Measuring Transverse Displacement Between the Drive and Witness Beams for PWFA

EAAC 2019 – WG5

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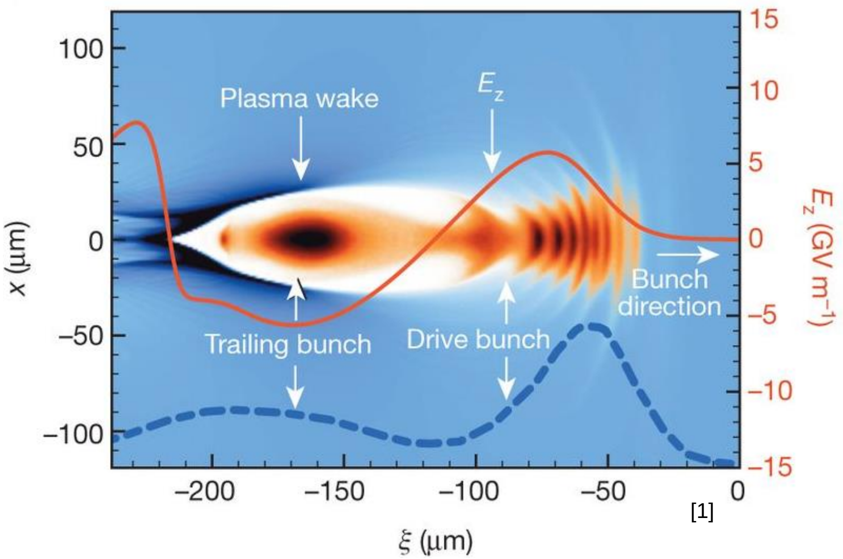
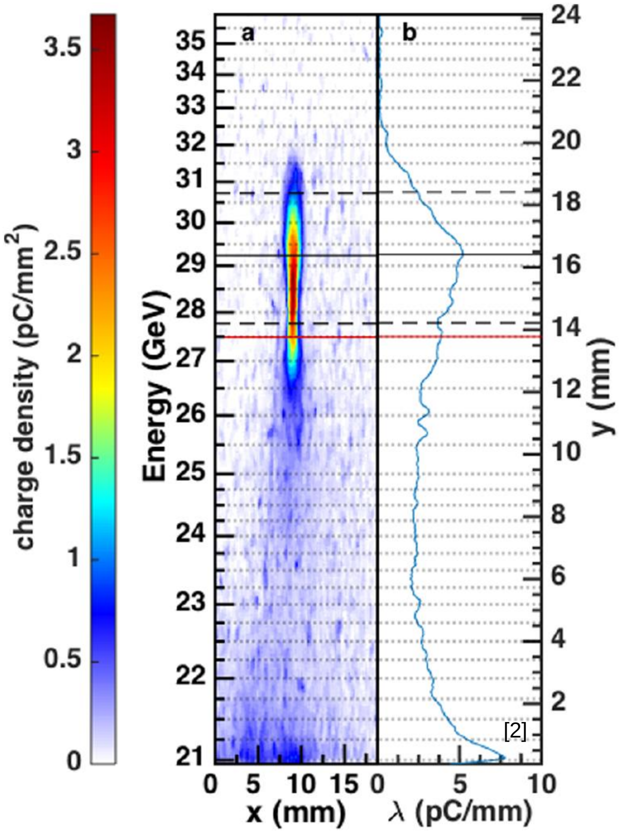
Plasma wakefield accelerators



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(~5 μm)

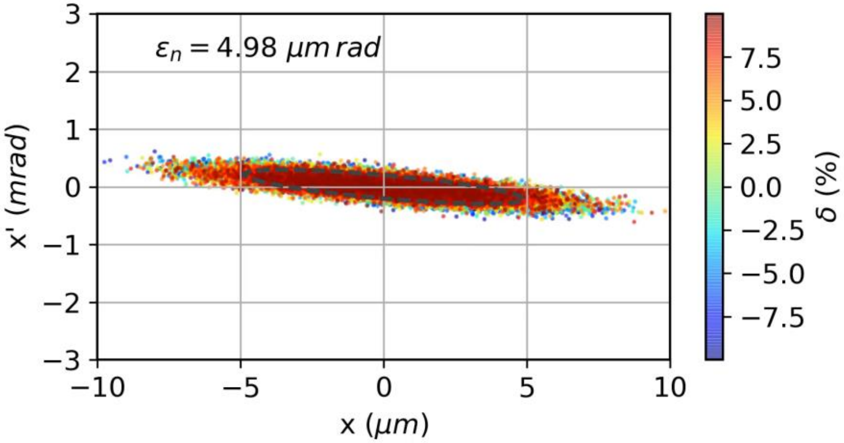


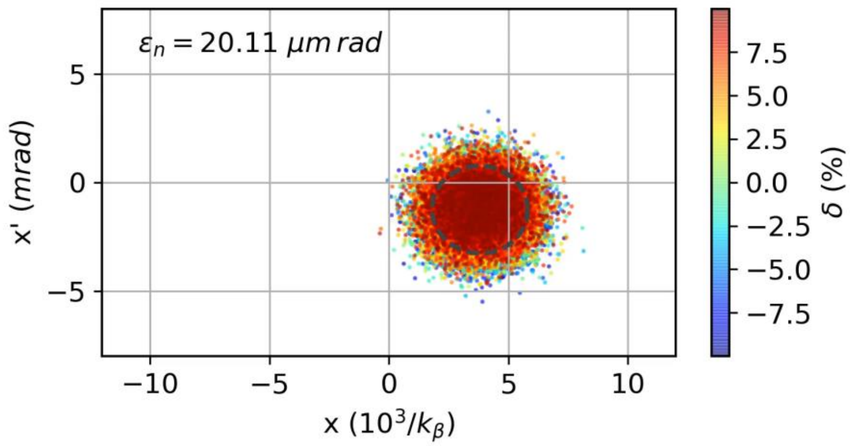
$$G_0 \approx 7\,\mathrm{GeV/m}$$

To date no PWFA has preserved beam's transverse emittance

[1] Litos *et al* Nature 2014, [2] Litos, et al. *Plas Phys. Cont. Fusion* (2016)

Witness bunch emittance growth





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

Mismatched beam:

Saturated, projected emittance is given by: [3]

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

subscript 'm': matched CS parameters

Offset witness beam:

Saturated, projected emittance is given by: [4]

