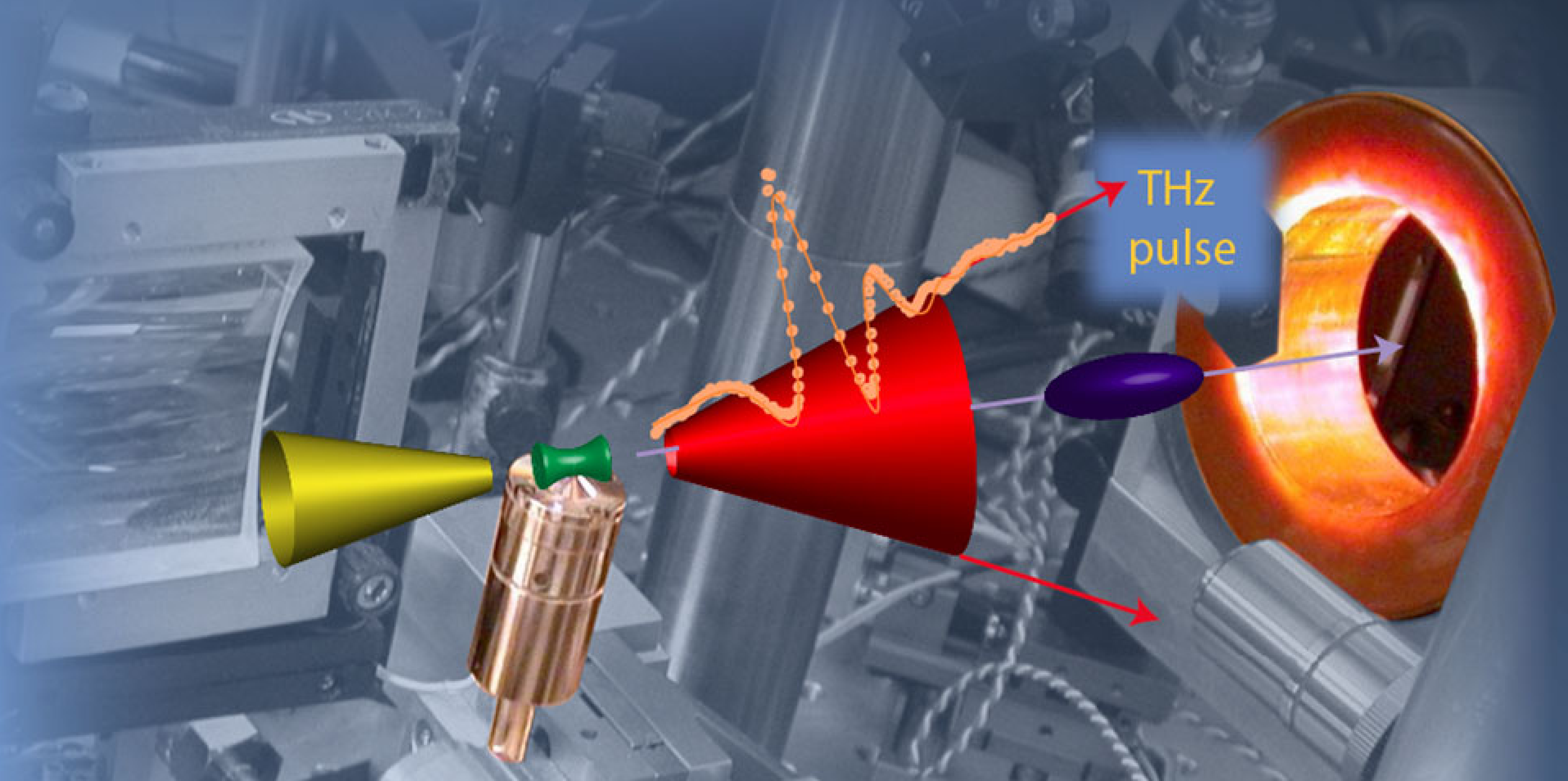


Electro-optic techniques in beam diagnostics

by Jeroen van Tilborg

Lawrence Berkeley National Lab

Beam Instrumentation Workshop 2008

Electron accelerators: Analysis of temporal profile

Electron accelerators:

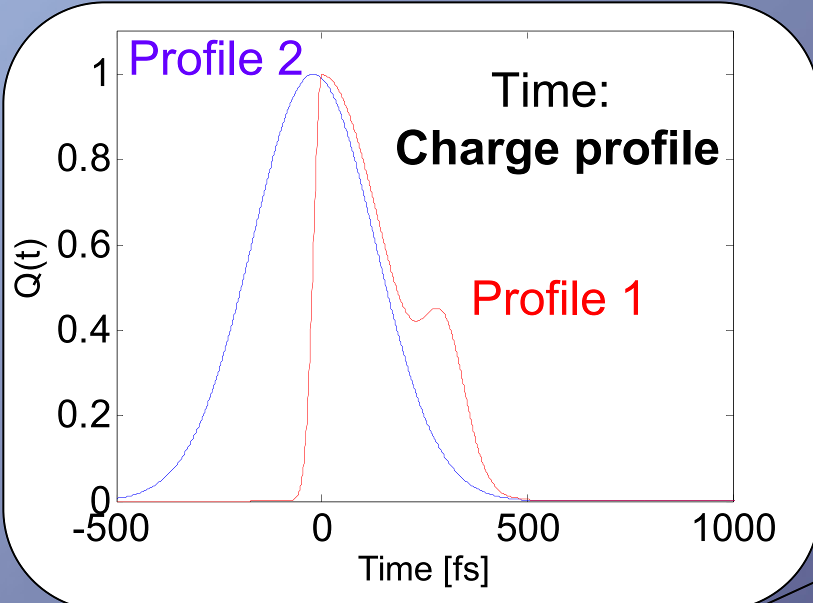
- Experiments utilizing electron bunches
    - Electron diffraction
    - Colliders
    - Magnetic switching
- Generation of radiation
    - X-rays
    - VUV radiation
    - THz and FIR

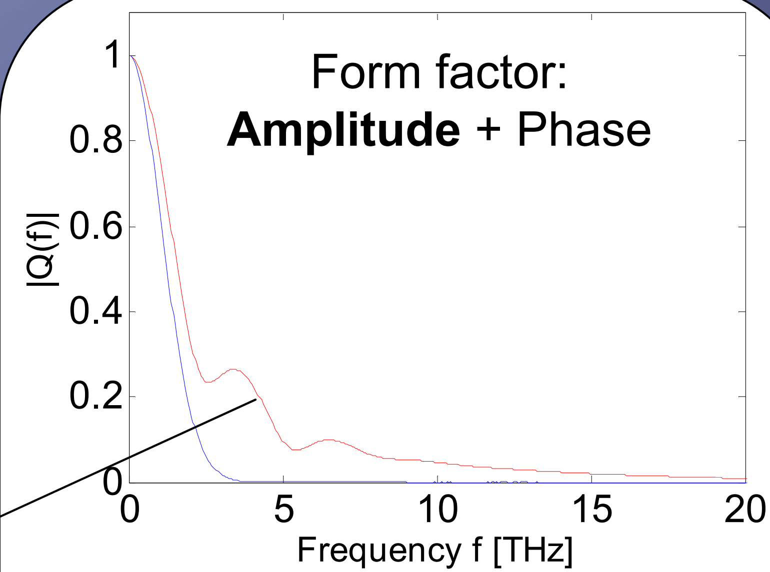
IMPORTANT:
Quality of electron bunch

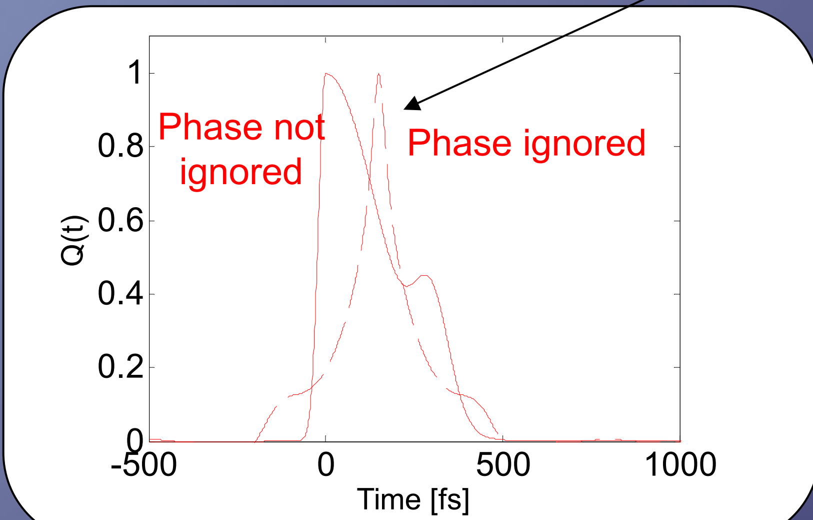
Quality of electron bunch

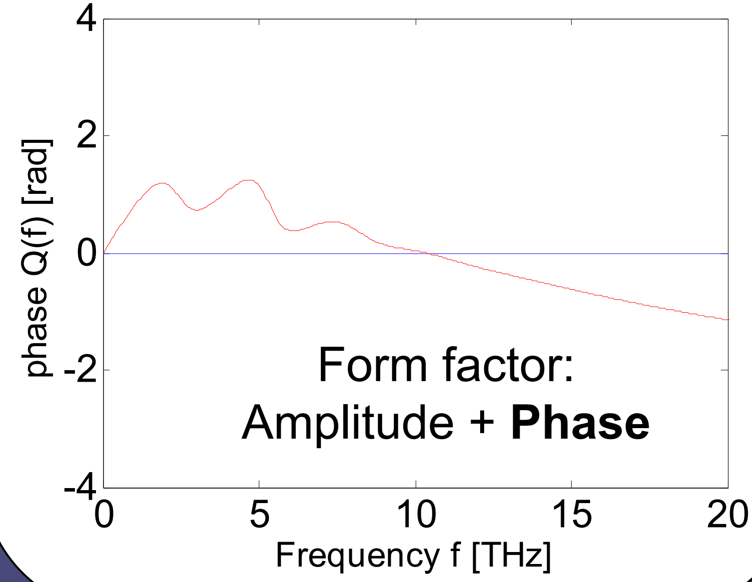
- Charge
- Divergence
- Energy
- Energy spread
- Transverse profile
- **Longitudinal/temporal profile**

