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# PLANNED HIGH-BRIGHTNESS CHANNELING RADIATION EXPERIMENT AT FERMILAB'S ADVANCED SUPERCONDUCTING TEST ACCELERATOR*

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*Abstract*

In this contribution we describe the technical details and experimental setup toward the production of high-brightness channeling radiation (CR) at the Fermilab's Advanced Superconducting Test Accelerator (ASTA). In the ASTA photoinjector area electrons are accelerated up to 40-MeV and focused to a sub-micron spot on a 168 micron thick carbon diamond, the electrons channel through the crystal and emit CR up to 80-KeV. Our study utilizes ASTA's long pulse train capabilities and ability to preserve ultra-low emittance, to produce the desired brightness.

## INTRODUCTION

Channeling is the process by which accelerated charged particle propagating through a crystal can be trapped in the crystal potential. In the classical description applicable to, e.g., > 100 MeV electrons, the particle oscillates around an axis or plane of the crystal lattice, respectively referred to as axial or planar channeling. This oscillatory transverse motion leads to the emission of undulator-like radiation in the forward direction. Quantum-mechanically (required to describe CR at lower beam energies) CR is described as the electronic transition between bounded states, Doppler shifted to the laboratory frame [1–6] with the resulting x-ray photon energy given by

$$E_x \sim 2\gamma^2 \frac{\epsilon_f - \epsilon_i}{1+\gamma^2\theta^2}, \quad (1)$$

where $\epsilon_f$ and $\epsilon_i$ are respectively the final and initial potential energies of the bounded states between which the transition occurs , $\gamma$ the Lorentz factor and $\theta$ the off-axis angle of observation. Figure 1, adapted from [7], depicts the crystal planes of a diamond crystal along which an electron can oscillate (left) and the bounded states associated of the (110) plane (right).

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The appealing features of CR are its simplicity and its favorable scaling with the electron-beam energy. CR is produced by impinging an electron beam on a thin crystal and producing x-ray radiation at moderate energies (40-MeV beam is needed to produce ~ 50 keV photons).

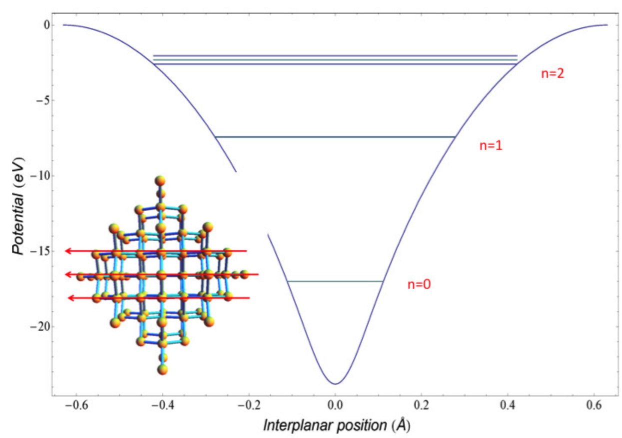


Figure 1: Potential and bounded state associated to a 20-MeV electron channeling along the (110) plane of a diamond crystal. The inset show the diamond-crystal structure with the (110) planes delineated with red lines.

The main challenge associated with CR pertains to pushing the limit of the concept toward to the high brightness regime. The brightness of the source [8] ($\mathcal{B} = dN/[(d\omega/\omega)d\Omega dAdt]$ where $d\omega/\omega$ is the relative bandwidth, $d\Omega$ the solid angle, and $dt$ the time) relies on the production of a large number of photon $N$ within a small area $dA$ while channeling requires the beam's divergence to be below the critical angle [9]. These two contradictory requirements put stringent demands on the beam transverse emittance. Considering a typical critical angle of 1 mrad requires a transverse emittance of $\varepsilon_\perp \sim 10$ nm to achieve the necessary spot size for brightness in excess of $\mathcal{B} \sim 10^{10}$-$10^{12}$ photon.sec$^{-1}$.mm$^{-2}$.mrad$^{-2}$.(0.1%

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bandwidth)$^{-1}$. Therefore a possible approach toward a high brightness, compact, x-ray source is to combine a field-emission electron source with CR [10]. Given the relatively low energy required for CR, the acceleration section between the source and the CR radiator could employ a high-frequency compact linac. This approach could provide a laser-free robust and portable x-ray source. Although recent progresses have been made in operating field-emission tips in a radio-frequency (RF) gun [11], our approach is to first carry out an experiment using a low-emittance beam produced from photoemission at sub 100-nm emittance. Such an experiment has recently been demonstrated [12].

