COMMISSIONING OF THE VUV-FEL INJECTOR AT TTF

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Abstract

The VUV-FEL at the TESLA Test Facility (TTF) at DESY is being upgraded to an FEL user facility serving high brilliance beams in the wavelength range from the VUV to soft X-rays. The photoinjector has been redesigned to meet the more demanding beam parameters in terms of transverse emittance, peak current, and energy spread. The first phase of the injector upgrade has been finished in spring 2004. We report on its commissioning, including first measurements of beam parameters.

INTRODUCTION

One project of the TESLA collaboration at present is the VUV-FEL at the TESLA Test Facility (TTF) at DESY[1]. The VUV-FEL will be the first user facility for VUV and soft X-ray coherent light experiments with impressive peak and average brilliance. It is a piloting facility for the XFEL project[2] and serves as a test facility for further TESLA linear collider[3] related research and development. Beginning of 2004, the installation has been mostly completed. The photoinjector has been redesigned to meet the demanding beam parameters in terms of transverse emittance, peak current, and energy spread. The successful commissioning of the new injector took place from March to June 2004.

THE VUV-FEL

The TTF linac phase 1 has been a great success in demonstrating the feasibility and operability of superconducting accelerating structures with TESLA design [4]. Moreover, it has been used to drive the first SASE-FEL at wavelengths in the range of 120 to 80 nm [5]. Based on this experience, the linac has been redesigned to extend the wavelength range to 6 nm. For a detailed discussion on the linac and the parameter choices refer to [1].

For the start-up phase this year, emphasis is on achieving lasing and saturation at a wavelength of 30 nm, which requires a beam energy of 461.5 MeV. With a slice emittance of 2 mm mrad, the saturation length will be less than 20 m well within the undulator length of 27 m. Since we measure only the projected emittance, we rely on the simulation to estimate the slice emittance from a measured projected emittance (see [6] for more information). A rough estimate indicates, that with a rather pessimistic projected emittance of 6 mm mrad, the saturation length is still below 27 m.[1] Later, lasing at longer and shorter wavelengths and finally down to 6 nm will follow, where stronger requirements on the emittance apply.

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THE INJECTOR CONCEPT

One of the main improvements compared to TTF phase 1 is the upgrade of the injector. It follows the proposal for the XFEL [7]. Figure 1 shows a schematic overview.

A laser-driven photocathode RF gun generates electron bunch trains with a charge of 1 nC each. The design normalized transverse emittance is 2 μm. It is obtained by choosing transverse and longitudinal flat laser pulses with a length of 20 ps (fwhh). The rms bunch length at the gun exit is long (2.2 mm), which leads to an RF induced curvature in the energy-phase plane after acceleration. To remove this curvature a superconducting third harmonic cavity (3.9 GHz) will be installed before the first bunch compressor.[8] This cavity is not available for the initial run this year. Therefore, the strategy for the start-up will be similar than for phase 1, where the strong energy-phase curvature lead to a high current spike in the kA range.[9]

A complete TESLA module with 8 accelerating structures boosts the beam energy to 150 MeV before the first bunch compression. Its first four cavities accelerate with moderate gradient (12 MV/m), to avoid strong focusing due to the ponderomotive force during acceleration. The last four cavities further accelerate with full gradient (20 MV/m). The bunch is then compressed down to 50 μm by magnetic chicane compressors in two stages at 150 MeV and 440 MeV. The second compressor has not been operated during this commissioning phase.

THE RF GUN

A new RF gun and an upgraded laser system have been successfully tested at PITZ [10]. It is a 1.5 cell L-band cavity (1.3 GHz, TM_{010} mode) powered by a 5 MW klystron. The RF gun design keeps the cylindrical symmetry around the beam axis as perfect as possible. A Cs_2Te photocathode is inserted via a load-lock system to the back of the half cell. The new cathodes have a higher than usual quantum efficiency.[11] The RF gun has been operated at 10 Hz with an RF power of 3 MW and an RF pulse length of up to 0.9 ms.[12] However, during most the commissioning time, 5 Hz repetition rate has been chosen for convenience. A low level RF system based on digital signal processors reads the forward and reflected power from the gun and regulates the RF power and RF phase in the gun by acting on the low level RF input to the klystron with a vector modulator.

