THE TRANSFORMATION OF THE TESLA TEST FACILITY INTO THE VUV FEL USER FACILITY AT DESY

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Abstract

After the end of the very successful operation of the TESLA Test Facility in November 2002, the modification of TTF into a VUV FEL user facility took place during the years 2003 and 2004. The injector complex was completely modified. By the beginning of this year 5 cryomodules were installed and the vacuum system was closed. For bunch length measurements there is a special S-band structure driven by a SLAC 5045 Klystron and an Electro-Optical-Sampling Experiment. Six undulator modules of 30 m total length have also been installed.

Until May 2004 the five cryogenic modules and their rf power input couplers were conditioned up to full rf power. In one cavity of the first module an accelerating gradient of 35 MV/m with beam could be demonstrated. The last module (No.5) can be reliably operated at an average gradient of 25 MV/m.

So far, beam has been sent only through the first module and through the first bunch compressor. First emittance measurements show values around 3 πmm mrad.

In the second half of this year completion of installation of technical components like power supplies, beam diagnostic elements etc. took place prior to full commissioning of the entire machine which started in the beginning of September.

INTRODUCTION

In 1993 the TESLA Test Facility was set up at DESY with the goal to demonstrate the feasibility of an e^+e^- Linear Collider based on superconducting L-Band cavities operated at the accelerating gradient 25 MV/m [1]. Only one year later efforts to extend it to a SASE FEL (Self Amplified Spontaneous Emission Free-Electron Laser) facility with initial operation in the 100 nm wavelength range started [2]. During this so- called TTF phase I production methods for superconducting 9-cell cavities operating at gradients above 25 MV/m and for the assembly of cryogenic accelerating modules of 12 metres length were successfully established. There are eight 9-cell cavities in a cryogenic module. Stable operation with beam at average gradients close to 23 MV/m in one cryogenic module has been demonstrated. With two cryomodules beam currents of several nC were accelerated up to 270 MeV. In February 2000 first lasing was achieved [3]. By the end of the TTF I operation saturation of the SASE gain was obtained in the entire FEL wavelength range of 80 – 120 nm [4].

The necessary conditions which had to be fulfilled in order to obtain these results were the acceleration of electron bunches with high peak current and low emittance and the high field quality in the undulator magnets [5]. Under these circumstances there was interaction between the photons and the electron bunches during the entire passage through the undulator which led to microbunching and finally gain saturation.

Since 1997 until November 2002, where TTF I operation ended, 15000 hrs. of beam time were accumulated. During the last two years about 50% of the time was allocated to FEL operation including a large percentage of scientific user time.

After the end of TTF I its transformation into the VUV FEL user facility began immediately. To reach saturation at the minimum design wave length of 6.4 nm the energy of the electron bunches must be increased to 1 GeV and the magnetic length of the undulators has to be doubled to six undulator segments with a total length of almost 30 m. Besides a new injector, an additional bunch compressor and 5 cryogenic modules, which have been installed so far, ultimately the installation of a third harmonic rf system, a seeding monochromator and an additional cryogenic module are planned .

The design beam parameters are:

Energy	1 GeV
Max. bunch charge	4 nC
Min. bunch spacing	110 ns
Bunch length	150 fs
Peak current	2500 A
Max. number of bunches per macrobunch	7200
Max. rep. rate of macrobunches	10 Hz
Normalized emittance at the undulator entrance	2 π mm mrad
Energy spread	2 MeV
Longitudinal emittance	40 keV mm
Beam size in the undulator	65 μm
Min. wave length of FEL radiation	6 nm

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In the following a description of the VUV FEL user facility and a discussion of performance and status of the major components will be given.

THE VUV FEL USER FACILITY

An overview of the VUV FEL is shown in fig. 1. The injector consists of a Cs_2Te photocathode which is mounted on the back plane of a 1.5-cell 1.3 GHz copper cavity with a peak accelerating field of 40 MV/m [6]. This cavity can be reliably operated up to the full pulse length of 800 µs. In contrast to the gun used in TTF I, the newly installed one has a cylindrically symmetric rf power input coupler to avoid asymmetric fields which cause transverse emittance growth.

