FNAL Accelerator Physics
& Technology Seminar
September 8th, 2011

Electro-optic sampling for ultra-fast diagnostics at the A0 photoinjector

Tim Maxwell

Motivation

Modern accel's/designs producing extremely compact bunches:

- Photoinjector-based systems
  - Routinely produce electron bunches with σ_t < 3 ps
  - e.g.: FNAL ILC Test Facility
    - σ_t = 1 ps (design)
- X-ray free-electron lasers
  - e.g.: European XFEL @ DESY and LCLS-II @ SLAC
    - σ_t < 100 fs (design)
- Laser-plasma wakefield accelerators
  - High gradient, compact design
  - e.g.: Laser-Wakefield Accelerator @ Lawrence Berkeley Lab
    - σ_t = 50 fs (measured)
      - J. van Tilborg *et al.*, Phys. Rev. Lett. **96**, 014801 (2006).

How does one verify such short bunch lengths…?

Motivation

Sub-picosecond diagnostics:

- Interferometry of coherent beam radiation
  - Sub-ps time resolution
  - Typically multi-shot
  - Loss of phase information (frequency domain measurement)
- Streak camera
  - Resolution limit 100 - 200 fs
- Transverse deflecting mode cavity
  - Transverse kick shears bunch in *x-z* plane, imaged on screen
  - Time resolution 30 fs achieved
  - Inherently destructive
- Single-shot electro-optic sampling
  - Responses of < 50 fs demonstrated
  - Non-interceptive methods also demonstrated

Outline

- Principles of Electro-Optic Spectral Decoding (EOSD)
- Installation details
- Results – Longitudinal diagnostics with CTR
- Potential of Balanced EOSD
- Proposed Application
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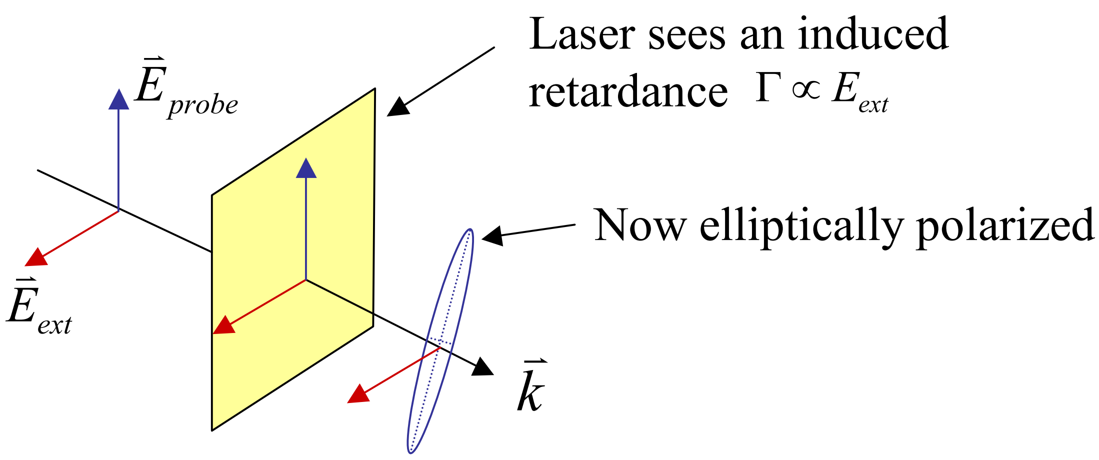
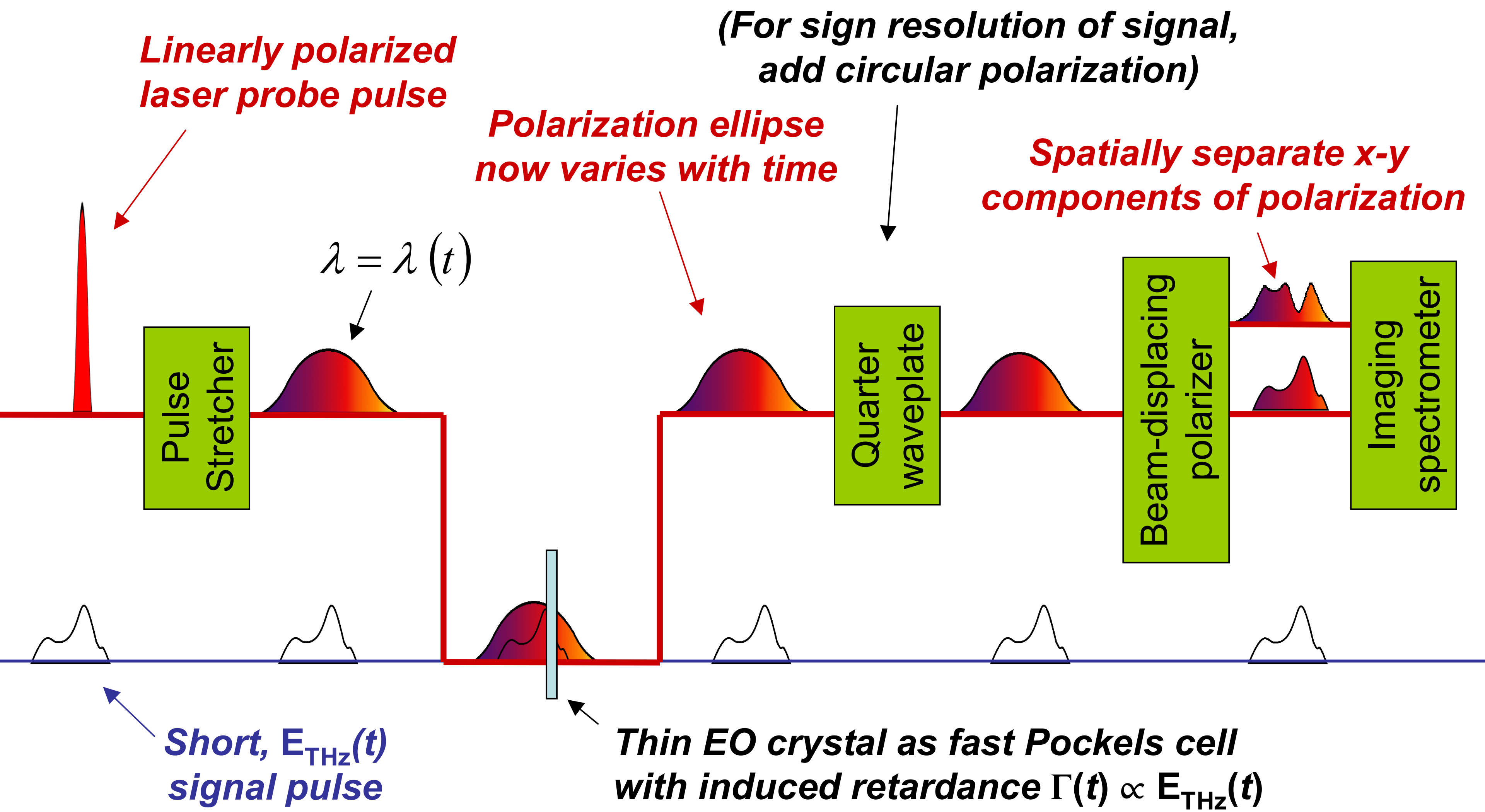
Electro-optic Sampling

- Fast, Pockels-like effect in an electro-optically active crystal



- Thin crystals can “optically switch” on the scale of tens of fs
- Beam diagnostics: Use THz pulse from beam as $E_{ext}(t)$
  - Coherent transition or synchrotron radiation pulse
  - Coulomb fields (ideal)
- Analyze changes in probe laser polarization
- Can decode a full waveform with a single shot…

EO Spectral Decoding



EO Spectral Decoding

Polarization analysis – Jones calculus formalism:

Quarter Wave Plate | EO Crystal | Probe Laser

$$\begin{bmatrix} E'_x(t) \\ E'_y(t) \end{bmatrix} = R(45^\circ)\,WP(\pi/2)\,R(-45^\circ)\,R(45^\circ)\,WP[\Gamma(t)]\,R(-45^\circ)\begin{bmatrix} 1 \\ 0 \end{bmatrix} E_L(t)$$

$$\vec{E}'(t) = \begin{bmatrix} 1 + i\,e^{i\Gamma(t)} \\ 1 - i\,e^{i\Gamma(t)} \end{bmatrix} \frac{E_L(t)}{2}$$

- Final polarizer spatially separates these components

EO Spectral Decoding

- Resulting temporal intensity profiles:

$$\Rightarrow \begin{cases} I'_x(t) = \frac{1}{2}\{1 - \sin[\Gamma(t)]\} I_L(t) \\ I'_y(t) = \frac{1}{2}\{1 + \sin[\Gamma(t)]\} I_L(t) \end{cases}$$

