Electro-optic diagnostics
concepts & capabilities

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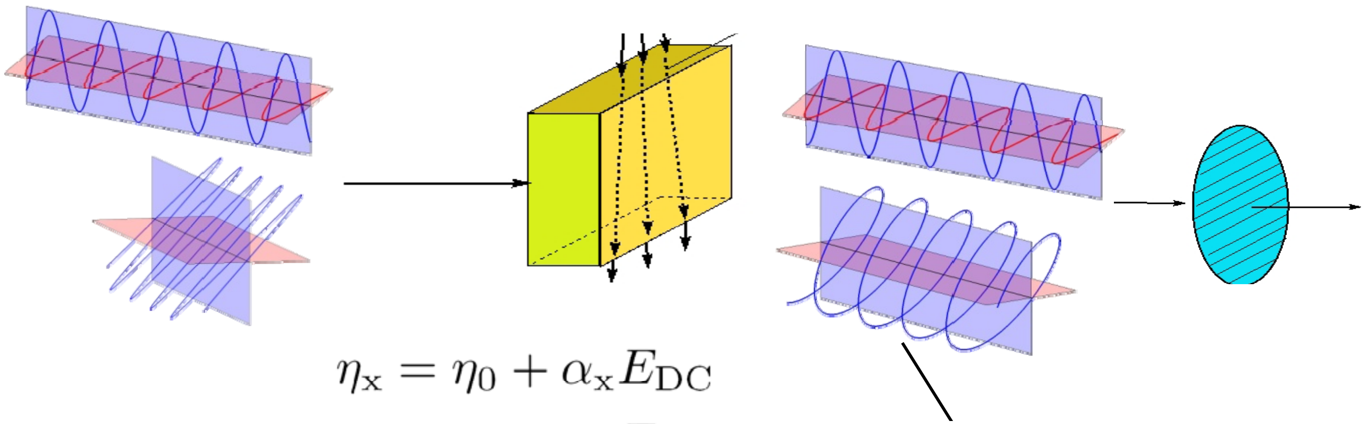
Electro-optic effect

Refractive index modified by quasi-DC electric field

laser pulse
(linear polarised)

elliptically
polarised



$E_x(t)$
$E_y(t)$

intensity dependent
on 'DC' field strength

$$\eta_x = \eta_0 + \alpha_x E_{DC}$$
$$\eta_y = \eta_0 + \alpha_y E_{DC}$$

$$E_x(t) \sim E_x(t)\exp(i\omega t - i\eta_x \omega z/c)$$
$$E_y(t) \sim E_y(t)\exp(i\omega t - i\eta_y \omega z/c)$$

Time varying field....replace with time varying refractive index

quasi-DC description OK if τ_{laser} << time scale of E_{DC} variations

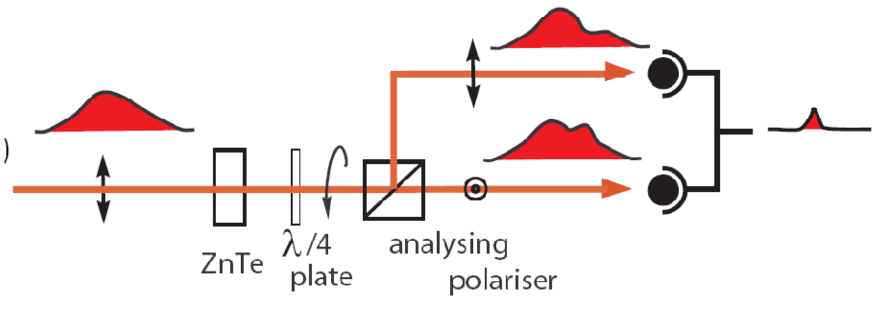
Basis for Pockels cells, sampling electro-optic THz detection, ...

Phase retardation into intensity change

Polariser & wave plate arrangement effects scaling

Phase retardation Γ proportional to (Coulomb) field

"Balanced detection"

