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ELECTRO-OPTIC SAMPLING BEAM POSITIONING MONITOR FOR RELATIVISTIC ELECTRON BEAMS

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Abstract

Non-destructive diagnostics able to resolve transverse offsets and longitudinal separation of ultra-relativistic, two-bunch electron beams are necessary for a variety of applications including the ion channel laser (ICL) and other plasma wakefield (PWFA) experiments. A prototype electro-optic beam positioning monitor (EOS-BPM) utilizing two independent laser pulses traveling through a pair of EO crystals has been installed at the SLAC National Accelerator Laboratory FACET-II facility. This system is capable of order 10 fs temporal resolution and order 100 µm transverse position resolution. To achieve better transverse resolution we introduce a new design using an axicon lens to create a donut beam and a multi-crystal structure placed around the axis of propagation of the electron beam. Experimental results of the prototype EOS-BPM along with the simulated response of the new EOS-BPM design to the ultra-relativistic, two-bunch electron beam used for PWFA experiments at FACET-II will be presented.

INTRODUCTION

Plasma wakefield accelerated (PWFA) beams are extremely sensitive to transverse and longitudinal offsets. The primary motivation for the Electro-Optic Sampling Beam Positioning Monitor (EOS BPM) is to improve the alignment of the beams for PWFA. For this we require independent transverse and longitudinal measurements of the drive and witness beams. The beams must have precise transverse alignment to avoid chromatic phase spreading in the witness beam [1]. This occurs when the witness beam is transversely offset from the wake created by the drive beam causing emittance growth. PWFA beams are also sensitive to longitudinal separation. Precise alignment of longitudinal separation is required for optimal beam loading which minimizes energy spread and maximizes the acceleration efficiency. We also require the precise transverse and longitudinal resolution the EOS BPM will provide for the Ion Channel Laser (ICL) [2] which relies on the transverse offset of the witness beam to create FEL-like coherent radiation.

For both PWFA and ICL applications we require a shot by shot non-destructive diagnostic able to resolve fs timescales and µm scale transverse beam offsets. Traditional electronic beam positioning monitors (BPMs) are unable to resolve shorter than ns time scales, resulting in single measurement of the charge-averaged transverse position of the two bunches. Another commonly available diagnostic, the transverse deflecting cavity (TCAV), is able to measure the longitudinal separation between the bunches, but only by destructively streaking the beams onto a screen downstream. The use of ultra fast optics to encode fs/µm scale information into a laser pulse with electro-optic sampling is a well proven method to resolve time of arrival and longitudinal separation between bunches. The EOS BPM builds on this technique to also resolve transverse beam offsets on the length scales required for PWFA experiments.

METHODOLOGY

We employ a cross polarization electro-optic sampling scheme depicted in Fig. 1 part a). As a relativistic electron beam passes by an electro optic (EO) crystal changing the birefringent properties of the crystal at the instant the electron beam passes by [3, 4]. The polarization of a laser pulse passing through the crystal at that instant has its polarization rotated. For this design, the laser goes through a polarizer before the crystal such that only horizontally polarized light enters the crystal. Another polarizer is then placed after the crystal to filter out the un-rotated part of the laser pulse such that the signal viewed by the camera corresponds only to the vertical component of the polarization rotated portion of the laser pulse. When the probe laser enters the crystal at an angle we are able to map the temporal information of the electron beam to the transverse profile of the laser pulse. This method is able to resolve on the order of 10s of fs bunch separations between the drive and witness beams and has been used at FELs and other accelerator facilities to measure the electron beam time of arrival.

