DEMONSTRATION OF SASE SUPPRESSION THROUGH A SEEDED MICROBUNCHING INSTABILITY*

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Abstract

Collective effects and instabilities due to longitudinal space charge and coherent synchrotron radiation can degrade the quality of the ultra-relativistic, high-brightness electron bunches needed for the operation of free-electron lasers. In this contribution, we demonstrate the application of a laser-induced microbunching instability to selectively suppress the SASE process. A significant decrease of photon pulse energies was observed at the free-electron laser FLASH in coincidence with overlap of 800 nm laser pulses and electron bunches within a modulator located approximately 40 meters upstream of the undulators. We discuss the underlying mechanisms based on longitudinal space charge amplification (LSCA) [1] and present measurements.

INTRODUCTION

Microbunching instabilities driven by longitudinal space charge (LSC) forces occurring in linear accelerators driving free-electron lasers (FELs) affect electron beam diagnostics as well as FEL operation. For instance, emission of coherent optical transition radiation (COTR) was observed at several facilities and it has to be mitigated for accurate measurements of the transverse beam profile [2–5]. The concept to use these instabilities for short-wavelength radiation production was proposed as longitudinal space charge amplifier (LSCA) in [1]. As illustrated in Fig. 1, an LSCA comprises multiple amplification “cascades”, each one consisting of a focusing channel (an electron beamline with quadrupole magnets) followed by a dedicated dispersive element. In the focusing channel, the electrons in the higher-density regions expand longitudinally introducing an energy change. The R_{56} value of the dispersive element (we consider chicanes here) converts these energy changes into a density modulation. Starting from shot noise, a strong density modulation can be achieved in two to four cascades.

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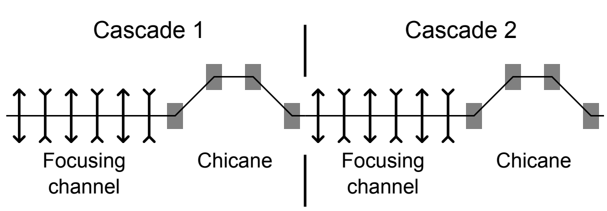

Figure 1: Schematic layout of an LSCA configuration with two cascades [1].

LSCA effects were studied experimentally at the Next Linear Collider Test Accelerator (NLCTA) at SLAC, where the impact of compression changes on spontaneous undulator radiation was measured [6]. At the National Synchrotron Light Source Source Development Laboratory (SDL) at Brookhaven National Laboratory (BNL), a modulated current profile was generated at the photoinjector with a modulated laser pulse. Microbunching gain was observed at wavelengths suitable for THz generation [7]. In [8] it is proposed to use longitudinal space charge effects to reduce the slice energy spread in HGHG seeding applications.

In this contribution, we give an overview of LSCA studies at FLASH in which the amplification process was initiated by modulating the electron bunch by means of an external laser pulse. The amplified energy modulation is shown to suppress the lasing process.

EXPERIMENTAL SETUP

The measurements presented in this contribution were performed at the FEL user facility FLASH at DESY, Hamburg [9]. The schematic layout of the facility is shown in Fig. 2. The superconducting linear accelerator (linac) driving the FEL delivers high-brightness electron bunches with energies up to 1.25 GeV. At a repetition rate of 10 Hz, bunch trains consisting of up to 800 bunches at a 1 MHz repetition rate can be produced. The facility has been upgraded by a second undulator beamline FLASH2, which is currently under commissioning. The hardware (fast kickers and a septum) needed for the distribution of electron bunches into the two undulator beamlines has been installed downstream of the linear accelerator.

