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ADVANCED FRESH-SLICE BEAM MANIPULATIONS FOR FEL X-RAY APPLICATIONS

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Abstract

The recent development of the Fresh-slice technique granted control on which temporal slice lases in each undulator section in an X-ray Free-electron laser. Fresh-slice has been used for several experiments at the Linac Coherent Light Source for the generation of customizable high power two-color beams, and increased the performance of self-seeding schemes. As a novel development of the technique we present the demonstration of multistage self-amplified spontaneous-emission amplification schemes for the production of high-power ultra short pulses and improved control of the temporal duration of each pulse in multi-pulse schemes.

INTRODUCTION

X-ray Free Electrons Lasers (XFEL) are used in several fields of scientific investigation, including physics, chemistry, biology, condensed matter, matter in extreme conditions, and atomic, molecular, and optical physics [1]. To push the frontiers of the scientific applications, the XFEL pulse shaping has been recently a very active field of investigation to establish novel schemes for producing X-ray pulses with tailored temporal profiles, spectra and polarization.

The recently demonstrated Fresh-slice technique [2] granted control on which temporal slice within an electron bunch is lasing in each undulator section, but unlike other techniques such as the slotted foil emittance spoiler [3] or optical laser heater shaping [4], the non-lasing temporal slices retain full lasing capability for the downstream undulator sections.

In this paper we first show the capability of controlling the lasing slice within an electron bunch, focusing on the dechirper-based orbit method. Subsequently, we show the generation of high-power XFEL pulses in multi-staged cascaded FEL. Finally we'll discuss the extension to two-staged two-color operation and its advantages over the standard Fresh-slice two-color scheme.

FRESH-SLICE BEAMS

Different schemes have been devised for enabling Fresh-slice control, based either on a slice time-dependent orbit or a slice time-dependent matching. The time dependent orbit solution requires a device imparting a strong time-dependent kick to the electron bunch, while the time-dependent matching requires a device or scheme imparting a time-dependent focusing. In both cases it is advantageous to manipulate the electron bunch operating at high energy and with the compressed bunch so that the procedure is minimally invasive compared to a standard bunch setup.

Fresh-slice control based on transverse orbits has been first demonstrated with a kick imparted by a passive corrugated structure called ‘dechirper’ [5] and subsequently the dispersion-based scheme has been demonstrated [6]. In both cases the lasing slice is controlled by manipulating the downstream orbit correctors. Another possibility to impart the kick the the beam is the active deflector [7] but has not been demonstrated yet. The matching-based Fresh-slice has been proposed [8], studied [9] and demonstrated [10] by using the time-dependent focusing of the dechirper and subsequent control from the quadrupoles.

The demonstrated benefits of Fresh-slice scheme include the high-power multi-pulse multi-color operation [2], where the limitations of the Split undulator [11] in terms of limited power and minimum intrinsic delay are overcome, and an improvement of the power for Hard X-ray self-seeding [12–14] operation. Other schemes that have been proposed taking advantage of Fresh-slice control include cascaded multi-stage operation for high-power ultra-short pulses [15] and coherence enhancement for subharmonically self-seeded beams [16]. The use of a time-transverse correlated electron bunches could also be used in two-color pulse generation for HGHG seeded FELs [17] and wide bandwidth pulse generation [18].

LASING SLICE CONTROL

An electron bunch travelling close to the metal jaw of a dechirper receives a strong time-correlated kick toward the closest metal jaw [19]. Downstream of the dechirper each temporal slice of the electron bunch travels on a different transverse orbit. The transverse kick however presents a non-linear parabolic-like shape in case of the short bunches used in XFEL facilities. In the strong focusing lattice. In the strong focusing transport lattice, the kicked bunch slices travel on oscillatory orbits. In the downstream undulator line, only the electron bunch slices travelling on axis lase effectively. Therefore, controlling which slice lases can be exerted by the correctors before and inside the undulator line.

To exemplify the lasing control capability we show an experimental dataset recorder at an energy of 6.3 GeV, to produce photons at 1.8 keV. Operation at 1.8 keV is less demanding than the experiments reported in [2] to establish fresh-slice because a smaller orbit is sufficient to suppress

