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Channeling and radiation experiments at SLAC

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ABSTRACT

Over the last years, a SLAC-Aarhus-Ferrara-CalPoly collaboration (augmented by members of ANL and MIT) has performed channeling experiments using bent silicon crystals at the SLAC End Station A Test Beam as well as the FACET accelerator test facility. These experiments have revealed a remarkable channeling efficiency of about 24% under our conditions, as well as shown the dechanneling rate to be independent of the beam energy; an unexpected result. Volume reflection appears to be even more efficient with almost the whole beam taking part in the reflection process. In our most recent experiment we have attempted to measure the spectrum of channeling and volume-reflection gamma radiation. The goal of this series of experiments is to develop a crystalline undulator capable of producing narrow-band gamma rays with electron beams. Such a device could have applications in gamma-ray radiography as well as spectroscopic applications.

1. Introduction

Channeling in bent crystals has been thoroughly studied for protons with the purpose of, e.g., proton extraction at accelerator facilities [1–3] and for collimation [4–6]. Until recently, much less has been known about channeling of electrons and positrons in bent crystals at high particle energy. Our group has been studying planar electron and positron channeling at the SLAC End Station A Test Beam (ESTB) and the Facility for Advanced aCcelerator Experiments and Tests (FACET) at beam energies up to 20 GeV. From the onset of these experiments we found the channeling efficiency to be significant even for electrons, albeit less than observed for protons at similar beam energy. The experiments were performed using a bent, quasi-mosaic (1 1 1) Si crystal of 60 μm thickness. The (1 1 1) plane has two different lattice spacings—0.76 and 3.2 μm effectively—which is considered an advantage for electron channeling as the highest density of channeling electrons is in the middle of the narrow channel, thus does not coincide with the "nuclear corridor" that would increase the dechanneling probability. A plot of the potential for our crystal is shown in Fig. 1 of Ref. [8]. These experiments—which have produced a body of data important for any practical application of crystals in collimation or other manipulations of electron beams at high energy—have enabled us to probe further and shift our experimental program towards the radiative aspects of channeling and volume reflection and begin investigating undulator structures. In this overview we will first summarize the channeling data and then describe our more recent experiments investigating the radiation generated. The experimental setup is shown in Fig. 1 which shows the recent additions of a sweeper magnet and a gamma-ray calorimeter to allow the isolation and detection of gamma rays. Not shown is a thin scintillator paddle upstream of the calorimeter which we used to verify the absence of charged particles when the sweeper dipole was energized. The 20-GeV positron experiment referred to below was done at FACET with a setup that was in substance the same even if the detailed detectors were different.

2. Electron channeling efficiency

Channeling efficiency and dechanneling-length measurements were carried out with our quasi-mosaic bent crystal of 60 μm

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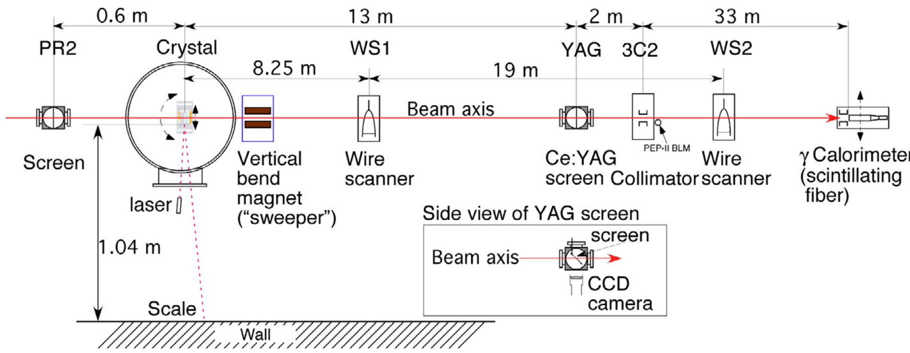

Fig. 1. Layout of the channeling and radiation experiments in the SLAC ESTB. "Counter" refers to the SciFi gamma detector.

thickness and 0.15 m bending radius [7]. A summary of the data is shown in Fig. 2 together with simple model calculations. The dechanneling length turns out to be roughly independent of beam energy between 40 and 60 μm, consistent with DYNECHARM++ simulations but requiring a modification of the usual theoretical model for the dechanneling length. This initially unexpected result is important in energy scaling. The fitting function is

$$L_D = 15.3\left[\frac{\mu\text{m}}{\text{GeV}}\right]\cdot E\left(1 - k_c\frac{2R_c}{R}\right) \quad (1)$$

with $k_c = 1.76$ determined by the fit. More details are given in [8]. It is clear that the energy dependence of the dechanneling length for electrons is qualitatively different from that for protons.

