IMAGING THE SPATIAL MODULATION OF A RELATIVISTIC ELECTRON BEAM*

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

Abstract

We describe 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 a two-beam situation can be set up where, for a particular thickness of Si, nearly 100% of the electron beam is diffracted. Plans are underway to carry out experiments showing this effect in UCLA's ultrafast electron microscopy lab with 3.5 MeV electrons. We will select either the diffracted beam or the primary beam with a small aperture in the diffraction plane of a magnetic lens, and so record either the dark or bright field magnified image of the strips. Our first goal is to observe the nanopatterned beam at the image plane. We will then investigate various crystal thicknesses and sample orientations to maximize the contrast in the pattern and explore tuning the period of the modulation through varying magnification.

INTRODUCTION

At ASU we are pursuing a novel method of generating electron beams with density modulations at nanometer scale [1] in order to drive a compact XFEL [2] based on inverse Compton scattering, resulting in a much smaller and less expensive XFEL, and at the same time producing fully coherent x-ray output. The output will be coherent in the time domain, unlike self-amplified spontaneous emission (SASE) because the bunching of the electrons is deterministically and repeatably produced by electron diffraction rather than being the product of shot noise amplification. 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 [3]. Initial experiments [4,5] on thin Si crystal membranes have been carried out at SLAC's UED facility [6] to demonstrate the basic diffraction dynamics.

In the present work we are designing proof-of-principle experiments to generate the transverse density distribution and study associated beam dynamics. Plans are underway to use UCLA's ultrafast electron microscopy facility [7] to carry out experiments. If successful this method may produce a coherent hard x-ray pulse that can seed the large SASE XFELs, improving their stability, spectral purity, and brilliance by perhaps two orders of magnitude over SASE amplification.

* Work supported by NSF awards 1632780, 1415583, 1231306 and DOE award de-sc0009914
† czhan178@asu.edu

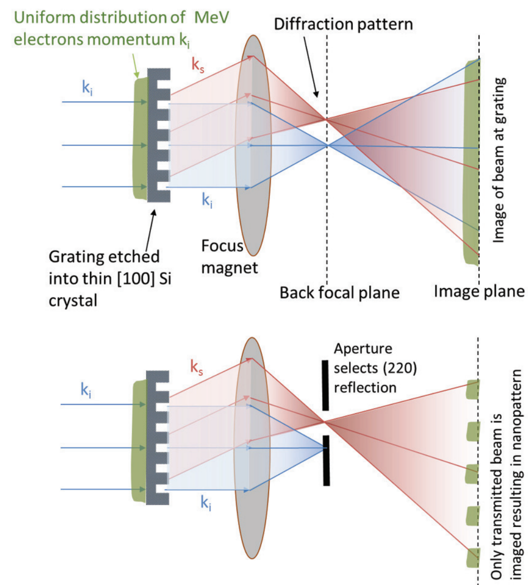

Figure 1: Upper diagram shows electron beam diffracting through crystal in two-beam condition and forming image downstream. Lower diagram shows how image changes if one of the diffraction spots in blocked. The image is then only of the grooves or ridges in the crystal, producing a nanopattern in transverse density, which may be magnified or demagnified with conventional optics.

The extinction length ξ_g of a crystal is the distance in which elastic scattering transfers essentially all of the incident electrons into particular Bragg spot for the two-beam case. It is found by solving the Howie-Whelan equation [8] yielding

$$\xi_g = \frac{\pi V_c cos(\theta_B)}{\lambda F_g} \quad (1)$$

where F_g is the structure factor of unit cell, V_c is the volume of a unit cell, λ is the wave length of incident beam, and θ_B is the Bragg angle of a particular diffracted beam. The intensity of Bragg-diffracted beam (two-beam condition) is then given by [8,9]

$$\Phi_g = (\frac{\pi z}{\xi_g})^2 \frac{\sin^2(\pi z S_e)}{(\pi z S_e)^2} \quad (2)$$

where z is the thickness of specimen and $S_e = \sqrt{s^2 + \frac{1}{\xi_g^2}}$ is an effective excitation error. Equation 2 indicates that the thickness, alignment, and extinction length of the crystal will determine the intensity of diffracted beam. When the crystal is well aligned S_e becomes $\frac{1}{\xi_g}$ so that Eq. 2 can be written

