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Comprehensive *z*-Dependent Measurements of Electron-Beam Microbunching Using COTR in a Saturated SASE FEL*

A. H. Lumpkin, R. Dejus. J. W. Lewellen, W. Berg, S. Biedron, M. Borland, Y. Chae, M. Erdmann, Z. Huang, K.-J. Kim, Y. Li, S. V. Milton, E. Moog, D. W. Rule[†], V. Sajaev, and B. X. Yang

Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439 USA

Abstract

We report the initial, comprehensive set of *z*-dependent measurements of electron beam microbunching using coherent optical transition radiation (COTR) in a saturated self-amplified spontaneous emission (SASE) free-electron laser (FEL) experiment. In this case the FEL was operated near 530 nm using an enhanced facility including a bunch-compressed photocathode (PC) gun electron beam, linac, and 21.6 m of undulator length. The longitudinal microbunching was tracked by inserting a metal foil and mirror after each of the nine 2.4-m-long undulators and measuring the visible COTR spectra, intensity, angular, distribution, and spot size. We observed for the first time the *z*-dependent transition of the COTR spectra from simple lines to complex structure/sidebands near saturation. We also observed the change in the microbunching fraction after saturation, multiple fringes in the COTR interferogram that are consistent with involvement of a smaller core of the *e*-beam transverse distribution, and the second harmonic content of the microbunching. The results will be compared to relevant calculations using GENESIS and/or GINGER.

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[†]Carderock Division, NSWC, West Bethesda, MD.

1. Introduction

We initially reported in FEL 2000 [1] the extraction of *z*-dependent information on electron-beam microbunching in a visible wavelength self-amplified spontaneous emission (SASE) free-electron laser (FEL) using coherent optical transition radiation (CTR or COTR) techniques. Since that time we have improved our understanding of the phenomena and addressed in the course of our recent studies several questions discussed at the conference. These items include the observed COTR cone angle, the asymmetries in the angular distribution patterns seen in the COTR interferograms [2,3], the use of the images for the coalignment of the electron beam and the SASE photon beam within the undulator [4], and the observation of the second harmonic content [5].

Perhaps more importantly, we have extended our measurements to the saturated SASE FEL regime as a complement to the Advanced Photon Source (APS) FEL project's thrust to the high-gain regime [6,7]. With an augmented set of diagnostics including a new 10-station transport line to an in-tunnel UV-visible spectrometer, we have observed the onset of sidebands in the COTR spectra for the first time anywhere (to our knowledge). In this case the FEL was operated near 530 nm using an enhanced facility including a bunch-compressed photocathode (PC) gun electron beam, a linac, and a 21.6-m undulator magnetic structure length. An initial comprehensive set of *z*-dependent measurements of COTR intensity, spectra, angular distributions, and spot size was obtained. In addition to observing the transition of the COTR spectra from single lines to complex structure (ascribed to synchrotron sidebands) after saturation, we also observed the change in the microbunching fraction, multiple fringes in the COTR interferogram that are consistent with the involvement of a smaller core of the e-beam transverse distribution, and the second harmonic content of the microbunching. Some initial comparisons of such results to relevant calculations using GENESIS [8] are also presented.

2. Experimental and Analytical Background

In this section the facility and experimental techniques are briefly described as well as some analytical background for the COTR.

2.1 Experimental Aspects

These experiments were performed with a significantly enhanced and altered gun and undulator configuration compared to our initial microbunching experiments. In both cases bunch compression was done so that bunch lengths were sub-0.5 ps (FWHM). However, in the present case we used a photocathode (PC) gun beam [9], a chicane bunch compressor [10], the APS linac, and nine undulators with a total undulator magnet length of 21.6 m as schematically shown in Fig. 1. The electron beam spectrometer at the end of the linac was employed for both energy/energy spread measurements and bunch length measurements. The bunch length technique used excess rf accelerator structure in a zero-rf phase mode to convert the arrival time information into correlated energy changes. The time profile was then displayed in the spectrometer. The emittance of the beam was evaluated by the three-screen emittance measurement technique in a straight section beyond the linac. The operating parameters are given in Table 1.

The diagnostics stations [11] before and between the undulators consist of a YAG:Ce converter, mirror, and thin foil position on an actuator with a camera viewing the YAG:Ce scintillator denoted as Y0-Y9. A second removable 45° mirror is located 63 mm downstream of each YAG actuator. When this mirror is inserted, another set of visible light detector (VLD) cameras were used to view either undulator radiation (UR) or COTR (when the 6-μm-thick foil upstream was inserted). Both near-field focus and far-field focus configurations were possible to provide beam profile and radiation angular distribution information, respectively. In addition, another set of flippable mirrors and lens pairs provided a relay path from each station to an in-tunnel Oriel M257 UV-visible spectrometer. Although four different grating options were available, we usually ran with the 300 lines/mm grating that provided a wavelength span of 80 nm with a resolution of 0.9 nm (FWHM). Both UR and COTR spectral information were obtained in a *z*-dependent manner. In all cases the images were digitized on-line and processed offline. Details of the techniques are reported elsewhere [5,11].

