On-Line SASE FEL Gain Optimization Using COTRI Imaging*

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Abstract

Overlap of the particle and the photon beams in a self-amplified spontaneous emission (SASE) free-electron laser (FEL) is one of the keys to optimizing gain. We have now directly demonstrated an on-line method for gain improvement at 540 nm on the Advanced Photon Source (APS) FEL. This was achieved by steering the e-beam with correctors before an undulator based on the fringe symmetry in coherent optical transition radiation interference (COTRI) images observed after that undulator. For these conditions we determined that both the SASE and COTR image intensities were improved by about a factor of three in one 2.4-m-long undulator section. The initial tuning had been based on rf beam position monitor (BPM) readings and the maximization of SASE image intensity in the cameras.

PACS codes: 41.60 Cr;41.60 Ap

Keywords: free-electron lasers, coherent optical transition radiation, microbunching, beam overlap

1. Introduction

Optimization of the gain in a self-amplified spontaneous emission (SASE) free-electron laser (FEL) is a critical step in the experiment. Besides generating and preserving the ultra-bright electron beam during transport, one must maximize the trajectory overlap of the particle and photon beams within the undulator where the exponential gain process takes place. In the course of performing SASE FEL high-gain experiments at 540 nm at the Advanced Photon Source (APS) low-energy undulator test line (LEUTL) [1], we have used a combination of trajectory adjustments based on rf beam position monitor (BPM) readings, an alignment laser, reference holes in a pick-off mirror, and the intensities observed for the SASE output after each of

*Work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.
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the eight undulators. Due to the inherent fluctuations in the SASE process and the onset of saturation effects, these techniques have some practical limitations.

We have now directly demonstrated a complementary method for gain improvement by steering the e-beam based on the observed fringe symmetry in the coherent optical transition radiation interferometry (COTRI) images obtained after the last of the eight undulators. The intensity of these images is related to the microbunching fraction. We had previously noted the dependence of the theta-x and theta-y planes' symmetries on steering [2,3], but these data are the first quantitative results for gain enhancement. For these experimental conditions we determined that both the SASE and COTRI image intensities improved by a factor of three in one 2.4-m-long undulator section when using this technique. Complementary SASE and COTR z-dependent gain measurements are also reported, and in addition we note further results on transverse profile effects.

2. Experimental Background

The APS SASE FEL experiments were implemented by using a photocathode (PC) rf gun [4], an S-band linac, a chicane bunch compressor [5], a betatron function matching section, and the LEUTL hall where a set of eight undulators are currently installed. These components are shown schematically in Fig. 1. Before and after each of the undulators are located a comprehensive set of diagnostics with a quadrupole magnet and corrector magnets. For completeness, a schematic of the UV-visible diagnostics is shown in Fig. 2 as described previously [6].

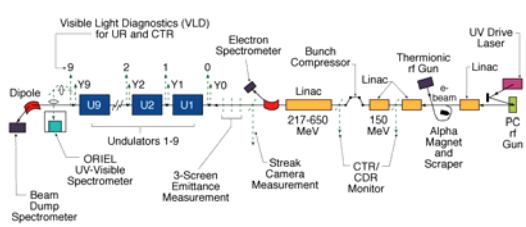

Figure 1. A schematic of the APS SASE FEL facility showing the PC gun, linac, bunch compressor, diagnostics stations, and the LEUTL undulator hall.

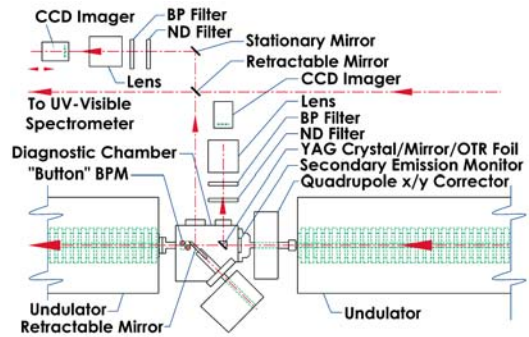

Figure 2. A schematic of the diagnostics stations located before the first undulator and after each of the eight undulators.

