TRANSVERSE PHASE-SPACE STUDIES FOR THE ELECTRON OPTICS AT THE DIRECT XUV-SEEDING EXPERIMENT AT FLASH (DESY)*

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Abstract

During the shutdown in 2009/2010 the Free-Electron Laser in Hamburg (FLASH) was upgraded with an experiment to study the high-gain-FEL amplification of a laser "seed" from a high harmonic generation (HHG) source in the XUV wavelength range - sFLASH. For an optimal FEL-performance knowledge of the electron bunch transverse phase-space as well as control on the electron optics parameters is required. In this contribution the technical design, the present status and the commissioning results of the sFLASH diagnostic stations will be presented. The possible options for transverse phase space characterization will be discussed. An emphasis will be put on the error analysis and the tolerance estimations. Analysis of experimental data from both OTR-screens and wire scanners will be presented and discussed.

INTRODUCTION

The free-electron laser user facility FLASH in Hamburg consists of a superconducting linac with a maximum energy of about $1.25\,\mathrm{GeV}$, reaching a wavelength of $4.12\,\mathrm{nm}$. Downstream the accelerating modules the variable gap sFLASH undulators with a total length of $10\,\mathrm{m}$ are installed, the sFLASH section is followed by $27\,\mathrm{m}$ of fixed-gap undulators operated in the SASE-mode to produce the XUV pulses for the users.

ELECTRON BEAMLINE AND DIAGNOSTICS

The electron beamline belonging to the sFLASH experiment can be subdivided into two parts. The about $10\,\mathrm{m}$ long section upstream of the sFLASH undulators (so-called "ORS-section", see figure 1) accomodates two electromagnetic undulators which are used for the optical replica synthesizer experiment [1] as well as a tool for the check of the temporal overlap between seed pulse and electron beam.[2] All the quadrupoles in this section are used to match the optical functions of the electron bunch into the seeding undulators. The ORS section is also equipped with four OTR diagnostic stations.

The next part of the electron beamline consists of the sFLASH undulators and undulator intersections with diagnostic blocks and quadrupoles.

Four diagnostic stations have been installed in order to measure both, the electron beam and the high harmonics used for seeding. Two of the stations are equiped with wire scanners and OTR-screens, the other two stations only contain OTR-screens but will likely be equipped with wire scanners during the planned shutdown of FLASH 2011.

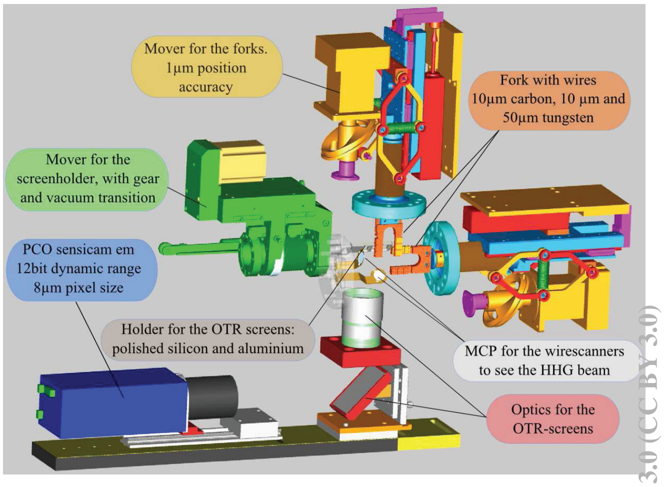

Figure 2: Tecnical drawing of the fully equipped diagnostic stations

The diagnostic blocks are located directly in front of the entrance of the sFLASH undulators in order to be able to measure the sizes and positions of both beams and ensure the spatial overlap of electron and HHG beam inside the undulators. Furthermore, with four screens it is possible to reconstruct the optical functions in front of the whole sFLASH experiment and therefore matching the twiss parameters to the desired values can be done.

The OTR-screens consist of two individual screens, one polished Silicon, and one Aluminium-coated. The archievable resolution has been measured [3] and is in the order of $10\,\mu\mathrm{m}$ for each of the OTR-screens which leads, together with the misestimation of the beam sizes to an error of the beam sizes of about $25\,\mu\mathrm{m}$. In contrast to this value the wire scanners deliver a resolution down to $5\,\mu\mathrm{m}$ but suffer from the fact that they just give the beam sizes and not the beam profiles.