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

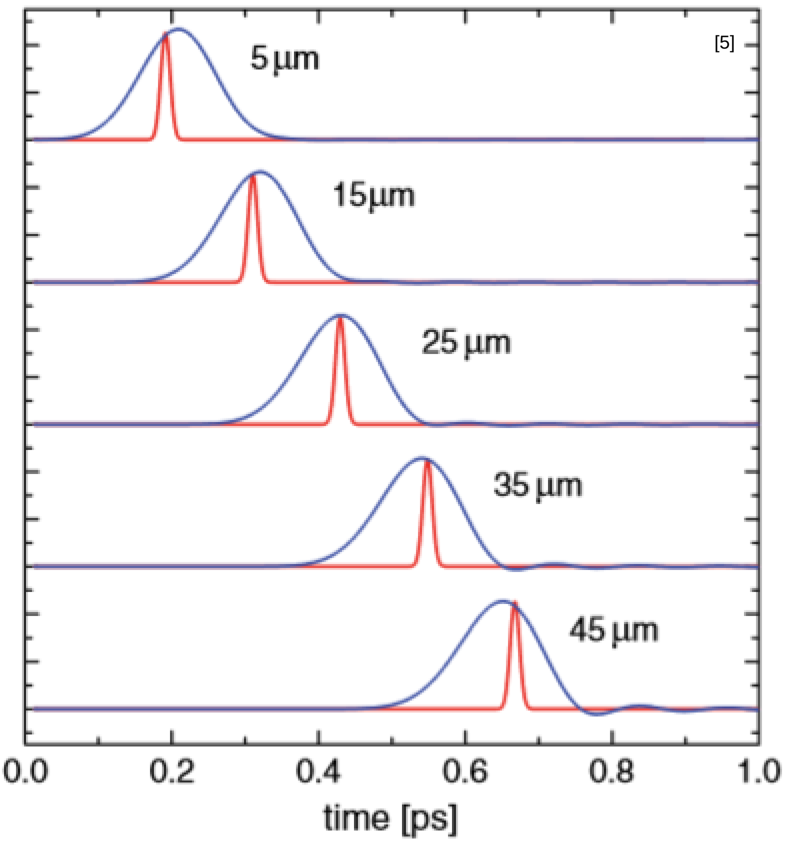
Matched witness bunch will still undergo emittance growth if it is transversely offset! O(~5μm)

[3] Xu *et al* PRL 2016, [4] Lindstrom *et al* IPAC Proceedings 2016

Electro-optic sampling

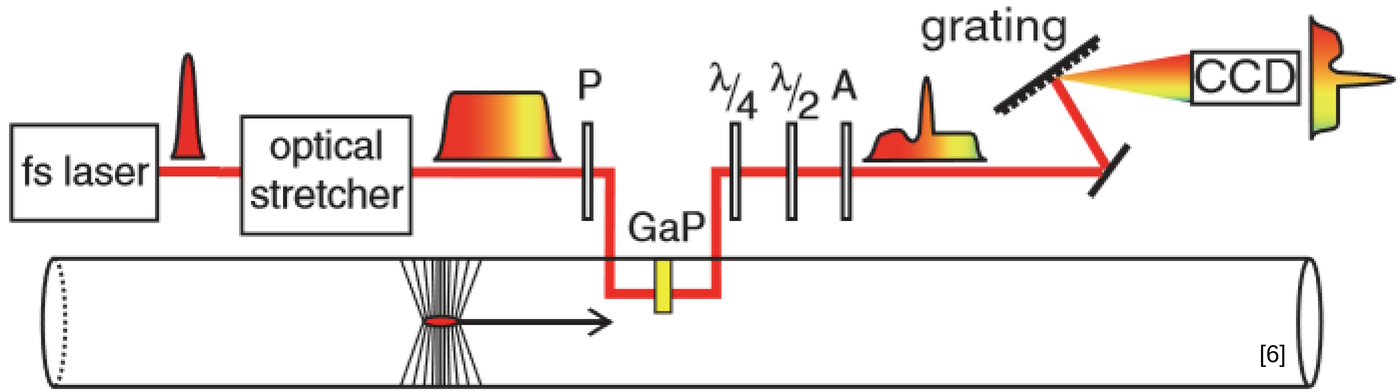
Principles of detection:

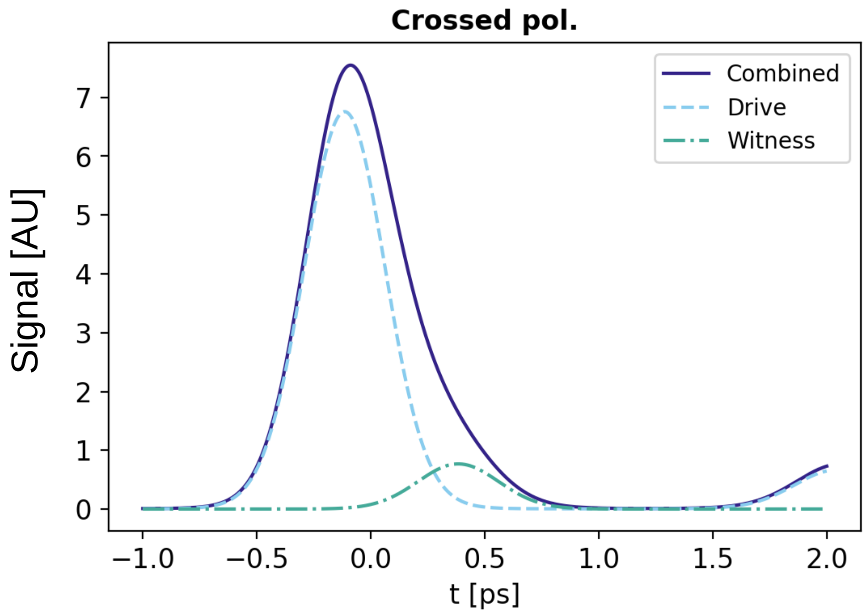
- Electron bunch passing by an EO crystal at speed *c* resembles a transient THz field travelling through the crystal.
- The THz field induces a birefringence on the crystal
- Phase retardation occurs between polarization components of a probe pulse
- Temporally scan probe to reconstruct full beam profile



[5] Cassalbuoni *et al* PRSTAB (2008)

Electro-optic spectral decoding



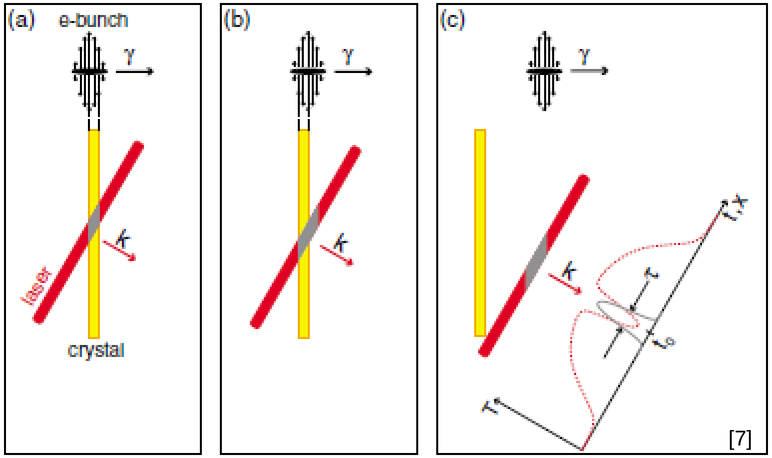


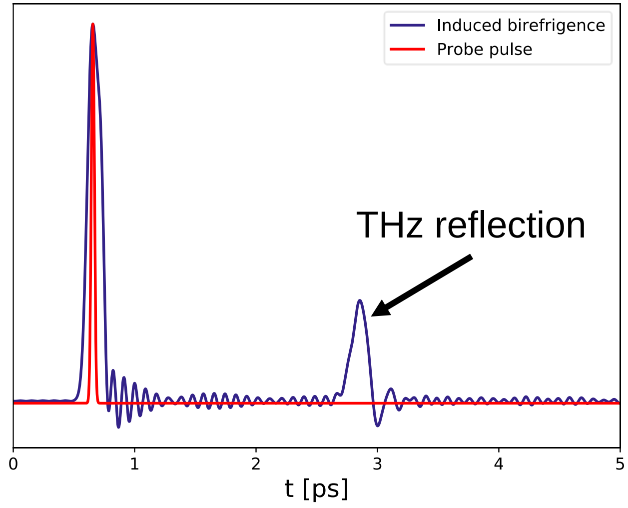
- Utilize a chirped probe pulse mapping the phase retardation for each frequency component into time.
- Due to signal broadening EOSD is non-ideal for observing two-bunch electron beams!

