EXPERIENCE WITH MULTI-BEAM AND MULTI-BEAMLINE FEL-OPERATION

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Abstract

DESY's free-electron laser FLASH provides soft X-ray pulses for scientific users at wavelengths down to 4 nm simultaneously in two undulator beamlines. They are driven by a common linear superconducting accelerator with a beam energy of up to 1.25 GeV. The superconducting technology allows the acceleration of electron bunch trains of several hundred bunches with a spacing of 1 microsecond or more and a repetition rate of 10 Hz. A fast kicker-septum system directs one part of the bunch train to FLASH1 and the other part to FLASH2 keeping the full 10 Hz repetition rate for both. The unique setup of FLASH allows independent FEL pulse parameters for both beamlines. In April 2016, simultaneous operation of FLASH1 and FLASH2 for external users started. This paper reports on our operating experience with this type of multi-beam, multi-beamline set-up.

INTRODUCTION

The superconducting soft X-ray free-electron laser FLASH [1–3] delivers FEL pulses in the wavelength range from 4 to 90 nm for user experiments. The FEL radiation is generated by the self-amplified spontaneous emission (SASE) process. The extension of the FLASH facility by a second undulator beamline [4, 5] allows multi-user operation. Both undulator beamlines are driven by the same linear accelerator. Figure 1 shows a schematic layout of the FLASH facility with its common accelerator part, the two undulator beamlines and the third FLASHForward beamline which is currently under construction for a pioneering plasma-wakefield acceleration experiment [6]. The common accelerator part consists of a laser driven rf gun with high QE cathode, seven superconducting accelerating modules, a third-harmonic module and two bunch compressors. FLASH is able to generate pulse trains with a duration of up to 800 µs. The first part of the bunch trains enters into the FLASH1 beamline which contains 6 fix gap undulators each with a length of 4.5 m. A fast kicker system and a Lambertson septum are used to extract the second part of the bunch train into the FLASH2 beamline. FLASH2 has 12 variable gap undulators each with a length of 2.5 m, which allow choosing the wavelength to a certain extent independently from FLASH1. In order to operate FLASH2 almost independently of FLASH1, three injector laser systems are available. They allow a certain flexibility to tailor the laser parameters (bunch charge, bunch pattern, laser pulse length) to the need of both beamlines independently. A flexible low level RF system enables steps in the high voltage of each accelerating module of more than 10 MV in amplitude and more than 5° in phase between the FLASH1 and FLASH2 part of the bunch train. Applying different RF phases in the acceleration modules before the two bunch compressors allows an individual setup of the compression for both beamlines.

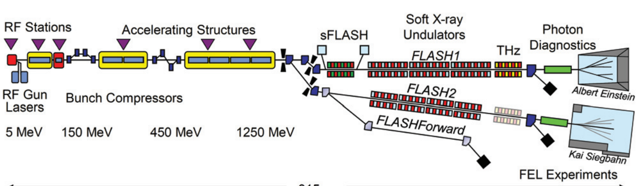

Figure 1: Layout of the FLASH facility.

First lasing of FLASH2 was achieved in August 2014 simultaneous to FLASH1 user operation [7]. On 8th of April 2016 two user experiments were running in parallel for the first time. The operation and capabilities of two user experiments in parallel with individually selected photon beam and pulse train characteristics is discussed.

CHALLENGES OF OPERATING TWO FEL-BEAMLINES

The simultaneous user operation entails some challenges.

- The setup of the common part of the beamline and the extraction region requires a beam in both beamlines FLASH1 and FLASH2. A later setup of one of the beamlines may cause beam losses in that beamline or changes in the other one and thus also a new setup.
- For the operation with long pulse trains, the available RF flat-top pulse duration needs to be shared between the FLASH1 and FLASH2 experiments but the bunch pattern can be chosen individually for both beamlines.
- Since FLASH1 is still equipped with fixed gap undulators all wavelength changes in FLASH1 require a change of the electron beam energy. In consequence, each change of wavelength in FLASH1 also requires a new set-up and SASE-tuning for FLASH2 as well. For FLASH2, a wavelength change is much easier. The variable gap undulators allow tuning the wavelength between 1 and 3 times the FLASH1 wavelength.
- The requirements on the FEL beam depend on the experiments. Experiments requests for short FEL pulses are typically set up with a low bunch charge of 100 to 200 pC. Contrariwise experiments requiring high FEL pulse energy are typically generated with a high bunch charge of up to 1 nC. At FLASH1 a planar electromagnetic undulator is installed downstream of the SASE undulators to produce —on request— THz radiation.

