Recent Progress at the TESLA Test Facility

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The goal of the TESLA Test facility [1] is to demonstrate the feasibility of a 500GeV e^+e^- Linear Collider with an integrated X-Ray-FEL based on 9-cell superconducting accelerating L-band structures with accelerating gradients in excess of 25 MV/m. Presently there are two cryogenic modules in operation. We report on latest results of cavity preparation, progress in the development of a 10 MW multibeam–klystron and on the first observations of 80–180 nm Self-Amplified Spontaneous Emission (SASE) FEL radiation.

INTRODUCTION

A picture of the TESLA Test Facility is shown in Fig. 1. The injector [2] of the test accelerator consists of a laser-driven photocathode in conjunction with a normally conducting 1½-cell 1.3 GHz cavity. It is operated at a gradient of 37 MV/m. The rf power fed into this cavity is 2.5 MW. It is generated by a conventional 5 MW klystron. A second 5 MW klystron is used for cavity and coupler conditioning on various test stands. The injector is followed by a 9-cell superconducting capture cavity. The latter is housed in an individual cryostat and typically operated at 12 MV/m. The necessary rf power in the range of 100 kW is generated by an individual VALVO YK 1204 klystron.

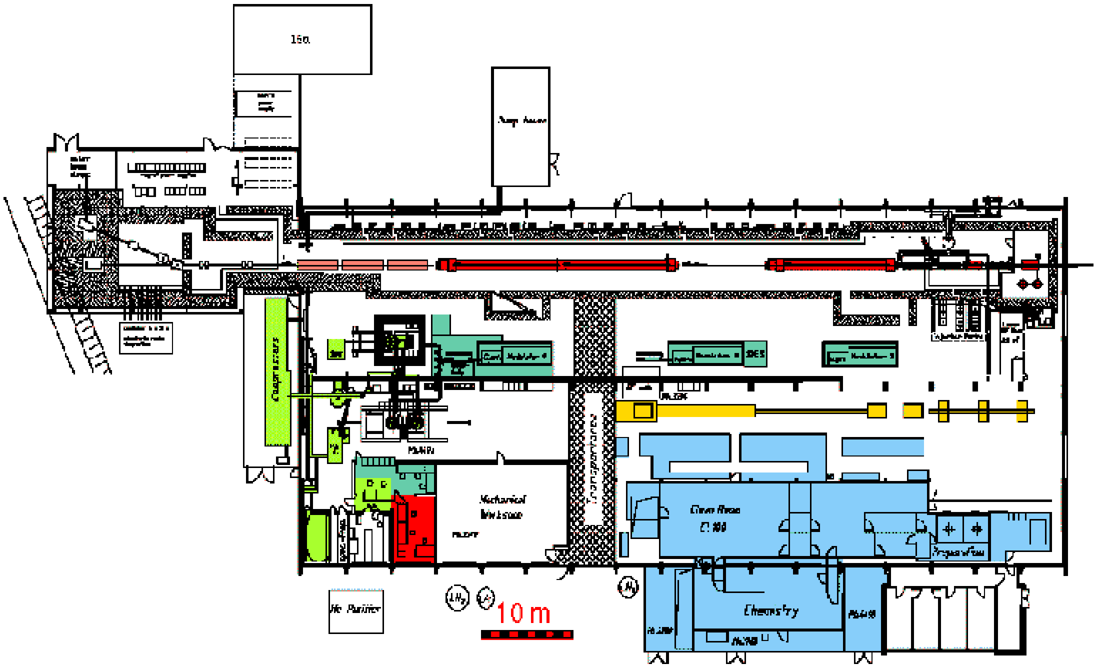

Figure 1: The TESLA Test Facility.

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There is also a large cleanroom area ranging from class 10000 down to class 10 visible in fig.1 since special emphasis has been given from the beginning in 1991 to procuring a dust free environment for cavity preparation. The cavities equipped with all high rf-power input couplers, higher order mode damping antennas and rf pick-up probes are closed off by all metal sealed flanges in the class 10 area before leaving the cleanroom and prior to cryogenic tests. The cleanroom area also houses facilities for high-pressure rinsing with ultra pure water, chemical treatment and an 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.