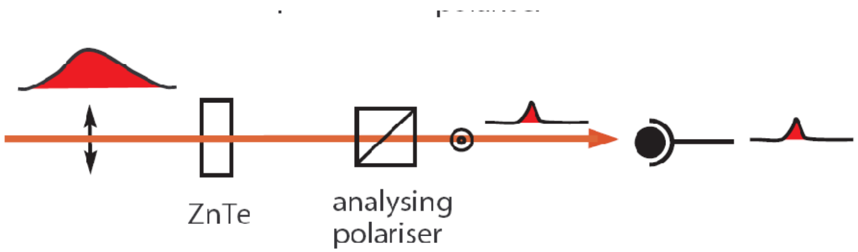


$$\Delta I_{out}^{probe} \sim \Gamma \sim E^{THz}$$

- linear scaling
- small signal on large background
- polarity measureable

  good for CSR, CTR etc

crossed polariser detection

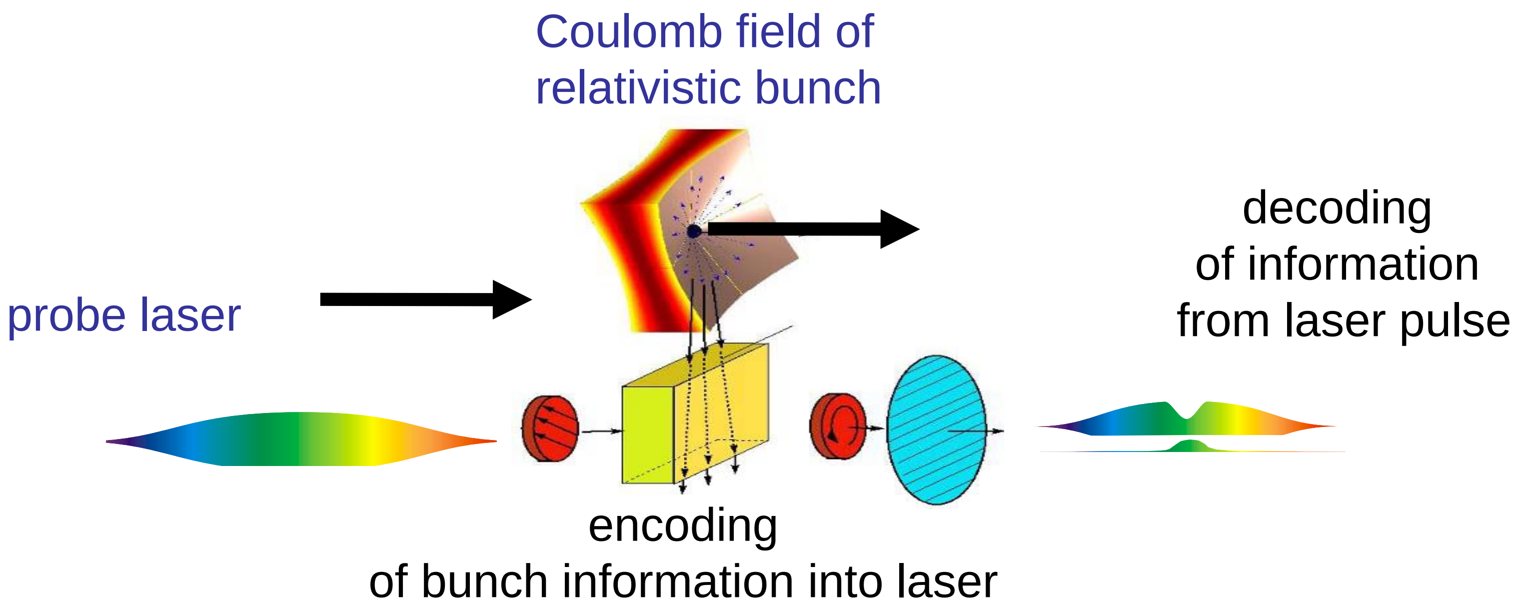


$$I_{out}^{probe} \sim \Gamma^2 \sim [E^{THz}]^2$$

- quadratic scaling
- background free
- polarity hidden

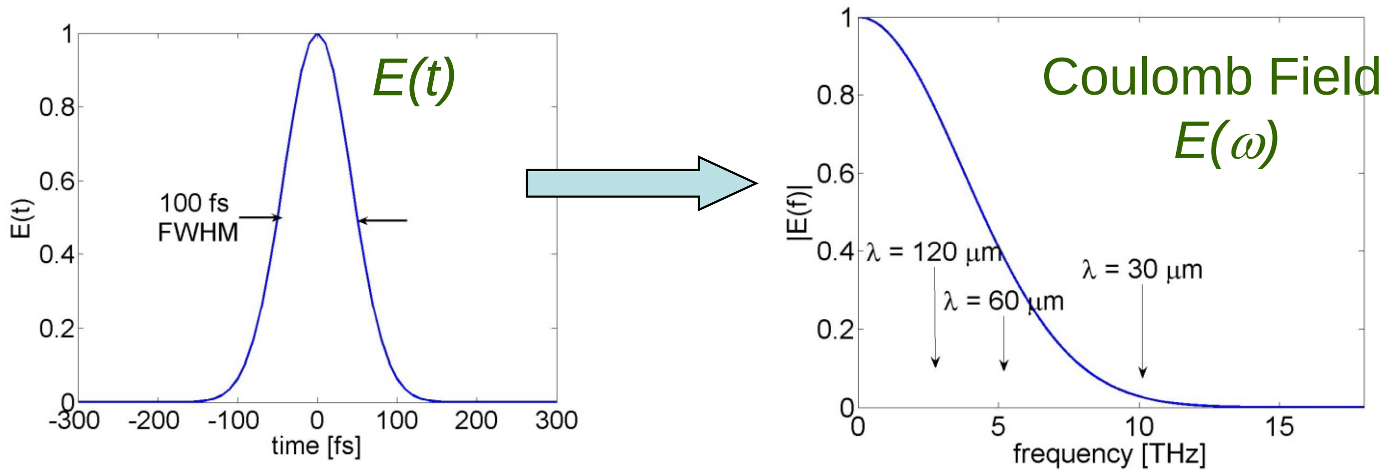
  Coulomb field OK

Electro-optic effect for bunch diagnostics



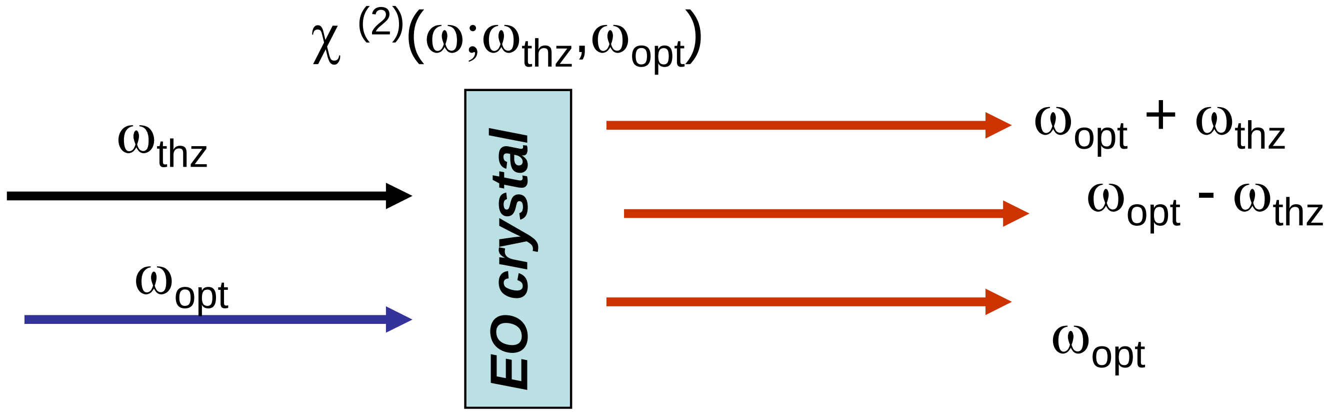
Measure electric fields of bunch : Coulomb field, CSR, CTR, wakefields, ...

Spectrum of field important for capability & technique choice



Electro-optic detection as sum- and difference-frequency mixing

frequency domain description of EO detection...



$$\tilde{E}^{probe}_{out}(\omega) \sim \tilde{E}^{probe}_{in}(\omega) + i\chi^{(2)} \int_{-\infty}^{\infty} \tilde{R}(\Omega)\tilde{E}^{THz}(\Omega)\tilde{E}^{probe}_{in}(\omega - \Omega)\mathrm{d}\Omega$$

geometry dependent (repeat for each principle axis)

convolution over all combinations of optical and Coulomb frequencies

propagation & nonlinear efficiency

THz spectrum (complex)

optical probe spectrum (complex)

Refractive index formalism comes out as subset of solutions (restriction on laser parameters)

This is "Small signal" solution. High field effects c.f. Jamison Appl Phys B **91** 241 (2008)

$$\tilde{A}(\omega, z) = \tilde{A}_0(\omega)\mathrm{e}^{-z\beta_{\mathrm{opt}}} + \frac{\mathrm{i}}{2c\eta}\mathrm{e}^{-z\beta_{\mathrm{opt}}}\omega \int \mathrm{d}\omega' \tilde{A}_{\mathrm{eff}}^{\mathrm{THz}}(\omega - \omega')\tilde{A}(\omega'),$$

DC “THz” field....

$$\tilde{A}(\omega, z) \rightarrow \tilde{A}_0(\omega)\left[1 + i\alpha A_{DC} z\right]$$
$$\rightarrow \tilde{A}_0(\omega)\mathrm{e}^{i\alpha A_{DC} z}$$

phase shift
(pockels cell)

Delta-Fnc
ultrafast pulse...

$$\tilde{A}_0(\omega) \rightarrow A_0 \mathrm{e}^{i\omega\tau}$$

$$\int A_0 \tilde{A}_{\mathrm{eff}}^{\mathrm{THz}}(\omega - \omega')\mathrm{e}^{i\omega\tau} \longrightarrow A_0 A_{\mathrm{eff}}^{\mathrm{THz}}(t - \tau)$$

temporal
sampling
of THz field

Monochromatic
THz & optical

$$\tilde{A}_{THz}(\Omega), \tilde{A}_0(\omega_0)$$

$$\tilde{A}_0(\omega_0) + i\alpha\tilde{A}_0(\omega_0 - \Omega)$$
$$+ i\alpha\tilde{A}_0(\omega_0 + \Omega)$$

optical
sidebands

Chirped optical

Parameter dependent results

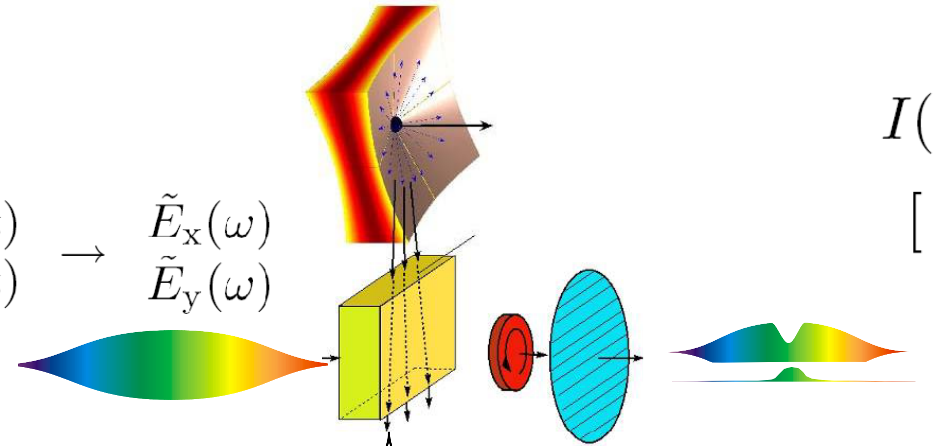
Electro-optic coulomb field Encoding

shifting Coulomb spectrum to optical region

OR

creating an optical “replica” of Coulomb field

$$E_x(t) \quad \rightarrow \quad \tilde{E}_x(\omega)$$
$$E_y(t) \qquad\quad \tilde{E}_y(\omega)$$



$$I(t) \propto E_{\rm Coul}(t)$$
$$\left[\text{ or } \quad \propto E^2_{\rm Coul}(t) \quad \right]$$