Channeling efficiency is hovering around 22%, which makes application of the channeling effect in beam-collimation systems for electrons a bit questionable. However, we found volume reflection (VR) to be effectively about 95% efficient and therefore a good candidate for collimation application.

The experiments also allowed us to assess the amount of multiple scattering, which shows itself in the "free" direction, i.e. vertically in our setup. We found that the *rms* width of the scattering angle goes up by about a factor of 2 compared to the width of multiple scattering in amorphous orientation of the crystal—see Fig. 3. The measured angular width in amorphous orientation agrees with the multiple-scattering formula [9] to within 10%. The naïve explanation for this effect is that the channeled electrons are oscillating around the crystal plane. In this region both nuclear and atomic electron density is higher than their average densities in the crystal. Therefore, the multiple scattering effect is stronger than in the amorphous case. In another report at this conference it is indicated

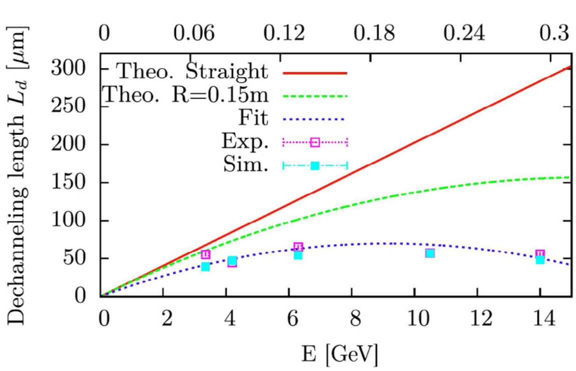

Fig. 2. Dechanneling length *vs* beam energy in our bent Si crystal with a bending radius of $\rho = 0.15$ m. The numbers on top are R_c/R (R_c is the Tsyganov radius).

that indeed the shorter dechanneling length of electrons are a density effect [10].

3. γ radiation

Electrons (and positrons) will radiate violently if deflected with sufficiently tight bending radii. In order to detect and possibly record a spectrum of the radiation emanating from crystals, our experimental setup in the ESTB was augmented by a sweeper magnet to deflect the electrons away from the γ beam and by a scintillating-fiber calorimeter (SciFi) mounted about 45 m downstream of the crystal, both shown in Fig. 1. A lead collimator slit of 8 mm width and 20 cm length defined the acceptance of the counter in the horizontal direction; vertically the full height of the SciFi of 9 cm was exposed to the incoming particles. The SciFi can be moved transversely in the horizontal plane, thus scanning the direction of the emitted photons. Data was taken both with full intensity of the electron beam (about 10^9 electrons/pulse) as well as a collimated secondary beam of up to 10 electrons per pulse, the latter giving less than one photon per pulse and therefore allowing spectroscopy of the photons. In a second run, a thin scintillator was placed in front of the SciFi detector in order to detect any contamination by charged particles. Such contamination was found to be well below 1% of the total counts seen in the SciFi, verified by comparing the counts with secondary electrons (i.e. with the sweeper dipole turned off) to those with the sweeper magnet on. The SciFi detector is about 25 cm long, sufficient to measure spectra up to about 5 GeV photons without significant escape of the shower created in the counter. The detector was calibrated by detecting single and low-multiples of electrons using the secondary beam.

As expected, measuring the spectra proved to be difficult due to both a low count rate and a low signal to background ratio, which was 1:1 (crystal-in + background relative to crystal out) in our first run but improved to about 4:1 in the second run. The significant improvement we made was augmenting the Pb shield around the collimator acting as electron dump by a further 20 cm.

