STATUS OF THE TESLA TEST FACILITY (TTF)

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Abstract

Within the frame of an international collaboration the TESLA Test Facility has been established at DESY to explore the technology needed for a large superconducting linear collider. The key activities are: - to develop quality control of Nb material and fabrication methods for high gradient resonators, - to apply and optimise preparation techniques like ultra clean chemistry, high pressure water cleaning, high temperature firing and high RF power processing, - to develop necessary but critical auxiliary components like couplers, tuners, highly efficient klystrons, - to design and test cryostats being optimised for a very long superconducting accelerator unit, - to build and operate a 1 GeV superconducting test linac. Up to now 23 9-cell cavities have been measured, the highest gradient being 28.5 MV/m. The gun, capture section and the first 8 cavity accelerating unit of the superconducting linac have been put to operation. Details of cavity and component tests as well as experience of the first linac operation are presented.

1. Introduction

Superconducting cavities are under operation in accelerators for electrons or positrons (ß = 1 structures) or for ions (ß < 1 structures). Several proposals suggest this technology also for acceleration of protons (ß < 1 structures). At present the largest installation of superconducting structures operates at CERN. It consists of 240 (final stage 288) four cell resonators at a resonance frequency of 352 MHz [1].

There are two major advantages of superconducting accelerating structures as compared to a normal conducting layout:

- higher accelerating gradients can be established under continuous wave conditions or for l ong pulses,
- larger iris openings are allowed because the shape optimisation is not driven by the need of a high characteristic impedance R/Q as in the normal conducting design. Therefore wake field effects are substantially reduced.

Niobium is the favourite material to build superconducting cavities. The intrinsic properties of this superconductor allow accelerating gradients up to 50 MV/m. Best single cell cavities reached Eacc = 40 MV/m whereas multicell structures with all auxiliary components lack behind in performance. Operating gradients between 5 and 10 MV/m have been demonstrated for low current application (Ibeam ≤ 10 mA), whereas high current cavities operate below 5 MV/m. In the second case, RF power restrictions at the input coupler or the higher order mode dampers limit the gradient. In the first case, the behaviour of the superconducting cavity itself determines the gradient.

There are two major limiting phenomena in superconducting cavities: thermal breakdown of the cavity or loading by field emission from cavity areas with high surface electric fields. The breakdown is the consequence of a thermal runaway, driven by the heat flux of normal conducting areas (“defects”). The preparation of an absolute clean surface, the quality control of the bulk niobium and of welds against foreign inclusions as well as the increase of the thermal conductivity of Nb are the major cures against breakdown. Field emission spots have been localised at mechanical protrusions but more dominant at small particles (10 - 50 µm size, “dust” particles) which both enhance the local electric field strength. Absolute clean surfaces are the most important conditions to avoid field emission.

Within the framework of an international collaboration the TESLA Test Facility TTF [2] has been established at DESY. The aim is to explore the technology of high gradient superconducting cavities and to demonstrate the feasibility of a superconducting linac for a linear collider TESLA (TeV Energy Superconducting Linear Accelerator) [3]. Infrastructure has been established for the investigation and production of high gradient cavities. A 1 GeV test linac will demonstrate the performance of the superconducting accelerating system under realistic beam conditions. In addition to the linear collider application this test linac will be used to set up a FEL source which is based on the amplification of the radiation by the SASE principle (self amplified spontaneous emission).

2. Infrastructure

At present the major activities for the TESLA Test Facility (TTF) are concentrated in a hall of the size 45 m times 90 m (see Fig. 1). The experimental area of the 380 MeV beam is attached to this hall. In a future stage the linac will be upgraded to 1 GeV and will serve mainly as a FEL source. The additional cryostats for the linac will be installed in a tunnel which extends the beam line in down stream direction.

The TTF hall shows three different working areas:

- treatment and assembly of cavities,
- vertical and horizontal tests of superconducting cavities,
- linac installation and operation.

