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Free-electron laser multiplex driven by a superconducting linear accelerator

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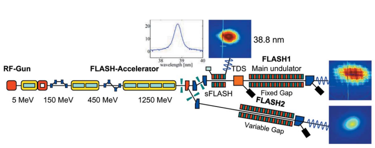
Free-electron lasers (FELs) generate femtosecond XUV and X-ray pulses at peak powers in the gigawatt range. The FEL user facility FLASH at DESY (Hamburg, Germany) is driven by a superconducting linear accelerator with up to 8000 pulses per second. Since 2014, two parallel undulator beamlines, FLASH1 and FLASH2, have been in operation. In addition to the main undulator, the FLASH1 beamline is equipped with an undulator section, sFLASH, dedicated to research and development of fully coherent extreme ultraviolet photon pulses using external seed lasers. In this contribution, the first simultaneous lasing of the three FELs at 13.4 nm, 20 nm and 38.8 nm is presented.



1. Introduction

Free-electron lasers (FELs) deliver ultra-short and high-intensity photon pulses with wavelengths down to a few angstroms (Ackermann *et al.*, 2007; Emma *et al.*, 2010; Allaria *et al.*, 2012; Ishikawa *et al.*, 2012), enabling the analysis of fundamental processes in matter with atomic spatial resolution on the femtosecond time scale (Ribic & Margaritondo, 2012). The radiation is generated by relativistic electrons traversing an insertion device of alternating magnetic dipoles (undulator), leading to transversely coherent pulses with energies up to several hundred microjoules and typical durations of a few tens of femtoseconds. This is a substantial improvement in peak brightness and coherent photon flux compared with other types of light sources operating in a similar wavelength range such as synchrotron storage rings. In the last decade, many breakthroughs in science with FELs have been achieved covering the broad range from fundamental research in life sciences (Redecke *et al.*, 2013) to future applications in material science and catalysis (Öström *et al.*, 2015).

Although the unprecedented X-ray pulse properties have opened new windows of opportunities for applications, the drawback of most present-day FELs is that they can only serve one user end-station at a given time. The next generation of FELs overcomes this limitation by operating several beamlines in both parallel and cascading configurations (Altarelli *et al.*, 2007; Pedrozzi, 2010; Albino *et al.*, 2011). Pioneering work on multi-beamline operation is underway at the FLASH facility at DESY (Hamburg, Germany). Since 2005 the FLASH user facility has been delivering high-brilliance extreme ultra-violet (XUV) and soft X-ray FEL radiation to experiments. The recently commissioned second undulator branch, constructed in 2011–2014, is currently being prepared for user operation. The first undulator beamline FLASH1 provides femtosecond pulses in the wavelength range from 4.2 nm to 52 nm with pulse energies up to several hundreds of microjoules (Faatz & Schreiber, 2015). The second, parallel, beamline, FLASH2, covers essentially a similar parameter range, with up to 80 nm in the long-wavelength limit (Faatz & Schreiber, 2015). In front of its main undulator, the FLASH1 branch is equipped with an experimental setup, sFLASH, dedicated to prototypical studies to establish full control of the XUV pulse properties using an external laser as a coherent seed source (Ackermann *et al.*, 2013; Bödewadt *et al.*, 2015).

The present layout of the facility allows for sequential lasing of two FELs in series at independent wavelengths using the same electron bunches. Moreover, as detailed below, the electron bunches can be multiplexed between the two parallel undulator beamlines enabling all three FELs to lase at the full macro-pulse repetition rate of 10 Hz.

While multi-color lasing from one electron bunch in one undulator line has already been demonstrated at several facilities (Hara *et al.*, 2013; Lutman *et al.*, 2013; Ninno *et al.*, 2013; Petrillo *et al.*, 2013; Roussel *et al.*, 2015), parallel beamline lasing has recently been demonstrated at SACLA (Hara *et al.*, 2016) and FLASH (Faatz *et al.*, 2016). The FLASH facility, however, utilizes dedicated photon extraction and transport optics at each of the three beamlines. In turn, this allows for multiple user experiments in parallel with different pulse properties. In this contribution, we present the simultaneous operation of all beamlines (cascaded and parallel) in self-amplified spontaneous emission (SASE) mode (Kondratenko & Saldin, 1980; Ribic & Margaritondo, 2012).

