Electro-optic sampling of coherent radiation

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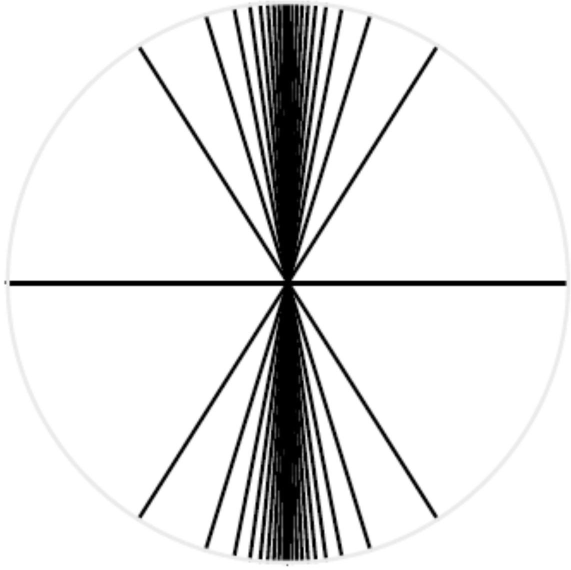
Overview

- General principle
- A few examples
  - –SDL (Henrik Loos)
  - –SPPS (Adrian Cavalieri)
  - –LBNL (Jeroen Van Tilborg)

Coulomb field of a relativistic particle



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

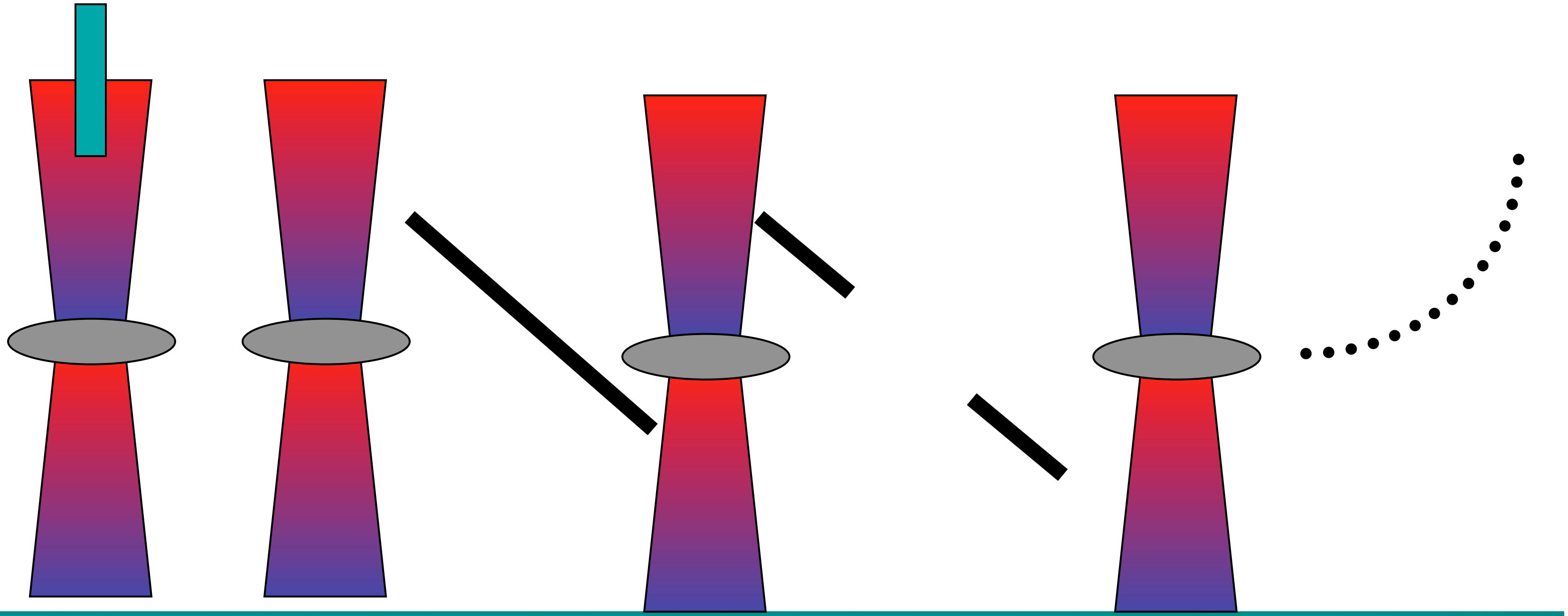
When $r/\gamma << \sigma_z$
The radial field component is

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

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.

Sampling beam fields

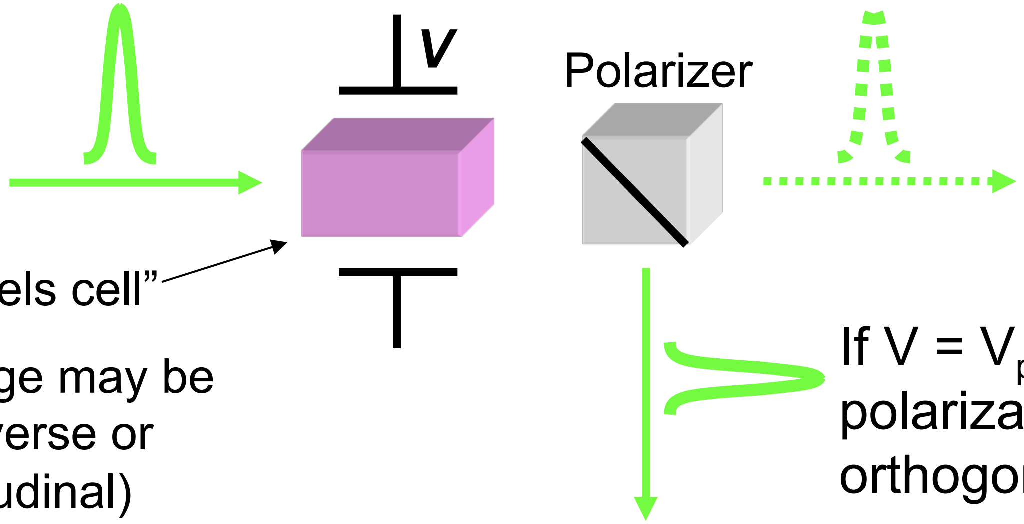
- The electron field can be sampled in several ways
  - directly in the vacuum chamber
  - Extracted via transition radiation
  - Extracted via diffraction radiation
  - Separated from the beam via synchrotron radiation



The Pockels Electro-optic Effect

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.



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

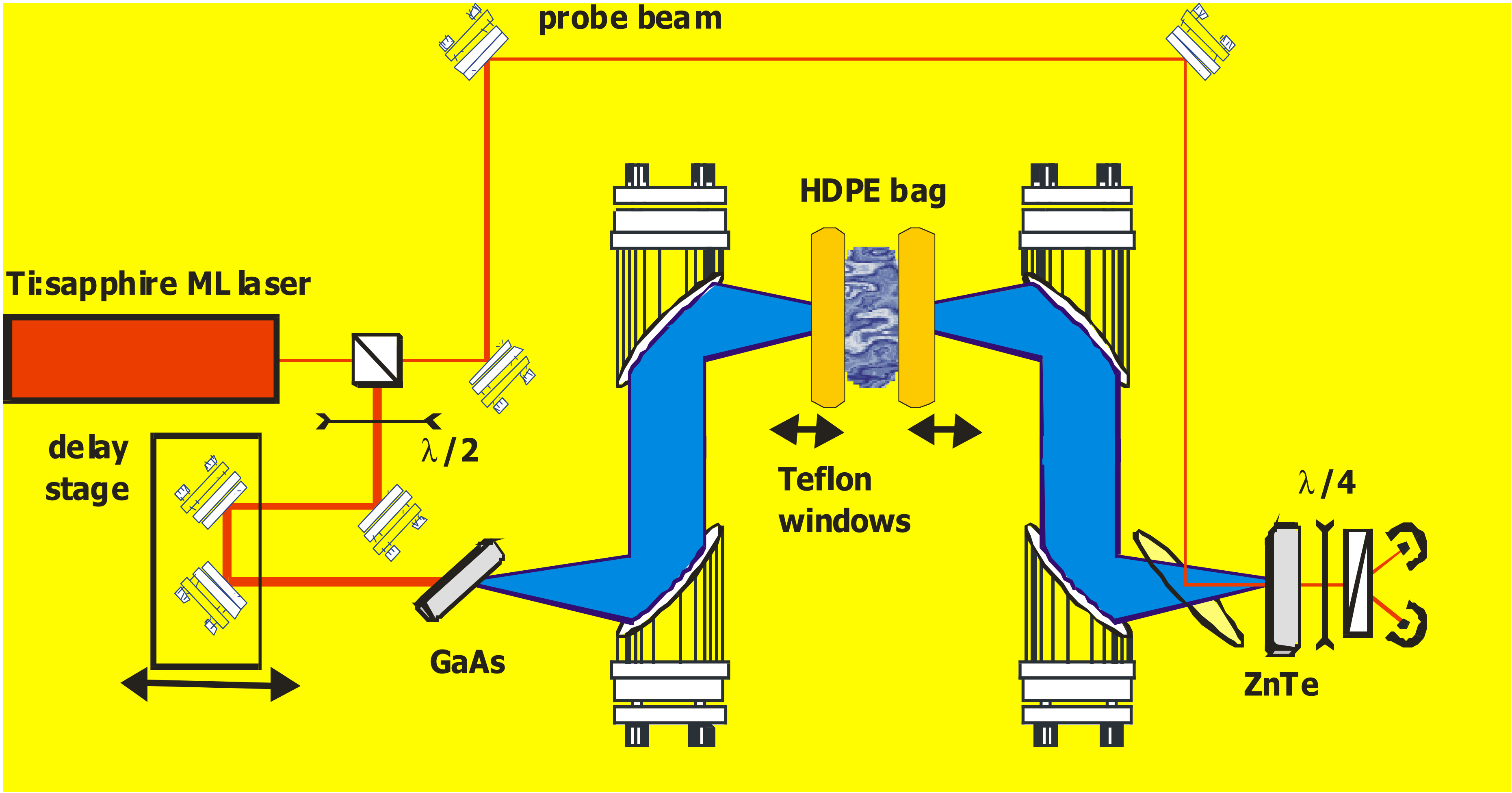
“Pockels cell”

(voltage may be transverse or longitudinal)

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.

Benchtop setup

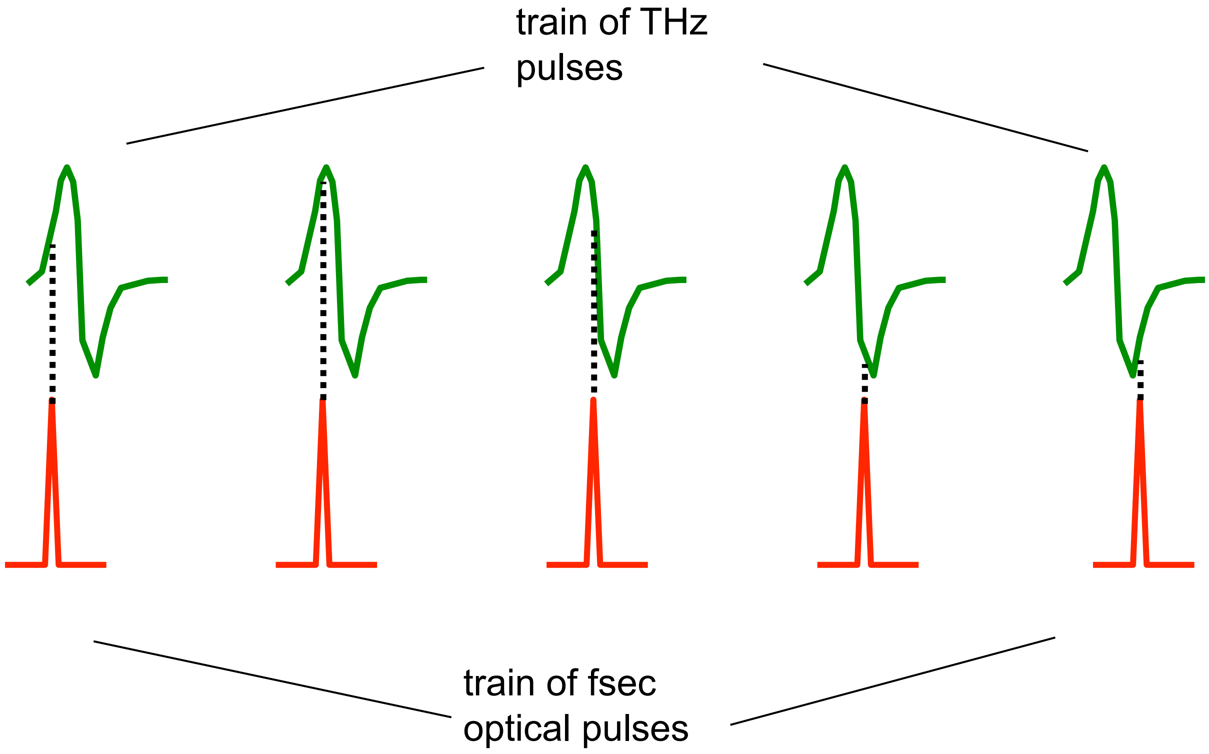


Benchtop setup

- 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 sampling

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

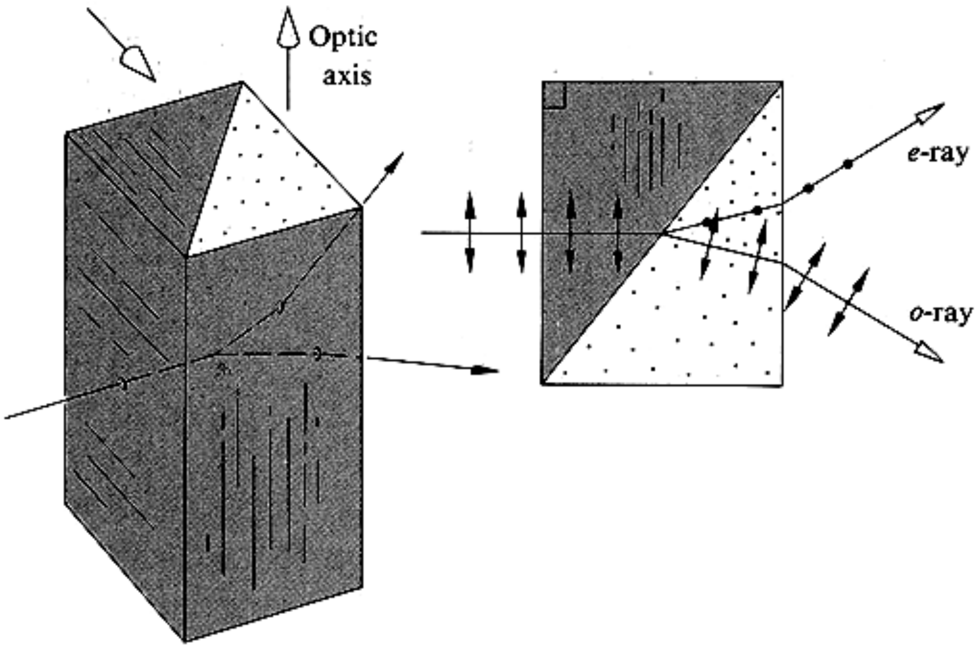


train of THz pulses

train of fsec optical pulses

Wollaston Polarizing Beam Splitter

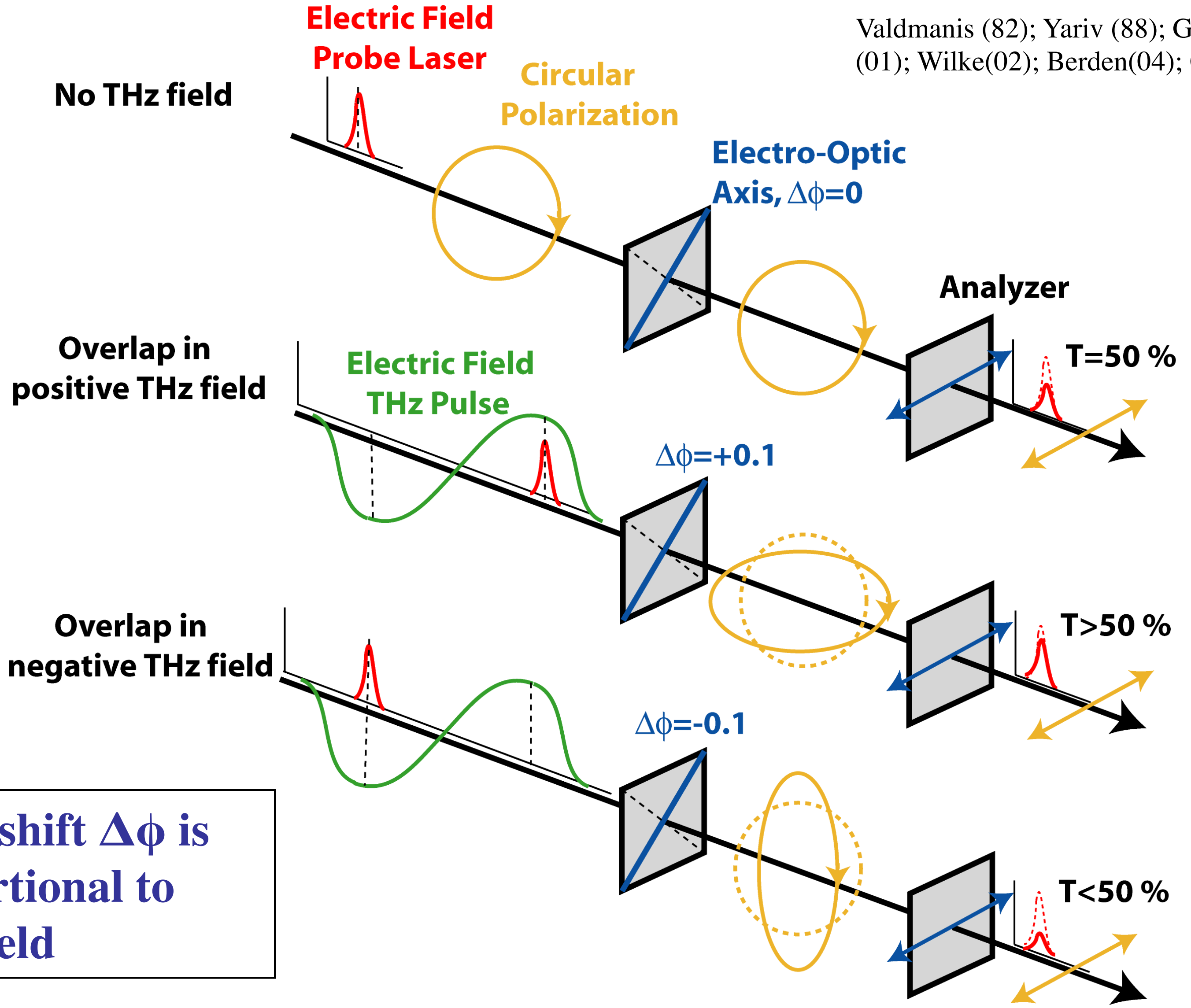
The Wollaston polarizing beam splitter uses two rotated birefringent prisms, but relies only on refraction.



The ordinary and extraordinary rays have different refractive indices and so diverge.

