INITIAL SEARCH FOR 9-keV XTR FROM A 28-GeV BEAM AT SPPS*

A.H. Lumpkin, J.B. Hastings,** and D.W. Rule***
Advanced Photon Source, Argonne National Laboratory
Argonne, IL 60439 USA

Abstract

The potential to use x-ray transition radiation (XTR) as a beam diagnostic and coherent XTR (CXTR) as a gain diagnostic in an x-ray FEL was proposed previously. At that time we noted that the unique configuration of the SLAC Sub-picosecond Photon Source (SPPS) with its known x-ray wiggler source, a special three-element x-ray monochromator, x-ray transport line, and experimental end station with x-ray detectors made it an ideal location for an XTR feasibility experiment. Estimates of the XTR compared to the SPPS source strength were done, and initial experiments were performed in September 2005. Complementary measurements on optical transition radiation (OTR) far-field images from a 7-GeV beam are also discussed.

INTRODUCTION

The use of x-ray transition radiation (XTR) as a beam diagnostic and coherent XTR (CXTR) as a gain diagnostic in an x-ray free-electron laser (XFEL) was proposed previously at FEL04 [1]. There have been a number of experiments to develop XTR as a source of x-rays in the past at several laboratories using moderate beam energies of a few hundred MeV to GeV [2-6], but there have been no applications in the FEL world to date. Partly based on recent experiments with a 7-GeV beam with optical transition radiation (OTR) and far-field or focus-at-infinity imaging [7], we projected that there should also be useful diagnostic information in the XTR field. In addition, we wanted to evaluate how to measure CXTR in an XFEL at 1.5 Angstroms. We identified the configuration of the SLAC Sub-picosecond Photon Source (SPPS) [8] with its known x-ray wiggler source, a special three-element x-ray monochromator, x-ray transport line, and experimental end station with x-ray detectors as a large-scale and ideal location for an XTR feasibility experiment. It was also the closest setup to what one might encounter in an x-ray FEL such as the Linac Coherent Light Source (LCLS) with its capability of translating in the 3-m undulator segments one at a time in the 100-m string of magnetic structures [9].

A test of XTR intensity with respect to the x-rays emitted by the SPPS wiggler when a 28-GeV beam transited it was proposed. Estimates of the XTR were done, the experiment proposal was approved, and initial experiments were performed in September 2005.

EXPERIMENTAL BACKGROUND

The OTR experiments were performed at the Advanced Photon Source (APS) as described elsewhere [7], and the XTR experiments were performed at the SPPS. The SPPS has been a short-pulse x-ray facility since 2004 [8]. The 28-GeV electron beam with a charge of Q = 3 nC, an emittance of 35 π mm-mrad, and bunch length of 230 fs was transported to the Final Focus Test Beam (FFTB) facility from the main SLAC accelerator [10] and through the single, permanent magnet wiggler as shown schematically in Fig. 1. The SPPS source was tuned to 9 keV by adjusting the wiggler gap, and a three-element x-ray monochromator is used to direct the x-rays down a 50-m long beamline to the end station. In addition, as noted in the schematic, there are several OTR stations with 1-µm-thick Ti foil installed in support of the series of experiments on beam driven plasma Wakefield acceleration by M. Hogan and his collaborators [11]. These Ti foils were used to generate the forward XTR for the trial experiments. A dipole at the end of the electron beam beamline directed the electrons to a beam dump.

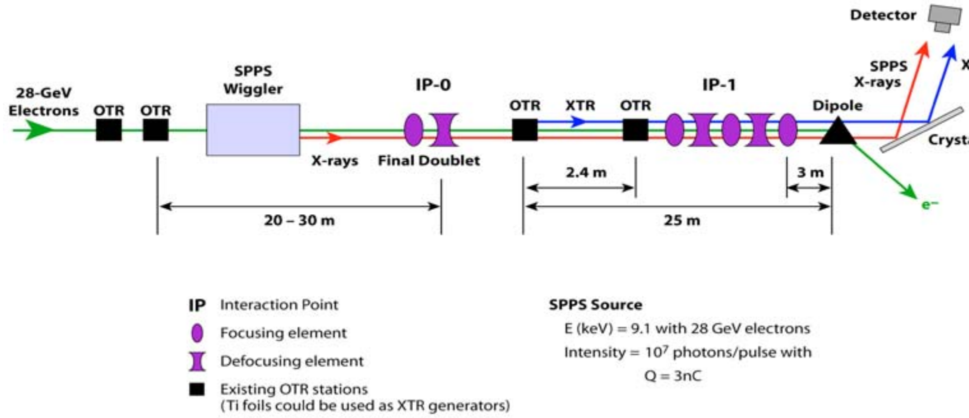

Figure 1: A schematic of the FFTB facility showing the beamline, SPPS wiggler, OTR stations, monochromator, and x-ray detectors.

