PRODUCTION OF TUNABLE X-RAYS BY INTRACAVITY COMPTON BACKSCATTERING IN AN INFRARED FREE-ELECTRON LASER

F. Glotin, J. M. Ortega, R. Prazeres, J.M. Berset, M. Bordessoule
R. Chaput, G. Devanz, M. Lemonnier, O. Marcouillé

LURE, bat. 209 D, Orsay, 91405 - France

Abstract

We demonstrate that an infrared free-electron laser, based on a low energy RF linac, can constitute an excellent source of X-rays by optimizing the Compton backscattered photons that are emitted in the optical cavity. The 10 keV spectral region is easily obtained, due to a large relativistic Doppler shift. Also, the X-ray energy can be swept over a large range by taking profit of the wide spectral tuning range of an infrared FEL using metal mirrors.

1 PRINCIPLE

Compton backscattering consists in 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 is given by :

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

where θ is the observation angle, with respect to the electron velocity.

The use of a visible or infrared light beam allows to produce photons in the X-rays spectral region with a low energy accelerator (10-50 MeV), although synchrotron radiation in a typical static undulator requires a several GeV electron beam.

Compton backscattering has been proposed for long as a source of tunable Γ or X rays[1]. Indeed, several experiments have been conducted in the past, particularly in order to produce Γ rays for nuclear physics. However, such a source requires a powerful external laser and an often unstable overlap between the photon and electron beams. Also, tunability is difficult since it requires either a tunable laser or electron energy. A widely tunable laser having the required characteristics, i.e. hundreds of Watts of average power and GW of peak power, is practically impossible with present technology and would be very costly and extremely difficult to operate reliably. On the other hand, varying continuously the electron energy by large amounts without changing the beam size and position by more than typically 0.1 mm and its phase by one degree is also out of reach of RF accelerators.

Here, we demonstrate a alternative solution in which the laser is an infrared free-electron laser fed by the electrons themselves and colliding with them in the optical cavity. The intracavity operation ensures a very high average and peak power necessary to produce noticeable amount of back-scattered photons. The X-rays are emitted on-axis and their wavelength can be continuously and rapidly tuned over a wide range by sweeping the FEL wavelength. The demonstrated operability and large tunability of infrared FELs make them ideal candidates for this process.

Due to relativistic Doppler shift, the wavelength is now :

$$\lambda_X = \frac{\lambda_{FEL}}{4\gamma^2}(1 + \gamma^2\theta^2) = \frac{\lambda_o}{8\gamma^4}\left(1 + \frac{K^2}{2}\right)(1 + \gamma^2\theta^2)$$

λ_o is the undulator period and K, the undulator parameter. The tunability can be obtained by varying K, typically between 0.5 to 3, in most operational FELs.

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 the "undulator" travelling at the speed c, there is a factor of 4 instead of 2 in the wavelength expression. Indeed, the undulator factor "K" should appear also 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 $\lambda_L/2$, of field $2B_o$, and of "K" parameter proportional to $B_o\lambda_L$, where B_o is the peak magnetic field of the wave. Under these conditions, the well-known formula of the undulator radiation apply to the process. The number of photons produced is :

$$n \approx 22.7NK^2\gamma^2\theta^2q$$

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 is small ($< 10^{-2}$) so that no harmonics are produced.

2 EXPERIMENTAL SET-UP

2.1 The CLIO accelerator

CLIO is an RF linac based infrared FEL facility[2]. It uses a thermo-ionic gun followed by a 500 MHz sub-harmonic buncher a 3 GHz buncher and accelerating section. 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-rays energies from 7 to 14 keV with the FEL in the range 3.5 - 7 µm. The pulse separation was chosen at 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 was avoided since in that case crossings would 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 emittance is approximately 200 π mm.mrad.

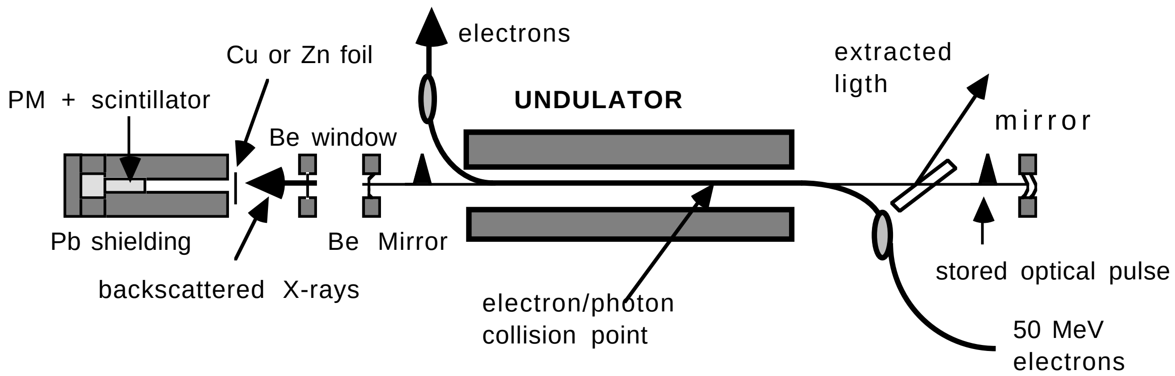
2.2 The CLIO FEL

The FEL is tunable from 3 to 50 µm, using wide band metal mirrors. The full spectral range is cover by energies ranging from 20 to 50 MeV with a tunability by a factor of 2 at each energy.

The laser output peak power is about 100 MW. The intracavity power is higher by several orders of magnitude, depending on experimental conditions : output coupling, intracavity absorption and diffraction losses. The latter are negligible in the spectral range of interest for the X-ray production.

