OPERATIONAL EXPERIENCE WITH THE TEST FACILITIES FOR TESLA

H. Weise, DESY, Hamburg, Germany

Abstract

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, 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 120 m long linac installation needed to investigate the cavity performance with beam. During approximately 13 thousand hours of operation components like a laser driven RF gun, beam diagnostics, RF modulators, and control systems including data acquisition at high repetition rate could be tested. With respect to the linac operation, beam parameters were almost identical to the TESLA beam. The use of the TTF Linac as a driver for a SASE free-electron laser at wavelengths below 100 nm demonstrated the reliability of the chosen technology.

Separate test stands for RF guns at Fermilab and DESY Zeuthen allow detailed studies of electron beam injector concepts. RF main input couplers are under study at Orsay / France. A new test stand for accelerator modules is projected. The present TTF Linac installation is going to be extended by additional modules.

1 INTRODUCTION

A superconducting electron-positron collider of initially 500 GeV total energy, extendable to 800 GeV c.m., with an integrated X-ray laser laboratory has been proposed by the TESLA (TeV Energy Superconducting Linear Accelerator) collaboration [1]. The challenge to the TESLA collaboration was to demonstrate the viability of its design. Results from operating the TESLA Test Facility (TTF) Linac as well as from other set-ups are presented.

2 TTF LINAC AND ITS PERFORMANCE

Superconducting cavity R&D has demonstrated the reliable production of 9-cell TESLA structures achieving gradients of 25 MV/m and higher at quality factors $Q_0 \geq 10^{10}$. Gradients of 35 MV/m and were reached by applying new preparation techniques like e.g. electrolytic polishing [2]. The Gradient of prototype single-cell cavities exceeded 40 MV/m. The TTF Linac at DESY was constructed to show that these high gradients achieved in individual 9-cell TESLA cavities could be maintained during assembly into a linac test string. The successful operation in a standard linac environment was the main goal of the TTF Linac. An electron beam with parameters as close as possible to the TESLA design was to be accelerated to a few hundred MeV.

2.1 General Layout

The TTF Linac in its present set-up consists of the following sections: injector area, two accelerator modules, bunch compressor section, and high energy beam analysis area. Until early summer 2002 a collimator section and an undulator, both downstream of the second accelerator module, were used to operate the TTF Linac as a driver for a SASE free-electron laser. A schematic of the linac is shown in figure 1.

2.2 Injector

The injector area includes the electron gun, the superconducting capture cavity, focusing lenses, and beam diagnostic equipment for the full characterization of the electron beam properties. In order to achieve electron beam parameters that are in terms of bunch charge and time structure very similar to the TESLA design, the injector [3] is based on a laser-driven photocathode. This cathode is installed in a 1.6-cell normal-conducting RF cavity operating at 1.3 GHz with a peak accelerating field of about 37 MV/m at the cathode plane. The Cs_2Te cathode is illuminated by a train of UV laser pulses generated in a mode-locked solid-state laser system synchronized with the gun and linac RF. Bunch charges of several nC can be produced with a repetition rate of up to 2.25 MHz. Although bunch trains with a length up to 800 μs are routinely produced at gradients above 30 MV/m, the peak accelerating field of 37 MV/m (needed for higher electron beam quality) with its RF power of about 2.2 MW is challenging. Some of the TTF Linac machine studies suffered from RF break down in the gun.

The gun section is followed by a standard 9-cell superconducting cavity, increasing the energy from approximately 4 MeV to 16 MeV. A feedback system allows the cavity to be operated with an amplitude stability of better than 0.1%, and a phase stability of better than 1 deg. The typical relative energy spread is 0.2% rms at 16 MeV. At 1 nC the normalized emittance was measured to be 4 mm mrad, and at 8 nC approx. 15 mm mrad [4].

