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SASE OPTIMIZATION APPROACHES AT FLASH

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Abstract

The free-electron laser FLASH at DESY can produce SASE-FEL pulses from the extreme ultraviolet to the soft X-ray regime. A superconducting linear accelerator drives two undulator lines (FLASH1 and FLASH2). The FLASH1 undulator beam line contains six fixed gap undulator which implies that the SASE wavelength can only be changed via the electron beam energy, while FLASH2 contains twelve variable gap undulators. Preparing different charges and compression schemes in the two parts of the bunch trains for the two undulator beamlines allows to adjust the phase space in wide range and meet the various requirements of photon pulse trains properties. In order to improve the SASE performance, reference files for standard energies and standard charges are regularly prepared. In the FLASH2 undulator beamline beam-based alignment and phase shifter scans have been applied to improve SASE operations and FEL beam quality. Improving set-up and tuning procedures allow to decrease setup times and optimize performance and stability. Procedures and optimization of FEL parameters towards a reliable SASE-FEL operation as well as the achieved results are discussed.

INTRODUCTION

FLASH [1–5] at DESY (Hamburg, Germany) is a free-electron laser (FEL), operated as a user facility since summer 2005. FLASH contains a normal conducting RF photo-injector with Cs_2Te-cathode and a superconducting linac which allows the acceleration of long bunch trains with several thousand electron bunches per second in 10 Hz bursts of up to 800 µs length. Downstream of the first accelerator module a third harmonic module is installed, to linearize the longitudinal phase space distribution of the bunch, followed by bunch compressor at a beam energy of 150 MeV. Another bunch compressor is installed after the third accelerator module, where the beam has reached an energy of 450 MeV.

The bunch trains are divided into two parts generated by two independent photo-injector lasers with selectable charge. A kicker-septum combination after the seventh accelerator module allows to split the bunch trains and serve two beamlines in parallel. The RF properties of the two beamlines can be chosen independently within a certain range allowing to adjust the phase space properties of the bunches. In standard operation the two beamlines are the undulator beamlines FLASH1 and FLASH2. FLASH2 beam can be diverted towards the plasma wakefield acceleration experiment FLASHForward in the FLASH3 beamline [6] by means of a DC dipole.

The FLASH1 beamline contains a seeding experiment Xseed [7], followed by a transverse deflecting structure (LOLA) [8] for longitudinal diagnostics. The SASE (Self Amplified Spontaneous Emission) undulator consists of six 4.5 m long fixed gap undulators. The fundamental wavelength of the FEL radiation based on the SASE ranges from 4.2 nm to about 50 nm.

The upgrade project "FLASH2020+" [9, 10] includes an energy upgrade from 1250 MeV to 1350 MeV which extends the wavelength range deeper into the water window and a seeding concept at FLASH1 using variable gap undulators.

The FLASH2 beamline contains an additional bunch compressor to further increase the flexibility of the compression. The undulator beamline in FLASH2 contains twelve 2.5 m long variable gap undulator segments. The tunable gap allows to control the undulator parameter K and thus the lasing wavelength in a certain range, depending on the electron beam energy. Behind these undulators a novel Apple-III type undulator will be installed next year as an afterburner which will cover the L-edge of the magnetic 3d metals (at about 1.8 to 1.4 nm) with variable polarization in the third harmonic of the FEL radiation. FLASH2 was equipped recently with a transverse deflecting structure (PolariX) [11, 12].

REFERENCE FILES

Since the FLASH1 undulators are fixed gap undulators employing each wavelength change in FLASH1 goes along with an energy change and thus a new setup of the linac and a new setup in beamline FLASH2. Smaller energy changes can be reached by scaling the magnet currents with the beam energy, but larger changes require a change in the optics. In order to improve the SASE performance and reduce the setup times, reference files for the standard energies 450 MeV, 750 MeV, and 1100 MeV are regularly prepared. The setup is done close to the theoretical energy profile. The goal is to prepare three reproducible, well-documented starting points (reference files) from which a non-expert can reach all standard machine states with a decent SASE pulse energy and long bunch trains with at most moderate beam losses, essentially by scaling the magnet currents. For the 450 MeV-reference file all accelerating modules after the second bunch compressor (ACC4,5,6 and 7) are set to zero volatage. For the 750 MeV-reference file only the last two accelerating modules (ACC6 and 7) are set to zero. In the 1100 MeV-reference file all accelerating modules are used at a high gradient, but not the maximum gradient.