- Note difference of intensities: $I'_y(t) - I'_x(t) = I_L(t)\sin[\Gamma(t)]$
- Without QWP this would have been: $I'_y(t) - I'_x(t) = -I_L(t)\cos[\Gamma(t)]$
  - Even in $\Gamma(t) \Rightarrow$ No sign resolution

EO Spectral Decoding

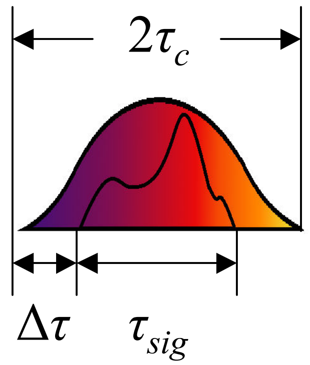
- Spectral decoding:
  - Chirped laser pulse so λ = [Linear function of t] = $\lambda_{inst}(t)$
  - Approximation: temporal modulation = spectral modulation
    - Improper treatment of spectrometer. We'll come back to this.
  - Map measured $\lambda \rightarrow t$, so that

$$I'_y[\lambda(t)] - I'_x[\lambda(t)] = I_L(t)\sin[\Gamma(t)]$$

- Approximation $\Rightarrow$ temporal resolution $\tau_{res} = (\tau_c\,\tau_0)^{1/2}$

Challenges

- EOSD "time window" for measurement $\sim 2\tau_c$
  - Minimize for optimum $\tau_{res} = (\tau_c\, \tau_0)^{1/2}$
  - Lower limit set by:
    - τ_{sig} = Duration of signal measured
    - $\Delta\tau$ = Temporal jitter between sig. and probe



Practical problems:

- Timing:
  - Way to find probe/signal overlap
    - 1 ps events @ 1 per second = 10^{-12} blind odds
  - Phase locking to minimize $\Delta\tau$
- Optics:
  - Chirped laser pulse, gated to signal rep. rate
  - Longitudinal laser phase diagnostics for $\lambda \rightarrow t$ map

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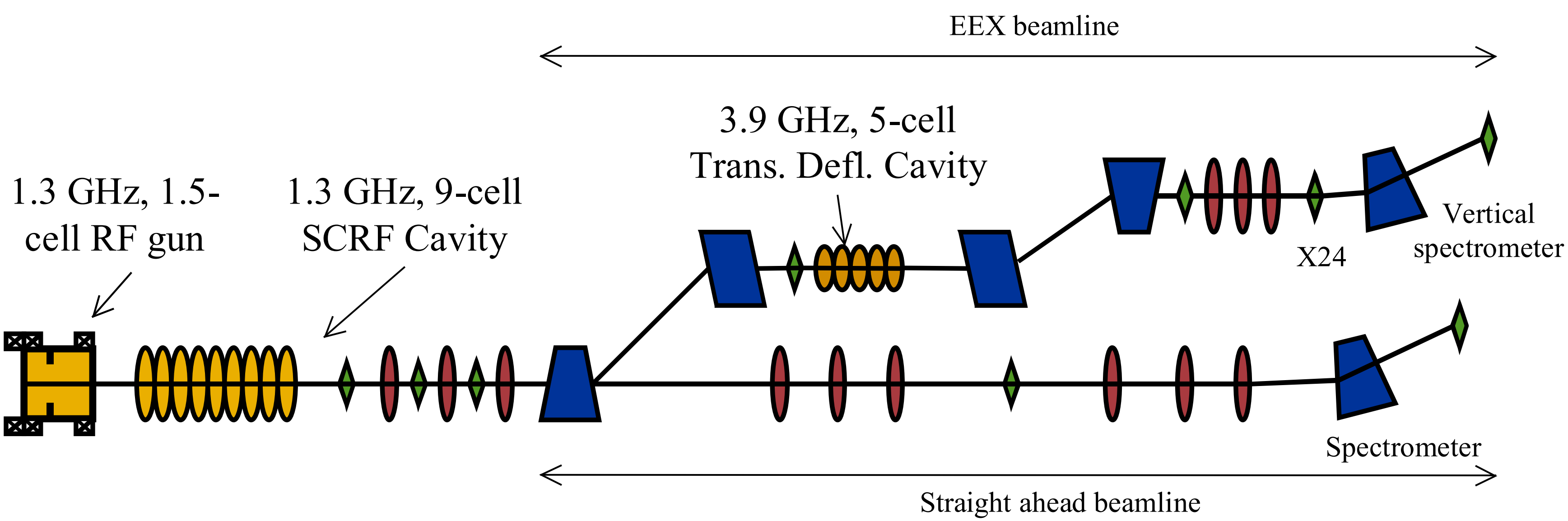
A0 Photoinjector



Beam Paramters:

- **16 MeV** electron linac
- Q_{max} = **1 nC**
- **1 Hz** macro pulse rep. rate comprised of 1 MHz bunch train
- σ_t **< 2 ps** fwhm typical after Emittance Exchange (EEX) line

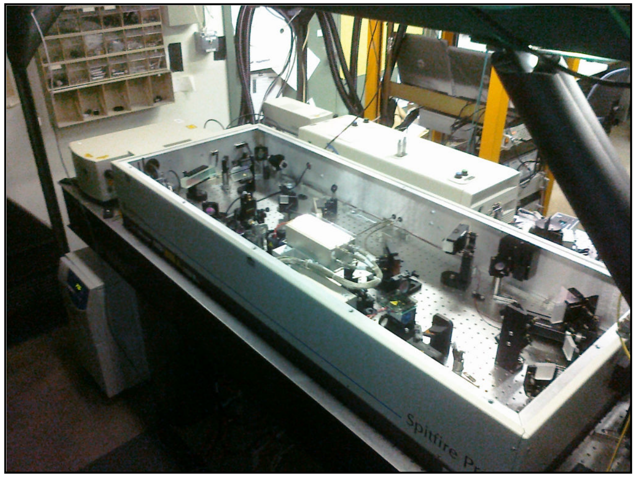
Probe Laser

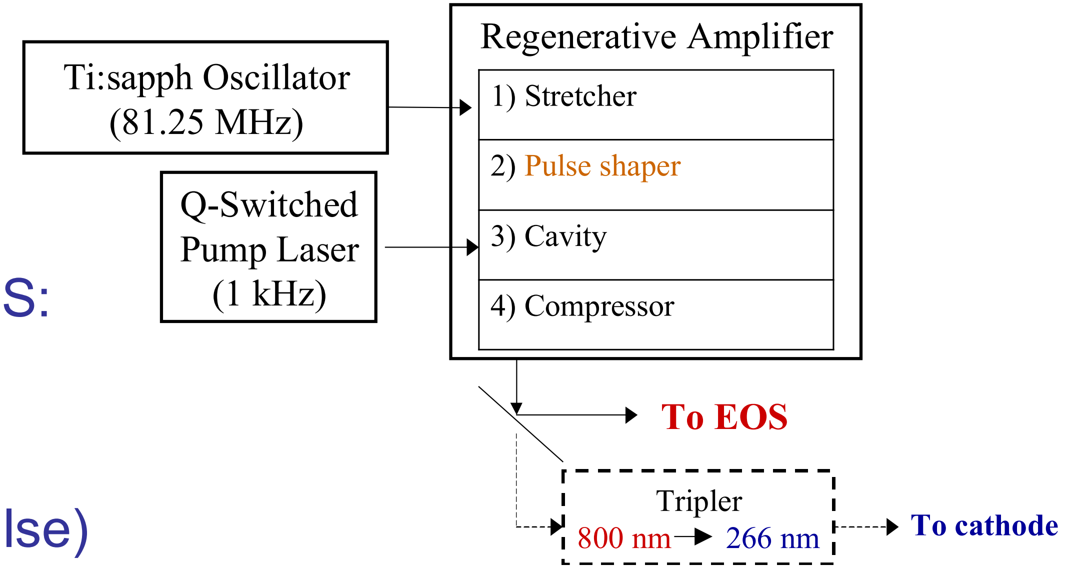
- Relocated from NIU for EOS and ellipsoidal bunch generation expt's
- Ti:Sapph system by Spectra-Physics
  - *Tsunami* seed laser
  - *Spitfire Pro XP* regen amplifier

    λ_0 = 800 nm

    τ_0 = 100 fs (fwhm)

