TRANSVERSE ELECTRON BEAM DIAGNOSTICS AT THE VUV-FEL AT DESY

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Abstract

The VUV-FEL is a new free electron laser user facility at DESY. High demands on the electron beam quality require sophisticated beam diagnostics tools and methods. At the VUV-FEL the transverse distribution of the electron beam is measured using optical transition radiation (OTR) monitors and wire scanners. This paper refers concepts, analysis, and results of the transverse phase space measurements. The main emphasis is on emittance measurements, in which we have regularly measured normalized projected rms emittances around 1.4 mm mrad for 90% of a 1 nC bunch at 127 MeV beam energy.

INTRODUCTION

The TESLA Test Facility (TTF) linac at DESY (Hamburg) has been extended to drive a new free electron laser user facility, the VUV-FEL [1], in the wavelength range from vacuum-ultraviolet to soft x-rays. The commissioning of the facility started in the beginning of 2004, and the first lasing was achieved in January 2005 [2, 3]. The first user FEL experiments started in summer 2005.

Figure 1 shows a schematic layout of the present stage of the VUV-FEL linac. Electron bunch trains with a nominal bunch charge of 1 nC are generated by a laser-driven RF gun. Five accelerating modules with eight 9-cell superconducting TESLA cavities are installed to provide electron beam energies up to ∼730 MeV. The electron bunch is compressed by two magnetic chicane bunch compressors. At the location of the first bunch compressor the beam energy is 127 MeV and at the second 370 MeV. During the commissioning the main emphasis has been on lasing with a wavelength of 32 nm, corresponding to an electron beam energy of 445 MeV.

The lasing process requires a high quality electron beam in terms of transverse emittance, peak current, and energy spread. In order to meet these demands, an accurate characterization of the electron beam properties is essential. In this paper we concentrate on measurements of the beam properties in the transverse phase space.

Presently, there are 27 optical beam profile monitors mounted along the VUV-FEL linac (see Fig. 1). Three of them, located in the RF gun area where the electron beam energy is low (∼5 MeV), detect light emitted by Ce:YAG screens. The other 24 monitors are based on optical transition radiation (OTR). Eight of the OTR monitors are combined with wire scanners. In addition there are seven wire scanner stations in the undulator section. All of these monitors are used for on-line optimization of the beam transport through the linac as well as for characterization of the transverse phase space by measurements of the beam shape, size, and emittance. The OTR monitors located in the dispersive sections are used for energy and energy spread measurements as well as for determination of the on-crest phase of the accelerating modules.

OTR MONITORS

The OTR monitors have been one of the main diagnostics tools during the commissioning of the VUV-FEL linac. Monitors in the injector area have been in operation since spring 2004, and the complete system since autumn 2004. Requirements for these monitors are demanding. They have to deliver on-line beam images to optimize the beam transport through the linac as well as provide high quality beam images for the characterization of the beam parameters in the transverse phase space. Since the electron beam size varies along the linac, as well as under different operation conditions, OTR monitors have to be able to measure transverse beam sizes from millimeter scale down to ∼50 μm (rms) with a high resolution. In addition, they have to be reliable, robust, and remote controlled.

The OTR monitor system is designed and constructed by INFN-LNF and INFN-Roma2 in collaboration with DESY. OTR monitors are based on measurements of backward optical transition radiation emitted by a screen at an angle of 45° with respect to the beam trajectory. All monitors have a remotely controlled stepper motor actuator to insert the OTR screen into the beam pipe. All stations, except the ones in the dispersive sections, have two screens: a polished silicon screen, and a silicon screen with an aluminium coating. Between the two screens, on the same plane, there are marks to adjust and calibrate the optical system.

Most of the monitors (18) have an optical set-up specially designed and constructed to meet the demands of the VUV-FEL. This set-up consists of a mirror deflecting the OTR light downwards, three achromat doublet lenses, three neutral density filters, and a CCD camera. The lenses and