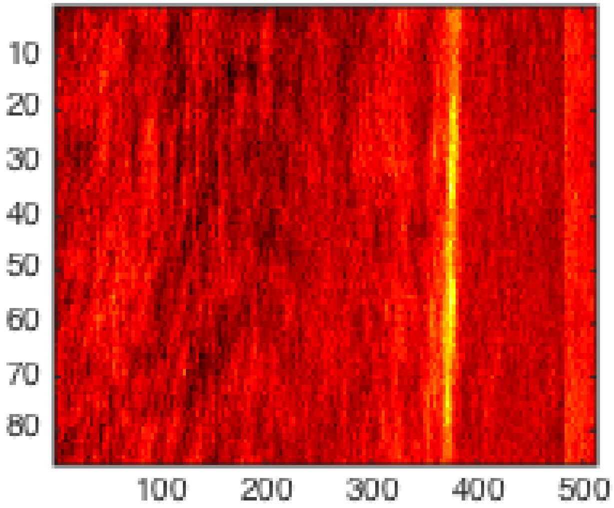
[6] Steffan *al* PRSTAB (2009)

Spatial Encoding

- Utilizes an ultrafast probe pulse swept through an EO crystal at an angle to perform EOS in a single-shot
- Minimal signal broadening
- Compact detector setup



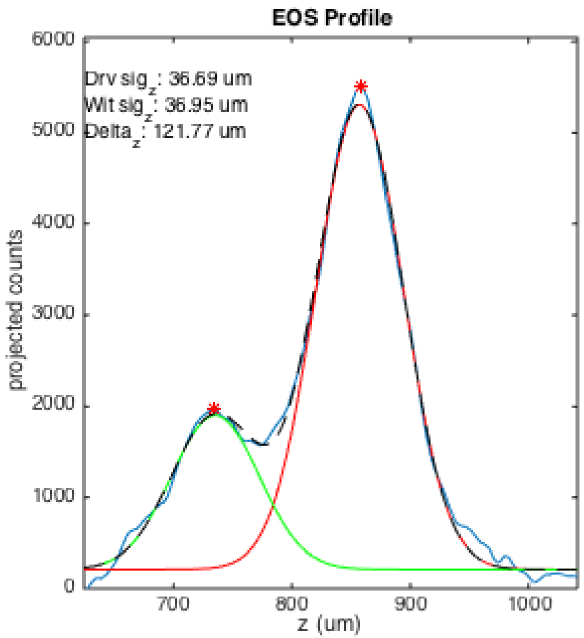


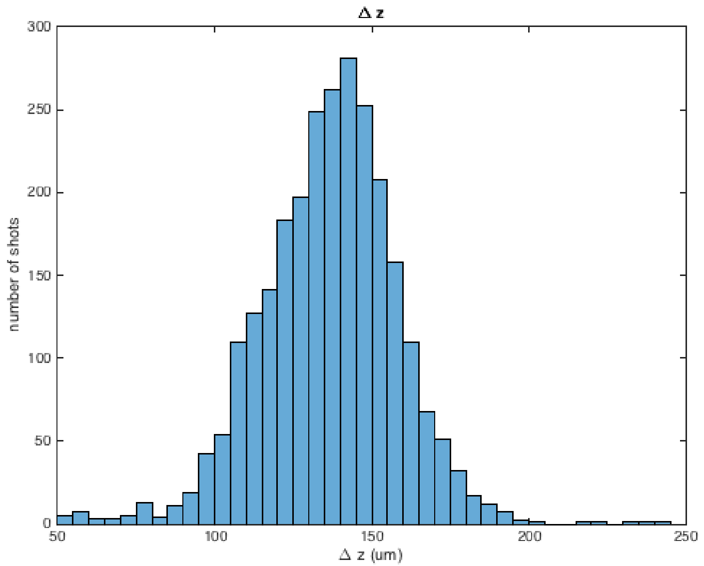


Single-shot, background subtracted signal using spatial encoding at FACET

[7] Cavalieri *al* PRL (2005)