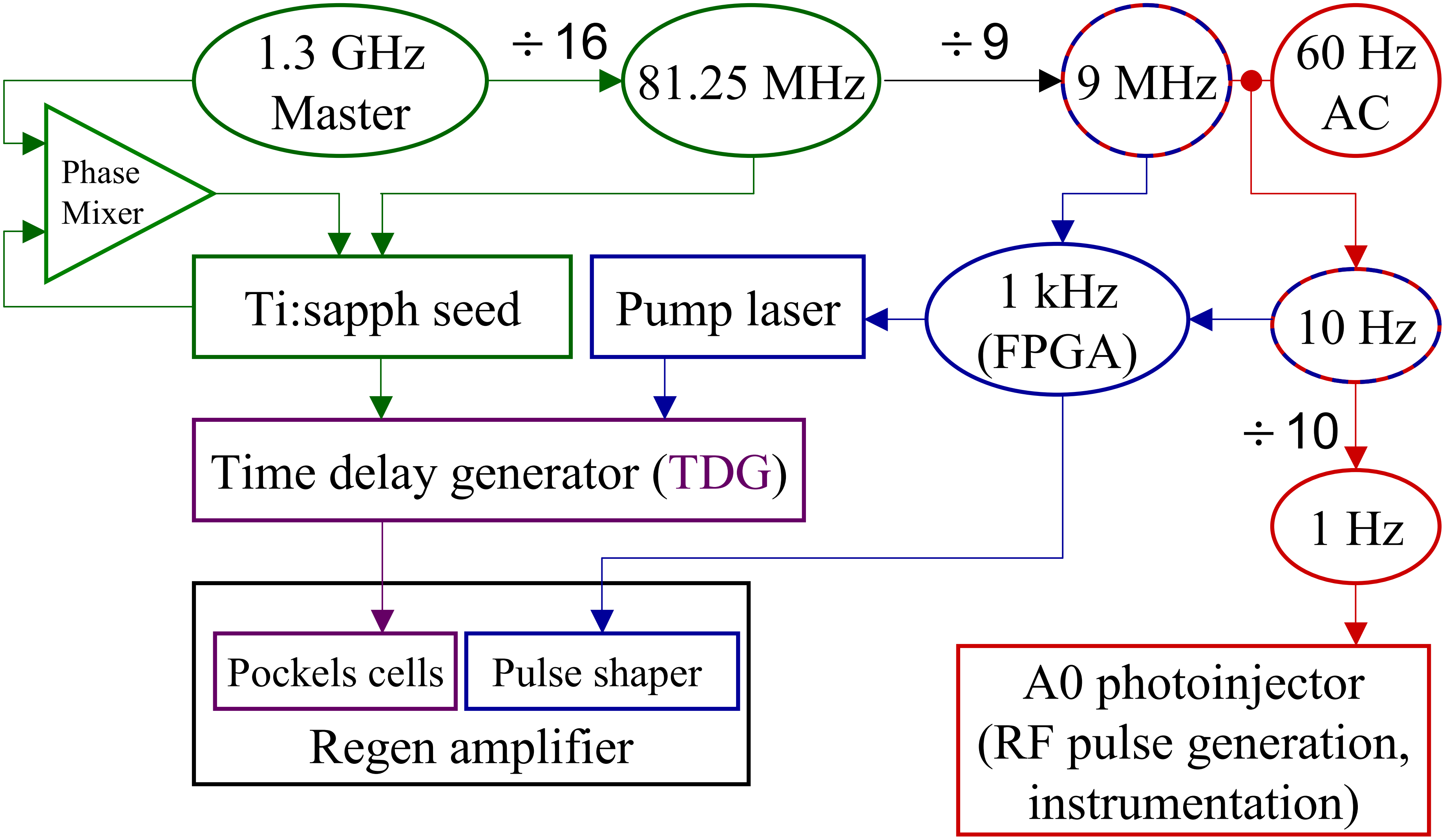
    3 mJ/pulse @ 1 kHz



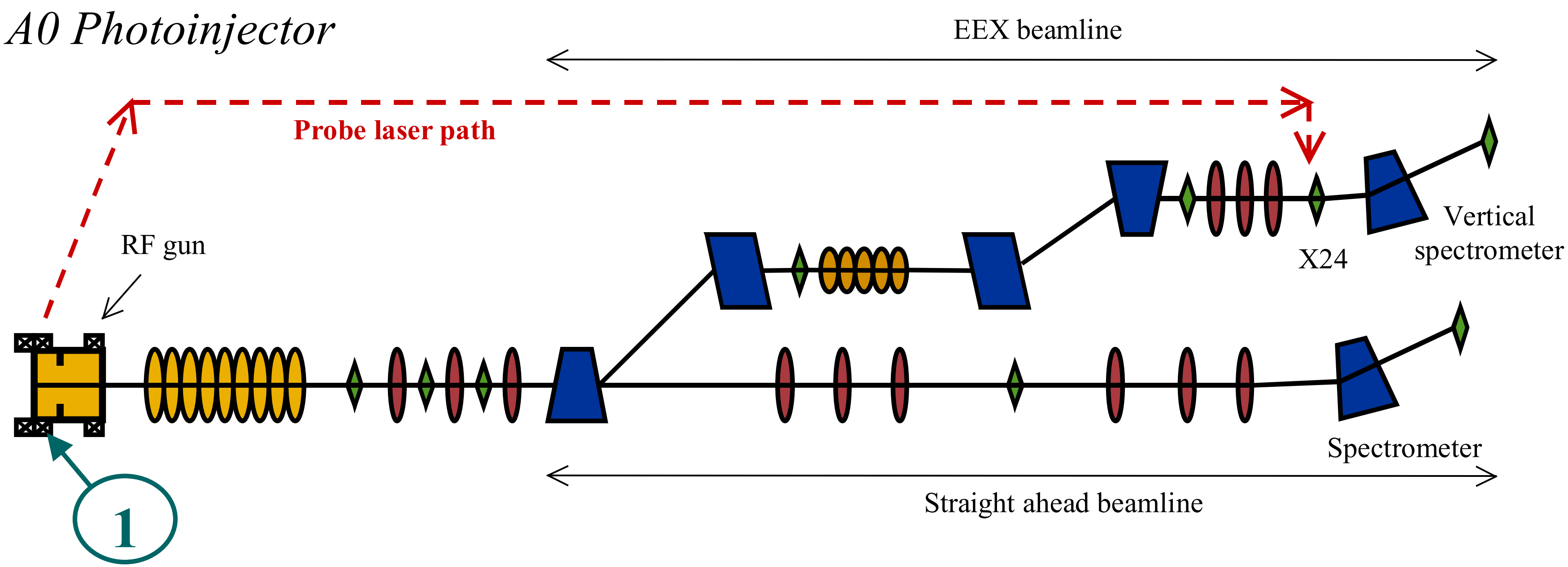


- Amplified output used for EOS:
  - Pulse length control
  - 1 Hz gated output
  - (Attenuated to < 20 nJ/pulse)

Syncing Ti:Sapph to A0PI

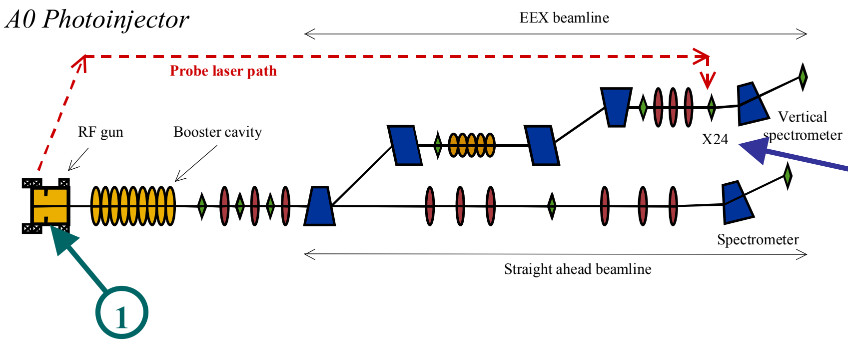


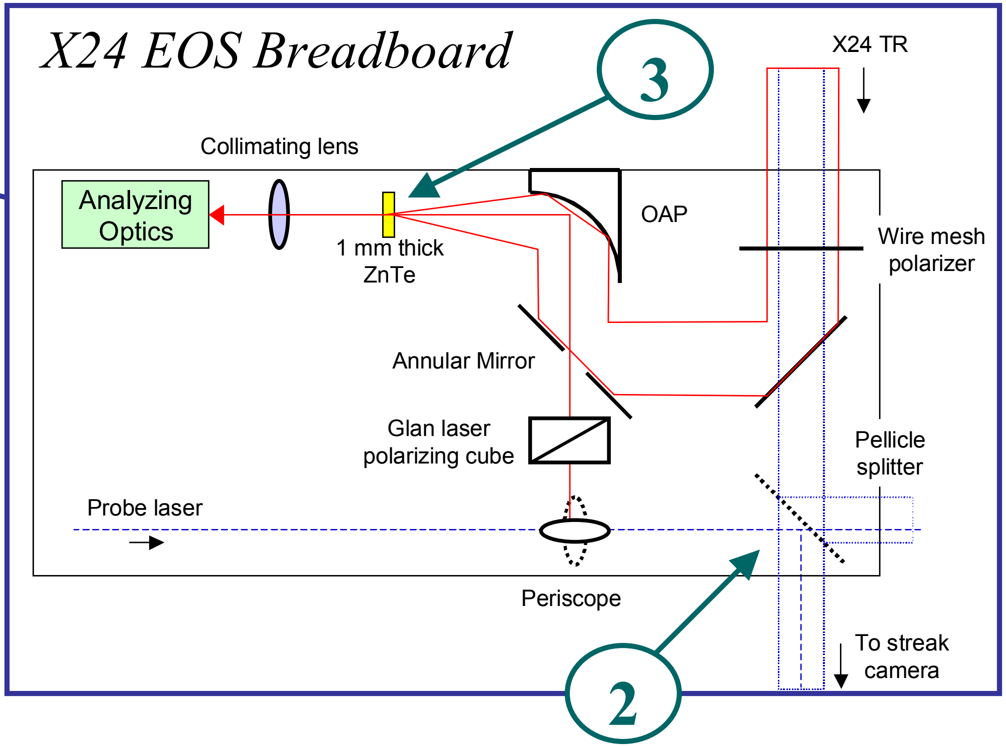
Time of Arrival Matching



1) **UV drive laser + IR probe on photodiode at photocathode (ns-scale).**
Adjust for 3.5 ns path difference (beam path vs. probe path from gun to X24).