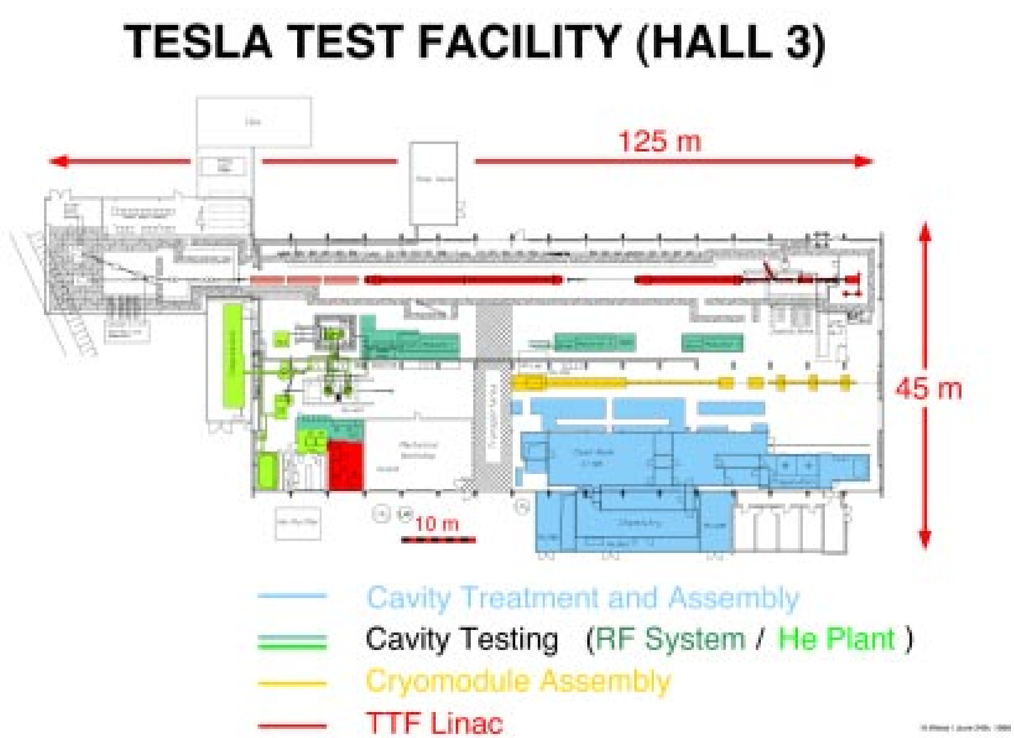

Fig. 1 Experimental hall of the TESLA Test Facility (TTF): chemical processing, clean room assembly and test preparation at the lower right; vertical and horizontal test areas at the lower left; linac installation in the upper half.

The necessary hardware for cryogenic and RF power as well as for 1400 °C firing of cavities is installed in the hall, too. The standard treatment of a 9-cell Nb cavity is as follows:

- RF tuning after fabrication,
- 30 - 50 µm surface removal by buffered chemical polishing (BCP),
- 1400 °C heat treatment of the Nb cavity together with a Ti cylinder in order to improve the thermal conductivity of the Nb and to homogenise the bulk material. After firing the Nb is very soft (the yield strength decreases from typically 60 N/mm to 20 N/mm) so that careful handling is needed not to deform the shape of the structure. Therefore some cavities were also measured after a first heating at only 800 °C;
- 100 µm surface removal by BCP. Ti will migrate along the grain boundaries during firing and must be removed to avoid additional RF losses;
- final RF tuning of the structure,
- last cleaning by 20 µm surface removal by BCP,
- cleaning of the inner surface by high pressure water,
- drying and assembly in class 100 clean room,
- vertical measurement (acceptance test for the cavity),
- welding of the LHe tank (Ti cylinder),
- horizontal measurement of the completely equipped cavity (input coupler, higher order mode couplers, tuner), acceptance test for installation in the module,
- assembly for the accelerator module.

3. Results of First Cavity Production

In total 23 9-cell cavities (see Fig. 2) from four different companies have been measured up to the autumn of 1997. Nine of these cavities reached accelerating gradients above 20 MV/m (see Fig. 3). Four cavities were only limited by available RF power, including the best cavity with Eacc = 28.5 MV/m. All 6 cavities of one company experienced an untypical slope in the Q vs. Eacc measurement (see Fig. 4). All cavities quenched between 11 and 14 MV/m. The problem could be localised at the equatorial weld and was traced back to insufficient cleaning and not adequate welding [4]. One additional cavity was produced by this company with improved handling and welding conditions. It showed good RF performance, limited at 25 MV/m by available RF power.

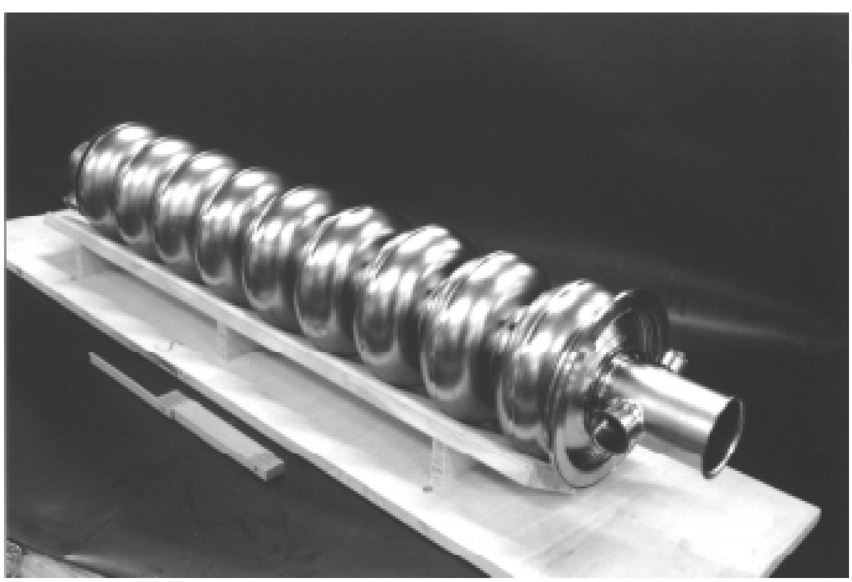

Fig. 2 9-cell TTF cavity. On the right beam pipe the port for the input coupler (front side) and the HOM coupler (back side) can be seen.

