A CONCEPT FOR Z-DEPENDENT MICROBUNCHING MEASUREMENTS WITH COHERENT X-RAY TRANSITION RADIATION IN A SASE FEL*

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Abstract

We present an adaptation of the measurements performed in the visible-to-VUV regime of the z-dependent microbunching in a self-amplified spontaneous emission (SASE) free-electron laser (FEL). In these experiments a thin metal foil was used to block the more intense SASE radiation and to generate coherent optical transition radiation (COTR) as one source in a two-foil interferometer. However, for the proposed x-ray SASE FELs, the intense SASE emission is either too strongly transmitted at 1.5 Å or the needed foil thickness for blocking scatters the electron beam too much. Since x-ray transition radiation (XTR) is emitted in an annulus with opening angle $1/\gamma$ = 36 μrad for 14.09-GeV electrons, we propose using a thin foil or foil stack to generate the XTR and coherent XTR (CXTR) and an annular crystal to wavelength sort the radiation. The combined selectivity in angle and wavelength will favor the CXTR over SASE by about eight orders of magnitude. Time-dependent GINGER simulations support the z-dependent gain evaluation plan.

INTRODUCTION

Previously, measurements in the visible-to-VUV regime of z-dependent e-beam microbunching in a self-amplified spontaneous emission (SASE) free-electron laser (FEL) have provided important information about the fundamental mechanisms [1-3]. In those experiments a thin metal foil was used to block the more intense SASE radiation and to generate coherent optical transition radiation (COTR) as one source in a two-foil interferometer. However, for the proposed Linac Coherent Light Source (LCLS), the intense SASE emission is either too strongly transmitted at 1.5 Å or the needed foil thickness for blocking scatters the electron beam too much. On-axis crystals used in Bragg or Laue configurations are also subjected to the intense x-rays and 14.09-GeV electron beams. In order to extend the COTR techniques to the x-ray regime, we have evaluated a novel concept that takes advantage of the fact that x-ray transition radiation (XTR) is emitted naturally into an annulus with opening angle $1/\gamma$ = 36 μrad for 14.09-GeV electrons. This angle corresponds to a projected annular radius of 850/425 μm at a distance of 24/12 m (where 12 m is the LCLS diagnostics station interval). We propose using a thin foil or foil stack to generate the XTR and coherent XTR (CXTR). Additionally, if the foil stack is designed appropriately, resonant XTR (RXTR) would be emitted with enhanced angular brilliance. We would use an annular crystal to wavelength-sort the radiation. The high-power e-beam, incoherent spontaneous emission radiation (SER), and SASE would each go through the on-axis hole in the crystal. Importantly, at the CXTR angular location of 24 m, the SASE and SER are red shifted and would not be Bragg-reflected into the converter crystal and detector. The combined radial position and wavelength selectivity will favor CXTR over SASE by at least eight orders of magnitude. A mosaic crystal would be needed to cover the expected CXTR normalized bandwidth of 0.1%. For the LCLS, time-dependent GINGER simulations indicate that sufficient coherent microbunching and concomitant detectable CXTR occur by z ~ 20 m. This should allow an evaluation of the z-dependent gain and microbunching from this point onward. We believe this to be more viable than sorting the on-axis SER and SASE before the z =40-m point.

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BACKGROUND AND PHYSICS CONSIDERATIONS

One of the major issues is the survivability of foils or crystals put into the intense x-ray and electron beams. Based on assessments done previously [4], it is actually the absorption of a significant fraction of the x-ray power that is the larger challenge. The nominal particle beam parameters of a 1.5 π mm·mrad normalized emittance beam of 1-nC charge and 14.09-GeV energy are projected to result in x-ray power of 10 GW at 1.5 Å.

Issues related to performing a z-dependent gain measurement using intraundulator diagnostic stations are daunting. In particular:

1. The high absorption of x-ray power for the full operating conditions is projected to melt any material at 15 Å and all above carbon at 1.5 Å.
2. The beam energy jitter of 0.1%, or 0.2% in wavelength, compared to the natural bandwidth of 10^{-5} for a diamond crystal monochromator creates a mismatch.
3. The high level of SER for a 3% bandwidth (BW) was projected to mask the SASE radiation in the first 40 m of the undulator string. Of course, in 0.3% BW the SASE would be apparent sooner in z.

