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Issues and Challenges for Short Pulse Radiation Production

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Abstract

A new generation of light source is being planned at many locations, pushing the frontiers of brightness, wavelength, and peak power well beyond existing 3rd generation sources. In addition to these large scale advances there is also great interest in extremely short duration pulses into the femtosecond and sub-femtosecond regime. Collective electron bunch instabilities at these scales are severe, especially in consideration of the high-brightness electron bunch requirements. Several new schemes propose very short radiation pulses generated with moderate electron bunch lengths. Such schemes include radiation pulse compression, differential bunch spoiling, staged high-gain harmonic generation, and selective pulse seeding schemes. We will describe a few of these ideas and address some of the electron bunch and photon pulse length limitations, highlighting recent measurements at the Sub-Picosecond Pulse Source (SPPS) at SLAC where $<$100-fs electron and x-ray pulses are now available.

INTRODUCTION

The fourth generation light source is being planned, such as the LCLS [1] and TESLA-XFEL [2], based on self-amplified spontaneous emission (SASE) in a linac-based FEL. Extremely high photon brightness and 1-Angstrom wavelengths will be possible along with GW peak power levels. In addition to these revolutionary features, there is also great interest in extending these designs to produce femtosecond and sub-femtosecond pulse durations, which will allow the study of sub-atomic dynamics. Although table-top lasers have achieved sub-femtosecond pulse lengths [3], the photon energy and power are still too low to compete with the X-Ray FEL. With this in mind, many ideas have recently been considered to push the typical (expected) 200-fs FEL pulse into the few-femtosecond and even sub-femtosecond regime. We review some of the electron bunch length and photon pulse duration limitations, and briefly describe some of the recent methods proposed to push these limits.

ELECTRON BUNCH LENGTH LIMITATIONS

The typical electron bunch length used to drive the SASE X-ray FEL's in references [1] and [2] are $\sim 25\ \mu$m rms, or 200 fs FWHM (full-width at half maximum). This choice, and the bunch charge choice of $\sim$ 1 nC, produces enough peak current ($\sim$4 kA) to saturate the SASE process in a reasonable length undulator (100-200 m), without introducing large collective bunch instabilities. This choice is also dependent on many other parameters, such as the transverse emittance available from the electron injector, the linac technology choice (superconducting or copper structures), and the radiation wavelength goals for the FEL.

With the very small longitudinal emittance available from present RF photocathode guns (see e.g., [4]) it is certainly possible to compress the electron bunch to well below this 25-μm level and still preserve the energy spread in the FEL to below 0.01% rms. Several issues arise, however, as the electron bunch length is further compressed, which can rapidly degrade the electron beam brightness or simply diminish the FEL gain.

Coherent Synchrotron Radiation

Electron bunch compression is typically accomplished magnetically, by bending an energy-chirped electron bunch through a series of magnets thereby providing a path length dependence on particle energy. For very short electron bunches, the coherent component of synchrotron radiation in bending magnets can be significant and may dilute the horizontal emittance by generating energy spread during passage of the dipole magnets. The energy spread is manifest mostly as a time-correlated energy gradient along the bunch and is not a stochastic process. For an rms bunch length, σ_z, dipole magnet length, L_B (=0.5 m), bend radius, R (=14 m), and N $(= 6.2\times 10^9)$ electrons per bunch, the CSR-induced rms relative energy spread per dipole magnet for a gaussian bunch under steady-state conditions is [5]

$$\frac{\sigma_\gamma}{\gamma} \approx 0.22\frac{N r_e L_B}{\gamma R^{2/3}\sigma_z^{4/3}}, \qquad (1)$$

where r_e $(\approx 2.8\times 10^{-15}$ m) is the classical electron radius and γ (=9000) is the beam energy in units of electron rest mass ($\sigma_\gamma/\gamma \approx 0.36\%$ for σ_z = 1 μm).

This energy spread is typically not a limitation in itself, but since it is generated inside a bend, particles will be deflected differently by the bend depending on their precise energy. This CSR-induced angular spread becomes a bend-plane emittance growth, which can rapidly destroy the electron beam brightness. A very simple description of this emittance growth (typically an under-estimate) is given by

$$\frac{\epsilon}{\epsilon_0} \approx \sqrt{1+\frac{\beta}{\epsilon_0}\left(\frac{L_B}{R}\frac{\sigma_\gamma}{\gamma}\right)^2}, \qquad (2)$$

where ϵ_0 (=0.5 nm) is the initial bend-plane emittance (unnormalized), and β (=5 m) is the beam envelope function in the bend.

