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INFLUENCE OF A NON-UNIFORM LONGITUDINAL HEATING ON HIGH BRIGHTNESS ELECTRON BEAMS FOR FEL

E. Roussel*, E. Allaria, M. B. Danailov, G. De Ninno, S. Di Mitri, E. Ferrari, D. Gauthier, L. Giannessi, G. Penco, Elettra-Sincrotrone Trieste S.C.p.A., Basovizza, Italy

Abstract

Laser-heater systems are essential tools to control and optimize high-gain free electron lasers (FELs), working in the x-ray wavelength range. Indeed, these systems induce a controllable heating of the energy spread of the electron bunch. The heating allows in turn to suppress longitudinal microbunching instabilities limiting the FEL performance. In this communication, we show that a long-wavelength energy modulation of the electron beam induced by the laser heater can persist until the beam entrance in the undulators, affecting the FEL emission process. This non-uniform longitudinal heating can be exploited to investigate the electron-beam microbunching in the linac, as well as to control the FEL spectral properties. Here, we present experimental, analytical and numerical studies carried out at FERMI.

INTRODUCTION

In free electron lasers (FELs), relativistic electron bunches are used to produce intense light from the far infrared to the EUV and X-rays domain [1]. This fourth generation light-source requires electron beams of high quality with very low emittance and high peak current. The control of peak current is achieved by compressing the electron bunch through dispersive magnetic chicane along the accelerator. Many FELs have shown up a longitudinal instability growing up in these chicanes, called microbunching instability which leads to the formation of structures in the electron bunch longitudinal phase-space (in position and energy) [2]. This instability, typically driven by the coherent synchrotron radiation (CSR) and the longitudinal space charge (LSC) effect, increases the electron beam slice energy spread and can limit the FEL emission. The use of the so-called laser heater (LH) is a possible technique to control or even suppress the microbunching instability [3]. This enables to carefully adjust the slice energy spread of the electron beam.

Here we show that a modulated LH pulse can induce a controllable modulation of the slice energy spread of the electron beam, i.e. leading to a non-uniform longitudinal heating. This modulation can be sustained by the microbunching instability in the linac and so, can survive until the entrance of the electron beam in the undulators. This induced modulation allows us to investigate the microbunching instability along the accelerator. Moreover, the FERMI FEL [4, 5] is based on the high gain harmonic generation (HGHG) seeding scheme [6] and the interaction of this modulated electron beam with the seed laser can lead to the emission of multi-color FEL light.

* eleonore.roussel@elettra.eu

MODULATED LASER HEATER

The laser heater system process consists in a resonant laser-electron interaction in an undulator placed after the photoinjector [7] (Fig. 1). The FERMI LH system [8] consists of a short undulator in the middle of a chicane in which the electron beam interacts with a near infrared laser pulse. The electron beam and the laser pulse overlap both transversally and longitudinally. The modulated laser heater pulse is obtained using the chirped pulse beating technique [9]. In this technique, two copies of a chirped laser pulse interferes with one copy delayed with respect to the other. This leads to an output laser pulse with a quasi-sinusoidal modulation whose frequency is proportional to the delay. The main LH parameters are given in Table 1. The delay between the two LH pulses is equal to 28.2 ps which leads to a modulation at a beating wavelength of 32.6 μm (Fig. 2(b)).

Table 1: Main Laser Heater Parameters

Laser heater parameters	
Wavelength	780 nm
Bandwidth (FWHM)	8.4 nm
Pulse duration (FWHM)	12.9 ps
Energy	≤70 μJ
Delay between the 2 pulses	28.2 ps
Beating frequency (wavelength)	9.2 THz (32.6 μm)

NON-UNIFORM HEATING

We apply this modulated LH pulse on the electron beam. Using numerical simulations based on Genesis [10], we checked that a modulation of the energy spread is induced in the LH undulator and survives after the half-chicane of the LH section. The main parameters are given in Table 2. The average power of the laser heater used for the numerical simulation is low (below 1 MW). Indeed, the modulated region of the LH pulse is located in the tail of the main LH pulse (Fig. 2(b)) where the intensity of the LH is weak.

