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PAIR SPECTROMETER FOR FACET-II*

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Abstract

We present the design of a pair spectrometer for use at FACET-II, where there is need for spectroscopy of photons having energies up to 10 GeV. Incoming gammas are converted to high-energy positron-electron pairs, which are then subsequently analyzed in a dipole magnet. These charged particles are then recorded in arrays of acrylic Cherenkov counters, which are significantly less sensitive to background X-rays than scintillator counters in this case. To reconstruct energies of single high-energy photons, the spectrometer has sensitivity to single positron-electron pairs. Even in this single-photon limit, there is always some low-energy continuum present, so spectral deconvolution is not trivial, for which we demonstrate a maximum likelihood reconstruction. Finally, end-to-end simulations of experimental scenarios, together with anticipated backgrounds, are presented.

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 an pair spectrometer, collimated gammas are incident on a target and converted into positron-electron pairs which are then subsequently tracked or recorded in some way to recover information about the parent gamma distribution [2–4]. The design of our pair spectrometer is outlined in Fig. 2. We opt for a symmetric design, where we record both electrons and positrons. There are a total of 128 silicon photomultipliers [5] (SiPMs), each coupled to a $3\times3\times10\,\mathrm{mm}^3$ quartz or acrylic Cherenkov cell. The 64 cells on either side of the detector are uniformly spaced on a logarithmic scale from 10 MeV through 10 GeV. The magnetic field is provided by two strips of permanent magnets. The open yoke design allows pairs to escape the magnet without striking the wall, minimizing scattering of radiation back into the spectrometer. The results given in this paper will be for operation of the spectrometer in single-shot mode, where we make no attempt to correlate individual electron-positron pairs. However, with careful upstream dumping of the depleted primary beam, which otherwise scrapes along the bottom of the beam pipe underneath the spectrometer, the radiation background is sufficiently low to allow practical detection of single electron-positron pairs and, therefore, full reconstruction of the incident gamma energy. Another way to boost the signal-to-noise is by arranging the Cherenkov cells normally to the design trajectories. Then, as the index of refraction exceeds $\sqrt{2}$, the Cherenkov cone is entirely captured [6], unlike obliquely incident charged particles (see Fig. 3).

At low energies, below around 40 MeV, the Compton cross section for scattering in beryllium is larger than the pair production cross section. Therefore, at these energies, the spectrometer is acting as a Compton spectrometer. This is a benefit, as Compton scattering has an intrinsic advantage over pair production for spectral recovery, being a two-body process rather than a three-body process. If there is a substantial fraction of gammas above around 30 MeV, we will see a pair continuum mixed in with our Compton spectrum, but can use recorded positron signal to effectively subtract out this continuum from the Compton spectrum. As the gamma energy drops, we see a broadening in the angular scattering of Compton scattering. To counter this and improve

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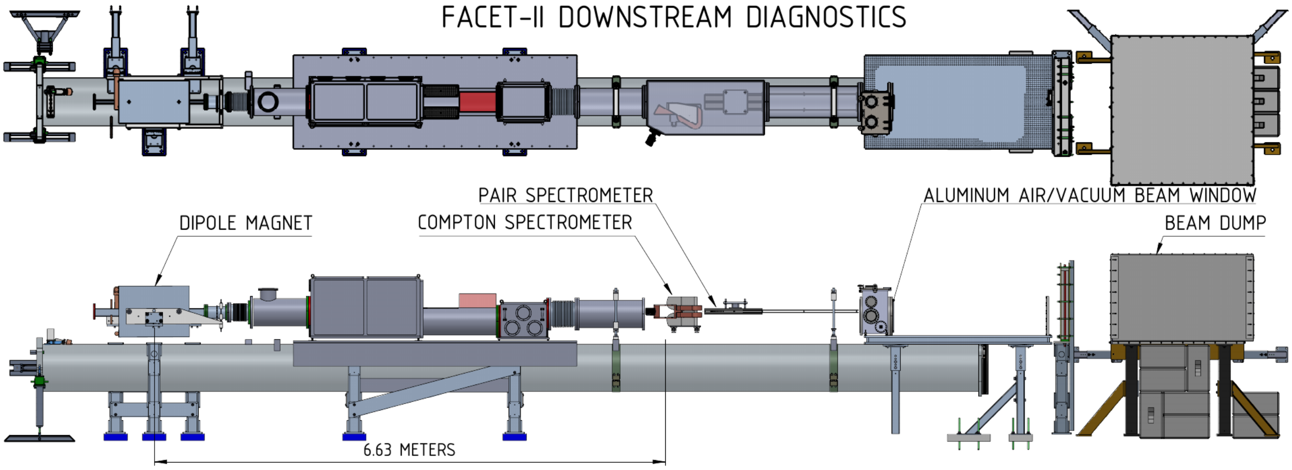

Figure 1: FACET-II diagnostic beamline downstream of interaction point. The interaction point (IP) is located 13.12 m upstream of the dipole magnet center.

