

INVESTIGATIONS OF ELECTRON-BEAM MICROBUNCHING AND BEAM COALIGNMENT USING CTR IN A HIGH-GAIN SASE FEL*

A. Lumpkin[†], W. Berg, S. Biedron, M. Borland, Y.-C. Chae, R. Dejus,
J. Lewellen, S. Milton, E. Moog, G. Travish, and B. Yang
Advanced Photon Source, Argonne National Laboratory, Argonne, IL

Abstract

We recently extended our experiments on z-dependent electron-beam microbunching using coherent transition radiation (CTR) into the high-gain, self-amplified spontaneous emission free-electron laser (FEL) regime. The UV-visible FEL at the Advanced Photon Source was operated at 530 nm and 385 nm using the bunch-compressed photocathode gun electron beam, linac, and 21.6 m of undulator length. The longitudinal microbunching of the electron beam was tracked by inserting a metal foil and a mirror after each of the nine 2.4-m-long undulators. The visible CTR generated by the electron-beam interaction was imaged and analyzed for z-dependent intensity, angular distribution, and spot size. Additionally, the image centroids and structures were used in evaluating the critical electron beam/photon beam overlap issue as a complement to the trajectory data from the beam position monitors.

1 INTRODUCTION

We report the demonstration of new diagnostic techniques that address two of the critical aspects of successful high-gain self-amplified spontaneous emission (SASE) free-electron laser (FEL) experiments. These techniques relate to the measurement of the critical electron-beam (e-beam) longitudinal microbunching and the e-beam/photon-beam overlap, or beam co-alignment. These two phenomena are intrinsically related to each other, and this interplay can be uniquely displayed by the imaging of the coherent optical transition radiation (CTR or COTR) generated by the interaction of the microbunched electron beam with a metal foil and a 45-degree mirror inserted after each undulator [1]. The resulting z-dependent sampling of the CTR intensity, angular distribution, and spot size can be evaluated for pattern structure and position relative to the undulator radiation images. Observed lobe patterns are shown to be affected by beam steering and may be explained by a developing analytical model of an asymmetric CTR bunch form factor [2] multiplied by the single-electron optical transition radiation interference (OTRI) function [3, 4]. We describe FEL/CTR experiments at 530 and 385 nm that are both at high gain and exhibit some features of saturation [5]. At the same time we point out the new

potential of diagnostics based on CTR with enhanced signal strengths of $>10^4$ over OTRI-based techniques. This signal level from a 150-pC micropulse is compatible with standard CCD camera sensitivities.

2 EXPERIMENTAL BACKGROUND

The experiments were performed principally in September and December 2000 following the upgrade of the Advanced Photon Source SASE FEL facility. The peak current in the accelerated photocathode (PC) gun [6] e-beam was increased by the implementation of a Chicane bunch compressor located at the ~ 150 -MeV energy point in the S-band linac [7, 8]. In addition, the number of 2.4-m-long undulators was increased from five to nine, providing 21.6 m of total length in the low-energy undulator test line tunnel. A schematic of the experiment is shown in Fig. 1. Digital cameras are used as visible light detectors (VLDs) after each undulator. Band pass filters and neutral density filters (NDF) are used to adjust signal levels into the cameras. With a normalized emittance of $6-8 \pi$ mm mrad, peak currents of ~ 250 A, and energy/energy spread of 217 MeV/0.1%, high gains were achieved ($>10^5$) and saturation of the undulator radiation (UR) gain at 530 nm and 385 nm was reported [5].

The complementary measurements of the e-beam microbunching using the CTR-based techniques were also pursued. In particular, tracking of the evolution of the CTR signal intensities and angular distribution images was performed in a z-dependent manner [1, 9]. The relative positions of the UR angular distribution centroid and CTR angular distribution center/centroid were assessed by the analysis of 100 images taken of each source after each undulator. The insertion of a 6- μ m-thick Al foil and a 45-degree mirror separated by 63 mm was used to generate the CTR interferogram. The foil also was used to block the much stronger UR. A series of rf beam position monitors (BPMs) located after each undulator was used to assess e-beam transverse trajectory through the undulator string. In these initial tests, the relative readings of the rf BPMs between two gain data sets were used. An in-tunnel, Oriel UV-visible spectrometer was implemented for the spectral measurements.