In Figure 3(a), one can see that at the exit of the LH undulator, the electron beam undergoes an energy modulation at the optical wavelength (here, 780 nm) but also an energy spread modulation at the beating wavelength of the LH pulse (here, 32.6 μm). However, the principle of the LH is to induce a controllable increase of the slice energy spread of the beam without modulation of the beam. In that purpose, the half-chicane of the LH is designed to smear out the modulation at 780 nm. By applying the transport matrix R corresponding to the half-chicane, we verified that the energy modulation is suppressed but the energy spread modulation is conserved

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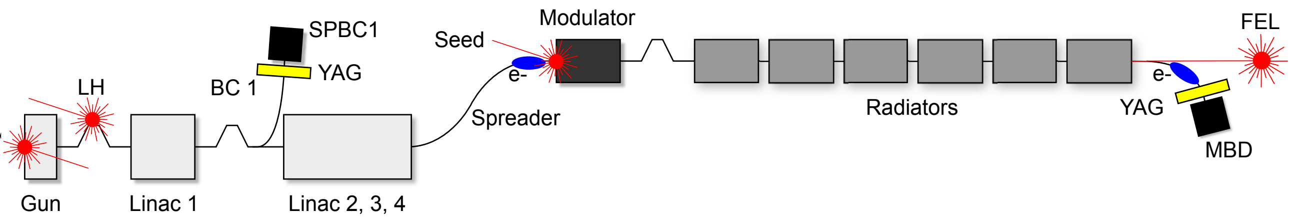

Figure 1: FERMI FEL-1 layout: Electron bunches are extracted from the photoinjector (Gun), propagate through the laser heater section (LH) and are then compressed in the bunch compressor (BC1). After being accelerated up to 1.5 GeV, they are sent to the FEL-1 undulators.

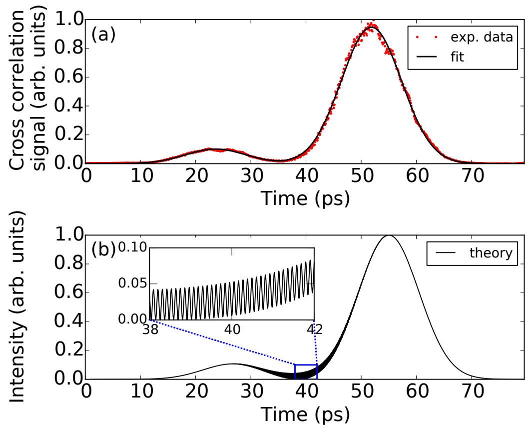

Figure 2: Laser heater pulse: (a) measured cross-correlation signal and (b) theoretical LH pulse shape. The beating region is localised in between the two pulses (inset).

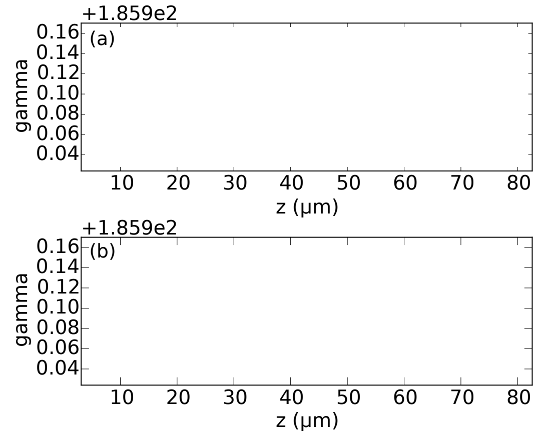

Figure 3: Numerical simulation of the longitudinal phase-space after the laser heater undulator (a) and after propagation through the half-chicane of the laser heater (b).

Table 2: Parameters Used in the Numerical Simulations

Laser heater parameters	
Wavelength	780 nm
Average power	0.1 MW
Beating wavelength	32.6 μm
Undulator parameters	
Wavelength	40 mm
Number of period	12
Strength parameter (a_w)	0.59
Electron beam parameters	
Energy	95 MeV
Slice energy spread	5 keV
Peak current	70 A

(Fig. 3(b)). The main element of the transport matrix are $R_{52} = 3.05 \cdot 10^{-2}$ m and $R_{56} = -1.61 \cdot 10^{-3}$ m.

At the exit of the LH chicane, the energy spread of the electron beam is modulated at the beating wavelength of the LH. This modulation wavelength is located in the gain curve of the microbunching instability of the linac. Preliminary experimental observations reveal that this modulation is amplified along the linac and is still present at the entrance of the undulators section. This non-uniform heating allows us to investigate the microbunching gain along the accelerator and will be further developed in future studies.