Taking typical parameters (in parenthesis above), but choosing an extreme goal of σ_z = 1 μm (in order to push to the femtosecond scale), the relative emittance growth reaches an unacceptable level of $\epsilon/\epsilon_0 > 12$ (see also Fig. 1). With such severe effects, it is very difficult to pursue magnetic bunch compression (with typical X-FEL parameters) down to the femtosecond level (0.3 μm) without loss of brightness. A reduced bunch charge is possible, but the peak current in the FEL must still approach a few-kA, given present injector emittance levels available (i.e., $\gamma\epsilon_{x,y} \gtrsim 1$ μm), which forces even more bunch compression with reduced charge.

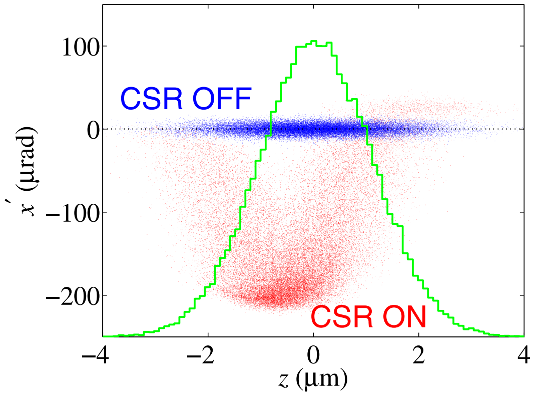

Figure 1: Bend-plane angle, x', vs. bunch length coordinate, z, after chicane compressor with (RED) and without (BLUE) CSR effects for a 1-μm rms bunch length. The emittance (with CSR) is increased here by a factor of 15.

The CSR effect on bend-plane emittance has been measured in the SPPS bunch compressor chicane with a 3.4-nC bunch charge and 50-μm rms bunch length [6]. The results are in reasonable agreement with current tracking codes [7, 8, 9].

Longitudinal Wakefields

With this CSR limitation for magnetic bunch compressors, new proposals have been made [10] to velocity compress the bunch in the low-energy injector and possibly do away with all magnetic compressors. This scheme is a possible alternative, but makes preservation of the transverse emittance in the low energy injector, and beyond, more difficult due to the strong space charge forces. But in addition, the extremely short bunch transported through the entire linac will generate a large longitudinal wakefield in the RF accelerating structures, which will significantly chirp the energy spread prior to the FEL. The maximum FWHM relative energy spread generated by the wakefield of a short bunch (see definition below) in periodic RF accelerating structures can be estimated using [11]

$$\Delta\gamma/\gamma \approx \frac{Ne^2 Z_0 cL}{\pi a^2 E_0}, \tag{3}$$

where e is the electron charge, c is the speed of light, Z_0 is the free space impedance, L is the linac length, a is the mean iris radius of the RF structures, and E_0 is the final electron energy. This estimate is valid only for a very short FWHM bunch length, Δz, which satisfies $(\Delta z/s_0)^{1/2} \ll 1$, where s_0 is the structure's characteristic wakefield parameter, typically a few millimeters.

The wakefields can be minimized by choosing large iris, superconducting RF structures, such as the TESLA structures [12] with $a \approx 30$ mm, and $s_0 \approx 2.3$ mm. The linac length necessary for a 15-GeV FEL, assuming a 20-MV/m RF gradient, is $L \approx 800$ m. In this case, a FWHM bunch length which is less than $\sim$ 100 μm $[(\Delta z/s_0)^{1/2} \approx 0.2]$ will produce, in Eq. (3), a FWHM energy spread of $\sim$ 0.2%, which is fairly large for an X-FEL. (For SLAC S-band copper structures with, $a \approx 12$ mm, and $s_0 \approx 1.3$ mm, the wake-induced chirp for a 1-μm bunch in this case is 1.3%.) With an extremely short bunch and typical RF reduced wavelengths of $\lambda/2\pi \approx 2$ cm, there is no way to control this chirped energy spread with standard RF phasing techniques and it will not be correctable (the RF appears as a DC voltage to this micro-bunch).

