Budker Seminar

Optical beam position monitor for sub-picosecond spatio-temporal correlation monitoring

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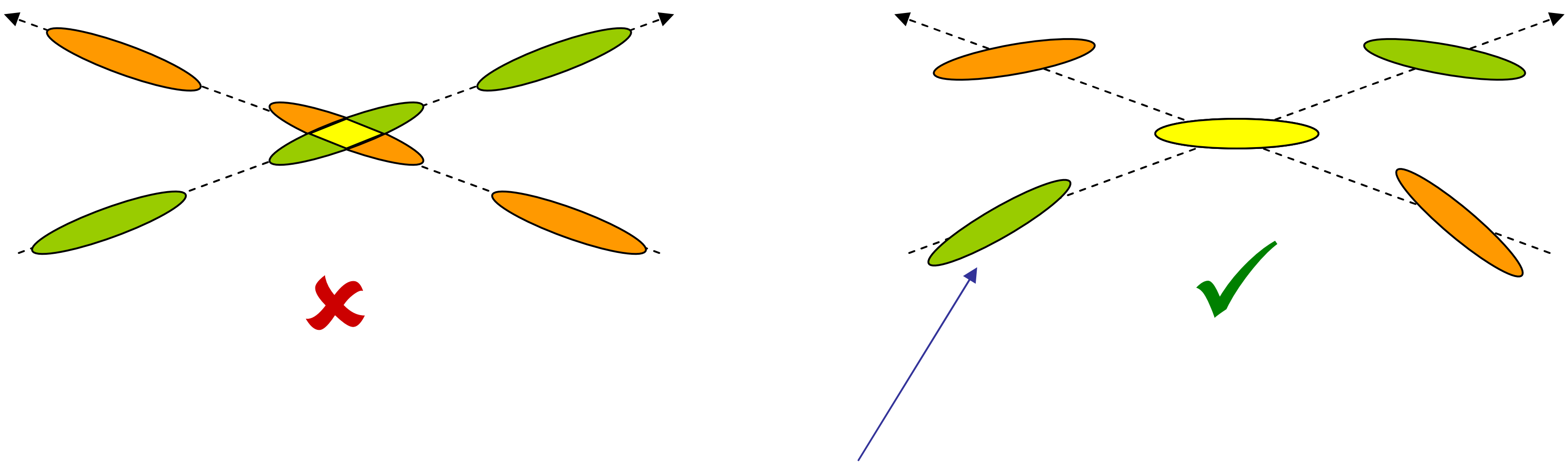
Motivation

Linear Collider

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

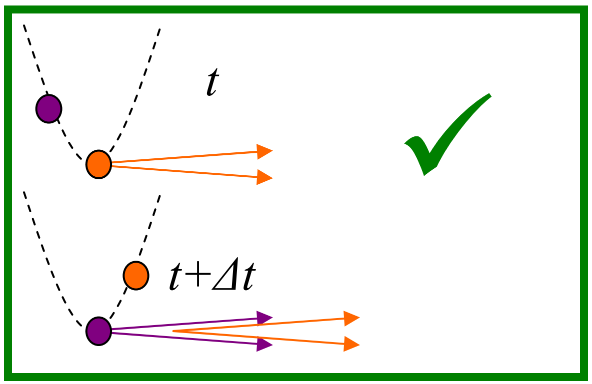


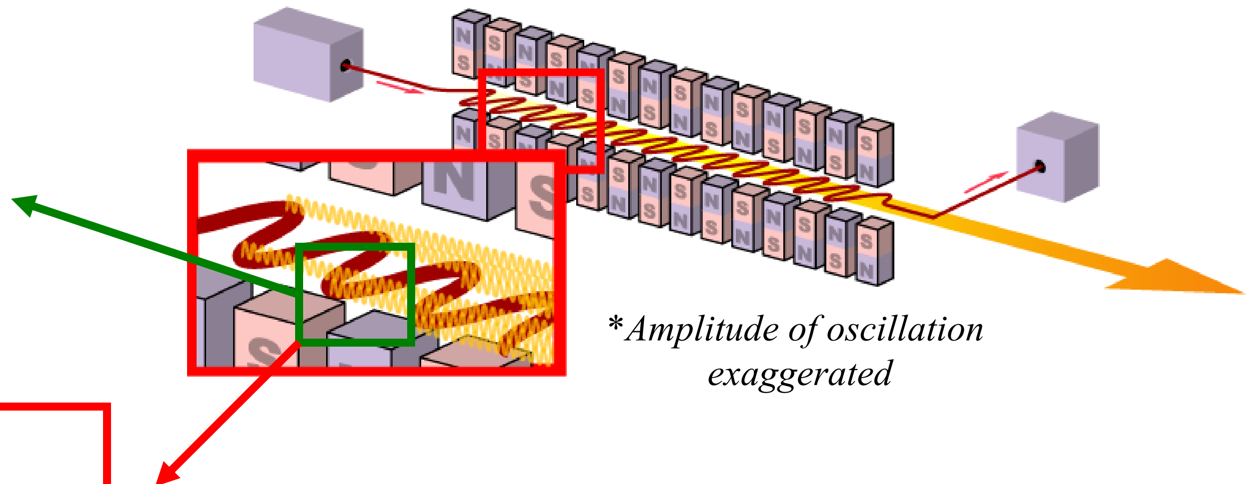
"Crabbing" the bunch through the crossing concentrates the collision over the shortest duration

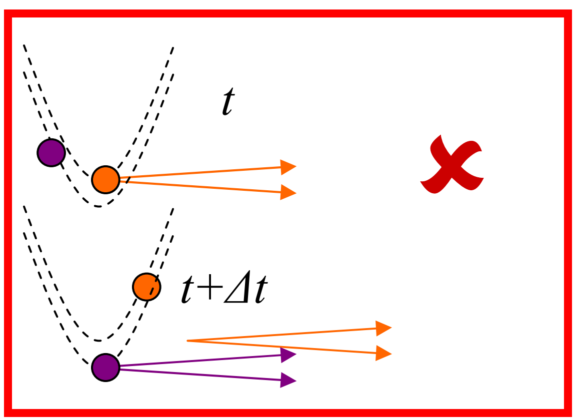
Motivation

Free electron laser

Build up of coherent synchrotron light in an FEL is impacted by transverse deviations in the bunch at injection







For maximum coherence (or gain tuning in general), want to control bunch confinement with respect to the $^1/_\gamma$ transverse opening angle of CSR