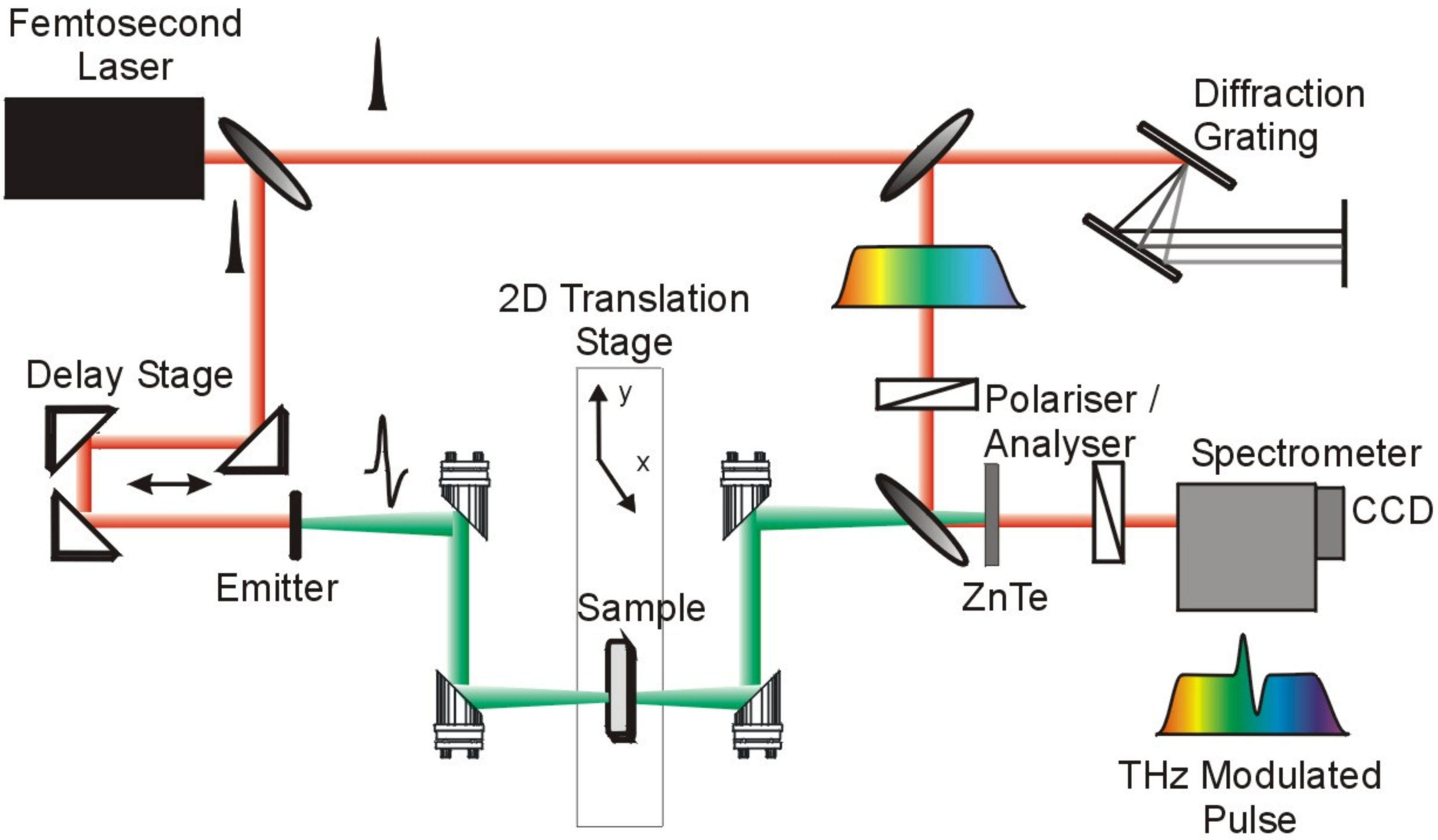
THz field sampling

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

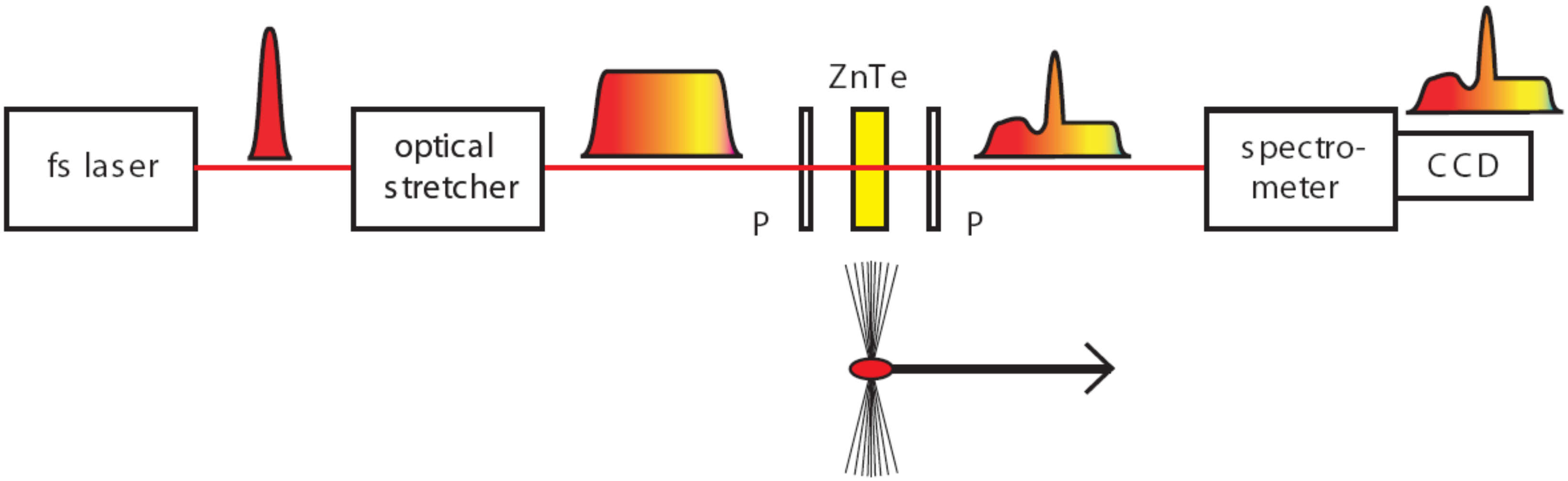


Phase shift $\Delta\phi$ is proportional to THz field

Bench-top THz source: spectral encoding

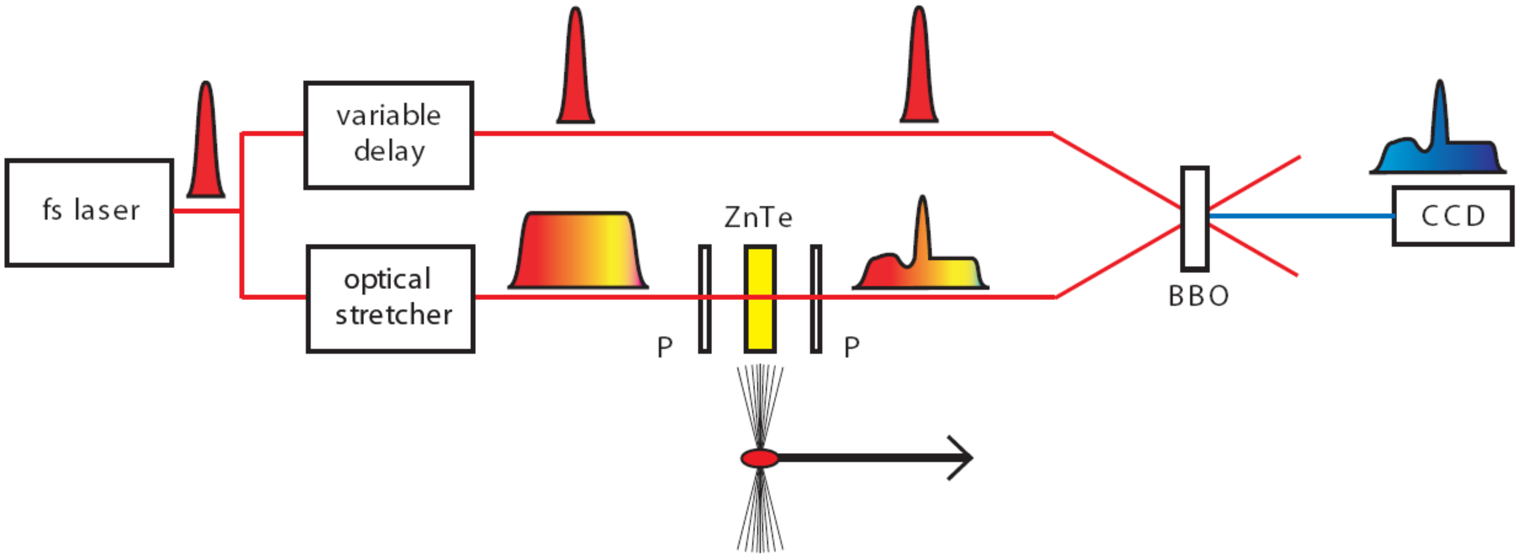


EO Sampling: spectral encoding



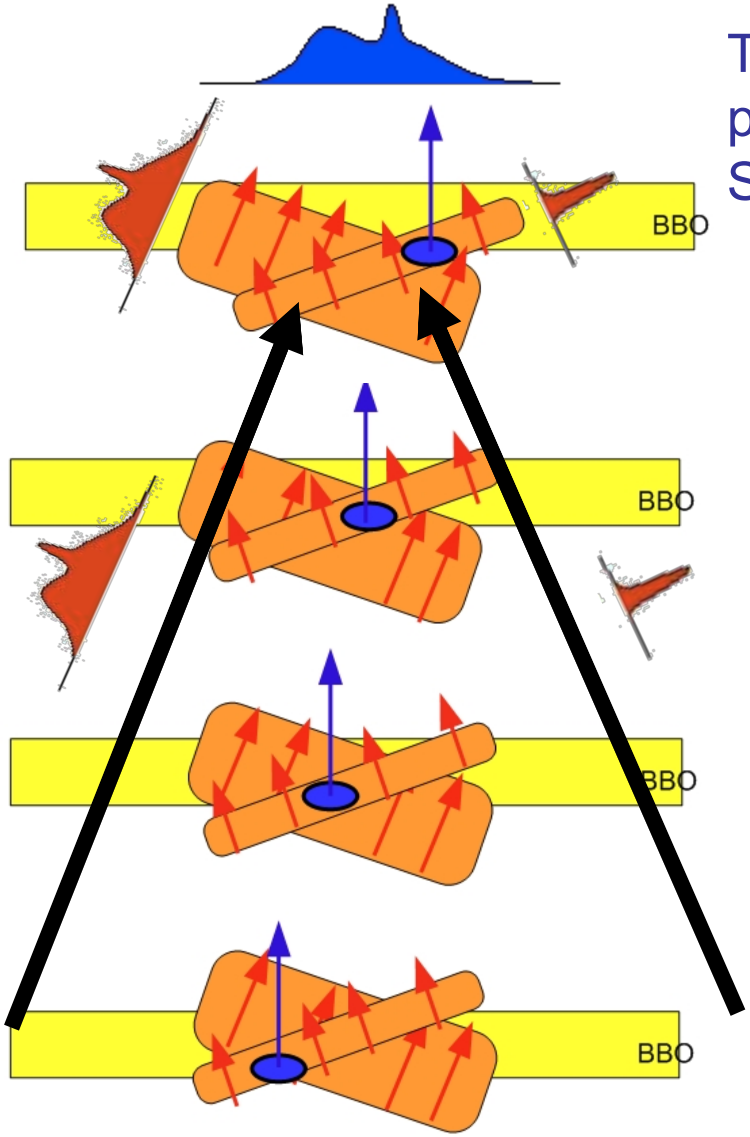
- Probe laser is optically stretched with time-wavelength correlation
- EO effect is imprinted on pulse
- Correlation is imaged from an optical spectrometer.

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

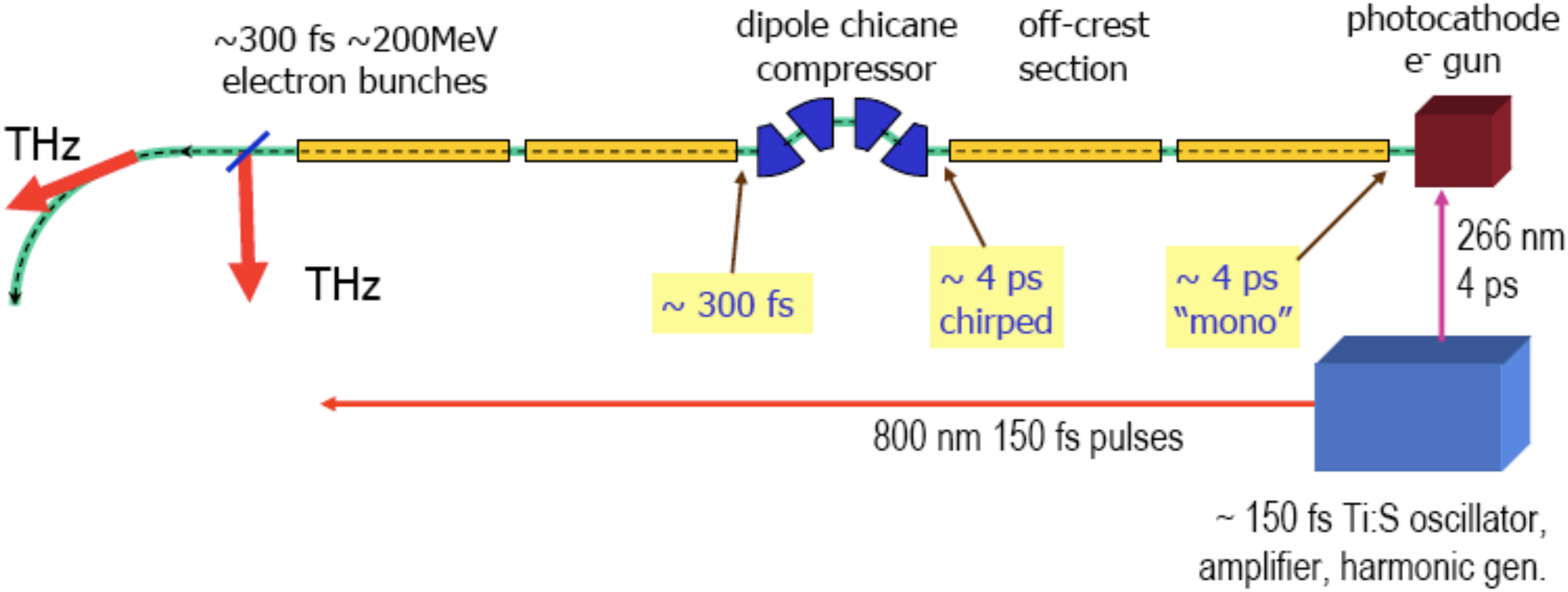


Temporal profile of probe pulse → Spatial image of SHG

Symmetrical optical arrangement
No temporal blurring with crystal thickness

Example:Deep UV Free Electron Laser at SDL

- Photocathode gun produces ~ 0.84nC (5x10^9 electrons) per "shot"



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

Characterization of High Intensity THz Pulses

- Coherent Transition Radiation (CTR)
- Experimental techniques
  - Pulse energy measurement
  - Electro-optic detection
- CTR simulation
- Experimental results
  - Pulse energy
  - Intensity distribution
  - Electric field

Coherent Transition Radiation

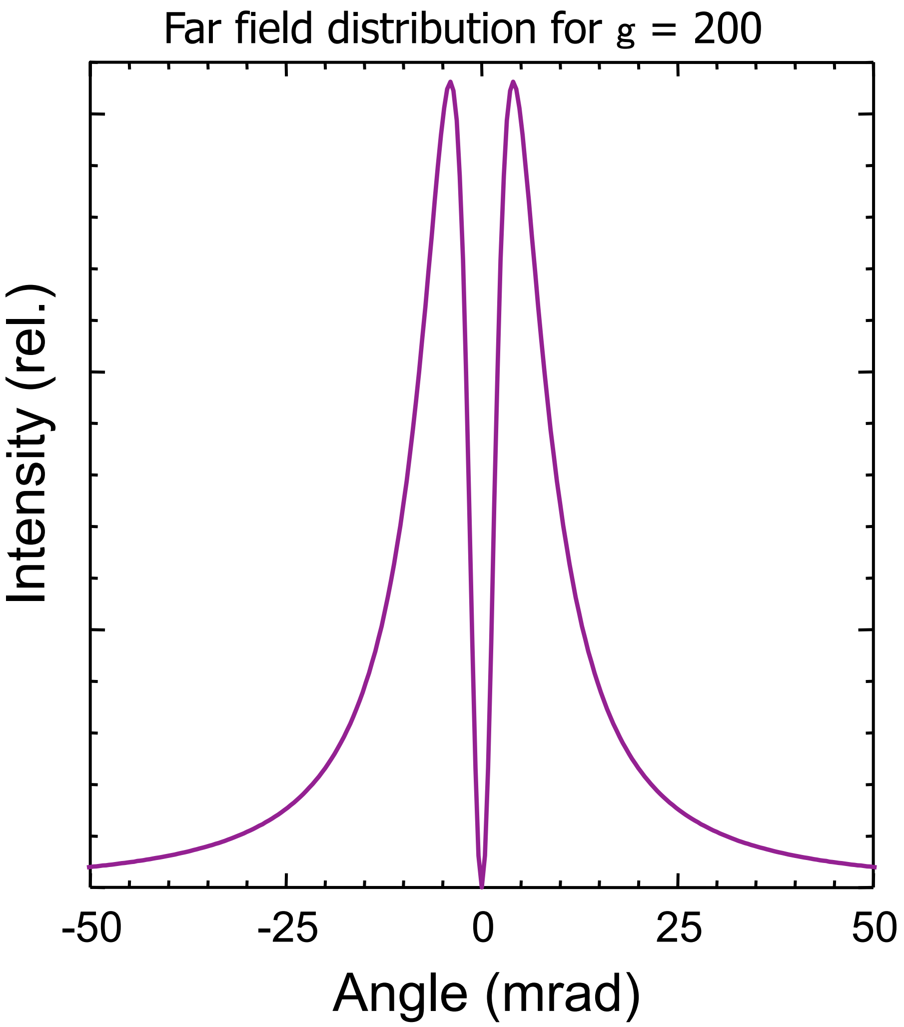
Transition radiation occurs when an electron crosses the boundary between two different media. For a relativistic electron (*b*° *v*/*c* @ 1) incident on a perfect conductor, the number of photons emitted per solid angle and wavelength range is:

$$\frac{dN}{d\lambda d\Omega} = \frac{\alpha}{\pi^2 \lambda} \frac{\beta^2 \sin^2\theta \cos^2\theta}{\left(1 - \beta^2 \cos^2\theta\right)}$$

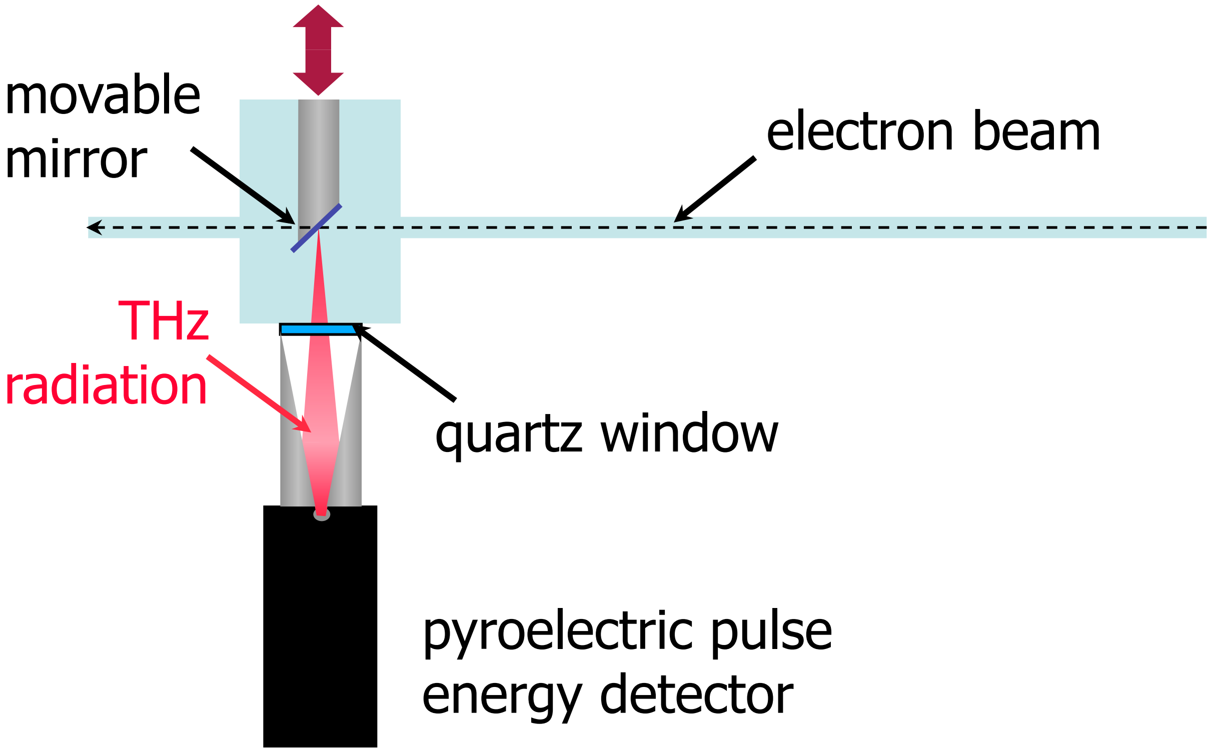
Intensity is 0 on axis, peaks at q ~ 1/g.

Coherent radiation emission:

$$dW_N / d\text{w} = N^2 \, dW_1 / d\text{w} \, |f(\text{w})|^2$$

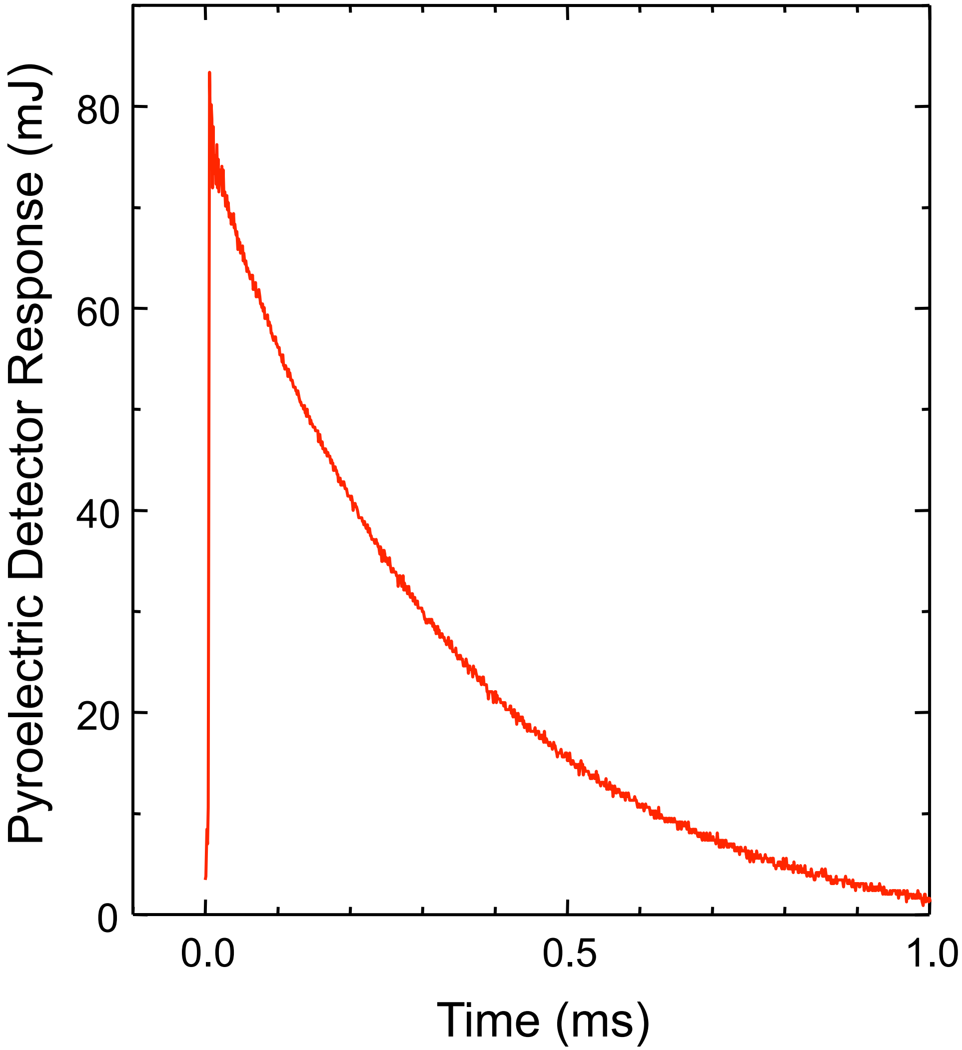

Far field distribution for g = 200

Setup for Pulse Energy



Energy per Pulse Exceeds 50 mJ

- Pyroelectric pulse energy detector (Molectron J4S-5) with 2.07x10^3 V/J responsivity.
- Light collection cone connected directly to quartz extraction window.
- Signal up to to 165mV => 80 mJ (!)
- Nearly 2 orders of magnitude larger than largest coherent THz pulses produced by laser methods.

