COMMISSIONING OF THE TTF LINAC INJECTOR AT THE DESY VUV-FEL

K. Honkavaara*, DESY, 22603 Hamburg, Germany
for the VUV-FEL Injector group

Abstract

The upgrade of the TESLA Test Facility (TTF) at DESY is almost completed. With electron beam energies up to 1 GeV, it serves the new SASE FEL user facility (VUV-FEL) in the wavelength range from VUV to soft X-rays. The first installation phase of the redesigned photoinjector is finished. We report on its commissioning during spring 2004, including the first measurements of electron beam parameters. Since this injector is also a prototype for the XFEL injector, the results obtained are important for future SASE XFEL drive linacs.

INTRODUCTION

The TESLA Test Facility Linac, phase 1 (TTF1) [1] has been operated at DESY until November 2002. Besides performing various tests and experiments related to the TESLA linear collider project [2], the TTF linac was used to drive a SASE free electron laser at wavelengths in the range of 120 nm to 80 nm [3, 4]. Presently the TTF linac is upgraded to drive a new SASE FEL user facility (VUV-FEL) [5]. The VUV-FEL is also a piloting project for the XFEL project [6, 7].

In present stage of the upgrade, five accelerating modules with eight 9-cell superconducting TESLA cavities in each are installed providing electron beam energies up to 800 MeV. Later, one or two more modules can be added to increase the beam energy to 1 GeV, or even beyond. Beginning of the year 2004 the installations in the accelerator tunnel have been almost completed, and from March to June 2004 the redesigned photoinjector has been successfully commissioned, which has already been briefly reported in [8].

THE VUV-FEL

With the electron beam energies available at TTF1 it was possible to produce SASE radiation down to the wavelength of 80 nm. To reach shorter wavelengths, the energy of the linac has to be increased. Also several other upgrades are needed to meet the more demanding beam parameter requirements in terms of transverse emittance, peak current, and energy spread. Taking these requirements and our experience at TTF1 into account, both the linac and the injector have now been redesigned to extend the wavelength range down to 6 nm. For a detailed discussion on the linac and the parameter choices refer to [5].

For the start-up and commissioning phase this year, emphasis is put on achieving lasing and saturation at a wavelength of 30 nm, which requires an electron beam energy of 450 MeV. For the longer wavelength the requirements on the beam parameters are relaxed, which eases the commissioning. Later, lasing at longer and shorter wavelengths will follow.

THE INJECTOR CONCEPT

The upgrade of the VUV-FEL photoinjector [9] implements the main ideas of the XFEL injector proposal [10]. The optimization of the XFEL injector concept is going on, and the experience and results achieved by the VUV-FEL injector are important for its final layout.

Figure 1 shows a schematic overview of the VUV-FEL injector. Electron bunch trains with a nominal bunch charge of 1 nC are generated by a laser-driven RF gun. The design normalized emittance is 2 mm mrad. In order to reduce space charge effects, the design shape of the laser pulse is flat, both transversally and longitudinally, having a length of 20 ps (FWHM). The design rms bunch length at the gun exit is 2.2 mm.

A complete TESLA module with 8 accelerating cavities is used to boost the beam energy to 130 - 150 MeV. To avoid strong focusing, the first four cavities are operated with a moderate gradient (12 MV/m). In the last four cavities full acceleration ($>$ 20 MV/m) is used. The first magnetic chicane bunch compressor is placed downstream of the first accelerating module. A second compression stage follows after two additional accelerating modules at a higher energy. With the two compression stages the bunch can be compressed down to 50 μm (design).

Off-crest acceleration is required for magnetic bunch compression. The sinusoidal accelerating field induces a curvature in the longitudinal phase space. The compression of the off-crest accelerated bunch leads to a longitudinal bunch structure with a high peak current spike and a long tail. This irregular bunch structure complicates the use of the second bunch compressor. The energy-phase plane curvature can be removed by using a superconducting third harmonic cavity (3.9 GHz) [11] before the bunch compressor. This cavity is under construction, and thus not yet available. Therefore the start-up lasing strategy is similar than at TTF1: The leading spike after the first compression stage is used to produce the required peak current [12].

