Design of a Compton Spectrometer with a detection range of 15 keV - 3MeV for Laser Plasma Experiments

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Abstract

Measuring the X- and γ-ray emission spectra from laser-produced plasmas is essential to enable the physical processes at play to be quantified and understood. Operating sensitive detectors capable of energy resolving the incident photons in the primary beam is difficult due to pulse pile up and possibly γ-ray energies of several MeV. Hence, the energy and flux of the incident radiation have to be adjusted to the specifications of the detector. Using Compton Scattering and placing the detector at an angle can potentially achieve this.
In this report a design is presented that places a pixelliated CdTe detector in a 90°angle towards a 1mm thin Carbon scattering target. Monte Carlo simulations have been used to evaluate the geometries performance and it has been computed that the detectors energy range of 10 - 600 keV was extended to 15 keV - 3 MeV with an energy resolution at 511 keV of 5%.

1 Introduction

Characterising X- and γ-ray radiation from laser-plasma interactions is critical in understanding the internal processes that are occurring and for that, measuring the spectra is essential. Ultra short pulse laser systems like the CLF's Gemini deliver laser pulses of a duration of tens of fs, typically producing X-ray pulses with durations of less than tens of ps. Spectrally resolving these emissions in the primary beam is challenging, as pulse pile up constitutes a major problem. The detector's readout time is longer than the time between impinging photons and multiple photons get counted as one. Furthermore, the probability of the detector material absorbing the incident radiation, i.e. the detection probability, decreases with energy.
Energy and/or flux of the incident radiation has to be adjusted to the specifications of the detector. One way to achieve this is the concept of a Compton scattering spectrometer developed by Yaffe et al. in 1976 [1].
Radiation of high energy and/or high flux is Compton scattered from a target and the energy of the photons detected at an angle. Using the incident angle onto the detector and detected energy, the spectra from the emission can be reconstructed.
Cippicia et al. demonstrated in 2013 [2] that the Compton scattering technique can be used to extend the spectral range of detectors and to attenuate the flux of high brilliance betatron sources.
The design presented in this report aims to extend the detectable energy range to MeVs and achieve an energy resolution $\Delta E/E$ better than that of scintillators like BaF_2 ($\Delta E/E = 9.8\%$ at 511keV [3]).

2 Working Principle

The working principle of a Compton Spectrometer is displayed in figure 1. An aperture with sufficiently low in-

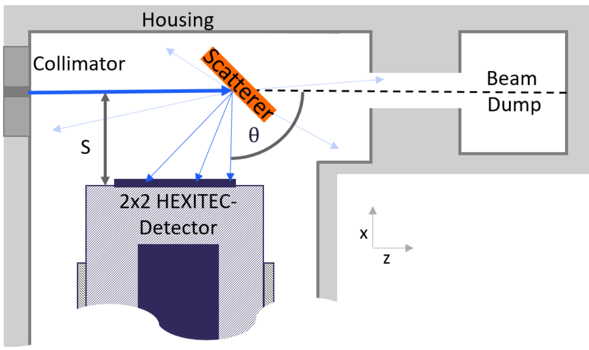

Figure 1: Geometry of the Compton Spectrometer

ner radius reduces the flux of incident radiation onto the scatterer. The X- and/or γ-rays Compton scatter of the target material. During this process energy and momentum are conserved. Therefore, the change of the photon's momentum due to change of propagation direction results in a recoil of the scattering electron and the energy of the incident photon is reduced by loss of kinetic energy to the recoil electron [4]. The energy of the scattered photon E' is given by:

$$E' = \frac{E}{1 + E/(m_e c^2) \times [1 - cos\theta]} \quad (1)$$

Where E denotes the energy of the photon incident on the target, m_e the rest mass of an electron, c the speed of light in vacuum and θ the scattering angle. If the energy of the scattered photon and its scattering angle are known, this relation can then be used to reconstruct E. E' in this case is measured by a pixelated spectroscopic CdTe-detector. The detector, referred to as HEXITEC [5], consists of 2×2 modules. Each having 80×80 pixels on a pitch of 250 μm, making up a sensitive area of 4 cm^2 and a sum of 25600 pixels.
The differential cross section, depending on E and θ can be mathematically described by the Klein-Nishina-Formula [6]:

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2} \left(\frac{E'}{E}\right)^2 \left[\frac{E'}{E} + \frac{E}{E'} - sin^2\theta\right] \quad (2)$$

r_0 describes the classical electron radius. The differential cross section for several photon energies between 20 keV and 20 MeV is illustrated in figure 2.

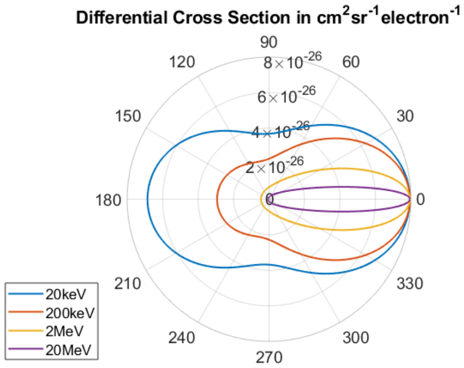

Figure 2: Differential cross section calculated with the Klein-Nishina-formula for different energies

3 Geometry

3.1 Detector Position

The energy of the scattered photon and the flux of the radiation incident on the detector are both angle dependent. From equation (1) it follows that E' decreases with increasing θ. And from (2) it can be inferred that the flux of photons onto the detector will be lowest at $\theta = 90°$.
Another important parameter is the distance between detector and scatterer s. The greater s, the better is the angular resolution per pixel. The smaller s, the greater is the detectable energy range. If the detector is mounted in a 90°central angle towards the scatterer, for energies of several MeV large distances are necessary in order not to expose the chip to energies above the detection limit of the HEXITEC of 600 keV.
Since the HEXITEC detector is single photon sensitive it is essential that the housing fully shields it to ensure that accurate and background free measurements can be made. Since there is only a limited amount of space in the experimental area, small s are desirable. This can be achieved by increasing the central angle by moving the detector in the negative z-direction.
The pixel resolution can be computed as a function of E', θ and s. Using equation (1) and a scattering angle difference of $\Delta\theta = tan^{-1}(pw/s)$, pw denotes the pixel width, it can be inferred that s needs to be larger than 3 cm to achieve a pixel resolution of better than 1 keV. At a distance of 5cm the pixel resolution is 0.64keV, better than the resolution of the HEXITEC detector of 0.87keV
From equation (1) and the upper HEXITEC detection limit of 600keV it follows that the scattering angle must be larger than 79.64°. Moving the right edge of the detector to a position where $z = 0$ and to a distance of $s = 5$ cm from the scatterer was found to be an adequate compromise between maximum energy incident on the detector, detectable energy range and angular resolution of pixels.

3.2 Scatter Material

The medium of the scatter body affects the characteristics of the scattered beam. In [7] Mateschko and Ribberfors give several reasons why a low Z material is the preferable choice of scatter material.
The lower the atomic number Z of a material, the larger is the region of energy where Compton scattering is the dominating attenuation process. As a measure of the efficiency of the Compton scattering mechanism, the probability of a photon being Compton scattered in a material has been computed and compared against the probability of being absorbed in that material. The results are displayed in figure 3. Furthermore, for sufficiently low Z, the characteristic X-rays from the scatterer will not be detected. The HEXITEC has, in low gain mode, a lower detection limit of 6-12 keV. Therefore,the energy of the characteristic X-rays of the scatter material should not be higher than 6 keV.
Also, photons interact in reality not with electrons at rest, but with moving electrons bound to atoms [8]. The scattering electrons have various energies, which causes a Doppler shift in the scattered photon energies [9]. The lower the Z of the scattering material, the lower the mean kinetic energy of the scattering electrons. Hence, the Doppler broadening decreases with decreasing atomic number.
Carbon was chosen as the preferred scatter material. Its $K\alpha$ emission line at ≈ 0.3 keV is well under the lower detection limit of the HEXITEC. It is a low Z material, but