$$\Phi_g = \sin^2(\frac{\pi z}{\xi_g}) \tag{3}$$

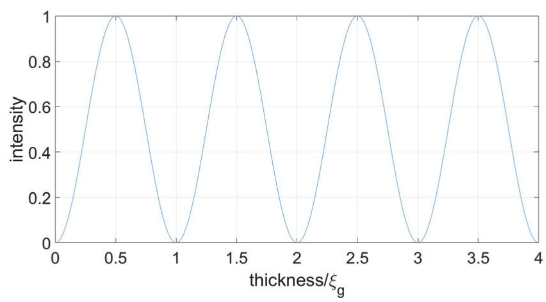

Figure 2: Plot of intensity variation in primary beam as thickness varies from 0 to 4 extinction lengths ξ_g.

Equation 3 shows that as the crystal thickness varies, the intensity of diffracted beam Φ_g changes periodically. This effect is plotted in Fig. 2. The period of intensity variation only depends on extinction distance ξ_g. One example of this effect is the well-known Pendellösung pattern of intensity fringes produced by wedge-shaped specimens. A varying thickness will produce repeated intensity minima and maxima. We are proposing to use a periodic thickness variation (grating) to generate similar intensity variation that can subsequently be converted to a periodic beam current modulation by emittance exchange.

EXPERIMENTAL SETUP

According to Eq. 3, a crystal membrane with a thickness of $t = (\frac{1}{2}+n)\xi_g$, where $n = 1, 2, 3...$ will maximize the intensity of diffracted beam while a membrane with a thickness of $t = n\xi_g$ will minimize the intensity of the diffracted beam. To produce a spatially modulated diffracted electron beam, one can set up a periodical crystal structure with alternating thin and thick strips.

This simple two-beam case ignores multiple and inelastic scattering which becomes more prominent for thicker crystals, reducing the intensity of the Bragg-diffracted beam and creating a diffuse background. This motivates the use of thin crystals, with the thickness determined by manufacturing processes and the need to maintain good structure. Thus setting $n = 0$ or equivalently having a thin strip with a zero thickness (cut through) and a thick strip with thickness of $\frac{\xi_g}{2}$ would be an effective way to reduce inelastic process and get the best contrast between dark and bright strips of the diffraction pattern. Figure 3 shows extinction length in Si as a function of beam energy up to 10 MeV. This calculation is relativistically correct [10], showing its dependence on velocity rather than beam energy, thus flattening out as the beam becomes fully relativistic.

At our planned operating energy of about 3.5 MeV, Fig. 3 shows that the extinction length is about 120 nm. Our initial crystals will have thickness of 200 nm (~ 2 extinction lengths) with the grooves cut all the way through, as shown in Fig. 4. This is a commercial Norcada UberFlat <100> Si device with several different cut-through grating periods, each in a 50x50 micron area. Ridge and slot widths are 200 nm (shown), 400 nm, 600 nm and 1000 nm.

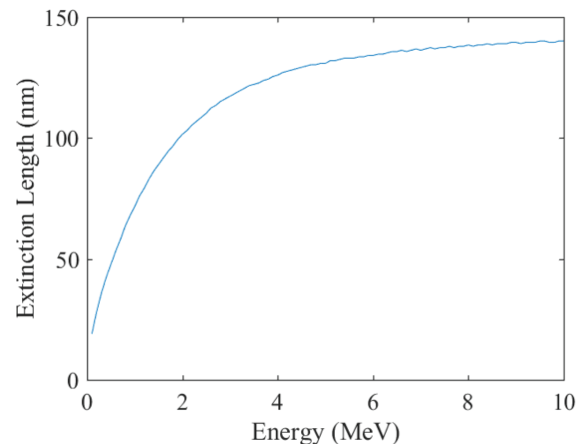

Figure 3: Extinction length vs beam energy including relativistic effects. The extinction length depends on velocity rather than energy.

The experiments will be performed at UCLA's Pegasus Laboratory, where a newly installed permanent magnet quadrupole (PMQ) triplet is used to image relativistic electrons [7]. The focal length is 1.3 cm, providing a magnification of 30X onto a scintillator screen 40 cm downstream that is then imaged with a microscope objective. The sample holder can be inserted and aligned in x and y. The PMQ can be remotely inserted, aligned in x and y, and inter-magnet distances adjusted to change focal length.

