Ultrafast Instrumentation for Accelerators II

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Lectures

- Lecture 1
  - Introduction
  - Coherent THz Radiation
    - Detectors
    - Interferometers/Spectrometers
  - Femtosecond timing and synchronization
  - Transverse Deflecting Structures
- **Lecture 2**
  - **Nonlinear optic techniques for short pulse measurement**
    - **Basics of nonlinear optics**
    - **Basics of mode-locked lasers**
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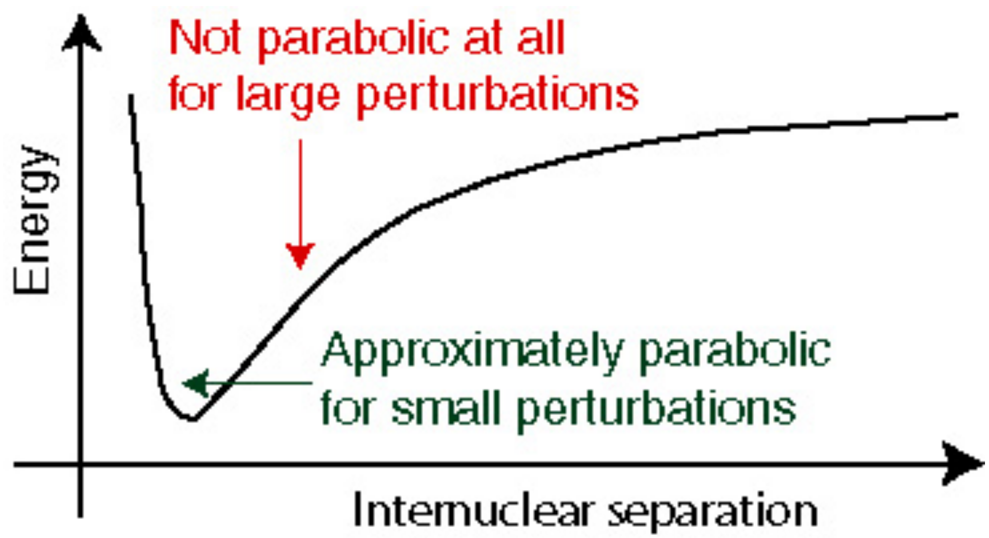
    - **Auto and cross correlation**
    - **FROG, etc.**
  - **X-ray Streak cameras**
  - **New directions…**

A brief introduction to nonlinear optical effects

Another way to look at nonlinear optics is that the potential of the electron or nucleus (in a molecule) is not a simple harmonic potential.

Example:



For weak fields, motion is harmonic, and linear optics prevails.
For strong fields (i.e., lasers), anharmonic motion occurs, and higher harmonics occur, both in the motion and the light emission.

Maxwell's Equations in a *Nonlinear* Medium

Nonlinear optics is what happens when the polarization is the result of higher-order (nonlinear!) terms in the field:

$$\boxed{\mathscr{P} = \varepsilon_0 \left[\chi^{(1)} \mathscr{E} + \chi^{(2)} \mathscr{E}^2 + \chi^{(3)} \mathscr{E}^3 + \ldots \right]}$$

What are the effects of such nonlinear terms? Consider the second-order term:

Since $\mathscr{E}(t) \propto E \exp(i\omega t) + E^* \exp(-i\omega t)$,

$$\mathscr{E}(t)^2 \propto E^2 \exp(2i\omega t) + 2\left|E\right|^2 + E^{*2} \exp(-2i\omega t)$$

2ω = 2nd harmonic!

Harmonic generation is one of many exotic effects that can arise!

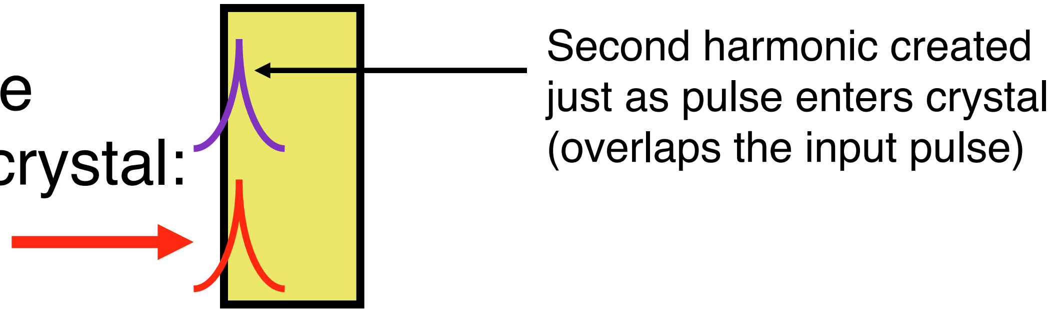
Group-velocity mismatch

Inside the crystal the two different wavelengths have different group velocities.

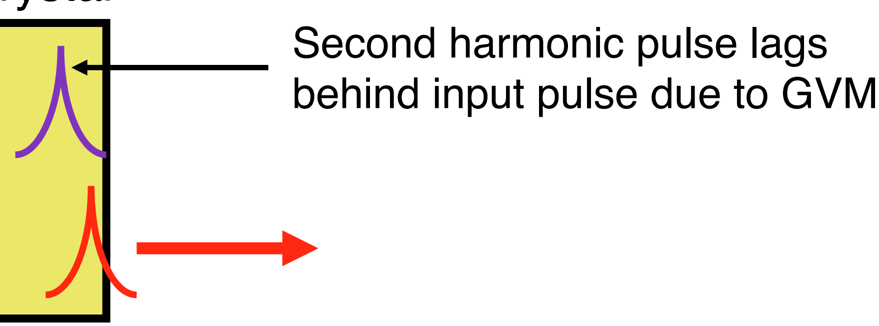
Define the Group-Velocity Mismatch (GVM):

$$\boxed{GVM \equiv \frac{1}{\mathrm{v}_g(\lambda_0/2)} - \frac{1}{\mathrm{v}_g(\lambda_0)}}$$

As the pulse enters the crystal:



As the pulse leaves the crystal:



Phase-matching second-harmonic generation

So we're creating light at $\omega_{sig} = 2\omega$.

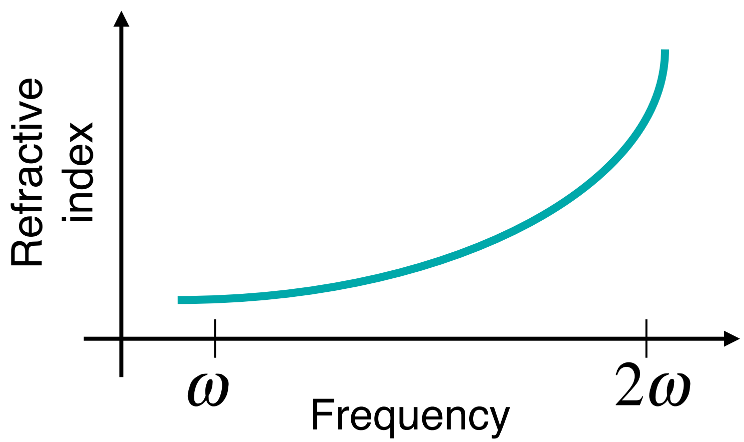
The k-vector of the second-harmonic is: $k_{sig} = \dfrac{\omega_{sig}}{c_0} n(\omega_{sig}) = \dfrac{(2\omega)}{c_0} n(2\omega)$

And the k-vector of the polarization is: $k_{pol} = 2\,k = 2\dfrac{\omega}{c_0} n(\omega)$

The phase-matching condition is: $k_{sig} = k_{pol}$

which will only be satisfied when:

$$\boxed{n(2\omega) = n(\omega)}$$

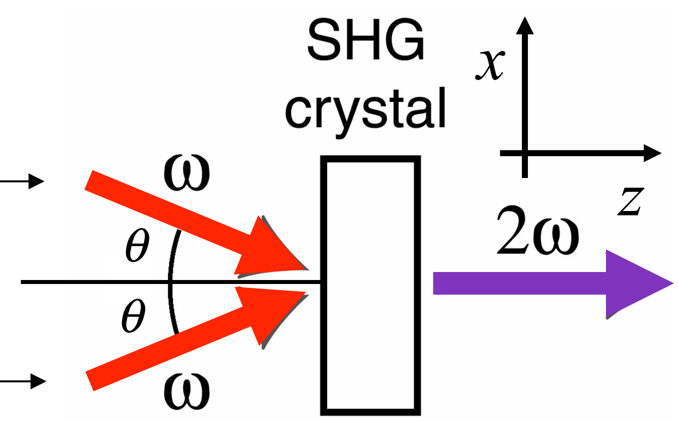


Unfortunately, dispersion prevents this from ever happening!

Noncolinear SHG phase-matching

$$\vec{k} \;=\; k\cos\theta\,\hat{z} \;-\; k\sin\theta\,\hat{x} \;\longrightarrow$$

$$\vec{k}' \;=\; k\cos\theta\,\hat{z} \;+\; k\sin\theta\,\hat{x} \;\longrightarrow$$



$$\vec{k}_{pol} = \vec{k} + \vec{k}' = 2\,k\cos\theta\,\hat{z}$$

$$\Rightarrow k_{pol} \;=\; 2\frac{\omega}{c_0}\,n(\omega)\cos\theta$$

But:

$$k_{sig} \;=\; \frac{2\omega}{c_o}\,n(2\omega)$$

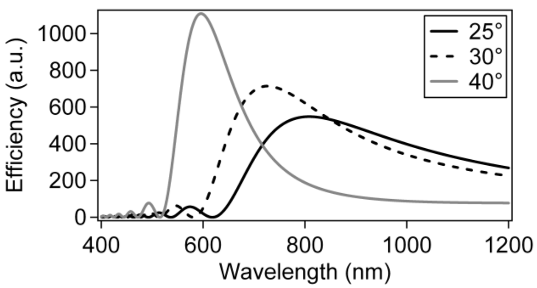
So the phase-matching condition becomes:

$$\boxed{n(2\omega) \;=\; n(\omega)\cos\theta}$$

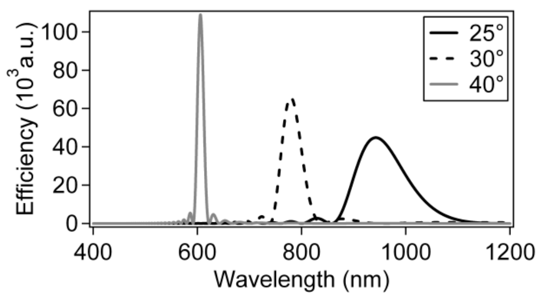
Phase-matching efficiency vs. wavelength for BBO and KDP

Phase-matching efficiency vs. wavelength for the nonlinear-optical crystal, beta-barium borate (BBO) and potassium dihydrogen phosphate (KDP), for different crystal thicknesses:

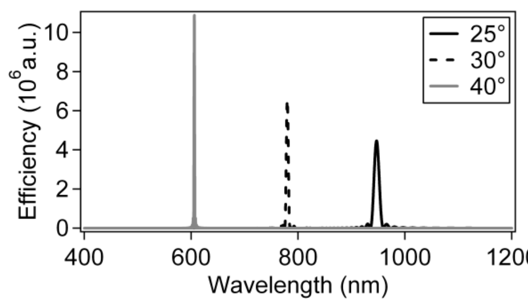
10 micron



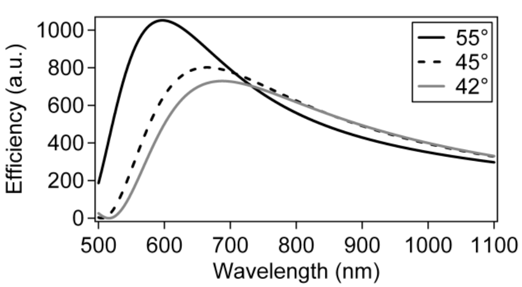
100 micron

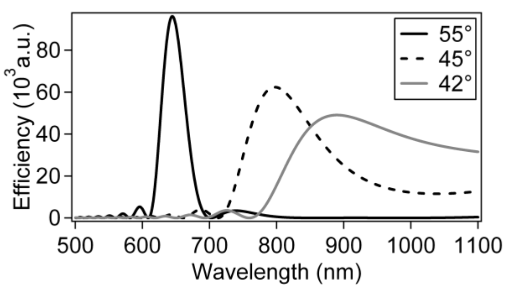


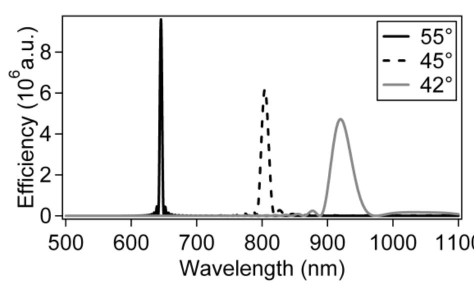
1000 micron



Note the huge differences in phase-matching bandwidth and efficiency with crystal thickness.



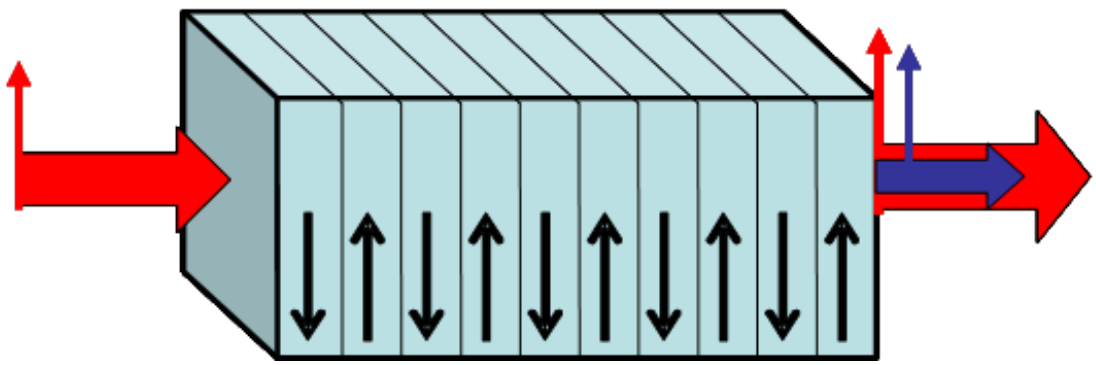




Alternative method for phase-matching: periodic poling

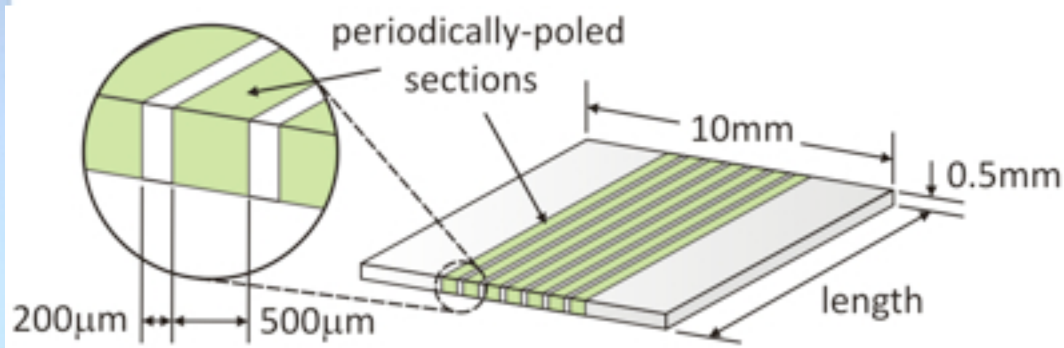
Recall that the second-harmonic phase alternates every coherence length when phase-matching is not achieved, which is always the case for the same polarizations—whose nonlinearity is much higher.

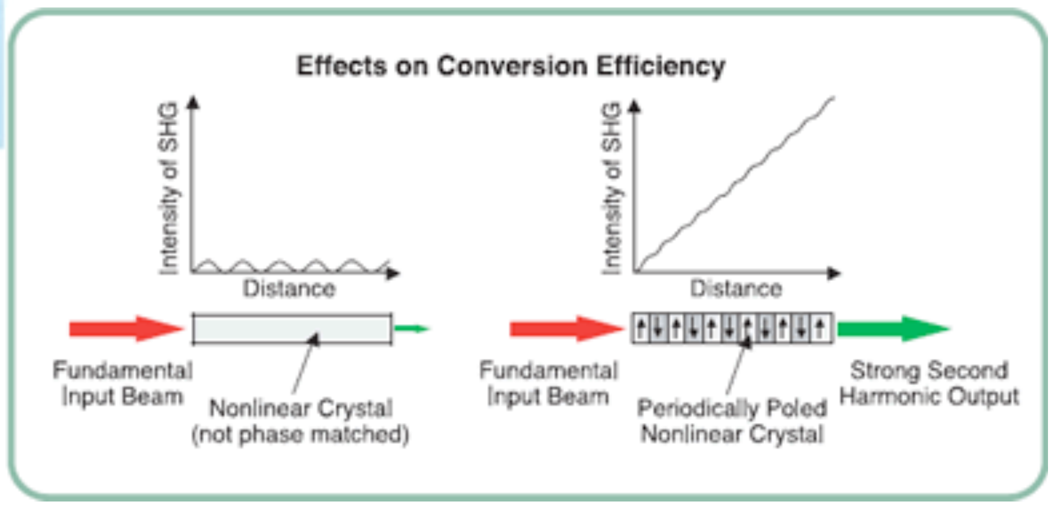
Periodic poling solves this problem. But such complex crystals are hard to grow and have only recently become available.



Example Products

- Covesion MgO:PPLN for Second Harmonic Generation

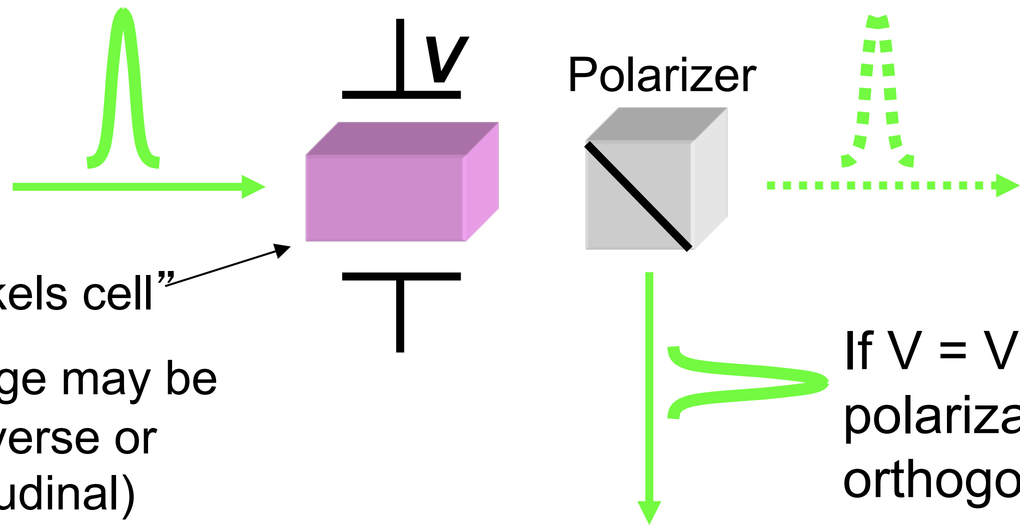




Another 2nd-order process: Electro-optics

Applying a voltage to a crystal changes its refractive indices and introduces birefringence. In a sense, this is sum-frequency generation with a beam of zero frequency (but not zero field!).

A few kV can turn a crystal into a half- or quarter-wave plate.



"Pockels cell"

(voltage may be transverse or longitudinal)

If V = 0, the pulse polarization doesn't change.

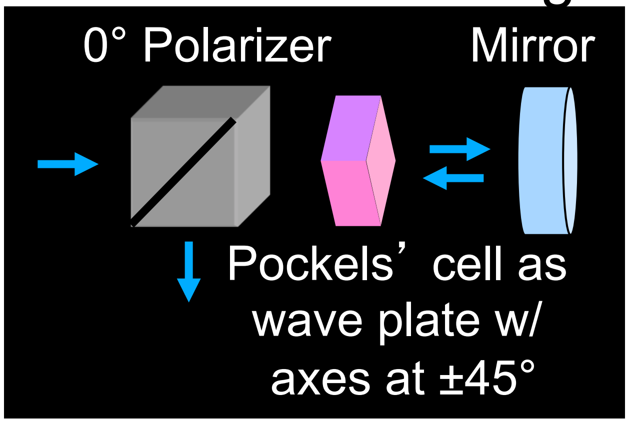
If $V = V_p$, the pulse polarization switches to its orthogonal state.

Abruptly switching a Pockels cell allows us to switch a pulse into or out of a laser.

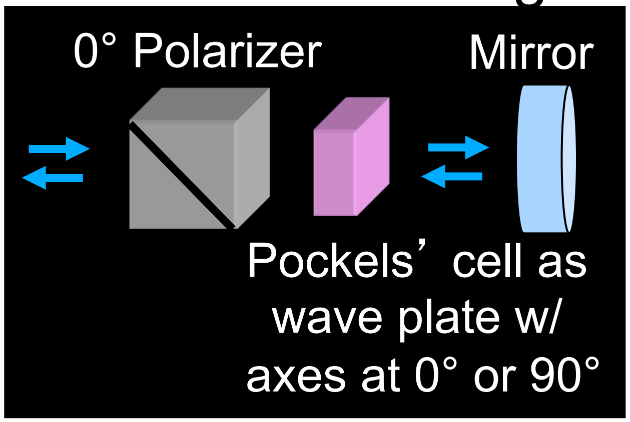
The Pockels' Cell (Q-Switch)

The Pockels effect is a type of second-order nonlinear-optical effect.

Before switching



After switching



The Pockels effect involves the simple second-order process:

$$\omega_{sig} = \omega + 0$$

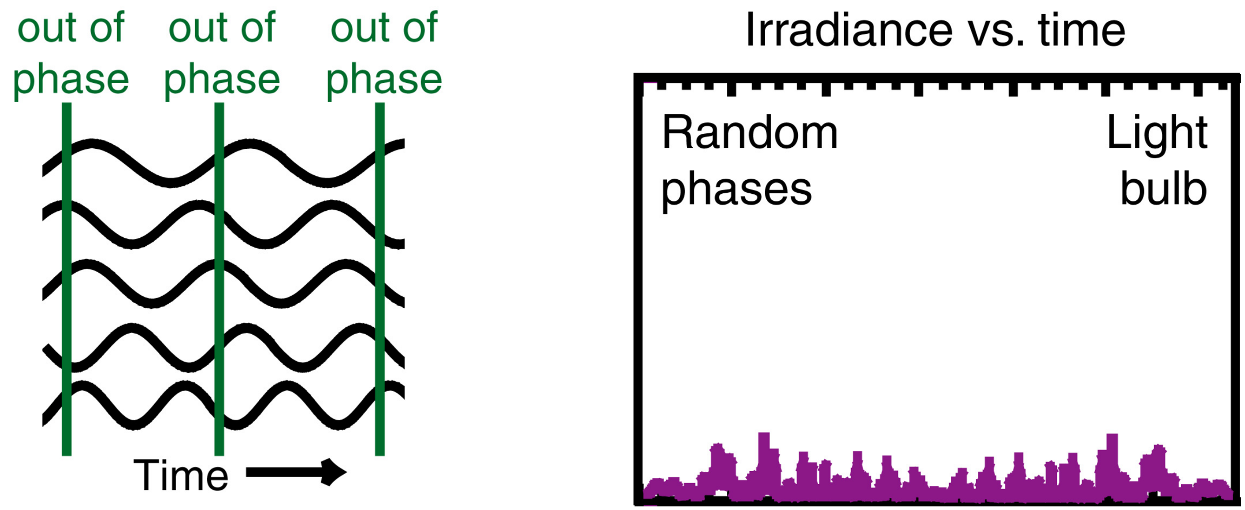
dc field

The signal field has the orthogonal polarization, however.

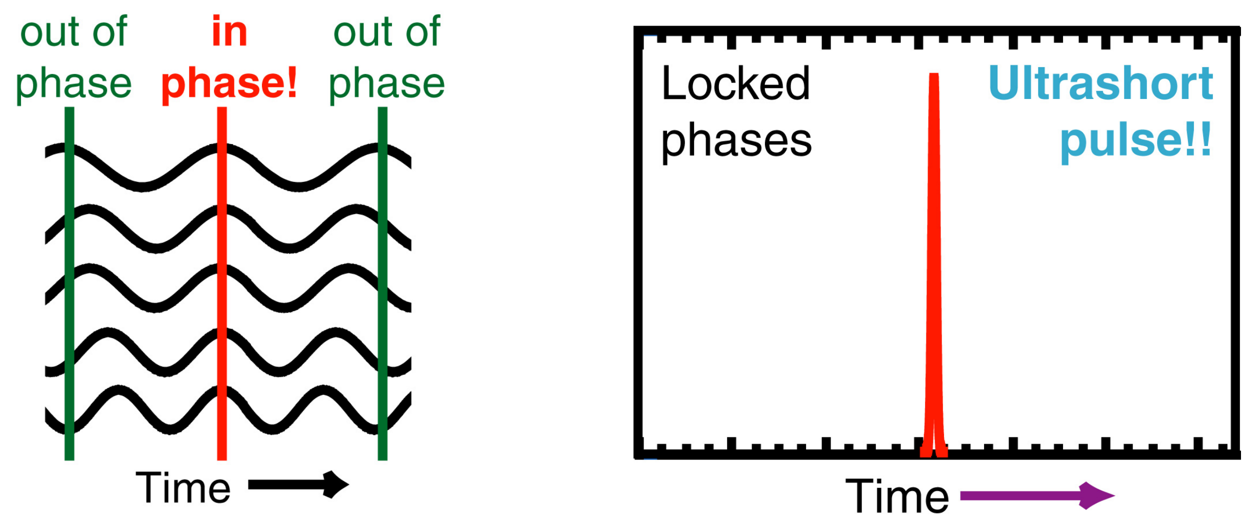
A brief introduction to mode-locked lasers

Locking the phases of the laser frequencies yields an ultrashort pulse.

