FEMTOSECOND RESOLVED DETERMINATION OF ELECTRON BEAM AND XUV SEED PULSE TEMPORAL OVERLAP IN sFLASH*

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Abstract

sFLASH is a seeded experiment at the Free-Electron Laser FLASH in Hamburg. It uses a 38 nm High-Harmonic-Generation (HHG) scheme to seed the FEL-process in a 10 m long variable-gap undulator. The temporal overlap between the electron and HHG pulses is critical to the seeding process. The use of a 3^{rd} harmonic accelerating module provides a high current electron beam with ∼400 fs bunch duration. The duration of the HHG laser pulse is ∼20 fs. The desired overlap is achieved in two steps. Firstly, the HHG drive laser is synchronized to the incoherent spontaneous radiation from an upstream undulator with picosecond resolution. Next, the coherent radiation from an undulator is used to determine the exact overlap of the electron beam in a modulator-radiator set-up.

INTRODUCTION

In order to obtain seeding the desired HHG harmonic is spectrally selected and spatially and temporally overlapped with the electron bunch in the 10 m long variable gap undulator section.[4, 5] Seeding an FEL with high-order harmonics generated in Argon gas is a good means for generation of short wavelength radiation having full coherence at high intensity. For the HHG part, the laser system which is used for the generation of HHG light, is based on chirped pulse amplification (CPA) Ti:Sapphire technology, which delivers a high power, short pulse 800 nm wavelength laser beam (35 fs FWHM, 40 mJ) at 10 Hz. Up to mid 2009, FLASH was operated with a compression scheme producing electron bunches with an effective length in the order of 10 fs after compression.[1] The rms bunch arrival-time jitter is about 70 fs (rms), which makes seeding with a short pulse difficult. In 2010, a module with four 3.9 GHz cavities [2] have been installed at FLASH [3] to linearize the longitudinal phase space. sFLASH takes advantage of this new feature: a bunch length of 400 fs FWHH is now possible, important to achieve and maintain overlap of the seed radiation with the electron bunch. In this paper two techniques are described to achieve the overlap. Firstly, a streak camera based approach measures the arrival time of the laser pulse and the electron bunch using spontaneous undulator radiation with a resolution sub-picosecond range. Secondly, for a finer resolution, a modulator-radiator-based system [6] is used in which the laser imprints an energy modulation onto the electron bunch similar to an optical klystron process. On temporal overlap, a coherent signal is produced. The resolution is expected to be better than 100 fs. In the following section, the concept, tolerance studies, and experimental results are presented.

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THE EXPERIMENTAL CONCEPT

The Coarse Temporal Overlap Setup

The experimental setup for finding the coarse longitudinal overlap is illustrated in Fig. 1. A silver coated screen

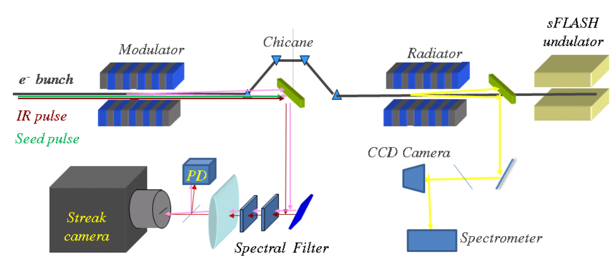

Figure 1: Schematic set-up for finding coarse and fine longitudinal overlap.

placed after a short undulator (the modulator, 1 m length, 5 periods, 200 cm periodic length), reflects the IR laser and synchrotron light of the undulator to a fast photodiode and to a streak camera [7] at the same time. Both light pulses traverse a joint beam line to reach the detectors. The large spectral range of the undulator radiation can cause an elongation of the pulse due to dispersion in the beamline. Therefore, a combination of different spectral filters with a bandwidth of 80 nm are used. The streak camera resolution is about 500 fs, limited by the finite slit size, photon wavelength, spatial photon profile, space-charge effects, and sweep rate.