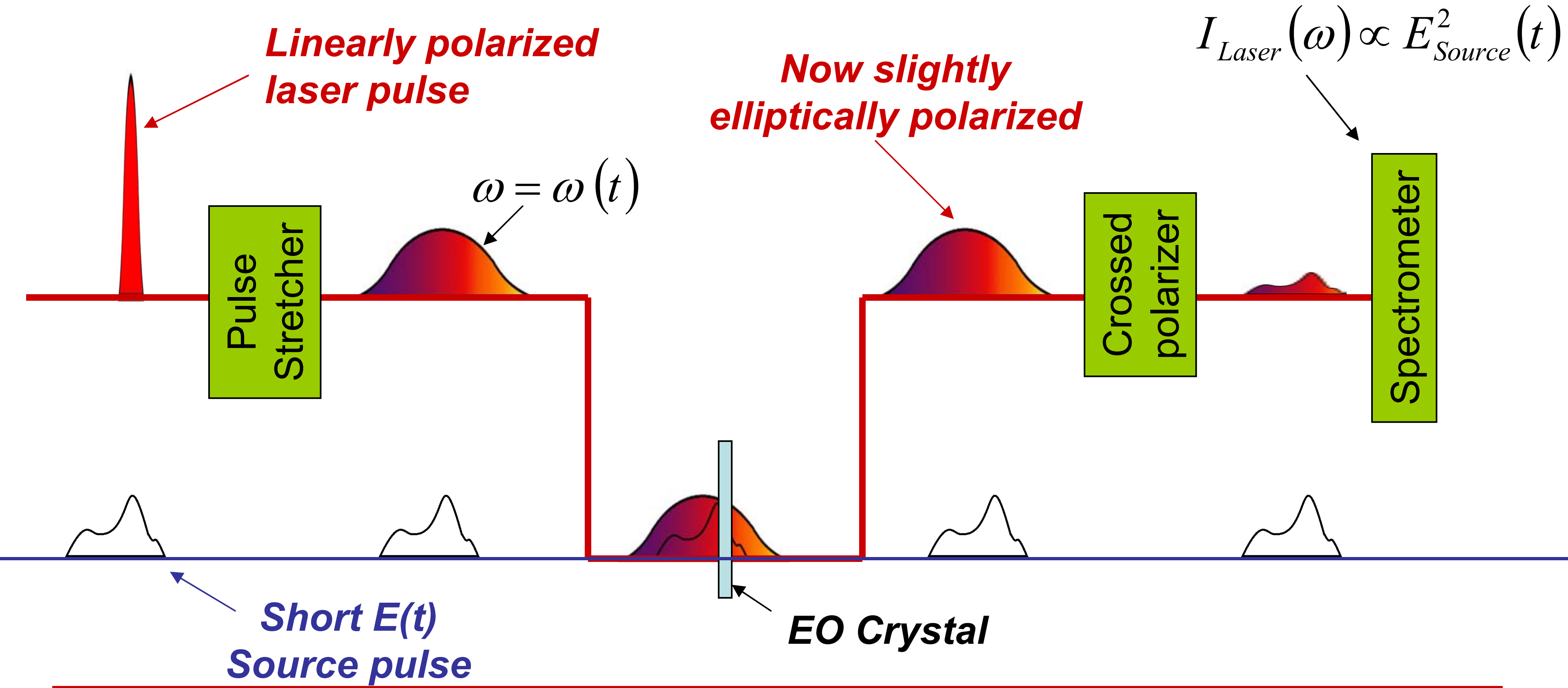
Outline

Current work is on a spatio-temporal correlation monitor to measure transverse beam position at time scales less than a bunch length **(**“The Optical BPM”**)**

- Electro-optic spectral encoding
- Application as spatio-temporal correlation monitor
- Current technical challenges and progress
  - Laser phase diagnostics
  - Synchronization
- Schedule of experiments to complete

Electro-Optic Spectral Encoding

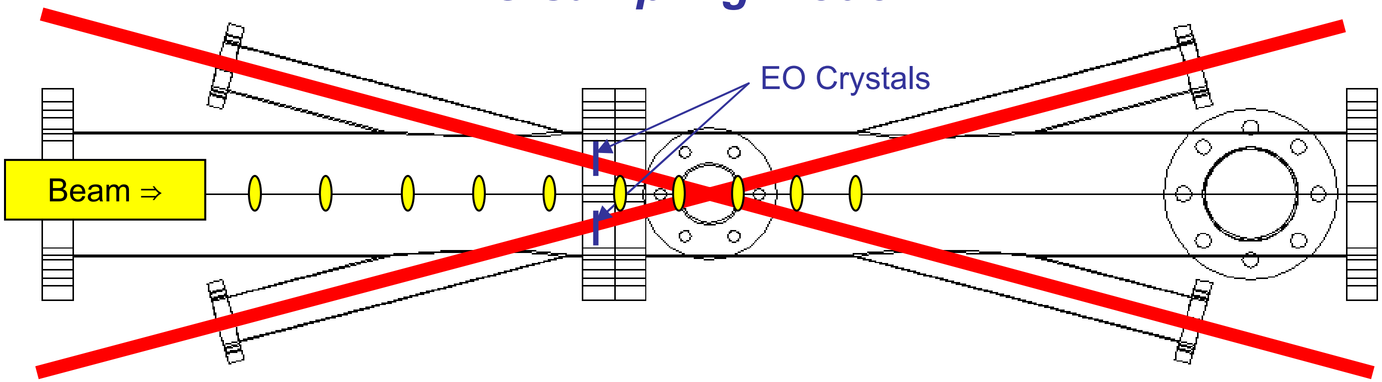
- Applied electric field induces birefringence in an EO crystal
- Resulting retardation is proportional to the local applied field
- Use this to probe very short time scale *E*-fields…



Proposed layout

- Probe the *t*-resolved E^2 at two symmetric points in the beam pipe

Direct Coulomb field
EO sampling mode



- EO signals are related to “applied field”
  - So in this case, the time evolution of the Coulomb field of bunch at these two points

What can these signals actually tell us?

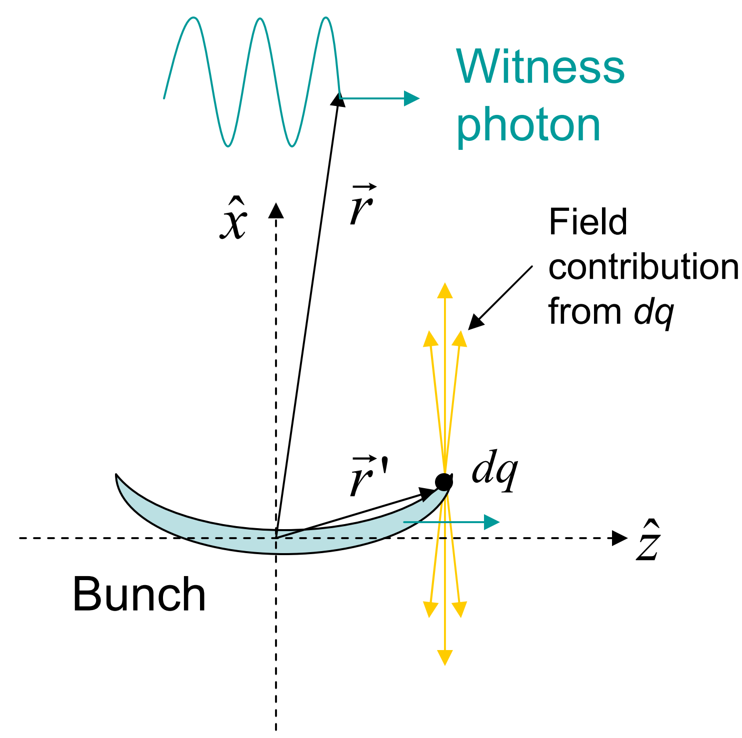
Leading Order Signal Analysis

- What field does photon travelling parallel to bunch witness?
  - Lab frame, assuming $\sigma_\rho << R, \beta \cong 1$, and beam divergence $< 1/\gamma$:

$$E_\perp(\vec{r}) \cong \int \rho(\vec{r}) \mathrm{E}_{\rho,e^-}(\vec{r} - \vec{r}\,')\, dr'^3$$