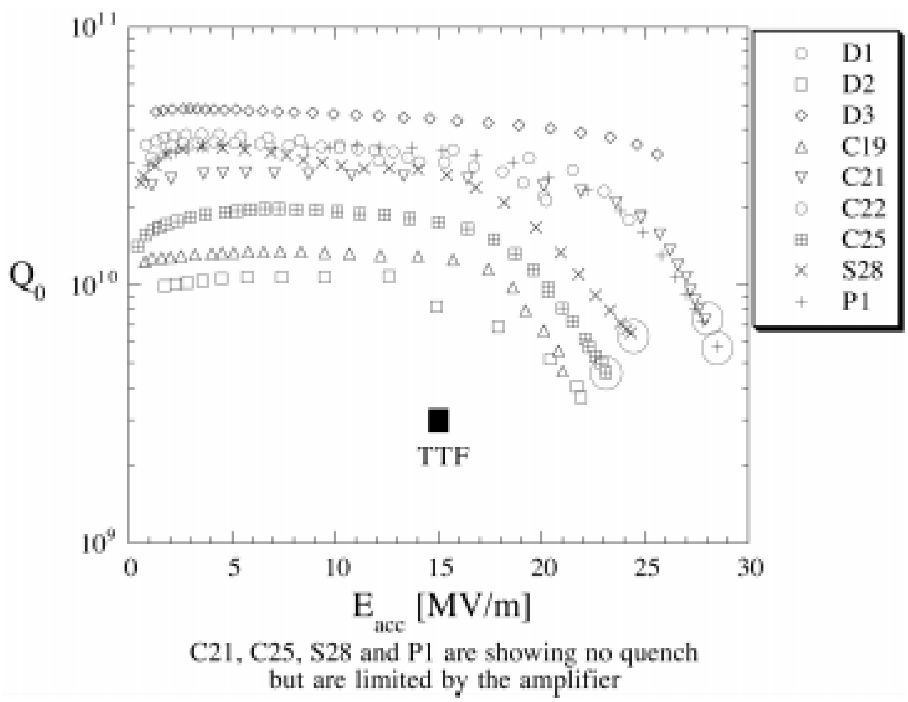

Fig. 3 Performance of “good” cavities in the vertical measurement. Four cavities (C21, C25, S28, P1) were limited by available RF power. The typical decrease of the Q value at high gradients is due to field emission.

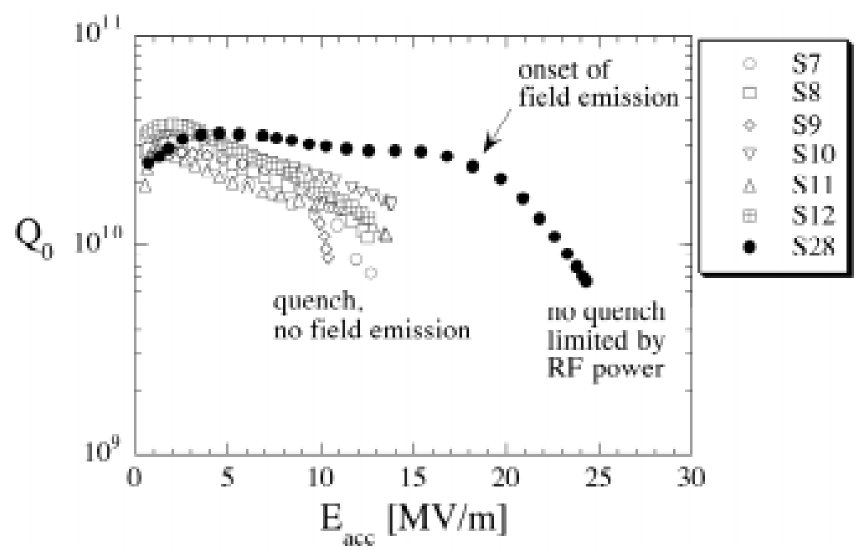

Fig. 4 Performance of 6 cavities from one vendor: decrease of the Q value at low gradients (but no field emission) and early thermal breakdown between Eacc 10 to 14 MV/m. The defects were localised at the equatorial welding and could be traced back to improper cleaning and not optimised welding parameters. One more cavity was fabricated with improved fabrication conditions and showed excellent performance (S28).

Two cavities quenched below Eacc = 10 MV/m. They did not improve after 1400 °C firing or more surface removal by BCP. One of these cavities was cut and the quench location was investigated. X-ray photography and eddy current measurements indicated a local contamination by foreign material in the bulk Nb. Qualitative and quantitative measurement by Roentgen Fluorescence identified a 300 µm x 300 µm cluster of Ta (content about 3000 wppm) [5].

In Fig. 5 the benefit of low and high temperature firing is demonstrated. After some surface removal by BCP the cavity quenched at Eacc = 16 MV/m. After 800 °C heating the quench location (at the overlap of the equatorial weld) was not changed, but a higher field of 20 MV/m could be gained. After additional 1400 °C Ti firing the maximum gradient could be raised to Eacc = 28.5 MV/m, limited by available RF power. The typical decrease of the Q value at high gradients was caused by field emission, marked by the onset of g-radiation. Similar improvements by the 1400 °C firing has been reported by other laboratories, too. It is known, that the impurity content is high at the front of the molten zone, when welding the equatorial path. The impurities are frozen in the bulk when stopping the welding action. Most likely these impurities give raise to enhanced losses and thus trigger a quench. Contaminations by oxygen or nitrogen will not dilute at 800 °C but at 1400 °C because of the exponential dependency of the diffusion constant from temperature.

