SHORT SASE-FEL PULSES AT FLASH*

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Abstract

FLASH is a high-gain free-electron laser (FEL) in the soft x-ray range. This paper discusses the generation of very short FEL pulses in the Self-Amplified Spontaneous Emission (SASE) - mode without an external seeding signal. In the optimal case a SASE-FEL can be operated in the so-called single-spike mode. At FLASH a new photo-injector laser has been commissioned, which allows the generation of shorter bunches with low bunch charge directly at the photo-cathode. This shorter injector laser reduces the required bunch compression for short pulses and thus allows a stable SASE performance with shorter pulses. First SASE performance using the new injector laser has been demonstrated and electron bunch and FEL radiation properties have been measured. These measurements are presented and next steps towards single spike operation are discussed.

MOTIVATION

The users of free-electron lasers (FELs) show a rising interest in very short vacuum ultraviolet (VUV), extreme ultraviolet (XUV) and X-ray pulses to study ultra-fast processes in different areas of science. Several schemes to achieve such short bunches have been proposed. In order to produce radiation pulses of a few femtoseconds at FELs like FLASH, the most robust method is to create an electron bunch, which is in the most extreme case as short as one longitudinal optical mode. The electron bunch length (σ_b) has to fulfill the condition $\sigma_b \leq 2\pi L_{coop}$ [1, 2], with L_{coop} the cooperation length. These so-called single spike SASE pulses [1, 2] attract the interest of several FEL facilities [3, 4, 5]. Such a single spike SASE pulse is bandwidth limited, longitudinally coherent and compared to other concepts (e.g. seeding) no long background signal disturbs the signal. The usage of short pulses also prevents damage of the studied object, since most applications of short pulses do not rely on a high photon count [6]. A single spike operation at FLASH [7, 8] requires an electron bunch with a duration of a few fs and to mitigate space charge forces, a bunch charge of about 20 pC is required. First beam dynamics studies have been performed [9] to estimate the required parameters.

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NEW INJECTOR LASER

The standard photo injector laser used at FLASH has an rms duration of 6.5 ps. To reach a bunch duration of about 3 fs a compression by more than a factor 2000 (as shown in Table 1) would be required. Such a strong compression would lead to strong instabilities in the machine caused by small phase fluctuations. A reduced photo injector laser

Table 1: Required Compression Depending on Injector Laser Pulse Duration and Aiming Bunch Duration

	typical FLASH operation	single spike operation	single spike operation
injector laser pulse duration	15.3 ps (FWHM)	15.3 ps (FWHM)	1-3 ps (FWHM)
bunch charge	0.08-1 nC	20 pC	20 pC
rms bunch duration	30-200 fs	3 fs	3 fs
compression	220 - 32.5	**2200**	**140 - 430**
FEL pulse duration	30-200 fs (FWHM)	3 fs (FWHM)	3 fs (FWHM)

pulse duration would help to relax the RF tolerances which scale linear with the compression factor. Thus a shorter injector laser pulse duration is required. Due to the usage of the lower bunch charge this reduction of the bunch length at the injector is possible. Therefore a new photo injector laser with sub-picosecond pulse duration in combination with a stretcher is used to optimize the initial bunch length. The commissioning of the new laser system are described in detail in [10]. Details about the synchronization of the laser system can be found in [11].

To judge the performance of the new short pulse injector laser the charge stability was measured in comparison to the standard injector laser in September 2012. In these measurements the short pulse laser and the standard injector laser showed a comparable charge stability. The short pulse injector laser beam line was designed such that the beam was collimated in both BBOs crystals. For the first SASE with the new injector, which was performed in January 2013 and is discussed in the next section, a different setup was used. Here the beam was focused into both BBO crystals. This setup was used to achieve a sufficiently high conversion efficiency, but unfortunately it increased also the instability by more than a factor of two. For future applications the beam line is modified for high conversion efficiency and high stability at the same time.

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FIRST SASE WITH SHORT PULSE LASER

After a commissioning of the new injector laser and it beam line first SASE performance has been demonstrated using this short pulse injector laser on the 9th of January 2013 and 11th of January 2013.

