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Single shot radiography using an all-optical Compton backscattering source

A. Döpp\textsuperscript{a,b,*}, E. Guillaume\textsuperscript{a}, C. Thaury\textsuperscript{a}, J. Gautier\textsuperscript{a}, A. Lifschitz\textsuperscript{a}, E. Conejero\textsuperscript{c}, C. Ruiz\textsuperscript{c}, V. Malka\textsuperscript{a}, A. Rousse\textsuperscript{a}, K. Ta Phuoc\textsuperscript{a}

\textsuperscript{a} Laboratoire d’Optique Appliquée, ENSTA ParisTech - CNRS UMR7639 - École Polytechnique, Chemin de la Hunière, 91761 Palaiseau, France

\textsuperscript{b} Centro de Laseres Pulsados, Parque Científico, 37185 Villamayor, Salamanca, Spain

\textsuperscript{c} Area de Óptica, Departamento de Física Aplicada, Universidad de Salamanca, Plaza de la Merced s/n, 37008 Salamanca, Spain

Abstract

The development of compact laser-based synchrotron sources is a field of active research. Here we present recent results on an all-optical Compton backscattering source using laser-accelerated electrons and a plasma mirror, as introduced in [K. Ta Phuoc \textit{et al.}, Nature Photonics 6 (5) (2012) 308-311].

Scattering of quasi-monoenergetic electrons of up to 200 MeV energy with their proper drive-beam leads to emission of femtosecond X-ray pulses, whose energies exceed 100 keV. We demonstrate that the photon yield from the source is sufficient to illuminate a centimeter-size sample placed 90 centimeters behind the source.

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* Correspondence to adoep@usal.es
1. Introduction

The production of X-radiation is primarily based on two processes to convert electron energy to high energy photon radiation: bremsstrahlung and synchrotron radiation [1]. The latter can provide collimated, polarized, low bandwidth radiation [2], yet the simpler bremsstrahlung scheme is by far more common as source of X-rays. The spread of synchrotron technology to a wider public is hindered by the substantial investments necessary to build such a facility, which typically consists of a GeV-level electron accelerator, a storage ring and beam lines with insertion devices to produce the radiation.

The need of a GeV-class electron accelerator arrises from the fact that modern synchrotrons use undulators and wigglers (arrays of alternating magnetic fields) to modulate the electron trajectory in transverse direction [3]. Electrons perceive the undulator period $\lambda_0$ doppler-upshifted and emit dipole radiation at the frequency $\gamma \lambda_0$, where $\gamma$ denotes the Lorentz factor $\gamma = (1 - (v_e/c)^2)^{-1/2}$. For an observer at rest this radiation is then perceived upshifted again and depending on the angle between electron and wiggling field $\phi$, the angle to the observer $\theta$ and the peak angular deflection $K/\gamma$ - the measured wavelength is [4]

$$\lambda = \frac{\lambda_0}{2\gamma^2(1 - \beta \cos \phi)} \left( 1 + \frac{K^2}{2} + \gamma^2 \theta^2 \right).$$

The periodicity of the magnet arrays is usually in the order of $\lambda_0 \sim 10^{-2}$ m and cannot be reduced significantly due to technological limitations. This implies that electron energies in the order of $\gamma \gtrsim 10^4$ are needed to reach X-ray wavelength of $\lambda < 10^{-10}$ m.

![Visualization of the undulator equation for a scattering beam with a laser of $\lambda_0 = 800$ nm wavelength, for an observer on axis ($\theta = 0$) and a weak wiggler parameter ($a_0 \ll 1$). The radius represents the energy of backscattered photons on a log$_{10}$ scale, while the angle $\phi$ is the incident angle of the scattering pulse with reference to the electron propagation axis. It is clear that the upshift is the most effect at 180 degree, where photons can be backscattered to MeV energies from electrons $\sim 200$ MeV.](image_url)

In contrast, a near-infrared laser pulse has a fundamental wavelength of $\lambda_0 \sim 10^{-6}$ m and the radiation produced from the interaction between an electron and a laser pulse is very similar to the above formula, just that in case of scattering of an electron with an electromagnetic wave, the undulator parameter $K$ has to be replaced with the normalized potential $a_0 \approx 0.85 [\mu m] \sqrt{[10^{18}W/cm^2]}$, cf. [5]. As a consequence of the substantially shorter wavelength, a synchrotron source based on Compton backscattering of lasers can typically operate at two orders of magnitude lower electron energies than conventional magnet-based
beamlines. Figure 1 illustrates this by visualizing solutions of the optical undulator equation (1) for electron energies up to 500 MeV and a scattering pulse of 800 nm wavelength. We see that for such a short optical undulator wavelength, MeV-level energies can be reached using electron beams of a few hundred MeV. This, and the short duration of the scattered pulse, are the principal advantages which have motivated the implementation of laser backscattering beamlines at many accelerator facilities, e.g. [6, 7].

Modern Laser-plasma accelerators (LPAs) [8, 9, 10, 11] allow acceleration of electron beams up to GeV energies [12] over short distances (millimeters to centimeters), with micrometer source size and femtosecond duration [13]. The combination of laser-wakefield accelerators with Compton backscattering therefore permits to create millimeter-sized, all-optical synchrotron sources. Additional advantages of such sources are that the radiation is inherently of femtosecond duration and profits from the electron beam source size of a few micrometers. The latter makes this source a promising candidate for phase contrast imaging [14] with hard X-radiation, similar to the also laser-plasma based betatron radiation [15, 16, 17]. Yet Compton backscattering can provide higher energies and a smaller bandwidth than betatron sources.

