

An aerial photograph of a university campus. In the foreground, a large building with a red-tiled roof and solar panels is visible. The middle ground shows a variety of campus buildings, a large green field, and a curved walkway. In the background, there are rolling green hills and a prominent, rocky mountain peak under a clear blue sky.

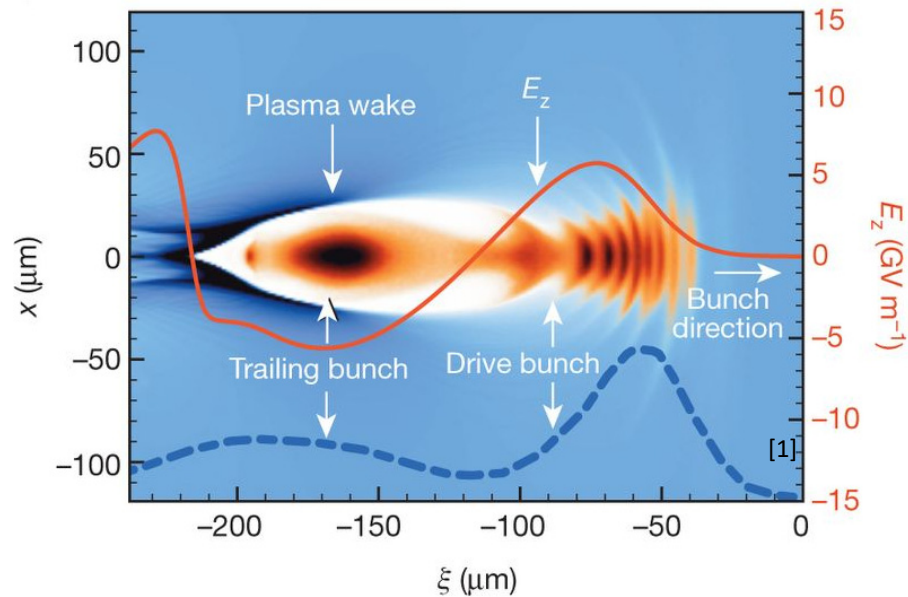
Electro-Optic Sampling Beam Position Monitor

Keenan Hunt-Stone, Robert Ariniello, Chris Doss,
Valentina Lee, John R. Cary, and Mike Litos

NAPAC 2019

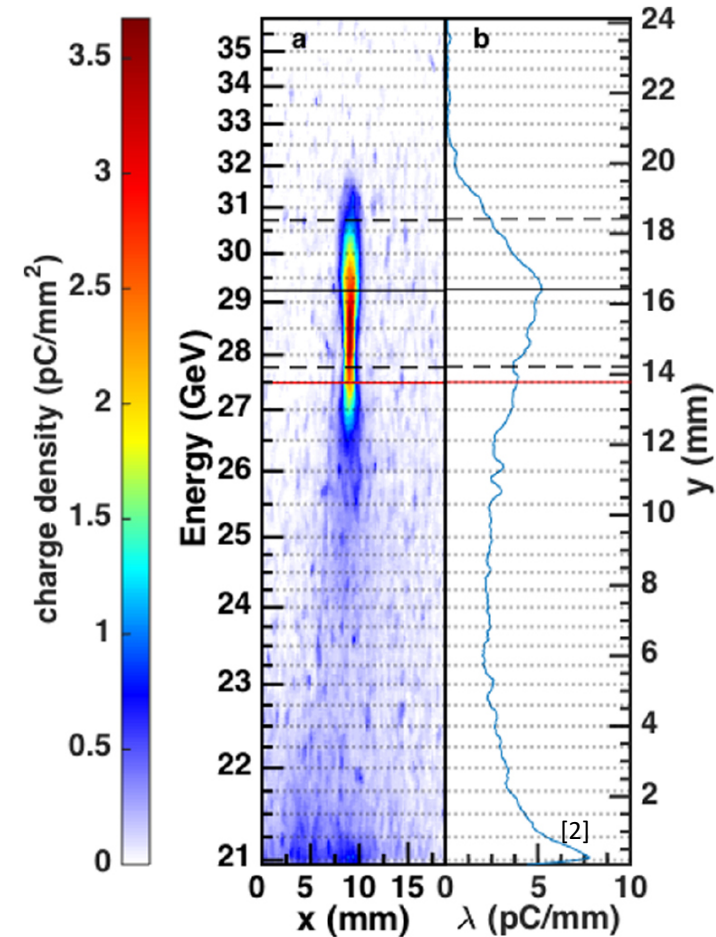


Plasma wakefield accelerators (PWFA)



Beam driven PWFA:

- Drive bunch blows out plasma electrons leaving behind a stationary ion column
- Witness bunch loaded into back of the wake “feels” large longitudinal electric field
- Accelerating gradient sensitive to bunch separation $O(\sim 5 \mu\text{m})$