Random phases of all laser modes

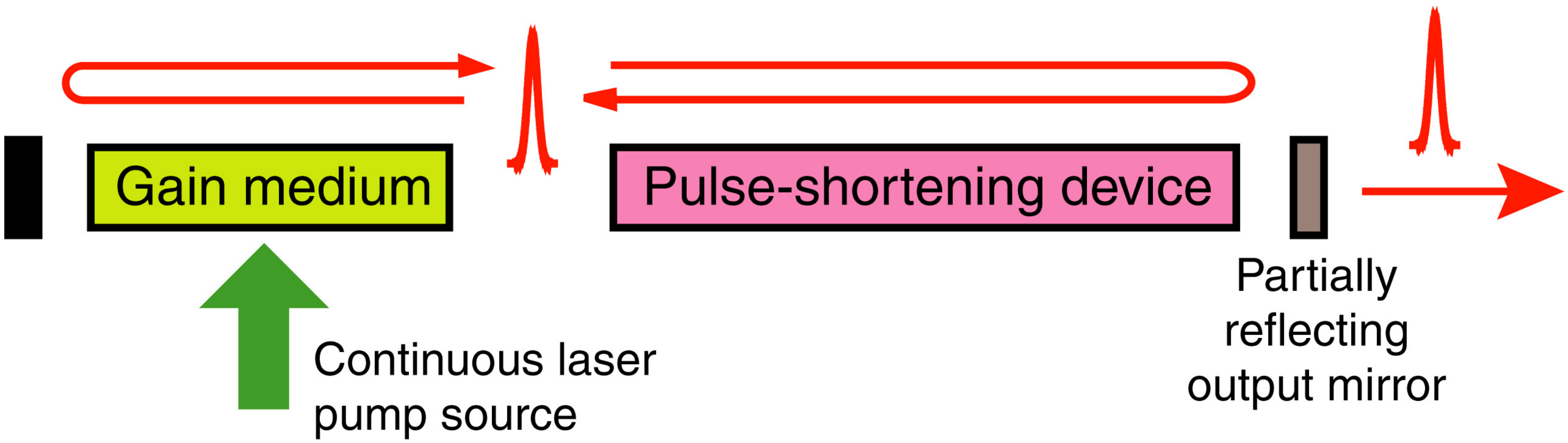


Locked phases of all laser modes



A generic ultrashort-pulse laser

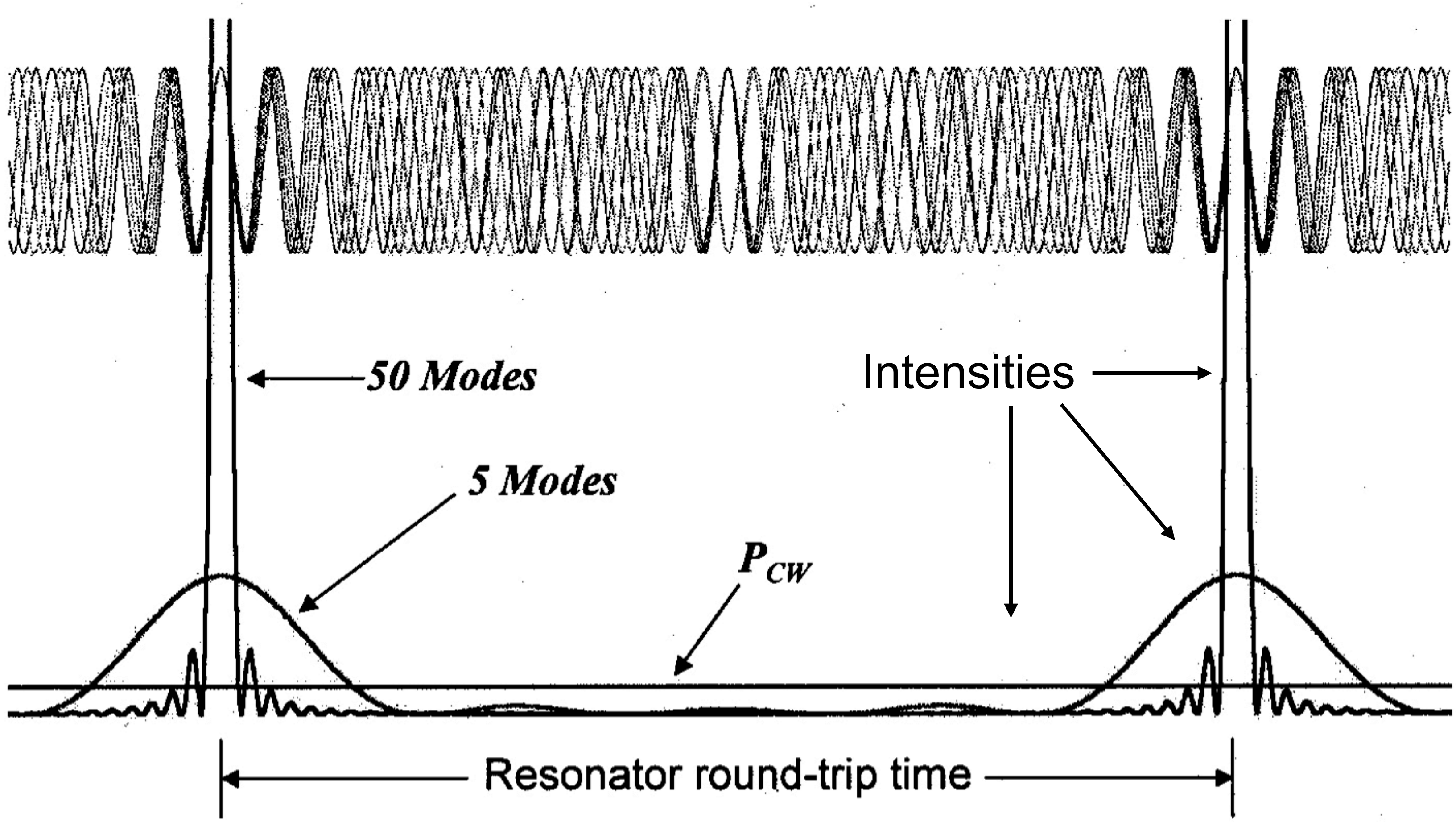
A generic ultrafast laser has a broadband gain medium,a pulse-shortening device, and two or more mirrors:



Pulse-shortening devices include:

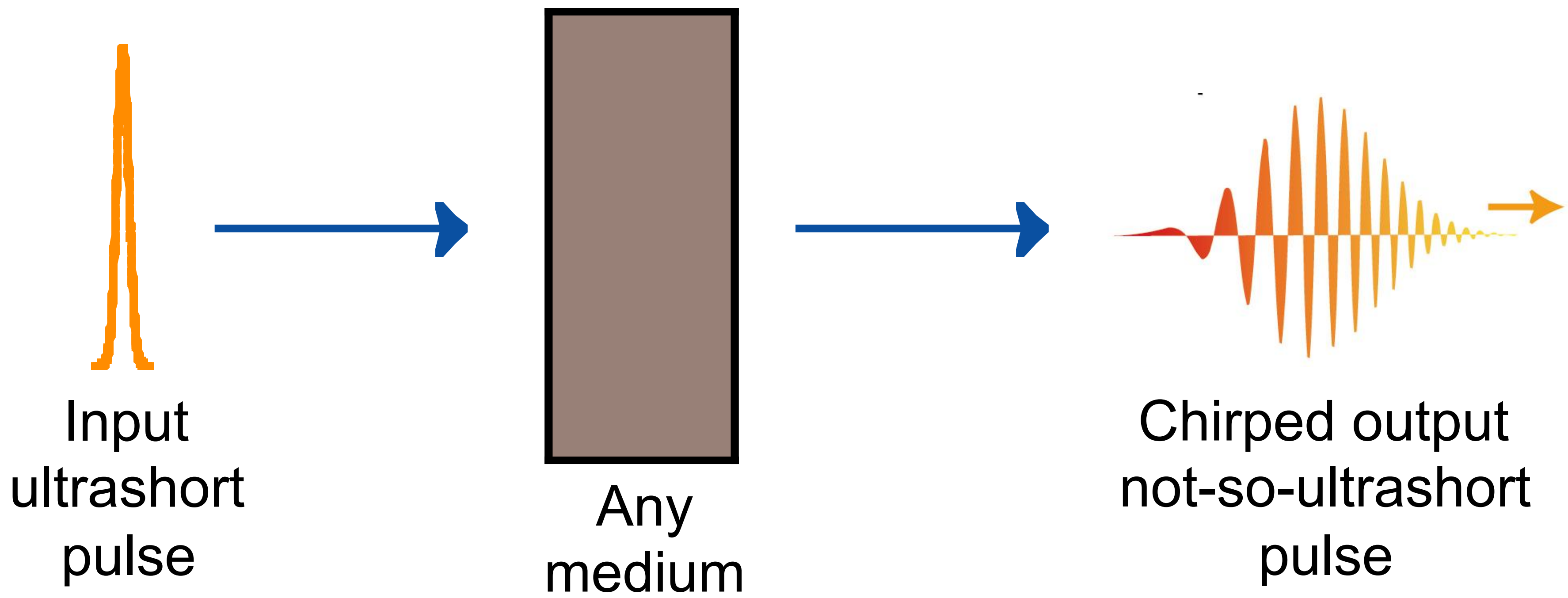
- Saturable absorbers
- Phase modulators
- Dispersion compensators
- Optical-Kerr media

Locking modes



Group velocity dispersion broadens ultrashort laser pulses

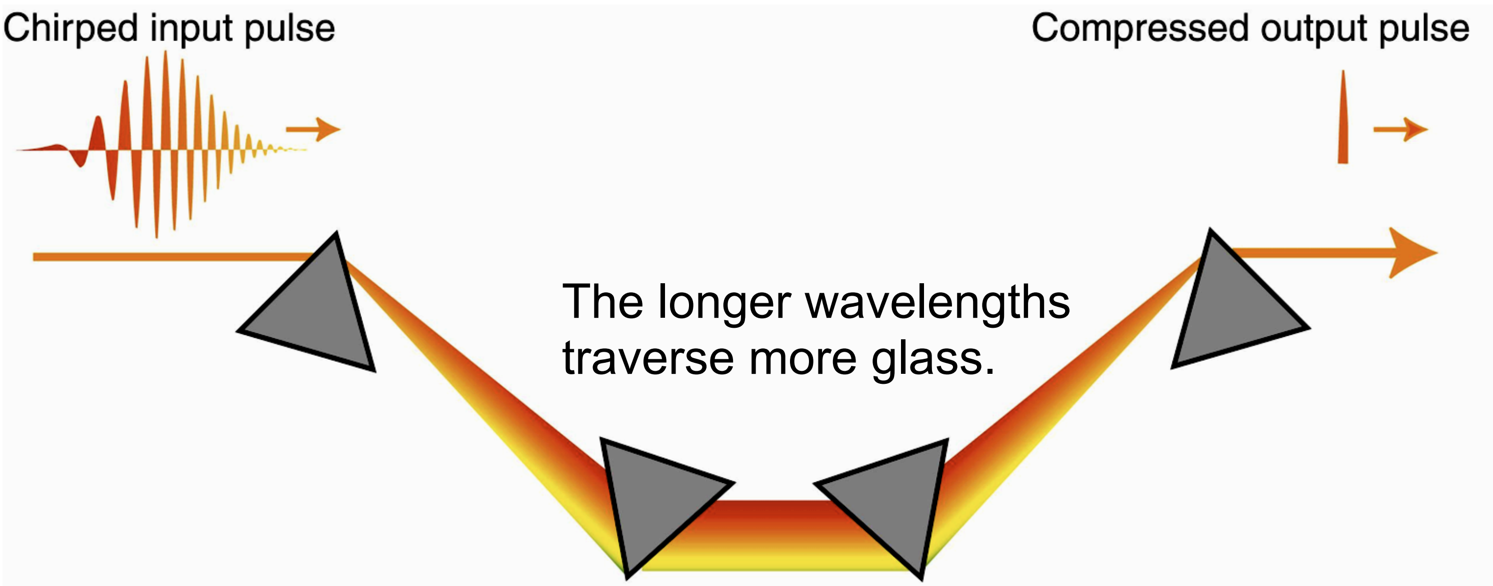
Different frequencies travel at different group velocities in materials, causing pulses to expand to highly "chirped" (frequency-swept) pulses.



Longer wavelengths almost always travel faster than shorter ones.

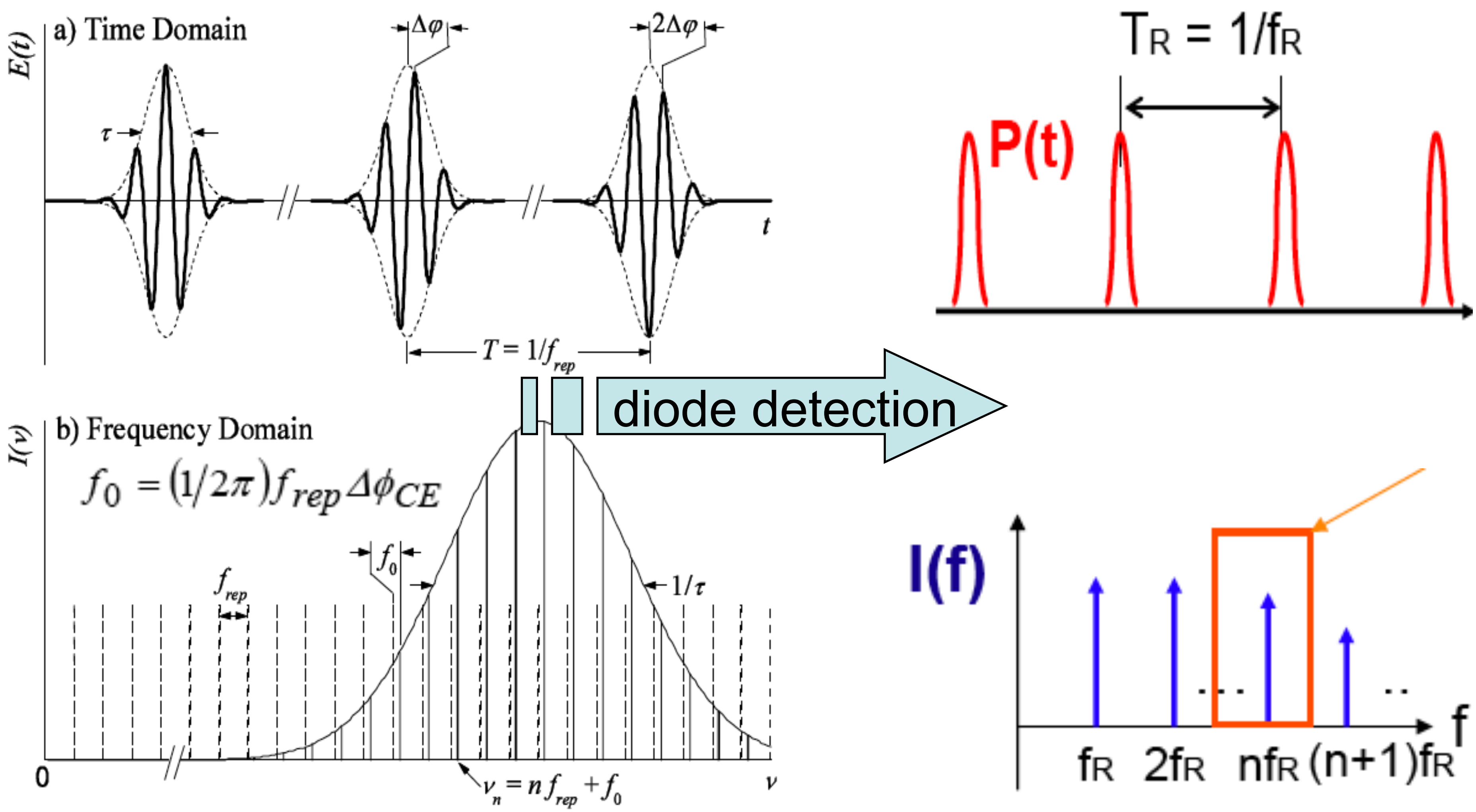
Pulse Compressor

This device has negative group-velocity dispersion and hence can compensate for propagation through materials (i.e., for positive chirp).

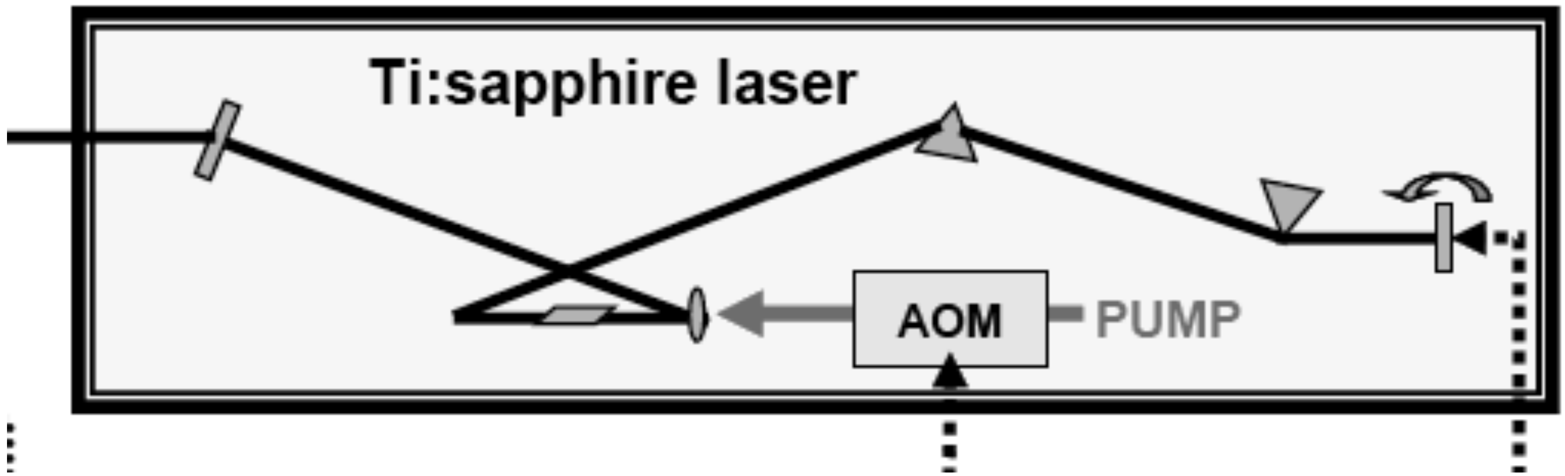


It's routine to stretch and then compress ultrashort pulses by factors of >1000

Femtosecond combs



Example:Ti:Sapph MLL



Repetition rate given by round trip travel time in cavity. Modulated by piezo adjustment of cavity mirror.

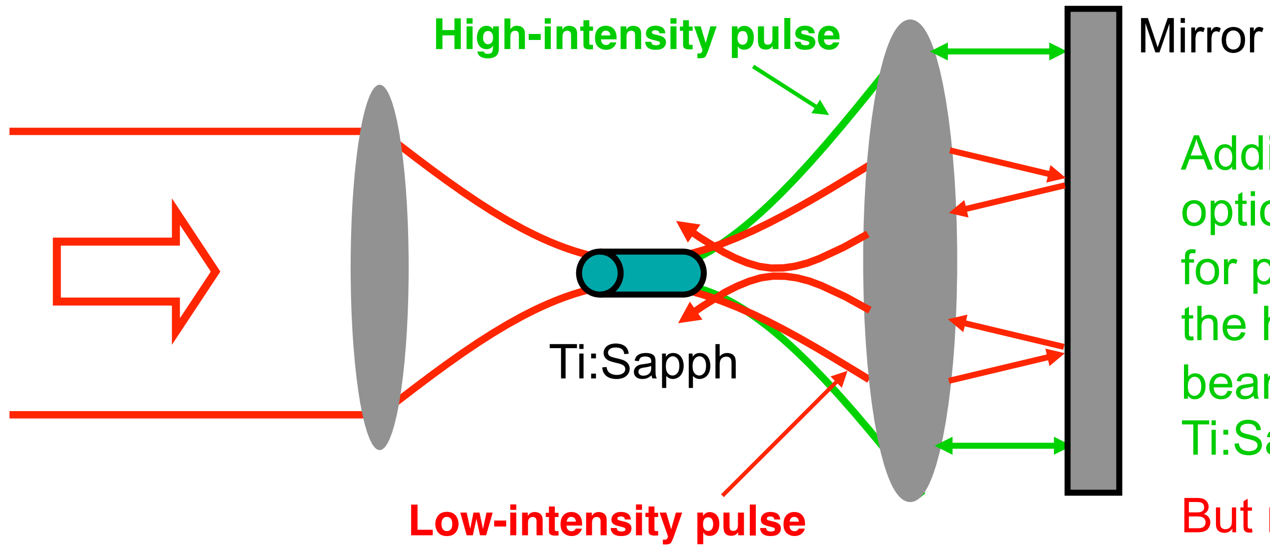
Passive mode locking achieved by properties of nonlinear crystal

Modern commercial designs include dispersion compensation in optics

Comb spectrum allows direct link of microwave frequencies to optical frequencies

Kerr-lensing is a type of saturable absorber.

If a pulse experiences additional focusing due to high intensity and the nonlinear refractive index, and we align the laser for this extra focusing, then a high-intensity beam will have better overlap with the gain medium.



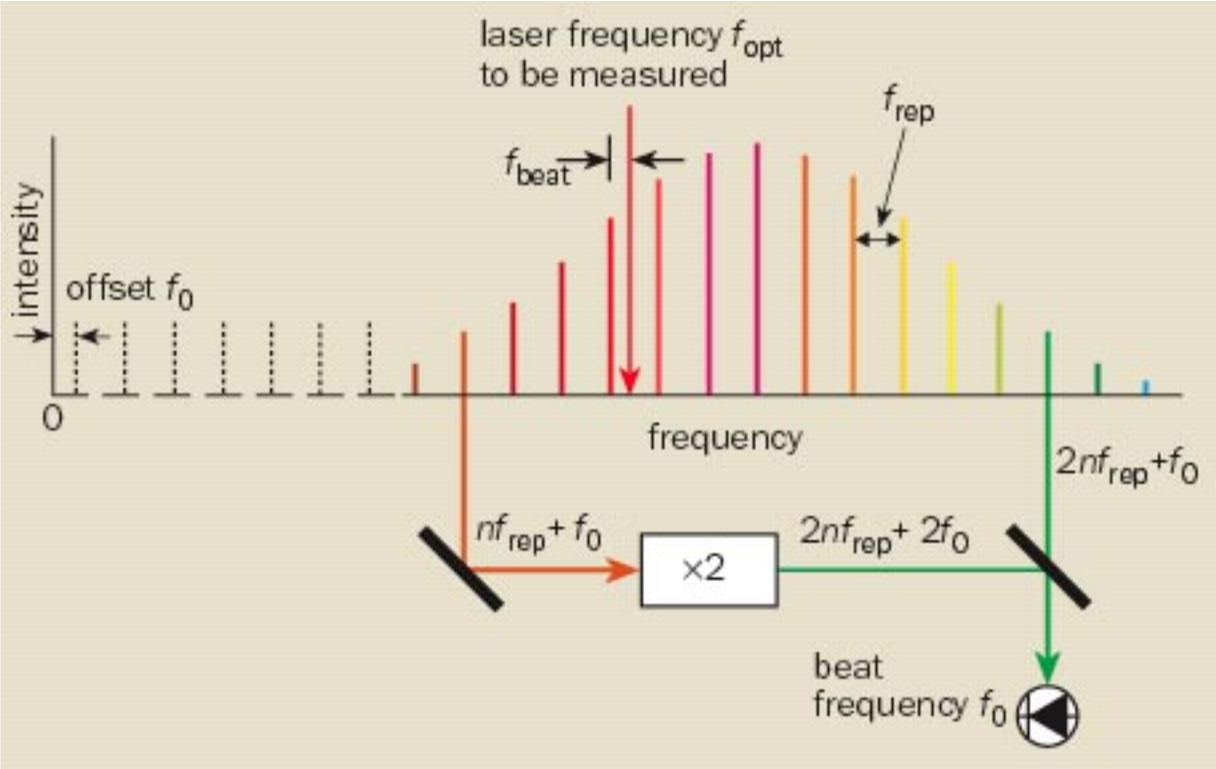
Additional focusing optics can arrange for perfect overlap of the high-intensity beam back in the Ti:Sapphire crystal.

But not the low-intensity beam!

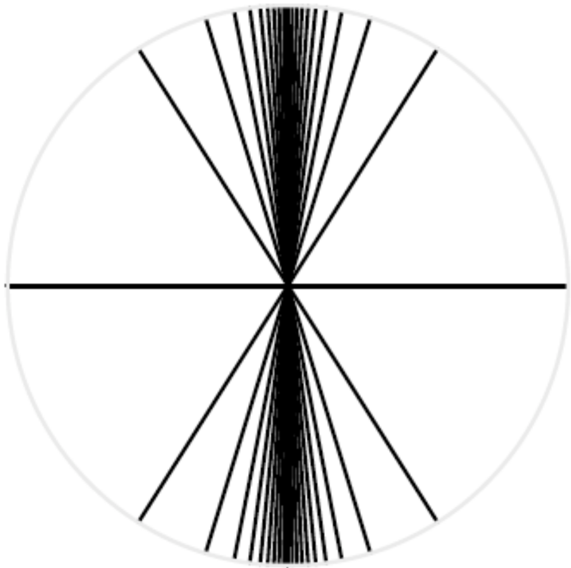
This is a type of saturable absorption.

Self-referencing stabilizer

CEO frequency can be directly measured with an octave spanning spectrum and stabilized in a feedback loop. This allows direct comparision (and or locking) with optical frequency standards.



