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Keywords: Femtosecond X-ray; Spatially Chirped Electron Bunch; Self-Amplified Spontaneous Emission

PACS codes: 41.60.Cr

1. Introduction

There is presently a great deal of interest in producing very short duration photon pulses at the femtosecond time scale for future x-ray free-electron lasers (FEL) based on self-amplified spontaneous emission (SASE). In typical SASE FEL designs the photon pulse is similar in duration to the electron bunch length, which is usually limited to 100-200 fs due to short-

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bunch collective effects in the accelerator. One possible method to shorten the photon pulse with respect to the electron bunch is to suppress the FEL gain for most of the bunch by somehow degrading or distorting the electron bunch quality over all but a very short duration.

To this end, we note that the FEL gain can be suppressed when an electron beam has an initial offset in the transverse coordinates x, y, x' or y', at the entrance of the undulator. Thus, by giving the electron beam a transverse offset (spatial or angular) correlated with the longitudinal bunch position, a shorter x-ray pulse can be generated because only the portion of the electron bunch with little transverse offset contributes significantly to the FEL process.

Such a spatially (or angularly) chirped electron bunch may be produced by a transverse rf deflecting cavity or by residual dispersion and time-correlated energy spread at the exit of a bunch compressor. For the linac coherent light source (LCLS) [1], transverse rf deflecting cavities are incorporated in the baseline design, hence no additional hardware is required for this short-pulse scheme. In the following section, we discuss the generation and transport of such a beam and show that a 30-femtosecond long pulse (fwhm) can be generated for the LCLS.

2. Method

2.1 General Description

A transverse rf deflecting structure is included in the LCLS design to provide absolute bunch length and slice emittance measurements [2]. The deflector is oriented such that it kicks (pitches) the bunch in the vertical direction. Near the zero-crossing rf phase, the head of the bunch is kicked (for example) in the positive vertical direction ($+y$) and the tail of the bunch in the negative vertical direction ($-y$). This produces a spatially chirped electron bunch which is immediately dumped onto an off-axis screen using a horizontal kicker magnet. The screen image is used to analyse the vertical beam size (*i.e.*, the bunch length) and the horizontal beam size at various vertical positions (*i.e.*, the horizontal slice emittance). If the kicker magnet is switched off, the spatially chirped bunch will propagate on axis through the accelerator (for reasonable chirp levels) and pass through the undulator. Since the head and tail of the bunch have large vertical offsets, only the central core of the beam will continually interact with the radiation field and produce exponential FEL gain. This short central core will generate a short x-ray pulse with duration set by the level of spatial chirp.

2.2 RF Deflector

As a numerical example, Figure 1 shows that a 1-m long, 5-MV (10 MW) vertical S-band rf deflector (2856 MHz) prior to the second bunch compressor (BC2), at 4.5 GeV, generates about $\pm 10 \cdot \sigma_{y'}$ chirp over the 210-fs bunch length at the LCLS undulator entrance. In this case the rf deflector was placed at a vertical betatron phase advance of $\Delta\psi_y \approx n\pi$ (n = 1,2,3,…) with respect to the undulator entrance, resulting in an initial angular (y') chirp and no significant spatial (y) chirp. It is also possible to set $\Delta\psi_y \approx (2n+1)\pi/2$, by relocating the deflector or adjusting the linac phase advance, to get a pure spatial chirp. FEL simulations indicate that the output power is similarly sensitive to spatial chirp at the undulator entrance as it is to angular chirp (when each is normalized to its un-chirped rms beam size). Therefore a similar pulse length will be produced, for the same normalized chirp, with $\Delta\psi_y \approx (2n+1)\pi/2$, as compared to $\Delta\psi_y \approx n\pi$.

The rf deflection (in units of rms angular beam size) is given by

$$\frac{y'}{\sigma_{y'}} = \sqrt{\frac{\beta_y}{\gamma_0 \varepsilon_N}} \frac{eV_0}{mc^2} \cos\varphi \cdot \omega t, \qquad (1)$$

where β_y (40 m) is the vertical beta function in the rf deflector, γ_0 (8880) is the electron energy in the deflector (in rest mass units), ε_N (1 μm) is the normalized vertical emittance, e is the electron charge, V_0 (5 MV) is the rf deflector voltage at crest phase, mc^2 is the electron rest mass, φ is the rf phase (zero-crossing at $\varphi = 0$), and ω is the rf frequency ($2\pi \cdot 2856$ MHz).