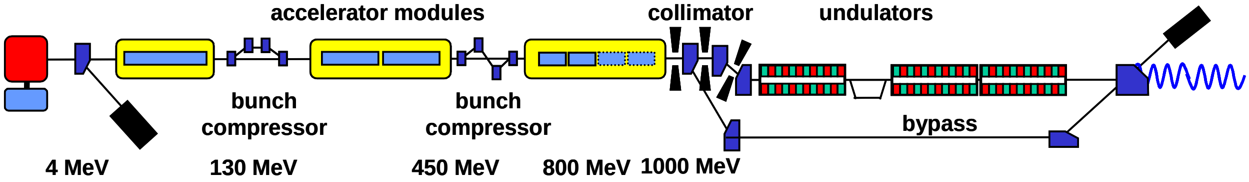

Figure 1: Overview over the VUV FEL. Five cryogenic modules have been installed so far. A sixth module will be installed by 2006. In the remaining space for a possible seventh module presently a transversely deflecting S-band structure has been installed for bunch length measurement.

The cathode is illuminated by UV laser pulses [7]. The gun was set up and optimized at the Photoinjector Test Facility PITZ at DESY Zeuthen. The best values for transverse emittance obtained at PITZ were close to 1.5 π mm mrad [8]. The electrons are accelerated in the 1.5 cell cavity of the gun to about 4 MeV and are injected into the first cryogenic module which is located only 2 metres downstream. In routine operation the first 4 superconducting 9-cell cavities in this module will be operated at the average gradient of 12 MV/m, the gradient in the remaining four cavities will be 20 MV/m. There is one cavity in this module which has demonstrated successful operation at 35 MV/m with beam. This cavity has been electropolished . Due to the acceleration of the electrons to 130 MeV in this module a strong suppression of the Coulomb forces in the space charge dominated low energy beam transport area is achieved.

Behind the first cryomodule the installation of an additional rf system operating at the third harmonic frequency 3.9 GHz is foreseen in the year 2006. It has been shown [9] that one can effectively enhance the bunched peak current by such an rf system which corrects the nonlinear distortions of the longitudinal phase space arising from the rather long bunch length of 10-20 ps full width. The pulse length is necessary to achieve low emittance.

The rms length of the bunches leaving the first cryomodule is about 2 mm. In the subsequent first bunch compressor they are compressed to about .4 mm rms.

Peak currents of the compressed bunches of 1 – 1.5 kA have been measured.

In the next two cryomodules the beam is accelerated to 450 MeV. The measured average gradients of the cavity voltage in these two modules are 19 MV/m and 20 MV/m respectively. In the second bunch compressor the rms bunch length is reduced to 50 µm [10] and the expected peak current in the electron bunches is 2.5 kA. From extensive start to end simulations the expected output power level of the SASE FEL radiation is near or above the 5 GW level for these beam parameters.

From the three additional cryomodules which will ultimately be located behind the second bunch compressor two modules have been installed so far. Both have demonstrated an average accelerating voltage gradient of 25 MV/m for the full flat top pulse length of 800 µs and 500 µs filling time. Acceleration up to 800 MeV is possible with these 5 modules. The sixth module will be entirely equipped with electropolished cavities which are expected to run up to 35 MV/m. Installation in the tunnel is planned for the year 2006.

Presently, in the location foreseen for a possible 7th module, a transverse deflecting S-band structure of 3.66 m length has been installed for bunch length measurements [11]. Both, the structure and its SLAC 5045 driving klystron are a contribution from SLAC. The cavity has been conditioned to the specified 20 MW input power pulses of 1µs length at 1 Hz repetition rate.