Charge profile analysis: Time or frequency domain

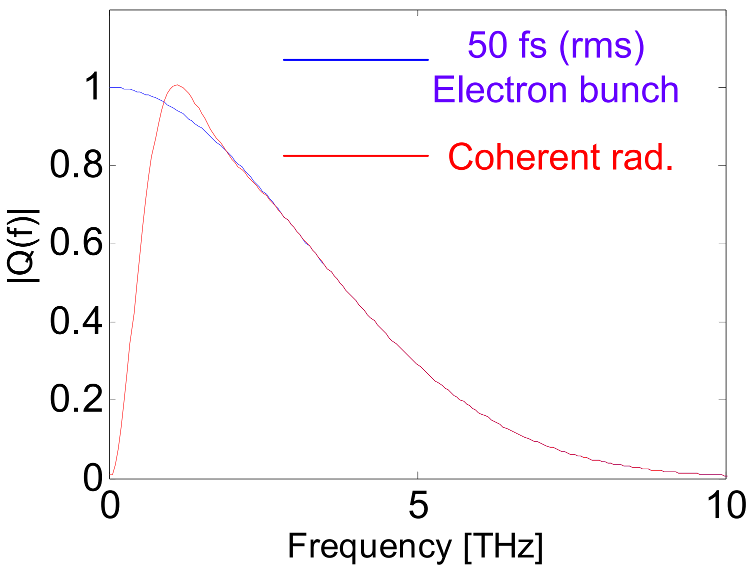


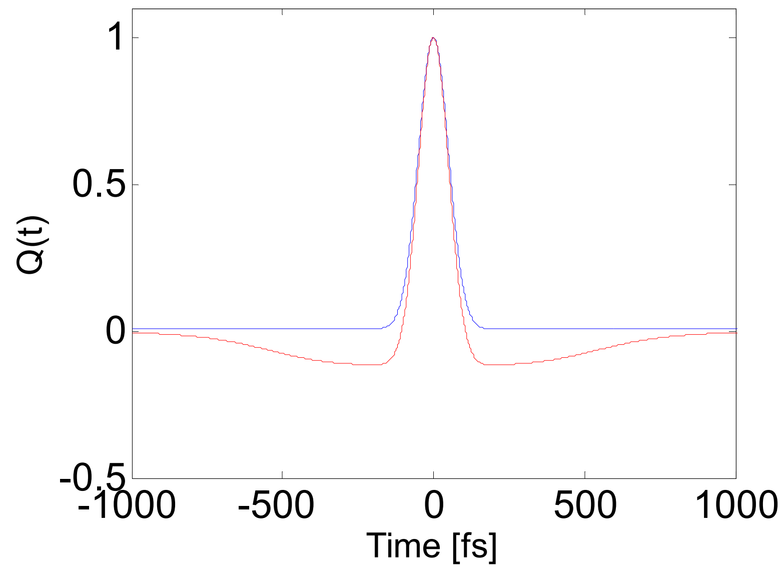






E-bunch and coherent radiation: Close correlation





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

Coherent Radiation
- Transition rad.
- Smith-Purcell rad.
- Diffraction rad.
- Synchrotron rad.

- μJ's of energy
- ~1 MV/cm

Why analysis on coherent radiation?
- Setup away from electron path (air)
- Setup can be used for THz applications
- THz beam path adds complications (alignment, aberrations, spectral change)

Talk outline

- Overview of diagnostic techniques
- Introduction to electro-optic sampling (EOS)
- EOS in time domain
- EOS in laser's frequency domain
- Summary

Overview of diagnostic techniques

Bunch diagnostic techniques

Direct e-beam

- EO sampling
- Pump/probe scattering
- RF zero-phasing

Convert e-beam to radiation

Incoherent Radiation

- Fluctuation Interferometry
- Streak camera

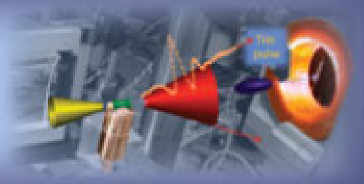
Coherent Radiation (THz regime)

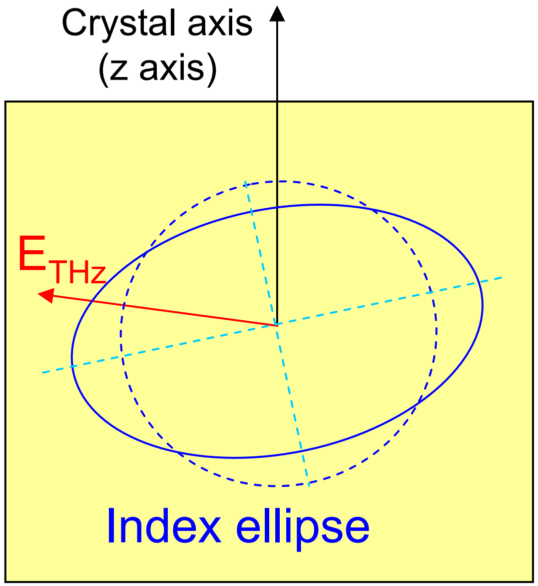
- Bolometer spectrum
- Interferometry
- EO sampling
- Angular emission pattern

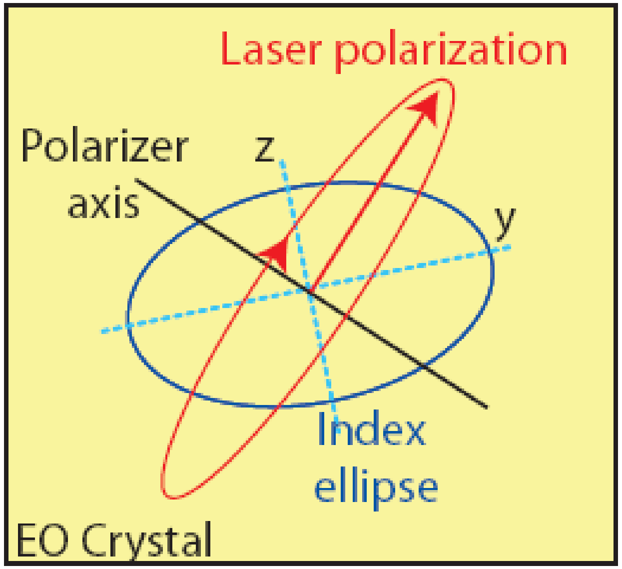
EO sampling

- Resolution of 10's of fs
- Exact charge profile
- Non-destructive
- Single-shot
- Relative timing for pump/probe
- Room temperature

Electro-optic sampling:
Mix laser + THz fields in EO crystal







Change index $\Delta n(t) \sim E_{THz}(t)$

$$E_m(t) = E_L(t) \cdot e^{i\Gamma_{THz}(t)}$$

Measurement of $\Gamma_{THz}(t)$:

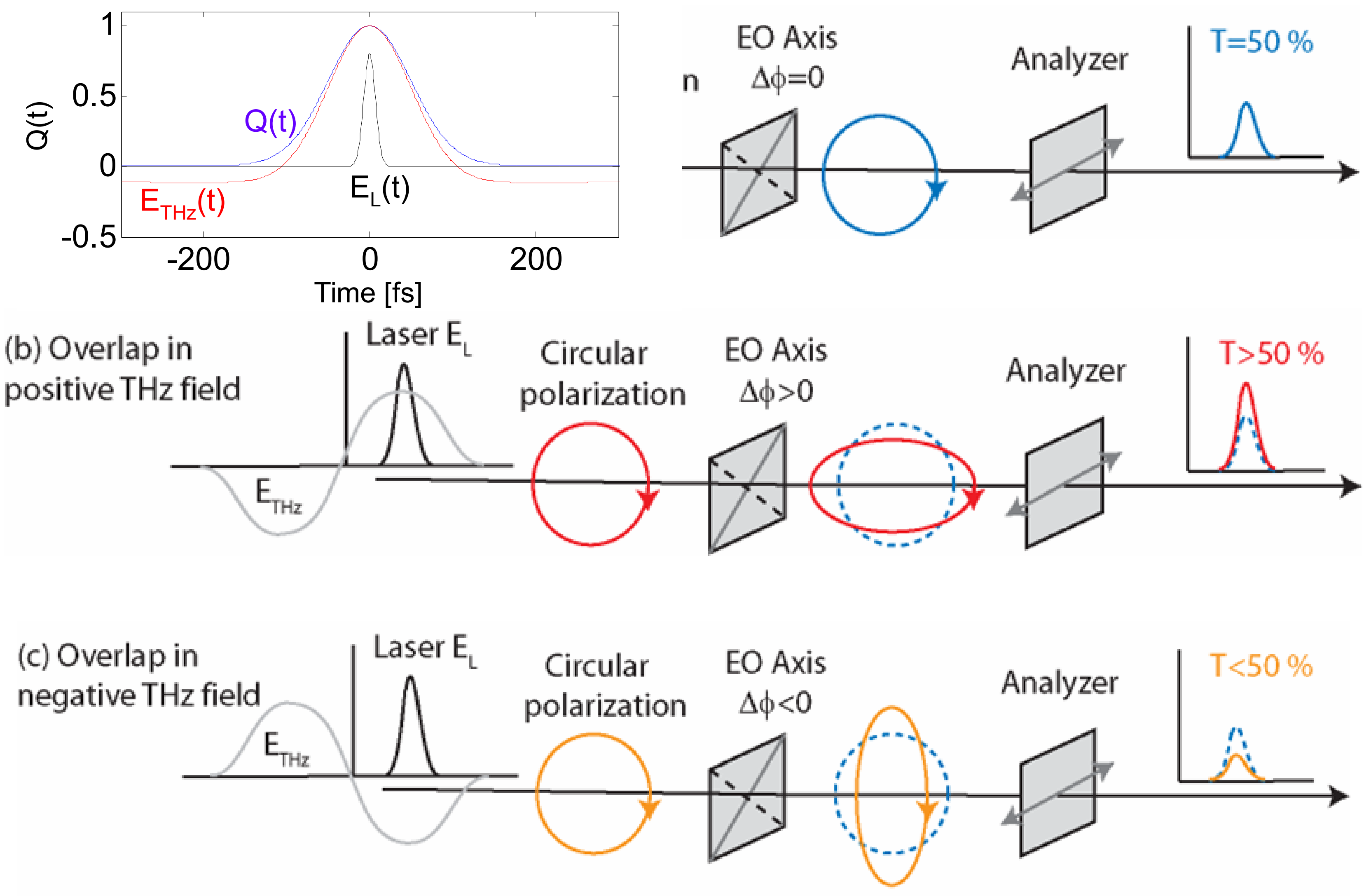
Use a probe laser and cross-polarizer

Phase modulation → amplitude modulation $|E_m(t)|$

Time domain laser

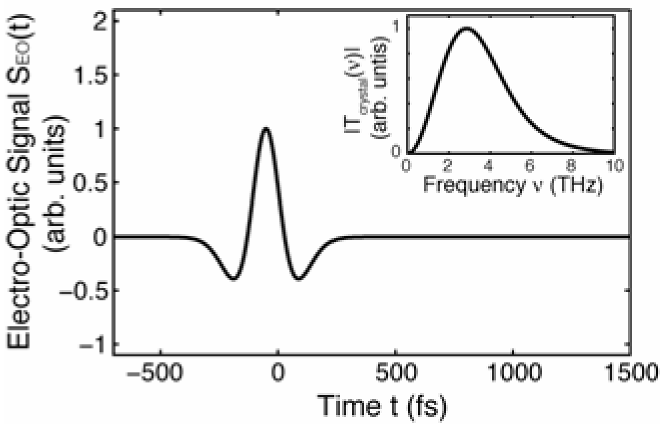
Frequency domain laser

Electro-optic sampling
Measuring polarization change

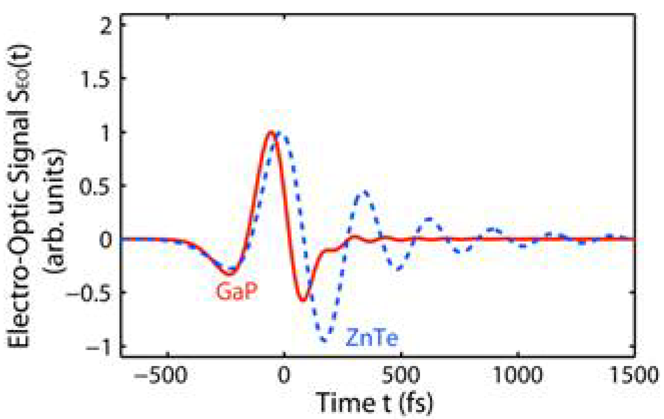


Electro-optic sampling
Crystal effects on spectral bandwidth

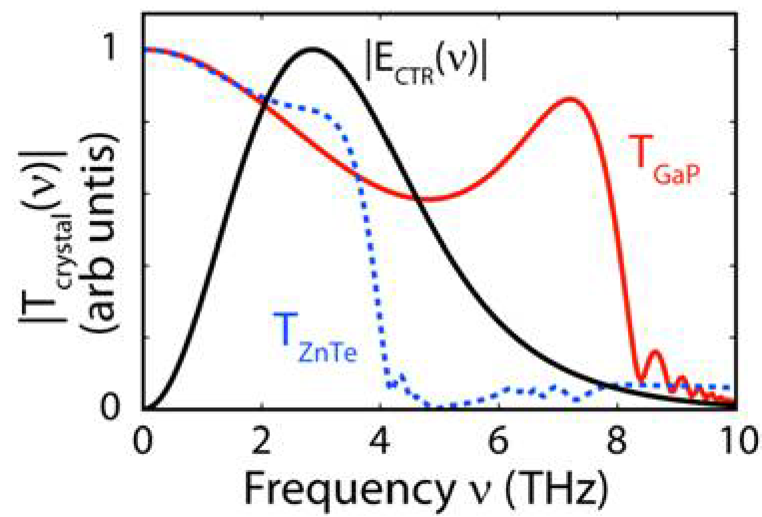
CTR 50 fs e-beam



Modeled EO measurement



Crystal effects:
- Absorption
- Dispersion
- Mismatch laser – THz



$$S_{EO}(f) \propto Q(f)\cdot D(f)\cdot E_{L,envelope}(f)\cdot T_{crystal}(f)$$

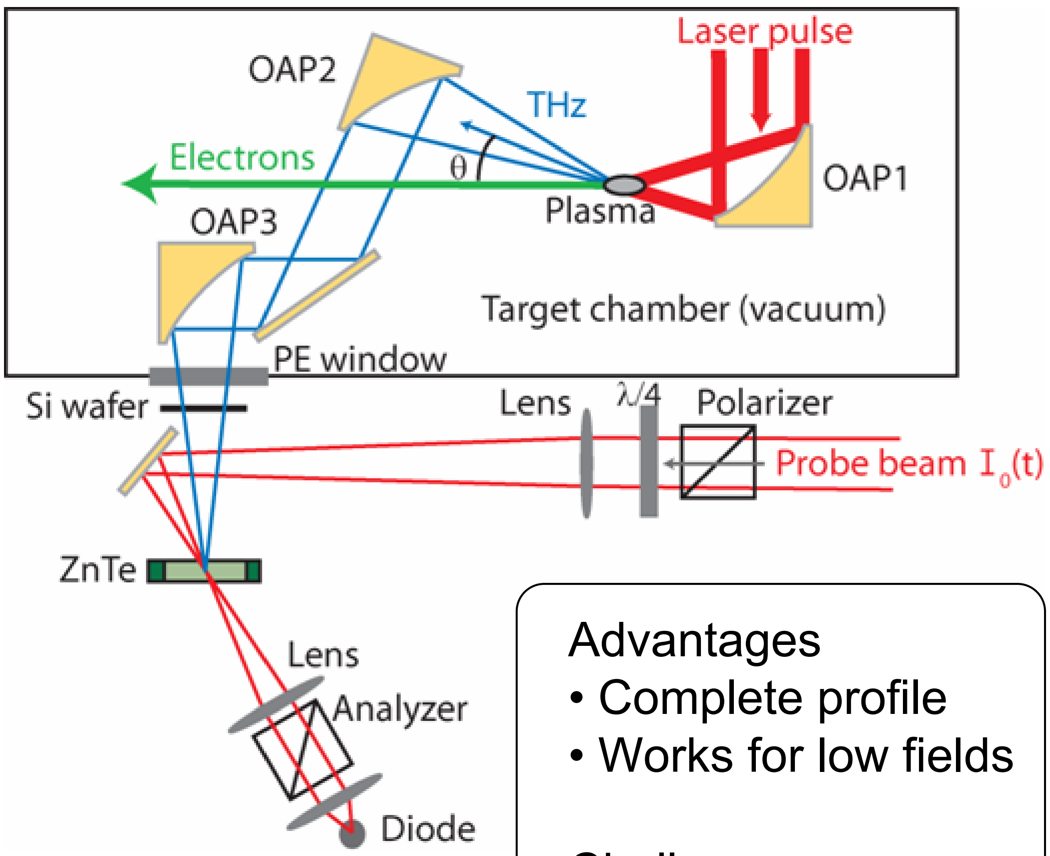
Charge bunch

Diffraction (radiation)

EO crystal

Spectrum envelope laser

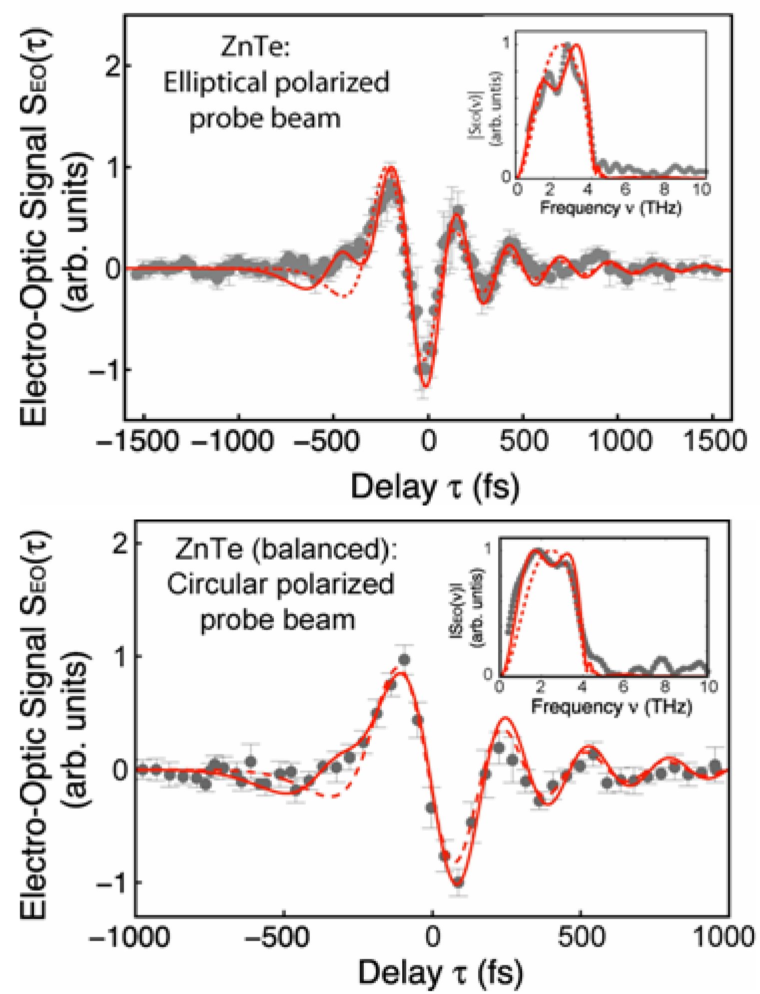
Multi-shot EOS
(use short laser pulse)



Advantages
- Complete profile
- Works for low fields

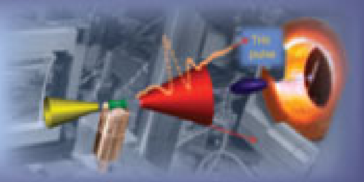
Challenges
- Takes many shots
- Reproducibility