However, the combination of LPA and backscattering is an experimentally challenging task, as it requires good control of two terawatt-class laser pulses, see for example [18, 19]. Instead, a more simple scheme based on a single laser pulse was used for this study [20].

First reported by a research group from Laboratoire d’Optique Appliquée in 2012, it was shown that the intense drive pulse of the LPA can be used itself for Compton scattering with the electrons travelling in its wake. To achieve this, the laser beam is retro-reflected by a plasma mirror, placed close to the exit of the LPA. The advantage of this scheme is that it provides an inherent alignment with the electron beam and operates at 180 degree, which permits the best conversion efficiency to high energy photons. While the proof-of-principle experiment showed a very broad energy distribution, recent experiments have reported the production of X-rays with tunable energy in the range of 75-200 keV with about 50 percent FWHM energy spread [21].

In the following section we will describe the experimental setup used for laser wakefield acceleration of electrons and Compton backscattering. This is followed by the results on X-radiation and we present radiographies taken with a single laser shot.

2. Laser-plasma accelerator

The experiment was performed in February 2014 with the upgraded Salle Jaune Ti:Sa Laser System at Laboratoire d’Optique Appliquée, which delivers linearly polarized laser pulses at 28 femtosecond duration at full width at half maximum (FWHM). Using a spherical mirror of 700 mm focal length the ∼ 1.6 J pulse that entered the experimental chamber was focussed at the entrance of a supersonic gas jet of 2 mm diameter. The focal spot contained 50-55% of the beam energy, leaving a pulse of ∼ 0.9 J for acceleration.

The laser-plasma accelerator was operated in the transverse self-injection regime, producing beams of 100 - 200 pC charge at beam energies mostly in the range of 100 - 150 MeV. Electron charge and spectra were measured using a dipole magnet spectrometer combined with an absolutely calibrated phosphor screen. In contrast to previous experiments [20] the electron beams in this study showed important quasi-monoenergetic features, as shown in Fig.2.

3. Compton backscattering using a plasma mirror

In order to reduce the amount of bremsstrahlung produced when the electrons pass through the plasma mirror, a 100 μm cellophane foil was used. The foil was mounted on a three-axis translation stage and slightly inclined with respect to the laser axis in order to avoid back-reflection to the laser chain. It also permitted to observe the plasma channel which reflected beam formed in the gas jet. Furthermore the reflected laser beam was imaged on a screen. After each shot the foil was moved to provide a flat, undamaged surface.

X-ray were detected using a GdOS based scintillator, fiber-coupled to a low-noise 16-bit CCD (Princeton Instruments Quad-RO 4320). The total detector area was 5 × 5 cm², divided into 2084 × 2084 pixels of 24
μm edge length each. It was placed on the laser axis at 90 centimeters from the interaction, leading to a field of view of ∼ 55 × 55 mrad².

When the foil is placed far from the gas jet, the laser is already diffracted and the signal is dominated by bremsstrahlung produced from electrons passing through the foil. In this experiment the peak value of this signal was 381 ± 39 counts (rms error). In contrast, close to the jet the signal increased to 1231 ± 235 counts, which is comparable to the results obtained before the upgrade of Salle Jaune in 2013. Please note that the scintillator response is non-linear and therefore signal values cannot be directly associated to physical quantities as photon number or emitted power.

In addition to this result, we could distinguish the signals due to their very different spectral content. For this, we placed a 5.1 mm copper filter in front of the detector, which cuts off the spectrum below ∼ 100 keV. Holes inside the plate permit reconstruction of the unperturbed signal level, cf. Fig.3. The ratio between both the filtered signal and the signal that passes through the holes allows to roughly estimate the spectral content. Even this estimation does not allow to deduce a complete spectrum, we do however observe an
important difference between the beams we attribute to bremsstrahlung and the beams from backscattering: While shots with the foil far from the jet show a contrast of $\text{counts}_{\text{filter}}/\text{counts}_{\text{free}} \sim 0.9$, the ratio at high signal level increases to $\text{counts}_{\text{filter}}/\text{counts}_{\text{free}} \sim 0.4$. This implies that these X-rays have more signal content below 100 keV, which is further evidence that the signal originates indeed from Compton backscattering.

Furthermore we measure a pointing stability of $8.3 \text{ mrad} / 6.4 \text{ mrad}$ in $x / y$ direction, where $x$ is horizontal plane. The beam profile is close to isotropic, with an FWHM beam divergence of $(12.7 \pm 3.6) \text{ mrad} / (13.0 \pm 4.0) \text{ mrad}$.

4. Radiography

To demonstrate that the X-ray flux from Compton backscattering is sufficient to be considered for imaging applications, we performed radiographies of macroscopic objects, placed in front of the detector. As an example, Fig. 4 shows the radiography of a clock. Its structural parts consist of metal alloys, while the gears are made of plastic. The different materials are clearly distinguishable in the radiography due to their distinct absorption coefficients. As discussed previously the bremsstrahlung component is very energetic ($>100$ keV) and therefore adds to the image mostly in form of a subtractable background noise.

![Fig. 4. Single shot radiography of a clock. The dark area in the upper part is a shadow cast by the dipole magnet employed to measure the electron spectrum. The signal values measured in this area are used to estimate the background signal. Signal outliers have been removed.](image)

Due to the small source size, it is expected that a subject placed closer to the source will show significant edge enhancement (propagation-based phase contrast imaging).

5. Conclusions

We have performed experiments on Compton backscattering of electrons from a laser-plasma accelerator and demonstrated that the single-shot photon flux is sufficient for imaging. Combined with the inherent micrometer source size, the source is a promising candidate for phase contrast imaging techniques, which will be an area of future investigations. Furthermore, the femtosecond nature of the source may be of interest for pump-probe experiments.
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