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Femtosecond and sub-femtosecond x-ray pulses from a SASE-based free-electron laser

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Abstract

We propose a novel method to generate femtosecond and sub-femtosecond photon pulses in a free-electron laser by selectively spoiling the transverse emittance of the electron beam. Its merits are simplicity and ease of implementation. When the system is applied to the Linac Coherent Light Source, it can provide x-ray pulses the order of 1 femtosecond in duration containing about 10^{10} transversely coherent photons.

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There is a growing interest within the community of synchrotron radiation and free-electron laser users in the availability of ever shorter pulses as experimental probes in several fields of research that include structural studies of single biomolecules, x-ray diffraction from a single protein molecule, and femtosecond chemistry. The interest in femtosecond pulses lies in the fact that electron transfer reaction dynamics in atomic and molecular systems, providing information about the most basic reaction mechanisms in chemistry (*e.g.*, forming and breaking chemical bonds), biology, and soft/condensed matter physics, are on the femtosecond scale (see *e.g.*, [1]).

Present state of the art synchrotron radiation sources routinely deliver intense photon beams, from infrared to x-rays, in pulses of 30-50 ps duration, and it does not seem feasible to deliver much shorter pulses without sacrificing other performance characteristics of the radiation. Free-Electron Lasers (FELs), like the Linac Coherent Light Source (LCLS) [2] planned for construction at the Stanford Linear Accelerator Center (SLAC), or the TESLA X-FEL [3], promise to deliver pulses of 200-fs duration with a peak brightness ten orders of magnitude greater than presently achievable in synchrotron radiation sources.

While proposals exist to produce femtosecond pulses from FELs [4, 5], these typically require significant changes to the machine design. We present a simple method, applicable to nearly any linac-based FEL, to select out a narrow time-slice of the electron bunch to generate very short duration x-ray free-electron laser radiation via the Self-Amplified-Spontaneous-Emission (SASE) process. The SASE gain process is highly sensitive to the transverse emittance (ϵ) of the electron beam, with *emittance* describing the position-momentum phase-space area occupied by the ensemble of particles. The method takes advantage of this high sensitivity, where the emittance must be evaluated over the radiation slippage length (number of undulator periods times the radiation wavelength). For example, the shortest FEL radiation wavelength produced by the LCLS is 1.5 Å, which requires a normalized emittance (phase-space area multiplied by beam energy, γ, in rest mass units) of $\gamma\epsilon \lesssim 1$ μm at 14.3 GeV, while a normalized emittance of $\gamma\epsilon \gtrsim 3$ μm suppresses the gain. Since the slippage length is only about 1 fs for a 100-m long, 3-cm period undulator, it is much shorter than the length of the electron beam (about 200 fs). Spoiling the emittance

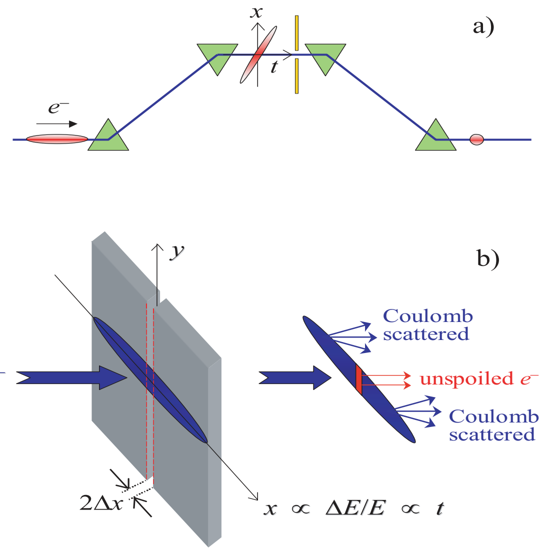

FIG. 1: a) Sketch of electron bunch at center of magnetic bunch-compressor chicane with tilted beam in horizontal, x, and longitudinal coordinates, t. b) The slotted foil at chicane center leaves a narrow, unspoiled beam center.

of most of the beam, while leaving a very short unspoiled time-slice, will produce an x-ray FEL pulse much shorter than the full electron bunch.