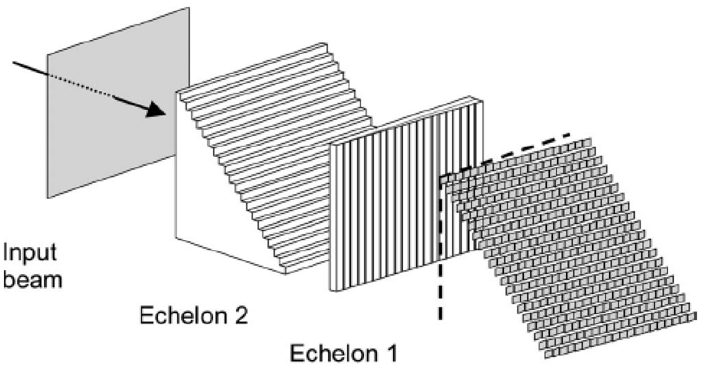
50 fs (rms) electron bunch

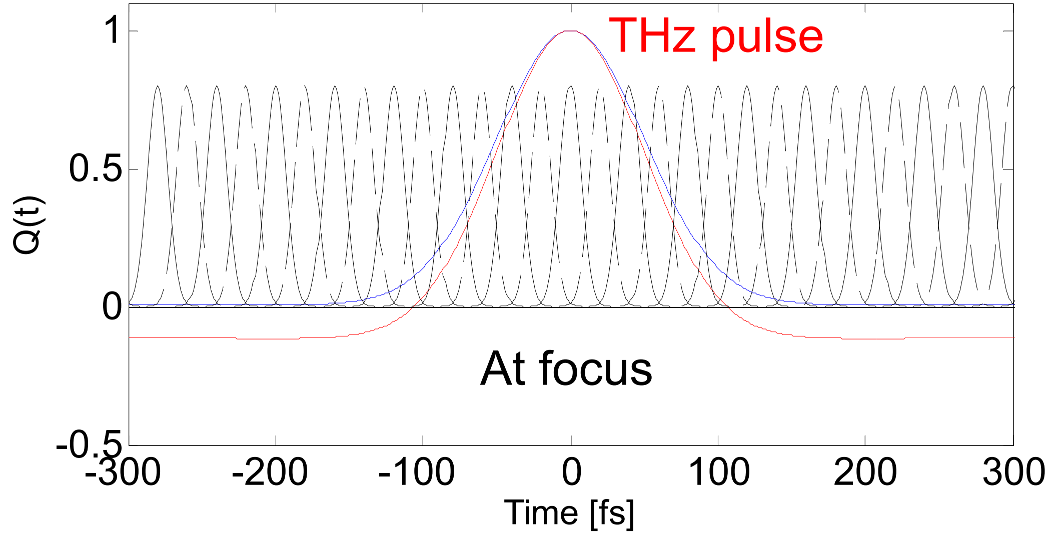


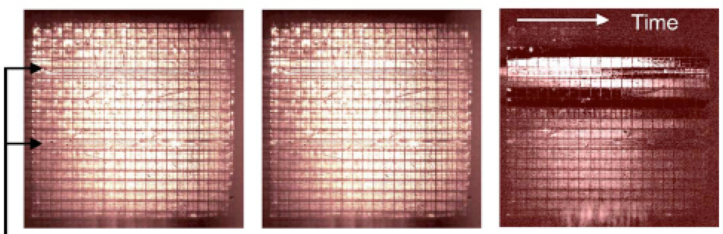
van Tilborg *et al.*, PRL **96**, 014801 (2006)

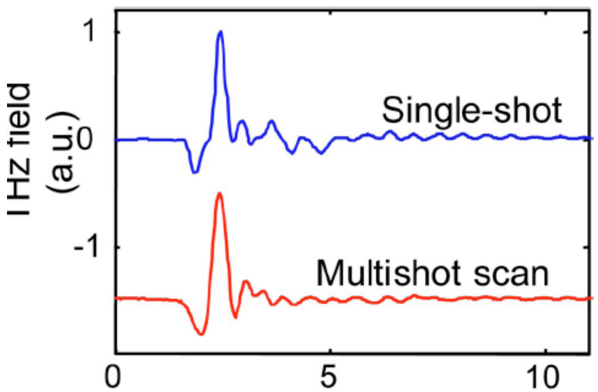
1) Single-shot EOS
Spatio-temporal mixing









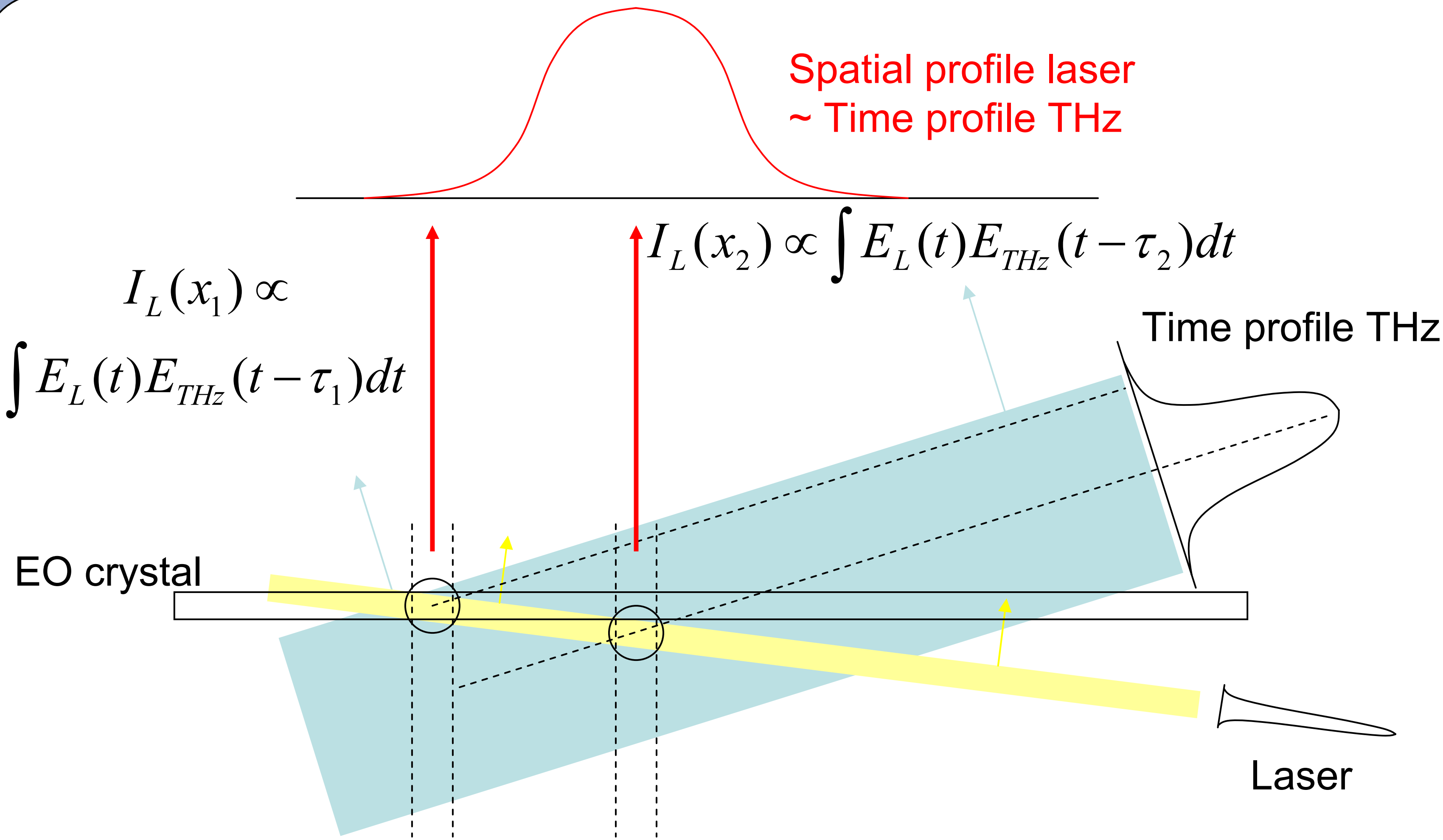


Kim *et al*., Opt. Lett. **32,** 1968 (2007)

Advantages
- Complete profile
- Single-shot

Challenges
- Complex imaging
- Availability echelons
- Resolution >30 fs

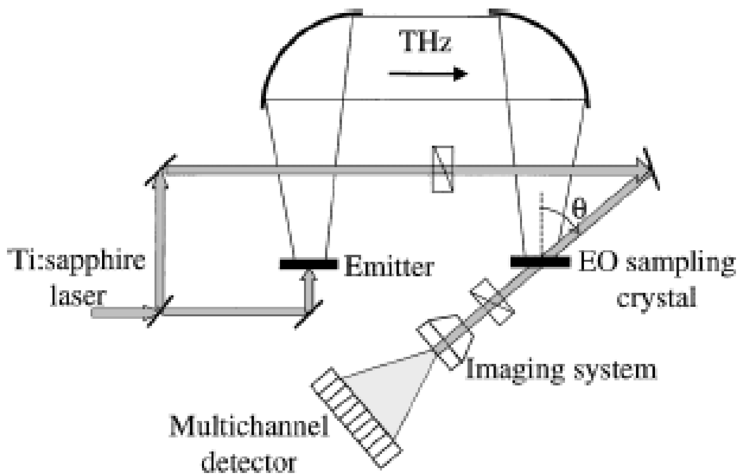
Non-collinear cross-correlation

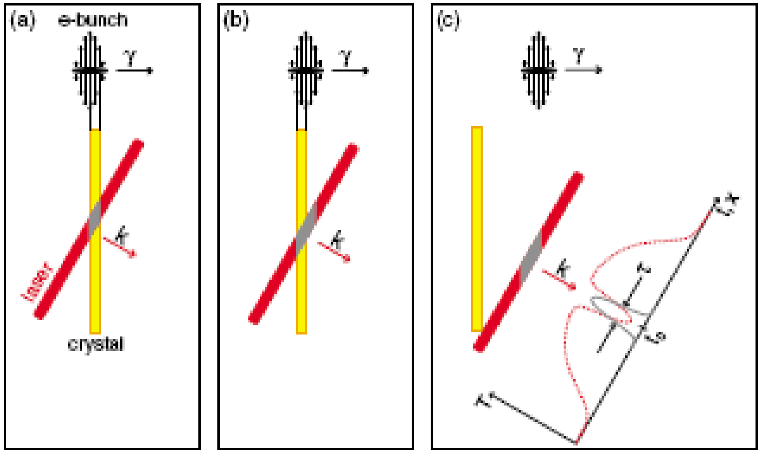


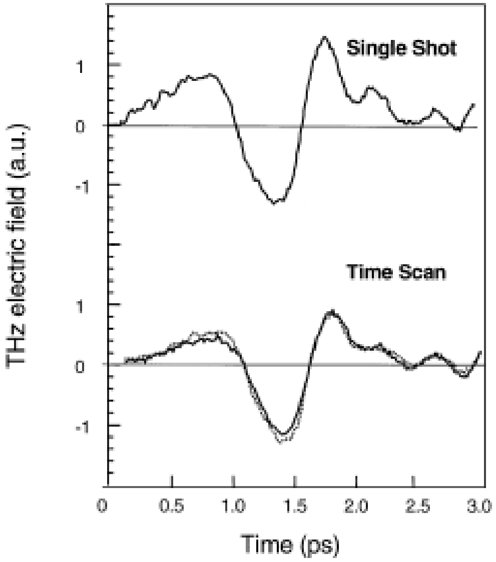
$$E_{THz}(\tau) \propto I_L(x) \propto \int E_L(t) E_{THz}(t-\tau)dt$$