The first actuator has positions for a YAG:Ce converter screen with a 45° mirror for SASE light redirection and the 6-μm-thick Al foil used for COTR experiments. A CCD camera with lens views the selected screen for e-beam or SASE light evaluation. At a second location 63 mm downstream, a 45° mirror on a stepper motor can be used to intercept the SASE light and redirect it to another CCD camera, lens, and filter wheel configuration. The lens was upgraded to fused silica to allow UV viewing down to about 220 nm. The camera is on a translation stage so that the distance to the lens can be adjusted for either near-field or far-field imaging. With the insertion of the upstream thin foil that blocks the SASE light, these systems can be used to view the OTR or COTR from the 45° mirror surface in either the near field or far field. In the latter case, the COTRI images are observed as there is interference between the forward COTR from the foil and the backward COTR from the mirror.

Fundamental to these experiments is the ability to use these imaging stations to make SASE gain measurements and to assess microbunching effects via COTR. For the latter, the spectral angular distribution function can be written as

$$\frac{d^2 N_{ph}}{d\omega d\Omega} = \left| r_{\perp,\parallel} \right|^2 \frac{d^2 N_1}{d\omega d\Omega} I(\boldsymbol{k}) \Im(\boldsymbol{k}) \ , \qquad (1)$$

where $$\frac{d^2 N_1}{d\omega d\Omega} = \frac{e^2}{\hbar c} \frac{1}{\pi^2 \omega} \frac{\left(\theta_x{}^2 + \theta_y{}^2\right)}{\left(\gamma^{-2} + \theta_x{}^2 + \theta_y{}^2\right)^2}$$

and $$I(\boldsymbol{k}) = 4 \sin^2\left[\frac{kL}{4}\left(\gamma^{-2} + \theta_x{}^2 + \theta_y{}^2\right)\right].$$

The last term is the coherence function $\mathfrak{I}(\boldsymbol{k})$, which depends on N_B, the number of microbunched particles in the beam, and the charge/bunch form factors [7]. The shape of this function in θ-space directly multiplies the single-electron spectral angular distribution. Mathematically, we can use an asymmetric, split-Gaussian profile or shift the origin or centroid of this function relative to the single-electron function and produce asymmetric product functions in θ_x and θ_y. Physically, we postulate that if the photon and electron beams are not coaligned, then asymmetric microbunching could occur. Currently, none of the SASE FEL codes address this practical issue to our knowledge.

3. Experimental Results and Discussion

The fundamental z-dependent intensity gain measurements were performed as a reference for the experiments. Transport through the undulators was first done using minor bunch compression so that saturation was avoided and the trajectory effects would be visible. The 330-pC bunch was then compressed strongly such that a bunch length of 0.25 ps (rms) indicated a peak current of 560 A. The measured normalized emittances after the compressor were 9.8 and 5.9 mm mrad for the horizontal and vertical planes, respectively.

3.1 Angular Alignment and Gain

As shown in Fig. 3, however, the gain is lower than expected in the first four undulators. Although we do approach the saturation level at a gain of 10^6 compared to the signal after undulator 1, we do not see the long saturated intensity plateau as reported in earlier experiments [1,3]. The SASE image intensities are about 1000 times stronger than the COTR image intensities. Under these operating conditions the far-field images were reviewed as a function of z. In almost all cases the COTRI images lacked symmetry in the θ_x and θ_y planes. We isolated our attention at undulator 8. Figure 4a shows the COTRI image from VLD-8 as we found it. We then used the horizontal and vertical correctors before undulator 8. Horizontal corrections immediately moved the observed fringe pattern towards a more symmetric double-lobe in θ_y as seen in Fig. 4b. There also was some effect observed by using the vertical corrector after the undulator (but still located before the 45° mirror in the diagnostics station). We then acquired another 100 images from the VLD-8 camera at this steering for both the SASE and COTRI cases. In post analysis, the images from before this final steering (DS#3) and after (DS#4) were processed using the same regions of interest, and the integrated intensities were determined. The 50th percentile averages are provided in Table 1, and the ratio of after/before steering is provided in column 4. The SASE gain improved by 3.7 and the COTRI gain by 2.8, just by steering for appropriate fringe symmetry after undulator 8. It is very clear that the charge form factor effectively changed in the COTRI, and mathematically this is simplest to explain as a shift of the centroid location in θ-space. We suggest that the microbunching form factor is dynamically altered when the electron beam and photon beam are not coaligned. Beam time did not permit our repeating the steering technique on the other five undulators where an asymmetric image was found, but we would expect similar improvements up to gain saturation.