The Fine Temporal Overlap Setup

For a more accurate overlap of the seed pulse with the electron bunch, we use the production of coherent radiation in the second undulator (the radiator), which is produced when the two pulses overlap. The 800 nm laser beam is focused at the beginning of the modulator interacting with electron bunch. In this process the electrons are energy modulated. This effect will induce a density modulation after the beam passes through the chicane with an R_{56} that can be varied up to 140 μm. The density-modulated beam then passes through the second undulator, the radiator, which is tuned to the fundamental or second harmonic of the modulator, emitting coherent radiation. This radiation is measured with a CCD camera and a UV-VIS spectrometer. An enhancement of the coherent over incoherent light can be observed in case of perfect overlap of the laser and the electron bunch. The fundamental component of the microbunching a_1 and the coherent radiation power P_r can be calculated using [8]:

$$a_1 = 2J_1\left(\Delta U\frac{2\pi}{\lambda_L}\frac{R_{56}}{E_e}\right)\cdot\exp\left[\frac{-\Delta E^2}{2}\left(\frac{2\pi}{\lambda_L}\frac{R_{56}}{E_e}\right)^2\right] \quad (1)$$

$$P_r = 4.7\times10^{-4}\cdot a_1^2\cdot P_{\mathrm{beam}} \quad (2)$$

Here the induced energy modulation is $\Delta U = 800$ keV, $R_{56} = 140\ \mu$m, the electron beam energy is $E_e = 700$ MeV, the laser wavelength $\lambda_L = 800$ nm, $P_{\mathrm{beam}} = 1$ TW is the total power of the electron beam and $\Delta E = 500$ keV the uncorrelated energy spread. The coherent light produced within the fundamental and second harmonic of the radiator as a function of the chicane R_{56}, is plotted in Fig. 2 for different values of energy spread.

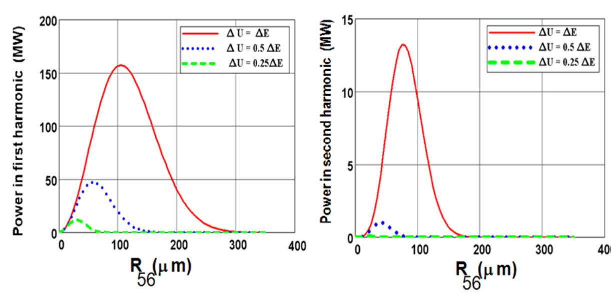

Figure 2: Enhanced coherent power produced as a function of R_56 of the chicane. The left plot shows the case for tuning the radiator to the first harmonic of the modulator, the right one the case for tuning to the second harmonics. The colors indicate the power for different energy spreads of the beam.

The produced coherent energy with $R_{56} = 140\ \mu$m is summarized in Table 1.

The sensitivity of the process to the energy spread of the electron bunch is plotted in Fig. 3. For large energy spreads, the power decreases drastically, and impacts the overall experimental result.

SIMULATION RESULT

In this part the effect of the relative jitter of the electron bunch to the seed pulse is simulated using GENESIS [9].

Table 1: Produced Coherent Power of First and Second Harmonics of the Radiator

Parameters	Fundamental	2nd Harmonic
Bunching	0.753	0.305
Peak power	304 MW	50 MW
Energy	12 μJ	2 μJ
Nb. of Photons	50×10^{12}	3×10^{12}

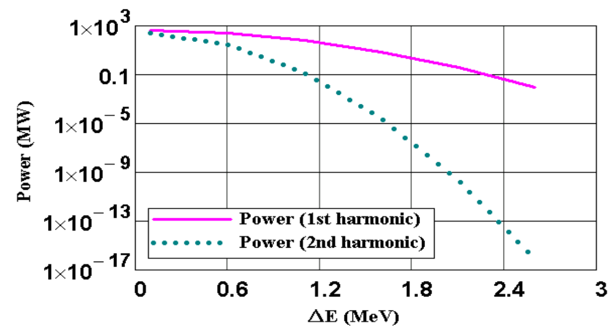

Figure 3: The effect of energy spread on coherent radiated power.

For this simulation, the measured longitudinal profile of the electron bunch (peak current 1.5 kA) is used. The measured slice energy spread and energy deviation of the slice to the nominal is plotted in Fig. 4. We assume a normal Gaussian

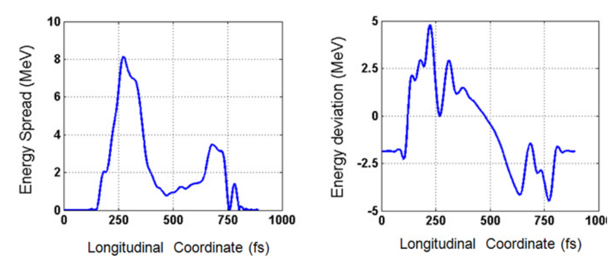

Figure 4: Measured slice energy spread (left), and deviation of the slice energy from the nominal (right).

distribution of the seed laser with an effective energy of 10 pJ, and a pulse length of 20 fs (rms). The effect of a relative jitter between the seed laser and the electron bunch on the total power and the spectrum is plotted in Fig. 5 and Fig. 6.

