

MEASUREMENTS OF TRANSVERSE EMITTANCE AT THE TTF VUV-FEL

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Abstract

The TESLA Test Facility (TTF) linac at DESY has been extended to drive a new free electron laser facility, the VUV-FEL. The 250 m long electron linac has been commissioned in 2004 and in the beginning of 2005. Characterization of the electron beam is an essential part of the commissioning. The transverse projected emittance has been measured at a beam energy of 127 MeV with the four-monitor method using optical transition radiation (OTR). We describe the experimental set-up and discuss the data-analysis methods. Experimental results as well as simulations are presented.

INTRODUCTION

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

Figure 1 shows the present layout of the TTF 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 energy up to 750 MeV. The electron bunch is compressed using two magnetic chicane bunch compressors. At the location of the first bunch compressor the beam energy is 127 MeV and at the second one 380 MeV. During the commissioning the main emphasis has been on lasing with the wavelength of 30 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. The design normalized emittance of the VUV-FEL is 2 mm mrad. A more detailed description of the machine and first experimental results can be found in [2, 3].

At the VUV-FEL, measurements of the transverse projected emittance are performed using a four-monitor method. In this method the transverse beam distribution is measured at four locations along the linac with a fixed beam optics. The emittance is calculated by two different techniques. The first one is based on fitting of the Twiss parameters and the emittance to the measured beam sizes. The second one uses a tomographic reconstruction of the phase space distribution. A detailed description of the emittance

measurements and analysis techniques presented in this paper can be found in [4].

EXPERIMENTAL SET-UP

The VUV-FEL has two diagnostic sections dedicated to emittance measurements (see Fig. 1). The first one is located downstreams of the first bunch compressor at the electron beam energy of 127 MeV. This section consists of four OTR monitors combined with wirescanners embedded in a FODO lattice of six quadrupoles with a periodic beta function. A second FODO lattice with four OTR monitors is located upstreams of the undulator. In this paper we concentrate on emittance measurements in the first section using OTR monitors only.

The OTR system is designed and constructed by INFN-LNF and INFN-Roma2 in collaboration with DESY. The system can be controlled remotely, and it provides three different image magnifications (1.0, 0.39, and 0.25). The read-out system is based on digital CCD cameras with IEEE1394 (firewire) interface. The measured resolution of the system is 11 μm rms for the highest magnification. More details of the OTR monitor system are in [5, 6, 7].

EMITTANCE CALCULATIONS

The four (multi) monitor method is based on measurements of the transverse beam distribution (shape and size) at four (or more) locations with a fixed beam optics. The transverse emittance is determined from the measured beam distributions and the known transport matrices between the monitors using two different methods. The first one uses a least square (chi-square) fitting of the Twiss parameters and the emittance to the measured beam sizes. A general description of the least square fitting technique can be found, for example, in [8], and an application for emittance measurements in [9]. The second method is based on a tomographic reconstruction of the phase space distribution using the maximum entropy algorithm [10].

In the error estimation for the fitting method, we take into account both statistical and systematic errors. Statistical errors are caused by fluctuations on the measured beam sizes, and they are calculated as in [9]. Systematic errors are estimated using a Monte Carlo simulation assuming 5% error in the beam energy, 6% error in the gradient of the FODO lattice quadrupoles, and 3% error in the calibration of the optical system. Statistical errors are typically 2-4% and systematic ones 5-6%. For the tomographic reconstruction, no error analysis is performed yet.

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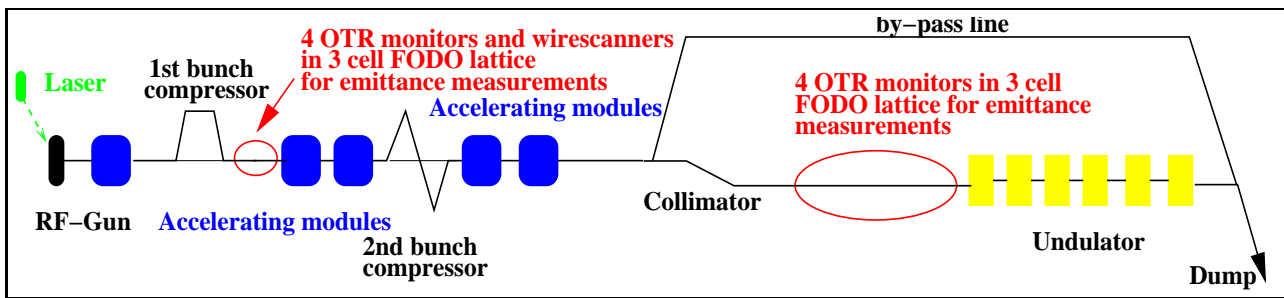


Figure 1: Present layout of the TTF VUV-FEL linac (not to scale). Beam direction is from left to right, and the total length is about 250 m. Locations of the diagnostic sections for emittance measurements are indicated.

IMAGE ANALYSIS

In a typical emittance measurement 20 beam and background images are recorded on each of the four OTR screens. In order to remove the influence of darkcurrent and damaged camera pixels as well as to correct off-sets generated by, for example, noise in the camera system, an averaged background image is subtracted from each beam image. A sophisticated analysis procedure is applied to each image to determine an elliptical region of interest (ROI) surrounding the entire beam. Remaining off-sets are corrected as well. If required, a wavelet filter can be used to reduce the noise further. Horizontal and vertical rms beam sizes as well as projections onto the horizontal and vertical axes are then calculated.

A small fraction of particles in the tails of the distribution can have a significant influence on the measured emittance. Therefore, in addition to the emittance of the entire beam, also the emittance of the high density core is of interest. We determine this core by cutting away 10% (an arbitrary choice) of particles in the distribution tails. After that the horizontal and vertical rms beam sizes of this core containing 90% of the beam intensity are calculated.

