Diagnostic Requirements for Offset Witness Bunch

FACET-II Science Workshop

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Beam Parameters

for "Nominal" Two-Bunch PWFA Beam

Parameter	Drive Beam	Witness Beam
Q	1.5 nC	0.5 nC
E_i	10 GeV	10 GeV
σ_δ	1%	1%
ε_n	5.3 mm-mrad	7 mm-mrad
β_i	10 cm	10 cm
$\sigma_{r,i}$	5.1 μm	5.9 μm
σ_z	5.2 μm	3.6 μm
Δz	75 μm	

In this talk: $n_p = 10^{16}$ cm^{-3}
(laser-gas plasma source)

Misalignment Consequences

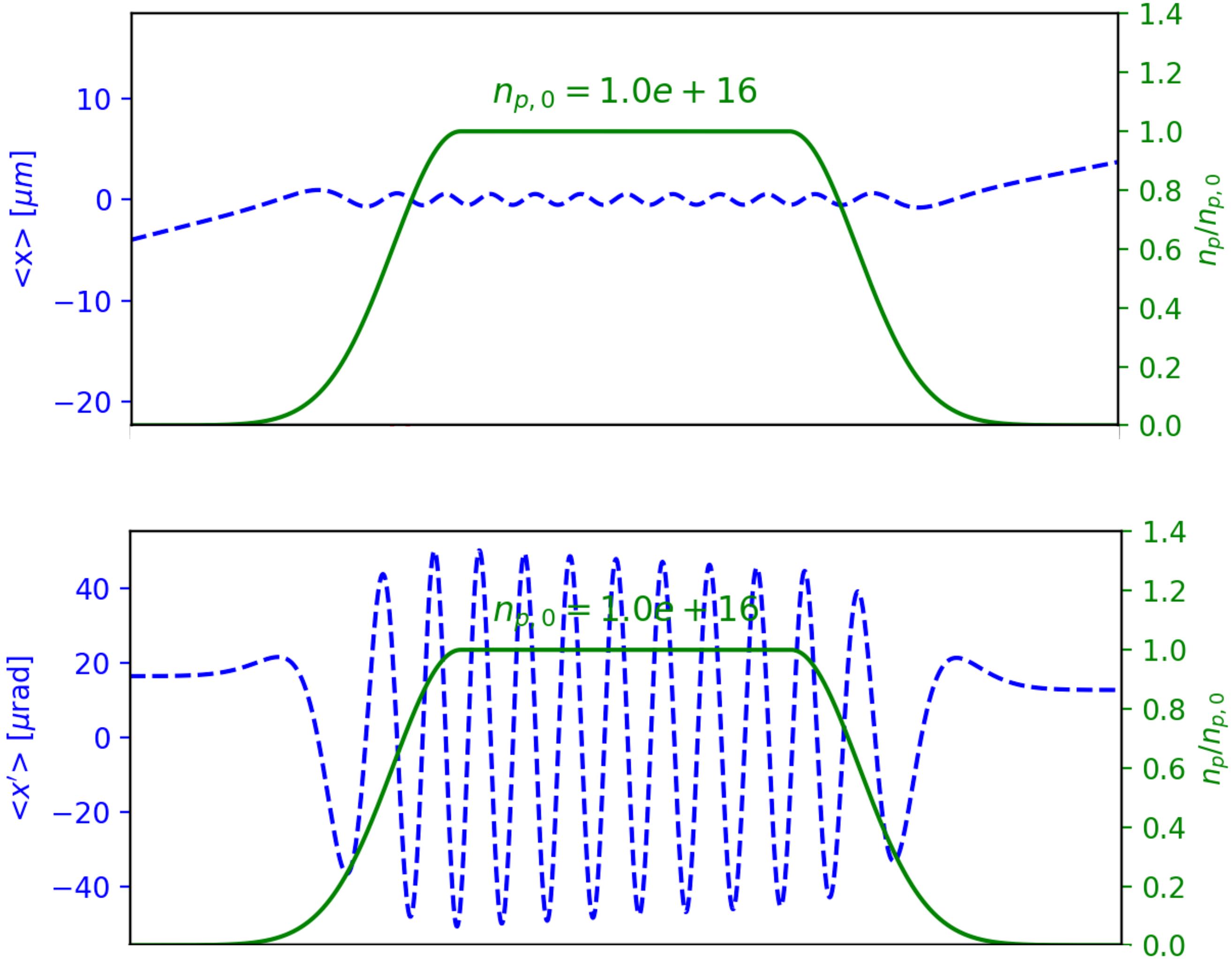
- Exit plasma at an angle
  → difficult to predict or control

- Emittance growth
  → nominally matched beam off-axis is no longer actually matched

- Could induce hosing
  → 'nuff said!