The two subsequent cryogenic modules are separated by a bunch compressor and followed by a three stage undulator [3] with a total length of 14.1 m. There are eight 9-cell cavities in each Module. The length of a module is 12.2 m. The achieved average gradient in one module is 23.5 MV/m and 18 MV/m in the other one. The two modules are powered by a newly developed 10 MW multibeam klystron.

A third module, where all cavities have been successfully conditioned to gradients larger 25 MV/m, is ready for installation into the accelerator tunnel.

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 71 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, and so far 16 cavities of a third series have been delivered to DESY in 2000.

Already in the first series the strict observance of clean treatment showed success by reaching gradients of 25 MV/m at Q values above $5\cdot10^9$ 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 normal conducting grains in the niobium.

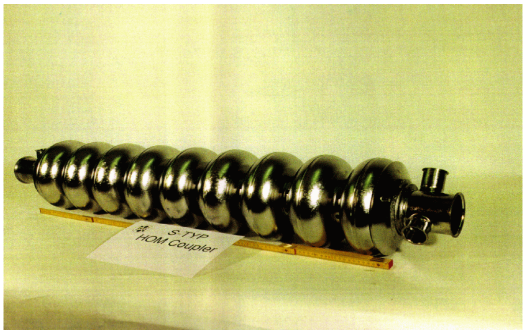

Figure 2: A 9-cell cavity.

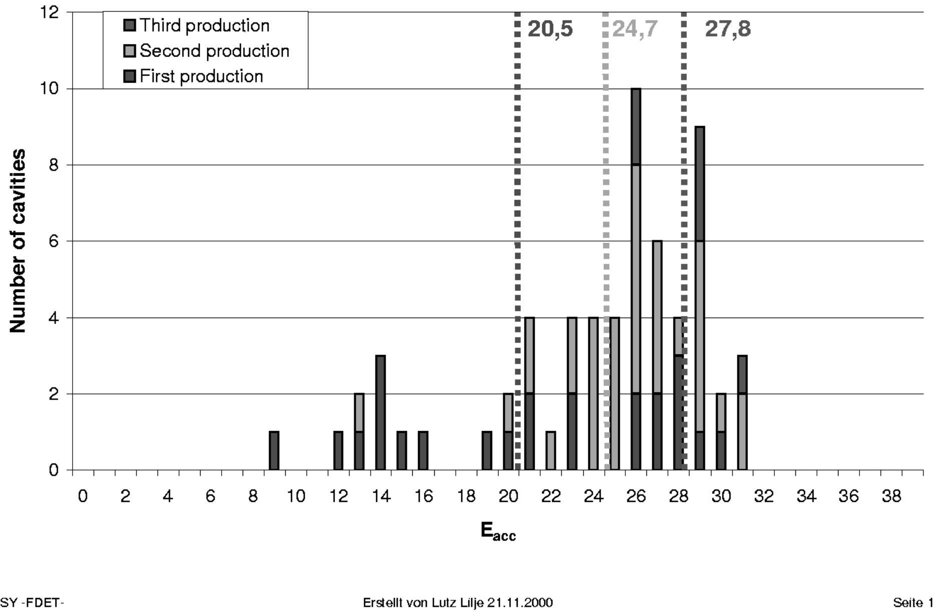

Figure 3: Maximum gradient of all 9-cell cavities measured in vertical tests during the past 5 years.

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 [4]. The success of these measures can be seen in fig. 3 where the maximum measured gradient is shown for all 9-cell cavities measured up to now.

Part of the increase in gradient can certainly also be attributed 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 $Q=5 \cdot 10^9$.

The progress in cavity production, treatment and handling is also manifested by the reduced scatter in cavity performance when looking at the three production series. For the first one the results range from 9 to 30 MV/m while the last series is located between 26 and 31 MV/m.