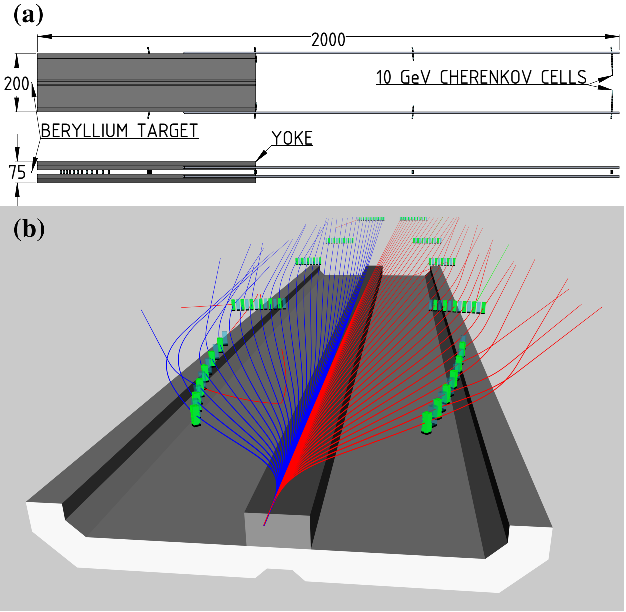

Figure 2: Design overview. For clarity, not all features, particularly the SiPM PCBs and associated cabling, are shown. **(a)** All dimensions given in millimeters. **(b)** Cutaway view of design trajectories. Electrons are shown in red, positrons are shown in blue, and photons are shown in green. Energies span 10 MeV through 10 GeV. Note that the Cherenkov cells are oriented normally to incoming design trajectories.

detector sensitivity in this critical region, we also introduce horizontal focusing (see Fig. 4).

RESULTS

We have developed an end-to-end detector simulation based on Geant4 [7, 8]. We simulate the spectrometer's response to a basis of quasi-monoenergetic gamma beams spanning the full range of the spectrometer (see Fig. 5). This response matrix can then be used in a maximum likelihood reconstruction [9] of an arbitrary incident gamma spectrum.

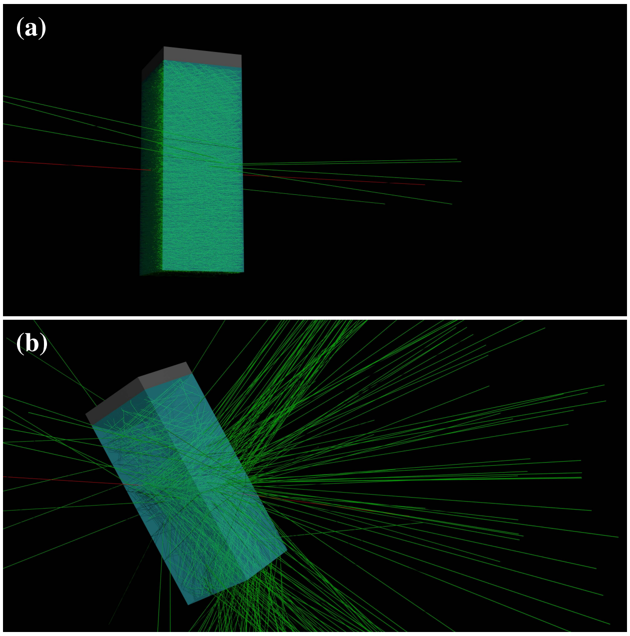

Figure 3: DIRC effect maximizes signal-to-noise ratio. **(a)** The Cherenkov cone of a normally incident charged particle, shown in red, is mostly captured and absorbed at the SiPM. **(b)** The Cherenkov cone of an obliquely incident charged particle, typically a result of background radiation and scattering, largely escapes.

For example, in Fig. 6, we show the spectrometer's raw response to the gamma spectrum of nonlinear Compton scattering (NLCS) and the subsequent statistical reconstruction of the gamma spectrum which recovers the harmonics above a few GeV. Another example, of relevance to the strong-field QED (SFQED) effort at FACET-II, is an observation of the finite formation length of emitted gammas in Fig. 7.

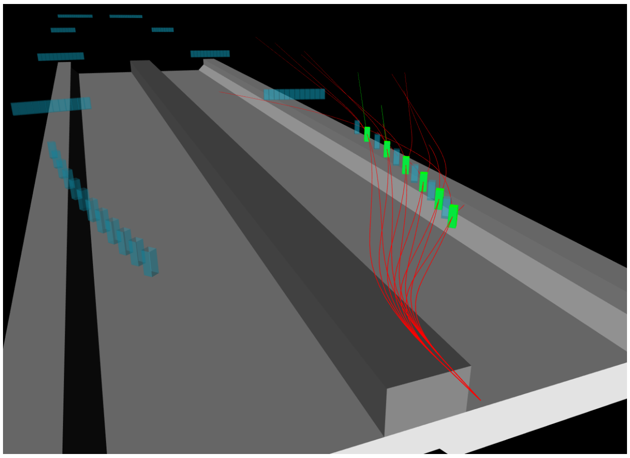

Figure 4: The converter target is located 20 mm downstream of the magnet entrance. The fringing magnetic field provides horizontal focusing, improving the resolution and sensitivity of the low-energy Compton portion of the spectrometer.