The photons from the crystal should reveal themselves by their energy spectrum as well as by their directionality. Radiation from channeling has a soft component from bending radiation and a harder component (sometimes called channeling radiation) from the oscillations of the channeling electrons. This component is broad in energy due to the amplitude-dependent oscillation period. VR produces very hard radiation due to all electrons experiencing the tight bending angles in the course of the reflection.

The spectrum in VR orientation can in principle allow determination of the effective bending radius of volume reflection, which is not a hard, instantaneous process. The shape of the radiation

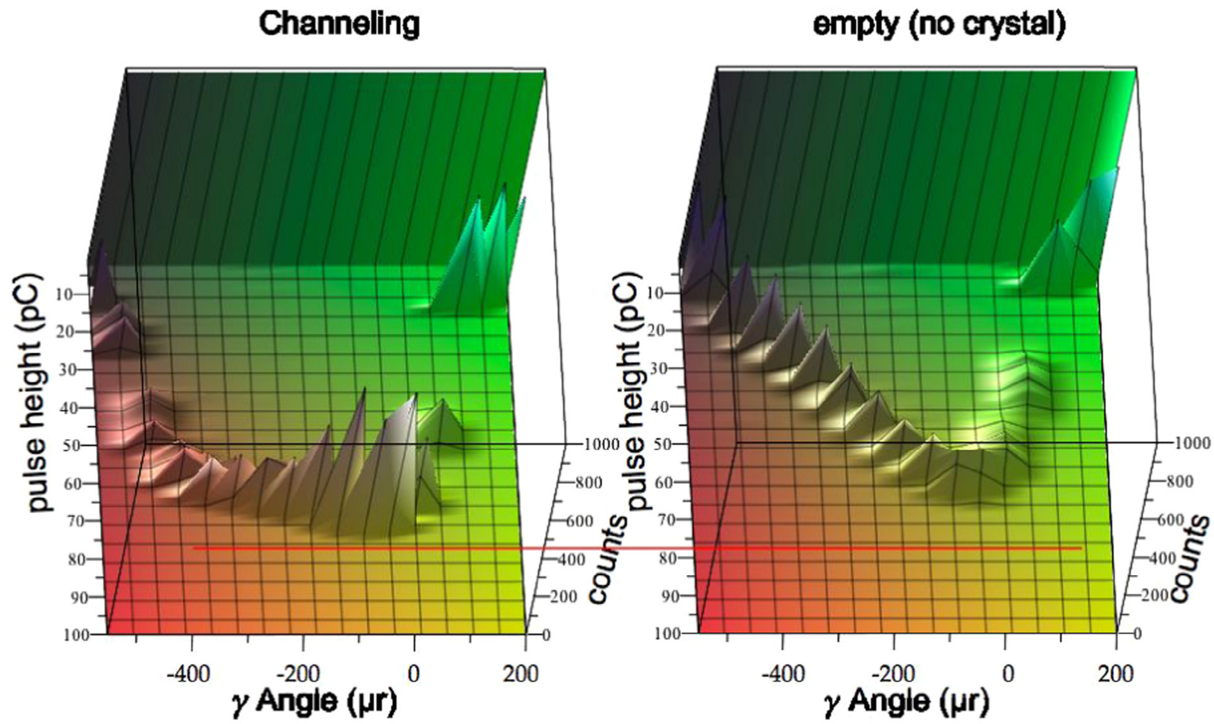

Fig. 3. Multiple scattering angle in the free, non-bending direction for channeled electrons *vs* beam energy in our bent Si crystal with a bending radius of $\rho = 0.15$ m. The multiple scattering angle was calculated using the formula in [9].

spectrum of a particle deflected by a certain bending radius is described by a Bessel-function integral [11]:

$$S\left(\frac{\omega}{\omega_c}\right) = \frac{9\sqrt{3}}{8\pi}\frac{\omega}{\omega_c}\int_{\frac{\omega}{\omega_c}}^{\infty} K_{5/3}(x)\mathrm{d}x \quad (2)$$

with ω_c the *critical energy* of the radiation. Fig. 5 shows our measured and background subtracted spectrum from 15 GeV electrons on the bent Si crystal compared to the result of Eq. (2) for 740 MeV critical energy. This critical energy would correspond to about 8 mm bending radius. Since the VR angle is about 40 μr at this beam energy we estimate the length of the reflection process to be about 8 μm. The quality of the data is not sufficient to make a strong claim, but the method should allow for a more precise determination of the geometry in VR in the future.

