FAST TRACK COMMUNICATION • OPEN ACCESS

Simultaneous operation of two soft x-ray free-electron lasers driven by one linear accelerator

View the article online for updates and enhancements.

New Journal of Physics

The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft **DPG**

IOP Institute of Physics

Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

CrossMark

FAST TRACK COMMUNICATION

Simultaneous operation of two soft x-ray free-electron lasers driven by one linear accelerator

B Faatz[1], E Plönjes[1,15], S Ackermann[1], A Agababyan[1], V Asgekar[1,2], V Ayvazyan[1], S Baark[1], N Baboi[1], V Balandin[1], N von Bargen[1], Y Bican[1], O Bilani[1], J Bödewadt[1], M Böhnert[1], R Böspflug[1], S Bonfigt[1], H Bolz[1], F Borges[1], O Borkenhagen[1], M Brachmanski[1], M Braune[1], A Brinkmann[1], O Brovko[3], T Bruns[1], P Castro[1], J Chen[4], M K Czwalinna[1], H Damker[1], W Decking[1], M Degenhardt[1], A Delfs[1], T Delfs[1], H Deng[4], M Dressel[1], H-T Duhme[1], S Düsterer[1], H Eckoldt[1], A Eislage[1], M Felber[1], J Feldhaus[1], P Gessler[5], M Gibau[1], N Golubeva[1], T Golz[1], J Gonschior[1], A Grebentsov[3], M Grecki[1], C Grün[1], S Grunewald[1], K Hacker[6], L Hänisch[1], A Hage[1], T Hans[1], E Hass[1], A Hauberg[1], O Hensler[1], M Hesse[1], K Heuck[1], A Hidvegi[7], M Holz[1], K Honkavaara[1], H Höppner[1,8], A Ignatenko[1], J Jäger[1], U Jastrow[1], R Kammering[1], S Karstensen[1], A Kaukher[5], H Kay[1], B Keil[9], K Klose[1], V Kocharyan[1], M Köpke[1], M Körfer[1], W Kook[1], B Krause[1], O Krebs[1], S Kreis[1], F Krivan[1], J Kuhlmann[1], M Kuhlmann[1], G Kube[1], T Laarmann[1], C Lechner[1], S Lederer[1], A Leuschner[1], D Liebertz[1], J Liebing[1], A Liedtke[1], L Lilje[1], T Limberg[1], D Lipka[1], B Liu[4], B Lorbeer[1], K Ludwig[1], H Mahn[1], G Marinkovic[9], C Martens[1], F Marutzky[1], M Maslocv[10], D Meissner[1], N Mildner[1], V Miltchev[11], S Molnar[1], D Mross[1], F Müller[1], R Neumann[1], P Neumann[1], D Nölle[1], F Obier[1], M Pelzer[1], H-B Peters[1], K Petersen[1], A Petrosyan[1], G Petrosyan[1], L Petrosyan[1], V Petrosyan[1], A Petrov[1], S Pfeiffer[1], A Piotrowski[12], Z Pisarov[1], T Plath[11], P Pototzki[1], M J Prandolini[13], J Prenting[1], G Priebe[1], B Racky[1], T Ramm[1], K Rehlich[1], R Riedel[13], M Roggli[9], M Röhling[1], J Rönsch-Schulenburg[1], J Rossbach[1,11], V Rybnikov[1], J Schäfer[1], J Schaffran[1], H Schlarb[1], G Schlesselmann[1], M Schlösser[1], P Schmid[1], C Schmidt[1], F Schmidt-Föhre[1], M Schmitz[1], E Schneidmiller[1], A Schöps[1], M Scholz[1], S Schreiber[1], K Schütt[1], U Schütz[1], H Schulte-Schrepping[1], M Schulz[1], A Shabunov[3], P Smirnov[1], E Sombrowski[1], A Sorokin[1], B Sparr[1], J Spengler[1], M Staack[1], M Stadler[9], C Stechmann[1], B Steffen[1], N Stojanovic[1], V Sychev[10], E Syresin[3], T Tanikawa[1], F Tavella[14], N Tesch[1], K Tiedtke[1], M Tischer[1], R Treusch[1], S Tripathi[1], P Vagin[1], P Vetrov[1], S Vilcins[1], M Vogt[1], A de Zubiaurre Wagner[1], T Wamsat[1], H Weddig[1], G Weichert[1,11], H Weigelt[1], N Wentowski[1], C Wiebers[1], T Wilksen[1], A Willner[1], K Wittenburg[1], T Wohlenberg[1], J Wortmann[1], W Wurth[1,11], M Yurkov[1], I Zagorodnov[1] and J Zemella[1]

1 Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, D-22607, Hamburg, Germany
2 Physics Dept., S P Pune University, Pune 411007, India
3 Joint Institute for Nuclear Research (JINR), 141980 Dubna, Russia
4 Shanghai Institute of Applied Physics (SINAP), 2019 Jia Luo Road, Jiading District, Shanghai 201800, People's Republic of China
5 European XFEL GmbH, Albert-Einstein-Ring 19, D-22761 Hamburg, Germany
6 Zentrum für Synchrotronstrahlung (DELTA), Technische Universität Dortmund, Maria-Goeppert-Mayer-Str. 2, 44227 Dortmund, Germany
7 Stockholm UniversityPhysics Dept., SE 10691, Stockholm, Sweden
8 Institut für Physik, Carl von Ossietzky Universität, 26111 Oldenburg, Germany
9 Paul Scherrer Institut, CH-5232 Villigen-PSI, Switzerland
10 Institute for High Energy Physics (IHEP), Nauki sq. 1, 142 281 Protvino, Russia
11 Physics Department and Center for Free-Electron Laser Science, Universität Hamburg, D-22761 Hamburg, Germany
12 FastLogic Sp. z o.o., al. T. Kosciuszki 123 office 324 PL-90441 Lodz, Poland
13 Helmholtz-Institut Jena, Fröbelstieg 3, D-07743 Jena, Germany
14 SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA
15 Author to whom any correspondence should be addressed.

