FEMTOSECOND SYNCHRONISM OF X-RAYS TO VISIBLE LIGHT IN AN XFEL*

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Abstract

A way is proposed to obtain intense infrared/visible light from an electron bunch in an x-ray free-electron laser in femtosecond synchronism with the x-rays themselves. It combines the recently proposed technique of emittance slicing in a free-electron laser with transition undulator radiation (TUR). The part of the electron bunch that is left unspoiled in the emittance slicing process is the source of both coherent x-rays and of coherent TUR at near-infrared wavelengths. An extension of the concept also exploits the fact that the electrons that participate in the free-electron lasing process lose a significant part of their energy.

INTRODUCTION

The elementary processes of chemistry and solid-state dynamics occur on the femtosecond time and Ångström length scales. These may be studied in pump-probe experiments, where a femtosecond pulse of visible or infrared light triggers a process, and a correspondingly short x-ray pulse probes the ensuing dynamics. The x-rays provide both the spatial resolution corresponding to the chemical bond lengths and, through near-edge spectroscopy, element-specific chemical information, such as the oxidation state of a particular elemental species.

Few-femtosecond intense pulses of laser light are readily available with current laser technology, but the production of intense x-ray pulses of similar duration is still a vision. To date, most of the ultrafast laser pump, x-ray probe studies have been done with laser-plasma x-ray sources, which have a rather low brilliance and an x-ray pulse duration of the order of 100 fs. Noteworthy are also the recent experiments on the SPPS facility at the Stanford linear accelerator, which have achieved a time resolution of about 200 fs. The raw output of an x-ray free-electron laser (XFEL) will be much more brilliant than that of the above sources but of similar duration. Several schemes have been proposed in the past few years to obtain shorter x-ray pulses from an XFEL. However, generating ultrashort x-ray pulses immediately brings up the problem of synchronizing them to the pump light at a commensurate level of precision. With two independent sources, i.e., a short-pulse laser for the light and an accelerator-driven x-ray source, synchronization to better than a few 100 fs seems extremely difficult, if not impossible. This is mainly due to timing jitter in the long accelerator structure. Ways to resolve this problem are (i) to derive both light and x-rays from the same source (the electrons in the undulator), or (ii) to cross-correlate the x-ray and light pulses on a shot-by-shot basis and to bin the data accordingly, or (iii) to measure the arrival time of the electron bunches using electro-optic sampling. The latter technique has been demonstrated at SPPS.

A well-defined timing relationship between the pump light and the x-rays is certainly preferable to a statistical timing, even if it becomes known after the event for each shot. The concept presented here provides the former with some minor modifications to existing XFEL beamline designs and a variation of the latter requiring even fewer changes. It is based on the recent proposal [1] to shorten the duration of FEL emission from an electron bunch by slicing its emittance with a scattering foil placed in an existing magnetic chicane bunch compressor. Only a short slice of the bunch that has not been scattered by the foil will emit x-rays through the process of self-amplified spontaneous emission (SASE). In the present proposal, the emittance-sliced bunch is also used to produce an intense single-cycle pulse of infrared light through the process of coherent transition undulator radiation (CTUR), originating from the same electrons that emit the SASE x-rays. CTUR itself is a synthesis of the concepts of transition undulator radiation (TUR) [2] and coherent synchrotron radiation (CSR), and has been considered previously for its effect on electron energy losses in the XFEL undulator [3]. TUR is strongly peaked in the forward direction at the angle of $1/\gamma$, where γ is the relativistic electron energy in rest energy units. This narrow angle makes the CTUR emission depend very sensitively on variations of the electron divergence along the bunch. With few-femtosecond slices in the electron bunch, the CTUR appears in the near-infrared wavelength range. The numbers given are based upon the simulations [1] and parameters available from the parameter database [4] of the Linac Coherent Light Source (LCLS). Some more details and calculations can be found in the literature [5].

