CHANNELING RADIATION WITH LOW-ENERGY ELECTRON BEAMS: EXPERIMENTAL PLANS & STATUS AT FERMILAB*

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Abstract

Channeling radiation is an appealing radiation process to produce x-ray radiation with low-energy electron beams. In this contribution we describe the anticipated performance and preliminary results from a channeling-radiation experiment to produce $\sim$ 1.2-keV radiation from a $\sim$ 4-MeV electron beam at Fermilab's high-brightness electron source lab (HBESL). We also discuss plans to produce x-ray radiation ($[10, 80]$-keV photon energy) at Fermilab's advanced superconducting test accelerator (ASTA).

INTRODUCTION

The quest for short wavelength compact light sources has applications in many fields including fundamental science, medical imaging and homeland security. For some applications, e.g., medical imaging, important requirements on the x-ray source include high brilliance, efficiency and compactness. Channeling radiation (CR) generated as ultra-low-emittance electron beams channel in thin crystals provide a viable path toward such requirements [1].

CR was first theoretically predicted by Kumakhov [2, 3] in 1974, and since then has been experimentally verified by several groups. It has generally been found that experiments and theory are in decent agreement [4, 5, 6, 7, 8]. Normally when relativistic electrons are accelerated into a crystal target they will be incoherently scattered emitting a broad spectrum of bremsstrahlung radiation. However, when relativistic electrons are focused onto a crystal target, at a small angle near to parallel with a crystallographic axis or plane the scattering becomes an oscillatory motion about the axis or plane not unlike that of electrons propagating through undulators and wigglers [9]. This motion emits electromagnetic radiation dubbed CR in a forward directed cone of $1/\gamma$. In the rest frame of the electron this radiation is in the optical region however the Doppler effect shifts it into the x-ray regime in the lab frame when the electron beam has a sufficient energy. This allows creation of x-rays from moderate energy electron beams (20-50 MeV). The frequency of CR scales as $\omega = 2\gamma^2\omega_0/(1+\gamma^2\theta^2)$, where ω_0 is the oscillation frequency about the lattice plane, θ is the observation angle with respect to the electron direction and γ is the Lorentz factor. The transverse force experienced by an electron traveling along a crystal plane are comparable to those in a 10^4-T magnetic undulator or a 1-TW laser undulator focused to a 10-μm spot [10].

For high-energy beams a description of channeling radiation is more concurrent with a classical treatment however below 100-MeV, the region we are concerned with, it is more accurately described by a quantum mechanical treatment. When the electrons enter the crystal lattice the ions making up the lattice planes are Lorentz contracted increasing the charge density of the plane causing it to appear as a sheet of charge in the rest frame of the electrons. While the longitudinal motion of the electrons is relativistic the oscillatory or transverse motion about the charged plane remains non-relativistic. The average potential associated to the crystal axis or plane can then be used in the Schrödinger equation to describe the non-relativistic transverse motion of the electrons [8, 11].

For the calculations presented in this paper, we use the MATHEMATICA©-based package described in [12]. The package was benchmarked with experiments [13] but some limitations were recently found and summarized in [14].

The brilliance $\mathscr{B}$ associated with CR scales with beam size $\sigma_\perp$, the two scale as $\mathscr{B} \propto \sigma_\perp^{-2}$ where $\sigma_\perp$ is the transverse root-mean-square (rms) beam size. In addition, the beam size has to satisfy $\sigma_\perp = \varepsilon_x/(\gamma\psi_c)$ where ε_x is the rms normalized beam emittance, and ψ_c is the critical angle. In order to channel, electrons must be incident on the crystal surface at an angle smaller than ψ_c [15]. Therefore in order to increase brilliance of CR the beam emittance must be decreased. One of the main goals of our CR studies is to produce x-ray radiation with photon energies $\mathcal{E} \in [10, 80]$ keV and brilliance $\mathscr{B} \sim 10^{12}$ photon.(mm-mrd)$^{-2}$.(0.1%BW)$^{-1}$.s^{-1}. Achieving such a goal requires electron beams with nano meter normalized transverse emittances and $\sim$ 200-nA average current.

Our experimental plans are two fold: we first plan to investigate the generation of CR using the low-energy beam produced at the Fermilab high-brightness electron source

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laboratory (HBESL). Eventually, we will also carry a CR experiment at the Advanced Superconducting Test Accelerator (ASTA) currently under construction at Fermilab with the aim of producing high-brilliance x-ray radiation.

