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First Observations of Electron-Beam Microbunching in the Ultraviolet at 265 nm Using COTR in a SASE FEL∗

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Abstract

We have recently extended our microbunching experiments in a self-amplified spontaneous emission (SASE) free-electron laser (FEL) using coherent optical transition radiation (COTR) to the deep ultraviolet wavelengths (265 nm) for the first time. These experiments were performed as a complement to the Advanced Photon Source (APS) SASE FEL project's thrust to shorter wavelengths. In order to do this, the optical diagnostics have been modified to include UV-sensitive cameras, and an optical transport has been installed that involves sets of mirrors and UV-visible lens pairs after each undulator. These optics provide transport to the in-tunnel Oriel UV-visible spectrometer. Since this is an imaging spectrometer, both spectral and *x*/*y*-plane spatial information are simultaneously available by performing the projections of the images on the *x* and *y* axes. The initial angular distribution data and beam size data have been obtained in a *z*-dependent manner by sampling after every other undulator, or every 4.8 m at four *z* locations. Experiments with sampling of the COTR angular distribution and spectra after each of eight undulators are planned.

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1. Introduction

The complementary information provided on electron-beam microbunching in a self-amplified spontaneous emission (SASE) free-electron laser (FEL) experiment using coherent optical transition radiation techniques (CTR or COTR) has been valuable in the visible regime [1-3]. We have recently extended such experiments to the deep ultraviolet (DUV) wavelengths at 265 nm for the first time using electron-beam energies at 308 MeV. These experiments were performed as a complement to the Advanced Photon Source (APS) SASE FEL project's thrust to shorter wavelengths [4]. In this initial phase the optical diagnostics have been modified to include UV-sensitive cameras, and a new optical transport has been installed that involves sets of mirrors and UV-visible lens pairs after each undulator to provide transport to the in-tunnel spectrometer. The initial angular distribution data and beam size data have been obtained in a *z*-dependent manner by sampling after every other undulator, or every 4.8 m at four *z* locations. Since the single-electron optical transition radiation (OTR) opening cone angle is narrower at 308 MeV than at the 217 MeV used for 530-nm operations, the bunch form factor overlap results in the visibility of additional fringes in the θ_x direction. An intensity gain ratio of about 1000 is observed between U8 and U2 in the COTR. We also report observations of COTR at the second harmonic of 530 nm.

2. Experimental Background

The schematic of the facility is provided elsewhere in these proceedings [5]. These experiments used the photocathode (PC) rf gun, the APS S-band linac, the chicane bunch compressor [6], and the low-energy undulator test line (LEUTL) hardware with a total undulator length of 21.6 m. However, the DUV data were sampled at 4.8-m intervals at four locations so the ninth undulator was not involved in this case. The visible light detectors (VLDs) were replaced in locations 2, 4, 6, and 8 by UV light-sensitive cameras (UVLDs).

The near-field and far-field focus options were retained in the optics and any COTR experiments were done with the appropriate 6-μm-thick *Al* foil inserted at each station.

An additional innovation involved the installation of a full set of mirror and UV-visible lens pairs after each undulator. The ZEMAX code was used to model the transport optics and resolution. This transport directed light to the Oriel M257 UV-visible spectrometer located in the tunnel, as shown in Fig. 1. The lens pair was located at ~1.34 m from the in-vacuum 45° mirror. The lenses had a separation of 36 mm at each station for 530-nm experiments. This transport was initially tested at 530 nm to provide *z*-dependent spectral information [5]. For operations at 265 nm the position of each of the lens pairs will be moved on the carriage on a rail to have z = 1.23 m with a separation of 240 mm. In principle this is an imaging spectrometer, so the 2-D information recorded by the readout camera involves wavelength on the horizontal axis and *x*- or *y*-spatial profile on the vertical axis. Such a system could detect the production of sidebands and the mode size change after SASE saturation. An alignment laser beam at 543.5 nm wavelength was injected into the chamber bore before the first undulator, and the switching mirrors were used to check light transport from all ten pick-off points. The laser line centroid was observed to be the same to ± 1 ch (~0.21 nm) for the 300 lines/mm grating. The slit width was generally used at a 50-μm value, which resulted in a limiting resolution of ~0.9 nm (FWHM) or about 0.2% at 530 nm. If the 1200 lines/mm grating and a 10-μm slit width were selected, then the resolution would be about 0.075 nm (FWHM). The spectrometer's functions, such as slit width, grating, output port, and filter wheel position, were controlled through EPICS as well as the *z*-position of the matching lens and the mirror tilt (pointing) in the optics just before the entrance slit. The gratings are operational down to ~180 nm, but the initial CCD readout camera was visible light sensitive only. With the ability to select a second exit port from the

spectrometer, a UV-sensitive CCD or a microchannel plate intensified (MCP) CCD can be employed. By illumination of a 600-μm diameter reference hole at the 45° mirror position, the optics were adjusted until this feature was clearly detectable in the spectrometer readout camera images. The video images were digitized with a Datacube MV200, and the profile projections from a region-of-interest (ROI) were saved.

3. Results and Discussion

The initial results for *z*-dependent intensity of the COTR, the angular distribution image of the COTR interferogram, the effective *e*-beam size, and spectra as available will now be discussed.

