OPERATION OF FLASH WITH SHORT SASE-FEL RADIATION PULSES*

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Abstract

This paper describes the experimental activity on the generation of very short FEL pulses in the soft x-ray range in the SASE-mode at the high-gain free-electron laser FLASH [1, 2]. The key element, a photo-injector laser which is able to generate laser pulses of about 2 ps FWHM has been optimized and commissioned. It allows the generation of shorter bunches with low bunch charge (of up to 200 pC) directly at the photo-cathode. Initially shorter injector laser pulses and thus shorter bunches eases the required bunch compression factor for short pulses below 10 fs duration which makes operation of the electron beam formation system to be more robust with respect to jitters and collective effects. As a result, overall stability of SASE FEL performance is improved. In the optimal case single-spike operation can be achieved. In this paper the experimental results on production of short electron bunches and the SASE performance using the new injector laser will be shown and the measured electron bunch and FEL radiation properties are discussed. In addition, optimizations of bunch diagnostics for low charge and short bunches are discussed.

MOTIVATION

Several user-oriented free-electron laser (FEL) facilities aim for very short vacuum ultraviolet (VUV), extreme ultraviolet (XUV) and X-ray pulses which allow to study ultra-fast processes in different areas of science. In order to achieve such short bunches several schemes have been proposed. The most robust method to generate pulses of a few femtoseconds at FELs is to create a short electron bunch. In the most extreme case the lasing part of the bunch is as short as one longitudinal optical mode and thus the electron bunch length (σ_b) has to fulfill the condition $\sigma_b \leq 2\pi L_{coop}$ [3, 4], with L_{coop} the cooperation length. These so-called single-spike SASE pulses [3, 4] are bandwidth limited, longitudinally coherent and compared to seeding concepts no long background disturbs the signal. At FLASH [1, 2] single-spike operation requires bunches whose lasing part have a duration of a few fs. To mitigate space charge forces, this can only be achieved by applying low bunch charges of about 20 pC.

SHORT PULSE PHOTO INJECTOR LASER

As discussed already in detail in [5] such a short bunch would require a very strong compression (about 2000) in the two bunch compressors at FLASH when applying the standard photo injector laser with an rms laser pulse duration of 6.5 ps, which is optimized for 1 nC. Such a strong compression would lead to strong instabilities in the accelerator caused by small phase fluctuations. Therefore a new photo injector laser with a reduced pulse duration was commissioned [6, 7, 8]. It is optimized for variable pulse length from 0.7 to 1.7. The laser system consists of an oscillator and a Yb:YAG amplifier [9]. In the infrared an average output power of up to 7 W has been achieved, which corresponds to a single pulse energy of about 7 μJ.

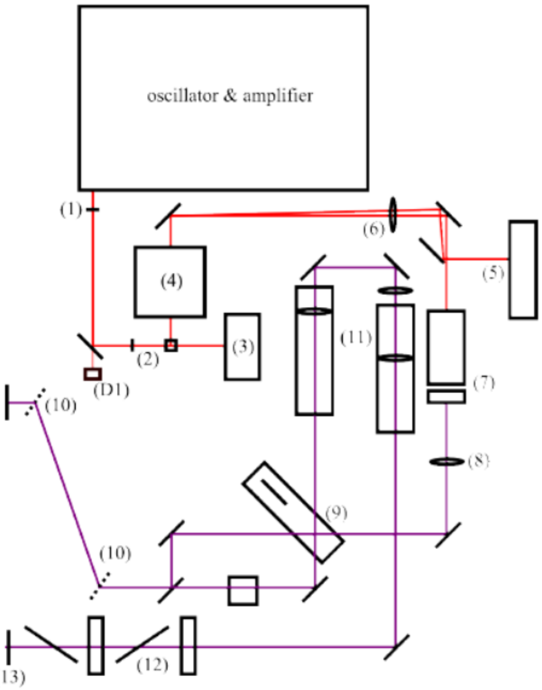

Figure 1: Scheme of the photo injector Laser beamline [8] with the following components: half-wave plate (1); photo diode (D1); beam splitter (2); power meter (3), acusto-optical modulator (AOM) (4); Beam-Dump (5); IR-lens, f = 300 mm (6); LBO-crystal and BBO-crystal (7); collimating UV-lens (8); remote controllable mirror for incoupling into the stretcher (9); pulse-stretcher (10); telescope (11); attenuator (12); aperture (13).

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Figure 1 shows a schematic layout of the optical beamline of the photo injector laser. An AOM (marked with (4) in Fig. 1) allows for arbitrary pulse picking to choose the pulse train length as it is typical at FLASH. The frequency is converted into its fourth harmonic by two non-linear crystals (marked with (7) in Fig. 1). In order to adapt the bunch length at the cathode to the charge, one can stretch the laser pulse with an optical stretcher consisting of two transmissive gratings with 4000 lines per cm. With the current setup, we are able to vary the distance of the gratings between about 50 to 450 mm and thus choose an arbitrary pulse duration between 0.7 to 1.7 ps rms [8].