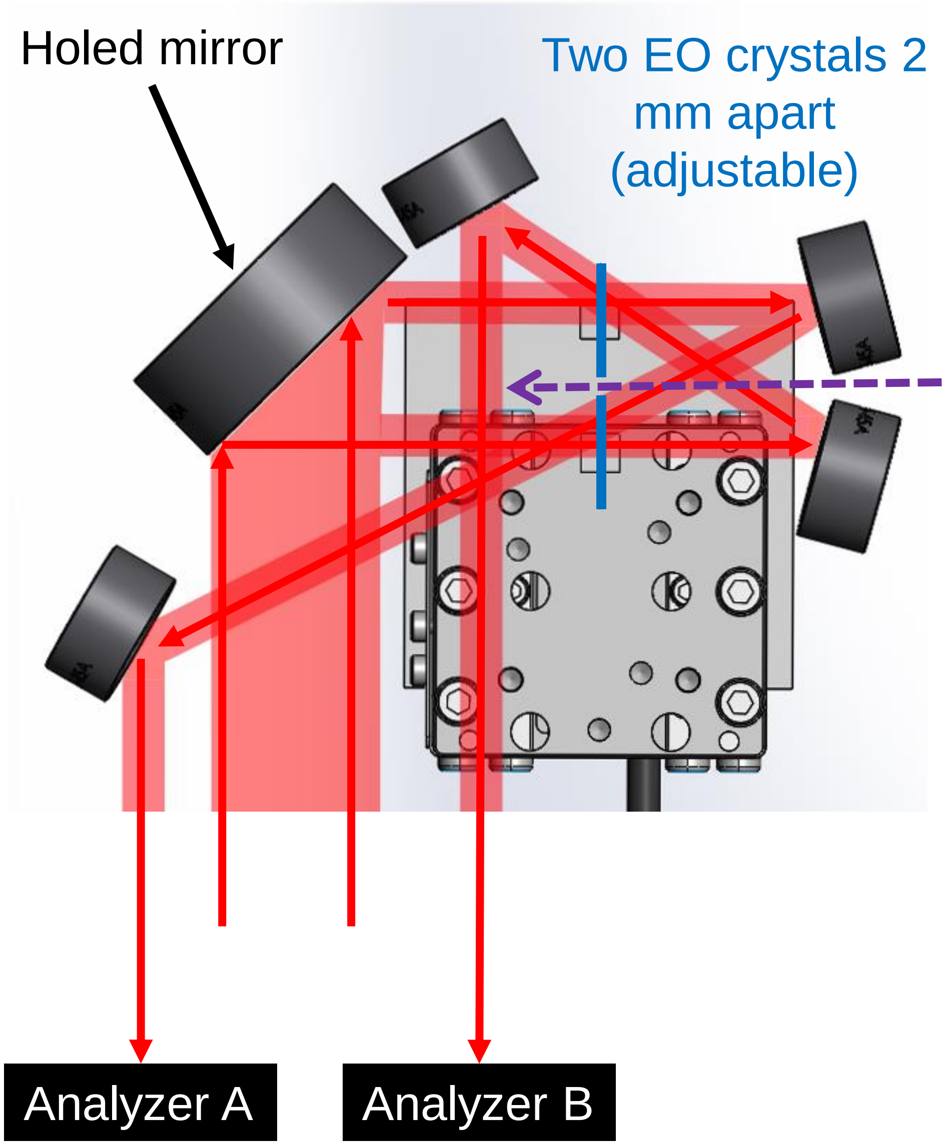
EOS at FACET



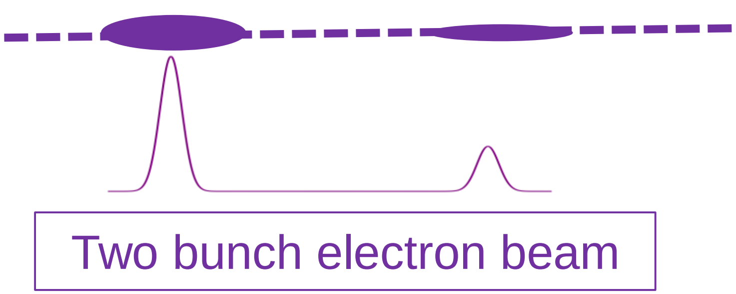


EOS was used at FACET to measure the longitudinal separation of the drive and witness beams (Δz) for a PWFA. It was calibrated against the X-band TCAV.

EOS-BPM at FACET-II



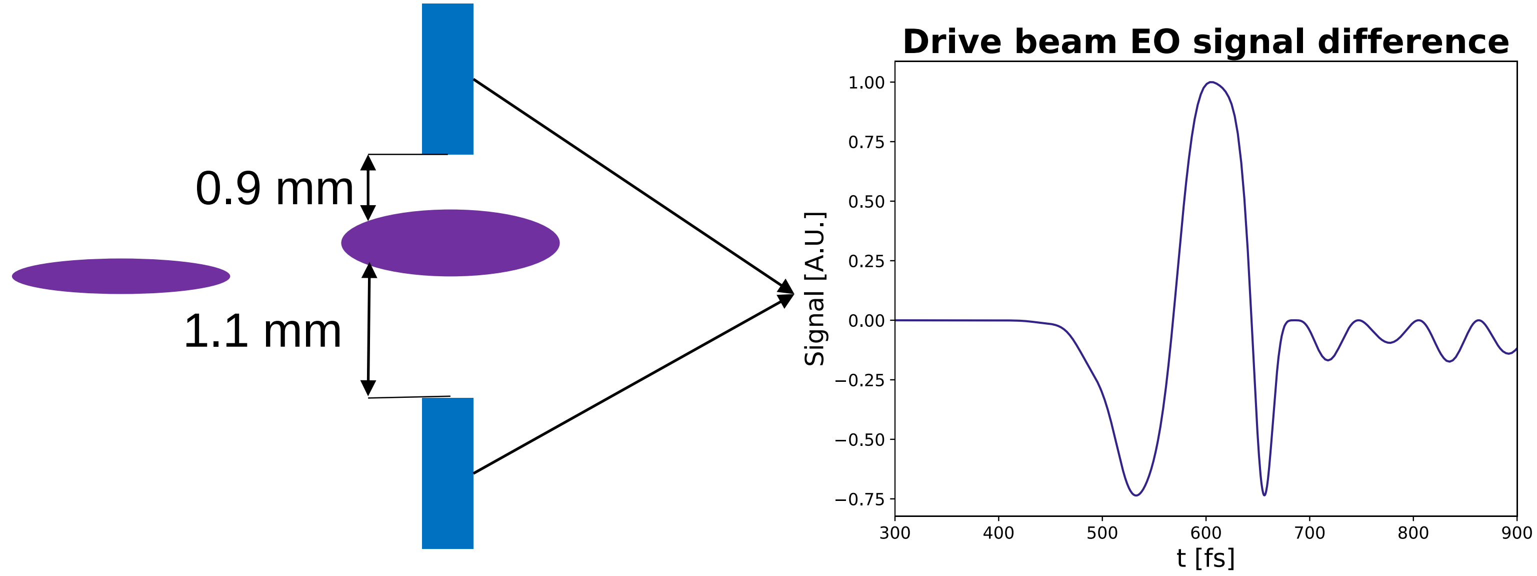
- Dual crystals measure horizontal offset
- Single crystal measures longitudinal and vertical offset