We propose that critical information on the FEL performance could be obtained by tracking XTR as it

evolves into significant intensities of CXTR. We take advantage of the fundamental angular distribution of XTR that is annular, in contrast to the on-axis SASE. This is schematically illustrated in Fig. 1.

The features of the diagnostic technique are summarized below. We assume that a low-z foil (carbon or Be) can survive in the 1.5-Å regime as reported, or a lower-power commissioning scheme might be used. In fact, this might be the selective emittance spoiler concept described by Emma et al. [5] to produce fs x-ray pulses with GW peak power, but much lower average power than the full LCLS mode.

Conversion Mechanism

The transition radiation generated at the boundary of a material and the vacuum as the e-beam transits the interface is the basis of this technique. Although the photon yield is lower in the x-ray regime than in the visible light regime, there are still detectable photons. For a single foil we have two interfaces producing x-rays in the forward direction. The signal scales as the square of the number of interfaces if the thickness is an integral phase step. The foil could be inserted at the intraundulator stations at 0 m, 12 m, 24 m, etc. We estimate there would be about 10^4 photons in a 1% BW at ~8 keV from a carbon foil and 1-nC beam.

Resonant X-ray Transition Radiation (RXTR)

To boost the XTR signal, we propose evaluating the RXTR technique developed by a number of laboratories a decade or more ago [6,7] to make an x-ray source based on relativistic e-beams transitioning a foil stack consisting of M foils. They demonstrated that by choosing the thickness and separations in integral phase steps, they could enhance the radiation angular density by a factor of M^2. We need to evaluate if one can scale the beam energies up by 50 and still make a realistic (compact) radiator at 8 keV. The sharpness of the annulus of RXTR depends partly on M, and intensity peak angle (θ_{opt}) depends on $1/\gamma$ and the material plasma frequencies. Even a simple nonresonant stack of five to ten foils would increase the XTR by five to ten over a single foil.

Coherent X-ray Transition Radiation (CXTR)

In addition, the microbunching of the e-beam in the SASE process would enhance the CXTR signal at 1.5 Å by a few orders of magnitude by the 100-m point. As shown in Fig. 2, the spectral content is already narrowed by the 18.5-m point as predicted by GINGER simulations. In Fig. 3, the z-dependent growth of the microbunched fraction of nearly 32% is shown. With high bunching fraction in mind, we now consider a calculation based on extending the model described in a companion paper on coherent optical transition radiation [8,9]. The CXTR spectral-angular distribution is given by a product of functions as shown in Eq. (1):

$$\frac{d^2N}{d\omega\, d\Omega} = \frac{d^2N_1}{d\omega\, d\Omega}\mathcal{F}(\boldsymbol{k}), \qquad (1)$$

where the single particle TR distribution is given by $\frac{d^2N_1}{d\omega d\Omega}$ in the case of a single foil, and the coherence function $\mathcal{F}(\boldsymbol{k})$ is given by

$$\mathcal{F}(\boldsymbol{k}) = N + N_B(N_B - 1)\left|H(\boldsymbol{k})\right|^2, \qquad (2)$$

where the bunching fraction $f_B = N_B/N$ and $H(\boldsymbol{k}) = \frac{\rho(\boldsymbol{k})}{Q} = g_x(k_x)g_y(k_y)F_z(k_z)$ is the Fourier transform of the charge form factors with Q = *Ne* = total charge of the micropulse. The transverse form factors are modeled as Gaussian $g_i(k_i) = \frac{1}{\sqrt{2\pi}}e^{-\sigma_i^2 k_i^2/2}$, i = x,y. In particular we consider $g_x(k_x)$ for the paraxial beam trajectories with $\theta_x << 1$, where $k_x \approx k\theta_x$ and $k = \frac{2\pi}{\lambda}$ with λ the radiation wavelength of 1.5 Å. In Fig. 4 we

