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# Angular sensitivity of modeled scientific silicon charge-coupled devices to initial electron direction

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ABSTRACT

Previously, scientific silicon charge-coupled devices (CCDs) with 10.5-μm pixel pitch and a thick (650 μm), fully depleted bulk have been used to measure gamma-ray-induced fast electrons and demonstrate electron track Compton imaging. A model of the response of this CCD was also developed and benchmarked to experiment using Monte Carlo electron tracks.

We now examine the trade-off in pixel pitch and electronic noise. We extend our CCD response model to different pixel pitch and readout noise per pixel, including pixel pitch of 2.5 μm, 5 μm, 10.5 μm, 20 μm, and 40 μm, and readout noise from 0 eV/pixel to 2 keV/pixel for 10.5 μm pixel pitch. The CCD images generated by this model using simulated electron tracks are processed by our trajectory reconstruction algorithm. The performance of the reconstruction algorithm defines the expected angular sensitivity as a function of electron energy, CCD pixel pitch, and readout noise per pixel.

Results show that our existing pixel pitch of 10.5 μm is near optimal for our approach, because smaller pixels add little new information but are subject to greater statistical noise.

In addition, we measured the readout noise per pixel for two different device temperatures in order to estimate the effect of temperature on the reconstruction algorithm performance, although the readout is not optimized for higher temperatures. The noise in our device at 240 K increases the FWHM of angular measurement error by no more than a factor of 2, from 26° to 49° FWHM for electrons between 425 keV and 480 keV. Therefore, a CCD could be used for electron-track-based imaging in a Peltier-cooled device.



## 1. Introduction

Gamma-ray imaging is useful for radioactive source detection, localization and characterization in diverse fields, including nuclear physics [1], oncology [2], astronomy [3], and national security [4]. In particular, imaging can separate the measurement of a localized gamma-ray source from the measurement of background radiation in the measurement environment. For sources of gamma rays in the energy range of 100s of keV to a few MeV, Compton imaging has been shown to be a useful method which does not require collimation and the accompanying reduction in statistics, but uses the measured energies and positions of the interactions of a gamma ray scattering in the detection system. The energy deposited in the first Compton scattering, and the total energy of the photon, are used to compute a scattering angle which defines a cone of possible gamma-ray source locations [5–7].

The cone represents the ambiguity resulting from measuring the trajectory of only one of the scattering products: the photon. The measurement of the trajectory of the Compton-scattered electron would, ideally, constrain the gamma-ray source location to a single ray in space [8]. However, electrons scattered from MeV gamma rays have a very short range in the dense detector materials which are normally chosen for gamma-ray interaction efficiency, and thus a very fine position resolution is required to perform electron track Compton imaging (ETCI). Uncertainties in the interaction positions, interaction energies, initial momentum state of the atomic electron, and initial trajectory of the electron after scattering broaden the ideal ray-like response. The trajectory uncertainty broadens the ray into a cone segment [9], while the other uncertainties broaden the ray in all directions, including the thickness of the cone as in conventional Compton imaging. Reducing the length and thickness of the cone segment reduces the image background and thus increases detection sensitivity. Fig. 1 illustrates an example of an ETCI cone segment, showing as an example our detector which is described next.

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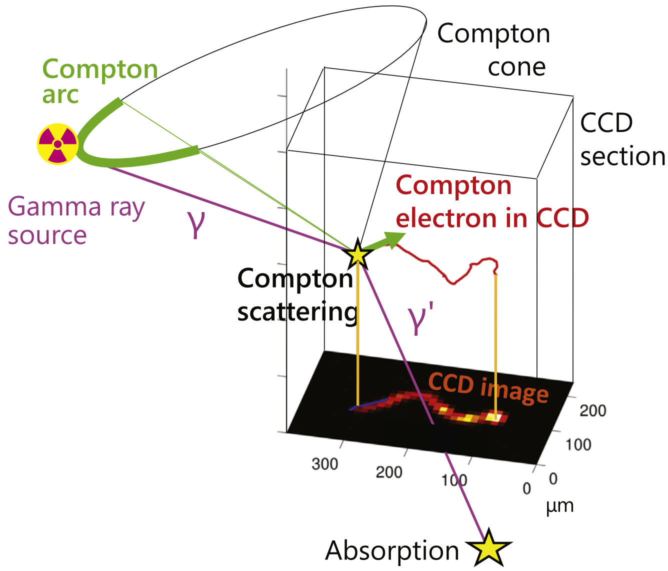


**Fig. 1.** Conceptual illustration of electron track Compton imaging with our device.

Electron track Compton imaging has been demonstrated in several instruments in recent years. Detection systems with thin double-sided strip silicon detectors have tracked electrons, but are limited by the high energy needed for an electron to traverse multiple layers [8,9]. A micro-TPC has been used for ETCI, but the low fill gas pressure results in a very low specific efficiency, e.g. $10^{-4}$ for sub-MeV photons in 30 cm of argon [10]. Our group has demonstrated ETCI using a thick (650 μm) fully depleted high-resolution silicon charge-coupled device (CCD) originally designed for infrared astronomy [11], and we have benchmarked the electron interaction physics and CCD response models [12].

