Visible/IR light and x-rays in femtosecond synchronism from an x-ray free-electron laser

B.W. Adams[a]

[a]Argonne National Laboratory, 9700 S. Cass Ave. , Argonne, IL 60439, USA

ABSTRACT

A way is proposed to obtain pulses of visible/infrared light in femtosecond synchronism with x-rays from an x-ray free-electron laser (XFEL), using the recently proposed emittance-slicing technique.[1] In an XFEL undulator, only the short section of an electron bunch whose emittance is left unchanged by the slicing will emit intense coherent x-rays in the XFEL undulator. At the same time, the bunch emits highly collimated transition undulator radiation (TUR)[2] into a cone whose opening angle is the reciprocal relativisticity parameter gamma. Due to the variation of the transverse momentum induced by the emittance slicing, the effective number of charges contributing to the TUR varies along the bunch, and is higher in the sliced-out part that emits the coherent x-rays. As with coherent synchrotron radiation (CSR), the TUR is thus coherently enhanced (CTUR) at near-infrared wavelengths. Coming from the same part of the bunch the CTUR and the coherent x-rays are perfectly synchronized to each other. Because both types of radiation are generated in the long straight XFEL undulator, there are no dispersion effects that might induce a timing jitter. With typical XFEL prameters, the energy content of the single optical cycle of near-IR CTUR light is about 100 Nano-Joule, which is quite sufficient for most pump-probe experiments.

Keywords: free-electron laser, coherent synchrotron radiation, transition undulator radiation, femtosecond synchronism

1. INTRODUCTION

Corresponding to the interatomic distances and the electron-Volt energies of chemical bonds, the most elementary processes of chemistry and solid-state dynamics take place on the femtosecond time and Ångström length scales. These can be addressed in pump-probe experiments, where a femtosecond pulse of visible or infrared light triggers a process whose dynamics are probed by a correspondingly short x-ray pulse. The x-rays can 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.

Whereas few-femtosecond, intense pulses of laser light are readily available with current laser technology, the production of intense x-ray pulses of similar duration is still a vision: laser-plasma x-ray sources have a low brilliance, and the duration of the x-ray pulses is of the order of 100 fs. The raw output from an x-ray free-electron laser (XFEL) is much more brilliant 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 immediatly 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 of the order of 1 ps seems extremely difficult, if not impossible. This is mainly due to timing jitter in the long accelerator structure. Two ways out of 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. Having 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 a way to achieve 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 a recent proposal[1] to shorten the duration of FEL emission from an electron bunch by passively

Further author information: (Send correspondence to B.W.A.)
B.W.A.: E-mail: adams@aps.anl.gov, Telephone: 1 630 252 6454

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slicing its emittance with a scattering foil placed in an existing magnetic bunch compressor. To achieve the synchronism of these short x-ray pulses with the pump light, the current proposal combines emittance slicing with the use of coherent transition undulator radiation (CTUR) emitted by the same electrons that participate in the SASE emission of x-rays. CTUR, itself, is a combination of the concepts of transition undulator radiation[2] (TUR) and coherent synchrotron radiation (CSR). It has been considered before for its effect on electron energy losses in the XFEL undulator.[3] TUR is strongly peaked in the forward direction at an angle of $1/\gamma$, where γ is the relativistic electron energy in rest energy units, making it depend very sensitively on the emission angle. Correspondingly, the CTUR emission will be determined by the variations along the bunch of the electron density over the transverse angular coordinates in phase space. For 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). This text is an outline of the basic concept behind the use of CTUR from an emittance-sliced electron bunch, and also contains a tutorial section on TUR. Some more details and calculations can be found in the literature.[5]

2. EMITTANCE SLICING

The emittance-slicing scheme[1] exploits the large time-correlated transverse spread of an energy-chirped electron bunch in a magnetic-chicane bunch compressor: a thin scattering foil with a narrow aperture spoils the low emittance necessary for the SASE process in most of the bunch, except for a small central part. Those electrons that pass through the slot remain almost completely unaffected (aside from weak wakefield effects), and thus retain the emittance required for the SASE effect. Their longitudinal position in the bunch leaving the compressor depends directly on the location of the slot relative to the transverse extent of the bunch. The electrons that traverse the foil are scattered, and their transverse and longitudinal emittances are increased in proportion to the foil thickness. With the parameters given in the original emittance-slicing proposal, the emittance increase is sufficient to suppress the SASE emission of intense and coherent x-rays, but not to yield a good contrast in CTUR emission (see below). For the latter, a thicker scattering foil or a sequence of secondary scattering foils with increasing aperture sizes should be used, or a combination of both.