The angular distribution of the channeling radiation qualitatively follows the expected trend, with enhancement seen towards the deflecting side of the transverse angular distribution esp. when compared to the background distribution, see Fig. 4.

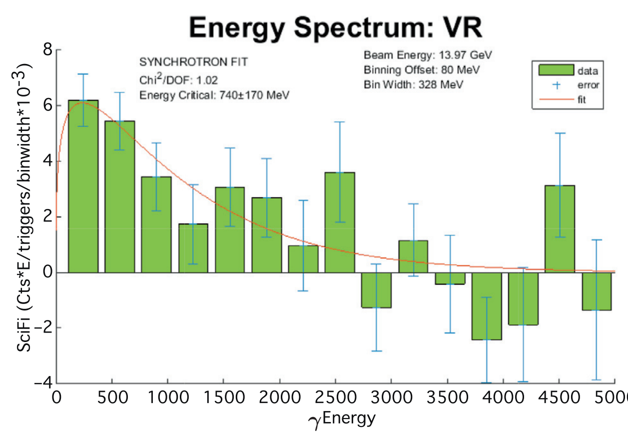

Fig. 5. Spectrum of single photons in the SciFi counter with the crystal in VR orientation. The background is subtracted.

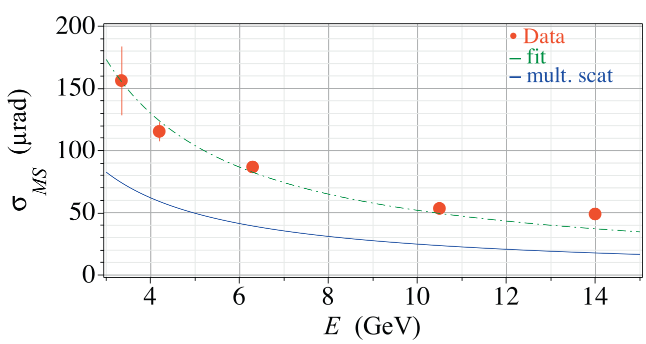

Fig. 4. Gamma-radiation intensity in channeling orientation *vs* angle of emission (*x* axis) and *vs* total energy per pulse (*y* axis). On the right the empty spectrum for comparison. The red line serves to indicate the increase in pulse height with the crystal in channeling *vs* the empty spectrum. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Crystal undulator

Crystalline undulators have inspired the minds of physicists ever since they were proposed by Kaplin [12] and Baryshevsky et al. [13] and investigated further by Greiner's group in Frankfurt [14]. The initially proposed structures had undulations of much longer wavelength than the betatron oscillations of the channeling particles; these are now also called "LALP" undulators (for large-amplitude-long-period undulator). Such devices have potential for operation with positron beams. Successful use with electron beams is prevented by the short dechanneling length of electrons. A promising new approach was proposed recently in form of the "SASP" (small-amplitude-short-period) undulator where the

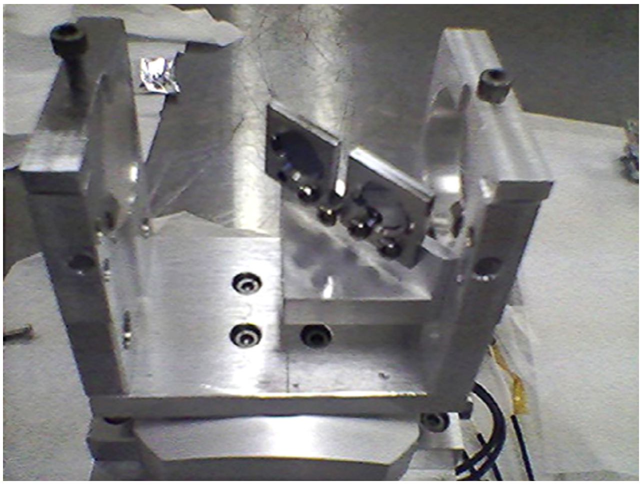

Fig. 6. The Aarhus Undulator (near the center) and a flat crystal in the target holder. At the bottom the rotating stage is visible.