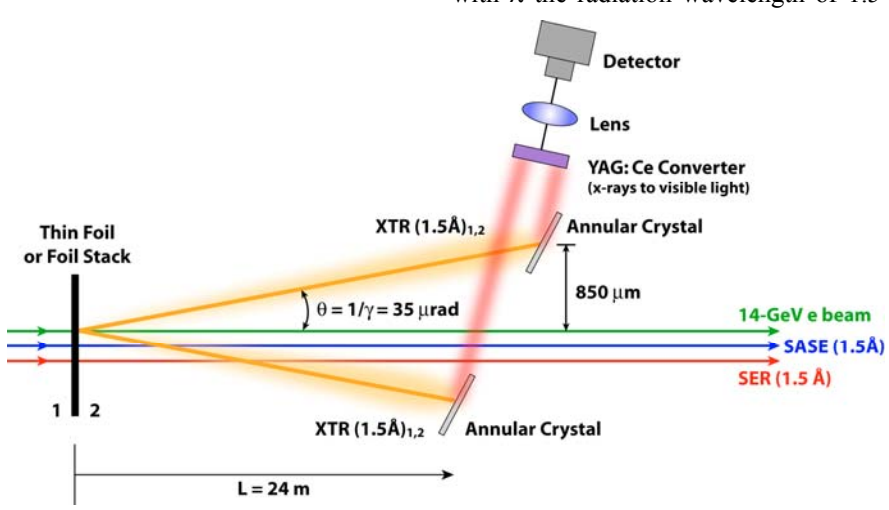

Figure 1: A schematic of the competing beams of SASE, SER, electrons, and XTR in the bore of the FEL vacuum chamber. The thin foil that generates XTR/CXTR and the annular crystal are shown as separated by 24 m in this example. The CXTR angle is expected to fall well inside of the XTR angle due to coherence function factors.

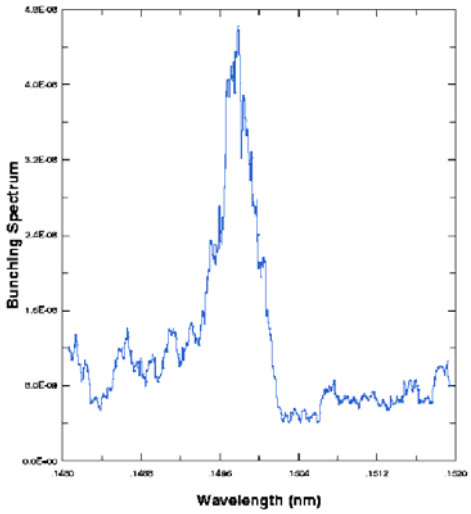

Figure 2: A GINGER simulation of the LCLS showing the microbunching spectral content at z =18.5 m.

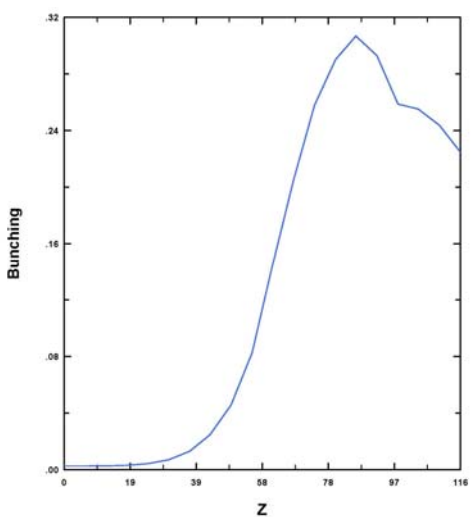

Figure 3: GINGER simulation predictions for the z-dependent microbunching fraction over the wavelength region shown in Fig. 1.