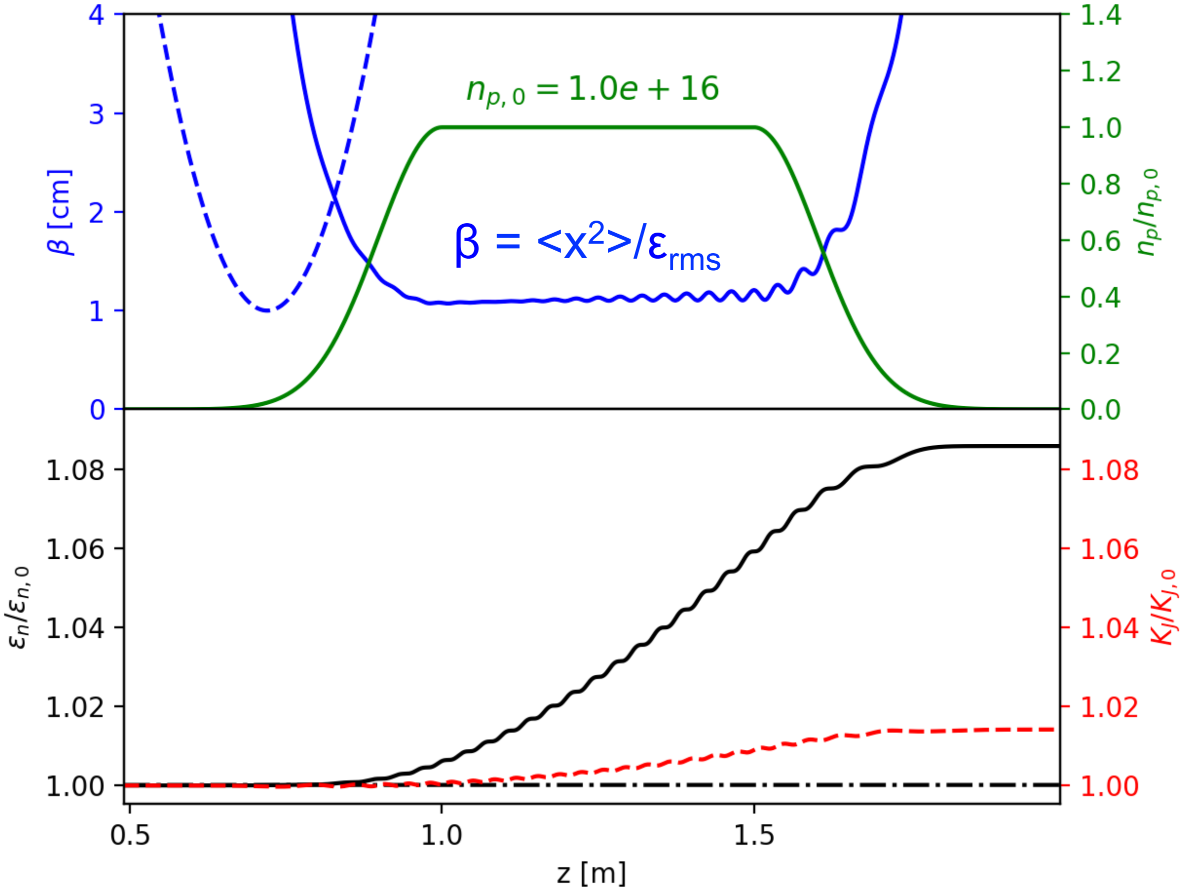
Exit Deflection

Transverse misalignment leads to deflection at plasma exit



Emittance Growth

example: <x>* = 10 μm



Beam begins to "smear out" in plane of offset.

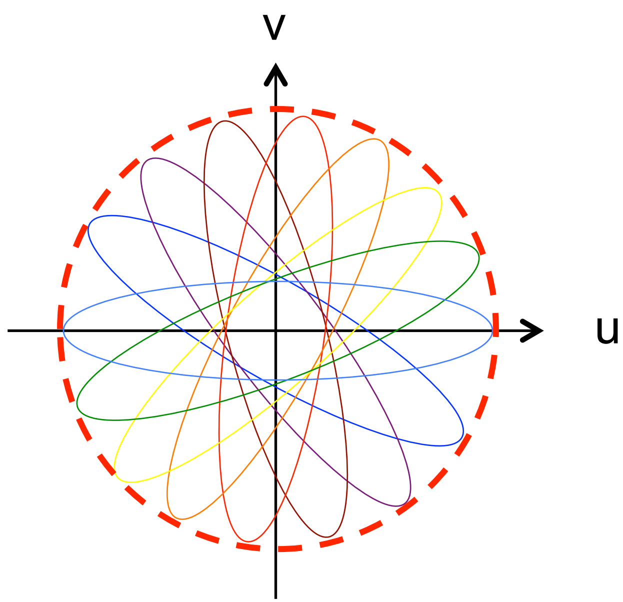
Note: B_{mag} of course doesn't predict this growth

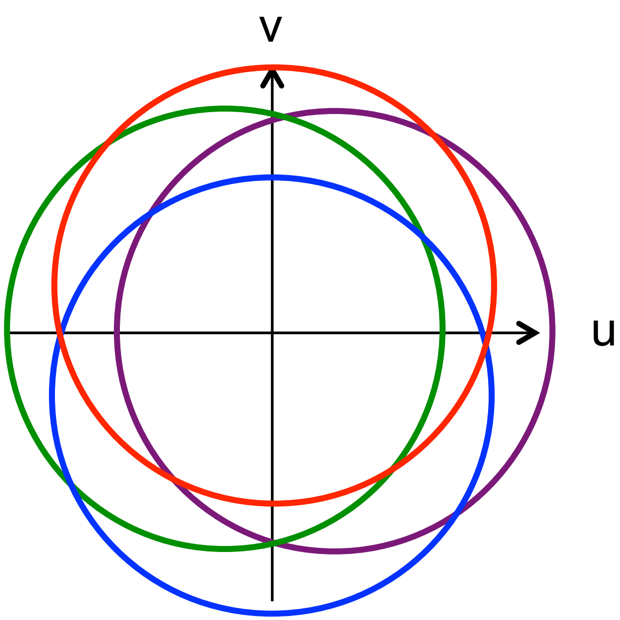
Example does NOT include hosing effects

Emittance Growth from Offset

- Beam rotates clockwise in phase space
- Matched beam is circular in normalized coordinates
  → no emittance growth
- **Unless** it's offset

$$u = x/\sqrt{\beta_m} \quad v = \sqrt{\beta_m}x' + \alpha_m x = \sqrt{\beta_m}x'$$





Deflection Sensitivity

$\langle x \rangle^*$, $\langle x' \rangle^*$: offsets at vacuum waist

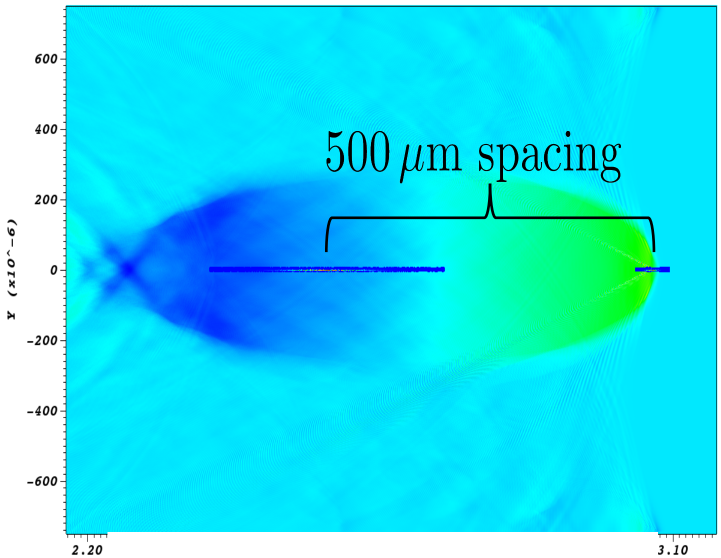
param.	offset	$\langle x_{exit}' \rangle$	$\varepsilon_n/\varepsilon_{n,0}$
$\langle x \rangle^*$	10 μm	63 μrad	1.07
$\langle x \rangle^*$	5 μm	30 μrad	1.03
$\langle x \rangle^*$	1 μm	6 μrad	1.00
$\langle x' \rangle^*$	10 μrad	6 μrad	1.00
$\langle x' \rangle^*$	5 μrad	6 μrad	1.00
$\langle x' \rangle^*$	1 μrad	2 μrad	1.00