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

Coulomb spectrum shifted to optical region

$$E^{\rm opt}_{\rm out}(t) = E^{\rm opt}_{\rm in}(t) + a\left[E^{\rm Coul}(t) * R(t)\right]\frac{\rm d}{{\rm d}t}E^{\rm opt}_{\rm in}(t)$$

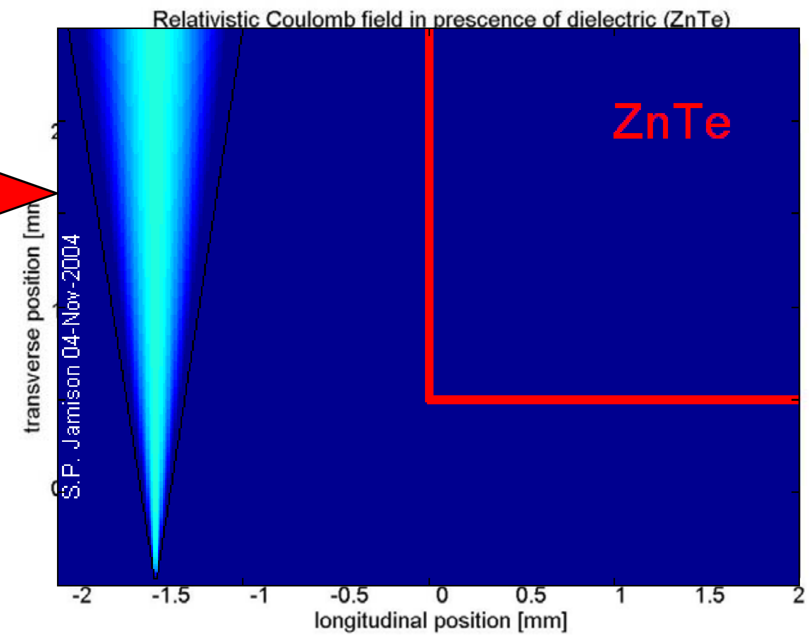
envelope — optical field

Coulomb pulse replicated in optical pulse

Jamison et al.
Opt. Lett **31** 1753 (2006)
Appl. Phys B. **91** 241 (2008)

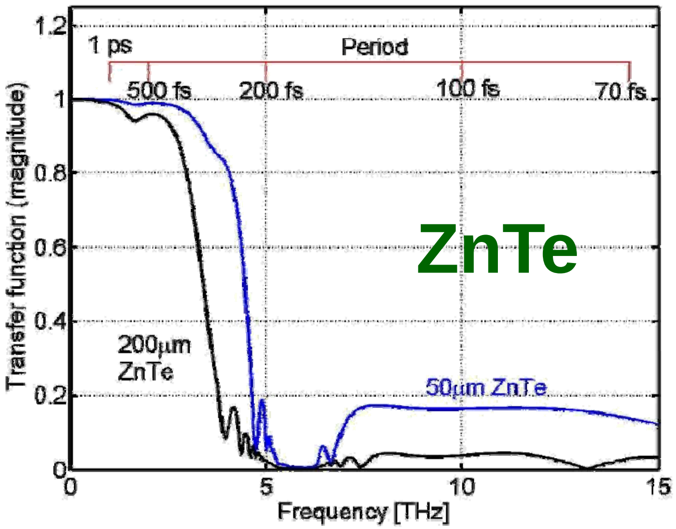
Material Response, R(ω)