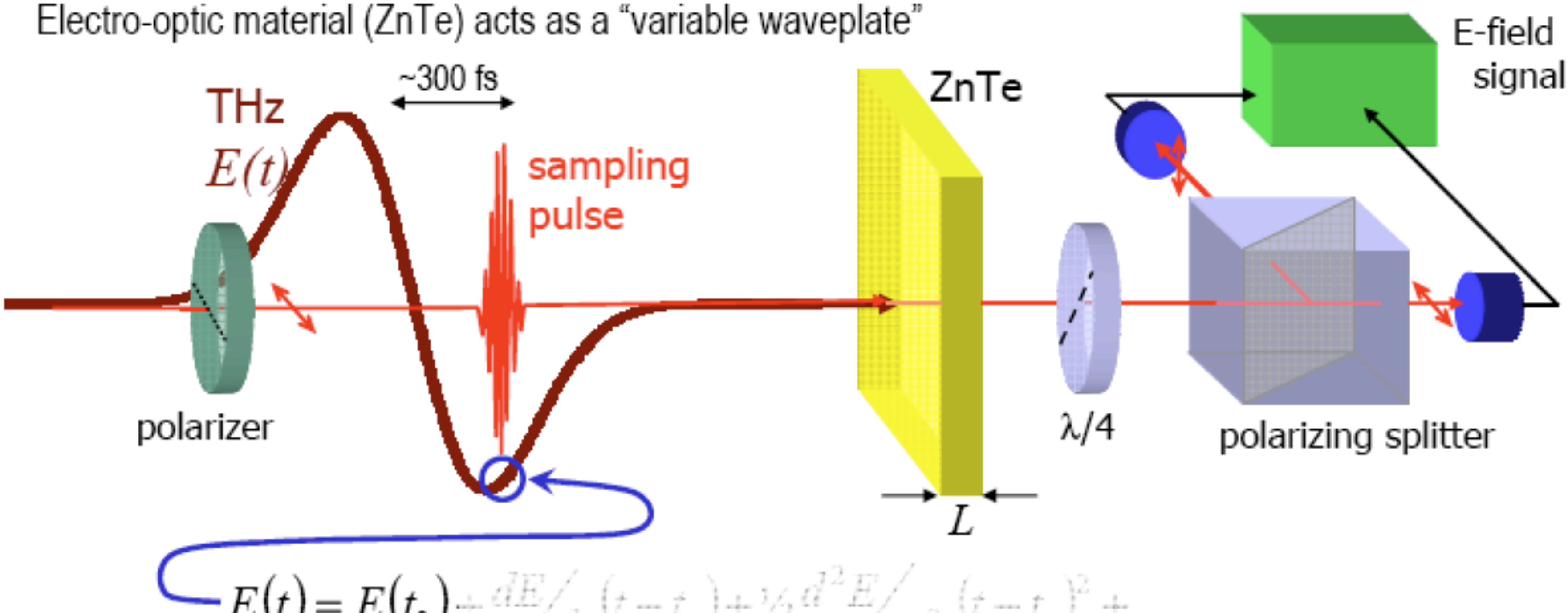


Electro-Optic Detection Method

Coherent detection setup for measuring THz waveforms using Pockels Effect: “THz Electro-Optic switch” (*Zhang et al, Heinz et al*)

$$E_{laser} \sim \cos\left[\left(2\pi n/\lambda_0\right) z - \omega_0 t + \Delta\phi_E(t)\right] \quad \text{where} \quad \Delta\phi_E(t) = \left(2\pi\, L/\lambda_0\right)\Delta n\left[E_{THz}(t)\right]$$

Electro-optic material (ZnTe) acts as a “variable waveplate”



$$E(t) = E(t_0) + \frac{dE}{dt}(t - t_0) + \tfrac{1}{2}\frac{d^2E}{dt^2}(t - t_0)^2 + \ldots$$

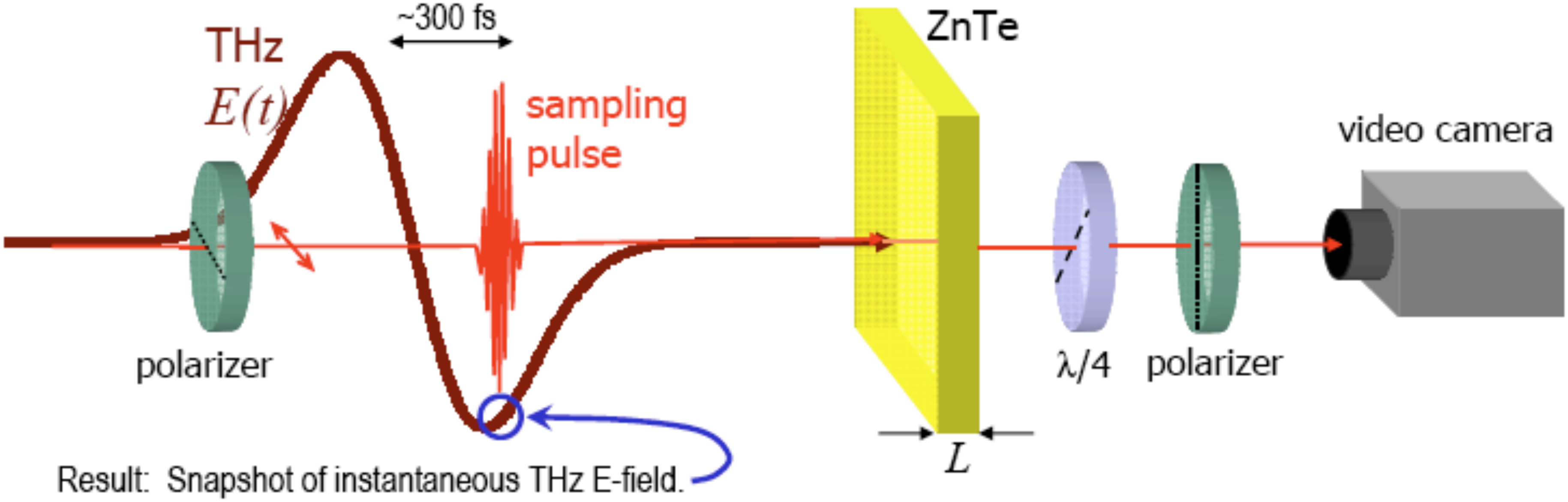
Result: Detector signal gives instantaneous THz E-field.

Electro-optic Imaging

Coherent detection setup for measuring THz waveforms using Pockels Effect: “THz Electro-Optic switch” (*Zhang et al, Heinz et al*)

$$E_{laser} \sim \cos\left[kz + \Delta\phi_E(t) - \omega t\right] \quad \text{where} \quad \Delta\phi_E(t) = \left(2\pi\, L/\lambda_0\right)\Delta n\left[E_{THz}(t)\right]$$

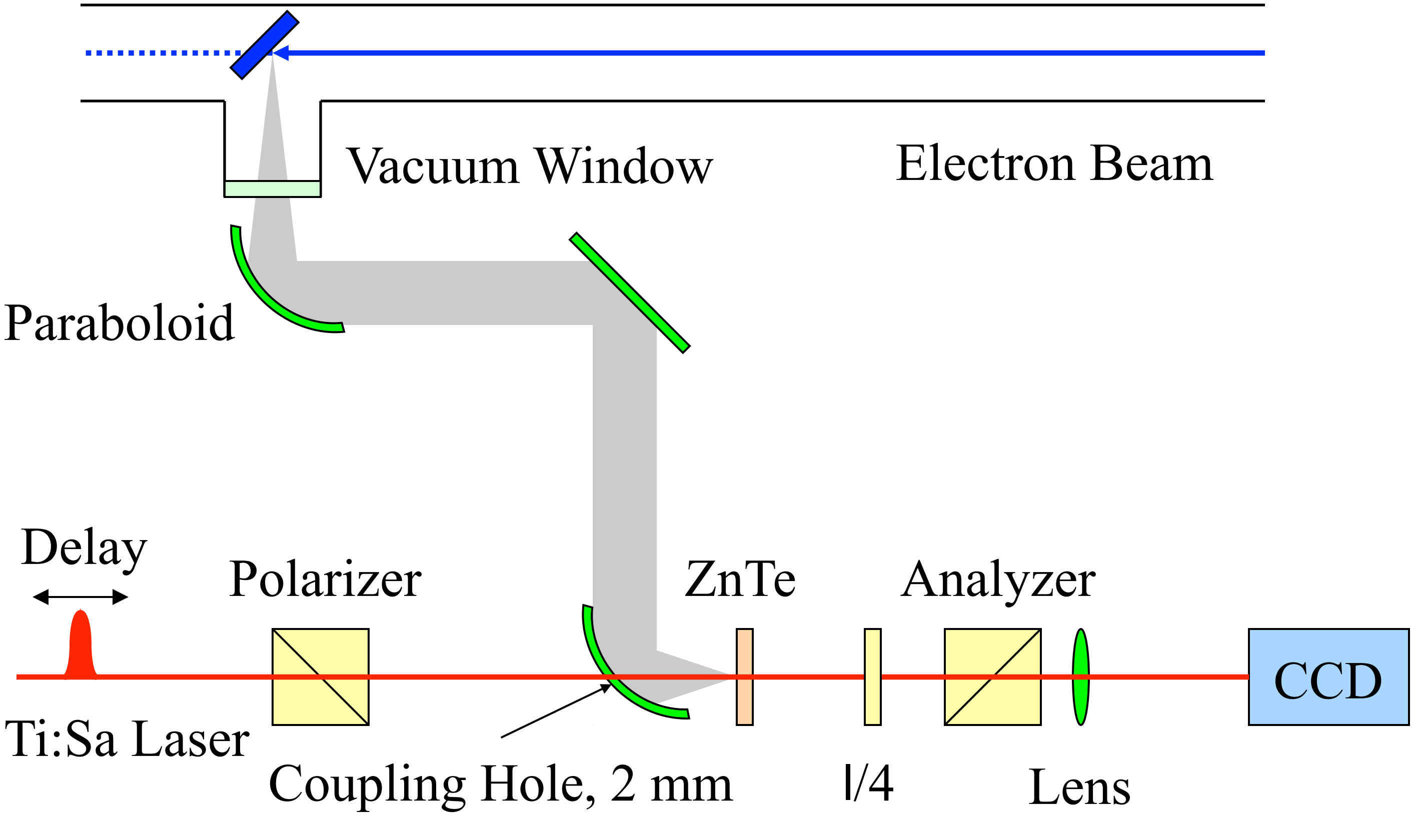
Electro-optic material (ZnTe) acts as a “variable waveplate”



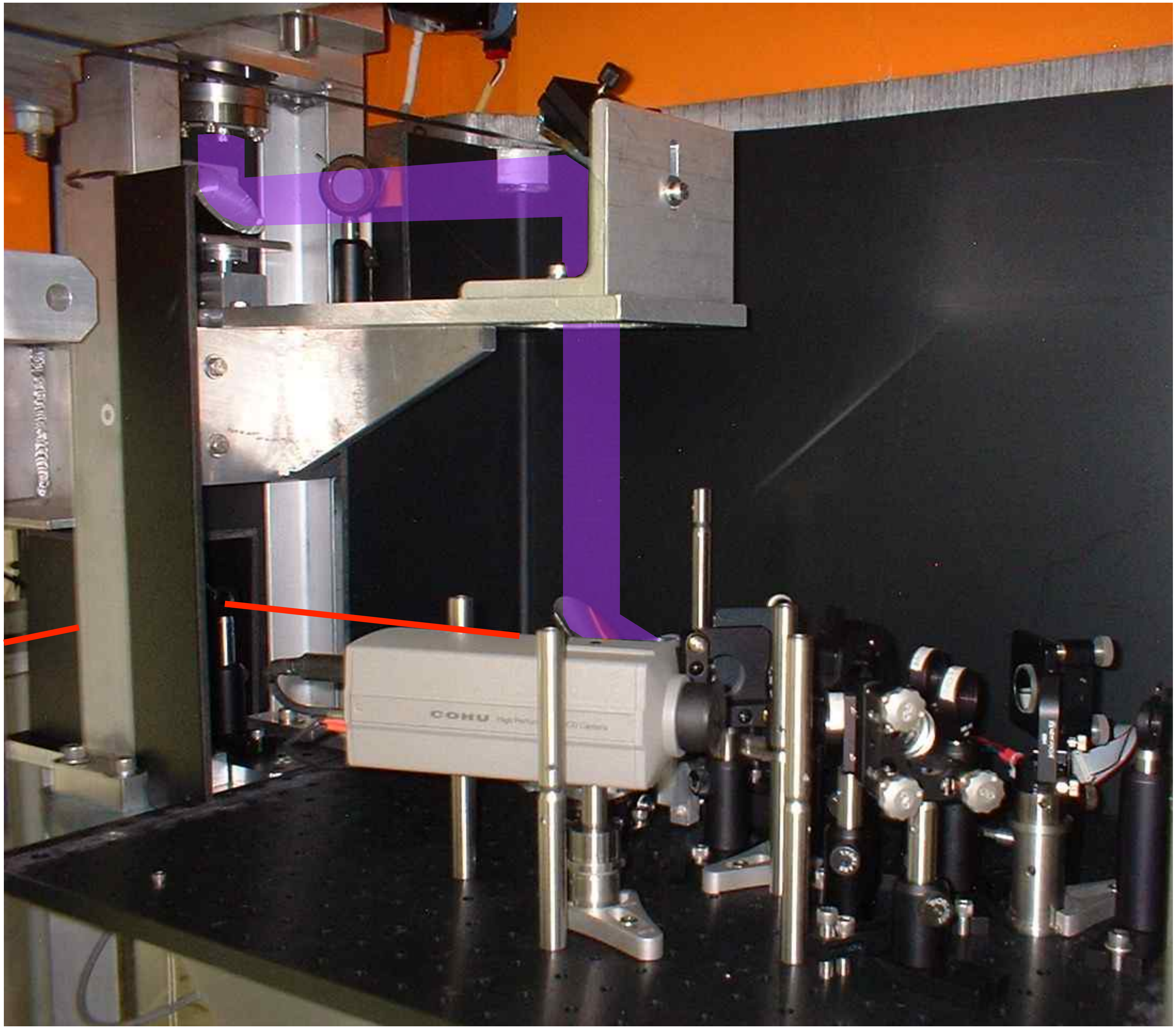
Result: Snapshot of instantaneous THz E-field.

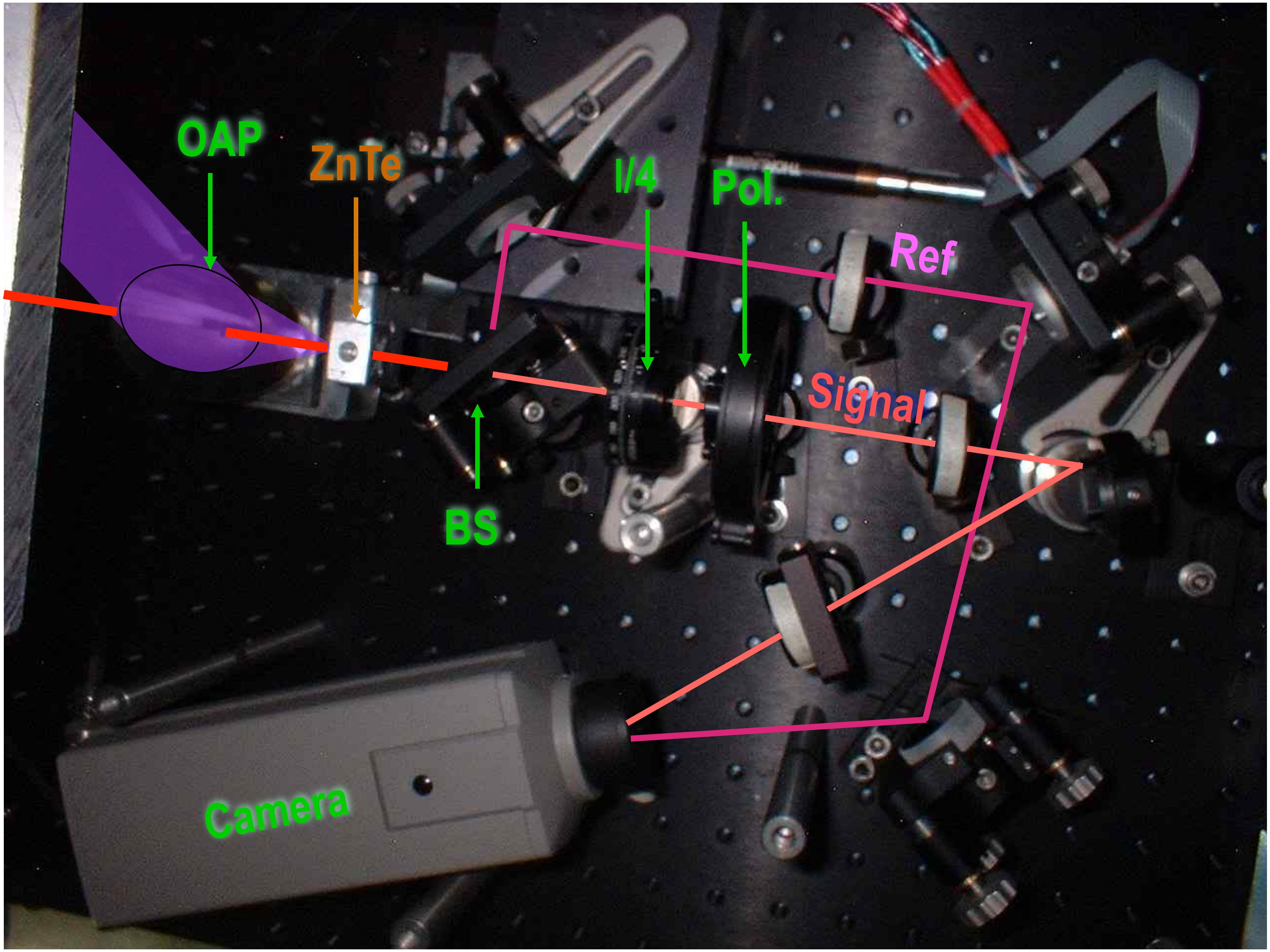
$$E(t) = E(t_0) + \frac{dE}{dt}(t - t_0) + \frac{1}{2}\frac{d^2E}{dt^2}(t - t_0)^2 + \ldots$$

Electro-Optic THz Radiation Setup



Some Pictures …


COHU


OAP
ZnTe
l/4
Pol.
Ref
Signal
BS
Camera

Focus Distribution of THz

- Focus spot size
  3 mm diameter.
- Single cycle oscillation.
- 300 fs rms length.
- Electric field strength
  more than 300 kV/cm
  at 300 pC charge.
- Pulse Energy 4 mJ.
  70 mJ (700 pC, 150 fs)

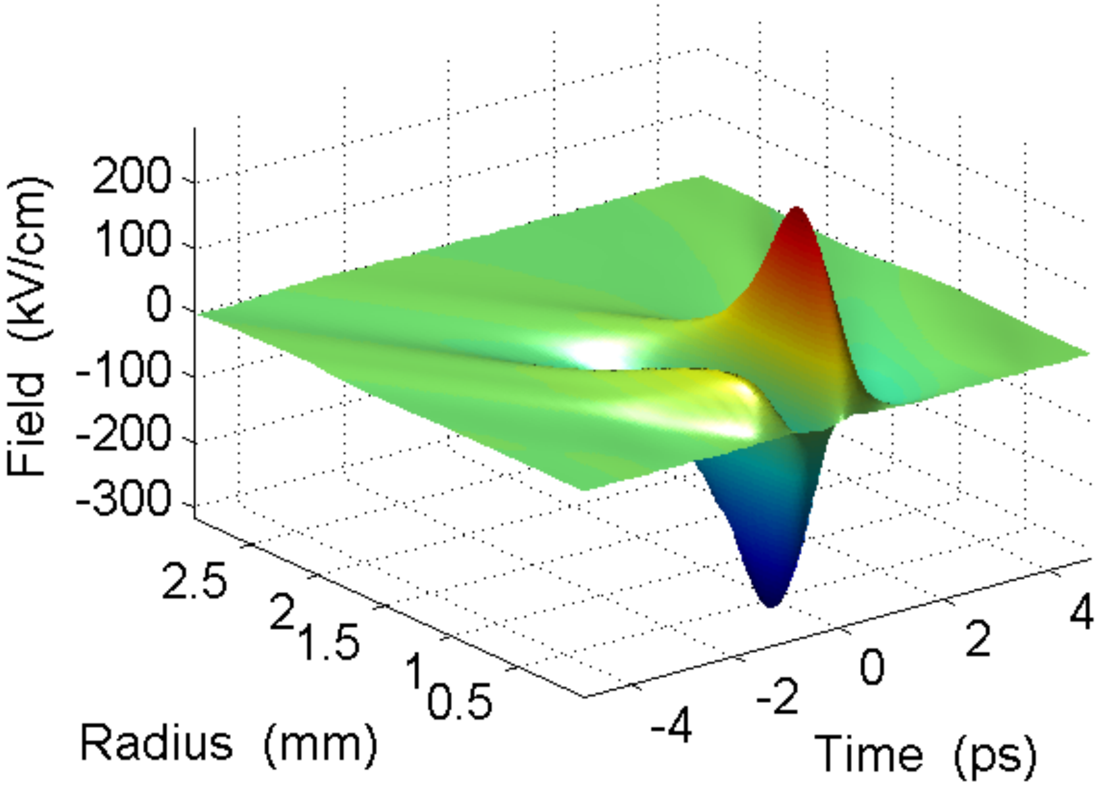
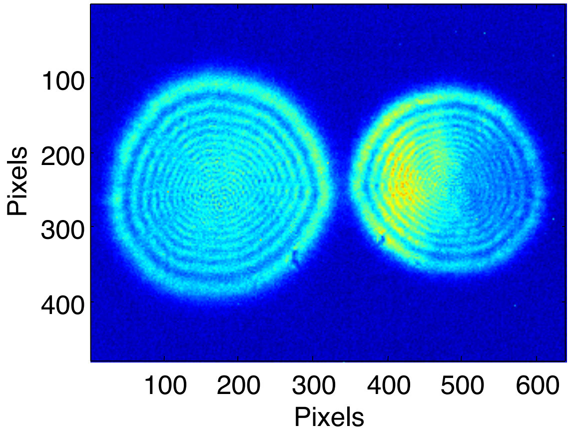
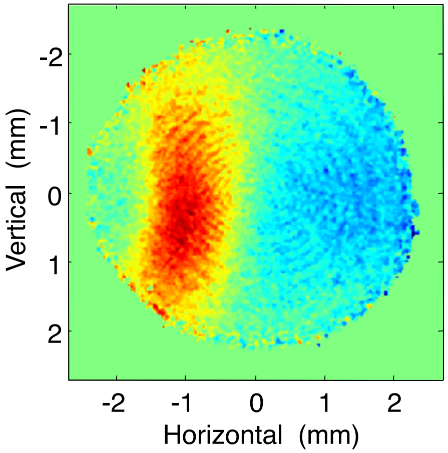


Image Processing for Field Measurement

- 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.



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

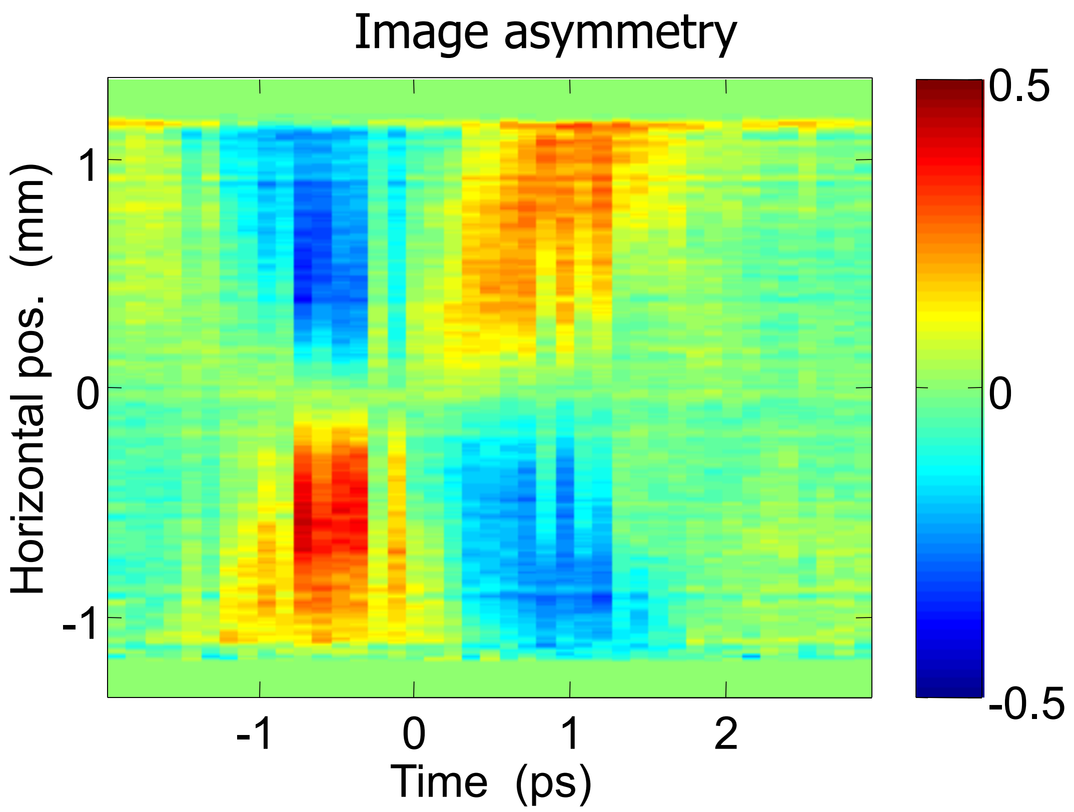


Time Dependent Measurement

- Use ‘mildly’ compressed bunch of 500 fs and 300 pC to get both 0-phasing and electro-optic measurement.
- Temporal scan by varying phase of accelerator RF to both sample and cathode laser.
- Approximately equivalent to varying delay between both lasers but much faster and computer controlled.
- Measured to be 1.2 ps/degree.

