Laser techniques for advanced accelerator researches:

EO sampling technique for femtosecond beam characterization

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Outline

- **Motivation**

  The need for ultrafast beams
  Tradition techniques

- **Current EO Technique and limitation**

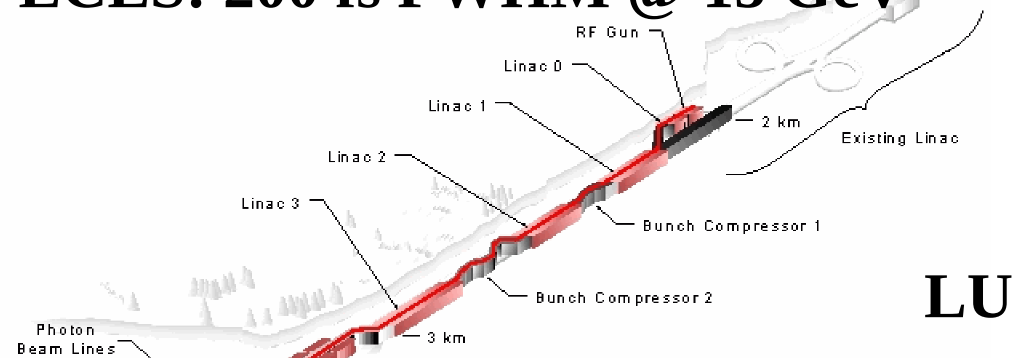
  Mechanism
  Characteristics
  Current status and limitation

- **A phantom experiment and the FROG tech**

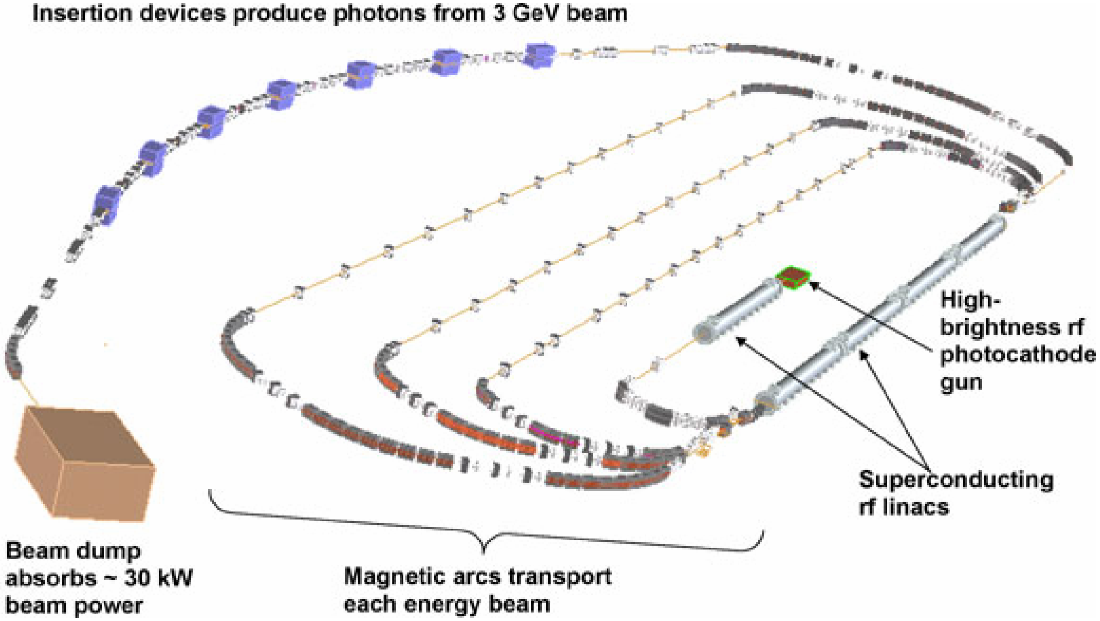
  The phantom and the method
  The experiment plan

The need for ultrafast beams

LCLS: 200 fs FWHM @ 15 GeV



LUX: 20 fs EUV @ 3 GeV



Some of the methods

INVASIVE

- **RF zero phasing**

  Wang et al, Phys. Rev. E 57, 2283–2286 (1998)
- **Beam tomography**

  Yakimenko et al., PRSTAB 6, 122801 (2003)

Limited by rf voltage and frequency
Complexity in the energy distribution
Multiple shots

NON-INVASIVE

- **Coherent radiation transition**

  Lumpkin et al., PRL 88, 234801 (2002)

Beam profile is assumed not measured

- **Streak camera**

  Lumpkin et al., PRL 82, 3605 (1999)

