TWIN-BUNCH TWO-COLOUR FEL AT LCLS

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Abstract

The recent development of two-color x-ray pulses from free-electron lasers has opened new avenues for ultra-fast x-ray science. Since its first demonstration, the twin-bunch scheme has been further developed, to meet the requirements of a wide range of user applications. Here we report on three new working points for the twin-bunch scheme: high and low charge working points, as well as the twin-bunch carving method. The latter is based on the combination of twin electron bunches with an emittance spoiler. Unlike other double pulse methods, this scheme allows users to scan the time delay of the two pulses through the exact time-overlapped condition and it gives a fivefold enhancement of the x-ray peak power over other published results at a similar photon energy.

INTRODUCTION

The x-ray free-electron laser is the brightest source of x-rays, delivering pulses with a peak brightness that is ten orders of magnitude higher than third generation synchrotron light sources [1–4]. Despite the enormous success of this new technology, the field is in continuous evolution and new capabilities for x-ray photon science are developed every year (see e.g. [4–6]). Two-color pulses are among the most exciting recent developments in free-electron laser (FEL) physics [7–12]. A two-color FEL generates two pulses of different photon energy with a variable time delay. At x-ray energies, pulses of a few fs duration and delays up to 100 fs have been demonstrated and are now routinely delivered to user experiments. Two-color x-ray pulses have attracted the interest of a broad user community. This tecnique can be used to study ultrafast dynamical processes triggered by x-rays in time-resolved x-ray pump/x-ray probe experiments by exciting a sample with the first pulse and probing it with the second pulse at a different energy [13]. These processes include the formation and evolution of warm dense matter [14, 15], stimulated x-ray Raman scattering [16–19] or the study of radiation damage in macromolecular femtosecond crystallography [20, 21]. Furthermore, two color FELs can be used for de novo phasing of macromolecular structures using multiple wavelength anomalous dispersion techniques [22].

In an FEL, the central emission wavelength is given by the well known resonance formula [23]

$$\lambda_r = \lambda_w \frac{1 + \frac{K^2}{2}}{2\gamma^2} \tag{1}$$

where λ_w is the wavelength of the periodic undulator magnetic field, γ is the beam's Lorenz factor, and K is the dimensionless undulator paramater which is proportional to the undulator magnetic field. Two-color x-ray pulses were originally demonstrated by using an undulator with two distinct values of K in either a split undulator configuration [7, 10], or in a gain-modulation scheme [11]. While these schemes grant excellent control of the temporal and spectral properties of the two pulses, the intensity of the two colors is limited by the fact that the same electron bunch is used for lasing twice and, at the same time, only half of the undulator is used for each color. More recently, it was shown that by using two electron bunches generated in the same accelerating bucket (twin-bunches), two-color pulses with the full saturation power can be generated, enhancing the peak power by an order of magnitude at hard x-ray energies [12]. The energy-separation of the twin-bunch method is ultimately limited by chromatic effects to the few percent level unlike single-bunch methods which can be tuned to arbitrary energy separations with a variable-gap undulator [10]. However, the twin-bunch method presents other unique advantages besides the enhanced peak power. First of all, it allows the generation of two seeded pulses with a single-crystal self-seeding scheme [12, 24]. Secondly, the two pulses have the same longitudinal source point, which corresponds to the saturation point of the FEL. Finally, the temporal profile of the two bunches can be measured on a single-shot basis using a transverse deflecting cavity [25].

HARD-X-RAY OPERATION

The twin-bunch scheme was originally developed in the hard-X-ray regime. At high-energy, the saturation length of LCLS is longer than half of the available undulator. In this regime single-bunch methods are particularly disadvantageous since the power lost due to the short undulator length is more than one order of magnitude for each color. The results reported in [12] show a gain in power of more than an order of magnitude by using the twin-bunch method with a charge of 80 pC per bunch.

To extend the range of applicability of this scheme we developed twin-bunch working points using charges of 20 pC per bunch and 150 pC per bunch.

The obvious advantage of the 20 pC working point is the shorter pulse duration, typically between 5 fs and 10 fs, with a pulse energy around 400 μJ equally distributed between the two colors. The shorter pulse duration results in better temporal resolution in pump/probe applications. The maximum delay in this case is reduced with respect to the standard 80 pC case due to the reduced strength of the