Where E_{ρ,e^-} is the transverse response function of a unit point charge given by the radial component of a relativistic charge. In cylindrical coordinates (r, z):

$$\mathrm{E}_{\rho,e^-}(r,z) = \frac{\gamma}{4\pi\varepsilon_0} \frac{r}{\left(r^2 + \gamma^2 z^2\right)^{3/2}}$$



Leading Order Signal Analysis

- Point charge contributions dq to total Coulomb field:
  - Effective over width/duration $\Delta t_{Coulomb} \propto R/\gamma c$
  - Strength falls as $\propto \gamma / R^2$

- For an entirely on-axis bunch, weakest possible signal given when:
  - Bunch length much longer than Coulomb field width above
  - Slowly varying bunch density (e.g: Gaussian or elliptical)
  - This results in:

$$E_\perp(R,z) \cong \frac{0.47}{\pi\varepsilon_0 R}\rho_z(z) \quad \text{or} \quad E_\perp(R,t) = 56\,\frac{\mathrm{V\cdot ps}}{\mathrm{pC}}\frac{\rho_t(t)}{R}$$

Leading Order Signal Analysis

- Allowing for a small $\left(\langle x\rangle << R\right)$, slowly varying transverse offset

$$E_{\perp}(R,t) \cong \frac{0.47\rho_t(t)}{\pi\varepsilon_0 cR}\left[1+2\frac{\langle x\rangle(t)}{R}\right]$$

- "Carrier signals" still proportional to longitudinal distribution-squared
- Extra modulation due to transverse offset

- Compare signals $E_{\perp}^2(\pm R,t)$ from points on opposite sides of beam axis
- Apply difference-over-sum, as is typical in button BPM:

$$\frac{\left|E_{\perp}(+R,t)\right|^2-\left|E_{\perp}(-R,t)\right|^2}{\left|E_{\perp}(+R,t)\right|^2+\left|E_{\perp}(-R,t)\right|^2} \cong 4\frac{\langle x\rangle(t)}{R}$$

Parameters (Feasibility)

- Summarizing, we can quantitatively conclude
  - Weakest field strength determined by longitudinal bunch density and distance from axis
  - A temporal resolution set by beam energy and distance from axis
  - Beam position accuracy given by signal to noise ratio of peak field at any given time slice
- Measurable birefringence is induced for fields 0.1 – 100 MV/m
- Use all of this to balance the working parameters

	Bunch parameters			**Diagnostic parameters**			
	Q	$\sigma_{z,\,fwhm}$	*Energy*	R	$\sigma_{t,rms}$	$E\,(100\% - 5\%)$	Δx
A0	1 nC	3 ps	16 MeV	4 mm	300 fs	4 – 0.2 MV/m	0.05 – 1 mm
NML	3 nC	1 ps	500 MeV	8 mm	20 fs*	18 – 0.8 MV /m	22 – 500 μm

*actual temporal resolution set by crystal response of ~50 fs in this case

Current challenges and studies

Probe laser phase space (chirp) control

- Need good measure of probe's λ-t correlation to map measured spectrum back to time (remember, $I_{Laser}(\omega) \propto E^2_{Source}(t)$ and $\omega = \omega(t)$)

Timing laser-beam phase lock at probe point

- Macro-scale problem: "*Finding a needle in a hay stack.*"
  - Trying to isolate 1 ps *e*-bunch width at 1 s repetition rate
- Micro-scale problem: "*Keeping the thread in the needle.*"
  - Once locked, stability of ~1 ps required (probe and signal are both on the order of picoseconds)

Our Probe Laser

- Recently relocated NIU laser system to A0PI including full tuning/realignment

- Tsunami oscillator
- SpitFire regenerative amplifier

- Tunable, broadband titanium-sapphire probe laser
  - Fundamental $\lambda_0 = 800$ nm, with bandwidth (fwhm) $\Delta\lambda = 15$ nm
  - Minimum pulse duration (rms) $\Delta t = 50$ fs
  - Pulse energy 10 nJ @ 81.25 MHz, or 3 mJ @ 1 kHz

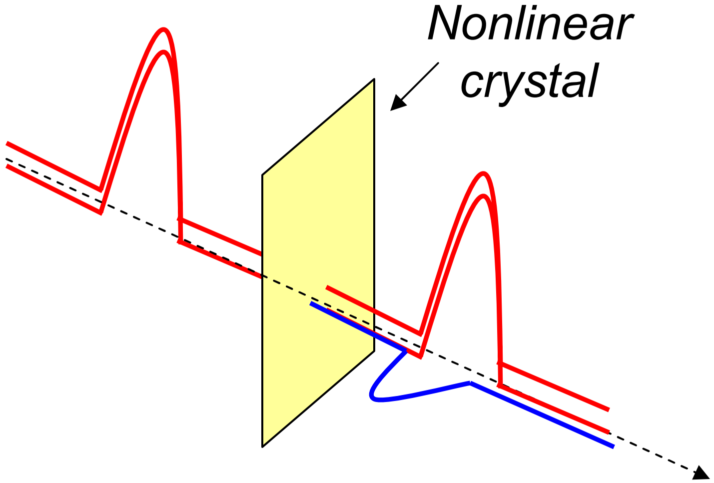
Diagnosing laser at fs scale

- Sources and controls for dispersion
  - Fiber transport line
  - Pulse stretcher (before fiber) and compressor (after fiber)
  - "Dazzler" (acousto-optic modulator for high order φ-corrections)
- How do we measure laser pulse chirp $\omega(t)$?
  - More solutions via second order nonlinear optics…

Type I "second harmonic generation"

Incident photon pair induces perpendicular polarization in nonlinear crystal resulting in frequency doubling when in-phase

