SUPERCONDUCTING RF STRUCTURES – TEST FACILITIES AND RESULTS

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Abstract

The design of the TESLA superconducting electron-positron linear collider with an integrated X-ray laser laboratory was presented to several international committees including the German Science Council, advising the German government in matters of science. In preparation of this large facility, the TESLA Test Facility was set up at DESY. More than 40 institutes from nine countries have designed, constructed, commissioned and operated accelerator components. In close collaboration, superconducting accelerator cavities with gradients between 25 and more than 40 MV/m were developed. The TESLA Test Facility includes the preparation and testing of superconducting cavities as well as a 260 m long linac installation. The cavity performance with beam has been investigated while operating the linac as a driver for a SASE free-electron laser as well as during dedicated high gradient tests. More than 16 thousand hours of operation demonstrated this technology. Results of single cavity tests as well as of module tests without and with beam are presented.

INTRODUCTION

Superconducting cavity R&D of the TESLA collaboration has demonstrated the reliable production of 9-cell structures achieving gradients of 25 MV/m and higher at quality factors $Q_0 \geq 10^{10}$. Since a number of years there is broad consensus that the TESLA 9-cell cavity is a good choice for linear colliders as well as for FEL linear accelerators. The agreement is based on the results achieved at the TESLA Test Facility (TTF). Gradients of 35 MV/m and above were reached by applying a new preparation technique, i.e. electrolytic polishing. The gradient of prototype single-cell cavities exceeded 40 MV/m. At present a module equipped with electro-polished 9-cell TESLA cavities is under construction.

TTF Linac at DESY was constructed to show that high gradients achieved in individual 9-cell TESLA cavities could be maintained after assembly in an operating linac.

SUPERCONDUCTING RF STRUCTURES IN VERTICAL AND HORIZONTAL TESTS

Cavity tests in vertical as well as in horizontal cryostats were done to investigate accelerating gradient, quality factor, quench behaviour, Lorentz-force detuning, and last but not least to demonstrate the success of the cavity surface preparation and assembly procedure. The needed infrastructure for the test of RF structures was set up by the TESLA collaboration and is located at DESY.

Standard TESLA Nine-cell RF Structures

The TESLA 9-cell cavity is a standing wave structure of about 1 m length whose fundamental π-mode has a frequency of 1.3 GHz. The cavity is made from solid niobium and is bath-cooled by superfluid helium at 2 K. Each cavity is equipped with its own helium vessel; a tuning system driven by a stepping motor; a coaxial RF power coupler; a pickup probe; and two higher-order mode (HOM) couplers. A detailed parameter list including the niobium specification is given in [1].

Cavity fabrication is a delicate but nowadays established procedure. The TTF cavity production was done at several companies. According to industrial studies, the developed procedures are suitable for large-scale series production. Nevertheless, a careful design review was started in preparation of the TESLA XFEL (see below), which requires almost 1000 cavities.

The standard cavity treatment used for the last years includes a first approx. 100 µm removal from the inner surface. Buffered Chemical Polishing (BCP), i.e. etching, is the used method. Next is a first rinsing with ultra-pure water followed by drying in a class 100 clean room; annealing at 800°C in an Ultra High Vacuum oven to relieve mechanical stress as well as to out-gas dissolved hydrogen; heat treatment at 1400°C for further removal of other dissolved gases in presence of a thin titanium layer being evaporated on the inner and outer surface. This so-called post-purification increases the thermal conduction and the residual resistivity ratio (RRR) by about a factor of two. The titanium layer is finally removed again using BCP. Before the acceptance test in vertical dewars the cavities are mechanically tuned to adjust the resonance frequency to 1.3 GHz and to obtain equal field amplitudes in all 9 cells. This is followed by a light BCP, three steps of high-pressure water rinsing (100 bar), and drying in a class 10 clean room.