show that CXTR falls well within the $1/\gamma$ cone of XTR for an assumed projected radius σ_x = 5 μm. This assumes some substructure on this length scale in the electron-beam transverse phase space such as occurred in our visible-UV COTRI experiments. The vertical axis is photon intensity per steradian-μbunch-0.1% BW. Since we estimate that 500 microbunches are in a coherence length, the incoherent curve intensity would be multiplied by 500 while the CXTR part would be multiplied by 500^2. The lobes are peaked in the 5-μrad angular regime and would move out in angle for smaller effective beam sizes. We analytically show the effects of a bunching fraction of 0.1, 0.2, and 0.3 as well in Fig. 4. In concept we do have the annular cone versus the on-axis SASE, but we need sufficient CXTR at an angle where the SASE radiation is red shifted out of the crystal bandwidth.

Details of the coherence length and the effective number of electron/microbunches radiating coherently need to be addressed. For a 0.1% BW we estimate that 500 microbunches would be coherent at 1.5 Å. In this case we assumed that the foil-induced scattering or energy straggling will not drastically reduce the microbunching fraction. This aspect needs to be evaluated in more detail.

Detection Concept

At a downstream position (+24 m from the foil for 14.1-GeV energy), we would use an annular crystal to interact with the off-axis XTR concentrated in a ring of radius 850 μm (the CXTR, Fig. 4, will be at a smaller angle/radius due to the coherence function). This crystal would Bragg-select the 1.5 Å x-rays to be directed with high efficiency in its BW (~2×10^{-4} for Ge or Si) to the x-ray detector. A mosaic crystal might increase the BW to 0.1%. The on-axis SASE, SER, and e-beam would each go through the on-axis hole in the crystal. The off-axis SASE or SER would be red shifted ~1.3% by the $\gamma^2\theta^2$ term (at 10 μrad) of the FEL resonance condition given in Eq. 1 for the generated wavelength λ,

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right), \qquad (3)$$

where γ is the Lorentz factor, λ_u is the period of the undulator (3.0 cm), K=3.5 is the undulator parameter, and θ is the angle relative to the beam axis. Unlike CXTR, these red-shifted photons will not satisfy the Bragg's law condition at 1.5-Å wavelength. The x-rays would be directed to an area x-ray detector or possibly converted to visible light with a YAG:Ce converter screen. The visible light would be detected by an area detector or an intensified camera.

GINGER Simulations

Additional information on the source strengths competing in the off-axis location is provided by GINGER simulations of the predicted LCLS performance. Based on 1.2 mm mrad normalized

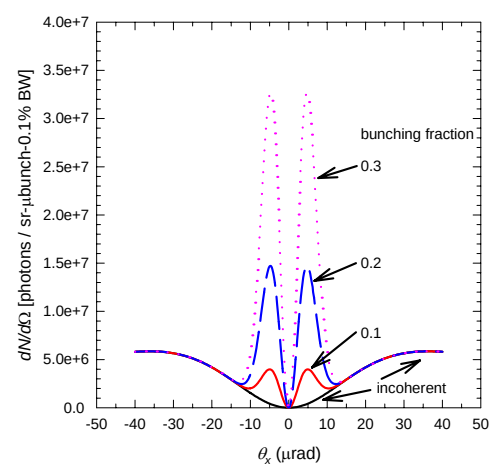

Figure 4: Calculated angular distribution for XTR and CXTR for an effective projected radius of σ_x = 5 μm and 14.1-GeV beam on a graphite foil. The incoherent intensity and those at bunching fractions of 0.1, 0.2, and 0.3 are shown.

emittance, the FEL power saturates at 85 m at a level of ~20 GW and has a power gain length of ~4.4 m as seen in Fig. 5. The peak of the time-averaged microbunching occurs at $z = 85$ m.

Using a GINGER diagnostic of microbunching phase and amplitude, one can calculate the instantaneous microbunching spectrum b(ω) at a given z. By $z = 15.7$ m, the coherent signal-to-noise ratio in 0.6% BW is better than 10:1. Another aspect is the strength of the SASE at the off-axis location. One analytically estimates that the intensity is down by a factor of 10^{-4} at a distance of 4σ for a Gaussian function, which is corroborated by the GINGER simulation at $r = 200$ μm for $z = 42.81$ m as seen in Fig. 6. This effect, combined with the Bragg angle selectivity, explains why we expect to see the CXTR detection favored by eight orders of magnitude over SASE.