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**SPPS/SLAC, Menlo Park, CA USA
***Carderock Division, NSCW, West Bethesda, MD USA

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This dipole was the source of broadband x-ray synchrotron radiation (XSR) that also would be interacting with the three-element crystal monochromator. The three-element monochromator was adjusted to transport 9-keV x-rays from the wiggler using a series of x-ray detectors along the beamline.

At the end station an ANDOR x-ray CCD camera and Photonic Science X-Ray Eye intensified camera were used as the principle diagnostic components. The wiggler x-rays were also aligned based on a series of x-ray APDs along the beamline. The ANDOR camera is designed to be cooled to reduce read noise and dark current. Unfortunately on these particular experiments, a small vacuum leak in the camera prevented the final cool down, so we ran it at room temperature. The X-ray Eye was positioned about 1 meter downstream of the CCD camera and was used for initial wiggler beam and hence monochromator alignments. The attenuation of the SPPS source x-ray was done with various selections of Al foil thicknesses that were calculated to attenuate 9-keV x-rays by factors of up to 4000. At 10-keV x-ray energy the counts per detected photon was about 391, resulting in a dynamic range of 167. This assumed a 16-bit device and a gain of seven photoelectrons per count in the CCD.

Aspects of the possible eventual XTR application to LCLS are shown in Fig. 2. In the schematic the beam energy is 14 GeV and the OTR and XTR are generated by a thin foil (or foil stack). For OTR an off-axis mirror might be used, but for XTR an annular crystal would be used. The expected opening angle of the radiation cones in either case would be $1/\gamma$ = 35 µrad. For OTR an imaging system would be used, and for XTR the YAG:Ce converter plus lens and CCD camera might be employed. A far-field imaging experiment with lenses appears feasible for the OTR. This would be done in a manner similar to our recent 7-GeV beam work at APS [7].

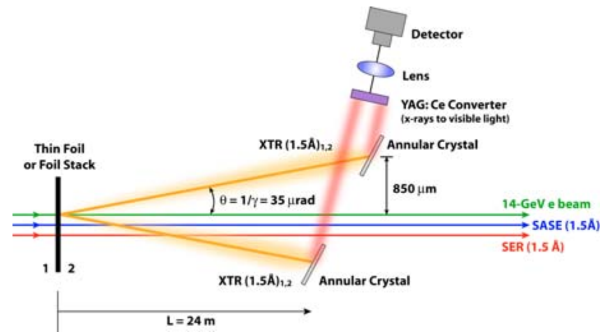

Figure 2: A schematic of the generation of XTR from a foil or foil stack from a 14-GeV beam and with competing wiggler x-rays or spontaneous emission in a SASE FEL.

EXPERIMENTAL RESULTS AND DISCUSSION

OTR Results at 7 GeV

As a point of reference, the results of complementary experiments on the 7-GeV beam at APS are included. In this case a single Al screen was used to generate the backward OTR. At this beam energy the expected OTR opening angle would be 70 µrad. This is within a factor of two of the angle in LCLS and of four in that for SPPS. In Fig. 3 we see the unpolarized, vertically polarized, and horizontally polarized images for the beam extracted from the booster synchrotron. For beam charges of 3 nC one could image these far-field angular distributions. The depth of the central minimum indicates the ensemble beam divergence is much smaller than 70 µrad, probably less than 10 µrad. An analytical model [12] was used to evaluate the expected profiles for different divergences. An example is shown in Fig. 4 for 3-µrad divergence.