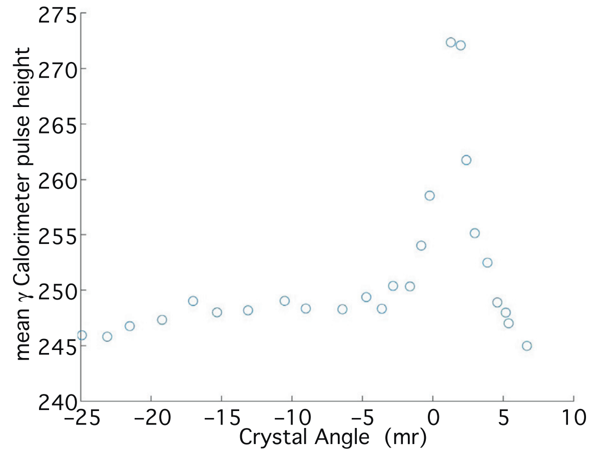

Fig. 7. Crystal-angle scan of the SASP Undulator. The width of the peak is about 2 mr rms. The gamma calorimeter was centered on the gamma beam for these data.

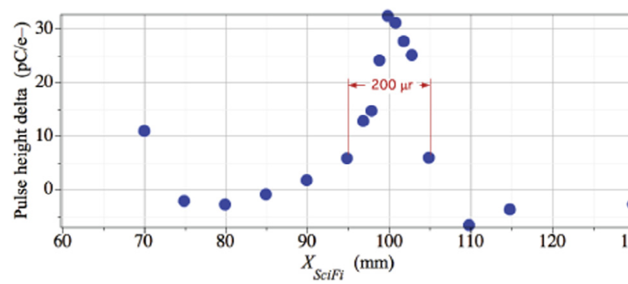

Fig. 8. Angular distribution of photons emitted from the 37 μm thick SASP undulator crystal in the aligned orientation. The distribution is corrected for experimental background as well as the angular distribution in amorphous orientation. Statistical errors of the individual points are about the size of the symbols used for plotting.

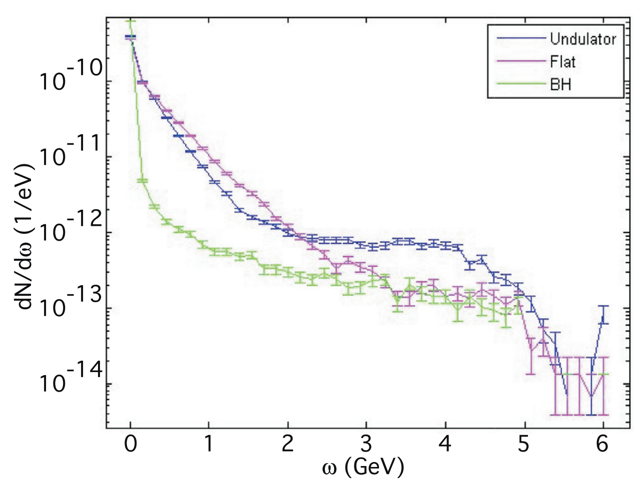

Fig. 9. Calculated photon spectrum from the SASP undulator at 16 GeV incident electron-beam energy in comparison to that from a flat crystal and the Bethe–Heitler spectrum (green). The curves are calculated for 30,000 counts in the whole spectrum. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