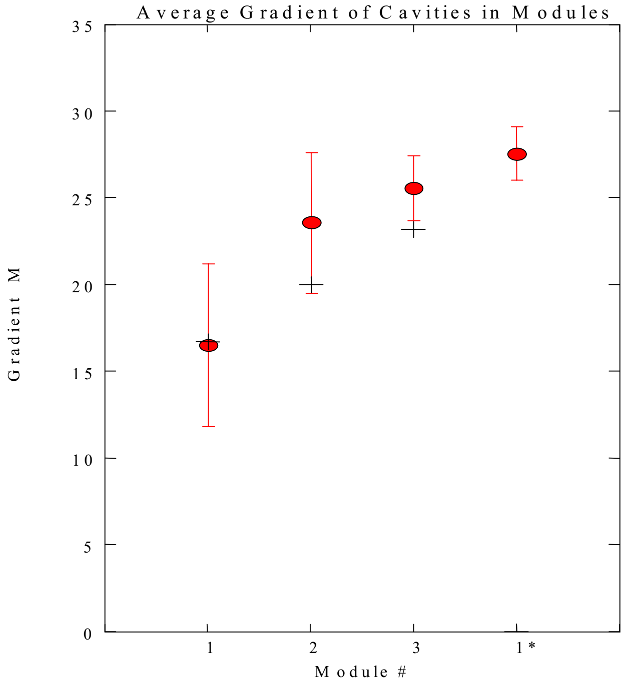

Figure 4: Average gradient, as measured in vertical tests, of the 9-cell cavities assembled into accelerator modules. Crosses indicate the gradients obtained in the module. The fig. has been taken from [6].

The same behaviour is apparent from fig. 4, where the average gradient measured in the vertical test cryostat of the cavities, which were installed into the three accelerating modules is shown. Mo-dule # 1 has been disassembled in the meantime and been equipped with new cavities after a modification [5] of the cryostat (module # 1*).

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 [6].

FURTHER R&D ON S.C. CAVITIES

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 [7] with electropolishing single cell niobium cavities, obtaining gradients close to 40 MV/m. In contrast to the chemical etching (Buffered Chemical Polishing) applied to the cavities at TTF, which leads to a rather rough surface, electropolishing leads to a very smooth and shiny surface [8].

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 [9].

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 [10]. 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 [11]. Very recently up to 43 MV/m were obtained on electropolished single cell cavities, see fig. 5.

To transfer these findings to 9-cell cavities, work is going on at KEK and is also underway at DESY, and CERN.

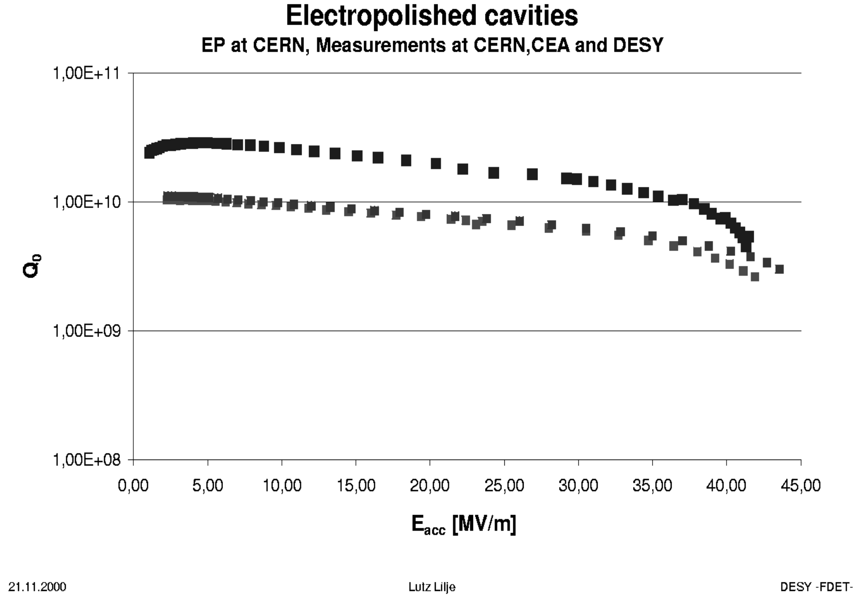

Figure 5: Results on electropolished single cell cavities. The fig. is taken from [12].

FIRST RESULTS ON THE 10 MW MULTIBEAM-KLYSTRON

At the time when the TTF activities began, the most attractive L-band klystron available on the market was the Thomson TH 2104 C tube. This conventional cathode pulsed (there is no modulating anode) 1.3GHz tube is capable of delivering 5 MW peak rf power at the maximum pulse length of 2 ms. The maximum repetition rate is 10 Hz. The electronic efficiency is typically 45%.