Table 1 indicates the energy/wavelength ranges in which the reference files are applied. Beam energies smaller than

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450 MeV are reached by decelerating the bunch after the second bunch compressor. The space charge dominated beam from the RF-gun is matched (on-crest, for reference charge of 400 pC and a reference laser beam spot and pulse duration) into the design optics of the 1st compressor chicane before setting up the reference files. This matching is universal for all final beam energies and is thus done once for all reference files. The main idea is to keep the magnetic injector settings up to the second bunch compressor (beam energy: 450 MeV) identical for all reference files. During the reference-file setup the dispersion of all dispersive section is closed and the spurious dispersion is minimized.

Table 1: Reference File – Range of Usage

Reference file beam energy (MeV)	**450**	**750**	**1100**
energy scaling range (MeV)	350 – 600	600 – 925	925 – 1250
wavelength range (nm)	52 – 17.6	17.6 – 7.4	7.4 – 4.2

All reference files are prepared with a standard charge of 400 pC in FLASH1 and 300 pC in FLASH2. The difference in charge between FLASH1 and FLASH2 is caused by the fact that the bunches are generated by two different injector lasers with different pulse duration (6.5 ps and 4.5 ps, truncated Gaussian). A transverse beam size at the photocathode of 1.2 mm has been chosen. The charge is adjusted such that the initial peak currents of the bunches in FLASH1 and FLASH2 are the same.

Then SASE is maximized, losses are minimized and the capability to run long bunch trains without losses is checked in both beamlines. Finally all FLASH magnets are cycled to compensate for hysteresis effects and reach a high reproducibility of the reference files. This procedure partly requires to cycle the magnets one-by-one to be able to restore the optimized conditions (pulse energy, losses, etc.).

All reference files are setup in FLASH2 for the shortest possible FEL wavelength (largest undulator gap) since this state has the longest gain length and is most sensitive to the undulator orbit. Tapering is not applied to deviations in the undulator setting for the reference files since optimal tapering can be quite different for each setup.

BALLISTIC BEAM-BASED ALIGNMENT

In FLASH2 quadrupole beam-based alignment (BBA) is applied twice a year to the undulator beamline to improve SASE performance and FEL beam quality. The ballistic BBAs have increased the FEL performance by up to about 50% in the past. The frequency (∼ every 6 months) has proven a good compromise between minimizing the effort and maximizing the reproducibility.

As a starting point of the BBA procedure we load and reinstate a recent, machine state with high FEL pulse energy and low losses. This defines our initial reference orbit. Then the ambient field correctors are set to their nominal values in order to compensate the earth magnetic field. All other steerer- and phase shifter-currents are set to zero and the undulators are opened to exclude the influence of undulator focusing. A special optics which matches well into a long flat waist with all intra-undulator quadrupoles off is loaded into the quads upstream of the undulator section. All quads are cycled to zero field. We use the launch steerers upstream of the undulators to optimize transmission close to the initial reference orbit inside the undulators. Then the orbit feedback is adjusted such, that it corrects only the orbit upstream the undulator section. Afterwards we iterate through the quadrupoles one by one using the following procedure:

- switch quadrupole on and drive some reasonable current;
- correct the emerged difference orbit using the corresponding quadrupole movers;
- store the new mover set points;
- cycle quad to zero field and switch off.

Finally an angle correction based on a linear regression through the new mover set points is applied in order to correct the radiation direction towards the user experiment. The results achieved during the ballistic BBA procedure are included into the following generation of reference files.

PHASE SHIFTER SCANS

The twelve FLASH2 SASE undulator sections are separated by intersections with a phase shifter, Beam-position-monitors with a resolution of 2 μm, quadrupoles and steerer. The phase shifters are electromagnetic chicanes which have to be tuned to enable the constructive interference of the radiation of the subsequent undulators for all wavelengths. The required current of all FLASH2 chicanes based on the magnetic measurement results are calculated by an analytical function (2nd order polynomials) for each phase shifter depending only on the K-parameter of the adjacent undulators. This relation is implemented in a server which automatically applies the phase shifter currents whenever the undulator gap is moved. An additional manual offset was introduced to be selected deliberately by machine operators [13].

The FLASH2 phase shifter scans have been performed with the aim to improve SASE operations and FEL beam quality. An increase of pulse energies could be achieved. But, since the total undulator length of 30 m is quite small while the bandwidth is large compared to a hard-X-ray FEL, the influence of phase shifter scans is limited and one has to carefully distinguish between orbit and phase changes.