The deflector is placed prior to the BC2 bunch compressor where the bunch length is longer than in the undulator (1.8 ps fwhm). Setting t = (1.8 ps)/2, as the half width, the normalized maximum chirp amplitude from Eq. (1) is ~10, which is the case of Figure 1. Note that the BC2 bunch compressor then compresses the bunch length to 210 fs fwhm, but does not alter the vertical chirp amplitude. (The curved head and tail sections in Figure 1 are a normal feature of the LCLS bunch and are produced by the linac longitudinal wakefields.)

This tracking example also includes the transverse linac wakefield, which (for this well aligned linac example) does not appreciably alter the spatial chirp.

2.3 FEL Interaction

Three-dimensional SASE code *GENESIS 1.3* [3] is used to study the FEL interaction of the spatially chirped electron bunch. Since the slippage length is about 1 fs for a 100-m long, 3-cm period undulator, the FEL interaction depends only on the local properties of the electron bunch. Thus, we model the spatially chirped electron bunch as consisting of many

thin time slices that have the same peak current and the same rms beam parameters but an initial angular offset correlated with the longitudinal position of each slice. By studying the dependence of the FEL output power as a function of the initial angular offset, we can trace out the time-dependence of the radiation power as well as the expected x-ray pulse length. Although the curved head and tail sections shown in Figure 1 produce larger current spikes, they do not contribute to the FEL gain because of their relatively large transverse offsets generated by the rf deflector.

Figure 2 shows *GENESIS* simulation results and indicate that a $2\sigma_{y'}$ angular offset degrades the final radiation power by more than one order of magnitude at the radiation wavelength 1.5 Å. Thus, we expect the final x-ray pulse will have a fwhm value of 29 fs for the given spatial chirp of the electron bunch described in Section 2.2 (see Figure 3). Since the maximum saturation power is $P_0 \approx 12$ GW, about 2.7×10^{11} x-ray photons are contained in this short pulse.

2.4 Timing Stability

The FEL gain with a spatially chirped electron bunch only produces x-rays within about ±15 fs of its zero-crossing point. Even if the rf deflector phase or bunch arrival time varies from shot-to-shot, as long as the electron bunch overlaps the zero-crossing phase, the short x-ray pulse is naturally phase locked to the rf deflector. Thus, the x-ray timing can be determined by the phase of the rf deflector alone, which may be synchronized to an external laser for pump-probe experiments [4].

The rf deflector phase jitter tolerance is determined by the electron bunch length. As long as the rf phase (or the bunch arrival time) varies from shot-to-shot by less than the rms bunch length, there will always be a portion of the electron bunch in the undulator which crosses at $y' = 0$, or $y = 0$ (see Figure 1 where this crossing occurs at $t \approx 0$). For the rf deflector located prior to BC2 where the bunch length is 1.8 ps fwhm, the rf phase jitter tolerance is about 0.6 ps (≈ 0.6 degree S-band), which is quite reasonable and has already been demonstrated [2]. Whereas placing the deflector after BC2 requires a much tighter rf phase tolerance of 0.07 degree S-band since the bunch length is 210 fs fwhm.

Placing the rf deflector before BC2 creates another source of x-ray timing jitter because the electron energy jitter becomes arrival time jitter after the chicane. BC2 has a net momentum compaction $|R_{56}| \approx 25$ mm, therefore rms shot-to-shot electron energy stability of $\sigma_\delta \approx 0.1\%$ will introduce additional timing jitter of $\sigma_t = |R_{56}|\sigma_\delta/c \approx 80$ fs. However, a beam

position monitor (BPM) located at the center of the chicane can be used to monitor the shot-to-shot energy fluctuations and provide a delayed signal to accurately reconstruct the arrival time per pulse. With a BC2 maximum momentum dispersion of $\eta_x \approx 340$ mm, and a BPM resolution of $\sigma_{BPM} \approx 20$ μm, this delayed signal has a timing resolution of $\sigma_\tau = \sigma_{BPM} |R_{56}/(c\eta_x)| \approx 5$ fs. The timing signal can then be provided to pump-probe experiments and used to accurately bin the experimental coincidence data with timing precision possibly approaching 10-20 fs, which is similar to the minimum x-ray pulse length achieved with this method.

