostat in pulsed power mode (500 μs rise time, 800 μs flat-top time at a 10 Hz repetition rate). The performance of the main power coupler, the higher-order-mode couplers and the cold tuning mechanism is checked here before the cavity is installed into the cryomodule.

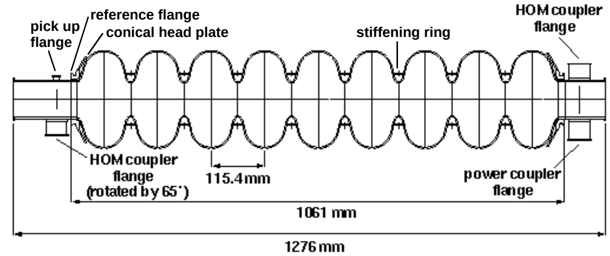
The cavities can be tested also after installation in the linac. As in the horizontal cryostat, the quality factor Q is determined by measuring the dynamic heat-load. The cryoplant of the TTF permits a heat-load measurement at 2 K with a resolution of 0.05 W (as a reference, a cavity operated at 25 MV/m and $Q = 5 \cdot 10^9$ gives a heat dissipation of 1.8 W with the TTF pulsed mode).

3 CAVITY PREPARATION AND TESTS

A cross section of the TTF nine-cell cavity is shown in figure 2. The cavities are fabricated from RRR 300 niobium by electron-beam welding of half cells that are deep-drawn from niobium sheet metal. Up to now 55 cavities have been ordered at 4 European companies. The first series of 28 cavities were ordered in 1994, the second series of 27 in 1997. So far, 41 cavities have been tested in the vertical and 18 cavities in the horizontal cryostat.

The presently used cavity preparation at DESY consists of the following steps:

- Removal of a damage layer from the inner cavity surface by 80 μm Buffered Chemical Polishing (BCP) using a mixture of HF (48 %), HNO_3 (65 %) and H_3PO_4 (85 %) in the ratio 1:1:2. This is followed by rinsing with ultrapure water until the resistivity of the water is higher than 18 MΩcm.
- Removal of 30 μm from the outer surface by BCP.
- A 2 hours heat-treatment at 800 °C for hydrogen degasing and recrystallisation.
- A 4 hours heat-treatment at 1400 °C with titanium getter for improvement of the thermal conductivity and homogenization of the niobium.
- Removal of the titanium layer by 80 μm inner and 30 μm outer BCP.
- Tuning to correct frequency and field flatness.
- Final 20 μm removal from the inner surface by BCP.
- High pressure rinsing with 100 bar ultrapure water.
- Drying by laminar flow in class 10 cleanroom, assembly of all flanges, leak-check.
- 2 times high pressure water rinsing, drying by laminar flow and assembly of input antenna.



Effective length	1036 mm
Aperture diameter	70 mm
Coupling cell to cell	1.98 %
$E_{\rm peak}/E_{\rm acc}$	2.0
$B_{\rm peak}/E_{\rm acc}$	4.2 mT/(MV/m)
R/Q per cavity	1036 Ω
$\Delta f/\Delta L$	315 kHz/mm
Cavity bandwidth ($Q_{\rm ext} = 3 \cdot 10^6$)	433 Hz

Figure 2: Cross section and some design parameters of the 1.3 GHz TTF 9-cell cavity

3.1 Vertical test results

The vertical test results are listed in table 1. Several cavities of the first series reached gradients up to 29 MV/m, but the distribution of achieved gradients is very wide. In cavities with low performance defects in the welds or in the bulk niobium were found [11].