EXPERIMENT PLANS AT HBESL

Experimental Setup

Our group has recently completed the commissioning of the HBESL facility at Fermilab [16]. The facility essentially consists of an L-band (1.3-GHz) 1.5-cell RF gun equipped with a cesium telluride Cs_2Te photocathode. Photoemission is realized by impinging the photocathode with an ultra-short laser pulse generated by a commercial Titanium-Sapphire laser system. The photoinjector is capable of producing $\sim$ 4-MeV electron bunches with a maximum charge on the order of 10 nC. The RF gun is

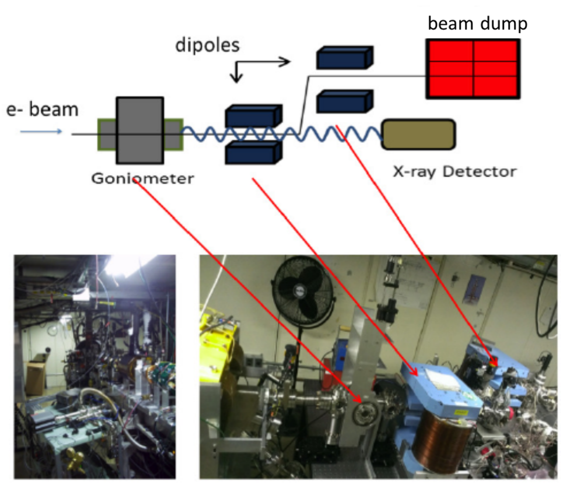

Figure 1: Experimental setup at the HBESL facility (top) and associated photograph of the beamline (bottom left) and CR experiment area (bottom right).

surrounded by three solenoidal lenses to control the beam transverse envelope and emittance. Downstream of the RF gun the $\sim$ 4-m long beamline includes quadrupole magnets, a horizontally-deflecting cavity and a vertical spectrometer. When the spectrometer is turned off, the beam is sent to the CR experiment area schematized in Fig. 1. A 10-μm thick diamond crystal mounted on a goniometer is remotely insertable [17]. After passage through the crystal the electron beam is separated from the x-ray radiation (and x-ray detector) by a dispersive section composed of two oppositely-bending dipole magnets arranged as a dog-leg. The x rays will be detected by an AMPTEK silicon drift detector (model X-123SDD).

Expected Results

The electrons will channel about the (111) plane of the 10-μm thick carbon target. The (111) plane was selected because of the associated "deep" potential well and larger number of bounded states; see Fig. 2. Other planes were considered but did not allow for sufficient energy separation between the bounded state for CR generation.

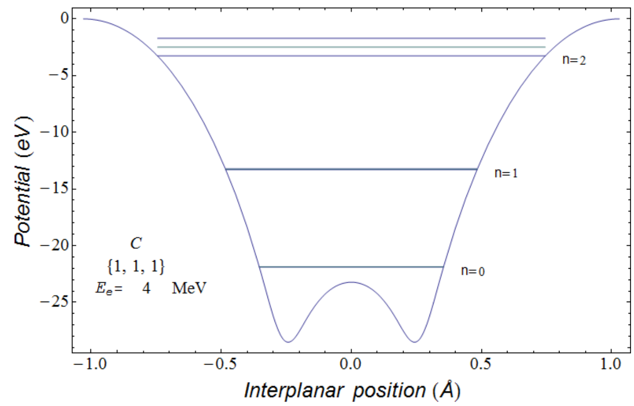

Figure 2: Potential well and bound quantum states for 4-MeV electrons channeling about the (111) plane of carbon.

