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COMPTON SPECTROMETER FOR FACET-II*

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Abstract

We present the design of a Compton spectrometer for use at FACET-II. A sextupole is used for magnetic spectral analysis, giving a broad dynamic range (180 keV through 28 MeV) and capability to capture an energy-angular double-differential spectrum in a single-shot. At low gamma energies, below 1 MeV, Compton spectroscopy becomes increasingly challenging as the scattering cross-section becomes more isotropic. To extend the range of the spectrometer down to around 180 keV, we use a 3D-printed tungsten collimator at the detector plane to preferentially select forward-scattered electrons at the Compton edge.

INTRODUCTION

In the upcoming program of experiment at the Facility for Advanced Accelerator Experimental Tests (FACET-II) [1] at SLAC National Accelerator Laboratory, a pulsed electron beam of energy10 GeV interacts with a variety of targets, including plasmas, solids, or a high-intensity laser. In each of these experiments, beam electrons are violently accelerated, producing a large downstream flux of gamma rays spanning a broad continuum of energies up to 10 GeV. As the shape of the gamma spectra reveal the underlying interaction dynamics, it is vital to measure these spectra.

The diagnostics beamline, downstream of the interaction point (IP), is shown in Fig. 1. The gamma rays emitted at the IP have a fairly narrow angular spread, as low as $1/\gamma \approx 1/20000$, so that the gamma spot size at the Compton and pair spectrometers is as small as a few millimeters. The dipole magnet bends the primary electron beam downwards so that the gamma beam can be analyzed.

DESIGN

In a magnetic Compton spectrometer, incident collimated gamma rays strike a converter target, and the resulting scattered Compton electrons are then magnetically analyzed, providing information about the incident gamma beam's spectrum and intensity [2–8]. Our Compton spectrometer design is shown in Fig. 2. Its magnetic design is most similar that of G. L. Morgan and coworker's 1991 design [4], in that both are based on the use of magnetic mirrors having mechanically similar trajectories [9, 10]. One difference is that our design uses a sextupole field rather than a quadrupole field (see Fig. 3). This was done to allow for a stronger dynamic-range compression of energy scale while giving a larger bore opening for reading gammas incident at large vertical displacements, corresponding to larger angular deviations from the interaction point. This leads to the ability to record single-shot angular-energy spectra. Another unique feature of our spectrometer is the use of a 3D-printed collimator at the focal plane (see Fig. 4). The collimator selects Compton electrons which were scattered in the forward direction, improving energy resolution, particularly at low energies – well below 1 MeV – where use of a Compton spectrometer becomes more difficult. Locating the collimator at the focal plane allows us to, apart from the converter target, keep the spectrometer's bore clear, while affording us flexibility in selecting which trajectories we wish to collect for double-differential spectra.

RESULTS

We have developed an end-to-end spectrometer simulation based on Geant4 [11, 12]. Figure 5 shows the detetor's simulated response to monoenergetic gammas. For this case, we assume a maximum allowed current density of 5 A/mm^2 for water-cooled copper coils, which leads to a maximum gamma energy of 28 MeV. The magnetic field is solved using an external nonlinear field solver, and we confirmed there was an acceptably low level of saturation in the steel yoke at this high current density. We do not include the focal-plane collimator in this case because the Compton scattering cross-section is already fairly forward-peaked at these energies. In contrast, Fig. 6a shows the detector response, at a lower current density, to low-energy monoenergetic gammas. We see that broadening of the Compton cross section at low energy smears the detector response. Running the simulation with collimator mounted (Fig. 6b) selects the forward-scattered Compton electrons, restoring the energy resolution at the cost of some detector sensitivity.

A typical use-case for the Compton spectrometer at FACET-II is to study emittance growth in a plasma wakefield accelerator (PWFA) [13]. Here, the double-differential energy-angular betatron spectrum provides a crucial probe into the witness beam's transverse dynamics. In Fig. 7a, we show the simulated detector response to a predicted PWFA spectrum. For the present case, we artifically constrain the incident gammas to be along the beam axis with zero transverse displacement. Using a maximum likelihood reconstruction [14], together with a basis of simulated monoenergetic response functions spanning the detector's full energy range, we deconvolve the gamma spectrum from the raw detector response (see Fig. 7b). Efforts are underway to use machine learning [15] improve these results and extend them deconvolution of single-shot energy-angular spectra.

