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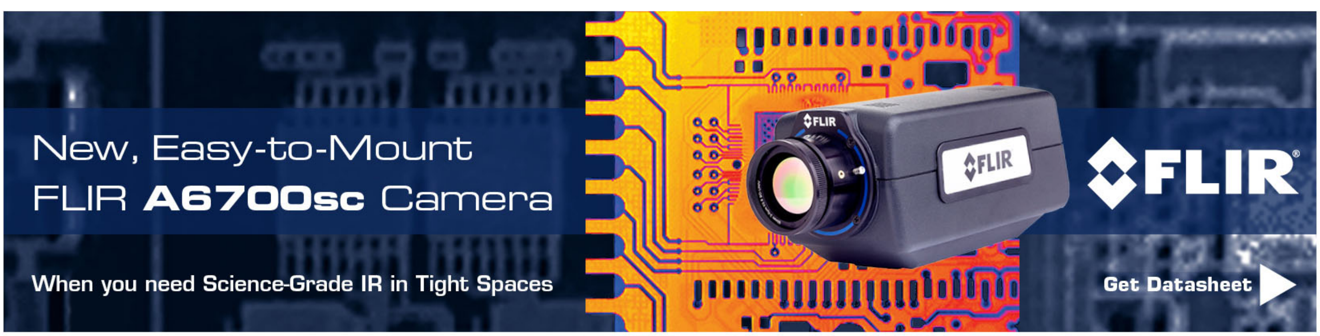

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REVIEW OF SCIENTIFIC INSTRUMENTS **84**, 113302 (2013)

Compton scattering for spectroscopic detection of ultra-fast, high flux, broad energy range X-rays

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Compton side-scattering has been used to simultaneously downshift the energy of keV to MeV energy range photons while attenuating their flux to enable single-shot, spectrally resolved, measurements of high flux X-ray sources to be undertaken. To demonstrate the technique a 1 mm thick pixelated cadmium telluride detector has been used to measure spectra of Compton side-scattered radiation from a Cobalt-60 laboratory source and a high flux, high peak brilliance X-ray source of betatron radiation from a laser-plasma wakefield accelerator. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4825374]

I. INTRODUCTION

X-ray radiation is used as a probe in the study of the structure of matter in a wide range of disciplines from the life sciences, through materials sciences, to plasma and fusion physics. It has been a strong motivation for the development of a new generation of X-ray free-electron lasers (XFELs), such as the Linac Coherent Light Source (LCLS)[1] and the European XFEL, which is under development. More recently, laser-plasma wakefield accelerators (LWFAs)[2] have been shown to be brilliant sources of high energy photons with GW peak powers and energies that extend into the MeV range.[5] These sources produce spatially coherent,[3–5] femtosecond duration, X-ray pulses. Betatron emission and Thomson back-scattering of laser light off high energy electron beams[6,7] can also lead to emission in the gamma-ray range. Laser-plasma based X-ray sources are attracting the attention of the scientific community because of their compactness, their short pulse duration, high peak power and their tunability. To exploit laser-plasma based X-ray sources and investigate their properties, single-shot, spectrally resolving X-ray detectors are required.[3,5] Their huge photon flux makes conventional X-ray detectors unsuitable.

We present a technique based on Compton side-scattering to reduce the photon flux while shifting the spectrum into a spectral region where a pixelated detector can be used to measure spectra in a single shot over a large spectral range. This configuration allows spectral measurements of high flux, broad bandwidth X-ray sources to be made in a single shot.

In Sec. II of the paper we show how Compton side-scattering can be used to increase both the detection range and reduce the photon flux. We also discuss the detector requirements. In Sec. III we describe modelling and calibration of the pixelated semiconductor detector Timepix, which is used to demonstrate our method. In Sec. IV we present experimental demonstrations of the method using Timepix to record 90° Compton side-scattered spectra of photons from a Cobalt-60 calibration source and, to demonstrate flux reduction, betatron X-ray radiation from a LWFA experiment. In Sec. V we discuss the limitations and suggest further development of the proposed technique.

II. THE COMPTON SIDE-SCATTERING CONFIGURATION AND DETECTOR REQUIREMENTS

One way of extending the energy and flux range of an X-ray detector is to use the Compton effect. This is inspired by Compton telescopes used in astrophysics[8] to determine the energy and source position of incoming gamma-ray photons. Compton telescopes utilise two detectors with one acting as a Compton scattering centre, where the Compton-produced electron is detected, while the other detects the scattered photons. From the energy deposited in each detector, it is possible to reconstruct the energy of the incoming radiation and the scattering angle to deduce the source position.