mechanical undulations in the crystal are much shorter than the betatron wavelength [15]. Such a crystal was tested recently at MAMI [16] using a very short crystal of 4 μm length with 10 undulations. We recently tested a similar but 37 μm long crystal with 120 undulations, shown in Fig. 6, at SLAC with a 16 GeV electron beam. The crystal has a $Si_{1-x}Ge_x$ graded composition with Ge content between 0 and 1%. With these parameters, Eq. (1) of [16] gives an amplitude of 0.09 Å. The shape is roughly sinusoidal. From trajectory simulations the effective undulator parameter is determined to be $K \approx 0.07$ at 16 GeV electron energy, and the first harmonic peak should appear at 4 GeV photon energy. These simulations take into account that at this beam energy the local bending radius is much tighter than the critical radius, so the electrons do not follow the undulations and significant dechanneling and rechanneling is expected. The spectrum can therefore be expected to be a mix of undulator radiation as well as bremsstrahlung of the dechanneled electrons. True undulator radiation can only be expected to appear when the crystal is properly aligned and should reveal itself in a narrow emission angle and the presence of a peak in the spectrum. We were therefore looking for enhancement as the crystal was rotated in the beam, passing through the aligned condition, and a narrow radiation cone when scanning the horizontal angular distribution with the SciFi detector, both measurements feasible at high beam intensity.

Fig. 7 shows the calorimeter pulse height against the crystal angle. We found a relatively prominent enhancement near the expected orientation. The width of this feature is about 2 mr in crystal orientation.

With the crystal orientation chosen at the center of this enhancement we scanned the horizontal angle by laterally moving the SciFi detector across the horizontal direction. To normalize, the same scan was taken with the crystal in amorphous orientation. Fig. 8 shows the difference between these two data sets. The width of the enhancement is about 200 μrad, consistent with the angular width of the slit collimator, therefore we can only set an upper limit to the width of the radiation beam. The expected spectrum, for a total count rate of 30,000, is shown in Fig. 9. Unfortunately we were not able to measure this spectrum due to difficulties with the experimental setup and variations in beam energy that were not expected.

5. Future work

With ongoing refinement of our experimental technique we will focus on radiation detection and on crystalline undulators as the devices most promising to deliver a breakthrough in radiation generation. Based on our results for channeling efficiency and the efficiency of the VR process as well as having been able to detect the γ rays from volume reflection we are investigating the

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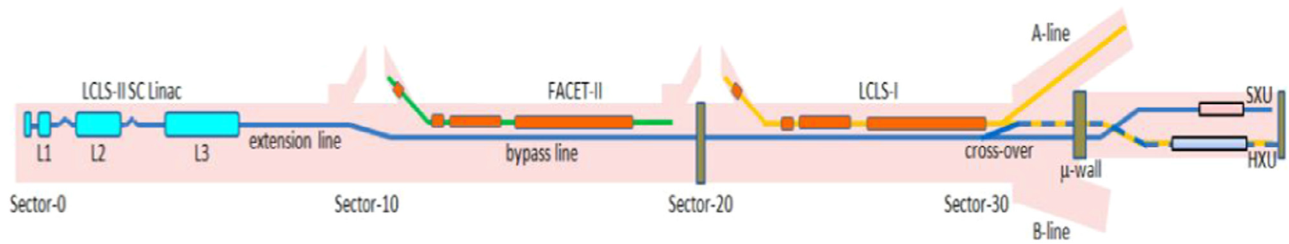

Fig. 10. Linacs and beam lines at SLAC after LCLS-II has been installed [18].

possibility of a volume-reflecting undulator. In its simplest form, this could be a device stacked out of several crystals not unlike our bent crystal. Driven e.g. by a 6 GeV electron beam, such a device should exhibit spectral lines at a few MeV as shown in a simple simulation. The energy of the photons is now in the ten MeV range; which may be a bit low for our SciFi counter and we are investigating the possible use of a Compton spectrometer like the device available at Los Alamos National Laboratory [17]. Such a device would allow us to gather spectra at full intensity; a distinct advantage from an experimental point of view.

SLAC's facilities are undergoing significant changes due to the installation of LCLS II. FACET will become FACET II with a new injector, to begin operation in 2018 and, eventually, a new positron damping ring, operating at 10 GeV instead of the present 20 GeV but at the same time potentially higher beam brightness due to the new injector. The ESTB is expected to be restarted late in 2017 once the LCLS-II related configuration changes are complete. Fig. 10 shows the SLAC linac and associated beam lines after the reconfiguration is complete.

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