2.2 Analytical Aspects

Some comment is appropriate for the COTR data. In a recently developed analytical model [3], the generation of coherent radiation by a bunch of electrons can be expressed as the product of a term representing the radiation process for a single particle and a term that takes into account the portion of charge that radiates together, constructively in phase. Thus, the number of photons per unit frequency per unit solid angle can be expressed as:

$$\frac{d^2W}{d\omega d\Omega} = \left[N + N(N-1)F(k)\right]\frac{d^2W_1}{d\omega d\Omega}, \tag{1}$$

where $\frac{d^2W_1}{d\omega d\Omega}$ is the single-particle spectral, angular distribution for a two-foil OTR interferometer [12,13]. This latter function has the single-foil OTR term and a $\sin^2$ term that gives the fringe modulations due to interference of the OTR from the two surfaces (thin foil and 45° mirror 63 mm apart). In these expressions N is the number of particles in the bunch and *F*(k) is the square of the Fourier transform of the spatial distribution of the bunch. In the more detailed expressions the transform function includes the beam rms transverse sizes σ_x and σ_y, a longitudinal size σ_z, and a term for the additional modulation in longitudinal distribution due to microbunching that results in enhanced radiation at the fundamental wave number $k = k_r = 2\pi/\lambda_r$ and its harmonics $k_n = nk_r$, n = 1, 2, 3. The fraction of the micropulse that radiates coherently changes with *z* in the SASE FEL in the exponential gain regime. The total number of emitted photons for forward COTR has been shown [14] to be proportional to $(Nb_n)^2$ and $(\gamma/nk_r\sigma_r)^4$, where b_n is the amplitude of the Fourier component of the electron distribution with spatial frequency k_n. In practical terms we thus see strongly enhanced COTR at the SASE FEL fundamental (around

530 nm), and we have initial evidence for second harmonic content. The spectral narrowing is easily seen in the spectrometer data, and then after saturation we observe the sidebands.

3. Results and Discussion

Examples of *z*-dependent gain results, *z*-dependent spectral results, angular distribution measurements, beam coalignment aspects, and the beam size measurements will now be presented.

3.1 COTR Gain

In Fig. 2 we display on a semi-log plot the variation and exponential growth (10^4 to 10^6) of the COTR and UR (for comparison purposes) as a function of *z* in the undulator. In Fig. 2a the saturation is after undulator 6 at 15 m, and in Fig. 2b this occurred a little earlier at ~12.5 m. In this latter case the COTR data clearly show a reduction in intensity at 15 m, which is consistent with a reduction in electron-beam microbunching fraction following saturation. Such a decrease is not seen in the complementary UR data because all the light in the vacuum chamber bore is measured, including significant contributions from the last one or two gain lengths. The COTR data, on the other hand, are generated/sampled at the discrete *z* location of the blocking foil and mirror. We suggest the COTR provides a cleaner signature than UR of the microbunching fraction after saturation, and the peaking of the fraction is one signature of saturation.

3.2 COTR *z*-dependent Spectra

We also for the first time tracked the COTR spectral evolution from the exponential gain regime into the saturation regime. The results are shown in Fig. 3 along with the UR spectra. We observed a single, narrow peak in Fig. 3a and 3a′ in the exponential gain regime (point A in Fig. 2a). After saturation (points B and C in Fig. 2a), the spectra are more complex. The striking, almost regularly spaced (4-5 nm apart) spectral lines are seen in both the COTR and UR spectra for U-7 and U-9. Again we emphasize that each of the six spectra displayed came from a single but different micropulse. They are also each just one example from 100 samples taken for each configuration.

The features in the spectra are reminiscent of those seen in some high-power oscillator experiments of the late 1980s [15-17]. In simulation of those sidebands, synchrotron oscillation/instabilities were used to generate spiking in the longitudinal axis of the micropulse that, when Fourier transformed, resulted in discrete lines in the calculated spectra. We have initial GENESIS SASE FEL simulations for comparable (but not identical) parameters that are shown in Fig. 4. The time domain is shown in Fig. 4a with spikes separated by about 200 fs. Roughly speaking the M spikes in time will be transformed to M discrete wavelength lines as shown in Fig. 4b. These were calculated after undulator 9.

