

CHANNELING RADIATION EXPERIMENT AT FERMILAB ASTA

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Abstract

Electron beams with moderate energy ranging from 4 to 50 MeV can be used to produce x-rays through the Channeling Radiation (CR) mechanism. Typically, the x-ray spectrum from these sources extends up to 140 keV and this range covers the demand for most practical applications. The parameters of the electron beam determine the spectral brilliance of the x-ray source. The electron beam produced at the Fermilab new facility Advanced Superconducting Test Accelerator (ASTA) meets the requirements to assemble an experimental high brilliance CR x-ray source. In the first stage of the experiment the energy of the beam is 20 MeV and due to the very low emittance (≈ 100 nm) at low bunch charge (20 pC) the expected average brilliance of the x-ray source is about 10^9 photons/[s-(mm-mrad) 2 -0.1%BW]. In the second stage of the experiment the beam energy will be increased to 50 MeV and consequently the average brilliance will increase by a factor of five. Also, the x-ray spectrum will extend from about 30 keV to 140 keV.

INTRODUCTION

Channeling radiation (CR) is generated by charged beams (typically electrons or positrons) passing through a crystal parallel with a crystallographic plane [1]. Electrons may oscillate perpendicular to the plane and generate CR which propagates in the same direction as the incident beam. The frequency of the CR is given by $\omega = 2\gamma^2\omega_0/(1 + \gamma^2\theta^2)$ and depends on beam energy (the relativistic factor γ) on crystal lattice (ω_0) and on the observation angle θ . Due to $\propto \gamma^2$ beam energy dependence the CR can reach the x-ray domain even for moderate electron energy (4 to 50 MeV) which means that relatively small accelerators can be used to build compact x-ray sources [2].

For beam energies below about 100 MeV, the X-ray spectrum consists of discrete lines and an accurate description of the CR requires a quantum mechanical calculation. Still, some of the classical interpretations are valid and offer an understanding of the requirements for the incident electron beam. In planar channeling the beam electrons oscillate quasi harmonically perpendicular to a certain crystal plane. Since the electron oscillation amplitude is limited by the inter-planar distances, the kinetic energy associated with the transverse motion can be related to the maximum potential energy V_{max} . The angle of the incident electrons is limited by a critical channeling angle related to V_{max} :

$\Psi_c = \sqrt{\frac{V_{max}}{pv}}$ where p and v are electron momentum and velocity respectively. With diamond as the crystal material, the depth of the potential in the (1,1,0) channeling plane is 23.8 eV. Hence the critical angle at 20 MeV is 1.54 mrad while at 50 MeV, it is 0.98 mrad. The value of the critical angle measured at SLAC [3], for diamond and electron beam energy of 23 GeV is 44 μ rad. Scaling this value with beam energy as $E^{-1/2}$ yields 0.94 mrad at 50 MeV, in good agreement with the theoretical value.

The figure of merit of the CR x-ray source is given by the spectral brilliance $B = dN/[(d\omega/\omega) \cdot d\Omega \cdot dA \cdot dt]$ defined as the number of photons per second emitted within solid angle $d\Omega$, from area dA , and within a relative spectral bandwidth $d\omega/\omega$. The expression for spectral brilliance in terms of electron beam parameters [4] can be written as:

$$B_{av} = \frac{I_{av}}{e} \cdot \frac{\gamma^2 Y \cdot \sigma_e'^2 \times 10^{-3}}{\epsilon_n^2 \cdot \Delta E_\gamma / E_\gamma} \text{Erf}f\left[\frac{\Psi_c}{\sigma_e'}\right] \quad (1)$$

where I_{av} is the average electron beam current, e elementary electron charge, γ Lorentz factor, Y photon yield per electron and unit solid angle, σ_e' , electron beam angular spread, ϵ_n normalized transverse emittance and $\Delta E_\gamma / E_\gamma$ relative spectral bandwidth and the error function accounts for the fraction of the beam within the critical angle.

The average current (over one second) I_{av} in Eq. 1 is proportional with charge per micro-pulse q , laser sampling rate f_L , RF duration pulse ΔT_{RF} and the RF repetition rate R :

$$I_{av} = q \cdot f_L \cdot \Delta T_{RF} \cdot R \quad (2)$$

In this paper we briefly present the relevant components of Fermilab ASTA beamline, preparations for the experiment and the expectations for CR properties as they are derived from theoretical models applied to our specific beam properties. Previous high brightness channeling experiments were reported [5] from the Elbe facility at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) in Germany.