During the injector commissioning reported here, the first accelerating module has been operated with a constant gradient of 12 MV/m in all the cavities yielding to beam en-

* katja.honkavaara@desy.de

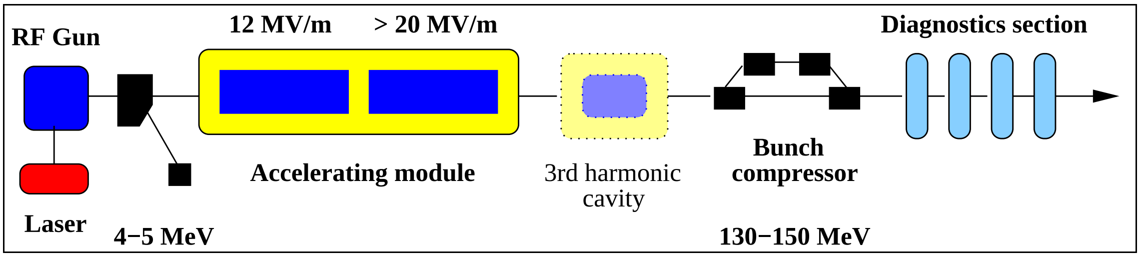

Figure 1: Schematic overview of the TTF VUV-FEL injector (not to scale). Beam direction is from left to right, and the total length is about 37 m. During the commissioning the beam was dumped into a small temporary beam dump before the second accelerator module. The 3rd harmonic cavity is not installed yet.

ergy around 100 MeV. The beam was dumped into a temporary beam dump before the second accelerator module.

THE RF GUN

The new RF gun has been successfully commissioned and characterized at PITZ (DESY Zeuthen) [13]. It is a 1.5 cell L-band cavity (1.3 GHz) powered by a 5 MW klystron.

The design of the photocathode system is the same as at TTF1. The Cs_2Te photocathode is inserted via a load-lock system to the back of the half cell of the RF gun. The new cathodes have higher quantum efficiency than the ones used at TTF1 [14].

The maximum accelerating field on the cathode is determined by the available klystron power, and it is currently limited to 42 MV/m. In order to reduce space charge induced emittance growth, the electron beam is focused by a solenoid magnet. A bucking solenoid is used to compensate the magnetic field on the cathode surface to zero. The RF power and the RF phase in the gun are regulated by a low level RF system based on digital signal processors.

The RF gun was transported from Zeuthen (PITZ) to Hamburg and installed at the TTF tunnel in January 2004. At PITZ, the gun has been operated at 10 Hz with an RF peak power of 3 MW and an RF pulse length of up to 0.9 ms [15]. After a short commissioning period a similar performance was achieved also at TTF. However, for convenience, during most of the commissioning time 5 Hz repetition rate, and shorter RF pulse length was used.

THE LASER SYSTEM

The TTF1 laser system [16] has been upgraded. A similar system is tested and operated at PITZ. The laser system is based on a mode-locked pulse train oscillator synchronized to the 1.3 GHz RF of the accelerator. In contrast to the old system, two of the four laser amplifiers use laser diodes instead of flashlamps for pumping. The remaining flashlamp pumped amplifiers will be replaced later. One advantage of using diode pumping is the increased laser pulse energy stability: before the upgrade the measured fluctuation in the electron bunch charge from shot to shot was 3 to 6 % rms, now it is only about 1 % rms.

After the conversion of the initial wavelength of 1047 nm to UV (262 nm), the laser beam is transported to the RF gun cathode by an optical beam line consisting of lenses and mirrors. The laser spot position on the cathode is controlled by a set of remote movable mirrors. A remotely controlled iris allows controlling the laser beam size on the cathode. The nominal laser spot size at the cathode is 3 mm diameter.