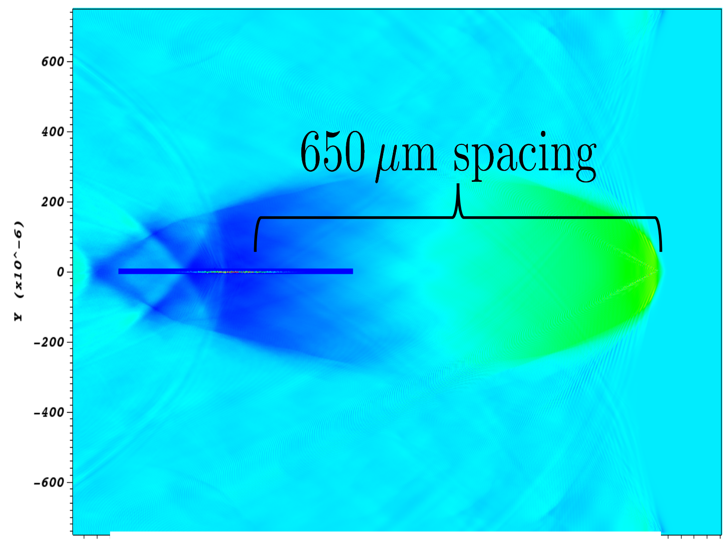
More sensitive to position offset than angle offsets.

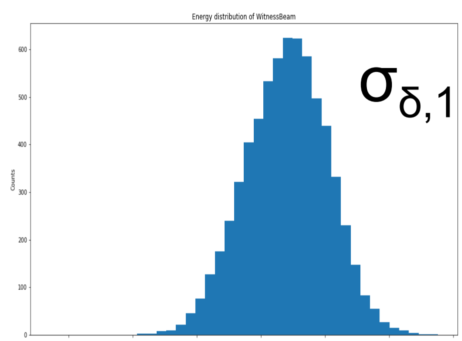
Need $|\langle x \rangle^*| < 10$ μm for <10% emittance growth.

Energy Gain and Spread

Hard to quantify without PIC sims, but we know sensitivity is ~10 μm for Δz.

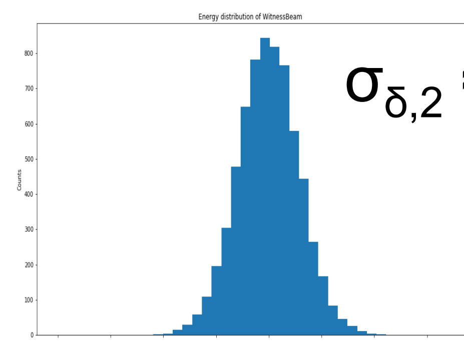






$\sigma_{\delta,1}$

E_1



$\sigma_{\delta,2} \approx \sigma_{\delta,1} / 2$

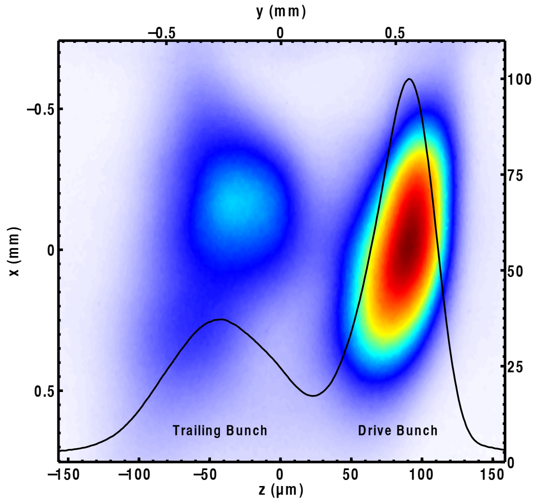
$E_2 \approx 2\, E_1$

FACET-II Tolerances

In general, want to monitor and control Δr and Δz between drive and witness to ~10 μm level.

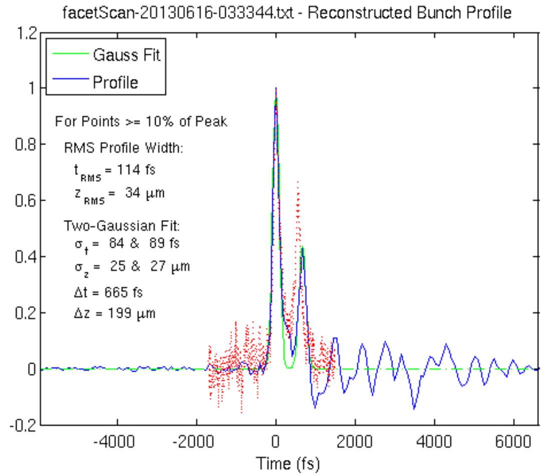
Relatively insensitive to angles below 10 μrad. (True for hosing??)

TCAV



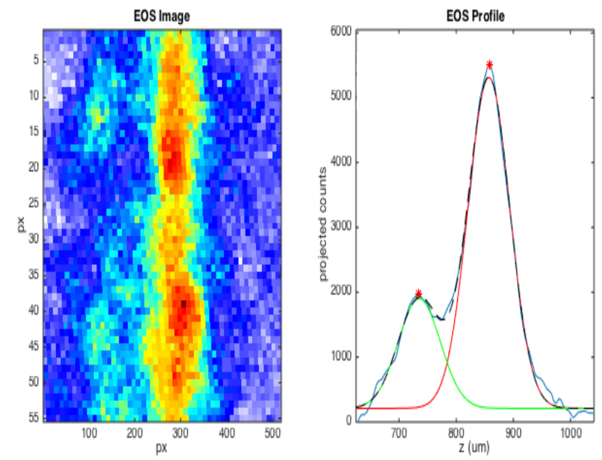
- Single Shot
- Resolution: ~10µm
- Destructive
- Subject to Chromatic Distortions