The University of Colorado Boulder Wakefield Acceleration and Radiation Generation (WARG) group along with Radiabeam Technologies have implemented a two crystal electro optic sampling beam positioning monitor (EOS BPM) Mk.1 design at FACET-II [6, 7]. We leverage the correlation between electron beam location with respect to the EO crystal and detected signal strength. This is similar to the method used by traditional electronic BPMs. A rough schematic of this design is shown in Fig. 1 part b), depicting two probe lasers entering the EO crystals which are oriented on either side of the axis of propagation of the electron beam.The strength of the signal—that is, the degree of the polarization rotation—is correlated with the distance between the signal encoded region of the laser pulse and the transverse position of the electron beam. With this we are able to independently measure the 3D centroid position of both the drive and witness beam.

We have conducted experiments testing the EOS BPM Mk.1's capabilities at FACET-II. Some results are shown in Fig. 2, the top and bottom plot represent the calculated

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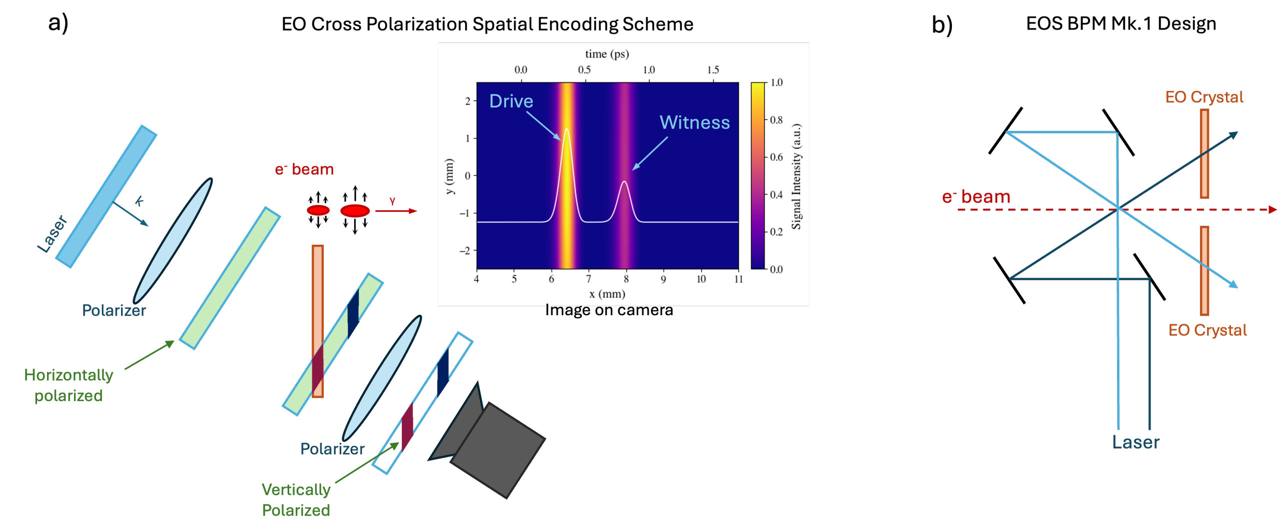

Figure 1: a) Cross polarization spatial encoding scheme [5]. b) Design of the EOS BPM Mk.1 installed at FACET-II [6]

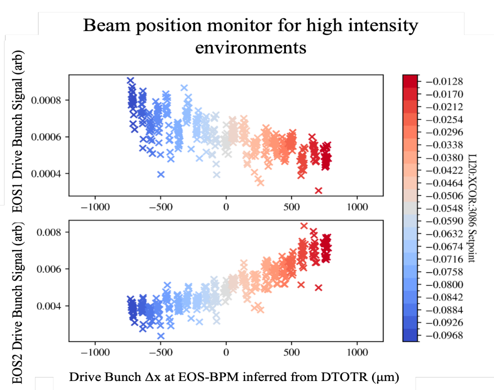

Figure 2: Experimental results from BPM Mk.1 installed at FACET-II.

electron beam position from the EOS2 and EOS1 crystals respectively. There is a clear linear trend between the two crystals; as the signal on one crystal gets increases the signal on the other decreases, this is representative of the relative electron beam position between the two as it is scanned across the central propagation axis. This was the first time the EOS BPM technique was experimentally tested. The experimental results were within 65 μm resolution.