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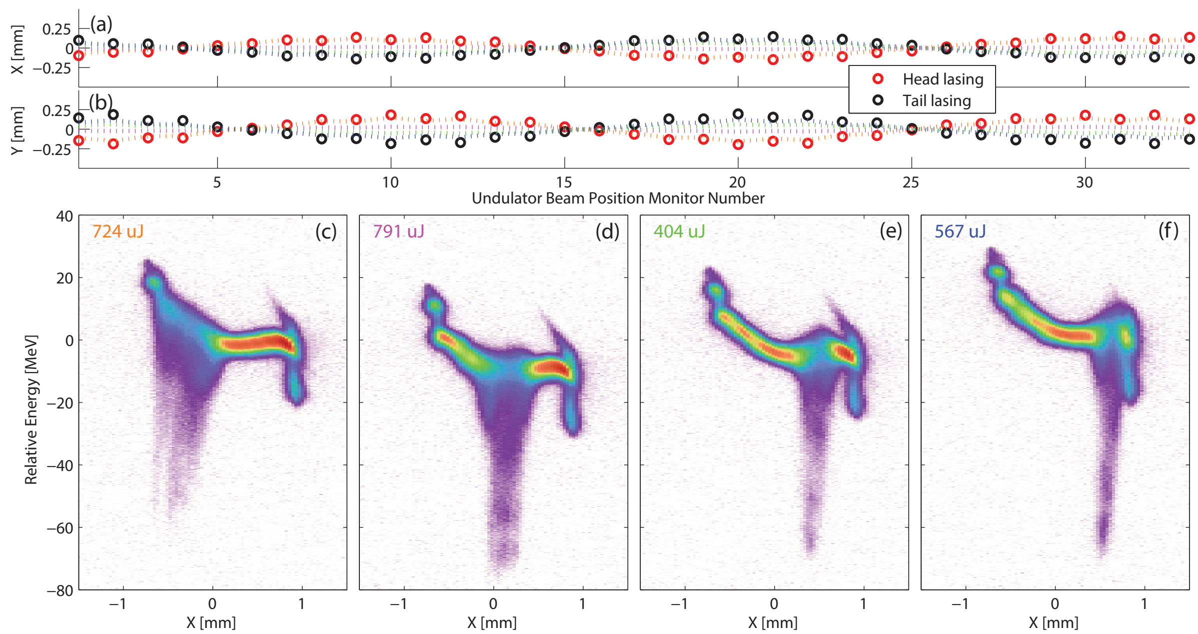

Figure 1: Electron bunch horizontal orbit recorded by the undulator cavity beam position monitors (a). Electron bunch vertical orbit recorded by the undulator cavity beam position monitors (b). The head lasing orbit is represented by red circles and a single shot orange orbit corresponds to the electron bunch phase space in (c). The magenta orbit corresponds to the bunch phase space (d), the green orbit to (e), and the blue orbit to (f).

the lasing process and more stable operation at an higher electron bunch energy.

The machine was first set up for lasing, operating at a current of 1.6 kA and producing X-ray pulses with an average of 3.2 mJ. In this condition, the beam was travelling in the undulator line one the zero Beam Position Monitor (BPM) orbit. Because of the beam based alignment procedure used at the LCLS, such orbit corresponds to the undulator line axis. Subsequently the transverse orbit feedbacks from the dechirper to the electron beam dump were turned off. Both the horizontal and vertical dechirper were moved close to the beam to tailor the electron bunch with the temporal-transverse correlation. In this condition the head lasing orbit, marked by the red circles in Figure 1(a,b) was recorded. The time-resolved electron bunch phase space was measured downstream of the lasing process [20], and Fig1(c) shows an example of head-lasing shot with an energy of 724 μJ. A nonlinear deflection was imparted, during this experiment, by the horizontal wakefield of the dechirper. Therefore the determination of the time-axis would require an analysis with the tools developed for passive streaking [21, 22]. In this work, instead, the horizontal axis was left in millimeters at the screen. Nevertheless, with the optics settings used during the experiment, the effect imparted by the transverse wakes was much smaller than the one given by the transverse deflector. The approximate electron bunch duration was of 100 fs.

By steering the electron bunch orbit in the undulator line other lasing slices can be selected. The target orbits were calculated from the recorded head-lasing one, and the new values of the dipole correctors were calculated deterministically operating with a linear machine model. The other presented phase spaces in Fig. 1(d-f) correspond to the magenta, red and green orbits in Fig. 1(a-b). Besides the moving of the lasing slice from head to tail, one can see that the duration of the lasing slice is shorter toward the bunch tail, because of the shape of the transverse wake. The electron bunch losses are comparable in the different cases showing that the efficiency of the lasing process is marginally influenced by the selection of the lasing slice.

