First Observations of COTR due to a Microbunched Beam in the VUV at 157 nm*

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Abstract

The self-amplified spontaneous emission (SASE) free-electron laser (FEL) experiments at the Advanced Photon Source (APS) are now operating in the VUV at 157 nm for a user experiment. In conjunction with these runs, we have obtained the first coherent optical transition radiation (COTR) data due to the microbunching of the electron beam in the VUV. We have used both near-field and far-field focusing by selecting the spherical mirror with the appropriate focal length for the distance to the CCD chip. The optics are such that much higher resolution than our visible system is attained with calibration factors of 11 μm/pixel and 10 μrad/pixel, respectively. Localized effects in the distributions in both focal conditions are being addressed.

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1. Introduction

Following the success of our self-amplified spontaneous emission (SASE) free-electron laser (FEL) high-gain experiments in the UV-visible regime [1,2], the project has pushed on to shorter wavelength work in the VUV near 150 nm. Work in this regime is strongly driven by the interests of a user program based on the single photon ionization and resonant ionization to threshold (SPIRIT) techniques [3]. In order to operate successfully in the VUV, a new set of intraundulator diagnostics was proposed, designed, and installed [4]. These diagnostics are basically analogous to the UV-visible stations only with the camera sensor in vacuum and the filter materials adjusted for the VUV regime.

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Reflective optics are used in these stations, which are currently located after undulators 2, 4, and 6 in the eight-undulator string. A VUV light transport to the endstation where the SPIRIT experiment resides has also been commissioned and is discussed elsewhere [3].

As a complement to the SASE optimization tests, we have preserved the option to perform coherent optical transition radiation (COTR) tests by using a thin foil at a location upstream of the 45º pick-off mirror to block SASE and serve as one element of the COTR interferometer. We also are taking advantage of the much higher resolution in the system to identify localized effects in the electron beam distributions and in microbunching.

2. Experimental Background

These experiments are conducted at the low-energy undulator test line (LEUTL) at the Advanced Photon Source (APS). The facility has been described previously [1], and a schematic is shown in Fig. 1 of our accompanying paper in these proceedings [5]. The rf photocathode (PC) gun is used as the source of bright electron beams. For these experiments the linac beam energy is near 400 MeV with normalized emittances of 6 to 8 π mm-mrad for peak currents of 400 to 500 A. The FEL is generally operated in the 157-nm regime for the user experiments.

In support of the thrust to the VUV, members of the Experimental Facilities Division (XFD) of APS upgraded the diagnostics. The initial plan was to use a Kirkpatrick-Baez (K-B) optics design with imaging capability down to 50 nm [4], but a compromise in the minimum operating wavelength specification for the FEL to 120 nm allowed the use of near normal incidence focusing mirrors without the alignment complications of the K-B mirrors. The final implementation is based on two simple reflective flat mirrors and two selectable spherical mirrors of focal length 900 mm and 2000 mm that provide both near-field and far-field imaging, respectively. The distance between the spherical mirrors and the CCD sensor plane is 2.0 m. This results in calibration factors of 11 µm/pixel and 10 µrad/pixel, respectively. The near-field value was checked by stepping the position of a mask with a known hole pattern through the object plane and recording the hole image positions. A schematic of this portion of the diagnostics is shown in Fig. 1. In addition to the thermoelectrically cooled frame transfer Roper Scientific CCD camera with a 512×512 pixel array sensor, a full suite of bandpass filters, neutral density filters, and attenuators is used. The cameras actually image from the VUV (120 nm) through the visible wavelength regime with a 120,000-electron well depth, and they are used with a 16-bit video digitizer. The camera is based on the Marconi VUV EEV57-10 back-thinned chip with no antireflection coating and can transfer the full image at a maximum frame rate of 3 Hz. A faster rate can be obtained by using a software-selectable region of interest or by binning the pixels. One set of VUV filters is characterized at the 120-nm regime based on metallic films on a MgF_2 substrate (Acton Research Corp.), and another set of metallic fused-silica filters is used in the UV-visible regime from 200 to 800 nm. Seven filter carriers are used to provide the attenuation flexibility needed to cover the OTR, COTR, and SASE intensity ranges. Bandpass filters can also be selected for harmonics measurements.