Table 1. Comparison of integrated image intensities obtained before and after the COTRI-guided steering for VLD-8

Radiation Type	Before (DS#3) Intensity units 10^5	After (DS#4) Intensity units 10^5	Ratio After/Before
SASE	2.61×10^5	9.56×10^5	3.7
COTR	2.41×10^2	6.78×10^2	2.8

The 50th-percentile integrated intensities are used.

3.2 Transverse Profile Observations

We also investigated the observed e-beam size using OTR and COTR in the first five VLD cameras using the near-field focus as addressed at last year's FEL conference [8]. The COTR beam images were generally two times smaller than the OTR-based beam sizes (which are presumably the real beam distributions). This effect is consistent with our explanation that microbunching is identifiable with a core of beam in the initial gain process, and we have low gain in this particular case. In principle, the

SASE beam centroid and the e-beam-generated COTR centroid could be located at each station and steering done to overlay them. In practice, the various sets of ND filters employed for the range of intensities seem to steer the light beams differently. More effort is needed in this area.

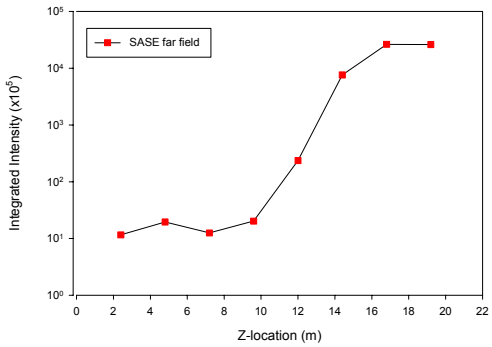

Figure 3. The z-dependent intensity (gain) measurements for SASE using the far-field focus.

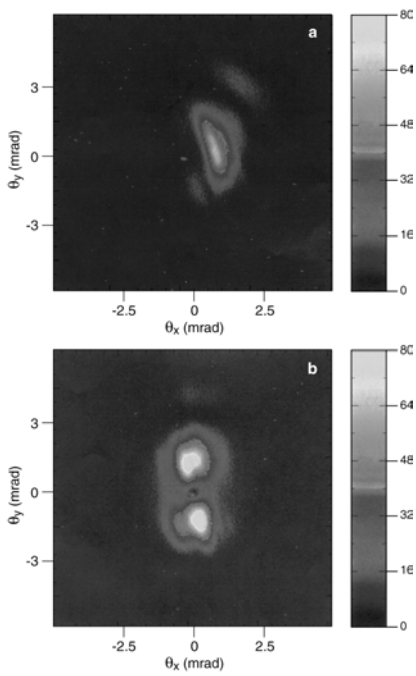

Figure 4. The COTRI image taken after undulator 8 under the gain conditions of Fig. 3, which indicates beam nonalignment (a), and the COTRI image taken after undulator 8 after using the symmetry to guide corrector adjustments (b).

4. Summary

In summary, we have reported a novel technique using COTRI for fine-tuning the electron and photon beam trajectories so that gain is improved. COTRI has the advantage of being more directly related to the SASE process than conventional alignment methods. A systematic application of this technique may lead to optimization of the z-dependent gain process. We have also added to available data in transverse profile effects that may impact the SASE process. We are now planning to extend these studies into the VUV regime, and preliminary results are reported elsewhere [9].

5. Acknowledgments

The authors acknowledge the support of R. Klaffky and R. Gerig of APS.

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