THz Michelson Interferometer



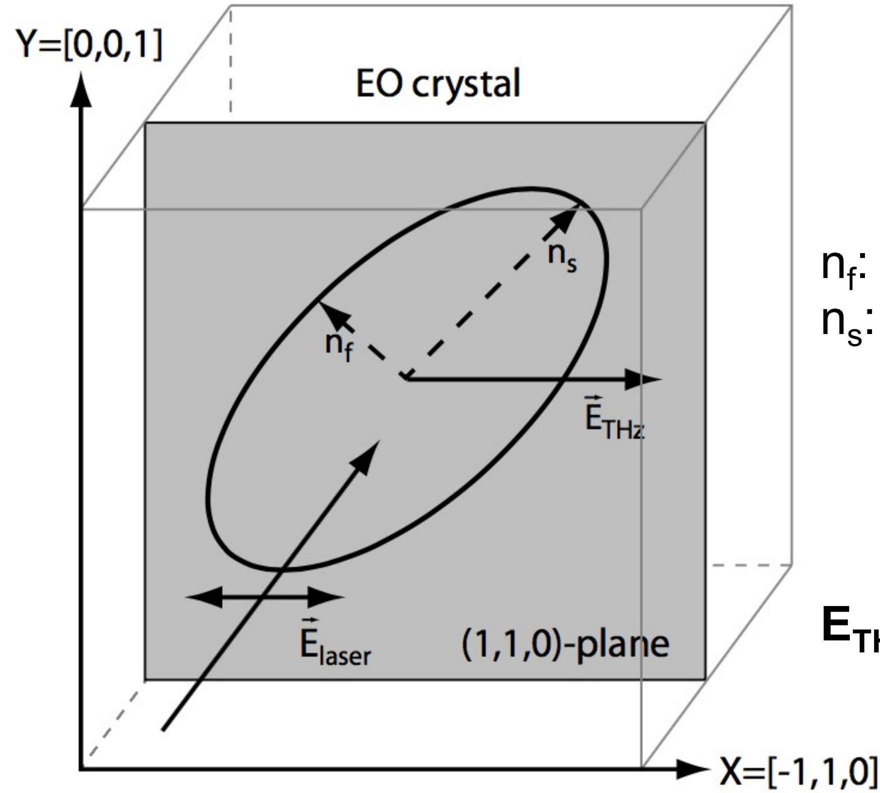
- Multi-Shot
- Resolution: ~5µm
- Non-Destructive
- Subject to Distortion from Beam Fluctuations

Electro-Optic Sampling



- Single Shot
- Resolution: ~10µm
- Non-Destructive
- Subject to Distortion from Laser Fluctuations

Relative Phase Retardation



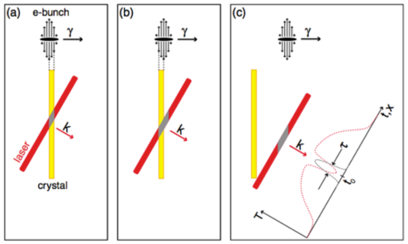
n_f: fast index
n_s: slow index

E_{THz} || E_{laser} || X

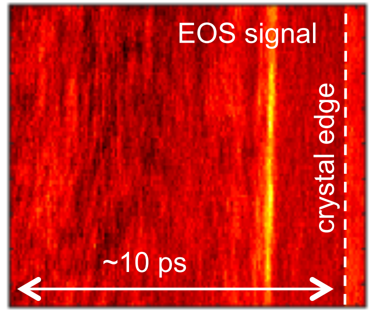
$$\Gamma = k_0 n_0^3 r_{41} E_{\mathrm{THz}} d_{\mathrm{cry}}$$

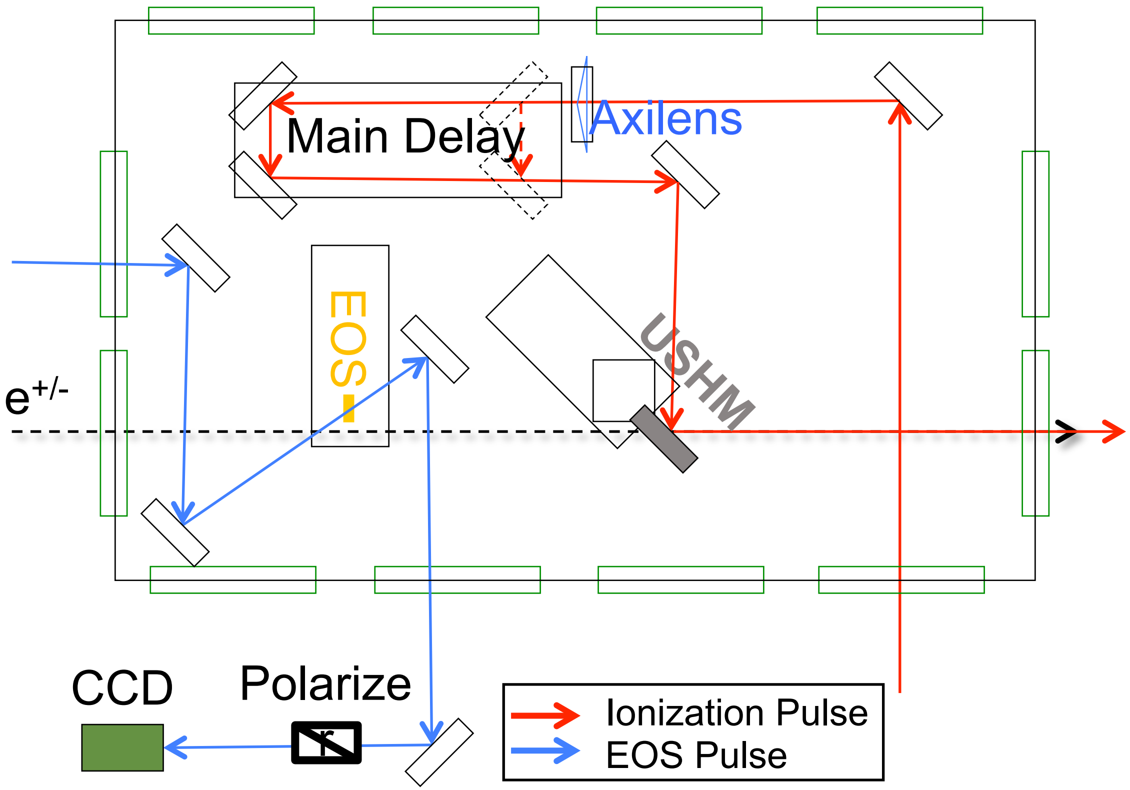
k_0 = laser wavenumber
n_0 = optical index of ref.
r_{41} = EO response func.
E_{THz} = THz (beam) field strength
d_{cry} = thickness of crystal