To avoid such defects, the welding technique was improved and all niobium sheets used for the second series were eddy current scanned [12] to eliminate foreign material inclusions. Almost all cavities of the second production reached gradients above 20 MV/m (see table 1). Two cavities (S34 and Z49) suffered from field emission and will be retested soon after a new high pressure water rinse. Cavity C43 shows a quench at a repaired equator weld where a hole was blown during electron beam welding. The ma-

Table 1: Performance of TTF cavities in vertical tests. $^{+}$: limited by available cw RF power (no quench observed).

cavity	$E_{\rm acc}$ MV/m	Q_0 10^9	status / comment
first production			
P1	29.1^{+}	6	prototype cavity
P2	16.3	22	prototype cavity
D1	24.7	17	linac operation (module 1)
D2	21.9	4	module 1
D3	25.6	29	module 1
D4	13.5	16	module 1
D5	8.6	24	material defect
D6	13.6	12	material defect
S7	13.8	8	module 1 / weld defects
S8	12.5	12	module 1 / weld defects
S9	11.4	11	weld defects
S10	14.2	16	module 1 / weld defects
S11	13.5	13	module 1 / weld defects
S12	12.6	13	used at FNAL / weld defects
A14	6.4	11	quench at repaired weld
A15	23.0^{+}	4	module 2
A16	20.8	6	field emission
C19	22.1	2	linac (capture cavity)
C21	29.3^{+}	8	module 2
C22	20.2	21	module 2 / weld defect
C23	25.3^{+}	8	module 2
C24	19.7^{+}	5	module 2
C25	28.4^{+}	9	module 2
C26	21.4^{+}	4	module 2
C27	26.7^{+}	8	module 2
second production			
S28	25.3^{+}	6	module 3
S29	26.7^{+}	6	module 3
S30	28.4^{+}	7	module 3
S31	28.1	4	
S32	26.5^{+}	7	module 3
S33	23.9	7	
S34	14.4^{+}	2	field emission
D37	20.3	5	
D38	19.5	3	
D39	25.2^{+}	7	module 3
D40	22.8^{+}	5	module 3
D41	23.3^{+}	5	module 3
D42	24.6	7	module 3
C43	12.9	20	quench at repaired weld
C44	25.5^{+}	6	
Z49	18.0^{+}	2	field emission

jority of the cavities reached their excellent performance already in the first vertical test. It is only occassionally necessary to repeat preparation steps.

The average gradient of all cavities is 20.5 MV/m. Neglecting cavities with identified material or fabrication errors gives an average gradient of 23.1 MV/m.

Figure 3 shows the time development of the best vertical test results. Since 1997 fabrication and material defects have been almost eliminated. Practically all of the new cavities reach gradients between 20 and 30 MV/m with an average of 25 MV/m.

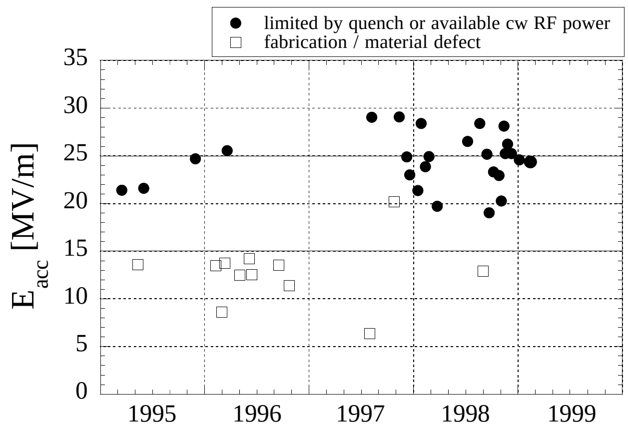


Figure 3: Time development of maximum gradient achieved in TTF 9-cell cavities.

3.2 *Horizontal tests*

After the successful vertical test, the helium vessel is welded to the conical head plates of the cavity (see figure 2). A 20 μm removal from the inner surface and a careful high pressure rinse follows. The last preparation step is the delicate assembly of the main power coupler.

The average gradient obtained in the 18 cavities tested in the horizontal cryostat was 22.5 MV/m and does not differ from the average value these cavities reached during the vertical tests (22.3 MV/m). The best horizontal test result was 33 MV/m with $Q = 4 \cdot 10^9$. Most of the good cavities are limited by RF breakdown in the main power coupler. Four of the eight cavities selected for module 3 were tested in the horizontal cryostat and all exceeded 25 MV/m with quality factors above $5 \cdot 10^9$.