Coulomb field of a relativistic particle



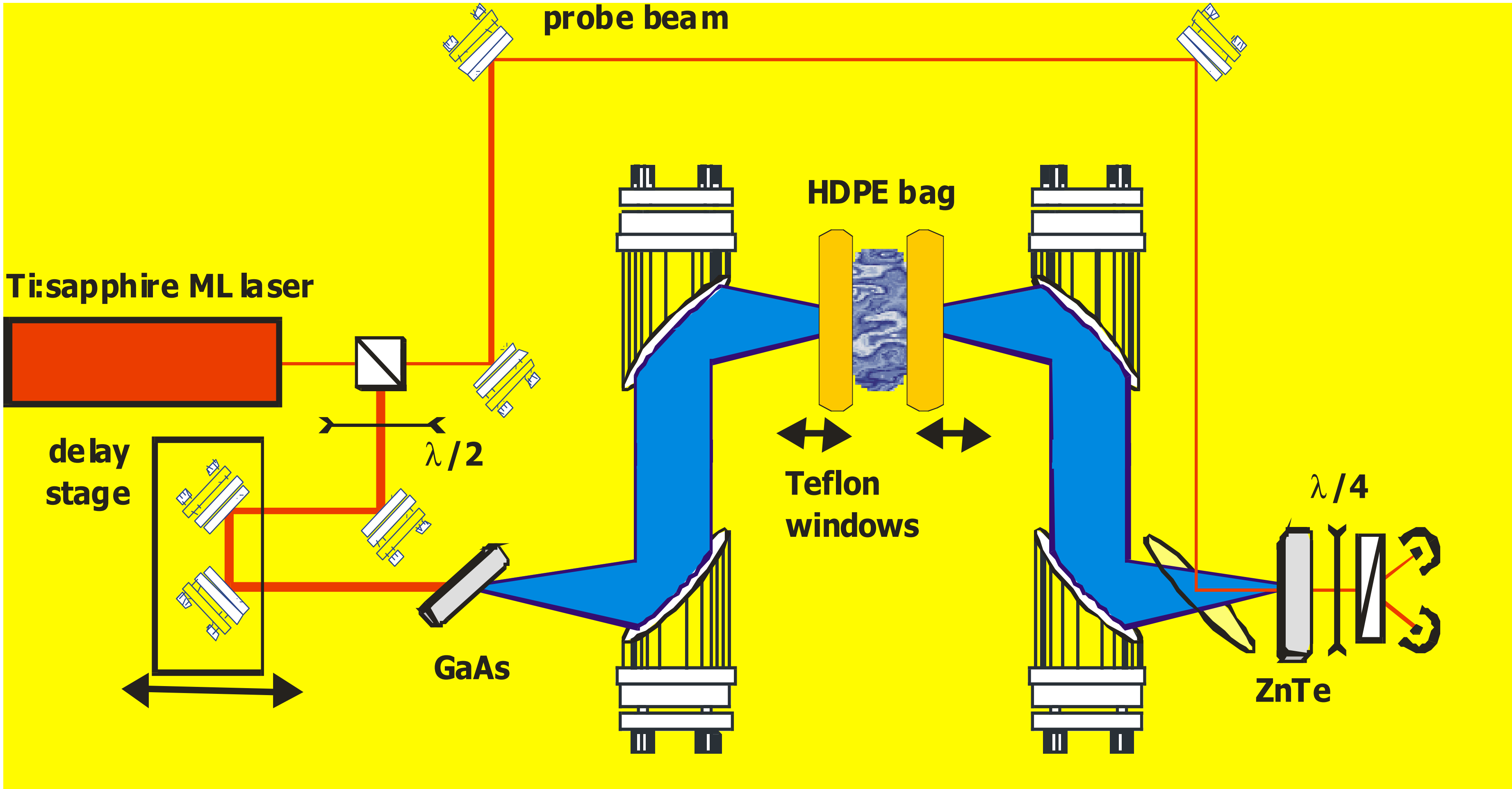
$$E_x = \frac{e}{4\pi\varepsilon_0}\frac{\gamma x}{(x^2+y^2+\gamma^2 Z^2)^{3/2}},$$
$$E_y = \frac{e}{4\pi\varepsilon_0}\frac{\gamma y}{(x^2+y^2+\gamma^2 Z^2)^{3/2}},$$
$$E_z = \frac{e}{4\pi\varepsilon_0}\frac{\gamma Z}{(x^2+y^2+\gamma^2 Z^2)^{3/2}},$$
$$\mathbf{B} = -\beta\times\mathbf{E},$$

When $r/\gamma << \sigma_z$
The radial field component is

$$E_r \approx \frac{q}{\sqrt{2\pi}\left(\varepsilon_0\sigma_z r\right)}$$

For q=1 nC, r=5 mm, σ_z= 150 micron (0.5 psec); γ=1e3
E_r=60 MV/m (!)
Use electro-optic effect to measure field and its time dependence.

Benchtop EO Sampling setup

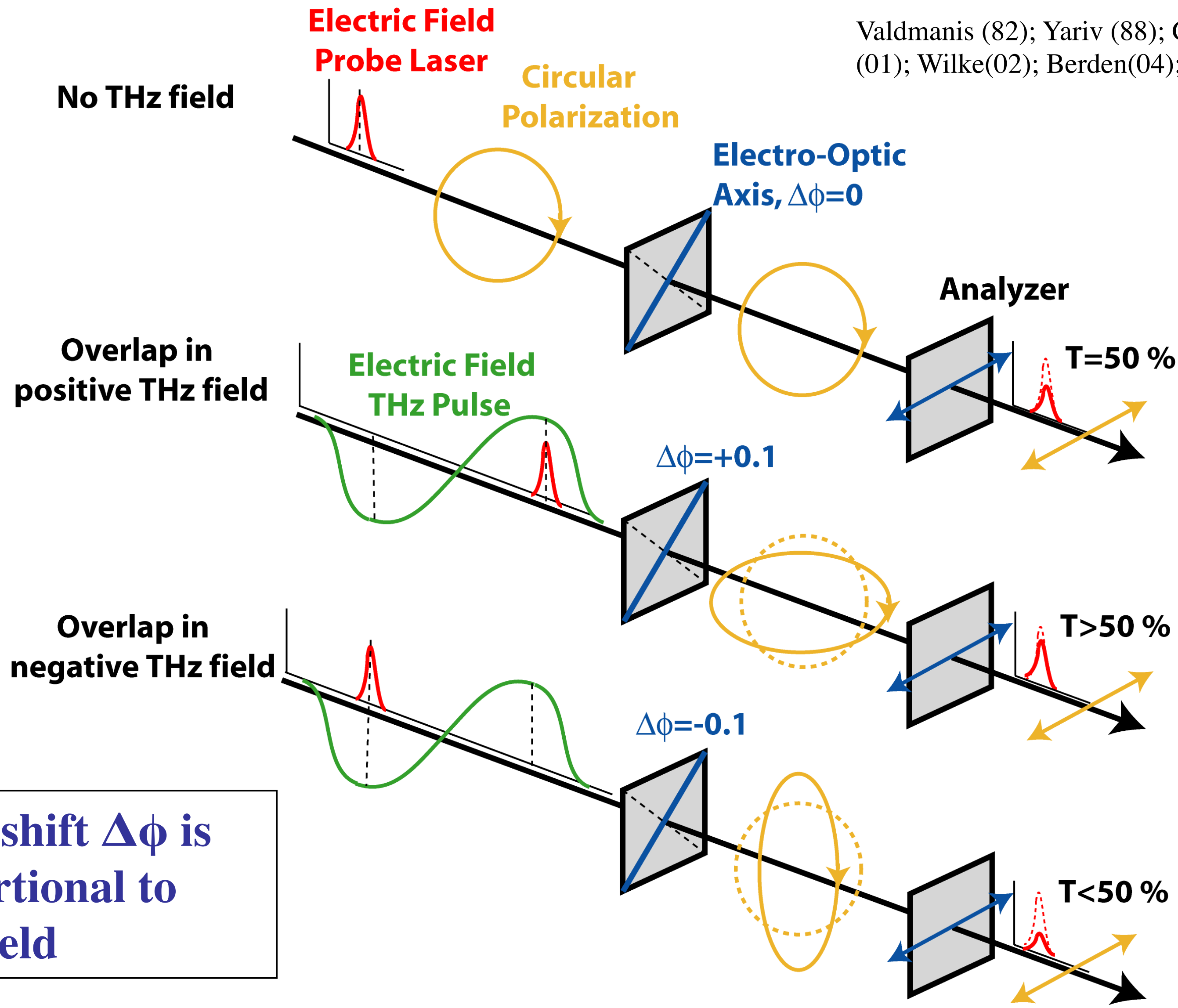


Benchtop setup

- Create THz field with fsec laser incident on an emitter.
- Use THz field to create EO effect on a crystal.
- Change in crystal index of refraction will vary polarization of probe laser proportional to THz E-field.
- Analyze change in polarization and detect.
- Bandwidth limited by response of EO crystal and time width of laser pulse.
- THz generator and probe inherently synchronized.

THz field sampling

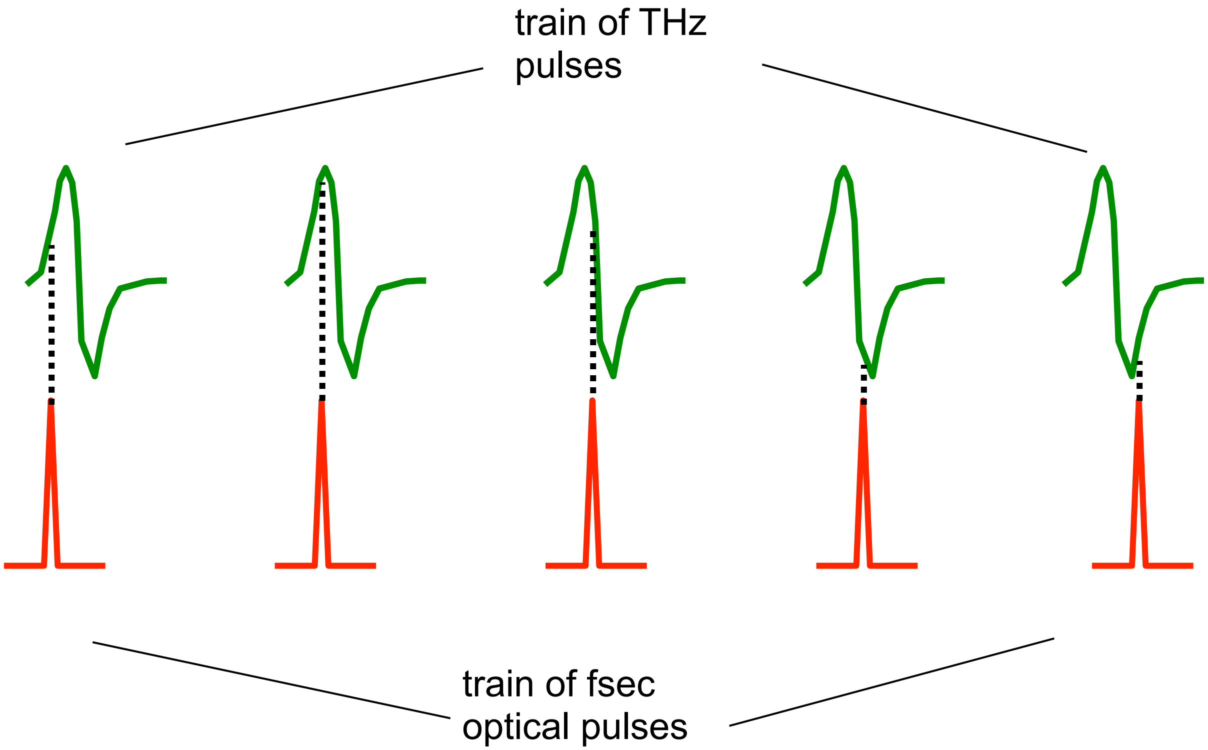
Valdmanis (82); Yariv (88); Gallot (99); Yan (00); Fitch (01); Wilke(02); Berden(04); Cavalieri(05)



Phase shift $\Delta\phi$ is proportional to THz field

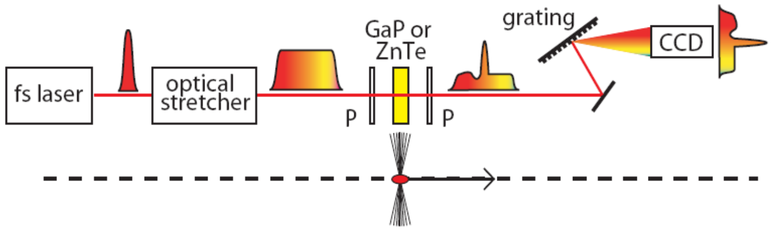
THz sampling

THz field is sampled by varying relative delay of generator and probe laser pulse. Synchronization between beam and sampling laser must be good.



Electro-Optic Detection of Direct Beam Fields

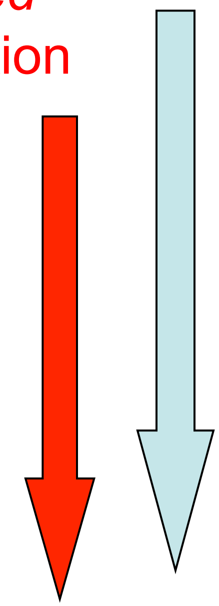
Spectral Decoding



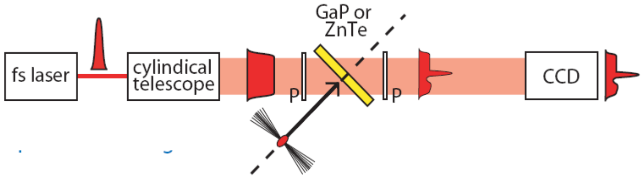
FELIX
DESY
LBNL
...

complexity

demonstrated
time resolution

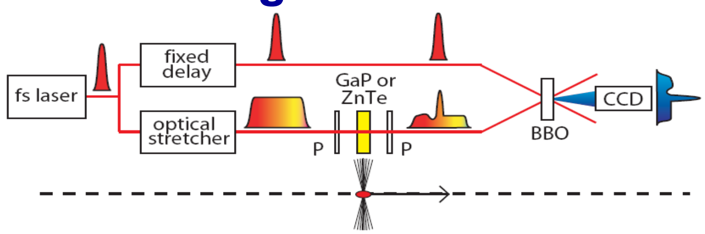


Spatial Encoding



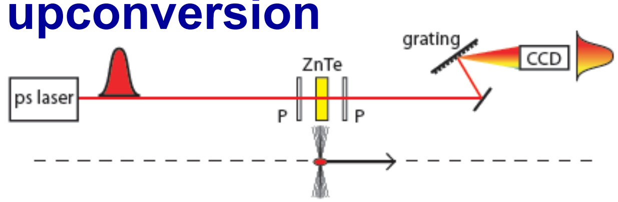
SLAC
DESY
LBNL, ...

Temporal Decoding

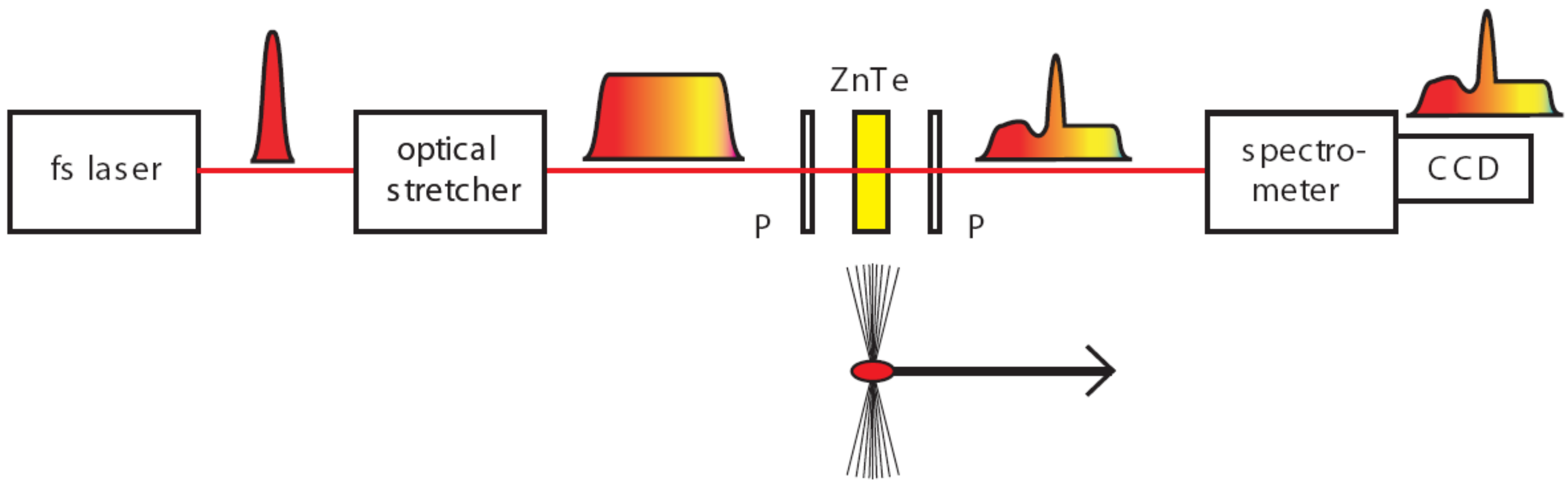


FELIX
DESY
RAL(CLF)
MPQ
Jena, ...

spectral upconversion

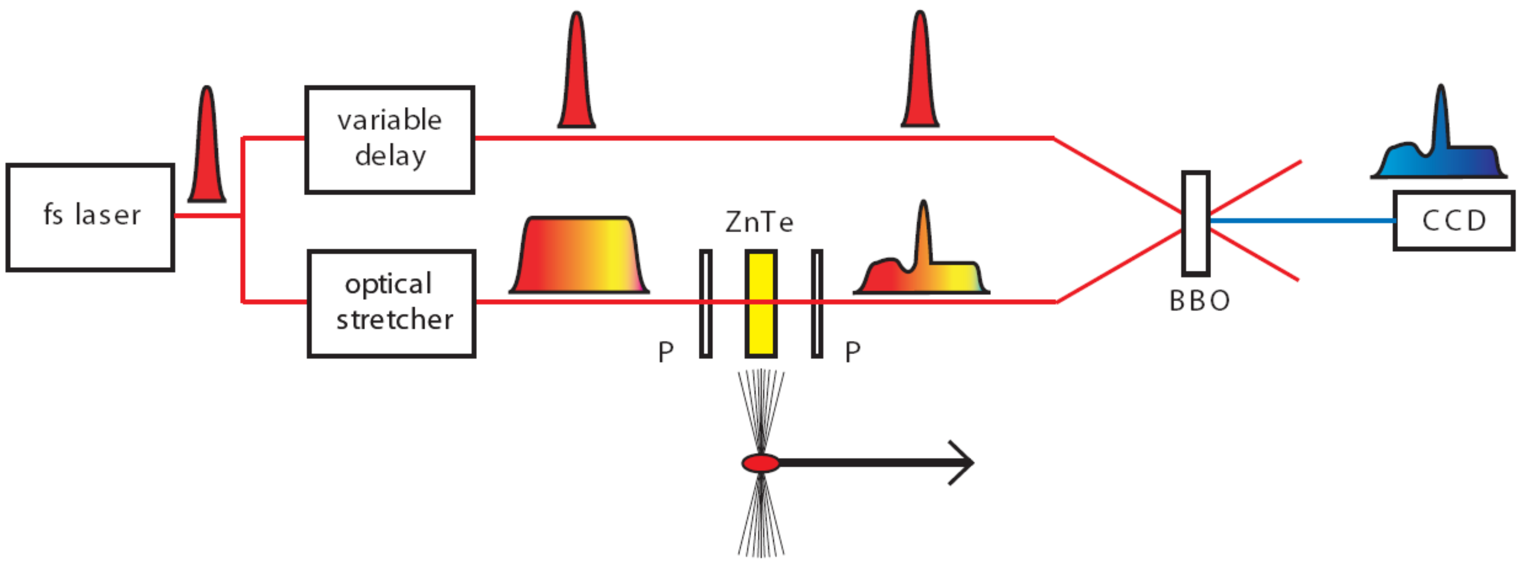


EO Sampling: spectral encoding



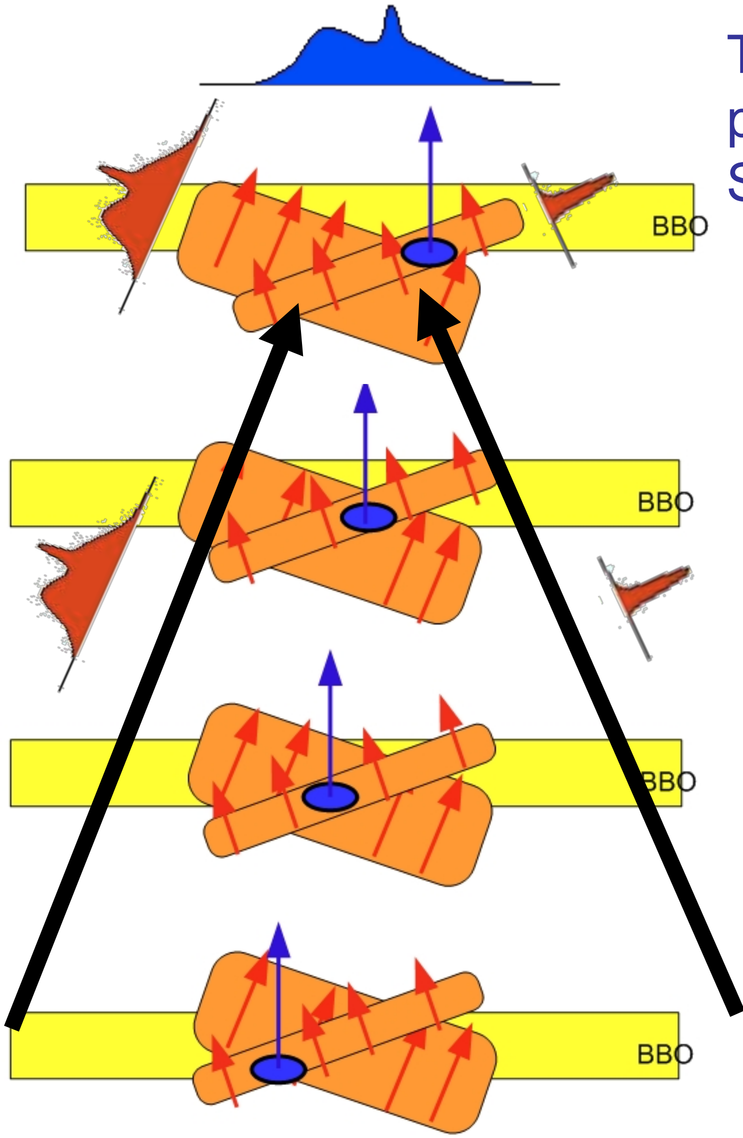
- Probe laser is optically stretched with time-wavelength correlation
- EO effect is imprinted on pulse
- Correlation is imaged from an optical spectrometer.

EO Sampling: temporal encoding



- Probe laser is optically stretched with time-wavelength correlation
- EO effect is imprinted on pulse
- Coincidence of stretched pulse and short pulse generates optical sum signal.
- Output angle is a function of sum signal frequency, creating an image.

Single-shot "temporal decoding" of optical probe



Temporal profile of probe pulse → Spatial image of SHG

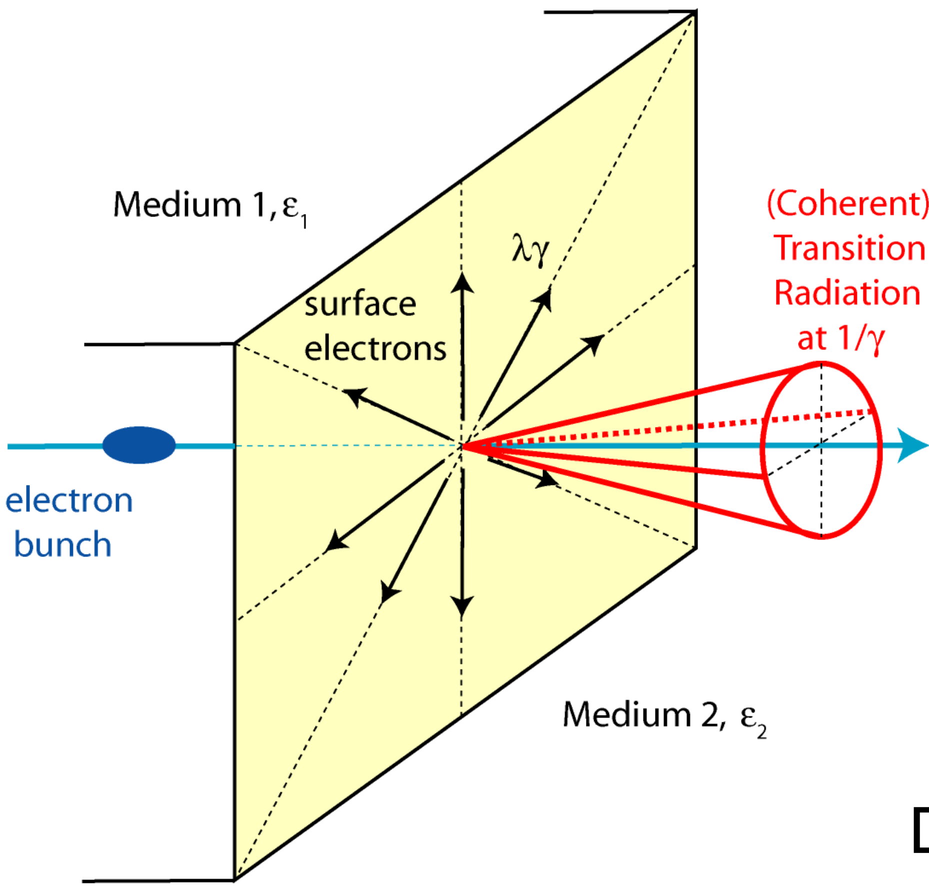
Symmetrical optical arrangement
No temporal blurring with crystal thickness

A few examples of EO sampling measurements

- Coherent transition radiation from <10 fsec bunches from a laser-plasma accelerator (J. van Tilborg, Berkeley Lab)
- CTR from linac bunches at the Source Development Lab (H. Loos, Brookhaven National Lab)
- Beam arrival time monitor at FLASH (F. Loehl, DESY)
- Coherent edge radiation from FLASH (G. Tavella, DESY)

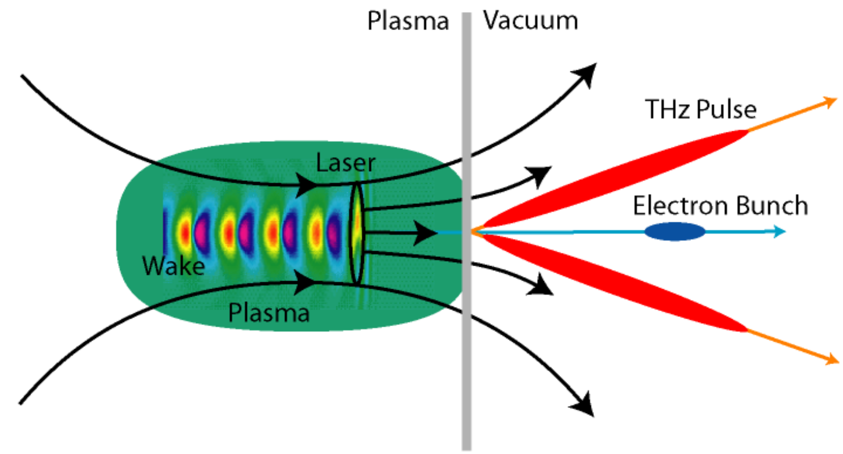
Coherent transition radiation from the plasma-vacuum boundary

Schematic for Transition Radiation



Boundary size ϱ

Laser-Wakefield Accelerator



Leemans *et al*., Phys. Rev. Lett. (2003);
Schroeder *et al*., Phys. Rev. E (2004);
Van Tilborg et al., Phys. Rev. Lett. (2006)