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The produced THz pulses are naturally synchronized with the SASE pulses. Also the set up of THz radiation is typically performed with a bunch charge of about 1 nC. Setting up such different settings in the two beamlines in parallel requires a careful setup of common accelerator beamline, since although the compression can be chosen independently, the beam optics in the common part is the same for both beams.

Operation of FLASH1 and FLASH2 with Different Bunch Charges

Two standard photo-injector lasers are available with an rms pulse duration of about 4.5 and 6.5 ps. A third one provides shorter, adjustable pulse length from 0.8 to 1.6 ps. Typically the injector laser with the slightly longer pulse duration is used at FLASH1 and the other at FLASH2 but an exchange is possible and has been demonstrated. Transverse shaping of the laser beams is obtained with a hard edge aperture imaged onto the photocathode of the RF gun. With this, a truncated Gaussian transverse beam shape is realized. The laser spot size on the cathode is determined by the diameter of this aperture. Various diameters can be selected. Unfortunately, two lasers share the same aperture, only the third laser has an own aperture. The optimal choice of the laser spot size depends on the bunch charge required.

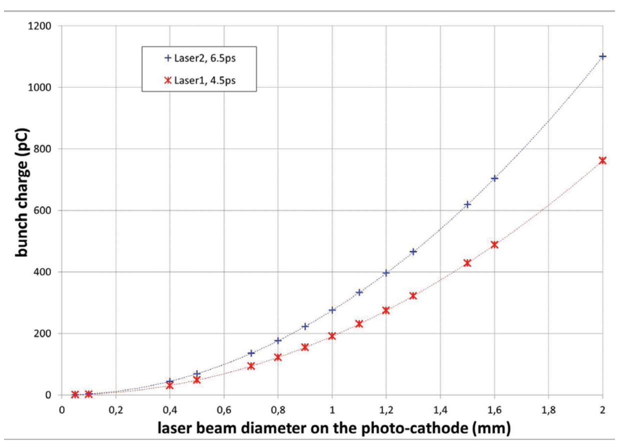

Figure 2: The beam size at the photo-cathode is selected depending on the emitted bunch charge in order to keep the charge density constant for the two standard laser at FLASH. The bunch charge is plotted as a function of the transverse laser beam diameter for the optimized setup.

In order to allow a simple setup of the common beamline and its optics, the beam size at the photo-cathode is selected depending on the bunch charge to keep the charge density on the cathode constant. The control of the space charge forces acting on the bunch in the RF gun at linear order allows to minimize the transverse beam emittance. Figure 2 shows the transverse laser beam size diameter at the photo-cathode and the corresponding optimized bunch charge. The markers represent the available apertures at FLASH. When operating with two completely different charges a compromise has to be found. Also the focussing with the solenoid around the RF-gun is charge dependent.

The following example illustrates the potential difficulties related to an injector set up for two apparently incompatible charges and our operational solution. A user experiment in FLASH1 was mainly interested in high THz-radiation pulse energy, while at the same time a FLASH2 user experiment requested short pulses. Thus a large difference in bunch charge is required to set up both experiments properly. For the specific user experiment, FLASH1 has been set-up with a charge of 680 pC and FLASH2 with 140 pC. The optimal transverse laser beam diameter at the photo-cathode would have been 1.6 mm in the first case and 0.9 mm in the second case. As a compromise, a diameter of 1.2 mm has been chosen which works well for both cases. The beam properties have been optimized for both cases independently using different RF-gun launch phases and different compression schemes.

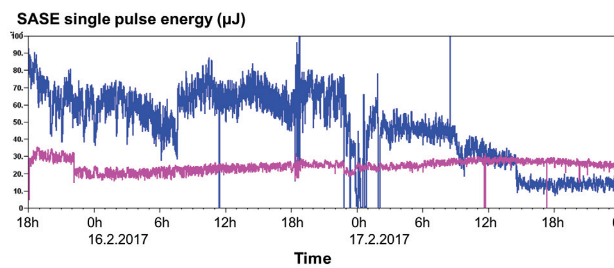

Figure 3: SASE single pulse energy at FLASH1 (blue) and FLASH2 (purple) during 54 hours of the experiments in parallel operation. The wavelength was 20.8 nm, single bunch with 680 pC, and 53 nm, 30 bunches with 10 µs spacing (100 kHz), and 140 pC resp. At FLASH1, also THz-radiation was produced.

Figure 3 shows an example of photon single pulse energy measured with an absolute calibrated gas monitor detector (GMD) [8] during 54 hours of the experiments discussed above. The plot illustrates, that while beam parameters at FLASH1 have been changed frequently, FLASH2 was operating stable and untouched by these changes.