The laser system is designed to produce pulse trains with up to 800 μs length with pulse spacing of 1 μs (1 MHz). A 9 MHz operation mode is in preparation. The laser pulse length and shape has been measured in the UV wavelength with a streak camera. The shape is near gaussian and has a length of $\sigma = 4.4 \pm 0.1$ ps, which is shorter than before the laser upgrade. However, in order to obtain a small transverse emittance, a flat laser pulse profile, both in transverse and longitudinal, is preferred. At PITZ, a laser pulse shaper producing longitudinal flat-hat profile laser pulses of ~ 20 ps has been tested. The measured transverse emittance has been reduced by a factor of two compared to a gaussian laser pulse [17]. However, since for the start-up of the VUV-FEL the gaussian laser profile is sufficient, this pulse shaper will be installed at TTF only later, when the development at PITZ is completed.

MEASUREMENTS OF BEAM PARAMETERS

The first electron beam was produced by the new RF gun at TTF in the middle of March 2004. The first month of beam operation was dedicated to the commissioning of the hardware and software components of different measurement and control devices as well as to study the basic beam parameters in the RF gun section.

In the gun section the charge can be measured by two devices: a toroid and a Faraday cup located close to each other at the gun exit. During the commissioning we operated with a charge of 1 nC per bunch. The number of bunches in a bunch train was 1 to 10.

The energy of the beam produced by the RF gun has been measured by means of a spectrometer dipole installed before the first accelerating module. The beam energy corresponding to the nominal 3 MW RF input power is 4.6

MeV. The measured data agree well with the expectation from the simulation [8].

Typically, in order to have the smallest transverse emittance, the RF phase of the gun with respect to the laser phase is tuned to a phase between 30 to 40° from zero crossing. The rms phase stability of the laser is estimated to better than 0.2° (0.5 ps) from shot to shot and within the pulses of the pulse train.

The commissioning of the injector including the first accelerating module, the first bunch compressor, and the diagnostics section started in April 2004. The accelerating module has been operated with a gradient of 12 MV/m yielding a beam energy around 100 MeV. An energy stability of $8.5{\cdot}10^{-4}$ rms has been achieved by using a feedback system regulating the phase and amplitude of the accelerating structures.

The uncorrelated energy spread has been estimated from the beam image on the dispersive section of the bunch compressor. The energy spread has a leading peak with an rms width of about 30 keV and a tail of about 200 keV.

One of the eight accelerating cavities in the first accelerating module has been prepared by using a surface treatment technique based on electropolishing. The performance of this cavity was tested with the electron beam. An accelerating gradient of 35 MV/m was achieved.[18]

The transverse beam shape and size after the acceleration is measured using optical transition radiation (OTR). The OTR system is designed and constructed by INFN-LNF and INFN-Roma2 in collaboration with DESY. The measured resolution (rms) of the system is 11 μm (magnification 1:1). More details of the system are in [19, 20].

For the measurements of the transverse emittance and Twiss parameters, 4 OTR monitors combined with wire scanners are embedded in a FODO lattice of 6 quadrupoles with a periodic beta function. During the commissioning only the OTR monitors were available. The emittance and Twiss parameters are obtained by fitting the measured beam sizes to the expectation from the lattice. The projected rms beam sizes are estimated from the beam images with different methods. In the first method, the sigma of a gaussian fit on the projected profiles is used to estimate the rms beam size. In the second, the true rms is calculated from the data within 90 % of the intensity of the beam. In the latter case, two different image analysis codes are used to determine the rms size. Especially when the beam shape is irregular and far from a gaussian shape, the different methods and codes yield different results.

Figure 2 shows the normalized horizontal and vertical emittance as a function of the solenoid current. The RF gun and the module have been operated with nominal parameters. The bunch compressor was by-passed to avoid dispersive effects. The data are partly taken at different days and with different optics to match into the FODO lattice. The emittance values using different analysis methods on the same data set are indicated. The expected emittance from simulation is shown as well.

For accurate emittance measurements it is important to have the FODO lattice well matched such that the beam image on each of the four monitors is regular and has similar dimensions. During this first commissioning phase, this was only sometimes the case. Therefore further measurements with better measurement conditions are needed to confirm the results. The study of measurement errors and systematic effects of different analysis methods is not yet finalized, and the data is still subject to a further analysis. Therefore, the emittance results shown here have to be treated preliminary.