Multiple shot, time resolution at 1 ps

MISC

- **Compton scattering**

  Leemans, PRL 77, 4182 (1996)

Complexity set up
Multiple shots

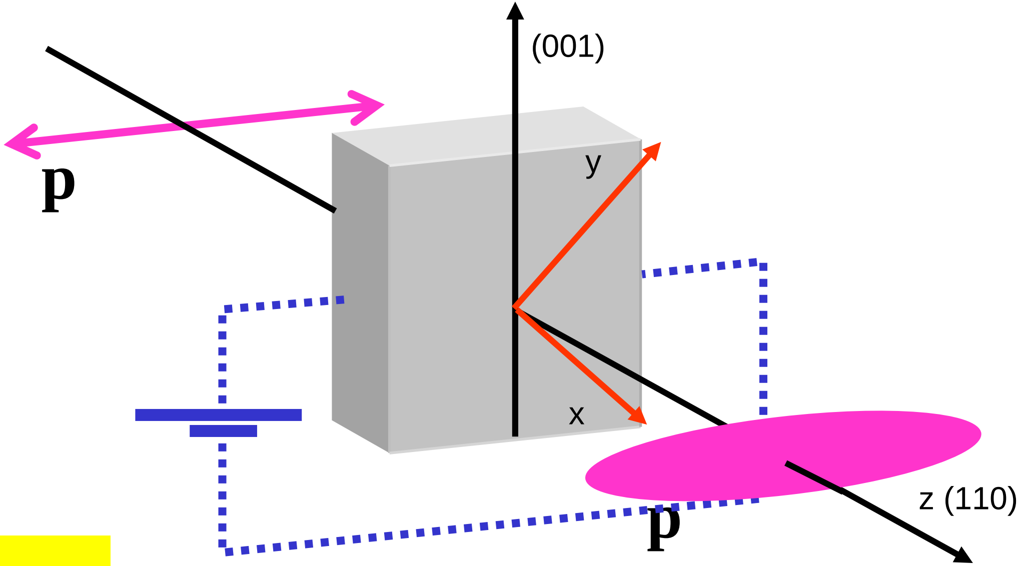
- **Spectrum statistics**

  Catravas, PRL 82, 5261 (1999)

Multiple shots

High spectrum resolution

EO Sampling technique: Pockel's effect (ZnTe)