EXPERIMENTAL SETUP

At ASTA the nominal values for the parameters in Eq. 2 are: bunch charge $q = 3.2$ nC, laser sampling rate $f_L = 3$ MHz, macro-pulse duration $\Delta T_{RF} = 1.0$ ms and repetition rate $T = 5$ Hz. The nominal energy is 50 MeV but in the first stage of the experiment "CAV1" (Fig. 1) will not be installed and the kinetic energy will be about 20 MeV. The

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sampling frequency of the laser of 3 MHz and it can eventually be lowered to 1 MHz to accommodate the maximum counting rate of the x-ray detector.

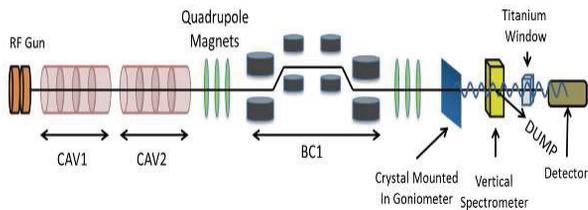


Figure 1: Overview of ASTA low energy section. The legends are: "L1", "L2" solenoidal magnetic lenses, "CAV1", "CAV2" superconducting TESLA style cavities, "BC1" magnetic bunch compressor.

The electron source consists of a 1.5-cell resonant RF gun operated at 1.3 GHz (Fig. 1). The RF power enters the gun through a coaxial input coupler. A CsTe photocathode is located on the back plate of the RF gun and it is designed to generate electron bunches of several nCs when illuminated with UV laser. With the nominal value of 40 MV/m peak field at the cathode the kinetic energy at gun exit is about 5 MeV. The cathode is also exposed to the magnetic field of two solenoids to minimize the beam correlated emittance growth. The energy of the electron beam is increased to about 40-50 MeV by two superconducting TESLA cavities located downstream of the gun. The beamline also includes several quadrupoles, a magnetic bunch compressor and a dipole for energy measurements.

An important beamline component for this experiment is the goniometer which holds the crystal and positions it such that the beam is parallel with one of the crystallographic planes. The goniometer, on loan from HZDR, is located just downstream of the magnetic bunch compressor. The crystal inside the goniometer can be translated horizontally and rotated around horizontal and vertical axes. In particular, the rotation precision is critical for this experiment and must be better than one tenth of the critical angle (0.005°). For this goniometer the rotation precision is better than 0.001° .

Electron beam and the CR produced in the crystal co-propagate for about 1 m when a vertical dipole deflects the electrons to a dump. The CR goes undeflected for another 1 m to a x-ray detector located just outside of the beampipe. At least in the first stage of the experiment we use the x-ray detector Amptek X-123CdTe with energy range 5 to 150 keV and energy resolution better than 1%.

Since the x-detector is outside the vacuum region it is important to choose a window as transparent to CR as possible [6]. The best choice (Fig. 2) is a beryllium window but instead we decided to use a high quality diamond single-crystal window we already have from a previous experiment. The transmission coefficient for this window is at least 50% in the domain of interest 10 to 50 keV. We estimate that about 1m long lead shielding will be required to block background sources of X-rays from entering the detector.

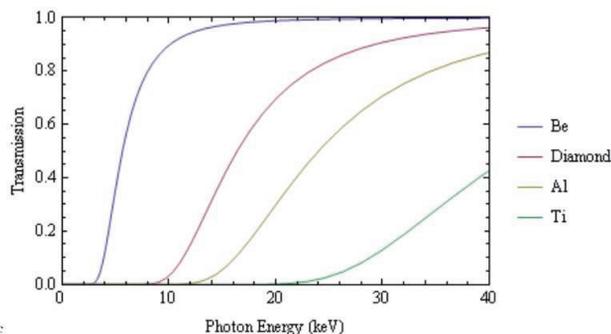


Figure 2: Transmission energy dependence for several windows.

EXPERIMENT STATUS AND EXPECTED RESULTS

ASTA beamline is in the commissioning process till the end of April 2014. So far, nominal values for laser sampling rate (3 MHz), macropulse duration (1 ms) and repetition rate (5 Hz) have been achieved. The laser intensity must still be increased to reach the nominal bunch charge of 3.2 nC from the present value of 0.25 nC. Beam kinetic energy is about 20 MeV.

The goniometer was cleaned and passed vacuum and radiation tests. Stepping motors controls were developed by HZDR and have been tested at ASTA. This goniometer was previously operated in the ELBE superconducting free-electron laser facility.

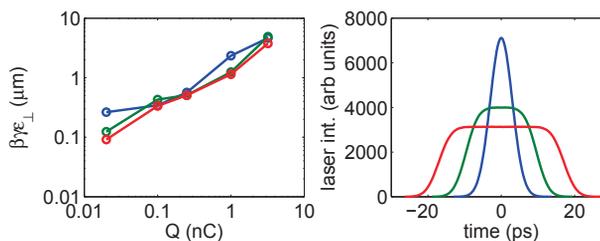


Figure 3: Left: simulations of transverse normalized emittance at ASTA for different bunch charges. Simulations were performed with different laser longitudinal profiles (right).

