NUMERICAL PERFORMANCE STUDIES ON THE NEW SLICED-BEAM-PARAMETER MEASUREMENT SETUP FOR FLASH

C. Behrens*, Ch. Gerth, I. Zagorodnov
Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany

Abstract

The free-electron laser (FEL) user facility FLASH at DESY operates a high-gain FEL and provides radiation in the vacuum-ultraviolet and soft X-ray regime. In order to improve the capability and performance of the facility, FLASH will be upgraded with a third-harmonic (3.9 GHz) RF system to linearise the longitudinal phase space in front of the bunch compressors. For the study of the phase space linearisation, a new diagnostic and matching section located directly in front of the undulators which are used for the generation of SASE (self-amplified spontaneous emission) was designed. This section makes it possible to determine sliced beam parameters with high longitudinal resolution. In this paper, we describe the design considerations for this diagnostic section and demonstrate the expected performance by means of particle tracking simulations.

INTRODUCTION

The free-electron laser FLASH at DESY is user facility for experiments with ultrashort and -bright radiation pulses in the vacuum-ultraviolet and soft X-ray regime. The capability and performance of the facility will be improved by several upgrades, scheduled for autumn 2009 [1].

The upgrade that affects the achievable photon pulse energy and tuning performance of the FEL most significantly, is the installation of a third-harmonic RF system in front of the magnetic bunch compressors. The compression process, necessary in order to achieve the high charge densities required for lasing, relies on a well-defined energy-time correlation, i.e. energy-chirp, in the longitudinal phase space. This energy chirp can be produced by off-crest acceleration in the accelerator modules located upstream of the bunch compressors. The curvature of the fundamental (1.3 GHz) sinusoidal RF field results in a non-linear energy chirp. As consequence for FEL operation, the final bunch shape consists of a sharp leading spike with high charge density followed by a long tail. Only the spike, which contains less than 25% of the total bunch charge [2], contributes to the lasing process. In order to make the bunch shape more uniform and increase the lasing part of the bunch, the longitudinal phase space in front of the bunch compressors can be linearised by a third-harmonic RF cavity. This phase space linearisation put stringent demands on the amplitude and phase stability of the 1.3 GHz and 3.9 GHz RF systems. [3].

In autumn 2009, a new diagnostic and matching section directly in front of the undulators which are used for the generation of SASE will be installed. In this paper, we describe the design considerations for this diagnostic section and demonstrate the expected performance by means of sophisticated particle tracking simulations. Furthermore, we show the impacts on the commissioning of the third-harmonic RF system.

DIAGNOSTIC AND MATCHING SECTION

During the upgrade shutdown, about $40\,\mathrm{m}$ of the existing FLASH beamline up to the undulators will be modified and replaced. The first two-thirds are allocated for the seeding experiment sFLASH [1]. The last third is dedicated for matching into the undulators and performing longitudinal beam diagnostics with high resolution.

Design Features and Goals

For years in operation, the LOLA-type transverse deflecting structure (TDS) at FLASH has been used for longitudinal bunch shape analysis with unprecedented resolution, transverse slice emittance measurements and time-resolved phase space tomography [2]. Nevertheless, there are two drawbacks of the current experimental setup. Firstly, the TDS setup is located upstream of the energy collimator which is in front of the undulators. This energy collimator generates longitudinal dispersion and is a source of coherent synchrotron radiation (CSR). Both affect the longitudinal phase space of the bunch, and the TDS measurements carried out up to now did not yield the precise shape of the bunches entering the undulator. Secondly, the present accelerator optics was not specifically designed for simultaneous FEL operation and high-resolution TDS measurements.

For the new matching and diagnostic section, the TDS will be moved to a position of about $12\,\mathrm{m}$ in front of the undulators. This new section will also include a dedicated dispersive beamline, acting as energy spectrometer, in order to investigate the longitudinal phase space. An important design criterion of the new section was to permit simultaneous FEL operation and high-resolution TDS measurements.