CAPABILITIES OF FLASH2 OPERATION

The FLASH2 wavelength is tuneable thanks to the variable gap undulators. In total, 12 undulators with a period of 31.4 mm and a length of 2.5 m each are installed [4]. A larger gap width decreases the radiation wavelength and increases the saturation length. Figure 4 shows the SASE single pulse energies reached in FLASH2 for different wavelengths. As a highlight, a single pulse energy of 1 mJ has been demonstrated at a wavelength of 21 nm. This corresponds to 10^{14} photons, never achieved before at this wavelength in a single pulse. Similar results have been achieved at other wavelengths as well. Single pulse energies above 200 µJ have been demonstrated for many wavelengths between 7 nm and 90 nm. The different colors in Fig. 4 represent different charge ranges. Typically FLASH2 is running with bunch

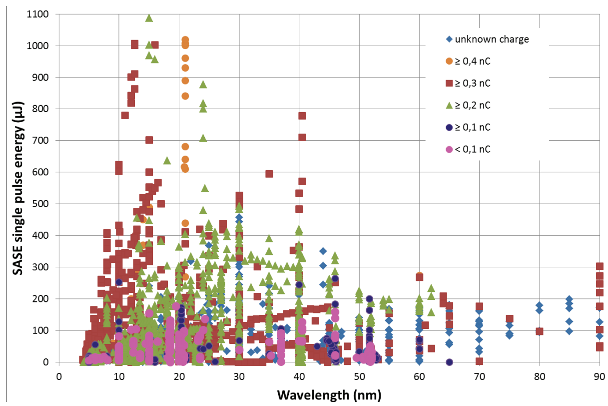

Figure 4: Single pulse SASE energies achieved in FLASH2 for the different wavelength.

charges between 20 pC and 350 pC but higher charges are possible as well. Figure 5 shows which wavelengths have been achieved at FLASH2 as a function of the beam energy. All these measurements have been performed in simultaneous operation with FLASH1. The black line represents the FLASH1 wavelength, while the gray line shows the upper limit with closed gap. The two lines limit the range of the design wavelength. The high SASE energies are reached for the small undulator gap width, where the saturation length is small. Some results in the plots of Figure 4 and 5 have been obtained using tapering techniques which allow a doubling of the SASE energy [9].

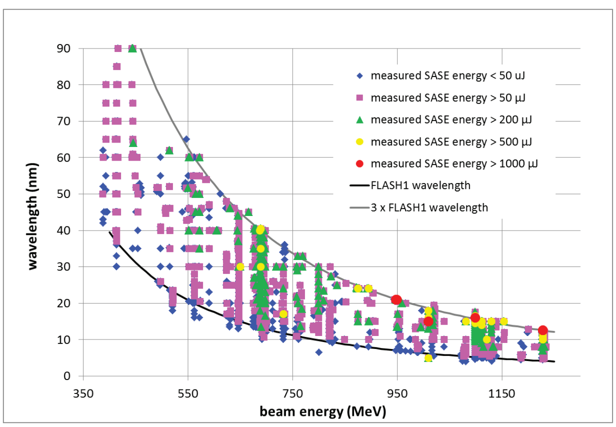

Figure 5: SASE single pulse energies at FLASH2 depending on the beam energy and wavelength defined by the undulator gap width.

Another important parameter required for a large class of user experiments is the FEL-pulse duration. Many experiments need pulses well below 50 fs. As mentioned above the pulse duration is controlled by changing the compression factor and adjusting the bunch charge accordingly. The FEL pulse duration, however, via slippage also depends on the effective undulator length relative to the gain length. In FLASH2 with its variable gap undulators it is possible to choose the effective undulator length by closing only those undulators required to just reach saturation. The last undulator closed defines the source point. Some experiments require high SASE energies for alignment purposes where the pulse duration does not play a role. This can be quickly achieved by closing upstream undulators without having to change any other parameter. Thus, in an experimental situation, one can easily switch between these two operation modes.

SUMMARY

Parallel operation of FLASH1 and FLASH2 for different machine settings has been demonstrated successfully. Even with a factor 5 difference in charge between FLASH1 and FLASH2 an independent setup of both beamlines is possible. Such a setup is challenging since the injector laser beam size at the photo-cathode can currently not be chosen independently but in future it is planed to modify the laser beamline to allow different beam sizes. This will further increase the flexibility of the setup.

The variable gap undulators at FLASH2 offers a high degree of freedom. Single pulse energies above 1 mJ at 21 nm have been achieved for the first time corresponding to 10^{14} photon per pulse. Energies above 200 µJ are easy to achieve and are demonstrated over almost the whole wavelength range.

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