MEASUREMENTS OF TRANSMITTED ELECTRON BEAM EXTINCTION THROUGH SI CRYSTAL MEMBRANES*

E. A. Nanni†, R.K. Li, C. Limborg, X. Shen, S. Weathersby
SLAC National Accelerator Laboratory, Menlo Park, USA
W. S. Graves, R. Kirian, J. Spence, U. Weierstall, Arizona State University, Tempe, USA

Abstract

A recently proposed method for the generation of relativistic electron beams with nanometer-scale current modulation requires diffracting relativistic electrons from a perfect crystal Si grating, accelerating the diffracted beam and imaging the crystal structure into the temporal dimension via emittance exchange. The relative intensity of the current modulation is limited by the ability to extinguish the transmitted beam via diffraction with a single-crystal Si membrane. In these preliminary experiments we will measure the extinction of the transmitted electron beam at zero scattering angle due to multiple Bragg scattering from a Si membrane with a uniform thickness of 340 nm at 2.35 MeV using the SLAC UED facility. The impact of beam divergence and charge density at the Si target will be quantified. The longevity of the Si membrane will also be investigated by monitoring the diffraction pattern as a function of time to observe the potential onset of damage to the crystal.

INTRODUCTION

X-ray free electron lasers (FELs) such as LCLS depend on self-amplified spontaneous emission (SASE) where the initial x-ray pulse generated from shot noise in the electron beam is amplified to several mJ. While the x-ray output is spatially coherent, it retains the broad spiky frequency spectrum of its origin as noise. The brilliance of the x-ray beam can be improved by about 2 orders of magnitude if it can be made temporally coherent, producing an x-ray pulse with full degeneracy.

To move from SASE to full coherence requires a seed pulse, i.e. a low power source of fully coherent radiation at or near the x-ray wavelength rather than its typical start up from shot noise. The seed must have a power significantly greater than that from the SASE startup noise of ~10 kW and high stability from shot to shot. A number of methods [1, 2] of seeding have been proposed including High Gain Harmonic Generation (HGHG), echo-enhanced harmonic generation (EEHG) and self-seeding.

An alternate proposed method to achieve coherence relies on using an electron bunch which is pre-modulated at the x-ray wavelength and colliding it with a laser pulse (inverse Compton scattering (ICS)) [3, 4]. The advantages of this proposed method over the other seeding methods include generation of high intensity x-rays and high shot-to-shot stability, which are both very challenging goals for the other methods. ICS sources use low energy electron beams of a few tens of MeV to produce tunable x-rays in the keV range by back scattering an intense IR laser pulse. The IR laser pulse plays the same role as an undulator for a high energy electron beam, but the much shorter wavelength of the laser light compared to the undulator period allows x-ray production at much lower electron energy resulting in a compact and inexpensive source.

The temporal electron modulation is produced by first creating a transverse spatial modulation through electron diffraction at an energy of a few MeV [4], then accelerating the beam to a few tens of MeV and re-imaging the diffraction grating using standard electron optics before transferring the spatial pattern into the temporal dimension [5] using emittance exchange (EEX) [6–8].

The required transverse spatial patterning of the electron beam will be achieved by passing the beam through alternating thick and thin strips of silicon in the form of a 40 nm-period grating. The thickness of the thicker strips (about 340 nm at 2.5 MeV) is chosen to completely extinguish the direct beam by multiple coherent Bragg scattering within the silicon, via the Pendellosung effect [9]. The thin strips are almost transparent to the electron beam. The result is a transverse spatial modulation of the beam across the downstream face of the grating, which can be re-imaged onto a conjugate plane using a lens with controllable magnification. This spatial period becomes a temporal period following EEX, and must be matched to the laser undulator. By varying the form of the grating and lens magnification, a wide range of time structures may be imposed on the beam.

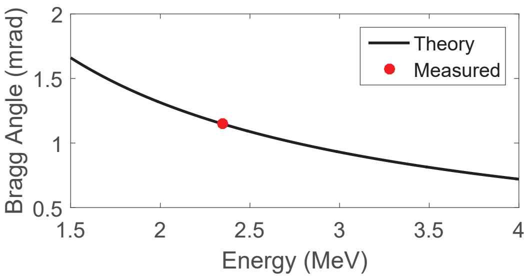

Figure 1: Bragg angle as a function of energy for the [022] peak of a (100) silicon crystal and the measured diffraction angle. The electron beam energy is 2.35 MeV.