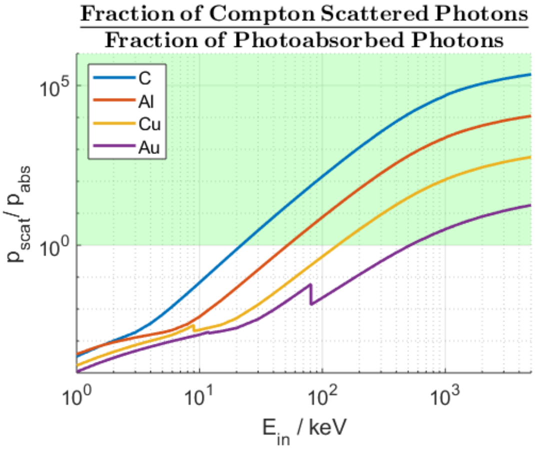

Figure 3: Fraction of the Compton Scattered Photons divided by the fraction of photoabsorbed photos. Foil thickness according to number of Compton scattered photons

has a sufficiently high interaction probability to allow for a thin thickness (cf. section 3.3).

3.3 Thickness of Scatterer

Ideally the scatterer would just be a point in space. Then the scatter position and hence also the scatter angle and the energy of the incident X-ray would be known as exactly as possible. Moreover, the possibility of multiple scattering is decreased to zero.
However, as the HEXITEC detector cannot be put in vacuum, the probability of scattering in the scatterer needs to be significantly higher than the probability of being scattered in air. The thickness of carbon equal in mass to 20 cm of air for X-ray energies above 200 keV tends towards 108 μm. A foil thickness of 1 mm was chosen, as it was found to have a scattering probability approximately 10 times higher than 20cm of air.
The error in terms of the incident energy correlated to the thickness of the scatterer can be estimated as follows:
If a photon is scattered at the front of the detector, the scattering angle is given by

$$\theta_1 = \frac{\pi}{2} + tan^{-1}\left(\frac{pw}{s}\right) \tag{3}$$

If it is scattered at the rear of the foil the angle is

$$\theta_2 = \frac{\pi}{2} + tan^{-1}\left(\frac{pw + b}{s}\right) \tag{4}$$

Now the energy of the incident X-ray can be computed with a rearranged form of equ. (1) and the error be estimated as the difference caused by θ_1 and θ_2.

$$\Delta E = E_{\theta 2} - E_{\theta 1} \tag{5}$$

The error cause by the thickness of the scatterer is shown in figure 4 for several energies of scattered photons.