$$n_x = n + \frac{1}{2} n^3 E r_{41},$$

$$n_y = n - \frac{1}{2} n^3 E r_{41},$$

With a balanced detector

$$I_x = I_p \sin^2(\phi + \delta),$$

$$I_y = I_p \sin^2(\phi - \delta),$$

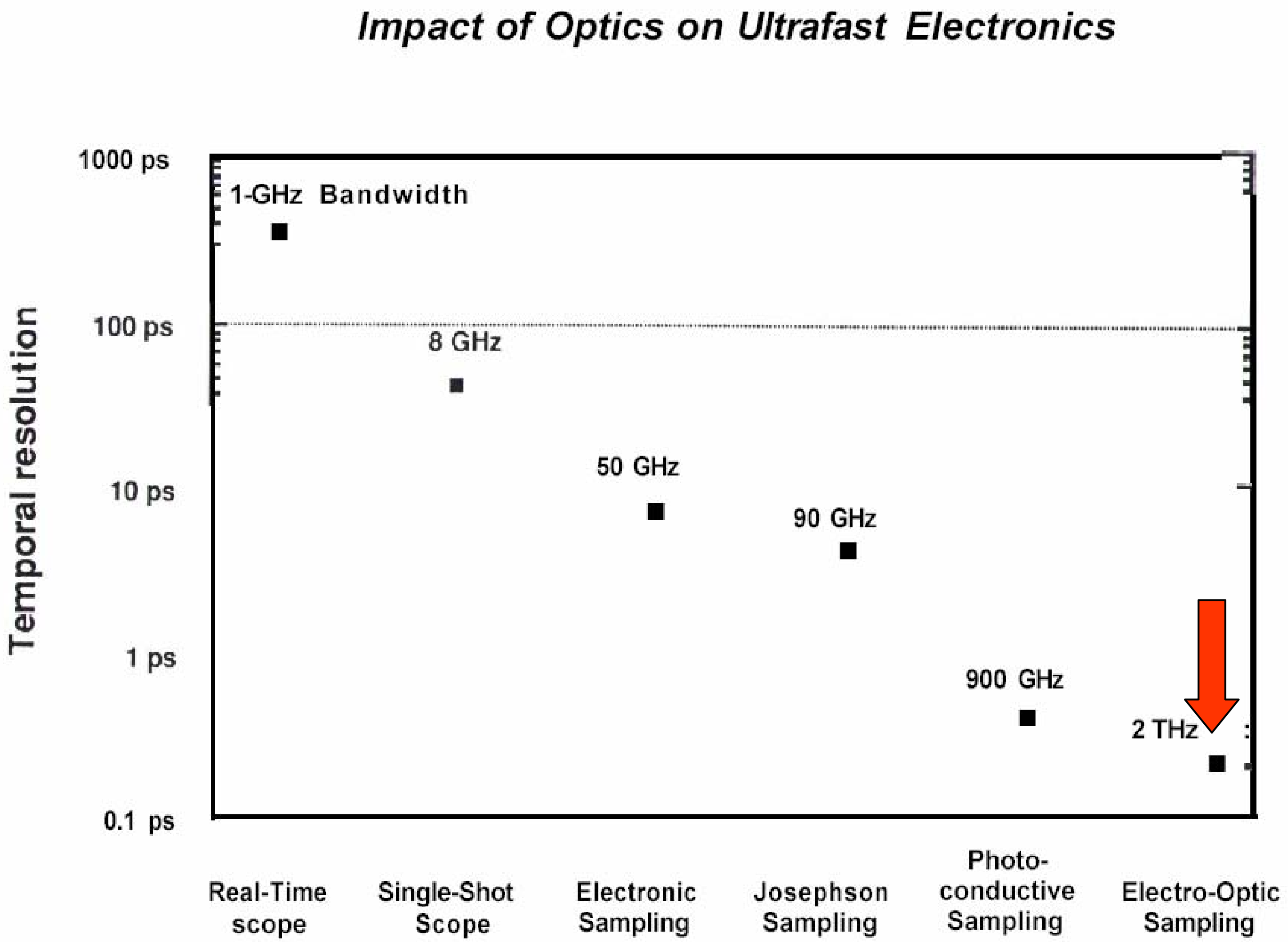
$$\Delta I = I_p \sin 2\phi \sin 2\delta \equiv I_p \sin 2\delta$$

$$\delta = \frac{2\pi n^3 E r_{41}}{\lambda} = 7.27 \times 10^{-4} El$$

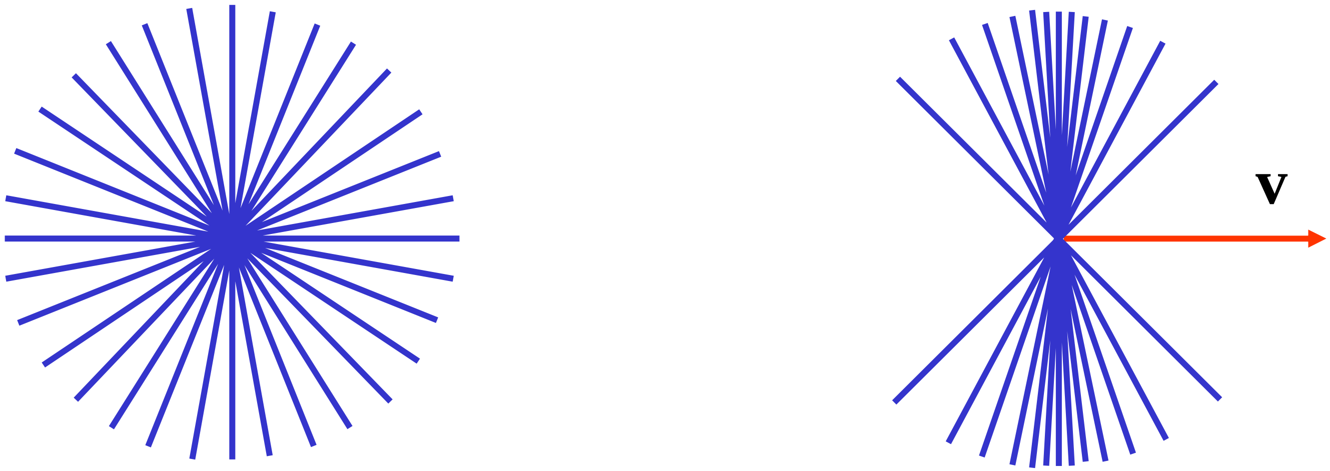
$\delta \ll 1$

$$E \propto \frac{\Delta I}{I_p}$$

Progress in time resolution



The field traveling with the beam



For a single charge q with v=βc:

$$\vec{E} = \frac{q\vec{R}}{4\pi\varepsilon_0 R^3 \gamma^2 (1-\beta^2 \sin^2\psi)^{3/2}}.$$

For a line charge density q(t) and γ>>1:

$$E_r(t) = \frac{q(t)}{2\pi\varepsilon_0 r}.$$

Past EO e-beam measurements

Fermi lab

Fitch et al, Proc Linac 2000, 155 (2000).

