# MEASUREMENTS OF PROJECTED EMITTANCE AT FLASH

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*Abstract*

FLASH is a SASE FEL user facility at DESY operating with photon wavelengths in the range from vacuum ultraviolet to soft x-rays. Although the slice emittance is a more appropriate parameter to characterize the SASE process, the projected emittance provides a useful measure of the electron beam quality. At FLASH, the projected emittance is measured at three locations along the linac: in the injector (130 MeV), after the collimator, and in the undulator section. The emittance is determined by using a multi-monitor method with OTR monitors and wire scanners. In this paper we describe the measurement set-up and procedure, and report recent results.

## INTRODUCTION

FLASH is a SASE FEL user facility at DESY (Hamburg, Germany). It produces short (in order of 10 fs) laser like pulses in the wavelength range from the vacuum ultraviolet to the soft X-ray [1].

Figure 1 shows a schematic layout of the FLASH linac as operated in 2006 and the first half of 2007. Electron bunch trains with up to 800 bunches are generated by a laser-driven RF gun. The macro-pulse repetition rate is 5 Hz, and the bunch frequency 1 MHz. During the measurements reported here, the linac is operated with one or two bunches per bunch train. The bunch charge is 1 nC.

Five accelerating modules, with eight 9-cell superconducting TESLA cavities each, 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 ∼130 MeV, and at the second one ∼370 MeV. During the measurements reported here, the total beam energy after acceleration is ∼500 MeV. The SASE radiation is produced by six undulator modules with length of 4.5 m each.

The SASE process requires a high quality electron beam in terms of transverse emittance, peak current and energy spread. In the characterization of this process, the slice parameters are the appropriate parameters to consider. However, also the projected emittance, which is relatively easy to measure compared to the slice emittance, provides an important measure of the electron beam quality. In addition to be able to produce a small emittance beam at the injector, it is important to conserve this small emittance up to the undulator, where the SASE radiation is produced.

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In this we paper describe the emittance measurements performed at three location along the FLASH linac: at the injector, after the collimation section and at the undulator. These measurements are also discussed in [2].

## EXPERIMENTAL SET-UP

We measure the transverse projected emittance using a multi-monitor method. This method is based on measurements of the transverse beam distribution (shape and size) at several locations with fixed beam optics.

There are two diagnostic sections dedicated to emittance measurements along the FLASH linac (see Fig. 1). The first one is located downstream of the first bunch compressor. This section has four OTR (optical transition radiation) monitors combined with wire scanners mounted into a FODO lattice of six quadrupoles with a periodic beta function. Below, we refer this section as the 'BC section'. A second FODO lattice with four OTR monitors is located upstream of the undulator, referred here as the 'SEED section'. A fifth OTR monitor placed upstream of the FODO lattice is used as an additional monitor in the measurements. Along the undulator, the emittance is measured using wire scanners located in front of each undulator module. A seventh wire scanner station is downstream of the undulator.

### *OTR monitors*

OTR monitors are based on detection of backward optical transition radiation. The OTR light is emitted when the electron beam passes through an aluminium coated silicon screen inserted at an angle of 45° with respect to the beam trajectory. The ligth is deflected downwards into an optical set-up consisting of three achromat doublet lenses, three neutral density filters, and a digital CCD camera. Each lens provides a fixed magnification, and can be remotely moved in and out of the optical axis. For accurate measurements we use the lens with the highest magnification (1:1). With this lens the measured resolution is 11 $\mu$m rms.

The digital CCD cameras with a firewire interface are connected to a PC in the accelerator tunnel. The PC is connected via local Ethernet to an "image server" in the control room. The read-out system, using a LabView based control software, provides beam images for the on-line visualization and for different applications.

More details of the OTR monitor system are in [3, 4].