E-mail: elke.ploenjes@desy.de

Abstract

Extreme-ultraviolet to x-ray free-electron lasers (FELs) in operation for scientific applications are up to now single-user facilities. While most FELs generate around 100 photon pulses per second, FLASH at DESY can deliver almost two orders of magnitude more pulses in this time span due to its superconducting accelerator technology. This makes the facility a prime candidate to realize the next step in FELs—dividing the electron pulse trains into several FEL lines and delivering photon pulses to several users at the same time. Hence, FLASH has been extended with a second undulator line and self-

amplified spontaneous emission (SASE) is demonstrated in both FELs simultaneously. FLASH can now deliver MHz pulse trains to two user experiments in parallel with individually selected photon beam characteristics. First results of the capabilities of this extension are shown with emphasis on independent variation of wavelength, repetition rate, and photon pulse length.

1. Introduction

X-ray free electron lasers deliver a billion times brighter and a thousand times shorter pulses than state-of-the-art synchrotron radiation sources, allowing for the first time investigations of matter on atomic length and time scales simultaneously. Laser-like features of the radiation (high temporal and spatial coherence), high photon flux (peak and average), and ultra-short pulse durations resulted in many breakthroughs in a wide range of applications. In the past decade, extreme-ultraviolet (XUV) and x-ray FELs have enabled fundamentally new science in many scientific fields ranging from atomic, molecular, and optical (AMO) and cluster physics to condensed matter physics, structural biology and studies of matter under extreme conditions [1–4]. Worldwide, a number of short-wavelength FELs are in operation or under development. FLASH at DESY (Germany) [5] and FERMI at ELETTRA (Italy) [6] operate in the XUV and soft x-ray region while LCLS at SLAC (USA) [7] and SACLA at SPring-8 (Japan) [8] work in the hard x-ray range down to 1 Ångström. The European XFEL [9], the SwissFEL at PSI (Switzerland) [10] and PAL-XFEL at Pohang (Korea) [11] are currently under construction and nearing completion.
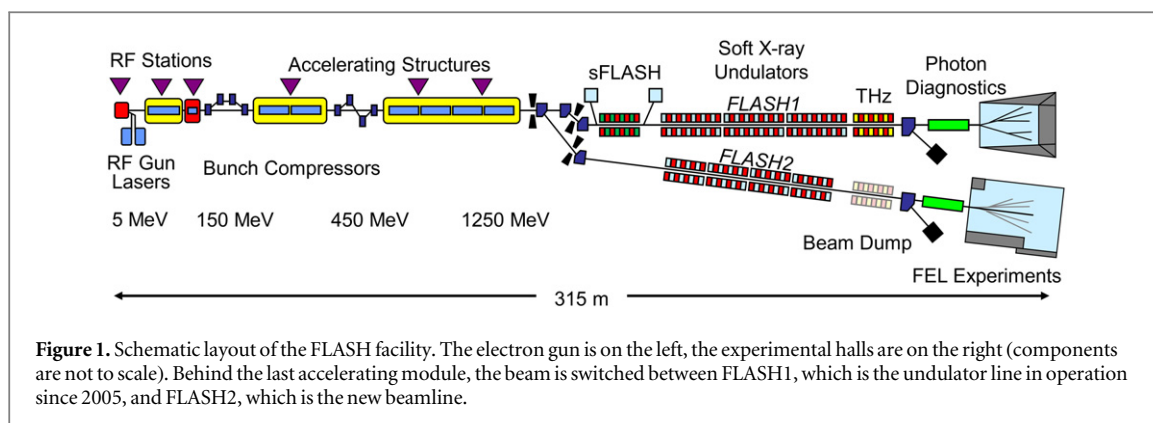
Short wavelength FELs produce high brightness, ultra-short photon pulses by means of a very well collimated mono-energetic and high-density electron beam. This beam quality is typically obtained by using a photo-cathode radio-frequency (RF) gun (left in figure 1), which accelerates the electrons immediately to relativistic energies. The bunches are longitudinally compressed to achieve the kiloampere peak currents needed for the amplification process. At FLASH, the world's first soft x-ray free-electron laser, this compression takes place in two stages, at energies of 150 and 450 MeV. Once the electrons are accelerated to their final energy of up to 1.25 GeV, they are sent through an undulator, a magnetic structure which consists of a large number of magnets with alternating magnetic field, forcing the electrons on a sinusoidal trajectory, from which they emit photons [5].

In contrast to synchrotron light sources at storage rings, the much improved electron beam quality with high peak currents and the long undulator achieve a coherent build-up of the photon beam. Interaction with the resulting radiation field bunches the electrons on the length-scale of the wavelength and the bunched electron beam emits even more radiation. This self-amplification of spontaneous emission (SASE) process results in exponential growth of the intensity along the undulator [12]. Photon pulses are created with durations of tens to hundreds of femtoseconds, containing a number of photons in a single pulse comparable to the number delivered in a synchrotron radiation storage ring in one second.

FLASH has been in operation as a user facility since summer 2005 [5, 13, 14]. The request for user beamtime has over the years typically shown a factor of 4 overbooking and similar user numbers are also reported from the other operating FEL facilities. This makes cost-effective extensions of these facilities a high priority and thus multi-beamline operation is pursued at FLASH and elsewhere [15]. FLASH has been upgraded to split the electron pulse trains for the operation of two FEL lines. The original electron gun and accelerator with its infrastructure now drive both undulator lines. In a new separate tunnel, a second undulator line, called FLASH2, with variable-gap undulators was installed, while a new experimental hall gives space for up to six experimental stations enabling a variety of experimental techniques. Civil and technical infrastructure have been foreseen for simultaneous operation of a third undulator line with two to three additional photon beamlines in the future. In addition, FLASH is again paving the way for the European XFEL, which will rely on similar technology to set up a multi-user FEL facility for the hard x-ray range.

2. Beam distribution for FLASH1 and FLASH2

The layout of the FLASH facility including the new FLASH2 beamline is sketched in figure 1. A detailed description of the accelerator can be found in [5, 16], only the components which are important for simultaneous operation are described below. As the electrons are emitted by the same gun and accelerated by the same accelerator, they have similar properties. An exception is the energy spread, which is increased due to coherent synchrotron radiation in the extraction arc behind the last accelerator module, as described in [18]. Furthermore, improved electron beam diagnostics in FLASH2 enable use of much lower bunch charge, which should make a further reduction of the photon pulse length possible. The orbit in the FLASH2 undulators is

Figure 1. Schematic layout of the FLASH facility. The electron gun is on the left, the experimental halls are on the right (components are not to scale). Behind the last accelerating module, the beam is switched between FLASH1, which is the undulator line in operation since 2005, and FLASH2, which is the new beamline.