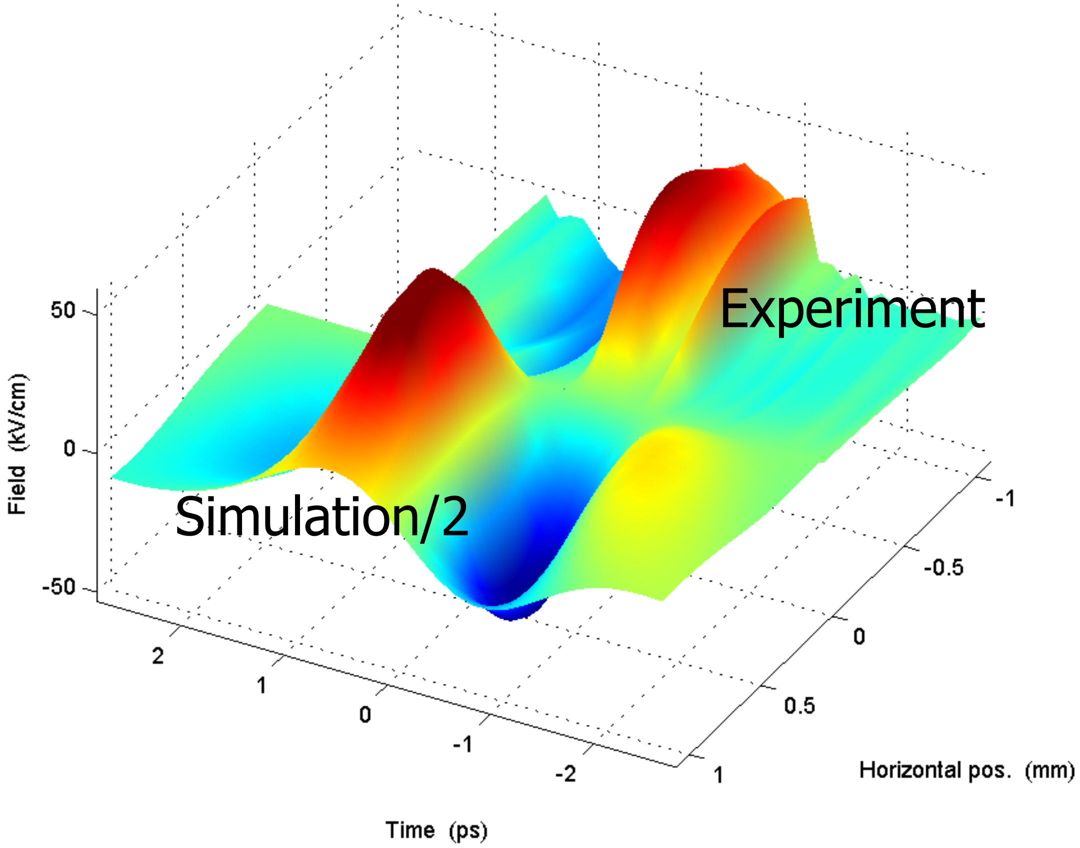
Transverse-Temporal Distribution

- Take horizontal slice through images.
- Asymmetry of 1 equals 170 kV/cm electric field strength.
- Charge 300 pC.
- Saturation and ‘over-rotation’ at higher compression.
- Needs crystal « 500 mm.



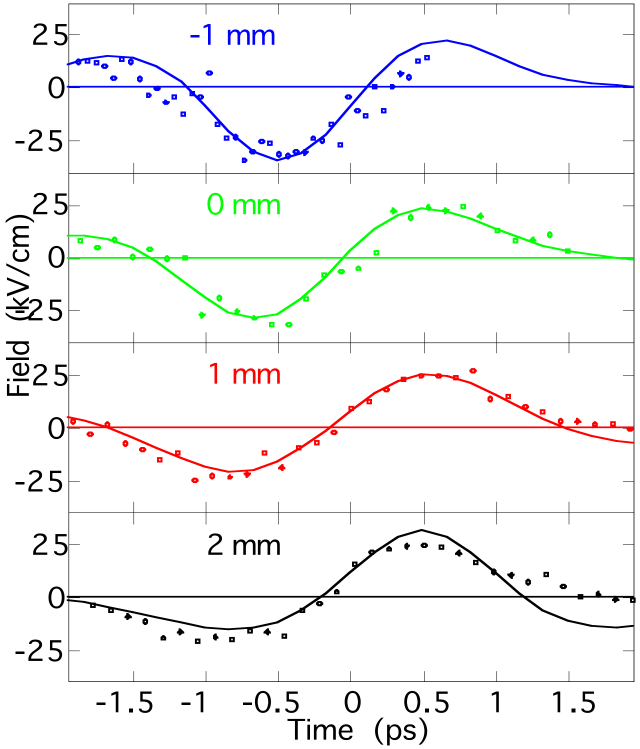
Simulation vs. Experiment

- Simulation gives 2 times more field.
- Tighter focus in simulation.
- Up to 50 kV/cm measured.



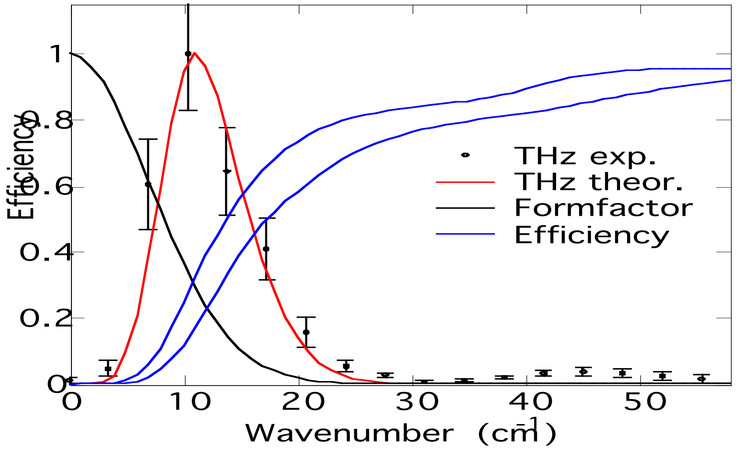
Single Cycle THz Pulses

- Pulse energy from field ~60 nJ.
- Pulse energy with Joule-meter 170 nJ.
- Pulse energy from simulation 800 nJ.
- Good match of temporal and spectral properties.
- Factor 2 and 4 difference in field and energy.
- Measured 80 mJ to have 1 MV/cm field in focus.



THz Spectrum

- Present intensity limited by geometric apertures.
- Low frequency cutoff at 15 cm^{-1} or 0.5 THz.



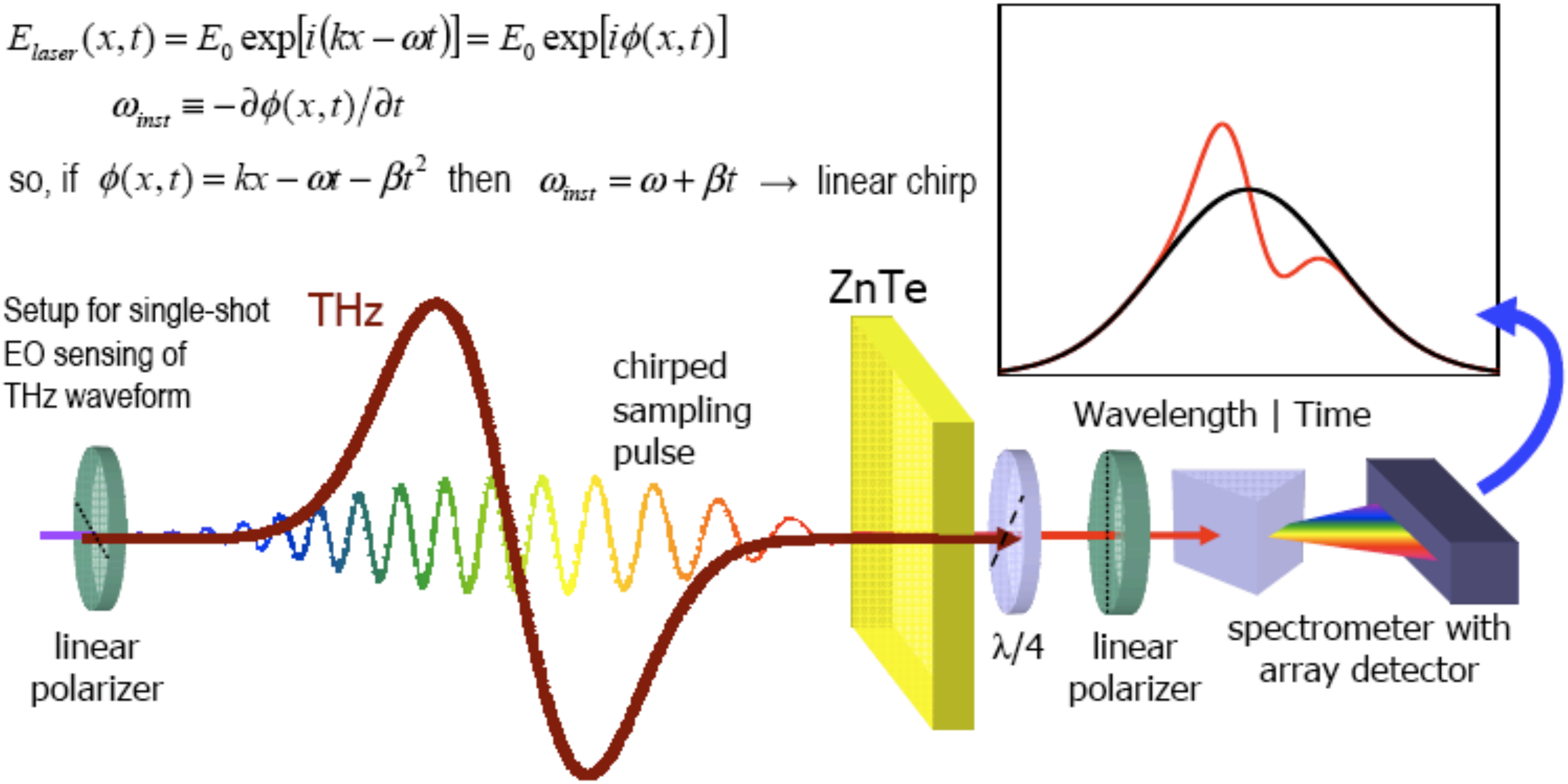
Single Shot Technique

Use chirped sampling laser to encode waveform's entire time-dependence onto different wavelengths of laser in a single pulse. Avoids need for multiple sampling.
[Jiang and Zhang, *Appl. Phys. Lett.* **72**, 1945 (1998)].

$$E_{laser}(x,t) = E_0 \exp[i(kx-\omega t)] = E_0 \exp[i\phi(x,t)]$$

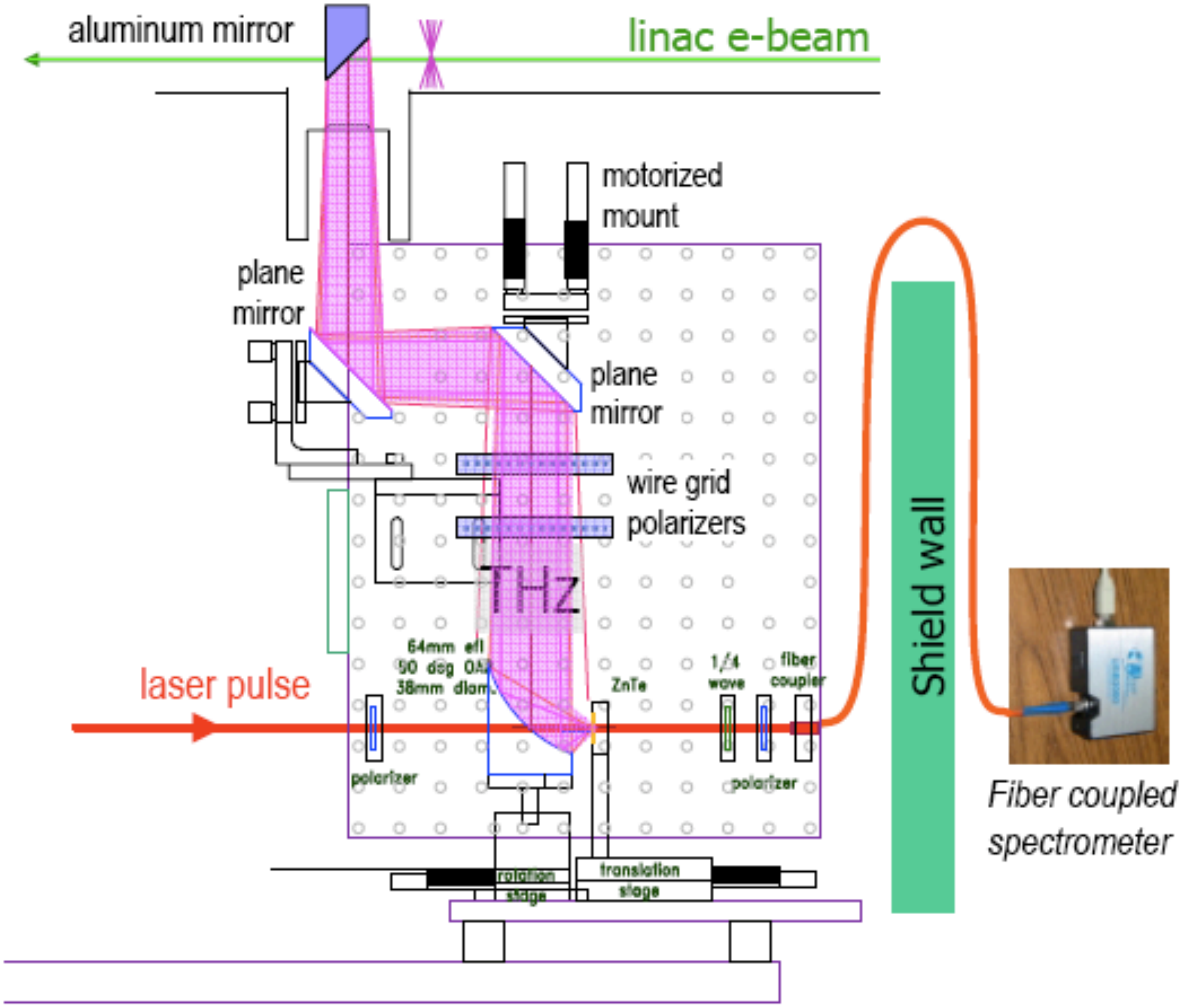
$$\omega_{inst} \equiv -\partial\phi(x,t)/\partial t$$

so, if $\phi(x,t) = kx - \omega t - \beta t^2$ then $\omega_{inst} = \omega + \beta t$ → linear chirp

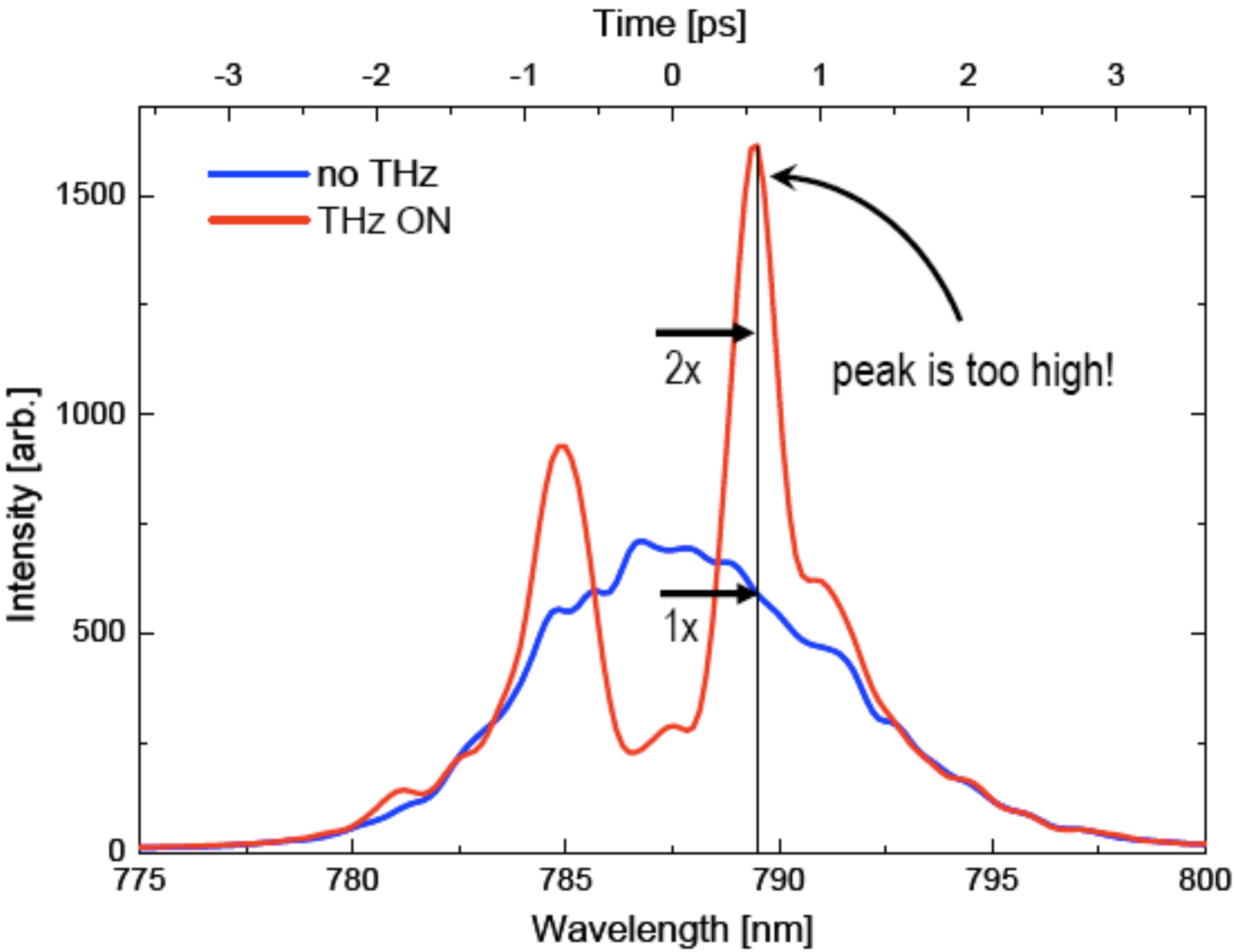


Setup for single-shot EO sensing of THz waveform

Single shot layout



Single Shot Results

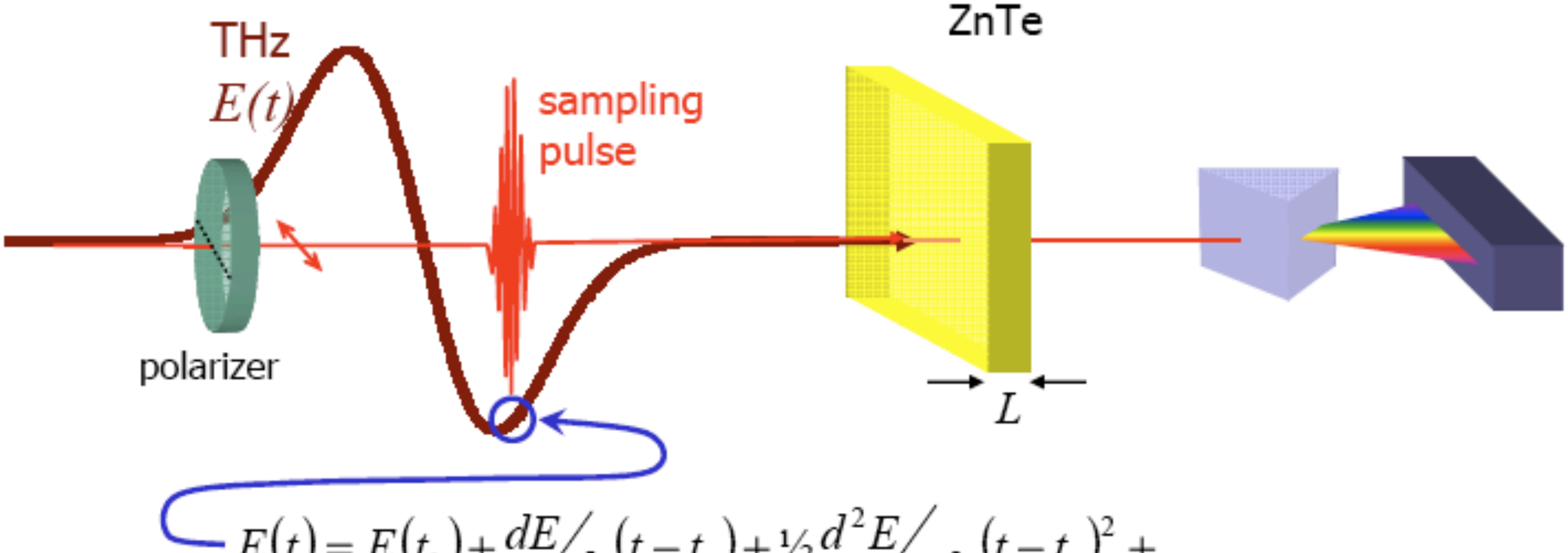


Strong THz give higher order effects

“Simple” EO setup to observe time-dependent phase modulation

$$E_{laser} \sim \cos\left[kz + \Delta\phi_E(t) - \omega t\right] \quad \text{where} \quad \Delta\phi_E(t) = \left(2\pi\, {}^{L}\!/_{\lambda_0}\right)\Delta n\left[E_{THz}(t)\right]$$

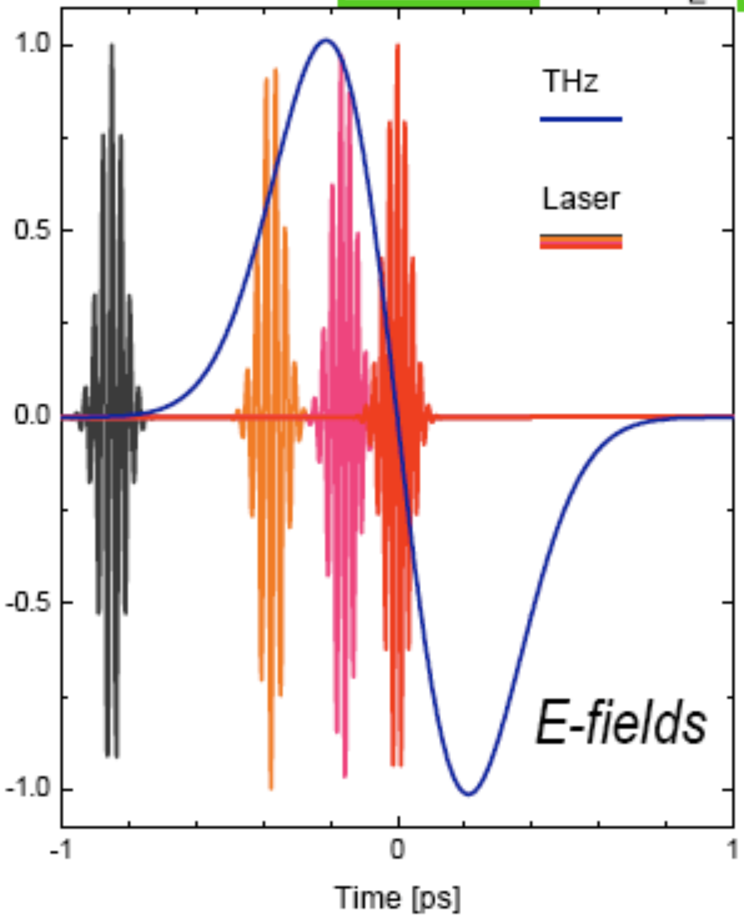
Electro-optic material (ZnTe) acts cross phase modulator



$$E(t) = E(t_0) + {}^{dE}\!/_{dt}\,(t - t_o) + \tfrac{1}{2}\,{}^{d^2E}\!/_{dt^2}\,(t - t_o)^2 + \ldots$$