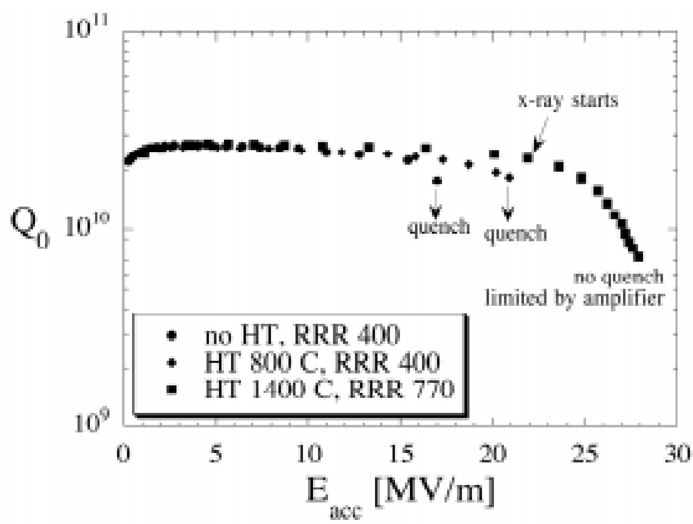

Fig. 5 Performance of a cavity after chemical cleaning, additional heating at 800 °C and additional firing at 1400 °C (Ti treatment). The quench was localised at the overlap of the equatorial weld. It improved slightly after 800 °C heating. After 1400 °C firing, the cavity field increased to Eacc = 28 MV/m, limited by available RF power. The RRR value (residual resistance ratio) is a measure of the purity, and thus of the thermal conductivity l of the material (RRR = 4 x $\lambda_{4.2K}$).

Three other cavities were limited by thermal breakdown between 15 and 20 MV/m, but were not investigated further. Two more cavities showed severe defects at the equatorial welds due to mistake during welding.

4. Vertical Test to Linac Installation

After the vertical test the Nb cavity (see Fig. 6) is welded into a tank, made from titanium (to match the thermal expansion of the niobium). In the linac cryostat, this tank is filled and pumped from the top with 1.8 K helium (see Fig. 7). One should note, that input and higher order mode couplers are placed outside the liquid room and are cooled only by conduction. The tuner consists of a stepping motor, gear box ("harmonic drive") and a level arm construction. The total length of the cavity can be changed by ± 3 mm (@± 1 MHz) at a resolution of a fraction of 1 Hz. The complete tuner is placed at the 4.2 K level (see Fig. 6). The input coupler consists of a coaxial line, a "cold" window at 70 K (conical disc or cylindrical arrangement for the two alternative designs), a transition from coax- to rectangular waveguide at room temperature and a second window in the waveguide section.

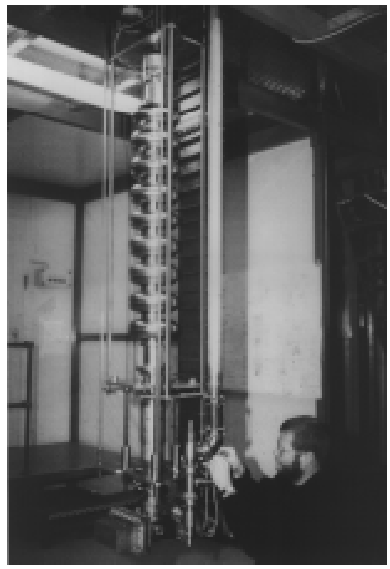

Fig. 6 Vertical test stand for acceptance test of the 9-cell cavities. The rectangular waveguide parallel to the cavity will transport RF power for high power pulse processing (HPP)

Fig. 7 A 9-cell cavity is welded into the LHe tank (lower cylinder). The cold end of the input coupler is visible at the right end, the tuner is assembled at the left end, the LHe line is shown on top of the structure.

After the helium tank welding, the Nb cavity will be slightly etched by a short BCP and cleaned again by a high pressure water cycle. The complete cavity with all couplers and its tuner is measured at cold in a horizontal cryostat. During this test, the cavity will be operated as in the linac: 530 µsec at 200 kW forward power for filling the resonator, a flat top of Eacc during 800 µsec and a decay of the cavity field after switching off the klystron. Because of the missing beam current in the horizontal test, the forward klystron power is ramped down by a factor of four during flat top. Conditioning of the input coupler for two days was needed to reach the design power level. The cavity losses and thus the unloaded Q value is determined by heat load measurements in the 1.8 K circuit. The accelerating gradient is determined from the measured forward power and the cavity reflection coefficient. Following this successful system test the eight cavities were assembled together in the clean room (see Fig. 8). After closing the beam vacuum of this string of eight cavities and one quadrupole, the following assembly work (diagnostic cables, radiation shields, thermal links, alignment arms, insertion into the vacuum vessel) is done outside the clean room (cryostat design, see Fig. 9 , Fig. 10). The assembly time of the first module summed up to 4 weeks in the clean room and 8 weeks outside. After placing the module at the beam line, three weeks were needed for cool down, coupler processing, and adjustment and calibration of electronics. Just one day was necessary to steer the beam through the module and establish stable accelerating conditions.

Fig. 8 Assembly of a string of 8 9-cell cavities and one quadrupole during handling in the clean room.