EMITTANCE SLICING

In a recent proposal [1], a way was shown to produce few-femtosecond pulses of intense coherent x-rays from a much longer electron bunch. The idea is based upon the large time-correlated transverse spread of an energy-chirped electron bunch in a magnetic-chicane bunch compressor, which is correlated to the longitudinal coordinate along the bunch after it leaves the chicane. By placing a thin scattering foil with a small central aperture into the path of the transversely spread beam, the emittance in most parts of the bunch is increased to the point where SASE becomes impossible. Only those electrons that pass through the cental aperture are left unaffected and will produce SASE in the XFEL undulator. Their longitudinal position in the bunch leaving the compressor depends directly on

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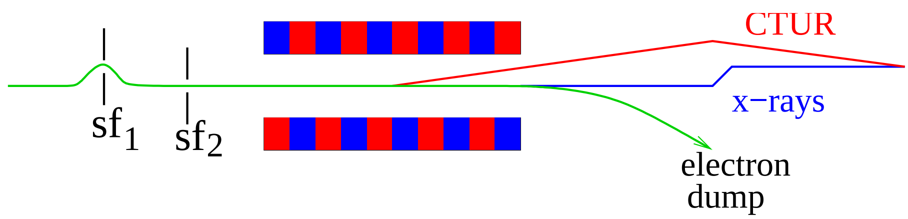

Figure 1: Schematic of the emittance-slicing scheme, with the scattering foil sf$_1$, as proposed in ref. [1], and the additional foils sf$_2$ (see text). The x-rays go through a double-bounce monochromator, which has the secondary purpose of delaying them relative to the CTUR light.

the location of the slot relative to the transverse extent of the bunch. Figure 1 shows a schematic of the XFEL with a primary scattering foil sf_1 in the bunch compressor and secondary scattering foils sf_2. The latter are needed to obtain a sufficient emittance contrast for the production of CTUR beyond that required for the suppression of SASE alone. This is discussed in more detail below.

TUR

Electrons moving through an undulator at relativistic velocities emit two types of radiation with very different characteristics. The commonly used undulator emission is directly due to the transverse oscillations of the electron in the undulator. It is strongest on axis and at wavelengths for which there is an integer-order (odd-integer-order on axis) slippage in each undulator pole between the electrons and the light. In addition to that, there is also the almost zero-order emission of transition undulator radiation (TUR). Almost zero order means that the slippage between the electrons and the light is much less than one wavelength for each undulator pole, and only the overall slippage in the entire undulator is relevant. As the electrons travel on an undulating path, their longitudinal velocity is slightly reduced relative to that of the electric field traveling with them, leading to a longitudinal electric field connecting the electric field lines moving ahead to the slightly delayed charge. This longitudinal electric field does not lead to on-axis far-field emission, but it can be seen from the side. Due to the highly relativistic motion of the electron, the side-on direction is folded forward, making the far-field radiation peak at an angle of $1/\gamma$. In analogy to transition radiation from a thin foil, this radiation is called TUR. Because the longitudinal electric field builds up gradually as the electrons travel through the undulator, the wavelength of the TUR is determined by the length of the entire undulator, instead of one undulator pole. Furthermore, due to the off-axis emission, the relativistic blue shift of the TUR is less pronounced than that of the on-axis undulator radiation. For these two reasons, TUR is most intense in the infrared wavelength range. A further consequence of the emission geometry is that TUR is polarized linearly in the radial direction relative to the axis of the emission cone.

CTUR

Just like conventional synchrotron radiation, TUR is subject to enhancement due to CSR. However, depending on the implemetation, this coherence enhancement may be a bit more subtle than in most other cases. In the simplest instance, if the projection of the electron phase-space density onto the longitudinal coordinate along the bunch exhibits a distinct modulation on the micrometer length scale, then TUR will be coherence enhanced at wavelengths longer than that of the modulation. Such a modulation may be achieved by using very thick/many scattering foils, so that the scattered electrons not only are spread out over a large phase-space volume but actually are lost before the bunch enters the undulator. However, even without such a loss, the narrow collimation of the TUR makes it very sensitive to variations in the angular parts of the phase-space density. Therefore, the larger divergence of the electrons in the emittance-spoiled parts of the bunch leads to a modulation of the effective number of charges contributing to the TUR observed at an angle of $1/\gamma$ in the far field, as shown in fig. 2. This, in turn, leads to coherence enhancement of the TUR.

