ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-TUP038

EXPERIMENTS IN ELECTRON BEAM NANOPATTERNING*

C. Zhang†, W.S. Graves, L.E. Malin and J.C.H. Spence, ASU, Tempe, USA
R.K. Li, E.A. Nanni, X. Shen, S.P. Weathersby and J. Yang, SLAC, Menlo Park, USA
D. Cesar, J.Maxson, P. Musumeci and A. Urbanowicz, UCLA, Los Angeles, USA

Abstract

We report on experiments in nanopatterning electron beams from a photoinjector as a first step toward a compact XFEL (CXFEL). The nanopatterning is produced by Bragg diffraction of relativistic electron beams through a patterned Si crystal consisting of alternating thick and thin strips to produce nanometer-scale electron density modulations. Multi-slice simulations show that the target can be oriented for a two-beam condition where nearly 80% of the elastically scattered electron beam is diffracted into the 220 Bragg peak. An experiment at the two-beam condition measurement has been carried out at the SLAC UED facility showing this effect with 2.26 MeV electrons. We successfully proved a large portion of the main beam is diffracted into 220 spot by tuning the orientation of the sample. Future plans at UCLA are to observe the nanopatterned beam, and to investigate various grating periods, crystal thicknesses, and sample orientations to maximize the contrast in the pattern and explore tuning the period of the modulation. The SLAC measurement results will be presented along with design of the UCLA experiments.

INTRODUCTION

Research to develop compact XFEL [2, 3] based on inverse Compton scattering are being carried on at ASU. We proposed to use a Si grating to generate nanometer scale bunched beam [7, 9] which can be an ideal source for seeding a room-size XFEL. The method depends on diffracting electrons through a thin silicon grating structure to produce a transverse modulation, and then transferring this modulation into the time domain via emittance exchange [5]. The high reproducibility and determinability of electron bunches generated by grating diffraction method will greatly improve the coherence of X-ray output. Proof-of-principle experiments [4,6] have been performed at SLAC's UED facility [8], and new experimental data presented here shows a close match of simulation and experiment showing that the photoinjector beam quality and the stability of the accelerator are adequate to achieve nanopatterning.

We present the results of these studies and discuss plans to carry out grating diffraction experiments at UCLA's Pegasus laboratory in the near future, and study associated beam dynamics.

* This work was supported by NSF Accelerator Science awards 1632780 and 1415583, NSF BioXFEL STC award 1231306, and DOE contract DE-AC02-76SF00515.
† czhan178@asu.edu

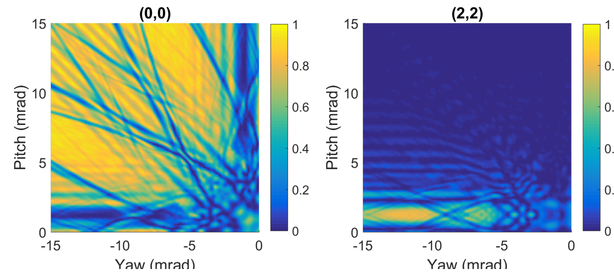


Figure 1: Simulated intensity maps of 200 nm thick planar Si membrane. The color of each pixel represents the normalized intensity of the selected beam. Left is the intensity map of (000) beam, right is the map of (220) beam.

SLAC RESULTS

Previous simulation of Si crystal electron diffraction using multislice method [4] showed a possibility to find a two-beam condition where 80% of the diffracted electron beam is in a single Bragg peak. In the laboratory frame we use pitch and yaw angles with respect to the horizontal electron beam to denote the angular deviation of the beam from the [001] normal to the silicon crystal. The aim of these experiments is to measure the variation in the transmitted (000) and (220) Bragg beams as the diffraction conditions are varied around the exact (220) Bragg condition. To determine the relation between pitch/yaw angle and diffraction intensity, 2D intensity maps shown in Fig. 1 have been created to predict the exact position where we can find the two-beam condition. To create the maps, scans of the pitch (rotation about x-axis) and yaw (rotation about the y-axis) angles have been performed while recording the diffraction pattern and then we processed the images to find the intensity of different Bragg spots as maps of pitch and yaw.