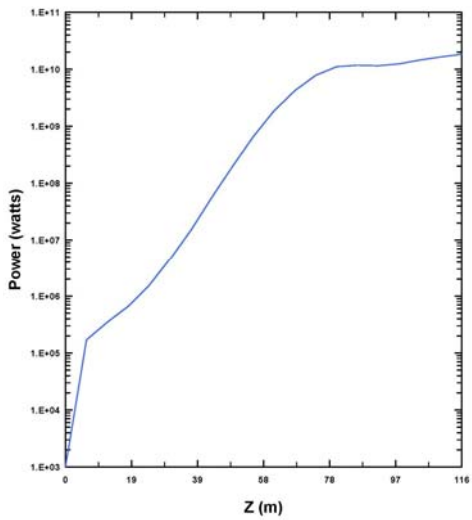

Figure 5: A GINGER prediction of the x-ray SASE power showing the z-dependent gain.

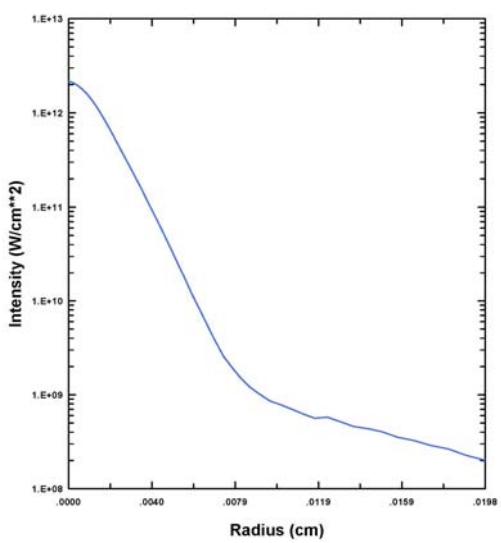

Figure 6: A GINGER simulation of the x-ray SASE FEL showing the SASE radiation intensity as a function of radial position. The intensity has already dropped by 10^{-4} at $r = 200$ μm for $z = 42.8$ m.

SUMMARY

In summary, we have described for the first time an experimental technique to measure the electron-beam z-dependent microbunching in an x-ray SASE FEL. We propose taking advantage of the fundamental annular angular distribution of CXTR as compared to the on-axis SASE radiation and the spectral red shift of the SASE to detect the CXTR at the fundamental x-ray wavelength. Initial experiments on XTR generation are being proposed on SLAC's Sub-Picosecond Pulse Source (SPPS) in the next year.

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REFERENCES

[1] A.H. Lumpkin et al., Phys. Rev. Lett., 86(1), 79, January 1, 2001.

[2] A.H. Lumpkin et al., Phys. Rev. Lett., 88(23), 234801, June 10, 2002.

[3] A.H. Lumpkin et al., "First Observations of COTR due to a Microbunched Beam in the VUV at 157 nm," Nucl. Instrum. Methods (in press 2004).

[4] R. Bionta et al., "Report of the LCLS Diagnostics and Commissioning Workshop," SLAC-R-715 and LCLS-TN-042, 2004.

[5] P. Emma et al., Phys. Rev. Lett., 92(10), 074801-1, 2004.

[6] M.L. Ter-Mikaelian, High Energy Electromagnetic Processes in Condensed Media (Wiley-Interscience, New York, 1972).

[7] M.A. Piestrup et al., Phys. Rev. A., 45(2), 1183, January 1992.

[8] D.W. Rule and A.H. Lumpkin, Proc. of the IEEE 2001 Particle Accel. Conf., Chicago, IL, pp. 1288-1290 (2001).

[9] A.H. Lumpkin, R.J. Dejus, and D.W. Rule, "First Direct Comparisons of a COTRI Analytical Model to Data from a SASE FEL at 540, 265, and 157 nm," these proceedings.