EOS Setup at FACET 2015-2016 Run



A. L. Cavalieri, PRL (2005)



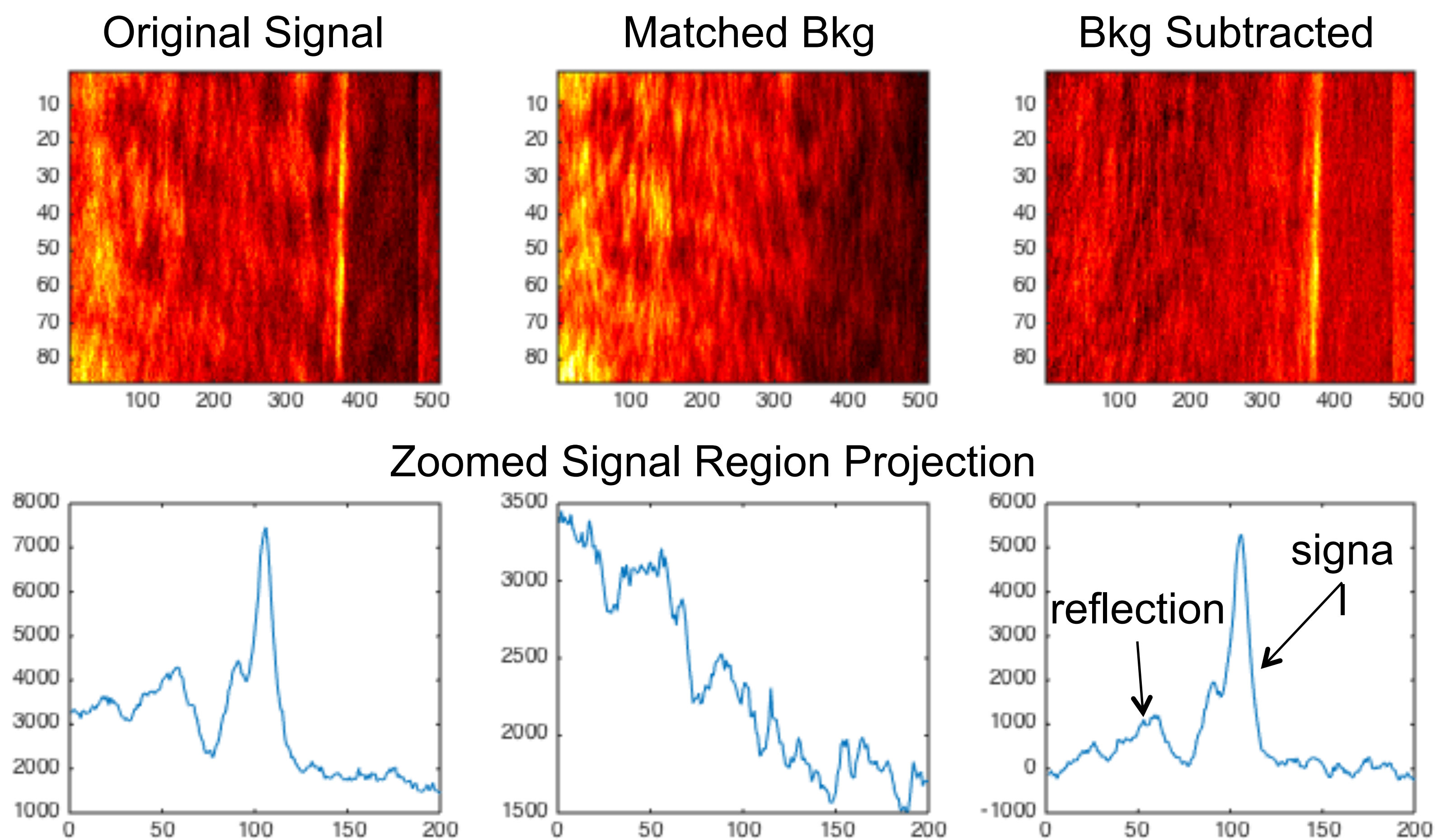


- Large vacuum chamber: “comfortable” setup
- Highly motorized
- Issues:
  - Laser profile
  - Laser jitter
- Excellent results:
  - Laser-beam timing
  - Two-bunch separation
  - Coarse bunch length
- What’s left? Perfection