Unsuccessful in generating bunch info

Brookhaven

Y. K. Semertzidis et al. *Proceedings PAC'99*, 490 (1999).

100 ps resolution.

FELIX

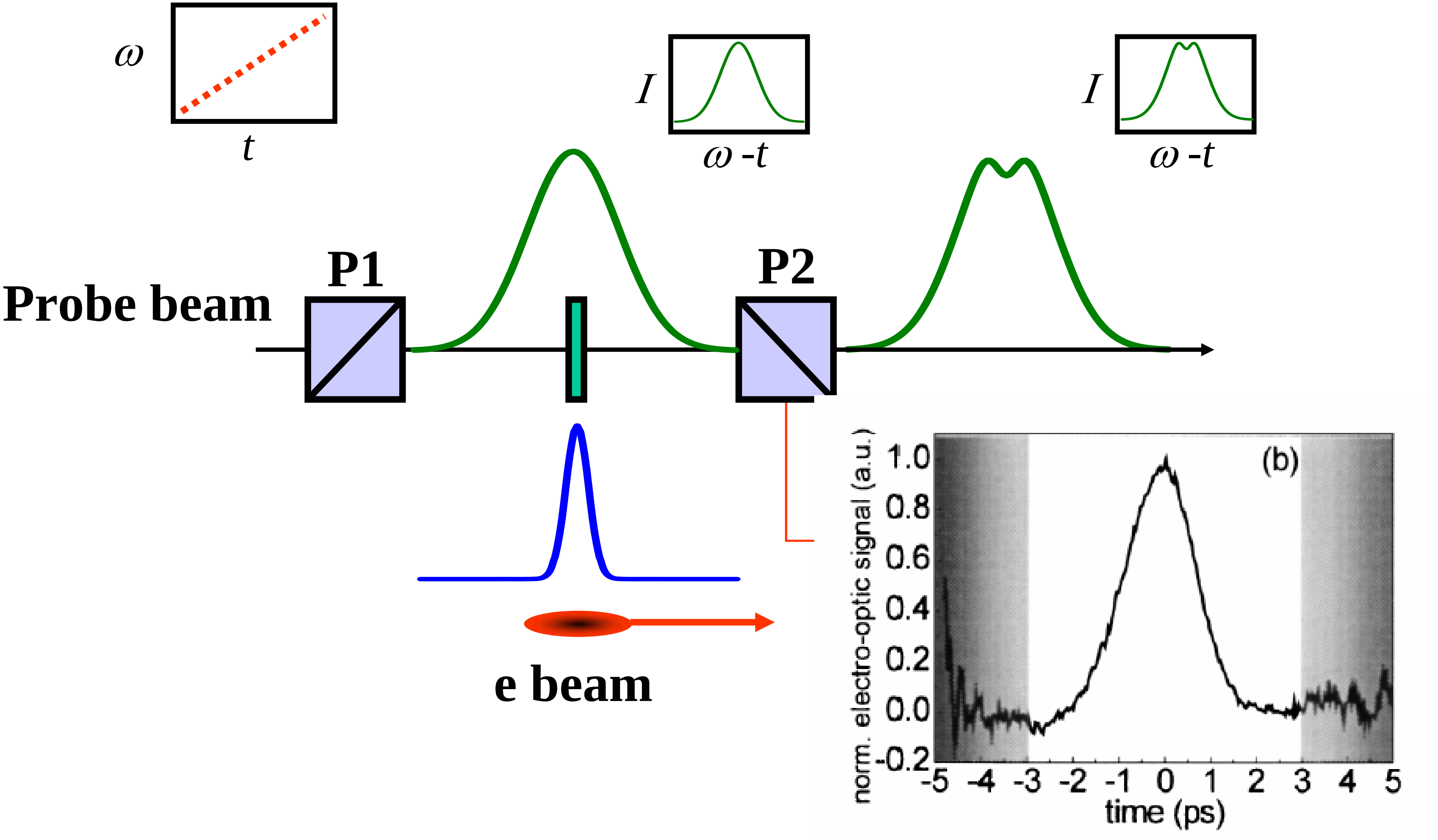
Yan et al., Phys. Rev. Lett. 85, 3404 (2000);
Wilke et. al., Phys. Rev. Lett. 88, 124801 (2002).