We have modified this scheme and combined the two effects into a single detector: the original first detector is replaced by a scattering centre while the second effectively detects a collimated beam of photons at a fixed angle defined by the positions of the source, scattering centre, and detector. Using this configuration it is possible to directly evaluate

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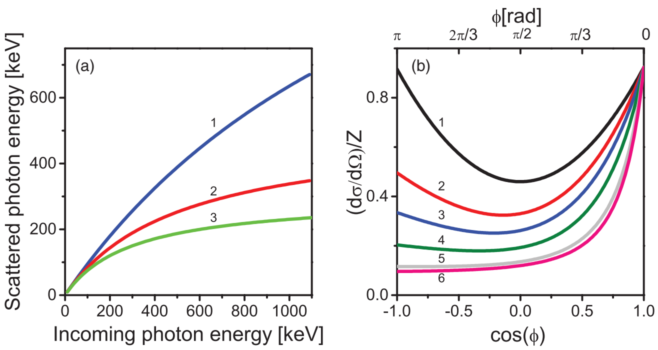

FIG. 1. (a) Compton side-scattered photon energy plotted as a function of the energy of the incoming radiation, for different incident angles: $\pi/4$ (line 1), $\pi/2$ (line 2), and $3\pi/4$ (line 3). (b) Angular cross section as a function of angle for different incoming photon energies: 1 keV (line 1), 100 keV (line 2), 200 keV (line 3), 400 keV (line 4), 800 keV (line 5), and 1000 keV (line 6).

the energy of the incoming photon. The scattered photon energy is downshifted by an energy difference that depends on the angle. By observing at an appropriate angle, it is possible to indirectly measure the photon energy outside the nominal detection range of the detector/spectrometer. However, in addition to downshifting, the Compton effect also contracts the spectrum thus reducing the resolution, as shown in Figure 1(a). The cross-section of the Compton effect is given by the Klein-Nishina formula,[9]

$$\frac{d\sigma}{d\Omega} \propto Z^* P(E_\gamma,\vartheta)^2(P(E_\gamma,\vartheta)+P(E_\gamma,\vartheta)^{-1}-1+\cos^2\vartheta), \tag{1}$$

$$P(E_\gamma,\vartheta) = \frac{1}{1+\frac{E_\gamma}{m_e c^2}(1-\cos\vartheta)}, \tag{2}$$

where E_γ is the energy of the incoming particle, ϑ is the scattering angle, and m_e is the electron rest mass. As $\frac{d\sigma}{d\Omega}$ decreases with increasing scattering angle (Figure 1(a)) the radiation flux incident on the detector is attenuated by factor that depends on the source and detectors sizes (Figure 1(b)). Depending on the angle, there is a trade-off between the energy range, spectral resolution, and signal intensity.

As an example, Figure 2 shows the detector resolution required at the energy for 90° scattered photons to guarantee a 10% resolution up to 50 MeV. The requirements are extremely stringent, however, but could be satisfied using a high resolution detector such as a Germanium detector,[10] which has an energy resolution <1 keV for photon energies up to 500 keV. This would give a resolution better than 10% up to 20 MeV and better than 20% up to 50 MeV for Compton-side scattering at 90°.

However, to apply the technique to the characterization of LWFA based X-ray sources measurements have to be carried out in a single-shot. For this application the detector is required to be pixelated for single shot aquisition. Array germanium detectors of up to few hundred elements are commercially available and could be used for this purpose to achieve the highest resolution. However, as a proof-of-concept demonstration of the Compton-side scattering technique we have used Timepix, a compact 65526 element pixelated semiconductor detector, which has lower energy resolution than a germanium detector but is more compact as it does not require a cryogenic cooling system.

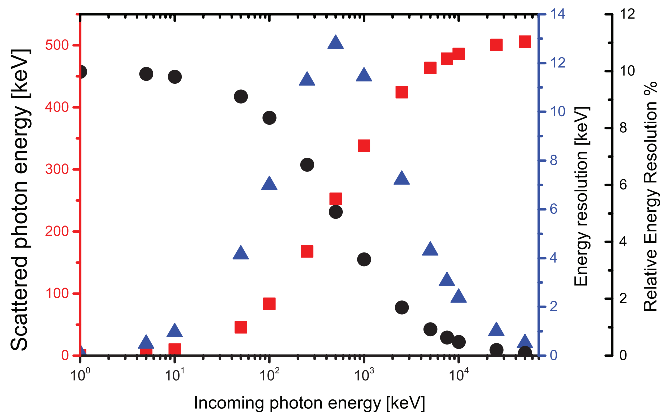

FIG. 2. Squares: Energy of the Compton-side scattered photon at 90°. Triangles: The detector energy resolution (in keV) required for the scattered energy to have a 10% resolution on the measure of the incoming photon. Circles: The detector resolution relative to the energy of the scattered photon.