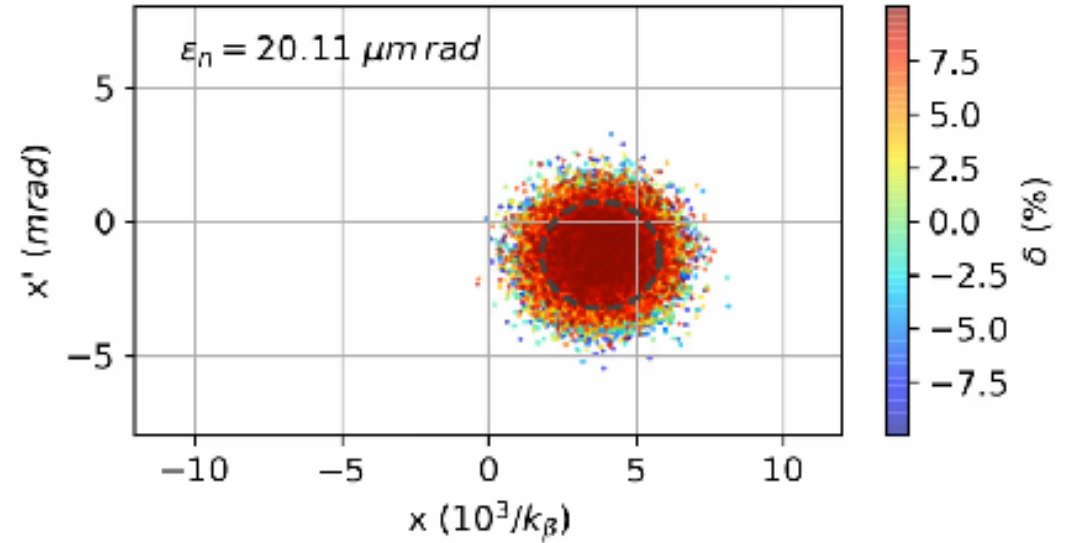


$$G_0 \approx 7 \text{ GeV/m}$$

To date no PWFA has preserved beam's transverse emittance



Witness beam emittance growth



Chromatic phase spread causes projected emittance growth in an ion column.

Mismatched beam:

Saturated, projected emittance is given by:^[3]

$$\frac{\epsilon}{\epsilon_0} = \frac{1}{2} (\beta\gamma_m - 2\alpha\alpha_m + \gamma\beta_m)$$

subscript 'm': matched CS parameters

Offset witness beam:

Saturated, projected emittance is given by:^[4]

$$\frac{\epsilon}{\epsilon_0} = 1 + \frac{1}{2} \left(\frac{\Delta x^2}{\beta_m \epsilon_0} + \frac{\beta_m}{\epsilon_0} \Delta x'^2 \right)$$

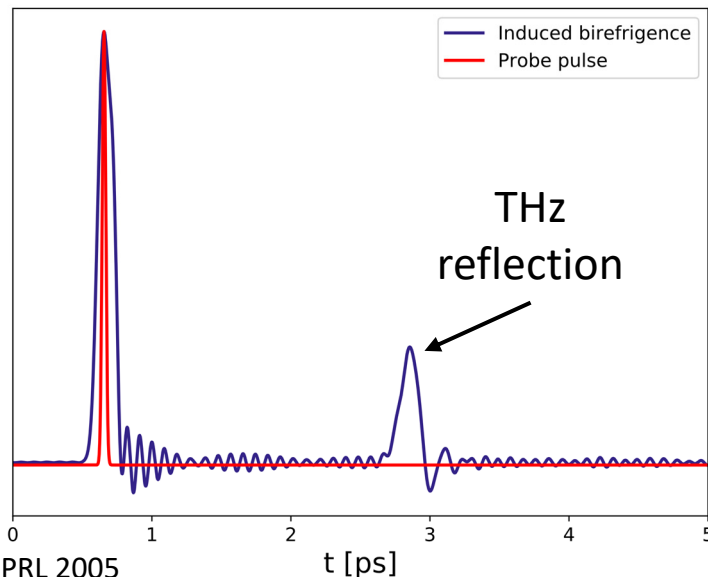
Matched witness bunch will still undergo emittance growth if it is transversely offset! $O(\sim 5 \mu\text{m})$