2-ps resolution.

Other institution (SPPS, DUV-FEL, GTF)

Trying …..

The FELIX experiment: chirped probe pulse



Temporal resolution limitation

- **Fundamental limitation: crystal response**

  Thickness related, for 0.1 mm crystals

  ZnTe: 5 THz; GaP: 9 THz: limited at 100 fs.

- **Fundamental limitation: bandwidth of the probe laser**

  $$\Delta t \approx \sqrt{\sigma_t T}\,.$$

  where σ_t~1/σ_ω .

  For σ_t =100 fs, T=100 ps, $\Delta t \approx$3 ps.

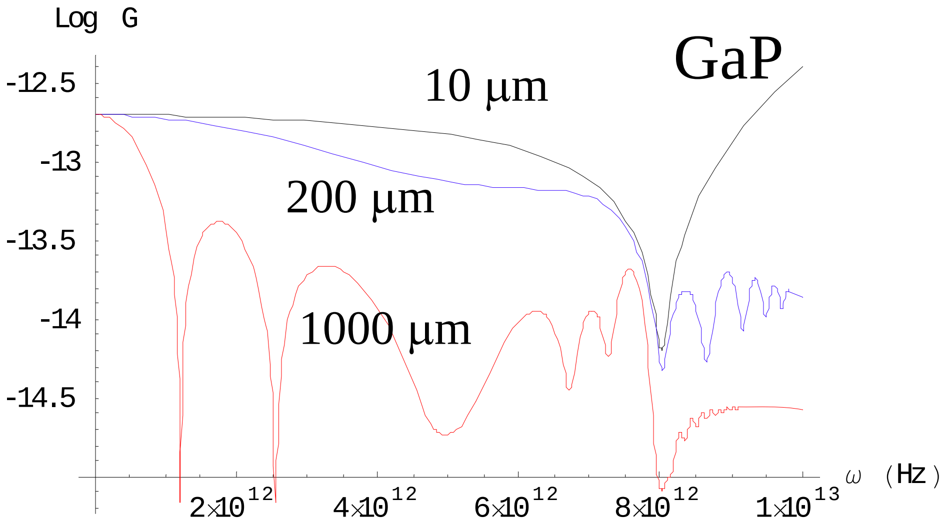
- **Geometry limitation: beam energy and distance**

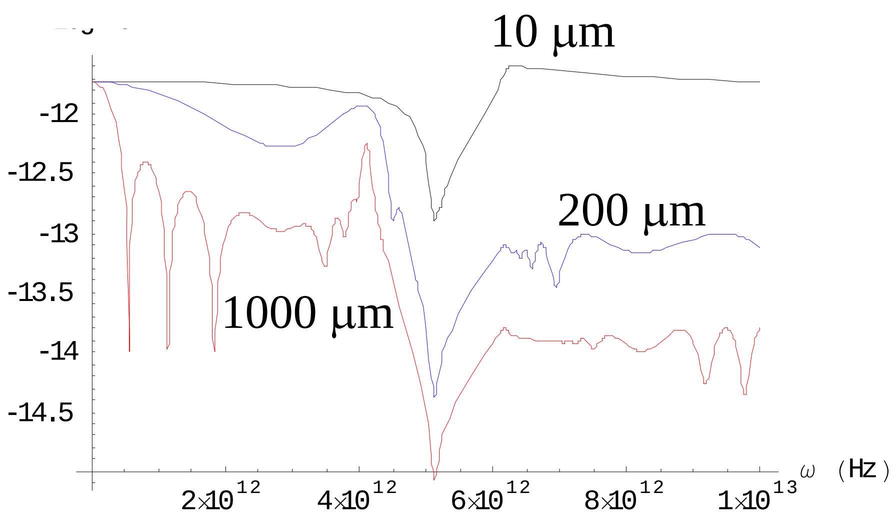
  $\Delta t = r/c\gamma$.