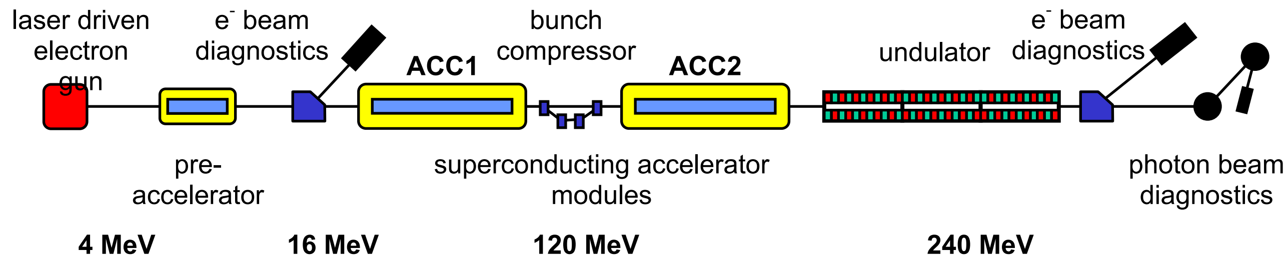

Figure 1: Schematic layout of the TESLA Test Facility Linac. The total length is approximately 120 m.

2.3 Accelerator Modules

The two installed accelerator modules (each 12.2 m in length) comprise the main body of the linac. Each module contains eight TESLA type 9-cell cavities operated in the standing-wave π-mode, a superconducting quadrupole / steerer package, and a cold cavity type beam position monitor. Each accelerating structure has one input coupler for RF power, and a small pickup antenna to measure the cavity field and amplitude. Two Higher Order Mode couplers provide sufficient damping. A frequency tuning mechanism is used to operate the cavities on resonance.

As of writing six accelerator modules have been assembled since the beginning of the TTF programme. Three of them have been operated in the TTF Linac. The last three are foreseen for the extension of the linac to higher energies (see section 4 below). The maximum gradients achieved at quality factors equal to the design value ($Q_0 = 10^{10}$) or above are given in table 1. Cavities operated in the TTF Linac have shown slightly lower gradients compared to the vertical and/or horizontal tests. This is due to the fact that all cavities are connected to one single klystron so that the worst cavity determines the maximum gradient. The RF properties of all cavities connected to one klystron should be almost identical.

Table 1: Accelerating gradients achieved in the TTF Linac accelerator modules. Module #1* is going to be tested in the present run, modules #4 and #5 are to be tested in February 2003.

Module no.	RF test ($Q_0 \geq 10^{10}$)	beam operation
#1	17.5 MV/m	14 MV/m
#2	21.2 MV/m	19 MV/m
#3	23.6 MV/m	22.7 MV/m
#4	25.4 MV/m	to be tested
#1*	25.3 MV/m	to be tested
#5	26.5 MV/m	to be tested

In the standard TTF Linac configuration 16 cavities are driven by one klystron. 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 (see section 3). The achieved relative amplitude stability of 2×10^{-3} and absolute phase stability of 0.5 deg complies with the requirements.

2.4 Long Pulse Operation

One of the measurements performed with long beam pulses is shown in figure 2. A 800 µs long macro pulse comprising 1800 bunches with more than 3 nC bunch charge each was accelerated operating module #3 at an average gradient of 21.5 MV/m (5% below quench). With the macro pulse current being 7 mA, the bunch charge was stable within ~10%. The achieved energy stability was σ_E / E = 0.07%. Similar results were obtained in a previous long pulse operation reported in [5], with both accelerator modules running at an average gradient of 14 MV/m.

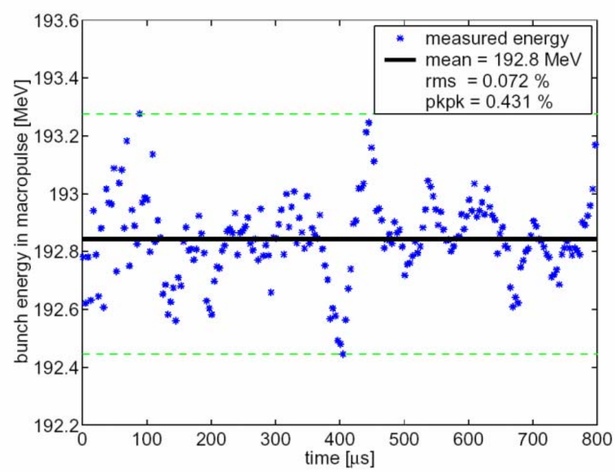

Figure 2: Acceleration of long macro pulses. The beam energy within one single macro pulse is shown. The RF control system is operated with beam loading compensation. The bunch spacing is 444 ns.