Performance of RF Structures

The excitation curve (unloaded quality factor Q_0 as a function of the on-axis accelerating field E_{acc}) of a high-performance 9-cell TESLA cavity shows an almost constant quality factor Q_0 of more than 10^{10} up to 25 MV/m, before the drop of Q_0 at higher gradients indicates that even such excellent multi-cell cavities are still far from reaching the theoretical limit of about 50 MV/m. In order to study this in detail, about 75 cavities, fabricated in three production series between 1993 and 2000, were subjected to the standard treatment mentioned above. Table 1 lists the achieved gradients at Q_0 above 10^{10}. Production series 3 has an average gradient of 26.1

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MV/m. At the TESLA-500 design gradient of 23.4 MV/m the measured Q_0 is $(1.39 \pm 0.35) \times 10^{10}$.

Table 1: Average acceleration gradients measured in the vertical test cryostat of the cavities in the three production series; for comparison the TESLA specification are listed as well.

Production Series	Gradient (MV/m) ($Q_0 \geq 10^{10}$)	σ (MV/m)
1	18.7	7.0
2	23.1	2.4
3	26.1	2.3
TESLA-500	23.4	
TESLA-XFEL	10…**17**…23.5	
TESLA-800	35 at 5×10^9	

Figure 1 shows the excitation curves of all 3rd production cavities. One cavity (AC67) had a cold Helium leak which could not be located so far. All remaining 3rd production cavities (AC70 to AC78) were used for the electro-polishing program (see below).

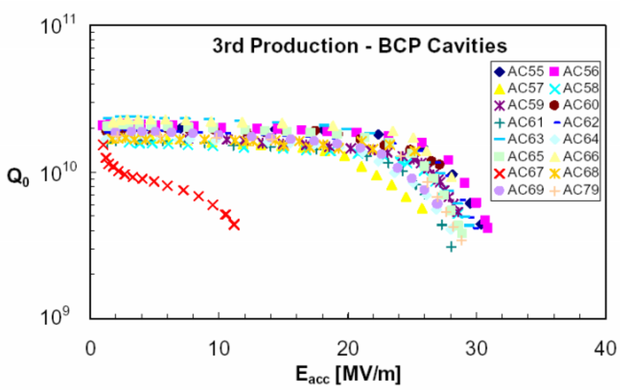

Figure 1: Excitation curves of cavities of the third production series. The measurement was done in a vertical test cryostat in 2 K superfluid helium. Systematic rms errors in the determination of the accelerating field and the quality factor are indicated in Fig.3.

Electro-polished RF Structures

The above mentioned BCP removal of niobium from the inner cavity surface produces a rough niobium surface with strong grain boundary etching. The achieved typical surface roughness is of the order of 1 µm rms. As an alternative method electro-polishing (EP) can be used in which a different acid mixture is used together with an additional electric current flow. Sharp edges and burrs are smoothed out and a very glossy surface can be obtained [2]. Since 1998 a joint R&D program of CERN, DESY, KEK and Saclay has been performed with this polishing method for single cell TESLA structures. Together with a succeeding 100 to 150°C baking of the evacuated cavity, accelerating gradients of 35 to 43 MV/m have been achieved in more than a dozen single-cell resonators [3]. This includes electron-beam welded as well as hydro-formed and spun cavities. The baking seems to be an essential prerequisite for reaching highest gradients without a strong degradation in quality factor.

The transfer of the electro-polishing method to multi-cell cavities has been studied at KEK for some years. Electro-polishing has been used by Nomura Plating for KEK's cavities for many years (e.g. Tristan, KEK-B). In a collaboration of KEK and DESY the electro-polishing of TESLA nine-cell cavities is being studied [4]. After some first tests with older 9-cell resonators, three electro-polished cavities from the last production achieved in a cw measurement the performance needed for TESLA-800: 35 MV/m at a Q_0 larger than $5x10^9$. The cavities were tested for several hours at cw. A fourth cavity of this batch achieved 34 MV/m. Figure 2 shows the results. To further study the EP technique of multi-cell cavities, an electro-polishing facility for 9-cell resonators has been set up at DESY. First tests with single cell cavities already qualified the facility.

