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A Compact Compton Backscatter X-ray Source for Mammography and Coronary Angiography

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Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). The project objective is to generate a large flux of tunable, monochromatic x-rays for use in mammography and coronary angiography. Our approach is based on Compton backscattering of an ultraviolet solid-state laser beam against the high-brightness 20-MeV electron beams from a compact linear accelerator. The direct Compton backscatter approach failed to produce a large flux of x-rays due to the low photon flux of the scattering solid-state laser. We have modified the design of a compact x-ray source to the new Compton backscattering geometry with use of a regenerative amplifier free-electron laser. We have successfully demonstrated the production of a large flux of infrared photons and a high-brightness electron beam focused in both dimensions for performing Compton backscattering in a regenerative amplifier geometry.

Background and Research Objectives

Our research objective is to develop a compact, tunable, monochromatic x-ray source in the kiloelectron-volt (keV) range for use in mammography and digital subtraction coronary angiography. At present, the diagnoses of breast cancer employ traditional x-ray tubes as the source of broadband (polychromatic) x-rays. Of the x-rays that are generated from the x-ray tubes, only those in the energy range between 14–20 keV contribute to the mammography image. The x-rays at higher energy become unwanted scattered light that reduce image sharpness; those at lower energy are absorbed by the patient's body. By using monochromatic x-rays tuned to the correct energy range, one can improve image definition and at the same time reduce the patient's x-ray dose. This new radiographic imaging technique has been demonstrated with monochromatic synchrotron radiation from the National Synchrotron Light Source [1]. The second application involves the use of 33-keV x-rays bracketing the iodine K-edge to obtain high-resolution images of the coronary

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blood vessels. In this application, the patient's blood stream is injected with an iodine contrast agent and the coronary blood vessels are imaged with monochromatic x-rays tuned to energies below and above the iodine K-edge. The digital subtraction angiography images reveal the coronary blood vessels with very high resolution and are extremely useful for diagnosing heart diseases. This technique has been successfully demonstrated with a dual beam of synchrotron radiation at the Stanford Synchrotron Radiation Laboratory [2]. Despite these recent success stories, synchrotron radiation cannot be adapted to a clinical scale facility due to the size of its high-energy electron storage ring. For clinical applications, we need to demonstrate the production of a large flux of tunable, monochromatic x-rays from a compact, low-energy electron source.

One of the most direct methods for generating monochromatic x-rays involves scattering an intense laser beam against a relativistic electron beam. This process is known as Compton backscattering, to differentiate from the traditional Compton scattering with the electron at rest. In Compton backscattering, the electrons travel near the speed of light when they encounter the laser photons. In the electrons' rest frame, the laser photons are Doppler-shifted to higher energy by a factor of 2γ , where γ is the ratio of the electron beam energy to its rest energy (0.511 MeV). The scattered photons are then transformed back into the laboratory frame with another 2γ Doppler shift in energy. The net result is a $4\gamma^2$ boost in the photon energy from the eV range (visible light) to the keV range (x-rays). The maximum energy of the Compton backscatter x-rays is given by

$$E_x = 4\gamma^2 E_p \quad (1)$$

where E_x and E_p are the energies of the generated x-rays and the incoming laser photons, respectively. If we choose an electron beam energy of 20 MeV ($\gamma \approx 40$) and a laser wavelength of 263 nm (photon energy = 4.6 eV) from a frequency quadrupled neodymium laser, the maximum x-ray energy becomes 30 keV. With a different choice of laser wavelength, we can vary the generated x-ray energy by a large amount. By changing the electron beam energy, we can also fine-tune the energy of the generated x-rays.

The rate of converting low-energy laser photons into high-energy x-rays by laser-electron collision depends on the electron number density, the laser photon flux and the collision cross section, as given by

$$N_x = \sigma_C N_e N_p / A \quad (2)$$

where N_x is the total number of x-ray photons, σ_c is the Compton cross section ($\sigma_c = 0.665 \times 10^{-24} \text{ cm}^2$), N_e is the number of electrons, N_p is the number of laser photons, and A is the effective collision area and is given by the sum of squares of the rms radii of the electron and laser beams. The small collision cross section can be overcome by employing a very intense laser beam and a high-current electron beam that can be focused to a small spot. The second requirement dictates the use of a high-brightness, low-emittance electron beam from a photoinjector.

Compton backscattering has been proposed by many organizations as a direct approach for generating tunable x-rays and gamma rays [3–5]. Many of these experiments involve large accelerators unsuitable for a clinical environment. Our objective is to demonstrate the proof of principle of the Compton backscattering process with use of a low-energy electron beam from a compact radio-frequency (rf) linear accelerator (linac). The demonstration of Compton backscattering from a low-energy electron beam could lead to the design of clinical machines that produce monochromatic x-rays for use in mammography and digital subtraction angiography.