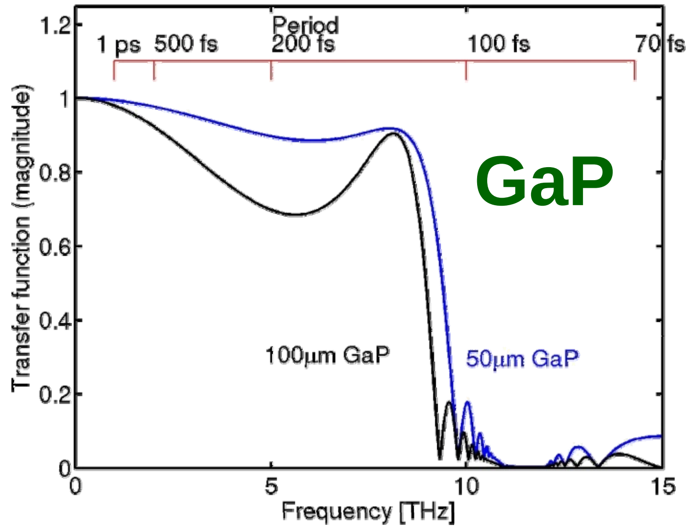
Co-propagates with Coulomb field



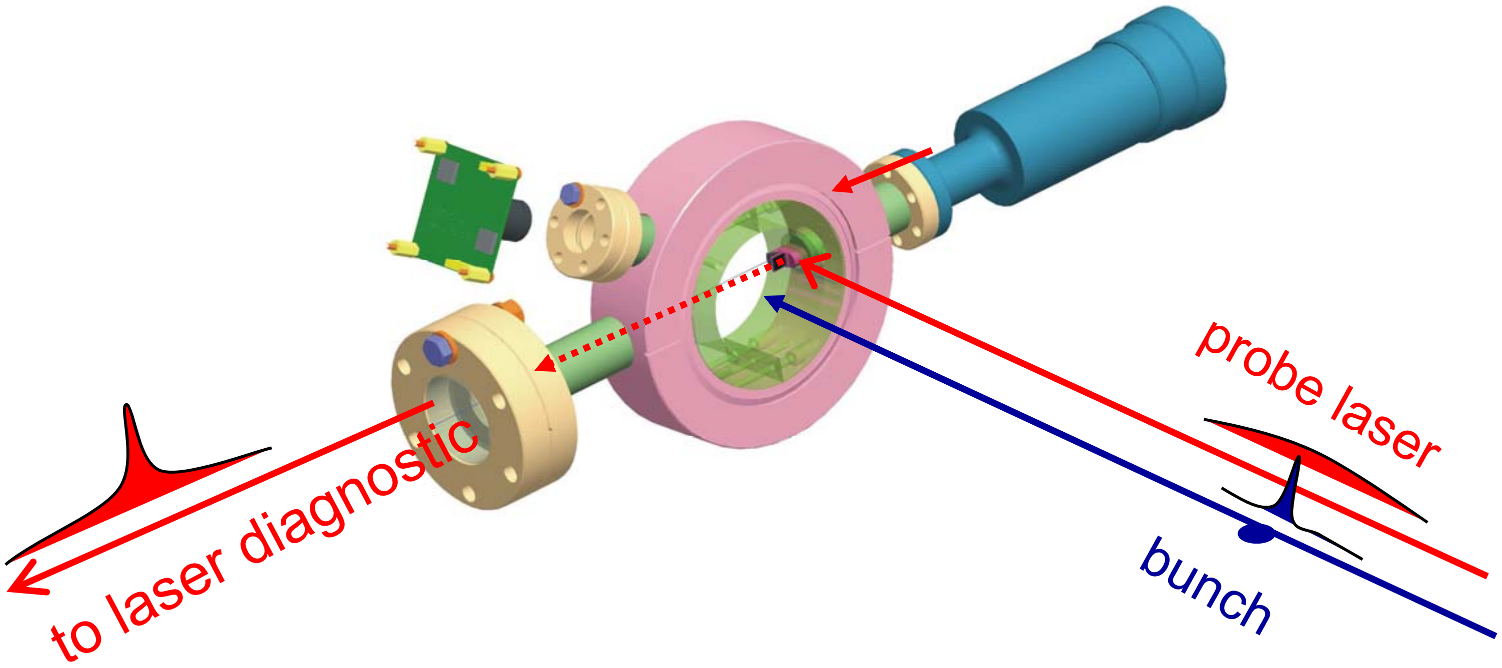
Measure "slowed down" Coulomb field

probe pulse velocity is matched to Coulomb field velocity

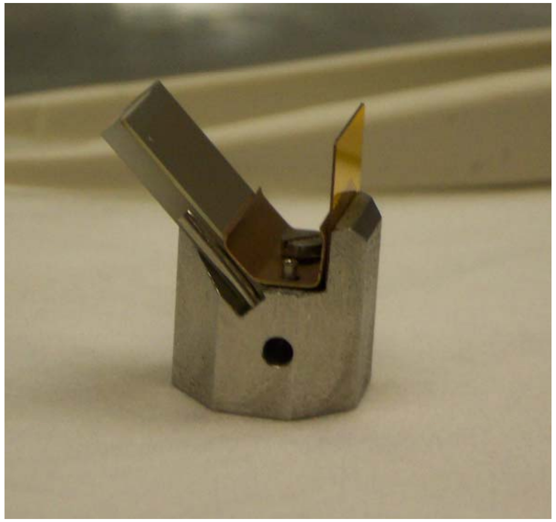




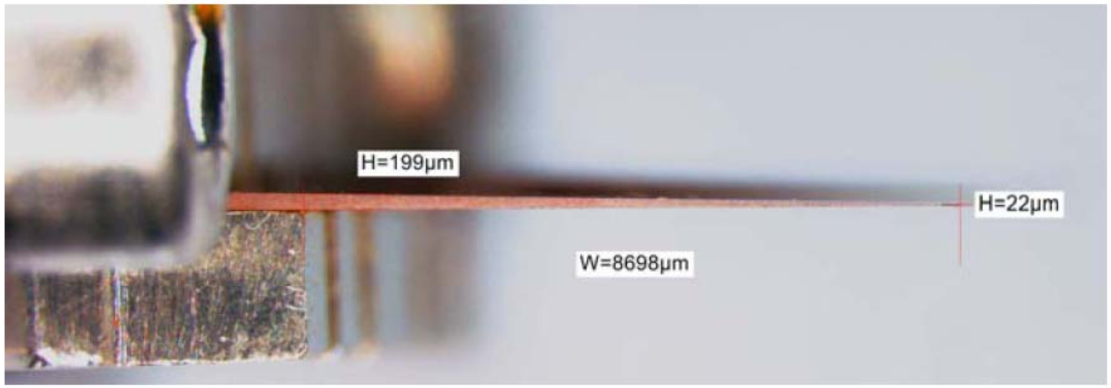
EO crystals...



