Exotic X-ray Sources from Intermediate Energy Electron Beams

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Abstract. High intensity x-ray beams are used in a wide variety of applications in solid-state physics, medicine, biology and material sciences. Synchrotron radiation (SR) is currently the primary, high-quality x-ray source that satisfies both brilliance and tunability. The high cost, large size and low x-ray energies of SR facilities, however, are serious limitations. Alternatively, “novel” x-ray sources are now possible due to new small linear accelerator (LINAC) technology, such as improved beam emittance, low background, sub-Picosecond beam pulses, high beam stability and higher repetition rate. These sources all stem from processes that produce Radiation from relativistic Electron beams in (crystalline) Periodic Structures (REPS), or the periodic “structure” of laser light. REPS x-ray sources are serious candidates for bright, compact, portable, monochromatic, and tunable x-ray sources with varying degrees of polarization and coherence. Despite the discovery and early research into these sources over the past 25 years, these sources are still in their infancy. Experimental and theoretical research are still urgently needed to answer fundamental questions about the practical and ultimate limits of their brightness, monochromaticity etc. We present experimental results and theoretical comparisons for three exotic REPS sources. These are Laser-Compton Scattering (LCS), Channeling Radiation (CR) and Parametric X-Radiation (PXR).

1. INTRODUCTION.

Despite the fact that the photon flux per electron of Radiation from relativistic Electron beams in Periodic Structures (REPS) sources are generally higher than that of Synchrotron Radiation (SR), SR sources are still the brightest sources in the UV and soft x-ray region. This is because storage rings are able to accumulate high average electron beam currents. REPS sources of x-rays, however, generally do not re-use the electron beam and, therefore, are not as bright as SR beams. Instead, REPS sources should primarily be viewed as complementary to synchrotron sources, rather than competitive, because each REPS source has a unique domain, in terms of energy, coherence, polarization where it has an advantage. The emitted radiation of REPS sources is highly directional, polarized, and the x-ray energy range varies from a few keV to a few hundred keVs. These sources, with varying degrees of monochromaticity, whether coherent or not, may be able to provide sub-picosecond x-ray fluxes that are higher than some other approaches now under development [1].

Sub-picosecond x-ray processes are of great interest because, for example, they can probe lattice vibration phenomena over a single oscillation or, for another example, because they can “image” bio-molecular reactions as they occur. Existing synchrotron light sources are several orders of magnitude away from this possibility [2]. Potential study topics using these x-ray sources include lattice vibration measurements, time resolved chemistry, microprobe, and 3-D motion of atoms and phase sensitive imaging.

Three REPS x-ray sources briefly investigated are Laser Compton Scattering (LCS), where a laser beam collides and scatters from the electron beam, Channeling Radiation (CR), where crystalline planes cause the electron beam to wiggle, and Parametric X-ray Radiation (PXR), where Bragg diffraction of the virtual photons provides the X-ray production mechanism. We will present current and previous experimental results; comparisons to theoretical expectations, and possible applications. LCS experiments were carried out at the Idaho Accelerator Center, while CR and PXR experiments were carried out by one us (K. Chouffani) at the S-DALINAC in Germany and Hiroshima University respectively. Experimental setups for LCS, CR and PXR can be found in the following references [3-5].

2. Results and Comparisons to Theory.

Laser Compton scattering (LCS) is the exchange of energy between a relativistic electron beam and a laser beam. Laser photons interact with high-energy moving electrons, and the electrons scatter these low energy photons to a higher energy at the expense of the electrons’ kinetic energy. This interaction results in the
emission of highly directed x-rays (peaked in the forward direction) with a divergence on the order of $1/\gamma$ ($\gamma$ is the electron beam energy in units of $m_ec^2$). Collimated LCS x-rays are monoenergetic (see below), highly polarized and energy-tunable x-ray beams.

Experimental observations of LCS x-rays have been reported in the literature by [6,7], and most recently by K. Chouffani et al. [3].

The scattered photon energy is given by:

$$E = 4\gamma^3 E_L / (1 + \gamma^2 \theta^2), \quad (1)$$

where $E_\gamma$ and $E_L$ are the photon and laser photon energy respectively, and $\theta$ is emission angle. LCS can occur at any crossing angle between the electron and laser beams. Two basic configurations are typically used in LCS: a head-on collision where the laser photon acquires the highest gain in energy and a 90° geometry where the electron beam and laser beam are orthogonal to each other. In the 180° geometry, the x-ray pulse duration is determined by the electron bunch length. In the 90° geometry, the x-ray pulse duration is determined by the crossing time of the electron and laser focus.