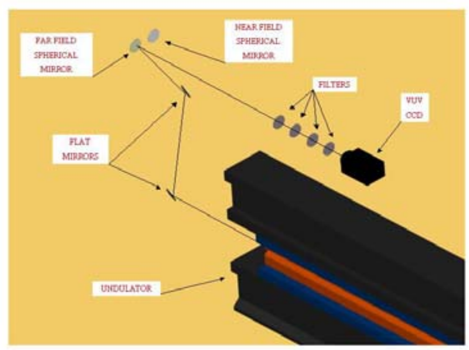

Figure 1. A schematic of the upgraded intraundulator diagnostic stations for the VUV experiments. Reflective optics, filters, and the VUV camera are shown.

3. Initial Experimental Results and Discussion

Beam time for commissioning the diagnostics stations has been limited in the last year due to the focus on user experiments. However, in the process of using the VUV camera to optimize the SASE FEL gain, some ancillary data have been obtained on the microbunched electron beam.

3.1 Near-Field Focus

From the electron beam diagnostics point of view, we have documented that our limiting resolution in the UV-visible system in the near field of 80 and 90 μm for the x and y axes, respectively, was too coarse for the structures we believe are occurring within the photo-injected, bunch-compressed, and microbunched beam. During these experiments we also tried to elucidate the effects of density variations in the beam on final FEL performance. Previously, we reported evidence for microbunching variations in the transverse plane [6], and we suggested that charge density variations generated in the PC gun or the bunch compressor could be reflected in the SASE process. Our work in the past using COTR interference images consistently required the use of beam sizes smaller (<30 μm) than the predicted matched beam size of 100 μm in the y plane to explain fringe visibility [2]. We have now used a high-resolution imaging system [7] at a location located after the chicane. As shown in Fig. 2, the 2-D spatial image of the electron beam after the chicane has several striations in intensity. These are similar to the variations seen by using the `elegant` particle tracking code [8]. Such striations can be generated in the bunch compressor due to coherent synchrotron radiation (CSR) effects depending on the degree of compression. We have suggested that these localized areas of more intense beam would be more likely to give SASE gain.

As part of this investigation, we show an example near-field image of the VUV SASE beam in Fig. 3a and the COTR image in 3b from VUV-4. The thin foil is inserted to allow us to see the COTR VUV radiations emitted from it. The localized intensities in the COTR would imply some hot spots in microbunching. Some features do appear to be sub-100 μm with a separation of about 400 μm. On recent runs we have viewed the high-resolution images at the chicane and then the COTR images for the same setup. The localized structures seen at the chicane seem to be carried over into the COTR microbunching images.

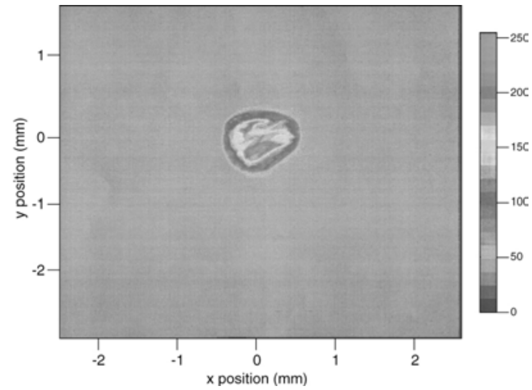

Figure 2. A high-resolution beam image obtained after the bunch compressor during a SASE FEL run. The striations in intensity are visible and may be subsequently accentuated in microbunching as viewed with COTR.

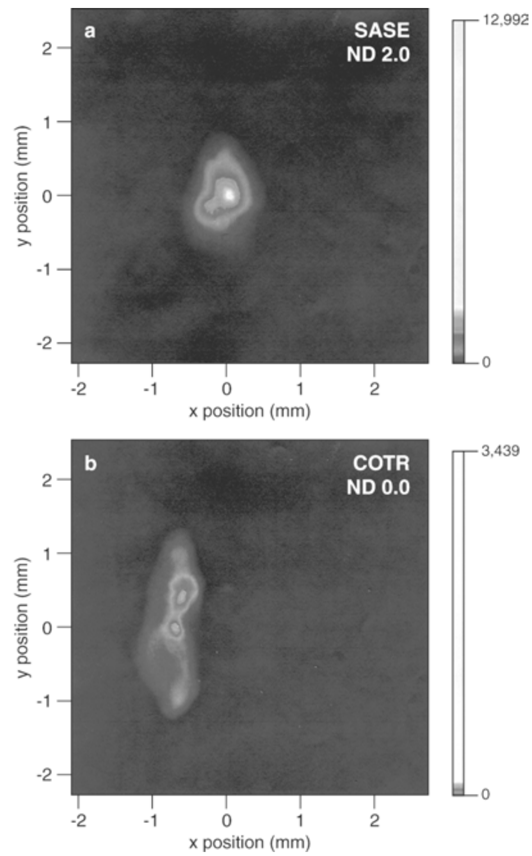

Figure 3. Examples of near-field focus images at 157 nm for a) SASE VUV light and b) COTR VUV light.