The (000) beam intensity map in Figure 1 shows a dark gap near pitch = 1 mrad, yaw = -12 mrad which is corresponding to the bright strips in the (220) beam map where the direct beam has been mainly diffracted into Bragg spots.

To make a precise measurement, careful calibrations of all rotation angles of the system are needed. The roll angle of the sample corresponding to holder pitch and yaw has been mounted less than 1 degree. Then the sample is aligned in both pitch and yaw angle within ± 0.02 degrees to normal position.

A fine 2D scan over the area of interest was performed to search for the two-beam condition. Figure 2 shows representative patterns of a two-beam condition where the majority of electron beam are scattered into either the forward (000)

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-TUP038

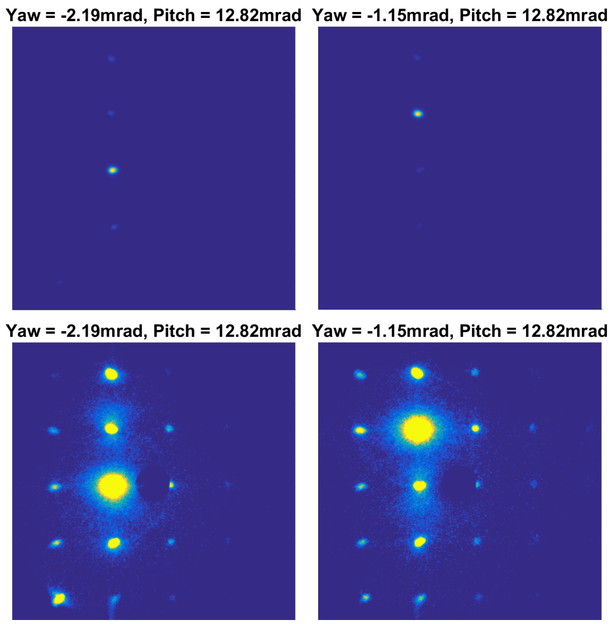


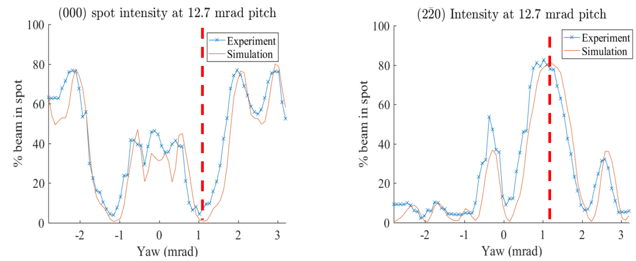
Figure 2: Original and contrast-enhanced Si electron diffraction patterns from SLAC UED facility. Central dark disk is a hole in the YAG:CE scintillator detector. Left column shows the condition where 80% of the forward beam is scattered into (000) spot. Right column shows 80% of the beam diffracting into the (2$\bar{2}$0) beam.

beam or the diffracted (2$\bar{2}$0) beam. Further data analyzing in Fig. 3(a) shows a lineout at pitch = 12.7 mrad illustrating how the intensity varies as a function of yaw. The vertical red dashed line calls attention to yaw = 1.1 mrad where the (000) intensity is nearly zero and the (2$\bar{2}$0) intensity is about 80%, indicating the main beam is diffracted into (2$\bar{2}$0) Bragg spot. Figure 3 (b) and (c) are the simulation and experimental 2D intensity maps of (000) and (2$\bar{2}$0) spot showing a strong agreement between simulation and experiment.

