ACTIVITIES AT DESY WITH HIGH GRADIENT SUPERCONDUCTING RF CAVITIES FOR E^-/E^+ LINEAR ACCELERATORS

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Abstract

Activities with high gradient superconducting RF cavities at DESY focus on applications for e^-/e^+ linear accelerators. Since several years the TESLA Test Facility (TTF) at DESY/Hamburg is operated by an international collaboration. It comprises the complete infrastructure for treatment, assembly and test of superconducting cavities as well as a superconducting linear accelerator. Superconducting cavities with gradients up to 35 MV/m for 9-cell structures and 40 MV/m for single-cell cavities were developed. In addition to the fabrication, preparation and test of TESLA 9-cell cavities an intensive research program on single-cell cavities is performed. Recently a facility for electro-polishing of 9-cell cavities as well as an electron beam welding machine have been set up and are in operation now. Further developments and improvements on components like couplers, tuners, klystrons etc. are ongoing.

Four modules, each containing eight resonators, as well as a module with two superstructures have been tested and operated with beam in the superconducting TTF linac. In addition the accelerator was used as a driver for a SASE free-electron laser (FEL). At present the linac is substantially modified to become a VUV-FEL user facility with tuneable wavelengths in the nm range.

Beginning of 2003 the XFEL project, a 1.4 km long superconducting linac with an X-ray free-electron laser radiation laboratory, has been approved by the German Federal Research Minister. The preparations to start building this machine have been initiated. In addition the high gradient program of superconducting cavities for a future e^-e^+ linear collider is continued.

INTRODUCTION

The TESLA collaboration has presented the design for a superconducting e^-e^+ linear collider with a center of mass energy of 500 GeV and an integrated X-ray free-electron laser (XFEL) laboratory [1] to several international committees including the German Science Council, advising the German government in matters of science. In order to demonstrate the technical feasibility of high gradients in superconducting cavities the TESLA Test Facility (TTF) has been set up at DESY/Hamburg with more than 52 institutes from 12 countries contributing. TTF includes the complete infrastructure for treatment, assembly and test of superconducting cavities as well as a 250 m long linac installation to develop and test machine components.

The TESLA collaboration has demonstrated the reliable production of superconducting 9-cell cavities achieving gradients of 25 MV/m and higher at quality factors $Q_0 \geq 10^{10}$. Gradients of 35 MV/m and above were reached by applying a different preparation technique, i.e. electro-polishing. The gradient of prototype single-cell cavities exceeds 40 MV/m. At present a module equipped with electro-polished 9-cell TESLA cavities is under construction for the TTF linac.

The cavity performance with beam has been investigated while operating the TTF linac as a driver for a SASE free-electron laser (FEL) as well as during dedicated high gradient tests. More than 16.000 hours of operation demonstrated successfully this technology.

SUPERCONDUCTING TESLA CAVITIES

Standard 9-Cell Cavities

The 1.3 GHz TESLA 9-cell cavity is made from solid niobium. After quality control of the sheets fabrication starts from deep drawing. The cups are welded using an electron beam welding machine. Each cavity is equipped with its own helium vessel to be bath cooled with superfluid helium to 2 K. A coaxial RF power coupler, a pickup probe and two higher-order mode (HOM) couplers are attached to each cavity.

The standard cavity treatment used for the last years includes buffered chemical polishing (BCP) as well as annealing at 800°C and heat treatment at 1400°C in presence of a thin titanium layer, both in an ultra high vacuum oven. Final steps are a light BCP, three steps of high-pressure water rinsing (100 bar), and drying and assembly in a class 10 clean room [2] [3].

Between 1993 and 2000 more than 70 TTF cavities have been fabricated at several companies in three series. Tab. 1 lists the achieved gradients at $Q_0 \geq 10^{10}$. Production series 3 has an average gradient of 26.1 MV/m [4].

Table 1: Average acceleration gradient as measured in the vertical test cryostat for the cavities of the three production series. For comparison the TESLA specifications 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	

Fig. 1 shows the excitation curves of all 3rd production cavities treated with BCP. 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 described below.

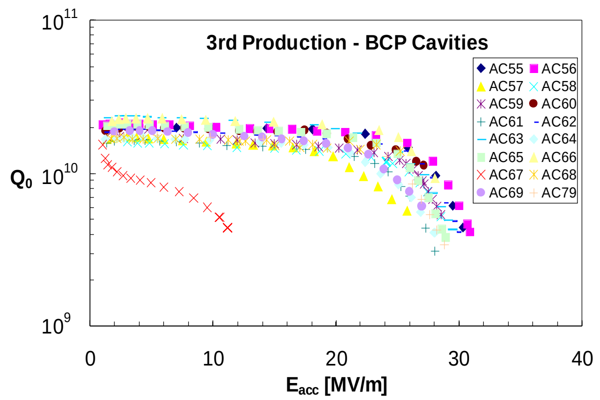

Figure 1: Excitation curves of all cavities of the third production series treated with BCP. The measurements were done in a vertical test cryostat at 2 K.