EOS BPM MK.2

We are working to improve this design with the EOS BPM Mk.2, which will be installed and commissioned at FACET-II during the next run. For this we will use an axicon lens which is a conical refractive optic that creates a donut beam with a tilted pulse front (Fig. 3). The temporal window for the spatial encoding scheme is dependent on the laser angle of incidence as well as the inner and outer radius of the donut beam from the axicon centered around the electron beam axis of propagation, allowing for measurement of both x and y transverse positions. Each of the 4 crystals are 10x10mm

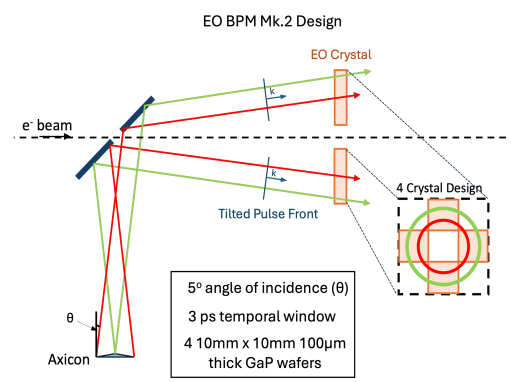

Figure 3: EOS BPM Mk.2 design using an axicon lens to create a donut beam that passes through 4 EO crystals arranged around the electron beam axis.

Table 1: EOS BPM Mk.2 Simulation Parameters

Parameter	Value	Unit
Laser Wavelength	800	nm
Laser Angle	5	degree
GaP Crystal Thickness	100	μm
Drive Beam Charge	1000	pC
Witness Beam Charge	800	pC
Time Delay btw. Beams	450/135	fs/μm
Transverse Beam Offset Drive	10	μm
Transverse Beam Offset Witness	10	μm
Bunch Length (Both)	50/15	fs/μm

100 μm thick GaP wafers. This design also allows for better time of arrival (TOA) resolution due to the additional signal from the 2 additional crystals, significantly enhancing the signal-to-noise ratio (SNR).

We have conducted simulations of the signal from the EOS BPM Mk.2 design. The simulation parameters, shown in Table 1, are similar to the parameters expected in ex-

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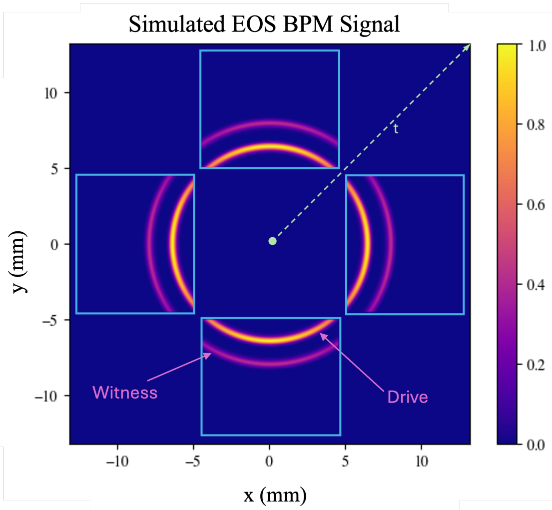

Figure 4: Simulated EOS BPM Signal.

periments at FACET-II. Figure 4 shows an example of a simulated signal including the 4 crystal design. Here, time scales as a function of radius for the donut laser beam such that the inner ring corresponds to the drive bunch and the outer ring corresponds to the witness bunch.