General Requirements

At FLASH, different optics solutions are needed in order to satisfy all operation modes. The different electron beams

---

* christopher.behrens@desy.de

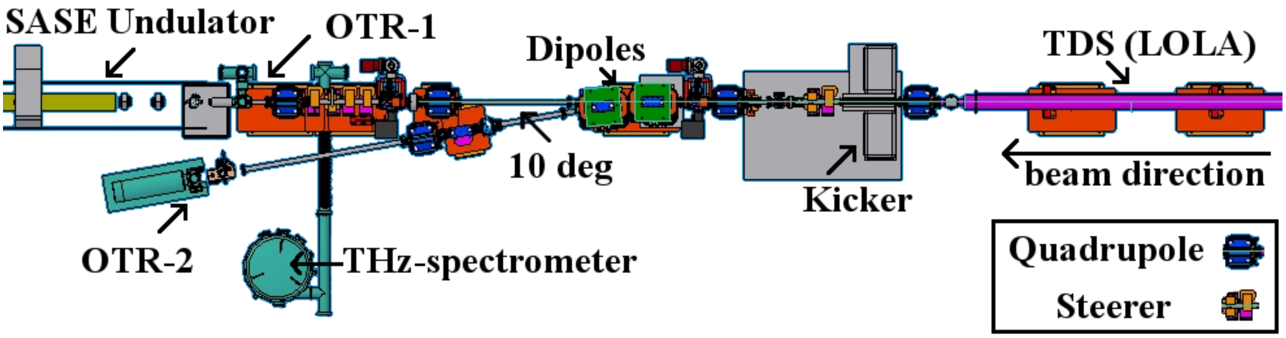

Figure 1: Layout of the new diagnostic and matching section at FLASH to be installed in the upgrade shutdown 2009 (top view). The straight section is called SMATCH and allows FEL operation and longitudinal beam profile measurements with high resolution at the same time. It is also intended for horizontal slice emittance measurements. The dispersive beamline emerging after the dipoles is called SDUMP and is dedicated for investigations of the longitudinal phase space.

energies, essential for changing the SASE wavelengths, result in different focusing properties of RF cavities and undulators. Furthermore, there exist different focusing variants for each electron beam energy. The seeding experiment sFLASH comes along with the installation of further undulators, with variable gap heights. This increases the number of optics solutions to be found even more.

In order to provide a good performance for standard FEL operation, the entire beamline has to be equipped with standard diagnostics like beam position monitors, charge monitors and beam imaging systems. A pair of steering magnets is required for sufficient orbit corrections.

In summary, a consistent design including magnets, standard diagnostics, and dedicated experiments is desired.

Beamline Components

All the different optics conditions and constraints by diagnostics were taken into account in order to find a flexible beamline lattice. The drawing in Fig. 1 gives an overview of the different beamlines and components.

The straight section is called SMATCH and begins with the TDS followed by a fast kicker magnet. The kicker magnet is able to steer two individual bunches from the bunch train onto different observation screens. Two dipole magnets, achieving a total deflection angle of 10 deg, will be used as dispersive elements for the energy spectrometer beamline. This beamline can also be used as beam dump for tuning issues, which is the reason for calling it SDUMP.

There are two experimental stations, OTR-1 and OTR-2, dedicated for longitudinal beam diagnostics. Both stations will be used for beam imaging with optical transition radiation (OTR) and scintillator screens. OTR-1 can also be used in connection with a novel THz-spectrometer for diagnostics with coherent transition radiation. In terms of sliced beam parameter measurements, OTR-1 is planned for longitudinal beam profile and horizontal slice emittance measurements. The station OTR-2 will be used for investigations of the longitudinal phase space.

PARTICLE TRACKING SIMULATIONS

In order to demonstrate the expected performance of the new diagnostic section, three-dimensional particle tracking simulations with self fields (space charge and CSR), using the simulation codes `ASTRA` and `CSRtrack`, were performed [3]. Furthermore, the interaction with wake fields by accelerator modules was taken into account. The simulation started at the electron source of FLASH and was performed up to the TDS, including the new third-harmonic RF system. The further particle tracking from the TDS to the observation screens was done with the code `elegant` [4], taken into account the shearing effect of the TDS. The main simulation parameters are listed in Table 1.

