NEW SCENARIOS OF MICROBUNCHING INSTABILITY CONTROL IN ELECTRON LINACS AND FREE ELECTRON LASERS

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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 increase of the energy spread of the electron bunch. The heating suppresses longitudinal microbunching instability which otherwise would limit the FEL performance. We demonstrate that, through the action of the microbunching instability, a long-wavelength modulation of the electron beam induced by the laser heater at low energy can persist until the beam entrance into the undulators. This coherent longitudinal modulation is exploited to control the FEL spectral properties, in particular, multicolor extreme-ultraviolet FEL pulses can be generated through a frequency mixing of the modulations produced by the laser heater and the seed laser in the electron beam. We present an experimental demonstration of this novel configuration carried out at the FERMI FEL [1].

INTRODUCTION

Over the last years, free electron lasers (FELs) have been used to produce intense radiation with tunable wavelengths from the far infrared to the hard x-rays. As the brightest lightsources in the extreme ultraviolet (EUV) and x-ray domain, the existing X-FEL facilities [2–6] have opened the way to new possibilities in scientific research.

High quality electron beams are mandatory for the operation of the X-FELs. The high peak current is obtained by compressing the electron bunch in a magnetic chicane. Collective effects, like microbunching instability, can develop and deteriorate the electron beam properties, e.g. increase the average energy spread and modulate the electron beam longitudinal phase-space [7]. This instability, typically driven by longitudinal space charge (LSC) [8] and coherent synchrotron radiation (CSR) [9], is a strong limitation for the operation of X-FELs at short wavelengths, especially in seeding condition where the deterioration of the spectral quality is associated to a reduction of the longitudinal coherence [10, 11].

The so-called laser heater (LH) is a possible technique to control or even suppress the microbunching instability [8] by introducing a controlled spread in energy via a laser-electron interaction prior to the bunch compressor. By a proper shaping of the LH laser pulse, it is possible to control the electron beam properties in the accelerator, as well as the FEL spectral properties. A preliminary experiment at FERMI [12] has shown the possibility to control the energy spread profile of the electron beam with the aim to reduce the FEL pulse duration.

Here, we show that an intensity modulated LH laser pulse can seed the microbunching instability along the linac. The modulated electron beam is then used for the generation of multi-color FEL pulses [1]. The modulated electron beam can also be used to produce intense narrow band THz radiation, as suggested in Ref. [13].

SEEDED MICROBUNCHING INSTABILITY

Laser Heater System

The FERMI laser heater (LH) system [14], localized in the injector part of the linac (Fig. 1), is normally used to induce a uniform heating of the electron beam in order to suppress the microbunching instability. The intensity modulated LH pulse is produced using the chirped pulse beating technique [15] in which two chirped laser pulses, temporally separated, interfere. This leads to an output envelope of the laser pulse with a quasisinusoidal modulation at a beating frequency that is proportional to the delay. The intensity profile of the LH pulse is shown in Fig. 2a where the beating wavelength in the central part is equal to $\lambda_B = 32.6\,\mu m$ in the experiment (see the caption of Fig. 2 for LH parameters).

Modulated Electron Beam

When the electron beam overlaps in time with the beating region of the LH pulse, a coherent modulation is induced in the electron beam energy distribution (Fig. 2b) whereas no modulation is visible in the case of the normal operation of the LH. Furthermore, the LH chicane is designed to smear out modulation at optical wavelength whereas the beating wavelength survived at the exit of the chicane [16]. The electron beam energy distribution is measured in the spectrometer SPBC1 (Fig. 1) where the beam has a strong linear energy chirp introduced in Linac 1 for compression purpose. For a linear energy chirp of $-20.2\,m^{-1}$ in the experiment, the modulation in the energy spectrum, equal to 0.18 MeV, corresponds to a modulation wavelength of 32.4 µm in the longitudinal position.

At the exit of the LH, the induced-modulation is mainly an energy spread modulation. However, due to microbunching instability gain, the modulation can be amplified and converted to a density and/or energy modulation along the linac and the bunch compressor. By increasing the compression factor C, a growth of the modulation amplitude has been observed that confirms the gain mechanism (Fig. 2c).

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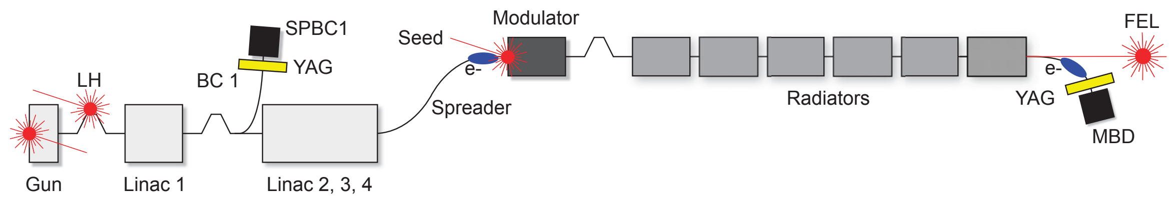

Figure 1: FERMI FEL-1 layout. After being extracted from the photoinjector (GUN), the electron bunches pass through the laser heater (LH) section and are then compressed in the bunch compressor (BC1). Following an acceleration to 1.0 – 1.5 GeV, the electron bunches are sent to the FEL-1 undulators.