2. Free-electron lasers

Key elements for the generation of the intense X-ray radiation are the ultra-relativistic electron bunches containing up to six billion electrons each and the undulator magnets comprising a series of alternating dipoles with typical periods of a few centimeters forcing the electrons on a sinusoidal trajectory. As a consequence of the deflection of the charged particles, synchrotron radiation is emitted tangential to the electron trajectory. If the generated radiation stays in overlap with the electrons, the light field can couple to the electrons and arrange them in micro-bunches. These periodic current spikes on the light-wavelength emit photons coherently with a power scaling quadratically with the number of electrons that radiate. Therefore, the radiated power exceeds that of synchrotrons by several orders of magnitude. The central resonance wavelength, λ_r, of the generated radiation is not only determined by the properties of the undulator magnets such as their period length, λ_U, or magnetic field strength on the electron axis but also by the electron energy,

$$\lambda_r = \frac{\lambda_U}{2\gamma^2}\left(1 + \frac{K^2}{2}\right), \quad (1)$$

with γ the relativistic Lorentz factor of the electron and $K = eB_0\lambda_U/2\pi m_e c$ the dimensionless undulator parameter, B_0 the on-axis magnetic peak field, e the elementary charge, m_e the electron mass and c the speed of light.

After a certain undulator length, the FEL process runs into saturation and the photon pulse reaches its maximum possible peak power. Since the described process starts from spontaneous undulator radiation, this mode of operation is called self-amplified spontaneous emission (SASE) (Kondratenko & Saldin, 1980).

A beam current of about 1 kA is necessary for the FLASH soft X-ray FELs to saturate within the available undulator length. While the electron bunch has a relatively low peak current at the cathode, it is compressed longitudinally along the linear accelerator to reach the peak current required for the lasing process. This is realised by introducing a longitudinal energy chirp along the electron bunch during acceleration in combination with a dispersive magnetic chicane (Schmüser *et al.*, 2014). At FLASH, the superconducting accelerator modules are regulated by a sophisticated low-level radio-frequency (RF) system allowing independent control of the amplitude and phase in the different parts of the RF pulse. Therefore, the electron beam energy and peak current can differ in the two parallel undulator beamlines (FLASH1 and FLASH2) (Faatz *et al.*, 2016).

When a FEL is operated in SASE mode, the peak power and time-frequency spectrum of the generated photon pulses are subject to fluctuations. To overcome these fluctuations one can use a weak but fully coherent optical laser field as external seed source to start the FEL process, allowing for better control of photon pulse properties and stability. This technique is called external seeding and is studied at FLASH at the sFLASH undulator beamline (Bödewadt *et al.*, 2015).

3. FLASH facility

A schematic layout of the FLASH facility is shown in Fig. 1. High-quality electron bunches generated by an RF-gun-based photoinjector are accelerated by a superconducting linear accelerator up to 1.25 GeV to serve two parallel undulator beamlines, FLASH1 with fixed-gap undulators and FLASH2 with variable-gap undulators. While variable-gap undulator systems at FLASH2 and sFLASH allow the magnetic field strength and thus K to be adjusted with a period of λ_U = 31.4 mm, the FLASH1 main undulator is a fixed-gap system with a constant undulator parameter of K = 1.19 and a period length of λ_U = 27.3 mm. Hence, the desired wavelength of FLASH1 determines the electron energy, whereas the other two can then be tuned within a certain wavelength range. For example, FLASH1 operation at 13.5 nm allows the wavelength at the variable-gap undulator systems to be tuned within 10.3 nm and 41 nm.

The repetition rate of the photon pulses is determined by the repetition rate of the electron bunches. The FLASH linear