Table 1: Main Simulation Parameters

Parameter	**Value**	**Unit**
Number of particles	200000	
Bunch charge	1.0	nC
Electron beam energy	1000	MeV
TDS deflecting voltage	20	MV
TDS frequency (S-band)	2856	MHz

The RF settings and working points, found by optimisation of longitudinal emittance, are given in [3] and are used for simulation of the particle distribution which serves as starting point for the performance studies on the new diagnostic section. The plots in Fig. 2 show the longitudinal phase space and sliced beam parameters of the the simulated particle distribution directly in front of the TDS. An additional intensity cut off was applied for calculations of the sliced beam parameters, in order to exclude particles with energies which are separated from the bunch core.

In order to check the RF tolerances of the third-harmonic RF system for FEL operation and find a strategy for commissioning, also fast one-dimensional particle tracking simulations [3], i.e. only linear tracking of the longitudinal phase space, were done and will be discussed below.

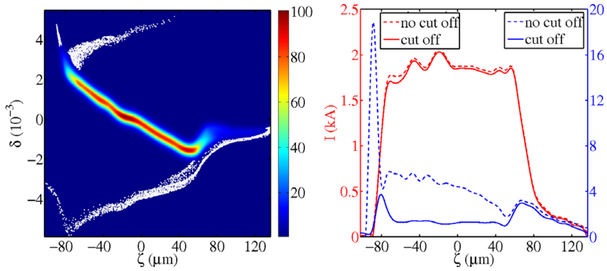

Figure 2: Results of the three-dimensional particle tracking simulation for FLASH with third-harmonic RF system. Left: Density plot of the longitudinal phase space. Particles in regions with an intensity of less than 5 % of the maximum are shown as white dots. Right: Beam current I and slice energy spread σ_δ. The cut off curves are associated with the distribution in the left plot removing the particles indicated as white dots.

DIAGNOSTICS PERFORMANCE

The particle distribution, shown partly as longitudinal phase space in Fig. 2, is used as input distribution for simulations, using the code `elegant`, including the accelerators optics of the new beamline shown in Fig. 1. The TDS settings are listed in Table 1. The observation point is at the position of OTR-2 in the dispersive section SDUMP, where the transverse distribution is measured. The conversion of scales for the longitudinal phase space can be done by means of the dispersion D and shear parameter S existing at the position of the observations screens [2, 5]. Both can be determined by measurements. The simulation of these measurements for the new beamline results in a dispersion of $D \approx 800\,\mathrm{mm}$ and a shear parameter of $S \approx 12$. Using the Twiss parameters of the given accelerator optics and the transverse emittance of the electron beam, the simulation results in a longitudinal resolution of about $8\,\mu\mathrm{m}$[1] and in an energy resolution of about $1.6{\cdot}10^{-4}$. The expressions for estimating the resolutions can be found in reference [2, 5]. For the stated energy resolution, the relation $\sigma_\delta \approx 2 \cdot \sqrt{\epsilon_h \beta_h}/D$ in [6] was used.

The plots in Fig. 3 show the reconstructed longitudinal phase space and sliced beam parameters by simulations of the transverse particle distribution at OTR-2, compared to the original ones in front of the TDS. The reconstructed phase space reveals a similar shape compared to the original. There are the same branches of separated energies, which contribute to the S-shaped appearance. These branches are indicated as white dots in the left plot of Fig. 2.