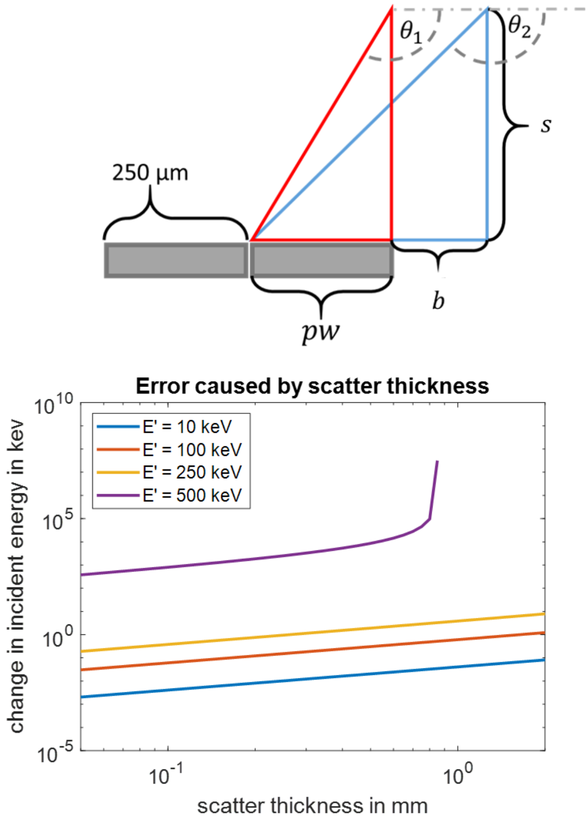

Figure 4: Error caused by scatter thickness: geometry on the left, change in reconstructed incident energy depending on thickness of the scatterer on the right

As the error increases with detector thickness, the scatterer was chosen not to be made thicker than the necessary minimum of 1 mm.

4 Simulations

The number of parameters involved in the theoretical evaluation of the spectrometer performance is large and obtaining analytical results difficult. Therefore, GEANT4 [10] has been used to conduct numerical modelling.
To investigate the performance of the spectrometer design, its response to monoenergetic photon beams in the range between 40 - 16500 keV has been simulated.
100 million particles are emitted, pass through the 5cm thick tungsten collimator with an inner diameter of 5mm, and interact with the 1mm thick carbon foil, which is oriented at 45 °. The 4cm x 4cm detector is placed with ΔZ=d/2 at a distance of 5cm from the target foil. The procedure of spectrum reconstruction, depicted in figure 5, is as follows:

- Only particles with an energy of 6 keV and above are considered as that is the minimum energy the HEXITEC detector can detect in low gain mode.