The peak power occurs in the point with the smallest energy spread along the bunch. For the points in which the relative jitter is larger than 45 fs, the contrast drops drastically. The increase in intensity of the seeded pulses is also visible in the simulated spectra (Fig. 6).

The simulation shows, that a resolution of the measurement of the delay between seed laser and electron bunch must be better than 100 fs in order to achieve a reliable

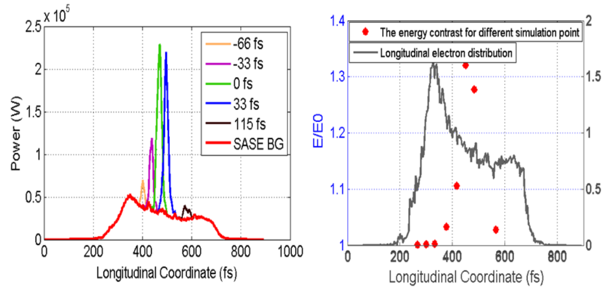

Figure 5: Total power of the seeded radiation pulse for different delays between the seed laser and the electron bunch (left). The energy contrast between seeded radiation and SASE for different delays. The longitudinal shape of the electron bunch is show for comparison.

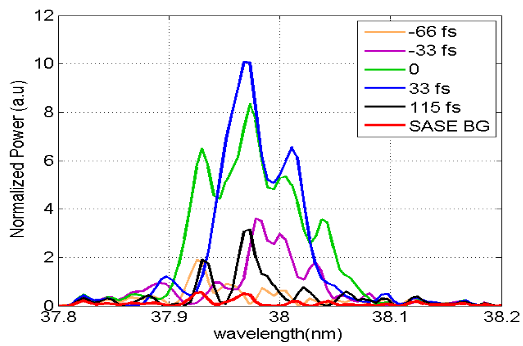

Figure 6: The spectrum of simulated seeded pulses for different delays between seed laser and electron bunch.

overlap and reasonable radiation power.

EXPERIMENTAL RESULT

The rough timing between the electron bunch and the laser to the 1 ns level is obtained with fast photodetectors. Now, using a delay line, the laser pulse is shifted in respect to the electron bunch with 10 ps steps. The time delay between the electron signal and the laser pulse is measured with the streak camera (Fig. 7). The resolution achieved is 0.3 ps. An example of streak camera image with both, the electron and laser pulse is shown in Fig. 7.

To fine-tune the overlap, the modulator-radiator setup is used. Figure 8 shows the result of a fine scan. The enhancement of intensity measured with the CCD camera is due to the coherent radiation produced by the radiator. Since this is a cross-correlation set-up, the scan also shows the longitudinal structure of the electron beam. The resolution achieved with this method is below 50 fs.

CONCLUSION

We have developed two methods to find the overlap between the electron bunch and the seed laser for the seeding experiment sFLASH. The coarse scheme uses a streak

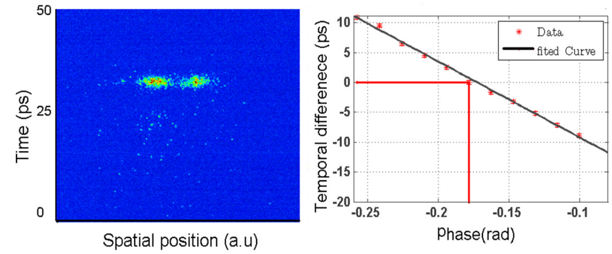

Figure 7: Left: Example of a streak camera image showing temporal overlap of the electron bunch (left spot) with the laser pulse (right spot). Right: Measured time difference of the electron to the laser as a function of the delay.

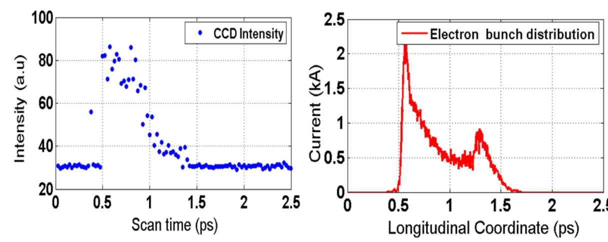

Figure 8: Left: The enhanced intensity of the radiation due to coherent light. Right: Measured longitudinal electron bunch profile.

camera giving a resolution of the time delay of 0.3 ps. A fine scan uses the production of coherent radiation when the bunch overlaps with the seed laser. Here, the resolution is better than 50 fs.

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