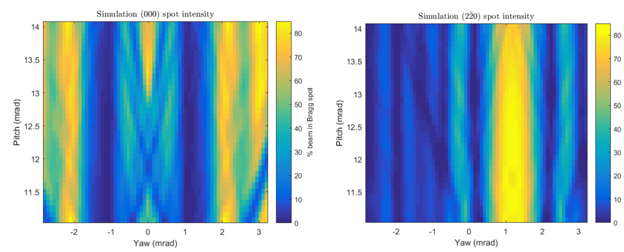
UCLA SETUP

The concept to form a nanopatterned beam is based on two-beam manipulation using a grating. The structure used to pattern the beam will consist of alternating strips of single-crystal silicon and cut through gaps running perpendicular to the beam. Prototype Si gratings are shown in Fig. 4. At the two-beam condition, the cut-through gaps will let all electrons pass through and result in a strong forward beam while other parts of the grating will diffract the beam mainly into the (220) Bragg spot, reducing the intensity of the forward beam. By blocking this forward beam, a grating patterned Si crystal with alternative gaps and thick strips will thus form a density modulated pattern like the grating itself.

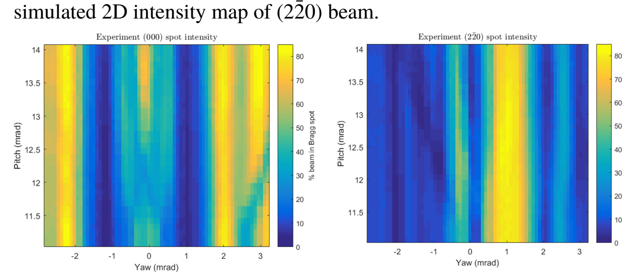
Figure 5 shows a schematic of the concept of nanopatterned beam. We first diffract forward beam at the sample plane by a Si grating, separate forward and diffracted beam by blocking either of them and then magnify or demagnify the pattern with conventional electron optics to get the pattern at image plane.



(a) 1D yaw scan of (000) and (2$\bar{2}$0) spots at pitch equal to 12.7 mrad.



(b) Left is the simulated 2D intensity map of (000) beam, right is the simulated 2D intensity map of (2$\bar{2}$0) beam.



(c) Left is the experimental 2D intensity map of (000) beam, right is the excperimental 2D intensity map of (2$\bar{2}$0) beam.

Figure 3: Experiment data and simulation comparison.

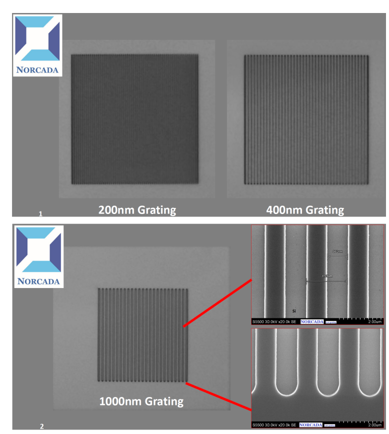


Figure 4: Prototype Si gratings at various pitches. Gratings have a 200 nm thickness and cut-through gaps.

We will take the advantage of UCLA's Pegasus Laboratory's permanent magnet quadrupole (PMQ) triplet which is capable of imaging relativistic electrons [1] to perform next grating diffraction experiment to generate nanometer scale bunched electron beam. The PMQ can be remotely inserted or removed and distance adjusted to change focal length. Their current sample holder setup offers a translational motion and alignment in both x and y. Two rotational stages will be installed to help us get a full scan range to search for

ISBN: 978-3-95450-179-3 doi:10.18429/JACoW-FEL2017-TUP038

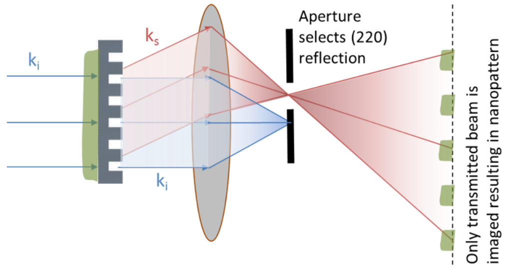


Figure 5: Concept of nanopatterned beam.

two beam condition. A second PMQ will be installed in the image system to give a magnification up to 900X.