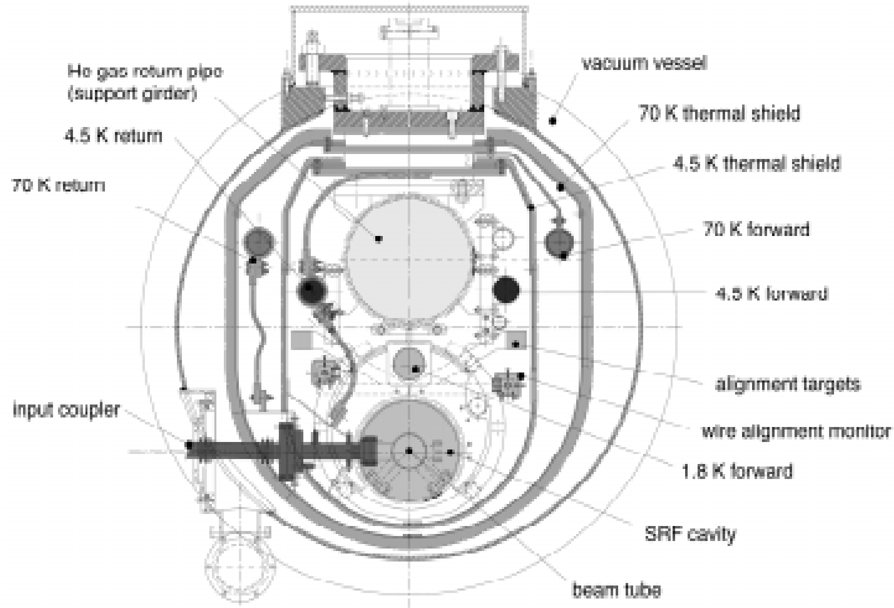

Fig. 9 Cross section of the cryostat for TTF

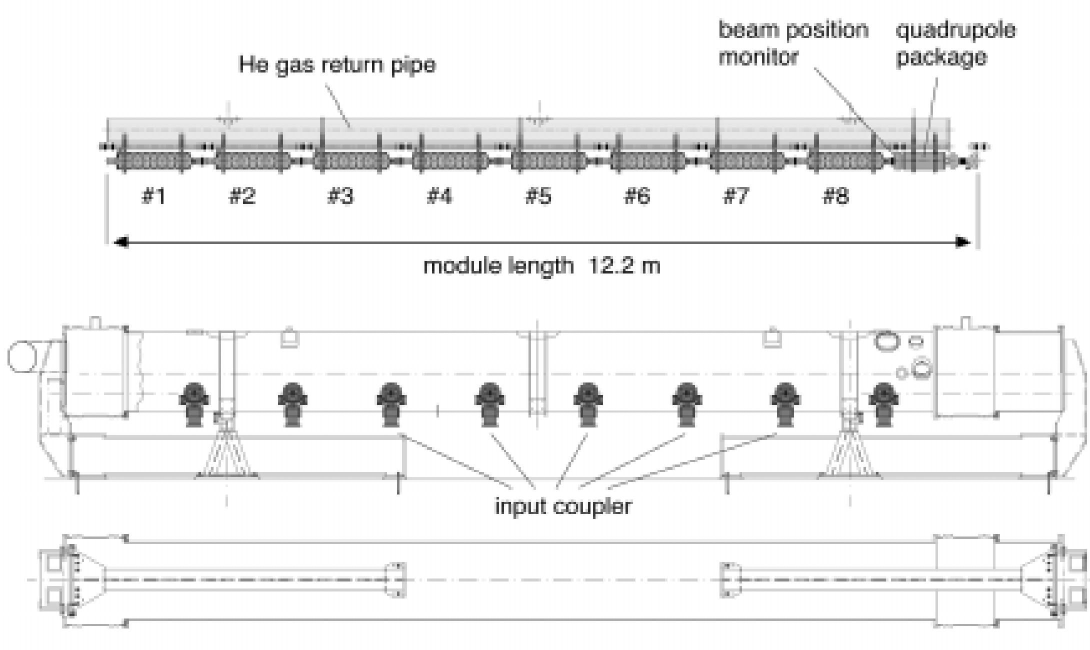

Fig. 10 Longitudinal cut through one module (8 cavities, one quadrupole) of the TTF cryostat.

5. Linac Operation

The following weeks many experiments with beam were carried out under the following conditions: beam pulse 30 - 40 µsec (limited by safety considerations due to some beam loss along the 100 m beam line), 100 µsec to 800 µsec flat top of cavity voltage and an average accelerating gradient of Eacc = 15 MV/m (max Eacc = 16.7 MV/m for short RF pulses).

The achievable gradient of the cavities in the vertical test and in the module are compared in Fig. 11. In the case of field emission loading the cryogenic losses will increase dramatically when surpassing the onset of field emission. Therefore an upper limit of 100 W of loss power for continuous operation and 1 W for pulsed operation (duty cycle is about 1 %) is accepted. Six out of nine cavities (eight cavities in the module, one cavity in the capture section) showed nearly unchanged performance. One cavity (DO2) reached a higher gradient because the time constant of the thermal breakdown is longer than the RF pulse in the module. Two cavities degraded (DO3, C19) due to enhanced field emission. One of these cavities (DO3) could be recovered at the end of the beam run by RF pulse processing.

The RF voltage in the flat top was stabilised in amplitude and phase to better than 0.5 ‰ and 0.003°, respectively, by a combined feed back and feed forward compensation (see Fig. 12). The second system samples the transfer functions of the beam to cavity voltage coupling by small steps in the forward RF power during the macro pulse of 800 µsec. With knowledge of the inverse function the transient effects of the micro beam pulses can be reduced accordingly.

