Tunable X-Ray Generation in a Free-Electron Laser by Intracavity Compton Backscattering

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A nearly monochromatic x-ray beam of 7 to 12 keV has been produced with an infrared free-electron laser (FEL). This is achieved when the intense laser field generated and stored in the laser optical cavity is backscattered by the FEL relativistic electron beam. [S0031-9007(96)01352-X]

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Compton backscattering consists of the backward reflection of photons by a relativistic electron beam. If λ_L is the photon wavelength and γ the electron relativistic factor, the wavelength of the reflected wave for head-on collision is given by

$$\lambda_X \cong \frac{\lambda_L}{4\gamma^2}(1 + \gamma^2\theta^2) \qquad (1)$$

for $\gamma \gg 1$, and where θ is the observation angle with respect to the electron velocity. This radiation is emitted forward, in a narrow cone of half angle $1/\gamma$. Furthermore, its linewidth is equal to that of the laser $(\Delta\lambda_L/\lambda_L)$ for an ideal electron beam, if one selects only photons emitted in a cone of half angle $\theta = \gamma^{-1}\sqrt{\Delta\lambda_L/\lambda_L}$ [1,2].

Compton backscattering has been proposed through the years as a source of tunable γ or x rays [3]. Indeed, several experiments have been conducted or are in progress, particularly in order to produce γ rays for nuclear physics [1,4–10]. However, such a source requires a powerful external laser and a good overlap between the photon and electron beams, in both space and time. For short pulses and beams focused on a few tens of microns, this represents a non-negligible challenge for reliable source operation. Furthermore, tunability requires one to sweep the electron energy or to use a tunable laser. Change in energy affects the electron size and position at the interaction point, while the tunability of a laser is a difficult requirement to meet.

In this Letter, we report the positive operation of an alternative scheme in which the laser is an infrared free-electron laser (FEL), fed by the electrons themselves and colliding with them in the optical cavity (see Fig. 1). Let us recall that in a FEL spontaneous emission corresponds to the radiation emitted by a relativistic electron beam as it passes through a periodic magnetic structure, called an undulator [11]. Amplification occurs as the electrons interact with the light and give away a fraction of their kinetic energy to the latter. This is a resonant process, which usually occurs only for a definite wavelength:

$$\lambda_{\rm FEL} \cong \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2}\right), \qquad (2)$$

where λ_0 is the undulator period and K the so-called deflection parameter of the undulator. Tunability can be obtained by varying K, which depends on the magnetic field, typically between 0.5–3 in most operational FELs.

In our scheme, intracavity operation ensures the very high average and peak power necessary to produce a noticeable amount of backscattered photons. Furthermore, and principally, the main existence of the FEL oscillation guarantees the good overlap between photons and electrons. X rays are emitted on-axis, and their wavelength can be continuously and rapidly tuned over a wide range by sweeping the FEL wavelength. With the above notations, this wavelength can be written as

$$\lambda_X = \frac{\lambda_{\rm FEL}}{4\gamma^2}(1 + \gamma^2\theta^2) = \frac{\lambda_0}{8\gamma^4}\left(1 + \frac{K^2}{2}\right)(1 + \gamma^2\theta^2). \qquad (3)$$

Indeed, this radiation is similar to the synchrotron radiation emitted in an undulator, the emitted wavelength resulting from a relativistic Doppler shift. The difference is that, for an "undulator" traveling at the speed c, there is a factor of 4 instead of 2 in the wavelength expression. Indeed, the undulator factor "K" should also appear in the wavelength expression. However, it is generally so weak in the case of a photon that it can be omitted in the wavelength calculation. Nevertheless, it has to be taken into account in the calculation of the backscattered intensity. By applying the first Lorentz equation, it appears that the light is equivalent to an undulator of period $\lambda_{\rm FEL}/2$, of field $2B_0$, and of K parameter such that $K_{\rm FEL} = 0.934 B_0[{\rm T}]\lambda_{\rm FEL}[{\rm cm}]$, where B_0 is the peak magnetic field of the wave. Under these conditions, the well-known formulas of the undulator radiation apply to the process [12]. The number of photons produced is

$$N_X \approx 22.7 N K_{\rm FEL}^2 \gamma^2\theta^2 q, \qquad (4)$$

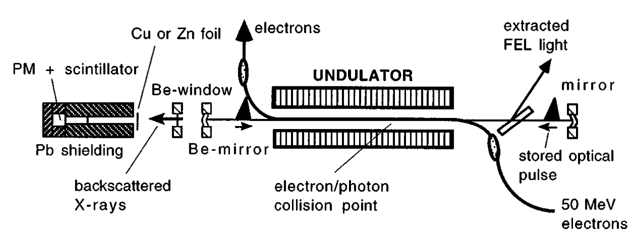

FIG. 1. Experimental setup. The relativistic electron bunches amplify infrared light pulses going forward, and reflect back in the x domain some of the photons going backward.

provided the electrons beam size is smaller than the laser mode, and where N is the number of periods of the wave, θ the observation angle (in mrad), and q the electron beam charge (in nC). In our case, K_{FEL} is small ($<10^{-2}$) so that no harmonics are produced. Let us also note that the radiation polarization is determined by the undulator symmetry, i.e., plane in our case.

