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Simulations of beam optics and bremsstrahlung for high intensity and brightness channeling radiation

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ABSTRACT

This paper presents X-ray spectra of channeling radiation expected at the FAST (Fermi Accelerator Science and Technology) facility in Fermilab. Our purpose is to produce high brightness quasi-monochromatic X-rays in an energy range from 40 keV to 110 keV. We will use a diamond crystal and low emittance electrons with an energy of around 43 MeV. The quality of emitted X-rays depends on parameters of the electron beam at the crystal. We present simulations of the beam optics for high brightness and high yield operations for a range of bunch charges. We estimate the X-ray spectra including bremsstrahlung background. We discuss how the electron beam distributions after the diamond crystal are affected by channeling. We discuss an X-ray detector system to avoid pile-up effects during high charge operations.

1. Introduction

Channeling radiation (CR) can be generated when charged particles such as electrons and positrons pass through a single crystal parallel to a crystal plane or axis [1]. The main advantage of CR is to produce quasi-monochromatic high energy X-rays using a low energy electron beam below 100 MeV [2–4]. As an example, CR from a 14.6 MeV energy electron beam has been shown to emit 16 keV X-rays [5]. By comparison synchrotron radiation, currently the main X-ray source, requires a few GeV electron beams to generate X-rays of 16 keV. Moreover, intensities of CR are higher than those of parametric X-ray radiation and transition radiation which are also produced using a crystal and an electron beam.

Our purpose is to produce high brightness X-rays using a low-emittance electron beam, and to demonstrate that CR can be used as a compact high-brightness X-rays source. We plan to conduct CR generation experiments at the FAST (Fermi Accelerator Science and Technology) facility in Fermilab. Low emittance electron beams can be generated at the FAST injector which consists of a CsTe photocathode located in a 1+1/2-cell RF gun followed by two L-band (1.3 GHz) superconducting accelerating structures [6,7]. The electron energy can reach up to ~50 MeV downstream of the last superconducting cavity. A diamond single crystal will be used because of its low atomic number Z, high Debye temperature, and large thermal conductivity. The crystal is oriented so that the electron beam propagates parallel to the (110) plane of the crystal. The expected spectra of CR at FAST were reported earlier [8,9]. In this report, we present detailed calculations of the beam optics, background to CR from bremsstrahlung, electron beam distributions after the diamond crystal with and without channeling, and the X-ray detector system for the CR experiments.

In Section 2 of this paper, the energy, yield, and brilliance of CR are described. In Section 3, the FAST photoinjector is shown, where the details of the superconducting cavities, magnets and expected emittances are described. The beam optics and the X-ray spectra including bremsstrahlung background for different charges are shown in Sections 4 and 5. The electron distributions after going through the crystal are shown in Section 6, an X-ray detector system using Compton scattering to avoid pile-up for high charge operations is described in Section 7 and conclusions are presented in Section 8.

2. Channeling radiation

This section briefly presents the energy, yield, and brilliance of CR. When an electron beam travels with a sufficiently small transverse momentum with respect to a crystal plane, the electrons can be captured in bound states of the crystal's transverse potential, and consequently emit CR. Electron motion in the crystal is similar to that in an undulator, and the vibration period is very short, therefore, high energy X-rays

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can be emitted using a comparatively low energy electron beam. An important requirement for CR is that the electron beam divergence at the crystal must be smaller than the critical angle θ_c [10]. If beam divergences are larger than the critical angle, electrons in the crystal have too large a transverse momentum to be captured by the crystal potential. The critical angle θ_c for CR is given by

$$\theta_c = \sqrt{\frac{2\gamma V_{max}}{mc^2(\gamma^2-1)}} \approx \sqrt{\frac{2V_{max}}{mc^2\gamma}}, \tag{1}$$

where V_{max} is the transverse potential of a crystal, m is the electron mass, c is the speed of light, and γ is the Lorentz factor. For an electron energy of 43 MeV and a diamond crystal with the (110) plane, the critical angle $\theta_c = 1.1$ mrad using Eq. (1).

The CR energy spectrum for electron energies below 100 MeV, derived by solving Schroedinger's equation, is discrete [2–5]. Electrons bound by the potential of a crystal plane or axis have discrete energy levels, and spontaneous transitions between the energy states generate quasi-monochromatic CR. On the other hand, for electron energies above ∼100 MeV, the energy spectrum of CR can be described by classical electrodynamics and it is broad and continuous [10]. The CR energies for electron energies below 100 MeV are given by [2,5]

$$E_\gamma = 2\gamma^2 \frac{(\epsilon_i - \epsilon_f)}{(1+\gamma^2\theta^2)}, \tag{2}$$

where θ is the angle of the emitted photon from the incident electron, ϵ_i and ϵ_f are the energy eigenvalues of electrons in energy levels i and f. This equation also shows that the CR energy can be tuned by changing the electron energy since $E_\gamma \propto \gamma^2$. The most intense spectral lines for 43 MeV electrons going through the diamond and for photons emitted along the direction of the incident electron beam are as follows: 67.5 keV (transitions from the excited state $|2\rangle$ to excited state $|1\rangle$), 110 keV (transition from state $|1\rangle \rightarrow |0\rangle$) and 51 keV (transition from $|3\rangle \rightarrow |2\rangle$). The spectrum is shown in Fig. 8.

The photon yield from state $|i\rangle \rightarrow |f\rangle$ can be found in [3,9,11] and explicitly depends on the occupation probability of the channeling state. This probability is essentially determined by the overlap integral of the electron eigenfunction in that state and a plane wave state. A low beam divergence increases the occupation probability of the excited states which in turn increases the photon yield from those states.