Between the last cryogenic module and the undulator section there is a collimator system [12] to protect the permanent NdFeB undulator magnets which are sensitive to radiation damage. There is transverse collimation to cut off particles from the beam halo and energy collimation to suppress particles resulting from dark current. The minimum value of the aperture radius is 2 mm. Within the considered range of energy deviations from -50% to +25% only particles with $|\Delta E/E_0| < 3\%$ will be transmitted through the collimator and enter the undulator section. The collimator efficiency defined as the ratio of energy deposit in the undulator due to particle loss to the energy in the beam is 10^{-6}.

The new undulator section [13] for the VUV FEL is made up of the same magnets as for TTF I. Compared to TTF I there are now 6 sections with the total length of 30 m. The integrated combined function focusing system has been replaced by an electromagnetic doublet structure.

At a later stage the so-called seeding option will be built. It will provide a fully coherent beam with narrow bandwidth. It requires the installation of three more undulators with a total length of 15 m.

For protection of the undulator magnets from radiation damage during commissioning, temporary tests and beam optimization procedures the entire section can be bypassed by a simple beam transport line which has been installed in parallel.

BEAM DIAGNOSTICS AND PROTECTION SYSTEMS

A necessary condition for the SASE process to occur is the spatial overlap of the low-emittance-high-peak-current electron beam with the photon beam over the entire 30 m length of the undulator with a precision of some 10 m. To achieve this goal, a very large and sophisticated amount of diagnostic elements in the VUV FEL for electron beam diagnostics, machine protection and photon beam diagnostics [14] is needed.

The electron beam diagnostic system has to measure beam position, charge and losses with single bunch resolution. Most methods for bunch length measurement are not suitable for single bunch resolution, but rely on many bunches. The standard stripline BPMs are located inside the quadrupole magnets. For each BPM, the position of the electrical centre with respect to the magnetic centre of the quadrupole was determined individually on a measurement bench with a precision of 10 m. Dark current from the gun will be measured with reentrant cavity monitors of about 500 nA sensitivity which are located in the injector and in the collimator section.

The ends of the undulator section and the diagnostic sections between the modules are equipped with button monitors and wire scanners.

In the flat wide parts of the dispersive sections of the bunch compressors there are arrays of 4 button monitors.

For beam size measurements we have about 25 OTR screens and 8 wire scanners. The obtained resolution is better than 20 µm for OTRs and 2 µm for the wire scanners.

The individual bunch charge in the range of .5 – 5 nC is measured by fast toroids with a time constant below 110 ns and an accuracy of better than $5x10^{-3}$. These signals are also used to measure the transmission for a fast (3 s) protection system. Other machine protection signals are derived from fast beam loss measurements with scintillators or aluminum cathode electron multipliers. The distribution of radiation-dose along the linac and the undulators is obtained from the measurement of the transmission attenuation of optical fibres on an hourly basis, and from TLD crystals on a weekly basis.

The beam phase can be measured with $.2^0$ precision by mixing down the 1.3 GHz signal component from impedance matched ring electrodes to the base band.

For bunch length measurement several methods are under consideration in addition to the afore mentioned S-band structure which acts like a streak camera with an expected resolution of about 100 fs. Similar resolution is expected from Electro-Optical sampling where the changes of the optical properties of a crystal under the influence of the electromagnetic field of the bunches are probed by an ultrashort laser pulse [15]. Autocorrelation measurements of far infrared transition radiation (FIR) in an interferometer are also used for bunch length determination. Qualitative optimisation of bunch compression is done by maximizing the output of a simple pyro detector. It is proportional to the coherent FIR emitted by the bunches.

SASE diagnostics and optimisation is done with the help of SASE photons scattered from a gold wire and amplified in a multi channel plate detector. The dynamic range is about 10^7 due to calibrations at different voltage settings. In addition the radiation pulse energy and the photon beam position can be measured with a newly developed detector which is based on the photoionisation of a rare gas at low density. It has also a very large dynamic range.