III. TIMEPIX MODELLING AND CALIBRATION

Timepix[11] is a hybrid pixelated semiconductor detector consisting of a 256 × 256 matrix of identical pixels, each occupying an area of 55 × 55 μm^2. When a high energy particle or photon interacts with the detector material, it deposits its energy and generates electron-hole pairs. The charge produced is collected by electrodes and the signal is processed by integrated circuit elements (one for each pixel) that are connected to the active material by solder bump bonds.

A single X-ray photon can generate signals in many adjacent pixels because the charge produced by a photon can diffuse between pixels. The size of the pixel cluster depends on the interaction depth and the particle energy.[12] The cluster size is defined as the number of pixels with nonzero response to a single photon when the threshold level is set above the noise level.[13] Therefore, to properly reconstruct the radiation spectrum, it is necessary to take into account charge sharing and sum up the energy deposited in each pixel cluster to determine the total energy deposited by each photon.

In pixel semiconductor detectors, the formation of the output signal is determined by many effects, such as distribution of energy inside the conversion layer, spreading of the generated charge during the drift and backscatter of photons from detector components behind the detector layer[14] etc. Backscattered photons become more important at higher photon energies. In addition, photons can be transmitted through the conversion layer without being absorbed to reach the readout chip, which is made up of high Z material. Here, photoelectric absorption can give rise to fluorescence of the readout chip material itself.[15] These fluorescence photons, which are emitted isotropically, in turn may reach the conversion layer and be absorbed adding noise to the detected signal.[16] The amount of additional counts depends on the material and thickness of the converting layer and on the energy of the incoming photons.[15]

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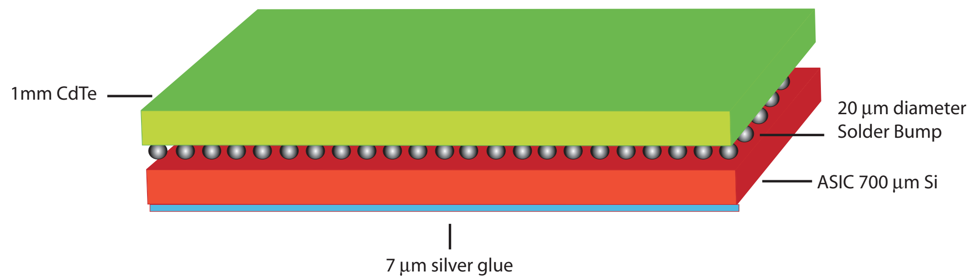

FIG. 3. A schematic of the modelled Timepix detector. A 1 mm thick CdTe active area is connected by 256 × 256 solder "bumps" (20 μm diameter) to the ASIC (700 mm Si). A 7 μm Ag glue is placed below the ASIC.

We have investigated a 1 mm thick Cadmium Telluride (CdTe) semiconductor layer bump-bonded onto the Timepix readout chip. To reproduce the behaviour of Timepix under X-ray irradiation, the detector has been modelled using GEANT4,[17] which simulates the interaction of particle with matter and implements a wide range of physics from low energy (>250 eV) to high energy (∼1 TeV)+. To reproduce the detector response under X-ray irradiation we have used the low energy Livermore model, which takes into account fluorescence, atomic deexcitation, and Auger effect,[18] in addition to basic electromagnetic process such as photoelectric effect, pair production, Compton scattering, multiscattering, ionization and bremsstrahlung process for electrons and positrons, and annihilation of positrons. The simulation output is the energy spectrum deposited in the active area of the detector. This spectrum is then convoluted by the detector energy resolution provided in Ref. 19, to obtain the expected output spectrum from the detector, which can then be compared with the measured one. A schematic of the simulated detector is shown in Figure 3, which includes a 1 mm thick cadmium telluride conversion layer with 20 μm diameter bump bonds of indium, a 700 μm thick silicon layer that represents the Application-Specific Integrated Circuit (ASIC), and a 7 μm thick silver layer for the silver-filled glue behind the electronics.[15]

To characterize the CdTe detector it has been calibrated using Americium 241. The X-ray emission peaks and the source activity are listed in Table I. The recorded spectrum and the corresponding GEANT4 simulation for a 59.5 keV line are presented in Figure 4, where the measured data show at lower energy the tail of the 13.9 keV line.

The CdTe Timepix detector can detect the photo-peaks of gamma-rays up to hundreds of keV, such Cesium-137 632 keV photons.[19] However, the detection capability of CdTe fails when the photon energy reaches the MeV range: the photo-electrons are not stopped inside the 1 mm thick CdTe substrate. As a test, the spectrum of a cobalt-60 (Co-60) calibration source (see Table I for emission lines and activity) has been recorded with Timepix and simulated with GEANT4 (see Figure 5).

TABLE I. Laboratory sources used for calibration and characterization of Timepix detector. Emission lines and source activity are listed.