Table 1. Parameters for FLASH1 (delivered to users) and FLASH2 (achieved during commissioning).

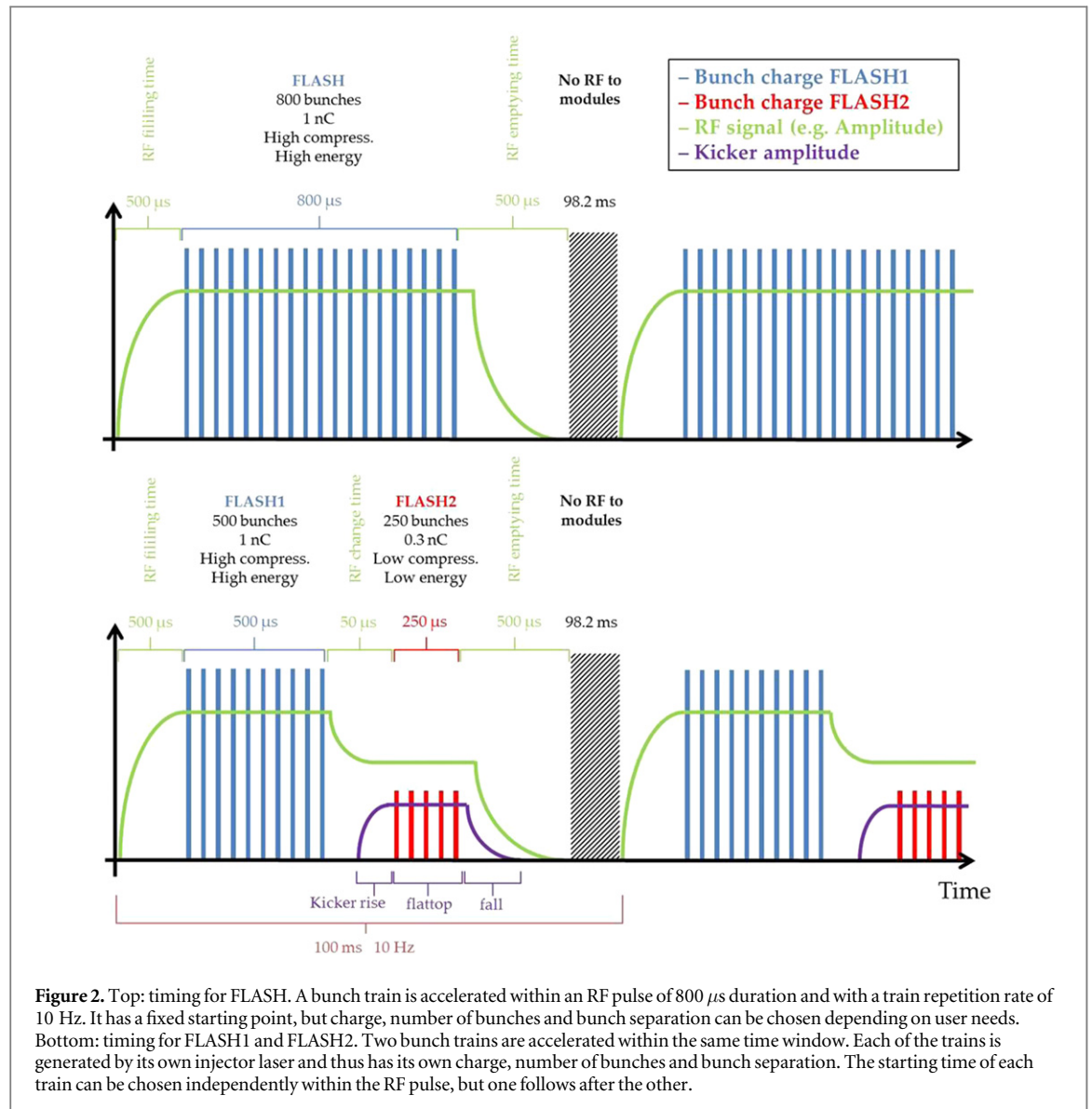|	FLASH1	FLASH2
Electron beam		
Energy range	0.35–1.25 GeV	0.4–1.25 GeV
Peak current	2.5 kA	2.5 kA
Bunch charge	0.06–1.2 nC	0.02–1 nC
Normalized emittance	1.4 mm mrad	1.4 mm mrad
Energy spread	0.2 MeV	0.5 MeV
Average β-function	10 m	6 m
Rep. rate	10 Hz	10 Hz
Number of bunches per second[a]	7500	7500
Bunch separation	1–25 μs	1–25 μs
Undulator		
Type	planar, fixed gap	planar, variable gap
Period	27.3 mm	31.4 mm
K_{rms}	0.9	0.7-1.9
Segment length	4.5 m	2.5 m
Number of segments	6	12
Photon beam SASE		
Wavelength range (fundamental)	4.2–52 nm	4–90 nm
Average single pulse energy	1–500 μJ	1–500 μJ
Pulse duration (FWHM)	30–200 fs	10–200 fs
Peak power	1–5 GW	1–5 GW
Spectral width (FWHM)	0.7 %–2 %	0.5 %–2 %
Peak brilliance[b]	10^{28}–10^{31}	10^{28}–10^{31}

[a] Shared between FLASH1 and FLASH2.
[b] Number of photons/s/mm^2/mrad^2/0.1% bandwidth.

measured with low-Q cavity BPMs providing sub-micron position resolution for individual bunches at 30–1000 pC bunch charge [19]. An upgrade of the beam diagnostics of FLASH1 is foreseen. In table 1, the parameters for FLASH1 and FLASH2 are summarized.