Time of Arrival Matching

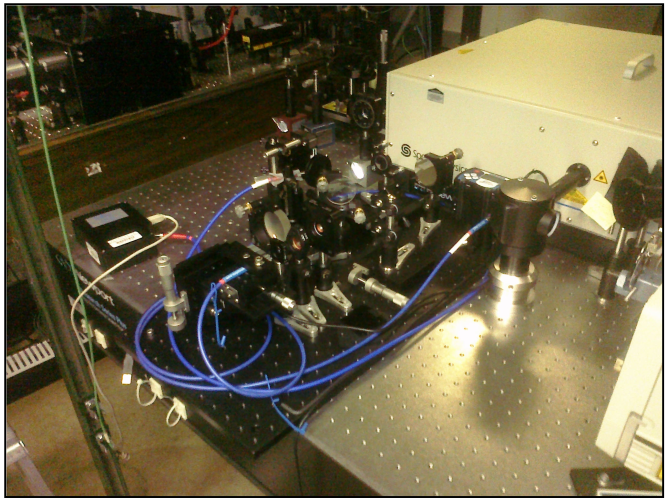


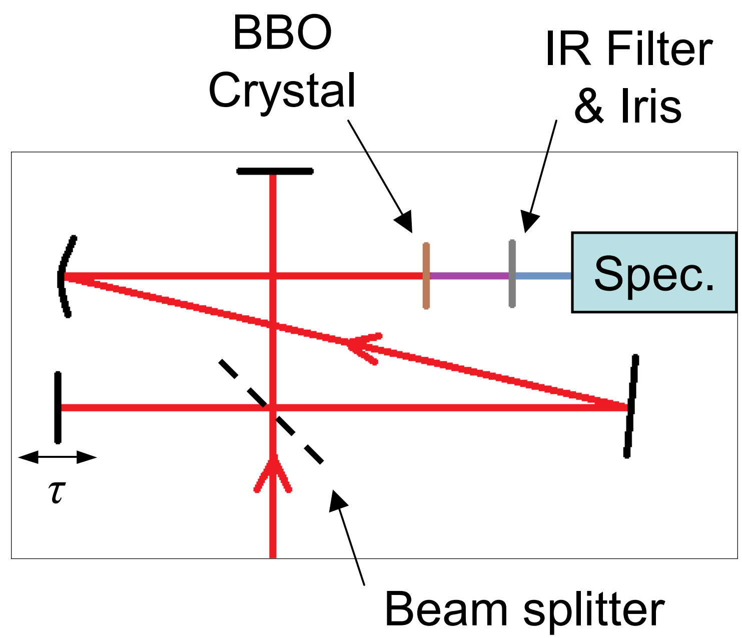


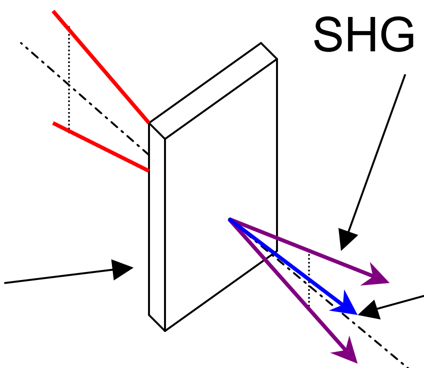
1) UV drive laser + IR probe on photodiode at photocathode (ns-scale).
Adjust for 3.5 ns path difference (beam path vs. probe path from gun to X24).
2) IR leakage + OTR sent to streak camera (tens of ps-scale).
Adjust for 260 ps path difference (TR path vs. probe path from pellicle to crystal).
3) Monitor EOS and scan ~20 ps range to find signal.
Laser phase feedback is enabled to maintain 1 ps FWHM lock.

Laser phase reconstruction

Frequency-Resolved Optical Gating





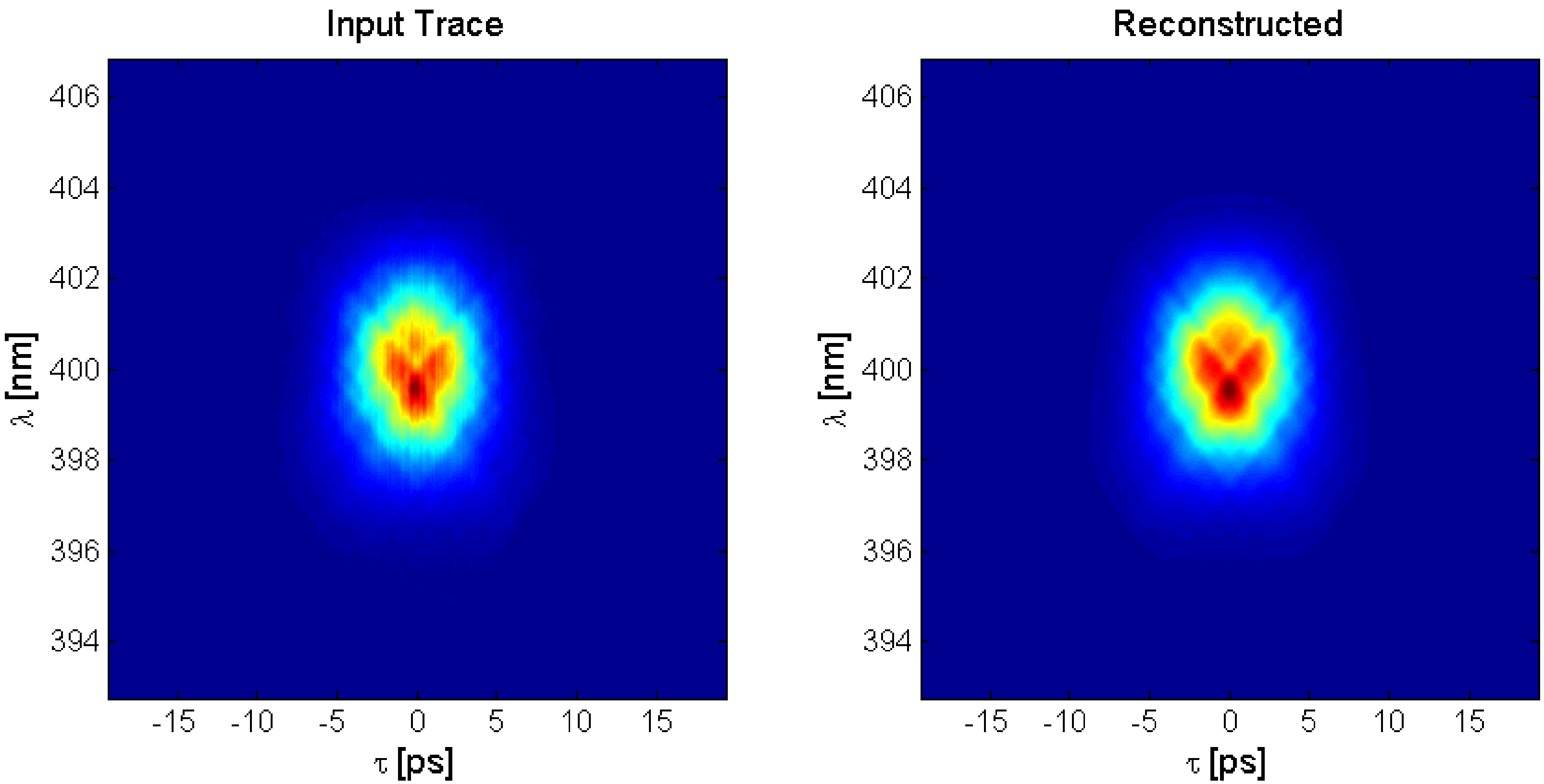


Sum-frequency generation of crossed beams:
The "SHG" FROG signal

$$I_{FROG}(\omega,\tau) = \left| \int \widetilde{E}(\omega')\widetilde{E}(\omega-\omega')e^{i\omega'\tau}d\omega' \right|^2$$