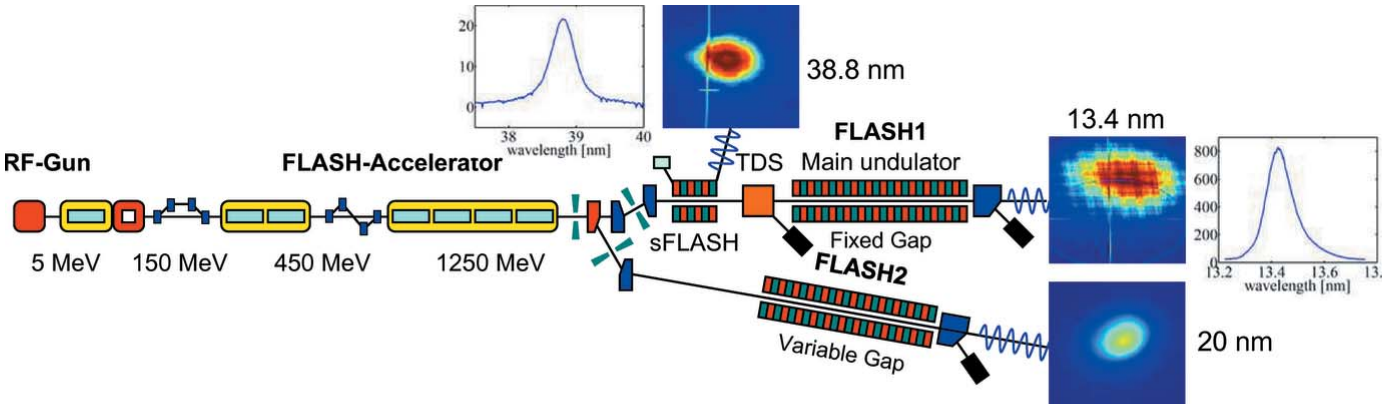


Figure 1
Schematic view of the FLASH facility (not to scale). In the radio-frequency (RF) gun electron bunches are generated by a picosecond laser pulse imaged onto the photocathode. Electron bunches are then accelerated by superconducting RF cavities and delivered to the downstream undulator systems. The FLASH facility features two parallel undulator systems, FLASH1 and FLASH2. In addition to its main undulator, the FLASH1 branch features a variable-gap undulator system dedicated to seeding studies (sFLASH). Images of the FEL radiation produced by each of the three beamlines, as well as an averaged wavelength spectrum of FLASH1 and sFLASH, measured during the simultaneous operation, are shown.

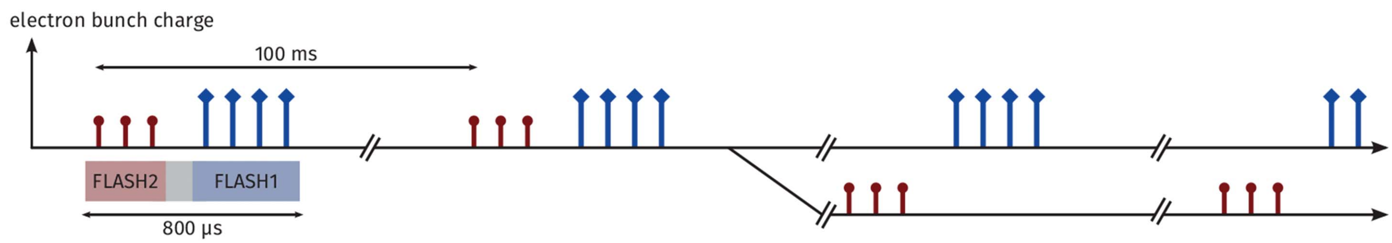


Figure 2
Temporal electron bunch pattern at the FLASH facility. The blue diamond-hatted vertical bars represent the bunch train dedicated to FLASH1, followed by a 30 µs gap that is used to ramp-up the kicker magnet in order to kick the remaining part of the bunch train to FLASH2 (indicated by the red dot-hatted bars). The maximum length of the bunch train is 800 µs with a minimum intra-bunch train spacing of 1 µs. The bunch train is shared between FLASH1 and FLASH2 beamlines, which are both served with the repetition rate of 10 Hz.

accelerator uses superconducting technology allowing operation with long RF-macro-pulses (up to 800 µs), *i.e.* with long electron bunch trains, which can be shared between FLASH1 and FLASH2 as shown in Fig. 2. The bunch trains can contain several hundred electron bunches with an intra-bunch spacing of 1 µs (Faatz *et al.*, 2016). In standard operation, the first bunches within a bunch train go to FLASH1 followed by a 30 µs gap that is used to ramp up the kicker magnet to deflect the remaining bunches of the train to the FLASH2 beamline. Thus, the full macro-pulse repetition rate of 10 Hz is achievable at both undulator beamlines. Thanks to two independent photoinjector lasers and a flexible low-level RF control system, the beam parameters like pulse pattern and pulse duration can be different at FLASH1 and FLASH2 to meet the requirements of the user experiments. A comprehensive description of the FLASH facility and parallel operation is given by Faatz & Schreiber (2015) and Scholz *et al.* (2015).