The uncertainty in the initial trajectory of the scattered electron depends on the position resolution of the measurement, because the fast electron scatters on electrons and nuclei in the detection material and deviates from its initial trajectory. Therefore, a device with finer position resolution would be expected to measure the initial electron trajectory more precisely, assuming the measurement algorithm makes effective use of the position information. In addition, the electronic noise on each pixel value has some impact on the trajectory measurement precision. The noise includes thermally generated dark current, but is normally dominated by noise in the first stage of signal amplification. The CCD in our lab is cooled to 140 K to reduce noise compared to a room-temperature device.

In a device in which each pixel is measured individually, such as a CCD, there is a trade-off between position resolution and noise. More pixels provide better position resolution, but also more independent sources of noise. Thus, for a given read noise, there will be an optimal pixel pitch for which the electron trajectory can best be measured.

We evaluated the uncertainty of the electron trajectory measurement and its dependency on pixel pitch and noise. Other parameters relevant to the algorithm performance include device thickness, and lateral diffusion which depends on the electric field. These latter parameters were not varied, because they are more strongly constrained by engineering considerations. The electric field must be strong enough to deplete the entire detector thickness, but a higher field can adversely affect the CCD's charge transfer. Device thickness should not be much thinner than 650 μm, in order to minimize electrons escaping the volume and maintain gamma interaction efficiency, while a much thicker device would be difficult to deplete without the electric field affecting the charge transfer. Other implementations that may circumvent these constraints are beyond the scope of this work.

We used models of CCDs with various pixel pitch and with a trajectory measurement algorithm similar to that used in previous work. The CCD modeled in each case was identical in thickness (650 μm) and electric field to the model of the device in our laboratory. The lateral diffusion from the back side of the device is $\simeq 30$ μm [13], which is larger than most of the pixel pitches studied; however, events closer to the pixel plane still benefit from the finer position resolution, and our approach does not require the track to be one pixel in width.

In addition, various levels of electronic noise were modeled at the pixel pitch of our laboratory device, and the resulting trajectory uncertainty evaluated. The electronic noise level was also identified experimentally at two higher temperatures, 180 K and 240 K.

## 2. Approach

Photon and electron interaction physics were modeled using Geant4, as described previously [12]. Photons of 662 keV incident on the CCD were modeled such that the distribution of initial directions of scattered electrons in the CCD was isotropic. The energy deposition and trajectory of each electron was evaluated in steps of 0.1 μm, with the position and energy deposition written to file every 1 μm, resulting in a table showing the energy deposition for each 3D position.

The positions and energies from the electron interactions were converted to the detector response using a MATLAB model of charge carrier drift, diffusion, and pixelization, which has been described previously [12]. The result of this CCD response model is a 2D array of energy values representing the calibrated CCD image, for each modeled electron.

The modeled CCD image is analyzed using image processing and ridge following to measure the initial electron trajectory in 3D, including the in-plane angle $\alpha$ and the magnitude of the out-of-plane angle, $|\beta|$. An earlier version of this algorithm has been previously described [12], and a complete description of the updated algorithm can be found in [13]. The measurement of $|\beta|$ is imprecise due to physical variations in the specific energy loss, as well as inefficiencies in the algorithm.

The initial trajectory returned by the algorithm, $(\alpha_{alg}, |\beta|_{alg})$, can be compared to the true values known from the model, $(\alpha_{true}, |\beta_{true}|)$, resulting in the angular errors $\Delta_\alpha$ and $\Delta_\beta$ as defined previously [12]. The distribution of values of $\Delta_\alpha$ and $\Delta_\beta$ from a selection of events can be characterized to quantify the performance of the algorithm on these events. Because the measurement of $|\beta|$ is imprecise, only $\alpha$ will be of interest in this paper.

Fig. 2a shows an example distribution of $\Delta_\alpha$, for electrons with energy between 250 keV and 300 keV. The distribution of $\Delta_\alpha$ can be characterized as a Gaussian component centered on $\Delta_\alpha = 0$ added to a flat (random) component. The distribution can be quantified by the FWHM of the Gaussian component and the fraction of events which are in the Gaussian component, $f$. These parameters are measured by fitting the distribution with a Gaussian plus a constant, which is not a perfect model but describes the main features closely, as shown in Fig. 2b. The random component represents events for which the algorithm misidentifies the initial track segment, or the initial track segment is obscured by overlapping segments of the track, so the direction measured is uncorrelated to the true direction. A high-precision measurement is represented by small FWHM and large $f$. For this distribution, FWHM = 36.8° ± 0.3° and $f$ = 78.2% ± 0.3%.

The pixel pitches modeled include 2.5 μm, 5 μm, 10.5 μm, 20 μm and 40 μm. Each pixel pitch was modeled with electronic noise of both 15 eV per pixel (approximately the noise measured experimentally at our standard operating temperature of 140 K)