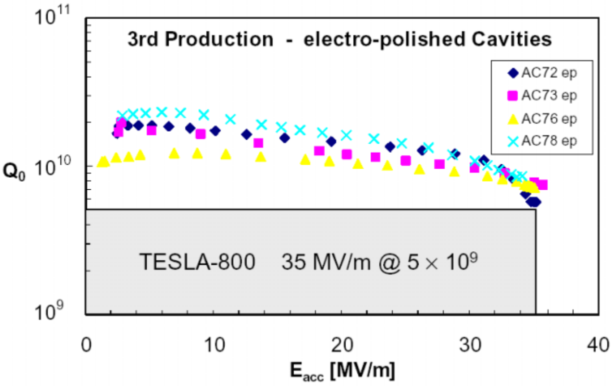

Figure 2: Excitation curve of a high-performance 9-cell TESLA cavity. The cavities are cooled by superfluid helium at 2 K.

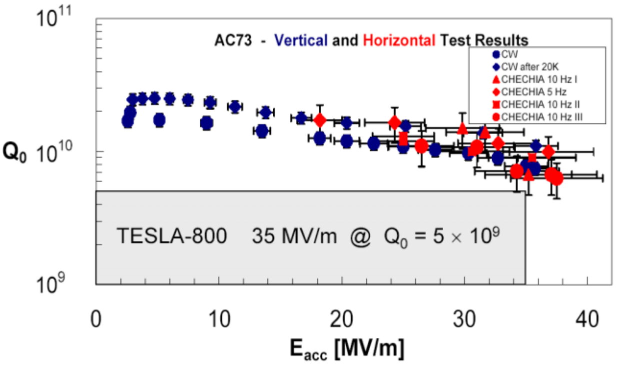

Figure 3: Excitation curves of the electro-polished high-performance 9-cell TESLA cavity AC73. Measurements in vertical as well as horizontal tests (CHECHIA) are shown. The systematic rms errors in the determination of the accelerating field and the quality factor are indicated.

Recently cavity AC73 has been measured in the horizontal test cryostat CHECHIA. For this purpose the helium vessel was welded onto the cavity and the RF power coupler was attached as well as the frequency tuner. In this horizontal test one eighth of the standard TESLA module's string can be installed. Figure 3 summarizes the results of AC73. The CW curves were measured in the vertical test dewar. The horizontal measurements in CHECHIA confirm the previous results within the indicated error bars.

ACCELERATOR MODULES AND TESTS WITH BEAM

In the frame of the TESLA R&D work a number of accelerator modules housing eight 9-cell cavities each were built and tested. The design of these so-called cryomodules has been primarily driven by the need to reduce static losses and costs compared to existing superconducting cavity systems. At present the 3rd cryomodule generation is used for the 1 GeV extension of the TTF linac. The TESLA Design Report includes the description of a 17 m long module which is, except for the length, basically identical.

TTF Accelerator Modules

The TTF cryomodules use a 300 mm diameter helium gas return pipe (GRP) as the main support structure for the string of eight cavities, the quadrupoles as well as steering magnets, and the beam position monitor. The GRP is supported from above by three posts. Via these posts the common axis of the cavities and quadrupoles can be aligned with respect to the linac coordinate system since the cavities and quadrupoles themselves are aligned relative to the GRP. Figure 4 shows a cross section of the last module generation. The cavity position, the RF main input coupler, and the different radiation shields are visible.

Altogether eight cryomodules were assembled so far. The used 55 cavities belong to the three fabrication series mentioned above, the first ones dating back to 1993. Some cavities have been used for a second assembly. Table 2 gives the achieved accelerating gradients.

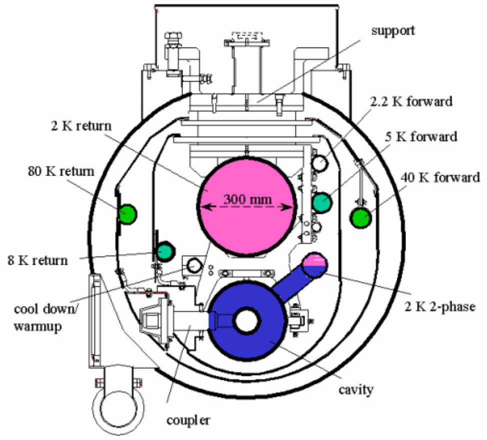

Figure 4: Cross section of the TTF Linac module (3rd generation).