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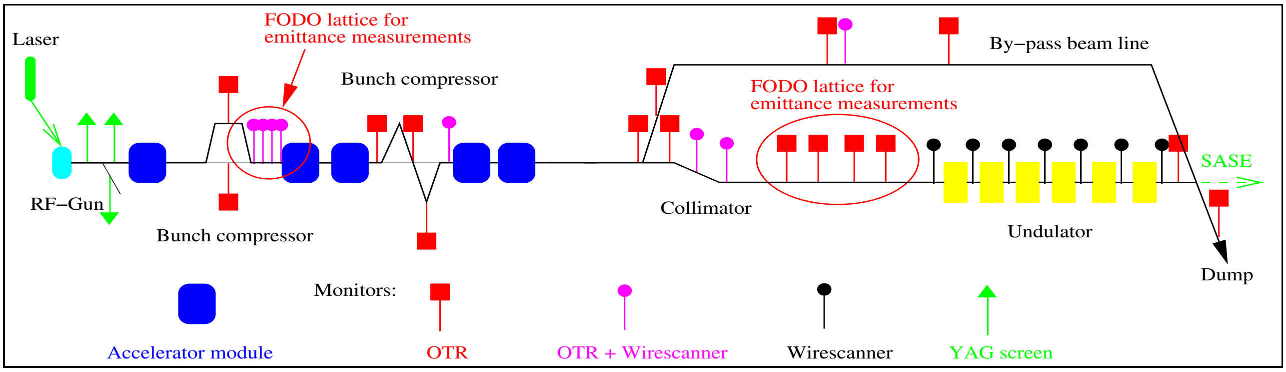

Figure 1: Present layout of the TTF VUV-FEL linac (not to scale). Beam direction is from left to right, and the total length is about 250 m. Locations of OTR monitors, wire scanners, and FODO lattices for emittance measurements are indicated.

the filters can be moved remotely in and out of the optical axis (transversal movement). Each of the lenses provides a fixed nominal magnification: 1.0, 0.39, and 0.25. The CCD camera has a lead shield against x-ray radiation, and the complete system is covered against external light. Prior to installation into the accelerator tunnel, all optical set-ups have been prealigned and calibrated in a laboratory. The measured resolution of the system is 11 μm rms for the highest magnification.

The OTR monitors in the bunch compressors and in the by-pass line, as well as the YAG screens in the RF gun area, have a simplified optical set-up: a CCD camera with an objective providing one fixed image magnification. Upgraded set-ups with a higher dynamic range and the possibility to change remotely the magnification will be available later for the monitors in the dispersive sections of the bunch compressors.

The read out system is based on the use of digital CCD cameras with a firewire interface (IEEE1394). The cameras are connected to compact industrial PCs, located in the accelerator tunnel, via firewire links (2-6 cameras to each). These PCs (8) are connected via local Ethernet to an "image server" PC in the control room. The image server, using LabView based control and image analysis software, is the main interface for the complete system. It controls the PCs and the cameras, displays beam images on-line, runs locally measurements and analysis programs, and provides beam images for applications running in other computers. House-made remotely controlled power switches allow to reset the PCs and the cameras from the control room.

More details of the OTR monitor system are in [4, 5, 6].

WIRE SCANNERS

Two different types of wire scanners are used at the VUV-FEL. Eight wire scanners along the linac are old devices, built in collaboration with CERN, and they are now combined with OTR monitors. Wire scanners at the undulator section have a new design, and they are constructed by DESY (Zeuthen and HASYLAB).

The first type has three tungsten wires with a diameter of 18 μm. The wires are mounted into a fork moving with an angle of 45° with respect to the beam. The wires are oriented such that one of them scans horizontally, an other one vertically, and the third one provides information of the coupling between the two planes. Since these wire scanners are mounted into a common vacuum chamber with an OTR screen, only 5 mm downstream of the screen, they can be used for complementary measurements of the transverse beam profile and size. A first cross-check between profiles measured by the OTR monitors and the wire scanners on the four OTR/wire scanner monitors downstream of the first bunch compressor is recently done showing a good agreement (see Fig. 2).

Seven wire scanner stations are mounted along the undu-

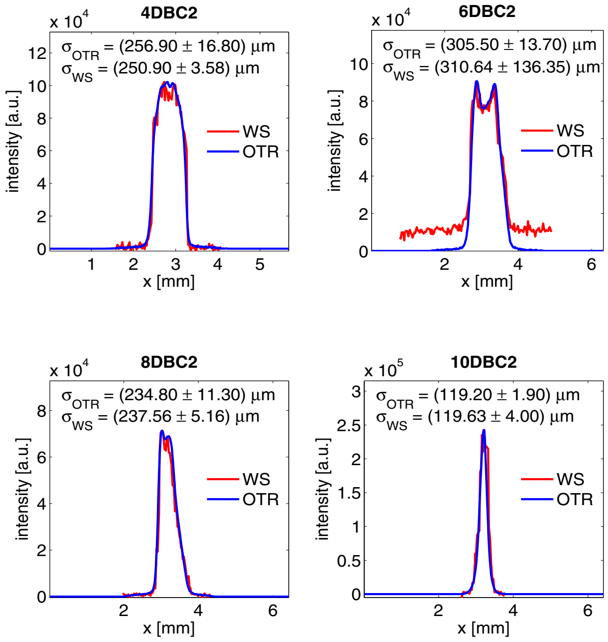

Figure 2: Comparison of transverse beam profiles measured by OTR monitors (blue) and wire scanners (red) downstream of the first bunch compressor. The measured rms beam sizes are shown as well.

lator. Each of these stations has two individual wire scanners: one scanning in horizontal direction and the other one in vertical. Each scanner has three wires: a 10 μm thick carbon wire, and two tungsten wires with diameters of 10 μm and 50 μm. At the moment, we use typically the carbon wire. The maximum scanning speed is 1 m/s. Since these wire scanners can measure the absolute beam position with respect to the undulator axis with a precision of 50 - 100 μm they are used, besides the measurements of the beam shape and size, also for measurements of the beam orbit along the undulator. More details of the undulator wire scanners are in [7].

