GENERATION OF ULTRA-SHORT ELECTRON BUNCHES AT FLASH*

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Abstract

In order to produce radiation pulses of a few femtoseconds at FELs like FLASH, different concepts have been proposed. Probably the most robust method is to create an electron bunch, which is in the most extreme case as short as one longitudinal optical mode. For FLASH this translates into a bunch length of a few micrometers only and thus in order to mitigate space charge effects, the bunch charge needs to be about 20 pC. The technical requirements to achieve this goal are discussed. This includes beam dynamics studies to optimize the injection and compression of small charge electron bunches. A reduced photo injector laser pulse duration helps to relax the RF tolerance which scales linear with the compression factor. 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 and first experiments are described. Limitations of the presently available electron beam diagnostics at FLASH for short, low charge bunches are analyzed. Improvements of the longitudinal phase space diagnostics and the commissioning of a more sensitive bunch arrival time monitor are described.

INTRODUCTION

The users of free-electron lasers (FELs) show a rising interest in very short vacuum ultraviolet (VUV), extreme ultraviolet (XUV) and X-ray pulses in order to study fast process in different areas of science. At FLASH for instance about a quarter of the scheduled user shifts request for pulses with durations below 50 fs (FWHM) [1]. Thus the idea to create electron bunches with lengths of one longitudinal optical mode to create the so-called single spike SASE pulses [2, 3] attracts the interest of several FEL facilities [4, 5, 6]. 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 rely on a high photon count [7]. The required electron bunch length (σ_b) has to fulfill the condition $\sigma_b \leq 2\pi L_{coop}$ [2, 3], with L_{coop} the cooperation length.

SINGLE SPIKE OPERATION OF FLASH

FLASH [8] is a single-pass high-gain Self Amplified Spontaneous Emission free-electron laser (SASE-FEL), which operates in a wavelength range from 4.12 to 45 nm. At FLASH typically FEL pulse durations down to 50 fs (FWHM) are generated and bunch charges down to 200 pC are used [8]. A single spike operation at FLASH requires an electron bunch with a duration of a few fs only. In order to create such a short bunch it is mandatory to reduce the charge to avoid the elongation of the bunch by space charge forces. Figure 1 shows as an example a comparison of the longitudinal distribution simulated using Genesis for electron bunches with an rms bunch length of 10μm and 1μm. An rms electron bunch length of about 10μm is about the minimum length which can be achieved during FLASH standard operation when using a charge of 200 pC[9]. This temporal distribution of the SASE-pulse

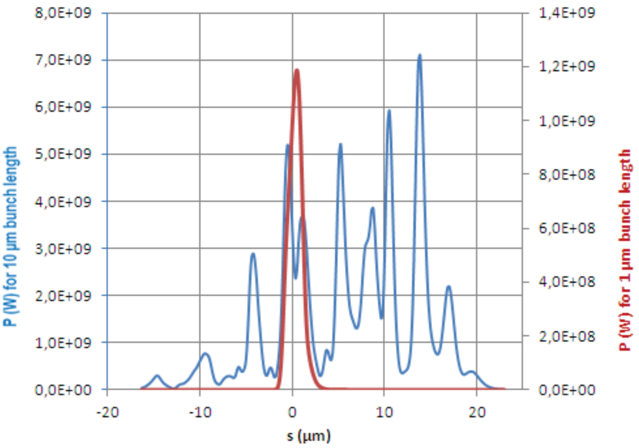

Figure 1: Genesis simulation of the longitudinal distribution of a SASE pulse at FLASH at a wavelength of about 13 nm when applying an electron bunch with a rms bunch length of 10 and 1 μm.

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still contains several spikes and has a duration of 15.3 fs FWHM. Reducing the rms electron bunch length by a factor of 10 while keeping the peak current constant reduces the duration of the SASE-pulse to about 1.8 fs. This single spike was reached before the end of the undulator and before saturation is reached, but a further propagation would excites additional modes, therefore the power of the single spike is lower. In [11] it is discussed how the properties of the electron bunch have to be chosen, that the radiation pulse does not slip out of the bunch before the end of the undulator section and a preliminary start-to-end simulation for single spike operation at FLASH at a wavelength of 13 nm using a bunch charge of 20 pC is presented. The usage of such a small charge induces less variation of the electron beam parameters along the bunch, a smaller transverse emittance, a reduction of the curvature of the longitudinal phase space distribution by the RF-field and a reduction of coherent synchrotron radiation in bunch compressors and of wakefields.