To calculate the strength of CTUR emission, the original equation (11) of ref. [2] must be modified to take into account the angular coordinates of the phase-space density $\rho(x, x', y, y', z, E)$ of the electron bunch. Here, x and y are the transverse real-space coordinates, x' and y' are the corresponding angular coordinates, z is the longitudinal real-space coordinate and E is the electron energy. This set of coordinates will be abbreviated with X. The result[1] for the number N of photons per electron and unit solid angle Ω is [5]:

$$\frac{dN}{d\Omega} = \frac{\alpha\omega\Delta\omega L^{\circ 2}\gamma^2 < \beta_\perp^4 >}{4c^2\pi^2} \left[\int dz_1 dz_2 d\mathbf{x}'_1 d\mathbf{x}'_2 e^{ik(z_1-z_2)}\tilde{\rho}(z_1,x'_1)\tilde{\rho}(z_2,x'_2)\right], \qquad (1)$$

where $\alpha \approx 1/137$, ω and $\Delta\omega$ are the frequency of the TUR

[1] Please note that this equation is in units of photons per electron passing the undulator, while eq. (11) of ref. [2] is in units of photons per second for a given current I

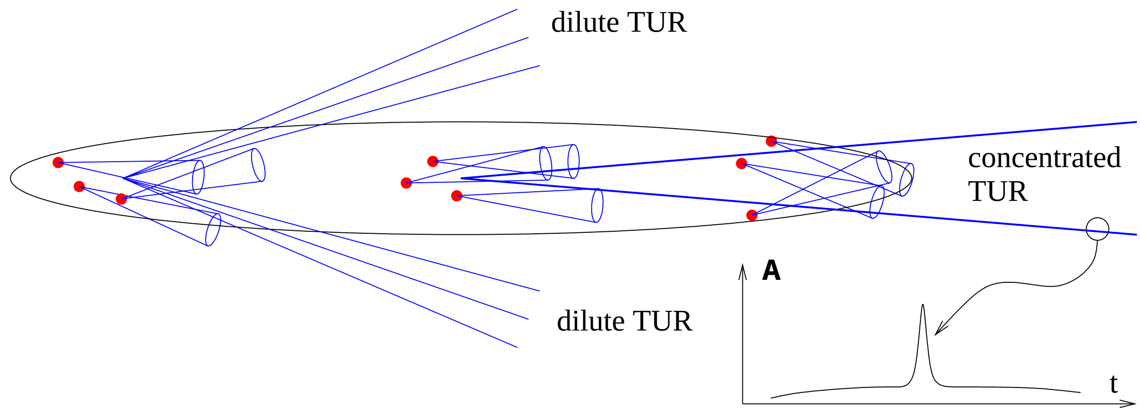

Figure 2: Schematic representation of the variations in the divergence along the bunch. The center has a smaller electron divergence, and thus a smaller TUR divergence, than the head (light rays not drawn) or the tail (divergent light rays shown). The insert shows the amplitude $\mathbf{A}$ over the time t at the location of the observer. Short-wavelength CTUR is due to the square of the peak over the slow pedestal.

and the bandwidth of interest, L° is an effective undulator length, $\beta_\perp$ is the transverse electron velocity in the undulator in units of the speed of light, and $\tilde{\rho}$ is a directional electron density defined below. The subscripts $1, 2$ are used to differentiate between integration variables instead of the customary prime $'$ to avoid confusion with the notation of angular variables. The effective undulator length L° contains a correction for the observer not being at an infinite distance and thus seeing a variable emission angle from different parts of the undulator [5]. With the parameters of the LCLS, L° and the real undulator length L differ by about 10 percent.

The directional electron density $\tilde{\rho}$ is defined as [5]:

$$\tilde{\rho}(z, x', y') = \frac{\gamma^{-1}|\mathbf{\Theta} - \mathbf{x}'|}{(\mathbf{\Theta} - \mathbf{x}')^2 + \gamma^{-2}} \int d(\beta, x, y)\rho(X), \quad (2)$$

where $\mathbf{x}$ and $\mathbf{\Theta}$ are the transverse angular coordinates and the observation angle relative to the beam axis, written as two-component vectors. For angles $|\mathbf{\Theta}| \approx 1/\gamma$, the fraction before the integral is about 1. If the bunch charge is concentrated along the z-direction to within less than a wavelength of the TUR of interest, the double integral in eq. (1) becomes equal to the square of the number of charges in the bunch.

EXAMPLE

Now to an estimate of the CTUR power to expect at the important wavelength of 800 nm (see ref. [5] for details). Inserting the LCLS design parameters into eq. (1), the number of photons to expect from a single electron is about $4.2 \cdot 10^{-4}$. The peak current in the LCLS is about 6 kA, giving a charge of 8 pC, or about $5 \cdot 10^7$ electrons in an optical half-cycle of 800-nm light. Assuming a contrast of 50 % in the square of the directional electron density, the number of CTUR photons is then about $1 \cdot 10^{12}$, giving a pulse energy of 120 nJ in an optical half cycle and a power of about 50 MW.