Diagnostic implementation:

- Use radiated field
- Couple out of vacuum chamber

CTR (THz) in spectral and temporal domain

Diffraction function (boundary size ρ)

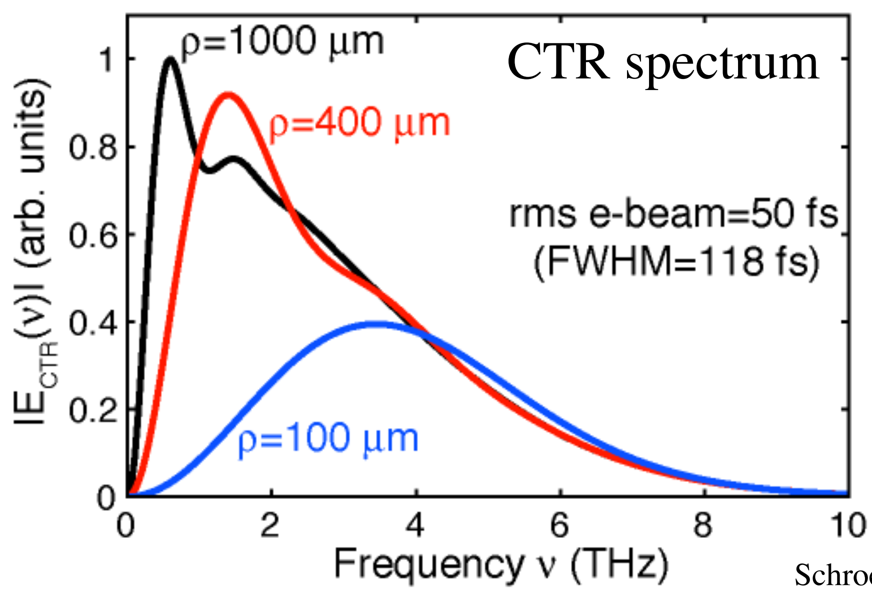
$$E_{\rm CTR}(\omega) \propto N\mathcal{E}(u)D(\omega,u,\rho)F(\omega)$$

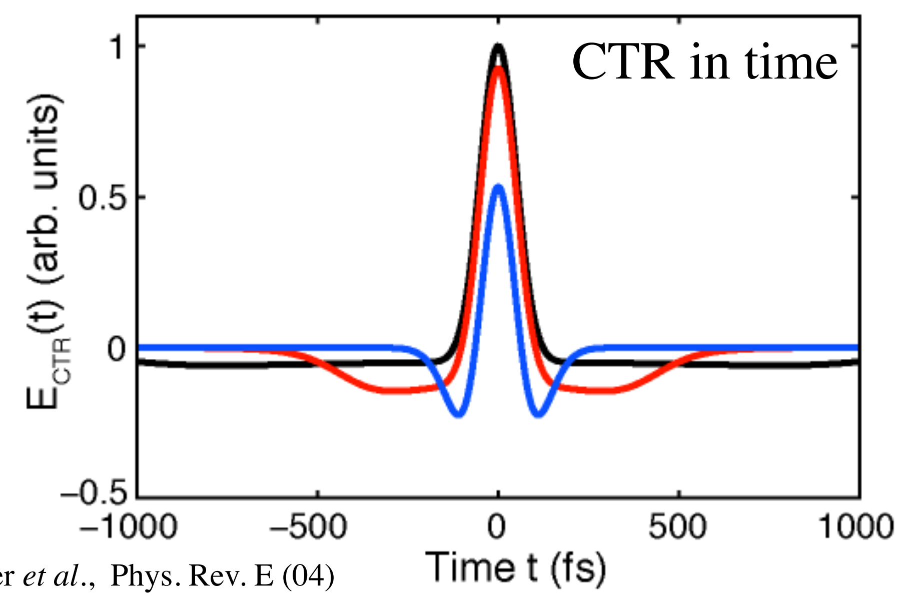
Single electron TR

Form factor

Intense THz source

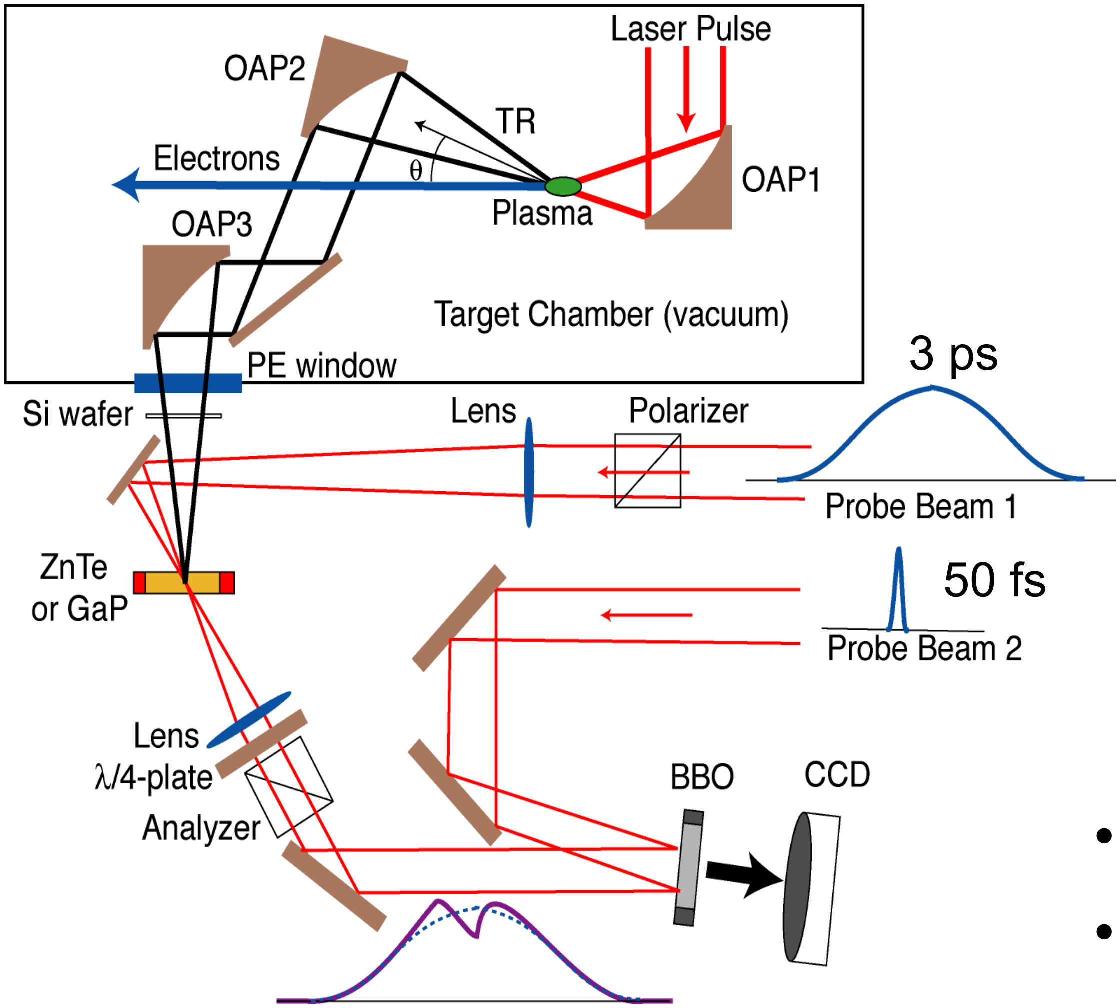
- **0.01-10 MV/cm** at focus (up to **10's of μJ** in THz pulse)
- 'traditional' laser-based sources deliver <100 kV/cm

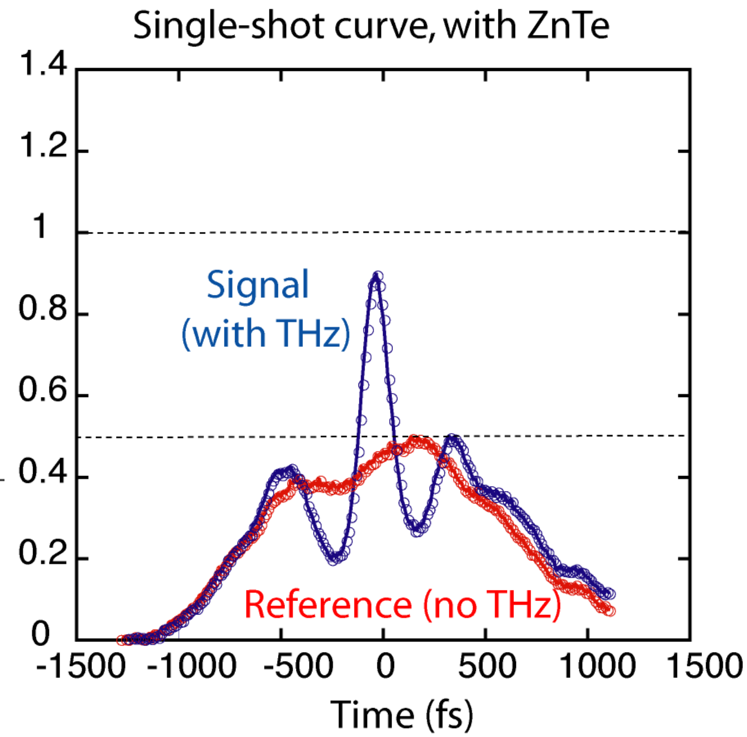




Schroeder *et al*., Phys. Rev. E (04)
van Tilborg *et al*., Laser Part. Beams (04)
van Tilborg *et al*., Phys. Plasmas, submitted

EO detection of THz pulses:





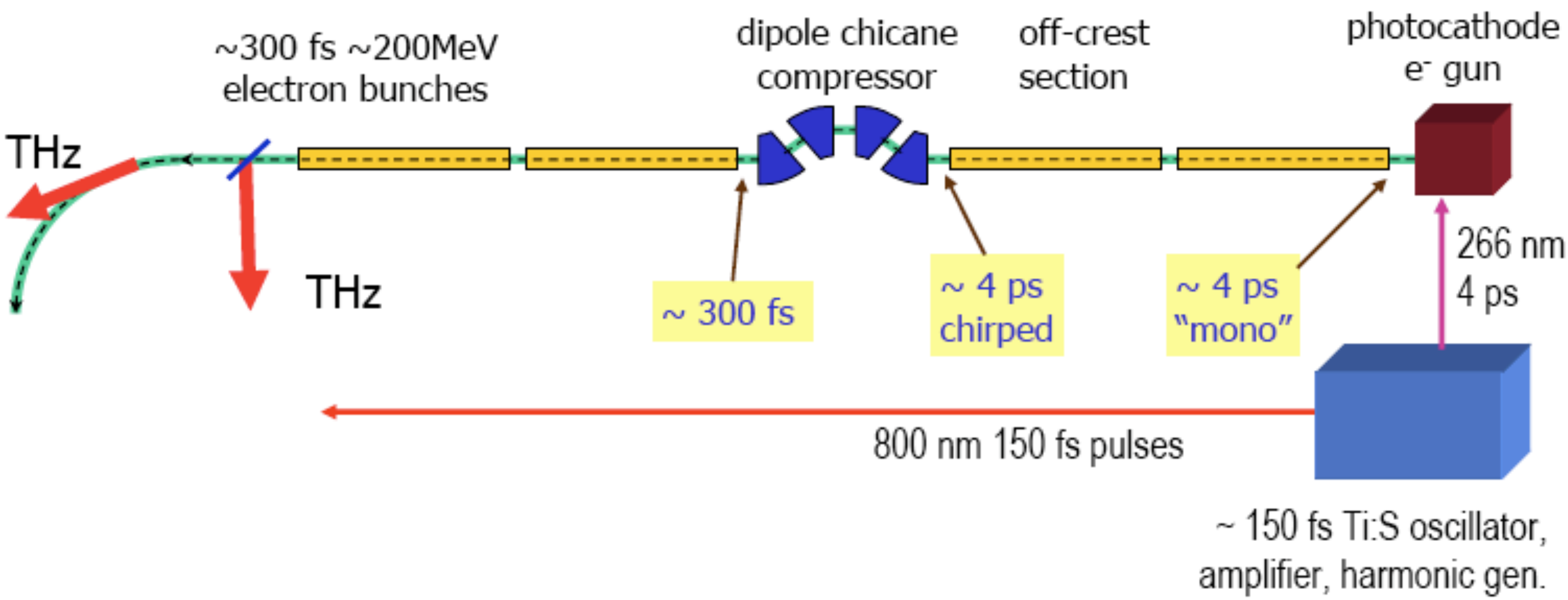
- < 50 fs bunches
- peak E-field of $E_{CTR} \approx 150$ kV/cm

G. Berden et al., Phys. Rev. Lett. 93, 114802 (2004)

J. van Tilborg et al., PRL

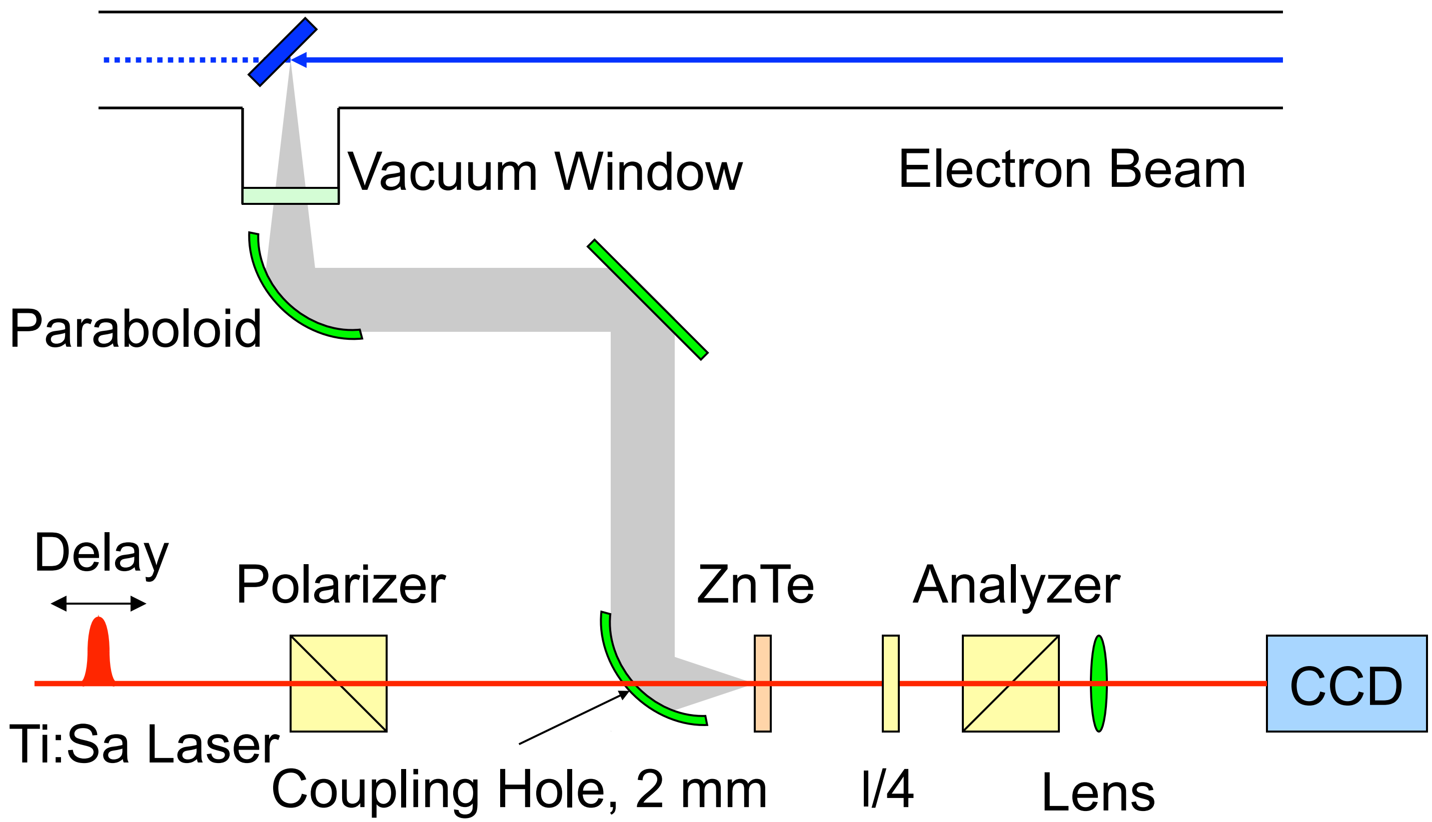
Example:Deep UV Free Electron Laser at SDL

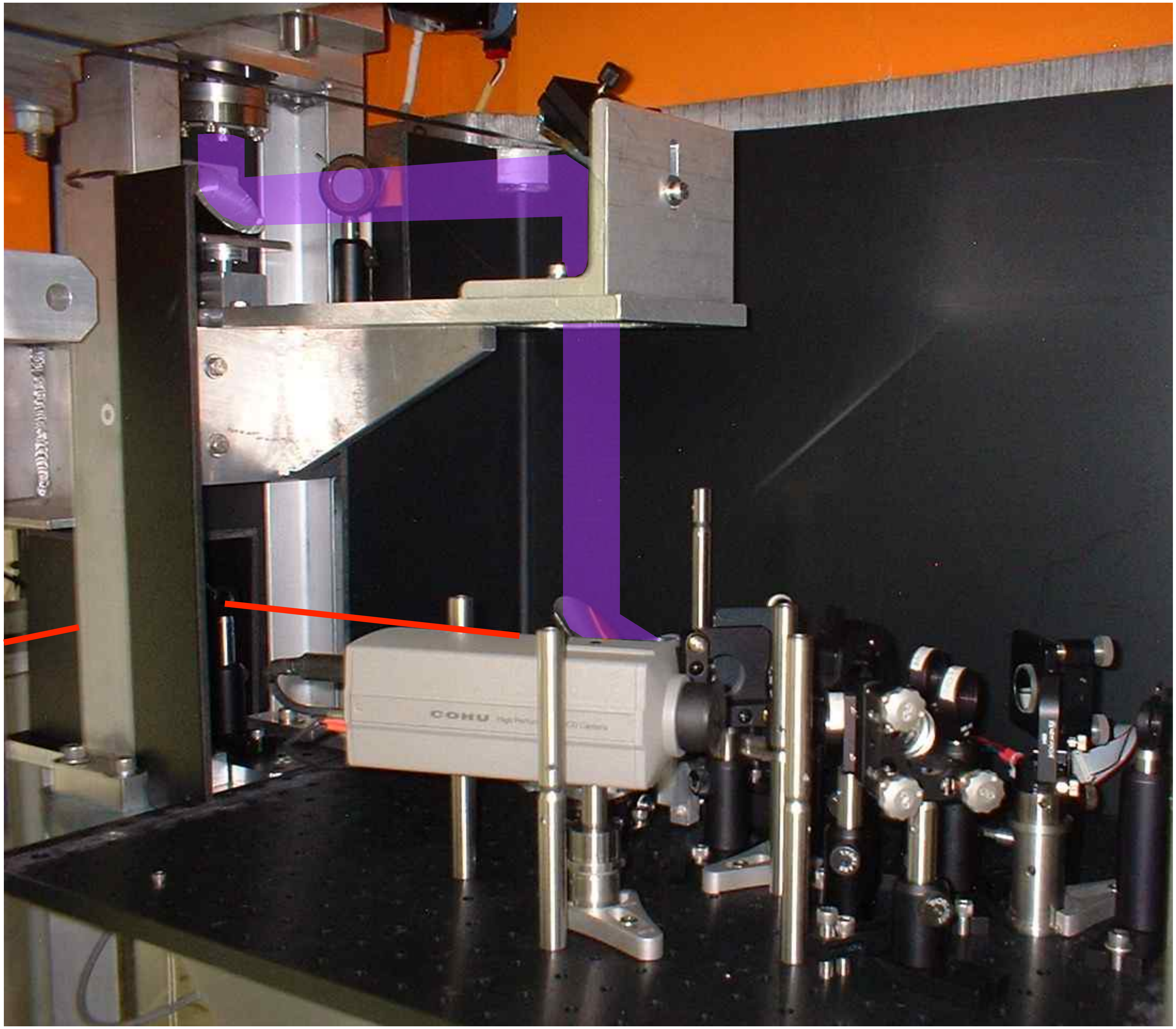
- Photocathode gun produces ~ 0.84nC (5×10^9 electrons) per "shot"

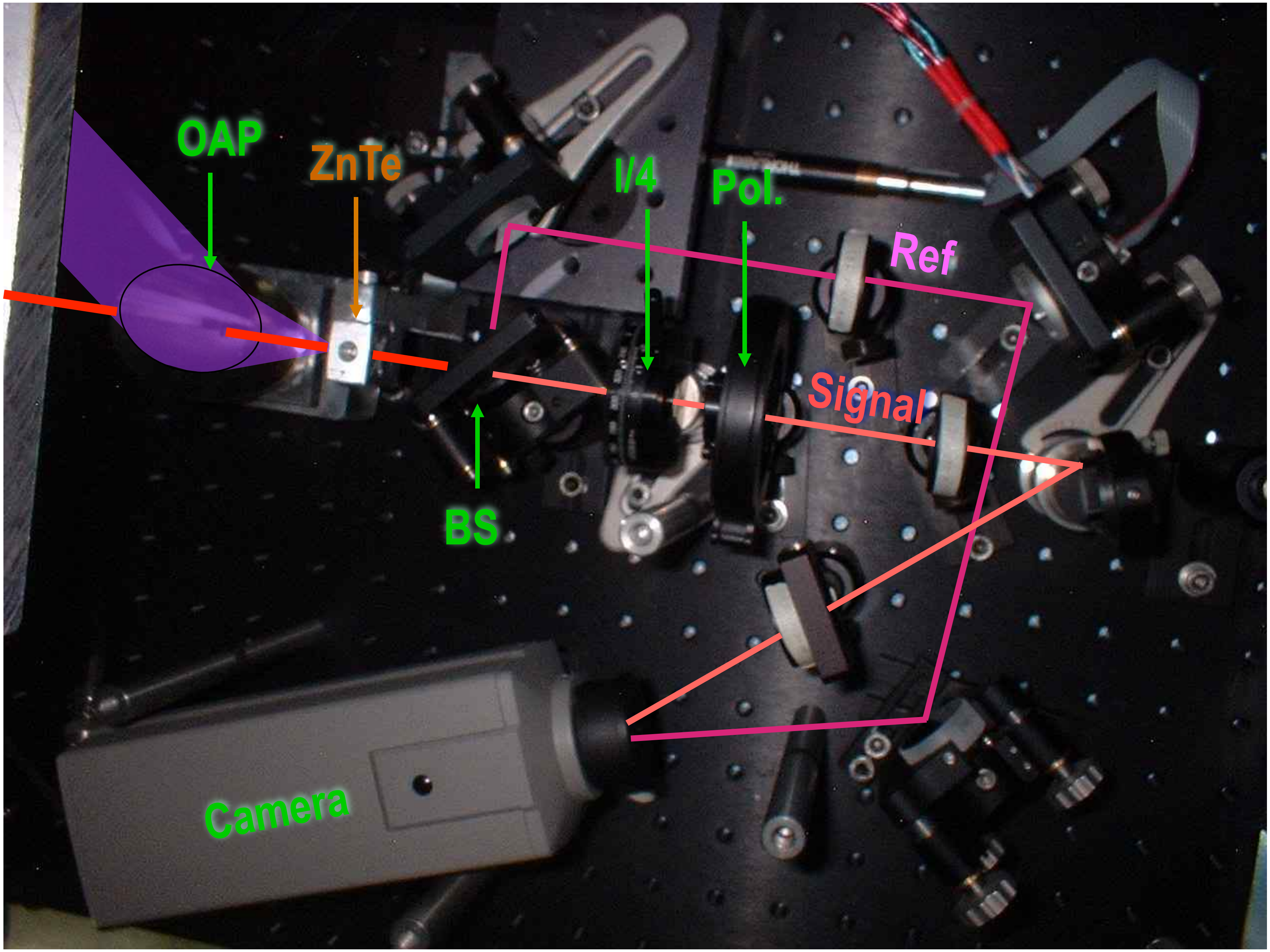


- Coherent output to over 1 THz. Potential for shorter bunches with less charge.
- Low rep. rate (1 to 10 Hz)

Electro-Optic THz Radiation Setup



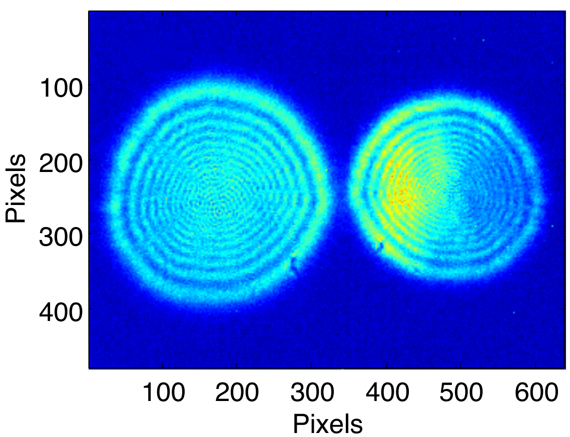

COHU



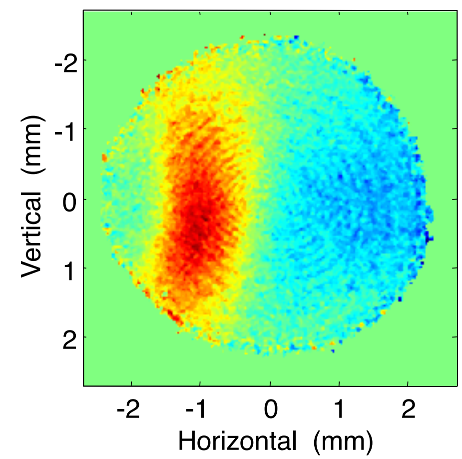
OAP
ZnTe
l/4
Pol.
Ref
Signal
BS
Camera

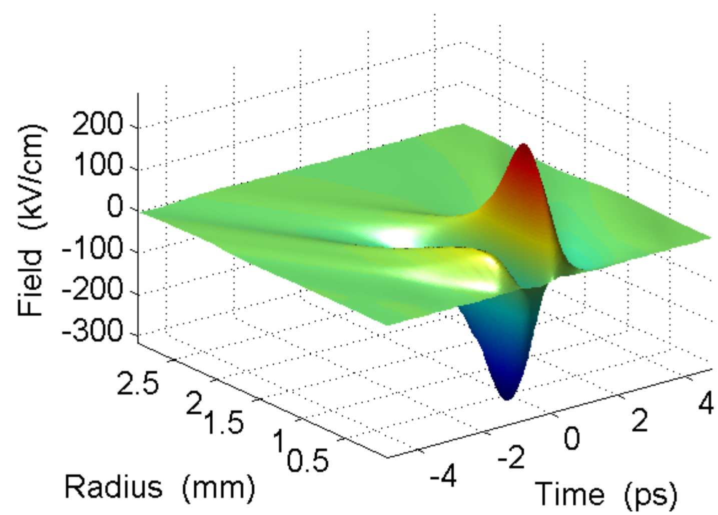
Image Processing for Field Measurement

- Use compensator waveplate to detect sign of polarization change.
- Reference I_R (left) and Signal I_S (right) obtained simultaneous.
- Rescale and normalize both.
- Calculate asymmetry A of Signal.
- Subtract asymmetry pattern w/o THz.