For a 4-MeV electron, the MATHEMATICA simulations predict a structured CR spectrum composed of a narrow-width peak with mean photon energy (at $\sim$ 1.05 keV) and several peaks located at photon energies $\mathcal{E} \in [1.2, 1.4]$ keV; see Fig. 3. The peak at $\mathcal{E} \simeq 1.05$ keV corresponds to pho-

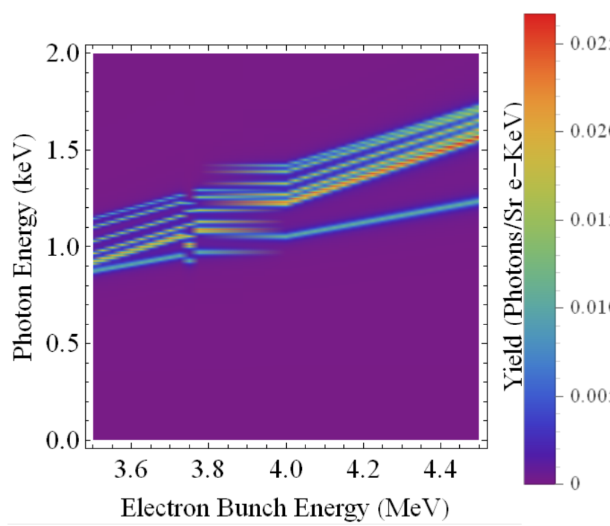

Figure 3: CR spectral yield as function of the electron energy. The electron is taken to channel about the (111) plane in a 10-μm-thick diamond crystal.

tons associated with the $1 \to 0$ transition between bound states, while the other peaks are associated with the $2 \to 1$ transition.

Finally, we note that HBESL is also used to explore another subsystem associated to the concept discussed in Ref. [1], i. e. the operation of diamond field-emitter array (DFEA) cathodes in an RF gun. Preliminary experiments on DFEAs were recently concluded and reported in Ref. [16].

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EXPERIMENTAL PLANS AT ASTA

Introduction

Given the scaling of channeling radiation photon energy, the beam must be accelerated to > 30 MeV energy in order to create hard x rays. At ASTA, the first-stage acceleration will occur in the RF-gun to energies up to 4-5 MeV and further acceleration to energies $E \in [20 - 50]$ MeV will happen in two superconducting RF cavities CAV1 and CAV2 in Fig. 4, further described in Ref. [18]. The ultimate goal would be to eventually use a field-emitter cathode in the RF gun to produce low charge bunches repeated at 1.3 GHz. The technology is still under development and our first experimental campaign will rather focus on producing low-emittance beams using the standard Cs_2Te cathode available at ASTA. Production of ultra-low transverse emittance (below 50 nm) from a photoinjector was recently demonstrated in Ref. [19]. Preserving the ultra-low transverse emittances produced by the cathode after subsequent acceleration and manipulation will be challenging. Chromatic aberrations due to energy spread in the beam, emittance dilution due to nonlinearity in the rf fields, geometric aberrations in the electron beam transport lines, and collective effects can be mitigated according to start-to-end numerical simulations [20]. The simulated electron beam parameters represent two orders of magnitude increase in electron beam quality, so other degrading effects which to date have been unnoticed, may also become important. One main concern, for instance, is the extent to which Coulomb collisions at low energies (Boersch effect) will contribute to phase space dilution, simulations remain to be carried out.

Because the x rays are produced by the interaction of the electron beam with the crystal, the maximum current of the electron beam is limited by heating of, and radiation damage to, the crystal. Measurements and computations show that for diamond at room temperature the effects of heating are acceptable up to a few mA of beam current, so this will not be a limitation even for cw operation [13]. Measurements show that radiation damage becomes significant above a total beam fluence on the order of a few C per square centimeter. Above this threshold, the 40-nm focal spot is destroyed in about 100 μs. For large duty cycles the crystal must be moved at ~ 1 mm.s^{-1}, and the crystal is destroyed at the rate of 0.1 square millimeters per hour. For the ASTA repetition rate we do not anticipate any damage on the crystal.

Experimental Setup

The production of channeling radiation will occur downstream of the bunch compressor (BC1) located in the ASTA photoinjector; see Fig. 4. Several crystal materials will eventually be tested but for the first series of experiments we will use a 40-μm diamond crystal mounted on a high-precision goniometer. The goniometer is situated just before the vertical spectrometer of the ASTA photoinjector to enable the separation of the electron beam from the generated x rays. In a first phase (while only the photoinjector can be operated), a thin Aluminum vacuum or fused-silica window will be mounted on the straight-ahead beamline to enable detection of x-rays using a detector located outside of the vacuum environment. After the Run 3 period, we plan to install a remotely-insertable crystal monochromator [e.g. a flat highly-ordered pyrolyctic graphite (HOPG) crystal; see [13]] so that x rays could be reflected off axis; see Fig. 4. The monochromator will also greatly reduce the bremsstrahlung background.