4 OPERATION OF CAVITIES IN THE TTF LINAC

The two modules installed in the TTF linac are supplied with RF power by one 5 MW klystron. In the future it is foreseen to supply 32 cavities by one 10 MW klystron (as in the TESLA design). The cavities are not controlled individually but only the sum of the electric field vectors of all cavities is regulated by a digital RF control system. In addition to the feedback control which suppresses stochastic errors, an adaptive feedforward is applied to correct for repetitive perturbations, induced by beam loading and dynamic Lorentz force detuning [13]. The remaining errors from noise and other sources are small and require only a low gain in the feedback loop. An amplitude stability of

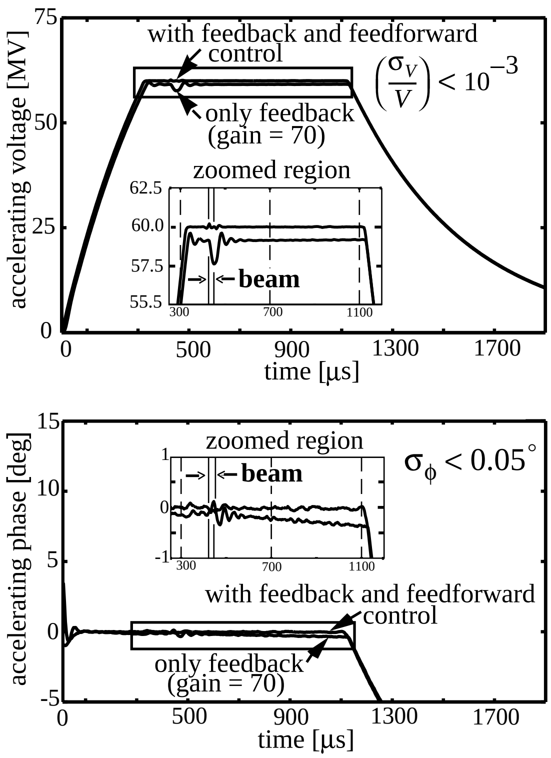


Figure 4: RF control system performance without and with adaptive feedforward. The beam pulse had a length of 30 μs.

$< 10^{-3}$ and a phase stability of $< 0.05°$ was achieved for the vector sum (see figure 4).

The cavities installed in module 1 reached an average gradient of 15 MV/m, two of them were already close to or above the TESLA specs (25 MV/m with $Q > 5 \cdot 10^9$) [7].

After the installation of module 2, there was only limited time for main coupler conditioning. No measurements of individual cavities were possible but an integral check of the whole module, with all cavities operating at the same gradient. With the full TTF pulse (10 Hz, 500/800 μs rise/flat-top time) 20 MV/m could be reached. The gradient could not be increased further because of coupler breakdowns. Heavy field emission was detected in one of the cavities. It was decided to apply in-situ high peak power processing (HPP) prior the second test and fields up to 29 MV/m were reached in this cavity. After the HPP the heat load of module 2 with all cavities operating at 20 MV/m was 6.5 W, corresponding to an average quality factor of $Q = 6 \cdot 10^9$. By detuning the cavity in which still some field emission was present the cryogenic load reduced to 2.9 W giving at 20 MV/m a Q of $1.3 \cdot 10^{10}$ of the remaining 7 cavities.

5 FUTURE CAVITY R&D

From the good test results of TTF cavities after mid 1997 one can conclude that the TESLA goal of 25 MV/m in 9-cell resonators has been established with the present fabrication and preparation methods. However for a possible energy upgrade of TESLA there is a strong motivation to push the cavities closer to the physical limit of 50 MV/m which is determined by the critical magnetic field of the superconductor niobium.

There are three main effects which prevent us from reaching gradients well beyond 25 MV/m: thermal breakdown at material defects, field emission and Q-drop at high fields.

Occasionally we observe quenches at about 25 MV/m. New vertical tests with temperature mapping of the outer cavity surface are necessary in order to find out, if the delicate equator welds or very small foreign material inclusions are responsible for the thermal breakdown. In addition the eddy current scanning apparatus [12] was improved significantly for a better diagnostic of polluted niobium sheets with tiny defects.

With the present preparation techniques, field emission may be observed at gradients above 20 MV/m. Efforts are undertaken to further reduce field emission by improvement of the high pressure rinsing system and a better in-situ particle control during the assembly in the cleanroom.