USER SET-UP

A set-up and tuning procedure has been developed to decrease the setup times and optimize performance and stability of FLASH. Typically, the setup starts from the well-maintained reference files, where important, but time con-

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suming steps, like closing the dispersion, and injector matching have already been performed. Setup usually begins with checking the on-crest phases of the gun and all accelerator modules. The sub train durations for FLASH1 and FLASH2 and their bunch repetition frequencies are set according to the conditions requested by the two experiments running in parallel simultaneously in both beamline. After recovering the reference state, i.e. after loading the file and establishing transmission and SASE, the settings are scaled to the required beam energy. The required beam energy is completely fixed by the requested FLASH1 wavelength due to the fixed gap undulators of FLASH1. The set-up is optimized for the requested special user conditions, including SASE optimization, the adjustment of the bunch number with low losses and of the bunch charge. High charge is mainly required for the operation of the THz-undulator to achieve high power. Lower bunch charge is used when tuning SASE for short FEL pulses. Tuning for short FEL pulses is done using the transverse deflecting structures LOLA (FLASH1) and PolariX (FLASH2) [8, 11, 12]. Afterwards compression feedbacks and orbit feedbacks are activated and optimized.

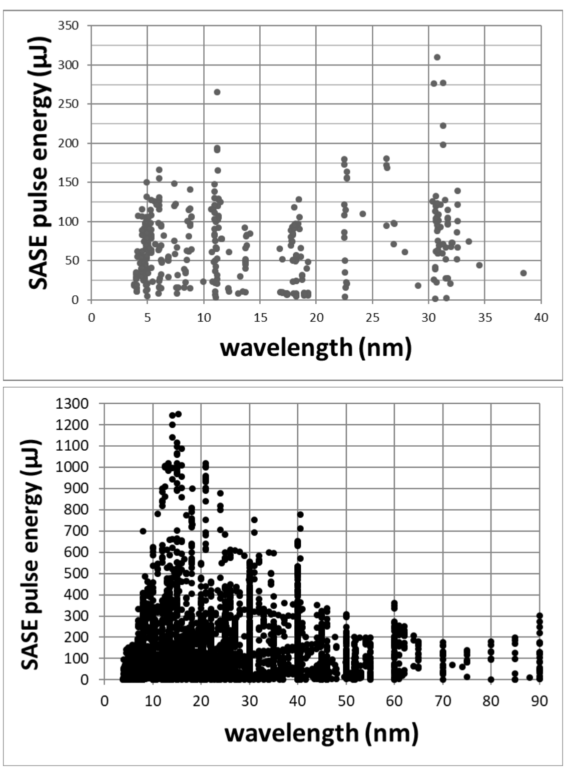

Figure 1: Examples of single pulse SASE energies as a function of the wavelength reached in FLASH1 (top) and FLASH2 (bottom).

Figure 1 shows examples of SASE pulse energies reached in FLASH1 and FLASH2. The range of parameter is quite large since the requirements of the experiments differ strongly. Many user-experiments are more interested in short pulses than in high pulse energies.

OUTLOOK

In the ongoing upgrade and refurbishment shutdown that started in November 2021, two old accelerator modules (modules 2 and 3) have been replaced by modern modules with higher maximum gradient. Thus the beam energy of the injector section is planned to increase from 450 MeV to 550 MeV. In addition the waveguide distribution of two of the linac modules (module 4 and 5) has been optimized. So we are positive that the maximum final beam energy will increase from 1250 MeV to 1350 MeV. The reference file parameter range discussed in Table 1 will be adapted to the parameters shown in Table 2. We note here that after the

Table 2: Reference File - Range of Usage from 2022 to 2024

Reference file beam energy (MeV)	**550**	**850**	**1200**
energy scaling range (MeV)	350 — 700	600 — 1025	1025 — 1350
wavelength range (nm)	52 — 13	13 — 6	6 — 3.5

next upgrade shutdown 2024/25 where FLASH1 will be equipped with variable gap undulators and we plan to run the machine with three fixed reference energies, 750 MeV, 950 MeV, and 1350 MeV only, i.e. without further energy scaling as we do now.

We are looking forward to further improve our lasing performance after recommissioning FLASH after the present shutdown [5, 10, 14]. We will study the influence of the laser-heater on the SASE performance in the XUV and soft X-ray range.

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