Laser phase reconstruction

- Iterative algorithm (FROG 3.2.2 by Femtosoft Tech.) reconstructs matching trace with corresponding longitudinal phase space



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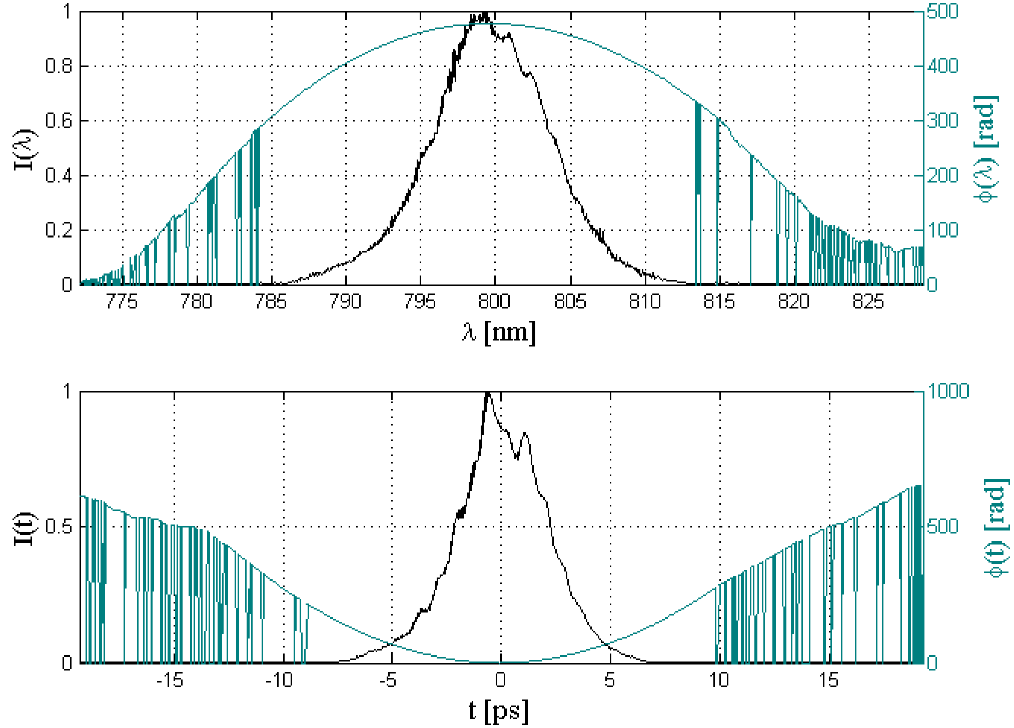

Compute $\lambda_{inst}(t)$ for map:

$$\lambda_{inst}(t) = \frac{2\pi c}{\omega_{inst}(t)} = \frac{2\pi c}{d\phi(t)/dt}$$

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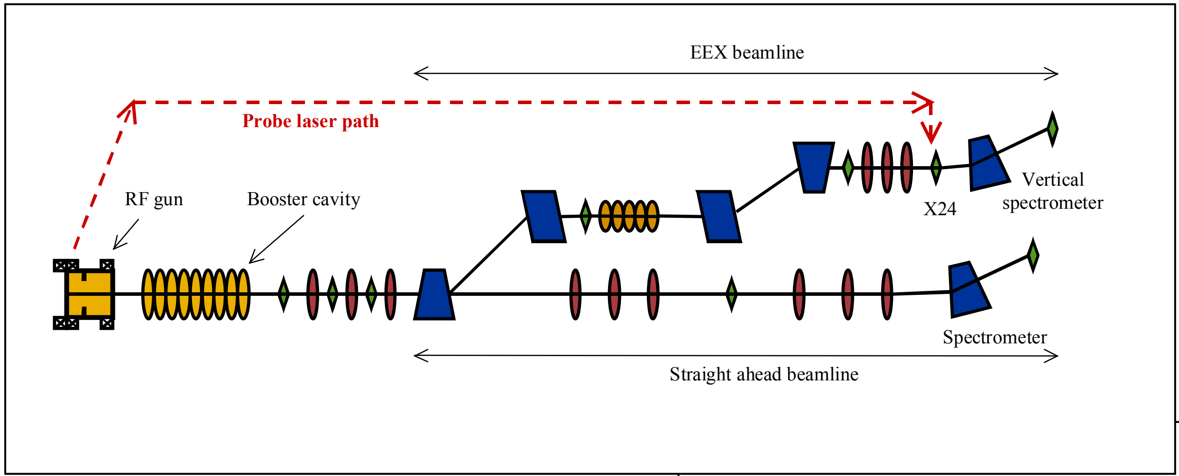
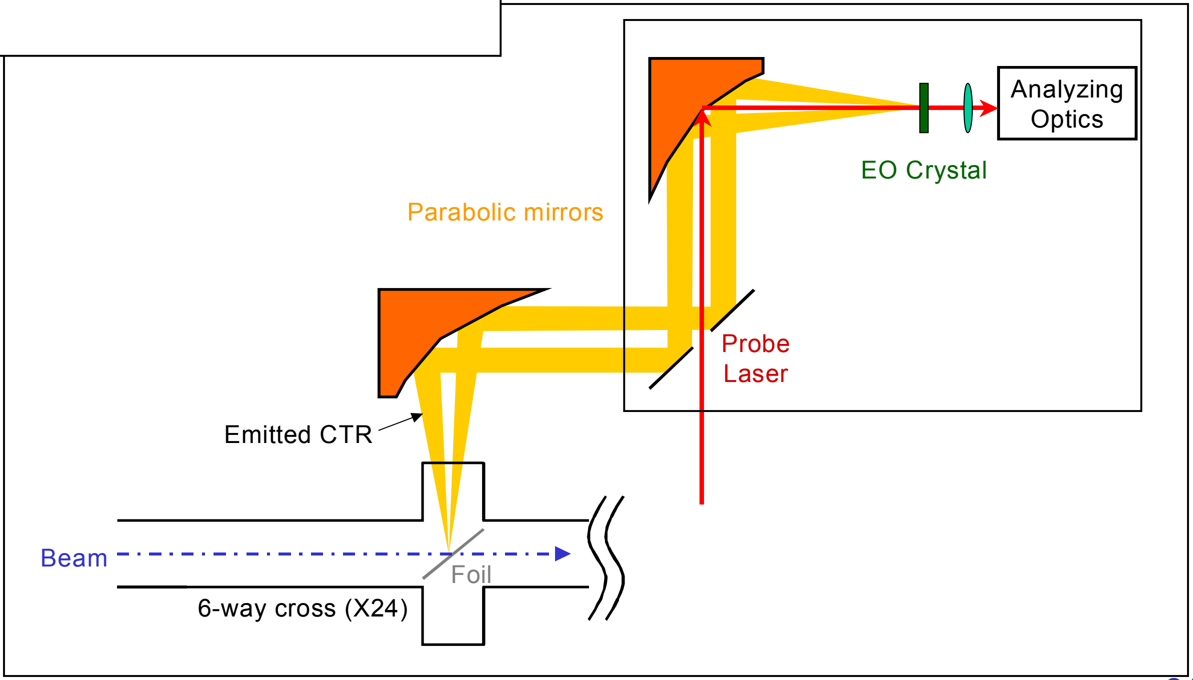
CTR Measurements



Bunches:
- 250 pC
- 14.3 MeV

Coherent Transition Radiation (CTR) imaged to crystal

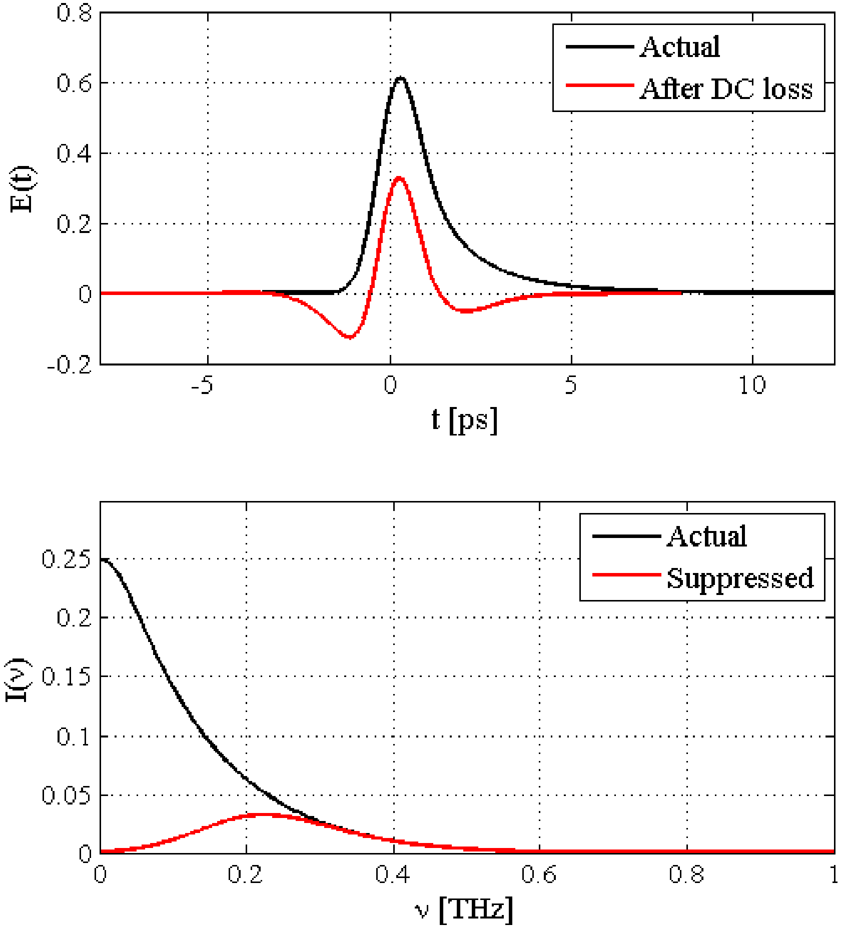


Laser pulse used:
- $\tau_c = 4.4$ ps
- $\tau_0 = 0.1$ ps
- $\tau_{res} = 0.66$ ps (fwhm)