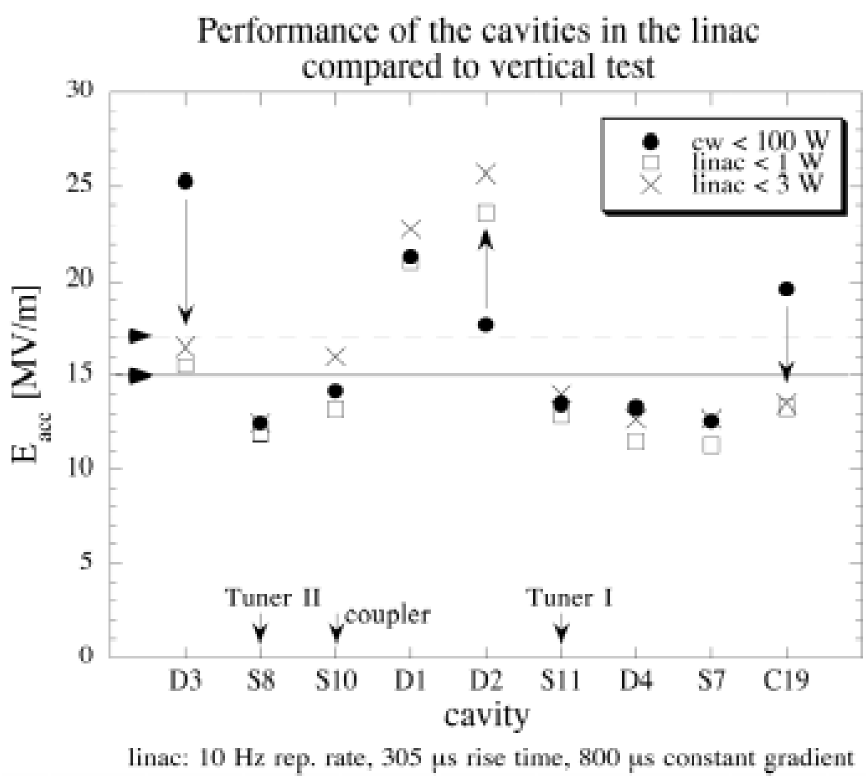

Fig. 11 Performance of the cavities in vertical tests (dark circle) and in the linac module (cross, open square). The gradient Eacc is noted just below thermal breakdown or at the onset of field emission. The cavity D2 upgraded in the linac operation because the time constant of the thermal breakdown is longer than the linac RF pulse. Cavities D3 and C19 degraded because of enhanced field emission.

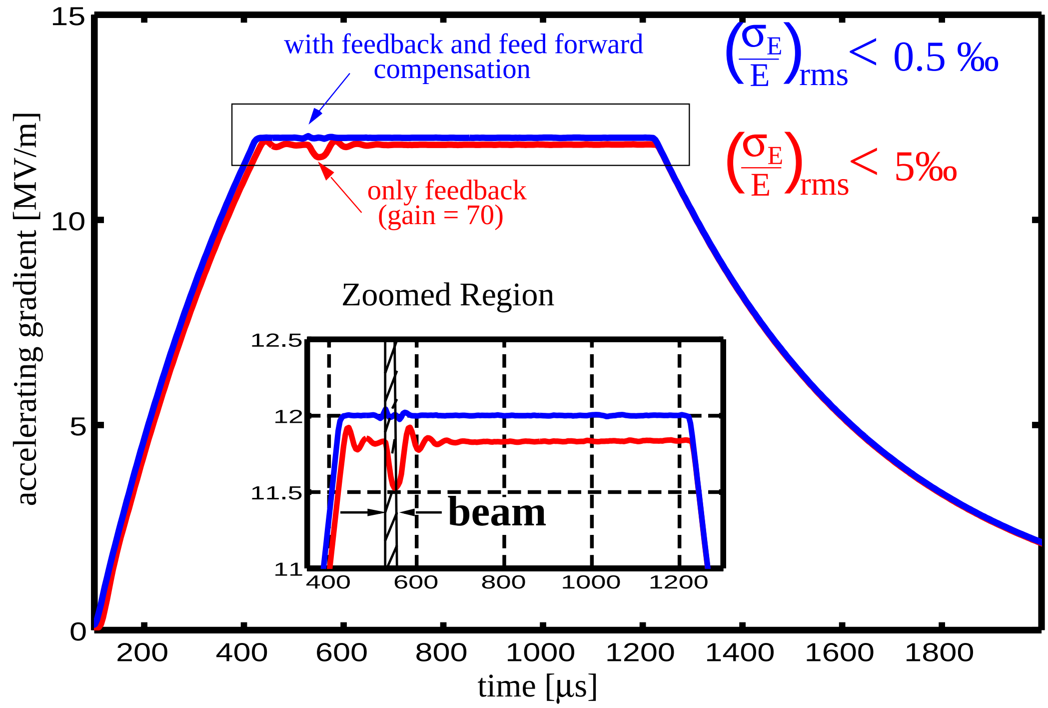

Fig. 12 Cavity voltage during pulsed operation with beam. The fluctuation of the cavity voltage is smaller 5 ‰ with feed back and reduced to smaller 0.5‰ with additional feed forward compensation.

Microphonics can be a danger for high Q cavities. It might be driven by external sources of noise (e.g. rotating pumps in the vacuum or cryogenic hardware) and will cause large fluctuations in cavity voltage amplitude and phase. Therefore an intensive search for microphonics was undertaken at all 8 superconducting cavities in the module. After switching off the generator power, the field in the cavities will decay at its resonance frequencies. This frequency was measured many times for each resonator and was statistically evaluated. Fig. 13 shows a typical result of such a measurement. The number of measurements is plotted versus the deviation from the nominal frequency (1.3 GHz). If the resonator experiences a sinusoidal vibration the resultant modulation of the cavity resonance frequency will lead to a symmetric population off the centre of the undistorted case. If the cavity does not vibrate, all frequency measurements should centre at the nominal frequency. In all measurements the undistorted case (as in Fig. 13) was observed so that microphonics was not present at the first module.