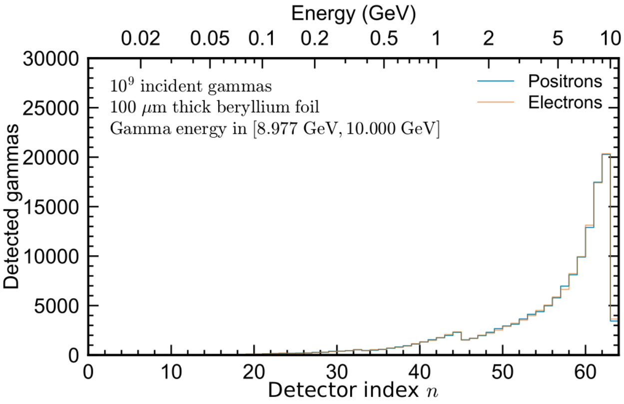

Figure 5: End-to-end simulations of the detector's gamma response are used as the basis of the statistical spectral deconvolution. In this case, we simulate 9 GeV to 10 GeV gammas and show the raw response of the 64 positron and 64 electron cells. The vertical scale corresponds to the number of detected charged particles in each cell.

CONCLUSION

We have presented the design for a pair spectrometer that can record a single shot gamma spectrum spanning 10 MeV through 10 GeV which will complement the Compton spectrometer [10] at FACET-II for a full suite of gamma measurements.

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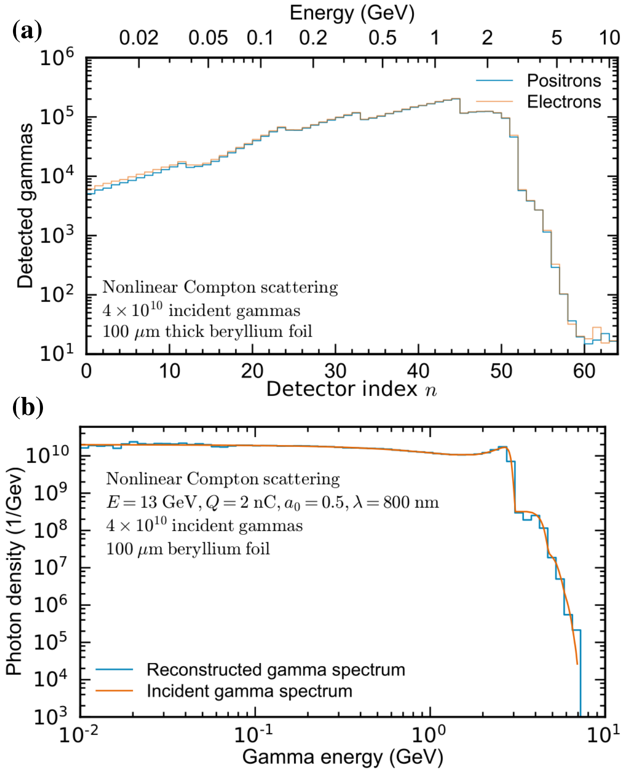

Figure 6: Nonlinear Compton scattering. **(a)** Raw detector response. **(b)** Deconvoluted spectrum (blue) resolves harmonics in the incident gamma spectrum (orange). Note that this is a blind reconstruction which makes no *a priori* assumptions about the spectral contents.

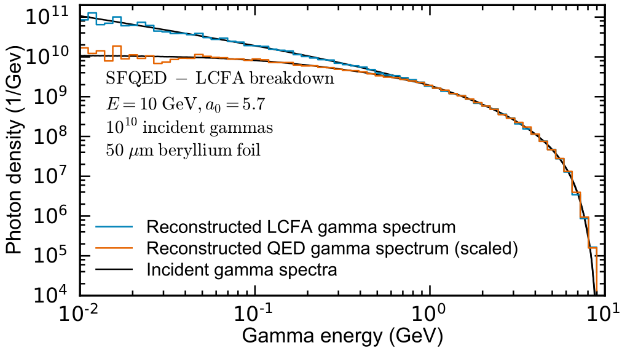

Figure 7: Breakdown of the locally-constant field approximation (LCFA). At high laser intensities, the finite formation length of emitted gammas leads to a depletion in the lower energy portion of the spectrum. As shown above, the pair spectrometer can resolve this consequence of a finite formation length. Note that a large dynamic range, covering the full range of 10 MeV through 10 GeV, is critical for this measurement.

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