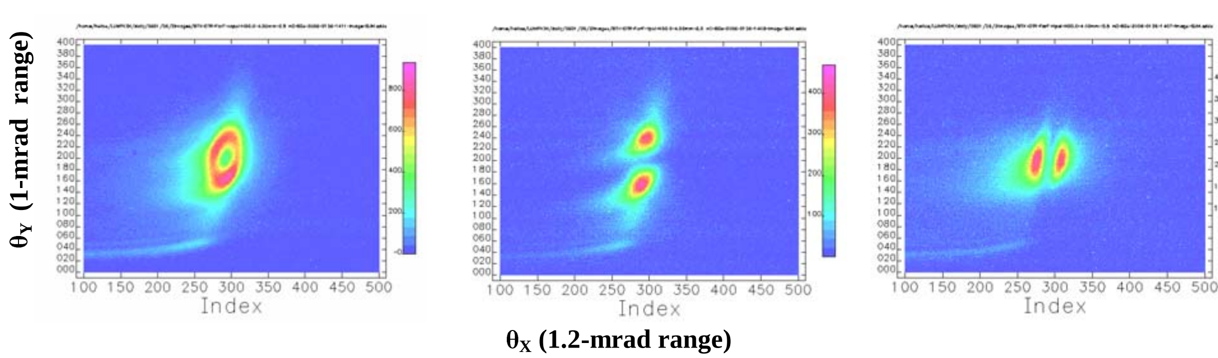

Figure 3: Example of far-field OTR images generated by a 7-GeV beam at APS; a) unpolarized, b) vertically polarized, and c) horizontally polarized.

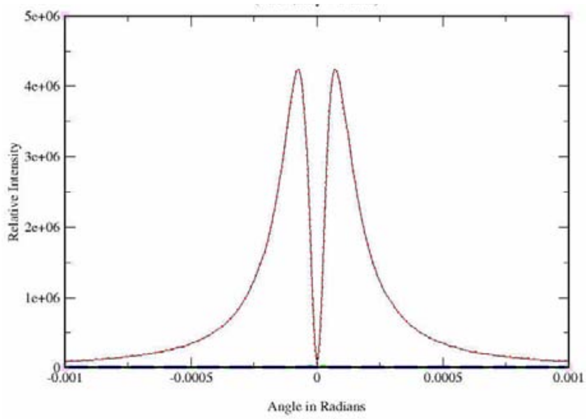

Figure 4: An analytical calculation of the OTR single foil angular distribution for a 7-GeV beam with 3-μrad divergence. The opening angle is ~70 μrad.

9-keV X-rays

In the case of the SPPS experiments we accepted the standard tuneup for 9-keV photons. The nominal intensity was projected to be 10^7 photons per 3 nC of charge. We had calculated the XTR yield from carbon foils as $\sim 10^3$ photons per 3 nC. The initial SPPS result is shown in Fig. 5 using the Al foil attenuation of 1000. The observed image corresponds to supported transport of 30×80 μrad^2. The three-element crystal monochromator is oriented in the horizontal plane with a spatial acceptance of about 1 mm, but subtends larger vertical angles. An example profile is shown in Fig. 6, indicating a vertical FWHM of about 20 μrad. In Fig. 7 we show the 9-keV x-ray image of the background XSR (attributed to the dipole upstream of the monochromator) obtained with the wiggler gap open and foils extracted. The gas nozzle from the experimental chamber just upstream of the x-ray CCD is actually inserted vertically from the top. It shadows the x-rays, and was seen in the horizontal axis because the CCD camera is rotated 90 degrees in the installation. The uniform stripe of the XSR from the vertically deflecting dipole is seen clearly. There is also a ghost image in the 10-shot average due to some camera trigger inconsistency.

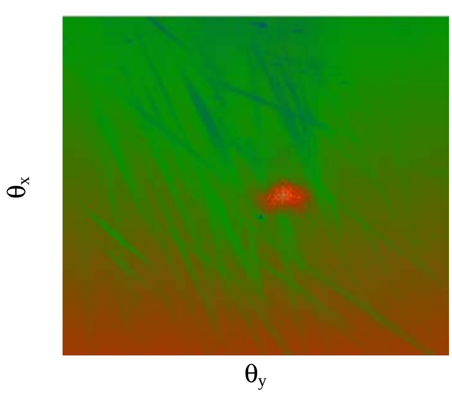

Figure 5: An x-ray CCD image of the SPPS 9-keV x-rays from the wiggler. The camera is rotated 90º so θ_y is along the image horizontal axis. The signal is attenuated by 1000.