3 EXPERIMENTAL RESULTS

Results on the z-dependent exponential gain of CTR due to the longitudinal microbunching of the

* Work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

[†]lumpkin@aps.anl.gov

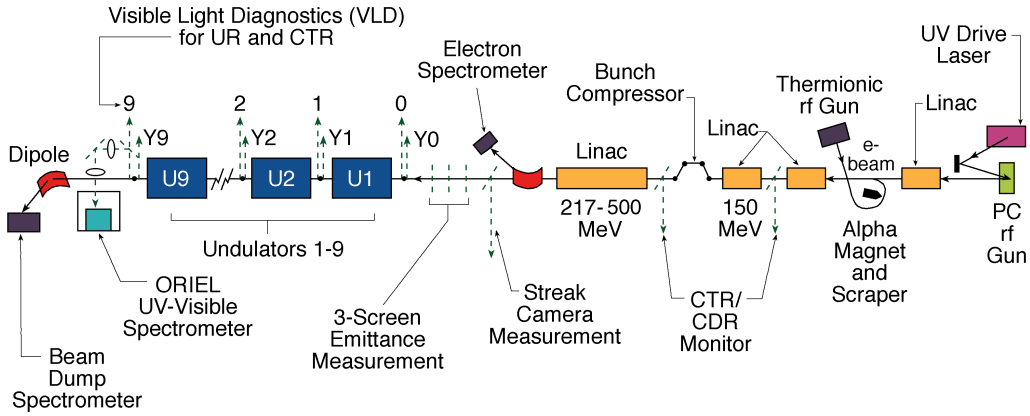


Figure 1: A schematic of the APS SASE FEL experiment showing the PC gun, linac, Chicane, undulators, and optical diagnostics stations.

e-beam and signatures of e-beam and photon beam coalignment are presented in this Section.

3.1 Exponential Gain and High-Gain Regime

Our initial CTR experiments were performed with a thermionic rf gun. We observed both UR and CTR gains of about 100 after five undulators [1]. With the PC gun electron beam, Chicane bunch compressor, and nine undulators, high gains in the 10^5 to 10^6 regimes were attained in the UR gain tests [5]. The CTR gains were similar. It is believed that non-ideal trajectories affected the gain in this particular run, as discussed below.

3.2 Beam Coalignment

In an effort to understand the non-ideal exponential gain curves, we analyzed the data in terms of “gain per undulator” and coalignment of the beams. We evaluated the coalignment of the beams partly by using the sets of observed centroids of the UR angular distribution images and the CTR angular distribution images obtained by each VLD camera. The differences in angular position in θ_x and θ_y were determined and the resultant magnitude calculated as the square root of the sum of the squares of θ_x and θ_y . These resultant angle differences ranged from ~ 0.2 mrad to ~ 1.0 mrad. Since the UR angular divergence is 0.8 mrad (FWHM), one would expect that any pointing difference between the two beams comparable to this divergence would result in reduced gain. In Fig. 2 the upper plot shows the angular difference versus undulator/ VLD station, and the lower plot shows the variation in CTR gain per undulator. The largest angular errors are correlated with the two locations of smallest CTR gain.

As an additional test of the angular pointing issue, we tuned up the SASE gain by peaking the UR signal after each undulator with various steering corrections. We then purposely changed the corrector current setting at station 2 and observed the CTR angular distribution images at VLD3. As shown in Fig. 3, the intensity symmetry of the vertical lobes in 3a becomes asymmetric for a small

steering up (3b) and down (3c) with the corrector power supply currents of +1.4 A and -0.4 A, respectively. We could not measure a definitive image center shift, but the centroids would have been pulled toward the more intense lobe. This may also be explained by an effective asymmetric bunch form factor [2].

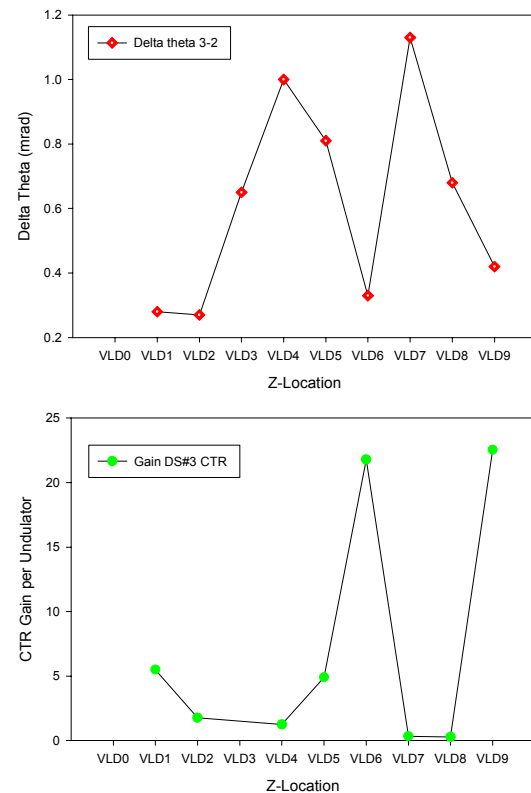


Figure 2: A comparison of the UR and CTR angular center difference after each undulator (*upper*) and the observed CTR gain per undulator (*lower*). Higher gains are correlated with low angular difference at VLD6 and VLD9 and, conversely, lower gains are seen at VLD4, VLD7, and VLD8.