Importance to LANL's Science and Technology Base and National R&D Needs

One of the stockpile stewardship missions at Los Alamos National Laboratory (LANL) is to understand the behavior of the nation's nuclear arsenal through the use of radiography. In addition to building the Dual-Axis Radiographic Hydrodynamic Test (DARHT) Facility, LANL is currently involved in the conceptual design of the next-generation Advanced Hydrotest Facility (AHF). Among the possibilities under consideration is the use of monochromatic gamma photons for imaging the implosion. In radiographic imaging, scattering is a major source of image degradation. With the use of monochromatic gamma rays, the gamma rays that traverse straight through the sample can be differentiated from those that undergo scattering. Using an energy filter to eliminate the unwanted scatter, one can significantly improve the quality of the images of the implosion compared to that from a bremsstrahlung source. The success of this project in developing a high-flux monochromatic beam of x-ray photons via Compton backscattering can be directly extended to the production of gamma photons with the choice of a higher energy electron beam, e.g. about 1 GeV. The Compton backscatter flux will be high since the opening cone angle is reduced for a high-energy electron beam.

Another application that may benefit from the success of this project is protein crystallography. Multiwavelength Anomalous Dispersion (MAD) phasing – a technique in which x-ray diffraction intensities are measured as a function of x-ray energy – is a

powerful tool in elucidating protein structures without the use of heavy-atom derivatives. These experiments are currently performed on large synchrotron radiation sources. If a large flux of x-rays can be generated with sufficiently narrow energy bandwidth, it will open up more opportunities to present MAD users and increase the number of researchers interested in the MAD technique.

Scientific Approach and Accomplishments

We have looked at three different approaches to Compton backscattering: the direct approach with a conventional laser, the intracavity approach with a free-electron laser (FEL), and Compton backscattering with a regenerative amplifier FEL. The first approach requires an external high-average-power laser that is synchronized with the electron beam. Our experiments in the first two years with the direct Compton backscatter approach were unsuccessful due to the low average photon flux of the conventional solid-state laser. The second approach requires the construction of an FEL oscillator and has been demonstrated recently by other researchers [3–5]. The third approach, Compton backscattering with a regenerative amplifier FEL, is in our view the most viable approach toward a high-flux Compton backscatter source. We have demonstrated a novel approach to a high-power free-electron laser that provides a large flux of photons for performing Compton backscattering. We have also designed the Compton geometry that takes advantage of the features of the high-flux regenerative amplifier FEL.

The main requirements for a high-flux Compton backscatter x-ray source are a high-current, low-emittance electron beam and a high-average-power scattering laser. We had earlier designed, built and tested a high-brightness electron gun called the Advanced FEL photoinjector [6]. The basic parameters of this accelerator are shown in Table I. This photoinjector-linac puts out a series of micropulses separated by 9.23 nanoseconds in 10–20 microsecond bursts called macropulses (Figure 1). The photoinjector is driven by a quadrupled frequency of a neodymium:yttrium-lithium-fluoride (Nd:YLF) laser. As the electron pulses are generated by the laser pulses, the two sets of pulses are perfectly synchronized to each other. In our first year experiment, we used the second harmonic of the drive laser at 527 nm to perform direct Compton backscattering.

Let us consider two uniform-density micropulses of electrons and photons with cross-section area A , containing N_e and N_p electrons and photons, respectively. The cross-sectional density of electrons in a micropulse is just the number of electrons divided by the cross-section area N_e/A . The probability that a single photon passing through this micropulse will backscatter and produce an x-ray photon is $P = \sigma_c N_e / A$ where σ_c is the total Compton cross section ($\sigma_c = 0.665 \times 10^{-24} \text{ cm}^2$). The total Compton backscatter yield

in colliding with N_p photons is $N_x = \sigma_c N_e N_p / A$. If we consider both the electron and the photon beams to have a gaussian profile, the cross-section area becomes the sum of squares of the beams' rms radii.

In our design of the compact Compton backscattering module, we use 5 nanocoulombs (a nanocoulomb is one-billionth of a coulomb) as the design point for the microbunch charge, 10 microjoules for the laser micropulse energy at the second harmonic frequency of a Nd:YLF laser (photon energy = 2.3 eV), and 50 microns as the rms radii of the electron and the laser beams. Plugging in the numerical value of the Compton cross section, we obtain a total Compton backscatter x-ray yield of 11,200 x-ray photons in each microbunch. If we repeat the microbunch at a repetition rate of 10^4 per second (see Figure 1 for the electron and laser pulse formats), we can generate 1.1×10^8 x-ray photons per second.