Source	Energy peaks (keV)	Activity (kBq)
Am-241	13.9, 26.3, 59.5	41.9
Co-60	1173.2, 1332.5	12.0

The measurements show a fluorescence peak (∼30 keV) that is larger than that predicted by simulations. The difference can be attributed to the lack of knowledge of the exact composition of the surrounding material. This characteristic emission, stimulated by the radiation from the Co-60 source, could produce additional fluorescence in the detector.

IV. COMPTON SIDE-SCATTERING DETECTION OF Co-60 PHOTONS AND PHOTONS EMITTED IN THE LWFA EXPERIMENT

As a test of the Compton side-scattering technique, we have measured the side-scattered spectrum of a Co-60 calibration source at 90° using Timepix. As mentioned above, the CdTe Timepix detector cannot detect the photo-peak of the 1.17 MeV and 1.33 MeV lines of Co-60 under direct irradiation. At 90°, the Compton side-scattered photons from the two gamma lines of Co-60 are expected at 355 keV and 369 keV, respectively. Detection with Timepix is challenging in this energy range due to the detector resolution, which is expected to be around 50 keV for 360 keV photons, thus it is not possible to discriminate between the two side-scattered emission lines (see Figure 6).

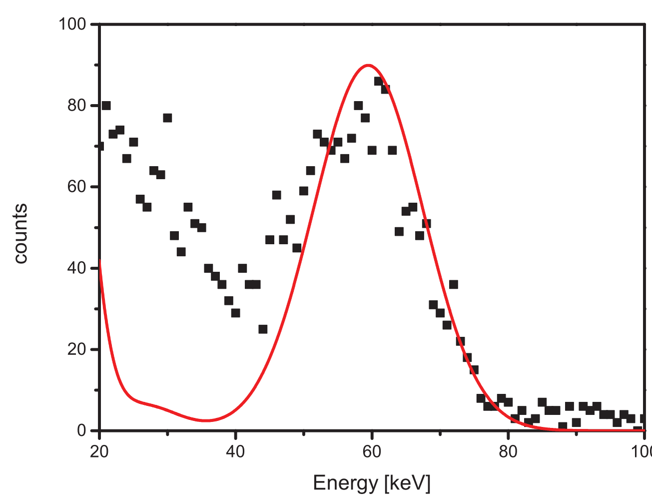

FIG. 4. The measured spectrum of Am-241 (squares) compared with the simulated spectral lines using GEANT4 (solid line curve). The experimental spectrum is the sum of 1000 acquisitions, each of 1 s duration. Timepix clock is set at 48 MHz. The higher experimental signal level at lower energies is attributed to radiation scattered by the surrounding material.

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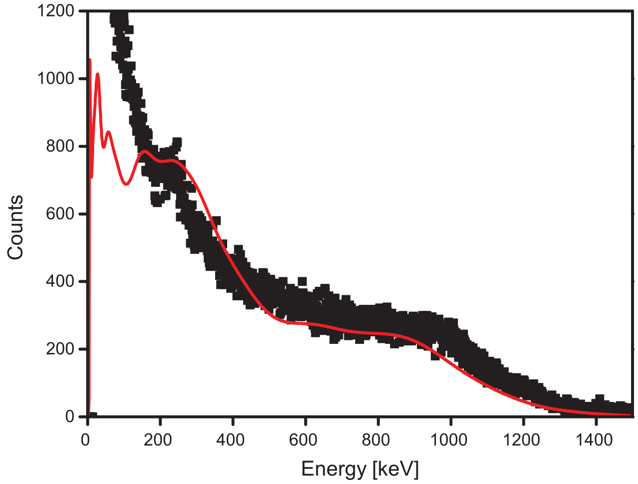

FIG. 5. The plot shows the comparison between the Co-60 spectrum recorded using the CdTe Timepix (squares: 5120 acquisitions of 0.1 s each at 48 MHz clock) with the simulated spectrum modelling the detector using GEANT4 (solid line curve). The photo-peak of 1.17 MeV and 1.33 MeV emission lines of the Co-60 are not detectable.

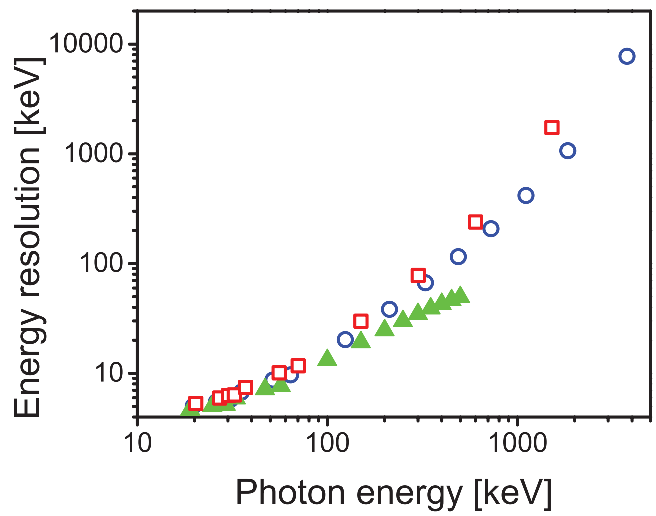

FIG. 6. Energy resolution, given in r.m.s., for different observation angles (0°: triangles, 90°: circles, and 135°: squares). The 0° data are based on experimental data from Ref. 19.