2) Single-shot spatial encoding

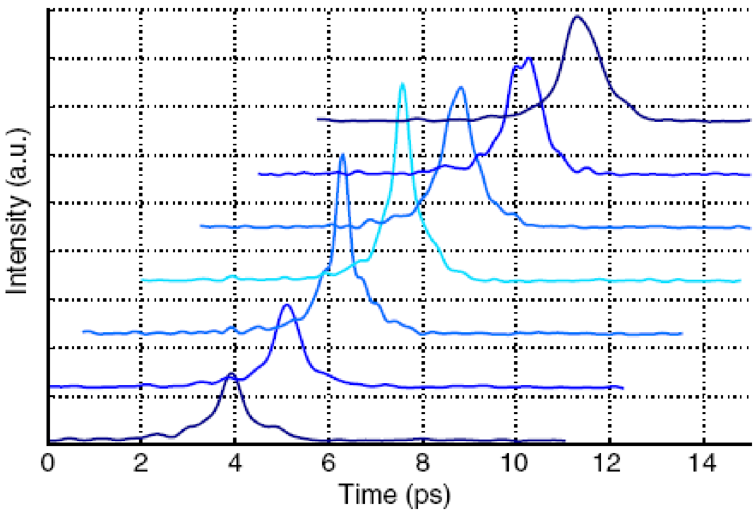
Non-collinear cross-correlation between laser and THz







Pulse duration 270 fs



Advantages
- Complete profile
- Single-shot

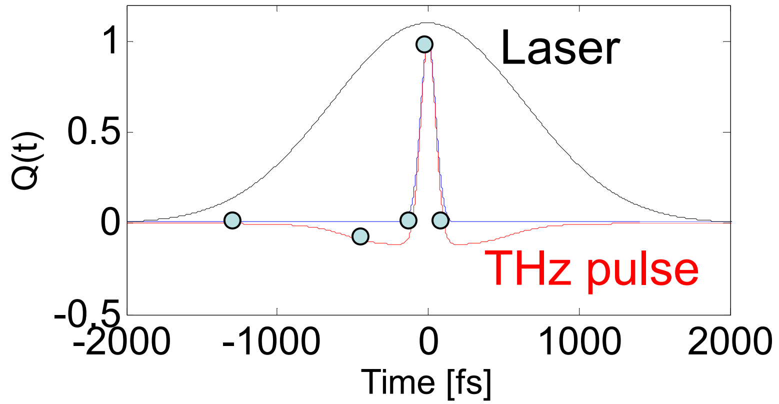
Challenges
- Transverse effects
- Weak THz fields

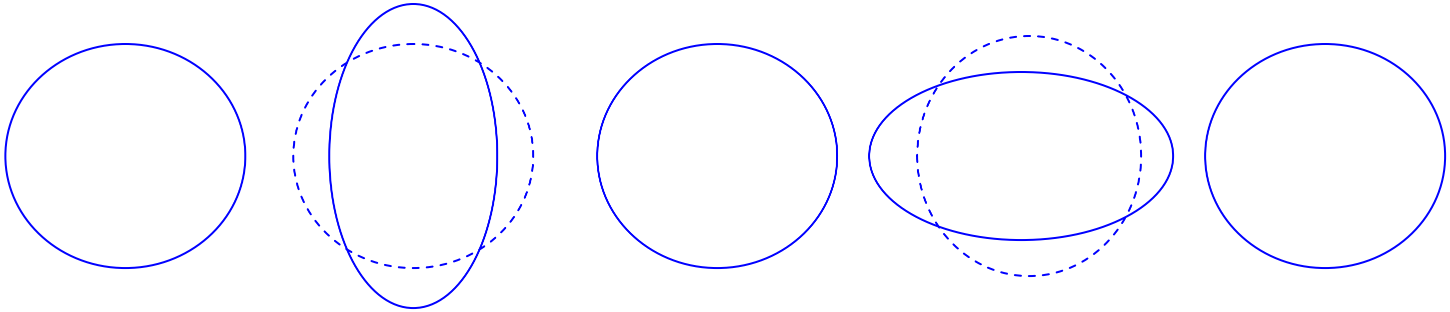
Shan *et al*., Opt. Lett. **25,** 426 (2000)

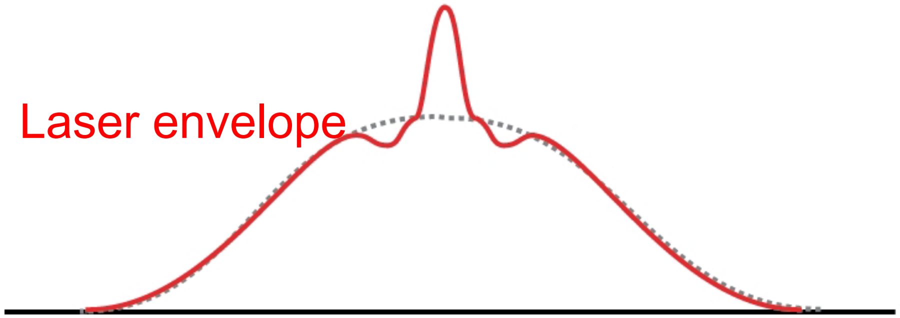
Cavalieri, Phys. Rev. Lett. **94,** 114801 (2005)

3) Single-shot spatial encoding

Non-collinear cross-correlation laser and THz-modulated laser

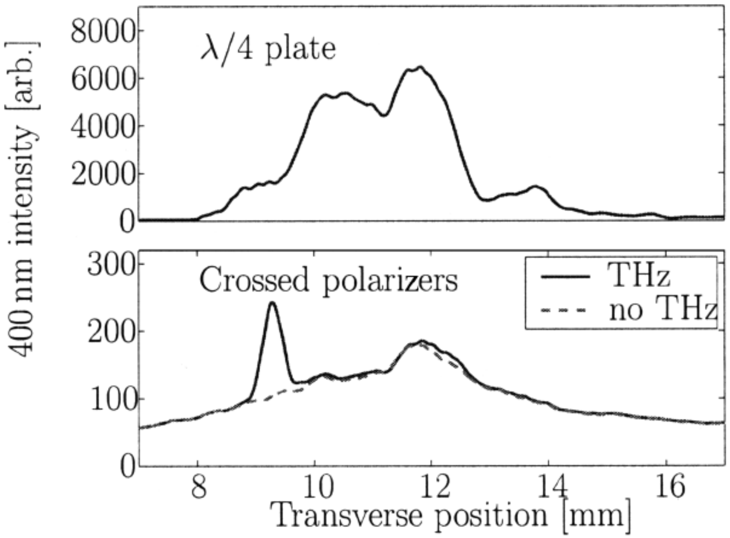


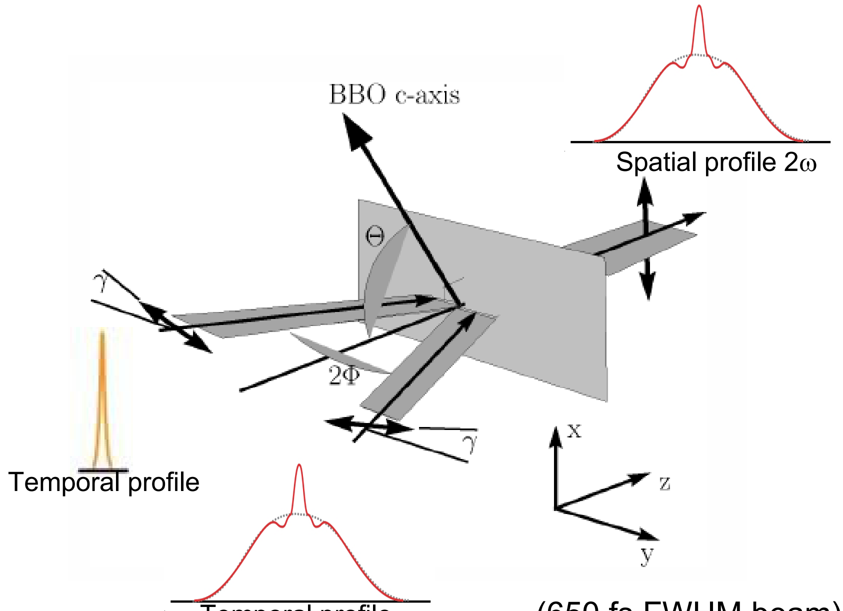


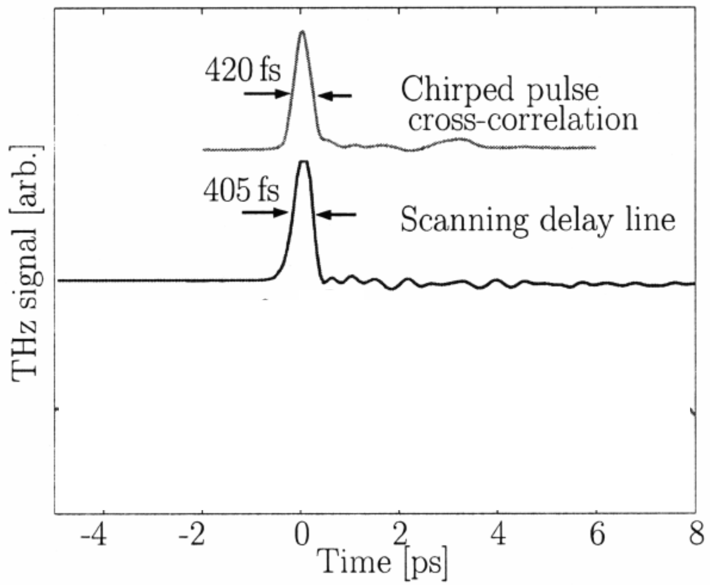


3) Single-shot spatial encoding

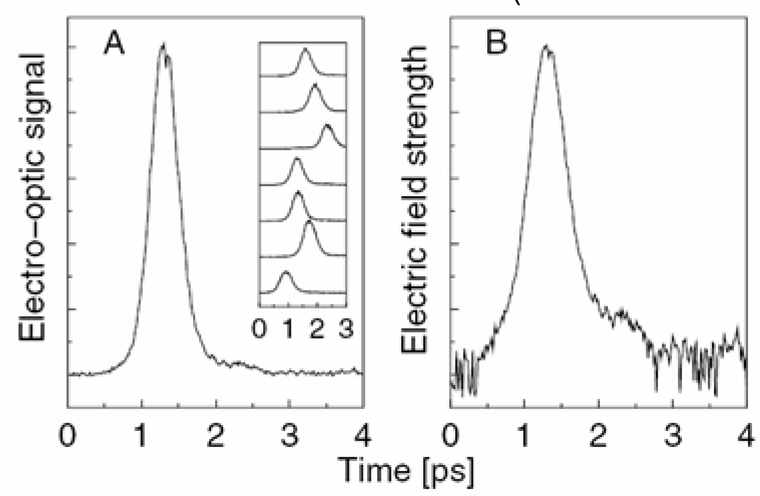
Non-collinear cross-correlation laser and THz-modulated laser