However, not all of the x-ray photons generated can be detected by the x-ray detector. The above calculation is for a beam of x-rays generated into an opening cone angle of $1/\gamma$. Due to the choice of a low electron beam energy, and thus small γ , the opening cone angle is large. For example, γ is about 33 in our case, and thus the opening cone angle is 30 milliradians. As most x-ray detectors are small, this opening cone angle presents a unique problem of collecting all the generated x-ray photons into the x-ray detector. This problem is compounded by the fact that we have to place the detector at a distance away from the collision region, thereby reducing the acceptance angle of the detector. The number of x-ray photons incident on the detector is determined by the acceptance angle θ of the detector, and can be approximated by $(3/2) (\gamma\theta)^2$ times the total number of x-rays generated

Our first attempts to detect 10 keV x-rays by scattering the second harmonic of the Nd:YLF laser at a wavelength of 527 nm (photon energy = 2.3 eV), were unsuccessful due to the low photon flux of the laser. At its best, the laser delivered only 6 mJ per 15- μ s macropulse at the collision point. This corresponds to a micropulse energy of only 3.7 microjoules (10^{23} photons). Another problem was focusing the electron beam. While the electron beam emittance could support a beam radius less than 50 microns, due to poor matching condition the measured electron beam radius was larger than 1 mm at the collision region. The combination of low laser photon flux, poor focusing and small detector's collection angle leads to a low expected x-ray counts. For detecting the Compton x-rays, we employed two kinds of x-ray detectors: the time-resolved x-ray detector (Amtek XR-100) and the time-integrated sodium iodide scintillator coupled with photomultiplier tube detection (Figure 2). In both attempts, the signal was overwhelmed by the large x-ray background that was present in the vicinity of the accelerator. We have tried shielding the

detector and using a crystal to reflect the Compton backscatter x-rays into the detector. None of these techniques produced a signal that was differentiable from the x-ray background. We concluded that our Compton backscatter experiment has to be modified to significantly increase the Compton backscatter x-ray flux. To this end, we designed a new approach of Compton backscattering based on the regenerative amplifier FEL.

The regenerative amplifier FEL is a new approach aimed at achieving the highest photon flux from a compact RF-linac FEL. The key idea is to re-inject a small fraction ($<10\%$) of the optical power into a high-gain wiggler ($>10^3$ in a single pass) to enable the FEL to reach saturation in a few passes. The use of large outcoupling increases the FEL output efficiency and reduces the risk of optical damage to the feedback mirrors. This feature also allows us to put an on-axis annular mirror downstream to reflect the infrared photons for performing Compton backscattering on the electron beams. The highest optical energy achieved thus far at $15.5\text{ }\mu\text{m}$ is 0.5 J over a train of 1000 micropulses. We infer a pulse energy of 0.5 mJ in each 10 ps micropulse, corresponding to a peak photon density of 4×10^{16} .

The design of Compton backscattering using a regenerative amplifier FEL is illustrated in Figure 3. The optical feedback is provided by a simple ring cavity consisting of two annular mirrors and two 90° paraboloids. The electron beam enters the high-gain wiggler from the left through the hole in the upstream annular mirror. Inside the wiggler, the electron beam is continuously focused by the wiggler's magnetic property to a small spot with radius less than 200 microns (Figure 4). The electron beam first emits spontaneous synchrotron radiation that co-propagates with the electron beam and grows exponentially with distance because of the large small-signal gain of the wiggler. A small fraction of the optical power exiting the wiggler is reflected by the downstream annular mirror and focused to the wiggler entrance by the two 90° paraboloids. In the next several passes, optical amplification starts from coherent optical power instead of spontaneous noise. This allows the FEL to reach a high power level in a few passes. Unlike an FEL oscillator, the feedback optics do not require careful alignment and are not subject to very high peak power that can cause optical damage. The output photon beam exiting the 45° annular mirror is allowed to expand over a distance and then reflected by a 0° spherical mirror. The spherical mirror focuses the infrared beam to a small spot near the exit of the wiggler where it collides with the electron beam. The complete design of the Compton backscattering x-ray source is shown in Figure 5.

In conclusion, we have demonstrated the large photon flux from the regenerative amplifier FEL. We have completed the design of a high-flux Compton backscattering x-ray source based on the regenerative amplifier. We have successfully tested a new retro-reflection optical system for matching the laser beam to perform Compton backscattering. We have shown that the electron beam can be focused in both directions through the use of two-plane focusing in the wiggler. Based on the new design, we expect the Compton

backscattering yield to be 10^{10} x-ray photons per second, with 10^6 photons/sec being detected at the x-ray detector.

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Table I
Beam parameters of the Advanced Free-Electron Laser accelerator

Beam Energy	E	16.5 MeV
Peak current	I_{peak}	3–300 A
Charge/bunch	Q	0.01–5 nC
Bunch length	τ	3.5–16 ps
Bunch separation	T	9.23 ns
Normalized emittance*	ε_n	<7 mm-mrad
Energy spread	$\Delta\gamma/\gamma$	<0.5%
rms radius inside wiggler	r_b	0.2 mm
Wiggler period	λ_w	2 cm (fixed)
On-axis field	B_0	0.7 Tesla
Wiggler length	L_w	1 m uniform 1 m tapered
Taper rate		30% in B
Wiggler gap		5.9–9.5 mm
Wavelength	λ	16.2 μm

* At 300 A peak current

Figure 1. Micropulse and macropulse formats of the electron and laser beams.

Figure 2

Figure 2. Direct Compton backscatter geometry.

Figure 3. Illustration of the Compton backscatter with regenerative amplifier FEL.

Figure 4. Measured electron beam radii in both x and y directions in the wiggler.

Figure 5. Compton backscatter geometry with the regenerative amplifier FEL.