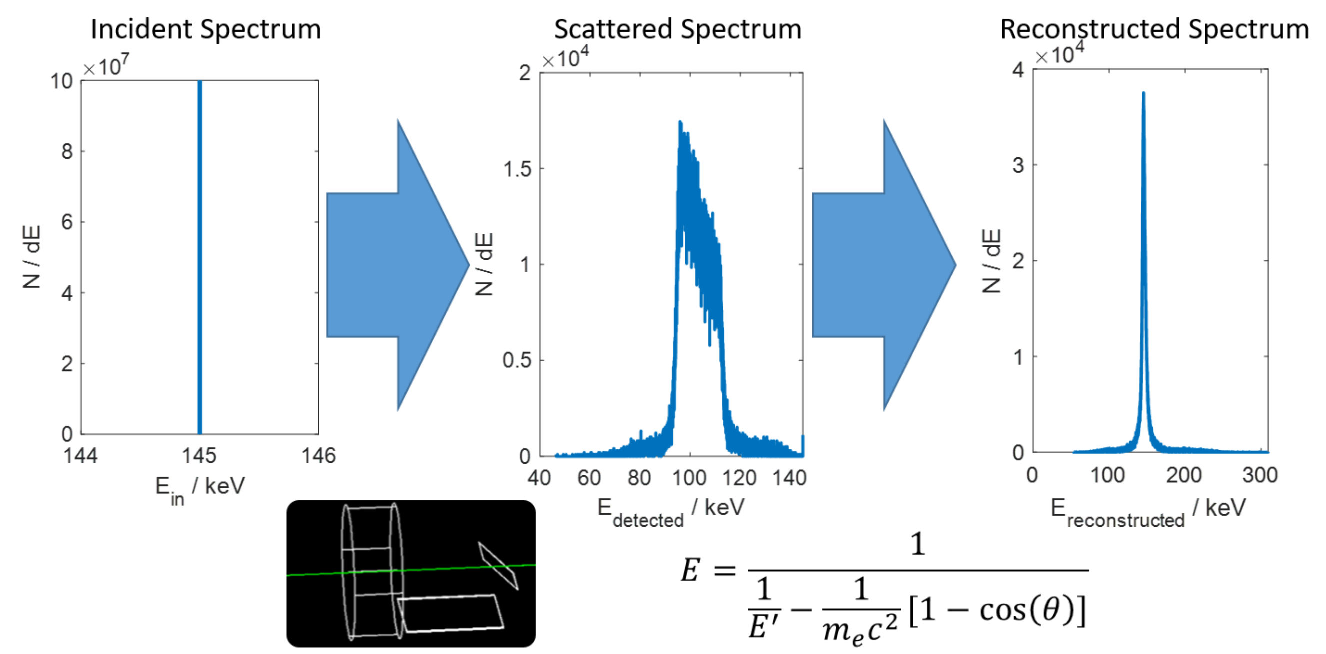

Figure 5: Procedure of reconstructing the incident spectra: The interaction of a monoenergetic beam of photons with the spectrometer geometry is modelled with Geant4. A histogram of the energy of the detected scattered photons constitutes the detected spectrum and the incident spectrum can be reconstructed by using the formula as shown above

- Based on their absorption probability in CZT, particles are allocated a probability of actually being detected, in order to adjust the data to real conditions.
- The Z position is determined as the pixel position.
- The scatter angle is calculated with $\theta = \pi/2 + tan^{-1}(z/s)$, where s is the distance between detector and scatterer.
- The incident energy is reconstructed using a rearranged form of equation (1).
- A histogram of the reconstructed energies yields the reconstructed energy spectrum

In order to access the spread of the energy spectrum, caused by the Compton spectrometer, the full widths at half maximum (FWHM) of the reconstructed spectra were determined. The results are plotted in figure 6.

The FWHM was found to increase from 1.9% of the incident energy at 40 keV (which is with 0.76 keV lower than the average pixel resolution of the HEXITEC of 0.87keV) to 15.9% of the incident energy at 2953 keV. Above this energy, the FWHM was not computed, as the number of detected photons was to low. At 511 keV the computed energy resolution (FWHM / E_{in}) is 5%, which is approximately half of the energy resolution of BaF_2.
The higher the incident energy, the more likely is it that the photons are scattered in the forward direction instead of onto the detector and the less likely are the photons to be absorbed by CdTe. Hence, the relative number of detected particles decreases. This is one reason for the increasing FWHM. The other is that with increasing energy the energy spread due to sample thickness (cf. section 3.3) increases.
This indicates the upper limit of the photon energies detectable with the Compton spectrometer. The lower detection limit, considering the probability of being scattered at the Carbon target, transmitted through the

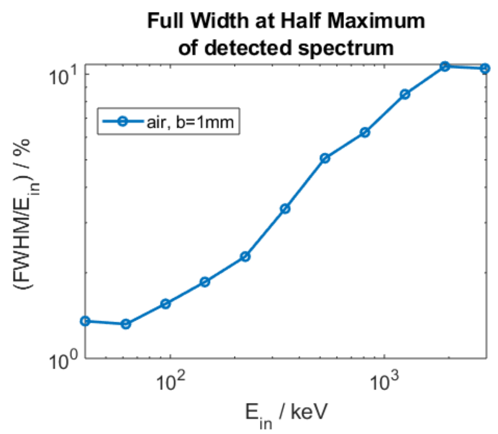

Figure 6: FWHM of spectrometer response to monoenergetic photon beam depending on incident energy

3mm Al front cover of the HEXITEC and absorbed by a 1mm thick layer of CdTe is at approximately 15 keV.

5 Summary

Compton scattering can be used to attenuate a high energy and flux photon beam and downshift its energy sufficiently to be detected by a detector placed at a 90°angle. Low Z materials are desirable to use as scatterer. This spectrometer design pairs a 1mm thin Carbon target with a 2x2 HEXITEC detector. Its range from 10-600keV was extended by the spectrometer design described in this report to approximately 15 keV - 3 MeV. At 511 keV the computed energy resolution is with 5% approximately half of the energy resolution of BaF_2's 9.8%.

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