In general, the quality of X-ray sources such as synchrotron radiation and XFELs is evaluated with the spectral brilliance [photons/s/mm^2/mrad^2/0.1%BW]. The average brilliance of CR emitted from electrons can be expressed as [9]

$$B_{av}\ [\text{photons/s/mm}^2/\text{mrad}^2/0.1\%\text{BW}] = \frac{I_{av}}{e}\frac{\gamma^2 Y(\sigma_e')^2 10^{-3}}{\epsilon_N^2 \Delta E_\gamma/E_\gamma} Erf[\frac{\theta_c}{\sqrt{2}\sigma_e'}], \tag{3}$$

where I_{av} is the average electron beam current, e is the elementary electron charge, Y is the total photon yield per electron, ϵ_N is the normalized emittance, θ_c is the critical angle, see Eq. (1), $\Delta E_\gamma/E_\gamma$ is the relative width of the X-ray line, σ_e' is the electron beam divergence, and Erf is the error function. According to Eq. (3), the average brightness is proportional to $1/\sigma^2$, which shows that beam sizes at a crystal location should be small to generate high brightness CR.

3. FAST photoinjector

In this section, the FAST photoinjector and parameters of the electron beam for CR experiments are described. The main components in the beamline are a Cs_2Te photocathode RF gun, two superconducting accelerating structures with TESLA style 9-cell cavities, quadrupole magnets, a chicane, a vertical bending magnet, and a beam dump [6]. Fig. 1 shows the layout of the photoinjector. The RF gun consists of a cathode with a molybdenum disk coated with Cs_2Te mounted on the back plate of a 1+1/2-cell normal-conducting cavity operating at 1.3 GHz with a repetition of 5 Hz. The RF gun is identical to the one developed for the FLASH facility at DESY [7]. A bunch train repeated at 3 MHz with 1-ms duration is produced by irradiating the cathode with an ultraviolet laser pulse (wavelength of 263 nm). The electrons have an energy of ∼5 MeV at the exit of the RF gun, and are accelerated up to energies in the range 43–50 MeV in the two superconducting structures operated at an RF frequency of 1.3 GHz.

Table 1
Twiss parameters, normalized emittances, and energy spreads for 1, 20, and 200 pC at 8 m from the photocathode, from ASTRA simulations.

Charge [pC]	ϵ [μm-rad]	α_x $(=\alpha_y)$	β_x $(=\beta_y)$ [m]	$\Delta E/E$ [%]
1	0.02	−43.3	309.5	0.1
20	0.19	−3.8	21.3	0.1
200	0.52	−3.6	18.9	0.2

Table 2
Beta functions, minimum beam sizes, and beam divergences at the crystal for the different charges. Initial conditions are shown in Table 1.

Charge [pC]	β_x $(=\beta_y)$ [m]	σ_x, σ_y [μm]	σ_x', σ_y' [mrad]
1	3	(1.3, 1.3)	(1.3, 1.3)
20	3	(4.1, 4.0)	(0.9, 0.9)
200	5	(9.6, 9.6)	(1.1., 1.1)

The goniometer housing the crystal and the X-ray detector for the CR experiment are located at 17 m and 18.5 m, respectively from the photocathode. The goniometer stage can be rotated around vertical and horizontal axes for an incident electron beam direction and can slide horizontally. The movable target holder houses: (1) a clear aperture, (2) the diamond crystal and (3) a 50-micron thick Al foil. The hole is used when the crystal is not needed. Intercepting the beam with the foil generates bremsstrahlung that can be used to calibrate the detection system. The bremsstrahlung also provides a coarse calibration signal to center the beam on the foil and indirectly on the crystal as the foil and crystal are inserted using a calibrated stepping motor.

This dipole magnet after the goniometer kicks the beam vertically by 22.5° towards the beam dump. The quadrupole magnets used to control electron beam sizes have a maximum gradient of 6.6 T/m at an energy of 50 MeV, their bore diameter is 54.6 mm and the effective magnet length is 617 mm. Also, eight steering magnets are inserted in the beamline to correct the electron beam trajectory. Each steering magnet is capable of a maximum kick of 7.5 mrad to a 50 MeV electron beam.

The chicane displayed in Fig. 1 is commonly used for bunch compression and energy collimation. The four dipole magnets in the chicane provide bending angles of (+, −, −, +) 18° respectively yielding a longitudinal dispersion of R_{56}. R_{56} is the matrix element that connects the path difference to the energy deviation and is given by $R_{56} = \int \frac{\eta_x}{\rho} ds = -0.18$ m, where ρ is the bend radius of the dipole magnet. In the CR experiment, the main purpose of using the chicane is to collimate away dark current of lower energy than the main photocathode current.

Electron beam dynamics from the photocathode to downstream of the second superconducting cavity (8 m) were simulated, including space charge effects, using the tracking program ASTRA [12] for bunch charges ranging from 1 pC - 3.2 nC. Table 1 shows the twiss parameters, the normalized emittances, and the energy spreads for bunch charges of 1, 20, and 200 pC. The rms bunch length is about 3 ps.

4. Beam optics solutions for CR

In this section, we present optics solutions for three values of the bunch charge and for two scenarios: (1) high brightness solutions with low beam sizes and divergences close to the critical angle (consistent with the beam emittance) and (2) high yield solutions with a large beam size and low divergences at the crystal.