The complete cavity fabrication process, preparation and test is documented using an ORACLE-based database [5] and an electronic data management system.

High Gradients in Multicell Cavities

The BCP removal of niobium from the inner cavity surface produces a rough niobium surface with strong grain boundary etching. 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 [1]. Together with a succeeding baking at 100 to 150°C of the evacuated cavity, accelerating gradients of 35 to 43 MV/m have been achieved in more than a dozen single-cell resonators [6].

In a collaboration of KEK and DESY electro-polishing of TESLA 9-cell cavities is being studied. As shown in Fig. 2 four electro-polished cavities from the last production achieved the performance needed for TESLA-800: 35 MV/m at a Q_0 larger than 5×10^9. The cavities were tested for several hours at cw-operation.

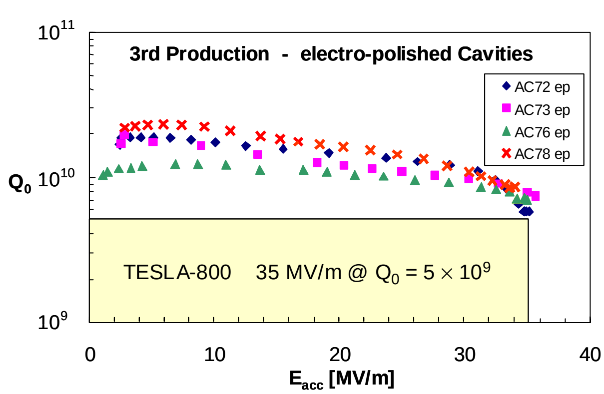

Figure 2: Excitation curve of high-performance 9-cell TESLA cavities treated with EP. The cavities are cooled by superfluid helium at 2 K.

Recently a long term high power test of cavity AC73 has been performed in a horizontal test cryostat [7]. For this purpose the cavity is completely equipped with helium vessel, RF power coupler and frequency tuner as in the TTF module. The cavity has been operated at 35 MV/m for more than 1100 h at 5 Hz and the TESLA puls conditions of 500 µs filling time/800 µs flat top. Neither cavity nor coupler event has interrupted the measurement nor has any degradation in gradient been observed. Fig. 3 summarizes the results. The horizontal measurements confirm the previous results in a vertical dewar within the indicated error bars. In addition a piezoelectric tuner has been operated successfully for more than 700 h to compensate Lorentz force detuning [8].

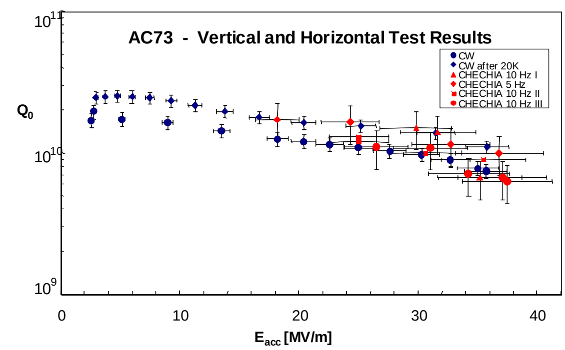

Figure 3: Excitation curves of the electro-polished high-performance 9-cell TESLA cavity AC73 in vertical (cw) as well as horizontal (CHECHIA) tests. The systematic rms errors in the determination of the accelerating field and the quality factor are indicated.

R&D on Single-Cell Cavities

In order study various techniques and parameters during cavity fabrication and preparation an extensive R&D program using single-cell cavities is performed.

Studies of the optimal parameters for the in-situ bake out with respect to temperature, time etc. indicate that bake out temperatures above 120°C result in highest Q values at maximum gradient [9].

Fig. 4 shows the development of the gradient of three single-cell cavities after storage under clean room air of up to 180 days. No degradation could be observed. To avoid field emission caused by assembly and venting, the cavities were high pressure water rinsed before each test.

Electro-polishing was applied at various facilities to check the reproducibility of good cavity performance and prepare the transfer of knowledge for industrial production of large cavity series [10].

Studies on alternative cavity fabrication techniques concentrate on seamless cavities by hydro forming (DESY) and spinning (INFN Legnaro) [11]. Both fabrication techniques reach gradients of up to 40 MV/m in single-cell cavities. Tests of two and three cell cavities are under preparation.

In addition material removal by tumbling is investigated as an alternative treatment to wet etching of the niobium damage layer after cavity fabrication as a more cost effective and environmentally compatible solution.

New material suppliers are in the process to be qualified.

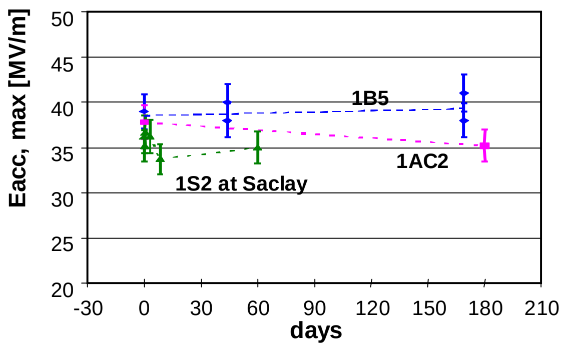

Figure 4: Development of cavity gradient after storage under clean room air.

