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.
Equation 3 shows that as the crystal thickness varies, the intensity of diffracted beam $\Phi_g$ changes periodically. This effect is plotted in Fig. 2. The period of intensity variation only depends on extinction distance $\xi_g$. One example of this effect is the well-known Pendelloesung 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 energy.

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.

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.

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 pi-
comotors 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.

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REFERENCES