A normal conducting accelerator typically uses short RF pulses of a few, up to several 10 microseconds at most. Within this RF pulse, one or a few bunches are accelerated. In contrast, the RF pulses in a superconducting accelerator such as FLASH and the European XFEL have a length of several hundred microseconds up to continuous wave, which can in principle be filled completely by electron bunches. This means, that between several thousands to millions of bunches can be accelerated.

At FLASH, the accelerator is operated in a so-called burst-mode. Every tenth of a second, an 800 μs long RF pulse can accelerate electron bunches up to an energy of 1.25 GeV. This is shown in the top image of figure 2. FLASH is able to deliver trains of up to 800 electron bunches, and consequently photon pulses, with a repetition rate of up to 1 MHz and with a bunch train rate of 10 Hz, i.e. a total of up to 8000 bunches respectively photon

Figure 2. Top: timing for FLASH. A bunch train is accelerated within an RF pulse of 800 μs duration and with a train repetition rate of 10 Hz. It has a fixed starting point, but charge, number of bunches and bunch separation can be chosen depending on user needs. Bottom: timing for FLASH1 and FLASH2. Two bunch trains are accelerated within the same time window. Each of the trains is generated by its own injector laser and thus has its own charge, number of bunches and bunch separation. The starting time of each train can be chosen independently within the RF pulse, but one follows after the other.

pulses per second. A kicker-septum system has been installed behind the FLASH accelerator to split the electron bunch train between two undulator lines and thus two users, as seen in figure 1. As it is able to switch the 1 MHz bunch train, both get the 10 Hz repetition rate, but the 800 μs burst is split in two parts, one sent straight to FLASH1 and the other kicked into FLASH2. The fraction of bunches delivered to each beamline can be chosen freely. However, in the case of FLASH, approximately 20–50 μs of the RF pulse are lost during the switching process.

In order to give maximum flexibility to FLASH1 and FLASH2 users, it is important that each user can choose its own photon beam parameters. The wavelength of FLASH2 can be chosen to a large extent independent from FLASH1 due to the use of variable-gap undulators. Each undulator line has its own photo-injector laser, which generates the electrons in the gun. The FLASH2 laser can be shifted in time with respect to the FLASH1 laser. As a result, the bunch separation, number of bunches, and the bunch charge can be set independently for FLASH1 and FLASH2 within the 800 μs long RF pulse. In order to make full use of this flexibility, the RF system allows for different RF amplitude and phase settings for FLASH1 and FLASH2, and therefore a different photon pulse length for either user due to different bunch compressions [24]. The change in RF parameters is done in the same 20–50 μs time window used by the kicker to switch between FLASH1 and FLASH2.