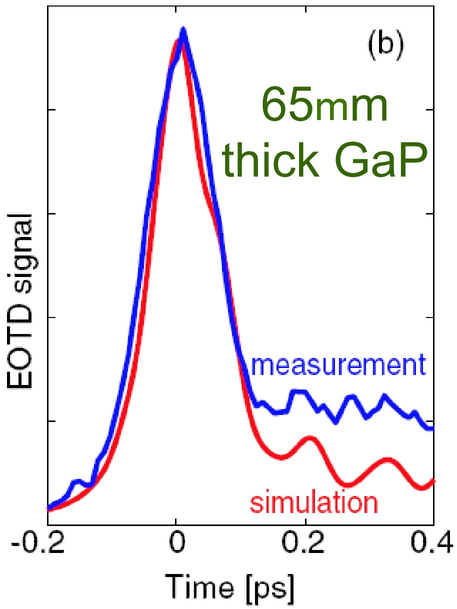
$$A = 2I_S/I_R - 1$$

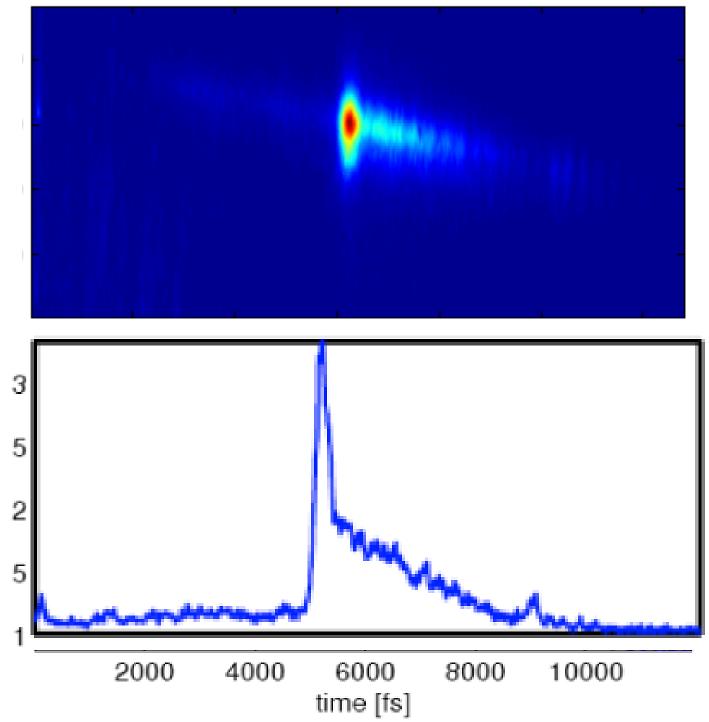


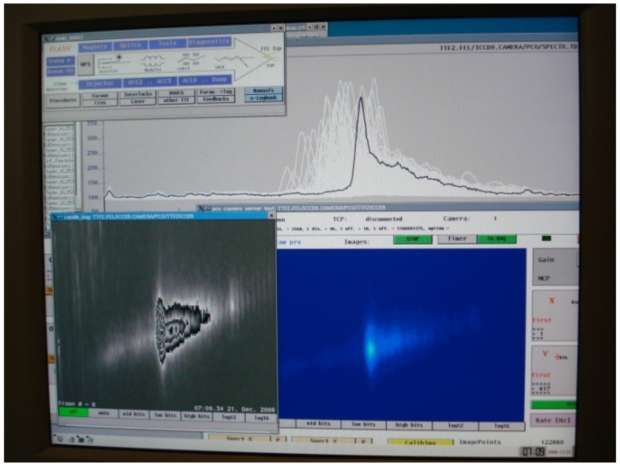


temporal decoding in practice..

currently the highest time-resolution
non-destructive diagnostic demonstrated







"Time resolution"

$\sigma_z \sim$ 90fs (rms)

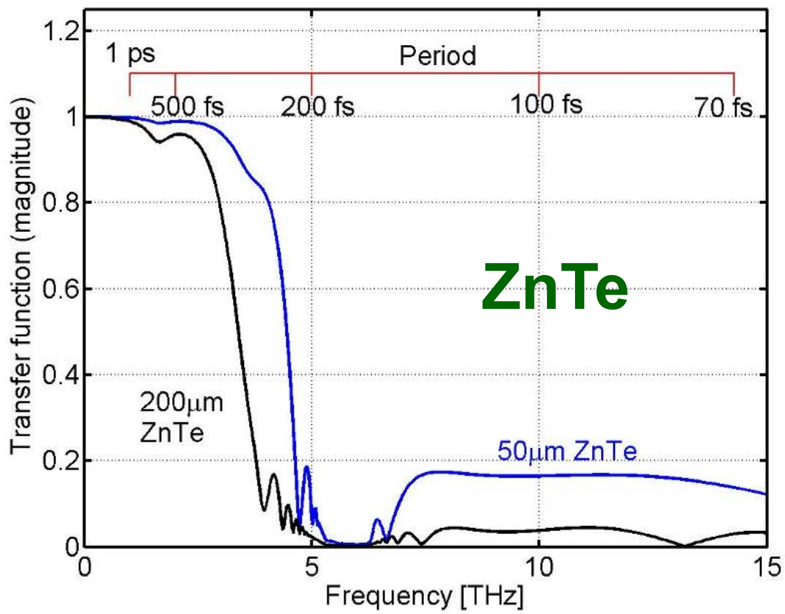
$\sigma_z^{actual} \sim$ 30fs $\rightarrow$ $\sigma_z^{measured}$ ~55 fs
$\sigma_z^{actual} \sim$ 90fs $\rightarrow$ $\sigma_z^{measured}$ ~90 fs

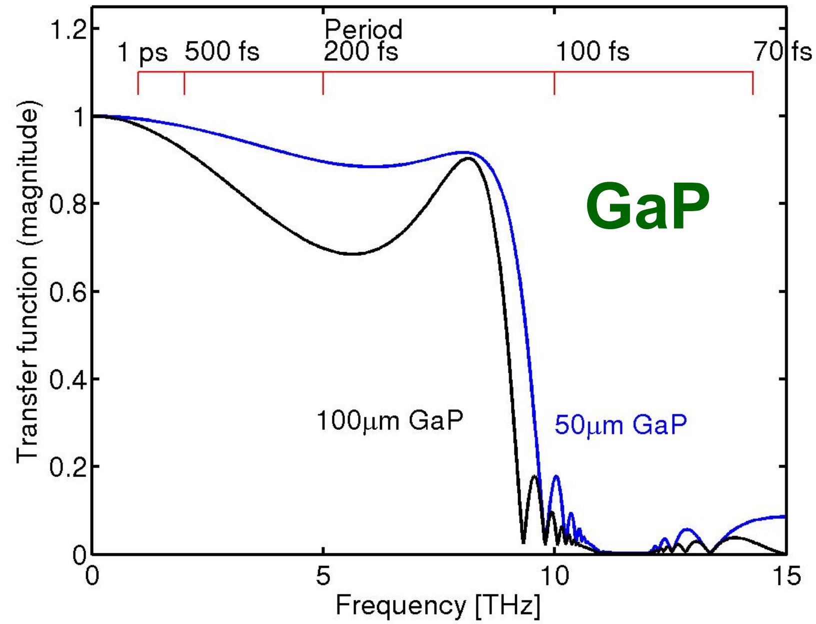
Courtesy, S. Jamison

Encoding Time Resolution...

material frequency response, R(ω)

- velocity mismatch of Coulomb field and probe laser
- frequency mixing efficiency, $c^{(2)}(\omega)$

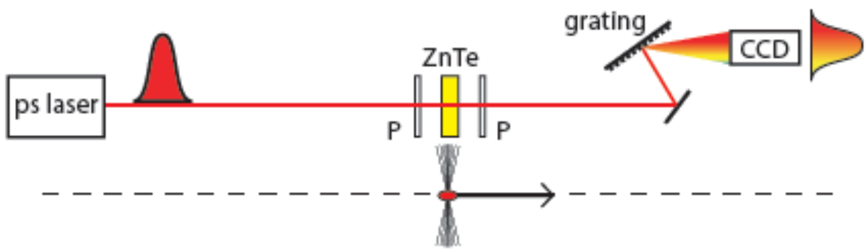




Courtesy, S. Jamison

Spectral upconversion diagnostic

Aim to measure the bunch Fourier spectrum...



... accepting loss of phase information & explicit temporal information

... gaining potential for determining information on even shorter structure

... gaining measurement simplicity

use long pulse, narrow band, probe laser

$$\tilde{E}^{\rm opt}_{\rm out}(\omega) = \underbrace{\tilde{E}^{\rm opt}_{\rm in}(\omega)} + i\omega a \underbrace{\tilde{E}^{\rm opt}_{\rm in}(\omega)} * \left[\tilde{E}^{\rm Coul}(\omega)\tilde{R}(\omega)\right]$$

≈ δ-function

same physics as "standard" EO

$$\tilde{E}(\omega_0+\Omega) = \tilde{E}(\omega_0) + i\omega a\tilde{E}(\omega_0)\left[\tilde{E}^{\rm Coul}(\Omega)\tilde{R}(\Omega)\right]$$

$(\Omega \text{ can be } < 0)$

different observational outcome

- ***laser complexity reduced, reliability increased***
- ***laser transport becomes trivial (fibre)***
- ***problematic artefacts of spectral decoding become solution***

NOTE: the long probe is converted to optical replica

Courtesy, S. Jamison

Spectral upconversion diagnostic

Theory / Expt. comparison

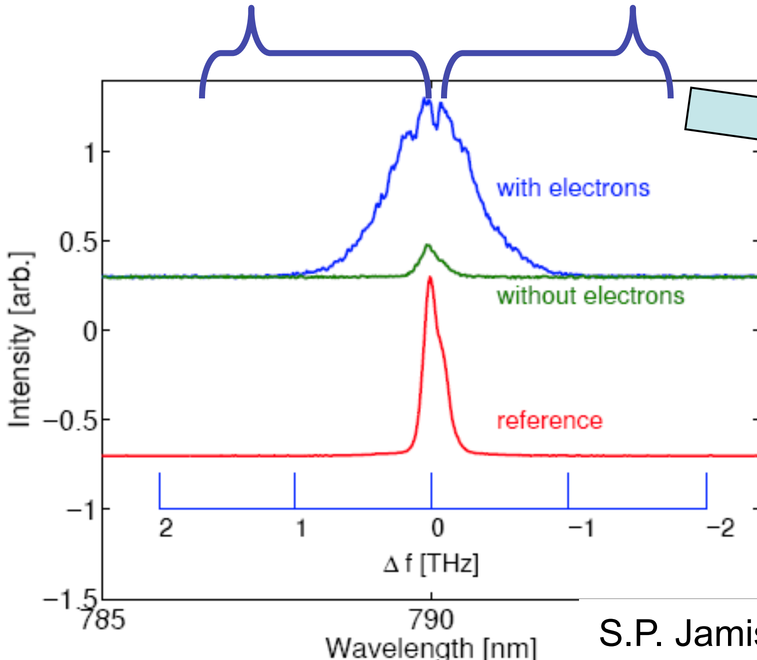
Results from experiments at FELIX (Feb 2009)
in FEL'09; (Appl. Phys. Lett.)

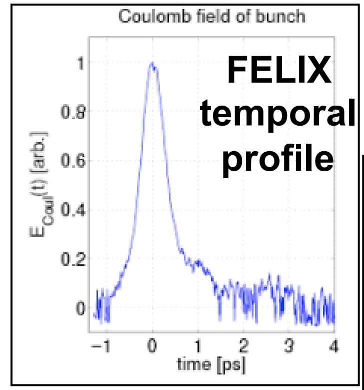
sum frequency mixing

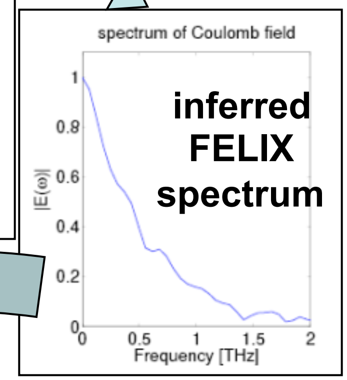
$$\tilde{E}(\omega_0+\Omega) = i\omega a\tilde{E}(\omega_0)\,\tilde{E}^{\mathrm{Coul}}(\Omega)\tilde{R}(\Omega)$$

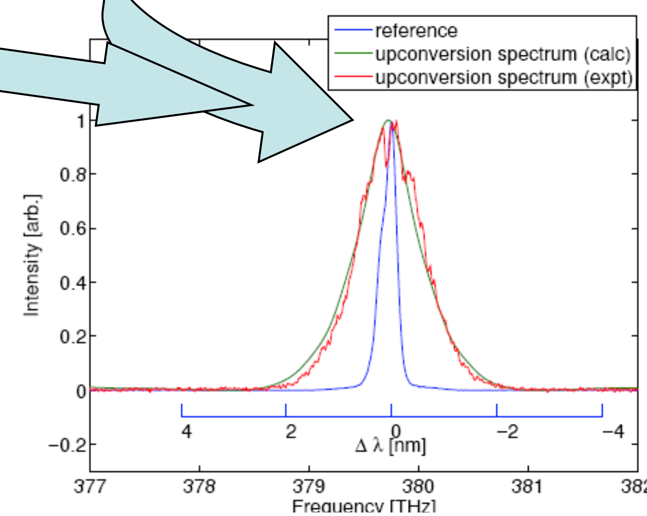
difference frequency mixing

$$\tilde{E}(\omega_0-\Omega) = i\omega a\tilde{E}(\omega_0)[\{\tilde{E}^{\mathrm{Coul}}(\Omega)\}^*\tilde{R}^*(\Omega)]$$



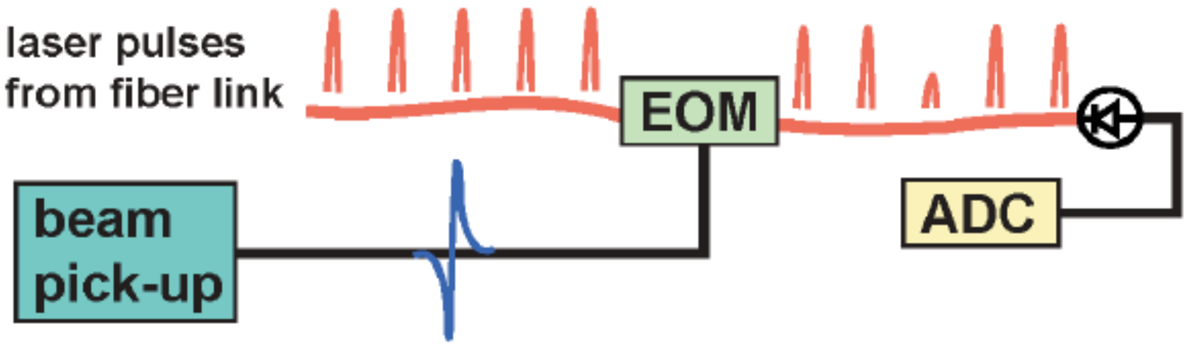






S.P. Jamison, G. Berden, P. J. Phillips, W.A. Gillespie, A.M. MacLeod
APL 2010: 96(23): 231114- 231114-3

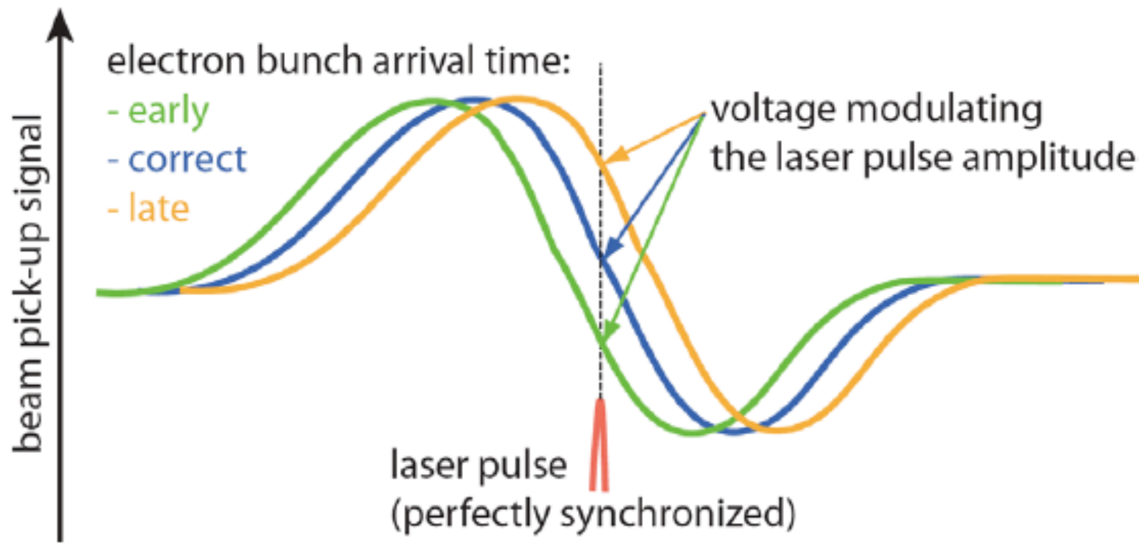
Example: Beam Arrival Time Monitor using MLL pulses



A laser pulse samples the zero-crossing of a beam induced pick-up signal.

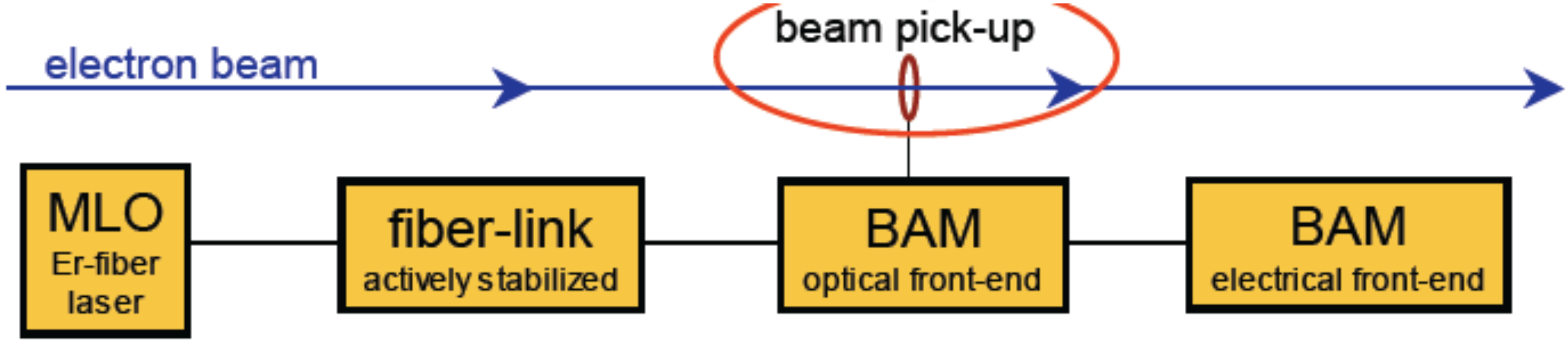
Variations of the bunch arrival-time result in a modulation of the laser pulse energies.

By measuring the energies of single laser pulses, the bunch arrival time can be deduced.

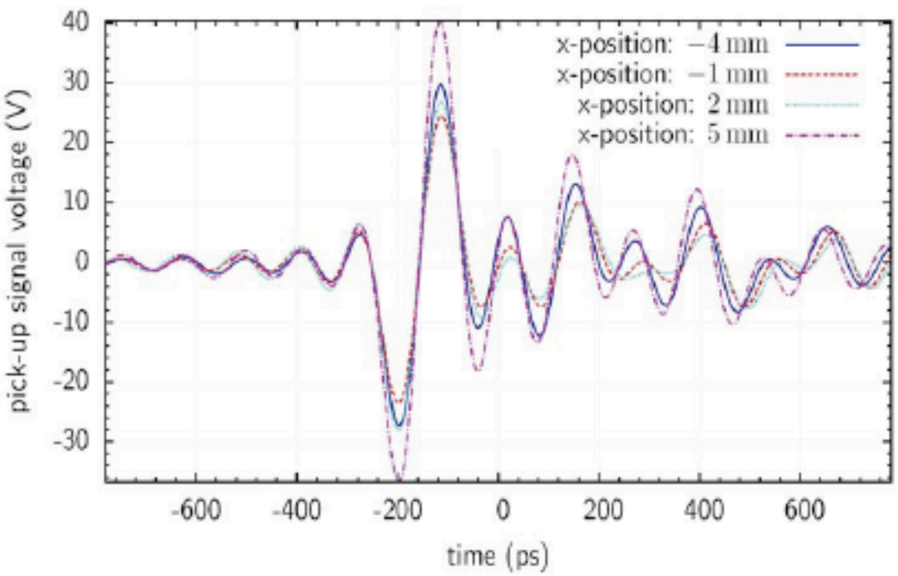


- Florian Loehl, et al., PRL 104, 144801 (2010)

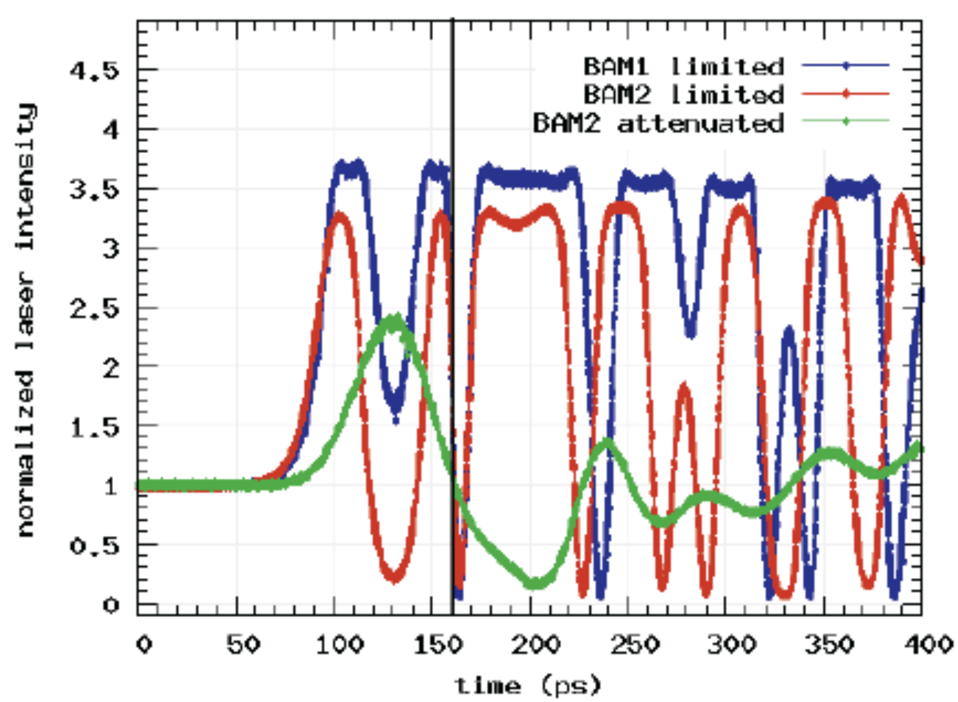
High bandwidth BPM signals to modulate laser pulse train