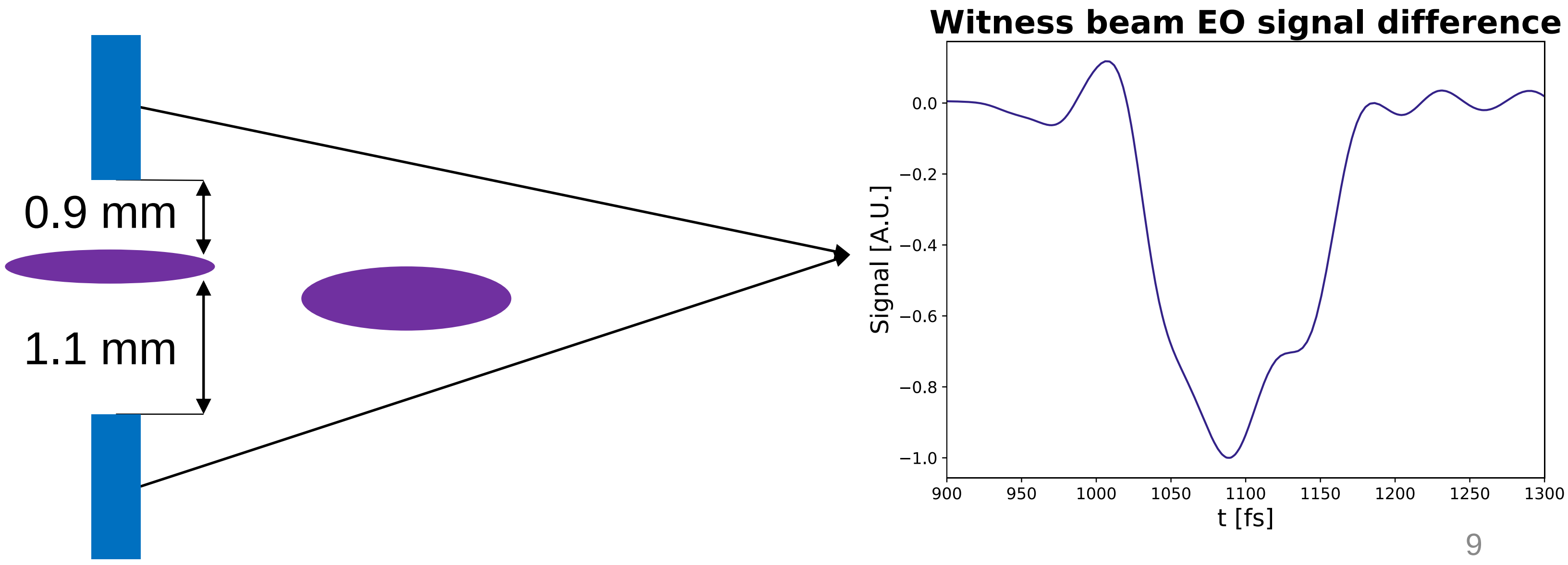


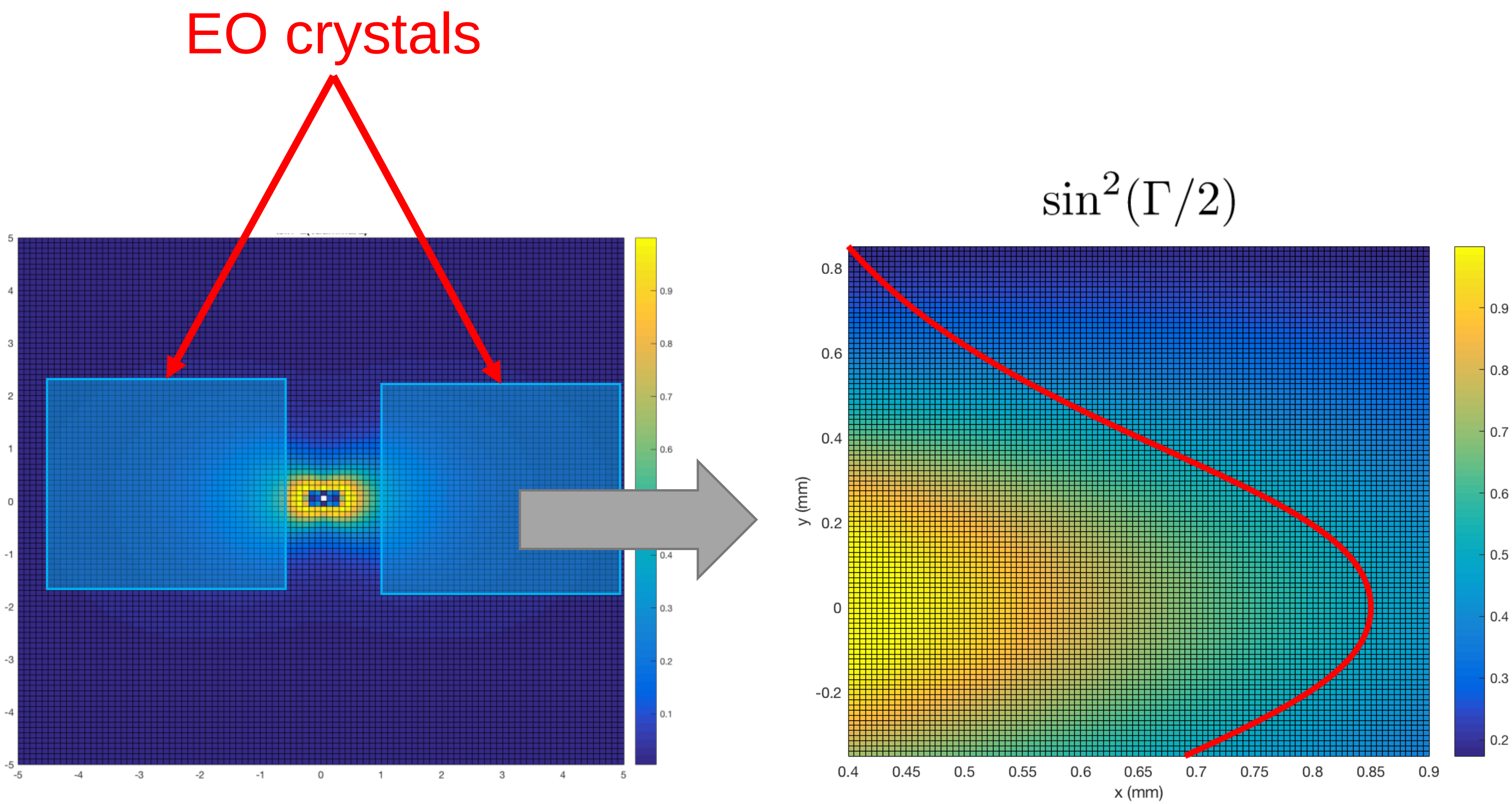
Beam parameter	**Value**
Q_{drive}	1.5 nC
Q_{wit}	0.5 nc
$\sigma_{z,drive}$	5.2 μm
$\sigma_{z,wit}$	5.2 μm
Δz	150 μm