CTR Measurements

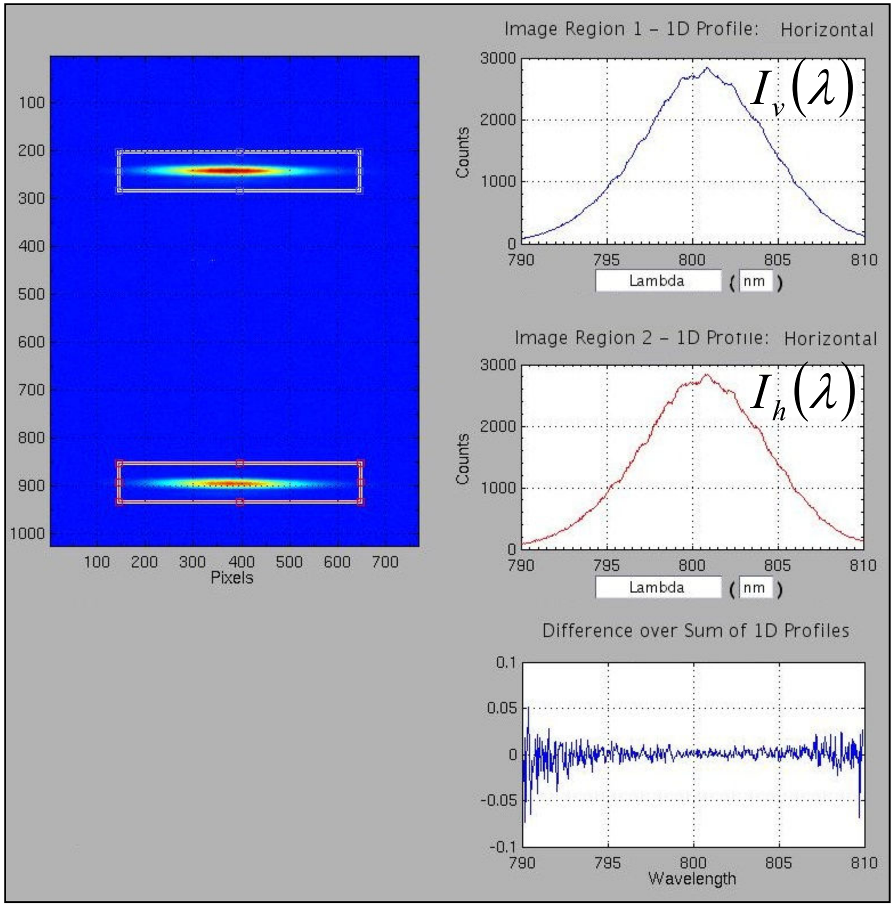
- Ideally: $E_{THz}(t) \propto \rho_z(t)$, but not so:
  - Low-f part of spectrum optically attenuated
  - Diffraction of large (> mm) waves prevents imaging
  - AC-coupled behavior

Simulated example

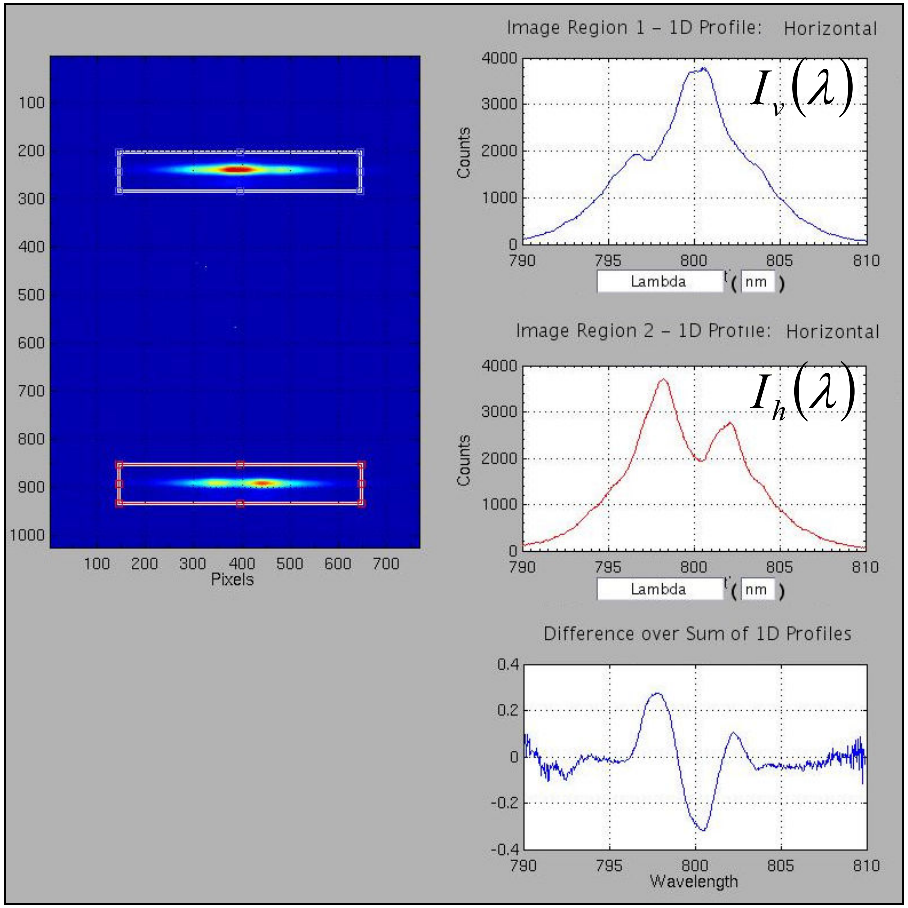


Online Images

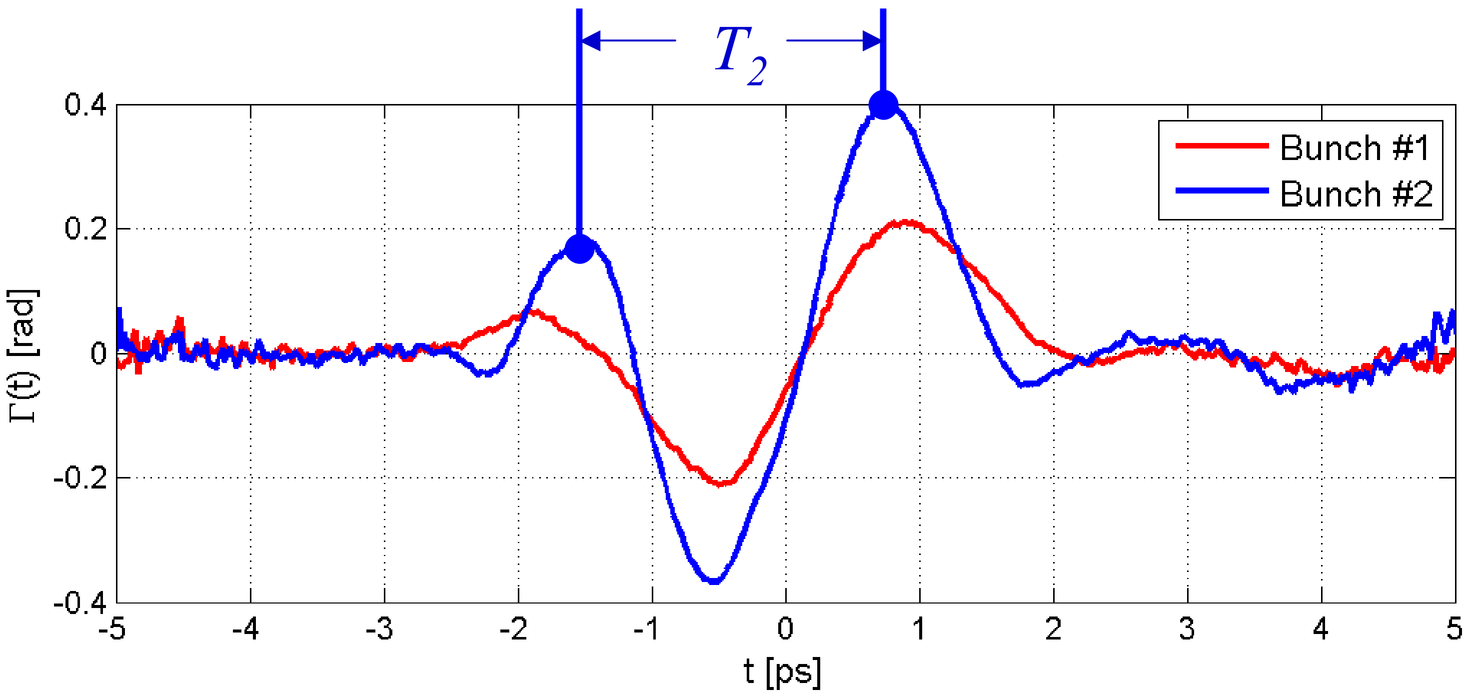
No crystal (Circularly polarized light)