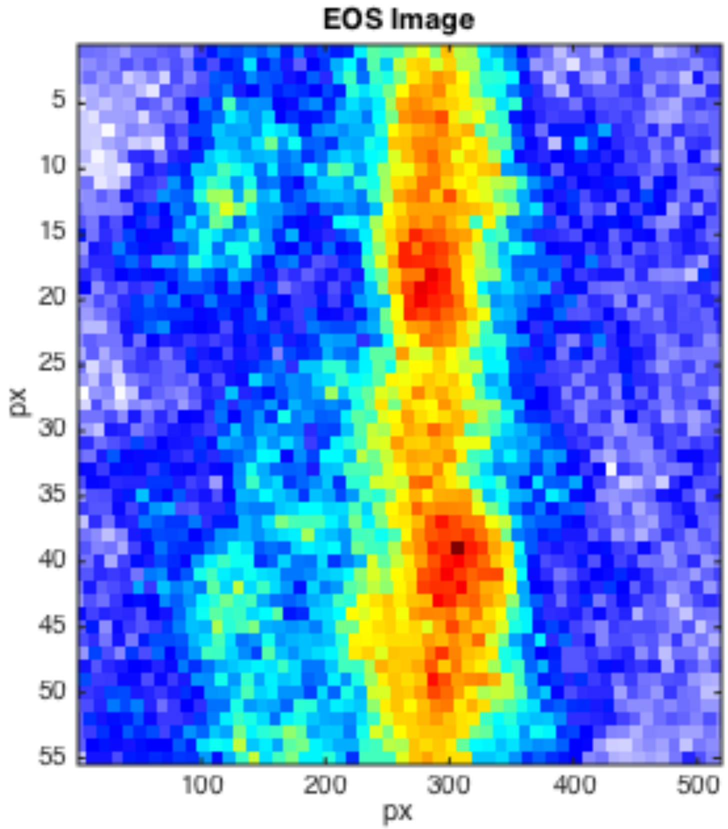
Background Subtraction

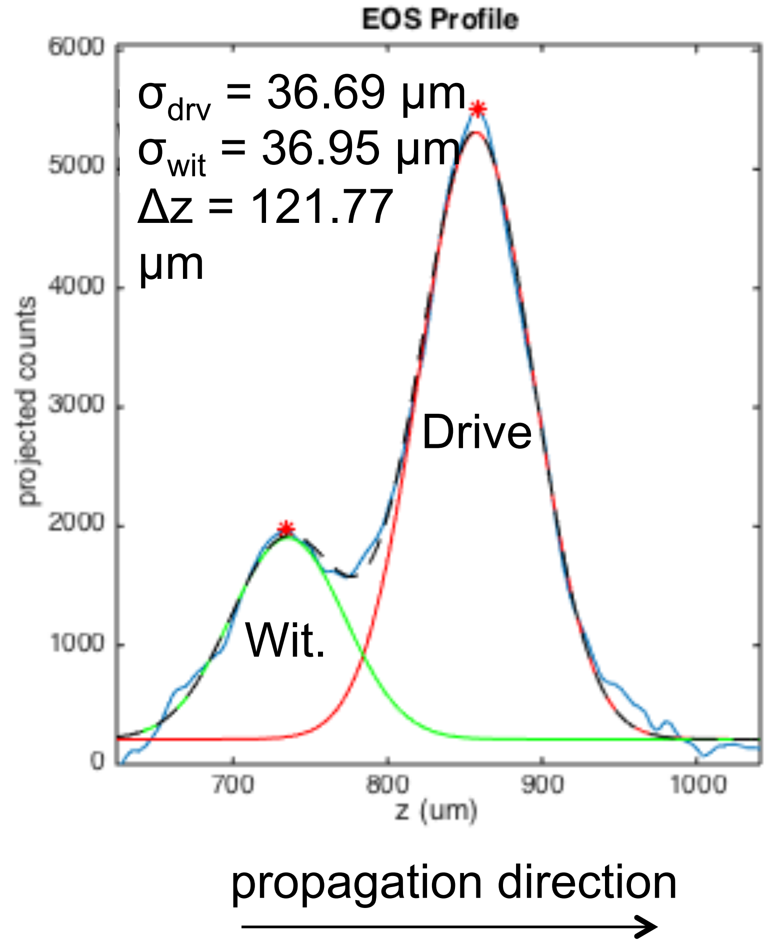
Challenges:

- polarization → low signal-to-background
- jitter → fluctuating background
- profile → lots of structure