CLIO is an infrared FEL facility, based on a small dedicated RF linear accelerator [13]. The electron peak current is 100 A in 8 ps long bunches separated by 4 to 32 ns during 11 μs macropulses. In this experiment the energy was 50 MeV in order to obtain x-ray energies from 7 to 14 keV with the FEL in the range 3.5–7 μm. The pulse separation was chosen equal to 16 ns so that there are 2 pulses simultaneously in the optical cavity (4.8 m long), and crossing occurs between stored photons and electrons. A higher repetition rate has been avoided since, in that case, crossings would also happen at the undulator output, where the electron energy spread has been strongly affected by the electron-FEL interaction and becomes several percent. The beam normalized rms emittance is approximately 40π mm mrad, and its FWHM energy spread is about 1%.

The optical cavity mirrors are usually both metallic, with a radius curvature of 3 m. In this experiment, one of them was replaced by an equivalent beryllium mirror, allowing the x ray to pass through but was still highly reflective in the infrared range ($R > 98.8\%$) due to a 0.1 mm thick gold coating. The mirror thickness is 5 mm except on a 12 mm diameter central area, where it is only 1.7 mm thick in order to improve the x transparency below 10 keV. The vacuum sealing is also made with a 0.2 mm thick Be window. A fraction of the infrared beam was coupled out of the cavity by a CaF_2 plate located near the Brewster angle (60°). The CaF_2 losses at this incidence are calculated to be 1% per cavity round trip. However, the measured cavity losses were 6%. This appeared later to be due to a damage inflicted to the Au-coated Be mirror by the high optical field. Therefore the intracavity power was lower than expected. The average extracted power was 2 W at 25 Hz repetition rate of the macropulses. Assuming a 2 ps long optical pulse [14], the intracavity peak power is then estimated at 7 GW. Let us point out that, in this setup, the laser mode was optimized for far infrared rather than for x-ray production, leading to only 250 GW/cm^2. In the future, the choice of a smaller laser waist will lead to a higher power density at the interaction point, while it will be diminished on the mirrors. The FEL linewidth in these conditions is about 1%.

With the above characteristics, the number of photons was calculated to be 4×10^2/micropulse, 2×10^5/macropulse, and 5×10^6/s emitted within an angle of 2 mrad. The x-ray linewidth results from the contributions of the FEL linewidth, the electron energy spread and emittance, and the aperture angle. Its expected value is 5%.

The detector was a NaI scintillator, with a 38 mm diameter sensitive area and a 0.2 mm thick Be window. It was located at 1.5 m from the FEL exit window and carefully shielded against the various ionizing radiations produced by the linac. In this first experiment, the space between the detector and the Be mirror was not evacuated. However, air transmittance is still adequate at 10 keV—but falling rapidly with lower energies.

Even in the absence of laser oscillation, a non-negligible background signal was observed. This background signal is due to ionizing radiations emitted along the beam axis, so that the shielding is inefficient. It can be attributed to the few electrons lost at the entry of the undulator chamber. This chamber is much narrower in the direction of the magnetic field. It was clearly seen that the background diminishes when closing the undulator gap, thus ensuring better focusing in that plane. Therefore this effect is probably due to the few electrons having an emittance much higher than the average of the beam. The energy spread has no influence, as it was defined by a collimator in an energy dispersive section in the accelerator bend.

However, by turning the laser on, one observes a substantial enhancement of the scintillator signal with a temporal structure similar to that of the laser, whereas the parasitic background structure is just the same as that of the electron beam. This appears clearly in a situation where the laser saturates late, as pictured in Fig. 2. With a laser optimized to the parameters exposed above, one can obtain a signal over background ratio up to 4. Turning the laser "on" or "off" is achieved by just modifying slightly the optical cavity length, a well-known feature of FEL physics [11]. In these first measurements, the number of x-ray photons detected by macropulse was roughly estimated by comparison with the signal given by a ^{55}Fe source to be in the 10^3 range.