THE RF SYSTEM

The high power 1.3 GHz rf system consists of four Klystrons manufactured by Thales (formerly Thomson). The normal conducting photoinjector cavity and the first cryomodule are each fed by a TH 2104C 5 MW tube. The following two cryomodules are connected to one TH 1801 Multi-beam-klystron (MBK) which was developed by Thales for the TESLA Project. The MBK prototype has delivered the specified 10 MW output power at an efficiency near 65% already in the year 2000. Since then two more MBKs were delivered to DESY. However, the tubes had to be returned because of gun arcing problems. After investigation and modification improved MBKs are expected to be delivered to DESY by the end of this year.

In the meantime there are two other manufacturers, CPI and Toshiba, who are building independently designed MBKs. The prototypes should also be delivered to DESY during this year. Unlike the Thales tubes, where all cavities operate in the fundamental TM 010 mode, there are cavities operating in higher modes (TM 020) in the tubes by the other manufacturers.

In principle the rf power needed for operation of the last three cryomodules at 25 MV/m can be provided by one additional MBK. For operation at much higher gradient – up to 35 MV/m seem realistic for module 6 – another klystron would be available.

The modulators must generate HV pulses up to 120 kV and 140 A. The max. pulse length is 1.57 ms and the max. rep. Rate is 10 Hz. The voltage droop in the flat top is below 1%. The three bouncer type modulators with a 1:12 step-up rate pulse transformer which were designed and built by FNAL are still in use at DESY. In the meantime 8 more modulators based on the same principle have been designed and built by joint efforts of DESY and German industry. The leakage inductance of the new pulse transformers has been significantly reduced. Its value is now below 200 μH which is almost half the value of the first transformers. Accordingly the pulse rise time to the 98% level decreased from almost 400 μs to below 200 μs. The increased efficiency (65%) of the MBK as compared to the single beam 5 MW klystron (45%) plus a few per cent gain in efficiency resulting from the smaller pulse rise time would lead to a significant reduction of operation cost for the TESLA Linear Collider where the average wall plug power for the rf supply is close to 75 MW.

A detailed description of the high power rf system is given in [16].

During several years of operation a very powerful digital low level rf system (LLRF) has demonstrated reliable beam operation with rf phase and amplitude stability of 0.5^0 and 0.5% respectively [17].

The vector sum of the rf signals of up to 32 cavities is calculated by a DSP. Deviations of the vector sum from the nominal signal are corrected in a vector modulator at the low rf power level at the klystron drive.

CAVITIES AND AUXILIARIES

The performance of the superconducting 9-cell cavities has continuously improved since 1994, where the first of the three production series' started [18]. By the year 2001 the average accelerating gradient has increased from values below 20 MV/m to above 25 MV/m at Q-values $>10^{10}$ as is shown in fig. 2. At the same time the spread in performance was reduced by the factor 3. The main reasons for this success can be attributed to improved welding techniques and stricter Niobium quality control.

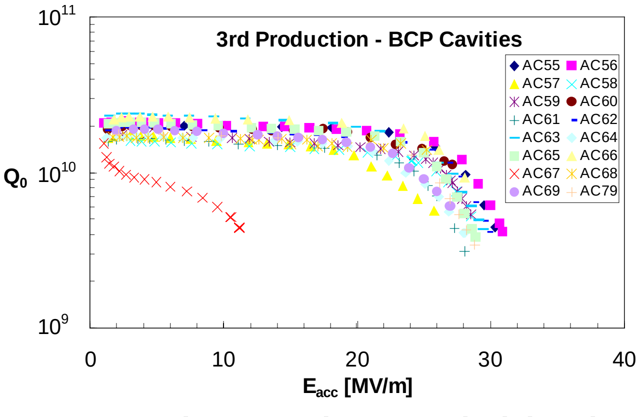

Figure 2: Accelerating gradient vs. unloaded quality factor for several 9 cell cavities from the last production series which have undergone standard Buffered Chemical Polishing treatment. Values well above 25 MV/m at $Q_0 > 10^{10}$ have been obtained routinely. The untypical performance of cavity AC 67 is due to a He-leak which became apparent only during the test.