## EXPERIMENTAL SETUP

The ASTA facility is described elsewhere [13] and consists of a ~ 50 MeV RF photoinjector coupled to a superconducting RF (SRF) linac. The CR experiment will be carried out in the photoinjector after the beam has been accelerated to an energy in the range [20, 50] MeV. For the first set of experiments described here, photoemission from a high-quantum efficiency CsTe cathode will be used to produce the required ultra-low emittance. Simulations have demonstrated the generation of sub-50 nm emittance for 200 fC bunches. The electron pulse format consists of 1-ms bunch trains (macropulses) containing 300 electron bunches. The bunch charge can be varied and the macro pulse has a 5-Hz frequency. After the accelerating section composed of two SRF cavities, the beamline consists of quadrupoles magnets, a four-bend magnetic compression chicane, and a vertical spectrometer; see Fig. 2 (d).

The CR experiment is installed just after the chicane and upstream of a vertical spectrometer. The diamond radiator is housed in a 3-axis goniometer on-loan from Dresden Institute of Nuclear Physics and is located ~12m from the photocathode. The three degrees of movement will allow the precise positioning of the crystal, necessary to support channeling and meet the critical angle requirement. After the electron bunch traverses the crystal it will be sent to a beam dump via vertical spectrometer just downstream of the goniometer. The x rays produced from successful channeling will be detected by a detector located on the straight-ahead beamline located downstream of the spectrometer shown in Fig. 2.

In a first phase of experiments occurring in parallel with the ASTA photoinjector commissioning, the straight-ahead beamline ends immediately downstream of the spectrometer and the x rays shine out from vacuum through a window. The choice of window is crucial as it needs to transmit x rays and possibly help in suppressing bremsstrahlung radiation (BR) thereby improving the signal-to-noise ratio. We selected a single-crystal diamond window available from a prior experiment. Although a beryllium window would be preferable to achieve a higher transmission, diamond is acceptable; see Fig. 3. The good transmission property in the optical region also enables the detection of forward optical transition radiation produced as the beam exits from

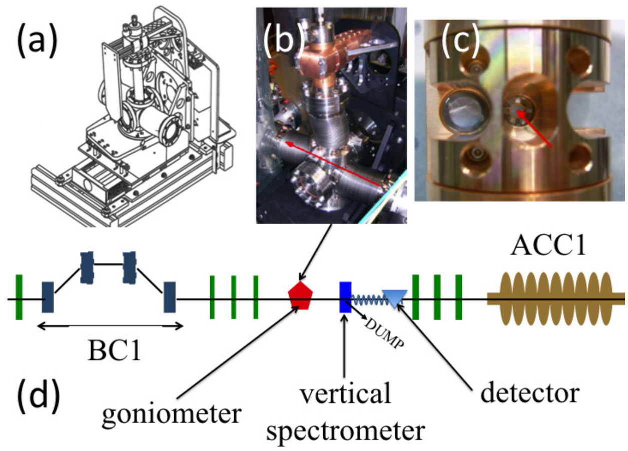


Figure 2: Sketch (a) and photograph (b) of the goniometer assembly on loan from HZDR. Diagram (d) shows the proposed location of the CR experiment in ASTA. Photograph (c) shows the water-cooled crystal holder.

the diamond crystal surface. OTR will provide a diagnostic to monitor the electron beam size and position on the CR target. Downstream of the diamond window other attenuator(s) (as discussed above) might be inserted to further attenuate the BR if necessary.

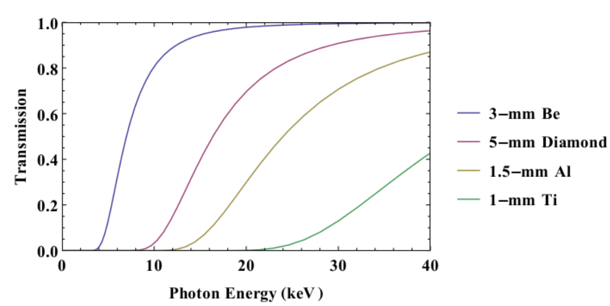


Figure 3: Transmission through different material considered for the radiation-extraction window as a function of photon energy.

At a later date when the installation of the straight beamline to inject the beam in the SRF linac is completed, we will install a remotely-insertable crystal monochromator [e.g. a flat highly-ordered pyrolytic graphite (HOPG) crystal] so that the x rays could be reflected off axis. The monochromator will also greatly reduce the BR background and the narrow CR bandwidth.

Several x-ray detectors will be used with the ultimate goal to completely characterize the properties.