3.2 Far-Field Focus

The far-field focus is achieved in principle by selecting the spherical mirror with appropriate focal length for the CCD camera sensor distance using a remotely controlled translation stage. For comparison purposes, the SASE far-field image is shown in Fig. 4a. Its shape is not ideal, but it is relatively smooth. In Fig. 4b the COTR interferometric (COTRI) image is shown. At this beam energy, the first lobes are much narrower in angle at about ± 1 mrad, and the overlap of the bunch form factor and the single-electron interference pattern results in more azimuthal symmetry than the 540-nm case. The calculated calibration factor still needs some validation because the two inner lobes seem to be observed at less than 2-mrad separation.

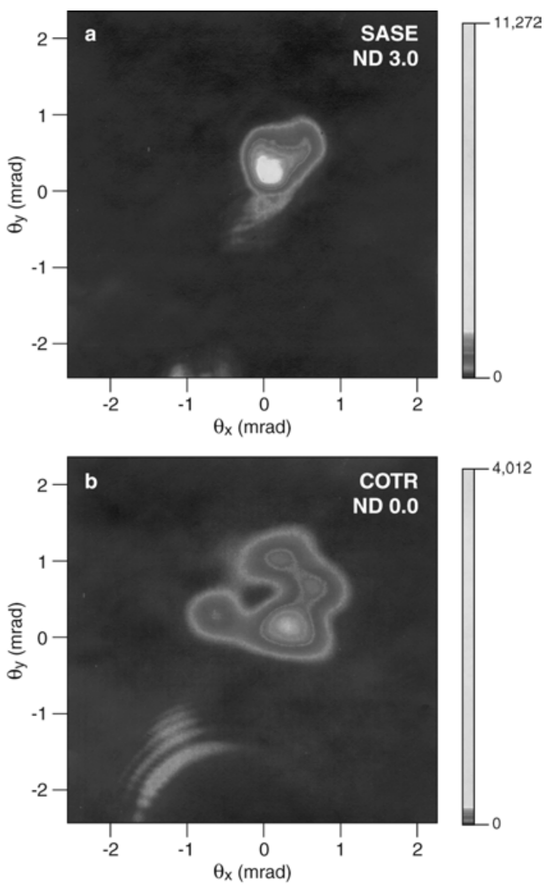

Figure 4. Examples of far-field focus images at 157 nm for a) SASE VUV light and b) COTR VUV light.

4. Summary

In summary, we have begun our experiments on SASE and COTR in the VUV with newly installed reflective optics and VUV-sensitive cameras. The COTR images are the first taken in the VUV, and the high spatial resolution available has facilitated our search for localized, microbunching structure. We are hopeful of cross-comparing beam sizes implied by the COTRI images and these direct measurements. Additional stations after undulators 5 and 7 are being installed, and we anticipate providing more complete z-dependent SASE FEL evaluations and microbunching tests in the VUV in the coming year.

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6. References

[1] S.V. Milton et al., Science **292** (2002) 2037.

[2] A.H. Lumpkin et al., Phys. Rev. Lett. **88**, No. 23, 10 June 2002, 234801.

[3] J.F. Moore, “Photoionization Studies with SPIRIT at the Advanced Photon Source Free Electron Laser,” these proceedings.

[4] P. Den Hartog et al., Nucl. Instrum. Methods A **483**, 2002, 407.

[5] A.H. Lumpkin et al., “On-line SASE Gain Optimization Using COTRI Imaging,” these proceedings.

[6] A.H. Lumpkin et al., Nucl. Instrum. Methods A **507** (2003) 200.

[7] B.X. Yang, E. Rotela, S. Kim, R. Lill, and S. Sharma, Proc. of BIW 2002, AIP Conf. Proc. **648** (2002) 393.

[8] M. Borland, private communication, August 2002.