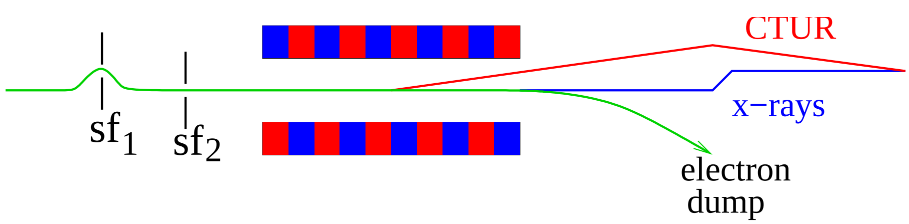

Figure 1. Schematic of the emittance-slicing scheme, with the scattering foil sf_1, as proposed in ref.,[1] and the additional foils sf_2 (see text). The x-rays go through a double-bounce monochromator, which has the secondary purpose of delaying them relative to the CTUR light.

3. CTUR

Before proceeding to CTUR, we will have to discuss briefly the distinctive features of TUR in comparison to the more commonly known undulator radiation used in all synchrotron radiation laboratories. Whereas the latter is of first or higher order, TUR is of almost-zero order, leading to very much different emission characteristics. So, what does almost-zero order mean? In the usual undulator radiation process, each undulator pole causes the electrons to go a curved trajectory that is longer than the straight path of the electromagnetic waves by one or several integer-order wavelengths of the emitted light. This multiple slippage leads to the distinct spectral interference pattern of undulator radiation. An observer looking into the undulator along the electron beam axis will see a charge oscillating at the x-ray frequencies of the undulator fundamental and higher harmonics, but not at infrared frequencies.

The undulator also has an overall effect on the electrons by slightly reducing the longitudinal (along the beam axis) part of their velocity. This longitudinal delay does not lead to on-axis far-field radiation. However, at off-axis observation angles, the longitudinal delay does have a transverse component, and far-field radiation is observed. It is most intense at an angle of $1/\gamma$ relative to the beam axis, where γ is the relativisticity parameter, because this is the side-on view in the electron frame, folded forward in the transformation to the lab frame. This is shown in fig. 2.

This type of radiation is called transition undulator radiation (TUR). Because its generation requires all of the undulator length instead of the individual poles, and because it is observed at an off-axis angle, TUR is typically in the infrared range. It is of almost-zero order because each pole contributes a slippage of much less than one wavelength between the electrons and the electromagnetic field. The name of TUR stems from an analogy to transition radiation, which is generated when a relativistic charged particle traverses a foil of some material. In this case, the refractive index of the foil material delays the electric field traveling with the charge, while the charge itself continues at almost the speed of light. This separation leads to a longitudinal electric field, connecting the delayed filed lines to the charge. In the case of TUR, the opposite happens: the electric field continues at the spee of light, while the charge is delayed. In either case, the electric field can be observed at off-xis angles around $1/\gamma$.