In the first round of experiments, a Amptek X-123CdTe detector will be employed to measure the X-ray energy. The detector will be installed in the straight-ahead section downstream of the extraction window and measure the on-axis photon energy. The acquisition system was developed and successfully tested on the Fermi-Linux control system. Preliminary experience with this spectrometer single-photon detector at HBESL has shown that BR produced, e.g., by

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dark-current can overwhelmed the detector and prevent the detection of the channeling radiation signal. This possible "pile-up" effect can be mitigated by insertion of thin-foil attenuators upstream of the detector.

At a later stage the transverse distribution of CR will be characterized using a x-ray CCD detector (Princeton instruments SCX TE/CCD 1242-F/1 90 MM) on loan from Northern Illinois University (NIU). Finally a novel fast detector capable of resolving single bunch within the 1-ms macropulse will also be tested. This detector combined with a K-edge-based energy measurement technique could be also use to monitor the pulse-to-pulse photon energy stability within the macropulse. Conversely it could also be used to characterize the pulse energy variation capability of ASTA by applying a programmed feedforward to vary the accelerating-field amplitude in the SRF cavities.

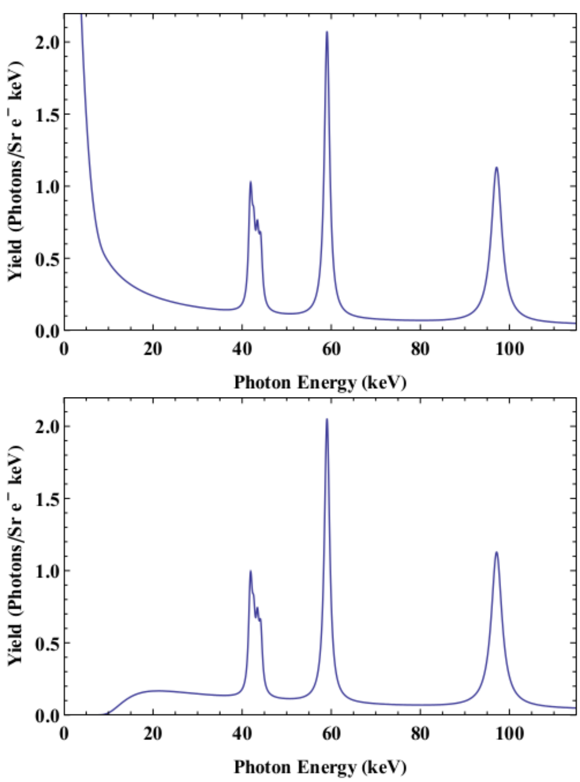


Figure 4: CR spectrum with BR background for a 40-MeV electrons channeling about the (110) plane of a 168-$\mu$m thick diamond before (top) and after (bottom) the diamond extraction window.

## X RAY PARAMETERS

The calculation of the CR spectrum was carried out using a MATHEMATICA© package Planar Channeling Radiation (PCR) described in [14]. In the first set of experiments, a 40-MeV beam will be focused on a 168-$\mu$m-thick carbon diamond. The crystal will be oriented to support channeling along the (110) plane. At this energy the predicted CR spectrum is characterized by 3 peaks located at ~42, ~60, and ~97-keV; see Fig. 4 (top). Along with CR we also anticipate BR from incoherent scattering of electrons that de-channel within the crystal. The combined spectrum of CR and BR can be seen in Fig. 4 (top). After transmission through the diamond the low energy BR (at energies below 15 keV) is strongly suppressed, while the higher energy CR spectrum is unaffected; see Fig. 4 (top).

The peaks in the CR spectrum increase in both intensity and energy with the electron-beam energy. The peaks intensity and energy associated mean energy can be tuned by altering the beam energy or angle of incidence on the crystal; see Fig. 4 (bottom).

At 40-MeV with a 200-nA beam focused down to a 50-nm we expect the 97-keV photons to have a brilliance on the order of $\mathcal{B} \sim 1.66 \times 10^{13}$ photon.sec$^{-1}$.mm$^{-2}$.mrad$^{-2}$.(0.1% bandwidth)$^{-1}$.

## STATUS

The goniometer was recently installed in the ASTA beamline. The interfacing of goniometer controls to the ASTA control system is being finalized. We expect to carry a first set of measurements in the summer at a reduced energy of 25-MeV. Once the second SRF cavity is installed in the photoinjector early in the Fall 2014, the CR experiment will be carried at 40 MeV. Although our initial experiment will us a 168 $\mu$m crystal, we plan to carry parametric study of the x-ray radiation properties for different experimental configurations (e.g. crystal thickness and material) and electron-beam parameters.

Several groups have expressed interest in possibly employing this source for x-ray imaging ranging from x-ray diffractive imaging to phase-contrast imaging. The latter method will possibly also be used to characterize possible coherent property of the CR source at a later stages.

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