The method relies upon the fact that in a magnetic bunch-compressor chicane the beam is tilted at a large angle relative to the longitudinal axis t (see Fig. 1). At the point of maximum tilt (center of the chicane) a thin foil is placed in the path of the beam. The foil has a vertically (y) oriented narrow slot at its center. The coulomb scattering of the electrons passing through the foil increases the horizontal and vertical emittances of most of the beam, but leaves a very thin unspoiled slice where the beam passes through the slit.

In the LCLS, the second bunch-compressor chicane is situated at the 4.54-GeV energy point along the SLAC linac. Prior to the chicane, an energy-time (E-t) correlation is generated by energy-chirping the 1-nC electron bunch in the linac by phasing about 40° off the crest of the radio-frequency (rf) accelerating field. This chirp results in an x-t bunch tilt at the center of the chicane due to its chromatic dispersion. Similar bunch-compressor chicanes are standard components in linac-based FELs, allowing general application of the method.

The electron bunch length is compressed with this arrangement, which is used to increase the peak current in the FEL. Figure 2 shows a simulation of an ensemble of electrons in

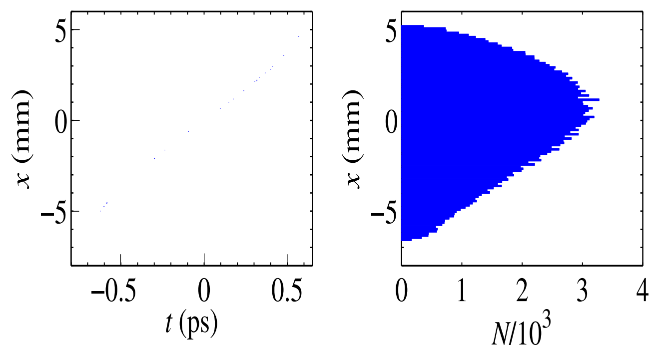

FIG. 2: Distribution of electrons at chicane center showing the very strong position-time (x-t) correlation (tilt).

the middle of the LCLS chicane, highlighting the very strong correlation (or tilt) in the x-t plane.

Since the x and t coordinates are correlated at the foil, the unspoiled beam passed through the slot (of half-width Δx) becomes a very short duration unspoiled slice of the electron bunch after the chicane. The remainder of the bunch has its emittance increased several times through coulomb scattering (depending on foil thickness and material – see below). At the end of the linear accelerator (14.3 GeV) the larger emittance of the blown-up beam suppresses FEL amplification in the undulator. The unspoiled, very short slice of the bunch, however, experiences exponential FEL gain and will reach full power saturation. The number of FEL photons produced is smaller in proportion to the pulse length reduction.

The advantage of this differential spoiling scheme over particle collimation is that the entire electron bunch is allowed to propagate through the linac, allowing normal function of critical beam diagnostics and trajectory stabilization with feedback systems. Also, collimator-edge wakefields can easily degrade electron beam brightness.

The minimum pulse length is achieved by setting the slit half-width, Δx, to a few times the rms transverse betatron beam size, $\sqrt{\beta\epsilon}$, at the chicane center,

$$\Delta x \gtrsim 3\sqrt{\beta\epsilon}, \tag{1}$$

where β is the bend-plane amplitude-function in the chicane and ϵ is the bend-plane emittance. The betatron beam size is that which would be produced if there were *no* energy

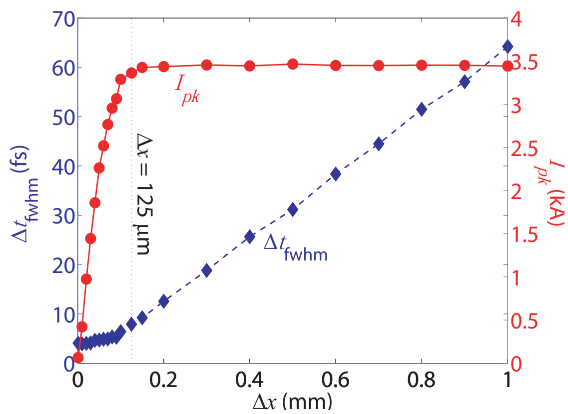

FIG. 3: Peak current (red $\bullet$) and fwhm pulse length (blue $\diamondsuit$) of unspoiled electrons vs. slot half-width, Δx. The minimum e^- pulse at full current is 8 fs ($\Delta x = 125$ μm).