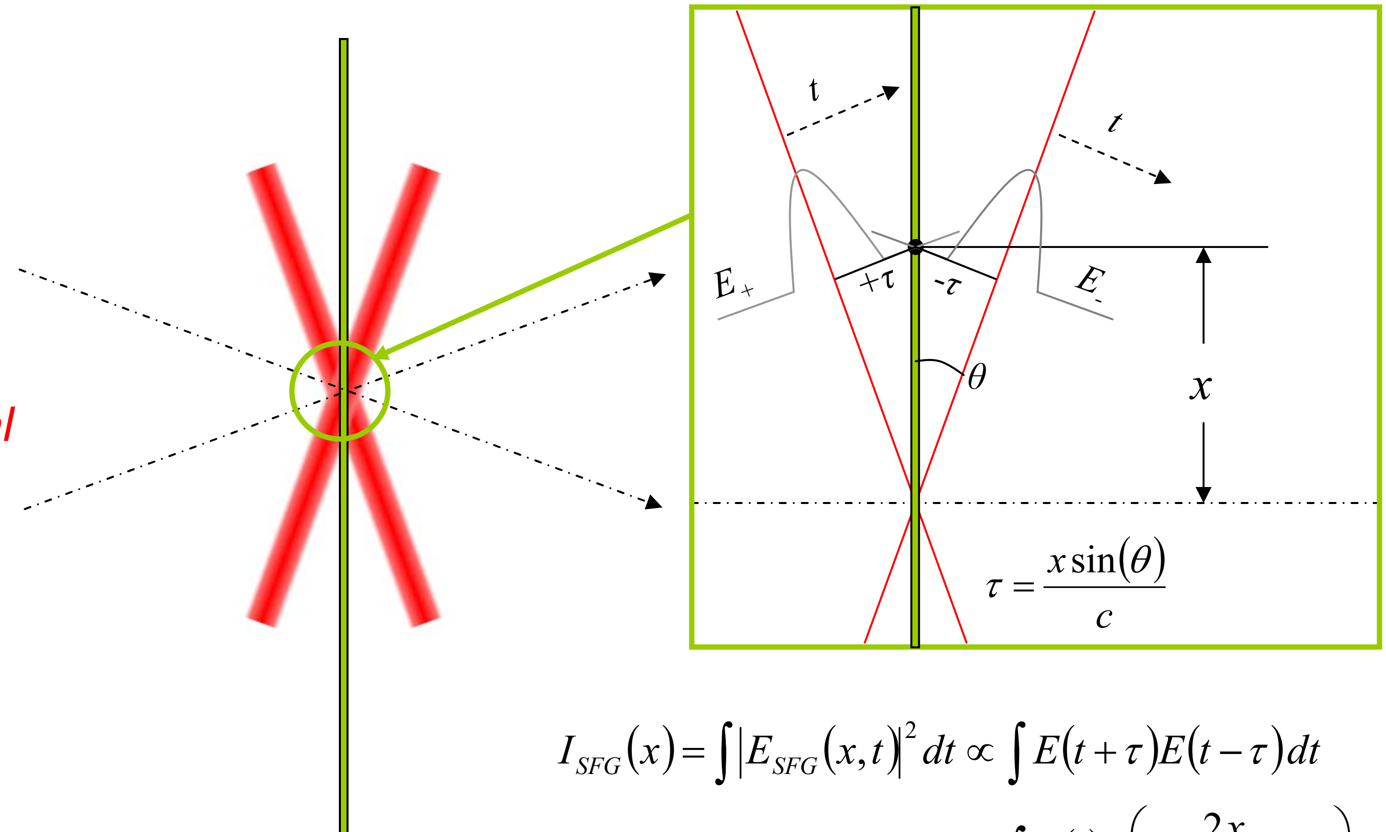
$$
\begin{aligned}
E_{SHG}(t) &\propto E_1(t)E_2(t) \\
&= \left[E_1 \cos(\underline{\omega t})\right]\left[E_2 \cos(\underline{\omega t})\right] \\
&= \frac{1}{2}E_1E_2\cos(\underline{2\omega t})
\end{aligned}
$$



Diagnosing pulse duration at fs scale

Single-shot autocorrelator (SSA) based on SHG

Split laser pulse, crossed in crystal



BBO Crystal

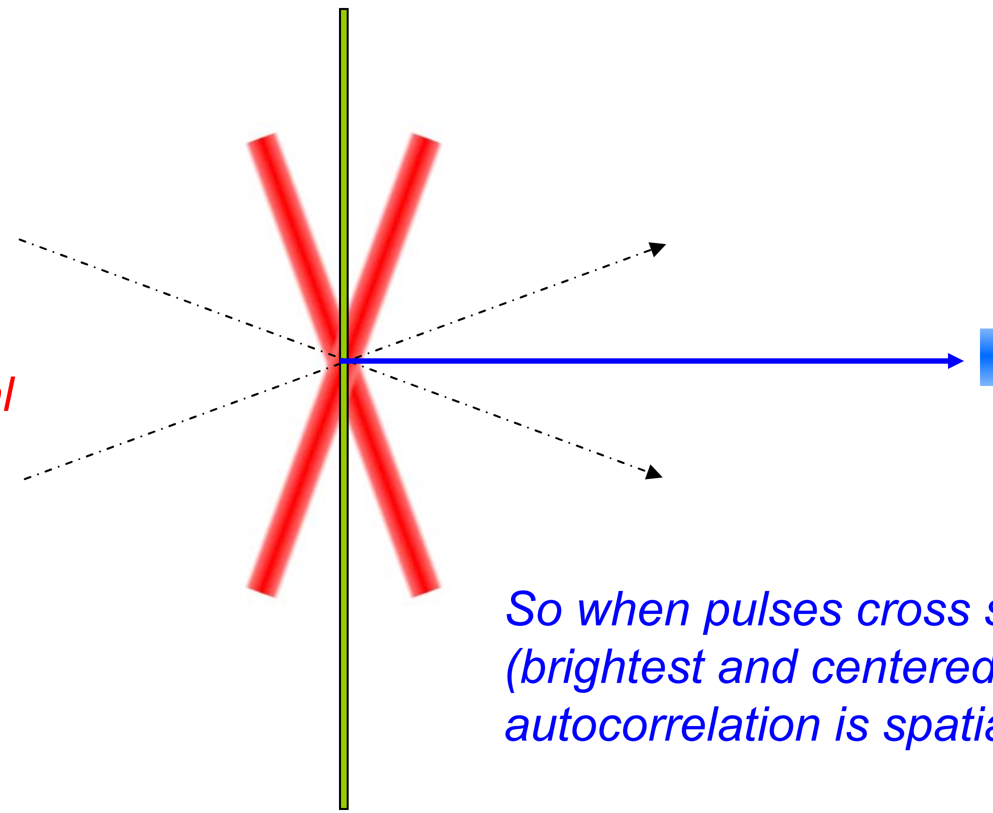
$$I_{SFG}(x) = \int \left|E_{SFG}(x,t)\right|^2 dt \propto \int E(t+\tau)E(t-\tau)\,dt$$