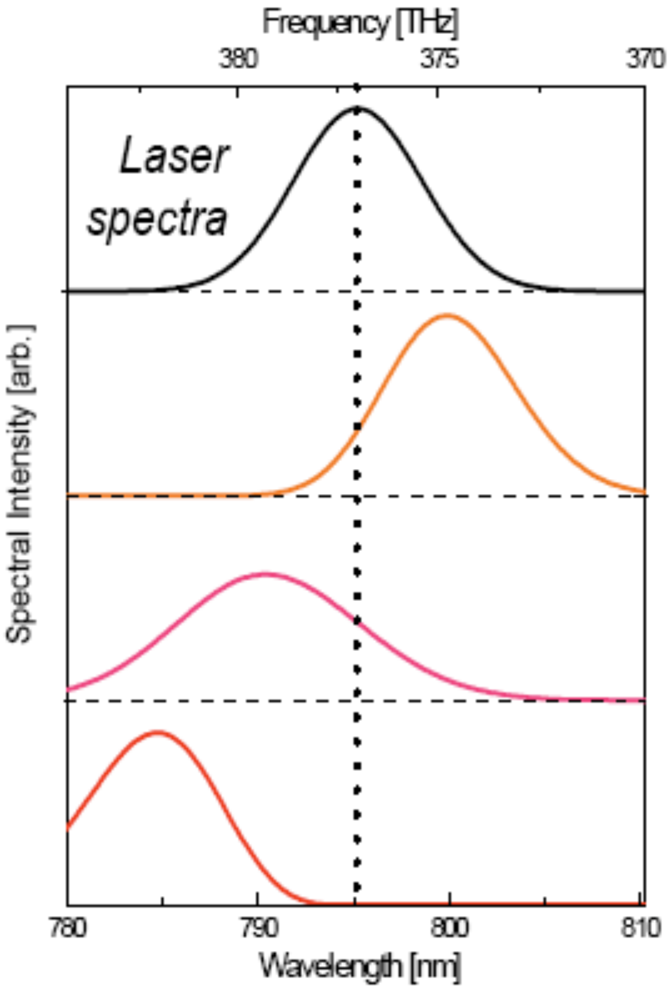
Calculated effects

$$\phi(t) = \eta\, E(0) + \left[\eta \boxed{\left({}^{dE_{THz}}\!/_{dt}\right)} - \omega\right] t + \left[\eta \boxed{\left({}^{d^2E_{THz}}\!/_{dt^2}\right)}\right] t^2 + \ldots$$



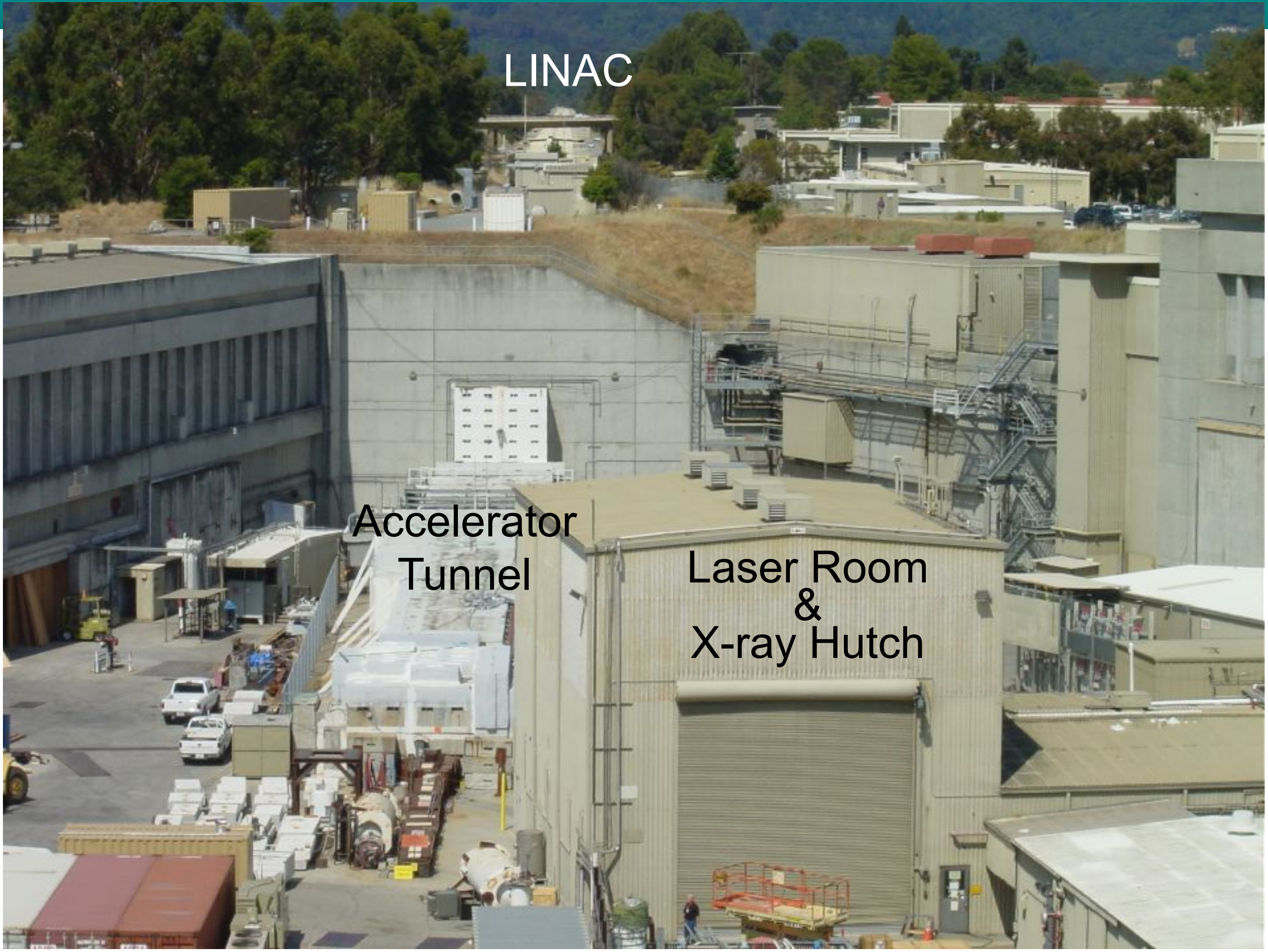
500 kV/cm field

0.5mm thick ZnTe

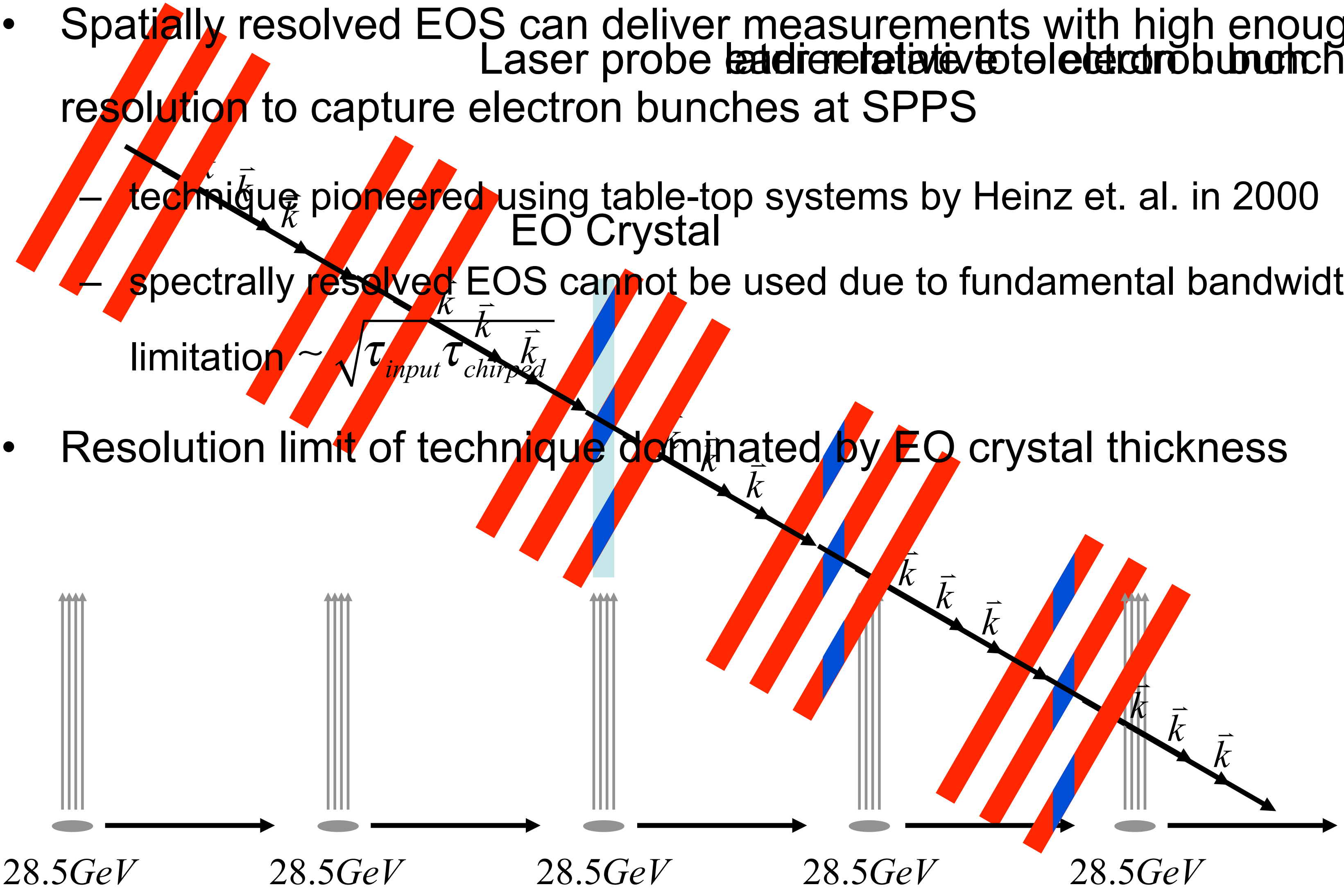


Other details: Lensing from spatial variation of $n(t)$ *(time-dependent gradient index lens)*

Example: SPPS Facility



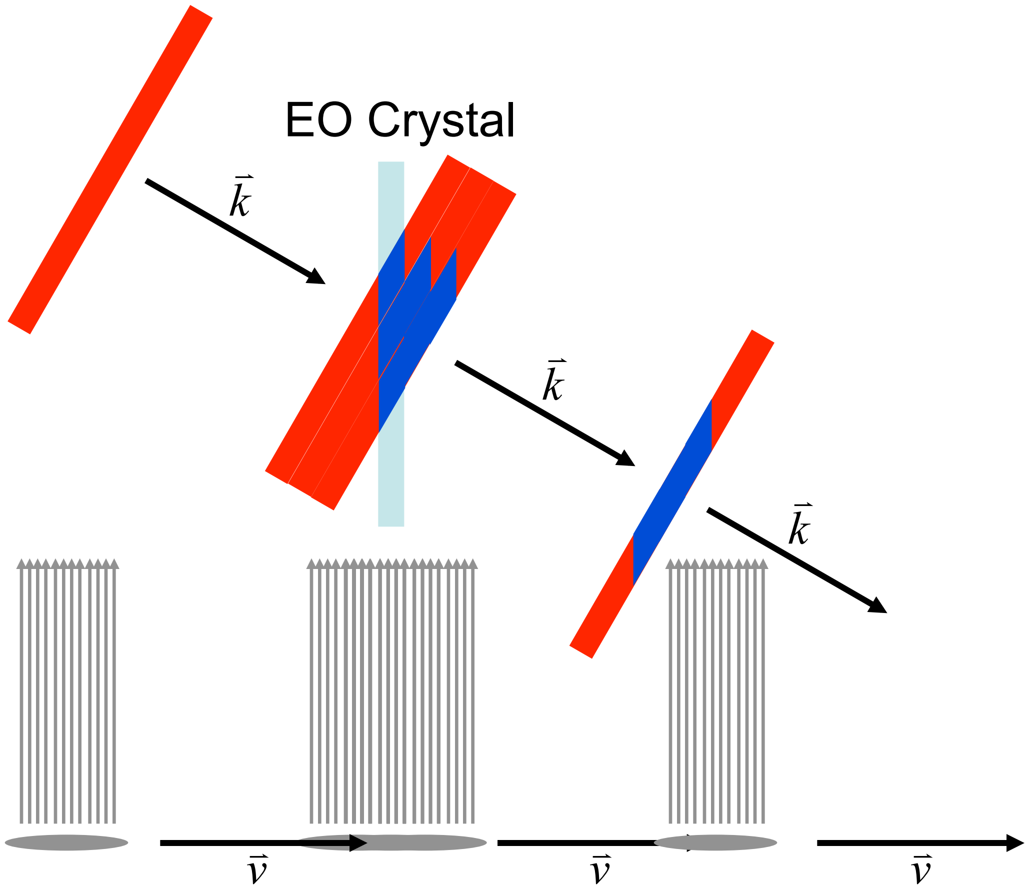
Spatially Resolved Electro-Optic Sampling (EOS)



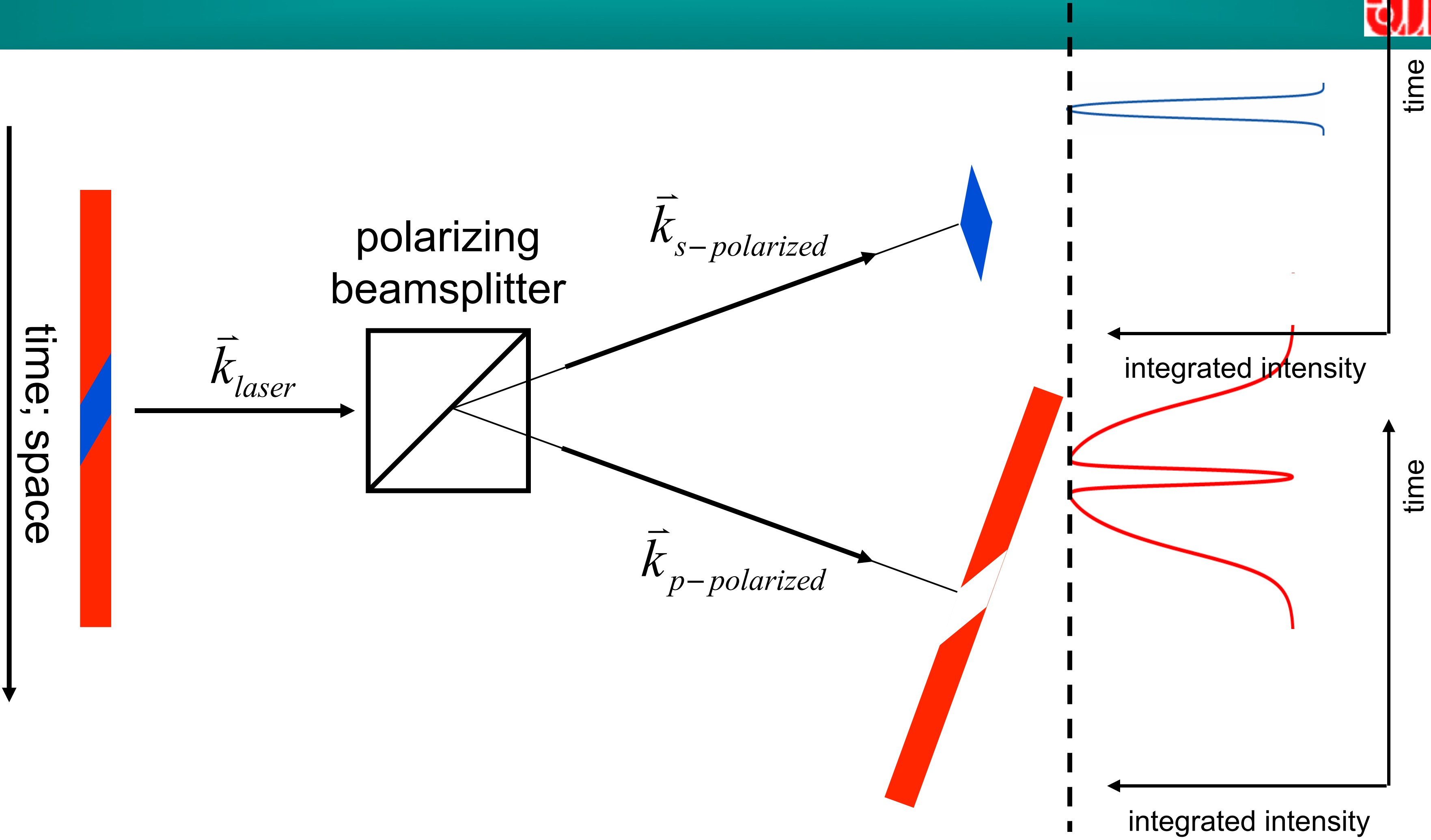
- Spatially resolved EOS can deliver measurements with high enough resolution to capture electron bunches at SPPS
  - technique pioneered using table-top systems by Heinz et. al. in 2000
  - spectrally resolved EOS cannot be used due to fundamental bandwidth limitation $\sim\sqrt{\tau_{input}\tau_{chirped}}$
- Resolution limit of technique dominated by EO crystal thickness

Spatially Resolved EOS

(long bunch)

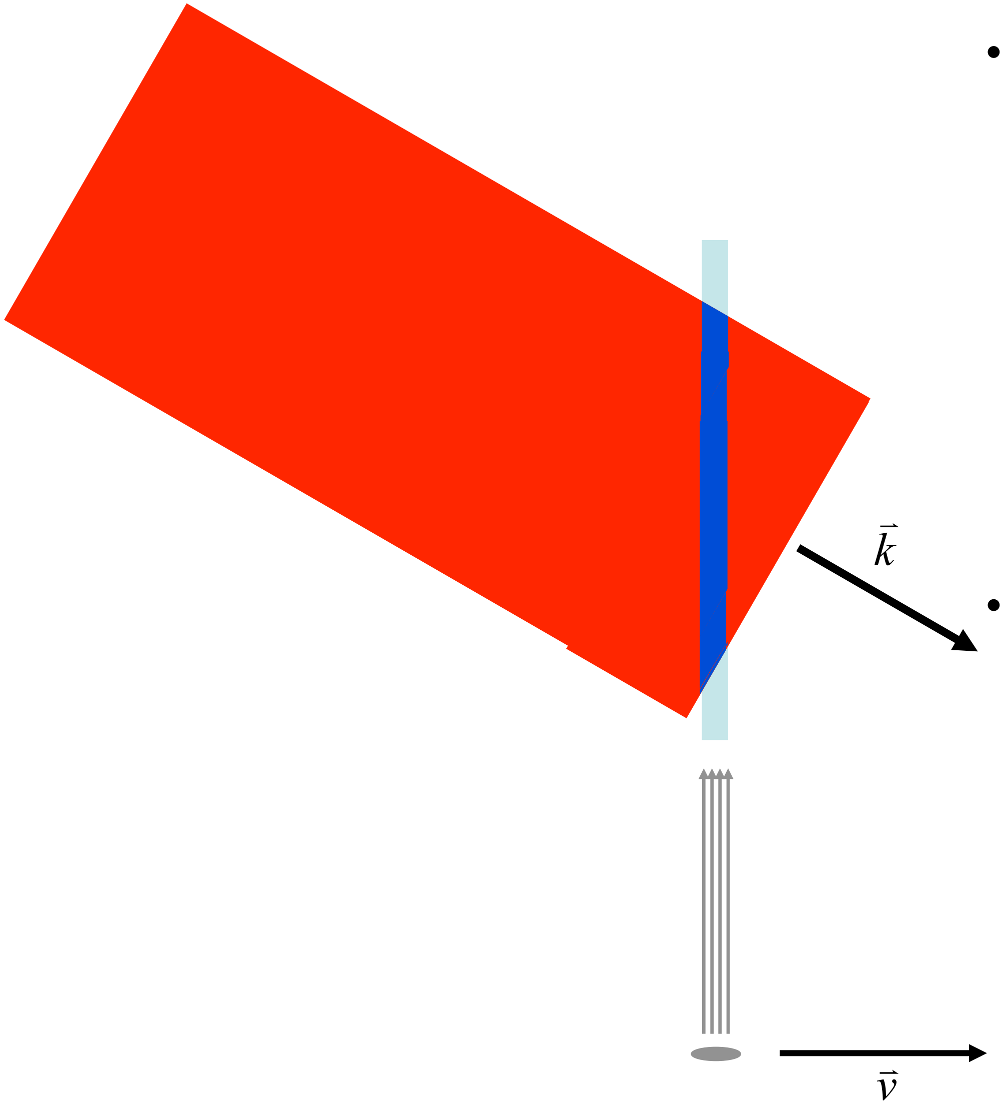


Spatially Resolved EOS



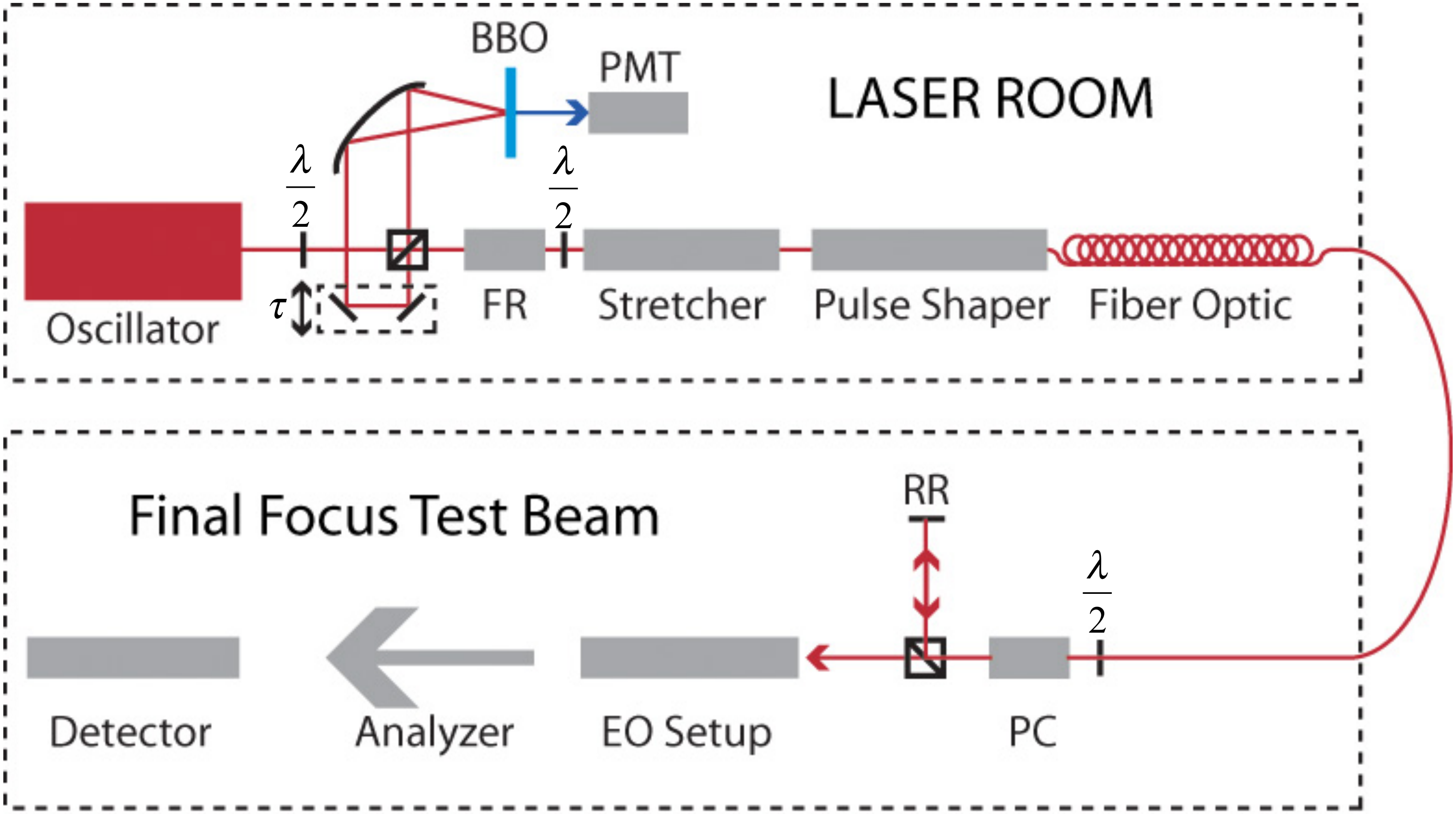
Arrival time and duration of bunch is encoded on profile of laser beam