A final case is present in Fig. 8. Here, we deconvolve the simulated raw detector response to a few narrowly spaced

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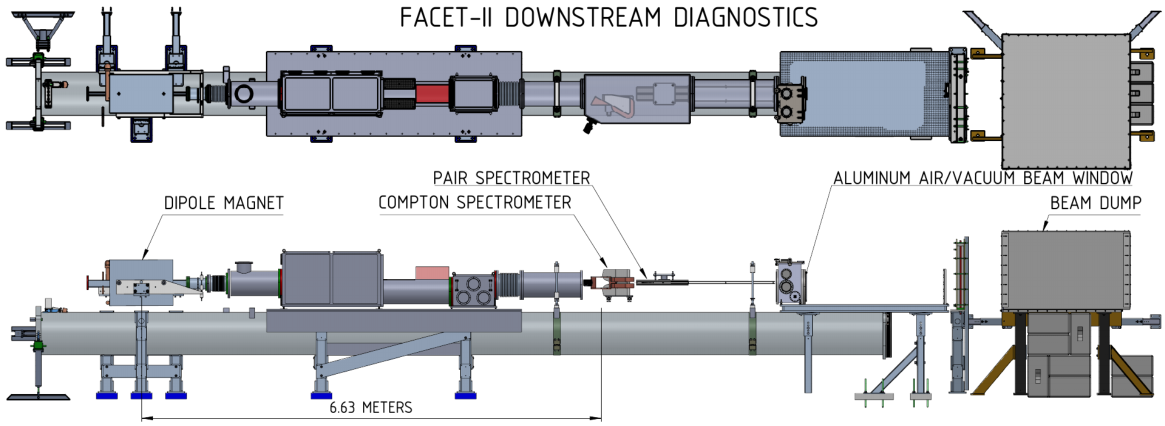

Figure 1: FACET-II diagnostic beamline downstream of interaction point. The interaction point (IP) is located 13.12 m upstream of the dipole magnet center.

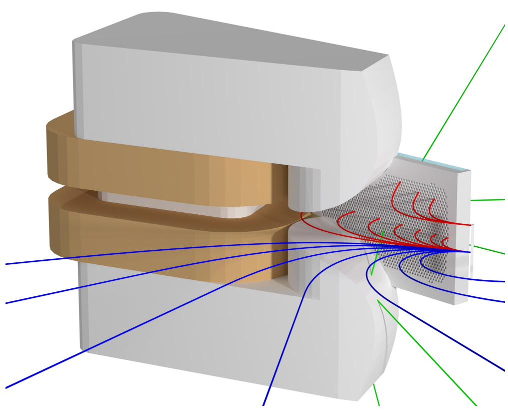

Figure 2: Compton spectrometer. Gammas incident on a beryllium target scatter forward Compton electrons (red), which are bent in a sextupole field and collimated at the focal plane, where a scintillator is located.

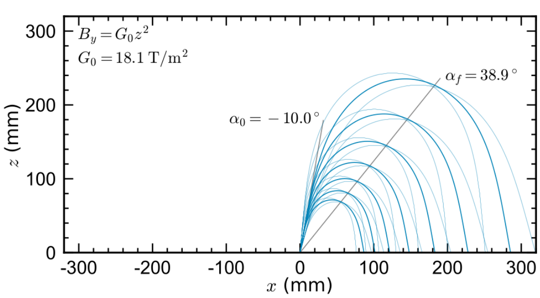

Figure 3: Mechanically similar trajectories in a sextupole. Forward-scattered Compton electrons are horizontally focused onto a focal plane.

monoenergetic gammas. We report an energy resolution of a bit better than 1% for gammas in the energy range of a few MeV. We should note that, in this case, the Shepp-Vardi ML-EM statistical deconvolution needed some amount of artifical damping below 300 keV, where there were no incident gammas. The machine learning approach has been demonstrated to not be susceptible to this issue.

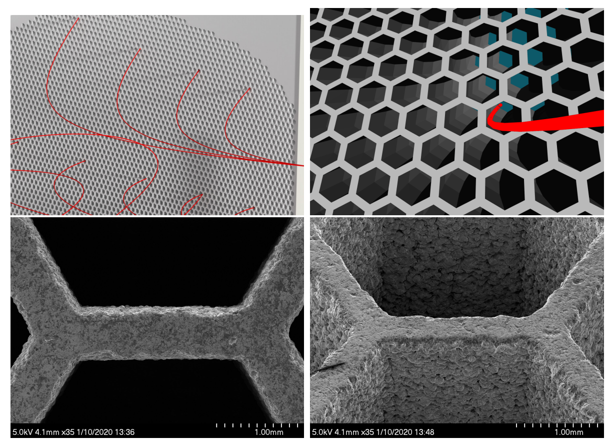

Figure 4: 3D-printed tungsten collimator. Pores follow curves of the design trajectories.

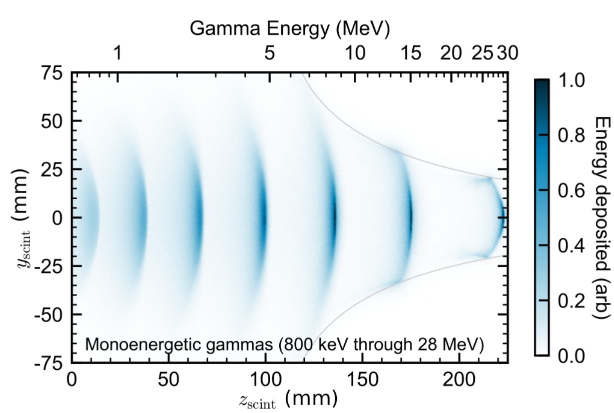

Figure 5: End-to-end simulation of Compton spectrometer's response to monoenergetic gammas. In this high-energy case, the focal-plane collimator is not included.