Figure 7 shows the acquisition setup: the source is placed 20 cm from a 5 cm long, 5 mm diameter lead scattering centre. Lead bricks are used to screen the detector active area from direct irradiation. Timepix is enclosed in a 2 mm thick aluminium box and additional aluminium and copper foils are placed around the detector to absorb the k-alpha emission of the lead excited by the source. Data are acquired for 7 days by recording one spectrum every 60 s. Background spectra are acquired under similar conditions after removing the source. Considering the source activity and using the Klein-Nishina formula for our geometry, we expect to have a scattering efficiency of $\sim 10^{-5}$ within the collection angle of Timepix. Therefore the expected signal of just few tens of counts can be detected with Timepix during an acquisition period of 7 days. The detected spectrum with the background subtracted is compared with that simulated using GEANT4 and shown in Figure 8. In both the recorded and simulated spectrum a broad peak appears around 360 keV. This corresponds to the 1.2 MeV photon, which corresponds to the mean of the two Co-60 emission lines. The expected low resolution merges the two emission lines. The experimental test using the Co-60 source successfully demonstrates the Compton side-scattering technique for extending the energy range of the detector, albeit with a loss in resolution.

The major difficulty of the proof-of-principle measurement described above is the low efficiency of the process making detection of a standard low activity calibration source very difficult and time consuming. However, the low efficiency and low resolution makes the technique very suitable for single-shot spectral analysis of high flux gamma-rays from LWFA experiments because high resolution is not required. In a LWFA the ponderomotive force of an intense laser pulse excites plasma density waves to produce a wake, which trails behind the laser pulse.[20] Electrons can "surf" on these electrostatic waves and rapidly accelerate to very high energies.[21–23] High energy photons are emitted by electrons oscillating transversely in the plasma wake bubble

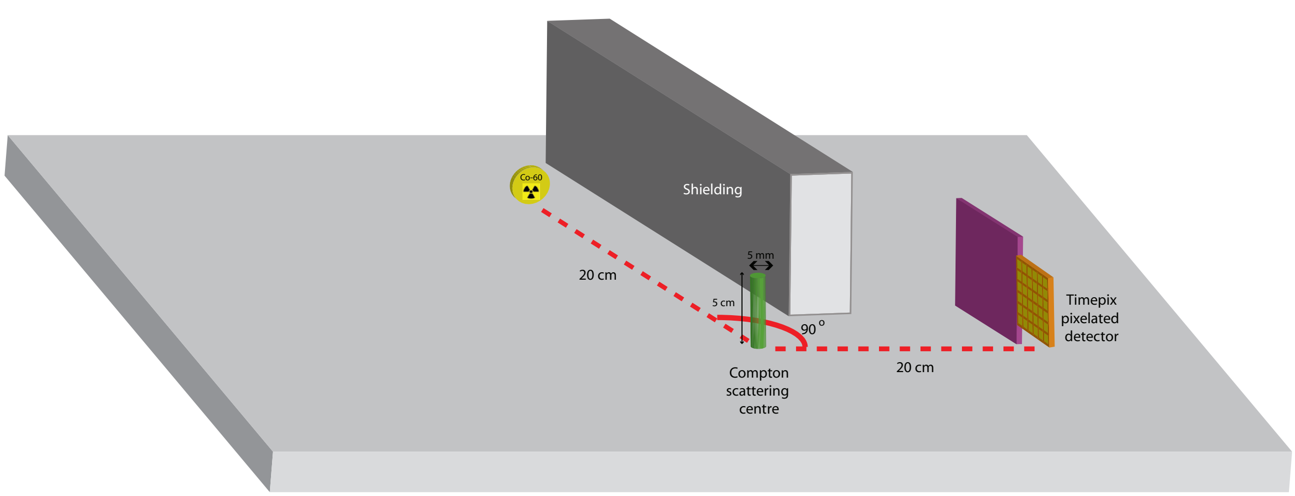

FIG. 7. Schematic of the Compton side-scattering setup. Timepix detects side-scattered photons at 90° by a lead post. The active area of the detector is shielded by the direct irradiation from the source.