A further characterisation of the x-ray beam has been achieved by performing a rough spectroscopic

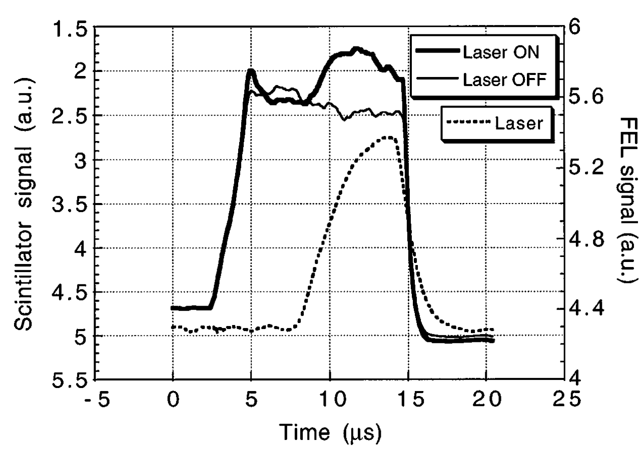

FIG. 2. X-ray detector signal with laser on and off. The background is due to lost electrons and has the time structure of the electron beam.

measurement. We simply inserted a thin foil of a metal, 20 μm thick, of which the K edge is in the spectral region of interest: Cu (9 keV) and Zn (9.6 keV). The foil was located just a few centimeters away from the scintillator. A 7 mm hole was also placed near the exit window to improve the beam collimation and to reduce the awaited linewidth to 3%. The x-ray line was then scanned by sweeping the FEL wavelength with the undulator gap. As the K transition is very sharp, such a measurement is also indicative of the x-ray linewidth. We present a spectrum for the Zn sample in Fig. 3. As expected, one can observe a clear signal attenuation due to the K transition wavelength. However, one must note that the x-ray energy at the transition calculated from the experimental parameters was upshifted by 6% relatively to the theoretical value. This slight disagreement can be explained by an angular tilt of the optical mode by 2.6 mrad relatively to the cavity axis, and this hypothesis has been taken into account in calculating the photon energy in Fig. 3. Such a misalignment would also account for the spectral width observed, about 10%. As a matter of fact, this assumption was backed, thereafter, when we examined the beryllium mirror, which appeared to be punctually damaged by the high optical field in its center over a circular area of radius 5 mm. Therefore, we conclude that this measurement is another positive check for the presence of backscattered photons, a demonstration of the source tunability in wavelength, and also an indication of the necessity to operate in the future with better coatings and/or a different optical cavity geometry in order to lower the power density on the mirrors.

In conclusion, we have demonstrated for the first time the generation of tunable x rays by intracavity Compton backscattering in an infrared FEL. With the CLIO FEL, an x-ray brightness during the micropulses of 10^{11} photons/(s mm^2 mrad^2 0.1% bandwidth) can be achieved, although we estimated it to be only 10^9 in our first experiments with a crude photon counting scheme. This brightness should be increased by 1 or 2 orders of magnitude by a proper choice of FEL cavity mirrors. In fact, CLIO was optimized for other purposes, so that improving the accelerator design to produce a smaller focus at the interaction point would also greatly enhance the x-ray brilliance. Therefore, this experiment opens the field of picosecond tunable x-ray sources driven by compact accelerators. In addition, two-color experiments at a picosecond time scale, using the infrared driving FEL, can be envisioned. Finally, one can also note that a FEL in this spectral region is very difficult to realize and would be very costly and cumbersome, with machine lengths in the 3×10^2 to 3×10^3 m range [15,16]. In our case, although potentially less power is produced and the degree of coherence is smaller than expected with a genuine laser oscillator, the problem of increasing the brightness reduces to that of optimization of a high power infrared FEL, which is far easier and well within the present state of the art.

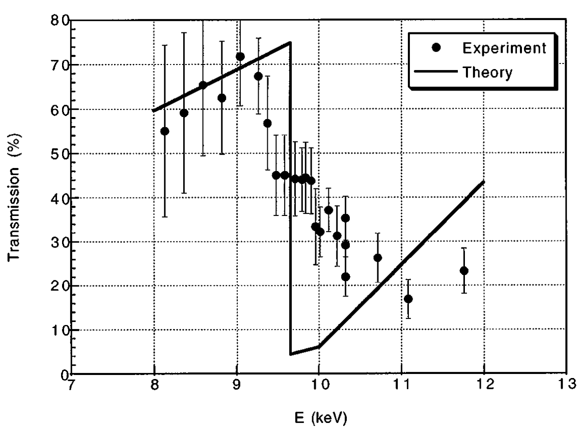

FIG. 3. Spectroscopic scan of a thin Zn foil at the K edge with the x-ray beam. An angular tilt by 2.5 mrad of the laser beam relative to the observation direction is assumed in calculating the x-ray energy.

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