NEW INFRASTRUCTURE AT TTF

Electron Beam Welding Facility

The new electron beam welding machine at DESY is under operation now. Experiences show, that during electron beam welding the RRR of niobium degrades in the weld area. However the degradation is moderate if the total pressure is below $5 \cdot 10^{-5}$ mbar, a typical value achieved with facilities in industry, and the preparation is done under clean condition. Therefore the new facility was optimised to be operated under clean conditions in the pressure range of 10^{-5}-10^{-8} mbar [12].

Electro-Polishing of 9-Cell Cavities

To further study the EP technique of multi-cell cavities, an electro-polishing facility has been set up [13]. Single-cell structures, TESLA 9-cell cavities as well as the proposed double 9-cell superstructures can be handled. The EP infrastructure has been commissioned and qualified using single-cell cavities reaching gradients close to 40 MV/m. First 9-cell cavities have been polished and further optimisation is ongoing.

Cleaning Facility for Particle Free UHV Components

For accelerators using superconducting cavities of high gradients contamination of the cavities by dust must be absolutely avoided. Therefore cleaning process of the vacuum components for the TTF linac are includes particle removal. To separate the particle cleaning of the UHV components from the cavity treatment a new cleaning facility has been installed inside a clean room [14]. The cleaning process follows similar procedures as for the cavities: fine degreasing of the components using an ultrasonic bath, rinsing with ultra pure water and drying using up to 110º C hot filtered air according to clean room class 100 requirements.

SUPERCONDUCTING TTF LINAC

The construction of the superconducting electron linac is divided into two stages. During phase I, which has recently been completed successfully, a 120 m long set up was mainly devoted to accelerator development [4], a proof of principle experiment of a free-electron laser (FEL) operating in the self-amplified spontaneous emission (SASE) mode [15] as well as FEL user operation.

Starting phase II the linac will become a VUV-FEL user facility with tuneable wavelengths in the nm range after commissioning in 2004. Together with partners of the TESLA collaboration, DESY is presently extending the actual TTF set-up to 250 m length and 1 GeV as shown in Fig. 5. Details of the TTF linac operation and its modifications are discussed in [16].

Phase I

During phase I the TTF linac was operated with up to two 12 m long accelerator modules, each containing a string of eight cavities and a superconducting quadrupole with integrated beam position monitor, as well as one booster cavity.

Five different modules, including the so-called superstructure containing two 2x7-cell structures fed by one RF power coupler [17], were tested with electron beam. No degradation of the cavity performance with time in the TTF linac has been observed. 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.

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

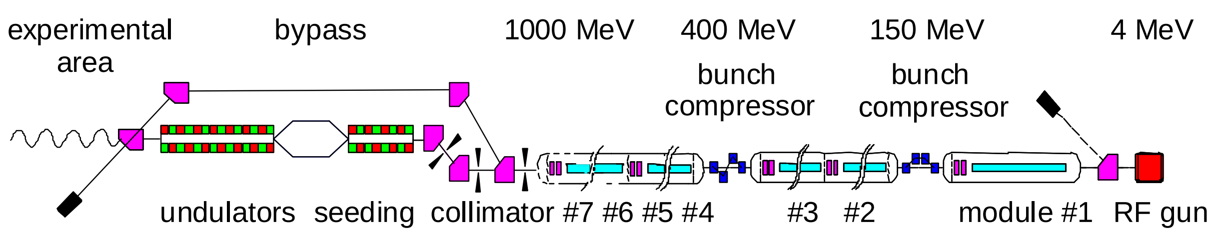

Figure 5: Schematic layout of the superconducting TTF linac for phase II. The electron beam direction in this picture is from right to left.

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.

Phase I of the TTF linac has been completed at the end of 2002 after more than 16.000 h of beam time.

Phase II

As shown schematically in Fig. 5 the TTF linac in its final set-up will consist of an injector area including the laser driven RF gun, several accelerator modules, two bunch compressor sections, a collimator, undulators, and a high energy beam analysis area in parallel to a photon diagnostic and transport section. A bypass line will enable setting up the machine without steering the beam through the undulators.

Recently an RF test without beam of three new modules installed into the linac has been performed. The achieved gradients are within the expectations from previous tests of the cavities in the vertical dewar.

FUTURE PERSPECTIVES

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, a 1.4 km long superconducting linac based on TESLA technology with an X-ray free-electron laser radiation laboratory [18]. Half of the costs are included into the long-term investment program of the government. The ministry announced negotiations on European cooperation to prepare a decision on construction within about two years, i.e. 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 as well as all other components needed. 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.

In addition the R&D program to reach routinely accelerating gradients of 35 MV/m will go on [7]. For this purpose part of the 30 cavities of the 4th production series, which will be delivered beginning of 2004, will be used. The research work on TESLA within the exiting international framework will be continued as well.

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