The hardware used in the measurements is located in the FLASH1 electron beamline between the collimation section and the undulator system, compare Fig. 3. The electron bunches arriving from the collimation section of FLASH1 are modulated in an electromagnetic undulator (5 periods of 20 cm, $K_{max} = 10.8$) by the $\lambda = 800$ nm laser pulses arriving from the seeding laser system. After the modulator, chicane C_1 with variable R_{56} is installed. For studies of the LSCA, we use a combination of a transverse-deflecting structure (TDS) and a dipole spectrometer installed about

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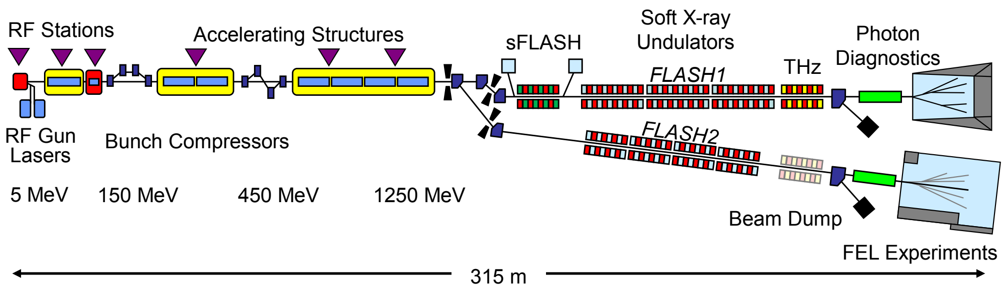

Figure 2: Schematic layout of the FLASH facility.

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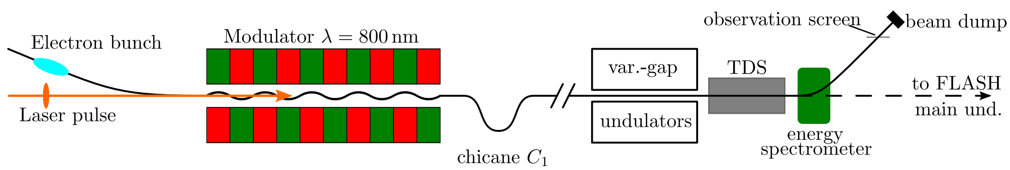

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Figure 3: Hardware used in the LSCA measurements. The electron bunch arrives from the collimation section of the FLASH1 beamline, the 800 nm pulse from the laser system. In the modulator, the electron-light interaction imprints an energy modulation into the bunch that is converted into a density modulation in the subsequent chicane C_1. We do not use the variable-gap undulators of the seeding experiment.

13 m upstream of the FLASH1 SASE undulators. First, an arrival-time dependent transverse kick is applied in the TDS, an RF structure operated at 2856 MHz. After this conversion of longitudinal to spatial position, the contents of the longitudinal phase space can be measured on the observation screen in the dispersive section downstream of the energy spectrometer.

For the measurements with SASE, the TDS and the energy spectrometer have to be disabled to allow for transport of the density modulated electron bunches to the FLASH1 main undulator. To measure the energy of the XUV pulses, the gas-monitor detector (GMD) was used. Additionally, spectra of XUV photon pulses were measured with a high-resolution spectrometer. On its way to the beam dump, the electron bunch traverses the THz undulator. Emission from this undulator was also sent to a spectrometer.

PHYSICS OF LSCA

The electron bunches arriving from the FLASH collimation section are energy-modulated by interacting with laser pulses in the near-infrared ($\lambda = 800$ nm). A chicane at the exit of the modulator transforms this energy modulation into a density modulation. As this current-modulated electron bunch is injected into a focusing beamline, an oscillation of the longitudinal charge density is initiated. The wavelength of this longitudinal plasma oscillation is [1]

$$\Lambda = \sqrt{\frac{I_A}{I}\frac{Z_0}{|Z'|}\frac{\lambda\gamma^3}{2}}. \quad (1)$$

Here $I_A = 17$ kA is the Alfven current, I the current of the electron bunch, $Z_0 = 377\,\Omega$ is the free-space impedance, λ is the wavelength of the modulation, γ is the Lorentz factor, and Z' is the LSC impedance per unit length. Electrons in regions of higher charge density expand longitudinally and an increase of the energy modulation amplitude may be the result while the current modulation becomes smaller. The maximum energy modulation amplitude, which is larger than the initial one, is achieved after drifting for $\Delta z = \Lambda/4$. This is the optimal position for the chicane of the next cascade of the amplifier.