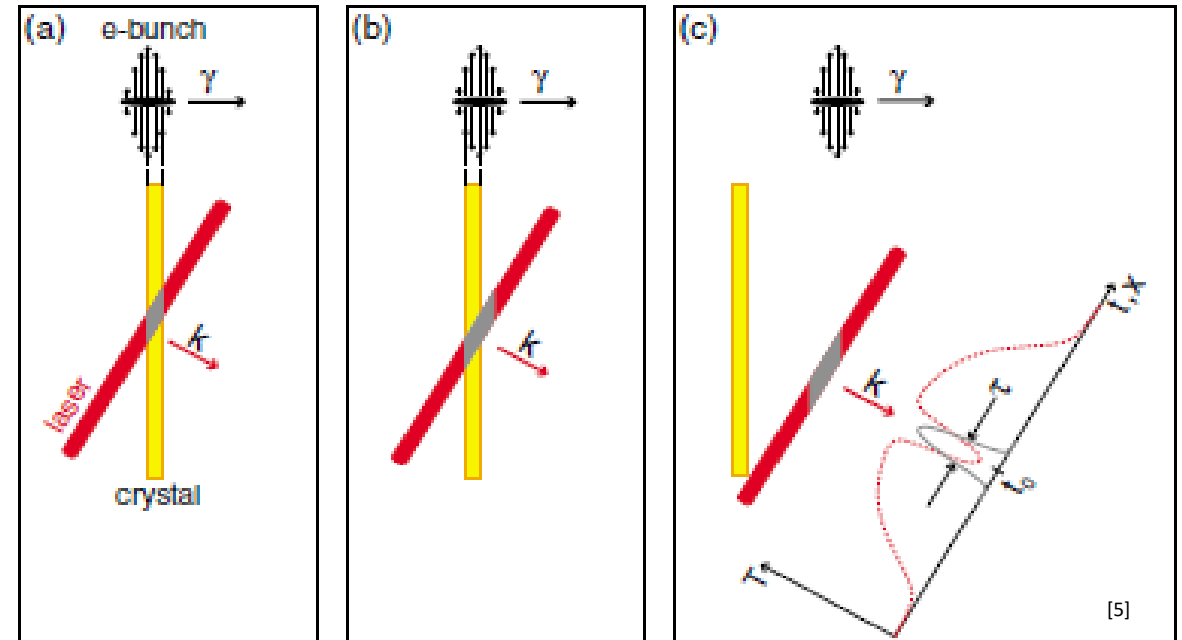
Electro-optic sampling and spatial encoding

Principles of detection:

- Electron bunch passing by an EO crystal at speed c resembles a transient THz field travelling through the crystal.
- The THz field induces a birefringence on the crystal
- Phase retardation occurs between polarization components of a probe pulse



[5] Cavalieri *et al* PRL 2005



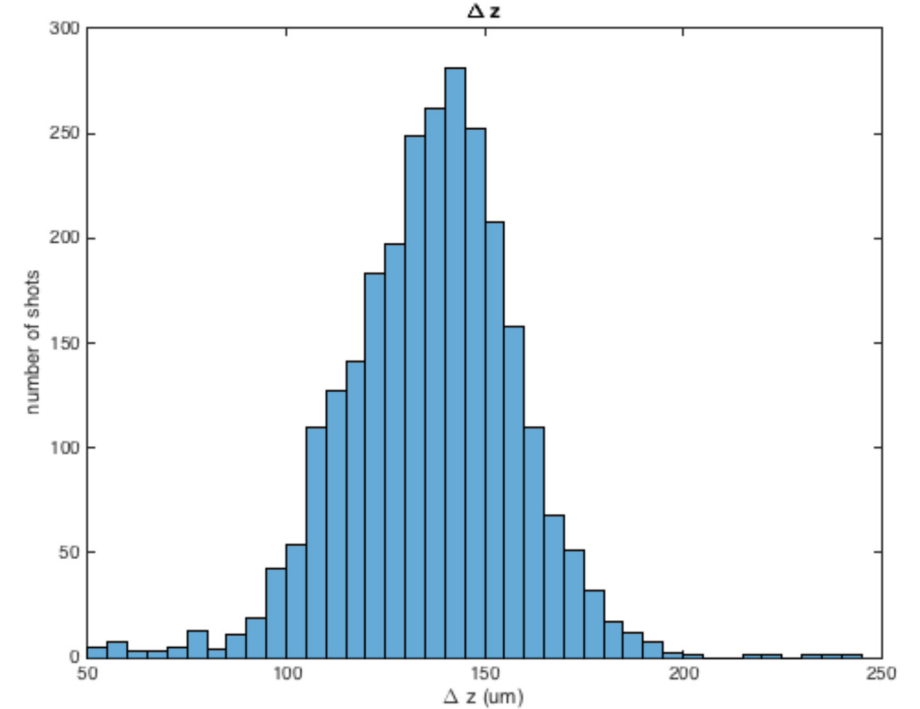
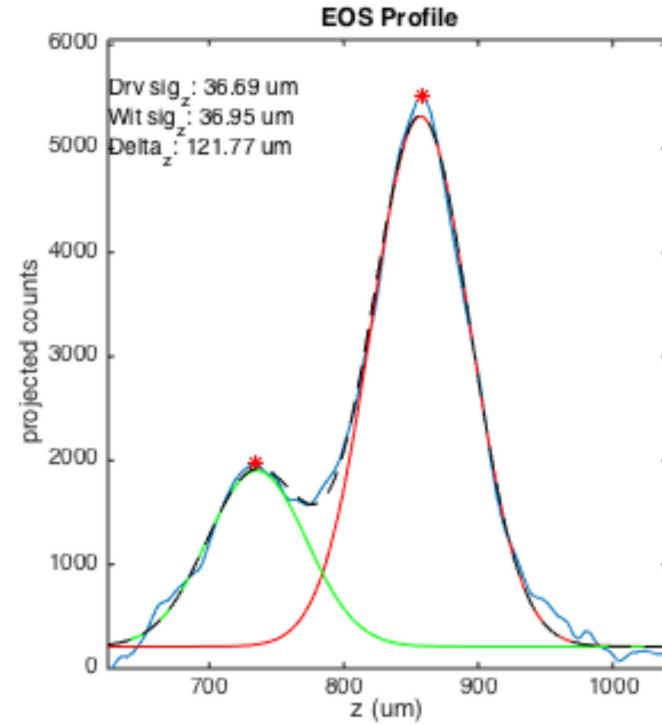
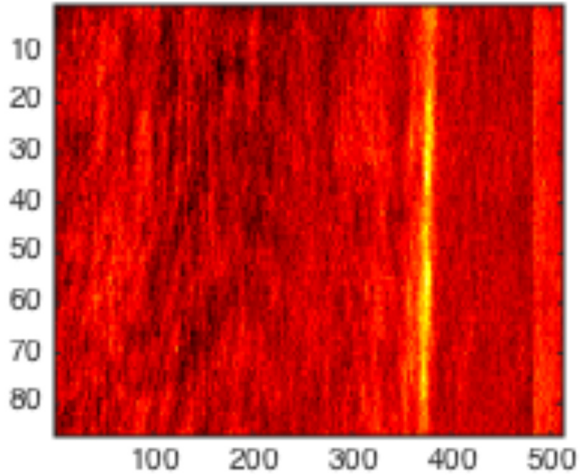
Spatial encoding:

An ultrafast probe pulse is sent into the EO crystal at an angle, sweeping across the whole crystal and mapping time into space.



EOS at FACET

Single-shot, background subtracted



EOS was used at FACET to measure the longitudinal separation of the drive and witness beams (Δz) for a PWFA. It was calibrated against the X-band TCAV.



EOS-BPM at FACET-II

Holed mirror

Two GaP crystals 2
mm apart
(adjustable)

$$\Gamma = \frac{\pi n_0^3 d}{\lambda_0} r_{41} E \sqrt{1 + 3 \cos^2 \alpha}$$

n_0	3.57
d	100 μm
λ_0	800 nm
α	90 deg.

Two bunch electron beam

Beam parameter	Value
Q_{drive}	1.5 nC
Q_{wit}	0.5 nc
$\sigma_{z,drive}$	5.2 μm
$\sigma_{z,wit}$	5.2 μm
Δz	150 μm

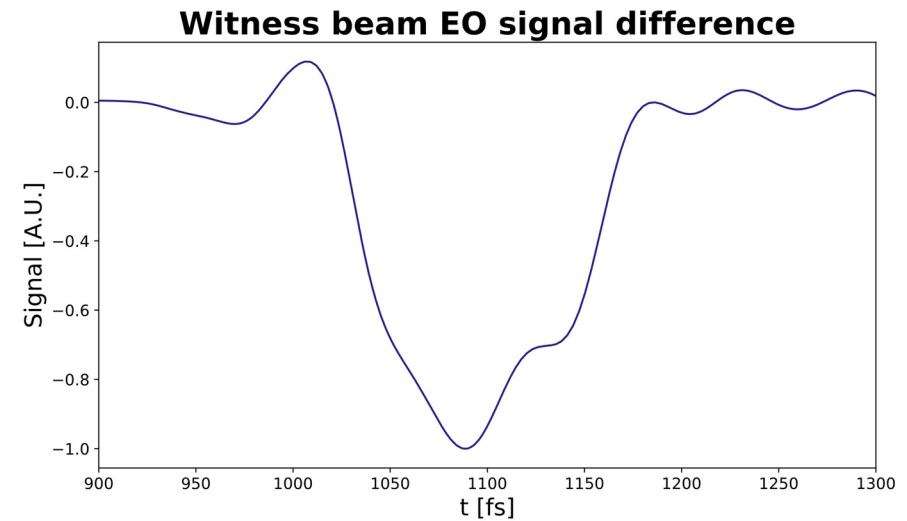
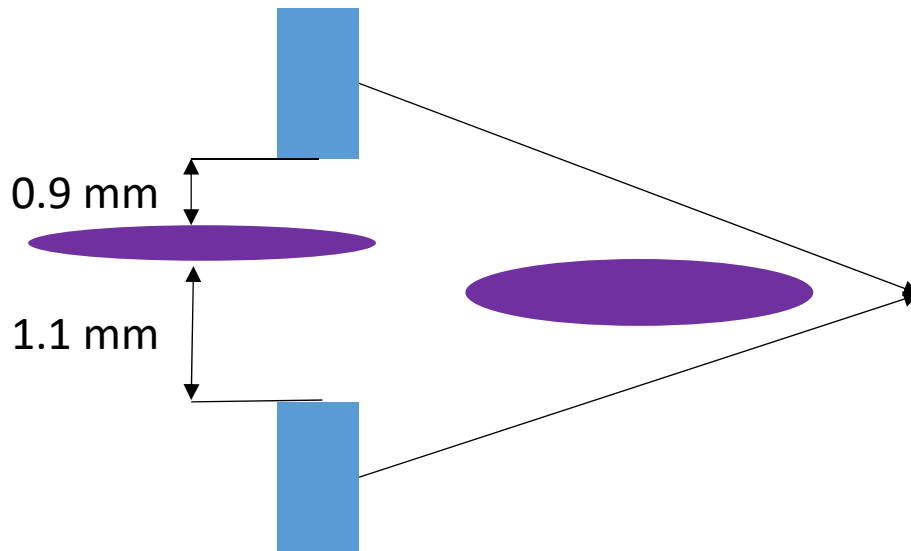
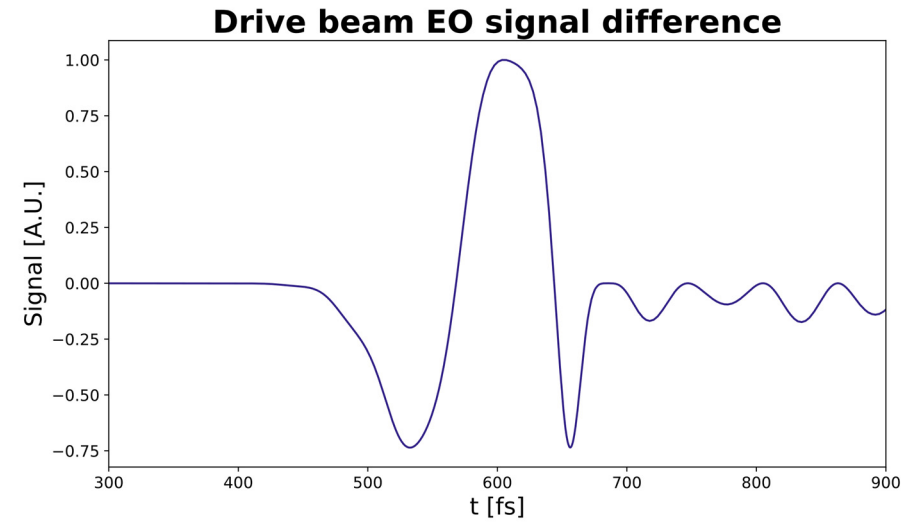
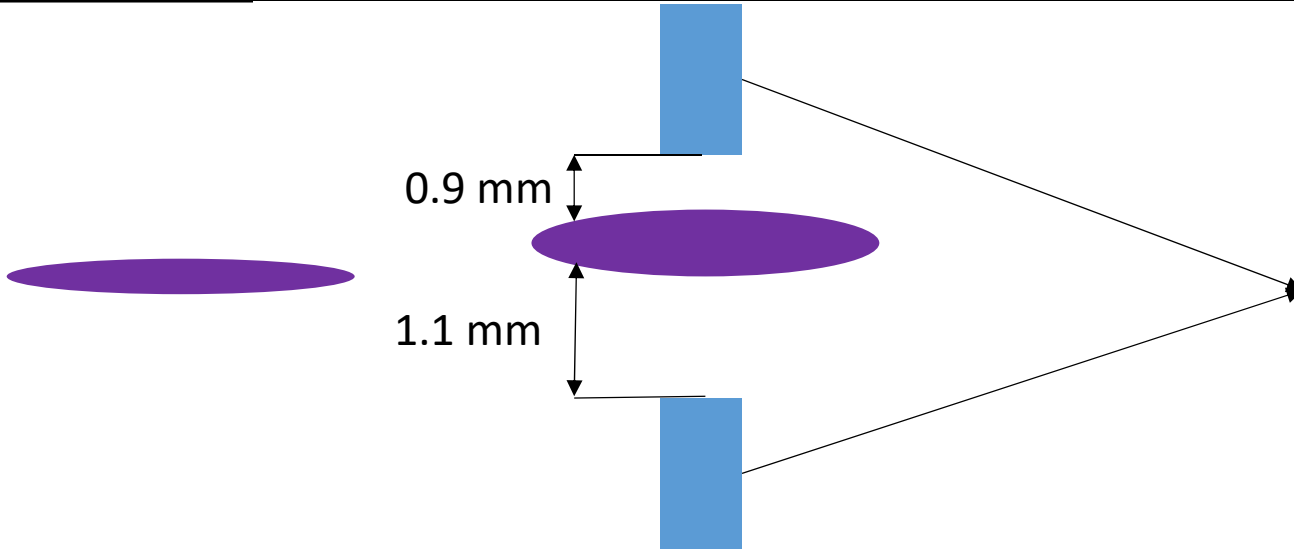
$$I_{det} \propto \sin^2 \frac{\Gamma}{2}$$

