SUPPRESSION OF FEL LASING BY A SEEDED MICROBUNCHING INSTABILITY*

C. Lechner†, A. Azima, M. Drescher, L. L. Lazzarino, Th. Maltezopoulos, V. Miltchev, T. Plath, J. Rönsch-Schulenburg, J. Rossbach, University of Hamburg, Hamburg, Germany
K. E. Hacker, S. Khan, R. Molo, DELTA, TU Dortmund University, Dortmund, Germany
S. Ackermann, J. Bödewadt, G. Brenner, M. Dohlus, N. Ekanayake, T. Golz, T. Laarmann, T. Limberg, E. Schneidmiller, N. Stojanovic, M. Yurkov, DESY, Hamburg, Germany

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 driving free-electron lasers (FELs). In this contribution, we demonstrate suppression of FEL lasing induced by a laser-triggered microbunching instability at the free-electron laser FLASH. The interaction between the electron bunches and the 800-nm laser pulses takes place in an undulator upstream of the FEL undulators. A significant decrease of XUV photon pulse energies has been observed in coincidence with the laser-electron overlap in the modulator. We discuss the underlying mechanisms based on longitudinal space charge amplification (LSCA) [1] and present measurements.

INTRODUCTION

The microbunching instability (MBI) due to longitudinal space-charge (LSC) forces in linear accelerators can compromise the quality of high-brightness electron bunches. This affects electron beam diagnostics as well as the FEL performance. For instance, emission of coherent optical transition radiation (COTR) was observed at several facilities [2–5] and it has to be mitigated for accurate measurements of the transverse beam profile. The longitudinal space-charge amplifier (LSCA) proposed in Ref. [1] is a concept to exploit these instabilities for the production of short-wavelength radiation. As illustrated in Fig. 1, an LSCA comprises multiple amplification stages, each one consisting of an electron beamline followed by a dedicated dispersive element. In the beamline, the electrons in the higher-density regions expand longitudinally introducing an energy change. The longitudinal dispersion R_{56} of the chicanes converts these energy changes into a density modulation. Starting from shot noise, a strong density modulation can be achieved in two to four stages.

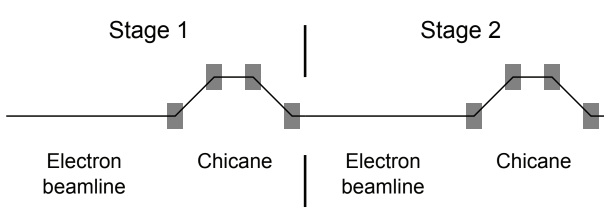

Figure 1: Schematic layout of a two-stage longitudinal space-charge amplifier (LSCA) configuration [1].

LSC amplification was 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 Source Development Laboratory (SDL) at the National Synchrotron Light Source (NSLS) 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 Ref. [8], detailed investigations of the MBI using direct measurements of electron bunches with an RF deflector are presented.

In this contribution, we give an overview of LSCA studies performed at the FEL user facility FLASH [9] in which the amplification process was initiated by modulating the electron bunch by means of an external laser pulse. The amplified energy modulation is applied to suppress the lasing process. First results of these experiments have already been presented in Refs. [10, 11].

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 [12].

For these measurements, the hardware of the sFLASH seeding experiment has been used. It is installed in the FLASH1 electron beamline between the collimation section (dogleg) 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 λ_u = 20 cm, K_{max} = 10.8) by the 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 LSC effects, we use a combination of a transverse-

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† christoph.lechner@desy.de

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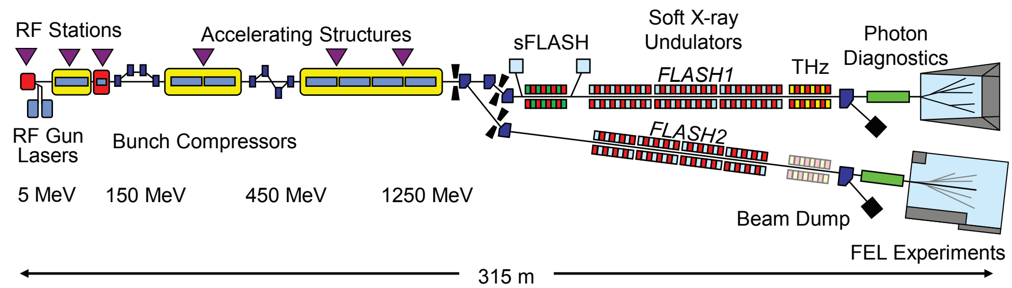

Figure 2: Schematic layout of FLASH user facility. The electron bunch is laser-manipulated in a combination of modulator and chicane installed in the *sFLASH* experiment.