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

Monitoring beam's horizontal offset

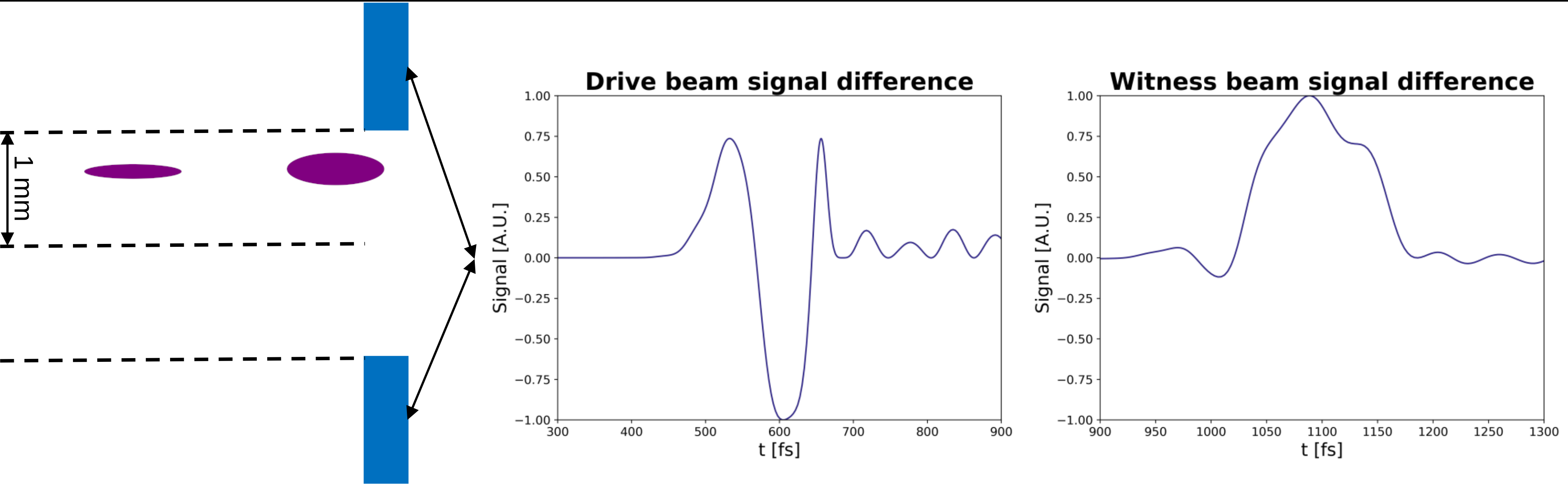


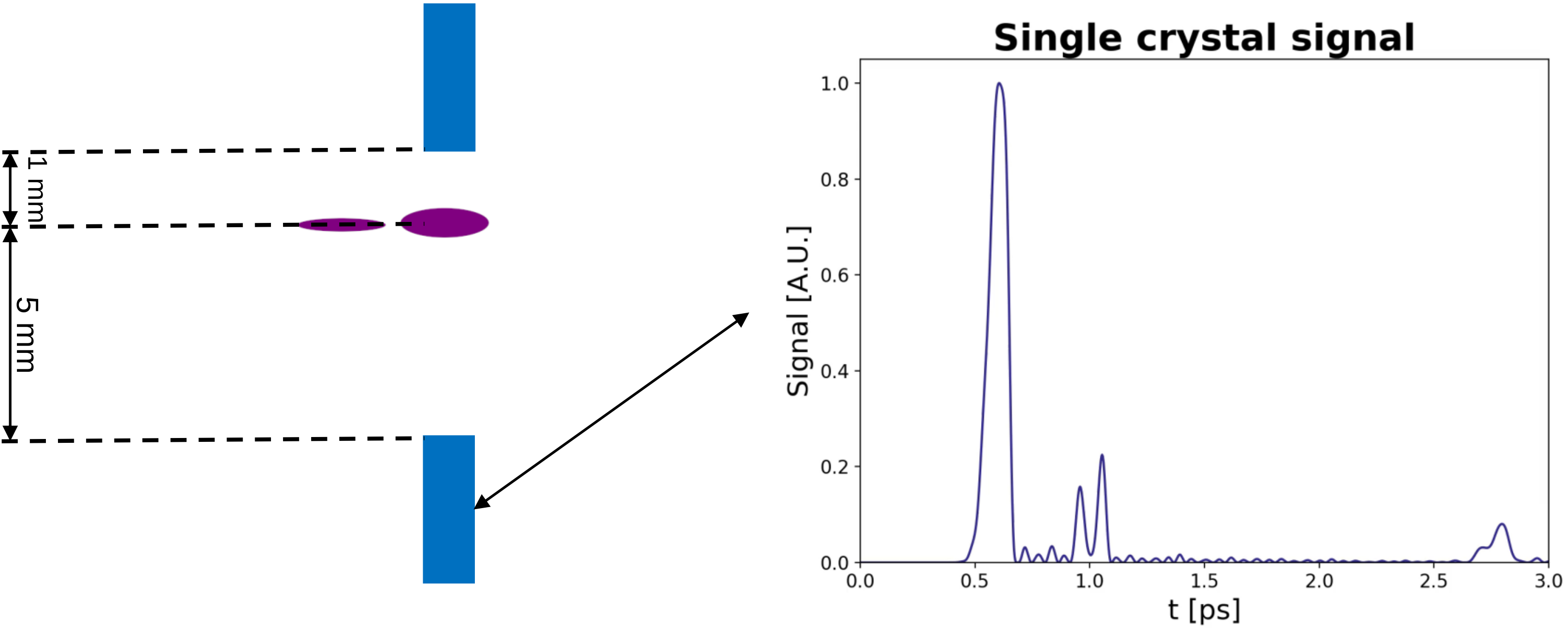




Look at 1D integrated peak from either/both crystal for information on bunch vertical offset