chirp (and no significant 'intrinsic', or uncorrelated, energy spread, which is typical in linac-based FELs). The betatron beam size in the chicane is typically much smaller than the full rms transverse beam size, σ_x, which is dominated by the large energy chirp and chromatic dispersion (see Fig. 2, where $\sigma_x \approx 2.6$ mm). In this case, and with Eq. (1) satisfied, the full-width-half-maximum (fwhm) duration of the unspoiled electron pulse after the chicane is given by

$$\Delta t_{\mathrm{fwhm}} \approx 2\frac{\Delta x}{\sigma_x}\sigma_{t_f}, \tag{2}$$

where σ_{t_f} is the final rms electron bunch length produced after the chicane, if foil were removed.

In the LCLS, the rms betatron beam size is $\sqrt{\beta\epsilon} \approx 50$ μm, the full rms beam size, including energy chirp, is $\sigma_x \approx 2.6$ mm (see Fig. 2), and the bunch length is $\sigma_{t_f} \approx 80$ fs. Therefore a slit full-width of $2\Delta x = 250$ μm selects a very small fraction of electrons ($\sim$4%, or 40 pC) and produces an unspoiled electron bunch slice after the chicane of 8 fs fwhm, as shown in Fig. 3. (As we will see, FEL gain-narrowing and further optimized electron parameters allow an x-ray pulse length of < 1 fs fwhm.)

A narrower slit width can be used to produce a shorter pulse length, but a half-width which is less than a few times the rms betatron beam size will begin to reduce the peak current of the unspoiled slice (see Fig. 3), which then may not reach full FEL power saturation. This betatron beam size, along with the very small intrinsic energy spread in the beam, sets a practical limit on the final x-ray pulse length, depending on the peak current available in the electron beam.

The method offers simplicity and flexibility and can be added to an existing FEL without significant cost or design alterations. The foil slot width can also be tapered, so that a varying vertical displacement of the foil allows a varying x-ray pulse length. In the LCLS, a slot-width variation from 0.25 mm up to 2 mm allows any unspoiled electron fwhm pulse length from 8 fs up to 100 fs. Removing the foil, of course, still allows the nominal LCLS pulse length of 200 fs with the full photon flux. Double-slotted foils might allow the generation of two very short, consecutive pulses, which are precisely separated in time based on the physical slot separation.

Detailed computer simulations of the accelerator with 200k macro-particles have been carried out to evaluate the performance of the slotted spoiler using the tracking code *Elegant* [6]. The simulation includes multiple coulomb scattering [7] in a very thin ($\Delta z \approx 15$ μm) slotted Beryllium foil with $\Delta z/X_0 \approx 4 \cdot 10^{-5}$, where X_0 is the radiation length of the material ($X_0 \approx 35$ cm for Beryllium). The choice of Beryllium keeps the foil reasonably thick and provides an average of >20 scattering interactions per electron, although a 10-μm Carbon foil is another possible choice. (The durability of the thin foil under 120-Hz electron bombardment is not an issue.) Also included in the tracking is the coherent synchrotron radiation (CSR) of the short electron bunch in the chicane bends, the spontaneous (incoherent) radiation of the bends, the linac wakefields, and a model for the transition radiation wakefield [8] of the foil, which adds an insignificant emittance growth and energy spread to the unspoiled beam slice. The electron bunch was tracked through the photo-injector, passed through the slotted foil with its scattering and wakefield, and accelerated in the linac up to the start of the FEL undulator, where the electron energy reaches 14.3 GeV. The longitudinal distribution of particles just before entering the undulator is shown in Fig. 4, where a small spike at the center of the bunch is due to the slot in the foil.