Analyzer A

Analyzer B

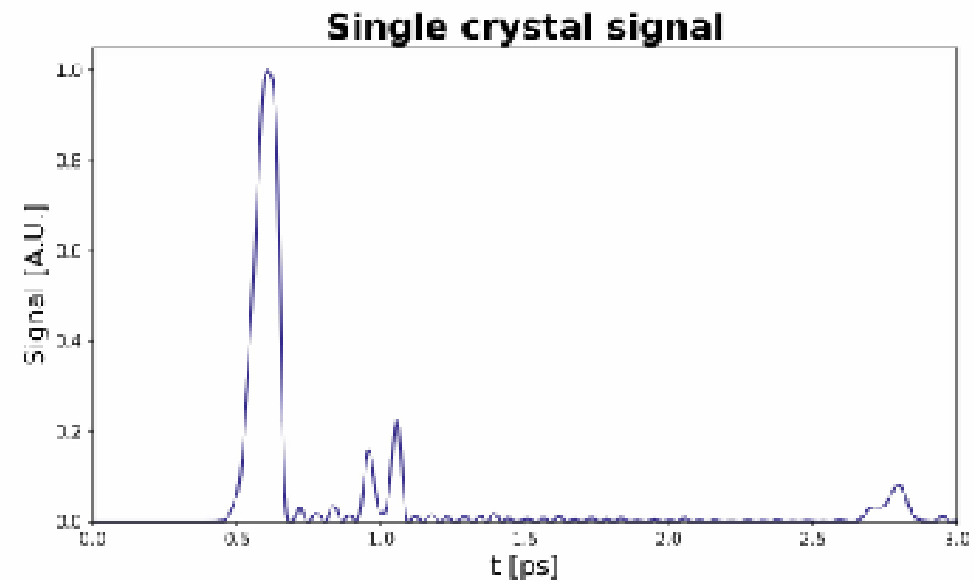
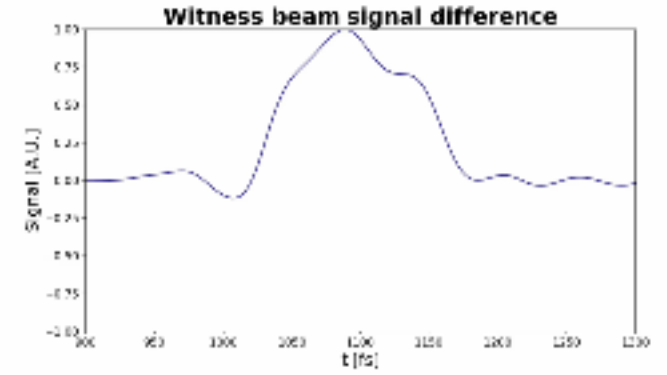
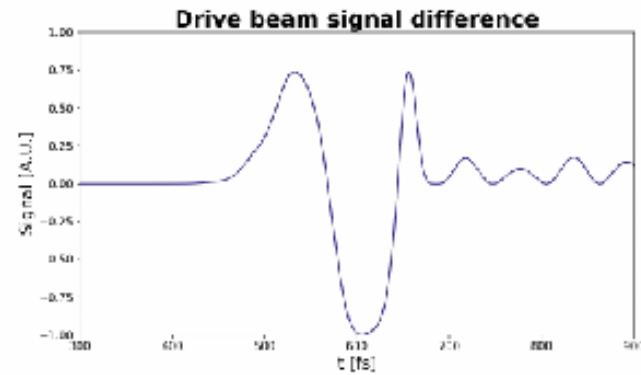
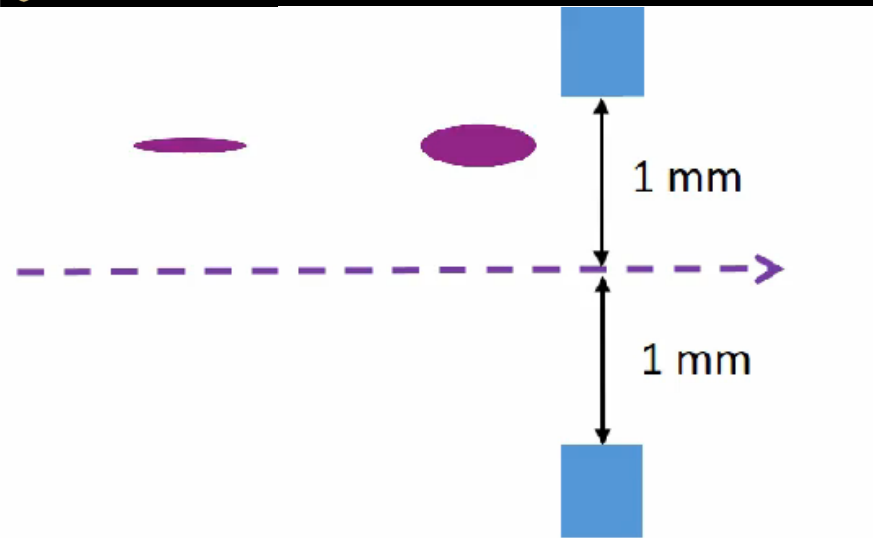