3.1 Gain Results

As shown in Fig. 2, the intensity increase with *z* position is plotted in a semi-logarithmic graph. In this experiment the parameters given in Table 1 were measured just after the gain measurement. The short bunch length of 0.14 ps (rms) with a peak current of 680 A and the emittances of around 11 and 9 π mm mrad for ε_{xn} and ε_{yn}, respectively, result in reasonable gain. The undulator radiation (UR) intensity ratio is about 1000 for the ratio of data from U8 over U2. The COTR data show a slight rollover in gain at U8 like the UR data. These results are from the processing and averaging of 100 images taken at each of the four locations.

3.2 COTR Angular Distribution Imaging

Due to the 63-mm spacing between the thin foil and the 45° mirror, the forward COTR and the backward COTR are in sufficient phase to form an interferogram. The nominal vacuum formation length is $L_v = \gamma^2\lambda\!\!\!^{-}\approx 15$ mm. An example of the COTR angular distribution image at UVLD-6 using the far-field focus is shown in Fig. 3. The single-foil

OTR opening angle would be $\frac{1}{\gamma} = \pm 1.6$ mrad, and the first interference fringe maximum is observed at ± 1.4 mrad. Due to this narrow opening angle in the single-electron function, the bunch form factor overlaps the second fringe position at 3.1 mrad on the θ_x axis. The θ_x - θ_y asymmetry indicates that $\sigma_x < \sigma_y$ at UVLD-6 (see Fig. 4). The analytical model is described in detail in Ref. 7.

3.3 Electron-beam Size

By using the near-field focus condition of the VLD cameras and inserting the thin foil to block the stronger UR, the electron-beam spot size can be measured using CTR. As shown in Fig. 4, the particle beam effective size at VLD4 is much larger than at VLD8. We have previously observed this in the 530-nm experiments. We ascribe this effect to microbunching occurring more intensely in a transverse core of the beam where the charge density is higher. For the nominal beta functions of $\beta_x = 2.7$ m and $\beta_y = 0.66$ m and measured emittances for $\varepsilon_{xn} = 9.0\ \pi$ mm mrad and $\varepsilon_{yn} = 8.0\pi$ mm mrad, one would expect *e*-beam sizes of $\sigma_x = 200\ \mu$m and $\sigma_y = 100\ \mu$m. At VLD8 we are not resolution limited at ~4.0 ch (FWHM) or 1.7 ch (σ). This implies an effective beam size $\sigma_x < 140\ \mu$m.

3.4 UV-visible Spectra

Beam time for spectral measurements at 530 and 385 nm have been allotted. The initial *z*-dependent spectral data at 530 nm are reported in Ref. 5. The actual tests at 265 nm are imminent with the spectrometer, but a surrogate measurement with bandpass filters has been done. This experimental demonstration relates to the observation of the COTR at the second harmonic, ~265 nm. In this case the optics after the sixth and eighth undulators were modified to handle UV wavelengths and the digital cameras were replaced by UV-sensitive ones. Under the conditions of high gain, two solar-blind bandpass filters were employed that

attenuated the 530-nm radiation by 10^4 each while only attenuating the second harmonic by about 40% each. The foil and mirror were inserted and UV radiation was indeed observed with an angular distribution pattern like the COTR for 217 MeV and 265 nm. The approximate intensity ratio of the fundamental to second harmonic was 40. This is supported by various models [8,9] that predict for microbunching the second harmonic content is stronger than that of the third. In particular, using the harmonic bunching parameters provided in Ref. 9, the COTR fundamental-to-second-harmonic intensity ratio is 25 for a SASE fundamental-to-second-harmonic ratio of 1000. In this experiment the optics and camera sensitivities precluded detecting the third harmonic at 176 nm.

4. Summary

In summary, we have obtained direct evidence of electron-beam microbunching using 265–nm DUV COTR, the shortest wavelength observed to date on the fundamental. The results on *z*-dependent intensity, COTR interference images, and beam size from 265-nm operations were described. A preliminary COTR second harmonic experiment was also reported. The *z*-dependent spectral measurements are imminent. The UV diagnostics are being augmented with additional cameras and optics after the other four undulators so that *z*-dependent images will be taken every 2.4 m. An extensive set of measurements will then be possible for comparison to the SASE FEL codes.

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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/%)	308/0.2
Micropulse charge (pC)	210
Micropulse duration (rms,ps)	0.140
Peak current (A)	680
Micropulse repetition rate (Hz)	6
Normalized emittance (π mm mrad)	11/9

Figure Captions

Fig. 1 A schematic of the optical transport at one station for the COTR and UR. The lenses are UV-visible transmitting with the requirement to adjust lens positions between 530-nm and 265-nm operations.

Fig. 2 An example of the *z*-dependent intensity gain curve for the COTR and UR at 265 nm. The radiation is sampled every 4.8 m.

Fig. 3 An example of the COTR angular distribution image obtained after U6. The first two maxima of the interference fringes are clearly seen in θ_x.

Fig. 4 A plot of the *z*-dependent spot sizes obtained with the near-field focus using COTR. The narrowing of the beam spot with increasing *z* is ascribed to the enhanced radiation from the microbunched transverse core of the beam.