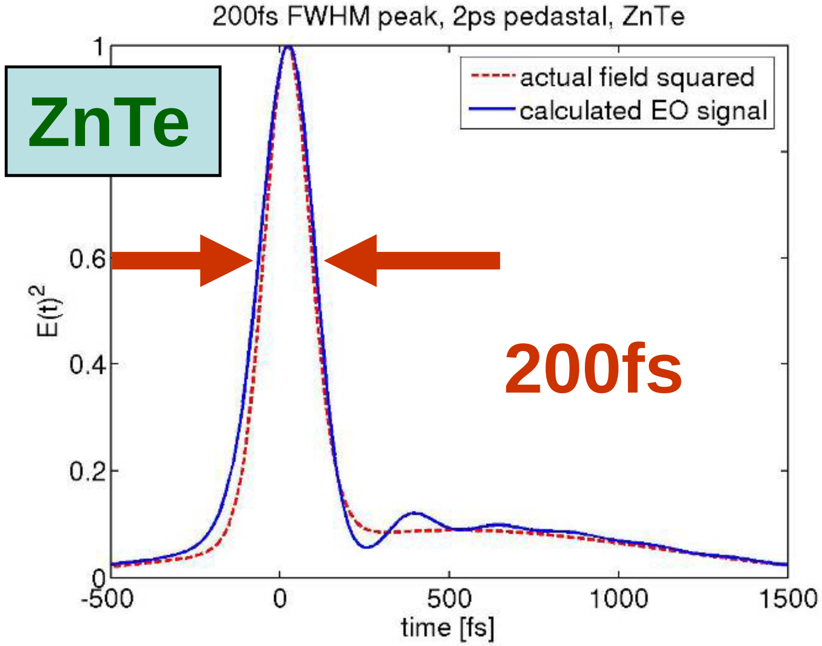
Crystal & mirror in ALICE expts

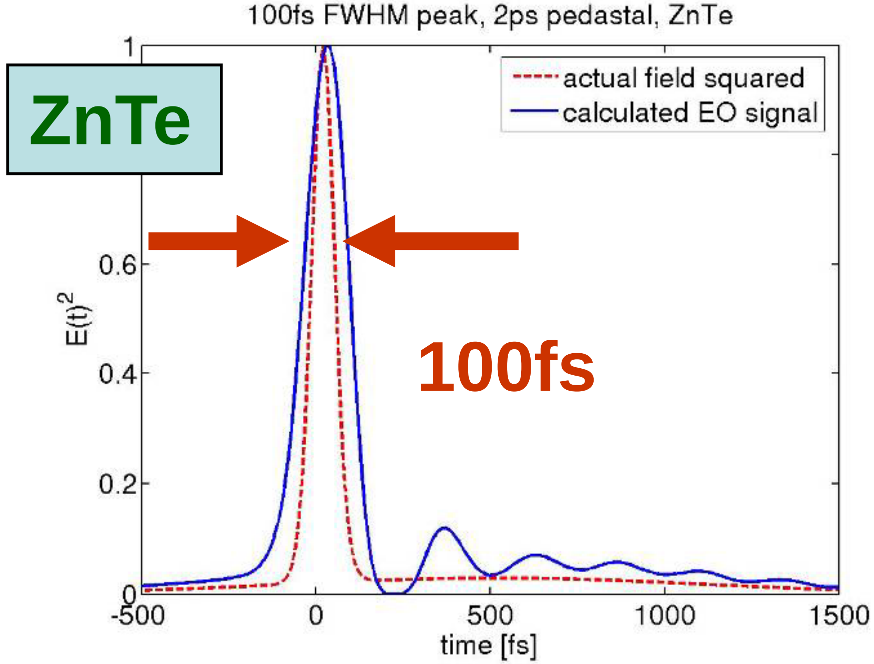


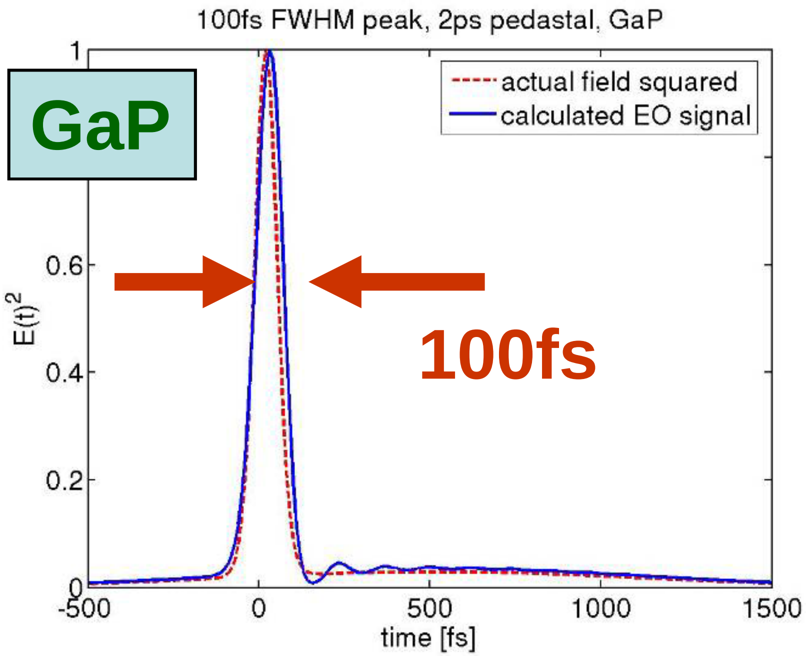
(one) crystal from FLASH expts

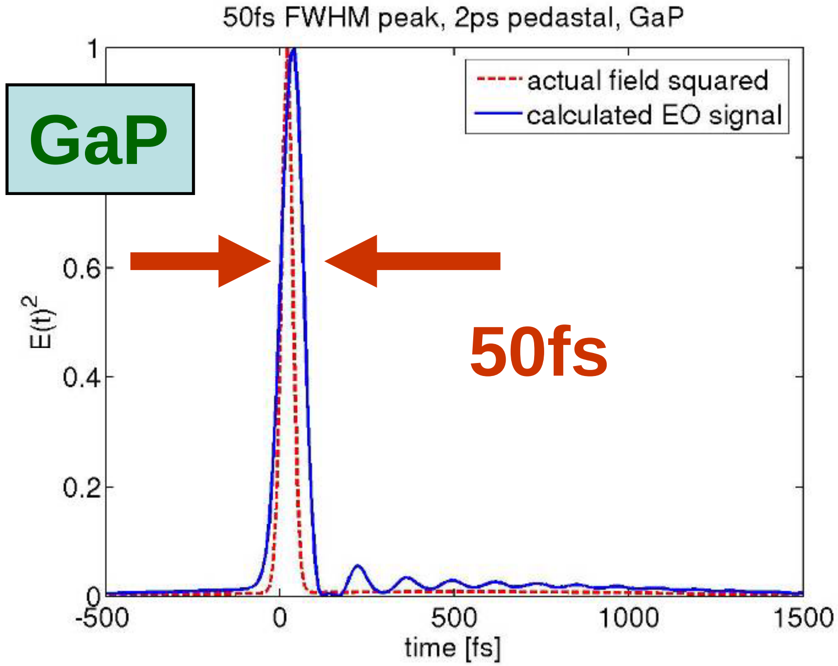


Effect of Material response...

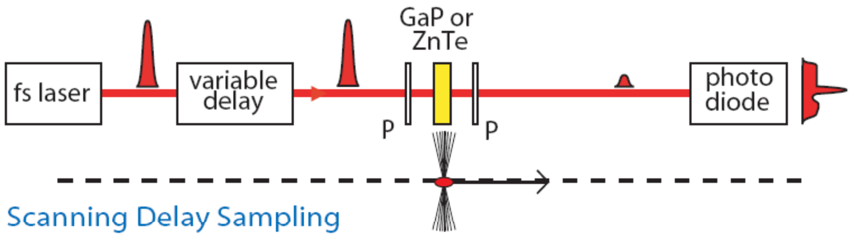




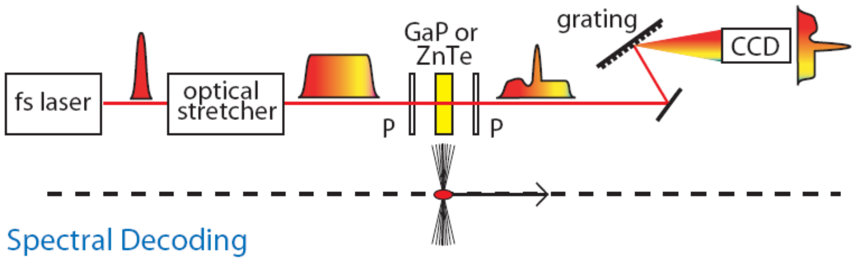




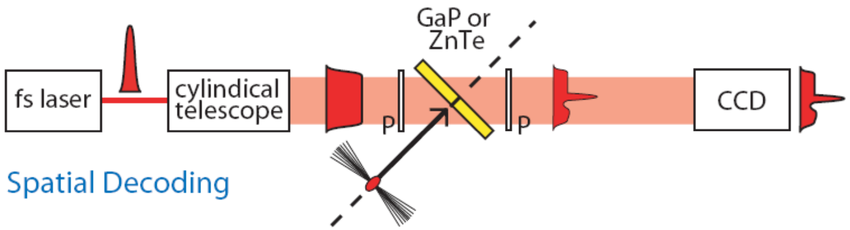
Decoding methods...



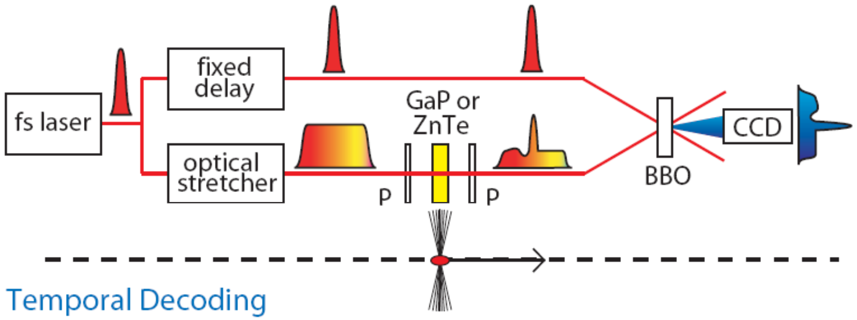
Scanning Delay Sampling



Spectral Decoding



Spatial Decoding



Temporal Decoding

increasing complexity

demonstrated time resolution

FELIX,
DESY
SLS
BNL
...

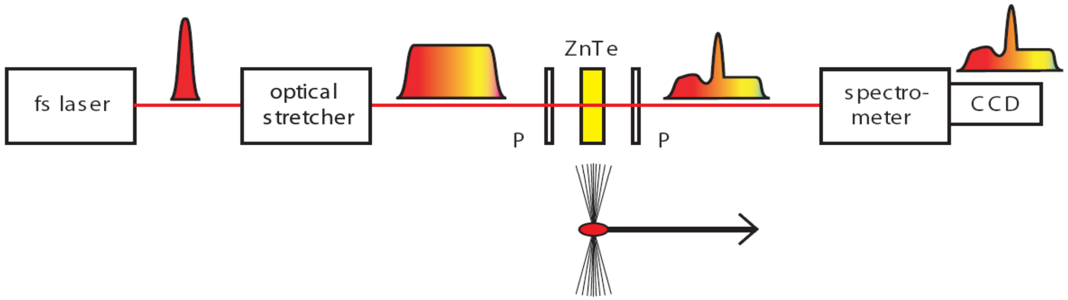
FELIX
DESY
BNL
ALICE
...

SLAC
DESY
SPARC / FERMI

FELIX
DESY
RAL/CLF
(laser wakefield)
ALICE

Spectral decoding

Simplest of single shot techniques



- Impose time-wavelength correlation on probe pulse
- Interact probe with THz (Coulomb, CSR etc...) pulse
- convert EO effect into Intensity variation
- Read out probe intensity spectrum

Limitations on measurement of ultrafast signals can be derived from frequency mixing description....