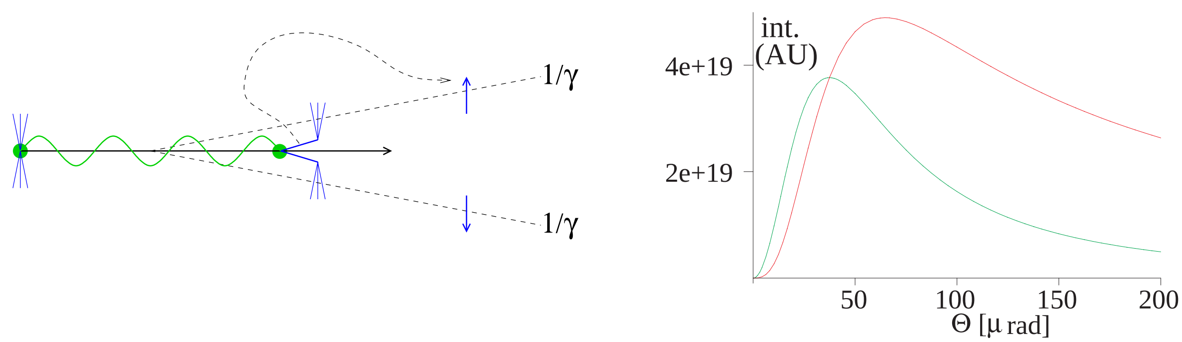

Figure 2. Left: a schematic representation of TUR. The electric field lines originating from a relativistic electron entering an undulator are concentrated close to a plane transverse to the direction of motion. Inside the undulator, the electron's forward motion is delayed, while the electric field continues at the speed of light. At the end of the undulator, there is a longitudinal field component that gives rise to a transverse electromagnetic wave in the far field (curved dotted line). The electric field vector of this radiation is directed radially outward. Right: Dependence of the TUR intensity from the LCLS undulator on the observation angle Θ at $\lambda = 1$ μm. Lower curve: into a constant solid angle (eq..[2] (11)), upper curve: into a constant interval in Θ, integrated over the azimuthal angle. For the lower curve, the units on the abscissa represent the photon flux at $\lambda = 1$ μm per second, mrad^2 and 0.1% bandwidth at a beam current of 5 kA. For the upper curve, the units are arbitrary.

Now to CTUR: Coherent synchrotron radiation (CSR) occurs at wavelengths where the charge density in an electron bunch has a strong Fourier component that does not vanish in a bunch-to-bunch average. The emission of synchrotron radiation is then not only due to individual charges, but rather due to all charges contributing to that particular Fourier component. CSR always occurs on wavelengths longer than the electron bunch itself. Annother example is, of course, the free-electron laser, where a coherent modulation of the electron bunch density builds up at the emission wavelength.

Actually, it is not only the real-space electron density that needs to be considered, but rather the full phase-space density, convoluted with the emission characteristics of the type of radiation being considered. This point becomes important in the context of emittance slicing of the low-emittance electron beams used for x-ray free-electron lasers: depending on the beta function of the electron beam, the increase in divergence of the parts that were scattered by the foil can exceed the TUR emission angle of $1/\gamma$. In that case, the number of electrons contributing to the TUR observed varies along the electron bunch, and is highest for the part that was left unspoiled.

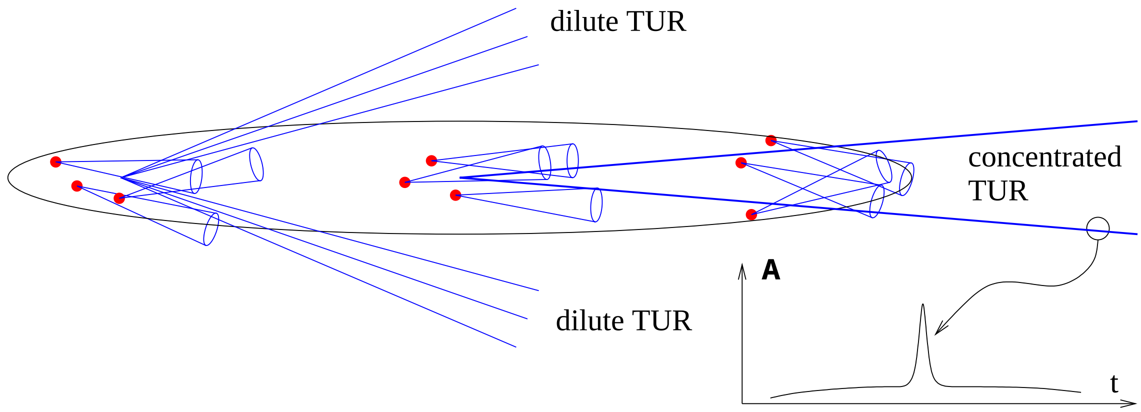

Figure 3. Schematic representation of the variations in the divergence along the bunch. The center has a smaller electron divergence, and thus a smaller TUR divergence, than the head (light rays not drawn) or the tail (divergent light rays shown). The insert shows the amplitude **A** over the time t at the location of the observer. Short-wavelength CTUR is due to the square of the peak over the slow pedestal.