Since, at this power level, for TESLA over 1200 tubes would be needed we decided to trigger the development of a 10 MW tube with increased efficiency close to 70%. The resulting cost saving is considerable since also the number of klystron modulators including pulse transformers is halved, and, furthermore, the operation cost is reduced substantially. The average ac power consumption for producing the rf of the 500 GeV version of TESLA is about 80 MW.

To achieve an efficiency in the 70% range the tube perveance must be near .5 10^{-6}. For a single beam klystron this implies a gun voltage of 240 kV. The design of a gun at this voltage level would be very critical because of the long pulse length of 1.5 ms.

Therefore we favoured the solution of a multibeam-klystron with 7 beams, each having the microperveance 0.5, which was proposed by Thomson. The successful commissioning of the prototype tube took place at DESY in May 2000. Now the tube has been running for about 1000 hours in routine operation. The nominal gun voltage and current are 117 kV and 131 A respectively. There are two output windows. The maximum measured output power is 10 MW, the measured efficiency is 65% and the gain is 48.2 dB.

TTF – FEL OPERATION

During the last year acceleration to the maximum energy of 280 MeV of a 1 nC beam was achieved with 99% transmission through the entire linac and through the undulator section. For a 8 nC beam the transmission was slightly below 90%. Since our beam transmission interlock has not yet been fully commissioned the beam pulse length was limited to 30 microsec. during the entire run to avoid damage of the undulator or other elements. The time interval between micropulses is 1 microsec. The macropulse repetition rate was 1-5 Hz. In the gun rf pulse lengths up to 800 microsec, were achieved, and in the cryogenic modules also the full rf pulse length of 0.54 ms filling time plus 0.8 ms flat top have been demonstrated.

Different techniques have been used to measure the emittance of the electron beam [13,14]: Magnet optics scanning ("quadrupole scans"), tomographic reconstruction of the phase space including space charge effects, and the slit system method. All methods use optical transition radiation emitted from aluminum foils to measure the bunch profiles and yield values for the normalized emittance of (4±1) π mrad mm for a bunch charge of 1 nC at the exit of the injector.

A bunch compressor is inserted between the two accelerating modules, in order to increase the peak current of the bunch up to 500 A, corresponding to 0.25 mm bunch length (rms) for a 1 nC bunch with Gaussian density profile.

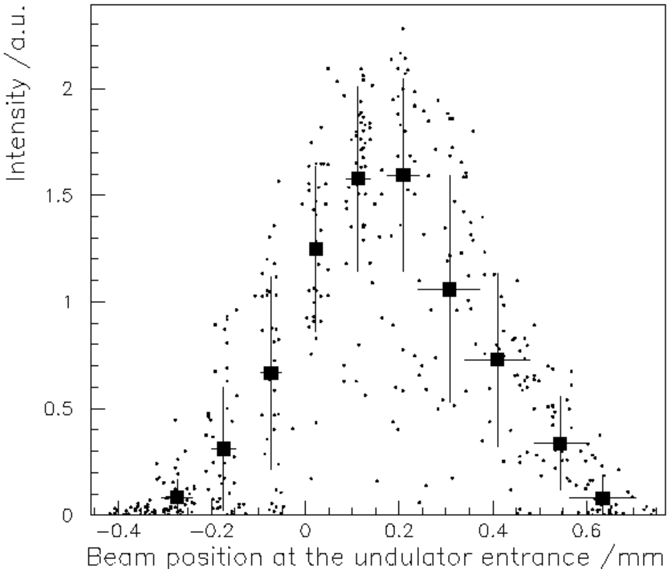

Figure 6: Sensitivity of radiation power to horizontal electron beam position at the undulator entrance. The dots represent mean values of the radiation intensity for each beam position. The horizontal error bars denote the rms beam position instability while the vertical error bars indicate the standard deviation of intensity fluctuations, which are due to the statistical character of the SASE process. The figure has been taken from [15].