Spectral decoding...

EO interaction....

$$\tilde{E}^{probe}_{out}(\omega) \sim \tilde{E}^{probe}_{in}(\omega) + i\chi^{(2)} \int_{-\infty}^{\infty} \tilde{E}^{THz}_{eff}(\Omega)\tilde{E}^{probe}_{in}(\omega - \Omega)\mathrm{d}\Omega$$

assume a linear chirped probe pulse...

$$\tilde{E}^{probe}_{in}(\omega) = \tilde{E}^{probe}_{0} \exp(i\beta(\omega - \omega_0)^2)$$

notational definition... $\tau \equiv 2\beta(\omega - \omega 0)$

$$\int_{-\infty}^{\infty} \tilde{E}^{THz}(\Omega)\tilde{E}^{probe}_{in}(\omega - \Omega)\mathrm{d}\Omega \longrightarrow \tilde{E}^{probe}_{in}(\omega)\int_{-\infty}^{\infty} \mathrm{d}\Omega \mathrm{e}^{i\Omega\tau}\mathrm{e}^{-i\beta\Omega^2}[\tilde{E}^{THz}(\Omega)]$$

functionally same as Fourier transform..

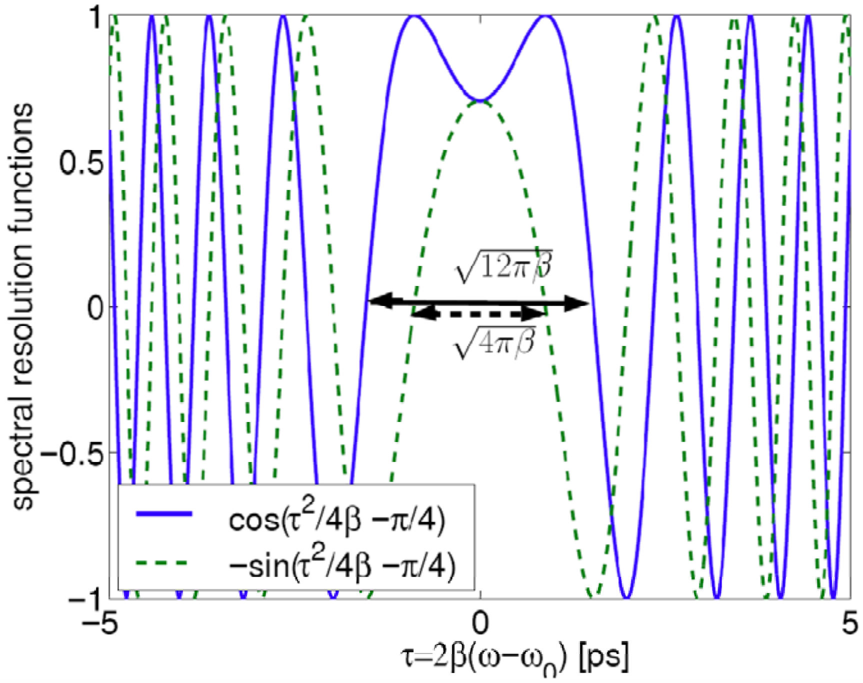
$$\longrightarrow \tilde{E}^{probe}_{in}(\omega)\left[\exp\left(i\frac{\tau^2}{4\beta} - i\frac{\pi}{4}\right) * E^{THz}(\tau)\right]$$

limiting convolution

wanted quantity

Spectral decoding...

Polarisation configuration determines final form of this convolution



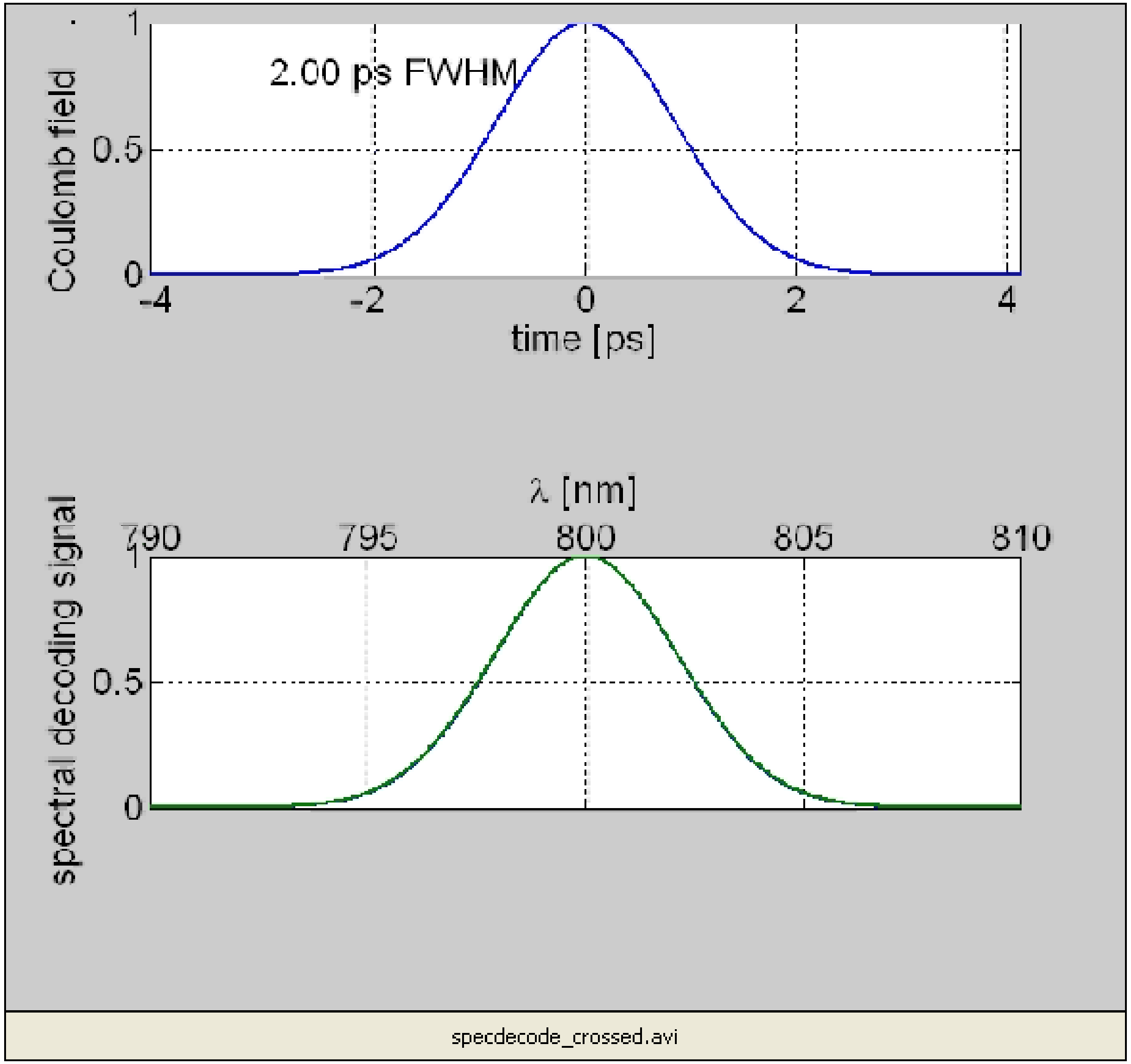
"Balanced detection"

$$S^{BD}(\omega) = \sqrt{\frac{2\pi}{\beta}} |\tilde{E}^x_{\rm opt}(\omega)|^2 A_2 \omega \left\{ E_{THz}(\tau + t_0) * \cos(\frac{\tau^2}{4\beta} - \frac{\pi}{4}) \right\}$$