As UCLA's UED/UEM facility is capable of imaging the diffracting sample itself, as well as its diffraction pattern, we will mount our sample with the PMQ removed to get the system in a diffraction mode and perform the same alignment procedures as we did in SLAC. Finding the two-beam condition by making 2D pitch/yaw scanning, we choose the spot where the contrast of the forward beam and Bragg-diffracted beam are maximized as optimized working point. After that, a knife-edge is introduced as shown in fig. 6 to block direct beam and let the bright Bragg-diffracted beam go through. Then we add PMQ back to image the pattern. The flexibility of UCLA setup will also allow us to test different modulation period of electron bunched by changing magnification and multiple contrast choices by changing pitch/yaw settings.

CONCLUSION

We presented crystal diffraction results at SLAC UED facility as a method of beam manipulation. By precisely controlling crystal thickness, orientation and rotation angle, one can tune the contrast between main forward beam and Bragg-diffracted beam within a considerable intensity range. Our results show single spot excitation can be predicted through modeling, and is experimentally achievable and repeatable. Further work at UCLA will focus on producing the spatial modulated electron beam with grating Si membrane and test different sample orientation to maximize the contrast between the bright and dark strips. Through EEX, the transform transverse pattern can be transformed into a longitudinal one, this work will provide an ideal bunched electron beam to seed an XFEL using inverse Compton scattering.

ACKNOWLEDGEMENT

We gratefully acknowledge support from the National Science Foundation Division of Physics (Accelerator Science) award 1632780, the NSF BioXFEL Science and Technology Center funded by award 1231306, and DOE grant DE-AC02-76SF00515. The UCLA component of this work is partially supported by STROBE: A National Science Foundation Science and Technology Center under Grant No. DMR 1548924 and by DOE STTR grant No. DE-SC0013115.

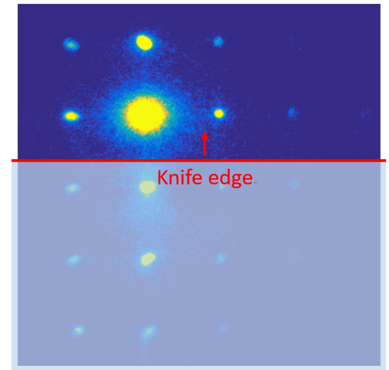


Figure 6: A knife-edge moving in one direction to block direct beam.

REFERENCES

[1] D. Cesar *et al.*, "Demonstration of single-shot picosecond time-resolved mev electron imaging using a compact permanent magnet quadrupole based lens," *Phys. Rev. Lett.* **117** (2016), 024801.

[2] W. Graves, F. Kärtner, D. Moncton, and P. Piot, "Intense superradiant X-rays from a compact source using a nanocathode array and emittance exchange," *Phys. Rev. Lett.* **108** (2012), 263904.

[3] W. Graves *et al.*, "ASU compact XFEL," *Proc. of FEL'17*, TUB03, Santa Fe, USA, August 2017.

[4] L. Malin *et al.*, "Comparison of theory, simulation, and experiment for dynamical extinction of relativistic electron beams," *Proc. of IPAC'17*, THPAB088, Copenhagen, Denmark, 2017.

[5] E. Nanni and W. Graves, "Aberration corrected emittance exchange," *Phys. Rev. ST Accel. Beams* **18** (2015), 084401.

[6] E. Nanni *et al.*, "Measurements of transmitted electron beam extinction through Si crystal membranes," *Proc. of IPAC'16*, TUPMY030, Busan, Korea, 2016.

[7] E. Nanni, W. Graves, and D. Moncton, "Nano-modulated electron beams via electron diffraction and emittance exchange for coherent x-ray generation," arXiv:1506.07053, 2015.

[8] S. Weathersby *et al.*, "Mega-electron-volt ultrafast electron diffraction at SLAC National Accelerator Laboratory," *The Review of Scientific Instruments* **86** no. 7 (2015), 073702.

[9] C. Zhang *et al.*, "Imaging the spatial modulation of a relativistic electron beam," *Proc. of IPAC'17*, MOPAB150, Copenhagen, Denmark, 2017.