8 GHz oscilloscope measurement

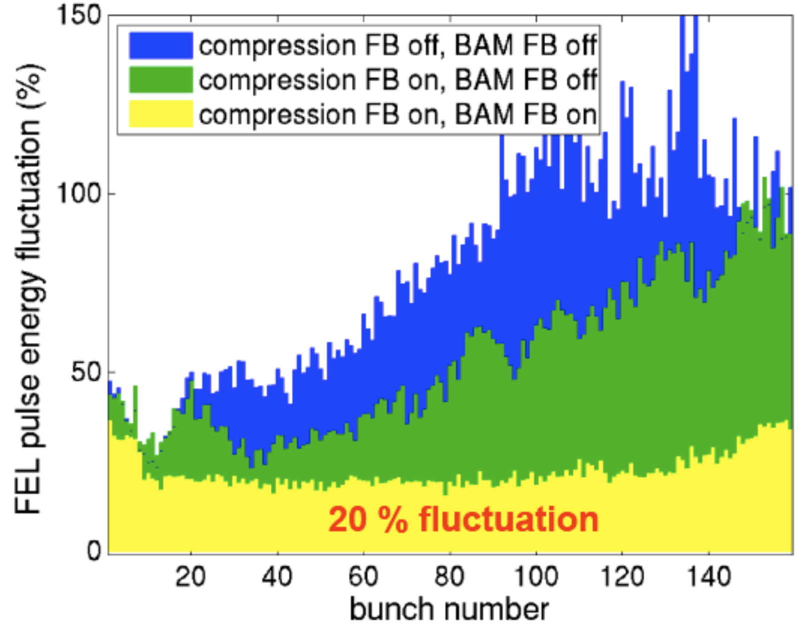


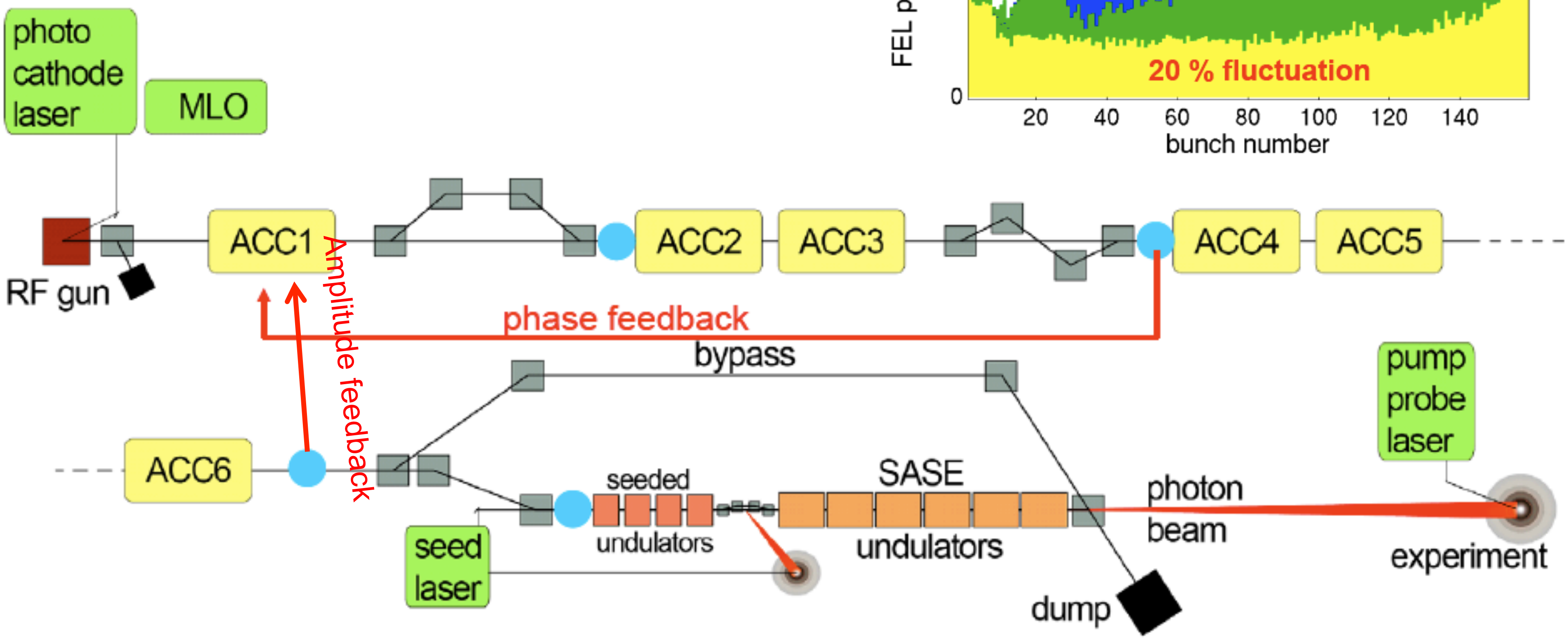
BAM measurement



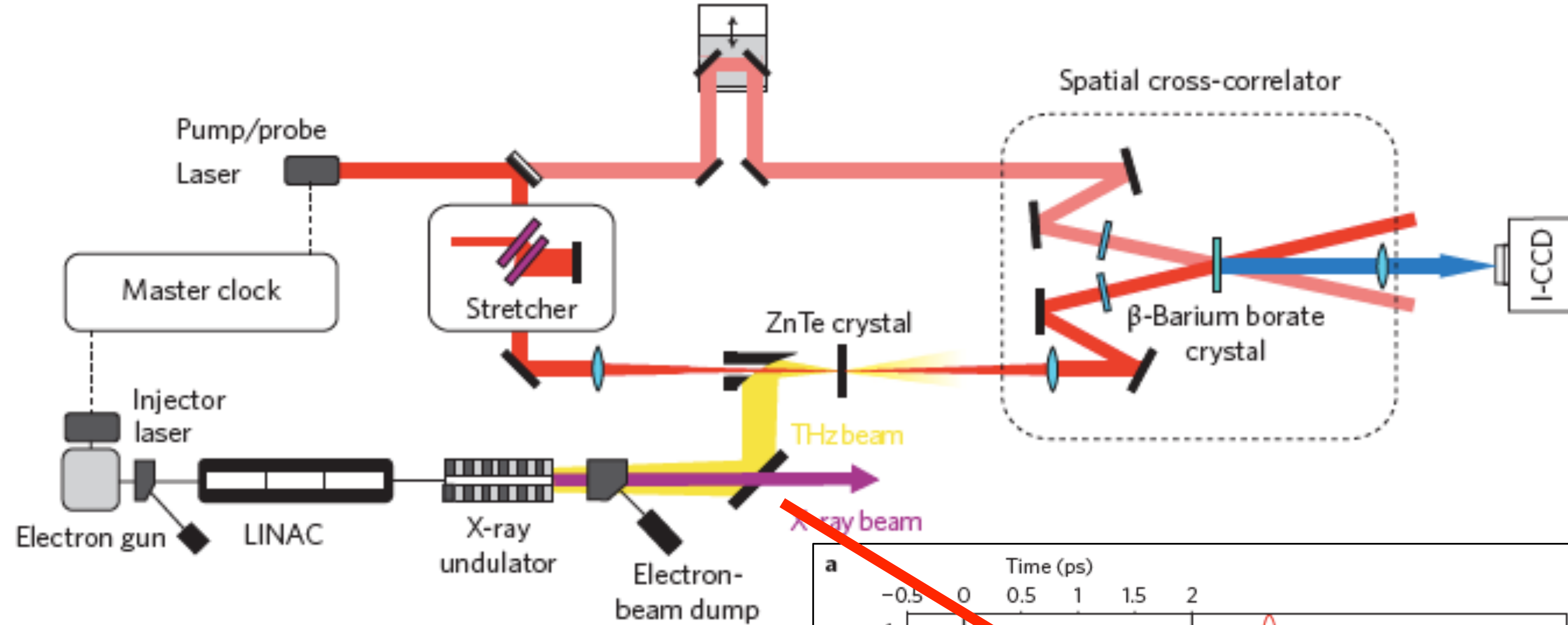
Use arrival time and bunch length to stabilize FEL output

- Coherent THz signal used as relative bunch length monitor
- BAM used for time (energy) jitter

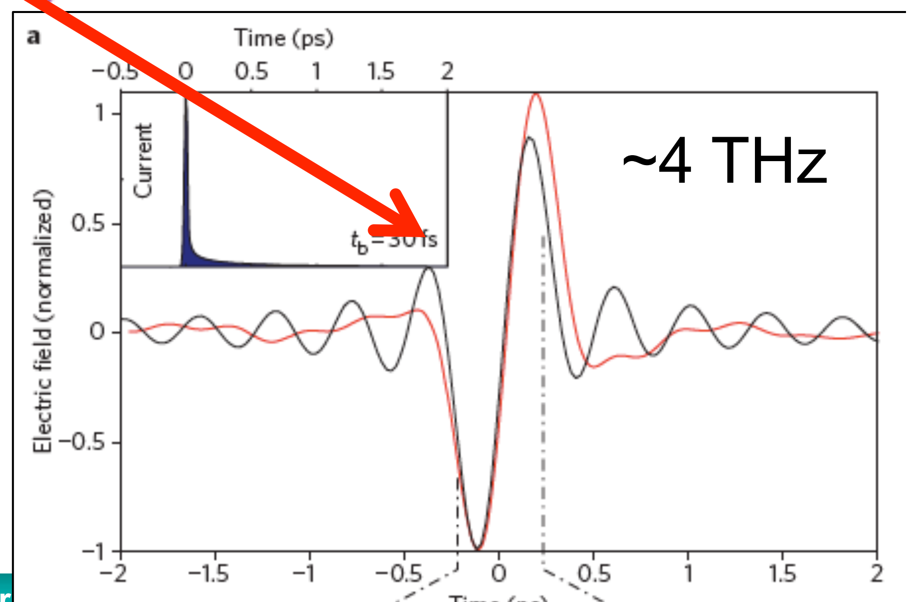




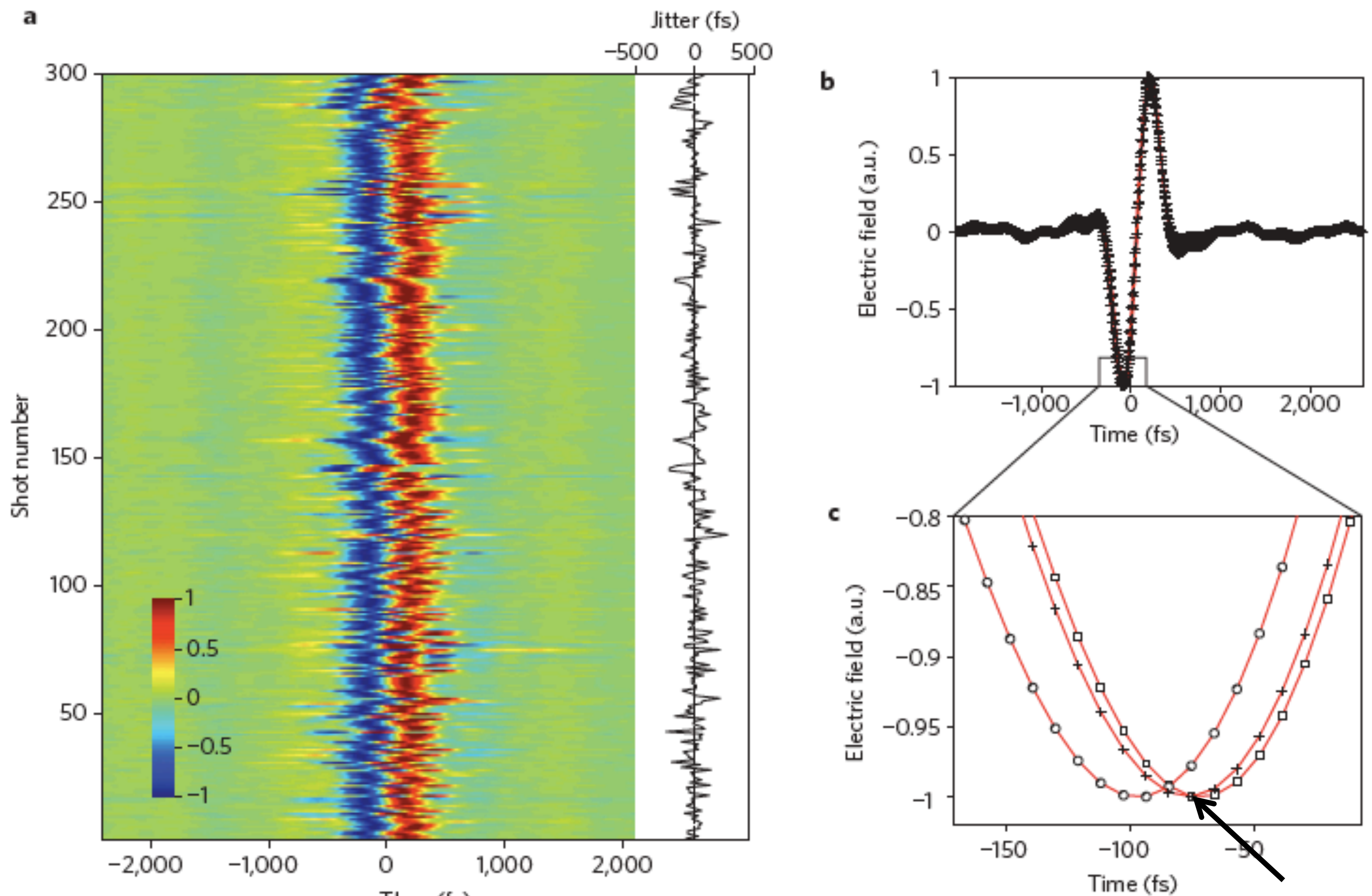
Using CER to measure timing: Flash example



- EO-sample coherent edge radiation in temporal decoding configuration.
- Large slope allows high arrival time sensitivity.
- Not much sensitivity to bunch shape for bunch length <30 fsec.



Timing with CER radiation at FLASH



Variation of 3 consecutive shots

- F. Tavella, et al., Nature Photonics, March 2011

A FROG is a spectrogram.

If $E(t)$ is the waveform of interest, its spectrogram is:

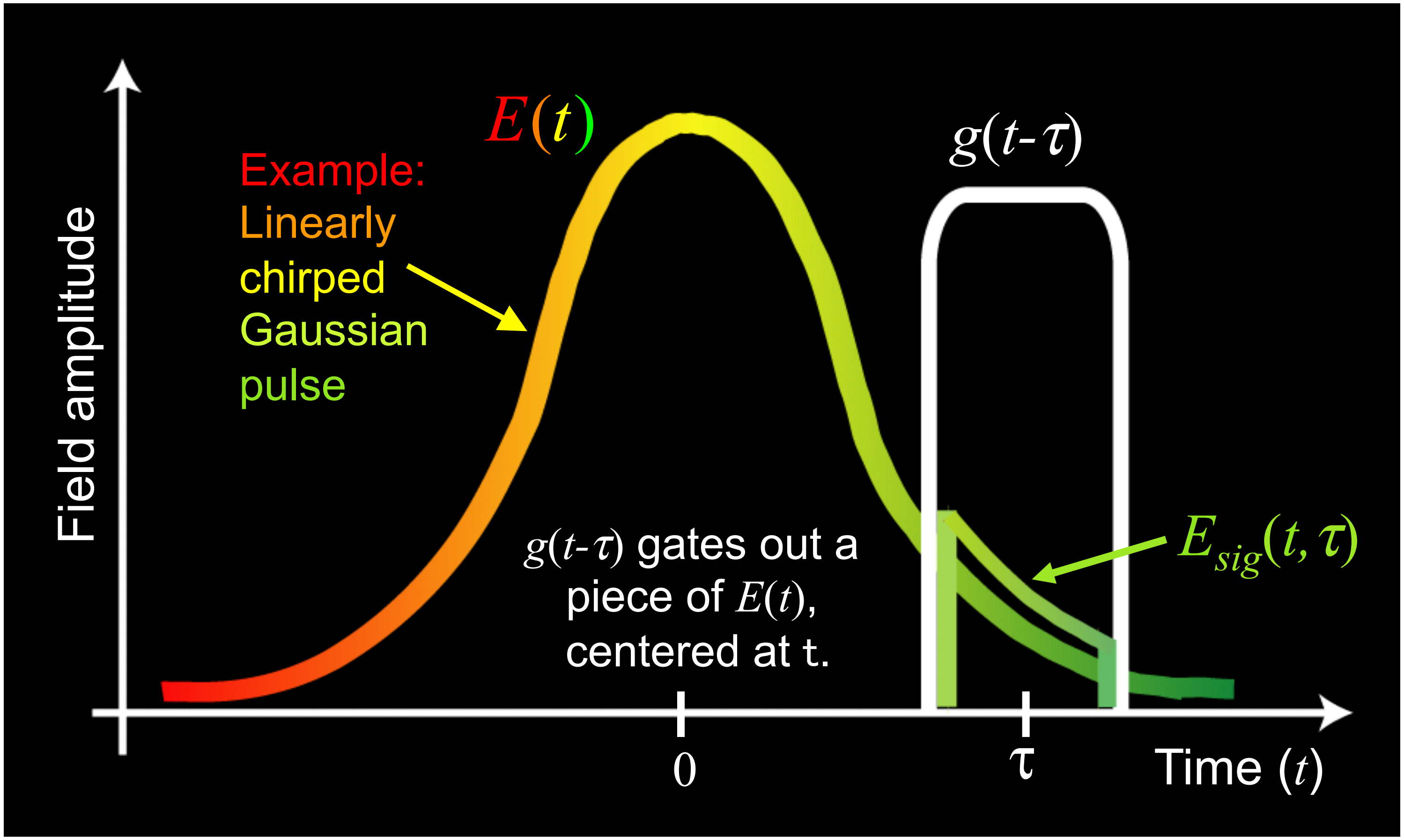
$$\boxed{\Sigma_E(\omega,\tau) \equiv \left| \int_{-\infty}^{\infty} E(t)\, g(t-\tau) \exp(-i\omega t)\, dt \right|^2}$$

where $g(t\text{-}\tau)$ is a variable-delay gate function and τ is the delay.

Without $g(t\text{-}\tau)$, $\Sigma_E(\omega,\tau)$ would simply be the spectrum.

The spectrogram is a function of ω and τ.
It is the set of spectra of all temporal slices of $E(t)$.

The Spectrogram of a waveform $E(t)$

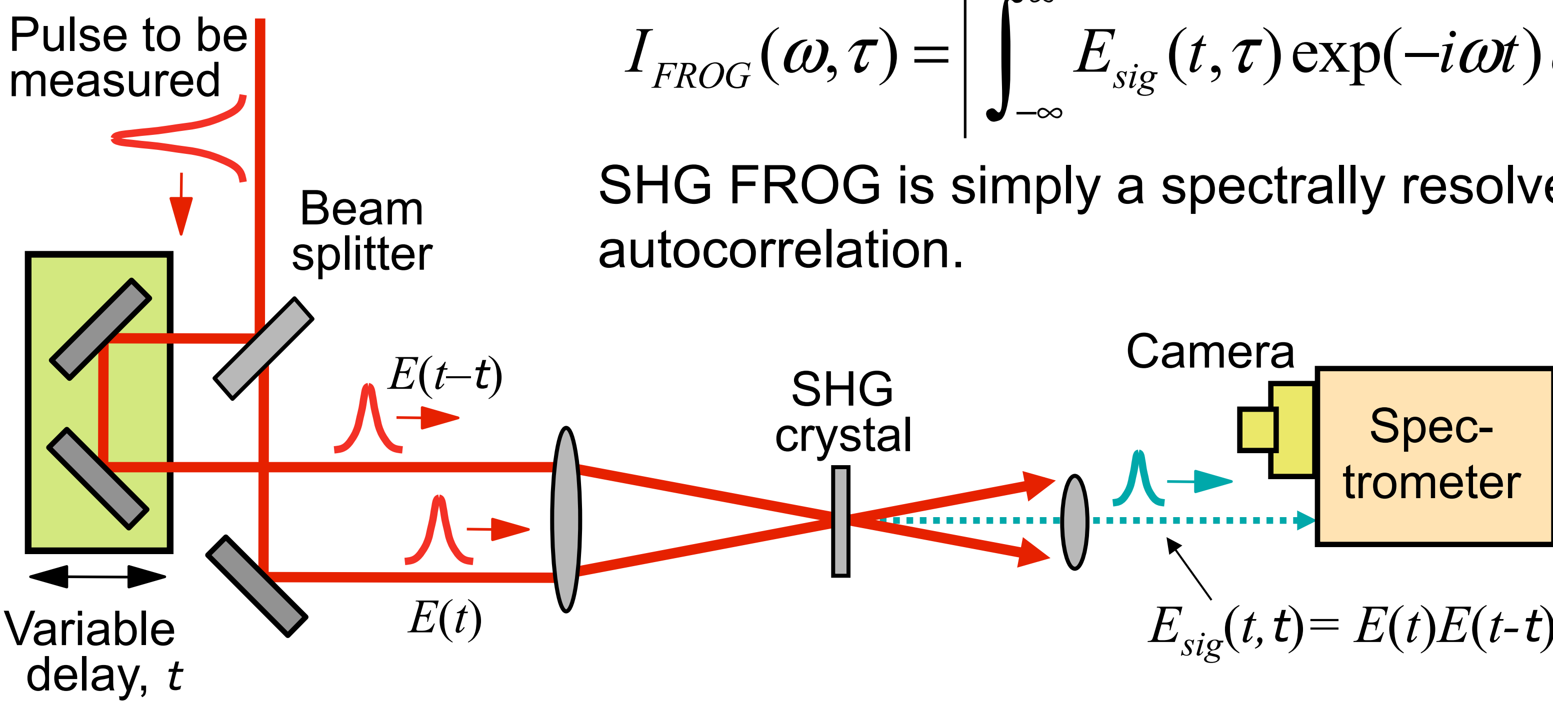


Frequency-Resolved Optical Gating (FROG)

FROG involves gating the pulse with a variably delayed replica of itself in an instantaneous nonlinear-optical medium and then spectrally resolving the gated pulse vs. delay.

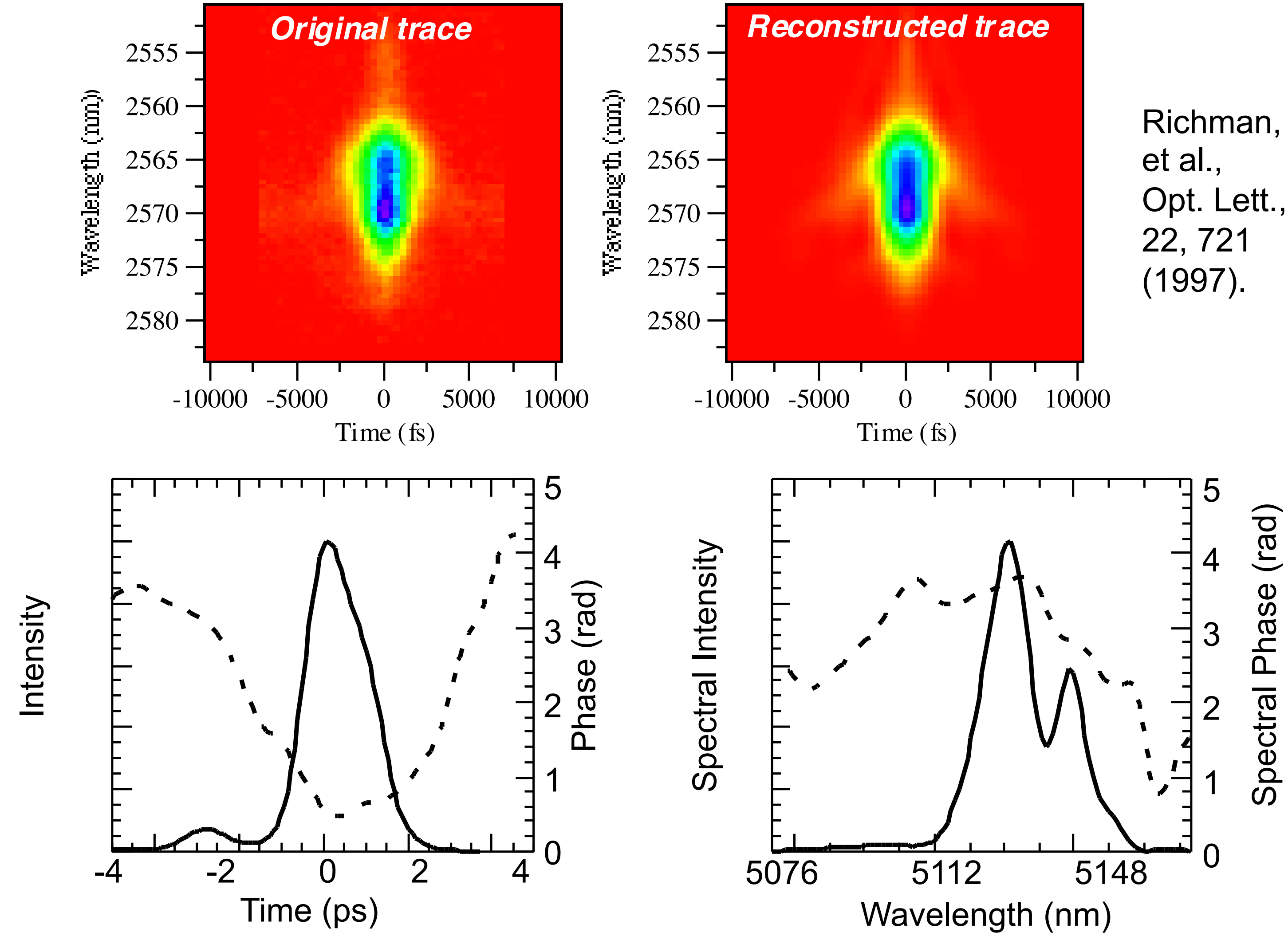
$$I_{FROG}(\omega,\tau) = \left| \int_{-\infty}^{\infty} E_{sig}(t,\tau)\exp(-i\omega t)\,dt \right|^2$$

SHG FROG is simply a spectrally resolved autocorrelation.



Use any ultrafast nonlinearity: Second-harmonic generation, etc.

SHG FROG Measurements of a Free-Electron Laser

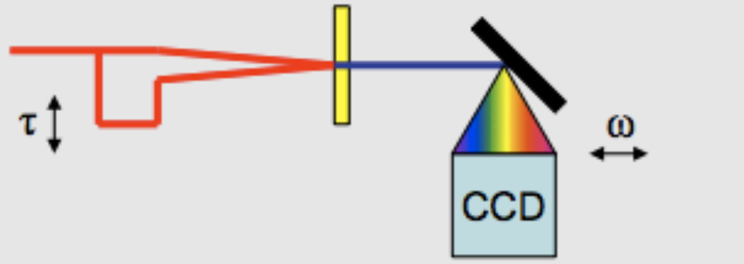


Richman, et al., Opt. Lett., 22, 721 (1997).

SHG FROG works very well, even in the mid-IR and for difficult sources.