The wakefield-induced energy loss of a micro-bunch has been measured at the SPPS in the SLAC linac ($s_0 \approx 1.3$ mm), with linac length $L \approx 1850$ m, $a \approx 11.6$ mm, a bunch charge of 3.4-nC, and a 50-μm rms bunch length [13] ($\Delta z \approx 120$ μm). These results are in good agreement with calculations, but with $(\Delta z/s_0)^{1/2} \approx 0.3$, the wakefield is $\sim$ 20% smaller than the short-bunch maximum wake represented in Eq. (3).

In addition to the RF structure wakefield, the resistivity of the beam pipe in the FEL undulator also induces an energy chirp [14]. This effect can be even more critical because it alters the electron energy during the exponential gain process and cannot be compensated over the whole bunch by tapering the undulator fields. (This effect is used in a proposal for a reduced x-ray FEL pulse length [15].) Equation (3) can also be used to estimate the resistive-wall wake-induced FWHM energy spread for a micro-bunch with length $\Delta z \lesssim s_0 \equiv (2a^2/(Z_0\sigma_c))^{1/3}$, where σ_c is the conductivity of the beam pipe surface. Figure 2 shows the resistive-wall wakefield over a 150-m long undulator at 15 GeV with a smooth, cylindrical, copper-plated beam pipe of radius $a = 2.5$ mm ($s_0 \approx 8$ μm) for two cases: 1) with a typical 25-μm rms bunch length, and 2) with a 1-μm bunch. The first case is tolerable for the X-FEL, while the second is, by far, not tolerable.

These wakefields have characteristic formation length, L_c, determined by the beam pipe radius, a, and the bunch length, σ_z. An estimate of this formation length is given by [16]

$$L_c \approx \frac{1}{2}\frac{a^2}{\sigma_z}. \tag{4}$$

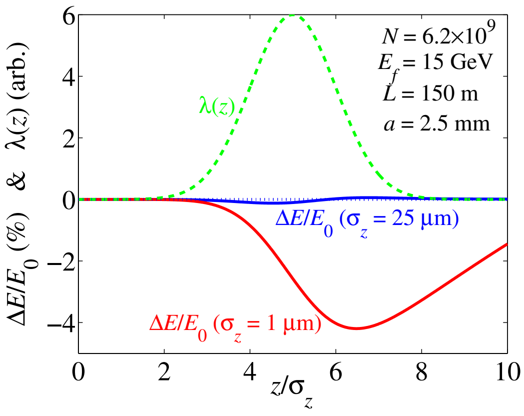

Figure 2: Resistive wall wakefield in 150-m (copper) undulator for 25-μm (BLUE) and 1-μm rms bunch (RED).

In each case described above, even with a 1-μm bunch length, the formation length is significantly less than the system length. Finally, we should point out that other physics that is not well understood (e.g., the high-frequency anomalous skin effect) may manifest for very short bunches and modify details of the wakefields. Nevertheless, for bunch lengths down to $\sigma_z \sim 1$ μm, the estimate in Eq. (3) should be valid.

Micro-Bunching Instabilities

Since the exponential gain in an FEL is a desired micro-bunching instability resulting from transporting a high peak current, very cold beam through an undulator, it should not be too surprising that a high peak current in the accelerator can also induce a similar micro-bunching instability, driven by space-charge forces in the linac [17] and CSR effects in the compressors [18]. A small longitudinal density modulation on the bunch, even at the level of 0.1%, which is likely initiated in the photo-cathode drive laser, can be amplified to extremely high levels depending on the intrinsic energy spread in the beam, linac length, peak current, and compressor strength. This instability can be Landau damped by adding a small, but significant random energy spread to the beam prior to the first bunch compressor [19]. This added energy spread must not exceed the FEL bandwidth (after acceleration and compression), and this cure becomes more difficult to implement as peak current is increased (bunch length is decreased).

Stability

Electron bunch compression relies on accurate RF phasing to properly energy-chirp the bunch. Small RF phase errors, such as shot-to-shot jitter, can cause significant bunch length (i.e., peak current) jitter. A nominal RF phase of ϕ_0, which also varies by $\Delta\phi$, prior to bunch compression by a large factor, $\sigma_{z_i}/\sigma_{z_f} >> 1$, will cause relative final bunch length variations of [20]

$$\frac{\Delta\sigma_{z_f}}{\sigma_{z_f}} \approx -\frac{\sigma_{z_i}}{\sigma_{z_f}}\Delta\phi\cot\phi_0. \tag{5}$$

For the LCLS BC2, with a nominal RF phase of $\phi_0 = 40$ degrees, and a compression factor of $\sigma_{z_i}/\sigma_{z_f} \approx 10$, a small phase error of 0.1 degree ($\Delta\phi \approx 1.7$ mrad) will cause a 2% relative peak current jitter. With other potential sources of jitter, such as RF voltage, gun timing, and bunch charge, this 2% level is only part of a 'jitter budget' which keeps the relative peak current jitter less than 10%. Increasing the compression factor another factor of ten may produce un-achievable RF phase tolerances.