(650 fs FWHM beam)

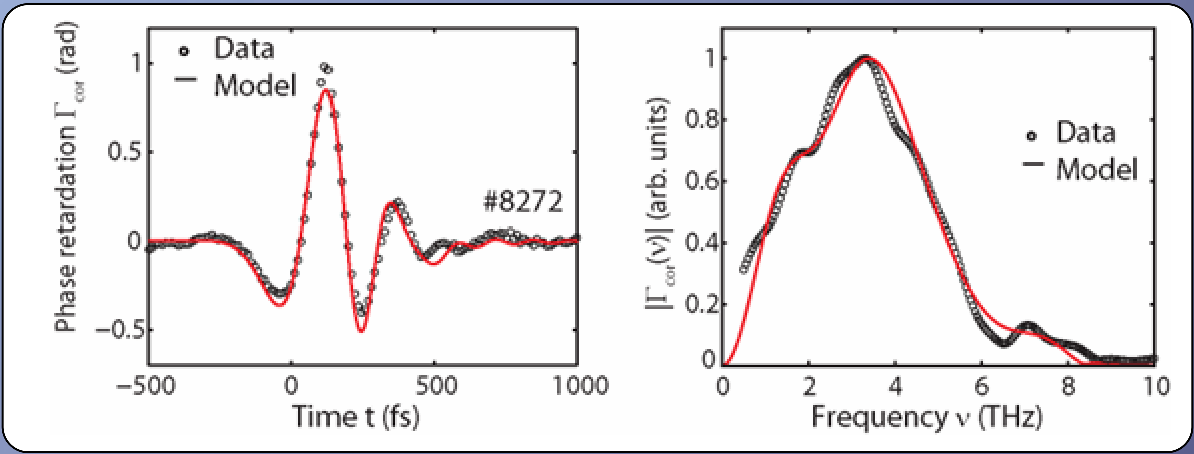


Jamison *et al.*, Opt. Lett. **28**, 1710 (2003)

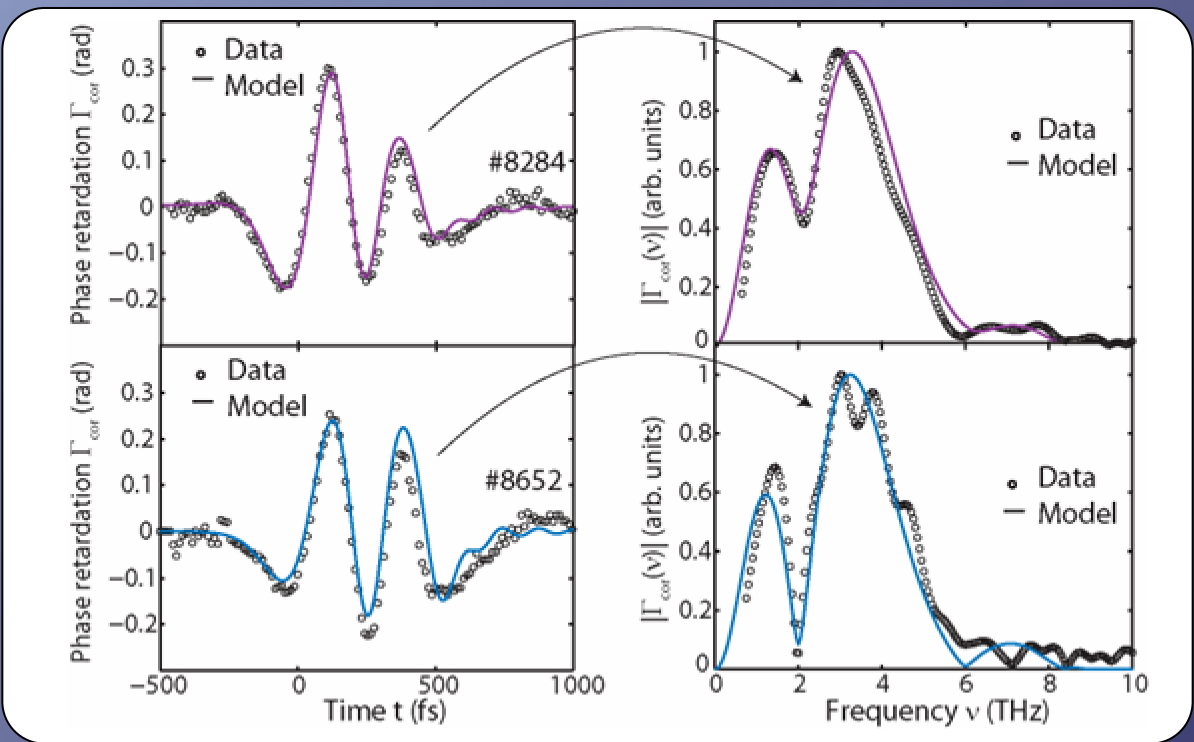
Berden *et al.*, Phys. Rev. Lett. **93**, 114802 (2004)

3) Single-shot spatial encoding

Non-collinear cross-correlation laser and THz-modulated laser



- Model (red curve) is based on a 45-fs e-bunch
- E-field of 0.4 MV/cm



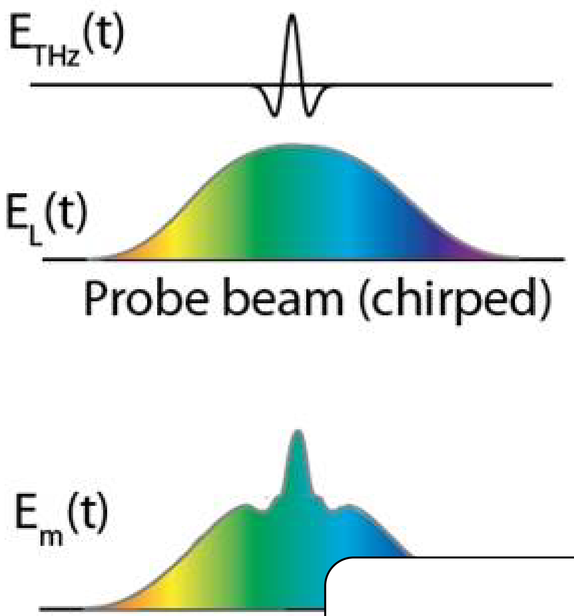
Advantages
- Complete profile
- Single-shot

Challenges
- Two laser beams
- Complex power balance
- 2 nonlinear crystals

van Tilborg *et al*., Opt. Lett. **32**, 313 (2007)

4) Single-shot spectral encoding

Direct relation laser wavelength and time



For $\tau_{ebeam} > \sqrt{\tau_{L,chirp} \cdot \tau_{L,FL}}$

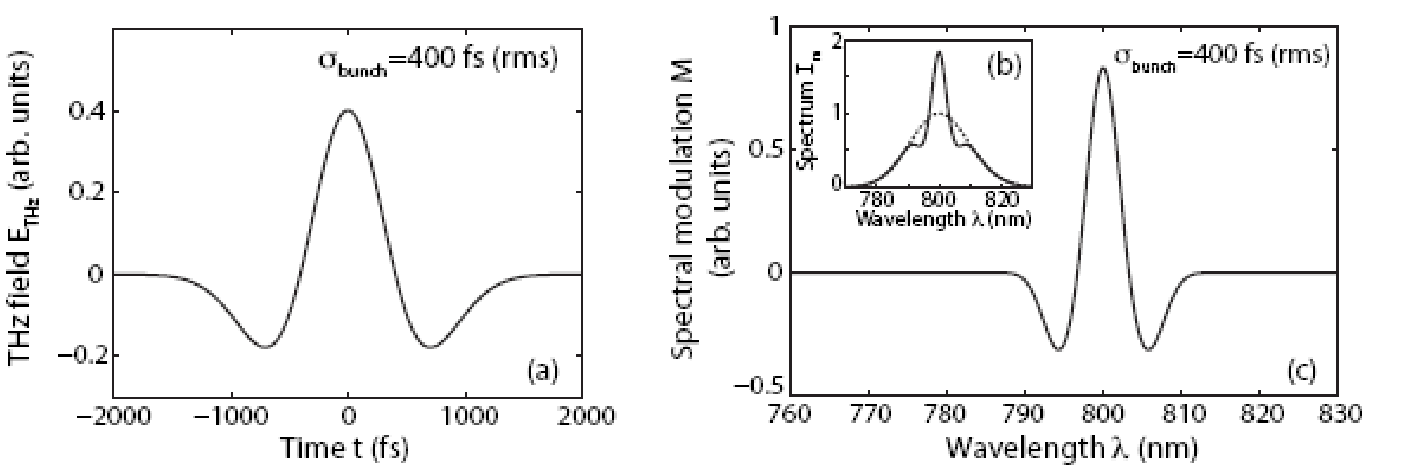
Example

$\tau_{L,chirp}$=2.8 ps

$\tau_{L,FL}$=40 fs

Yields τ_{ebeam}=330 fs

Direct relation λ to time $\omega_{\mathrm{inst}}(t) = \omega_0 + \frac{b}{2\tau_{\mathrm{FL}}^2(1+b^2/4)}t$