We simulated the transport of the modulated electron bunch with the 3-D periodic space charge solver QField [10]. At the position of the modulator, we prepare a one-period long central slice of the modulated electron bunch. This slice is then tracked through the quadrupole optics assuming periodic conditions. To account for the impact of the chicane on the longitudinal phase space, a 2x2 matrix is applied at a dedicated longitudinal position.

OVERVIEW OF MEASUREMENTS

Investigation of Space Charge Amplification

For the studies of laser-induced longitudinal space charge amplification, we used mildly compressed electron bunches with an peak current of 0.3 kA and an rms bunch duration of 0.3 ps. The energy of the electron bunches was 700 MeV. These electron bunches are modulated by the $\lambda = 800$ nm laser and in chicane C_1 the bunching is generated. The electron beamline from this chicane to the TDS, which we use for measurements of the longitudinal phase space, is configured as a drift space of about 24 m length.

Using the TDS, the effect of variations of the laser pulse energy (pulse duration 60 fs FWHM) as well as R_{56} variations of chicane C_1 was studied in the longitudinal phase space.

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SASE Suppression

With the FLASH1 FEL beamline in SASE operation at $\lambda \approx 13$ nm, we re-established the temporal overlap between laser pulses and electron bunches. The energy of the XUV photon pulses was measured with the "gas-monitor detector" (GMD), a gas-filled volume in the XUV photon beamline leading to the FLASH experimental hall. There, the photons ionize gas atoms and the ion and electron currents indicate the FEL pulse energy.

As for the studies of LSCA, we used external laser pulses to generate an initial density modulation in the electron bunch. Propagating to the SASE undulator, the energy modulation amplitude grows at the expense of bunching. This degradation of the electron bunch parameters results in a reduction of the XUV photon pulse energy, as shown in Fig. 4. We studied this SASE suppression effect for different laser pulse energies and electron beamline configurations.

High-resolution spectra of the FEL radiation were recorded for several laser pulse energy settings. Finally, we acquired spectra of the emission of the electron bunches in the THz undulator, which was tuned to 800 nm for these measurements.

We reported on first SASE suppression results already in [11]. These results were obtained before the FLASH 2013 shutdown with the injection beamline constructed for the study of direct-HHG seeding at 38 nm [12]. The suppression results summarized in this section have been obtained after the shutdown with a different laser beamline [13] that will be used to study the high-gain harmonic generation (HGHG) and echo-enabled harmonic generation (EEHG) seeding options [14].

SUMMARY

We successfully reproduced the SASE suppression effect after the FLASH 2013 shutdown with a different laser injection beamline. The laser-induced density modulation initiates a growth of the energy modulation amplitude, hampering the FEL process and significantly reducing the XUV photon pulse energy. This process was studied for different laser and electron beamline configurations. Furthermore, in this contribution, we reported on measurements of the underlying laser-seeded LSCA mechanism. The detailed data analysis is still on-going and the final results will be presented in [15].

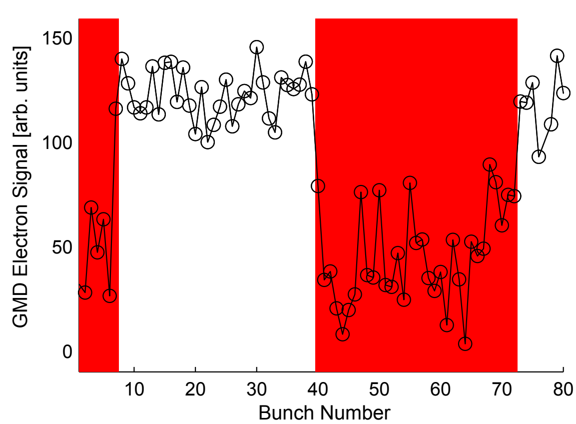

Figure 4: Impact of the amplified laser modulation on SASE energy. With laser switched on *(red background)*, a significant reduction of the XUV photon pulse energy is observed, as compared to SASE with laser off.

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