Except for some small deviations in the peak current, the reconstructed longitudinal bunch profile and length show a good agreement. The rms (root mean square) values of some bunch parameters for the original and reconstructed case are listed in Table 2. The slice energy spreads show the same longitudinal dependency, but the reconstructed values show an overall increase, which is partly not within the expected resolution. The behaviour of this energy spread increase can be explained by the use of the TDS itself. The transverse gradient of the longitudinal electric field inside a TDS induces an energy spread along the bunch [5, 7]. This additional energy spread depends on the beam size in the streaking direction, i.e. the vertical at FLASH, and the working conditions of the TDS. The left plot of Fig. 4 compares the the slice energy spread directly upstream and downstream of the TDS. As expected, the slice energy spread increases due to the use of the TDS.

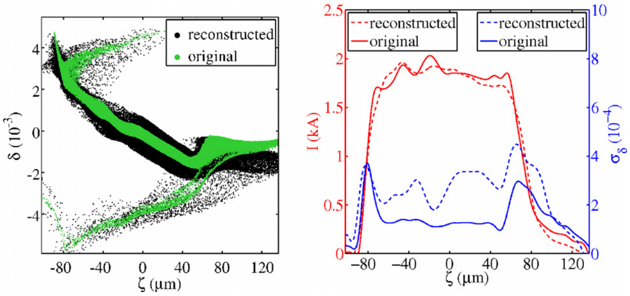

Figure 3: Simulated measurement at the observation screen of OTR-2. Left: Reconstructed longitudinal phase space compared to the original in front of the TDS. Right: Reconstructed beam current and slice energy spread compared to the original ones in front of the TDS. The same cut off as in Fig. 2 was applied for calculation.

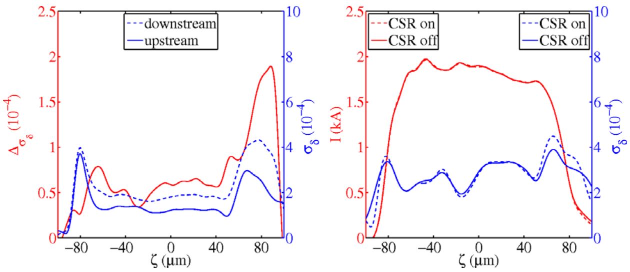

Figure 4: Left: Slice energy spread upstream (0) and downstream (1) of the TDS. The difference $\Delta_{\sigma_\delta} = \sigma_{\delta,1} - \sigma_{\delta,0}$ is plotted as red curve. Right: Comparisons of the reconstructed sliced beam parameters for two self-field interaction scenarios, CSR on and off.

Table 2: Beam Parameter Comparisons (rms)

Parameter	**Original**	**Reconstructed**
Bunch length σ_ζ (μm)	48	49
Energy spread σ_δ (10^{-3})	1.27	1.36
$\sigma_\zeta \cdot \sigma_\delta$ (nm)	61	67
Long. emittance ϵ_ζ (nm)	33	35

Self-field interactions with CSR in the dipole magnets do not have a big influence on the measurable beam parameters, because the longitudinal phase space is not determined

---

[1] The same resolution is achieved for OTR-1 in SMATCH.