A strong evidence for the FEL process is a large increase in the on-axis radiation intensity if the electron beam is so well aligned that it overlaps with the radiation during the entire passage through the undulator. Fig. 6 shows the intensity passing a 0.5 mm iris, located on axis 12 m downstream of the undulator, as a function of the horizontal beam position at the undulator entrance. The observed intensity inside a window of ±200 µm around the optimum beam position is a factor of more than 100 higher than the intensity of spontaneous radiation. This intensity gain was first observed with the photodiode and later confirmed with the CCD camera of the spectrometer. The central wavelength for this first SASE demonstration at the TTF FEL was 108.5 nm [15].

The wavelength of 108.5 nm was consistent with the measured beam energy of (233±5) MeV. From the user point of view a most important feature of FELs starting from noise is the tunability of wavelength. At TTF FEL this was demonstrated by tuning the electron beam energy between 272 MeV and 181 MeV, corresponding to wavelengths from 80 nm to 181 nm.

Within this range, SASE was achieved at several energies, see Fig. 7. Typically, a SASE gain (for definition see [15]) above 1000 was observed.

SUMMARY

The design goal of the TESLA Test facility to demonstrate the possibility of routine operation at 15 MV/m with superconducting 9-cell cavities has been more than achieved. We have reached average accelerating gradients in the cryomodule up to 23 MV/m. Average gradients well above 25 MV/m have been achieved for the 9-cell cavities from the latest production series. For electropolished one-cell cavities up to 43 MV/m have been reached.

The rf source for TESLA, the 10 MW multibeam-klystron has produced full power at 65% efficiency, and it has been operating now at the TTF for over 1000 hrs.

We have demonstrated high gain SASE at wave lengths ranging from 80 to 181 nm.

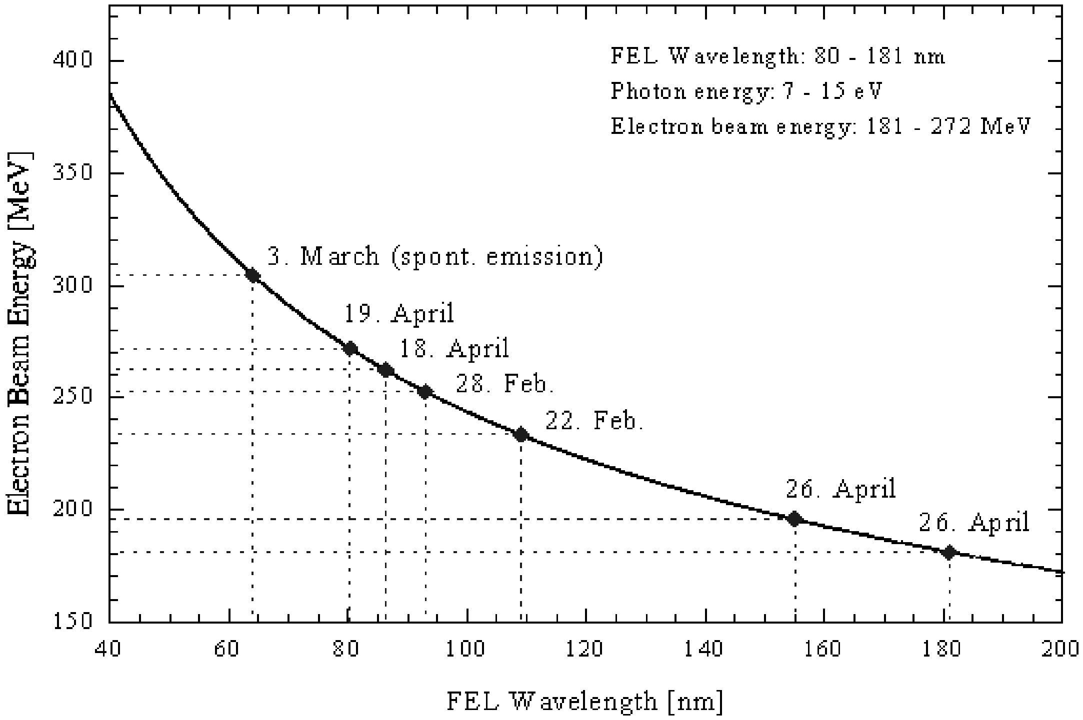

Figure 7: Wavelength of the central radiation cone (collimation angle ±0.2 mrad) as a function of electron beam energy. The FEL gain was typically >1000. The bunch charge was 1 nC. The fig. has been taken from [16].

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