We have conducted several studies to determine the limiting factors on both the TOA and BPM resolution for this device. We are able to leverage the donut signal over the 4 crystals to greatly increase the SNR in our TOA calculations by radially binning and azimuthally summing the signal. The BPM measurement is done with a 4 parameter fit to find the transverse locations of both the drive and witness beams with the following model where α is the azimuthal angle and r is the position with respect to the transverse ebeam position.

$$I(r,\alpha) = A_1 \sin\left(\frac{A_2}{r}\sqrt{1+\cos^2\alpha}\right) \tag{1}$$

The primary limiting factor of the EOS BPM in both TOA and BPM measurements is the SNR. Figure 5 part a) illustrates the effect of noise on the resolution of the TOA measurement with a noise level of 0% to 40%. The resolution of the TOA was roughly 3 fs with up tp 40% added noise. Part b) shows the BPM error for simulations from 800 pC to 100 pC with added noise from 0% to 40%. We have better than 5 µm resolution in BPM measurement for up to 40% noise. We also note that beam charge has no effect on resolution; rather it is primarily dependent on SNR.

CONCLUSION

The EOS BPM is a novel ultra-fast optical device for measuring 3D beam centroid location with fs/µm level precision which is required for emittance preservation of PWFA, minimizing energy spread and maximizing efficiency. We have successfully commissioned and tested the EOS BPM Mk.1 at FACET-II and were able to resolve around 65 µm transverse offset. We expect to achieve 3 fs/1 µm longitudinal resolution and less than 5 µm transverse resolution for signals with up to 40% noise with the EOS BPM Mk.2. We plan to install and commission the EOS BPM Mk.2 at FACET-II during the next run. In the future we will also explore the utility of the EOS BPM Mk.2 to diagnose tilted beams.

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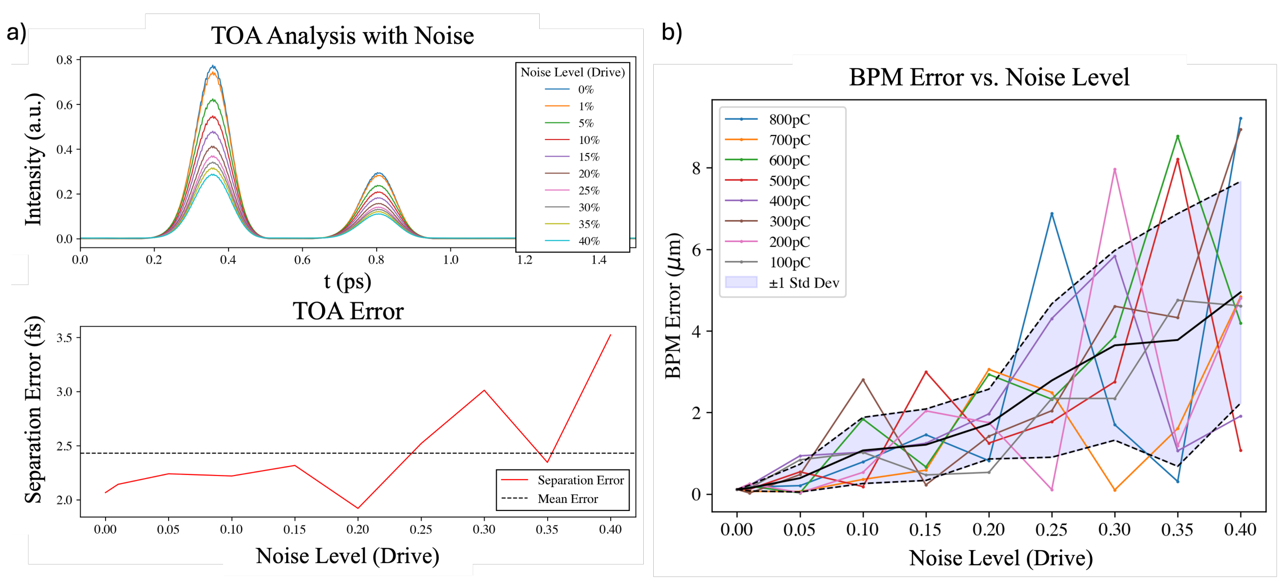

Figure 5: a) TOA Results from the simulation. b) BPM Results from simulation.

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