A transverse-deflecting structure (TDS) at the entrance of the FLASH1 main undulator is used to measure the projections of the longitudinal phase space of electrons, *i.e.* their temporal momentum distribution. As shown in Fig. 3, a TDS operates very similar to a streak camera for photons. It provides the electrons with an arrival-time-dependent deflection in one transverse plane using an RF cavity. A dipole magnet allows for deflection in the other transverse plane creating enough dispersion to resolve the kinetic energy and longitudinal position of the electrons (Behrens *et al.*, 2012).

4. Multi-beamline lasing

During the experiment reported here, the electron beam energy was 700 MeV. This leads to the generation of FEL radiation at 13.4 nm in the main undulator. At the same time, the variable-gap undulator modules at sFLASH and FLASH2 have been tuned to generate 38.8 nm and 20 nm radiation, respectively. For this proof-of-principle experiment, one electron bunch was delivered to each of the two parallel beamlines. The two bunches were separated by 500 µs though; as discussed before, the minimal required gap can be as short as 30 µs. Using the TDS, the peak current was measured to be 1.3 kA and the electron bunch duration was 83 fs (r.m.s.) for the electron bunch lasing first at sFLASH and then at FLASH1.

While there is no longitudinal diagnostic for the electron beam installed at FLASH2 yet, one can assume that the electron bunch length and peak current are similar. The accelerating RF settings were only slightly changed from those at FLASH1 to optimize the SASE output at FLASH2.

Since each undulator beamline is equipped with separate photon diagnostics, it is possible to characterize the photon pulse properties individually at each beamline. The photon pulse energies measured using a gas-monitor detector (Tiedtke *et al.*, 2008) at FLASH1 and a calibrated micro-channel plate (MCP) at sFLASH are shown in Fig. 4. The photon pulse energy was measured to be 83 ± 39 nJ in sFLASH and 77.6 ± 2.9 µJ in FLASH1. Simultaneously, FLASH2 delivered about 146.7 ± 25.4 µJ, also measured with a calibrated MCP. The standard deviation of the respective series of measurements is given.

The photon energies generated at FLASH1 and sFLASH have been measured and the averaged spectra are shown in Fig. 1. The FEL wavelength of FLASH2 is derived from equation (1).

As discussed above, the pulse energy generated by the SASE process is subject to statistical fluctuations. Simulations show that the sFLASH undulator length corresponds to about 14 gain lengths for these experimental parameters, while a SASE FEL only saturates after 20 gain lengths (Schmüser *et al.*, 2014). Accordingly, its pulse energies follow a gamma distribution as shown in Fig. 4, being in agreement with FEL theory (Saldin *et al.*, 1998). Though the photon pulse power gain is already exponential within the last meters of the undulator, it is not suffice to have any effect on the electron bunch and thus the FLASH1 photon energies.

In general, the pulse energy distribution of an FEL operated in saturation deviates from the gamma distribution (Saldin *et al.*, 1998). This is observed for the long main undulators in both parallel beamlines (see bottom histogram in Fig. 4 for FLASH1). Table 1 summarizes the electron, photon and undulator parameters of the three FELs during the experiment reported here.

Table 1
Electron and photon parameters of the multi-beamline lasing experiment.

	sFLASH	FLASH1	FLASH2
Electron bunch energy (MeV)	674	674	692
Charge (nC)	0.26	0.26	0.29
Undulator parameter K	2.57	1.19	1.53
Undulator period λ_U (mm)	31.4	27.3	31.4
Wavelength λ (nm)	38.8	13.4	20
Photon pulse energy	(83 ± 39) nJ	(77.6 ± 2.9) µJ	(146.7 ± 25.4) µJ
r.m.s. energy stability	47.0%	3.7%	17.3%
Relative spectral width (FWHM)	1.2%	0.84%	No measurement

5. Summary and outlook

Sharing a costly linear accelerator between multiple undulator beamlines is a concept being applied at future X-ray FEL facilities such as the European XFEL (Altarelli *et al.*, 2007). At FLASH we have demonstrated the feasibility of beamline multiplexing and cascaded FEL lasing using one linear accelerator. These pilot studies have been performed with a single electron bunch per beamline. Future studies on this operation mode will focus on multibunch operation and achieving simultaneously high photon pulse energies at all undulator beamlines.