2.5 Aperture Restrictions

The minimum pulse length obtainable with this method is ultimately limited by the chirped beam size generated in the accelerator and the undulator. In the above numerical example the rf deflector has been limited to 5 MV based on the rms beam size in the accelerator, which has increased to 10-times its nominal size due to the large spatial chirp. This produces a maximum rms beam size in the linac of 0.5 mm (see Figure 4), which is small compared with the 12-mm iris radius of the accelerator structures. It may be possible to increase the rf deflector power to further reduce the x-ray pulse length, but this is better determined experimentally given realistic apertures and shot-to-shot phase jitter.

3. Summary

We have described a very straightforward way to produce SASE x-ray pulses with fwhm duration of ~30 fs, which are 7-times shorter than the LCLS electron bunch length. The method uses an S-band rf deflecting structure already included in the LCLS design (although not optimally located for this purpose). It may be possible to push this method to ~10 fs fwhm depending on aperture restrictions. For example, an octupole magnet located after the deflector might be used to roll over the large transverse amplitude at the head and tail sections and provide an increased spatial chirp in the beam core without exceeding aperture limits. To take full advantage of these naturally phase-locked x-ray pulses, a dedicated X-band rf deflector (four times the S-band frequency) located just before the undulator entrance may provide a similar level of spatial chirp and a closer distance to the experimental stations for better synchronization with an external laser [4].

The spatial chirp method might also be implemented, without the need for a transverse rf deflector, by taking advantage of the transverse wakefields of the linac accelerating structures or by generating a large dispersion function in the linac in the presence of a time-correlated energy spread, which already exists in the BC2. The dispersion can easily be added with adjustable gradient quadrupole magnets inside the bunch compressor chicanes, which are standard components in short-wavelength FELs. Thus, this method will be useful for SASE FELs to produce bright x-rays with pulse length much shorter than the electron bunch length.

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4. References

[1] LCLS Conceptual Design Report, SLAC-R-593, April, 2002, http://www-ssrl.slac.stanford.edu/lcls/CDR/.

[2] R. Akre, *et al*., EPAC'02, Paris, France, June 3-7, 2002, pp. 1882, http://accelconf.web.cern.ch/accelconf/e02/PAPERS/THPRI097.pdf.

[3] S. Reiche, Nucl. Instrum. Methods Phy. Res., Sect. A **429**, 243 (1999).

[4] J. Galayda and J. Hastings, private communications.

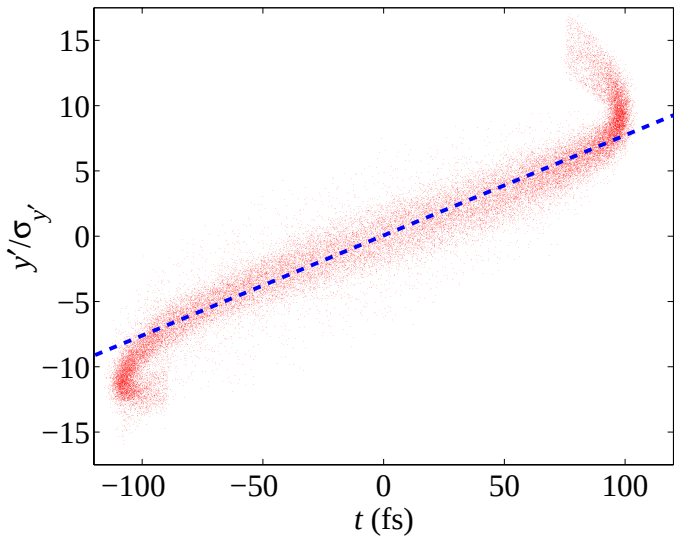

Figure 1. Angular (y') chirp on the LCLS electron bunch, in units of rms angular beam size ($\sigma_{y'}$), at the undulator entrance (14.3 GeV), induced by a 5-MV S-band rf deflector prior BC2.