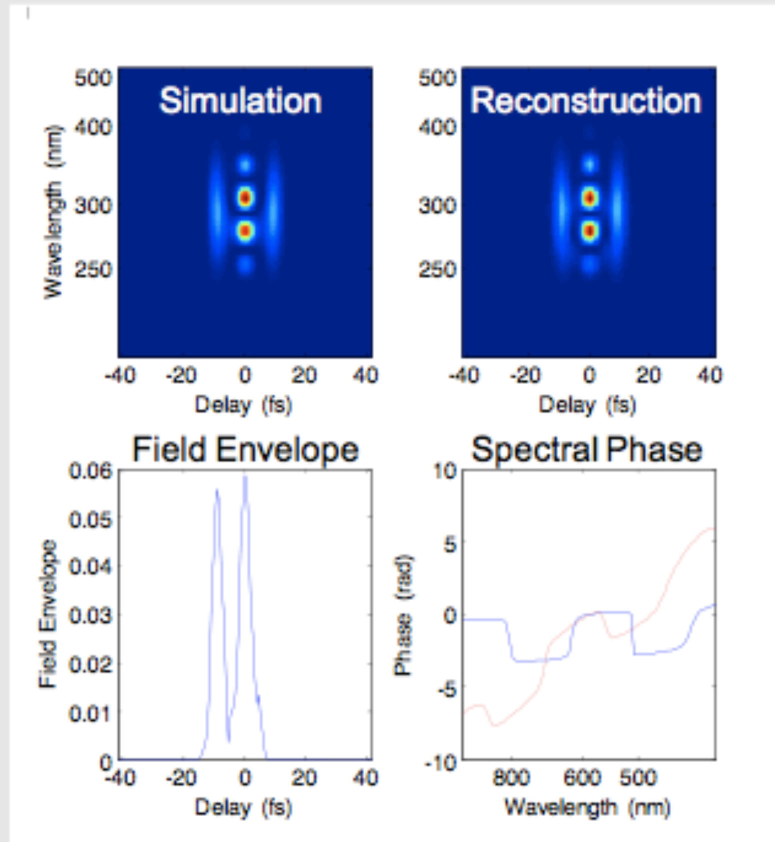
Optical techniques: FROG

- Measure spectrum of SHG in BBO vs. delay

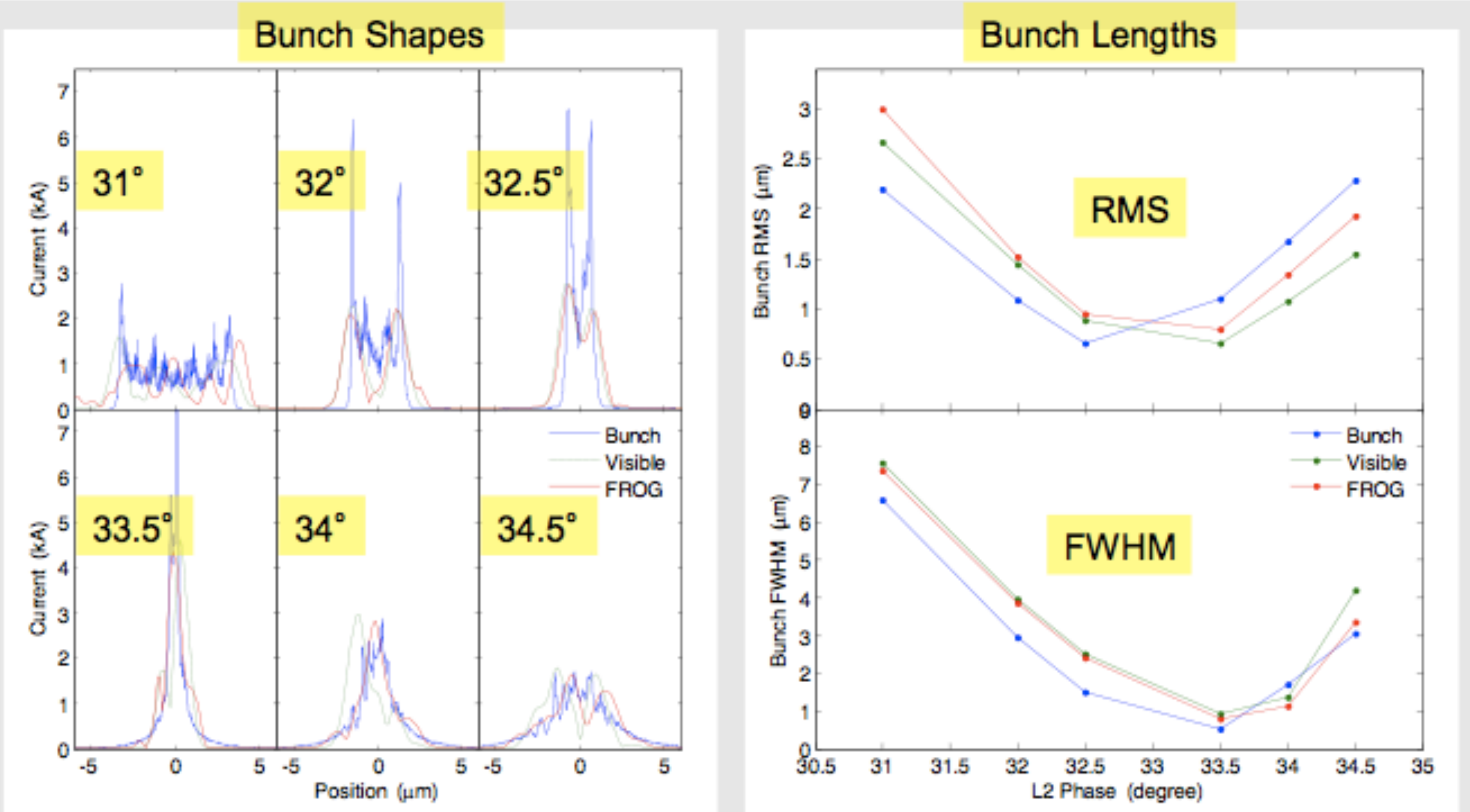


$$I(\omega,\tau)\propto\left|\int E(t)E(t-\tau)e^{-i\omega t}dt\right|^2$$

- Remove carrier frequency from reconstructed field
- Envelope is $|E(t)|^2$
- Required pulse energy is few 100 nJ
- COTR energy between 0.1 – 1 μJ
- Phase matching over 300 nm BW requires few μm crystal

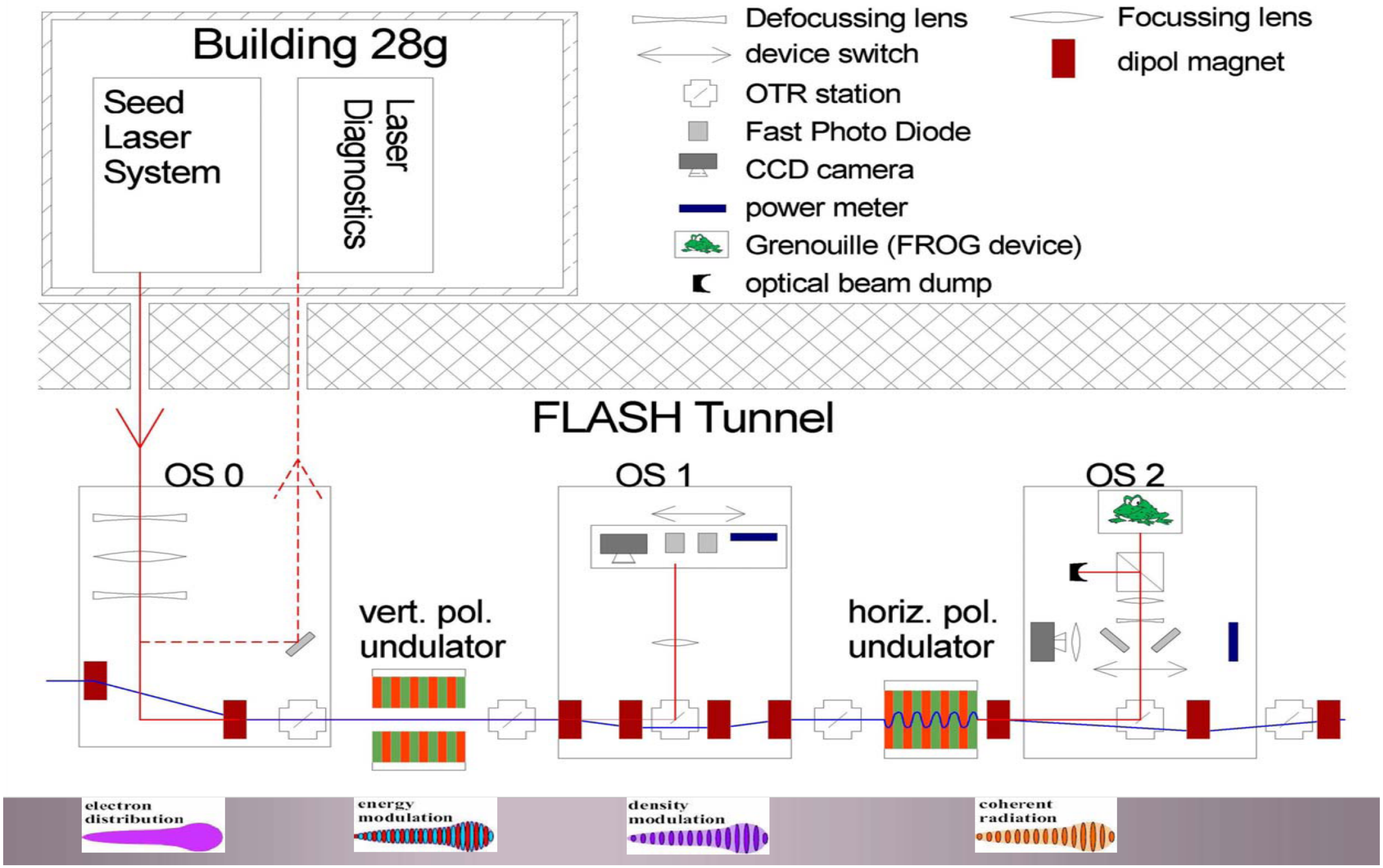


Simulated FROG results for LCLS



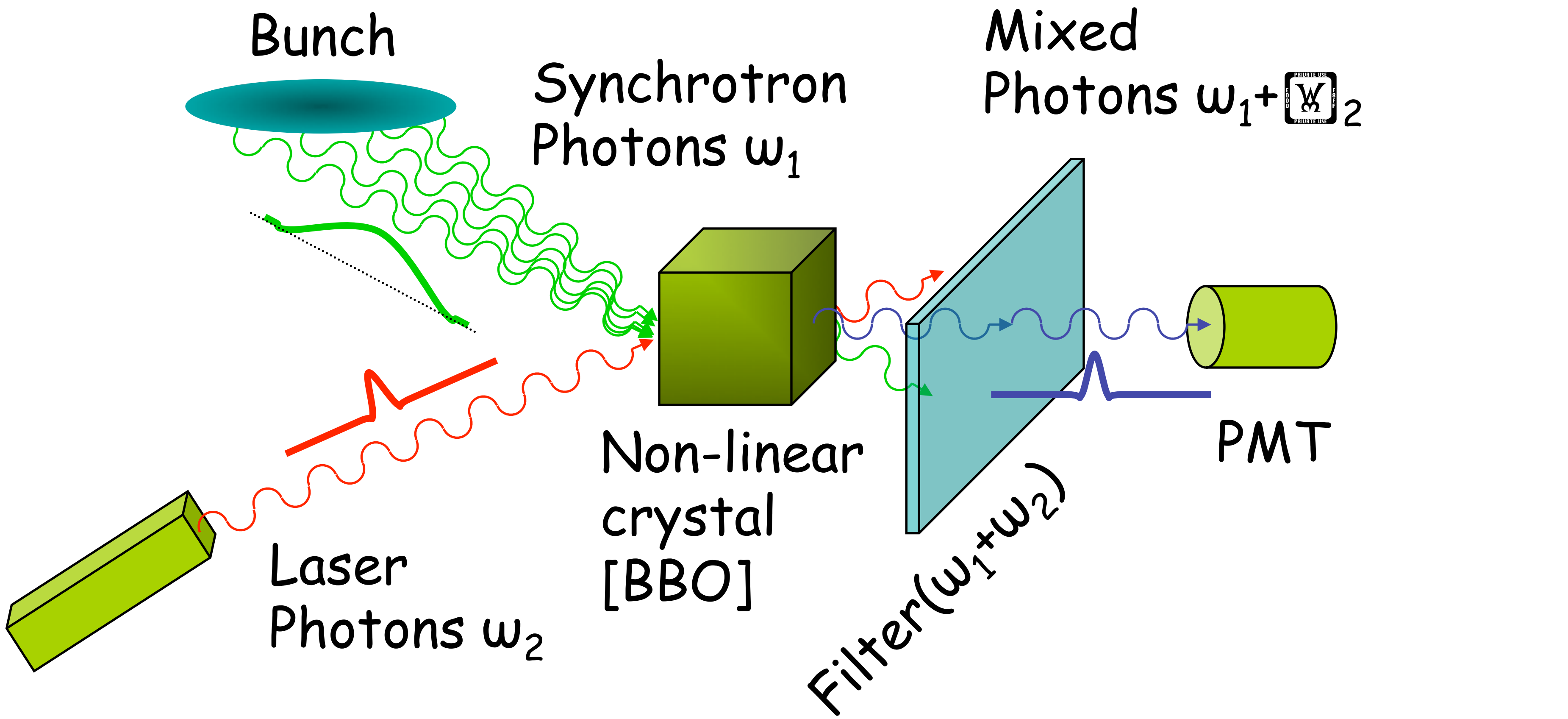
- Reconstruction longer for undercompressed and shorter for overcompressed bunches

ORS: Optical Replica Synthesizer



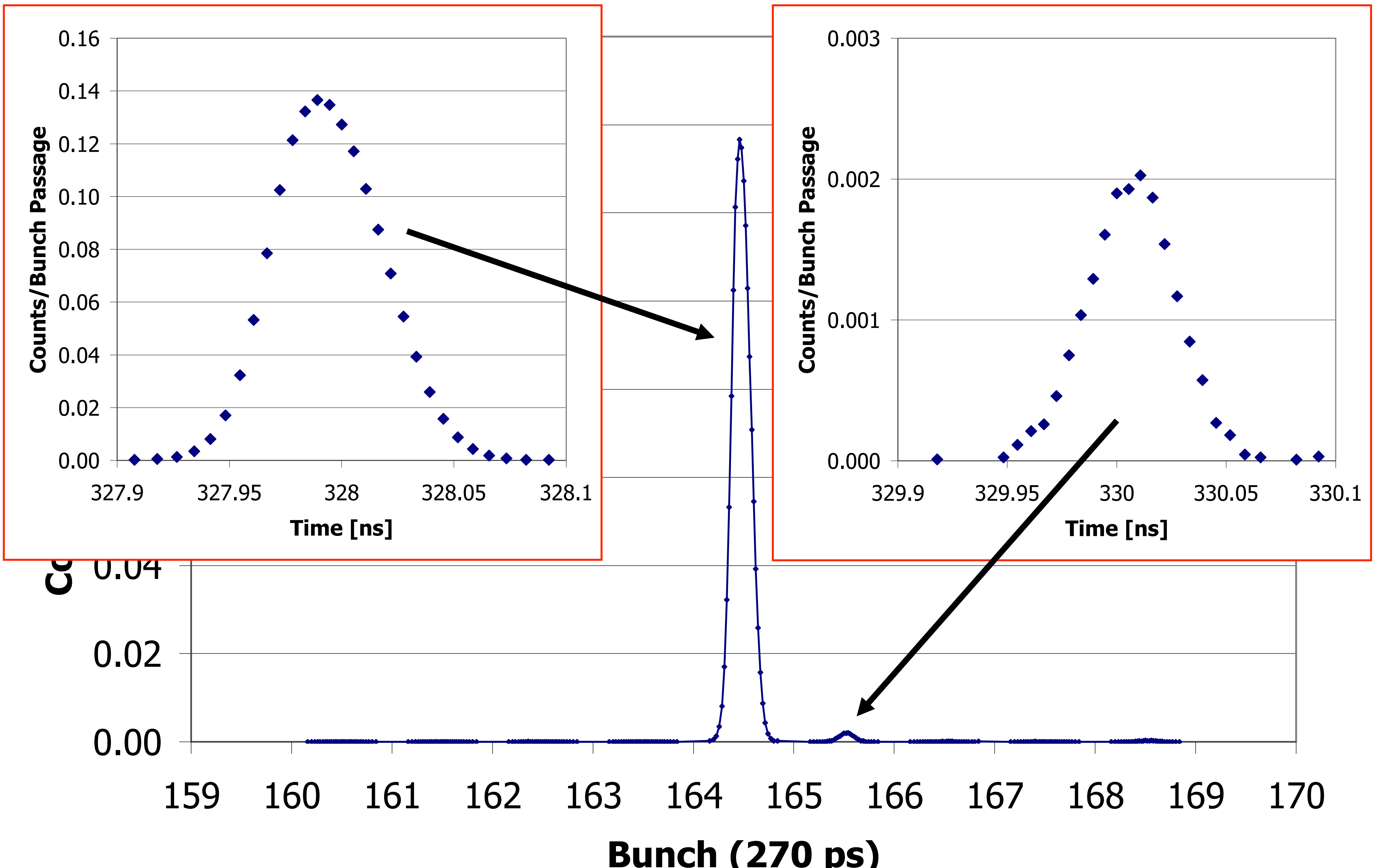
Cross-correlator with SR

$\omega_1+\omega_2$ = visible wavelength

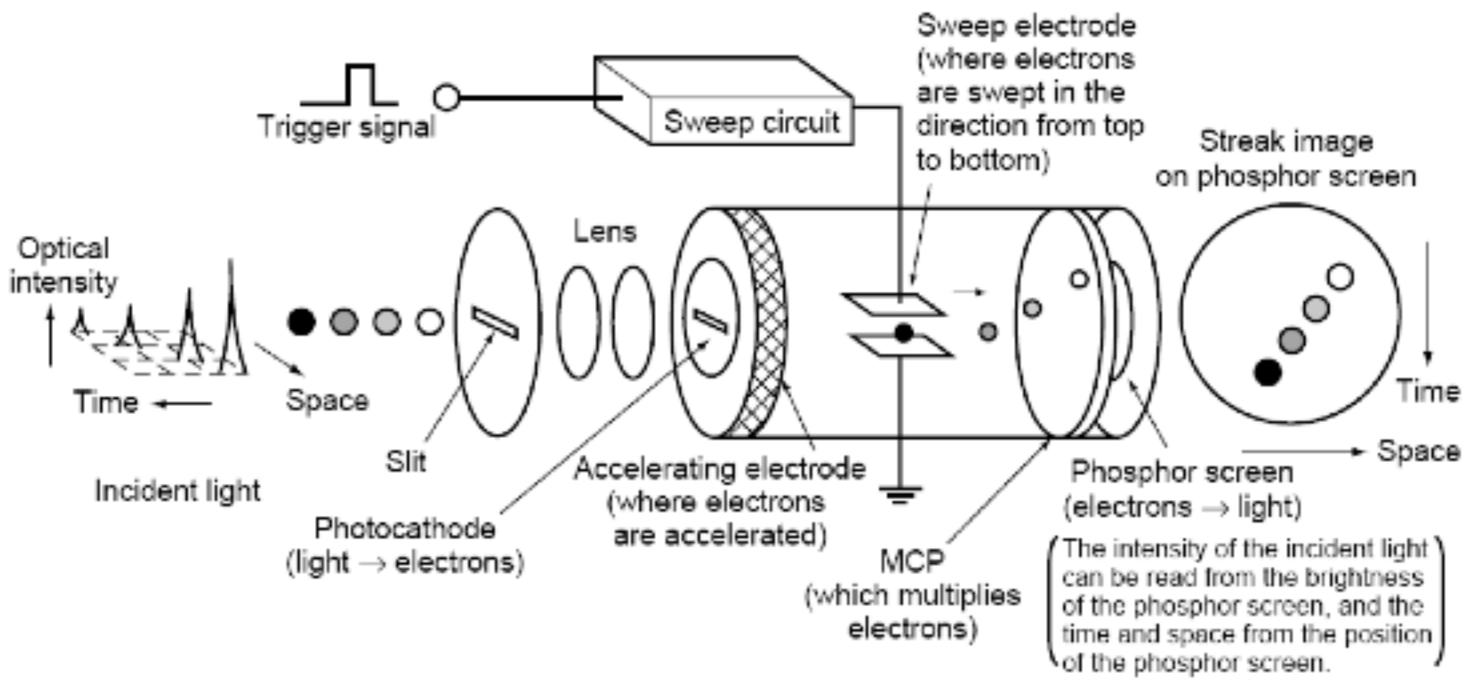


laser pulse length << bunch length

ALS Cross-correlator measurement



Principle of the Streak Camera

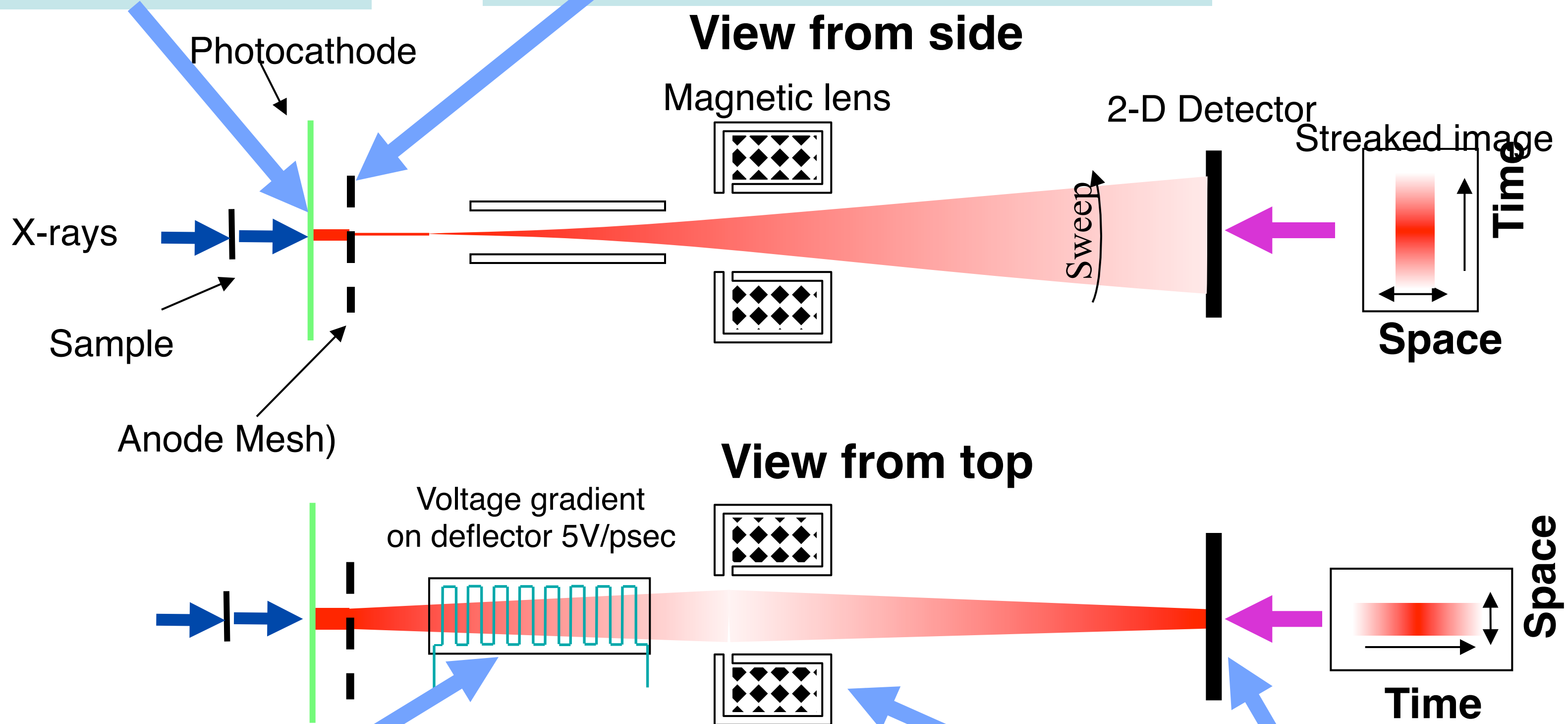


- Compare streak camera to gated camera:
  - Light→Photocathode→Electrons→MCP→Screen→CCD as before, but…
  - Remove: Vertical spatial information, with a tight focus and a thin slit.
  - Add: Accelerating electrode after the photocathode
Fast vertical sweep in drift space before the MCP
  - Vertical coordinate now displays the arrival time of the photons.

ALS X-ray streak camera

Au transmission photocathode

10 kV accelerating voltage over 1 mm gap; anode mesh

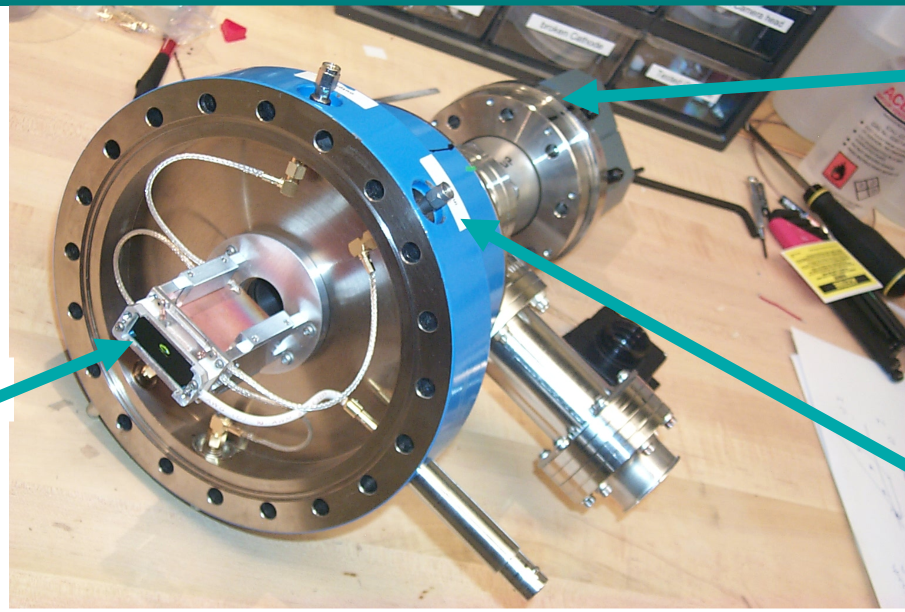


solenoid focussing

meander line stripline deflector for low b beam

microchannel plate+CCD imaging

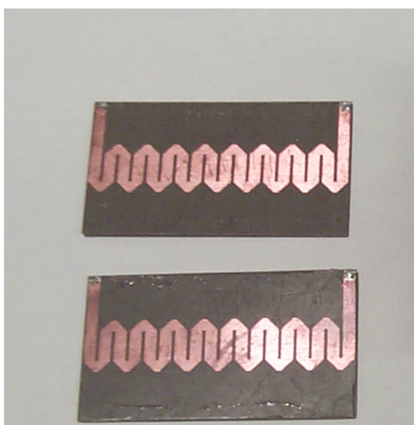
ALS x-ray streak camera



microchannel plates and imaging CCD

Photocathode / slit

Solenoid magnet



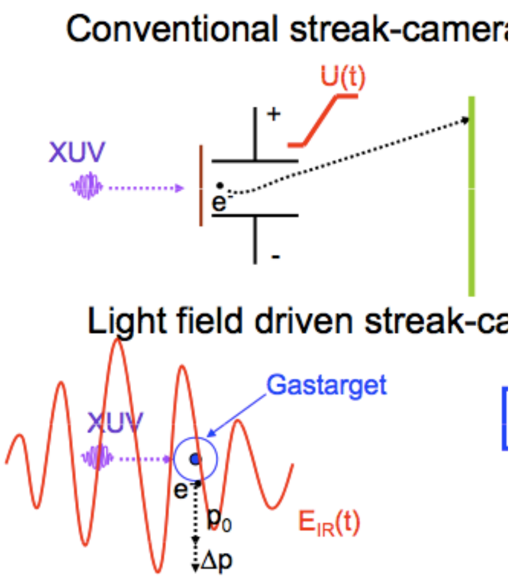
Meander strip line

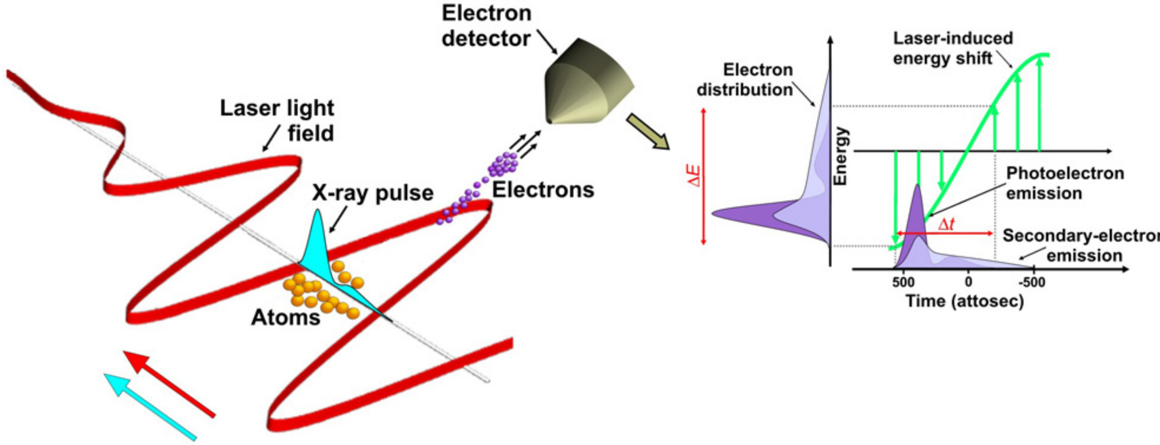
Photoconductive GaAs switch for triggering