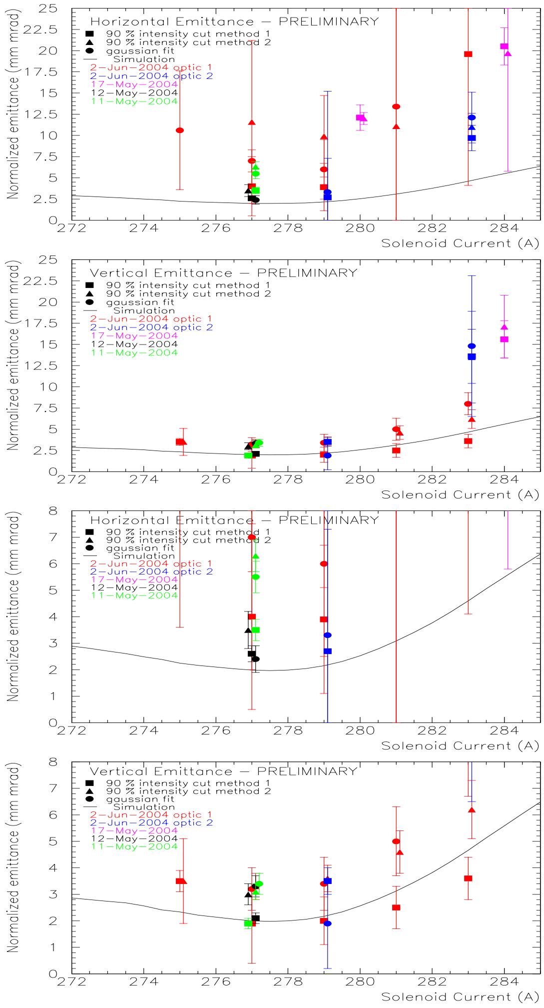

Figure 2: Normalized emittance measured at 100 MeV for a bunch charge of 1 nC as a function of the solenoid current. Horizontal and vertical projected emittances are shown for different beam conditions and matching optics. In addition, three different ways to obtain the rms beam size are shown: the rms size from a 90 % intensity cut with 2 different image analysis methods and an estimate from a gauss fit. Error in beam size is assumed to be 10 %. The two lower plots are zooms of the upper ones. The data are still object to further analysis and have to be treated preliminary.

Nevertheless, the emittance results obtained are already now useful to determine a tentative working point in terms of a preferred solenoid current. We can also see that in the horizontal case, the data scatter largely. Typically the beam quality in the horizontal plane is worse than vertical. The reason is not yet understood, but possible candidates are non-optimized injection into the first module, a non-uniform laser beam, and a beam passing too close to the laser mirror, which is inside the beam pipe. The latter has been observed at PITZ as well.

The rms bunch length has been measured using synchrotron radiation (SR) from the last dipole of the bunch compressor. This radiation is guided out of the accelerator tunnel and used in bunch length measurements by an interferometer and a streak camera [21]. The analysis of the interferometer data is on going.

The uncompressed bunch length measured by the streak camera is σ = 1.7±0.2 mm as expected. In the compressed case, we expect to have a bunch structure consisting of a 100 μm leading peak (FWHM), and a tail (rms size of 0.5 mm). We observed that the bunch shortens as expected when the phase of the accelerating module is changed. However, accurate measurements of the shape and size of short bunches have not yet been possible due to too low number of SR photons on the streak camera, which prevents us from using a wavelength filter. The filter is essential to avoid smearing the data due to dispersion effects in the streak camera optics [22]. Since the number of SR photons increases with the electron beam energy, the situation should be improved when the full acceleration in the last four cavities of the first accelerating module is used.

SUMMARY AND OUTLOOK

The new photoinjector of the TTF linac driving the VUV-FEL has been successfully commissioned. Beam parameters are mostly understood, although fine tuning and more accurate measurements are still needed. Improvements in the reliability and beam stability are also necessary. After the short shutdown from June to August 2004, the beam operation of the whole linac will start in the beginning of September. The goal is to obtain first lasing at 30 nm by the end of this year.

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