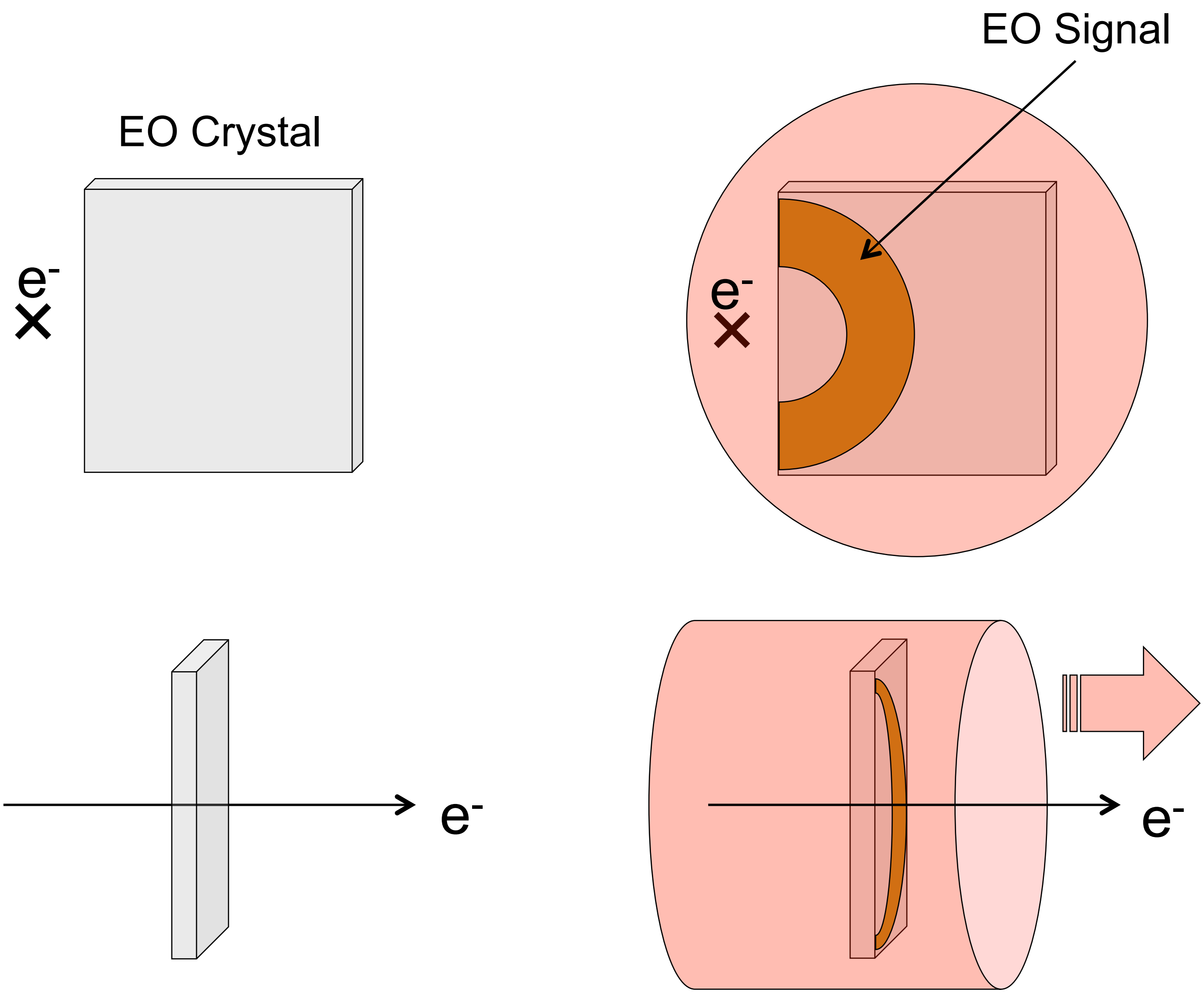
Example Signal from FACET





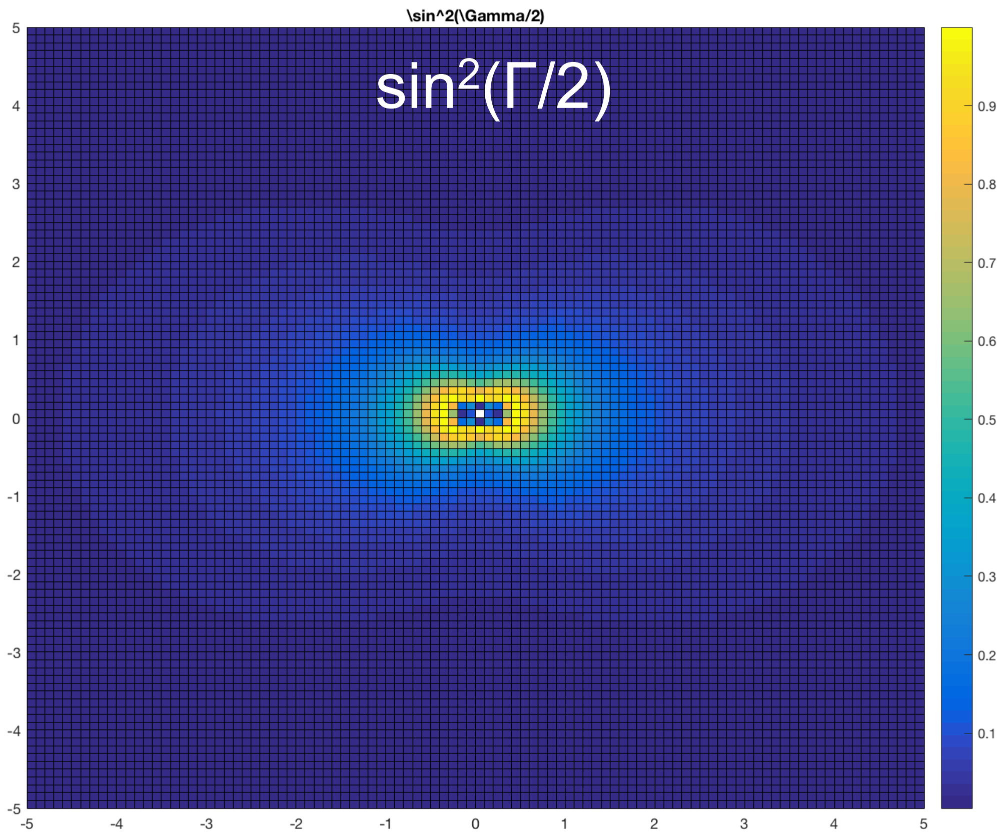
<10 μm resolution for peak-to-peak separation.

Collinear, Long(ish) Pulse

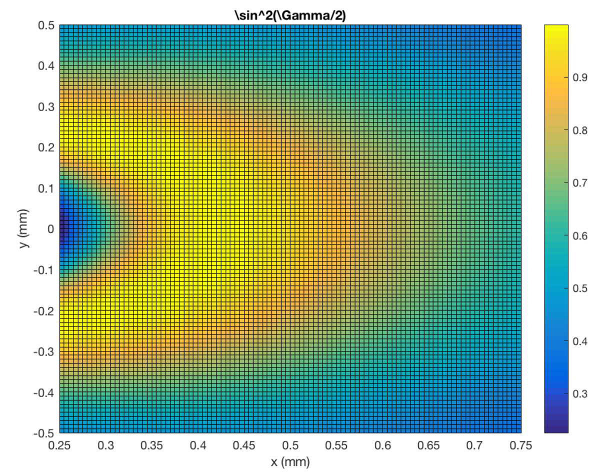


Angular Dependence of EOS Signal

Phase retardation: $\Gamma \propto r^{-1}\sqrt{1 - 3\cos^2\alpha}$

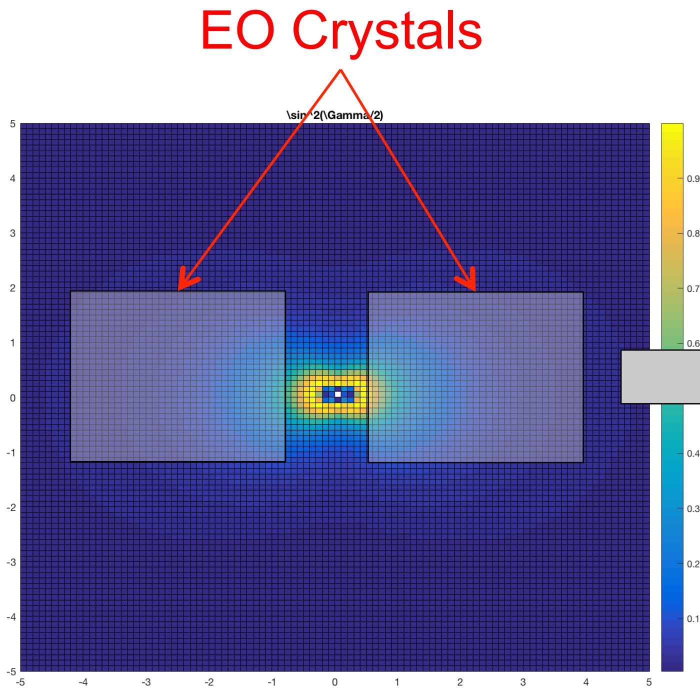


zoomed view

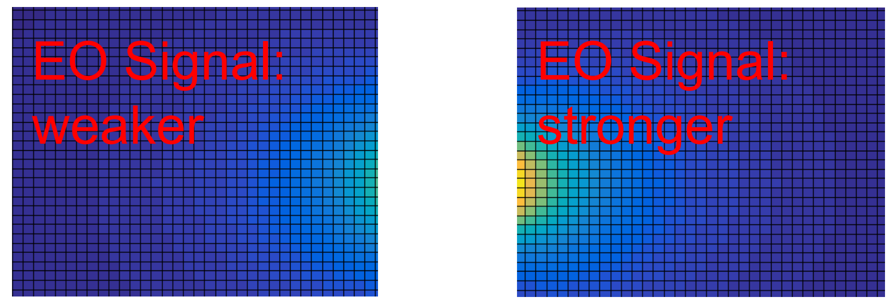


Can we exploit for beam position??