The entire machine is controlled by a central timing system [25]. As shown in figure 2, it defines the time at which the injector lasers for FLASH1 and FLASH2 are started and stopped, and when the kicker, kicking the bunches into the FLASH2 beamline, is switched on and off. Also, it determines what phase and amplitude each of the accelerating modules has. This is needed, because the photon pulse duration is normally controlled by the electron charge and the longitudinal compression of the bunch, which can be changed fast by changing the phase of each module.
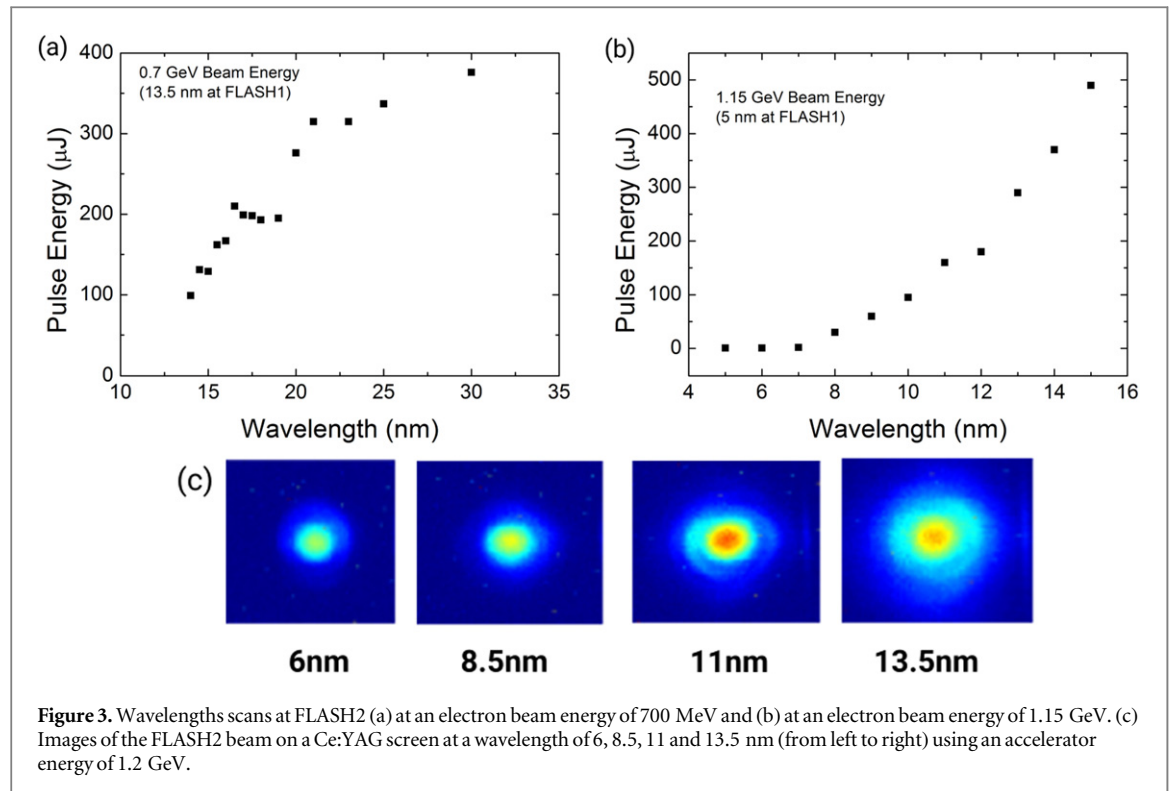
Figure 3. Wavelengths scans at FLASH2 (a) at an electron beam energy of 700 MeV and (b) at an electron beam energy of 1.15 GeV. (c) Images of the FLASH2 beam on a Ce:YAG screen at a wavelength of 6, 8.5, 11 and 13.5 nm (from left to right) using an accelerator energy of 1.2 GeV.
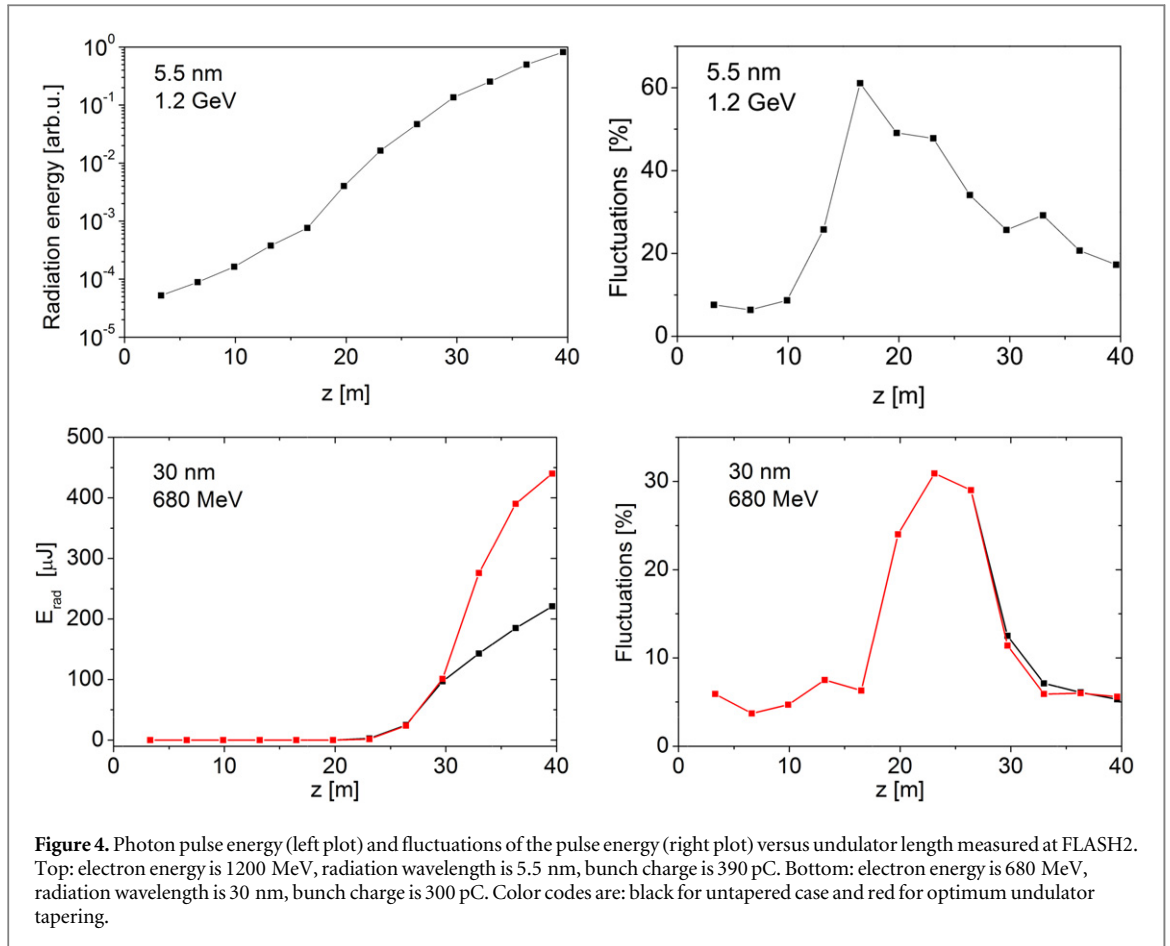
A third beamline is already foreseen in the timing system, and, in principle, it can be extended to an arbitrary number of beamlines. However, because the kicker has a certain rise- and fall-time and RF parameters can only be changed in tens of microseconds due to the high quality factor of the cavities in the superconducting modules, some fraction of the total flat top is lost with each additional beamline [26].

3. Simultaneous operation of FLASH1 and FLASH2

First lasing of FLASH2 was achieved in summer 2014 while FLASH1 was running simultaneously with 250 bunches at 1 MHz [17]. One bunch at the end of the accelerator RF pulse was used to realize lasing at 40nm in FLASH2, while FLASH1 was running a photon pulse train at 13.5 nm, with pulses of about 100 μJ pulse energy and 100 fs pulse length (FWHM). Figures 3(a) and (b) show FLASH2 photon pulse energies measured using a gas monitor detector (GMD) [20] during wavelengths scans performed by changing the gap of the undulators. FLASH1 is typically always operated simultaneously in a stable mode. In the measurements presented in figure 3(a) the accelerator is operated at an electron beam energy of 700 MeV, corresponding to a FLASH1 wavelength of 13.5 nm. Due to a smaller undulator K-value, the FLASH2 photon pulse energy decreases towards shorter wavelengths. Tuning of the photon pulse energy by readjusting the beam pointing into the undulator at each wavelength point typically takes on the order of a few minutes including the required diagnostics. Figure 3(b) shows a wavelength scan at a high FLASH electron beam energy of 1.15 GeV where the photon pulse energy decrease is even more pronounced towards the short wavelength end, because in addition to the smaller K-value, the SASE process requires a longer undulator length to reach saturation and thus the tolerances on beam pointing become more and more stringent. During the few tests performed at electron beam energies above 1 GeV, photon beam energies of a few μJ were generated in the range of 4–6 nm. Further tests are on-going, but operation at highest accelerator energies has to be coordinated with the user program at FLASH1.