Likewise, these results are a first step towards a simultaneous seeded operation at sFLASH. Seeding a FEL does not only control the properties of the resulting photon pulse but also reduces the undulator length needed for saturation. The sFLASH undulator length suffices to achieve photon energies of about 100 µJ in seeded mode of operation. Thus, the energy drawn from the electron bunch is much higher than in SASE mode. This deteriorates its longitudinal phase space distribution, which may lead to less photon pulse energy being generated in the main undulator. However, thanks to the superconducting technology, more than one electron bunch

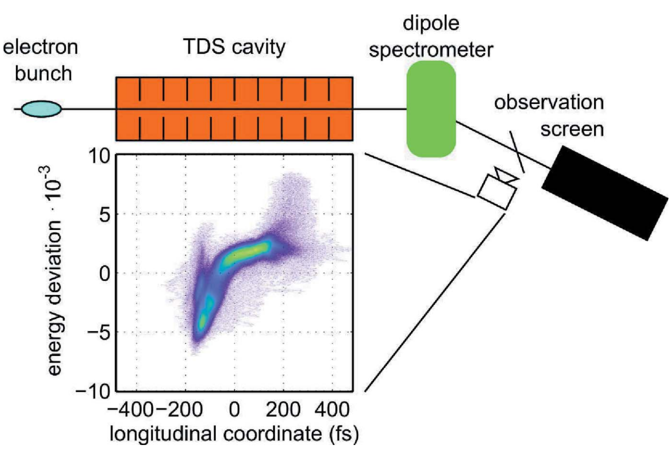


Figure 3
Schematic view of a transverse-deflecting cavity (TDS) followed by an energy spectrometer. The electron bunch travels from left to right. It experiences an arrival-time-dependent deflection in the cavity in the y-plane. Passing through a subsequent dipole the electrons are dispersively kicked in the x-plane. This leads to an image that shows the longitudinal profile in one direction and the energy spectrum in the other. A characteristic measurement of the longitudinal phase space distribution is shown at the bottom.

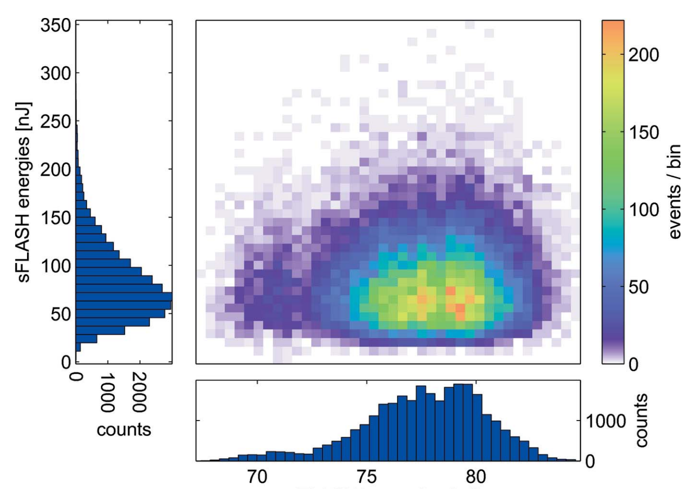


Figure 4
The central plot shows the correlation of measured photon pulse energies of FLASH1 and sFLASH of about 29000 consecutive shots. The color code shows the events per bin. Next to both axes the respective histograms are shown. The sFLASH histogram shows a gamma distribution, while FLASH1 shows a more Gaussian-like distribution as expected from a FEL running into saturation.

can be accelerated per macro-pulse. If one electron bunch of the train is seeded, the remaining electron bunches are still able to deliver high-intensity SASE pulses in the main undulator. In this mode of operation the FLASH facility can serve three experimental stations with high-energy photon pulses simultaneously.

In the future, the combination of three FEL pulses with very different wavelengths such as THz, soft- and hard X-rays in a single experimental station may point towards novel pump-control-probe schemes. For example, THz pulses drive chemical processes or phase transitions, the transient electronic structure during the reaction is traced by element-specific soft X-ray spectroscopy and the molecular (geometric) structure is followed online by X-ray diffraction. Such investigations hold the key to unravelling the full picture of functionality in real time with atomic spatial resolution. Beam multiplexing and cascaded FEL operation is an essential step in this direction.

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