The mentioned operation of module #3 (ACC1 in figure 1) has been at high gradient and long pulse. The main goals of this run were to exercise the module at near its maximum gradient and to accelerate long bunch trains. 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 [6]. 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 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 12000 hr and that for this run they were operated very close to their limit, a situation that will not occur for the 500 GeV TESLA collider.

2.5 Long-run Operation

Since 1997 the TTF Linac was operated for approximately 13,000 hours. The set-up described above was used for about 80% of this time. Since 1999 the linac is operated 7 days a week, 24 hours per day. Approximately 50% of the time is allocated to FEL operation including a large percentage of user time. Figure 3 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 time for tuning.

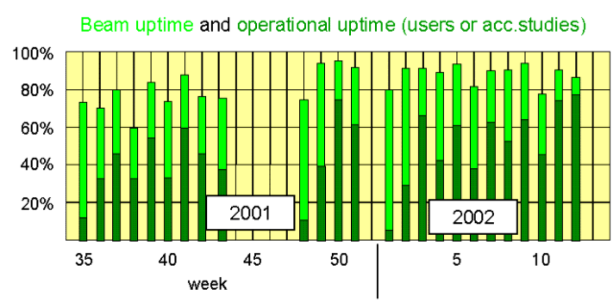

Figure 3: Beam uptime and operational uptime in the 2001/2002 run. The operational uptime was used for either FEL user operation or accelerator studies.

3 TTF FEL OPERATION

The original proposal for the TTF Linac was for a linac test string of four superconducting accelerator modules. But shortly after finishing the first design it became clear that the linac would be almost ideal to drive a free-electron laser based on the principle of Self Amplified Spontaneous Emission (SASE): therefore the overall layout was changed and the FEL became part of the TTF programme. The original proposal was adopted to perform a proof-of-principle experiment of a SASE FEL in the vacuum ultraviolet wavelength region. As mentioned above, a bunch compressor section between the two accelerator modules, a collimator section and an undulator, both downstream of the second accelerator module, were added to operate the TTF Linac as a driver for a SASE free-electron laser.

3.1 Bunch Compressor

The FEL operation mode requires short electron bunches with high intensity. Therefore the bunch compressor section between the two accelerator modules is used to reduce the electron bunch length produced in the electron gun by roughly a factor four. This shortening of the bunch increases the peak bunch current to several hundred Amperes, which is required for a high gain of the FEL. The compression is achieved by making use of the path length difference for particles of different energies in a bending magnet system (chicane). By accelerating bunches slightly off-crest in the RF wave of ACC1, particles in the bunch head have a lower energy than in the tail and thus travel a longer distance in the chicane. At the achieved bunch lengths of approximately 0.4 mm rms, coherent synchrotron radiation produced in the magnetic chicane affects the emittance and the energy spread of the bunch [7].

3.2 Collimator and Undulator

The second installed accelerator module of the TTF linac is followed by a collimator section [8] which combines the transverse matching of the electron beam to the undulator with the protection of the undulator magnets and vacuum chamber. As a consequence of the small beta function in the undulator - typically 1m, corresponding to an rms beam sizes of ~100 μm - it only requires 10 bunches with 1nC charge to burn a hole into the vacuum chamber. In addition radiation damage of the Sm_2Co_{17} permanent magnets in the undulator from either beam halo (dark current) or direct beam loss could degrade the field quality. The collimator consists of a pair of spoiler / absorber units, and the optics (quadrupole settings) is matched so that the physical apertures of the downstream undulator lie within the collimator shadow.