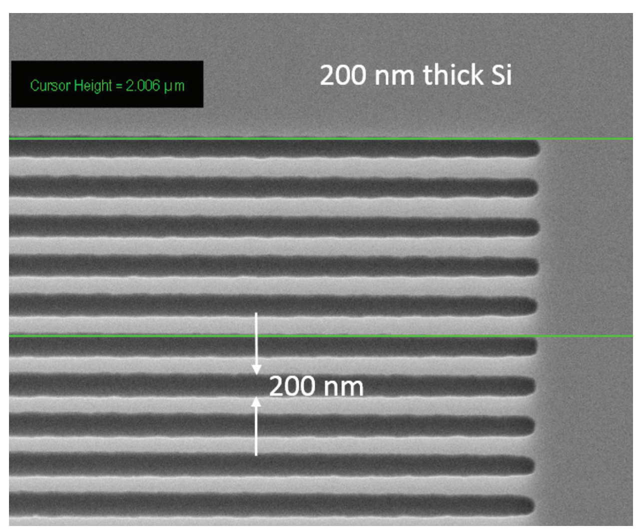

Figure 4: Example Si grating with 400 nm period and 200 nm thickness, courtesy of Norcada.

The Si grating will be mounted in a TEM holder attached to a standard mirror mount driven by picomotors as shown in Fig. 5, giving control of pitch and yaw. Because the picomotors are not reproducible, the absolute angle will be determined by finding the (000) position using the diffraction pattern, and then measuring relative yaw and pitch by reflecting a green HeNe laser from the mirror mount.

From Eq. 2, when the thickness of the specimen is fixed, we can still attenuate the intensity of the diffracted beam by tilting the membrane plane to change the effective excitation error S_e. This provides us a chance to block either the direct beam or the diffracted beam and would be helpful to get dark field and bright field image. Hence we plan to start our measurement at the perfect alignment position of the crystal (incident beam is perpendicular to the membrane plane) and then rotate the crystal in pitch and yaw direction separately to scan the whole area within 0.5 degrees offset from the start point to find the best place that gives us a spatial modulated electron bunches with highest contrast. We will test angles ranging from 0 to 0.58 mrad which is the angular difference between (000) beam to (880) beam at 4 MeV to record extinction data.

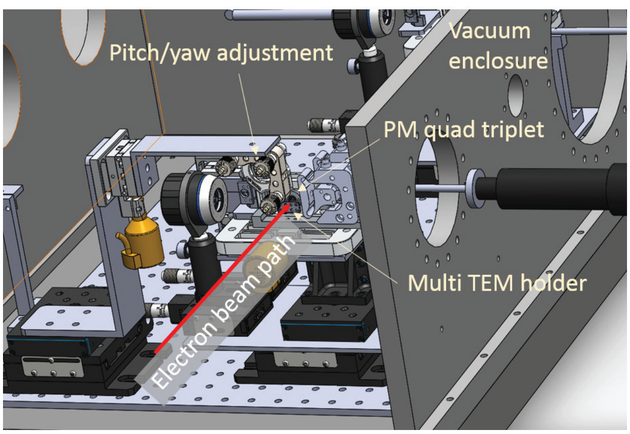

Figure 5: Experimental setup at UCLA showing UHV chamber containing TEM holder in which grating will be mounted, permanent magnet quadrupole triplet to image the diffracted beam, and related equipment.

CONCLUSIONS

We have described upcoming experiments to verify a new approach to generating modulated electron beams using electron diffraction through a thin Si crystal grating. The purpose of this work is to prepare an electron beam for lasing as an XFEL using inverse Compton scattering. If successful, this will creat a fully coherent output beam with a single spike in the frequency spectrum, improving the spectrum, stability, and brilliance of XFEL emission over SASE. We will conduct a set of experiments at UCLA's Pegasus lab to produce the spatial modulation needed in a first step toward these goals.

ACKNOWLEDGEMENTS

We thank Pierre Stadelmann for supplying a relativistic version of the JEMS electron diffraction code and for valuable discussion and technical assistance. We gratefully acknowledge support from NSF Division of Physics (Accelerator Science) award 1632780, the National Science Foundation BioXFEL Science and Technology Center funded by NSF 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. Travel support to IPAC'17 was provided by the NSF Division of Physics (Accelerator Science Program) and the Division of Beam Physics of the American Physical Society.

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