$$= \int E(t)E\left(t - \frac{2x}{c}\sin\theta\right)dt$$

Diagnosing pulse duration at fs scale

Single-shot autocorrelator (SSA) based on SHG

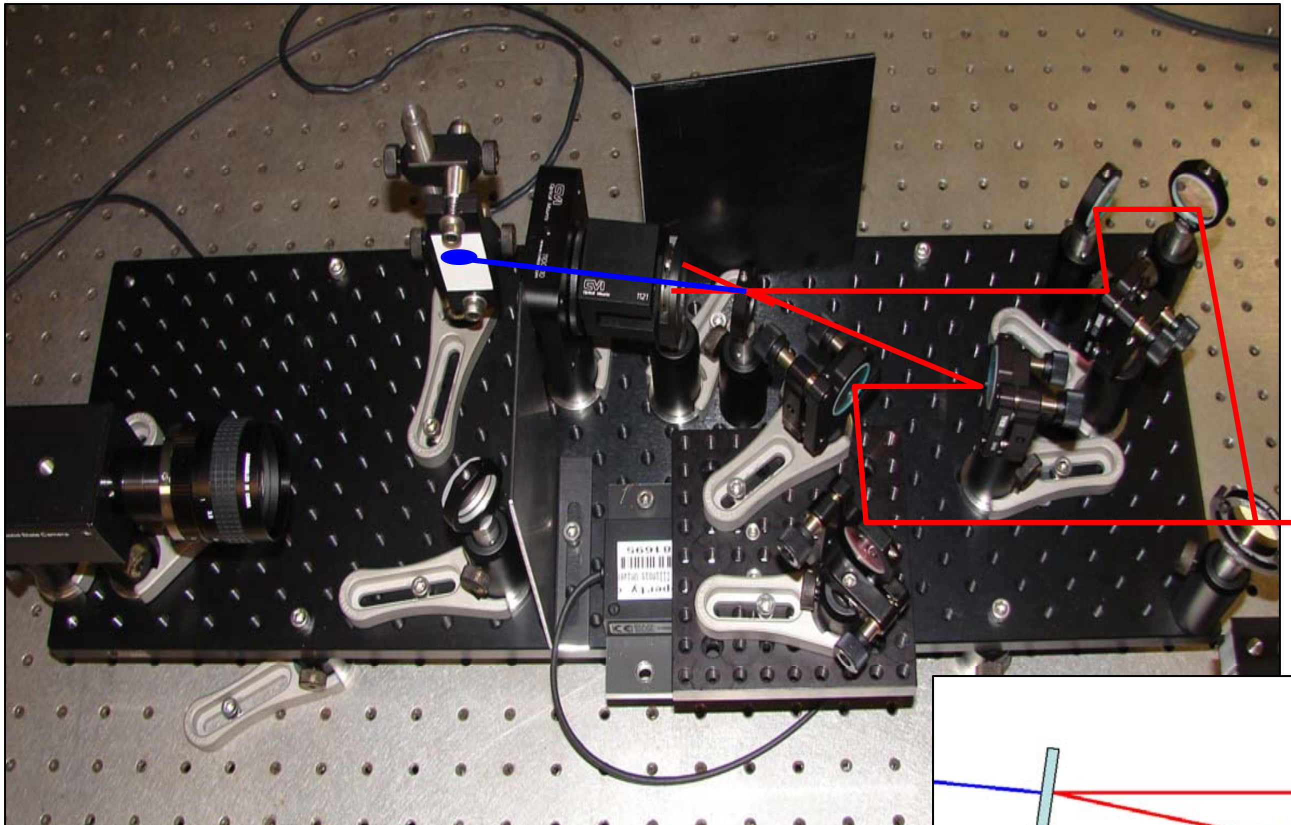
Split laser pulse, crossed in crystal

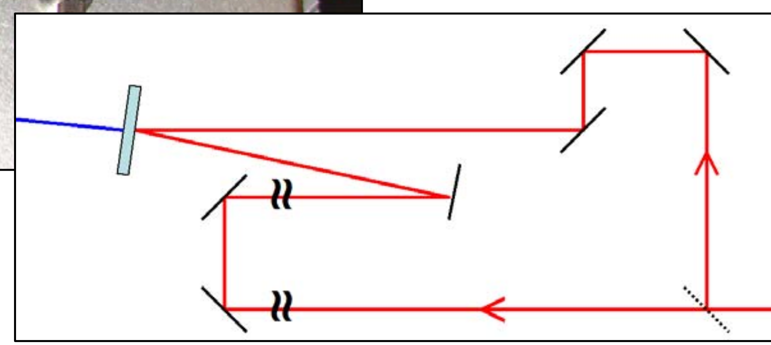


So when pulses cross simultaneously (brightest and centered blue spot) autocorrelation is spatially encoded on spot

Result: Fast single-shot pulse duration or laser pulse synchronization diagnostic

Diagnosing pulse duration at fs scale





Our SSA

- MATLAB controls, calibrates, and analyzes
- Tested to 60 fs resolution currently
- 25 fs resolution possible after final adjustments

Diagnosing laser phase at fs scale

- Need to convert spectrally encoded data back to temporal
  - Requires phase analysis of laser pulse
- Consider spectral phase of pulse as expansion about fundamental

$$\phi(\omega) = D_0 + D_1(\omega - \omega_0) + \frac{D_2}{2}(\omega - \omega_0)^2 + \frac{D_3}{3!}(\omega - \omega_0)^3 + \dots$$

Arbitrary phase

Overall group delay (temporal shift of pulse)

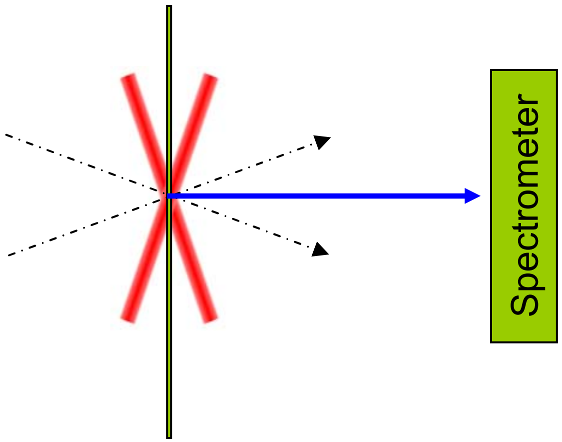
Group delay dispersion (linear ω-t relation)

Third order dispersion (quadratic ω-t relation)

- Pure group delay dispersion desired (linear chirp)
- Will need significant dispersion on broadband pulse
  - May encounter higher order dispersion

Diagnosing laser phase at fs scale

- Phase reconstruction by Frequency Resolved Optical Gating (FROG)
- Similar to autocorrelator, but with output sent to spectrometer



Resulting 2D trace is mod squared Fourier transform of the SHG light:

$$I_{SHG\ FROG}(\omega,\tau) \propto \left| \int E(t)E(t-\tau)e^{-i\omega t}dt \right|^2$$

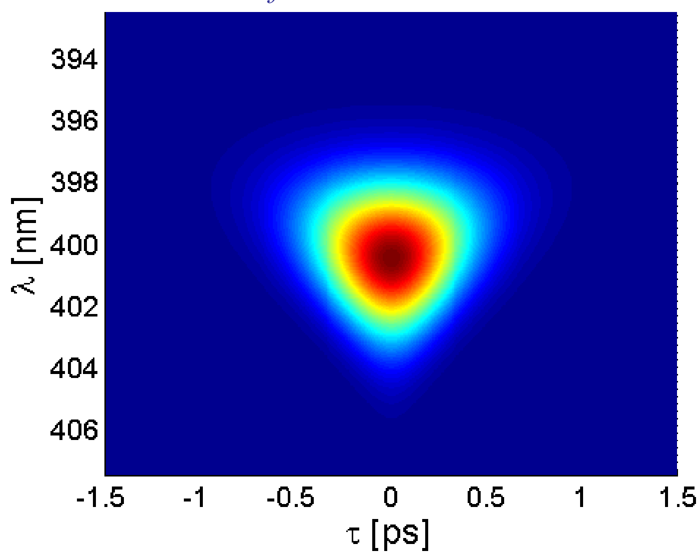
- SHG FROG advantages:
  - Largest signal of various FROG configurations
  - Simplest set up and alignment
- Downside: “Spectrograms” somewhat unintuitive, must make assumptions to reconstruct phase