The undulator [9] is a permanent magnet device with a 12 mm gap and a period of 2.73 cm. The system is subdivided into three segments, each 4.5 m long and containing 10 permanent-magnet quadrupoles with alternating gradients, which are superimposed on the periodic undulator field. The vacuum chamber incorporates beam position monitors and orbit correction magnets (one for each quadrupole).

3.3 TTF FEL Performance

The first lasing of the high gain FEL at the TTF Linac was observed in February 2000 [10]. Since then the performance of the SASE FEL has been steadily improved. By varying the electron beam energy, full wavelength tunability in a wide range from 80 to 180 nm has been demonstrated (figure 4). First users requested further work to be focused on the range from 80 to 120 nm. In this wavelength region saturation has been achieved.

The successful operation of the SASE FEL was based on the high field quality of the undulator, which assures the needed good interaction between the electron and photon beams, and on the capability of the linac components to deliver electron bunches with high beam quality, i.e. small emittance at high peak currents.

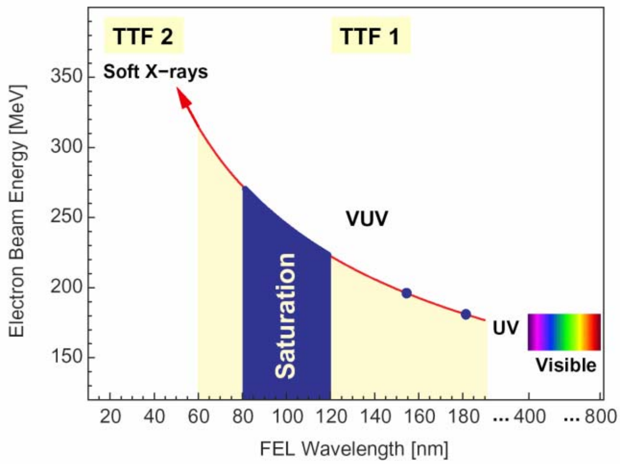

Figure 4: VUV wavelength range within which lasing has been obtained at the TTF FEL. The wavelength was tuned by changing the electron beam energy. The individual dots outside the range in which saturation has been achieved represent an FEL gain of typically > 1000 demonstrated in an earlier stage of the experiment.

4 TTF EXTENSION TO 1 GeV

Based on the operational experience with the TTF Linac and its FEL we are going to increase the electron beam energy by adding additional accelerator modules (see also table 1). These additional modules take advantage of the third superconducting cavity production [2] and will be used to gain further long-run experience.

Together with the installation of modules the overall layout of TTF will be modified. The injector will be shortened by removing the capture cavity, and the bunch compressor will be lengthened in order to include a third harmonic accelerating cavity [11]. Together with a second bunch compressor located between modules ACC3 and ACC4 (see figure 5) a normalized emittance of 2 mm mrad at peak currents of 1.5 kA is expected for the high energy electron beam. Reference [12] gives the complete design of the extended TTF installation which will be operated as a FEL user facility after the commissioning in 2003.

A first step on the way to the 1 GeV installation was done this summer. Both accelerating modules ACC1 (module #3) and ACC2 (module #2) were removed and replaced by a so-called superstructure design (ACC1) and by module #1*. The superstructure [13], a possible alternative to the standard TESLA design, should be tested before the conversion of TTF into a user facility. Results of module #1* operation are needed on the way towards the TESLA linear collider. During the next shut-down period the linac string is going to be completed. Tests of all new accelerator modules are scheduled for February 2003.

5 TESLA STUDIES AT A0 AND PITZ

Since the effort towards a TESLA linear collider is driven by more than 40 institutes, the TTF linac is not the only test facility. RF input couplers are under study and tested at Orsay / France, beam diagnostic equipment is built at INFN Frascati / Italy and Saclay / France, and cavity R&D is done at many different laboratories. Two test facilities are used to study electron beams with beam parameters close to the TESLA design. At FNAL Batavia / U.S.A. and at DESY Zeuthen / Germany complete photo-injectors were set-up.