Table 2: Accelerating gradients in MV/m achieved in the TTF Linac accelerator modules. Modules #3*, #4 and #5 are to be tested in late spring 2003, module 2* in fall 2003. The increased gradient spread for the recently assembled module 2* is caused by the fact that older cavities are re-used: The TTF2 injector requires only 15 MV/m for the first four cavities.

Module no.	RF test $(Q_0 \geq 10^{10})$	σ MV/m	Beam operation	Assem. Date
#1	17.5	6.2	14 MV/m	10/97
#2	21.2	6.3	19 MV/m	09/98
#3	23.6	2.2	22.7 MV/m	04/99
#1*	25.3	2.0	20.3 MV/m	02/00
#4	25.4	2.7	spring 2003	10/01
#5	26.5	1.4	spring 2003	01/02
#3*	23.6	2.4	spring 2003	03/03
#2*	22.6	3.5	fall 2003	05/03

The column 'RF test' shows the average gradient per module at a quality factor $Q_0 \geq 10^{10}$, while 'beam operation' refers to the gradient determined by measuring the energy gain of accelerated electron bunches. The module number actually refers to the cryostat vessel, a '*' hints to a replacement of one or more cavities either following the ongoing cavity test program or due to a required repair. The inter-cavity connection was modified using a new flange design. Some other auxiliaries like the RF main input coupler are now used in a revised version.

Modules #2 and #3 were used for approximately 10,000 hours at a gradient of about 14 MV/m providing a 240 MeV beam for different experiments including stable FEL operation [5]. The achieved relative amplitude stability of 2×10^{-3} and absolute phase stability of 0.5 deg was within the requirements. In this standard TTF Linac configuration 16 cavities were driven by one klystron.

Module 1*, assembled in 02/2000, was tested with beam in fall 2002. The gradient, obtained in vertical and horizontal tests, promised an average module gradient close to 25 MV/m. The actually achieved gradient was 20.3 MV/m, a result being dominated by cavities 2 and 6 of this module. Both cavities have an extremely low onset for X-rays: approx. 12 MV/m. In both cases the maximum gradient was reduced from above 25 MV/m down to 18 MV/m. As a consequence the average gradient was determined using a modified power distribution scheme with additional 3 dB attenuators in front of the RF main input couplers of cavities 2 and 6. Under these conditions the average gradient for stable beam operation was measured to be 20.3 MV/m. A detailed cryogenic load measurement was not performed. Figure 5 summarizes the single cavity tests.

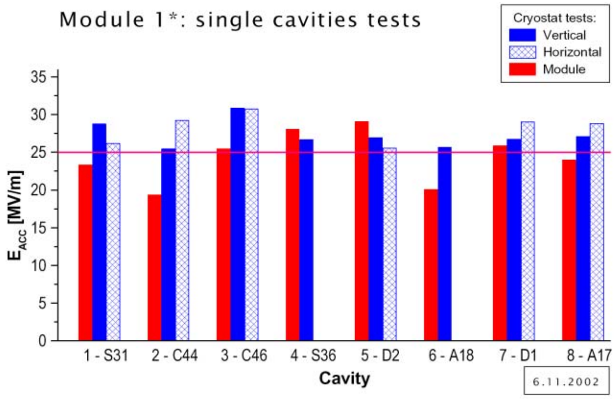

Figure 5: Comparison of gradient measurements in the vertical and horizontal test, and the TTF linac installation.

Careful analysis of the module 1* preparation and of assembly protocols especially in comparison to previous and succeeding modules could not completely explain the gradient reduction of both cavities 2 and 6. However, some problems during the string assembly were identified.