Another systematic wavelength scan was performed at an accelerator energy of 1.2 GeV covering a total of 16 wavelengths ranging from 6 to 13.5 nm in 0.5 nm steps. A total tuning time of 30 minutes was required for this measurement. A number of images of the FEL beam have been generated on a Ce:YAG fluorescence screen for different wavelengths shown in figure 3(c). Each step, including correction of the horizontal orbit and characterization of the photon beam, took around 2 minutes. Only the injection orbit into the undulator has been changed while other parameters have not been touched. Although the vertical orbit varies, because of different undulator focusing when the undulator gap is changed, this did not significantly influence the spatial mode structure, as can be seen on the Ce:YAG-screen images. Wavelength changes of up to 10% can be performed without visible orbit changes. For larger wavelength changes, if needed, an orbit feedback can be used at several positions in front of or within the undulator to keep the electron beam orbit through the undulator

Figure 4. Photon pulse energy (left plot) and fluctuations of the pulse energy (right plot) versus undulator length measured at FLASH2. Top: electron energy is 1200 MeV, radiation wavelength is 5.5 nm, bunch charge is 390 pC. Bottom: electron energy is 680 MeV, radiation wavelength is 30 nm, bunch charge is 300 pC. Color codes are: black for untapered case and red for optimum undulator tapering.

stable. Similarly, in the near future, it is planned to include an automatic adjustment of the electron beam focusing by quadrupole magnets when the undulator gap is changed, thus keeping the beam size along the undulator constant.

In figure 3(c) the images at 11 nm and 13.5 nm reveal several transverse modes. This increasing number of modes occurs at longer wavelengths, because saturation is reached earlier in the undulator at lower electron energies and additional modes can develop in the deep saturation regime. An advantage of variable-gap undulators is that this effect can be prevented by opening undulators upstream, thus keeping the source point for the users fixed. This takes an additional few minutes once it becomes necessary. A gain curve was measured at 5.5 nm in FLASH2 (figure 4 top), by consecutively opening the undulator gaps of the individual undulator sections while FLASH1 was operated at the edge of the water window at 4.5 nm. It demonstrates the onset of saturation of the pulse energy even at short wavelength.

Tapering of the undulator gap leads to an increase in radiation power in the post-saturation regime [21–23]. This option was successfully tested at FLASH2 at a lower electron energy of 680MeV and a wavelength of 30 nm as illustrated in figure 4 bottom. First, the amplification process in the uniform i.e. untapered undulator (orbit, matching, RF phases, etc) was optimized. Then, optimum tapering [23] was applied which increased the output pulse energy by a factor of two, from 220 μJ to 440 μJ. These experimental results were obtained again during parallel operation of FLASH1 (13.5 nm) and FLASH2 (30 nm) using bunches with the same charge of 300 pC for both beamlines and with the FEL process optimized for maximum pulse energy. Operation of both undulator beamlines with an untapered undulator led to similar radiation pulse energies (both on the order of 200 μJ), but tapering of the FLASH2 undulator demonstrates great benefit in the increase of the radiation pulse energy.