  For APS, γ=14000, with r=1cm, Δt=2 fs

- **Instrumental limitation: spectral resolution**

Crystal properties





- **Z. Jiang and X. C. Zhang, IEEE J. Quantum Electron. 36, 1214 (2000).**
- **H. J. Bakker et al., JOSA B 15, 1795 (1998).**
- **A. Leitenstorfer et al., APL 74, 1516 (1999).**

Some formula

The probe pulse

$$E_{pin}(t) = \exp\left[-\frac{1}{2}\left(\frac{t}{T}\right)^2 - i\left(\omega + \frac{\sqrt{4T^2\Delta\omega^2 - 1}}{4T^2}t\right)t\right].$$

Given, electron beam field, E(t) in the time domain and E(ω)= *F*[E(t)] in the frequency domain, and the complex response function G(ω), in the FELIX exp, one measured

$$I_{pout}(\omega) = \left|F[E_p \cdot F^{-1}(E \cdot G)]\right|^2.$$

The other possibility is to do a different measurement, to get

$$E_{pout}(t) = E_{pin}(t) \cdot E(t) * G(t).$$

Which is equivalent to intensity +phase.

How about a FROG?

= Frequency Resolved Optical Gating

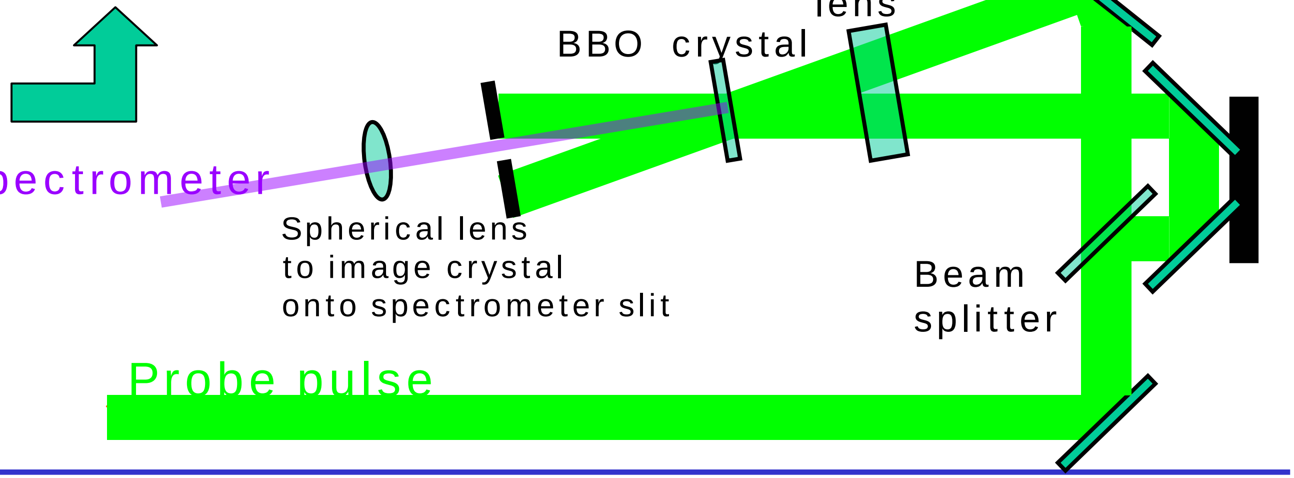
Kane and Trebino, JQE, 29, 571 (1993).
DeLong and Trebino, JOSA B, 11, 2206 (1994).