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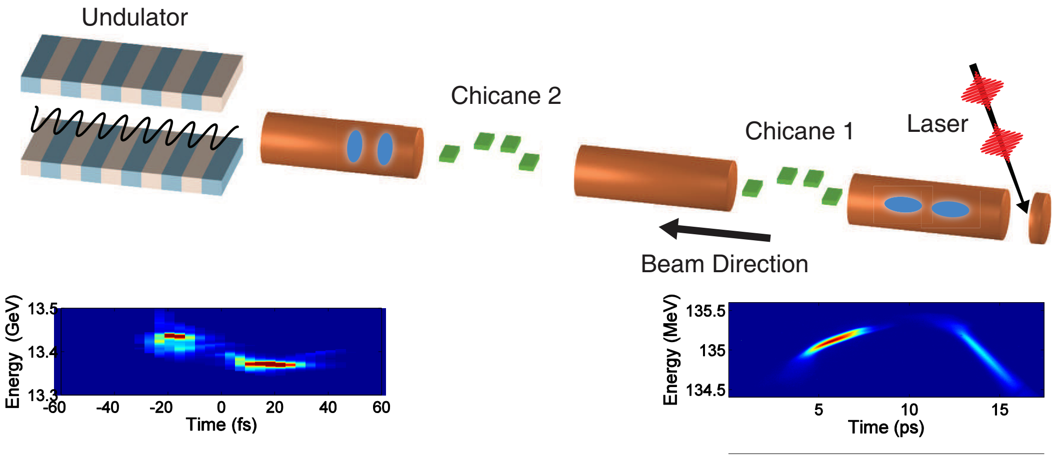

Figure 1: Conceptual illustration of the twin-bunch scheme.

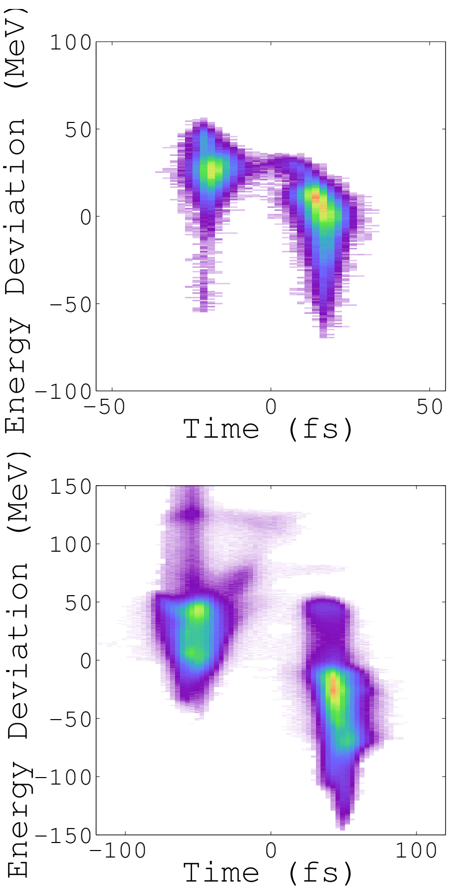

Figure 2: Longitudinal phase-space of the twin-bunches for the 20 pC working point (left) and 150 pC working point (right).

longitudinal wake. The maximum observed delay is around 60 fs.

The 150 pC working point was developed to enhance the pulse energy with an eye to applications in macromolecular femtosecond crystallograpy. In this case the pulse energy can be enhanced to roughly 2.3 mJ evenly divided between the two colors. The pulse duration is roughly 25 fs, with a maximum observed delay of 125 fs.

Figure 2 shows the longitudinal phase space of the two bunches for both working points, at an energy of roughly 13 GeV, measured at the end of the undulator with lasing on.

SOFT-X-RAY OPERATION: TWIN-BUNCH CARVING.

Applying the twin-bunch method at soft x-rays presents several challenges, due to the fact that the bunch duration at these energies is typically between 50 to 100 fs at the LCLS, which is comparable to the maximum achievable delay between the two bunches. In the soft x-ray regime, applications in time-resolved resonant x-ray spectroscopy require pairs of x-ray pulses of few fs duration. Low charge operation can be used to shorten the duration of each bunch, but this yields lower flexibility in using longitudinal wake fields to tune the delay [26] due to the reduced amplitude of the linac wakefield.

In this paper we report the demonstration of a new two-color XFEL scheme, which we term twin-bunch carving. This method combines the high-intensity of the twin-bunch method with the exquisite time-domain control granted by an emittance spoiler [27, 28]. The experimental setup is shown in Fig. 3. Two electron bunches are generated in a photocathode by a laser pulse train and are subsequently accelerated and compressed in the LCLS linac. Unlike the regular twin-bunch setup, where the two bunches are delivered to the undulator with a delay larger than their duration, here we overlap the two bunches at the exit of the linac. Since the two bunches have different energies, they can be