Monitoring beam's transverse offset



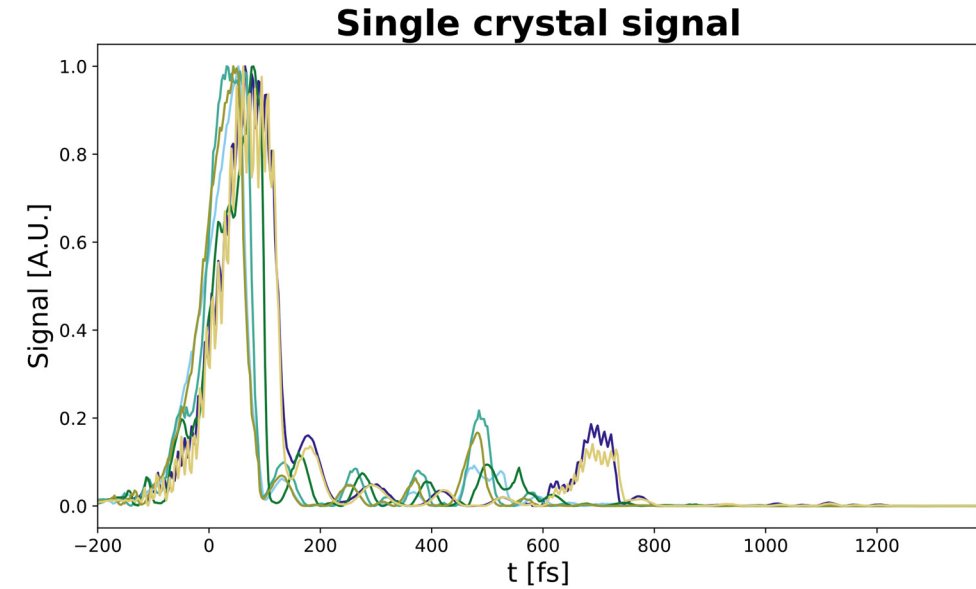
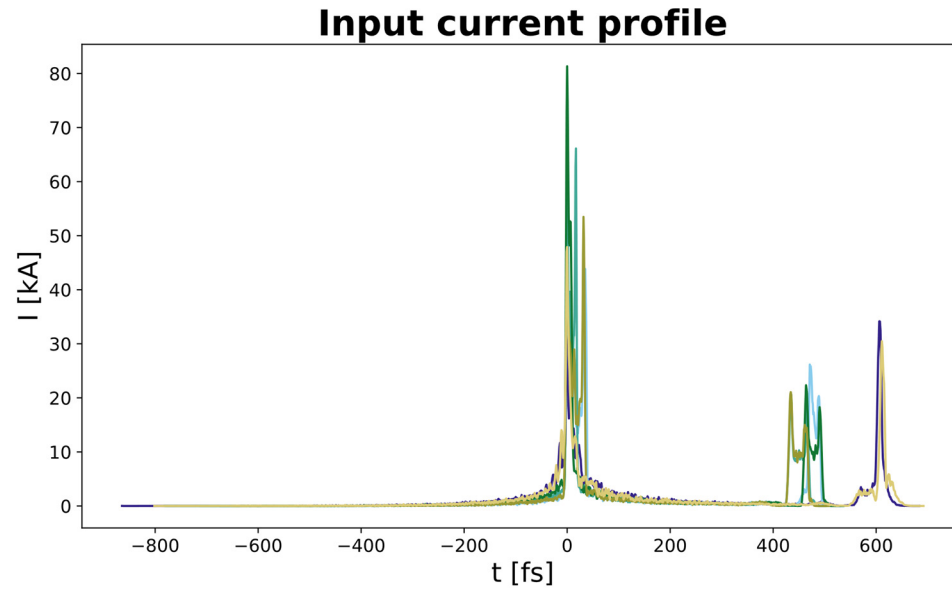