Detector operating modes

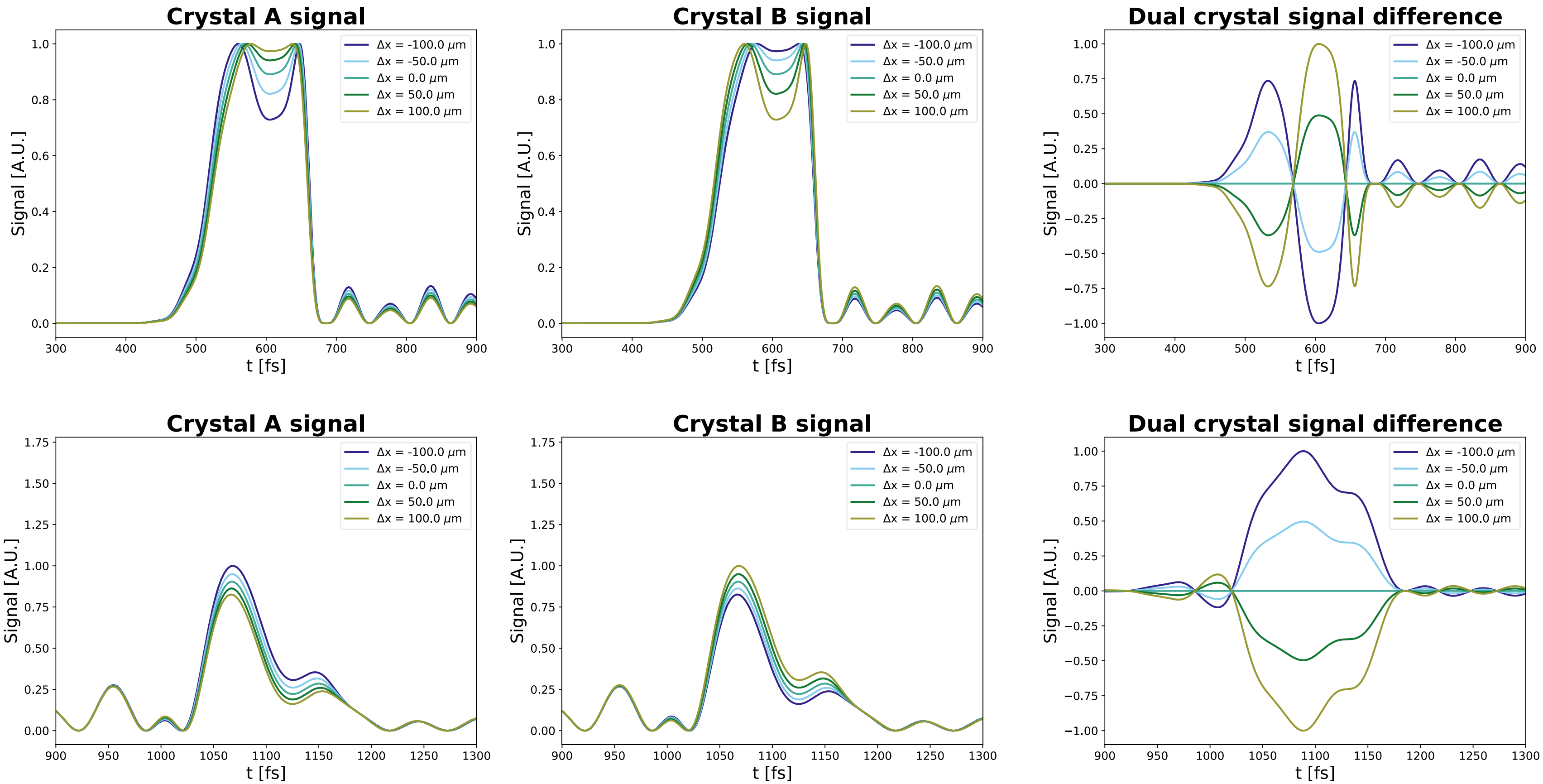




Transverse horizontal resolution

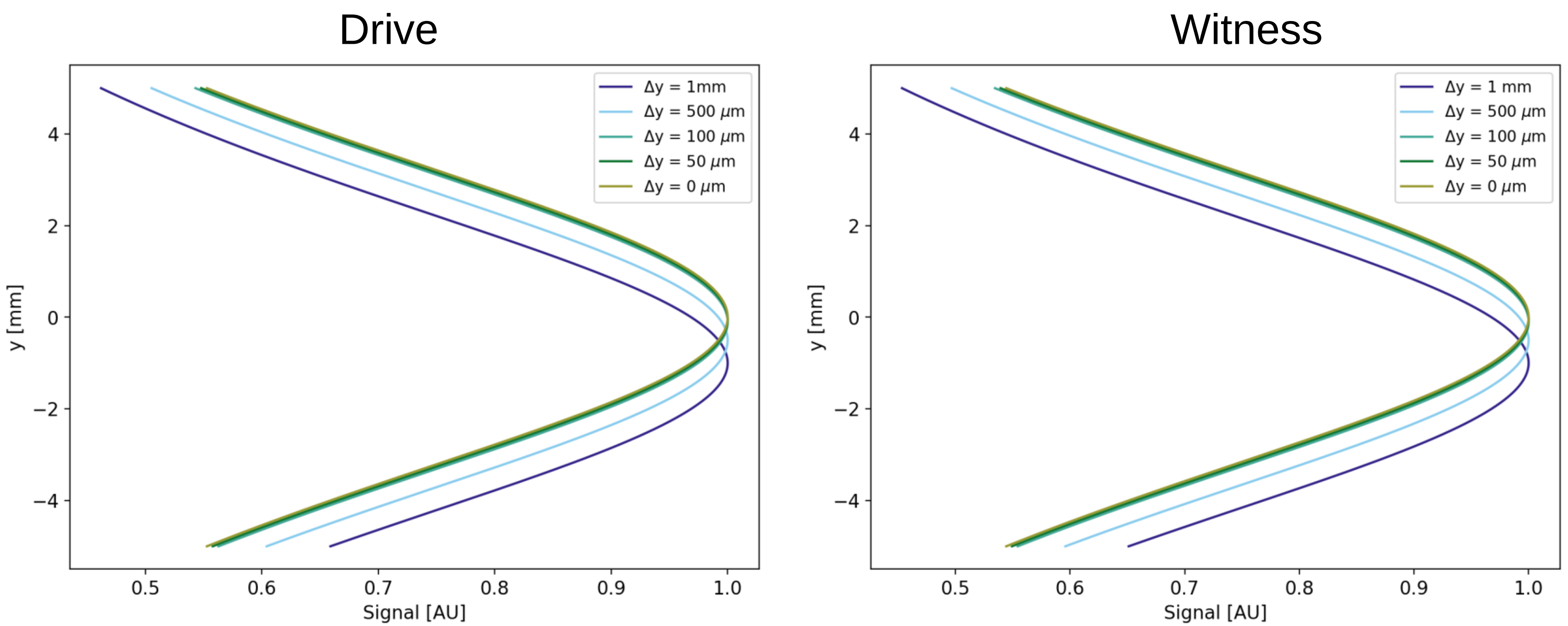
Drive Bunch

Witness Bunch



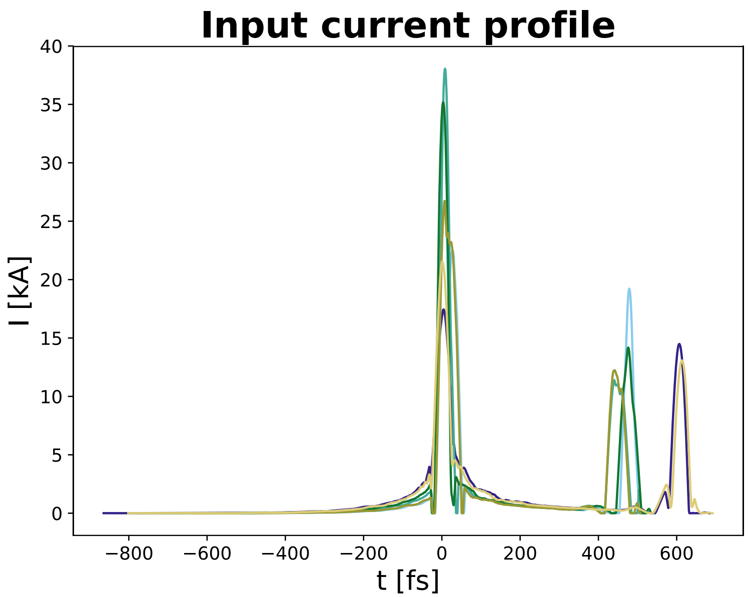
For both beams observe ~1% drop in signal (signal difference) per micron of beam offset.

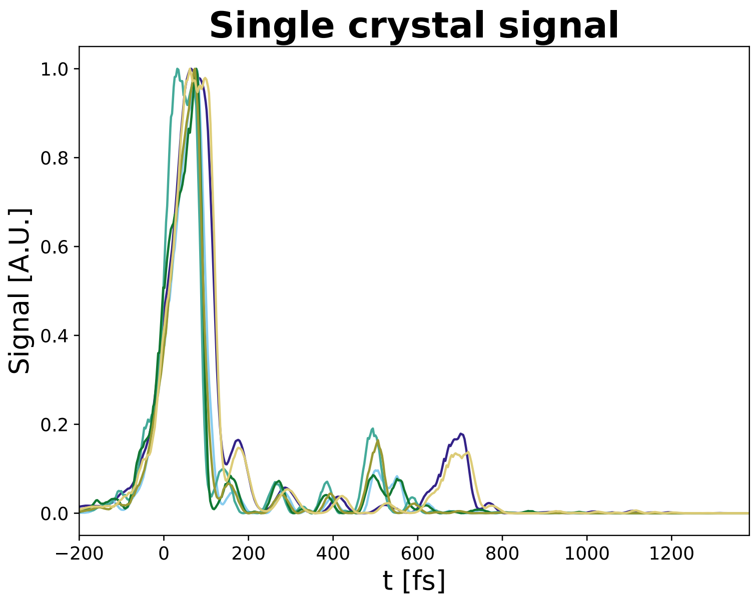
Transverse vertical resolution



1D peak sensitive to ~ 0.5 mm vertical offsets – not great
4 crystal EOS-BPM would give same resolution in x and y