4. Flexibility of operation

An important feature is that user experiments at FLASH1 and FLASH2 can choose their desired photon beam parameters largely independently. This includes of course the wavelength, which can be tuned in FLASH2 by varying the undulator gap, while the electron beam energy is determined by the wavelength needed in FLASH1 due to its fixed-gap undulator (see figures 3(a) and (b)). Also, the number of pulses and pulse separation can be
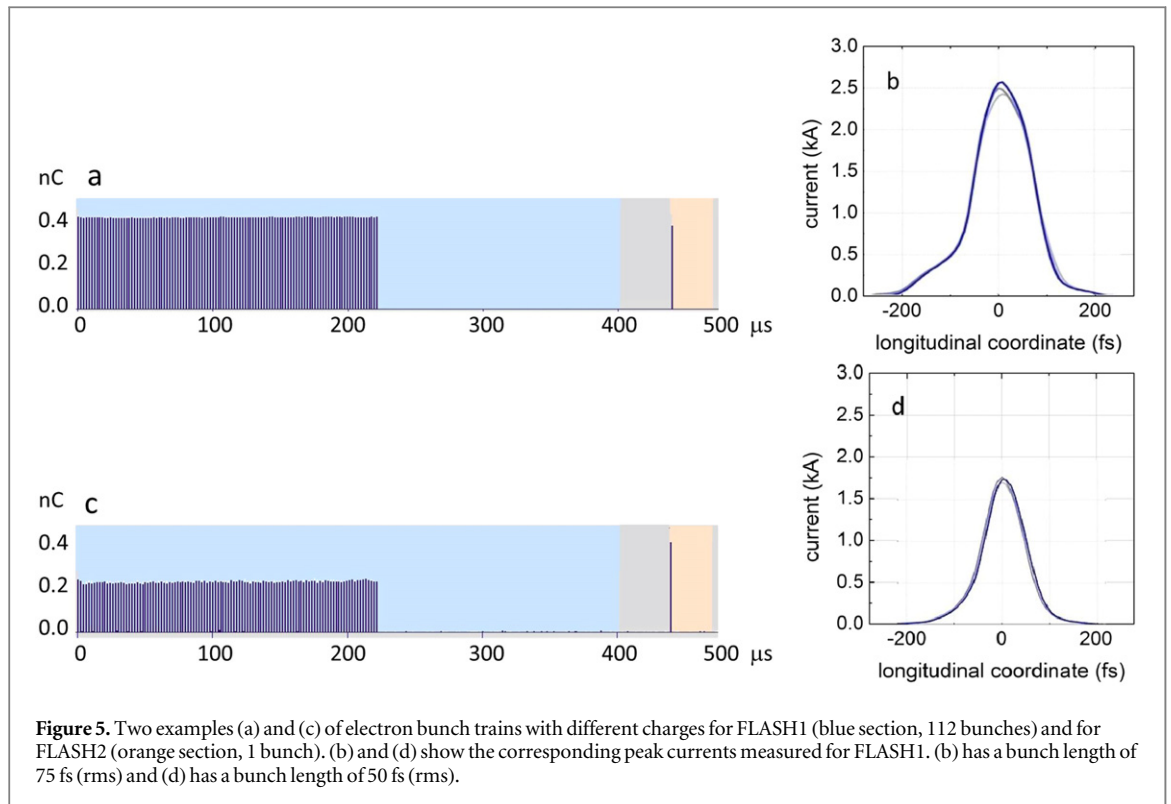
Figure 5. Two examples (a) and (c) of electron bunch trains with different charges for FLASH1 (blue section, 112 bunches) and for FLASH2 (orange section, 1 bunch). (b) and (d) show the corresponding peak currents measured for FLASH1. (b) has a bunch length of 75 fs (rms) and (d) has a bunch length of 50 fs (rms).
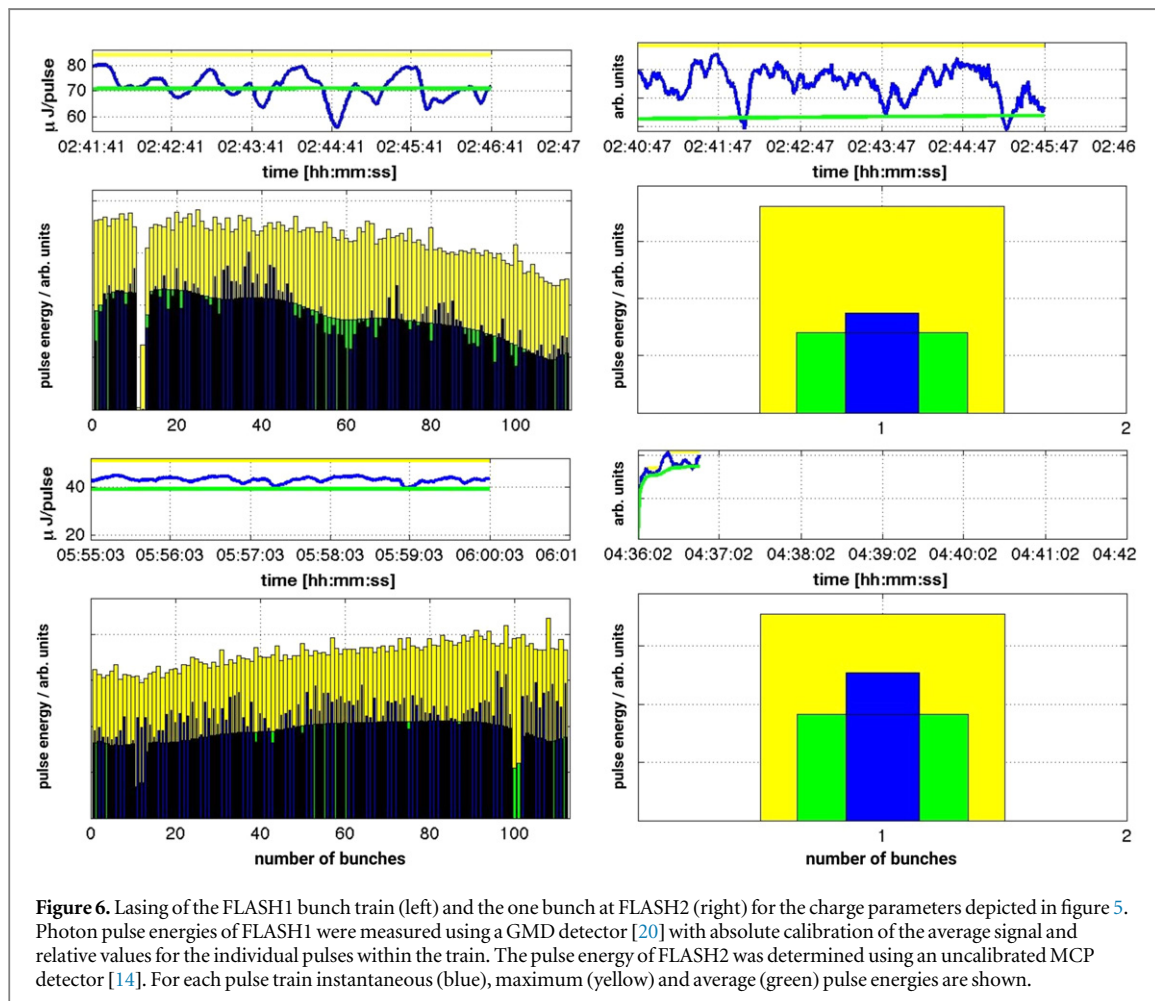
Figure 6. Lasing of the FLASH1 bunch train (left) and the one bunch at FLASH2 (right) for the charge parameters depicted in figure 5. Photon pulse energies of FLASH1 were measured using a GMD detector [20] with absolute calibration of the average signal and relative values for the individual pulses within the train. The pulse energy of FLASH2 was determined using an uncalibrated MCP detector [14]. For each pulse train instantaneous (blue), maximum (yellow) and average (green) pulse energies are shown.

chosen freely by both users, provided that the total duration is within the 800 μs pulse duration of FLASH and the fixed repetition rate of 10 Hz.

Due to separate injector lasers for FLASH1 and FLASH2 and a very flexible RF system, the photon pulse duration can be chosen independently by varying bunch charge and compression. Figures 5(a) and (c) show a change in charge in FLASH1 from 400 to 200 pC while the parameters of FLASH2 remained unchanged. The pulse train for FLASH1 contained 112 bunches at a repetition rate of 500 kHz, out of which one bunch was used to perform the bunch length and peak current measurement. FLASH2 was filled with only one bunch during this measurement. By changing RF settings of the accelerator only for FLASH1, keeping the parameters constant for FLASH2, the compression can be changed, resulting in a different bunch length. This was confirmed by measurement of the bunch length with the transverse deflecting cavity [27, 28] (shown in figures 5(b) and (d)). For FLASH1, the change in charge and thus in bunch length resulted in a reduction of the photon pulse energy (figure 6 on left top and bottom), again indicating that the duration of the photon pulse was reduced significantly. The pulse energy at FLASH1 changed by about a factor of two, which is consistent with a reduction of the charge by this factor. As can be seen on the right top and bottom of figure 6, lasing at FLASH2 was not influenced by the changes in FLASH1. The pulse energy at FLASH2 measured using a multi-channel plate (MCP) detector [14] remained unchanged. During commissioning, also operation of long pulse trains at FLASH2 was tested. Pulse trains of up to 350 pulses were generated at, for example, a wavelength of 25 nm with single-pulse energies of up to 200 μJ while FLASH1 was operated in single-pulse or short-pulse-train mode with up to 30 pulses.