IMPACT OF THE ORS-UNDULATORS

For the direct XUV seeding experiment at FLASH two electromagnetic undulators are used to find the temporal overlap between the high harmonic laser pulse and the electron bunch [2]. The electromagnetic field in the ORS undulators has a vertical focussing effect on the electron bunch. Therefore it is important to verify if the avaible quadrupoles downstream are able to compensate these fo-

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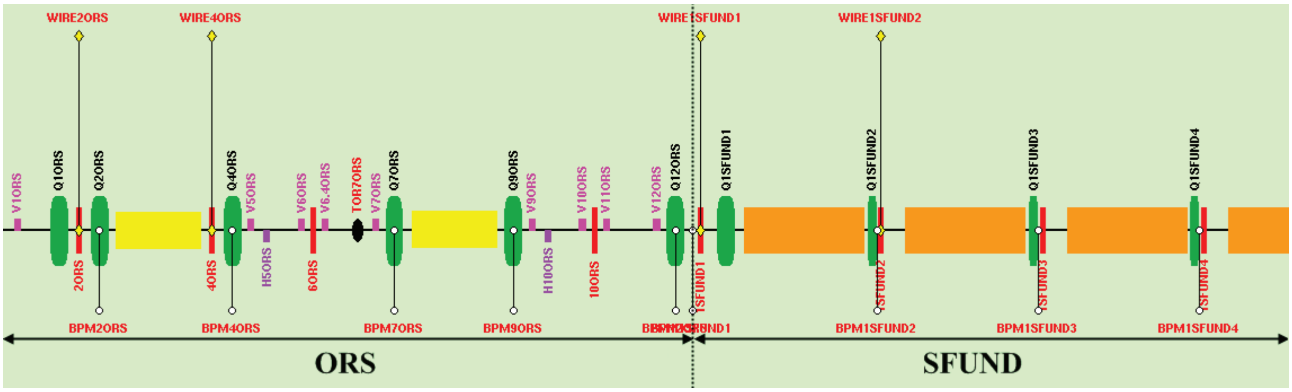

Figure 1: Electron beamline belonging to the sFLASH experiment. Yellow denotes the electromagnetic ORS undulators, orange the moveable gap sFLASH permanent undulators.

cussing effects.

Simulations

The effect of the vertical focussing of the ORS undulators has been studied with numerical simulations using the code “elegant” [4]. The ORS undulators have a period of 20 cm and a maximum K-value of about 7.7. The hardware limitations imposed by the maximum currents supported by the quadrupol power supplies have been considered as well.

The results of these simulations studies show that the undulator focussing can very well be corrected without exceeding the limits for the electric currents of the quadrupoles for any undulator K-value. The simulation shows also, that the undulator focussing influences the betafunction by a very small amount - at the end of the ORS section, the β-function differs by less than half a meter in either direction. The evolution of the beta functions can be seen in Fig. 3 starting from the entrance of the ORS section.

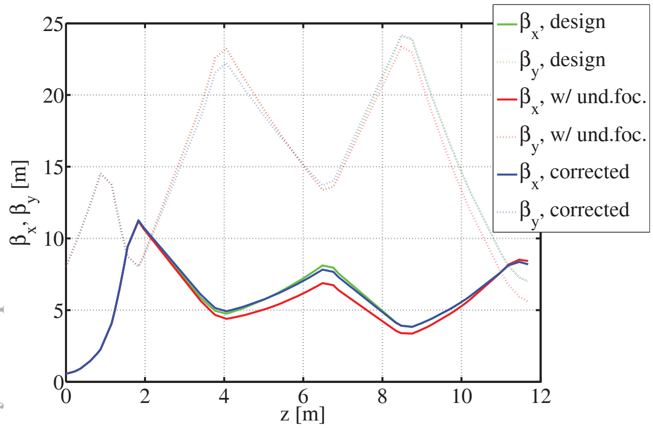

Figure 3: Evolution of the beta functions in the ORS section

Measurements

The electron beam sizes have been measured downstream of each electromagnetic undulator for two cases: Undulator K-value ≈ 7 and with the undulators switched off (K$=0$). The comparison of the measured data verifies the simulation results - the difference between the beam sizes is on the level of the resolution of the OTR stations. If one assumes a normalized emittance of about $2\,\mathrm{mm}\cdot\mathrm{mrad}$, then a change of the β-function of $0.5\,\mathrm{m}$ yields to a beam size change of about $5\,\mu\mathrm{m}$, which is below the resolution of the OTR-screens.