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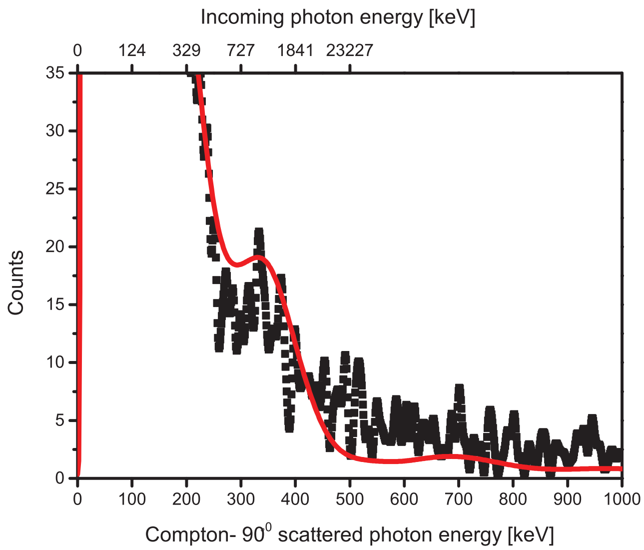

FIG. 8. The recorded (squares) Timepix spectrum of Co-60 radiation scattered through 90° and corresponding simulated spectrum using GEANT4 (solid line). The top axis gives the actual photon energy from the source, while the bottom axis gives the corresponding Compton-scattered photon energy. Parts of the spectrum above 511 keV is due to photons emitted by the Co-60 source being transmitted through the shielding to the detector active area.

trailing behind the driving laser pulse.[5] This radiation, known as betatron radiation, is a tuneable, bright, spatially coherent source.[3–5] Betatron radiation can also record the history of the electron motion during acceleration and is therefore a powerful tool for providing insight into the electron beam motion inside the plasma. Despite the apparent simplicity of the LWFA, the electron motion is determined by a highly nonlinear process that depends on the coupling of plasma, electron beam, and laser fields. The stability and control of the process is still one of the major challenges in the LFWA. Therefore, detecting and monitoring betatron radiation in a single shot is essential.

We have applied the Compton side-scattering scheme using Timepix as a detector to record single-shot betatron spectra. An experiment has been carried out at the Rutherford Appleton Laboratory using the Astra Gemini laser[24] to measure betatron gamma-ray radiation properties. The experimental setup is shown in Figure 9. High energy electrons of mean energy of 630 ± 70 MeV and charge ∼30 pC are produced by focussing a 70 fs duration, 800 nm wavelength, high intensity laser pulse into a pre-formed plasma capillary discharge waveguide.[25] To minimise the bremsstrahlung background, the electron beams are bent away from the laser axis using a 0.7 T dipole magnet placed immediately after the accelerator and a perspex window placed in the chamber end wall allows the emitted X-ray radiation to be transmitted onto a 12 mm diameter aluminium rod placed on-axis 3.4 m from the source, which acts as the Compton scattering element.

The Timepix detector is placed in a shielded enclosure to restrict detection only to Compton side-scattered radiation. The scattering angle is fixed at 90° as a compromise between resolution, energy shift, and flux attenuation. At this angle of detection, the energy range is significant for the CdTe detector (beyond MeV as demonstrated with the Co-60 side-scattering experiment discussed above). The detection efficiency for the experimental configuration, calculated using GEANT4, is 10^{-6}–10^{-7}. The expected emission is about 1 photon per electron and therefore the expected scattered signal is extremely weak (only tens to hundreds of counts). Alternative configurations that may have a higher Compton efficiency, and a different scattering angle, were not possible in this experiment because of geometric constraints in the experimental area and the detector energy range.

To process the measured spectra we apply the following procedure. The efficiency of the Compton side-scattering detection system is calculated for a range of different incoming photon energies using GEANT4 to obtain a transfer function. The measured spectra are then deconvoluted using this transfer function and the actual incoming spectra calculated. To reduce amplification of noise in processing, the measured signal is filtered using a Wiener deconvolution technique, which assigns a weight based on the signal-to-noise ratio.[26]

A typical single-shot X-ray spectra recorded using the 1 mm thick CdTe Timepix detector is shown in Figure 10. In the recorded spectrum the fluorescence peak due to CdTe resonance at 30 keV is evident.[27] However, there is a clear shift in the measured spectral peak energy from 90 keV to 150 keV, which takes into account the Compton shift.