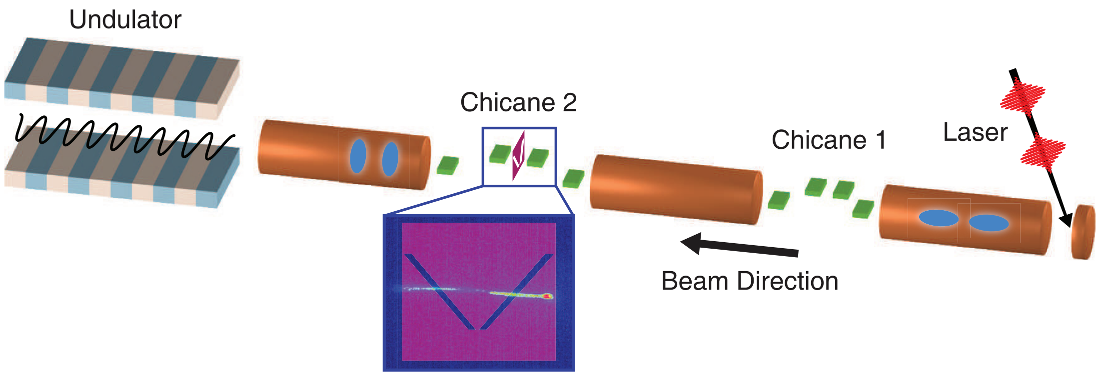

Figure 3: Conceptual illustration of the beam-carving scheme.

separated spatially in a dispersive region such as the middle of a magnetic chicane. Furthermore, both bunches have a strong time-energy correlation in the middle of the chicane, which translates directly into a time-x correlation due to the chicane dispersion. By inserting a thin metal foil with a double slot in the beam path, we can allow only a short fraction of each bunch to lase by spoiling the emittance of the part of the bunch that scatters through the foil. The emittance spoiler is a 3μm thick aluminum foil with two slots of variable separation and a width of 340μm each. The separation of the two slots can be varied from 1mm to 5mm by moving it's vertical position. Scattering through the aluminum foil increases the slice emittance of the electrons by a factor 5, effectively suppressing the lasing process in the scattered bunch regions [27].

The temporal profile of the x-rays can be reconstructed with an x-band deflecting cavity, as described in Ref. [25], the root mean square resolution of this diagnostic is 1 fs at this energy. The relative arrival time of the two x-ray pulses can be changed by varying the spatial separation of the slots. If the twin bunches are tuned so that they arrive in the undulator roughly at the same time, by scanning the position of the slots we can continuously scan the relative arrival time of the two x-ray pulses from negative to positive delays going through the time-overlapped configuration. Figure 4 shows an example of this time-domain scan. The longitudinal phase-space of the twin-bunches, as well as the normalized reconstructed x-ray temporal profiles are shown for three different configurations with the high-energy pulse is tuned to arrive after the low energy pulse (a), simultaneously (b) and before the low-energy pulse (c). The average photon energy is 850eV. The total pulse energy is 100μJ, roughly evenly distributed between the two colors. The duration of the high-energy pulse is 6 to 7 fs FWHM, while the low energy pulse is typically slightly longer (10-11 fs). The corresponding peak power is roughly a factor 5 higher than what reported using single-bunch methods at a similar energy [7, 11]. The maximum time-delay is limited by the duration of the pulses generated by the unspoiled bunches (on the order of 50 fs for this setup). Larger delays can be achieved by increasing the arrival time delay of the twin-bunches, which can be done by varying parameters such as the initial delay at the cathode or the dispersion of the bunch compressor [12, 26]. The arrival time jitter is typically between 3 and 10 fs RMS, however the effect of the jitter can be eliminated by measuring the arrival time on a shot-by-shot basis using the x-band deflector.

We note that this scheme allows scanning the temporal separation exactly through the 0-delay without changing the undulator configuration. This is possible because the time-overlapped configuration corresponds to selecting the center of each bunch in the dispersive region. This implies that inverting the arrival time of the two pulses does not change other properties such as the longitudinal source point. Furthermore, this is the only technique that allows to scan exactly through the zero delay, unlike the single-bunch double slotted foil method or the split undulator [7] which have minimum delays of a few femtoseconds at soft-x-ray energies.

Figure 5 shows an example of a two-color spectrum using this configuration, taken under the same conditions as the data in Fig. 4. The blue line shows the spectrum averaged over 100 shots. The fluctuations of the central electron beam energy were measured on a shot-by-shot basis and used to sort the spectral data. The spectrum shows two different colors with roughly the same intensity. The energy separation in this case is 13eV. As discussed in [12, 26], the energy separation of the two electron bunches can be varied independently of the time delay and the peak current. This is accomplished by varying the temporal separation of the two bunches in the second linac (i.e. between the two bunch compressors) using the accelerating phase of the first linac. Energy separations up to 3% where observed at soft-x-rays. The energy separation is ultimately limited by chromatic effects in the beam transport and we estimate that the observed 3% separation is close to the energy acceptance of the beam transport system.