PHOTON PULSE LENGTH LIMITATIONS

With length limitations on the electron bunch, it becomes more attractive to compress (or slice) the photon pulse. Similarly, however, photon pulse compression (or slicing) techniques have associated limitations. The first, and most fundamental limitation is the Fourier transform limit

$$\sigma_t\sigma_\omega \geq \frac{1}{2}, \tag{6}$$

which is expressed in the uncertainty principal. The time-bandwidth product, $\sigma_t\sigma_\omega$, is fixed. For 1-Å ($= \lambda_r$) SASE light ($\omega_0 = 2\pi c/\lambda_r$) with relative angular frequency spread $\sigma_\omega/\omega_0 \approx 5\times10^{-4}$ rms, the minimum pulse length is then $\sigma_t \approx 100$ as rms.

An energy-chirped electron bunch can also be used to drive an FEL producing a frequency-chirped photon pulse. An optical compressor, although typically a lengthy and challenging device for x-rays, will produce a minimum pulse length, ignoring optical compressor bandwidth limits and second-order effects, of

$$\sigma_t \approx \frac{\sigma_\omega}{|h|}, \tag{7}$$

where σ_ω is the intrinsic rms photon bandwidth (approximately equal to the FEL parameter, ρ, at SASE saturation), and h is the slope of the time-frequency chirp (twice the electron chirp). For a 200-fs FWHM pulse length ($\equiv \Delta T$) and a reasonable photon chirp of $h\Delta T/\omega_0 \lesssim 2\%$, the compressed pulse length is $\sigma_t \gtrsim 5$ fs rms.

Similarly, a narrow energy band can be sliced out of a chirped photon pulse [21] by using a monochromator. As seen in Fig. 3 (taken from reference [21]), the pulse duration cannot be made smaller than $\sigma_\omega/|h|$, and is even further lengthened by the monochromator bandwidth, σ_m.

The sliced pulse duration using the monochromator is

$$\sigma_t = \sqrt{\frac{\sigma_\omega^2+\sigma_m^2}{h^2}+\frac{1}{4\sigma_m^2}}, \tag{8}$$

where the second term is the Fourier transform limit due to the monochromator bandwidth. The total pulse length, σ_t, is typically dominated by an upper limit acceptable photon

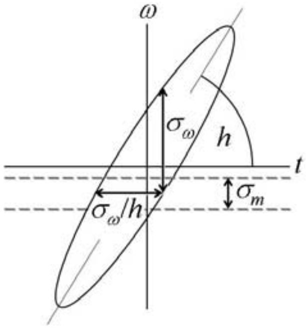

Figure 3: Chirped photon pulse is sliced with a monochromator of bandwidth σ_m.

chirp and is much longer than the Fourier transform limit. The minimum pulse duration is achieved for a monochromator relative bandwidth of [21]

$$\frac{\sigma_m}{\omega_0} = \sqrt{\frac{|h|}{2\omega_0^2}}. \tag{9}$$

A relative bandwidth of $\sigma_m/\omega_0 \approx 6 \times 10^{-5}$, using the example numbers from above, produces a 5-fs rms minimum pulse, still a long way from the Fourier transform limited 100-as spike length.

PROPOSALS TO PRODUCE SUB-FEMTOSECOND FEL PULSES

Several proposals have been made to produce femtosecond and sub-femtosecond radiation pulse durations in future FELs. These typically rely on radiation pulse compression, differential bunch spoiling, staged high-gain harmonic generation, and selective pulse seeding schemes. Here we describe a few of these schemes as a brief review.

Statistical Attosecond Spike Selection

Reference [22] proposes 8th harmonic radiation in a multistage HGHG (High-Gain Harmonic Generation) FEL, extending down to 1-Å radiation. The statistical character of the high-harmonic radiation in a SASE FEL is used to select single 300-as (300×10^{-18} sec) FWHM, 10-GW spikes. An energy trigger is used to reject multiple spike events, enabling single spike occurrence with probability at the level of $\sim 1\%$.