Effect of Long Pulse Probe Laser

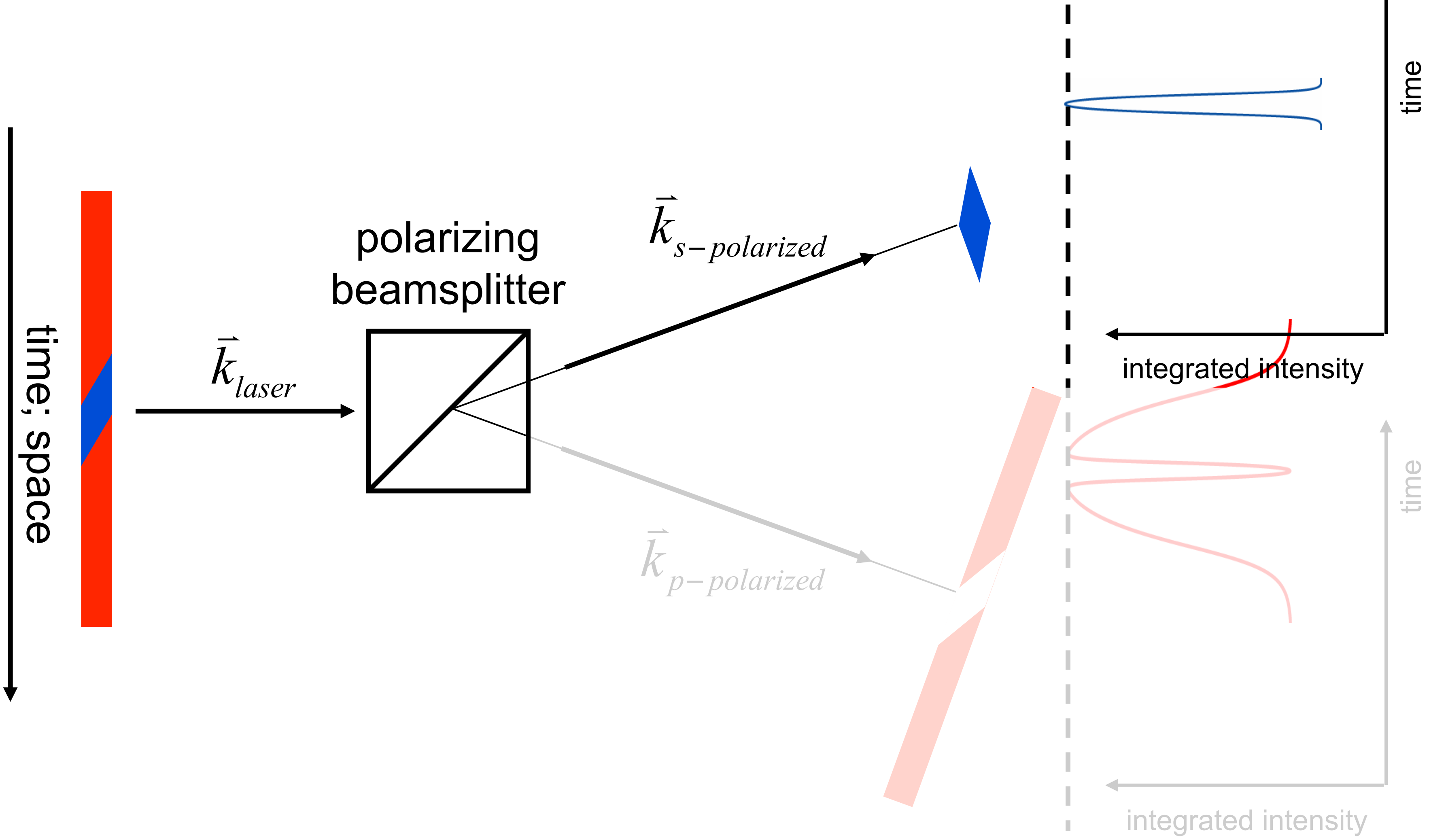


- Probe pulse longer than e-bunch
  - EO signal will be broadened
  - If probe pulse shape is very well known, we should be able to deconvolve e-bunch shape
  - Signal to background problems introduced
- Probe pulse uncompressed (~10's of picoseconds or longer)
  - Measurement will yield no spatially dependent signal

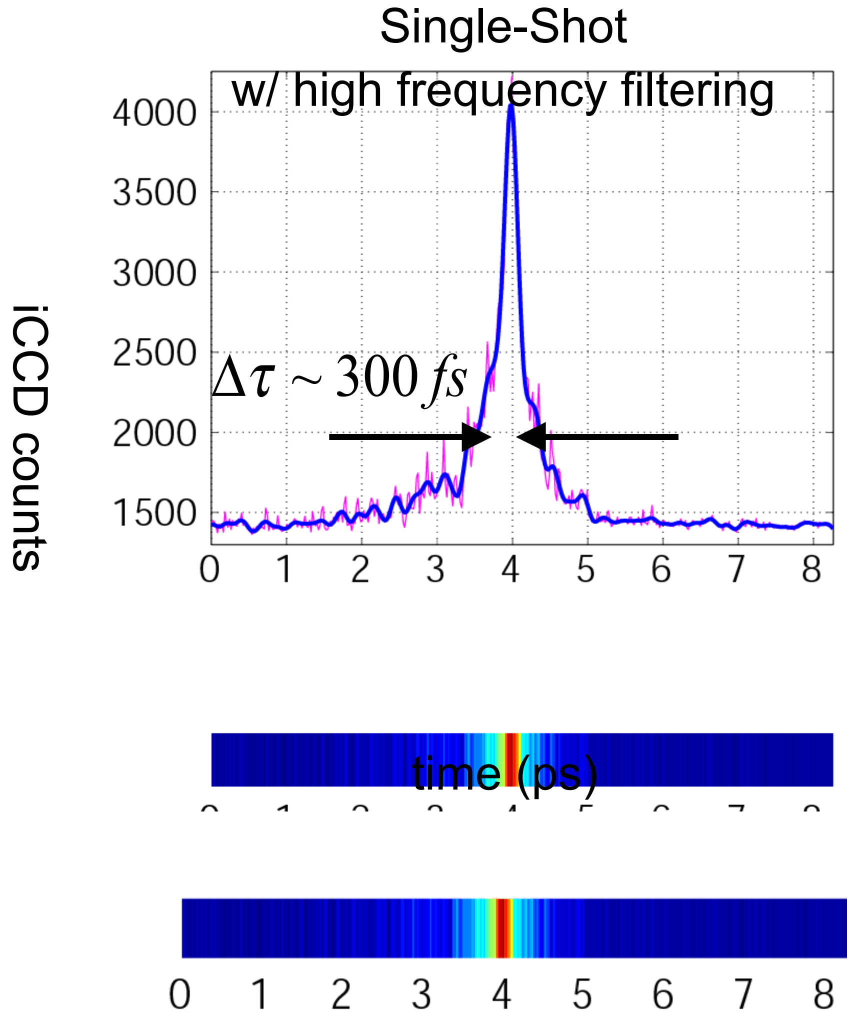
Ultrafast Laser Transport



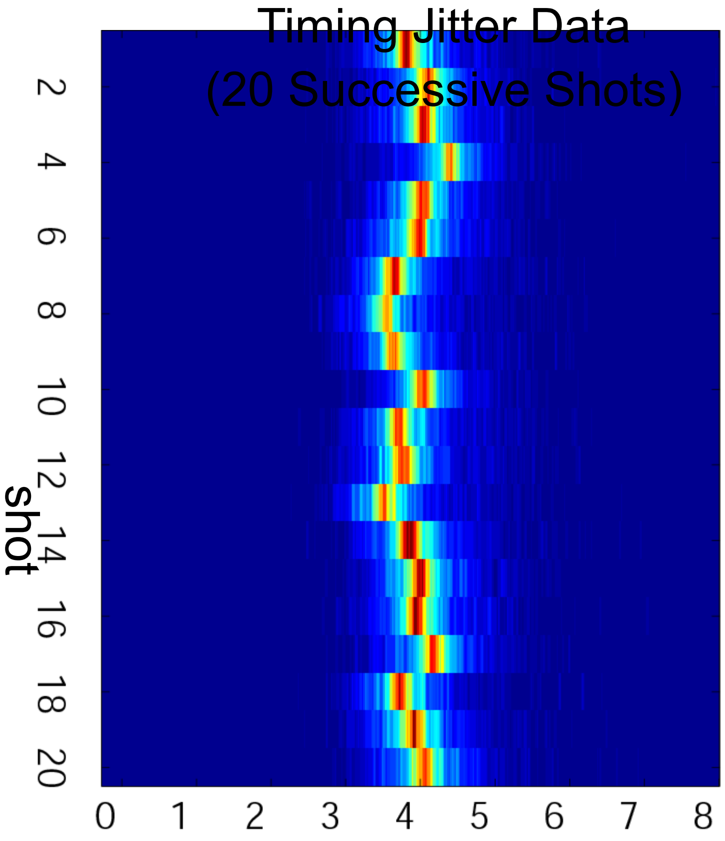
Spatially Resolved EOS Data



Single-Shot Data acquired 200 micron ZnTe



color representation

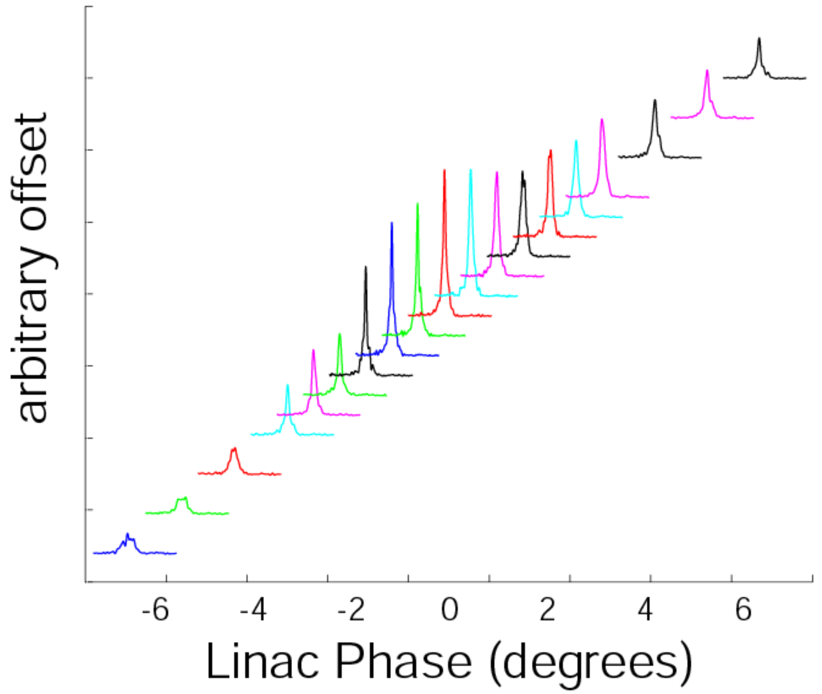


time (ps)

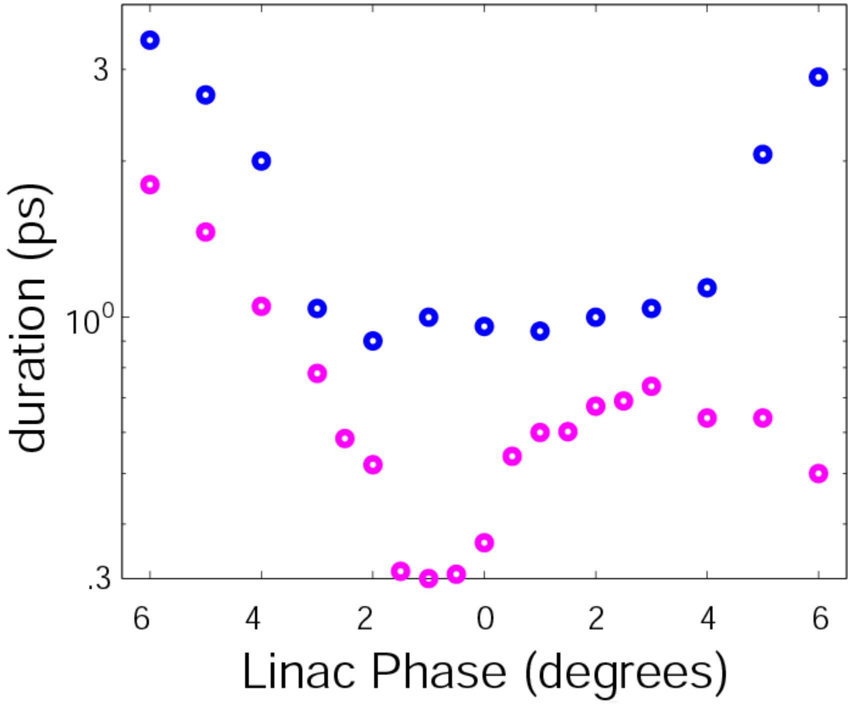
Effect of accelerator parameters on EO signal: Observation of resolution limit

- Changing Linac Phase detunes electron bunch compressor

Single-shot Feature vs. Phase Ramp
200um ZnTe

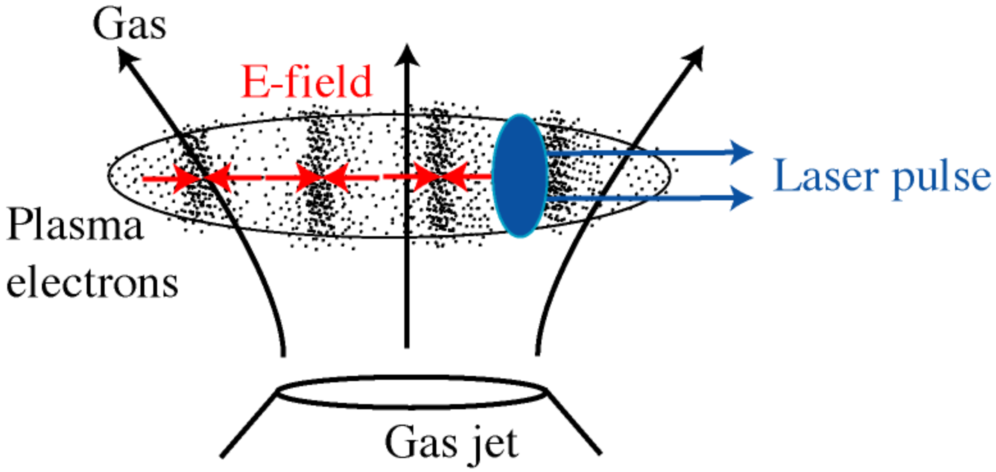


Estimated Feature FWHM



Example: laser wakefield accelerator

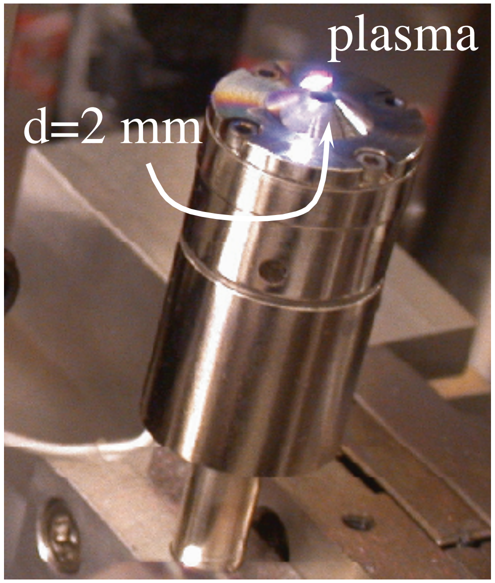
1. Ionization of gas by laser
2. Ponderomotive push of plasma electrons
3. Restoring force from due to charge separation
4. Density oscillation: strong electric fields (100 GV/m)



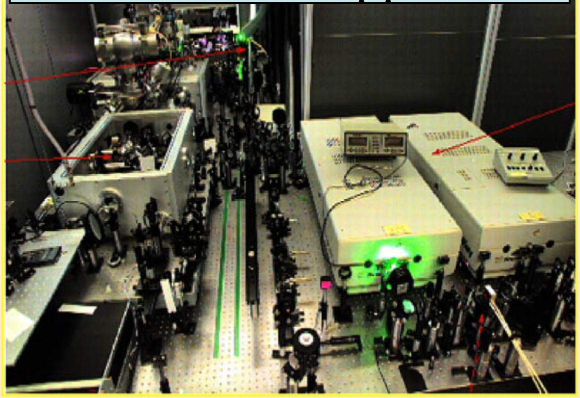
LWFA: two regimes for bunch production

- Large-energy-spread bunch (unchanneled)
- Quasi-mono-energetic bunch (channeled)

Sprangle *et al*. (92); Antonsen, Mora (92); Andreev *et al*. (92); Esarey *et al*. (94); Mori *et al*. (94)

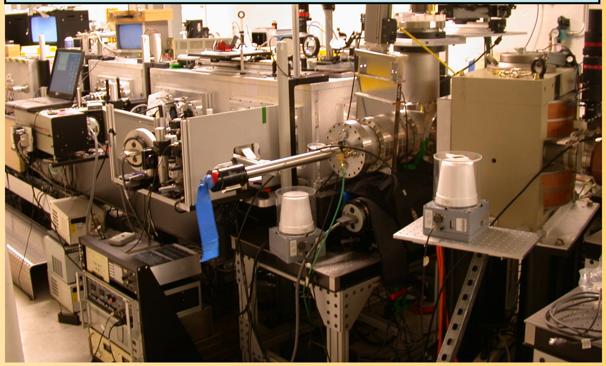


Tool: LOASIS multi-terawatt laser



10 TW Ti:sapphire

100 TW-class Ti:sapphire



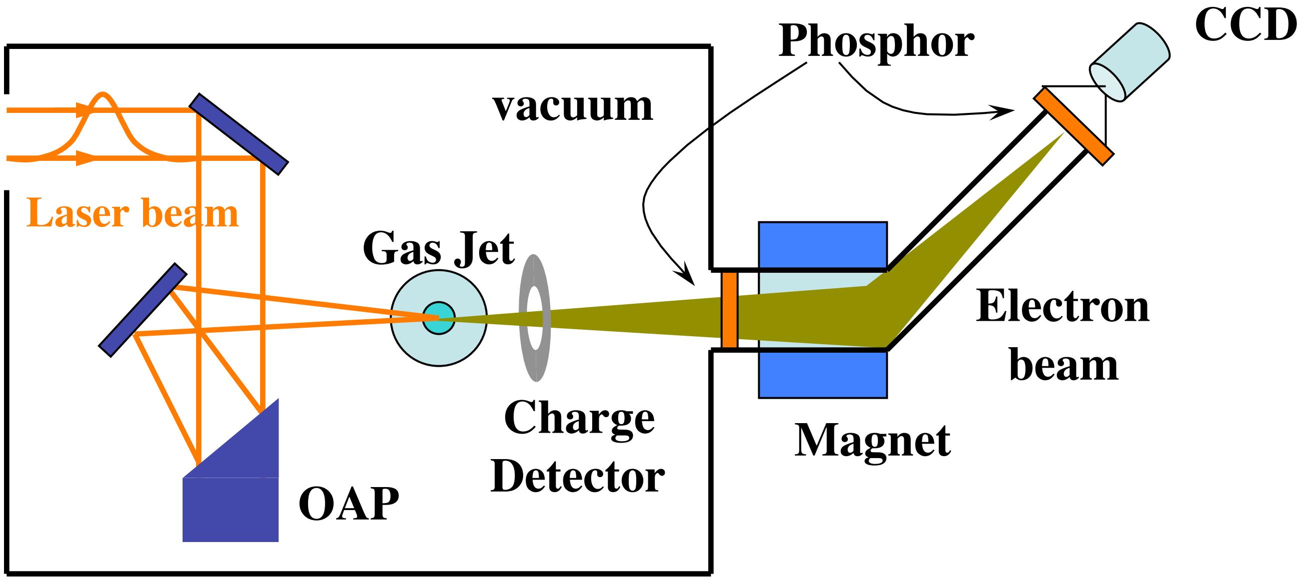
Shielded target room

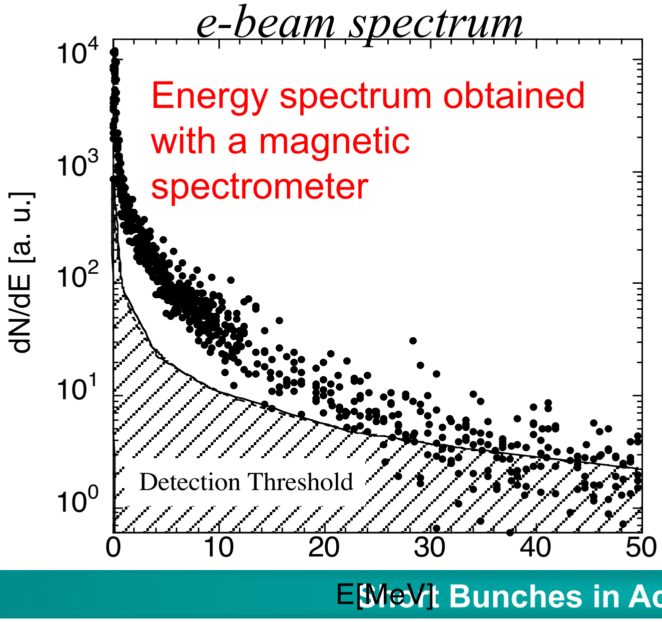
<u>LOASIS laser system</u>

<u>Three main amplifiers (Ti:sapphire,10 Hz):</u>

- Godzilla:
  - 0.5-0.6 J in 40-50 fs (10-15 TW) ===> main drive beam (to date)
- Chihuahua:
  - 20-50 mJ in 50 fs ===> ignitor beam } guiding
  - 250-300 mJ in 200-300 ps ===> heater beam } guiding
  - 100-200 mJ in 50 fs ===> colliding beam
- T-REX:
  - 2-3 J in 30-40 fs ===> capillary experiments

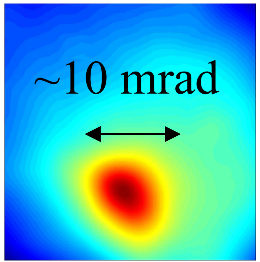
Mid 90's -2003: short pulse laser systems generate electron beams with 100 % energy spread




e-beam spectrum

Energy spectrum obtained with a magnetic spectrometer

e-beam on phosphor screen



LWFA experiments produce electrons with:

1-100 MeV, multi-nC,

~100 fs,

~10 mrad divergence

Modena *et al*. (95); Nakajima *et al*. (95); Umstadter *et al*. (96); Ting *et al*. (97); Gahn *et al*. (99); Leemans *et al*. (01); Malka *et al*. (01)

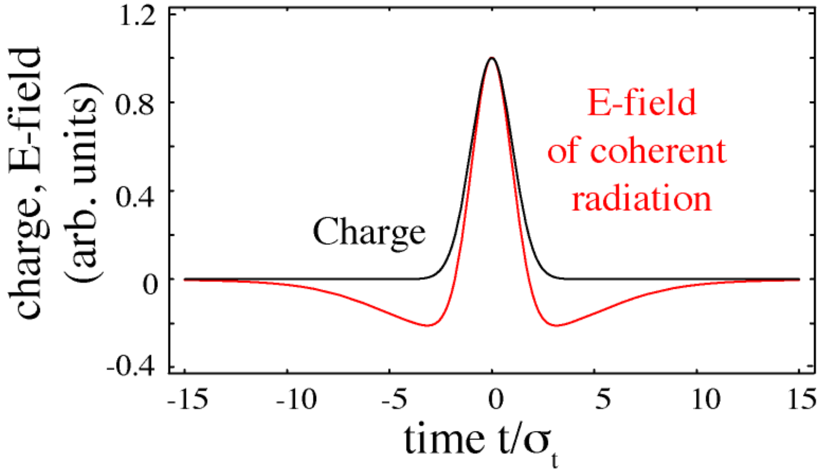
How short are the bunches ?