Longitudinal resolution

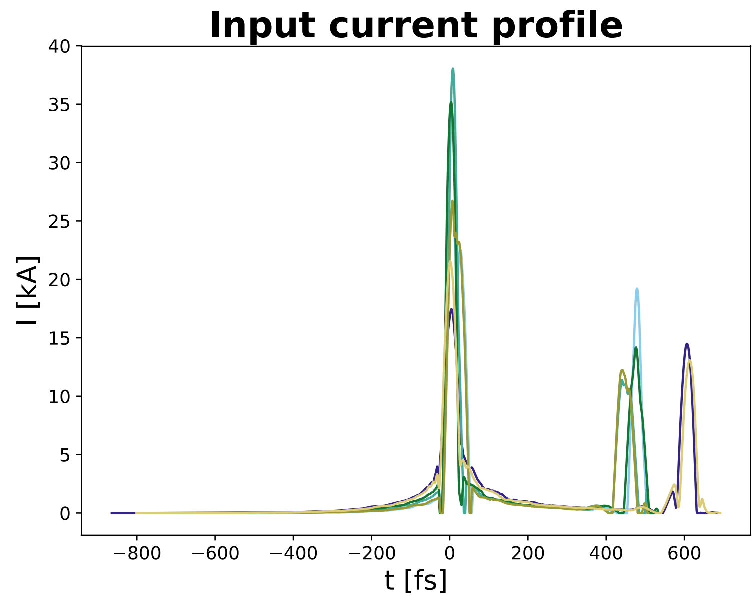


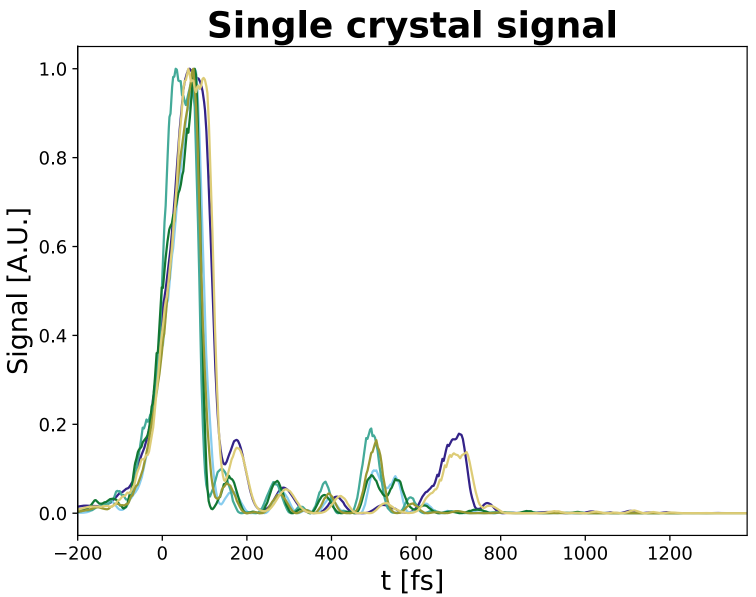


Δz input (μm)	Δz measured (μm)	Error (μm)
125	136	+11
131	127	-4
139	126	-13
142	147	+5
182	186	+4
183	188	+5

Longitudinal resolution with smoothed profiles

Laser heater at FACET-II could smooth beam's current profile





Δz input (μm)	Δz measured (μm)	Error (μm)
129	134	+5
132	135	+3
138	140	+2
142	143	+1
182	186	+5
183	188	+5

Summary

- PWFAs sensitive to ~ 10μm 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.

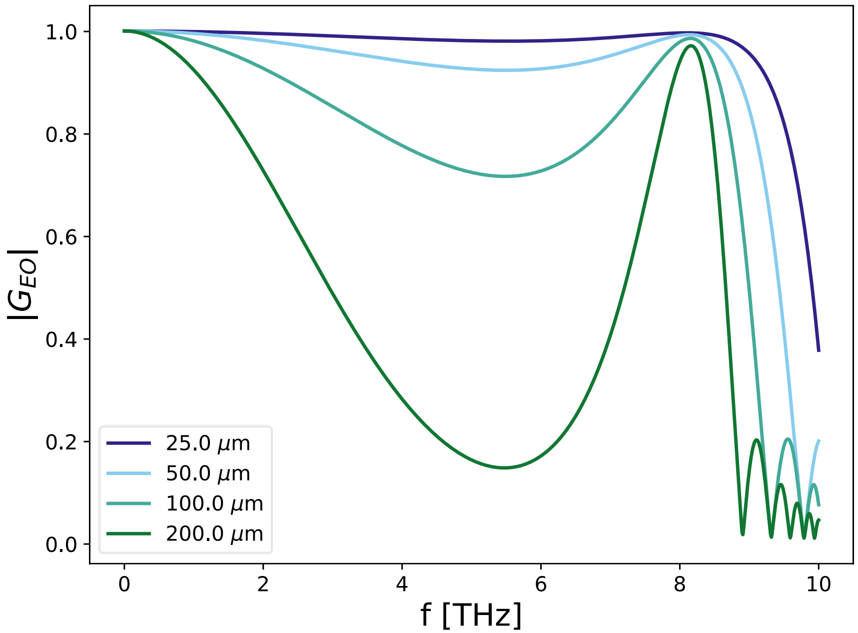
- Single crystal (EOS) measures drive-witness separation with ~10 $\mu\mathrm{m}$ resolution.

- Dual crystal (EOS-BPM) measures transverse drive-witness offset with ~ 5 $\mu\mathrm{m}$ resolution in the horizontal. For vertical measurements need more crystals.

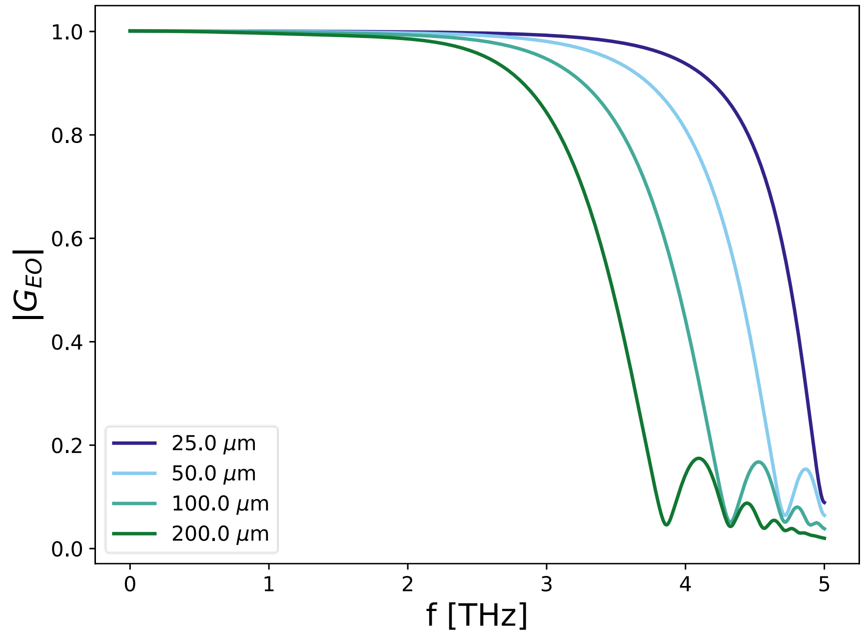
Thanks!

Characterizing EO crystals

Gallium phosphide
(GaP)



Zinc telluride
(ZnTe)



Crystals geometric response accounts for signal degradation due to slippage between the probe pulse and the THz pulse. Our simulations utilize **100 µm thick GaP**.