The expression of brilliance (Eq. 1) shows that lowering the beam emittance is more important than increasing the beam current. However, the bunch charge cannot be arbitrarily decreased in order to also decrease the emittance because ASTA diagnostics are not effective below about 10 pC and, more importantly, emittance dependence on bunch charge was never tested beyond this range. Previous beam dynamics studies at ASTA [7] show that the transverse normalized emittance can be as low as 100 nm and the angular spread 0.1 mrad (Fig. 3) when bunch charge is 20 pC. With these values the average current given by Eq. 2 is 300 nA and the only unknown parameter in the brilliance equation 1 is the differential photon yield Y .

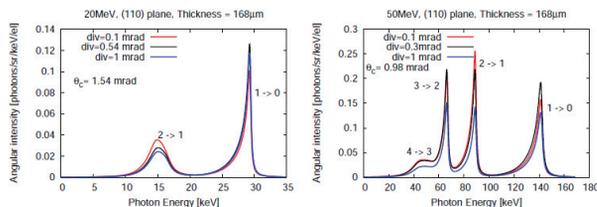


Figure 4: Channeling radiation angular intensity around the 110 plane for a 168 μm thick diamond crystal. The simulations were performed for three values of the electron beam angular divergence and two values of the beam energy: 20 MeV (left) and 50 MeV (right).

A reliable evaluation of the photon yield (as well as the spectral lines widths) can be done only within the framework of quantum mechanics. A MATHEMATICA package Planar Channeling Radiation (PCR) described in [8] and upgraded [4] to eliminate several discrepancies between theory and previous experimental data [5] was used to evaluate photon yield for the specific conditions of the CR experiment at ASTA.

Figure 4 shows the photon yield for a 168 μm thick diamond crystal when the incident beam is parallel with the (1,1,0) plane and beam energy is 20 MeV (left plot) and 50 MeV (right plot). The results for differential yield, x-ray energies and line widths are summarized in Table 1.

Table 1: Summary of expected photon energy, line width and differential yield for $1 \rightarrow 0$ transition in diamond crystal with thickness 42.5 μm and 168 μm and for electron beam energies 20 and 50 MeV.

e^- KE MeV	Thickness μm	γ Energy keV	Width keV	Yield ph/ e^- sr
20.0	42.5	29.3	1.21	0.075
	168	29.3	1.85	0.17
50.0	42.5	89.3	3.83	1.00
	42.5	141.9	6.1	0.65
	168	89.3	5.65	1.7
	168	141.9	8.96	1.6

The average spectral brilliance can be evaluated for each case with Eq. 1 and data from Table 1. We expect that with a emittance of 100nm and a beam divergence of 1mrad, the average spectral brilliances of 0.8×10^9 photons/[s-(mm-mrad)² -0.1%BW] and 4.8×10^{10} photons/[s-(mm-mrad)² -0.1%BW] when the beam energies are 20 MeV and 50 MeV respectively and the diamond crystal thickness is 168 μm . The photon yield and brilliance increase with increasing crystal thickness up to about 400 μm , then level off and decrease for thicker crystals due to photon self-absorption [4].

The number of photons produced by a 20 pC electron bunch that arrive at the x-ray detector can be evaluated based on the beamline geometry, the differential spectral yield Y from Table 1 and the transmission of the diamond

window. In the case of the 168 μm thickness diamond crystal, 20 MeV electrons and 29 keV photons, the x-ray detector could receive about 20 photons during about 3 ps which is the duration of the electron bunch. Since the time resolution of our detector is much longer (about 120 ns) additional shielding or aperture reduction may be needed.

The detected amplitude of the x-ray spectrum may still be affected by dead time and pile-up, even if the beam current is low enough to ensure that on average only about one CR photon arrive at the detector from one electron beam pulse. Essentially, if a CR photon and one or more background photons arrive at the detector within the very short time duration of the electron pulse the valid CR photon is lost and instead a count corresponding to a hypothetical photon whose energy is the sum of all photons is recorded. To correct the x-ray spectrum from these fake events we implemented the algorithm described in Ref. [9]. Simulations performed with toy spectra show that the corrected amplitude for the first order peak differs from the real one by less than 5%.

CONCLUSIONS

The commissioning of the ASTA beamline is expected to be completed by the end of April 2015. The CR experiment is scheduled to begin immediately after the beamline commissioning and it will be the first to be carried out at ASTA. In the first stage of the experiment (20 MeV beam, 100nm emittance and 300nA beam current) we expect the average brilliance of the x-ray source at about 10^9 photons/[s-(mm-mrad)² -0.1%BW] and will increase by an order of magnitude with 50 MeV beams. These will be about three-four orders of magnitude higher than the results from the ELBE facility.

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