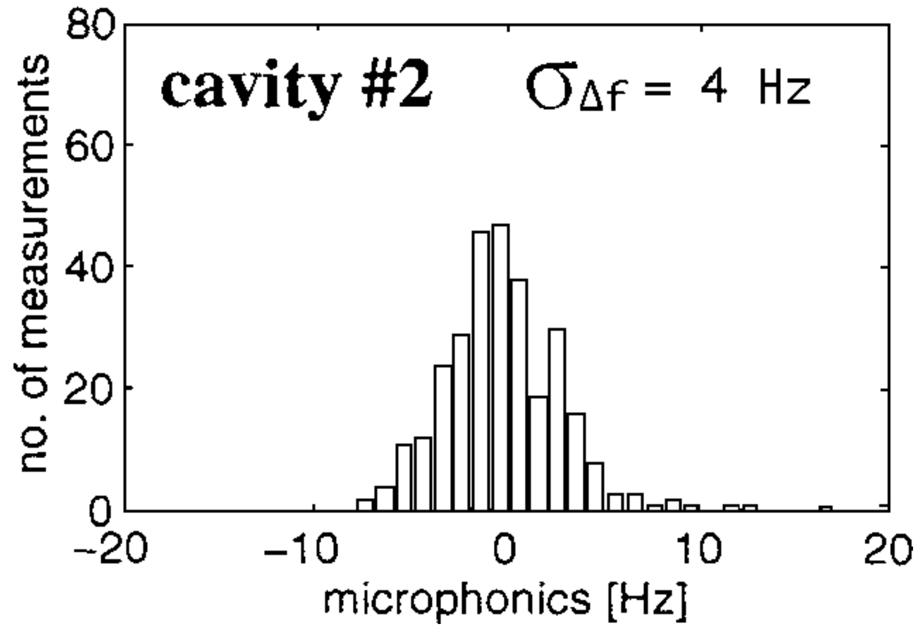

Fig. 13 Result of the search for microphonics: the resonance frequency of a cavity in the module is measured and statistically evaluated. No microphonics is present because the frequencies are centred around the nominal value.

Two problems were encountered during operation of the superconducting module: a warm window of one coupler sparked at 250 kW so that this cavity was disconnected from the RF power. This sparking has been identified and is due to an unfavourable geometry of the window ceramic next to the brazing area [5]. A modified design avoids this problem and has also been successfully tested up to 800 kW. But the tight assembly schedule of the first module did not allow an exchange before the first cool down.

Two tuners blocked during operations. At the end of the beam time the module was warmed up, opened and both tuners were examined. Parts of the harmonic drive showed extraordinary wear, indicating that lubrification at cold was not sufficient. Following tests with coatings by TiN and WS2 demonstrated proper functioning now.

6. Second Cavity Production

The remaining cavities of the first production will be installed in the second module. The next three modules will be equipped with cavities from the second production. Four companies started to produce 26 more resonators. All 721 new Nb sheets have been scanned by eddy current (see Fig. 14). The apparatus has been developed in collaboration with BAM (Bundesanstalt fuer Materialpruefung, Berlin). The eddy current signal depends on the conductivity of the scanned material. Any change by foreign inclusions, clusters, laminations, cracks etc. will be detected. Suspicious sheets were sorted out and investigated further by other quantitative and qualitative methods (x-ray, roentgen fluorescence, neutron activation) [6]. The defect rate is low but differs considerably between Nb vendors. The highest rate of defects was due to Fe inclusions in the bulk Nb.

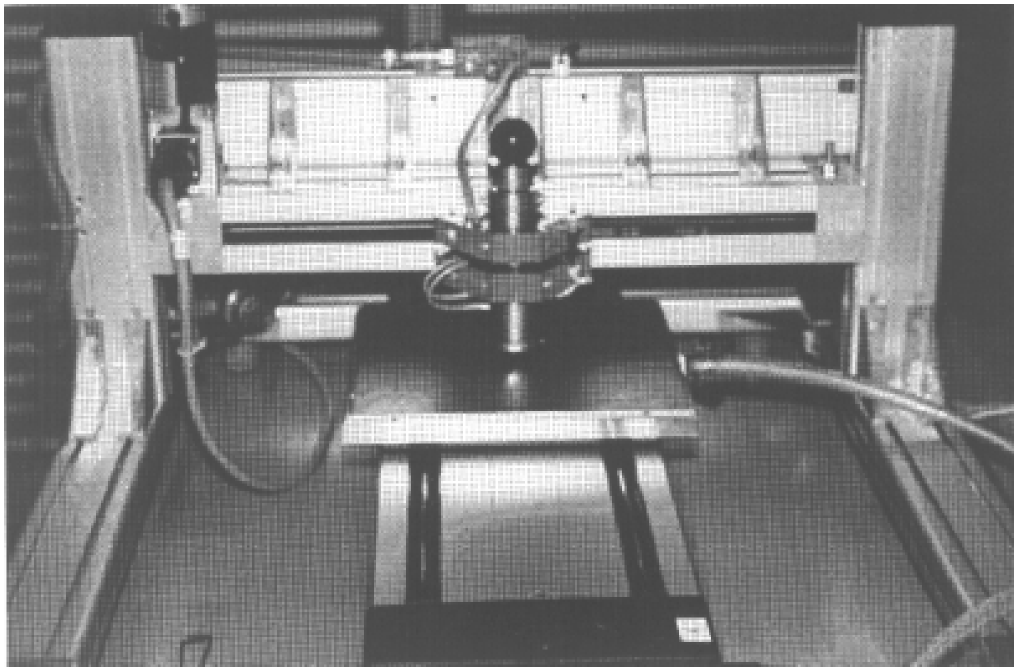

Fig. 14 Eddy current scanning apparatus for quality control of Nb sheets.