The rms beam sizes defined as above are used to calculate the emittance using the fitting technique resulting in the rms emittance of the entire beam (referred here as 'Fit 100%') and the rms emittance of the beam core including 90% of the particles (referred here as 'Fit 90%').

In the tomographic reconstruction an averaged beam profile of the entire beam on each screen is used. In order to avoid broadening of the 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 emittance of the entire beam is then determined by the maximum entropy algorithm (referred here as 'Tomo 100%'). In order to obtain the 90% core emittance (referred here as 'Tomo 90%'), 10% of the particles in the tails of the reconstructed phase space distribution are cut away.

MEASUREMENTS AND RESULTS

The measurements presented here are performed in the first diagnostic section using OTR monitors. During these measurements the injector was operated with nominal pa-

rameters, but it was not tuned to obtain the minimum emittance. The beam energy was 127 MeV, and one bunch of 1 nC was used. The beam was transported through the bunch compressor without compression (on-crest acceleration in the first accelerating module).

Figure 2 shows the normalized horizontal and vertical rms emittances measured ten times during ~ 1.5 hours without changing the machine parameters. 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.

In order to reduce space charge induced emittance growth in the RF-gun, the electron beam is focused by a solenoid magnet. Figure 3 shows the normalized horizontal and vertical rms emittances as a function of the current in this solenoid. The beam is matched to the FODO lattice for each solenoid current. This is important, since matched Twiss parameters inside the FODO lattice are required for accurate emittance measurements [4]. The measurement was repeated twice for each solenoid current. The result from ASTRA [11] simulations using normalized projected emittance of 2 mm mrad is shown as a solid line. We can see that the behavior as a function of the solenoid current predicted by the simulations agrees well with the measurements. Both show that the optimal solenoid current, from the emittance point of view, is around 277 A, which corresponds to a magnetic field of 0.163 T.

SUMMARY AND OUTLOOK

The emittance measurement system based on a four-monitor method using OTR monitors is commissioned and in routine use by operators to measure and to optimize the electron beam parameters in the VUV-FEL injector.

Wire scanners in the injector diagnostic section are still under commissioning, but in the near future they will provide a complementary measurement of the beam sizes and the emittance to be compared with the results obtained by the OTR monitors.

Due to present priorities at the VUV-FEL, it has not yet been possible to optimize the measurement conditions in

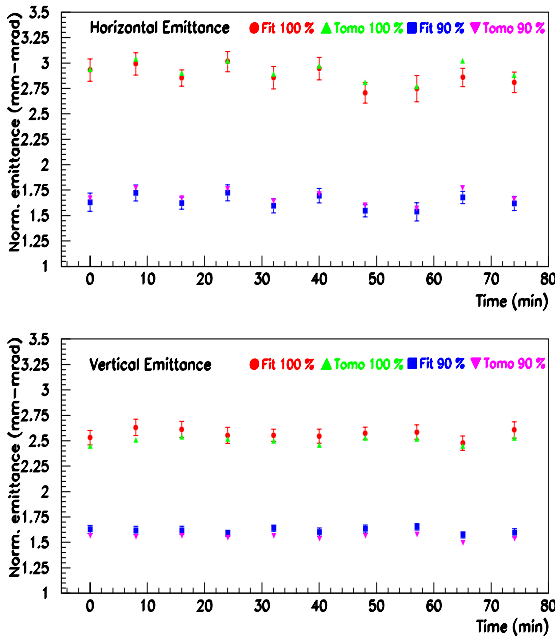


Figure 2: Horizontal (top) and vertical (bottom) normalized rms emittances. The measurement is repeated 10 times during ~ 1.5 hours. Results obtained by fitting for 100% (red) and 90% (blue) beam intensity as well as by tomography for 100% (green) and 90% (magenta) intensity are shown. Error is the statistical error only.

the second diagnostic section. Therefore, accurate emittance measurements at the full beam energy have not been done yet. However, when the emittance measurements can be performed simultaneously both in the injector and before the undulator, useful information about the emittance transport through the linac can be obtained.

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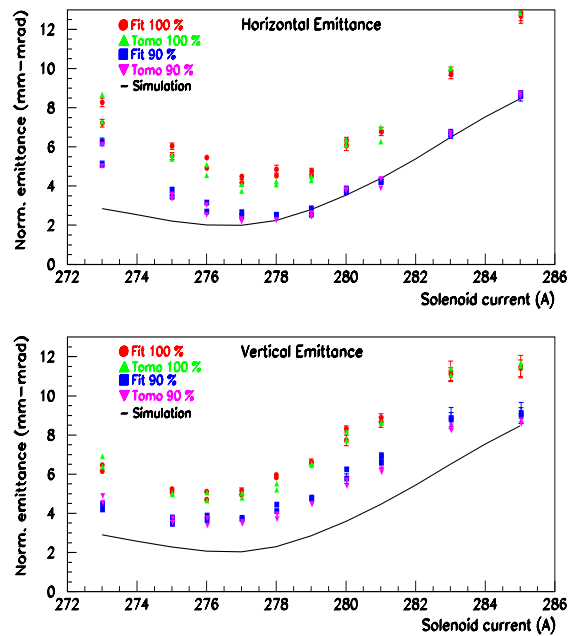


Figure 3: Horizontal (top) and vertical (bottom) normalized rms emittance measured as a function of the solenoid current. Results obtained by fitting for 100% (red) and 90% (blue) beam intensity as well as by tomography for 100% (green) and 90% (magenta) intensity are shown. Error is the statistical error only. The solid line is a prediction from simulations.

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