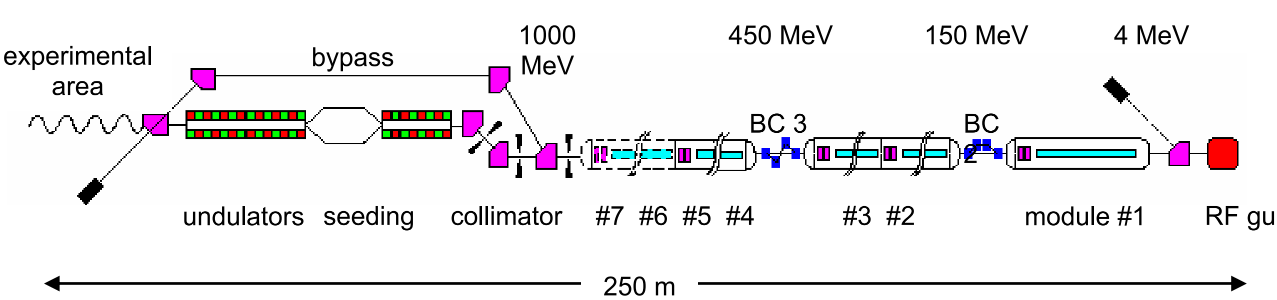

Figure 5: The extension of the TTF Linac to 1 GeV electron beam energy. The electron beam direction in this picture is from right to left.

The FNAL / NICADD photo-injector is operated at the A0 hall of Fermilab. This photo-injector is nearly identical to the TTF photo-injector installed at DESY. In fact, the RF gun at DESY was supplied by FNAL. The FNAL installation includes the gun with its laser, the cathode preparation system, the modulator and L-band klystron, the superconducting capture cavity, and a beam diagnostic section at the high-energy end. A magnetic chicane composed of four dipoles is installed after the 9-cell cavity to produce longitudinal compression of the beam. A number of important experiments including the production of flat electron beams [14] were carried out at FNAL while the TTF linac was used for the SASE FEL proof-of-principle experiment.

The Photo Injector Test facility at DESY Zeuthen (PITZ) [15] is built to develop electron sources for free electron lasers and future linear colliders. The main goal is to study the production of minimum transverse emittance beams with short bunch length at medium charge (~1nC). The facility includes a 1.6 cell L-band cavity with coaxial RF coupler and solenoid for space charge compensation, a laser capable to generate long pulse trains, an UHV photo cathode exchange system, and different diagnostics tools.

The photo injector test facility at DESY Zeuthen has gone into operation. Until spring 2003 the complete characterisation of the RF gun is foreseen and afterwards the set-up will be extended by the installation of a booster cavity. This allows further machine studies independent of the TTF linac's user operation.

6 TESLA and Global Accelerator Network

The size and costs of future large research facilities like TESLA exceed the resources of a single region. This is true not only for the installation phase, but also for running the accelerator complex in the case of TESLA. A possible strategy is the framework of an international collaboration, very similar to the collaborations which operate high energy physics experiments. This approach is currently discussed as Global Accelerator Network (GAN). Some GAN aspects could already be studied during the set-up of the TESLA Test Facility. One further step is to establish remote operation of test facilities like the TTF linac.

Reference [16] is the first paper describing the study of the FNAL/NICADD photo-injector's magnetic chicane using remote operation from the DESY control room. Energy modulation of a compressed electron beam has been observed and attributed to CSR effects.

At present further studies concerning the remote operation of the TTF Linac are discussed between Cornell University and DESY as well as between KEK and DESY.

7 CONCLUSION

The TTF Linac as well as the test facilities at FNAL and DESY Zeuthen were 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 [17].

Together with partners of the TESLA collaboration, DESY is going to extend 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 2003. This extension is based on the good experience with running TESLA like accelerator modules. Thanks to the efforts towards superconducting accelerator technology, concentrated in the TESLA collaboration, further linacs and FELs are proposed worldwide.

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