MATCHING IN THE SEEDING UNDULATORS

It is not only important to measure the electron optics, but to correct it to the design value as good as possible. One of the limiting factors are the quadrupoles, whose electric currents are limited and therefore the maximum achievable gradients. Monte Carlo simulations have been performed with different initial optics parameters. The mismatch parameter $\xi = \frac{1}{2}\left(\beta\gamma_D + \gamma\beta_D - 2\alpha\alpha_D\right)$ has been calculated for each of these parameter sets. A mismatch parameter of $\xi = 1.05$ has been taken as a guideline for the maximum tolerable mismatch. The ratio between the number of the sets were this matching limit has not been exceeded and the total number of trials can be interpreted as matching probability. As shown in Fig. 4 the cumulative probability is over 75% for all sets.

TRANSVERSE EMITTANCE MEASUREMENT

In order to measure the emittance and to reconstruct the optical functions of the electron beam, the so-called “multi-screen method” has been used. If one starts from a position $z = 0$ with the six unknown beam parameters $\langle x_0^2\rangle$,$\langle x_0 x_0'\rangle$,$\langle x_0'^2\rangle$,$\langle x_0\delta_0\rangle$,$\langle x_0'\delta_0\rangle$ and $\langle\delta_0^2\rangle$ the transverse beam sizes will transform according to formula 1.

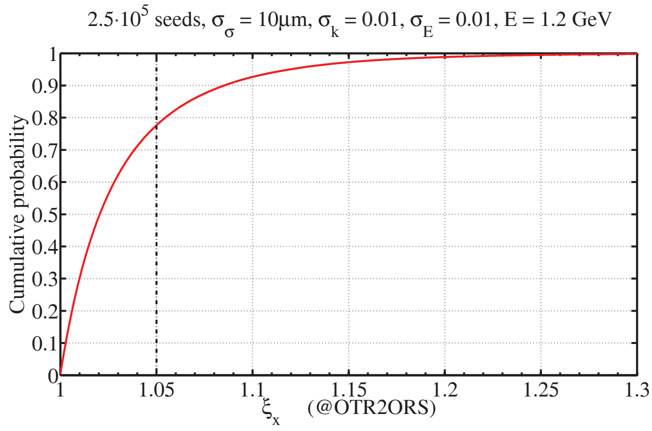

Figure 4: Matching probability for different mismatch parameters, x-plane

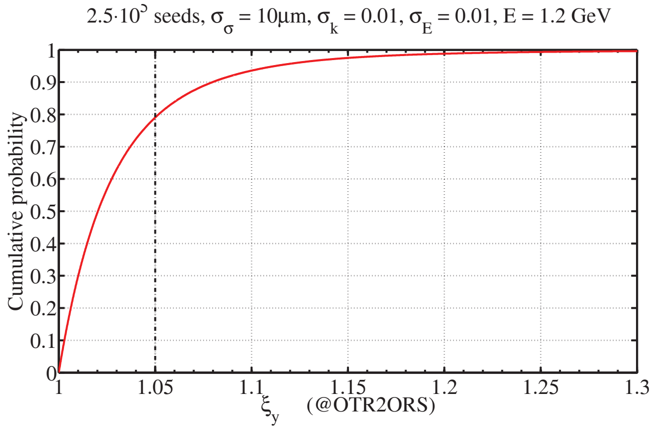

Figure 5: Matching probability for different mismatch parameters, y-plane

$$\sigma^2_{x,(i)} = \left\langle x^2_{(i)} \right\rangle = \qquad (1)$$

$$= \left(R^{(i)}_{1,1}\right)^2 \left\langle x_0^2\right\rangle + \left(R^{(i)}_{1,2}\right)^2 \left\langle x_0'^2\right\rangle + 2R^{(i)}_{1,1}R^{(i)}_{1,2}\left\langle x_0 x_0'\right\rangle$$

$$+2R^{(i)}_{1,1}R^{(i)}_{1,6}\left\langle x_0\delta_0\right\rangle + 2R^{(i)}_{1,2}R^{(i)}_{16,}\left\langle x_0'\delta_0\right\rangle + \left(R^{(i)}_{1,6}\right)^2\left\langle\delta_0^2\right\rangle$$