The goniometer on loan from Helmholtz-Zentrum Dresden-Rossendorf (HZDR) appears in Fig. 5. It was shipped to Fermilab last February and is currently being cleaned and readied for installation in the ASTA beamline. Its controls developed by HZDR are standalone and have been tested, and the goniometer is ultra-high-vacuum compatible (it was operated in the ELBE superconducting free-electron laser facility). The x-ray detector was procured from Amptek (model 123CdTe) and the corresponding acquisition system, based on XMGRAVE open-source software, was developed and tested on the HBESL Fermilinux-based control system. In summary all hardware and associated controls and acquisition software are ready.

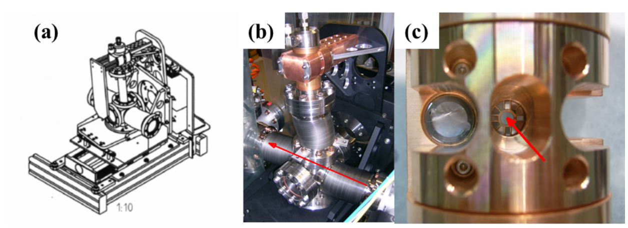

Figure 5: Sketch (a) and photograph (b) of the goniometer assembly on loan from HZDR. Photograph (c) shows water cooled crystal holder used by the goniometer. .

Expected Results

Run 1 will focus on (i) the production of ultra-low emittance beams and (ii) the use of these beams to produce CR. We plan on using a ~ 40-μm diamond crystal oriented to support channeling about the (110) plane; see Fig. 6. The goal of this run will be to produce CR and assess the impact of the bremsstrahlung background. Ideally beam sizes on the order of ~ 50 nm are desirable. Although this might be practically hard to achieve, numerical simulations indicate that a sufficient number of electrons can be channeled within a 50-nm spot to reach our anticipated spectral brilliance of 10^{12} photons/s/mm^2/mrad^2/0.1%BW. The issue will reside in potentially large bremsstrahlung depending on the ratio of channeled electrons and total bunch charge. This clearly will need to be optimized during the experiments and most of this optimization/sensitivity study will be realized during Run 2.

Run 3 main goals are to carry parametric studies of the channeling radiation properties on the beam energy, electron-beam parameters (beam size, energy spread and possibly emittance and charge). Examples of expected

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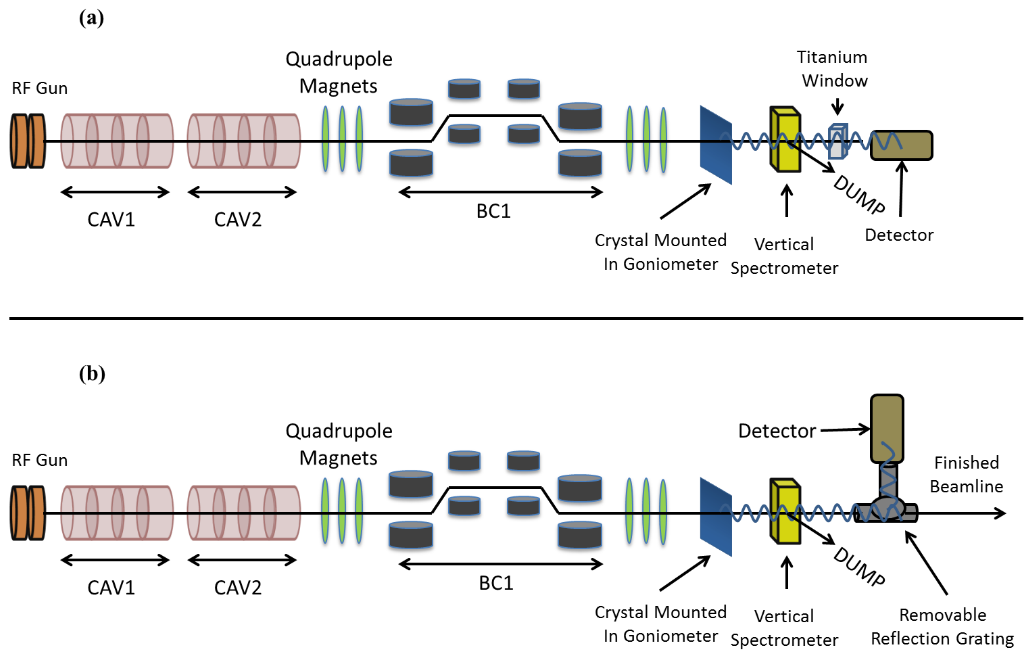