THE LASER SYSTEM

The TTF phase 1 laser system[13] has been upgraded as well. The laser is based on a mode-locked pulse train

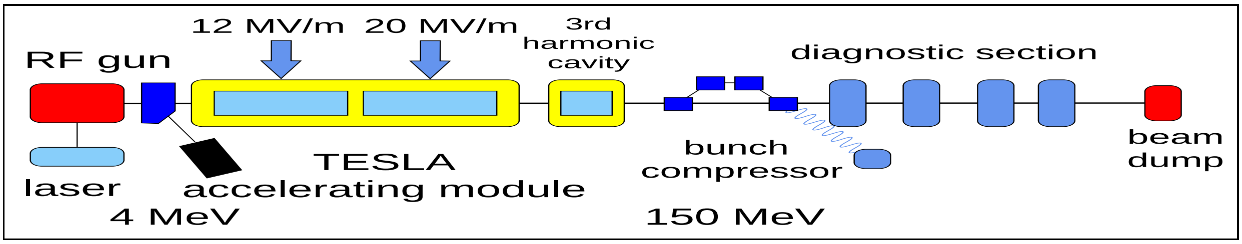

Figure 1: Schematic overview of the TTF VUV-FEL injector (not to scale). Beam direction is from left to right, the total length is 37 m. During the commissioning the beam is dumped into a small temporary beam dump.

oscillator synchronized to the 1.3 GHz RF of the accelerator. It uses now laser diodes for pumping. Amplification is obtained with a linear chain of amplifiers. Two amplifiers are already pumped with laser diodes, the last two are still from TTF1 and pumped with flashlamps. Finally, the wavelength is converted into the UV (262 nm) with two non-linear crystals (LBO and BBO). Movable mirrors allow to control the position of the laser spot on the cathode. The system is designed to produce pulse trains with up to 800 μs length. The pulse spacing is usually 1 μs (1 MHz). A 9 MHz mode is presently being in preparation.

Due to the diode pumping, the laser has gained in pulse energy stability. The fluctuation measured in the electron bunch charge from shot to shot is 1 % rms compared to 3 to 6 % before the upgrade. The pulses length in the UV measured with a streak camera is $\sigma_1 = 4.4 \pm 0.1$ ps, half the value before the upgrade.

An essential design parameter to achieve a small emittance is to have a flat-hat laser profile transverse and longitudinal. A pulse shaper to obtain longitudinal flat-hat profiles has been tested at PITZ and lead to a reduction in transverse emittance by a factor of 2 compared to a gaussian longitudinal profile.[14] This pulse shaper is not yet installed at TTF, since it is still in an experimental stage.

MEASUREMENT OF BASIC BEAM PARAMETERS

Two major diagnostic tools are available after the bunch compressor. A section with four screens[15] and wire scanners serve to measure beam sizes to determine the Twiss parameters. A far-infrared interferometer and a streak camera use the synchrotron radiation of the last chicane dipole to measure the bunch length.

The screen system uses optical transition radiation generated by the electrons when they pass through a silicon waver with an Al coating. The measured rms resolution is 11 μm (1:1 magnification). The system has been successfully commissioned and has been used to measure the transverse emittance.[16]

The four screens are embedded in a FODO lattice of 6 quadrupoles with a periodic beta function. The emittance and Twiss parameters are obtained by fitting the measured beam sizes to the expectation from the lattice. Fig. 2 shows the horizontal and vertical emittance as a function of the solenoid current. The data are partly taken at different days and with different optics to match into the FODO lattice. The expected emittance from simulation using gaussian shaped laser pulses is shown as well. The RF gun and module have been operated with nominal parameters: 3 MW RF power to the gun, an RF phase gun/laser of 32° in respect to zero crossing, an accelerating gradient in the module of 12 MV/m at a charge of 1 nC.

The rms beam sizes are estimated from projections with two methods. In the first method, the sigma of a gaussian fit on the projected profiles is used to estimate the rms, in the second, the true rms is calculated from the data within 90 % of the intensity of the beam. For further discussion, refer to [16]. The emittance data shown here are still preliminary, since the study of systematic effects have not been finalized yet. Nevertheless, they are already now useful to determine the working points of the injector, in this example the preferred solenoid current. In the horizontal case, the data scatter largely for different days and optics. Depending on the set-up, the horizontal beam shape develops a large halo and is ununiform, making the determination of the rms spot size difficult. This is probably due to non-optimized injection into the first module or if the beam is passing the laser mirror too close. However, for a well matched beam and when care is taken to correctly inject the beam into the module, the emittance for a solenoid current of 277 A is well below 6 mm mrad required for the start-up lasing at 30 nm.