Calculations for the effects of “knock-on” ballistic radiation damage show that it will take many months to affect the Bragg diffraction, since the current density for this relatively wide beam is much lower than that used in high-voltage CW

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[†] nanni@slac.stanford.edu

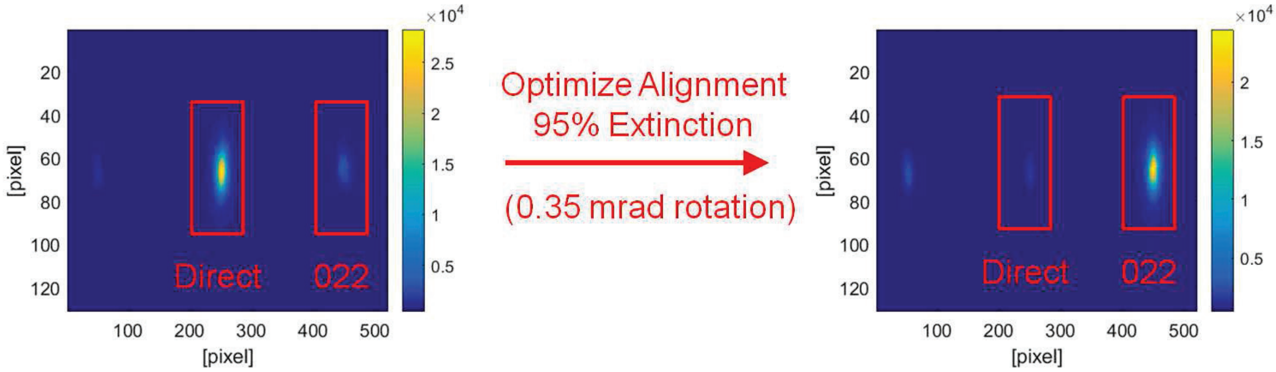

Figure 2: Measured electron diffraction pattern for two crystal orientations.

electron microscopes operating at MeV energies [9]. Following the grating, an aperture is used to block all higher-order Bragg diffracted beams from the crystal planes of the silicon. Since the coherence width of the electron beam is less than 40 nm, no diffraction is expected from the 40 nm grating structure.

DIFFRACTION EXPERIMENTS

The performance of the proposed x-ray source is fundamentally limited by the ability to extinguish the transmitted beam via diffraction with a crystalline target. To investigate the performance of a single-crystal target under realistic operating conditions we used SLAC's ultrafast electron diffraction (UED) facility [10] which is able to produce beam parameters required by this concept.

A uniform thickness single-crystal Si membrane target was used because the SLAC UED setup does not have the imaging optics required to reimage the grating. To determine the electron beam extinction with a uniform thickness we compare the charge between the entire electron bunch, the directly transmitted electron beam ([000] Bragg peak) and the lowest order diffraction peak ([022]). The sample was 340 nm thick (100) silicon which provides a strong elastic interaction with electron beams of a few MeV for the lowest order Bragg peaks. The electron beam energy for these experiments was 2.35 MeV, which was determined by fitting the observed diffraction at the Bragg angle for the lowest order [022] diffraction peak for this crystal orientation, see Fig. 1.

With constant electron beam energy the total bunch charge was varied from a few fC up to 1 pC. The operation of the UED setup was not optimized with increasing charge, but it was found to operate reliably across this full range. The diffraction patterns were recorded with the electron beam converging at the detector located a few meters downstream of the sample. Solenoid scans were performed at each charge in order to determine the emittance [11]. The orientation of the crystal angle was manipulated to maximize the transmission in either the [000] transmitted beam or the [022] diffracted beam. The measured diffraction pattern at these two extremes is shown in Fig. 2. In Fig. 2 the total electron bunch charge is 12 fC with a normalized transverse emittance of $\epsilon_x = 7$ nm-rad $\epsilon_y = 10$ nm-rad. The solenoid scan used to determine the emittance for this charge is shown in Fig. 3. With only a 0.3 mrad tilt it is possible to transfer over 90% of diffracted electrons from the [000] to the [022] peak. No degradation in emittance was observed for either the transmitted or diffracted electron beams as shown by comparison in Fig. 4 and Fig. 5.

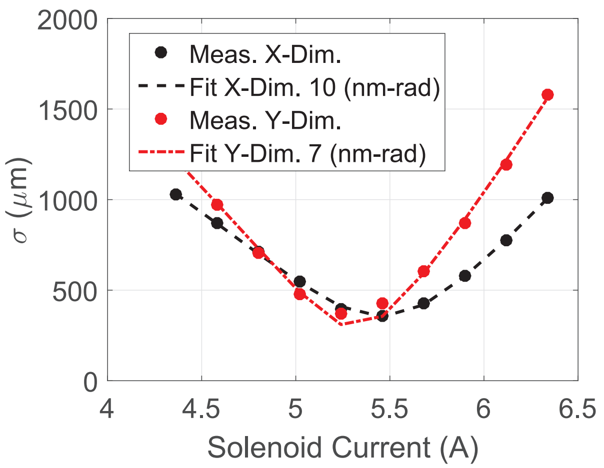

Figure 3: The measured and fitted beam waist at the detector as a function of the solenoid current.