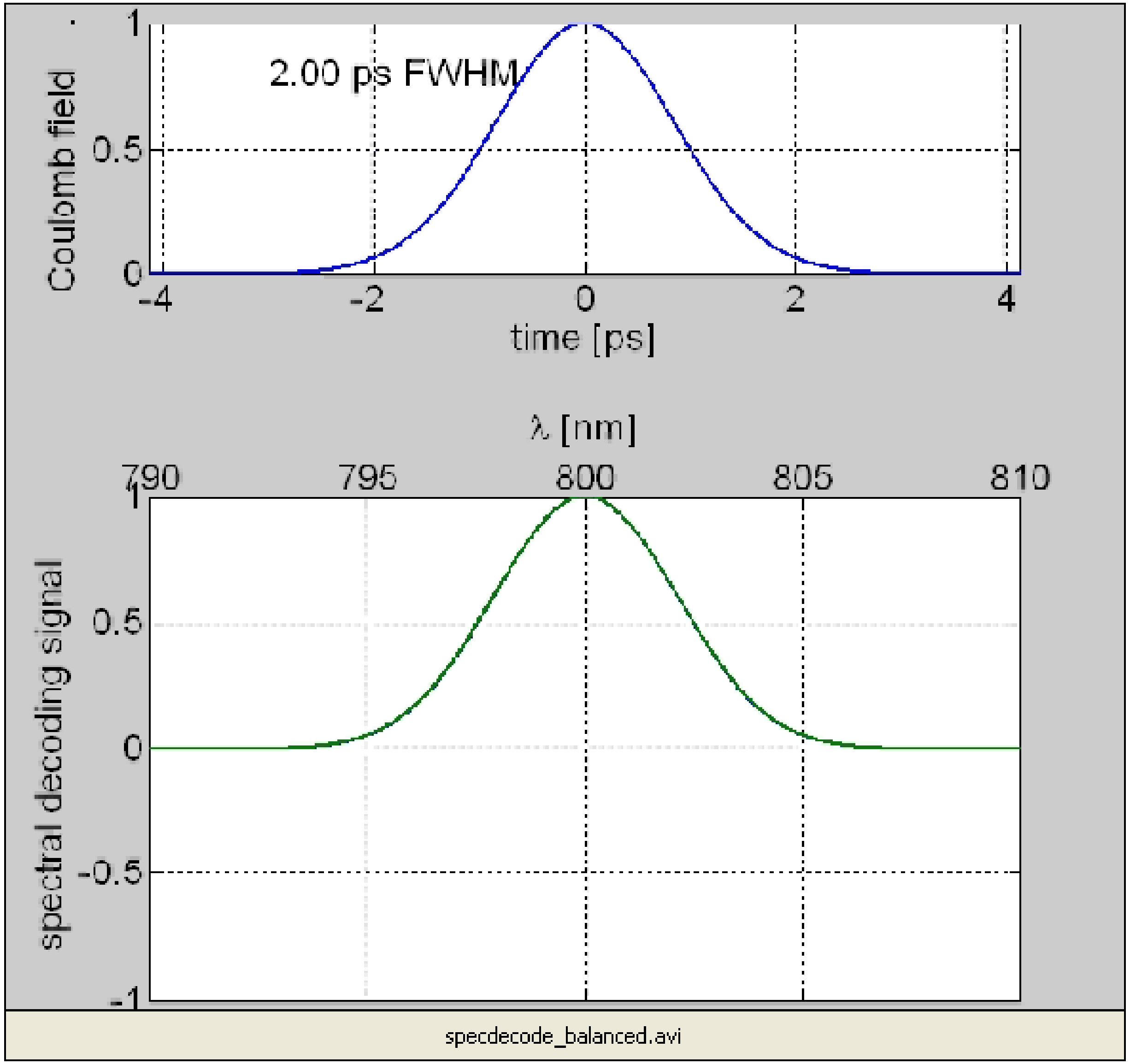
Crossed polarisers

$$S(\omega)^{CP} = A_2^2 \omega^2 \frac{\pi}{2\beta} |\tilde{E}^x_{\rm opt}(\omega)|^2 \left\{ \left[E_{THz}(\tau + t_0) * \cos\left(\frac{\tau^2}{4\beta} - \frac{\pi}{4}\right)\right]^2 + \left[E_{THz}(\tau + t_0) * \sin\left(\frac{\tau^2}{4\beta} - \frac{\pi}{4}\right)\right]^2 \right\}$$

Spectral decoding – crossed polariser configuration



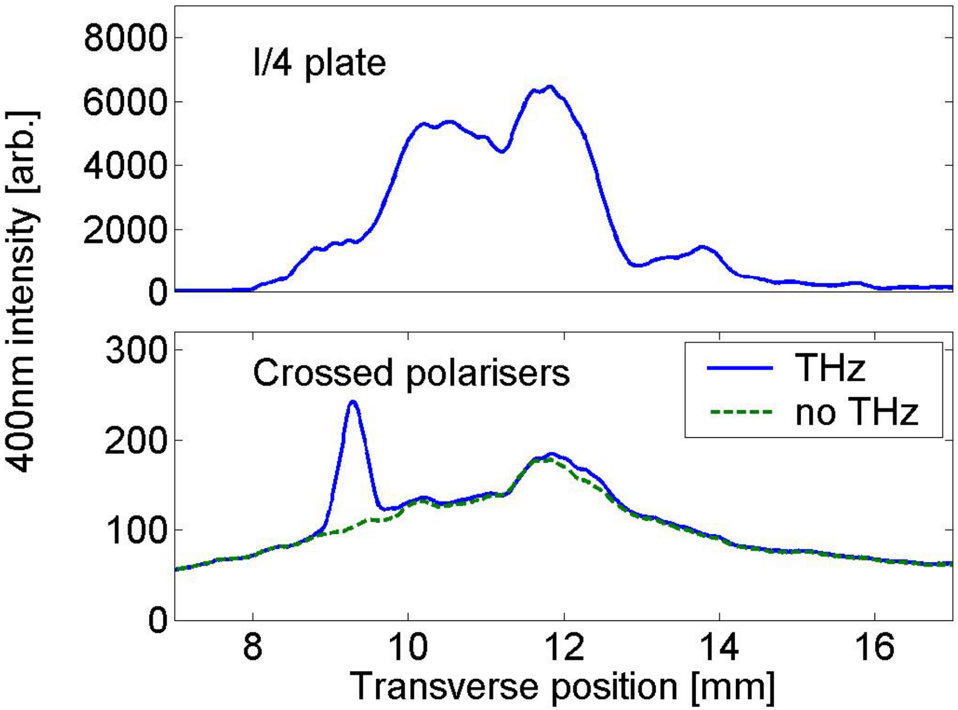
Spectral decoding – balanced detection configuration