Detector operating modes





Longitudinal resolution

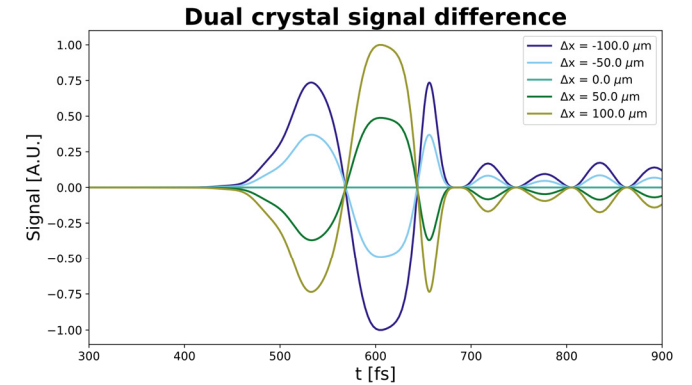
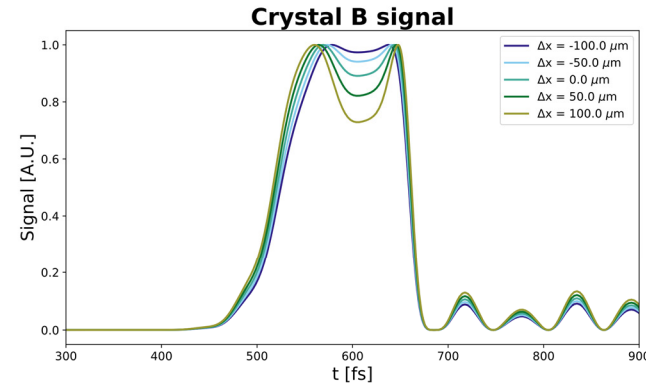
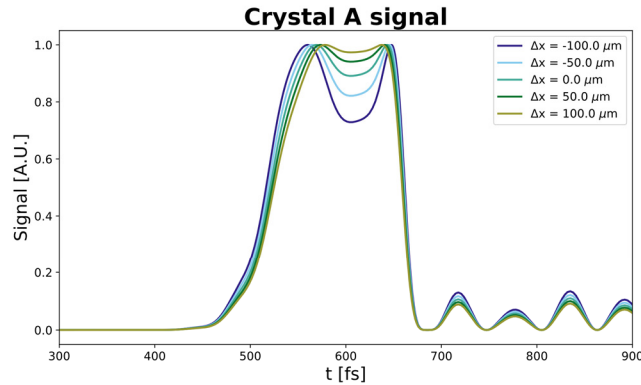


Δz input (μm)	Δz measured (μm)	Error (μm)
125	136	+11
131	127	-4
139	126	-13
142	147	+5
182	186	+4
183	188	+5

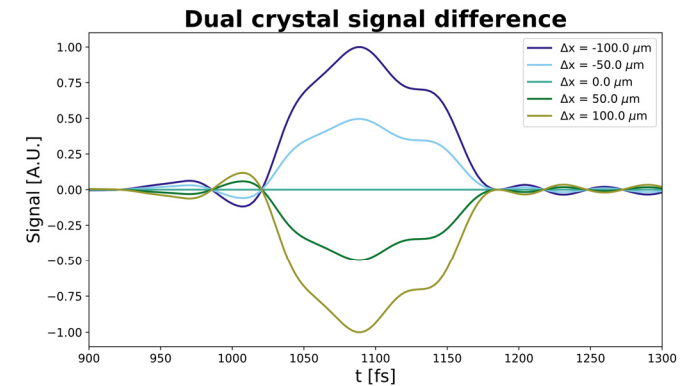
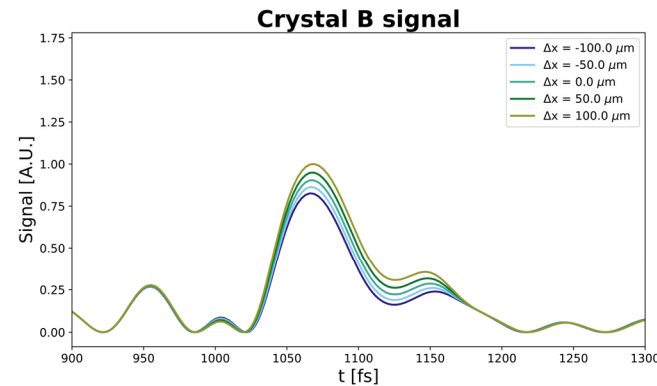
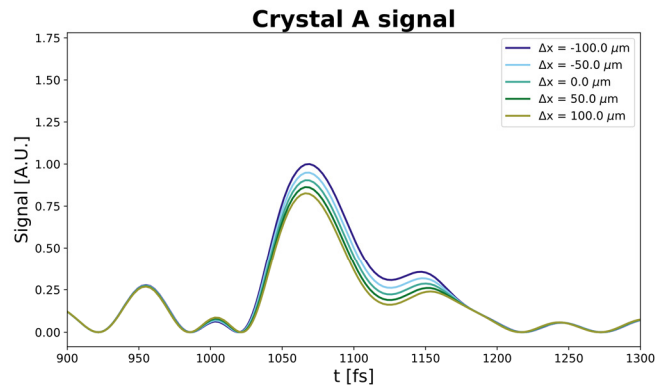


Transverse resolution

Drive
Bunch



Witness
Bunch



For both beams observe $\sim 1\%$ drop in signal (signal difference) per micron of beam offset.



Summary

- PWFAs sensitive to $\sim 5\mu\text{m}$ errors in drive-witness longitudinal separation and transverse offset
- EOS-BPM compares relative strength of signal between twin crystals on opposite side of e-beam
- Ultra-short laser pulse incident to EO crystal at an angle provides compact, non-destructive signal in a single-shot
- Single crystal (EOS) measures drive-witness separation with $\sim 10\mu\text{m}$ resolution
- Dual crystal (EOS-BPM) measures transverse drive-witness offset with $\sim 5\mu\text{m}$ resolution



Thanks!



This work was funded by the U.S. Department of Energy grant number DE-SC0017906.