Advantages

- Complete profile
- Single-shot
- Only low-power laser beam

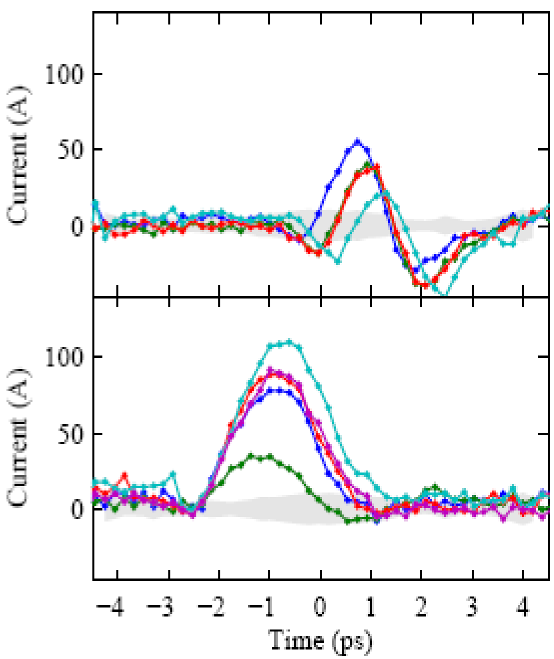
Challenges

- Poor resolution

4) Single-shot spectral encoding

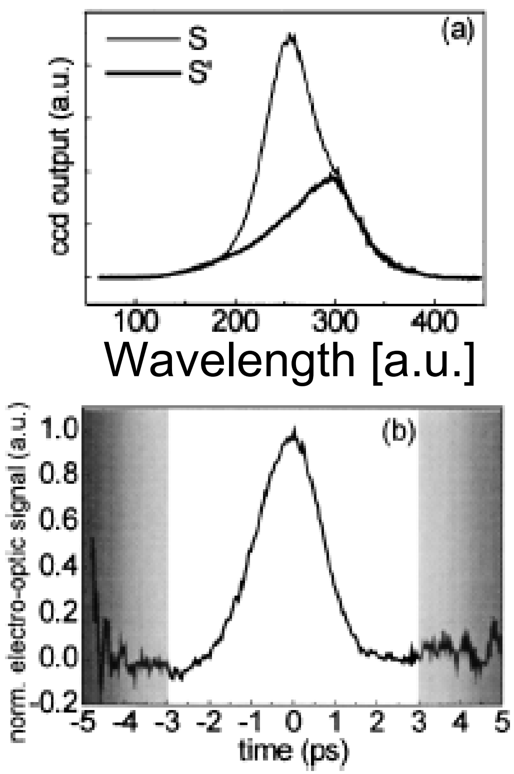
Direct relation laser wavelength and time

Loos et al, Proceedings PAC 2003



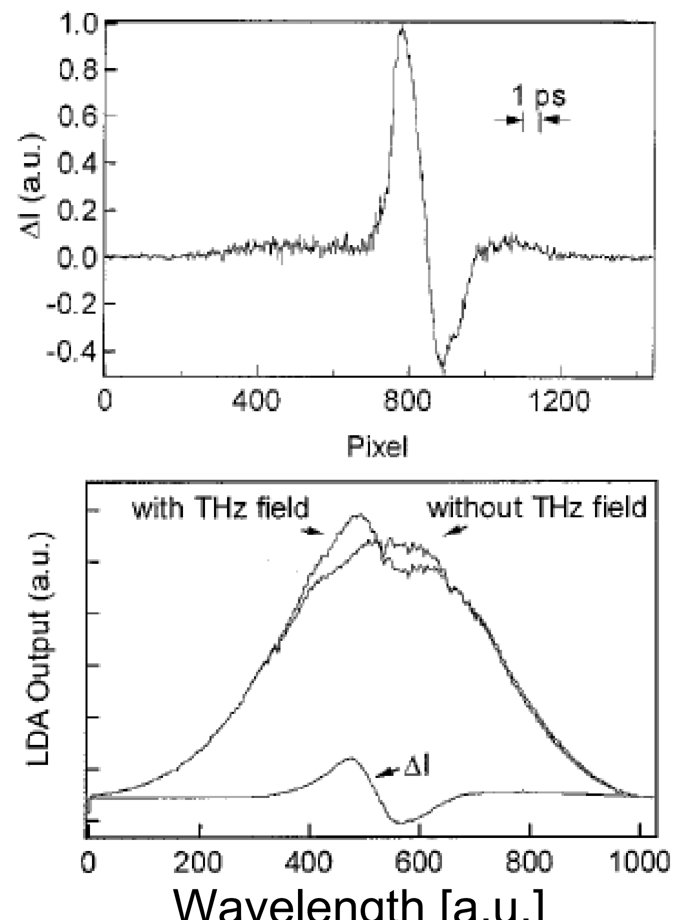
Bunch duration 1.7 ps

Wilke *et al.*, Phys. Rev. Lett. **88**, 124801 (2002)

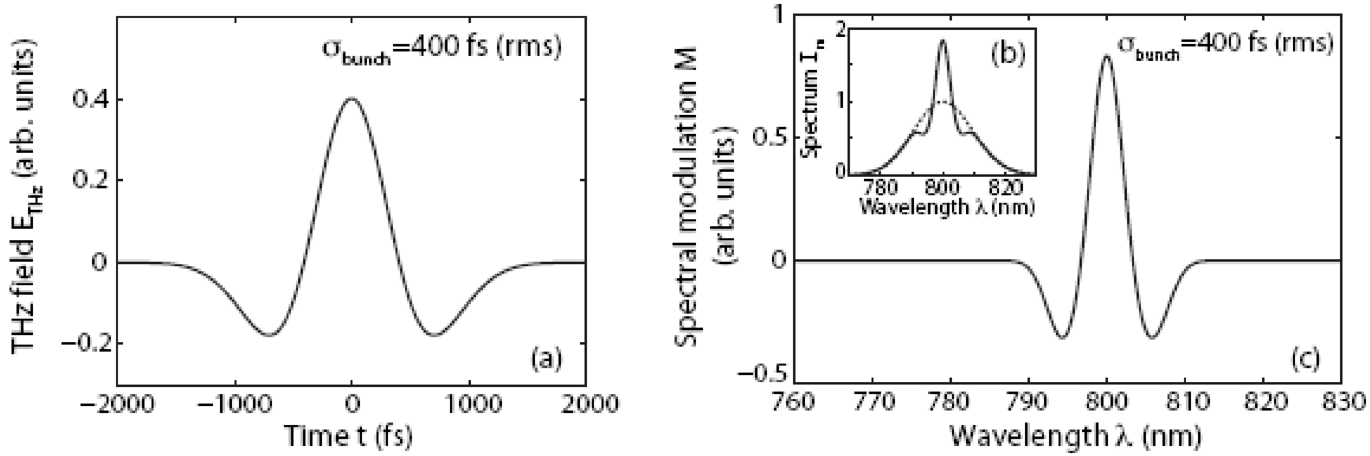


Bunch duration1.7 ps

Zhiping Jiang *et al.*, IEEE J. Quant. Electr. **36**, 1214 (2000)

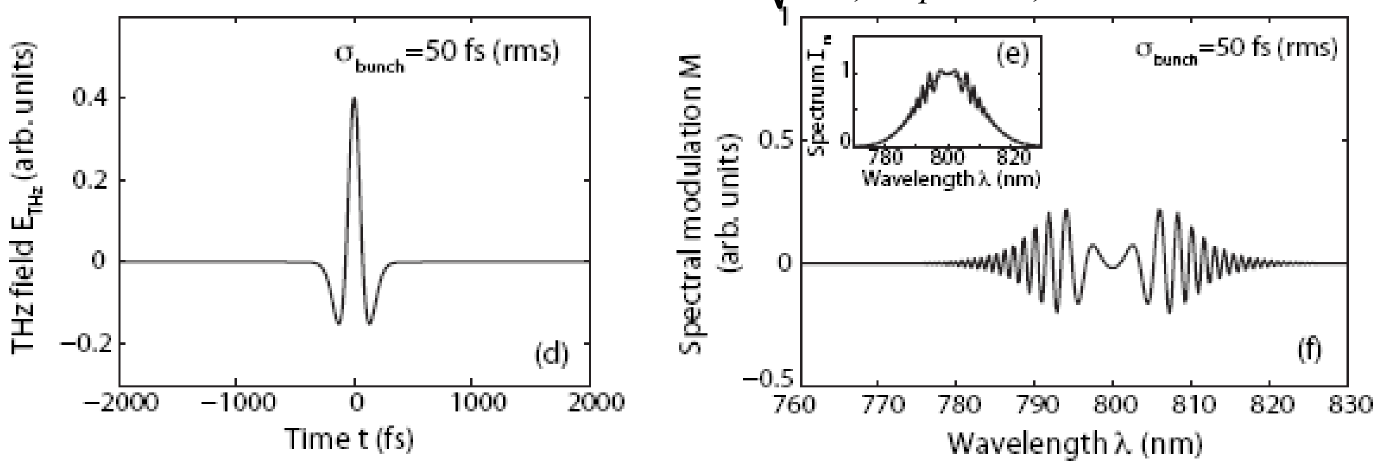


Limited time resolution
Complex spectral modulations

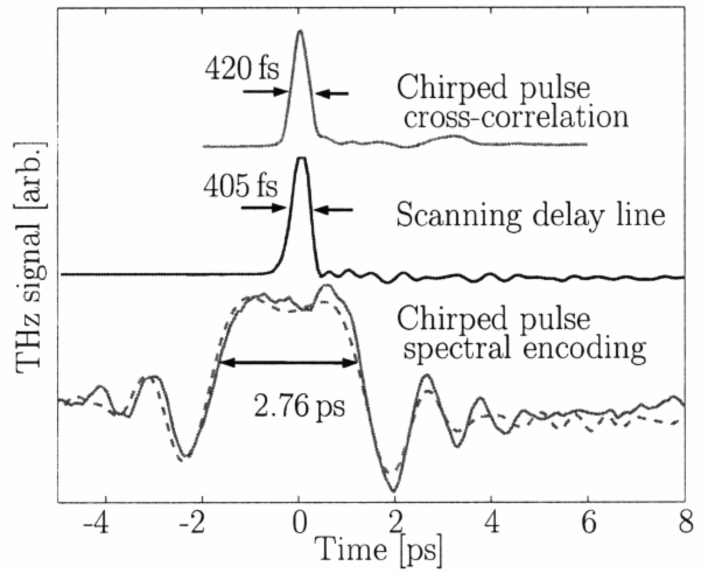


For $\tau_{ebeam} > \sqrt{\tau_{L,chirp} \cdot \tau_{L,FL}}$

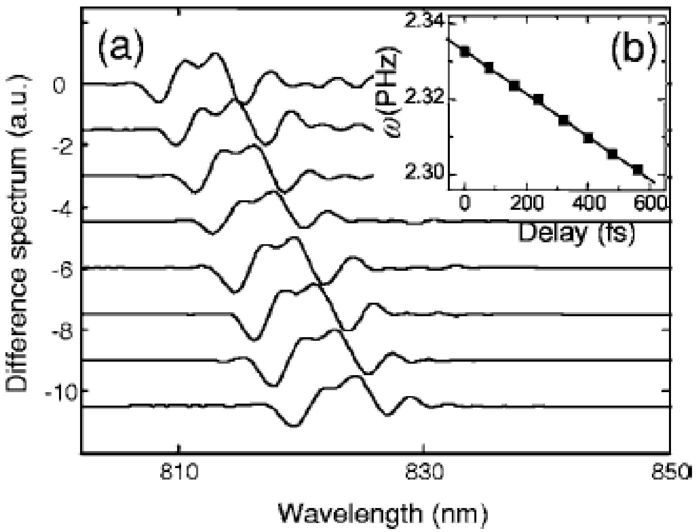
For $\tau_{ebeam} < \sqrt{\tau_{L,chirp} \cdot \tau_{L,FL}}$



Examples of spectral modulations….

