Two-Color Pulses at the Femtosecond Timescale in LCLS-II

LCLSII-TN-15-18

5/29/2015

A.Marinelli
SLAC, Stanford, CA 94036 USA

SLAC National Accelerator Lab
LCLS-II TN-15-11
May 2015

Two-Color Pulses at the fs-Time Scale

A. Marinelli*, T. Raubenheimer
SLAC, Menlo Park, CA 94025

Abstract

We discuss two possible upgrades of LCLS-II to generate two-color pulses of few fs duration and a delay on the order of tens of femtoseconds.

*marinelli@slac.stanford.edu

1 Introduction

Two-color pulses are routinely available at LCLS and other free-electron laser facilities worldwide. While two color schemes are not in the baseline design of LCLS-II, they can be implemented with a modest modification of the baseline hardware.

2 Two-color pulses

The generation of two-color pulses with delays in the 0-200 fs range can be accomplished in two ways. The split undulator scheme [1] is the basic two-color option for an x-ray FEL. A conceptual illustration of this scheme is shown in Fig.1. The undulator is divided in two sections tuned to different photon energies. The FEL process is interrupted before saturation in the first undulator, to preserve the beam quality necessary for lasing in the second undulator. Two pulses of different photon energies are emitted in the two undulators. A variable time delay between the pulses is introduced by means of a magnetic chicane placed between the two undulators, which delays the electrons (and thus the second radiation pulse) with respect to the first x-ray pulse. Since both radiation pulses are emitted by the same electron bunch, this scheme cannot reach the saturation power on either color. Based on operational experience at LCLS-I, the maximum peak power is typically between 8 to 20 times lower with respect to the full saturation power on the standard single color mode. The maximum energy separation of this scheme is limited by the tunability of the undulator. For the SXR LCLS-II undulator the two-color energy range is then between 250 eV and 1200 eV. The maximum time delay, instead, is limited by the strength of the magnetic chicane. Delays of up to a few ps are easily obtained. The minimum delay is fundamentally limited to few fs by the group velocity of the FEL. Short pulses can be generated by either operating a low charge or by temporally shaping the laser heater and allowing only a short fraction of the electron bunch to lase efficiently.

Figure 2 shows a typical spectrum from a three-dimensional start-to-end simulation in the soft x-ray regime, showing the capabilities of the LCLS-II undulator to generate 2-colors spectra with a large energy separation. While the result shown was mostly limited by the maximum bandwidth allowed by the GENESIS simulation code, the photon energy separation is ultimately limited by the tunability range of the LCLS-II undulator.

In cases where the peak power needs to be maximized or the experimenters need to scan the delay through 0 the twin-bunch scheme is the preferred option [2]. This scheme is schematically illustrated in Fig. 2. Two electron bunches with a few ps delay are generated at the cathode by splitting the cathode laser a pulse stacker. The two bunches are accelerated and compressed in the linac. The compression system generates two bunches of different energies $\gamma_{1,2}mc^2$ with a final delay on the order of tens of femtoseconds. Since each pulse is emitted by its own electron bunch, both colors can be amplified to the full saturation power, dramatically improving the output pulse energy.

Scanning through zero-delay can be accomplished by allowing only a short fraction of each electron bunch to lase. While this is accomplished at LCLS by means of a dedicated slotted foil, at LCLS-II a temporally shaped laser heater will be employed. Figure 3 shows