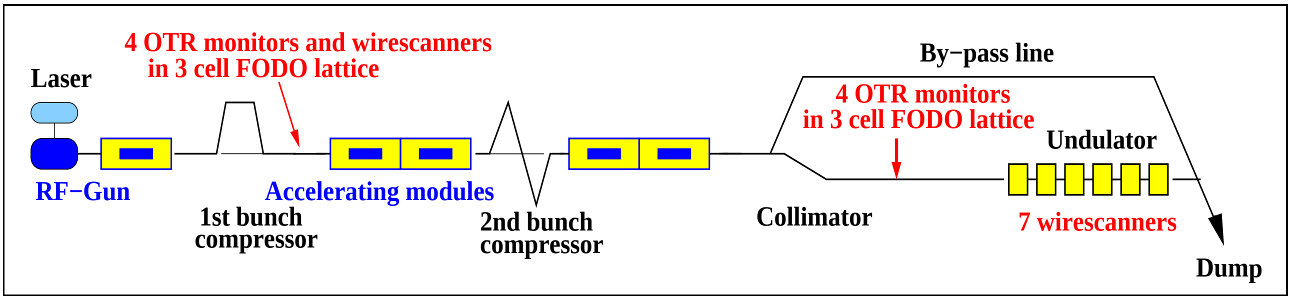


Figure 1: Layout of the FLASH linac (not to scale). Beam direction is from left to right, and the total length is about 250 m. Locations of OTR monitors and wire scanners, used for the emittance measurements, are indicated.

### *Combined OTR and wire scanner monitors*

The OTR monitors in the BC section are combined with wire scanners. Each scanner has a fork with three tungsten wires with a diameter of 18 $\mu$m. The wires are oriented such that one of them scans horizontally and another one vertically; the third wire provides information of the coupling between the two planes. The wire scanner is mounted into a common vacuum chamber with an OTR screen, located 5 mm downstream of it. The read-out system, consisting of scintillator panels and photomultipliers, detects secondary particles emitted when the wire passes the electron beam.

In the emittance measurements reported here, we used the OTR monitors only. However, a cross check between profiles measured by the OTR monitors and the wire scanners have been performed showing a good agreement [5].

### *Undulator wire scanners*

Seven wire scanner stations are mounted along the undulator. Each of these stations has two individual wire scanners: one scanning in horizontal direction, and the other one in the vertical. Each scanner has three wires: a 10 $\mu$m thick carbon wire, and two tungsten wires with diameters of 10 $\mu$m and 50 $\mu$m . The read-out is based on detection of secondary emission particles measured with scintillator panels and photomultipliers. More technical details of the undulator wire scanners are in [6].

## MEASUREMENTS AND ANALYSIS

During an emittance measurement with OTR monitors, we record 20 beam and background images for each OTR screen. The averaged background is subtracted from each beam image. After that, a sophisticated image analysis procedure is applied to each image [7].

Not only the emittance of the entire beam, but 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 tails of the two dimensional transverse beam distribution. After that, the horizontal and vertical rms beam sizes of the entire beam and of the 90% core are calculated. These rms sizes are used to calculate the emittance.

In the case of wire scanners, the beam profile is recorded over several macro-pulses (one point per macro-pulse), and only one profile is used when determining the beam size. The rms size of the entire beam is used in the emittance calculations.

The transverse emittance is determined from the measured beam sizes and the transport matrices between the monitors using a least square fitting. A second method is a tomographic reconstruction of the phase space using the maximum entropy algorithm. The results obtained by both methods agree well [7]. Since the fitting technique is faster, we use it in our measurements.

## EXPERIMENTAL RESULTS

The projected emittance in the BC section has been routinely measured since early 2005. The emittance measurement procedure is well understood, and we have performed systematic studies on the dependence of the emittance on different machine parameters. A detailed description of these measurements, results and error analysis is in [8].

In the two other sections accurate emittance measurements have been possible only since the beginning of 2007.