The large leading and trailing spikes are a normal feature of the LCLS due to the slight non-linear x-t correlation shown in Fig. 2. These will not be amplified by the FEL since they are spoiled by the foil. The central spike, however, is the result of electrons near the

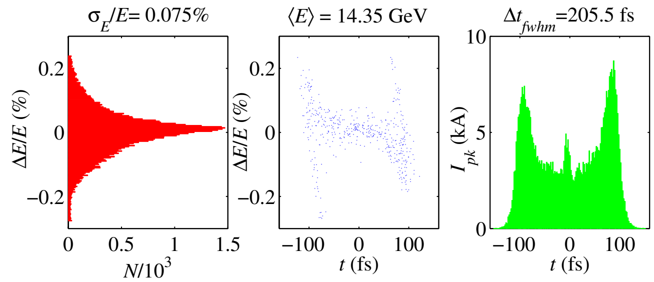

FIG. 4: Temporal (right) and energy (left) profiles, and phase space (center) at undulator entrance. The central spike in the temporal profile is due to the slotted-foil.

edge of the slit scattering in the foil. The scattering generates a slightly different path length for the electrons through the last half of the chicane and causes a small time-smearing inside the bunch according to

$$\Delta\sigma_t \approx |\eta|\sigma_\theta/c, \tag{3}$$

where η is the chromatic dispersion in the chicane (340 mm), σ_θ is the rms coulomb scattering angle (10 μrad), and c is the speed of light. Some of these scattered electrons will then overlap in time with the unspoiled time-slice, raising the local peak current, and creating both an unspoiled core (the electrons that pass through the slit) and a spoiled halo (the time-smeared electrons from near the edge of the slit). The FEL process amplifies only the cold beam core and is unaffected by the halo.

The fwhm length of the unspoiled electron pulse is 8 fs and its distribution is nearly Gaussian; an important feature which is the result of selecting a narrow time-slice of the bunch. Since the slippage length of the FEL ($\sim$1 fs) is much smaller than the length of the unspoiled slice of electrons (8 fs), the FEL gain process is localized and determined only by the local current. The unspoiled current may be approximated by a Gaussian distribution:

$$I(t) = I_0 \exp\left(-\frac{t^2}{2\sigma_{t_s}^2}\right). \tag{4}$$

In the exponential gain regime, the radiation generated by the highest local current grows the fastest. As a result, the length of the x-ray pulse is 'gain-narrowed' compared to the bunch length of the unspoiled electrons, σ_{t_s} ($\approx \Delta t_{\rm fwhm}/2.355$). To estimate this gain-narrowing effect, we apply the one-dimensional FEL theory [9] to express the FEL power gain length

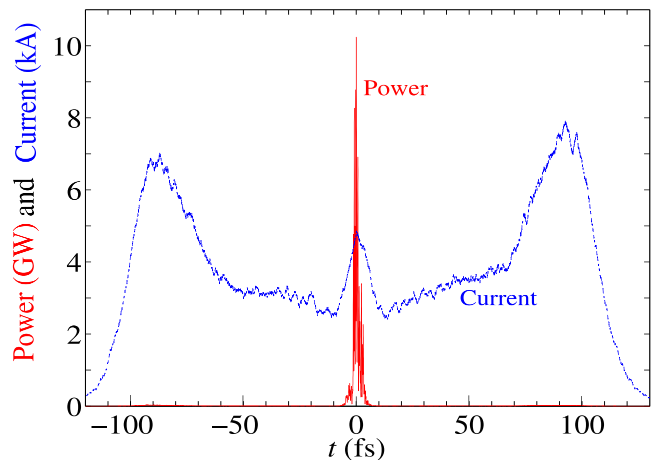

FIG. 5: Electron current and *GENESIS* simulation of 2 fs fwhm LCLS x-ray pulse at saturation ($z \approx 60$ m).

as

$$L_G(t) = L_{G0} \left\{ \frac{I_0}{I(t)} \right\}^{1/3}, \tag{5}$$

where L_{G0} is the gain length corresponding to the peak current I_0. The x-ray power at location z along the undulator as a function of time t along the bunch is

$$P(t) \propto \exp\left[\frac{z}{L_G(t)}\right] \approx \exp\left(\frac{z}{L_{G0}} - \frac{t^2}{2\sigma_{t_X}^2}\right), \tag{6}$$

where $\sigma_{t_X} \equiv \sigma_{t_s}\sqrt{3L_{G0}/z}$ is the rms x-ray pulse duration. At saturation $z \approx 20L_{G0}$, yielding $\sigma_{t_X} \approx 0.4\sigma_{t_s}$. Thus, the unspoiled beam section of length 8 fs (fwhm) generates roughly 3 fs (fwhm) x-rays at saturation. This bunch length reduction factor, 2.6, applies to any distribution of charge which is Gaussian in time at the onset of saturation. After saturation, the lower peak-current sections of the unspoiled beam will continue to amplify, and the pulse length will increase relative to the minimum x-ray pulse length at saturation.