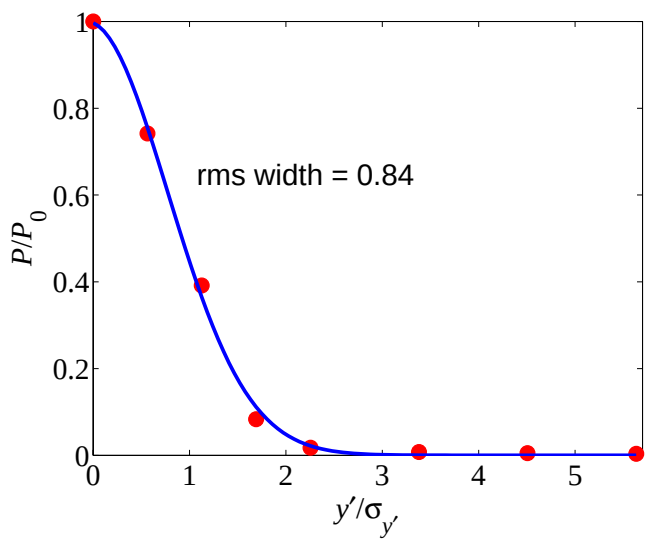

Figure 2. Simulated output radiation power, relative to the maximum saturated power P_0, as a function of the normalized angular offset at the undulator entrance. The solid line is a Gaussian fit with rms width of 0.84.

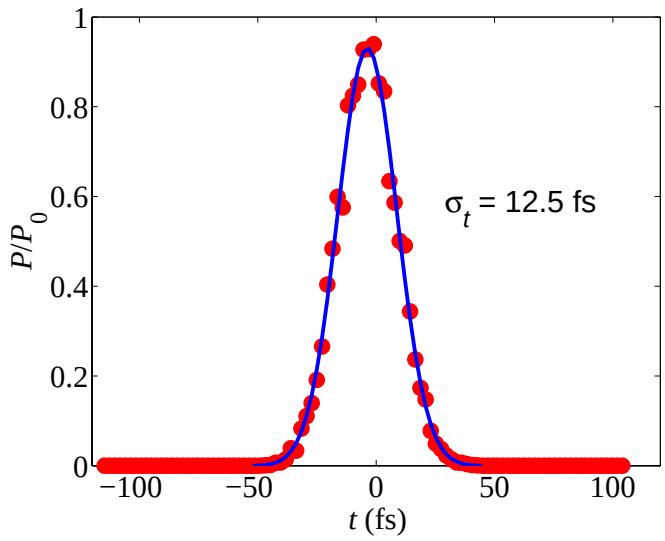

Figure 3. FEL x-ray pulse versus time formed by convoluting the spatial chirp in Figure 1 with the power sensitivity curve of Figure 2. The rms pulse length is 12.5 fs and the fwhm value is 29 fs.

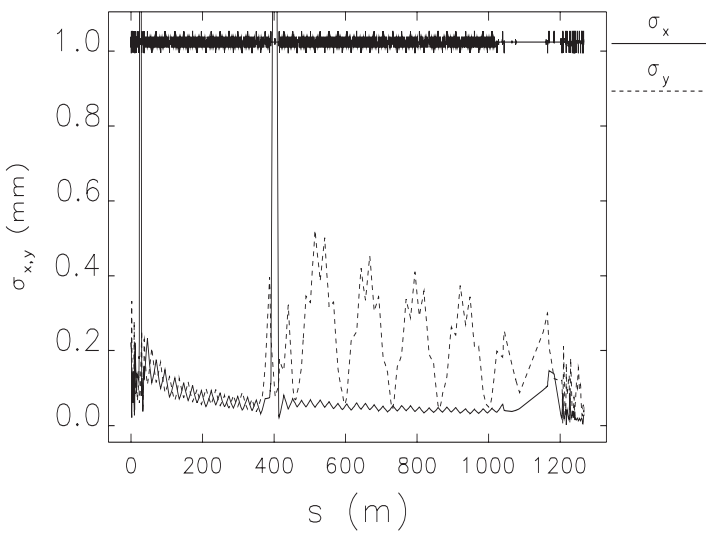

Figure 4. Horizontal (solid) and vertical (dashed) rms beam sizes along LCLS accelerator with rf deflector switched on and located at s = 360 m, prior to BC2. The large horizontal beam sizes at s = 25 m and s = 400 m are in the two compressor chicanes (BC1 and BC2).