Figure 4: Overview of the ASTA photoinjector with location of the foreseen CR experiment. Diagram (a) and (b) respectively depicts the phase 1 and 2 of the experiment (in phase 1 the x-ray detector will be located straight ahead of the crystal while in phase 2 the x-ray radiation will be reflected and collimated off a remotely-insertable monochromator). The "CAV1" and "CAV2" labels corresponds to the superconducting accelerating cavities and "BC1" to the magnetic chicane used for longitudinal bunch compression.

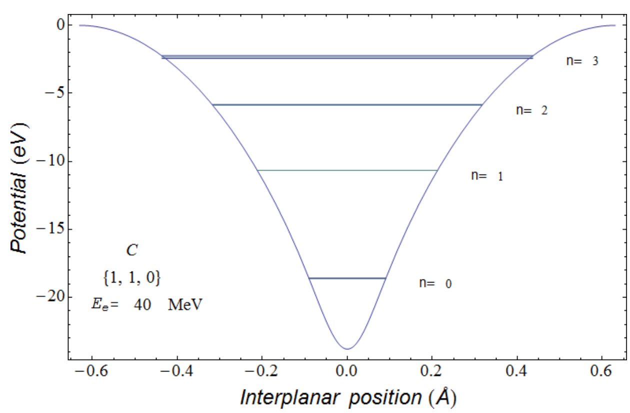

Figure 6: Potential well and bound quantum states for a 40-MeV electron channeling about the (110) plane of carbon.

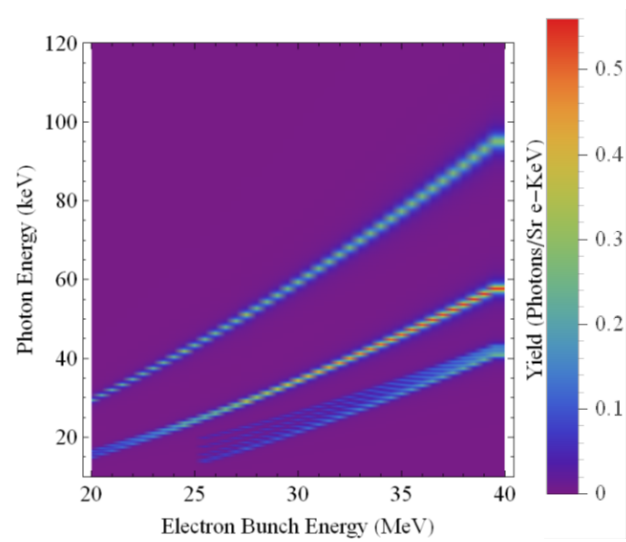

Figure 7: CR spectral yield as function of the electron energy. The electron is taken to channel about the (111) plane in a 42.5-μm-thick diamond crystal.

spectral yield appear in Fig. 7. During this study we also hope to test other types of crystal (different material and thicknesses).

Finally, in Run 4 the CR x-ray brilliance will be measured using point-projection microscopy or ptychography [21]. The generated x-rays would also be used to carry out an imaging experiment. Currently, several options are under consideration. One of them includes the possibility of using an array of electron beams to attempt a phase-contrast imaging experiment [22]. The required multi-beam bunch could easily be created by, e.g., masking the photocathode drive laser or imaging it using a microlens array.

At a later stage, when the development of gated DFEAs is mature, we plan on incorporating such a cathode in the ASTA RF gun. Such an addition would enable the production of low-charge bunch trains repeated at a frequency of

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1.3 GHz over a 1-ms pulse. This type of electron-beam format combined with CR will enhance the brillance of our x-ray source by ~ 2 orders of magnitude.

OUTLOOK

Channeling radiation when combined with low-emittance low-charge bunches produced by a high-repetition-rate linac can provide high-brilliance x rays. The concept to be tested at ASTA is also scalable to compact footprint. Finally, when combined with DFEA-based electron source, Channeling-radiation x-ray sources will be compact and laser-free. These features should make this type of source operationally robust and portable.

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