HGHG SCHEME WITH A NON-UNIFORM HEATED BEAM

The FERMI-FEL is a seeded FEL based on the HGHG scheme where an external laser imprints a coherent modulation in the electron beam which is then amplified and lead to light emission at harmonics of the initial laser frequency. The presence of a pre-modulated beam in the modulator affects the HGHG process. After the modulation by the seed laser, the presence of two different frequencies in the beam, i.e. the frequency of the seed laser and the frequency of the energy spread modulation, leads to a frequency mixing process [11, 12]. After the dispersive section, the electron beam bunch factor contains frequency components at the harmonic of the seed laser but also, components at some combinations of the two frequencies.

The principle can be reproduced using a simple model in which the longitudinal phase-space is represented by N_{mp} macro-particles characterized by their longitudinal position z in meter and their relative energy $p = (E - E_0)/\sigma_E$ (with E the electron energy, E_0 the average energy and σ_E the energy spread). Figure 4 shows the electron bunch longitudinal phase-space at each step of the process. We assume an initial electron beam phase-space with a Gaussian distri-

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bution in energy and a uniform distribution in z (Fig. 4(a)). After the interaction with the modulated LH pulse, the electron bunch is modulated in energy spread at a modulation wavelength $\lambda_b = 3.26\,\mu\text{m}$ (Fig. 4(b)). To simplify the calculation, the modulation is scaled by a factor 10 assuming a bunch compression factor in BC1 of 10. As the electron beam propagates through the accelerator, we assume that it undergoes some dispersion (Fig. 4(c)). Then, the seed laser-electrons interaction leads to an energy modulation of the electrons at the seed laser wavelength, here $\lambda_s = 260\,\text{nm}$ (Fig. 4(d)). Finally, the electron bunch goes through the dispersive section which induces a change of longitudinal position proportional to the relative energy of the electrons (Fig. 4(e)). Looking at the frequency components of this final electron bunch distribution, i.e. by looking at its bunching factor $bf(k) = 1/N_{mp} \left|\sum_{n=1}^{N_{mp}} \exp\left(-ikz_n\right)\right|$, we observe the frequency mixing process (Fig. 4(f)). For instance, if we look at the 8$^{\text{th}}$ harmonic of the seed laser, we also observe sidebands. These sidebands are located at exactly $8k_s + k_b$ and $8k_s - k_b$ with k_s the wavenumber of the seed laser and k_b the wavenumber of the energy spread modulation. This electron bunch can then initialize the amplification process in radiators part. Only frequencies in the FEL bandwidth will be amplified. And this can lead to the emission of FEL pulses with two colors.

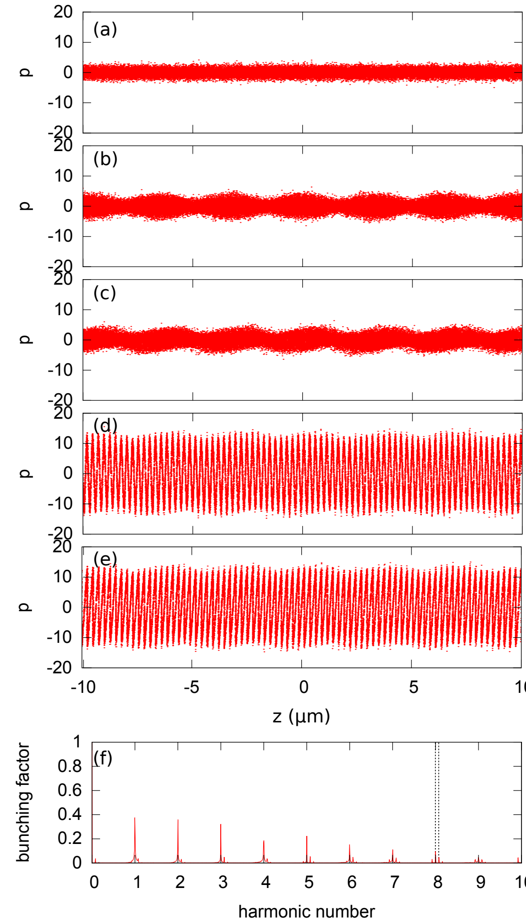

Figure 4: Numerical simulations of the longitudinal phase-space: (a) initial condition, (b) after laser heater, (c) assuming dispersion along the linac, (d) after seed modulation and (e) after the dispersive section. (f) corresponds to the bunching factor at the end, i.e. of the phase-space in (e).

CONCLUSION

We show that an energy spread modulation induced by the laser heater modifies the spectral properties of the FEL emission. A main characteristic is the presence of sidebands in the FEL spectrum. This non-uniform heating will also allow us to investigate the microbunching instability in the linac.

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