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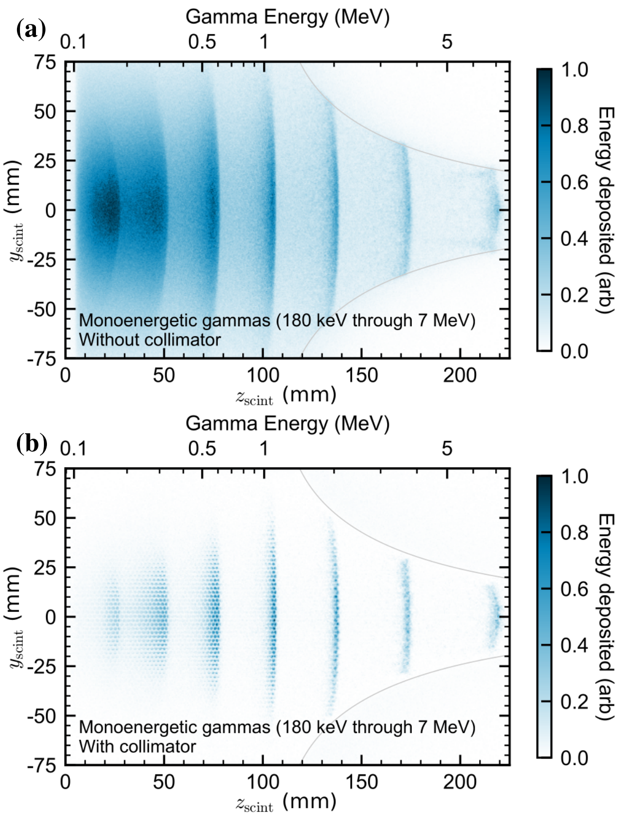

Figure 6: End-to-end simulation of monoenergetic gammas. **(a)** As the gamma energy decreases, the angular spread of the scattered Compton electron increases. **(b)** With collimator. We only want to collect electrons scattered in a nearly forward direction, because those electrons have energy near the Compton edge of the incident gamma. Adding the collimator to the simulation shows this effect.

CONCLUSION

We have presented the design for a Compton spectrometer that is particularly suited for the study of betatron radiation down to low as a few 100 keV which will complement the pair spectrometer [16] at FACET-II for a full suite of gamma measurements.

ACKNOWLEDGEMENT

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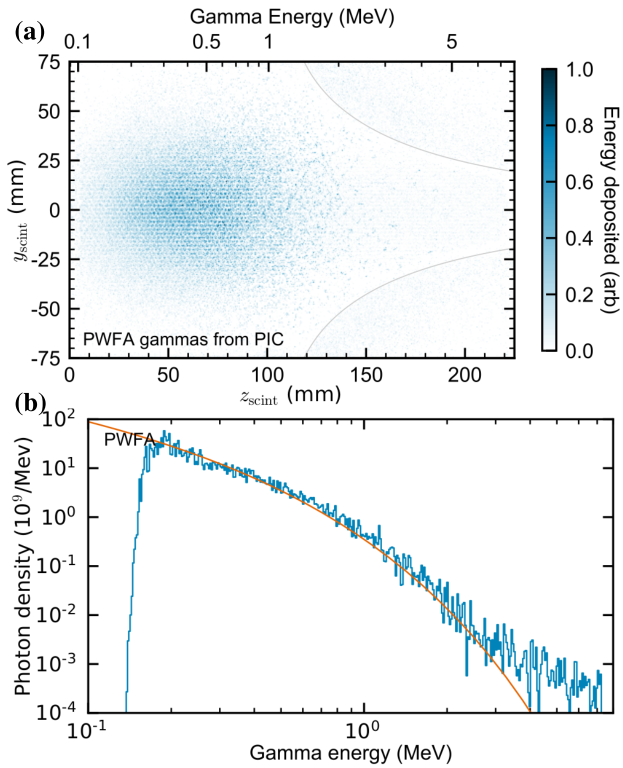

Figure 7: Simulation of plasma wakefield accelerator (PWFA). **(a)** Raw scintillator response **(b)** Deconvoluted spectrum (blue) matches the incident gamma spectrum (orange) fairly well out to a few MeV.

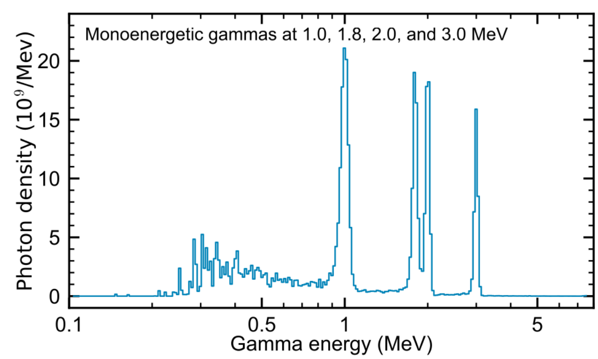

Figure 8: Spectral deconvolution of simulated monoenergetic gammas. In the energy range of a few MeV, the energy resolution is a bit better than 1%, and we can resolve 1.8 MeV gammas from 2.0 MeV gammas.

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