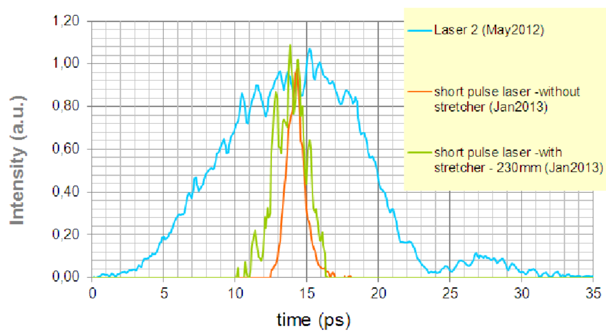

Figure 1: Measured temporal distribution of standard FLASH injector laser compared to short pulse laser.

Figure 1 shows streak camera measurements of the temporal distribution of standard FLASH injector laser compared to short pulse laser. Without usage of the stretcher a pulse duration of about 1.3 ps (FWHM) was measured. For both shift the pulse duration was adjusted using the stretcher to 2.4 ps (FWHM). The transverse laser spot was formed with an iris which had a diameter of 1 mm.

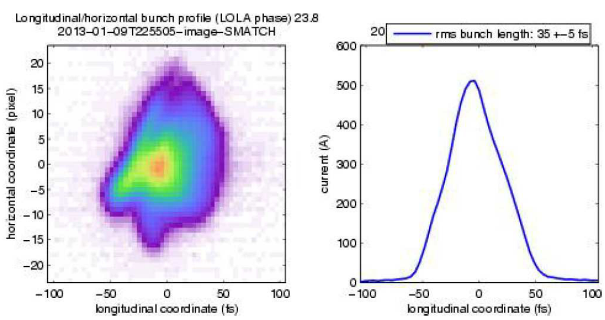

Figure 2: Measured longitudinal bunch duration using the transverse deflecting cavity during SASE performance for 35 pC.

On the 9th of January 2013 SASE was generated for a bunch charge of 35 pC as shown in Table 2, which shows the parameters during the first SASE operation with the short pulse injector laser. The using the short injector pulse a bunch duration of 35 fs (see Fig. 2) could be reached with a very weak compression and thus the SASE performance was very stable.

In a second shift using the new injector laser (on the 11th of January 2013) SASE was generated for a bunch charge of 80 pC, see last column of Table 2. The temporal bunch distribution was determined during the SASE performance by a transverse deflecting cavity (see Fig. 3) with 78 fs. Additionally the longitudinal distribution of the bunch was measured using a broadband THz spectrometer

Table 2: Parameters of the First SASE Operation using the Short Pulse Injector Laser

parameters	9th of Jan.	11th of Jan.
transv. laser shape	truncated Gaussian	Flat-top
long. laser shape	Gaussian	Gaussian
injector laser pulse duration	2.4 ps (FWHM)	2.4 ps (FWHM)
bunch charge	35 pC	80 pC
rms bunch duration	35 fs	78 fs
wavelength (λ_{rad})	13.5 nm	13.0 nm
power	5 μJ	25 μJ
FEL pulse duration	unknown	~50 fs

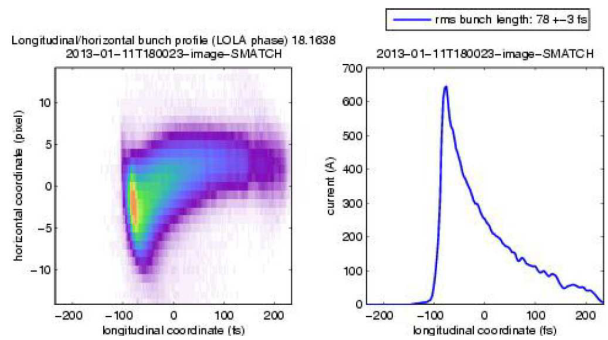

Figure 3: Measured longitudinal bunch duration using the transverse deflecting cavity during SASE performance for 80 pC.

(see Fig. 4). Both measurements show a peak current of 700 A. The emittance of the electron bunch has been measured for this setup after the first bunch compressor with 0.7 mm mrad in vertical direction and 0.9 mm mrad in horizontal direction.