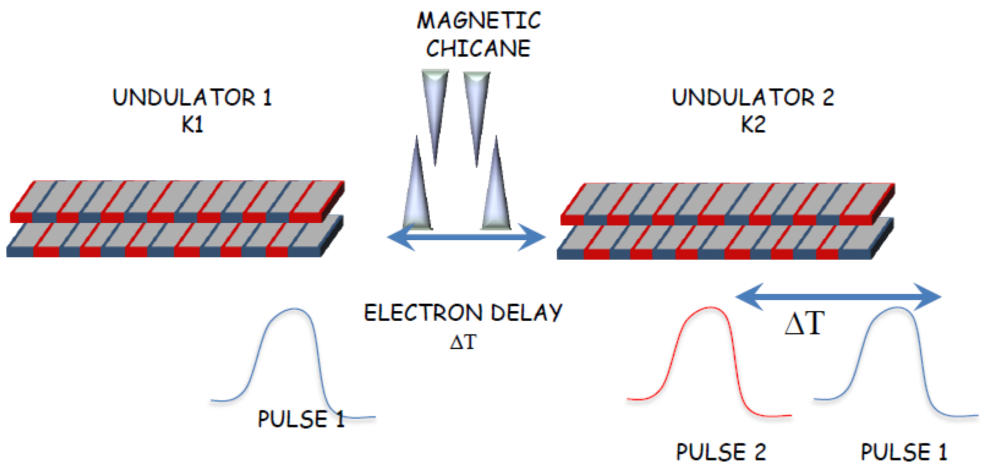

Figure 1: Schematic of the split undulator scheme

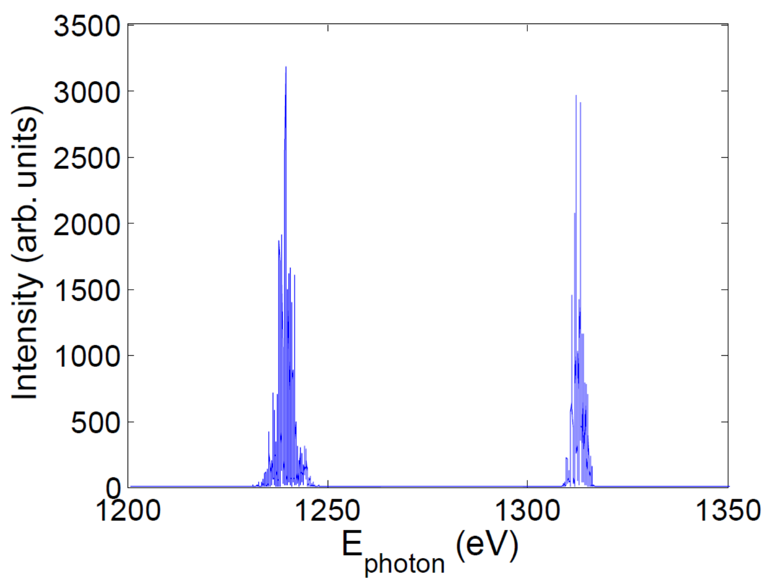

Figure 2: Typical two-color spectrum from a start-to-end simulation of the split-undulator configuration, showcasing the large energy separation achievable with the LCLS-II variable gap undulators.

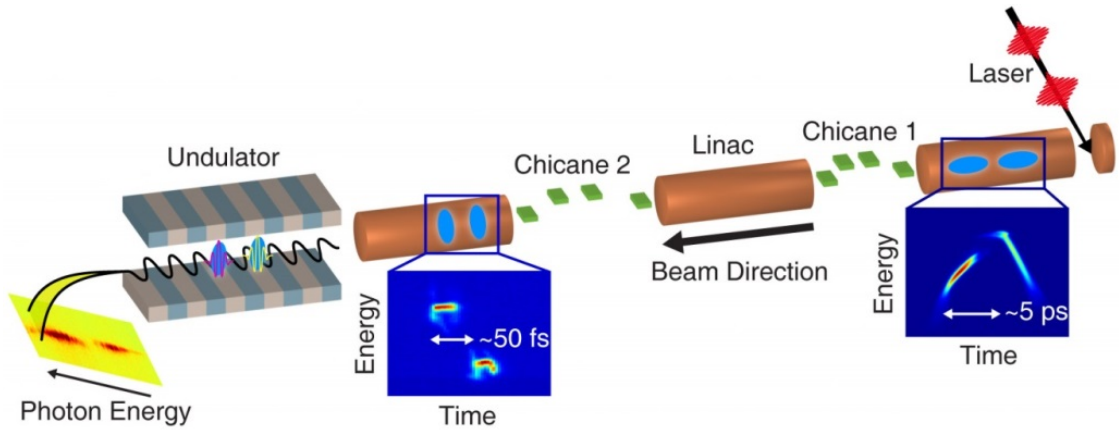

Figure 3: Schematic of the twin-bunch scheme

an example of a temporal scan through the time-overlap condition at 850 eV from a recent LCLS experiment.

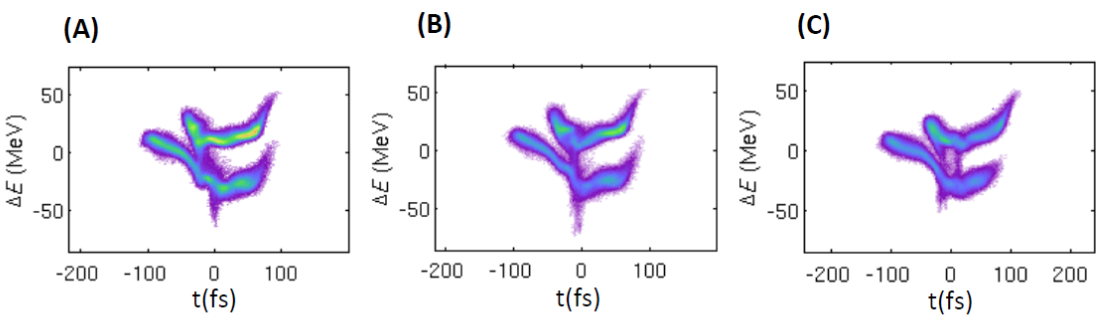

Figure 4: Twin-bunch carving: data from LCLS. Example of a temporal scan: by scanning the position of the slotted foil one can scan the relative delay of the two pulses through the time-overlapped configuration (B).