Crystal in, signal applied (modulation)



Decoded Signals



Est. FWHM as half period of strongest cycle: $\Delta t_n = \frac{1}{2} T_n$

$\mathbf{\Delta t_1 = 1.44\ ps}$

$\mathbf{\Delta t_2 = 1.14\ ps}$

Comparison to Interferometry

- CTR can be alternatively sent to Martin-Puplett interferometer
  - [R. Thurman-Keup *et al,* Proc. BIW 2008, 153-157 (2008).]

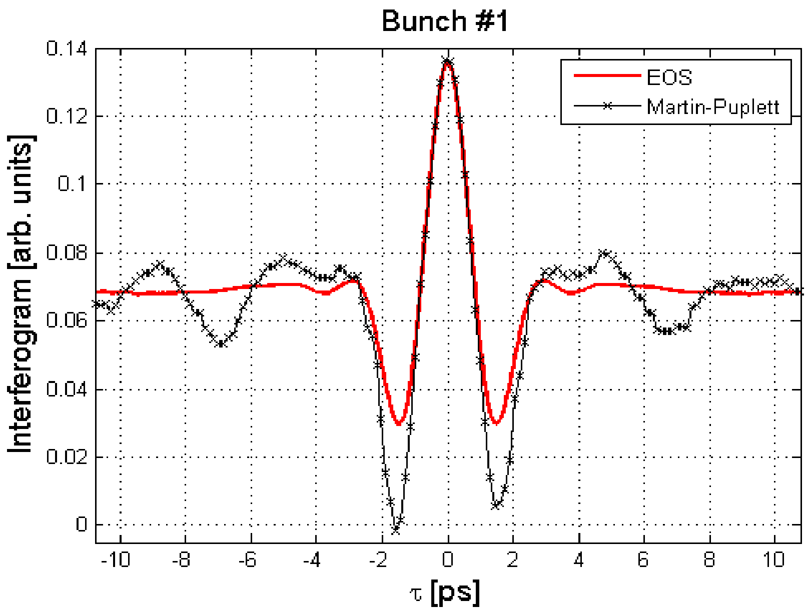
- Measures interferogram of same $E_{CTR}(t)$:

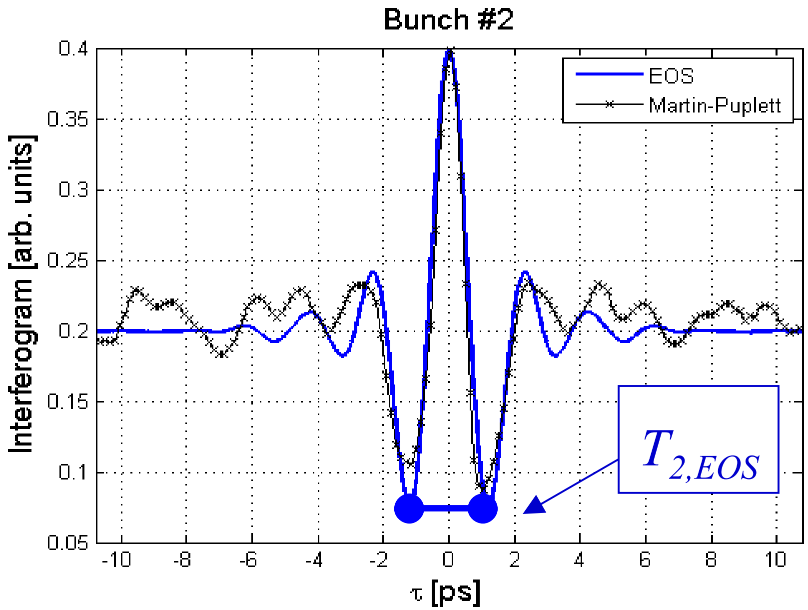
$$IF_{MP}(\tau) \propto \int \left| E_{CTR}(t) + E_{CTR}(t-\tau) \right|^2 dt$$

- If $\Gamma(t) \propto E_{CTR}(t)$, interferogram EOS signal should match:

$$IF_{EOS}(\tau) \propto \int \left| \Gamma(t) + \Gamma(t-\tau) \right|^2 dt$$

Comparison to Interferometry





½T [ps]	#1	#2
EOS	1.48	1.21
Martin-Puplett	1.50	1.17

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Balanced Decoding

- Back to theory… after polarizing splitter we had [w/ $E(t)$ = $E_{Laser}(t)$]:

$$E'_{x/y}(t) = \frac{1}{2}\left[1 \pm i\, e^{i\Gamma(t)}\right] E(t)$$

- Spectrometer actually resolves |Fourier transform|²
- Introduce:

$$E_{ret}(\omega) \equiv \frac{1}{\sqrt{2\pi}} \int E(t)\, e^{i\Gamma(t)} e^{i\omega t}\, dt$$

- $E_{ret}(\omega)$ is spec. of laser pulse after additional *t*-dep. phase retardation
  - When $\Gamma(t) = 0 \Rightarrow E_{ret}(\omega) = E(\omega)$

$$\Rightarrow \quad E'_{x/y}(\omega) = \frac{1}{2}\left[E(\omega) \pm i\, E_{ret}(\omega)\right]$$

Balanced Decoding

- Resulting intensities (interference pattern):

$$I'_{x/y}(\omega) = \frac{1}{4}\left\{\left|E(\omega)\right|^2 + \left|E_{ret}(\omega)\right|^2 \pm 2\,\mathrm{Im}\left[E(\omega)E^*_{ret}(\omega)\right]\right\}$$

- In absence of signal, just circ. pol:

$$I'_{0,x/y}(\omega) = \frac{1}{2}\left|E(\omega)\right|^2$$

- With $I'_x(\omega)$, $I'_y(\omega)$ and $I'_0(\omega)$ can get phase and amp of $E_{ret}(\omega)$
  - Can in principle IFT $E_{ret}(\omega)$, reconstruct $\Gamma(t)$
  - No approximations made (though phase matching still ignored…)
    - In principle lift τ_{res} from approximation
    - Temporal res. now driven by spect. res. and laser bandwidth (100fs)
- Inversion of real signal not yet achieved
  - (an effect is still observable…)

Balanced Decoding

- Balanced scheme:

$$I'_x(\omega) - I'_y(\omega) = \mathrm{Im}\left[E(\omega)E^*_{ret}(\omega)\right]$$

- Historically EOSD done using only [one pol. – unmodulated signal]:

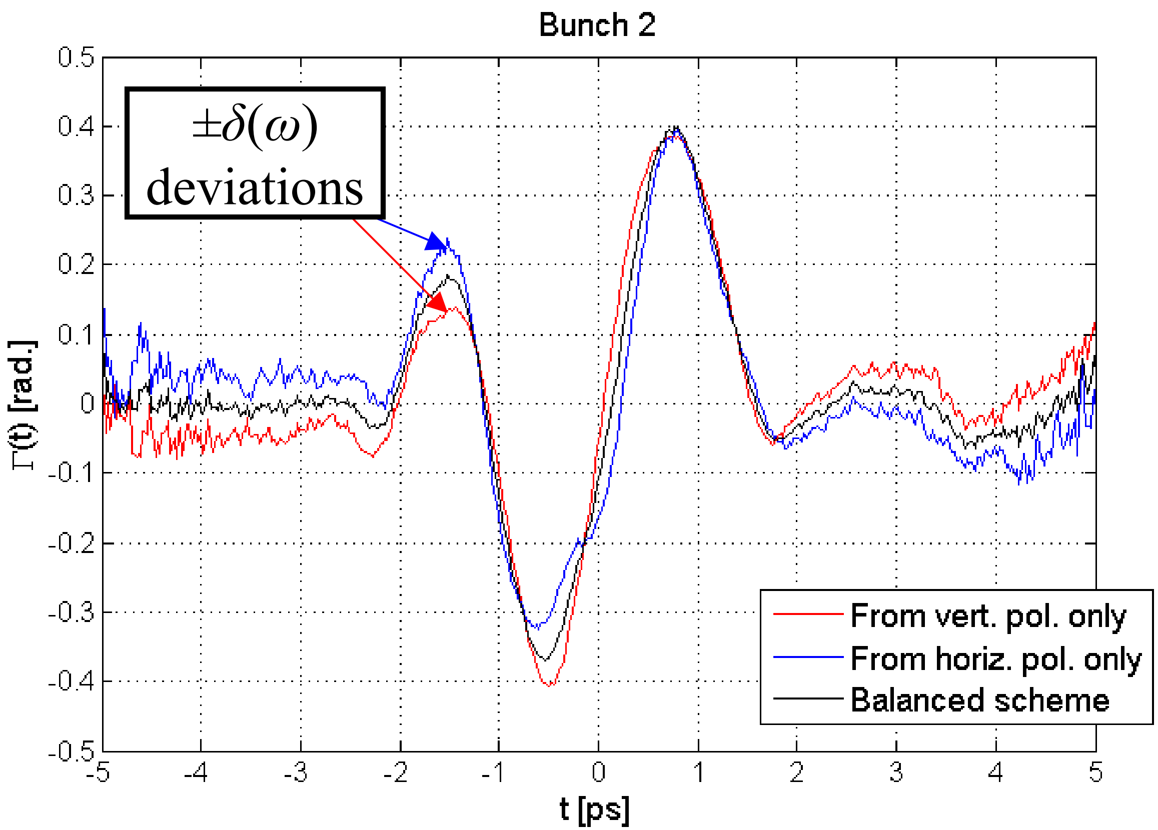
$$I'_x(\omega) - I'_{0,x}(\omega) = \mathrm{Im}\left[E(\omega)E^*_{ret}(\omega)\right] \quad + \frac{1}{2}\left[\left|E_{ret}(\omega)\right|^2 - \left|E(\omega)\right|^2\right]$$

$$-\left[I'_y(\omega) - I'_{0,y}(\omega)\right] = \mathrm{Im}\left[E(\omega)E^*_{ret}(\omega)\right] \quad - \frac{1}{2}\left[\left|E_{ret}(\omega)\right|^2 - \left|E(\omega)\right|^2\right]$$

Balanced Decoding

Observation of relative distortion of differently recovered signals under EOSD approximation

$$\delta(\omega) = \frac{1}{2}\left[\frac{|E_{ret}(\omega)|^2 - |E(\omega)|^2}{|E(\omega)|^2}\right]$$



EOSD Reconstruction

- Approximate numerical inversion studied by B. Yellampalle *et al* [Appl. Phys. Lett. **87**, 211109 (2005).]
  - Numerical artifacts with real data [K. Y. Kim *et al*, Appl. Phys. Lett. **88**, 041123 (2006).]
  - Neglects $\delta(\omega)$ contribution

- Continuing investigation including
  - Analytical reconstruction utilizing balanced approach
  - Phase mismatch in crystal (dispersion effects)
  - Polarization effects

- Comparison against interferometric measurements

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- **Principles of Electro-Optic Spectral Decoding (EOSD)**
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- **Higher order effects in EOSD**
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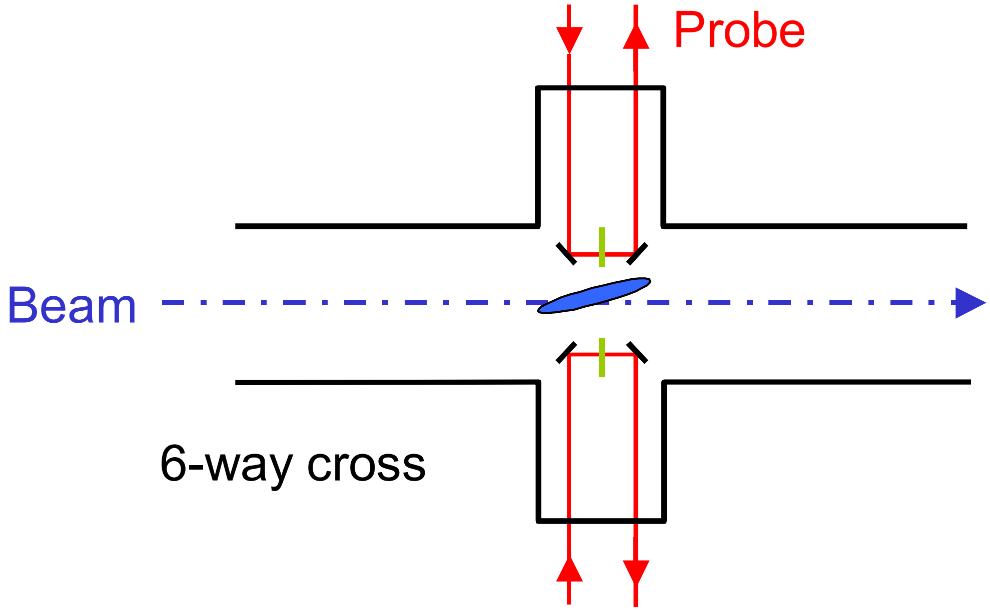
Spatio-temporal correlation monitor

- Simultaneously probe Coulomb field of bunch on two sides, in pipe

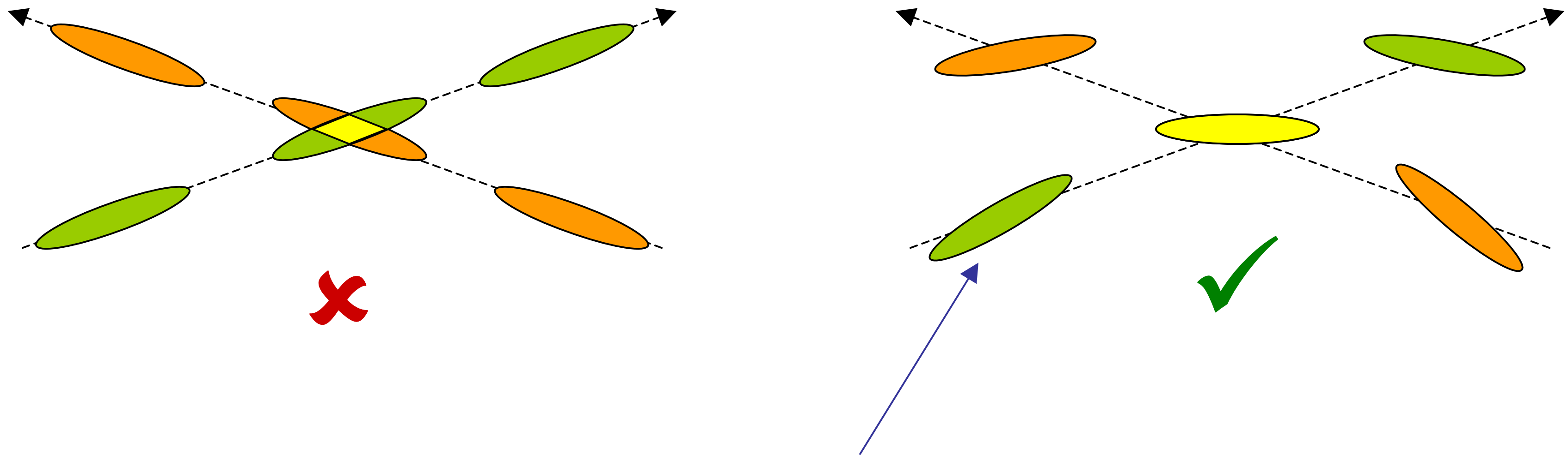


- Signals appear as $\rho_z(t)$ with relative modulation related to $<x(t)>$
- Proof of principle using EOS polarization sensitivity demonstrated at FLASH using just one crystal/probe
  - [B. Steffen *et al*, Phys. Rev, ST-AB **12**, 032802 (2009).]

Spatio-temporal correlation

Linear Collider

To maximize instantaneous luminosity at non-zero crossing angles, tilted beams are desired at the point of collision to offset angle



"Crabbing" the bunch through the crossing concentrates the collision over the shortest duration

Summary

- EOSD diagnostics have been installed at A0PI including
  - Installation and synchronization of a Ti:Sapph laser system
  - Full longitudinal laser phase diagnostics
  - Procedures for probe-signal matching
- Recovered CTR transients resolve structure on the order of 1 ps
- Direct comparison to independent measurements in good agreement
- Additional information recovered by balanced detection suggests a rigorous analytical reconstruction is possible for EOSD
- With continuing effort in electro-optic sampling, extension to time-resolved 2D charge distribution monitoring of short bunches can be realized

Thank you.

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