5. Conclusion

At FLASH, simultaneous operation of two soft x-ray FEL undulator lines driven by the same linear accelerator in tandem has been established. It has been demonstrated that both beamlines lase with photon parameters largely independent of each other. The kicker system can deliver bunch trains with a flatness and stability that does not influence the overall stability of FLASH. Changes in RF settings within an RF pulse can be realized that allow for different compression settings and therefore different bunch lengths. First lasing of FLASH2 was demonstrated at 40 nm while FLASH1 was delivering bunch trains of 250 photon pulses at 13.5 nm to users. Since then, FLASH2 has been lasing regularly during user runs of FLASH1 at electron beam energies between 0.5 to 1.2 GeV and at wavelengths between 4 and 90 nm. Further tests are under way to extend the parameter range in wavelength, intensity, tunability and photon pulse length to the limits. Starting in 2016, user operation is scheduled for both beamlines in parallel. For FLASH this provides the opportunity to double the scientific output at the cutting edge of femtosecond nano science. Parallel operation of two independent FEL lines at FLASH is the first demonstration of a path to multi-user FEL facilities. High repetition rate FELs such as FLASH and the European XFEL enable simultaneous distribution of FEL pulses to FEL lines with different characteristics. This will be even more so when FELs operating in the MHz regime in cw mode will come online as it is planned for LCLSII and also envisaged for FLASH2020, the next major upgrade of the FLASH facility.

Acknowledgments

References

[1] Feldhaus J *et al* 2013 AMO science at the FLASH and European XFEL free-electron laser facilities *J. Phys. B: At. Mol. Opt. Phys.* **46** 164002
[2] Bostedt C *et al* 2016 Linac Coherent Light Source: the first five years *Rev. Mod. Phys.* **88** 015007
[3] Barty A, Küpper J and Chapman H N 2013 Molecular imaging using x-ray free-electron lasers *Annu. Rev. Phys. Chem.* **64** 415–35
[4] Glenzer S H *et al* 2016 Matter under extreme conditions experiments at the linac coherent light source *J. Phys. B: At. Mol. Opt. Phys.* **49** 092001
[5] Ackermann W *et al* 2007 Operation of a free-electron laser from the extreme ultraviolet to the water window *Nat. Photon.* **1** 336
[6] Allaria E *et al* 2012 Highly coherent and stable pulses from the FERMI seeded free-electron laser in the extreme ultraviolet *Nat. Phot.* **6** 699–704
[7] Emma P *et al* 2010 First lasing and operation of an angstrom-wavelength free-electron laser *Nat. Phot.* **4** 641–7

[8] Tanaka H, Yabashi M *et al* 2012 A compact x-ray free-electron laser emitting in the sub-angström region *Nat. Phot.* **6** 540–4

[9] Altarelli M 2011 The European x-ray free-electron laser facility in Hamburg *Nucl. Instrum. Method* B **269** 2845–9

[10] Patterson B D *et al* 2010 Coherent science at the SwissFEL x-ray laser *New J. Phys.* **12** 035012

[11] Kang H S, Kim K W and Ko I S 2014 Current status of the PAL-XFEL project *Proc. of IPAC2014 (Dresden, Germany)* THPRO019, 2897–9

[12] Saldin E L, Schneidmiller E A and Yurkov M V 2000 *The Physics of Free Electron Lasers* (Berlin: Springer)

[13] Ayvazyan V *et al* 2006 First operation of a free-electron laser generating GW power radiation at 32 nm wavelength *Eur. Phys. J.* D **37** 297–303

[14] Tiedtke K *et al* 2009 The soft x-ray free-electron laser FLASH at DESY: beamlines, diagnostics and end-stations *New J. Phys.* **11** 023029

[15] Hara T *et al* 2016 Pulse-by-pulse multi-beam-line operation for x-ray free-electron lasers *Phys. Rev. accelerators and beams* **19** 020703

[16] Schreiber S and Faatz B 2015 The free-electron laser FLASH *High Power Laser Science and Engineering* **3** e20

[17] Schreiber S and Faatz B 2014 First lasing at FLASH2 *Proc. of FEL2014 (Basel, Switzerland)* MOA03, 7–8

[18] Scholz M, Decking W, Faatz B and Limberg T 2012 Extraction arc for FLASH II *Proc. of FEL2012 (Nara, Japan)* TUPD33, 305–7

[19] Keil B, Marinkovic G and Stadler M 2014 Beam-based calibration and performance optimization of cavity BPMs for SwissFEL, E-XFEL and FLASH2 *Proc. of IBIC2014 (Monterey, CA)* WEPD11, 665–9

[20] Tiedtke K *et al* 2008 Gas-detectors for x-ray lasers *J. Appl. Phys.* **103** 094511

[21] Kroll N M, Morton P L and Rosenbluth M N 1981 Free-electron lasers with variable parameter wigglers *IEEE J. Quantum Electron.* **17** 1436

[22] Fawley W M 1996 Optical guiding limits on extraction efficiencies of single-pass, tapered wiggler amplifiers *Nucl. Instrum. Methods Phys. Res.* A **375** 550

[23] Schneidmiller E A and Yurkov M V 2015 Optimization of a high efficiency free electron laser amplifier *Phys. Rev. ST Accel. Beams* **18** 030705

[24] Ayvazyan V *et al* 2015 Low level RF control implementation and simultaneous operation of two FEL undulator beamlines at FLASH *Proc. of ICALEPCS2015 (Melbourne, Australia)* MOC3O07, 42–5

[25] Rehlich K *et al* 2013 *XFEL Timing System Specification* (http://ttfinfo2.desy.de/doocs/Timing/CDRv2.2short.pdf)

[26] Obier F and Kahl J 2014 FLASH2 extraction *Accelerators 2014* Highlights and Annual Report, DESY, Hamburg

[27] Behrens C *et al* 2012 Constraints on photon pulse duration from longitudinal electron beam diagnostics at a soft x-ray free-electron laser *Phys. Rev. ST Accel. Beams* **15** 030707

[28] Yan M, Behrens C, Gerth C, Kammering R, Langner A, Obier F, Rybnikov V and Wychowaniak J 2013 First realization and performance study of a single-shot longitudinal bunch profile monitor utilizing a transverse deflecting structure *Proc. of IBIC2013 (Oxford, UK)* TUPC36, 456–9