- Simulations predict 10-20 fs
- Can we measure them? (Is the linac stable enough?)
- Coherent emission

$$I_{total}(\omega)=\left\{N+N(N-1)\left|g(k)\right|^{2}\right\}I_{e}(\omega)$$

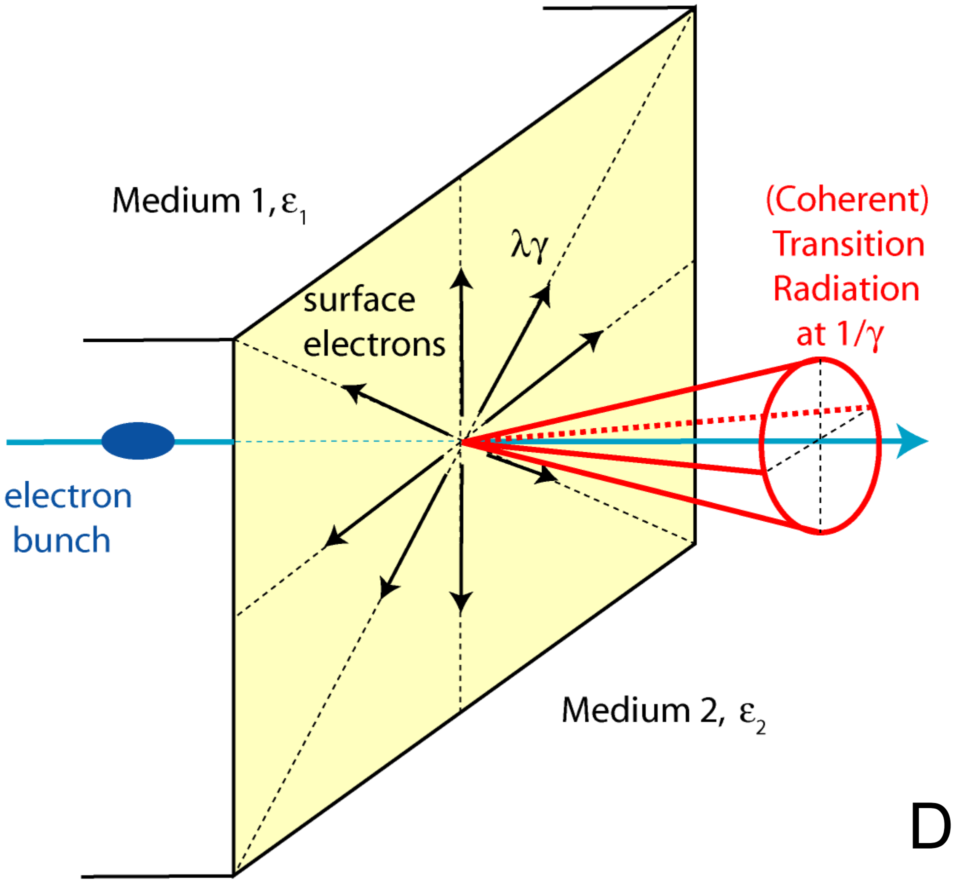
$$g(k)=\int_{-\infty}^{\infty}\rho(z)e^{ikz}dz$$

Dominates if $s_z < l$

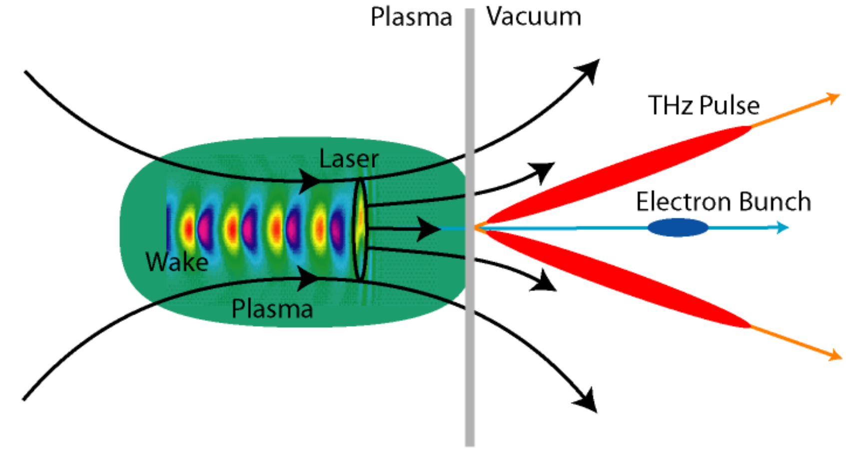


Coherent transition radiation from the plasma-vacuum boundary

Schematic for Transition Radiation



Laser-Wakefield Accelerator



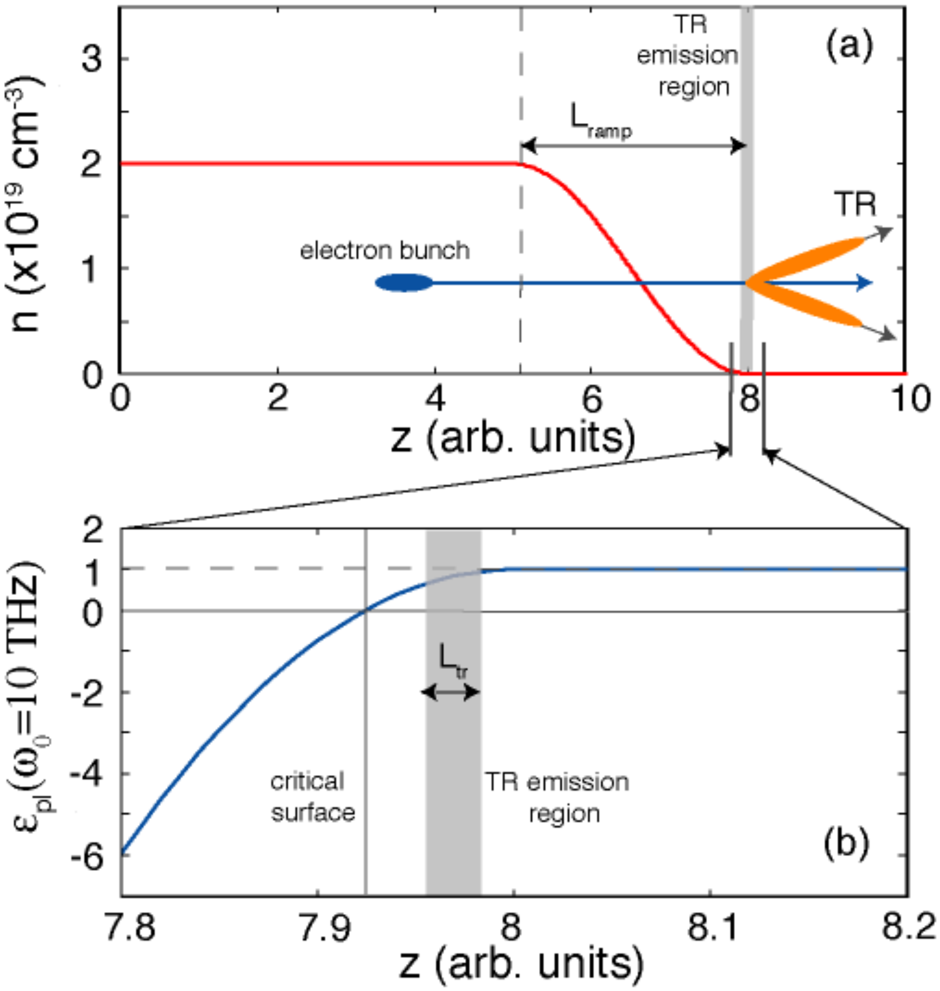
Leemans *et al*., Phys. Rev. Lett. (2003);
Schroeder *et al*., Phys. Rev. E (2004);
Van Tilborg et al., Phys. Rev. Lett. (2006)

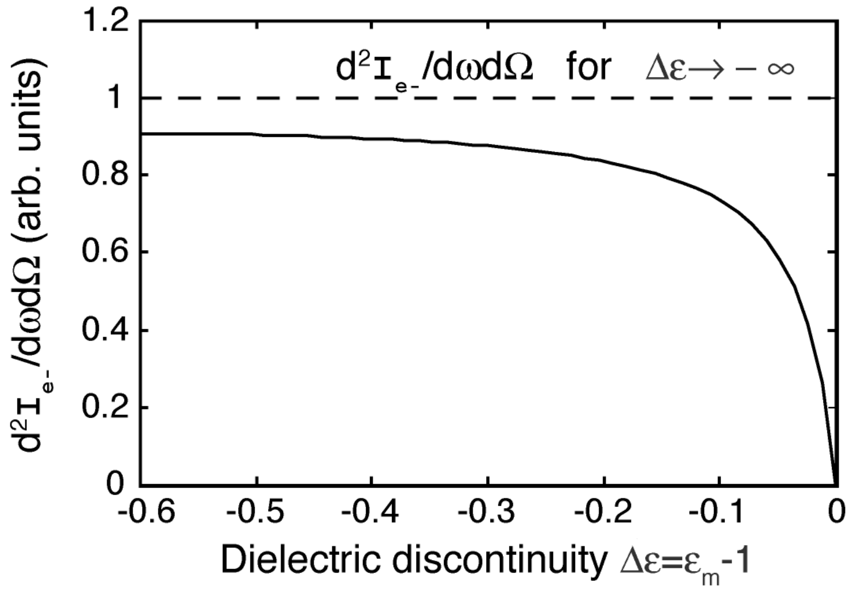
Boundary size

Diagnostic implementation:

- Use radiated field
- Couple out of vacuum chamber

CTR from Plasma-vacuum boundary





CTR (THz) in spectral and temporal domain

Diffraction function
(boundary size)

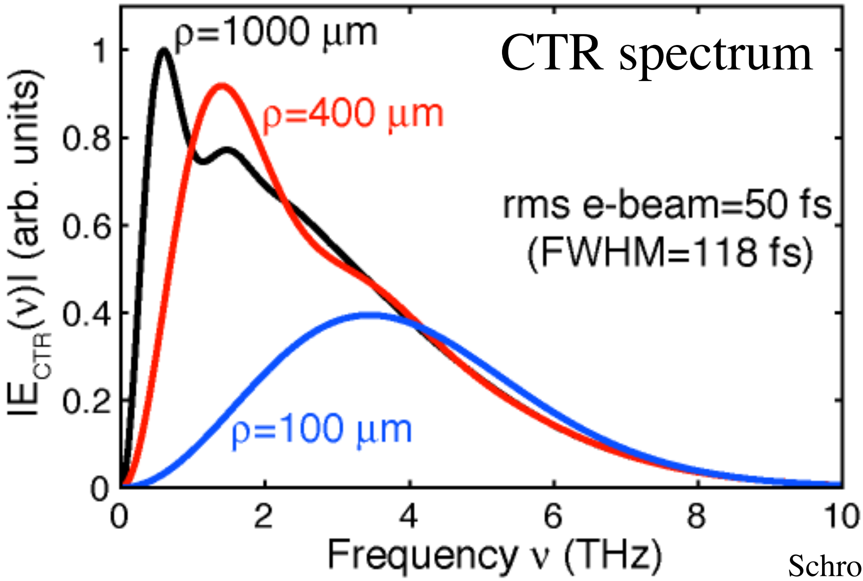
$$E_{\mathrm{CTR}}(\omega) \propto N\mathcal{E}(u)D(\omega,u,\rho)F(\omega)$$

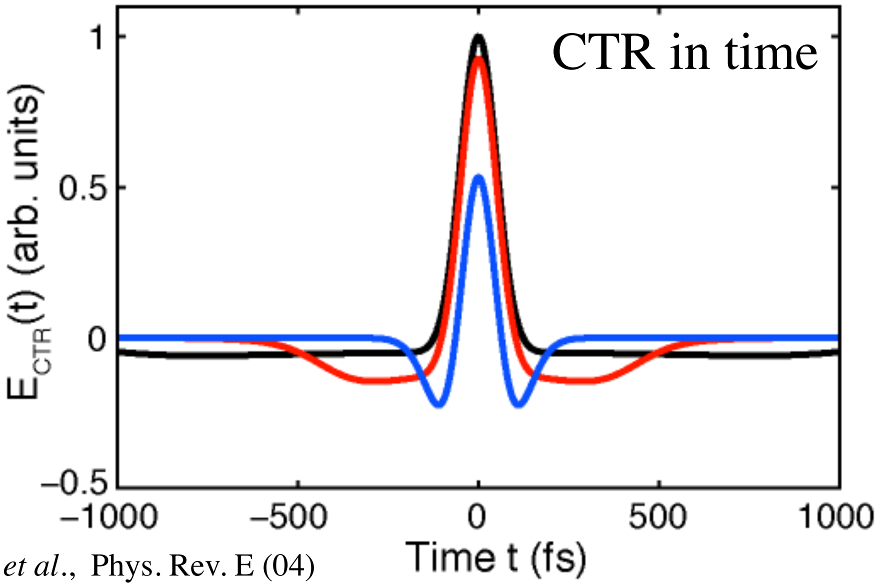
Single electron TR

Form factor

Intense THz source

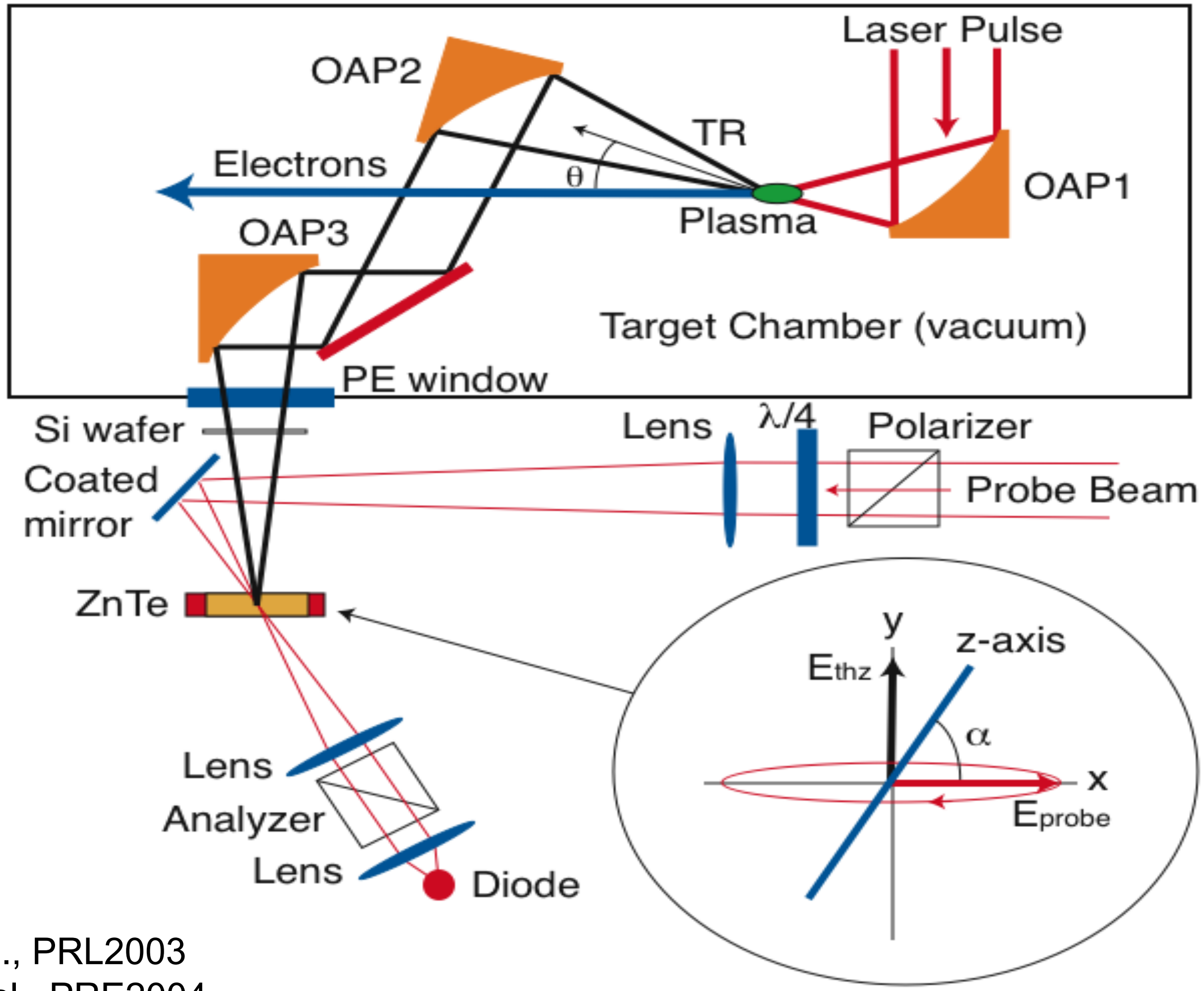
- **0.01-10 MV/cm** at focus (up to **10's of J** in THz pulse)
- 'traditional' laser-based sources deliver <100 kV/cm





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

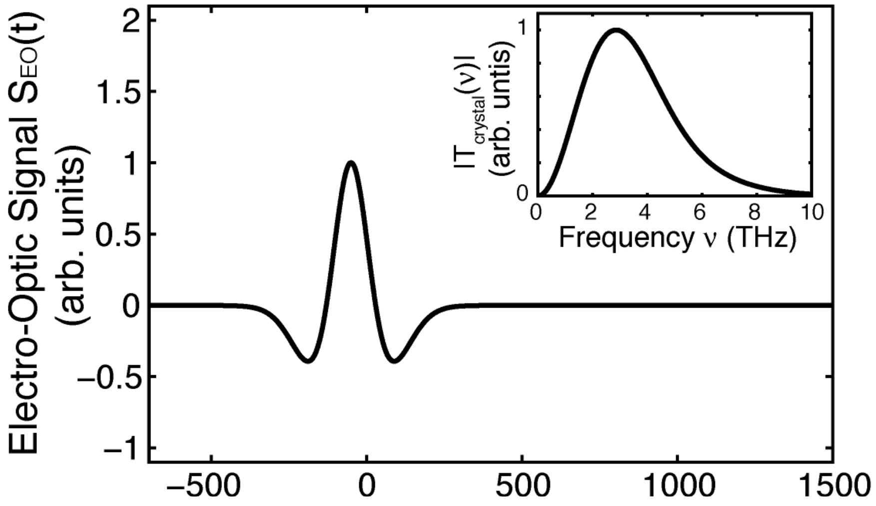
Multi-shot sampling setup



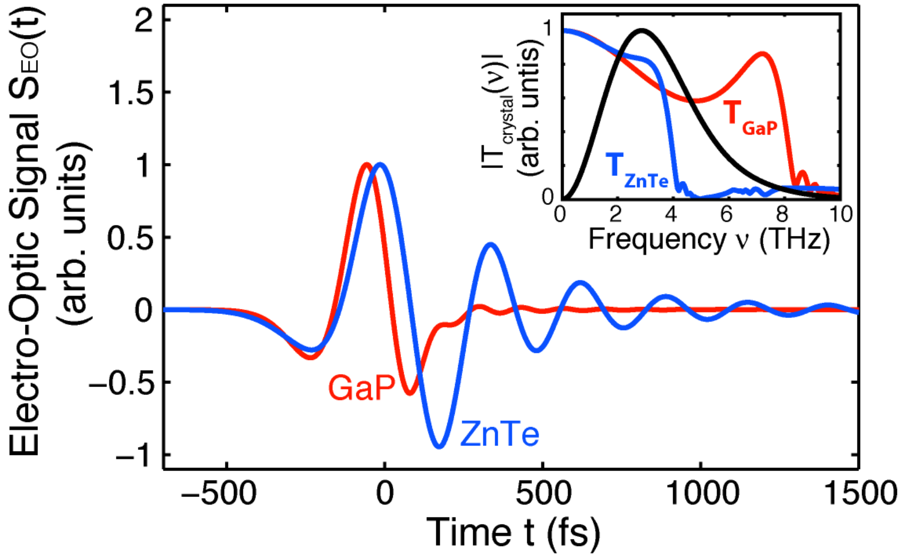
W.P. Leemans et al., PRL2003
C.B. Schroeder et al., PRE2004
J. Van Tilborg et al., Laser and Particle Beams 2004; PRL 2006

EO Crystal Bandwidth

- CTR based on 50 fs (rms) Gaussian electron bunch

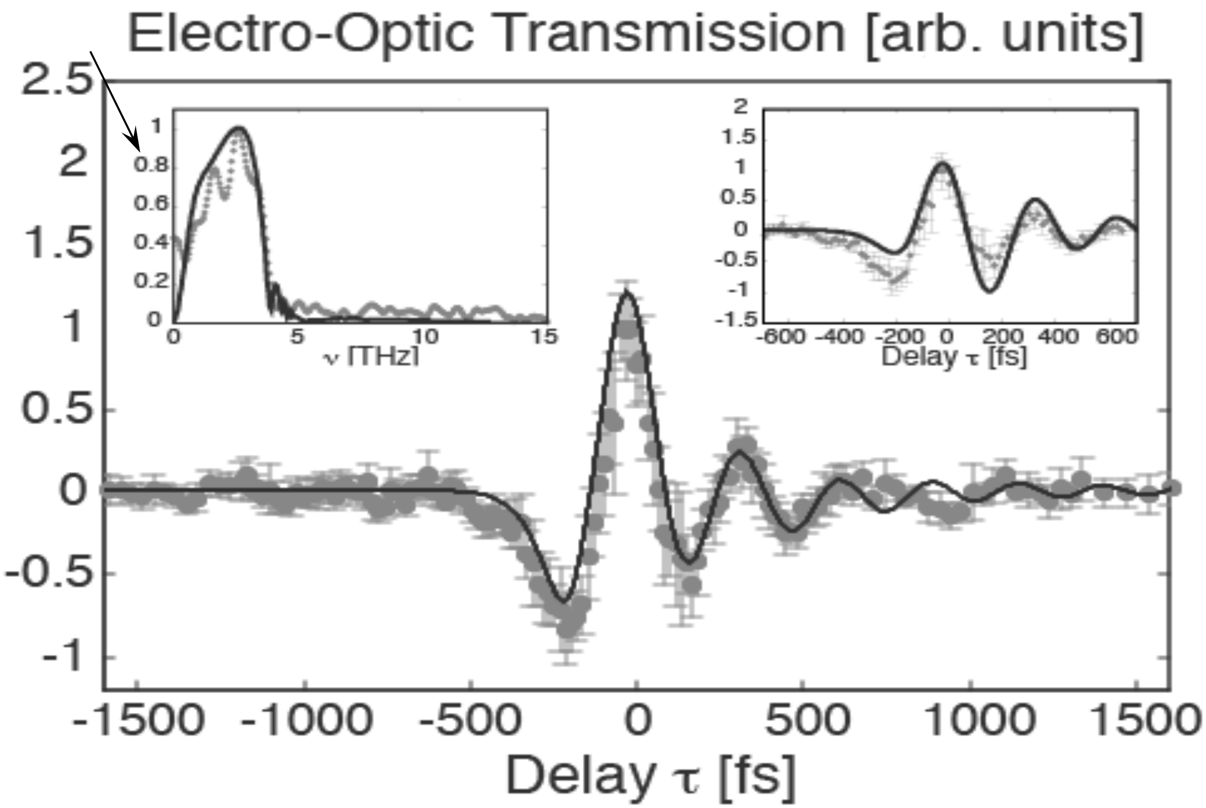


- ZnTe vs GaP:
  - ZnTe cutoff ~ 4 THz
  - GaP cutoff ~ 8 THz



Scanning technique provides bunch duration: Resolution limited by crystal properties