LCS can also provide information on the electron beam direction, beam energy, and beam energy dispersion [7]. One of the attractive features of LCS is the easy control of the polarization of the emitted photons because it is the same as the polarization of the applied laser. Equation (1) shows a direct relationship between the emitted x-rays energy and electron beam energy. LCS, when summed over all scattering angles $\theta$, has a relatively broad energy spectrum. Because the lowest energy of the spectrum is determined by the angle $\theta$ for a fixed crossing angle, a collimator in the forward direction is necessary to narrow the photon spectrum to a quasi-monochromatic region between $E_\gamma^{\text{Max}}$ and some low energy cut-off $E_\gamma^{\text{Min}}$. Monochromaticity is, however, achieved at the expense of the photon yield. LCS energy spread depends on the energy spread of the laser $\Delta E_L$, the electron beam’s energy and angular spread $\Delta E_B$, $\Delta E_\gamma$, and the spread of the scattering angle subtended by the detector $\Delta E_\gamma^0$ [7-9]. The narrowest x-ray line observed to date, with a $\Delta E_\gamma/E_\gamma \approx 1.5\%$, was recorded at the IAC [7].

Figure 1 shows our LCS spectrum for an observation angle equal to 3 mrad. The spectrum shows a distinct and monochromatic x-ray peak resulting from the interaction of the 20 MeV electron beam with the 532 nm laser line on top of a low bremsstrahlung background. The additional higher energy peak is due to pile up from the major line. Figure 2 shows the variation of the x-ray energy as a function of the electron beam energy (squared), together with Equation 1. There is good agreement between experiment and theory. The discrepancy at higher energy is due to a change in the electron beam direction.

The yield of backscattered x-rays $N_x$ into a cone of angle $\theta_c$ is equal to [11]:

$$N_x = 2N_eP_LL_e/\pi \sigma_c, \quad (2)$$

where $N_e$ is the number of electrons in the electron bunch, $P_L$ is the laser peak power, $L_e$ is the interaction length, $c$ is the speed of light, $A_{\text{int}}$ is the interaction area and $\sigma_c$ is the Compton cross section for photons scattered into a cone of angle $\theta_c$. K. Chouffani et al. [12] and Pogorelsky [13] recorded a peak flux of $5.6 \times 10^{13}$ photons/s and $3 \times 10^{18}$ photons/s respectively. With the availability of table-top-terawatt ($T^3$) lasers based on chirped-pulse amplification (CPA) Hard x-ray pulses of the order of $10^{10}$ photons/bunch or higher, using moderate energy electron beams, can be achieved [10].

![Figure 1](image1.png)

**Figure 1.** LCS spectrum using the Nd:YAG laser 532 line. The solid angle was on the order of 0.61 µsr.

![Figure 2](image2.png)

**Figure 2.** LCS x-ray energy as a function of $\gamma^2$ [3].

The second REPS source that we discuss is Channeling Radiation (CR), which is emitted by relativistic electrons passing through single crystals along a direction of high symmetry, such as a plane or an axis. In the planar case, the
electrons undergo periodic oscillations similar to undulator radiation.

CR radiation is forward directed into a narrow cone with an angle of emission \( \theta \approx 1/\gamma \). Quantum mechanically, the electron can be considered bound by the transverse electrostatic potential of the crystal planes or axes, and channeling radiation results from spontaneous transitions between the quantum states. In the electron rest frame, the emitted radiation is in the UV and in the laboratory frame the radiation is Doppler shifted to the x-ray region. The CR energy is given by:

\[
E_\gamma = 2\gamma^2\Delta E^L / (1 + \gamma^2\theta^2),
\]

where \( \Delta E^L \) is the electron transverse energy spacing in the laboratory frame [14,15]. CR can only occur when the angle of incidence with respect to a plane or axis is less than the Lindhard angle [15]. Depending on the electron beam energy and channeling direction (channeling axis or plane), CR consists of one or several spectral lines [4,15,16]. Since CR is emitted in the forward direction, and because CR spectra include an incoherent bremsstrahlung background, it is always convenient to use low Z crystals such as diamond or silicon [16].