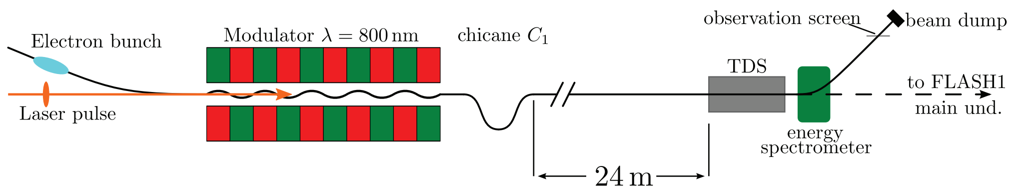

Figure 3: Hardware used for the measurements. The electron bunch arrives from the collimation section (dogleg) of the FLASH1 beamline and the 800-nm pulse from the laser system. In the modulator, the electron-light interaction imprints an energy modulation onto the bunch that is converted into a current modulation in the subsequent chicane C_1. After propagating along a 24-meter-long electron beamline, the electron bunches are characterized by the combination of a transverse-deflecting structure (*TDS*) and a dipole spectrometer.

deflecting structure (TDS) [4] and a dipole spectrometer installed about 13 m upstream of the FLASH1 SASE undulators. First, an arrival-time dependent vertical kick is applied in the TDS, an RF-structure operated at 2856 MHz. After introducing this longitudinal-to-vertical correlation, the longitudinal phase-space distribution can be measured on the observation screen in the dispersive section downstream of the energy spectrometer.

For the measurements with FEL operation, 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. The energy of the XUV photon pulses is measured with the "gas-monitor detector" (GMD) [13], a gas-filled volume in the XUV photon beamline leading to the FLASH1 experimental hall. In the GMD, the XUV photons ionize gas atoms and the ion and electron currents indicate the FEL pulse energy. Additionally, spectra of XUV photon pulses were measured with a high-resolution spectrometer.

OVERVIEW OF MEASUREMENTS

The experiment was designed to meet two objectives: (i) investigation of the LSC-driven amplification mechanism and (ii) study of the impact of the LSC-amplified initial energy modulation on the FEL process in the FLASH1 SASE undulator.

Characterization of Amplification Process

To study the LSC-driven evolution of the electron bunches, we used electron bunches with an energy of 700 MeV, a peak current of 0.3 kA, and an rms bunch duration of 0.3 ps. After generating an energy modulation by interaction with 800-nm, approx. 60-fs (full-width half maximum, FWHM) laser pulses in the modulator, a current modulation is generated in a chicane installed at the exit of the modulator. The manipulated electron bunches are then transported along a 24-m-long electron beamline. There, LSC forces drive the longitudinal expansion of high-current regions of the electron bunch. This process entails the accumulation of an energy modulation amplitude at the expense of the current modulation. At the end of this beamline, the longitudinal phase-space distributions of the seeded electron bunches have been characterized using the TDS in combination with a dipole energy spectrometer. From these measured longitudinal phase-space distributions, the slice energy spread has been extracted. This analysis has been carried out for a set of energies of the modulating laser pulses as well as for different longitudinal dispersions R_{56} of the chicane used to generate the current modulation. The initial parameters have been deduced by applying a fitting procedure based on an LSC model simulated with the code `QField` [14].

Suppression of FEL Lasing

In the second part of the experiment, the electron bunches were re-compressed to enable the SASE FEL process in the FLASH1 SASE undulator at $\lambda = 13.1\,$nm. Here, the initial current modulation was generated using 0.2-ps-long (FWHM) laser pulses while the relative temporal jitter between the laser pulses and the electron bunches was 58 fs rms [15]. With this ratio of the temporal jitter to the laser

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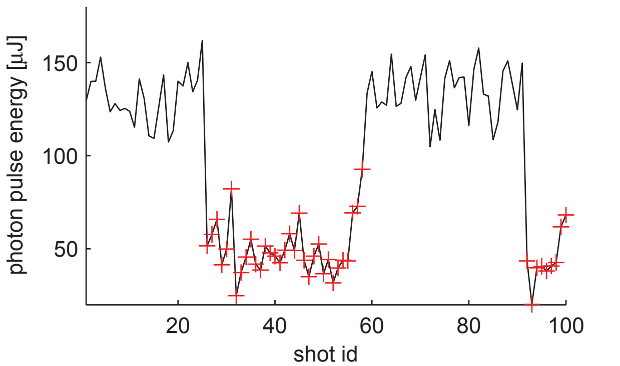

Figure 4: Suppression of FEL lasing for moderate initial laser modulation. The photon pulse energies emitted by the electron bunches have been measured with the GMD detector. Samples obtained with the modulating laser switched on are marked with *red crosses*.

pulse duration, the initial modulation is supposed to be well-reproducible [16]. As the manipulated electron bunches propagate to the FLASH1 SASE undulator, the energy modulation amplitude grows. This degradation of the electron bunch parameters results in a reduction of the XUV photon pulse energy, as shown in Fig. 4. Using the GMD to diagnose photon pulse energies, we studied this suppression of FEL lasing for different laser pulse energies and electron beamline configurations. In particular, a significantly stronger suppression effect has been observed in a configuration with two chicanes. Moreover, measurements have been performed with a high-resolution spectrometer installed at the PG beamline in the FLASH1 user hall [17, 18] for various settings of laser-generated initial energy modulation amplitude and longitudinal dispersion R_{56} of the chicane.

SUMMARY AND OUTLOOK

We reported on measurements of a laser-seeded longitudinal space-charge oscillation. The laser-induced current modulation initiates a growth of the energy modulation amplitude, which has been used to study suppression of FEL lasing. These measurements have been performed for different laser and electron beamline configurations. A more detailed data analysis will be presented in [19].

Potential applications of these seeded LSC effects include the reduction of slice energy spread in HGHG-seeded FELs [20–22] and the selective suppression of FEL lasing [19].

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