NEW PHOTO-INJECTOR LASER

The RF tolerance scales linear with the compression factor and thus a large compression factor (≈1000) demands a high stability of the accelerator. Therefore, it should be avoided to compress the bunch too strongly and as discussed in detail in [12] it is useful for the generation of a short electron bunch at FLASH to reduce the photo-injector laser pulse duration compared to the standard operation. Since the available photo-injector laser does not offer the opportunity to shorten the duration a further photo-injector laser was installed at FLASH. This laser allows to choose a shorter electron bunch duration directly at the photocathode to reach an optimized single spike operation and a very strong compression which can cause instabilities in the SASE performance can be avoided. Figure 2 shows the schematical layout of the laser system. The laser system contains a commercial SESAM[1]-based laser as a seed[2], which produces infrared (IR) pulses with a wavelength of 1030 nm, a power of 260 mW with a repetition rate of 54 MHz and a duration of 400 fs. Two commercial InnoSlab amplifier [10] stages[3] increases the power to 10 W at 1 MHz with a pulse duration below 800 fs. The las er oscillator is synchronized to the RF master-oscillator. An acousto-optic modulator is used as a pulse picker where the pulse structure can be chosen and thus the required number of electron bunches can be chosen. The remaining electron bunches are dumped, while the chosen IR-pulses of 10 μJ are converted into ultra-violet pulses with a wavelength of 257.5 nm using a BBO forth harmonic stage[4]. The expected pulse energy in the ultra-violet is 1 μJ. In order to optimize the bunch parameter the length of the injector pulse can be adjusted by a stretcher consisting of two transmission gratings and a periscope. The second grating and the periscope are mounted on a linear stage. This reduces the laser pulse energy by about 50 %. The transverse laser beam size at the photocathode is determined by a so-called beam shaping aperture (BSA) (an iris) which is imaged onto the cathode. Behind this aperture the laser pulse is induced in the optical transmission line of the standard photo-cathode laser at FLASH. Expecting 75 % losses at the BSA and in the optical transmission line and a quantum efficiency larger than 0.5 % a bunch charge above 125 pC is expected.

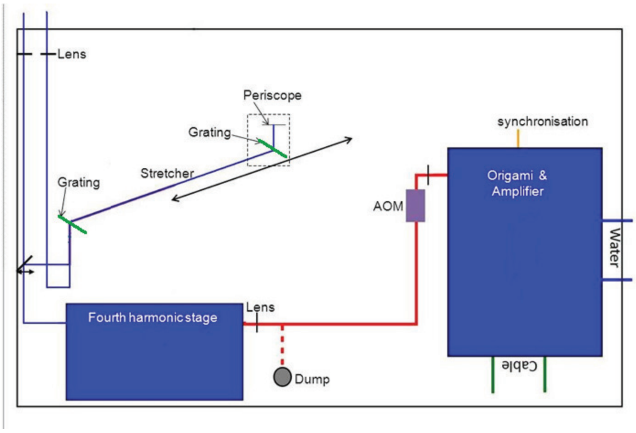

Figure 2: Schema of the new photo-injector laser including the fourth harmonic stage and the pulse stretcher.

First Operation with the New Photo-Injector Laser

During the first measurement using the new injector laser, it did not yet fulfill the specification completely, but since the quantum efficiency of the photo-cathode was high during the commissioning of the laser a bunch charge of 200 pC was observed in a measurement without stretcher and BSA. The usage of a BSA with a diameter of 0.8 mm reduced the charge to 80 pC. This bunch could be transported through FLASH without losses and bunch length measurements of this bunch have been performed. Figure 3 shows the result of the bunch length measurement, which will be discussed in the following section. Probably due to the fact that the laser is not yet running in saturation a laser energy stability of only about 20 % could be reached. The phase stability during the measurement was about 2°. After fixing the energy of the injector laser the stability should be strongly improved.

DIAGNOSTICS

The beam diagnostics installed at FLASH (for the measurement of bunch length, the bunch arrival time, transverse beam position and size, including transverse emittance, beam energy and bunch charge) is optimized for 1 nC so it has to be checked if the available diagnostics is able

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[1] semiconductor saturable absorber mirror