Streak camera issues

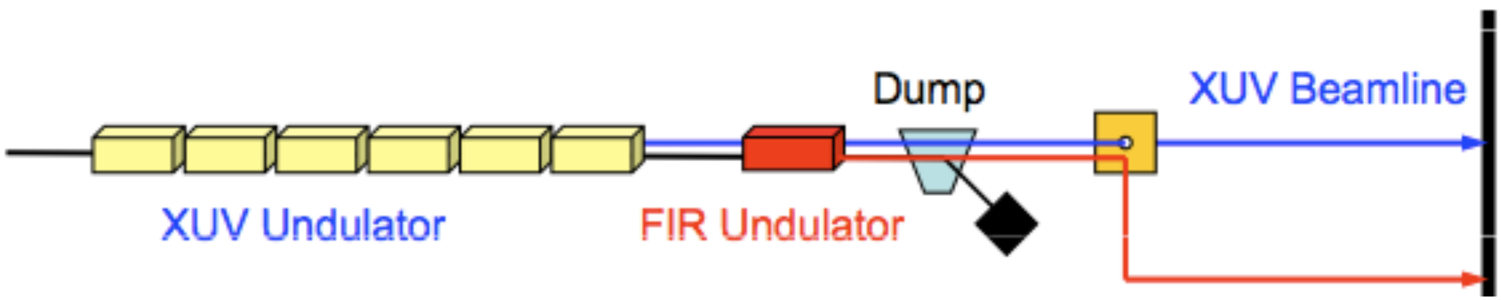
- Ballistic expansion from energy spread at photocathode
  —reduced by higher voltage accelerating gaps
  —space charge increases energy spread
- Maximize streak speed (slope of angular deflection)
  —transmission of fast pulse
  —effective beam voltage
  —synchronization of deflection pulse with source
- High resolution imaging of electron beam
  —avoid aberrations from solenoid
  —minimize chromatic effects
  —efficiently detect electrons

Terahertz Streak Camera





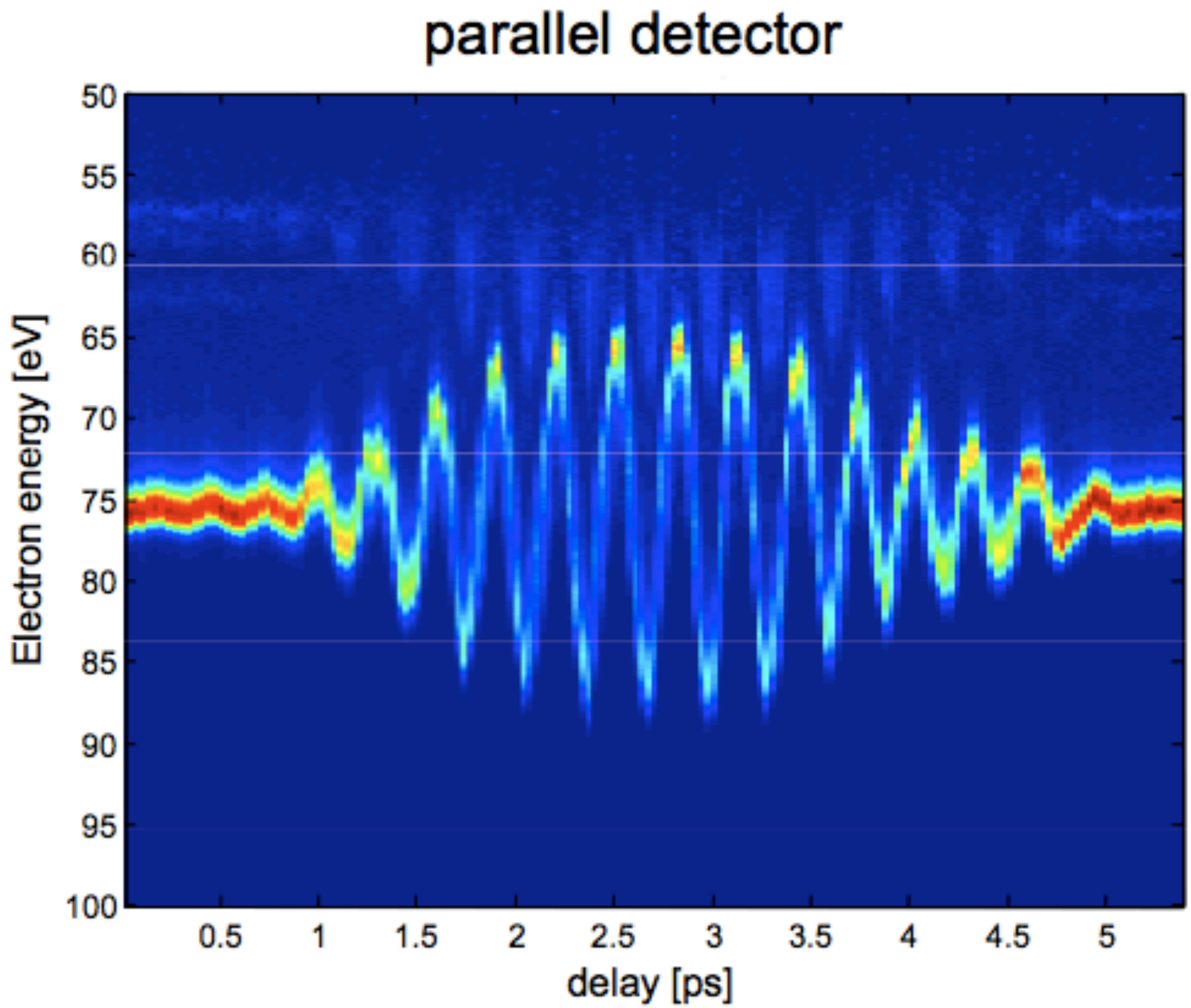
- Optical field modifies energy spectrum of ionized electrons
- Use the Terahertz field from an undulator as the streak deflector



Fruehling, U. et al, Nature Photon. 3, 523–528 (2009).

Streaking with FIR light

Undulator tuned to 85μm, bandpass filter, polarizer



FLASH: 13.5 nm
Gastarget:
Krypton (4p)

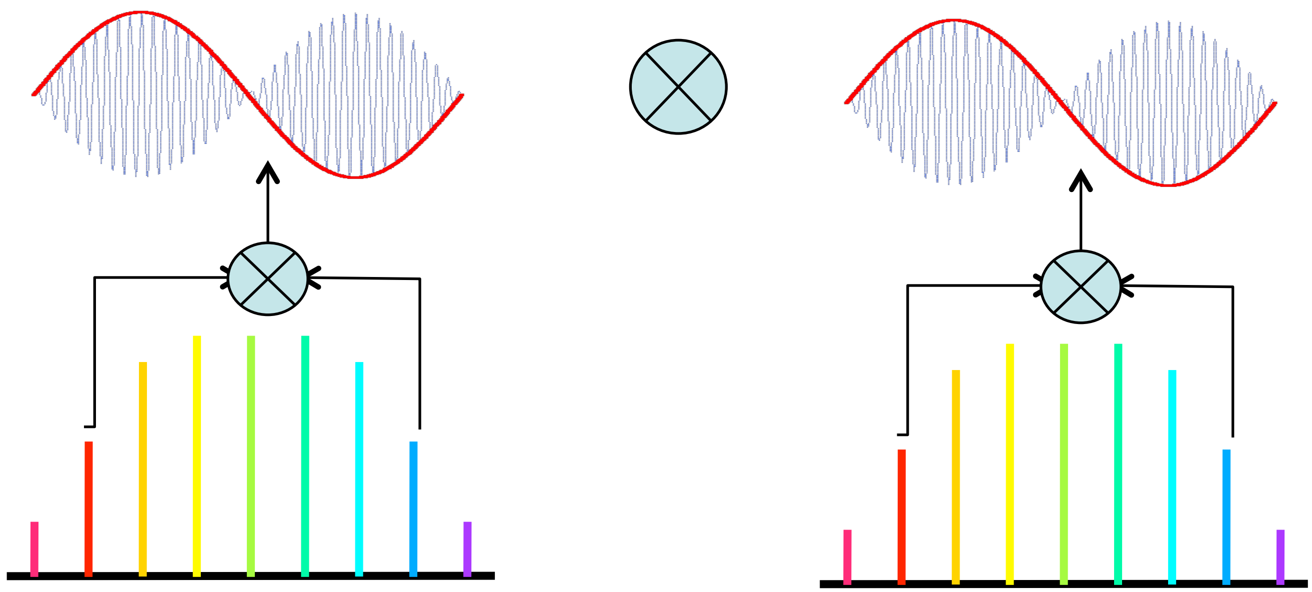
Future directions

A few examples at Berkeley and SLAC

- All optical laser synchronization
  - Locking optical comb spectral lines
- E-beam arrival time/bunch length monitors
  - Electro-optic modulation of THz beat wave
- X-ray/laser arrival time monitor
  - X-ray/optical cross-correlation
  - X-ray phase cavity

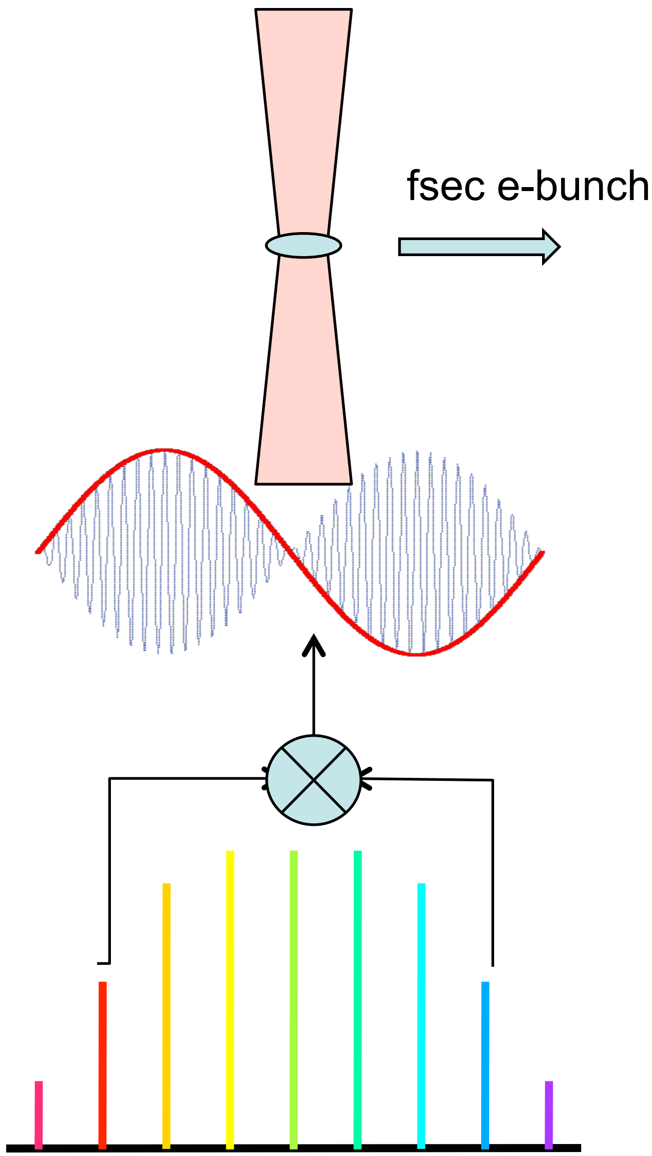
All-optical lock schemes

- Synchronization of lasers with RF signals limited by resolution in phase(0.01 deg@3GHz=10 fsec)
- Go to optical frequencies…



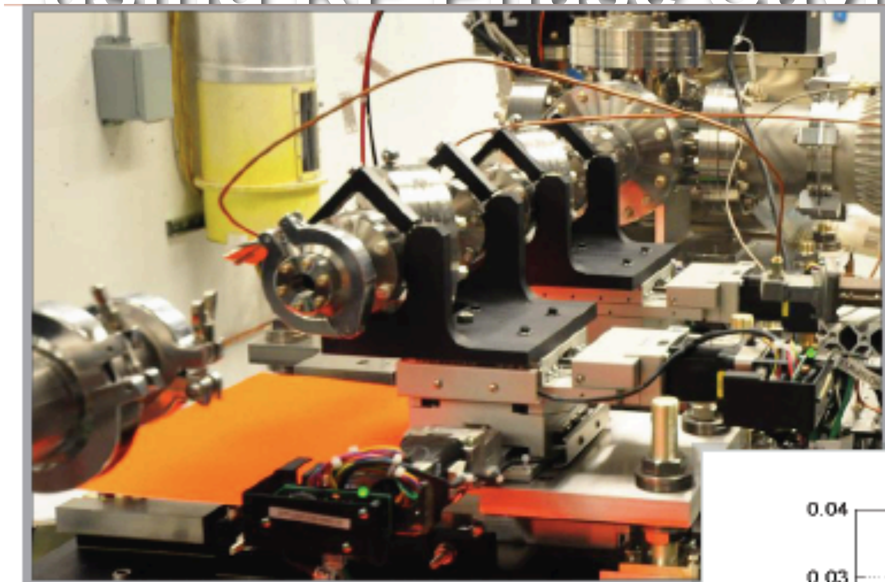
- Create a beat wave generated from two mode-locked comb lines (up to a few THz)
- Lock the beat wave of one laser with a remote laser

Sub-fsec arrival monitor



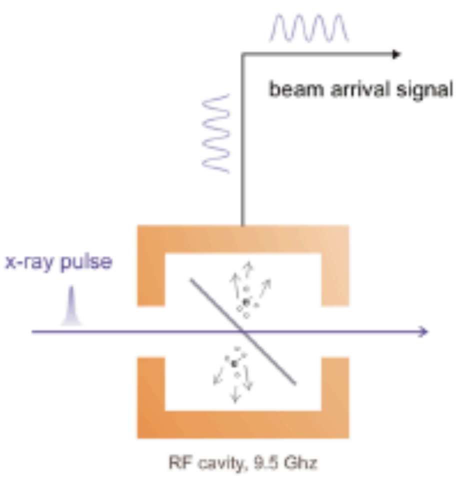
- Sensitivity of e-beam arrival monitors proportional to reference frequency.
- Use THz beat wave as a reference frequency.
- Electro-optically modulate beat wave with e-beam electric field.

X-ray Pulse Arrival Time Measurement using RF Phase Cavities

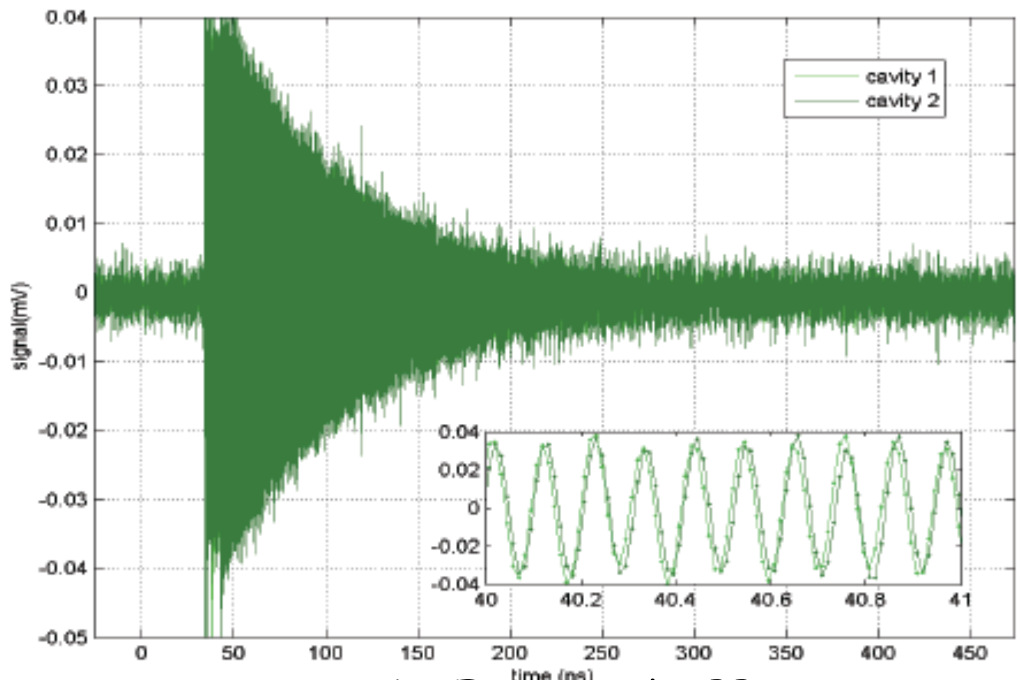


• photoelectrons induced by the x-ray pulse from a thin film target (30 nm silicon nitride membrane) excites the 9.5GHz RF cavity. The timing information is encoded in the phase of the cavity oscillation.

• A first test experiment was performed during LCLS Run 3. Cavity ring down signal was observed as expected from both cavities, as shown below.

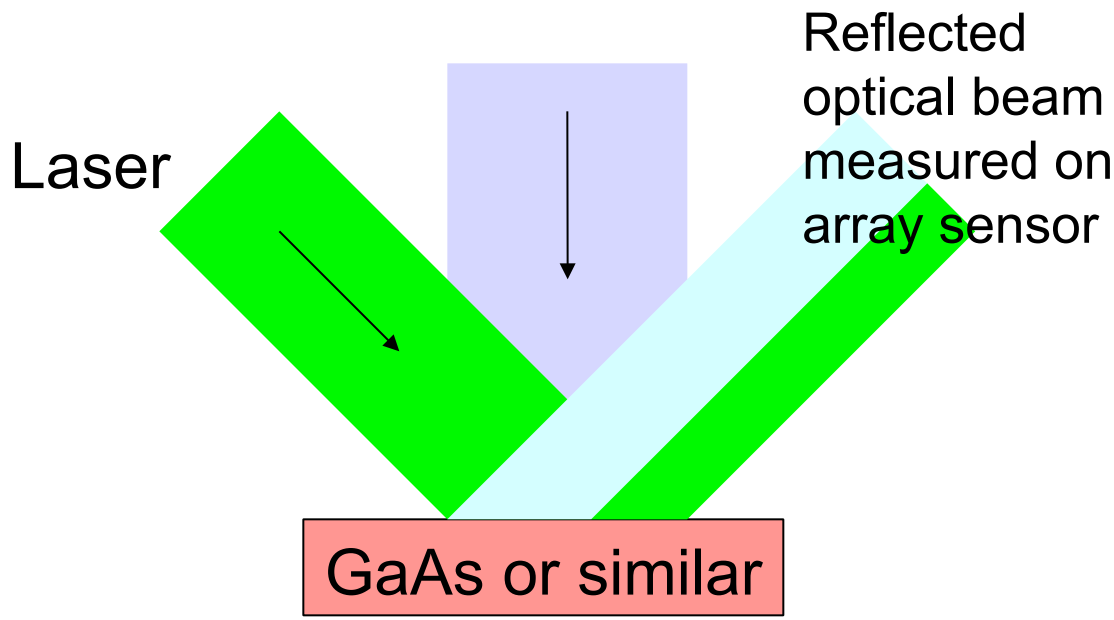


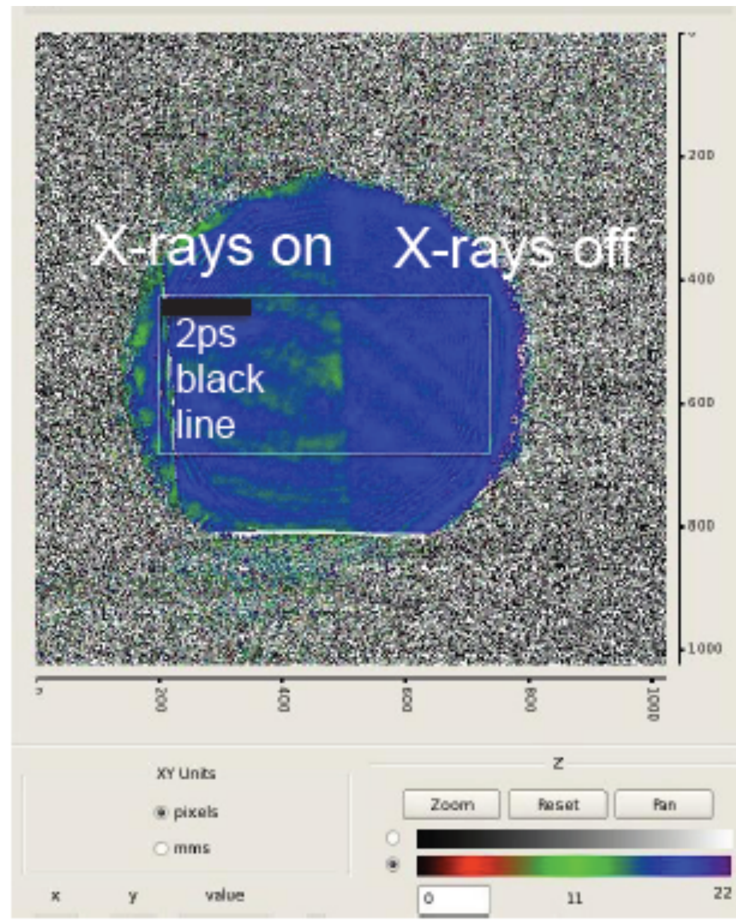
The inner working mechanism of the X-ray Cavity



D. Fritz and XPP Team

X-ray/optical cross-correlator

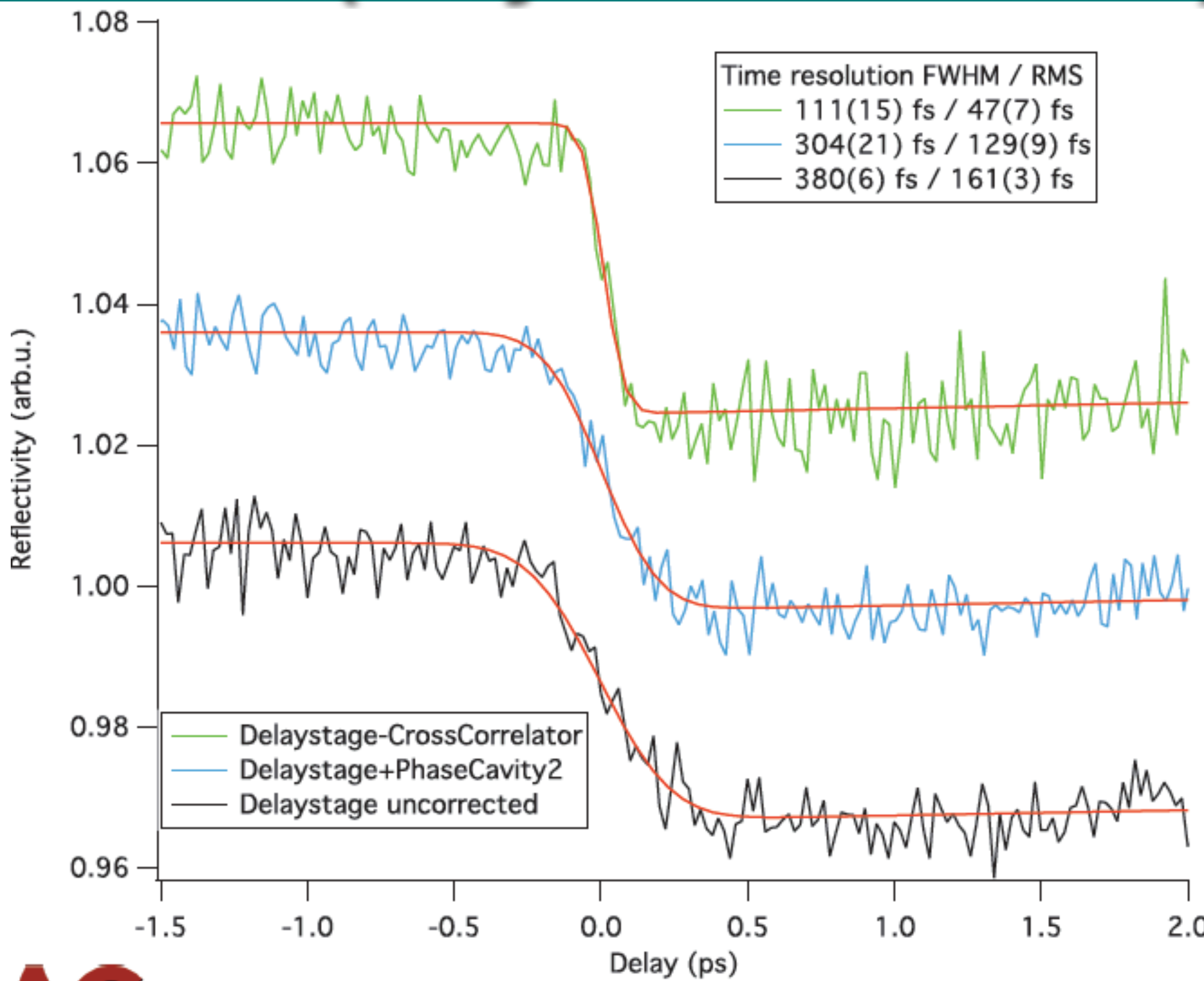




- Use the x-ray induced change in reflectivity on GaAs as a cross correlator

0 ps
143.3 mm on delay stage

X-ray induced reflectivity (very recent results)



Martin Beye

With correlator
111 fs FWHM

With phase
cavity
304 fs FWHM

Intrinsic
380 fs FWHM