One may define a directional electron density $\tilde{\rho}$ as the real-space electron density ρ times the fraction of electrons contributing to the TUR at a given observation angle. A formal definition is given by eq. (B2) in a previous work.[5] Figure 4 shows this directional density for the LCLS value of $\gamma = 26693$. Thus, even though the projection of the electron density onto the beam axis may not exhibit any sharp variations, the modulation of the beam divergence is the cause of a coherent synchrotron radiation effect. The cutoff wavelength of the CSR is given by the length of the unspoiled section. In the original proposal,[1] most of the simulations were done for a sliced section of 8 fs in duration, or 2.4 μm in length. The lower CSR cutoff wavelength would thus be at approximately 5 μm. However, slices of shorter duration, down to about 1 fs, are also discussed in that proposal, yielding correspondingly shorter-wavelength CTUR of 800 nm, which lends itself to the application of standard Ti:sapphire laser technology.

4. EXAMPLE OF THE LINAC COHERENT LIGHT SOURCE

In the LCLS design,[4] the relativisticity parameter γ has a value of 26693, 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. The emission of TUR peaks at the angle of $1/\gamma = 37$ μrad (see fig. 2). In order to give a good contrast in the directional electron density, the electron beam divergence in the spolied sections of the bunch must be increased to more than about 40 μrad (see fig. 4). With the given beta function, the emittance must thus increase more than 1000-fold over its unspolied value. The 4-fold emittance increase due to the scattering foil in the original emittance-slicing proposal[1] is clearly not enough. According to the simulations in that proposal, the effect of the foil on the unspoiled part of the bunch through wakefield interactions is negligible, and therefore, a somewhat thicker scattering foil is feasible. The major part of the emittance increase would however come from additional scattering foils placed somewhere downstream of the bunch compressor, such as shown schematically in fig. 1. These make use of the fact that the spoiled parts of the electron bunch have an increased beam cross section, as well as in increased divergence. A total foil thickness of about 4 mm will be required for a 2000-fold emittance increase.[5] As the emittance of the spoiled parts increases, the beam-cross-section contrast relative to the unspoiled part improves, and the foils further downstream can have larger apertures. This will help to minimize adverse wakefield effects on the unspoiled parts of the bunch. The LCLS design incorporates a collimator before the undulator, which would be a good place for the additional scattering foils. There is, however, one caveat: if the apertures in the scattering foils are not symmetric to the beam axis, then the emittance increase will also be asymmetric, making beam diagnostics difficult.

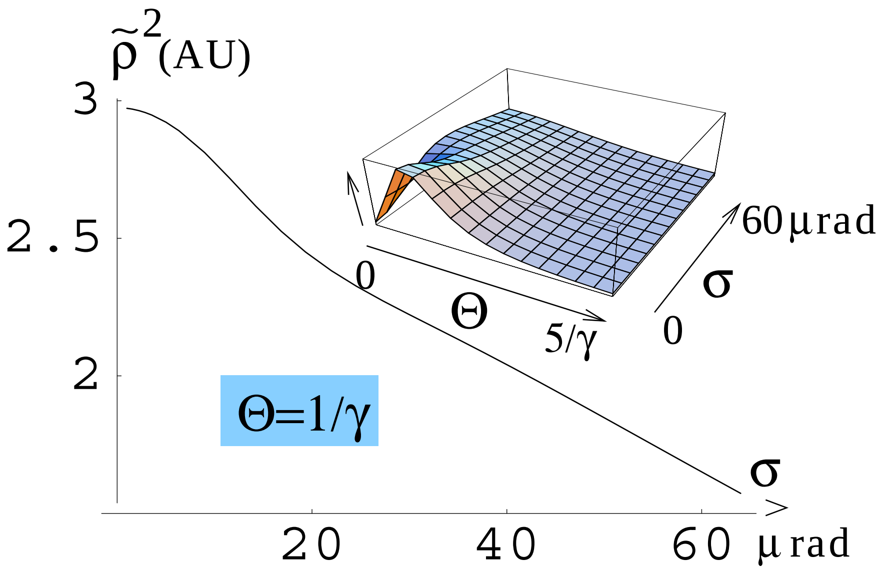

Figure 4. Dependence of the directional electron density $\tilde{\rho}$ on the electron beam divergence σ and the observation angle Θ for the LCLS value of $\gamma = 26693$. Main graph: $\tilde{\rho}^2$ over σ, for $\Theta = 1/\gamma = 37\mu$rad. Insert: the same over σ and Θ.