3.3 COTR Interference Patterns

The COTR angular distribution images are obtained by the optics being focused at the far field at each station and with the relevant thin foil and 45° mirror inserted into the beam. The images generally have a number of key features. The asymmetric e-beam size results in asymmetric enhancements in θ_x and θ_y. As shown in Fig. 5, there are weaker horizontal first maxima at ± 1.0 mrad and the stronger vertical first maxima at ± 1.8 mrad. In addition, the θ_y axis shows clearly three to four fringes for both positive and negative angles. The visibility of these fringes in a COTR interferogram has been analytically modeled as described in Reference [3]. In Fig. 6 we show a comparison of the fringe visibility for σ_y=30, 20, and 15 μm. The transform of these beam sizes results in wider and wider bunch form factors in θ_y space, and this factor multiplied the single-electron interference pattern. The vertical fringe peak intensities in Fig. 5 are reproduced fairly well by the σ_y=30 μm case. We ascribe such an effect to the preferential microbunching of a transverse core of the particle beam. The fringe peak positions at ± 1.8, ± 4.5, and ±6.3 mrad are within 5% of the calculated ones for a beam energy of 220 MeV and foil separation of 63 mm.

3.4 Beam Coalignment

Although space precludes a complete description of our emerging studies on the coalignment of the electron beam and photon beam to optimize the FEL performance, significant progress has occurred in the last year [4]. We have shown a clear correlation between plots of gain per undulator and the COTR image intensity and asymmetry in θ_x or θ_y. As a specific proof of the change in the relative intensity of the first vertical fringe maxima, Fig. 7 shows the shift of these VLD3 image peaks from balanced (a) to the $+\theta_y$ side (b), and to the $-\theta_y$ side in (c) due to steering with corrector number 2 located just before undulator 3. The power supply changes of ± 0.9 A generate an angle change of ≈50 μrad. FEL optimization is thus possible by balancing the peak intensities.

3.5 Electron-beam *z*-dependent Size

In some of our other experimental runs, the *z*-dependent COTR intensity scan was performed with all the stations' cameras focused in the near field, i.e., for beam size and profile. A clear decrease in the "observed" electron-beam size is seen from VLD1 to VLD9. In fact we basically reach the resolution limit of the present optics at $\sigma_y \approx 80$ μm. Therefore, beam size would be <80 μm, and this is consistent with the interferogram in Fig. 5. The concept of a transverse core being affected in the microbunching is not normally modeled.

3.6 Harmonic Content

For completeness we briefly report evidence that harmonic content of microbunching has been observed in our experiments as described elsewhere [5]. In this case two solar-blind filters were used to block the fundamental at 530 nm, leaving the COTR image to be attributed to second harmonic radiation since the fringe peaks matched our calculated positions for 265 nm radiation and 220 MeV beam energy.

4. Summary

In summary several new issues have been addressed by a comprehensive set of COTR measurements in a SASE FEL experiment:

a) Direct evidence of the *z*-dependent evolution of microbunching has been measured in the exponential gain regime and even the saturated regime.

b) Spectral sidebands have been observed for the first time in both COTR and UR spectra after saturation.

c) The *z*-dependent far-field COTR images show clear interference phenomena that are related to critical aspects of the microbunching process.

d) The evidence for a transverse “core” of beam being involved in microbunching include both *z*-dependent beam size and fringe visibility results.

e) Initial evidence for COTR second harmonic content has been observed.

f) Comparisons to GENESIS and GINGER are underway.

The full simulation of the details of microbunching and the formation of spectral sidebands could be critical to the extrapolation to the x-ray regime.

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Table 1. Electron-Beam Parameters for the APS Linac with the PC Gun Injector

Rf frequency (MHz)	2856
Beam energy/spread (MeV/%)	217/0.1
Micropulse charge (pC)	110-150
Micropulse duration (rms,ps)	0.2-0.5
Peak current (A)	250-300
Micropulse repetition rate (Hz)	6
Normalized emittance (π mm mrad)	6-8

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Figure Captions

Fig. 1 A schematic of the APS SASE FEL facility. In these experiments the PC gun beam and the chicane bunch compressor were used. The electron-beam diagnostics stations and the optical diagnostics stations between the nine undulators are indicated.

Fig. 2 Examples of the *z*-dependent COTR and UR intensity gain curves at (a) 530 nm and (b) 539 nm exhibiting evidence for gain saturation near 15 m and 12.5 m, respectively.

Fig. 3 A composite of *z*-dependent COTR (left column) and UR spectra (right column) showing the development of sidebands sampled at points A, B, and C in Fig. 2a. A single electron-beam micropulse generated each spectrum.

Fig. 4 An example of initial GENESIS simulations showing the structure in the time domain (a) whose Fourier transform to the frequency/wavelength domain (b) has similar structure at $z = 21.6$ m.

Fig. 5 An example of the COTR interference pattern taken after saturation at VLD-8. The θ_x - θ_y asymmetry implies the effective e-beam size $\sigma_y < \sigma_x$.

Fig. 6 Calculated interference fringes as a function of vertical beam size, σ_y=30, 20, and 15 μm. The relative peak intensities for σ_y=30 μm are consistent with the data of Fig. 5.

Fig. 7 Examples of VLD 3 COTR images showing the effects of beam steering: (a) balanced, (b) steered up, and (c) steered down. The relative peak intensities move with steering at corrector number 2.