In this experiment the FEL was outcoupled by an intracavity CaF_2 plate located at near Brewster angle (60°). The CaF_2 losses at this incidence are close to 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. Therefore, assuming a 2 ps long optical pulse[3], the intracavity power is estimated at 7 GW and 250 GW/cm^2. Let us point out that, in this set-up, the laser mode was optimised for far-infrared rather than for X-ray production. 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.

Experimental Set-up



2.3 X-rays calculated characteristics

With the above characteristics, the number of photons was calculated to be 4 10^2/micropulse, 2 10^5/macropulse and 5 10^6/sec. emitted within an angle of 2 mrad. The X-ray linewidth results from the contributions of the FEL linewidth, the electron energy spread and the aperture angle :

$$\left[\frac{\Delta\lambda}{\lambda}\right]_x^2 \approx \left[\frac{\Delta\lambda}{\lambda}\right]_{FEL}^2 + \left[\frac{2\Delta\gamma}{\gamma}\right]_{e^-}^2 + \left[\frac{\overline{\gamma^2\theta^2}}{1+\gamma^2\theta^2}\right]_{obs}^2$$

The above number of photons correspond to an aperture which do not affect substantially the X-ray linewidth. With an FEL linewidth of 1% and a CLIO energy spread of 0.5% FWHM, the expected bandwidth is 1 - 2 %.

2.4 Detection of the X-ray beam

The X-ray beam is extracted from the optical cavity by putting a forward infrared mirror manufactured in 1.7 mm thick Be. The vacuum sealing is made with a 0.2 mm thick Be window. In this first experiment the detection was in air, which transmittance is good at 10 keV and falling at shorter energies. The detector was a NaI scintillator, with a 0.2 mm thick Be window. It had to be carefully shielded against the various ionizing radiations produced by the linac.

In order to measure the X-ray spectrum, we simply inserted a thin foil, 20 µm thick, of a metal, of which the K edge is in the spectral region of interest : Cu (9 keV) and Zn (9.6 keV). The X-ray line was then scanned by sweeping the FEL wavelength with the undulator gap.

The X-ray recorded signal is the integral of the line in the transmitting part of the metal edge, from which the linewidth can be deduced. The edge being very sharp, the ultimate resolution is better than 10^{-3}, limited by the noise in practice.

3 RESULTS

3.1 Number of photons

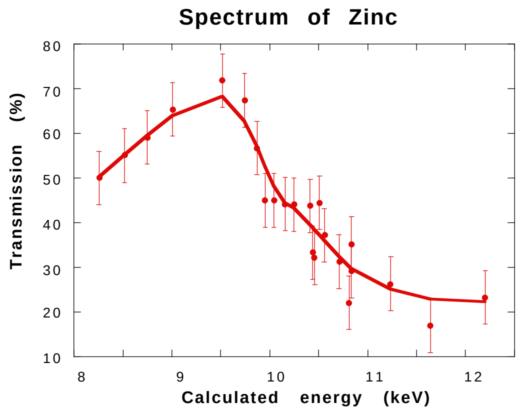
The X-ray signal was observed[4] by measuring the difference between the total intensity with the laser "on" and the parasitic signal observed at laser "off". Then an X-ray signal having exactly the time structure of the FEL appears, the parasitic background signal having the time structure of the electron current. The ratio of signal over background was approximately 4. The number of photons agrees roughly with the calculated one. Typically, one order of magnitude is lost in air and through the windows.

The 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 a better focalisation 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, since it was filtered by a collimator in an energy dispersive section in the accelerator bend.

3.2 Spectral distribution

The spectral distribution of the X-rays was measured as indicated above, by scanning the line across a metal K edge. However, then, the signal/background ratio diminishes, which makes the measurements noisy. Also, the necessity to perform each measurement with the FEL successively on and off made it difficult to accumulate data. Nevertheless, the spectrum shows that the line is located close to the theoretical wavelength and that its spectral width is nearly 5%.

The fact that the wavelength is located about 5 % above the theoretical one and that the linewidth is somewhat larger than predicted is explained by the effect of the observation angle, θ. Indeed, when we examined the damaged Be mirror, it appeared that the spots where located off-center by about 5 mm. This corresponds to a misalignment between the observation (cavity axis) and electron velocity of 2 mrad, accounting for a 4% difference in wavelength and a contribution to the inhomogeneous broadening of the line of 2-3%.



3.3 Conclusion

We have shown that Compton backscattering in an infrared FEL constitutes an operational source of tunable X-rays. During the micropulses, the X-ray flux is about 10^{14} photons/(s.mm^2.mrad.1% bandwidth), which constitutes an appreciable brightness. This number will be increased by at least 2 orders of magnitude by a proper choice of FEL cavity mirrors. In fact, CLIO was optimized for other purposes so that, redesigning the accelerator bend to produce a smaller focus at the interaction point would also enhance the emission by several orders of magnitude.

The peak brightness obtained here is comparable to what is produced on storage rings, although the average brightness remains much smaller due to the low duty cycle of linacs. Therefore, this experiment opens up the field of picosecond tunable X-ray sources driven by compact accelerators. In addition, 2-colors experiments, using the driving FEL, at a ps time scale, can be envisioned.

Tunable X-ray lasers do not exist. An FEL in this spectral region is very difficult to realize and would be very costly and cumbersome. In our case, although potentially less power is produced, the problem of increasing the brightness reduces to the optimization of a high power infrared FEL, which is far more easier.

3 REFERENCES

[1] R. H. Milburn, Phys. Rev. Lett., 10, 75 (1963)
[2] J. M. Ortega, Nucl. Instr. & Meth., A341, 138 (1994)
[3] F. Glotin et al., Nucl. Instr. & Meth., A341, 49 (1994)
[4] F. Glotin et al., Phys. Rev. Lett., submitted