Diagnosing laser phase at fs scale

Calculated FROG trace

$D_2 = 10^4$ fs^2, $D_3 = 2.5 \times 10^5$ fs^3

$\Delta\lambda_{fwhm} = 12$ nm



- D_2 elongates ellipse along τ
- Additional D_3 term generates asymmetry about λ (horseshoe shape in trace)

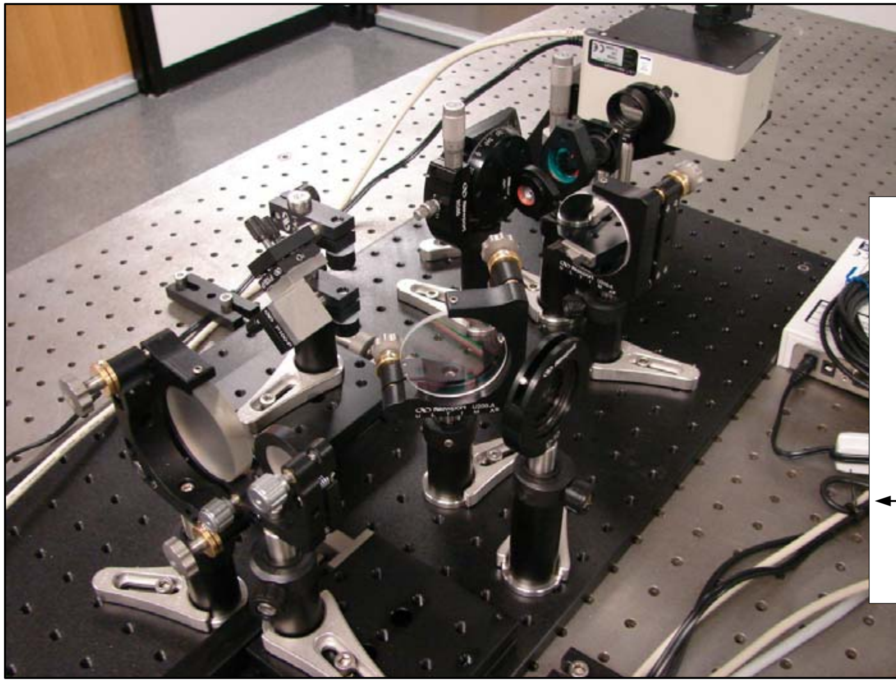
Second order moment analysis yields relationship between RMS widths $\sigma_\tau(\omega)$ of trace and dispersion:

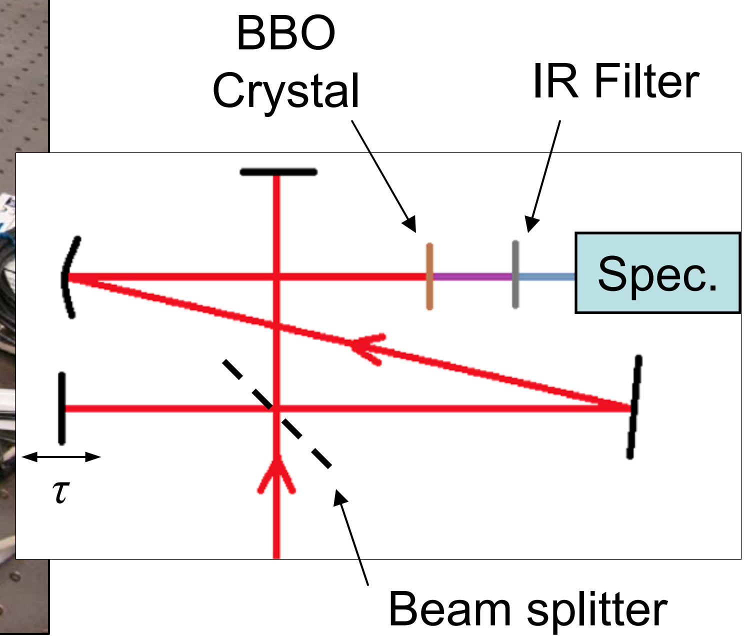
$$\sigma_\tau^2(\omega) = \frac{2}{\sigma_\omega^2} + 2\sigma_\omega^2\left[D_2 + \underline{\frac{1}{2}(\omega - 2\omega_0)D_3}\right]^2$$

With σ_ω the laser's spectral field bandwidth, measured independently

Absolute sign on dispersion terms lost and must be otherwise inferred

Diagnosing laser phase at fs scale



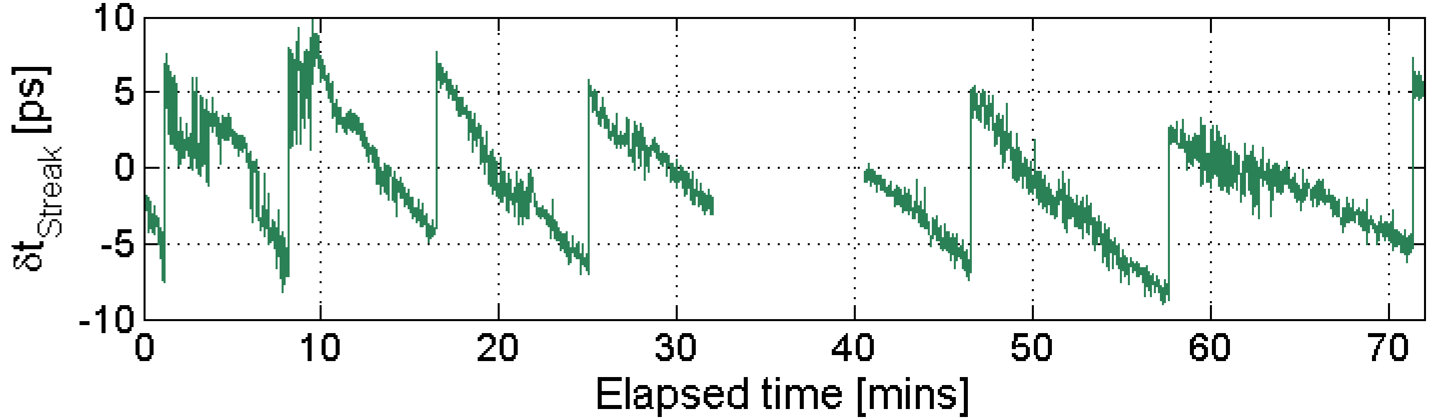


- Real FROG trace analysis still being refined
  - Using “Dazzler” and pulse compressor as baselines
- Subsequent measurements:
  - Laser pulse stretcher performance
  - Transport fiber dispersion properties (as yet unspecified)