The $R^{(i)}_{n,m}$ are the elements of the six dimensional transfer matrices from the reconstruction point at $z = 0$ to the screen (i) and therefore determined by the known quadrupole currents. For the vertical plane, the matrix elements change from $R^{(i)}_{1,1}$ to $R^{(i)}_{3,3}$, from $R^{(i)}_{1,2}$ to $R^{(i)}_{3,4}$ and from $R^{(i)}_{1,6}$ to $R^{(i)}_{3,6}$. If one measures at six different positions along the machine, one gets a six dimensional system of linear equations with the initial beam parameters as unknowns which can be solved e.g. by SVD algorithm. The energy spread δ_0 can be measured alternatively using the transverse deflecting structure called LOLA [5] which is situated downstream the sFLASH experiment. The measurement shown in Fig. 6 gives us an r.m.s. energy spread of $\delta = 1.0\cdot10^{-3}$ at 700 MeV.

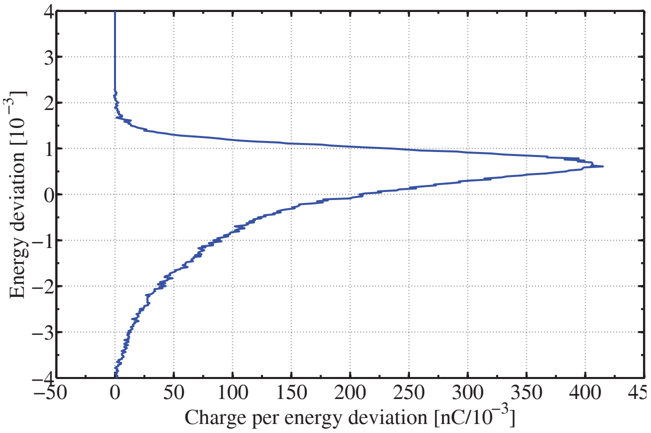

Figure 6: Energy deviation measured with LOLA

MEASUREMENTS

Measurements for the beam sizes have been performed at all diagnostic blocks in the ORS and SFUND sections (see Fig. 1).

Table 1: Measurements

Property	**x-plane**			**y-plane**		
ϵ_n [mm·mrad]	1.35	±	0.67	1.35	±	0.36
β [m]	2.86	±	0.66	18.77	±	4.68
α	−5.25	±	1.39	−4.64	±	1.09
η [mm]	−5.29	±	1.75	52.00	±	13.14
δ $[10^{-4}]$	8.80	±	2.92	9.80	±	2.47

The measurement results are listed in table 1. All the measurements have been done on-crest with an energy spread as shown in Fig. 6. The reconstruction point is the screen OTR2ORS, located about 14 m upstream the sFLASH undulators. The measurement errors are estimated as explained in the section below.

In addition, the electron beam sizes have been simulated with the code elegant using the initial parameters from the measurements. The results of the simulation are shown in Fig. 7. The transverse beam sizes predicted by elegant in the vertical plane agree well with the measured data while in the horizontal plane there is still a discrepancy which can be explained with spurious, non compensated dispersion.

ERRORS

There are several error sources (see table 2) that can effect the measurement results and therefore have to be considered carefully. Their influence has been studied by the means of a Monte Carlo simulation and the code elegant.