During the last years a further amelioration of cavity performance has been achieved by the KEK-DESY collaboration on electropolishing. After several single cell cavities had reached gradients in excess of 35 MV/m, there are now also several electropolished 9 cell cavities which have been operated at gradients above 35 MV/m [19]. An example is shown in fig. 3.

There are no signs of degradation neither in the cavities nor in the power input couplers. One cavity in the first cryomodule has reached 35 MV/m with beam.

Detuning of the cavities due to Lorentz forces during the pulse becomes an important issue at these gradients. At 35 MV/m it amounts to 1.2 kHz, i.e. four loaded bandwidths. The possibility of active compensation of the Lorentz force detuning during the macropulse of 1.3 ms length by a mechanical tuner based on piezo-electric elements has been demonstrated. The cavities in the cryogenic module 6 will be equipped with these elements.

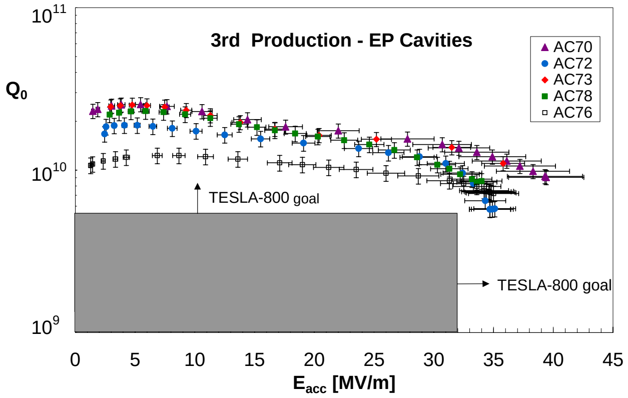

Figure 3: Accelerating gradient vs. unloaded quality factor for several 9 cell cavities from the last production series. These cavities have been electropolished. The results which lie well above 35 MV/m at $Q_0 > 10^{10}$ surpass the requirement for the 800 GeV version of the TESLA linear collider.

The rf power input couplers have also been improved in several iterations. The very robust and reliable couplers from the last version have been tested at full pulse length (1.3 ms) and 10 Hz repetition rate with cavities up to 35 MV/m and up to 1 MW for traveling wave operation at 2 Hz operation on the test stand. Over 60 couplers of this type have been built so far.

SUMMARY

During 10 years of combined effort within the international TESLA collaboration convincing evidence for the feasibility of a Linear Collider based on superconducting technology was given. Cavity production- and module assembly techniques have resulted in the production of complete cryogenic modules which are providing an average accelerating gradient up to 25 MV/m. Even 40 MV/m have been reached in tests of electropolished 9-cell cavities. At least 35 MV/m seem also realistic as an average gradient for the next module.

Besides the wide field of developments directly related to the cavities (welding techniques, material science, chemistry, coupler development, extensive field calculations and measurements) sophisticated digital low level rf techniques which guarantee high field stability in the presence of beam loading and lorentz forces and microphonics, high efficiency Multibeamklystrons, long pulse high voltage modulators, beam diagnostics techniques, optical laser systems and many other things needed to be developed.

As a result a beam of very high quality could be accelerated in the TESLA Test Facility. It was used to drive a SASE FEL. Saturation at wavelengths around 100 nm was obtained and first scientific user experiments have taken place. TTF is now being transformed into a VUV FEL user facility. We hope for first lasing in the optimal wavelength range around 30 nm by the end of this year and for saturation in the beginning of 2005.

The ultimate goal is reliable user operation in the wavelength range from 100 to 6 nm.

Finally we would like to mention that the International Technical recommendation Panel (ITRP) which had the charge to recommend a Linear Collider Technology – the choice was between the cold L-band TESLA Technology and the warm X-band JLC-X/NLC Technology – had published its recommendation in favour of the cold Technology a few weeks ago on August 20th. Amongst the reasons for this recommendation the planned construction of the superconducting XFEL free electron laser, which is based on the technology described in this paper and which will test many aspects of the linac, as well as arguments related to the reduced power consumption of superconducting cavities and to the comparatively low rf frequency were quoted.

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