Both wire scanner types use photomultipliers to detect secondary particles emitted when the wire passes the electron beam. The measured beam profile and size are calculated and displayed on-line. A sophisticated control and display software being an integral part of the VUV-FEL control system is under commissioning [8].

EMITTANCE MEASUREMENTS

The transverse projected emittance is measured using a four-monitor method. This method is based on measurements of the transverse beam distribution (shape and size) at four locations along the linac with a fixed beam optics. A detailed description of the emittance measurements and analysis techniques presented here are in [9].

Experimental set-up and data-analysis

There are two diagnostic sections dedicated to emittance measurements along the VUV-FEL linac (see Fig. 1). The first one is located downstream of the first bunch compressor at an electron beam energy of 127 MeV. This section has four OTR monitors combined with wire scanners mounted into a FODO lattice of six quadrupoles with a periodic beta function. A second FODO lattice with four OTR monitors is located upstream of the undulator.

The transverse emittance is determined from the measured beam distributions and the known transport matrices between the monitors using two different techniques. The first method is based on a least square (chi-square) fitting of the Twiss parameters and the emittance to the measured beam sizes. An application of this method for emittance measurements can be found in [10]. The second method is a tomographic reconstruction of the phase space using the maximum entropy algorithm [11].

Sofar, routine emittance measurements have been performed in the first diagnostics section using OTR monitors. In a typical measurement 20 beam and background images are recorded at each of the four OTR screens. After subtraction of an averaged background from each beam image, a sophisticated analysis procedure is applied to determine an elliptical region of interest (ROI) surrounding the entire beam, as well as to correct remaining off-sets. If required, a wavelet filter can be used to reduce the noise.

Besides the emittance of the entire beam, we are interested in the emittance of the high density core. This core is determined by cutting away 10% (an arbitrary choice) of particles in the tails of the two dimensional transverse beam distribution. After that the horizontal and vertical rms beam sizes of the entire beam and of the core containing 90% of it are calculated. These rms beam sizes are used in the fitting method to calculate the emittance of the entire beam and the core emittance including 90% of the beam intensity.

In the tomographic reconstruction, an averaged beam profile at each screen is used. In order to avoid broadening of this profile due to a beam position jitter, the measured profiles are rebinned, and the center of each profile is moved to the same position before averaging. The phase space distribution is reconstructed using the maximum entropy algorithm, and the emittance is then determined from this distribution. In order to determine the 90% core emittance, 10% of the particles in the tails of the reconstructed phase space distribution is cut away.

An error estimation taking into account statistical and systematical errors has been performed for the fitting method. Statistical errors due to fluctuations of the measured beam sizes are calculated as in [10]. Systematical errors are estimated using a Monte Carlo simulation assuming a 5% error in the beam energy, a 6% error in the gradient of the FODO lattice quadrupoles, and a 3% error in the calibration of the optical system. Statistical errors are typically 2-4%, and systematical ones 5-6%. For the tomographic reconstruction, no error analysis is performed yet.

Experimental results

The measurements presented here are performed in the first diagnostic section using OTR monitors. Figure 3 shows the normalized horizontal (ϵ_x) and vertical (ϵ_y) projected emittances measured ten times during 75 minutes without changing the machine parameters. The geometrical average ($\sqrt{\epsilon_x \epsilon_y}$) is shown as well. The electron beam energy is 127 MeV, and the bunch charge 1 nC. The beam is transported through the first bunch compressor without compression (on-crest acceleration in the first accelerating module). The results obtained by fitting and by tomography are presented for 100% and 90% beam intensity. We can see that the results by the two techniques agree well, and that the stability of the measurements is good. The rms jitter of the 100% emittance in the horizontal plane is $\sim$3.5% and in the vertical $\sim$2%, in agreement with the statistical error estimated above.

During the measurements above the injector was operated with the nominal laser and RF settings. The optimal settings of the solenoid magnets were used [12], whereas the injection to the first accelerating module was not completely optimized. When the injector is carefully tuned, we regularly measure normalized projected emittances around 1.4 mm mrad for 90% of a 1 nC bunch. For the entire beam, this value is around 2 mm mrad.