Among the most useful characteristics of CR are: It is coherent, energetic, bright, linearly polarized, and energy-tunable. CR x-ray energy scales with electron energy according to \( E_\gamma \approx E_0 \gamma^\alpha \) where \( \alpha \) is of the order of 1.5-3 [4], and \( E_0 \) is a constant. Figure 3 shows a CR spectrum from K. Chouffani et al [4] resulting from the 1-0 and 2-1 transitions along the (110) plane, after background subtraction. The two lines result from the deeper crystal potential in the electron rest frame (when compared to spectra at 6 MeV) [4]. The CR spectral width depends on several factors, some of which are the electron beam energy deviation, the multiple scattering inside the crystal and incoherent scattering of electrons from phonons [14-16]. CR has a relatively narrow band-width with \( \Delta E_\gamma/E_\gamma \approx 0.1-0.5 \) [4,17].

Figure 4 shows our measurements of the dependence of the CR energy on the electron beam energy, and shows the relatively easy energy-tunability of CR. Because channeling radiation has the same time structure as the incident electron beam, the pulse of radiation can be of extremely short duration, on the order of a few picoseconds or less [16]. Channeling radiation intensity scales as \( \gamma^{3/2} \) [4,16]. Diamond, due to its large thermal conductivity and high Debye temperature, can withstand intense electron beam currents and has produced the largest intensities observed so far \( \approx 2 \times 10^{10} \) photons/s [16], which is several orders of magnitude less than observed LCS.

Lastly, we consider Parametric X-ray Radiation (PXR), which is created when an electron beam strikes a crystalline target and the virtual photons, which make up the electric field of the electrons, exit the crystal by means of Bragg scattering [17]. The photons may exit on the same side of the crystal as the electron beam enters (Bragg case diffraction) or on the opposite side (Laue case diffraction).

Figure 3. CR spectrum from 10.2 MeV electron beam in a Ge crystal along (110)-Plane [4].

Figure 4. Channeling radiation energy as a function of electron beam energy [4].

PXR leaves the crystal in discrete beams, just as in conventional x-ray diffraction [5,17]. Each beam subtends a narrow angle \( \theta \approx \gamma^{-1} \). PXR has many characteristics that are important for potential applications. First, PXR energy is independent of the electron beam energy and has an extremely narrow energy band-width of \( \Delta E_\gamma/E_\gamma \approx 10^{-3} \) [18]. Second, it is linearly polarized and third, because it is emitted at large angles with respect to the electron beam direction, it is virtually free of incoherent bremsstrahlung.

PXR spectra show prominent peaks at energies defined by the Bragg angles relative to the
crystallographic planes. Figure 5 shows PXR spectra from the (111) plane from K. Chouffani et al. [5]. By tilting the crystal, spectra from the (011) and (331) planes were also observed for a fixed observation angle [5].

Figure 5. PXR spectrum from the (111) -Plane [5].

The x-ray energy can be changed continuously simply by tilting the crystalline planes with respect to the electron beam direction as shown on Figure 6, or by changing the observation angle. This makes it easy to achieve energy tunability. PXR energies can be “tuned” to a relatively broad range; from 5 to 100 keV depending on the choice of the crystallographic plane and Bragg angle.

Figure 6. Variation of PXR energy as a function of tilt angle [5].

PXR intensity and angular distribution depend on the electron beam divergence and multiple scattering angle of the electron beam in the crystal but unlike channeling radiation, PXR can still be observed even when the electron beam divergence is of the order of the multiple scattering angle. PXR intensity increases with crystal thickness but saturates at a critical thickness [5,19]. The maximum PXR intensity is 3 orders of magnitude lower than that of CR [19], however, its potential advantages, such as higher x-ray energies, and smaller bandwidth, may outweigh its intensity disadvantages in certain applications.

3. Conclusions.

REPS X-ray sources from moderate energy electron beams, though still in their infancy, offer a broad range of energies and picosecond or less x-ray bursts. Our results, so far, indicates that LCS is likely to be the brightest among the REPS sources, but methods of enhancement for the other REPS sources such as interference of PXR, diffracted transition radiation, and diffracted CR [5,20] are currently being pursued aggressively.

With the availability of high duty factors LINACs and TW lasers, REPS sources could match or even surpass SR x-ray flux. A more likely scenario, however, is for REPS sources to provide complementary x-ray capabilities in terms of x-ray energy, coherence, etc. Moreover, the compactness and potential portability of such sources are extremely useful for many industrial, academic or military applications.

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5. References.