In order to monitor the laser parameters and correlate those with the corresponding properties of the electron bunch, additionally new diagnostics have been installed. These include a set of quadrant diodes to monitor the transverse laser stability of single pulses in a train, a UV camera to optimize the laser position of all three injector lasers available at FLASH and a UV spectrometer [6, 7].

SHORT PULSE OPERATION

First SASE performance using the new photo injector laser could be demonstrated in January 2013 at a wavelength of 13 nm and a bunch charge of 35 and 80 pC [5].

Another measurement performed in May 2014 will be presented in this section. SASE was optimized for a bunch charge of 110 pC and afterwards it was stepwise reduced down to 55 pC. The laser pulse duration was chosen with 1 ps rms, which means the pulse during the measurements presented in this section is about six times shorter than in standard operation. The transverse distribution of the laser at the photo cathode was a truncated Gaussian [6, 7, 10] with a diameter of 1 mm. These parameters are chosen in such a way that at a bunch charge of about 50 pC the charge density at the photo cathode is comparable to the density at FLASH standard operation.

The spectral FEL pulse distribution has been measured by high resolution monochromator [11, 12]. Figure 2 shows six randomly chosen examples of single shot FEL-spectra measured at a bunch charge of 80 pC. The spectra typically show a few spikes. An analysis of 1768 events has counted in average 3.8 spikes and 2.7 within the FWHM.

An additional measurement of the FEL pulse length with the optical afterburner [13, 11] has been performed under the same conditions. An analysis of the data led to the conclusion, that the upper limit for the pulse duration is 30 fs. An exact value could not be determined due to low statistics during the measurement. In order to shorten the bunch even more, the bunch charge was reduced further down to 55 pC; the machine parameters were readjusted and the spectrum was measured again. Figure 3 shows six randomly chosen examples of single shot spectra measured at a bunch charge of 55 pC.

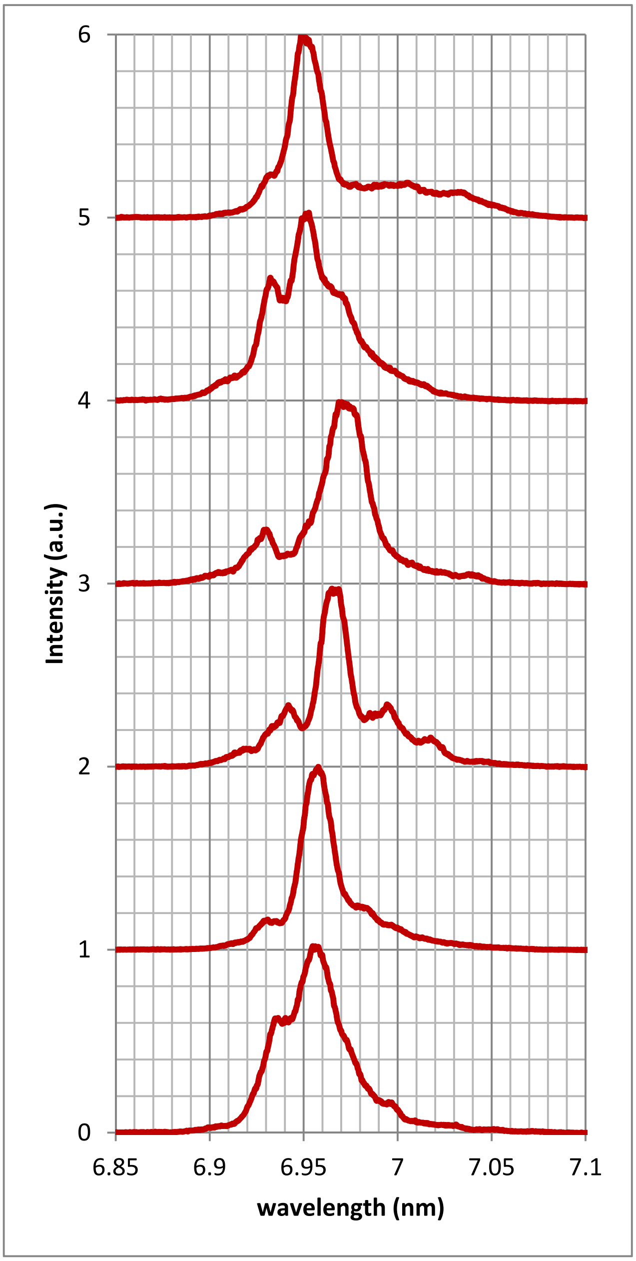

Figure 2: Six typical examples of FEL-spectra measured at FLASH, when the short-pulse laser was applied at a bunch charge of 80 pC.