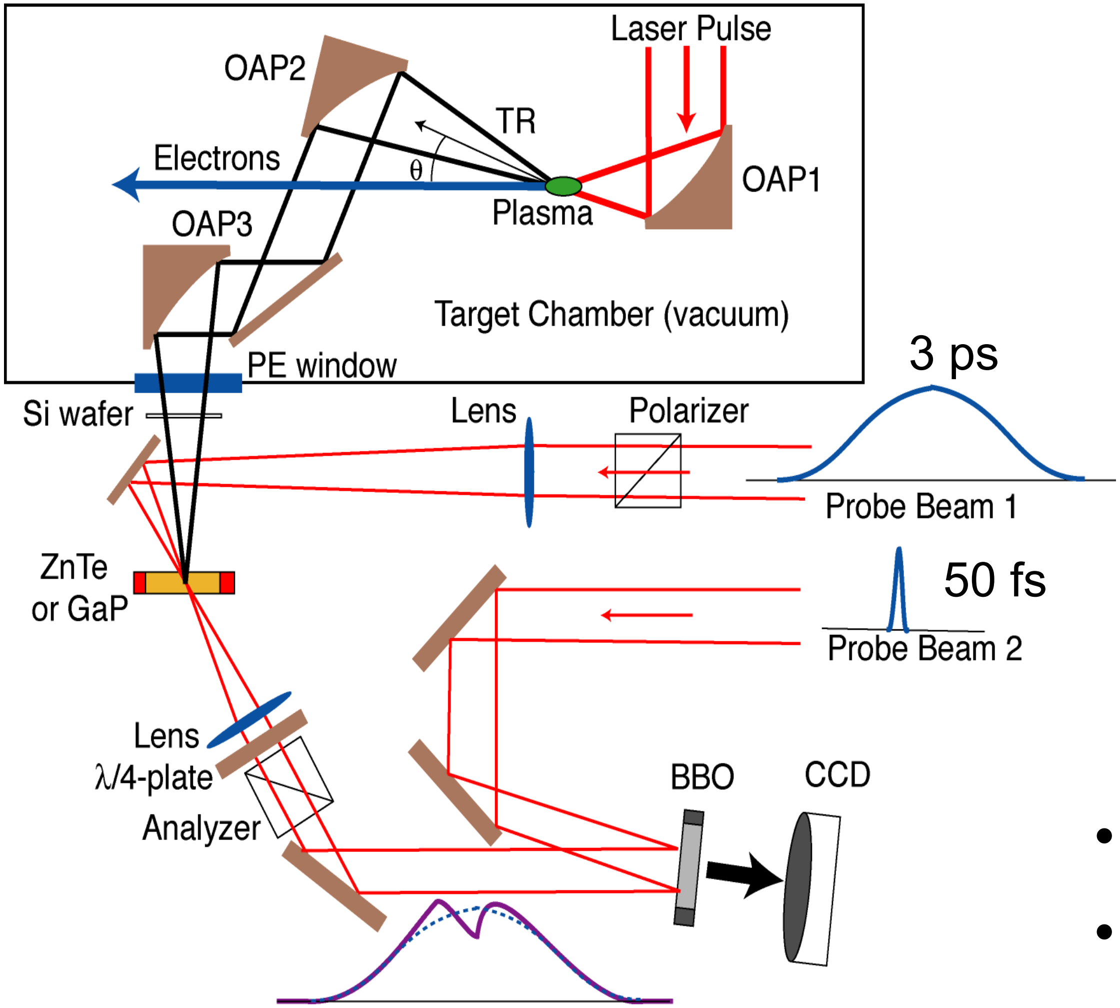
Scanning technique
(takes 1.5 hours)

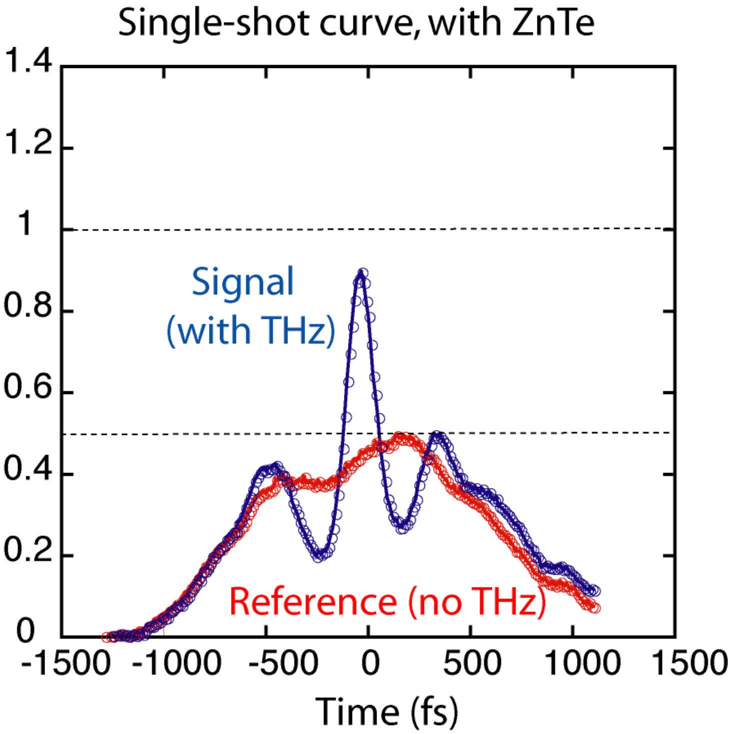


Van Tilborg et al., PRL2006, Phys. Plasmas06

- **< 50 fs bunches**
- **Synchronization**
- **Charge and bunch stability**

Single-Shot Technique





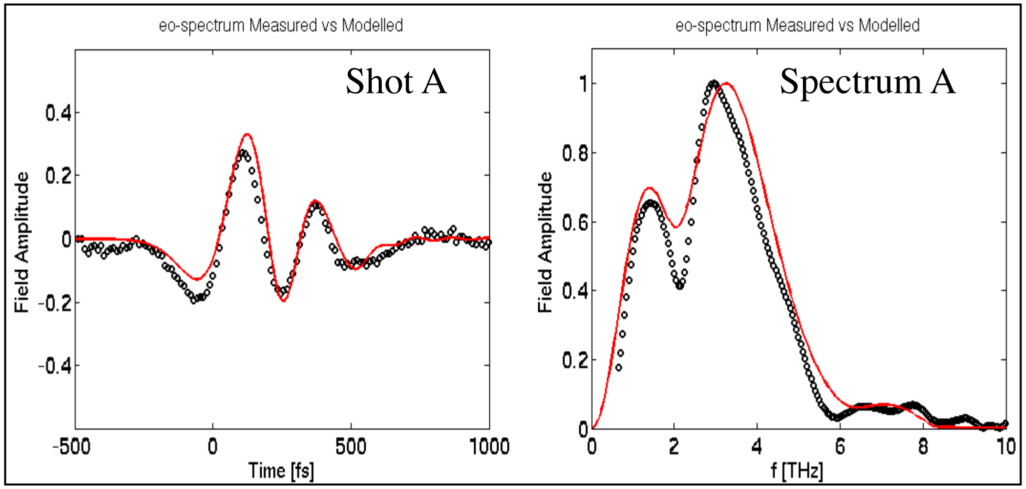
- < 50 fs bunches
- peak E-field of $E_{CTR} \approx 150$ kV/cm

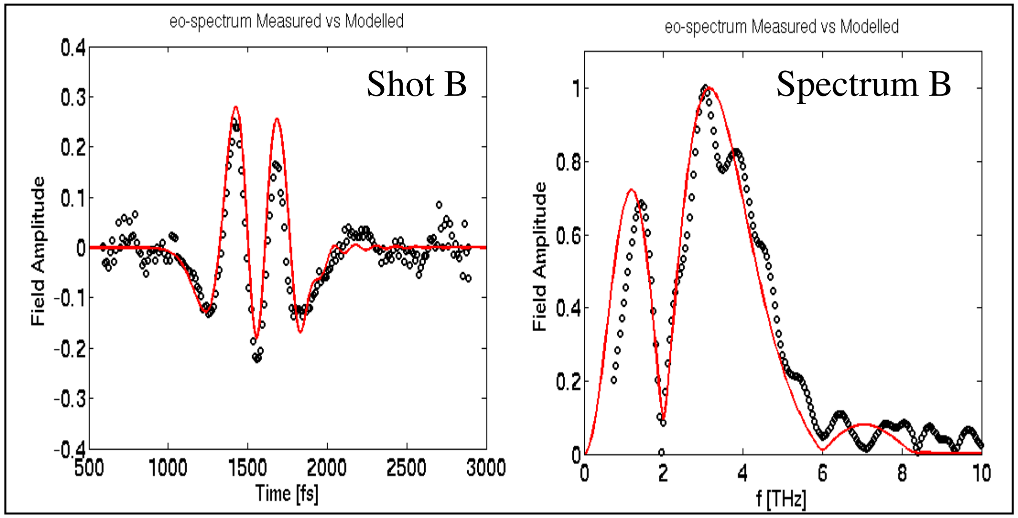
G. Berden et al., Phys. Rev. Lett. 93, 114802 (2004)

J. van Tilborg et al., submitted to PRL

Experiments show double THz pulse

Red curves are double-THz-pulse-based waveforms and spectra





Use GaP instead of ZnTe

- Higher bandwidth

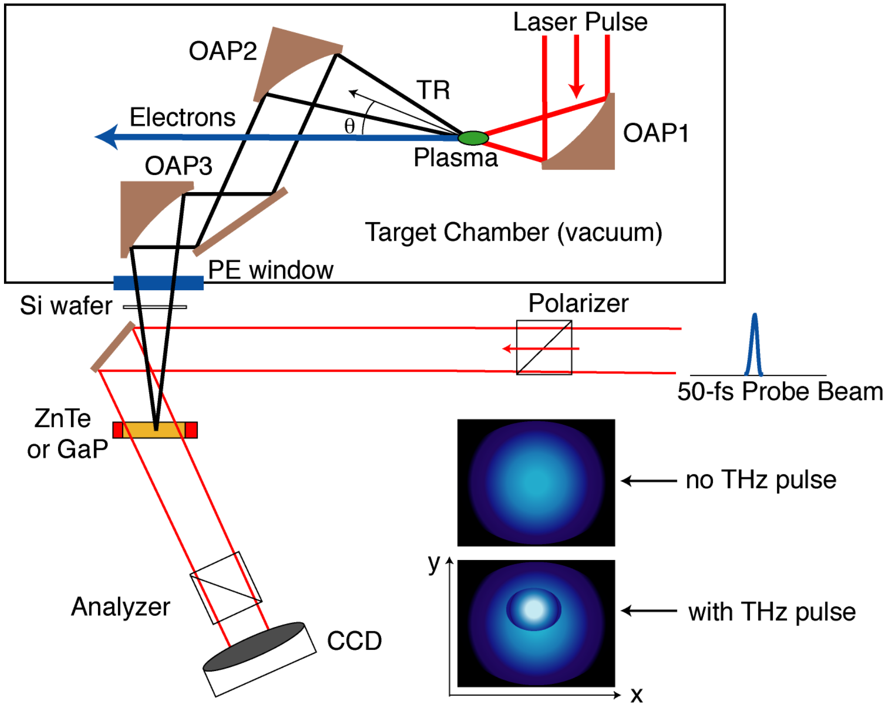
Observation

- Temporal waveform: double pulse
- Spectral modulation

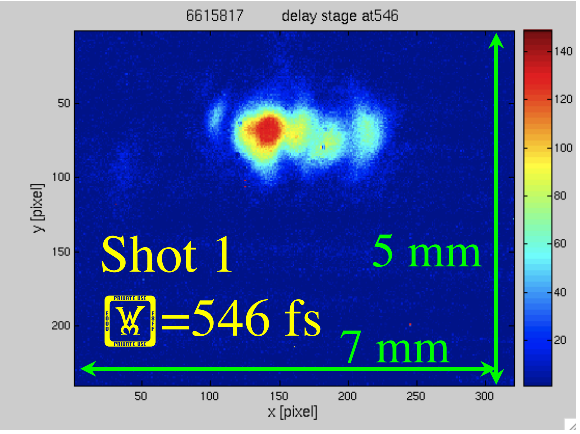
Why?

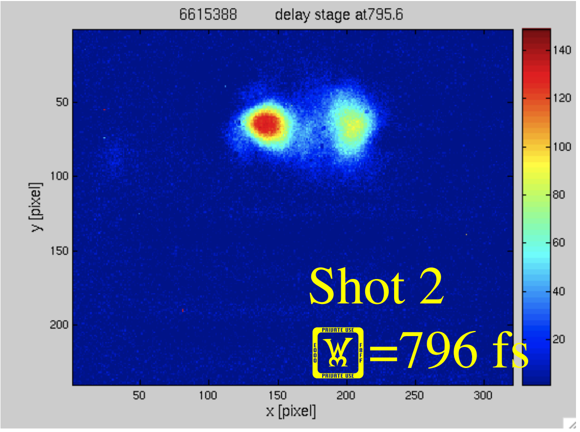
- Double bunch e-beam ?

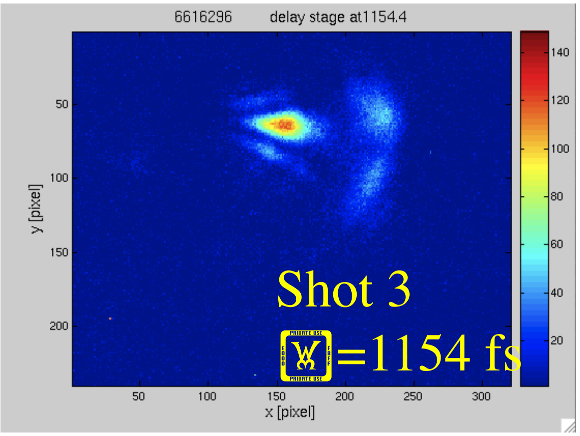
Single-shot 2D EO imaging provides spatial profile of THz beam



- Measure 2 D THz profile
  - Focused THz beam
  - Collimated laser beam
  - Step laser beam in time

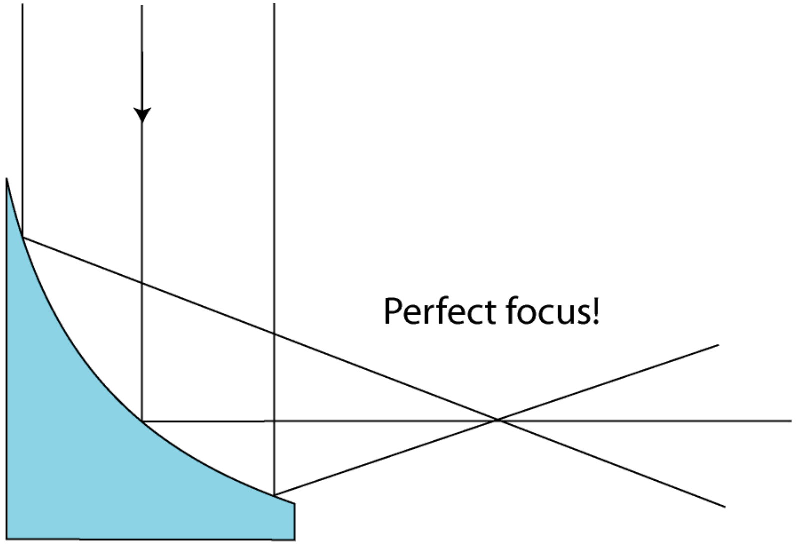




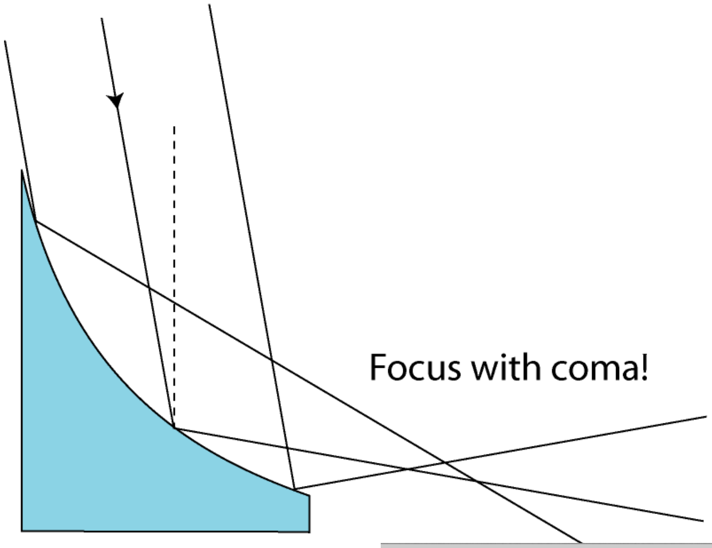


Van Tilborg *et al*., to be published

‘Ray Optics’ approach to analyze spatio-temporal effects of coma



Perfect focus!



Focus with coma!

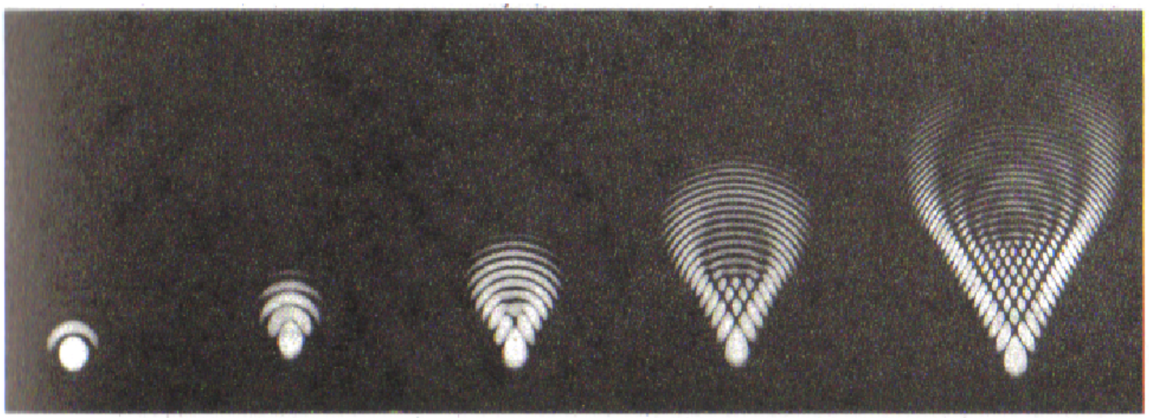
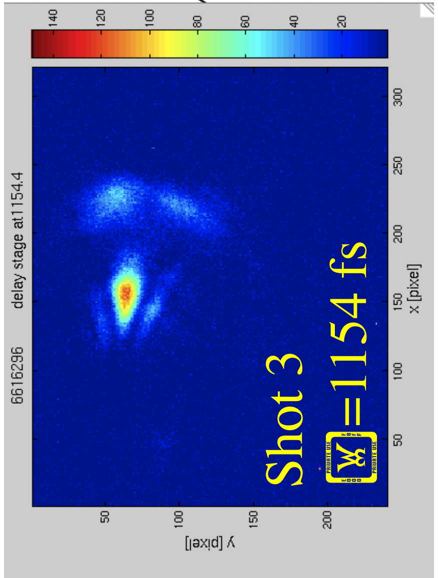
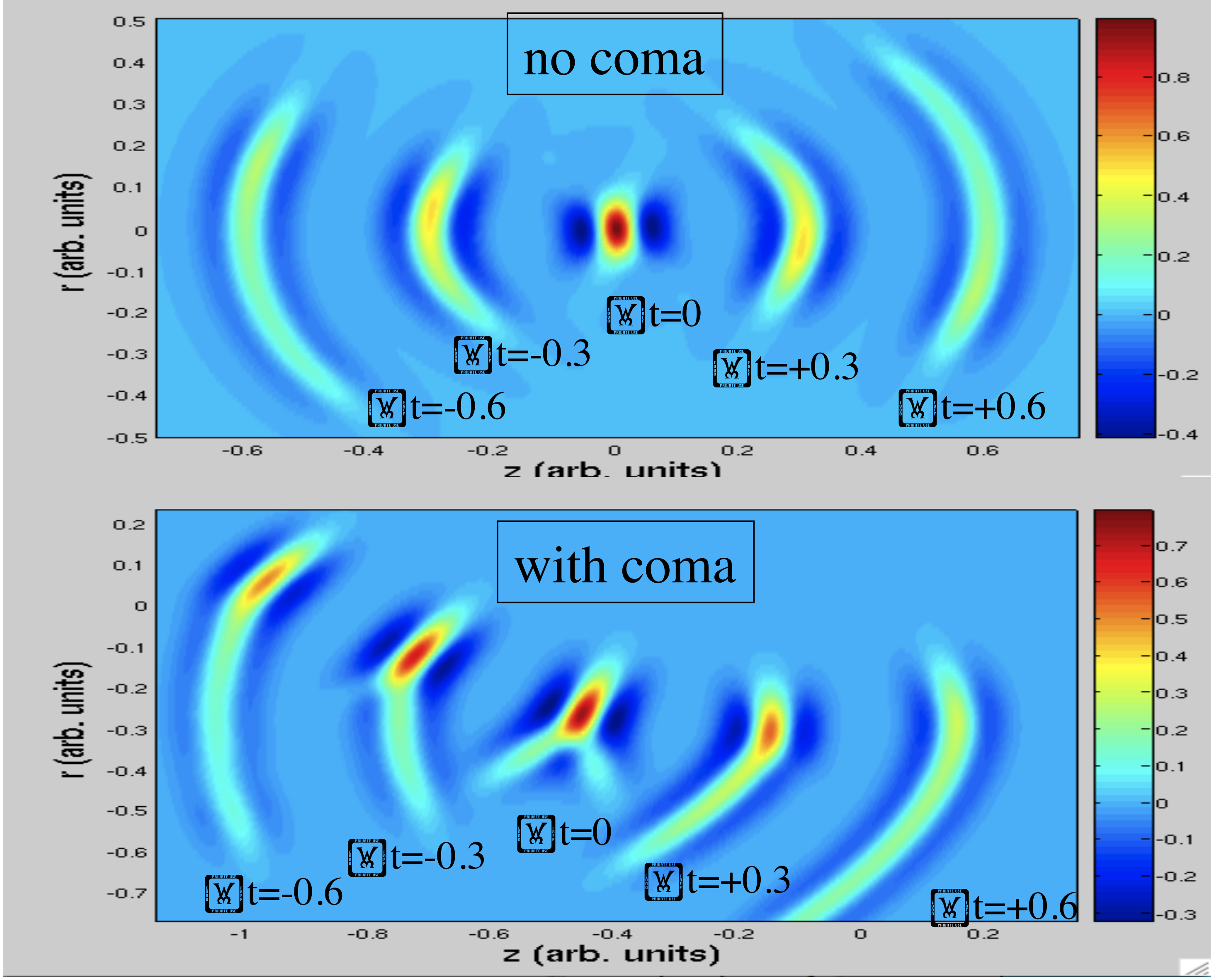


Fig. 9.8 Images in the Gaussian focal plane in the presence of coma $\Phi = 0.3\lambda\rho^3\cos\theta,\ \lambda\rho^3\cos\theta,\ 2.4\lambda\rho^3\cos\theta,\ 5\lambda\rho^3\cos\theta,\ 10\lambda\rho^3\cos\theta$. (After K. Nienhuis, Thesis (University of Groningen, 1948), p. 40.)



Propagation of a single-cycle pulse through focus



‘Ray optics’ model for waveform and spectrum