Laser-to-bunch synchronizing

- Phase lock must remain stable at ~1 ps to maintain signal overlap with smallest possible laser chirp
- Performed beam-to-laser phase jitter analysis (*Beams-doc-3396-v1*)
- Three techniques used to corroborate findings:
  1. Monitor laser time of arrival via streak camera
  2. “Charge fluctuation” technique
     - Set RF gun phase on rising edge of phase-to-accelerated charge curve
     - Small phase changes are then mapped to bunch charge
  3. Dispersion technique
     - Assume time of arrival jitter at entrance to accelerating cavity
     - Result is shot-to-shot energy fluctuation as bunches see different parts of RF crest
     - Monitor energy fluctuation w/ dipole and map to phase jitter

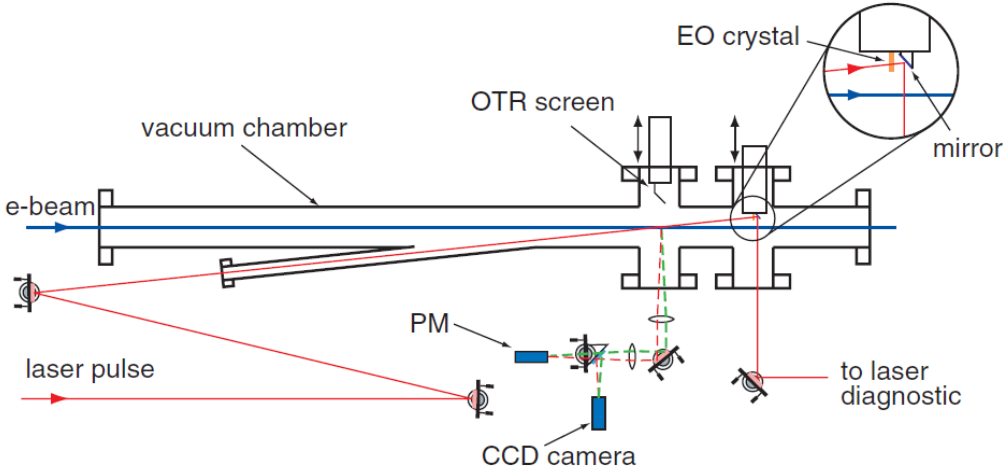
Laser-to-bunch synchronizing



- Relative drift of up to 1 ps/min observed
  - Associated with cold laser operation
- Time of arrival jitter determined to be 0.5 – 1 ps, rms
- Summer student Wilbert Rossi created phase lock loop system
  - Drifts corrected, jitter reduced
  - Can duplicate for phase lock of our *Tsunami* laser system
- Behavior of *Tsunami* so far compares well to existing A0 laser

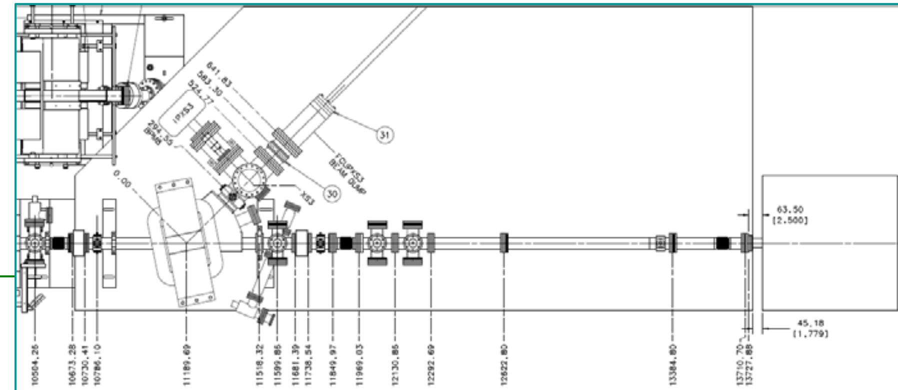
Laser-to-bunch synchronizing

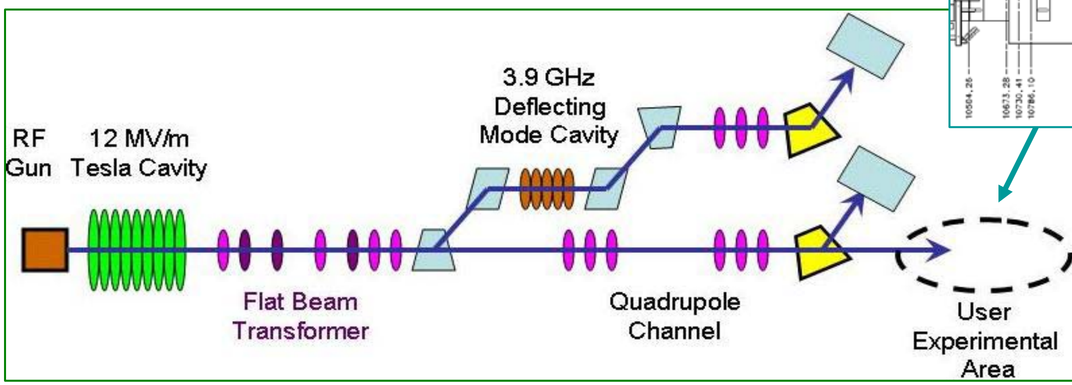
- Both bunch and laser probe duration ~1 ps with bunch at rep. rate of 1 Hz make initial phase scan difficult
  - Insert OTR screen at point where laser crosses beam path
  - Reflected OTR+Laser into streak camera (dual sweep mode)
  - Scan beam phase to get phase matched within ~10 ps
  - Observe EO signal and scan optical path delay to get final lock



Arrangement and graphic taken from EO work at FLASH:
B. Steffen *et al,* Phys. Rev. ST Accel. Beams **12**, 032802 (2009)