The spectral FEL pulse distribution has been measured by the Plane Grating Monochromator Beamline (PG2) [12]. Figure 5 shows an example of the spectral and energy distribution of the SASE-FEL pulse measured in the

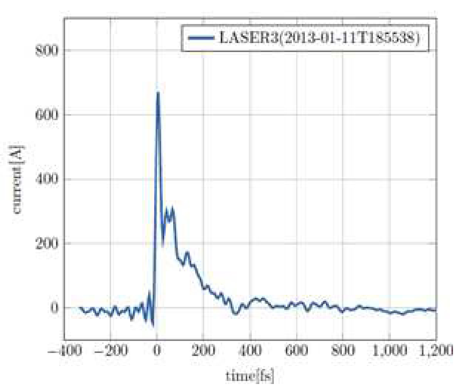

Figure 4: Measured longitudinal bunch duration using a broadband THz spectrometer during SASE performance for 80 pC.

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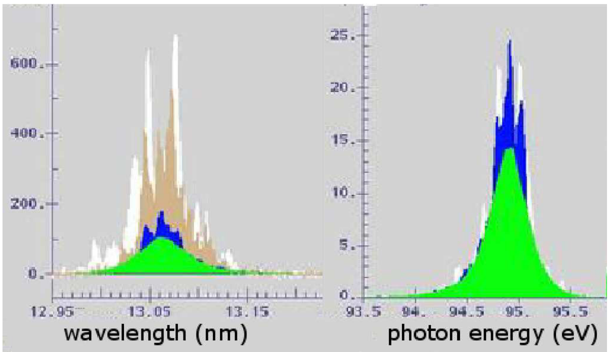

Figure 5: Spectral distribution of the FEL pulse in the saturation regime measured on the 11th of January 2013.

saturation regime.

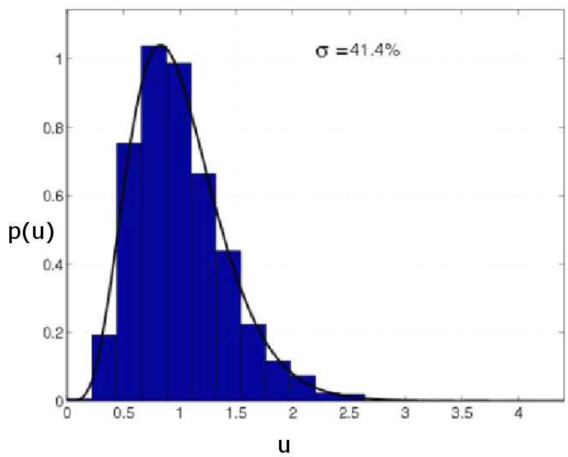

Figure 6: Fluctuation of the SASE pulse energy measured in the exponential gain regime. The solid line shows the gamma distribution.

Fluctuations have been determined in the regime of exponential gain (see Fig. 6) with $\sigma = 41.4\%$. The number of modes is determined by $M = \frac{1}{\sigma^2} = 5.8$. In saturation 13% fluctuations were determined. The saturation length was about $L_{sat} = 22\,m$. Spectral bandwidth was determined with 0.35% (FWHM) in the regime of exponential growth and 0.42% (FWHM) in the saturation regime. This means the spectral bandwidth of the radiation is pretty close to that generated by monochromatic electron beam, this means the natural SASE bandwidth. Thus, lasing part of the beam is not disturbed by a chirp, which is typically caused by beam formation procedures or collective effects. Due to the weak compression these effects could be avoided. Thus the radiation pulse length L in the regime of exponential gain has been derived with statistical methods, according to [13, 14], with: $L = \frac{M \cdot \lambda_{rad} \cdot L_{sat}}{5 \cdot \lambda_{Und}} = 12\mu m$, with $\lambda_{Und} = 27.3mm$. This corresponds to an FEL pulse duration of 40 fs (FWHM). The radiation pulse duration at the end of the FLASH undulator is estimated as 50 fs. The rms duration of the lasing fraction of the electron bunch is estimated with 40 fs. Assuming Gaussian shape of the electron bunch the peak current is estimated with about 700 A. These parameters are consistent with measured properties of the radiation.

SUMMARY AND OUTLOOK

In order to allow a stable single spike operation a new short pulse injector laser was installed, synchronized with FLASH and taken into operation. First SASE operation was demonstrated using this new injector laser. The seeded pulse showed a narrow spectral bandwidth and a high stability. In the current FLASH shut-down the laser and the optical beam line is optimized and automatized and additional laser diagnostics is under installation. The achieved SASE performance is currently studied using ASTRA and Genesis 1.3 to optimize the setting towards single-spike operation. Additionally new diagnostics for low charge and short bunch operation is under development, e.g. a new THz-spectrometer and a new bunch arrival time monitor [15].

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