Table 1 shows the measured projected emittance at three locations along the FLASH linac. All of the three measurements have been performed within a few hours with the same machine conditions. The second column (Day 2)

| | Day 1 | | Day 2 | |
|---|---|---|---|---|
| Location | $\epsilon_x$ | $\epsilon_y$ | $\epsilon_x$ | $\epsilon_y$ |
| BC | 3.7 (2.0) | 3.2 (2.0) | 3.7 (2.4) | 3.8 (2.5) |
| SEED | 3.7 (2.2) | 4.7 (3.2) | 2.7 (2.0) | 3.0 (2.2) |
| Undulator | 4.4 | 4.1 | 4.3 | 4.4 |

Table 1: Projected emittances measured at three locations along the FLASH linac in two different days. The presented values are normalized rms emittances in units of mm mrad. The value in the bracket is the rms emittance of the 90% beam core. Estimated error of the measured emittances is 0.5 mm mrad.

shows the same measurements repeated 4 weeks later. The presented values are normalized rms emittances of the entire beam. In the BC and SEED sections, where the measurements have been performed using OTR monitors, the rms emittance of the 90% beam core is presented as well. In all the cases, the electron beam charge is 1 nC and the electron beam is accelerated on-crest through the accelerating modules.

The error analysis, taking into account errors in the measured beam size, in the beam energy, and in the transverse matrices, leads to an error estimation of 0.5 mm mrad for the measured emittance values.

No substantial change in the projected emittance can be observed along the linac (Table 1). Similar results have been obtained also on other days, when the linac has been well-tuned.

During these measurements, our goal was not to optimize the emittance but to study the emittance transport. In well optimized conditions, a projected emittance below 2 mm mrad in the BC section has been measured [8].

## TECHNICAL ISSUES

The last OTR screen in the SEED section is located only a few meters upstream of the undulator. Losses created when the beam passes through the screen are so high that they may cause degradation of the permanent undulator magnets. Recently, this problem has been solved by mounting a deflecting magnet and a lead shield after the last screen.

At high electron beam energies, the emitted OTR light is concentrated in a very narrow cone. As a consequence, the alignment of the OTR monitors becomes critical. During the measurements in the SEED section, we have observed low beam spot intensities on some of the screens. Especially when the beam is not well-optimized, the intensity depends on the position of the spot on the screen. This indicates a misalignment of the system. During the shutdown in spring 2007, the OTR monitors have been replaced by combined OTR and wire scanners monitors (similar to the ones in the BC section). In addition, the OTR monitors have been realigned.

Matching of the beam to the FODO lattice is important for accurate emittance measurements [8]. In the BC and SEED sections matching works well. In the undulator section, however, it is difficult due to the fact that the so-called transfer matrix condition number is large, an order of magnitude larger than in the BC section. As a consequence, a small error in the measured beam size may lead to a large error in the calculated emittance and Twiss parameters. An additional complication is caused by the small undulator aperture. The beam tube inside the undulator has a diameter of about 10 mm only. In order to avoid losses due to too large beam sizes or missteering of the the beam, matching must be done carefully. Matching has been improved by using more quadrupoles with less changes in the currents, and by cycling the magnets after each matching iteration. We have also observed that the matching to the undulator works better, when we use the sigma of a Gaussian fit instead of the rms beam size as input for the Twiss parameter calculation.

Saturation of the photomultiplier signal has been another problem when measuring the emittance in the undulator. The photon shower generated by the electron beam is squarely proportional both to the wire diameter and to the atomic number of the wire material. As a consequence, when using a 50 $\mu$m tungsten wire the amount of light input to the photomultiplieris much larger than with a 10 $\mu$m carbon wire. The used photomultiplier has a nonlinear behavior when the light input is too large. This causes an increase of the measured beam size, which leads to an increase of the measured emittance. In order to avoid this artificial increase, the measurements presented here are performed by using the carbon wire only. During the shutdown, filters with an attenuation factor of 32 have been mounted in front of each photomultiplier. This should allow us to use the tungsten wires as well.

## SUMMARY AND OUTLOOK

The projected emittance along the FLASH linac has been measured at three locations. No substantial change of the emittance has been observed.

During the shutdown in spring and summer 2007, a sixth accelerating module has been installed in the FLASH linac. This, together with the upgrades of the other accelerating modules, will provide beam energies up to 1 GeV in the near future. We have improved our measurement system in the SEED and undulator sections. In the SEED section, the OTR monitors have been replaced by the combined OTR and wire scanner monitors. In the undulator, attenuators are installed in front of the wire scanner photomultipliers.

Studies on the emittance transport will continue in autumn 2007.

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