For the second harmonic FROG

$$E_{sig}(t,\tau) \propto E(t)E(t-\tau).$$

And the measured signal on the spectrometer is

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



Cylindrical lens

BBO crystal

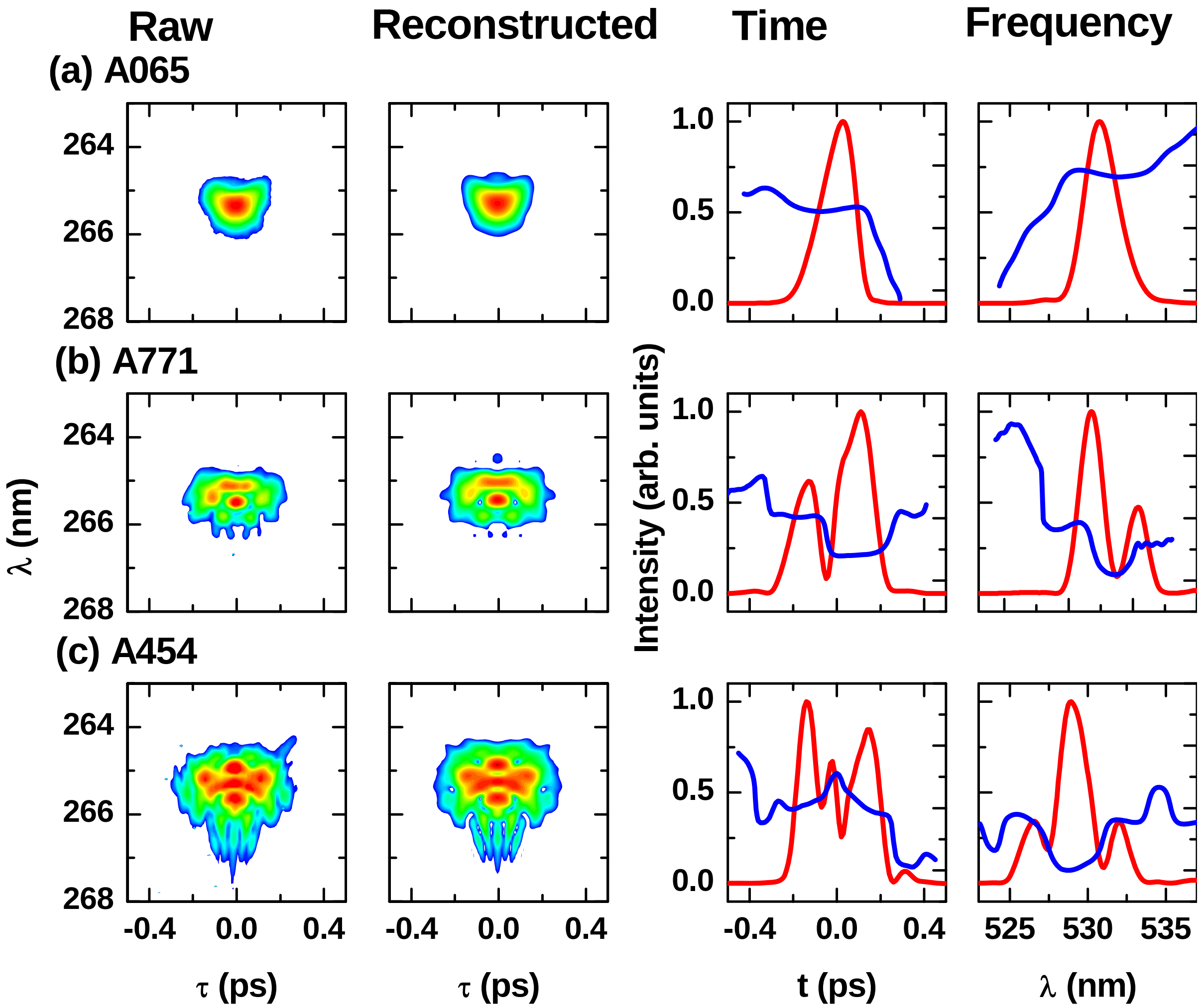
Correlated
Signal to spectrometer

Spherical lens
to image crystal
onto spectrometer slit

Beam
splitter

Probe pulse

Sample traces: FEL experiment



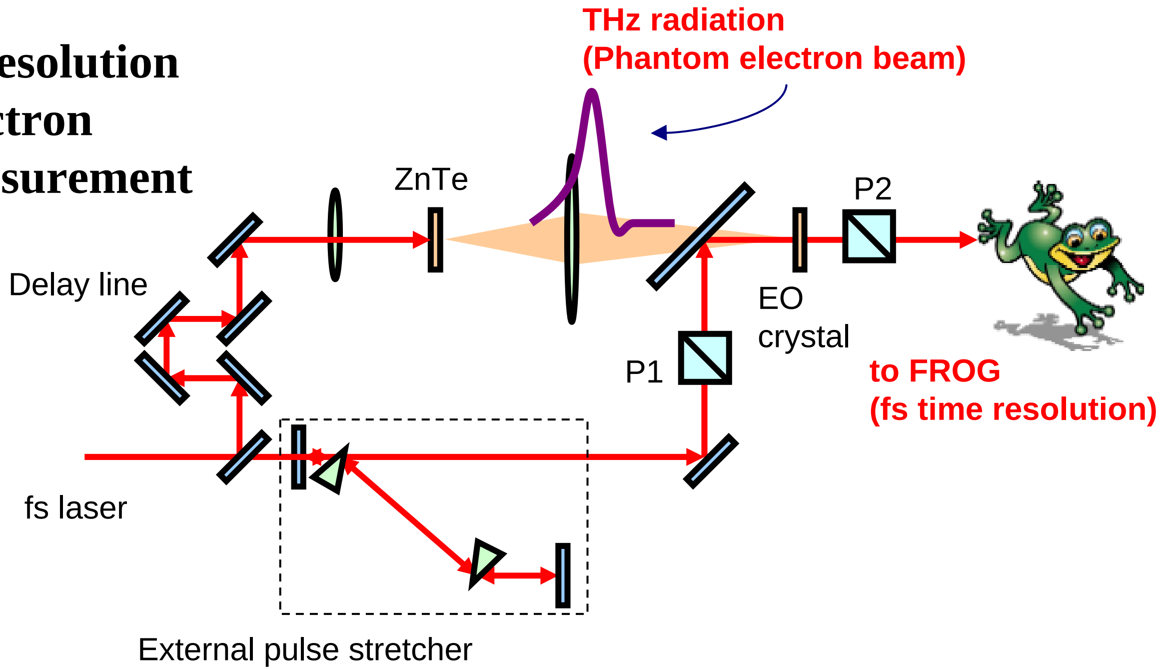
APS Experimental goal and setup

Key features

- **Use laser-generated THz radiation as an electron beam phantom, in a lab setting**