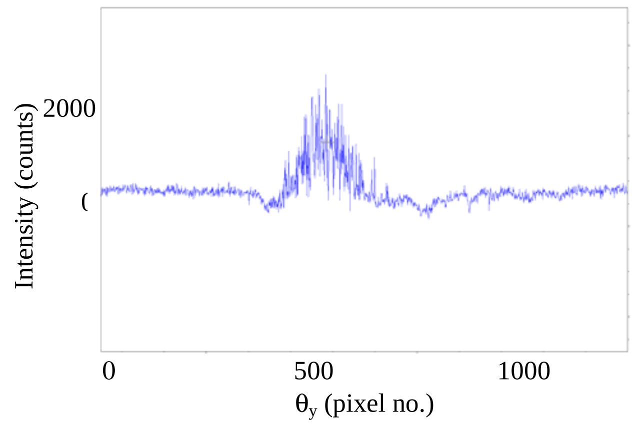

Figure 6: A vertical angular distribution profile from Fig. 5.

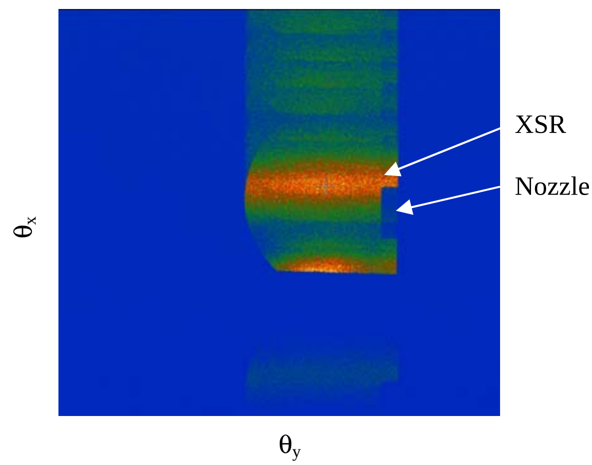

Figure 7: An x-ray CCD image of 9-keV XSR background coming down the beamline. The gas jet nozzle in a chamber upstream of the camera is shadowed. It is vertically insertable.

In Fig. 8 we show the observed x-ray image signal with all three foils inserted using a selected region of interest (ROI) with 4x4 pixel binning and with background subtraction of the signals with the wiggler gap open and all three foils out. This is a localized ROI pixel binning to improve statistics and camera sync. In Fig. 9 the profile in θ_y is shown. There is a hint of an annular shape, and the opening angles are marked on the profile as might be for the middle foil distance. Based on a calibration factor of 1.1 μrad per 4-pixel bin, the 18-μrad location is estimated for a foil at 80 m. In Fig. 10 a calculation for OTR from a 28-GeV beam is shown as a point of comparison for a divergence value of 5 μrad. The central minimum is deeper in the calculation than in the data profile.

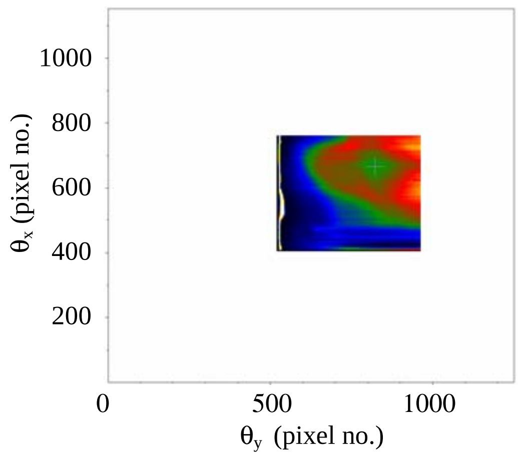

Figure 8: A background subtracted x-ray CCD ROI image of the 9-keV x-rays with three Ti foils inserted.