2.1 Laser-shaping of X-ray pulses

Laser-shaping of X-ray pulses will be discussed in a separate document. Here we briefly introduce the concept and show a numerical example. Figure 5 shows an example of a laser-heater shaped electron bunch for the generation of few-femtosecond pulses at LCLS-II. The laser heater is temporally shaped to only allow a short fraction of the electron bunch to emit x-rays by generating a flat high-power heater pulse with a short temporal notch. After compression only a few-fs long part of the bunch has enough brightness to laser efficiently, generating a short x-ray pulse. The same concept can straightforwardly be applied to the twin-bunch scheme by generating two temporal notches in the heater profile.

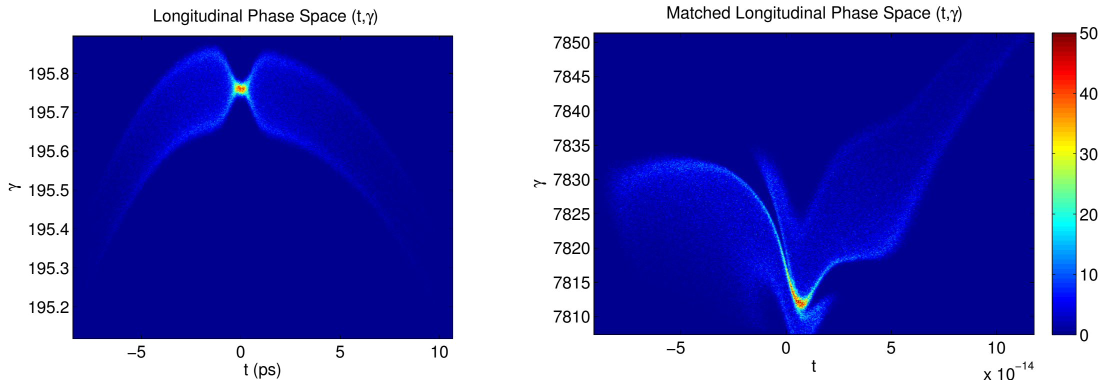

Figure 5: Start-to-end simulations of the heater-spoiled beam. The left plot shows the longitudinal phase-space of the electron bunch at the exit of the laser heater. The right plot shows the phase-space at the undulator entrance, after acceleration to 4 GeV.

3 Near Fourier-limited two-color pulses

While seeded two-color pulses can be delivered with the single-crystal hard x-ray self-seeding system currently used at LCLS [2, 3], the same goal is significantly more difficult at soft x-rays. There are two possibilities that are currently being investigated.

The first option requires external seeding with echo-enabled harmonic generation (EEHG) [4]. Two-color seeding is a natural byproduct of EEHG, which generates many closely spaced harmonics that are combined multiples of the seeding laser frequencies. Seeding with a 266nm laser would give an energy spacing of on the order of 1% or higher for two consecutive harmonics.

The second option requires a self-seeding grating with a periodic modulation of the line density in the dispersion plane. The periodic modulation allows the grating to simultaneously disperse two separate frequencies. After transport through the monochromator, two separate narrow spectral lines interact with the electron bunch. The separation between the two self-seeded colors can be tuned continuously by varying the periodicity of the grating density modulation along the vertical direction.

Both options require the use of twin electron bunches to amplify the two seed signals to saturation. In either case, laser-heater assisted pulse carving is needed to shape the temporal profile of the X-rays and generate pulses of 10-20 fs duration. The use of the twin-bunch scheme limits the maximum time separation to roughly 100 fs and the energy separation to a few percent.

4 Cost estimate

The split undulator scheme can be easily implemented by adding a magnetic chicane in the middle of either undulator. For a maximum delay on the order of a 1 ps the cost can be estimated to be roughly 500k$.

The twin-bunch scheme requires the installation of a pulse stacker, which is a small expense (on the order of a few tens of thousands of dollars). The cost of the heater shaping system can be estimated to be in the range of 20k$ to 50$.

The two-color seeding options are being investigated separately and a cost estimate will be provided elsewhere.

References

[1] A. Lutman et al., Phys. Rev. Lett. 110, 134801 (2013)

[2] A. Marinelli et al., Nature Communications 6, Article number: 6369 (2015)

[3] A. Lutman et al., Phys. Rev. Lett. 113, 254801 (2014)

[4] D. Xiang and G. Stupakov, Phys. Rev. ST Accel. Beams 12, 030702