If the increase of the electron beam diameter due to the emittance slicing does not lead to a significant loss of electrons, the only contrast in the directional electron density is due to the the beam divergence increase. It has to be at least of the order of $1/\gamma$ to cause a good contrast in $\tilde{\rho}$, as is illustrated by fig. 3. In the LCLS design [4], the normalized slice emittance $\gamma\epsilon$ is $1.2 \cdot 10^{-6}$ m, and the average β function in the LCLS undulator is 29 m/rad, giving an rms transverse beam size $\sqrt{\beta\epsilon} = 36$ μm, and a divergence of 1.25 μrad. For good CTUR contrast, the emittance slicing should make the electron beam divergence increase to about 60 μrad, corresponding to an emittance increase of about 2500, which is much more than the about fourfold increase in the original proposal [1]. Therefore, additional, and perhaps thicker scattering foils are required. Probably the best way of increasing the emittance outside of the central slice of the bunch is to place secondary scattering

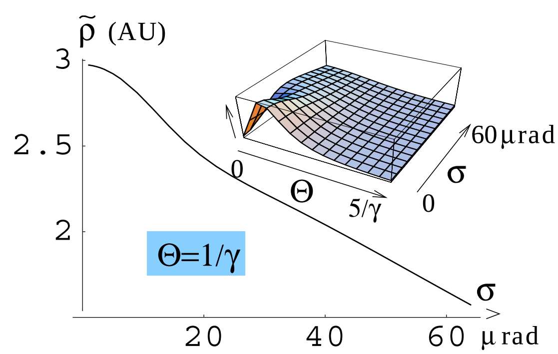

Figure 3: Main graph: Square of the directional electron density $\tilde{\rho}$, eq. (2) for an observation angle $\Theta = 1/\gamma = 37\mu$rad over the electron beam divergence σ. Insert: the same over σ and Θ.

foils between the bunch compressor and the undulator. Because the emittance-spoiled parts of the bunch have a larger beam cross section than the unspoiled parts, a scattering foils with an aperture of a 50 to 100 microns will interact mostly with the already spoiled parts of the bunch. Several (at least two) secondary foils within one beta-function length will be required to scatter the majority of electrons in the spoiled sections. One would probably use many secondary scattering foils to spread out the damage loading. These can have ever-increasing apertures as the beam cross section of the spoiled parts grows. Outside of the undulator, the beta function can easily be modified, which may be exploited to increase the beam cross section and thus relax the tolerances on the placement of the secondary scattering foils.

The 2500-fold increase in the emittance is, in fact, so large that some electrons will get lost in narrow sections of the beam pipe. This can be turned into an advantage. By replacing the last few of the secondary scattering foils with collimators, not only the directional, but also the total electron density of the spoiled parts can be reduced by about 1/2. There is, however, one concern with this [6, 7]: The beam position monitors in the LCLS are designed to reach the required accuracy down to about 1/10 of the nominal bunch charge of 1 nC. Losing most of the electrons outside of the unspoiled part will reduce the bunch charge below this limit (see above example with an unspoiled charge of 8 pC). This problem can be solved by making use of the strong dependence of CSR on the spatial frequency of the electron density modulation. If the primary scattering foil(s) is shaped in such a way that it scatters strongly close to the central aperture and gradually tapers off towards the edges, then there will be a strong modulation of the directional electron density at short (micron) wavelengths only close to the unspoiled section. The outlying parts of the bunch are modulated at lower spatial frequencies, which emit only longer wavelength CTUR. This is sketched in fig. 4. Such a scattering foil will thus preserve most of the bunch charge in a beam of only minimally increased emittance, while still providing the electron density modulation required for CTUR.

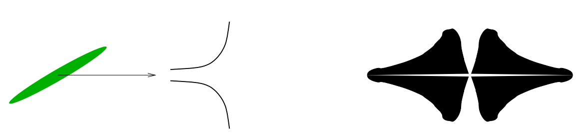

Figure 4: Left: a tilted electron bunch in the magnetic chicane, hitting a shaped primary scattering foil (middle) that scatters strongest close to the central aperture. This results in an emittance sketched schematically to the right, which will emit shorter wavelength (micron) CTUR only from the central part.

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