The detailed particle distribution at undulator entrance shown in Fig. 4 is used in the three-dimensional FEL code *GENESIS 1.3* [10] to characterize the FEL performance. Figure 5 shows a 2 fs fwhm FEL x-ray pulse at saturation ($z \approx 60$ m) along with the 200-fs long electron current pulse. The nearly imperceptible baseline power is dominated by the spontaneous undulator radiation emitted from the 200-fs long electron bunch.

Figure 6 shows the radiated power varying along the undulator length for three values

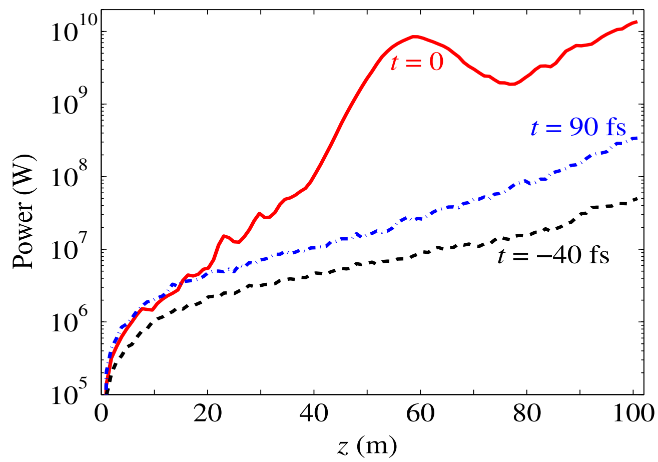

FIG. 6: *GENESIS* simulation showing radiation power for three values of t, varying along the undulator length.

of t, where $t = 0$ is the unspoiled slice (saturating at $z \approx 60$ m) with core emittance of $\gamma\epsilon_{x,y} \approx 0.8$ μm, and core relative energy spread of <0.01%. The other values of t can be related to Fig. 5 and have spoiled core emittances of $\gamma\epsilon_{x,y} \approx 5$ μm. The number of 8-keV photons in this 2-fs, 10-GW pulse is estimated to be 1.6×10^{10}.

It is also possible to push the machine parameters to achieve sub-femtosecond pulses in the LCLS by further compressing the electron bunch to 120 fs fwhm ($\sigma_{t_f} \approx 50$ fs rms), rather than the nominal 200 fs fwhm. This is accomplished by phasing the pre-chicane linac rf a few degrees farther off accelerating crest, which also increases σ_x from 2.6 mm to 2.9 mm. In this case the peak current at bunch center becomes nearly 6 kA, rather than the nominal value of 3 kA. The higher peak current allows the slot half-width to be decreased to $\Delta x \approx 25$ μm until the unspoiled current is again lowered to 3 kA for a 1-fs fwhm unspoiled electron pulse length.

Equation (2) is not valid in this configuration because the slit width is now comparable to the betatron beam size (i.e., Eq. (1) is not satisfied). To achieve this 1-fs electron pulse, the intrinsic rms relative energy spread must be $\lesssim 10^{-5}$ rms at chicane entrance (or $\lesssim 10$ keV rms at the electron injector). This requirement has had some verification in simulations and measurements [11].

At 1 fs, the unspoiled electron bunch length is comparable to the FEL slippage length and the assumption of a localized gain, discussed above, is no longer applicable. This requires a full FEL simulation with *GENESIS 1.3*, which takes into account radiation slippage and shows the 1-fs length of unspoiled electrons is gain-narrowed near FEL saturation to ~0.5 fs fwhm, close to the prediction of Eq. (6). Detailed studies for this more extreme configuration are described in [12].

The shortest possible x-ray pulse length generated by this technique, as well as other techniques, is limited by the intrinsic bandwidth of the SASE process. In the case of the LCLS, the rms SASE bandwidth near saturation is 5×10^{-4}, indicating a 0.3-fs coherence time determined by the time-bandwidth product. Reducing the pulse length of the unspoiled electron bunch on this level, which appears to be possible, will generate a single coherent x-ray spike of about 300 attoseconds.

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