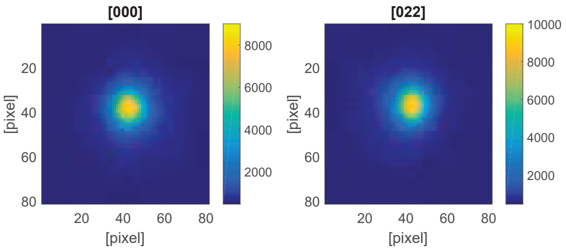

Figure 4: (left) The [000] transmitted and (right) the [022] diffracted electron beam.

The total counts detected for the transmitted and diffracted electrons is shown as a function of the pitch angle in Fig. 6. Also plotted is the total charge appearing in all observable diffraction peaks (roughly the $[0, \pm 3N \times 2, \pm 3N \times 2]$) and the total charge detected in the image. This figure shows

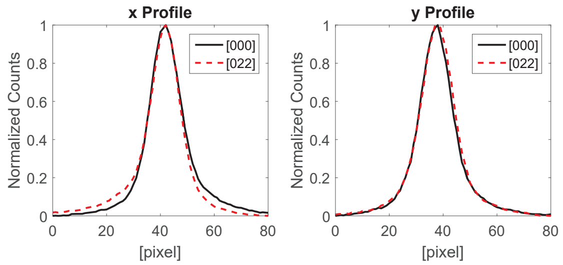

Figure 5: Comparison between the (left) transverse and (right) vertical charge density profiles of the [000] transmitted and the [022] diffracted electron beam.

that the majority of the charge is in fact found in either the [000] transmitted or the [022] diffracted electron beam for our optimized crystal orientation. The difference in total charge and the sum of transmitted and diffracted electron is negligible indicating that almost no electrons undergo inelastic scattering. The decrease in the total number of counts for large angles is attributed the increased participation of higher order diffraction processes which result in electrons diffracted outside the detection area.

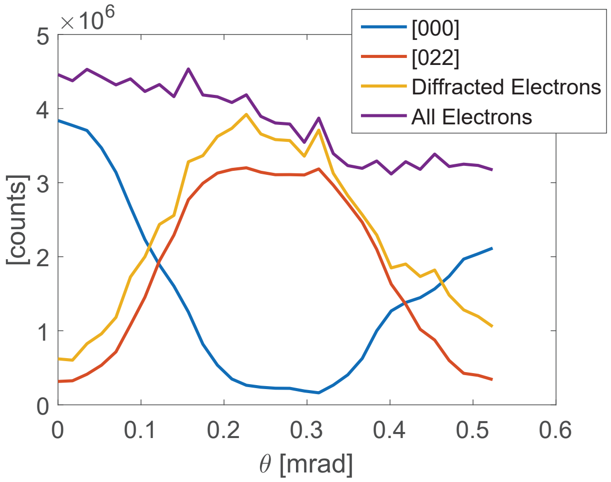

Figure 6: A comparison between the measured counts for the [000] transmitted beam and the [022] diffracted electron beam as a function of rotation angle.

With the low emittance beam produced by the SLAC UED setup we observed that the efficiency with which we can extinguish the direct beam was not adversely affected until reaching charges of nearly 1 pC. In Fig. 7 we show the measured extinction as a function of total electron charge either normalized to the total charge incident on the sample or scattered into the [022] peak. An extinction of greater than 90% would produce an excellently modulated electron bunch for subsequent manipulation by the accelerator required for the x-ray source. By optimizing the operation of the RF photo-injector with a charge of a few pC we believe it will be possible to maintain sufficiently low emittance and extend this approach to higher charges which increases x-ray production as the square of the total charge.

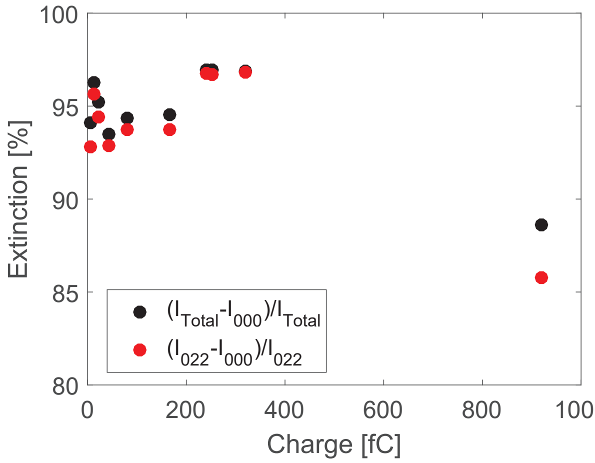

Figure 7: The beam extinction as a function of electron bunch charge.

CONCLUSION

In a preliminary set of experiments using a uniform thickness perfect crystal silicon membrane at SLAC's UED facility we demonstrated the achievable modulation depth with MeV transmission electron diffraction in thin crystals and provided a benchmark for the ability of thin crystals to resist damage from the electron beam. With the correct orientation we can extinguish the incident (direct) beam by over 90% by matching the scattering condition for the [022] Bragg peak. This extinction shows that the depth of the electron bunch modulation we can produce is excellent with a low emittance beam. This behavior was observed for electron bunch charges up to 1 pC which was the highest available charge during the experiment.

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