The measured flux is about 10^8 photons/shot emitted into a narrow cone of 0.6 × 90 mrad^2. The overall size of the detector configuration is very compact even though the detector

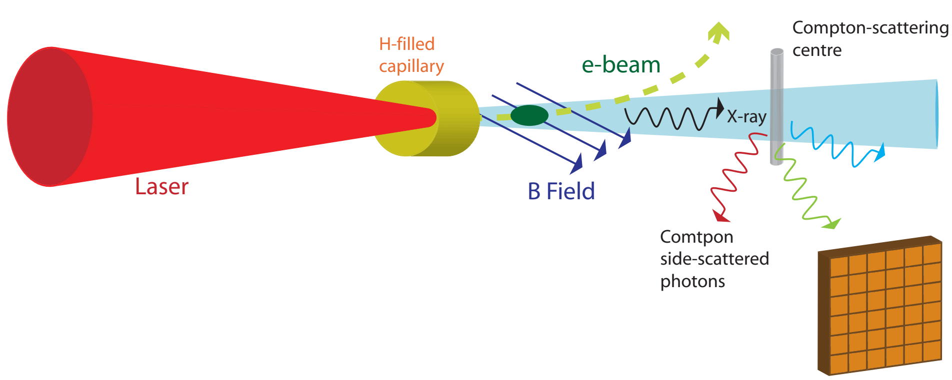

FIG. 9. Experimental LWFA setup. An F/16 spherical mirror focuses the laser pulse (3.5 J, 70 fs, 800 nm) to a 35–45 μm diameter spot at the entrance of 4 cm long, 300 μm diameter, pre-formed plasma capillary discharge waveguide with an on-axis plasma density of $n_p = (1–6) \times 10^{18}$ cm^{-3}. The laser beam has an intensity of 9×10^{18} W cm^{-2}. The laser beam is blocked after the capillary by a 600 μm thick Al foil.

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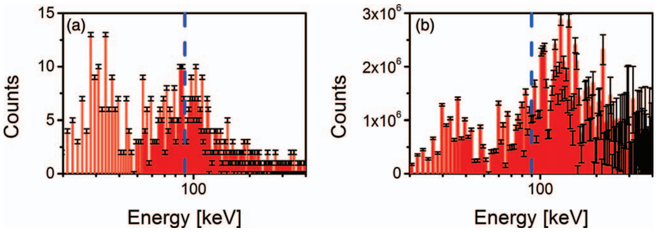

FIG. 10. (a) Betatron X-ray spectrum recorded with the 1 mm CdTe Timepix in the Compton side scattering configuration and (b) the calculated incoming spectrum. The vertical dashed line at 90 keV is to aid the eye.

is placed only 3.4 m from the source. An analogous direct on-axis measurement would require the detector to be placed 150 m from the source to attenuate the flux to single photon levels. The use of filters to attenuate the flux would result in a loss of information and distortion of the spectrum.

The single-shot measurements taken together with other experimental parameters provide insight into the influence of the laser field on the electron motion in the bubble regime. From single-shot X-ray spectra, it has been possible to classify three different regimes of electron-laser interaction, where electrons are driven through different stages of resonance by the laser pulse.[5] A strong resonance corresponds to the emission of high energy photons. Depending on the application and spectral range, X-ray beam properties, etc., different regimes can be chosen. Furthermore, a single-shot detector is useful in studies to improve the stability and to tune a radiation source whose energy may span a few tens of keV up to hundreds of keV, as shown in Figure 10.

V. DISCUSSION AND CONCLUSIONS

In summary, Compton side-scattering has been proposed as a method of simultaneously extending the spectral range and reducing the photon flux seen by X-ray detectors. The resolution challenge of the technique and the requirement of the detector resolution have been discussed. The use of the Compton side-scattering scheme in single-shot spectral measurements has been demonstrated and the need for a pixelated detector underlined.

As a proof of principle of the Compton side-scattering technique we have calibrated and numerically modelled a pixelated semiconductor detector, Timepix. An initial experimental demonstration of the Compton side-scattering scheme using Timepix was carried out with a Co-60 laboratory calibration source and then in an LWFA experiment to study betatron radiation. This shows that the Compton side-scattering scheme could be a valuable tool to extend the spectral range of detectors and to attenuate the flux of high brilliance gamma-ray sources (e.g. betatron and coherent X-FEL sources[28]) in a challenging parameter range.