In parallel to the module 1* test, the repair of a leak between the helium system and the insulating vacuum in module 3 was started. The required disassembly of the outer RF main input coupler parts taught us that due to unfortunate handling the inner conductor might touch the niobium surface of the coupler port. The latest coupler generation uses an electrically isolated inner conductor (dc bias to suppress multipacting). Therefore the electrical resistance between the inner and outer conductor can be measured. For module 1* X-ray photographies were taken since an older type of RF input coupler is assembled. Indeed, some of the couplers have touched and may still touch the niobium. Better assembly procedures are required and under study.

Input and HOM Coupler

For TTF several coaxial power input couplers have been developed, consisting of a cold section which is mounted on the cavity in the clean room and closed by a ceramic window, and a warm section which contains the transition from the coaxial line to the waveguide. For TESLA a pulse power of 230 kW has to be transmitted to provide a gradient of 23.4 MV/m for a 950 µs long beam pulse of 9.5 mA. The external quality factor of the coupler can be adjusted by varying the penetration depth of the inner conductor. All couplers needed some conditioning, but then performed according to the specification. The conditioning time depends on the design of the coupler vacuum system which was clearly improved for the most recent coupler type. The maximum transmitted power was 1.5 MW in travelling mode operation

The intense electron bunches can excite eigenmodes of higher frequency in the resonator which must be damped to avoid multibunch instabilities and beam breakup. This is accomplished by extracting the stored energy via higher-order mode (HOM) couplers mounted on the beam pipe sections of the nine-cell resonators, the so-called cut-off tubes. At TTF the excitation of HOMs was studied in detail by accelerating the electron beam off-axis and modulating either the electron beam current or position. Main focus were the so-called trapped modes whose energy is concentrated in the central cells of the cavity. As a consequence of the measurement one of the two HOM couplers per cavity had to be rotated. With this new geometry the HOM quality factors will not exceed 10^5.

TTF Linac Layout

Until early summer 2002 the TTF Linac was operated with up to two accelerator modules as well as one capture cavity. Different modules, including the so-called superstructure were tested with electron beam. Two of the accelerator modules were operated for approximately 10,000 hours at a gradient of about 14 MV/m providing a 240 MeV beam for different experiments including stable FEL operation.

The TTF Linac in its final set-up will consist of the following sections: injector area including the RF gun and a first accelerator module, 150 MeV bunch compressor section, two standard accelerator sections, a second bunch compression section at 450 MeV, another two standard accelerator modules, collimator, undulator, and high energy beam analysis area in parallel to a photon diagnostic and transport section. A sixth accelerator module using electro-polished cavities can be installed between the end of the TTF linac and the collimator. A schematic of this layout is given in figure 6.

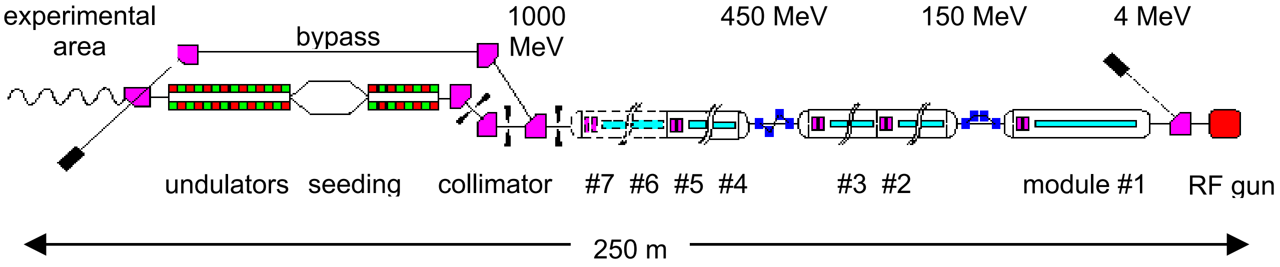

Figure 6: The extension of the TTF Linac to 1 GeV electron beam energy. The electron beam direction in this picture is from right to left.