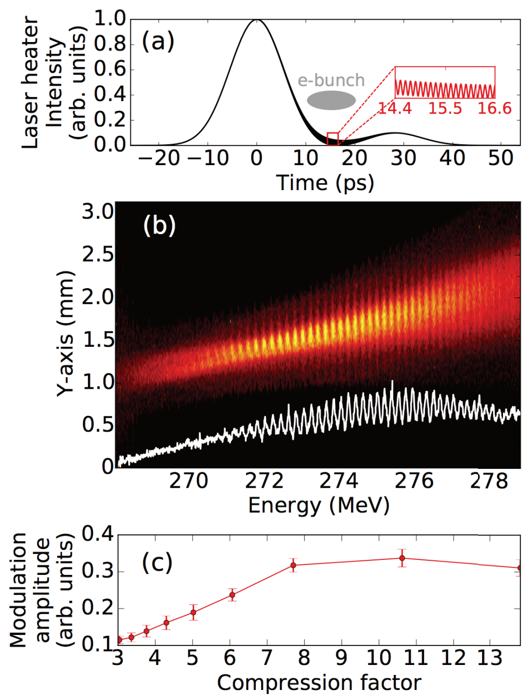

Figure 2: (a) Theoretical LH laser pulse, (b) electron beam spectrometer image and energy spectrum (white line), and (c) amplitude of the energy modulation (white line in b) versus compression factor. The LH parameters are: central wavelength = 780 nm, bandwidth = 8.4 nm (FWHM), pulse duration = 12.9 ps (FWHM), delay = 28.2 ps.

MULTICOLOR FEL PULSES

The FERMI FEL-1 is a seeded FEL based on the high-gain harmonic generation (HGHG) scheme [17] where an external laser is used to initiate the FEL process, combined with a frequency up-conversion process. In the presence of the frequency beating in the LH laser pulse, the FEL emission is no longer monochromatic. In that condition, a premodulated beam interacts with the seed laser and leads to the emission of multicolor FEL pulses (Fig, 3a) via a frequency mixing process [18, 19], at wavenumbers:

$$k = hk_S \pm mCk_B, \tag{1}$$

where h is the harmonic number of the seed laser, m is an integer corresponding to the sideband number, k_S the seed laser wavenumber, k_B the LH beating wavenumber and C the compression factor of the electron beam.

It is possible to carefully tune the wavelength of the sidebands by acting either on the compression factor C or on the LH beating wavenumber k_B (Eq. (1)). Figure 3b shows the shift of the sidebands as the compression factor is increased. Since the energy spread modulation induced by the LH beating is applied before the bunch compression, the final effective FEL wavelength is modified by the compression factor.

A proper tuning of the radiator resonance permits to select the frequency components, i.e. which sideband, to be amplified (Fig. 3c). Such a possibility can be very useful to reach FEL emission at wavenumber lying outside the available tuning range of the seed laser. For example, at FERMI, the standard operation of the tunable seed laser, ranging from 230 to 260 nm, does not allow to cover the range 43.3 – 46 nm, but can be reached thanks to the frequency mixing process (Eq. (1)).

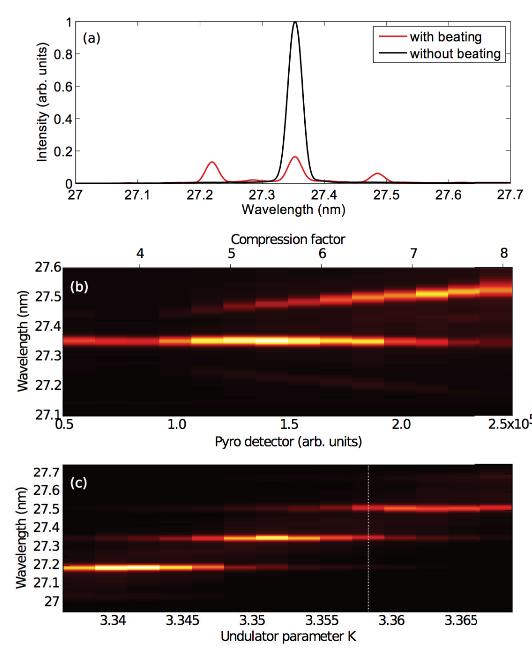

Figure 3: (a) FEL spectra in the nominal LH configuration (black line) and in the LH beating configuration (red line) (average over 20 shots). (b) Evolution of the FEL sideband position versus compression factor. The pyro detector signal is proportional to the compression factor. (c) FEL emission spectra versus radiator tuning.

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NARROWBAND THz EMISSION

The modulation of the slice energy spread has already been used in storage rings to generate narrowband sub-THz emission [20] and possible application of this technique to linac has been recently studied [13]. With a proper tuning of the delay for the LH chirp pulse beating, one can obtain strongly modulated LH laser pulses at frequency in the sub-THz and THz range. By taking advantage of the compression of the beam occurring in BC1, typically of the order of 10, that is following the laser heater, one can easily reach frequency in the THz and tens of THz range.

We have performed a preliminary experiment in order to verify the efficiency of the technique. Experimental observations of the current profile of the electron beam at the end of the linac present strong modulation in the tens of THz range (Fig. 4). These first observations open new possibilities for the generation of narrowband, tunable THz radiation at the TeraFERMI beam line [21] which is localized at the end of the undulator chain, in the main beam dump area (MBD, Fig. 1).

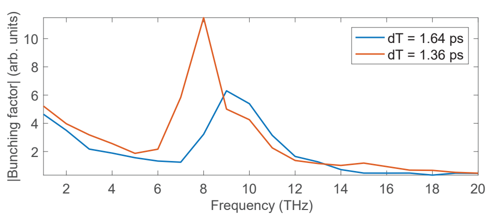

Figure 4: Fourier transform of the current profile of the electron beam at the end of the linac for two delays of the LH beating.

CONCLUSION

We have shown a new strategy to produce FEL pulses with several colors in a seeded FEL, that are independently controllable by exploiting the microbunching instability that develops along the linac. The LH pulse shaping is also a promising technique for the generation of intense tunable radiation in the THz frequency range.

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