A new type of field limitation, first observed in single cell cavities at Saclay, and recently also seen at DESY, is the decrease of the quality factor at fields around 25 MV/m without any evidence for field emission (see figure 5). In a collaboration between Saclay and KEK it was shown that electropolishing of the surface reduces this Q-drop and enhances the high-field capability compared to a buffered chemical polished surface [14]. An R&D effort has been launched in collaboration with CERN, KEK, Saclay and an industrial company to apply electropolishing to the 9-cell TESLA structures.

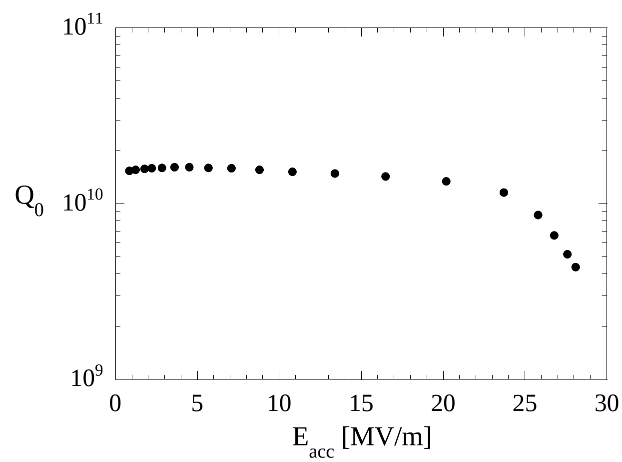


Figure 5: Observation of Q-drop at high gradient without any evidence of field emission in a TTF 9-cell cavity.

New cavity fabrication methods [15] like spinning or hydroforming [16] are under development and have the potential of reducing the costs. First test results on prototype cavities are promising (figure 6). A spun five-cell 1.5 GHz

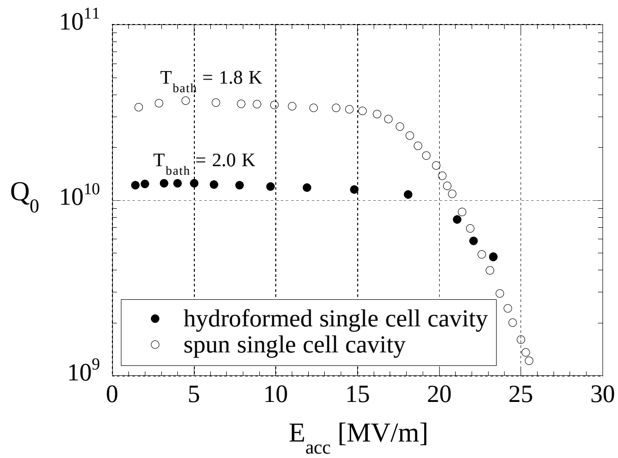


Figure 6: Vertical test results of prototype 1.3 GHz single cell cavities manufactured by hydroforming and a spinning technique.

cavity measured at CEBAF reached even 30 MV/m [17].

A new way of cavity reinforcement is plasma jet spraying of copper or other metals onto a niobium cavity [18]. The stiffening rings (see figure 2), presently used to counteract the Lorentz forces in pulsed operation, can probably be eliminated and additional stiffening at the equator can be achieved using this method.

In the superstructure concept [19] several multi-cell cavities are coupled to each other by a shorter and larger diameter beam pipe. Only one main input coupler is foreseen for such a group of cavities. This year a design for a 4 $\times$ 7-cell superstructure will be completed and 7-cell 1.3 GHz superstructure cavities will be ordered. The number of main couplers can be reduced to 1/3 as compared to the present TESLA design and the filling factor, the ratio of the linac active length to the total length, is increased from 0.66 to 0.76. We hope to test a superstructure with beam in 2001, in order to study beamloading and wakefield effects.

6 CONCLUSIONS

The results obtained so far in the framework of TTF are very encouraging and the technical possibility to built TESLA is becoming reality. In particular the cavities are now routinely reaching the TESLA requirements of 25 MV/m at $Q > 5 \cdot 10^9$. No degradation of cavity performance is found between vertical test, horizontal test and after installation in the linac.

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