The analysis of the RF measurements of 9-cell cavities from the first production uncovered that in many cases only one cell (or only one half cell) limited the performance of the whole structure [7]. Defects have been localised in the bulk Nb or in equatorial welds. Quality control of the Nb material by eddy current should therefore raise the average value of cavity performance. The majority of the new cavities will be delivered until early summer 1998, so that assembly of module 3 will start in May that year.

7. Further Developments and Next Plans

Pulsed klystrons are on the market which deliver 5 MW, 2 msec at an efficiency of 45 %. A development contract has been placed with one company for the design of a multibeam tube with 10 MW output power. According to simulation codes, an efficiency of larger than 70 % should be possible. The first prototype tube is under construction and should be delivered before the end of 1998.

There is activity to fabricate seamless Nb cavities:

- At Legnaro single cells, one 4-cell and one 5-cell cavity have been fabricated recently by spinning [8]. The first single cells reached gradients above 20 MV/m, but the Q value degraded above 15 MV/m [7]. Heat treatment at 1400 °C and more chemical cleaning will be investigated in the near future.
- At DESY hydroforming is investigated for Nb cavity production. The main difficulty is the lack of “good” Nb tubes: non uniform mechanical properties result in early rupture during forming. Different ways of adequate tube production are tried out at several Nb producers.

The present operating experience with input couplers for TTF indicates two major problems: multipacting in the coaxial line and degassing of the ceramic or of copper plated parts. Multipacting can be eliminated by the choice of a larger coax diameter because multipacting resonances scale with the fourth power of dimensions [9]. Also a DC bias between both conductors will suppress multipacting if the geometry cannot be changed. Degassing of coupler parts will create a bad vacuum and initiates sparking. Fig. 15 shows the latest version of the input coupler for TTF [5]: an enlarged coax diameter in the warm part and DC bias for the smaller "cold" part will suppress multipacting. Consequent heating of all parts at 950 °C and clean handling should reduce the risk of sparking. A somewhat simplified prototype was measured up to 1 MW at 1.3 msec pulse length, limited by RF power restrictions.

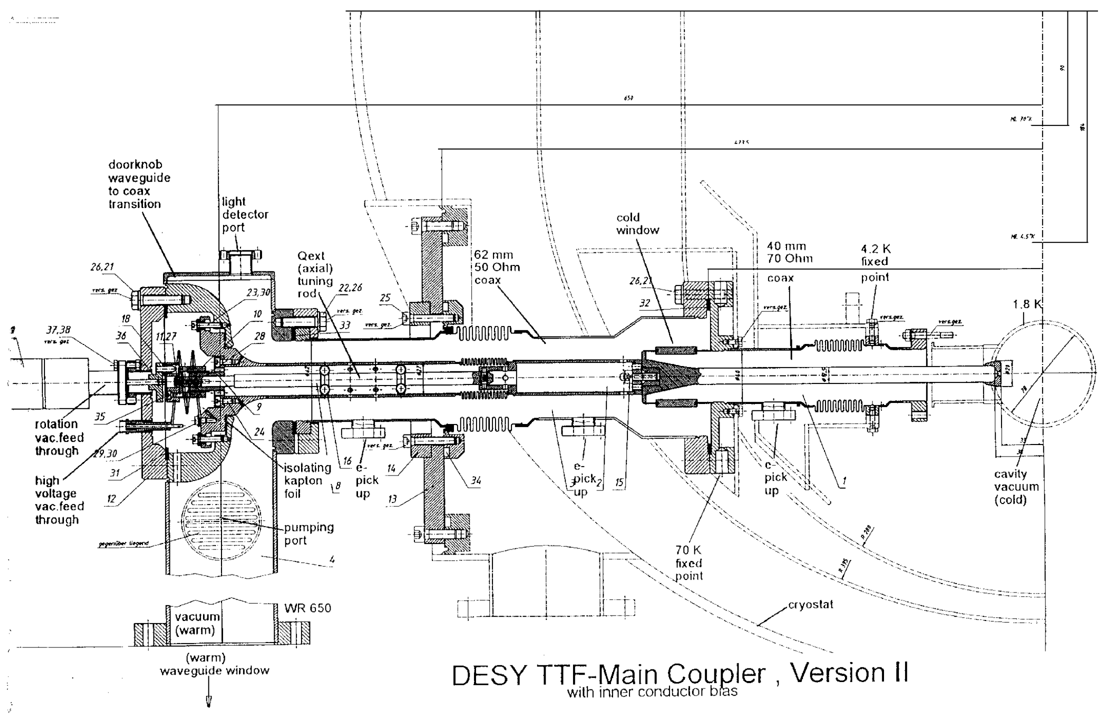

Fig. 15 Improved input coupler for TTF: the cold window is of cylindrical shape; the inner coaxial line will be biased with a DC voltage of 3 kV in order to suppress multipacting in the small diameter coax line next to the cavity.

The milestones of the TTF linac installation and operation are:

- second beam test with module I will start in February 1998,
- installation and test of the photo gun during spring 1998,
- module II and module III ready in late summer 1998,
- installation of the bunch compressor late summer 1998.

Acknowledgement

Support of data from and helpful discussions with members of the TTF collaboration are gratefully acknowledged.

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