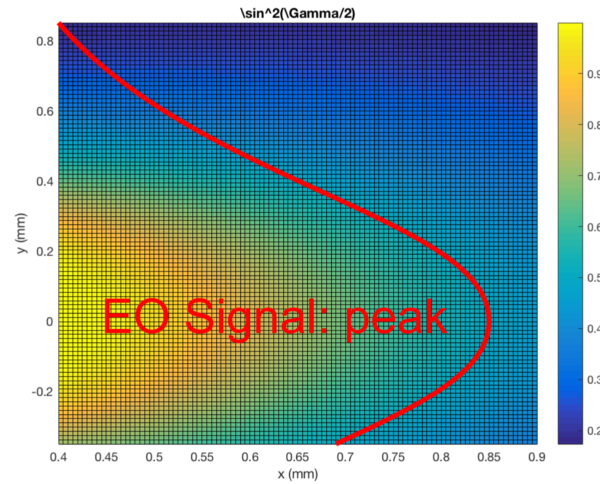
EOS-BPM, Single Bunch



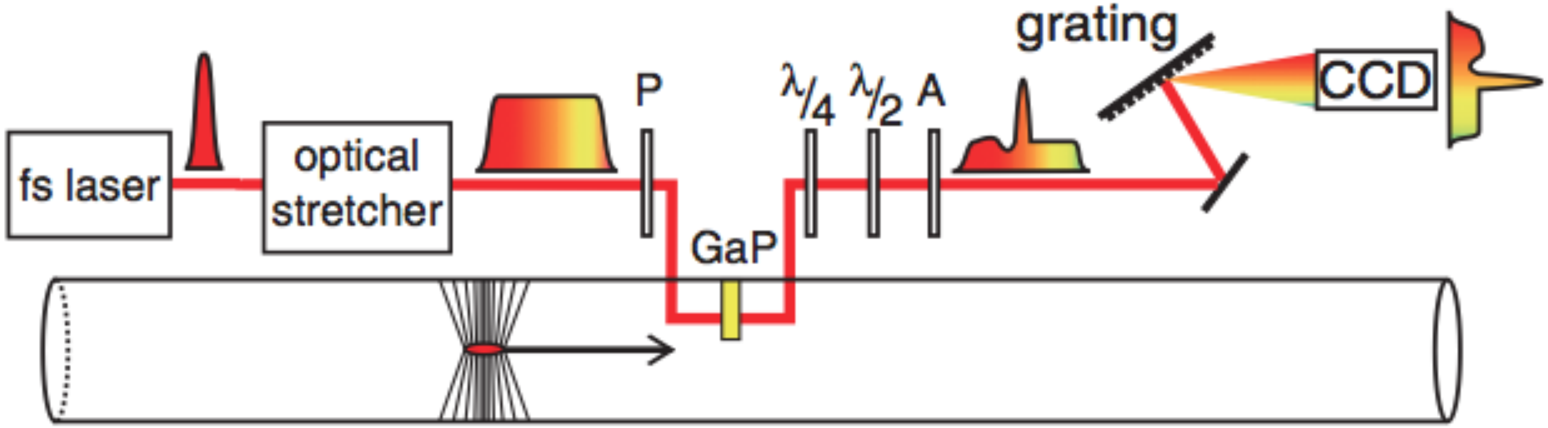
Integrated signal from each crystal: x-position



1-D integral peak from either/ both crystals: y-position



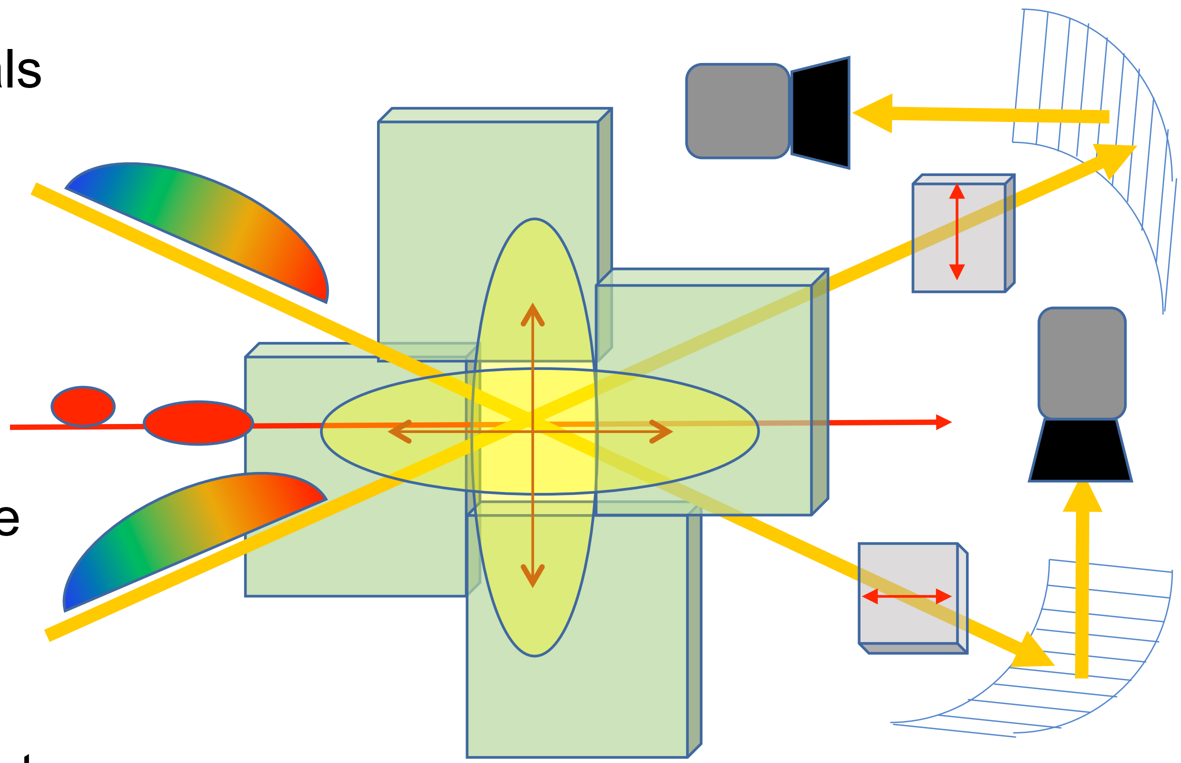
Spectral Encoding



- Collinear, long, chirped laser pulse
- Spectral intensity after polarizer ∝ $\sin^2(\Gamma(t)/2)$
- Imaging spectrometer allows simultaneous spatial **and** spectral decoding!

Single-Shot, 3-D Profiler

- One or two pairs of crystals
- Use chirp for longitudinal profile and to distinguish drive and witness signals
- Use spatial signal to determine position of drive and witness separately
- Imaging spectrometer inherently 1-D spatially, but can use optical fibers to et around that



Maybe two pulses with crossed polarization(?)
Note: vert. and horiz. crystal pairs rotated by 90º w.r.t. each other

EOS Resolution

- 1800 grooves/mm gives ~0.9 nm/mm @ 800 nm
  → 1 mm on chip leaves 1 nm of bandwidth to cover drive and witness bunch
- Drive-witness separation 100-500 μm: up to ~1 ps
- Chirp on laser must be ~5 x 10^{14} Hz/s
- Can fit ~100 fibers into spectrometer slit
  - can use 25 per EO crystal
  - if ~10 μm cross section, and stacked next to each other, could give sufficient resolution
  - or alternate stacking (ala DB25 connector pins)
  - or multiple spectrometers(?)
  - **needs study**

Summary

- For emittance preservation and exit angle control, want drive-witness vac. waist offset <10 μm

- Witness angle not terribly important—except maybe for hosing(??)

- FACET-style EOS can do longitudinal profile with sufficient resolution

- Double (or quadruple) EOS-BPM may be able to resolve drive and witness transverse position **and** longitudinal profile in single shot, non-destructively… **needs further study, but appears feasible**.

Thanks!

SLAC UCLA radiabeam TECHNOLOGIES TECH-X

Don’t like the weather in Boulder?

Thanks!