Due to the small emission angle of $1/\gamma$, the source size $\sigma = \gamma\lambda/2$ that contributes to one transverse mode of the infrared radiation is rather large. At $\lambda = 1$ μm, it comes out to be $\sigma \approx 13$ mm. Therefore, the emission of TUR is insensitive to emittance-induced electron beam cross section variations. This transverse source size is projected onto the electron beam at the very small angle of - again - $1/\gamma$. The resulting length of the electron trajectory is thus $L = \gamma^2\lambda/2$, which comes out to be 356 m for $\lambda = 1\mu$m and $\gamma = 26693$. To fulfil the assumptions made in the calculation of TUR emission, the electron beam follow a straight path within this length. A large part of it is occupied by the LCLS undulator, which is going to be 112 m long; and the rest consists of straight electron beam transport sections. The TUR in fig. 1 is focused onto the sample by a long (several m, depending on the imaging ratio) parabolic mirror. Because of the radial polarization of the TUR light (see fig. 2), focusing the whole emission cone onto the sample would lead to destructive interference. Therefore, one can use only about 1/3 of the cone to get an optical single-cycle burst of infrared radiation (one-half cycle of the vector potential) or two opposing sections of the cone with a $\lambda/2$ phase shifter for a 3/2-cycle burst (one full cycle of the vector potential).

At the undulator exit, the SASE-generated x-rays and the CTUR-generated infrared light are coincident to better than one femtosecond. There are no dispersive sections in the electron beam path that might induce a timing jitter from orbit fluctuations due to electron energy jitter. TO be useful in a pump-probe-type experiment, the infrared light must, however arrive slightly before the x-rays. In the case of ultrafast science to be done at the LCLS, this time difference is typically less than a few picoseconds. The x-rays can easily be delayed by a fixed amount of many picoseconds by use of a double-crystal monochromator, which provides enough timing difference to introduce a scanning delay stage for the infrared light.

According to calculations of the CTUR intensity,[5] the pulse power in the CTUR from the LCLS is of the order of 50 MW in a single optical cycle, corresponding to a pulse energy of about 100 nJ. This is sufficient for many pump-probe experiments, but may be boosted, if necessary, using laser amplifiers in a straight-through geometry (i.e., without resonator or beam path folding mirrors).

The CTUR is also useful without a double-crystal monochromator to delay the x-rays. In such a configuration, a standard short-pulse laser would be used to provide the pump light, and the CTUR would be used to correlate the x-rays, "tagged" by the CTUR to the pump light. This requires only optical correlation, which is much easier to do than x-ray/light correlation. Although a few proposal for the latter have been advanced,[6,7] none of them are tested, yet. Using the CTUR for optical correlation only also has the advantage that a much lower CTUR intensity would be sufficient, thus relaxing the requirements on the emittance increase in the slicing process. A setup with a laser for the production of pump light will, of course, have the disadvantage of not being able to do deterministic timing scans. Instead, the data will have to be sorted statistically into timing bin, as determined by the correlation on a shot-by-shot basis. Therefore, from the experimenter's point of view, it is very much preferable to use the CTUR directly as a source of pump light.

5. CONCLUSIONS

In order to do the femtosecond-resolving pump-probe-type experiments envisioned for the LCLS and other x-ray free-electron lasers, the timing of the x-rays relative to visible/infrared pump light must be controlled, or at least known, at the femtosecond level. Due to phase jitter in the radiofrequency-driven linear accelerators driving the free-electron lasers, synchronisation to an external light source, such as a laser oscillator, will probably be no better than about 1 ps. The present proposal outlines a way to solve this problem by deriving the pump light from the same source that produces the x-rays, or using this light for optical femtosecond-resolving correlation with laser light. The proposal requires only minimal changes to existing designs of x-ray free-electron laser facilities.

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