Experiments at A0 Photoinjector





30” reserved
for EOS

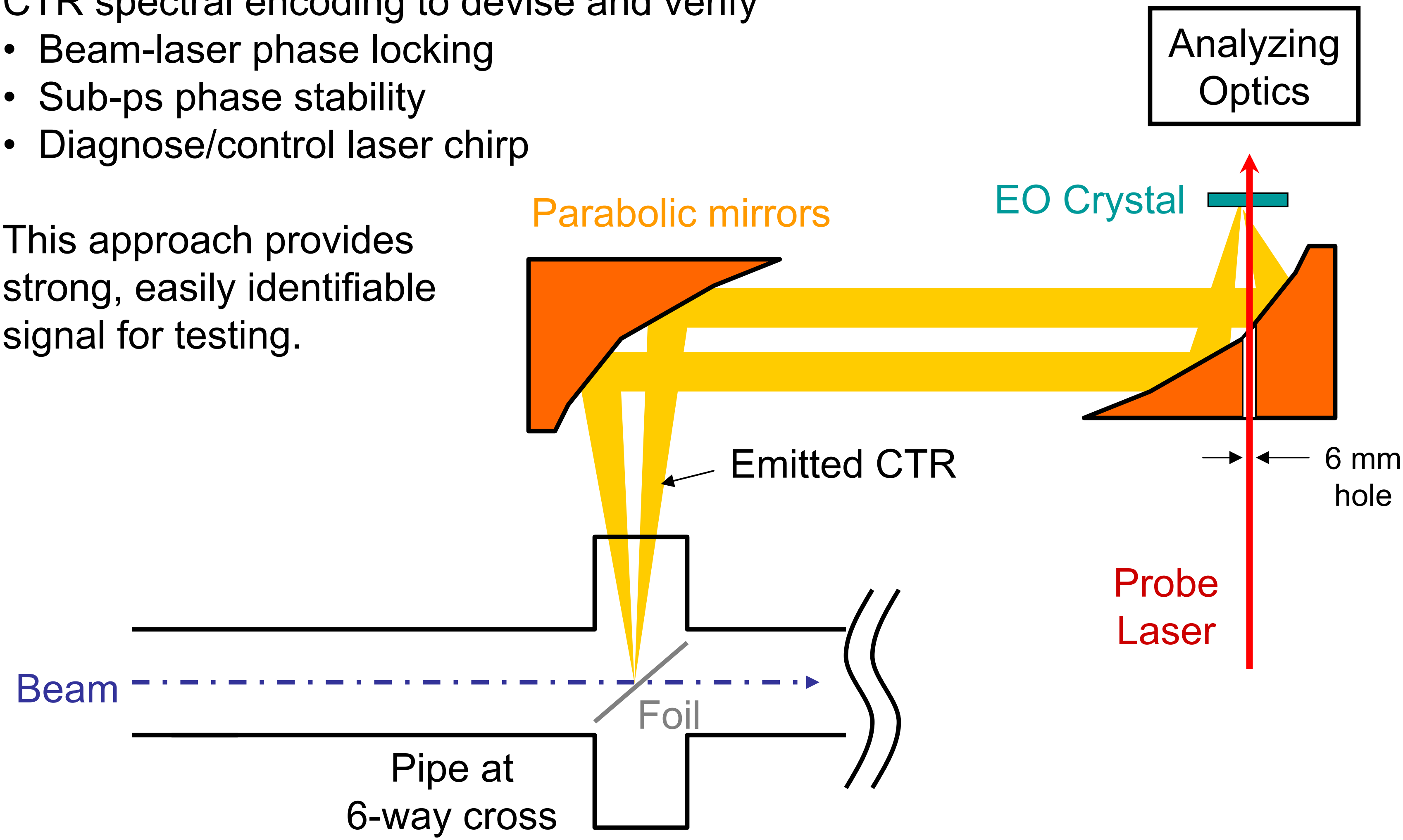
- A0 PI: 1 nC, 16 MeV electron beam, 2 ps minimum bunch length
- Two stage experiment planned:
  1. EO sample the transient of coherent transition radiation (CTR)
  2. Build out final, dual probe Optical BPM experiment

Experiment #1

CTR spectral encoding to devise and verify

- Beam-laser phase locking
- Sub-ps phase stability
- Diagnose/control laser chirp

This approach provides strong, easily identifiable signal for testing.



Detailed Timetable

2010						
May	**Jun**	**July**	**Aug**	**Sept**	**Oct**	**Nov**
Written analyses & laser disp'n studies	Laser disp'n control *USPAS*	Laser disp'n control & install	OTR/laser timing install, coarse tests	Timing tests & analysis Chamber fabrication	CTR EOS experiment (ICCD spectro'r)	CTR EOS experiment, analysis & repairs

2010	***2011***					
Dec	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**
Analysis and report	Probe-split optics (split, relative phase control), Probe injection optics (transport/focusing), Dual trace spectrometer calibration			Installation, alignment, test & calibrate	Installation, alignment, test & calibrate	Optical BPM

2011					
July	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Optical BPM	Analysis and last chance for data	Draft thesis	Iterate thesis	Defense	***Thank you***

Backup Slides

Leading Order Signal Analysis

- In principle, can solve analytically
- For illustration, to a good approximation:

$$\mathrm{E}_{\rho,e^-}(r,z) \cong \frac{\gamma}{4\pi\varepsilon_0 r^2} \exp\left[\frac{-z^2}{2\sigma_z^2}\right]$$

with $\sigma_z = 0.75\, r/\gamma$

- Point charge contributions *dq* to total Coulomb field:
  - Effective over width/duration $\propto R/\gamma$
  - Strength falls as $\propto \gamma / R^2$
- So, for an entirely on-axis bunch:

$$E_\perp(R,z) \cong \frac{\gamma}{4\pi\varepsilon_0 R^2} \int \rho_z(z')\exp\left[\frac{-(z-z')^2}{2\sigma_z^2}\right] dz'$$

Leading Order Signal Analysis

- With proper normalization

$$E_\perp(R,z) \cong \frac{0.47}{\pi\varepsilon_0 R}\int \rho_z(z')\left\{\frac{1}{\sigma_z\sqrt{2\pi}}\exp\left[\frac{-(z-z')^2}{2\sigma_z^2}\right]\right\}dz'$$

- Assume ρ_z is long and slowly varying with respect to σ_z
  - e.g: Gaussian or elliptical bunch
  - Why: Results in weakest signal (no γ enhancement…)
  - Problem: Neglects strong effects for "peaky" bunches (large $\rho_z'(z)$)

- Then as $\sigma_z \to 0$, {Gaussian}$\to \delta(z-z')$ and we have

$$E_\perp(R,z) \cong \frac{0.47}{\pi\varepsilon_0 R}\rho_z(z) \qquad \text{or} \qquad E_\perp(R,t) = 56\,\frac{\mathrm{V}\cdot\mathrm{ps}}{\mathrm{pC}}\frac{\rho_t(t)}{R}$$

Second order nonlinear optics

- Basic driving principle behind entire project
- Use materials with sufficient second order susceptibility $\chi^{(2)}$

$$P^{(2)}(t) \propto \chi^{(2)} E^2(t)$$

- When field applied to material is sum of two fields, induced polarization generates interesting secondary photons
- Noting that $E(t)$ is real, $E(-\omega)$ = $E^*(\omega)$ we find for two photons $\omega > 0$

$$E(t) = E_1(t) + E_2(t)$$

$$= \widetilde{E}_1\, e^{i\omega_1 t} + \widetilde{E}_1^*\, e^{-i\omega_1 t} + \widetilde{E}_2\, e^{i\omega_2 t} + \widetilde{E}_2^*\, e^{-i\omega_2 t}$$

Second order nonlinear optics

- So the polarization induced for these two photons is

$$P^{(2)}(t) \propto \left[E_1(t) + E_2(t)\right]^2$$

$$= \underbrace{\tilde{E}_1^2\, e^{i(2\omega_1)t}}_{} + \underbrace{\tilde{E}_2^2\, e^{i(2\omega_2)t}}_{} + \underbrace{\tilde{E}_1\,\tilde{E}_2\, e^{i(\omega_1+\omega_2)t} + \tilde{E}_1^*\tilde{E}_2^*\, e^{-i(\omega_1+\omega_2)t}}_{}$$

Second harmonic generation (SHG)

Sum frequency generation (SFG)

$$+\underbrace{\tilde{E}_1^*\tilde{E}_2\, e^{i(\omega_2-\omega_1)t} + \tilde{E}_1\,\tilde{E}_2^*\, e^{-i(\omega_2-\omega_1)t}}_{} + \underbrace{\left|\tilde{E}_1\right|^2}_{} + \underbrace{\left|\tilde{E}_2\right|^2}_{}$$

Difference frequency generation (DFG)

DC rectification