[2] "Origami 10", manufactured by company OneFive

[3] manufactured by Amphos

[4] LG450, manufactured by Solar Laser Systems

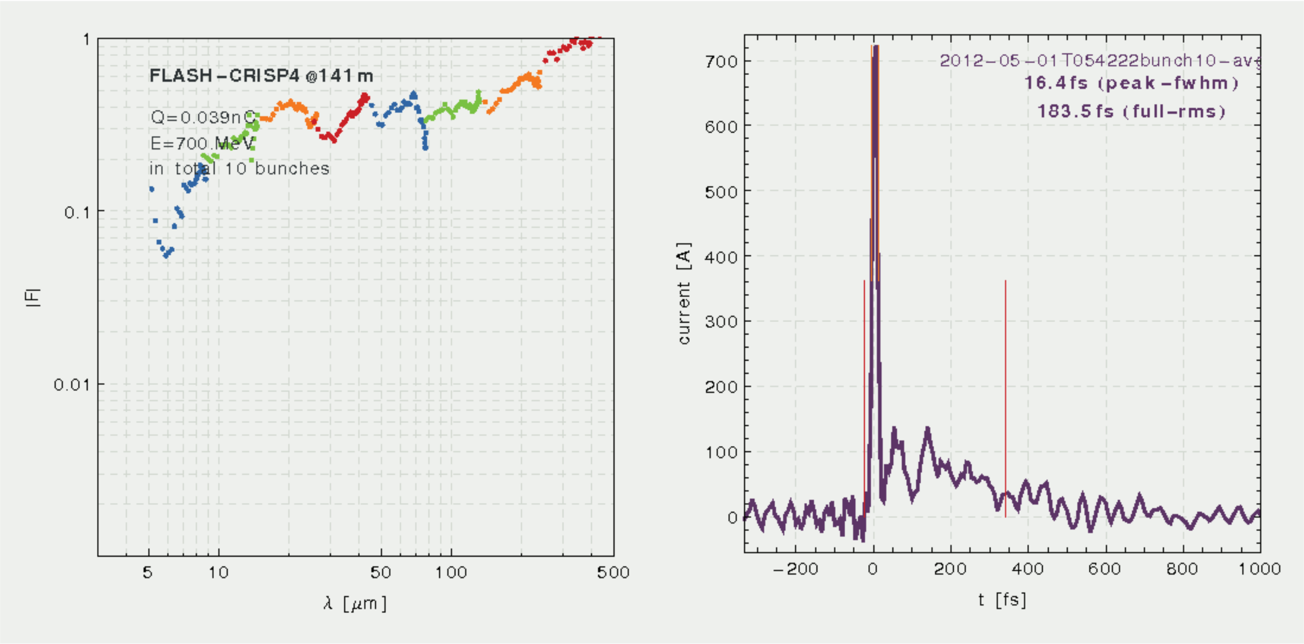

Figure 3: Bunch length measurement using THz spectroscopy. Measured longitudinal form factor as a function of the wavelength for an electron bunch of 80 pC (left) and the resulting reconstructed temporal distribution of the electron bunch (right).

to work at small charges and shorter bunches as well, otherwise it has to be adapted.

Transverse Beam Properties

The beam position monitors available at FLASH are not able to determine the beam position of 20 pC bunches. But the beam position and sizes can be determined using wirescanners and OTR screens. Wire scanners are also available between the undulators and thus the position of the bunch can be adjusted. Also an emittance measurement using four screens and bunches of 70 pC charge could be performed in a test. The OTR and the YAG screens showed a signal at a charge of only 8 pC and one bunch. But the optics of the screen-stations has to be optimized for the smaller beam sizes produced by bunches with low charges.

Bunch Charge

FLASH-type toroids give a resolution of about 3 pC. The dark current monitor installed at FLASH is able to determine charges in the sub-pC regime [14]. Thus an exact determination of the charge is possible.

Bunch Length Measurement

At FLASH the compressed bunches are typically measured by the transverse deflecting cavity and / or a broadband spectrometer for coherent transition radiation emitted by electron bunches [15]. Figure 3 shows a measurement using the spectrometer of an 80 pC electron bunch. A bunch duration of 16 fs FWHM could be achieved, but this measurement is just above the noise level of the detectors additionally and the threshold of the lowest measurable bunch duration is reached, because the limit of the dynamic range of the spectrometer is reached [15]. This also means this 80 pC bunch is only measurable due to its high peak current and 80 pC bunches with a duration above 67 fs are also not measurable, because the signal of the pyrodetectors relies on the charge density. Generally spoken, this means for low charge bunches the usable range is very narrow. Therefore this spectrometer has to be redesigned for short bunch length and low charges, because the wavelength range changes and the pyro-electric detectors are not sensitive enough when a smaller charge is used.

High Bandwidth Bunch Arrival Time Monitor

An important beam parameter is the arrival time of the electron bunch, because only a bunch with stable arrival time is usable for user-experiments. The Bunch Arrival Time Monitors (BAMs) currently used at FLASH achieved a time resolution better than 10 fs for bunch charges of above 500 pC [16]. But since the design is bandwidth limited by 10 GHz for charges below 200 pC [16] the achievable time resolution degrades fast and thus, they are not useable for a charge of 20 pC. Hence a new high bandwidth pickup for the new BAM has been designed [17] and a vacuum tight prototype has been installed at FLASH. As a next step the performance of the pickups will be tested, the 40 GHz readout electronics will be installed and first arrival time measurements with the BAM prototype are foreseen in the end of this year.

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SUMMARY AND OUTLOOK

A new photo-injector laser was taken into operation and a bunch charge up to 200 pC could be achieved. The installation and commissioning of different diagnostics for a detailed analysis of the properties of the new photo-injector laser is under progress. This includes transverse, spectral and longitudinal distribution, pulse energy and stability of these properties. Also the analysis of the influence of different components on the stability is foreseen. After recommissioning the laser a detailed comparisons of measurements with start-to-end simulations will be performed to approve the simulation results presented in [11, 12]. An upgrade of the THz-spectrometer is under development and a high bandwidth BAM was installed at FLASH and will be commissioned in the end of this year.

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