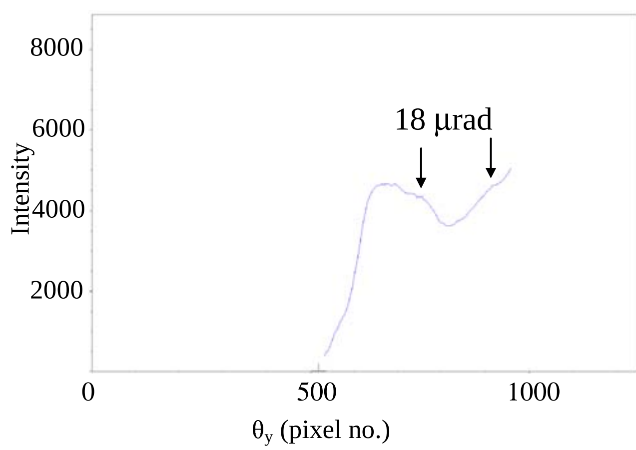

Figure 9: An x-ray CCD region of interest for the three XTR foils inserted case including background subtraction of the XSR source.

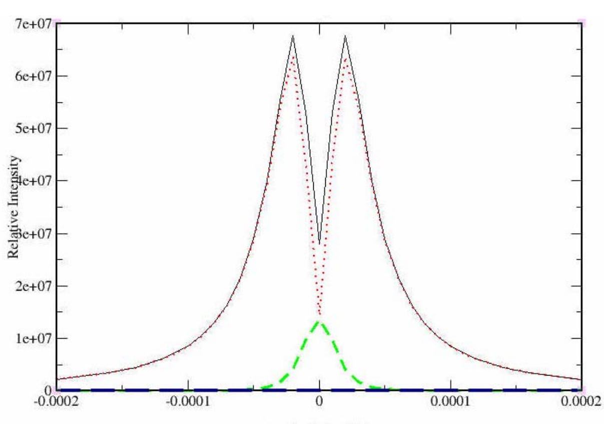

Figure 10: A calculation of the OTR angular distribution for a 28-GeV beam and 5-μrad divergence.

SUMMARY

In summary, we have shown the possibilities of OTR far-field imaging for a 7-GeV beam and report our initial attempts to extend such research to XTR from a 28-GeV beam. Due to the unfortunate event that the x-ray CCD camera could not be cooled during the XTR trials, the results are inconclusive. Certainly, XTR was generated by the Ti foils, but the unambiguous imaging of that radiation was problematical. The concept of a foil stack to enhance the XTR signal and the ability to actually cool the CCD were next on the agenda. The closing of the SPPS facility occurred before these experiments could be done, but the LCLS or SABER facilities at SLAC may provide a future opportunity to test the concepts.

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REFERENCES

[1] A.H. Lumpkin, W.M. Fawley, and D.W. Rule, "A Concept for Z-dependent Microbunching Measurements with Coherent X-ray Transition Radiation in a SASE FEL," Proceedings of the 2004 FEL Conference, Trieste, Italy, Editors: Bakker, Giannessi, Marsi, and Walker, 515 (2005).

[2] A.N. Chu et al., J. Appl. Phys. **51** (3) 1290 (March 1980).

[3] Michael J. Moran, Nucl. Instrum. Methods **B24/25** 335 (1987).

[4] Michael J. Moran, Nucl. Instrum. Methods **B33**, 18 (1988).

[5] M.A. Piestrup et al., Phys. Rev. **A 45** (2) 1183 (1992).

[6] H. Backe et al., Z. Phyz. **A 349** 87 (1994).

[7] A.H. Lumpkin et al., "Developments in OTR/ODR Imaging Techniques for 7-GeV Electron Beams at APS," submitted to Proceedings of BIW06, Batavia, Illinois, May 1-4, 2006, AIP (in press).

[8] J.B. Hastings, "Sub-Picosecond Pulse Source: Recent Results," presented at PAC2005, Knoxville, Tennessee, TOPB002.

[9] R.M. Bionta, "Characterization of X-ray FEL Radiation," presented at FEL2005, Stanford, CA, THOB003.

[10] P. Emma et al., Proceedings of the PAC2003, 3129 (2003).

[11] M.J. Hogan et al., "Review of Beam-Driven Plasma Wakefield Experiments at SLAC," presented at PAC2005, Knoxville, Tennessee, TOPA002.

[12] D.W. Rule, code Singlef, transported to APS Unix system 1992.