CONCLUSIONS

In conclusion, we have reported an update of the twin-bunch scheme at LCLS. Two new working points with bunch charges of 20 pC and 150 pC have been developed at hard-X-ray energy. The 20 pC working point enhances the time-resolution of twin-bunch experiments by a factor 2 with

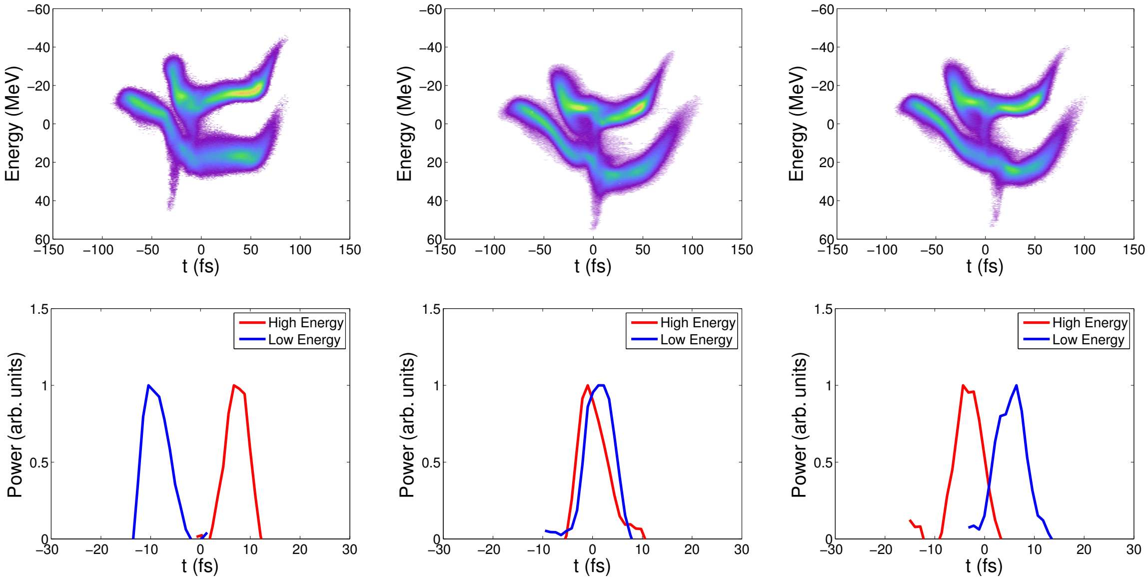

Figure 4: Longitudinal phase-space and associated x-ray temporal profile profile for the spoiled twin-bunches with variable relative arrival time of the two pulses.

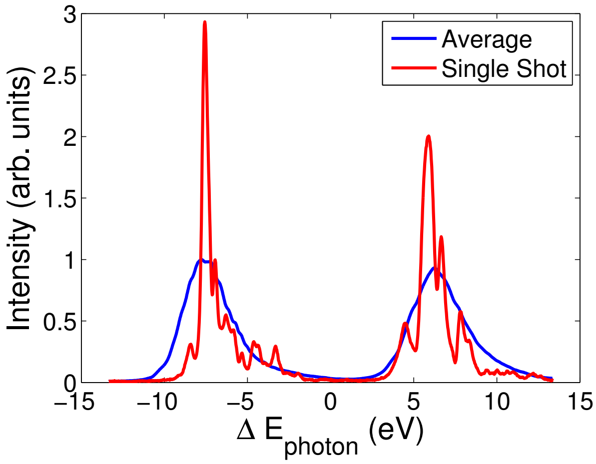

Figure 5: Average (blue) and single-shot (red) x-ray spectra generated by the spoiled twin-bunches.

respect to previous results, while the 150 pC case yields increased pulse energy, up to 2.3 mJ. To overcome the limitations of the twin-bunch scheme at soft-X-rays we developed a new scheme termed "Twin-bunch carving". This scheme relies on generating two relatively long electron bunches (∼100 fs) that arrive to the undulator with different energies but overlapped in time. By combining this bunch structure with a double slotted foil two short pulses (∼6 fs) can be generated. The time-delay of the two pulses can be varied by simply varying the horizontal separation of the two slots in the emittance spoiler. This scheme presents several advantages over other methods available at the same energy. First of all, it allows the generation of two pulses with the full saturation power. Secondly, the time delay of the two pulses can be scanned smoothly passing through the time-overlapped position simply by moving the position of the emittance spoiler. Finally, this scheme allows users to go from negative to positive delays without changing the focusing conditions of the two pulses (e.g. the longitudinal source point).

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