Differential Electron Bunch Spoiling

A simple proposal to produce femtosecond, and possibly sub-femtosecond radiation pulse durations, relies on a thin vertically-slotted foil placed within a horizontally bending bunch compressor chicane [23]. The large transverse position-time correlation on the electron bunch at the center of the chicane allows emittance spoiling of all but a very short temporal section of the bunch. The short unspoiled electron section produces SASE light which is further shortened by gain-narrowing in the FEL. In the LCLS the simple addition of the foil can produce 10-GW, 2-3 fs FWHM, 8-keV X-ray pulses with $> 10^{10}$ photons per pulse, and no change to the baseline design or parameters. It also appears possible to produce sub-femtosecond pulses, down to perhaps 500 as FWHM, with some minor adjustments to the second bunch-compressor chicane [24].

Attosecond Pulses from Laser Interaction

Reference [25] describes a scheme using a harmonic cascade (HC) FEL and a few optical cycle laser pulse to generate 110-as FWHM soft X-ray pulses (10 Å). A 2-ps electron bunch is used to drive a 100-MW harmonic cascade FEL, with 2-nm radiation, where the exiting electrons are then energy modulated with a 100-fs long, 800-nm few optical cycle Ti:sapphire laser pulse and resonant undulator. The carrier phase of the laser is locked to the center of the pulse envelope and this high-energy, short duration (~ 500 as) section of the electron bunch is selected as the only portion to interact with the propagating 2-nm HC-FEL pulse in the next stage, a 2-nm energy modulator. A chicane buncher then produces 2-nm bunching, and harmonics, on the 500-as section of the electron bunch and this is passed to a 1-nm tuned resonator producing a 4-MW pulse with 2×10^6 photons and a 110-as FWHM duration. The FEL pulse is naturally synchronized to the modulating laser allowing accurate pump-probe synchronization.

Laser Interaction and Monochromator

Another idea uses the 800-nm few optical cycle laser pulse to energy-modulate the electron bunch prior to an X-ray SASE FEL [26]. The resulting 10-keV X-ray pulse is frequency modulated at 800 nm and a wide bandwidth monochromator, such as Ge crystal diffracting on the (1 1 1) plane, is used to select only the high-frequency spike with 300-as FWHM duration and $\sim$ 1 GW peak power. A pre-monochromator can be used to cut the unmodulated photon sections and reduce the power on the Ge crystal. As in the previous proposal, this method requires an intense, TW-scale, few-cycle laser pulse with stable carrier envelope phase; the latter two aspects having recently been demonstrated [27]. Electron energy jitter from shot to shot will need to be well controlled in this scheme to one half the level of the monochromator bandwidth ($\lesssim 3 \times 10^{-4}$), a level more easily achieved with superconducting linac RF. Pump-probe synchronization, as above, is a natural outcome here. A similar scheme, without the monochromator, but using a second off-energy resonant undulator with field tapering, has also been proposed [28], which can reach 100-150 GW power levels.

Short Pulse Laser Seed

There is also much interest in the development of short wavelength laser seeds based on high-harmonic gain (HHG; see for example [29]) to produce ten nanometer-scale wavelengths. This technique uses millijoule pulses of 800-nm light from a Ti:sapphire laser, which are compressed in a hollow fiber to 5-fs duration and then focused into a gas jet to produce high harmonics. The proposal in reference [30] uses an 8-nm wavelength, 1-fs duration HHG laser pulse, with 10 nJ, to seed the 5th harmonic of a 1st stage radiator (1.6 nm). This is used as a seed to a second 5th-harmonic stage (with a small electron delay to slip to a fresh part of the 50-fs long electron bunch). The final output is 400-as long with 0.32-nm wavelength and 4 GW of peak power. The HHG technology for an 8-nm pulse with sufficient energy is not yet advanced enough to support this strategy, but many believe that it will advance quickly.

CONCLUSIONS

Because of collective bunch instabilities, it is difficult to extend future FEL performance to include femtosecond pulse durations by simply further compressing the electron bunch. Chirped photon pulse compression and slicing techniques are possible, but are also limited by diffraction and reasonable chirp limits. Nevertheless, several proposals have been made which promise femtosecond and sub-femtosecond pulse durations from X-ray FELs. In consideration of the unprecedented brightness, power, and spatial resolving power (wavelength) of these future machines, the expected advances in temporal resolving power should revolutionize ultra-fast science in the very near future.

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