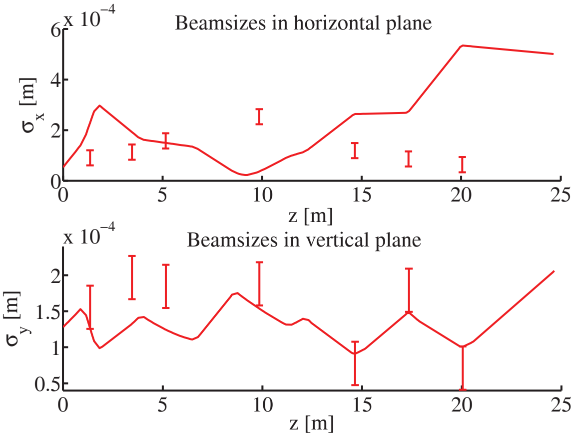

Figure 7: Measured and simulated beam sizes

Table 2: Error Sources

Beam size	25 μm	OTR-resolution Wire scanner position
Energy	10^{-2}	Energy server error Synchrotron radiation losses
Lattice errors	10^{-2}	Misaligned magnets Field errors Powersupply errors Different k-parameter (due to energy)
Charge errors	$(< 10^{-4})$	Toroid error Space charge

The simulation applied randomly distributed gaussian errors to the nominal values listed in the table 2. The simulation mainly changed four parameters by adding a gaussian distribution of error values to the original values. For the beam sizes a σ_σ of 25 μm was choosen. The energy was changed by $\sigma_E = 0.01E$, which correspondingly changes the k-parameter of the quadrupole magnets in the lattice $k = \frac{k_0}{1+\Delta E}$. Furthermore, each individual k-parameter has been changed by $\sigma_k = 0.01k$. From the simulations, we extract a histogram containing the reconstructed values. The error will then be the standard deviation of the gaussian distribution that builds up the histogram. The errors for the normalized emittance, β- and α-functions in the horizontal and the vertical plane are shown in Fig. 8

SUMMARY

The impact of the undulator focussing upstream of the XUV seeding undulators has been investigated. The possibilities to match the electron beam in the sFLASH undulators have been studied in simulations and experimentally tested. The construction of the electron beam parameters based on beam size measurements has been presented. An estimation of the emittance measurement errors has been

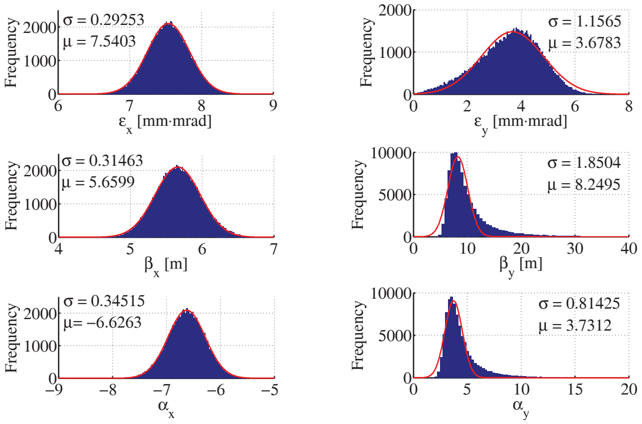

Figure 8: Histogram of reconstructed beam sizes using monte carlo simulation

discussed.

OUTLOOK

In the shutdown of FLASH in 2011 the remaining two diagnostic blocks will be equipped with wire scanners which will make a wire scanner based emittance measurement possible. Right now, at least two OTR-screens have to be used. Right now, studies are performed on scintillator screens which might have a better resolution and - with the right geometry or a fast gated camera - do not suffer from coherent OTR [7]. Furthermore the possibility of installing a pair of slits for the emittance measurements is undergoing investigation.

ACKNOWLEDGEMENTS

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REFERENCES

[1] J. Boedewadt et al., Proc. FEL'08, Gyeongju, Korea, 500

[2] R. Tarkeshian et al., Proc. PAC'11, New York, USA, WEOCN6

[3] J. Boedewadt et al., Proc. DIPAC'09, Basel, Switzerland, TUPB16

[4] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source LS-287, September 2000.

[5] C. Behrens et al., Proc. FEL'11, Shanghai, China, THOCI1

[6] K.T. McDonald and D.P. Russell, "Methods of Emittance Measurement", Joseph Henry Laboratories, Princeton University, Princeton, NJ08544

[7] M. Yan et al., Proc. FEL'11, Shanghai, China, THPB16