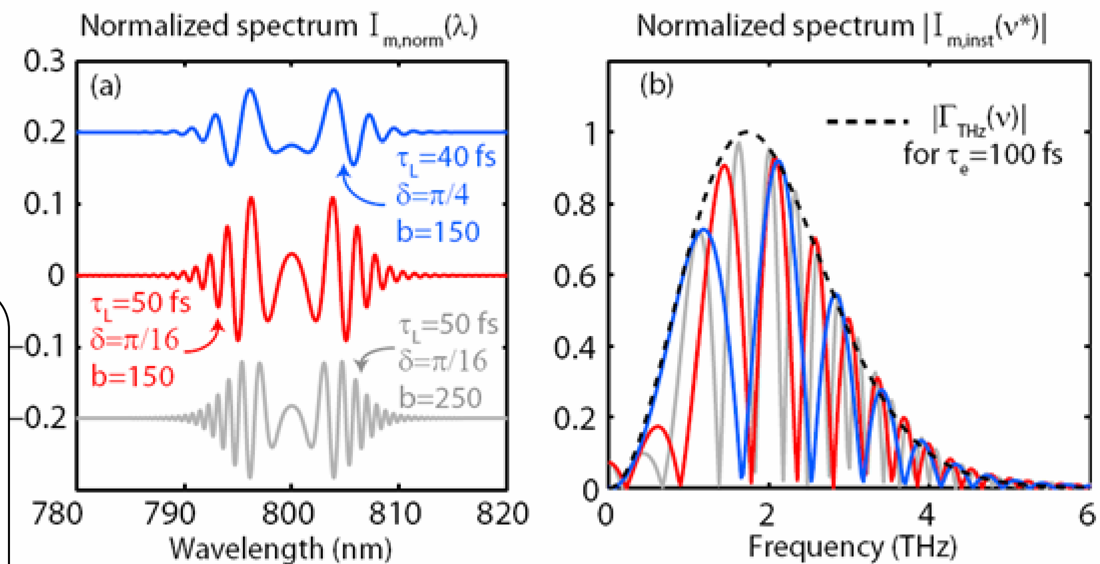


Jamison *et al.*, Opt. Lett. **28**, 1710 (2003)

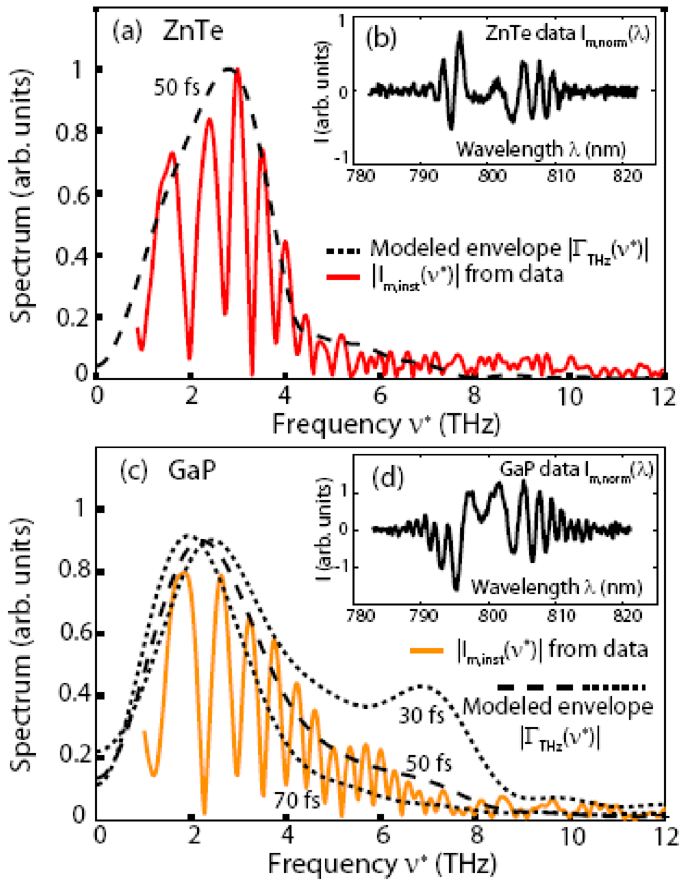


Kim *et al.*, Appl. Phys. Lett. **88**, 04112 (2006)

5) Single-shot spectral encoding spectral envelope only



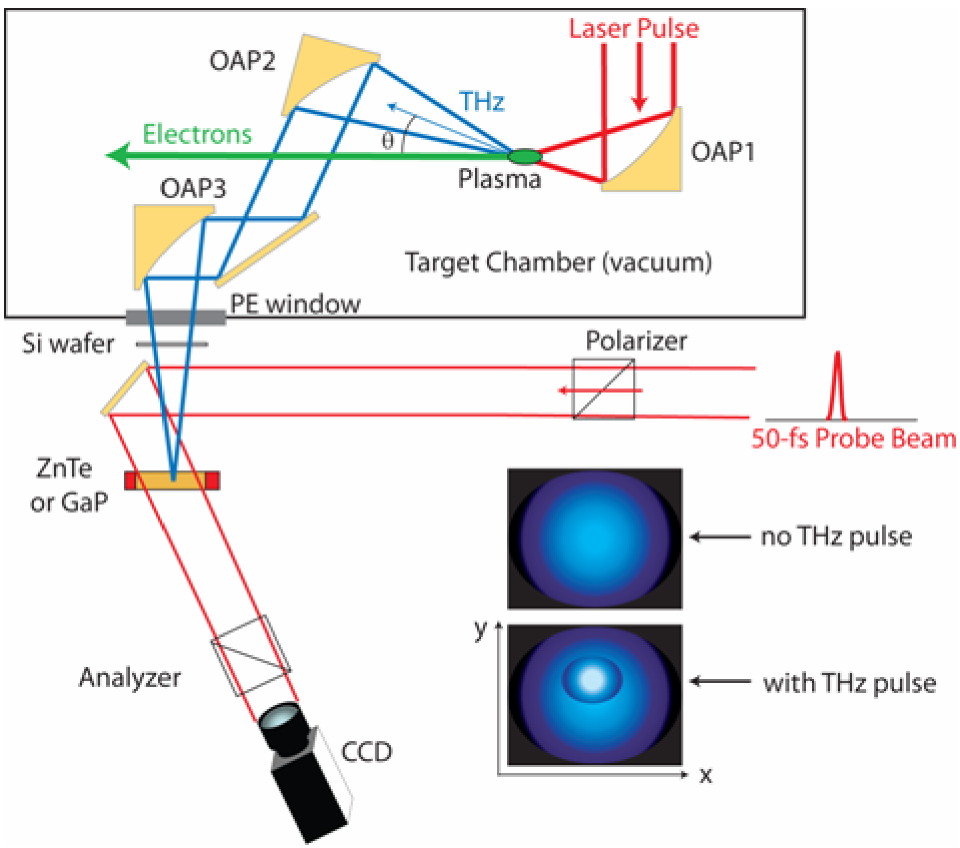
van Tilborg *et al.*, Opt. Lett., accepted (2008)

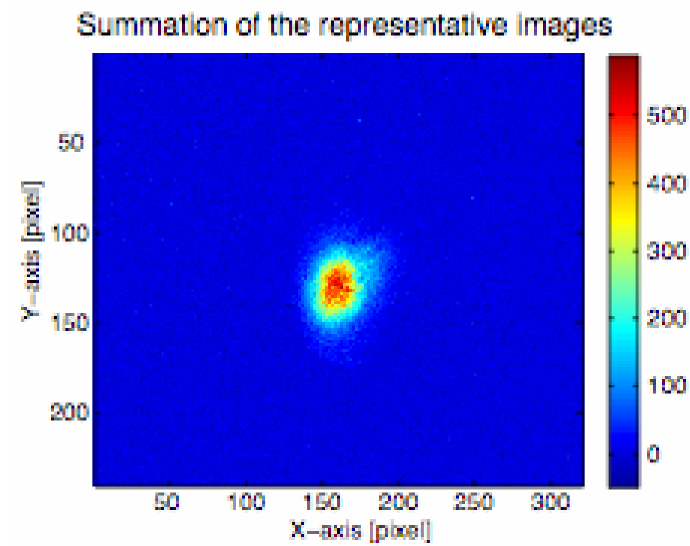


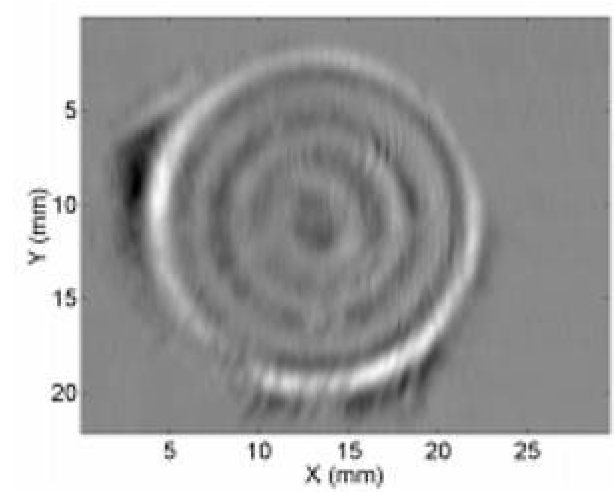
Advantages
- Single-shot
- Only low-power laser beam
- High resolution

Challenges
- Limited information

Transverse (2D) electro-optic sampling

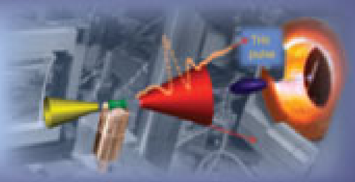






Zhiping Jiang *et al*, Opt. Express **5**, 254 (1999)

Conclusion



- Many variations of EOS available

- Time resolution (~ laser pulse length)
- Single- vs. multi-shot
- Minimum THz field strength (weak to stronger)
- Number of laser pulses (1 or 2)
- Number of nonlinear crystals (1 or 2)
- Full or limited charge profile retrieval

- Future: resolution ~10 fs
    - Shorter laser pulses
    - Thinner EO crystal

- EOS has now been proven to be a very reliable technique in many labs worldwide

Template….