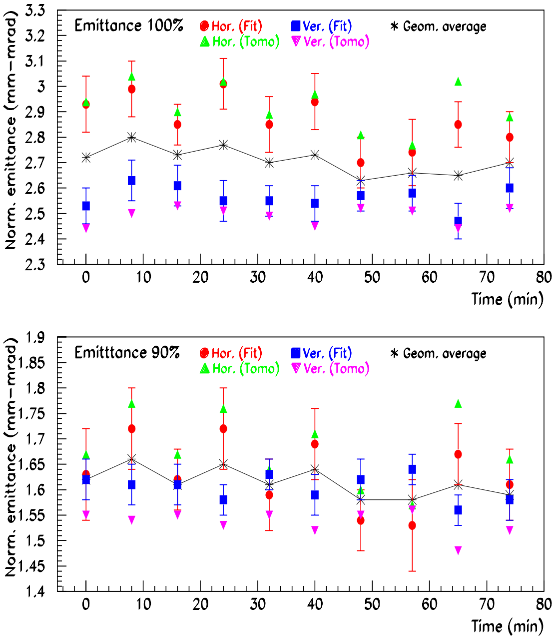

Figure 3: Horizontal (fitting=red, tomography=green) and vertical (fitting=blue, tomography=magenta) normalized emittances. The measurement is repeated 10 times during 75 minutes. Results obtained for 100% (top) and 90% (bottom) beam intensity are shown. Error is the statistical error only. The black curve shows the geometrical average ($\sqrt{\epsilon_x \epsilon_y}$) of the horizontal and vertical emittances obtained by the fitting method.

SUMMARY AND OUTLOOK

The OTR monitors are in routine use to measure and optimize the electron beam parameters along the VUV-FEL linac. A first cross-check of the beam profiles measured simultaneously by the OTR monitors and the wire scanners in the first diagnostics section has been done showing a good agreement. The control software for these wire scanners is still under commissioning, and therefore they are not yet routinely used. The wire scanners in the undulator section are regularly used to measure the beam sizes and the beam orbit along the undulator.

The emittance measurement system based on a four-monitor method using OTR monitors is commissioned and routinely used to measure projected emittances at the VUV-FEL injector. Normalized emittances around 1.4 mm mrad for 90% of a 1 nC bunch at 127 MeV beam energy are regularly measured.

Optimization of the emittance measurement conditions in the second diagnostics section is not yet finished, and therefore accurate emittance measurements are not yet performed there. First tests to use the undulator wire scanners for the emittance measurement have been successfully done, and they are now available for emittance measurements along the undulator.

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REFERENCES

[1] The TTF FEL Team, “SASE FEL at the TESLA Test Facility, Phase 2”, DESY-TESLA-FEL 2002-01

[2] B. Faatz for the DESY VUV-FEL project team, “First Results from the VUV-FEL at DESY”, PAC 2005, Knoxville, Tennessee, May 16-20, 2005

[3] S. Schreiber for the VUV-FEL team, “First lasing at 32 nm of the VUV-FEL at DESY”, these proceedings

[4] K. Honkavaara *et al.*, “Design of OTR beam profile monitors for the TESLA Test Facility, phase 2 (TTF2)”, PAC 2003, Portland, Oregon, May 12-16, 2003

[5] A. Cianchi *et al.*, “Commissioning of the OTR beam profile monitor system at TTF/VUV-FEL Injector”, EPAC 2004, Luzern, Switzerland, July 5-9, 2004

[6] L. Catani *et al.*, “A large distributed digital camera system for accelerator beam diagnostics”, Review of Scientific Instruments **76**, 073303 (2005)

[7] M. Sachwitz *et al.*, “Wire scanners in the undulator section of the VUV-FEL at DESY”, DIPAC 2005, Lyon, France, 6-8 June, 2005

[8] E. Sombrowski *et al.*, “Wire scanner control and display Software”, PCaPAC 2005, Hayama, Japan, March 22-25, 2005

[9] F. Löhl, “Measurements of the transverse emittance at the VUV-FEL”, to be published as DESY-THESIS 2005-014 and TESLA-FEL 2005-03, Diploma Thesis, Hamburg University, 2005.

[10] M. Minty and F. Zimmermann, *Measurements and control of charged particle beams*, Springer, 2003

[11] J. Scheins, “Tomographic Reconstruction of Transverse and Longitudinal Phase Space Distribution using the Maximum Entropy Algorithm”, TESLA Report 2004-08, May 2004

[12] K. Honkavaara for the VUV-FEL team, “Electron beam characterization at PITZ and the VUV-FEL at DESY”, these proceedings