MULTI-STAGE AMPLIFICATION

The fresh-slice technique can be used to produce a single powerful pulse starting from a short X-ray pulse produced on the bunch tail, further amplified in cascaded stages in downstream undulator sections. This scheme was initially proposed to achieve terawatt power levels in several cascaded stages [23]. With the current LCLS layout including two chicanes as delay stages, the amplification process can occur in three cascaded stages. A very short pulse is produced in a first undulator section lasing on the far electron bunch tail. A chicane delays the electrons of few femtoseconds so that the X-ray pulse produced upstream is temporally overlapped with fresh-electrons in the bunch core. The orbit is steered to have the corresponding lasing slice on axis. Previously we have shown how the temporal position of the lasing slice can be controlled continuously by steering the orbit of the electron bunch. To set up the second stage, the procedure includes setting a strong quadratic taper in the second section. In this way, only the electrons overlapped by the seed can

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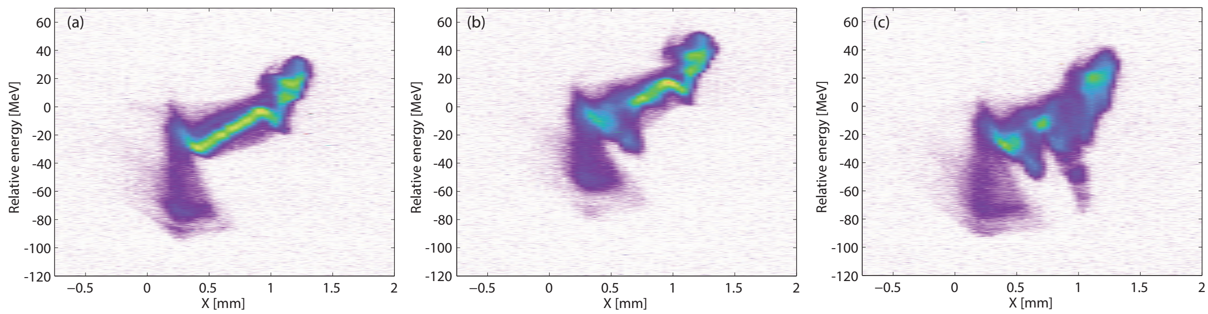

Figure 2: Examples of single-shot electron bunch phase spaces measured downstream of the XTCAV transverse deflection. The horizontal axis corresponds to time, but has been left calibrated in millimeter at the screen because of the horizontal tranverse wake effect. (a) lasing off. (b) Two stages amplification. (c) Three stages amplification.

lase effectively because a lasing process starting from shot-noise is quickly moved out of resonance. After setting the delay, the orbit is steered to maximize the FEL output of the second stage, ensuring good overlap of the photon pulse with on-axis electrons. The undulator taper is then further optimized. A steeper taper allows only the stronger spikes from the seed to grow in an amplification stage, a shallower taper lets the weaker spikes to catch up, or even to let the entire slice duration to lase starting from shot noise. The delay plays also a role in the pulse shaping. A long delay allows the full pulse produced in the first section to overlap with Fresh electrons in the second section, thus the entire pulse will be amplified. A short delay instead allows only the head part of the seed to overlap with fresh-electrons and thus it can be used to clean the temporal profile of the pulse in the second stage.

The third stage can be set following the same procedure as the second stage to further amplified the upstream X-ray pulse.

Figure 2 shows the experimental results for a two and three stages amplificated SASE pulses. The experiment was performed at the LCLS operating at an energy of 670 eV. The electron bunch energy was 3900±3.2 MeV, and the bunch current 4100 ± 380 A. Figure 2(a) shows a time-resolved electron bunch phase space when the lasing is suppressed by a large orbit in the entire undulator line. Figure 2(b) shows the electron bunch phase space for a 146 μJ single shot amplified in two cascaded stages. Figure 2(c) shows the electron bunch phase space for a 1.1 mJ single shot amplified in three cascaded stages. The average intensity on the recorded set was of 619 μJ. It is difficult to retrieve the pulse duration information form the XTCAV based temporal X-ray reconstruction for multi-stage amplified pulses.

The XTCAV based temporal X-ray reconstruction for such pulses may be inaccurate for several reasons, including the fact that losses from different bunch slices cooperate to build a single short pulse, slippage effects, non-linearity of the time axis when the horizontal dechirper is in use, and resolution limit. A reliable measurement of the produced X-ray pulses could be performed with the angular streaking method that recently achieved sub-femtosecond resolution [24, 25]. Nevertheless, the lasing footprint for the third stage of Figure 2(c) was analyzed yielding a footprint duration of 5.7 fs FWHM, neglecting the non linearity of the time scale. However, since the footprint is on the bunch head, we don't expect a large effect due to the horizontal wake.

DISCUSSION

As extension of this work, the multi-stage technique can be used in double pulses schemes to improve the pulse duration control for both pulses. The first stage is used to produce an X-ray pulse with ultra-short duration at the first color. The second stage is set with a delay long enough to leave only a short part left for lasing toward the bunch head in the third stage. The pulse duration of the first pulse is not affected, as the strong undulator strength taper suppressed the lasing process starting from shot-noise, even if the bunch slices travel on axis. Downstream of a magnetic chicane used to set the delay between the two pulses, a second pulse is produced at the second color starting from shot-noise. The duration of this pulse is controlled by the length of the electron bunch left unspoiled by the previous lasing process rather than from the length of the on-axis temporal slice.

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