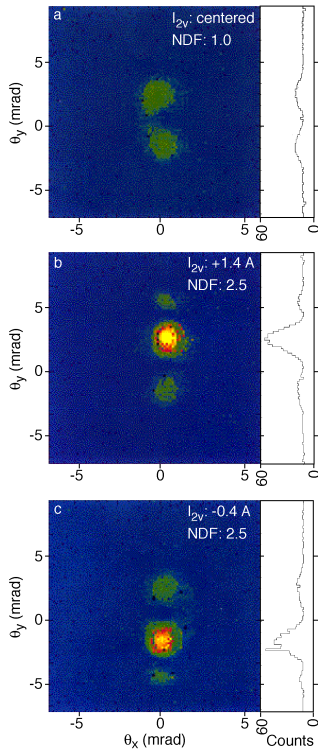


Figure 3: A composite of CTR angular distribution images recorded at VLD3 for different corrector #2 power supply settings for (a) centered for SASE gain run, (b) $I_{2v} = +1.4A$, (c) $I_{2v} = -0.4A$. The change in vertical lobe relative intensity is evident.

As another example, we considered the beam transverse position by using the rf BPMs installed after each undulator. Since the offsets to quad centers were not well known at that time, we relied on a relative trajectory measurement taken between data sets 1 and 3 on December 3, 2000. The two UR gain curves are shown in Fig. 4. Data set 3 shows a shorter gain length in the first five undulators and attains a higher final power. The difference trajectory from the rf BPMs shows a significant horizontal position variation with peaks of $\pm 500 \mu m$. Such a poor trajectory is consistent with the low gain curve of data set 1. A GENESIS simulation of an initial off-axis injection of $300 \mu m$ exhibits a qualitatively similar trajectory with reduced gain compared to an on-axis injection.

3.3 Saturated FEL Regime Spectral Effect

As reported elsewhere [5], the saturated gain regime for the UR has been discussed for the data of the September 2000 run period. The CTR experiments were limited at that time, but one key observation was obtained with the in-tunnel, UV-visible spectrometer. By sampling the 385-nm radiation after undulator 9 in the FEL-saturated regime, we observed multiple spectral lines with 6-to 7-nm spacing in both the CTR and UR. Such a sideband

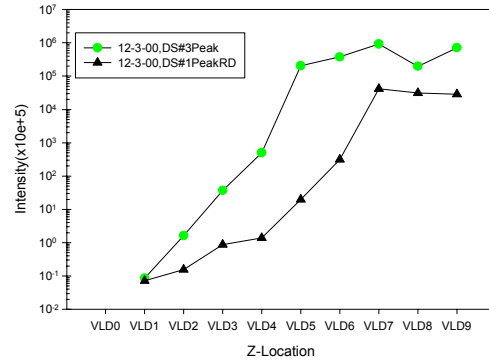


Figure 4: Two UR z-dependent gain curves for different e-beam trajectories as measured by the rf BPMs. Data sets 1 and 3 from 12/3/00 are compared.

spacing might be expected from the synchrotron oscillation of the e-beam in the ponderomotive potential well of an optical field related to a 100-MW peak power. This observation is one of the first such behaviors in a UV SASE FEL.

4 SUMMARY

In summary we have discussed the new diagnostics potential demonstrated by using visible wavelength CTR to track the critical e-beam microbunching z-dependence in SASE FEL. The CTR interferometer offers e-beam diagnostics information (beam divergence and angle) and provides a means to coalign the electron and photon beams, and hence to optimize FEL performance.

5 ACKNOWLEDGMENTS

The authors acknowledge the support of K.-J. Kim, A. Raugas, and J. Galayda at the Advanced Photon Source.

6 REFERENCES

- [1] A.H. Lumpkin et al., Phys. Rev. Lett. 86, 79 (2001).
- [2] D. Rule and A.H. Lumpkin, "Analysis of Coherent Optical Transition Radiation Interference Patterns Produced by SASE-Induced Microbunches," these proceedings (2001).
- [3] L. Wartski et al., J. Appl. Phys., 3644 (1975).
- [4] A.H. Lumpkin et al., NIM A296, p. 150 (1990); D.W. Rule et al., NIM A296, p. 739 (1990).
- [5] S.V. Milton et al., Science (May 18, 2001).
- [6] S. Biedron et al., "The Operation of the BNL Gun-IV Photocathode Gun at APS," Proc. 1999 PAC, p. 2024 (1999).
- [7] M. Borland, J. Lewellen, and S. Milton, "A Highly Flexible Bunch Compressor for the APS LEUTL FEL," Proc. 2000 Linac Conference, Monterey, CA (2000).
- [8] G. Travish et al., "High Brightness Beams from a Light Source Injector," Proc. 2000 Linac Conference, p. 899 (2000).
- [9] E. Gluskin et al., NIM A429, p. 358 (1999).