TTF Linac Operation

Between its first commissioning in 1997 and the modifications in spring 2002, the TTF Linac was operated for approximately 13,000 hours, since 1999 for 7 days a week, 24 hours per day. Approximately 50% of the time was allocated to FEL operation including a large percentage of user time. Figure 7 gives the beam uptime and the operational uptime for a long run between summer 2001 and spring 2002. The percentage is given with respect to the scheduled operation time per week. The difference between beam and operational uptime is due to the time needed for tuning.

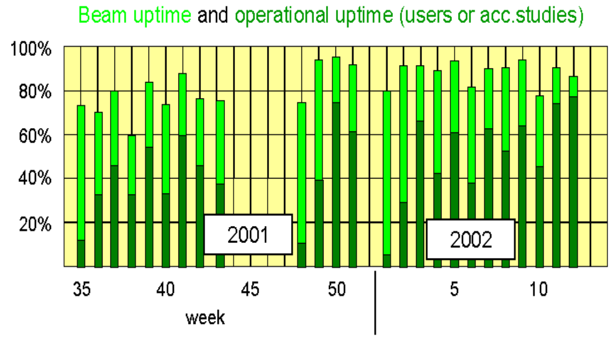

Figure 7: Beam uptime and operational uptime in the 2001/2002 run. The operational uptime was used for either FEL user operation or accelerator studies.

In a dedicated beam time period the high gradient performance of module #3 was studied. The main goals of this run were to operate the module near its maximum gradient, and to accelerate 800 μs long macro pulses comprising 1800 bunches with more than 3 nC bunch charge each. At an average gradient of 21.5 MV/m (5% below the quench limit) a macro pulse current of 7 mA with a bunch charge variation of 10% was accelerated, The achieved energy stability was $\sigma_E / E = 0.07\%$.

The run was carried out under dynamic conditions with beam tuning going on and various levels of operator expertise. The machine interlock system had to check for dangerous beam losses along the TTF Linac. Seven of the eight cavities in the module were operated at gradients between 19 and 22 MV/m. The overall average gradient was between 19.5 and 21.5 MV/m as measured with the beam. Typical module on time was ~ 90%. Trips have been counted but their source has not been investigated.

Over a total of 42 days, 291 trip events were recorded, an average of 8.4 events/day @ 5Hz for the 8 cavity module. This trip rate includes amongst other things both cavity and coupler trips. Partway through the run time a software RF inhibit was implemented so that potential quenches could be detected without tripping the interlock system. The recovery time after a trip depends on the trip reason and is of the order of one minute.

Though this run was not a test for extrapolation to the TESLA linac operational reliability of the superconducting cavities we believe these experiences are positive and point out some of the basic differences between superconducting and normal conducting cavity operation. We also believe that a sophisticated but flexible low-level RF system will be needed to handle a variety of exceptions. We note as well that the cavities in this test have been in operation for over 10,000 hours and that for this run they were operated very close to their limit, a situation that, assuming the high gradients of electro-polished cavities, will not occur for the 500 GeV TESLA collider.

OUTLOOK - CONCLUSION

The TTF Linac at DESY was used to demonstrate the viability of a superconducting linear collider. Based on the above mentioned and referenced results the TESLA Technical Design Report has been published in 2001. The proposal was evaluated by the German Science Council, advising the German government in matters of science [6].

Together with partners of the TESLA collaboration, DESY is extending the actual TTF set-up to 1 GeV. A FEL user facility with wavelengths down to 6 nm will be offered after the commissioning in 2004.

Based on the evaluation of the German Science Council and based on the successful operation of the TTF Free-Electron Laser, the German Federal Research Minister approved the XFEL and included half of the costs into its long-term investment program. The ministry announced negotiations on European cooperation to prepare a decision on construction within about two years, i.e. early 2005.

In view of this support for the XFEL, the TESLA Collaboration has started a careful design review of basically all components which were tested at the TTF. This includes the RF structures itself but is not limited to the accelerating sections; injectors, beam diagnostics, undulators have to be studied as well. Most of this work has large overlap with the continuing international research towards the TESLA Linear Collider. The need for industrial manufacturing of all accelerator components will push the superconducting technology in industry.

ACKNOWLEDGEMENT

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