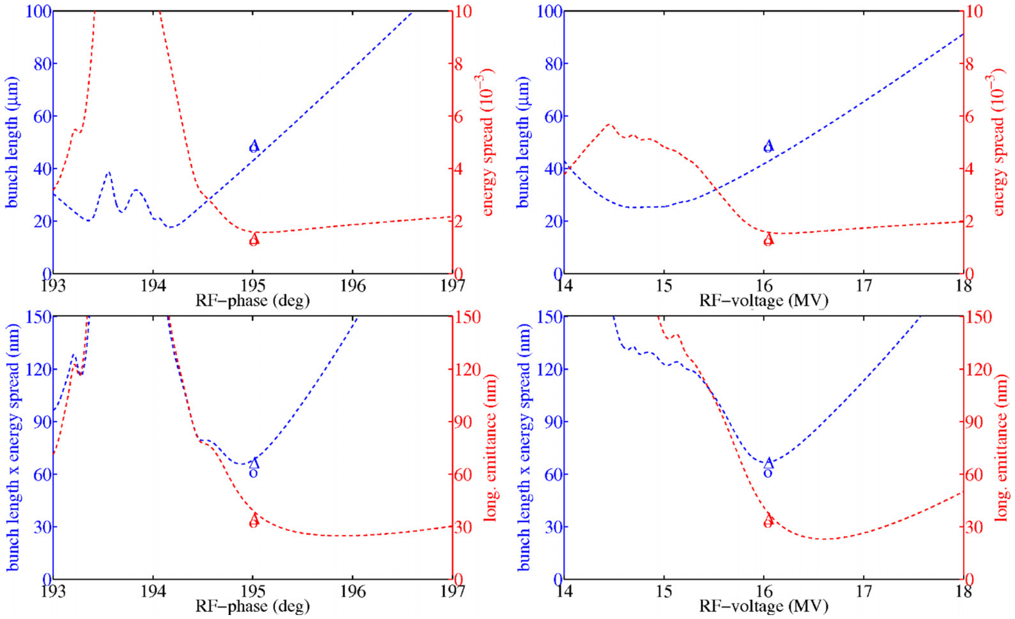

Figure 5: Results of one-dimensional particle tracking simulations. The phase and voltage of the third-harmonic RF cavity were scanned in small steps around the working points defined in [3]. The left column shows the phase scans, and the right column the voltage scans. The upper row presents the rms bunch lengths and energy spreads. The lower row shows the longitudinal emittances, and the products of bunch length and energy spread. The results of the three-dimensional simulation are indicated as symbols: Circle for the original value, triangle for the reconstructed value (Table 1).

directly. The energy and longitudinal coordinates are translated into transverse coordinates, and in particular for the longitudinal coordinate, this translation happens before the bunches enter the dipoles. The right plot of Fig. 4 show the reconstructed sliced beam parameters for both cases, CSR effects in the energy spectrometer dipoles switched on and off. There is only a small energy spread growth in the front of the bunch, which is typical for tail-head interactions of CSR.

COMMISSIONING

As pointed out in [3], there are stringent demands on the RF tolerances of the third-harmonic RF system. The new diagnostic section will be very useful in order to find the proposed working points. Not only the linearisation of the longitudinal phase space can be monitored and adjusted, but also the projected rms values of bunch length and energy spread can be measured. The product of these values and the longitudinal emittance, which can also be determined, provide further helpful information. The plots in Fig. 5 show the results of the one-dimensional particle tracking simulation, scanning the phase and voltage of the third-harmonic RF module. There are significant dependencies on phase and voltage which are useful for the commissioning of this new third-harmonic RF system.

CONCLUSIONS

A new diagnostic and matching section directly in front of the undulators of FLASH was designed and will be installed in the upgrade shutdown 2009. This new section permits simultaneous FEL operation and high-resolution TDS measurements. The expected performance was demonstrated by means of three-dimensional particle tracking simulations, including the new third-harmonic RF system for longitudinal phase space linearisation. The benefit of the new diagnostic section for commissioning of this third-harmonic RF system was studied by one-dimensional particle tracking simulations.

REFERENCES

[1] K. Honkavaara *et al.*, “FLASH Upgrade”, PAC’09, Vancouver, May 2009, TU5RFP059

[2] Michael Röhrs *et al.*, “Time-resolved electron beam phase space tomography at a soft X-ray free-electron laser“, Phys. Rev. ST Accel. Beams 12, 050704 (2009)

[3] I. Zagorodnov, “Expected Radiation in FLASH with 3rd Harmonic Module”, DESY, Hamburg, May 2009, `http://www.desy.de/xfel-beam/talks_2009.html`

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

[5] C. Behrens and Ch. Gerth, “On the Limitations of Longitudinal Phase Space Measurements using a Transverse Deflecting Structure”, DIPAC’09, Basel, May 2009, TUPB44

[6] H. Wiedemann, “Particle Accelerator Physics I: Basic principles and linear beam dynamics.”, Berlin, Germany: Springer (2004) p. 176

[7] D. Alesini *et al.*, “Sliced Beam Parameter Measurements”, DIPAC’09, Basel, May 2009, TUOA01