- **Employ the Frequency-Resolved Optical Gating (FROG) for single-shot fs resolution**

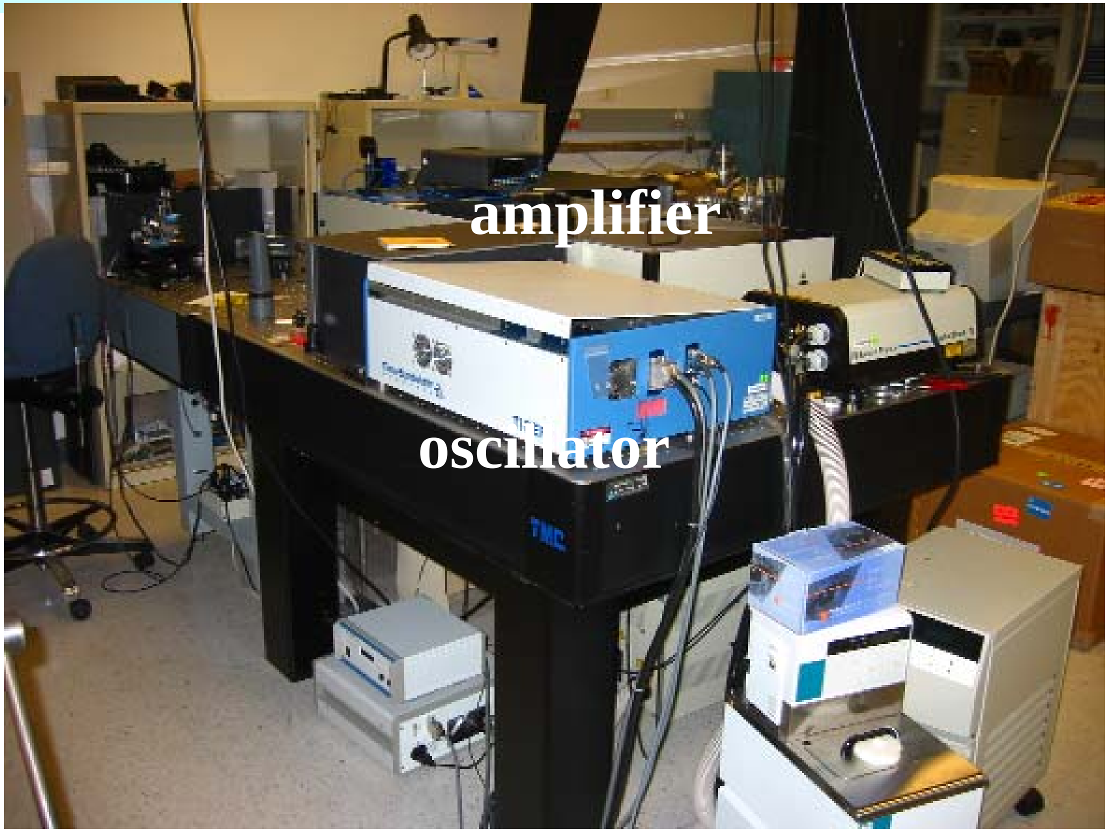
Goal

- **A system with fs resolution for single shot electron bunch profile measurement**



Lab

Bandwidth	**16 nm**
Pulse duration	**70 fs**
Rep Rate	**1 kHz**
Energy	**~ mJ**



Plan

Generating the phantom

Optical rectification

Z. Jiang and X. C. Zhang, IEEE J. Quantum Electron. 36, 1214 (2000).
H. J. Bakker et al., JOSA B 15, 1795 (1998).

A. Leitenstorfer et al., APL 74, 1516 (1999).

Probing the phantom

EO sampling + FROG
Try different crystals
Try different laser pulses

Application in the lab?