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[1] P. Emma *et al.*, "First lasing and operation of an angstrom-wavelength free-electron laser," Nature Photon. **4**, 641–647 (2010).
[2] E. Esarey, C. B. Schroeder, and W. P. Leemans, "Physics of laser-driven plasma-based electron accelerators," Rev. Mod. Phys. **81**, 1229–1285 (2009).
[3] S. Kneip *et al.*, "Bright spatially coherent synchrotron X-rays from a table-top source," Nature Phys. **6**, 980–983 (2010).
[4] R. C. Shah *et al.*, "Coherence-based transverse measurement of synchrotron x-ray radiation from relativistic laser-plasma interaction and laser-accelerated electrons," Phys. Rev. E **74**, 045401 (2006).
[5] S. Cipiccia *et al.*, "Gamma-rays from harmonically resonant betatron oscillations in a plasma wake," Nature Phys. **7**, 867–871 (2011).
[6] E. Esarey, S. K. Ride, and P. Sprangle, "Nonlinear Thomson scattering of intense laser-pulses from beams and plasmas," Phys. Rev. E **48**, 3003–3021 (1993).
[7] K. T. Phuoc *et al.*, "X-ray radiation from nonlinear Thomson scattering of an intense femtosecond laser on relativistic electrons in a helium plasma," Phys. Rev. Lett. **91**, 195001 (2003).
[8] P. Bloser and J. Ryan, "New material advance gamma-ray telescope," SPIE Newsroom (2008).
[9] O. Klein and Y. Nishina, "Über die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac," Z. Phys. A: Hadrons Nucl. **52**, 853–868 (1929).
[10] Canberra Industries Inc., *Germanium Detectors* (2008), see http://www.canberra.com/products/detectors/pdf/Germanium-Det-SS-C36151.pdf.
[11] X. Llopart, R. Ballabriga, M. Campbell, L. Tlustos, and W. Wong, "Timepix, a 65k programmable pixel readout chip for arrival time, energy and/or photon counting measurements," Nucl. Instrum. Methods Phys. Res. A **581**, 485–494 (2007).
[12] J. Jakubek, A. Cejnarova, M. Platkevic, J. Solc, and Z. Vykydal, "Event by event energy sensitive imaging with TimePix pixel detector and its application for gamma photon tracking," Proc. IEEE Nucl. Sci. Symp. Conf. Rec. **65–71**, 3451–3458 (2008).
[13] J. Jakubek *et al.*, "Spectrometric properties of TimePix pixel detector for X-ray color and phase sensitive radiography," Proc. IEEE Nucl. Sci. Symp. Conf. Rec. **1–11**, 2323–2326 (2007).
[14] A. Korn, M. Firsching, G. Anton, M. Hoheisel, and T. Michel, "Investigation of charge carrier transport and charge sharing in X-ray semiconductor pixel detectors such as Medipix2," Nucl. Instrum. Methods Phys. Res. A **576**, 239–242 (2007).
[15] A. Korn, J. Giersch, and M. Hoheisel, "Simulation of internal backscatter effects on MTF and SNR of pixelated photon-counting detectors," Proc. SPIE **5745**, 292–298 (2005).
[16] M. Hoheisel, A. Korn, and J. Giersch, "Influence of backscattering on the spatial resolution of semiconductor X-ray detectors," Nucl. Instrum. Methods Phys. Res. A **546**, 252–257 (2005).
[17] S. Agostinelli *et al.*, "GEANT4-a simulation toolkit," Nucl. Instrum. Methods Phys. Res. A **506**, 250–303 (2003).
[18] V. Ivanchenko *et al.*, "Recent improvements in Geant4 electromagnetic physics models and interfaces," Prog. Nucl. Sci. Technol. **2**, 898–903 (2011) (available online at http://www.aesj.or.jp/publication/pnst002/data/898-903.pdf).
[19] D. Maneuski *et al.*, "Imaging and spectroscopic performance studies of pixellated CdTe Timepix detector," J. Instrum. **7**, C01038 (2012).
[20] T. Tajima and J. M. Dawson, "Laser electron accelerator," Phys. Rev. Lett. **43**, 267–270 (1979).
[21] S. P. D. Mangles *et al.*, "Monoenergetic beams of relativistic electrons from intense laser-plasma interactions," Nature (London) **431**, 535–538 (2004).

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[22] C. G. R. Geddes *et al.*, "High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding," Nature (London) **431**, 538–541 (2004).
[23] J. Faure *et al.*, "A laser-plasma accelerator producing monoenergetic electron beams," Nature (London) **431**, 541–544 (2004).
[24] C. J. Hooker *et al.*, "Commissioning the Astra Gemini petawatt Ti:sapphire laser system," *CLEO/QELS 2008*, 4–9 May 2008, San Jose, CA (IEEE, 2008), pp. 1–2.
[25] S. M. Wiggins *et al.*, "Straight and linearly tapered capillaries produced by femtosecond laser micromachining," J. Plasma Phys. **78**, 355–361 (2012).
[26] R. C. Gonzalez, R. E. Woods, and S. L. Eddins, *Digital Image Processing Using MATLAB* (Pearson Prentice Hall, 2003).
[27] J. Jakubek, "Precise energy calibration of pixel detector working in time-over-threshold mode," Nucl. Instrum. Methods Phys. Res. A **633**, S262–S266 (2011).
[28] B. McNeil, "First light from hard X-ray laser," Nature Photon. **3**, 375–377 (2009).

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