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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 (111) Si crystal of 60 μm thickness. The (111) 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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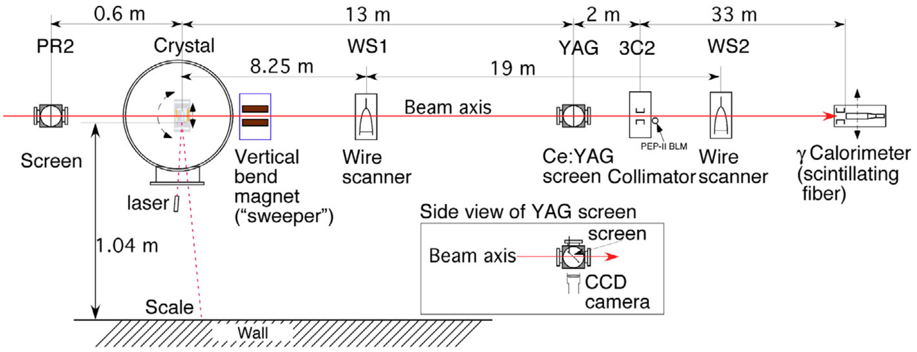

Fig. 1. Layout of the channeling and radiation experiments in the SLAC ESTB. "Counter" refers to the SciFi gamma detector.

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

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

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

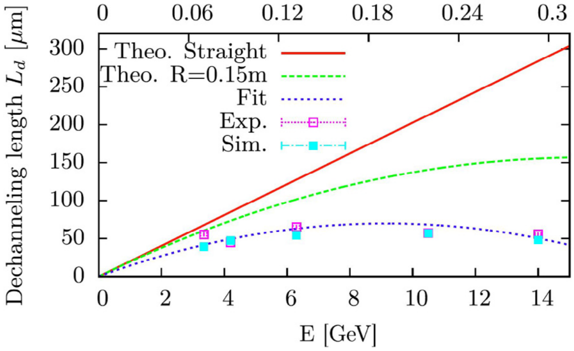

Fig. 2. Dechanneling length *vs* beam energy in our bent Si crystal with a bending radius of $\rho = 0.15$ m. The numbers on top are R_c/R (R_c is the Tsyganov radius).

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