Basic measurements like the energy and energy spread of the electron beam show the expected values and give us confidence, that we fully understand the basic properties of the beam. For example, Fig. 3 shows the beam momentum measured after the RF gun with a spectrometer dipole as a function of RF power. The data agree well with the simulation and show, that the acceleration in the RF gun is well understood.

The accelerating module has been operated with a gradient of 12 MV/m yielding a beam energy around 100 MeV. With the feedback system regulating the phase and amplitude of the accelerating structures, the energy stability is better than $8.5{\cdot}10^{-4}$ rms. The uncorrelated energy spread has been estimated to be in the range of 25 to 30 keV. This is only an upper value limited by the resolution of the chicane dipoles. This number is important, since it determines the width of the leading spike in the longitudinal charge

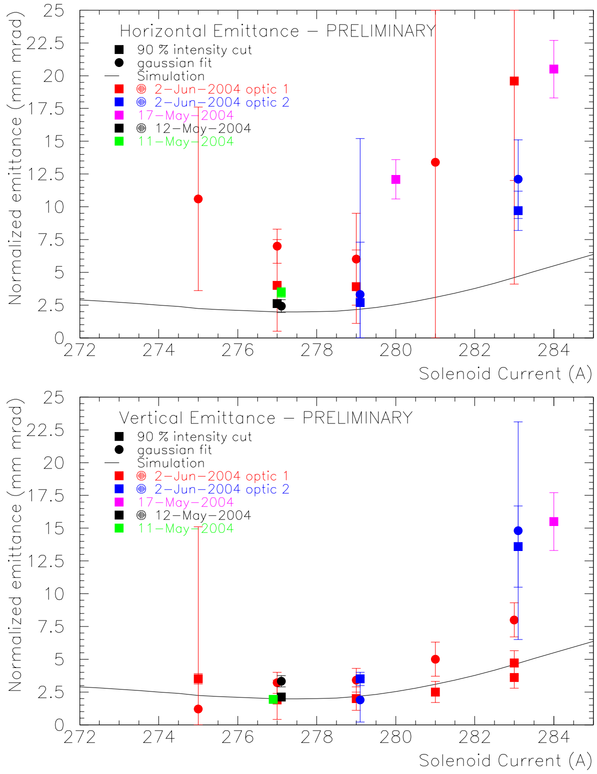

Figure 2: Emittance measured at 100 MeV for a bunch charge of 1 nC as a function of the solenoid current. Horizontal and vertical projected emittances are shown for different beam conditions and matching optics. In addition, two different ways to obtain the rms beam size are shown: the true rms from 90 % of the beam intensity and from a gauss fit. The data are still object to further analysis and have to be treated preliminary. (A solenoid current of 280 A corresponds to 0.165 T.)

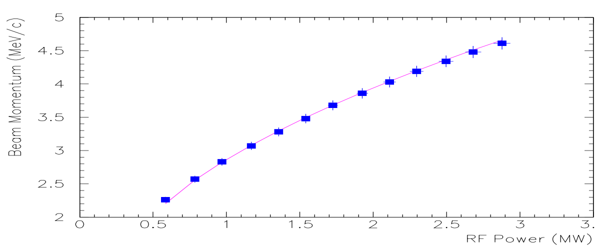

Figure 3: Electron beam momentum measured after the RF gun as a function of RF power in the gun (squares) with simulation (line).

distribution after compression (see the discussion above).

The rms bunch length has been measured with the interferometer and the streak camera. The uncompressed bunch length is 1.7 ± 0.2 mm as expected. In the compressed case, where the leading spike is expected to have a fwhh width of 100 μm and an rms bunch length of 0.5 mm, the measurement is more difficult. In the case of the streak camera, the amount of synchrotron radiation was just too small to apply wavelength filtering to avoid dispersion effects in the camera optics; the data of the interferometer are not fully analyzed yet and need more systematic study. The situation will improve when the design energy of 150 MeV is reached.

OUTLOOK

The injector for TTF and the VUV-FEL has been successfully commissioned. Beam parameters are mostly understood, a good working point in terms of small emittance and short bunches has been established. Nevertheless, fine tuning of the parameters has to follow, and improvements in launching the beam into the accelerating structure and in setting up a matched optics are necessary. After the short shutdown from June to August 2004, beam operation will start beginning of September with the goal of injecting the beam into the linac and to obtain first lasing at 30 nm by end of this year.

ACKNOWLEDGEMENT

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