The analyzed spectra at 55 pC show less spikes, than in the 80 pC case, typically only one or two of the spikes is strongly emphasized. Here an average of 1.5 spikes within the FWHM has been determined. The reduction of the number of spikes with the bunch charge in the FEL spectra may presume also a reduction of the FEL pulse duration. Assuming a bandwidth of 0.4% and a Gaussian electron bunch distribution would lead to an rms FEL-pulse duration of 2.4 +/- 0.2 fs. But a lower bandwidth and thus a longer pulse length might be possible.

According to beam dynamics studies a further reduction of the bunch charge should allow the generation of a pure single spike. The experiment will be carried on soon.

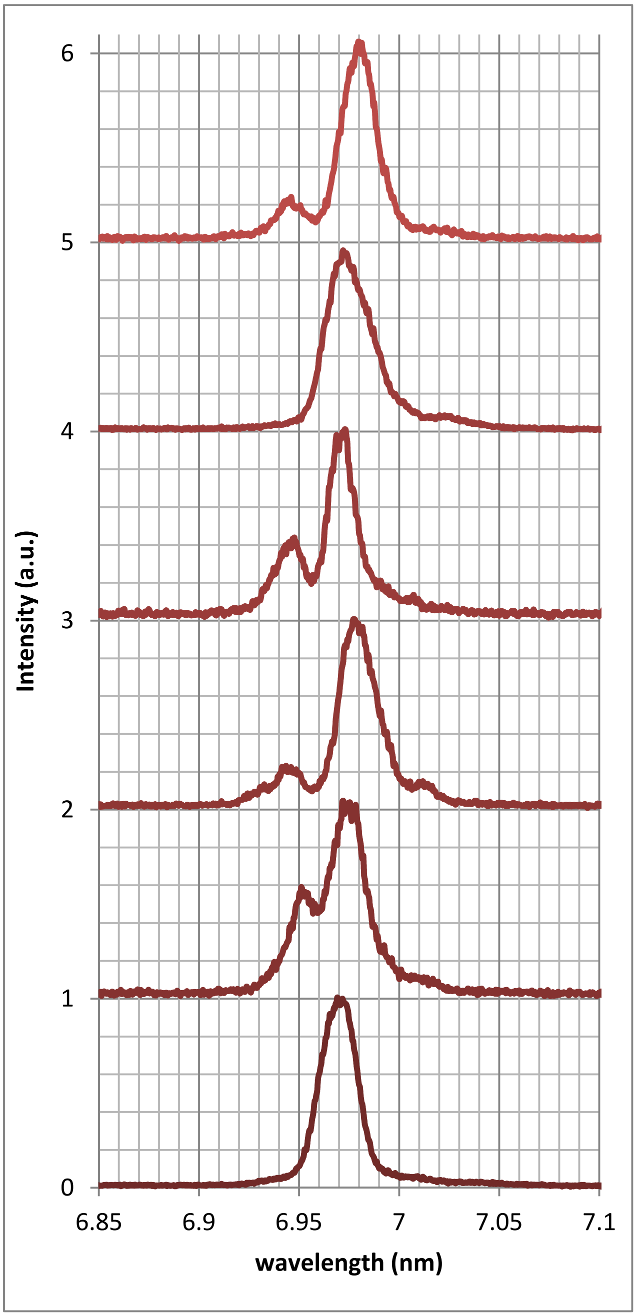

Figure 3: Six typical examples of single shot FEL-spectra measured at FLASH, when the short-pulse laser was applied at a bunch charge of 55 pC.

Start-to-End Simulations

A start-to-end simulation for single spike FEL radiation based on real machine settings for standard short pulse operation at FLASH is presented in [14]. The results of the measurement presented above are currently used as a basis for s start-to-end beam dynamics simulation with the codes ASTRA, CSR-Track and Genesis 1.3. Additionally an optimization of these machine parameters is foreseen in order to achieve pure single-spike pulses in the next experimental run.

DIAGNOSTICS

In order to achieve short bunches and understand the beam dynamics of low charge bunches reasonable diagnostics elements are mandatory. Therefore different types of optics and cameras have been studied in order to optimize the readout system of the transverse deflecting cavity [15]. Additionally also the bunch arrival time monitor [16] and the THz-Spectometer for bunch length measurement [17] have been redesigned for the operation at low charge. Also the measurements of the duration of the FEL pulses are an important challenge which has been studied in detail in [11].

CONCLUSION

The generation of short FEL pulses, close to single spike in the VUV and soft x-ray range in the SASE-mode at the high-gain free-electron laser FLASH using a short photo-injector laser pulse has been achieved. At a bunch charge of 55 pC the spectra of the SASE pulse with one to four spikes only, in average 1.5 spikes with in the FWHM has been observed. Taking into account a coherence length of about 3 fs (measured at a wavelength of 8 nm) at FLASH [18, 19] an FEL pulse duration of only some fs can be assumed. With further optimization of low charge operation, single spike SASE is within reach.

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