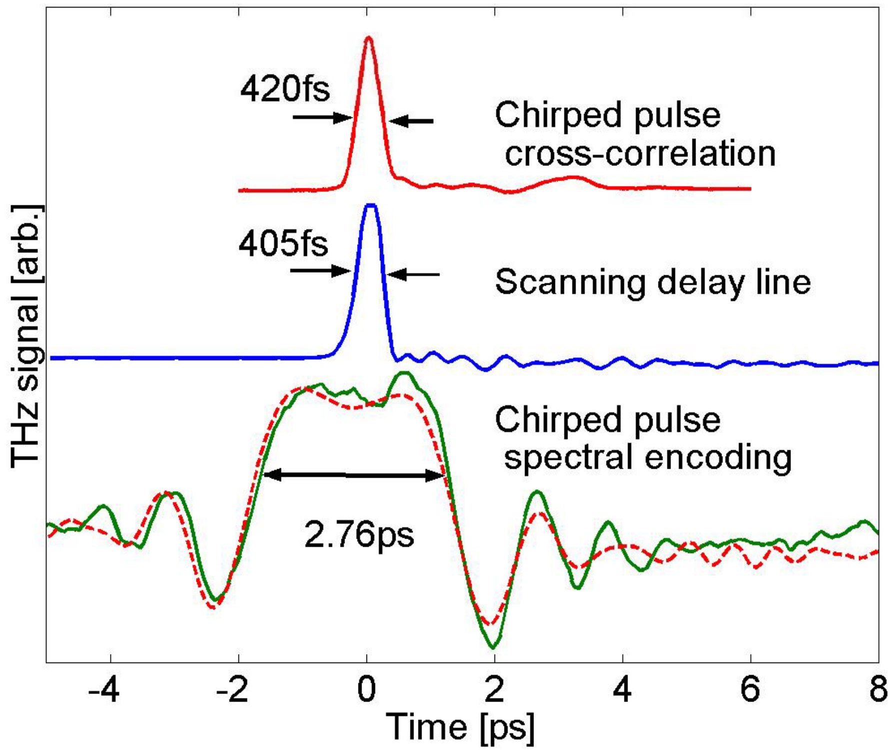


Comparison of Temporal & Spectral decoding

Laser lab tests...

Unipolar pulses generated by near–field photo-conductive antenna (mimic for electron bunch)

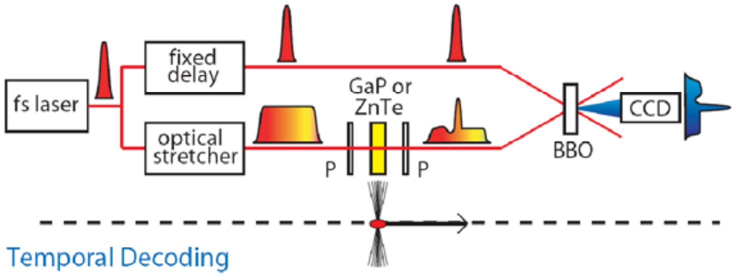




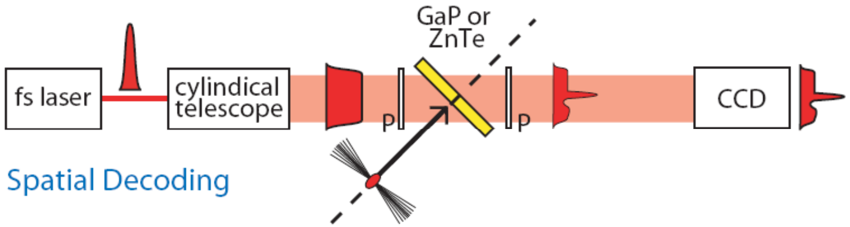
Jamison et al. Opt. Lett. **18** 1710 (2003)

Direct Temporal techniques...

Temporal decoding



Spatial encoding



- Encoding of signal exactly as before..
- measure temporal profile of probe pulse directly using spatial-temporal cross-correlation

$$E_{\mathrm{out}}^{\mathrm{opt}}(t) = E_{\mathrm{in}}^{\mathrm{opt}}(t) + a\left[\underbrace{E^{\mathrm{Coul}}(t) * R(t)}_{\text{envelope}}\right] \underbrace{\frac{\mathrm{d}}{\mathrm{d}t} E_{\mathrm{in}}^{\mathrm{opt}}(t)}_{\text{optical field}}$$

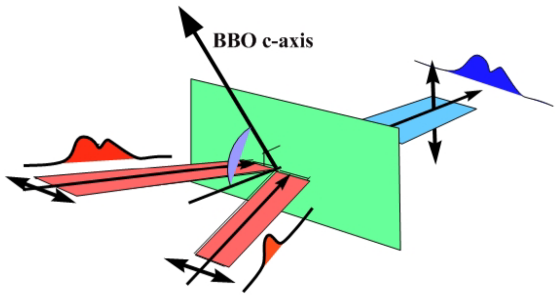
envelope **optical field**

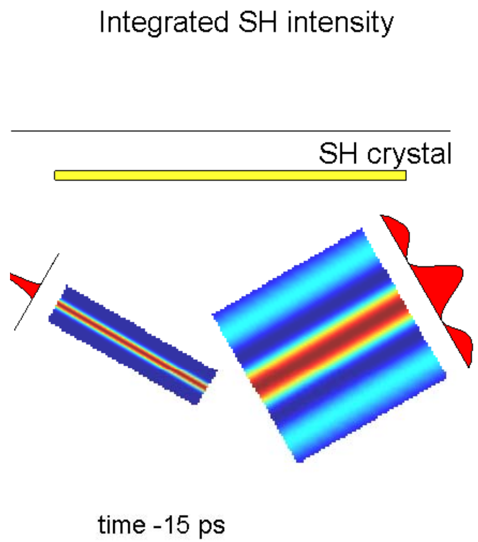
Cross-correlation – temporal decoding

Rely on EO crystal producing a optical temporal replica of Coulomb field

crossed polariser geometry

$$I_{out}^{probe}(t) \sim [E_{out}^{probe}(t)]^2 \sim [E_{eff}^{THz}(t)]^2 I_{in}^{probe}(t)$$





measure optical replica with *t-x* mapping in 2nd Harmonic Generation

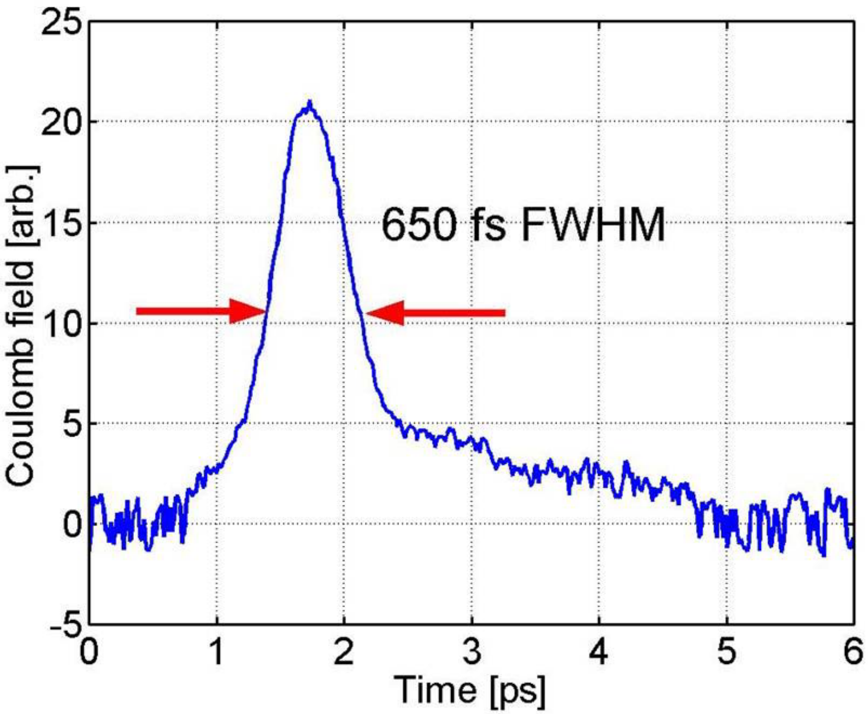
$$S^{CP}(t) \equiv \int I_y(\tau) I_{\rm gate}(t-\tau) {\rm d}\tau$$
$$= B_2^2 \left[(2\alpha t - \omega_0)^2 E_{\rm THz}^2(t) I_{\rm opt}(t)\right] * I_{\rm gate}(t)$$

limited by

- gate pulse duration (although FROG etc could improve)
- EO encoding efficiency, phase matching

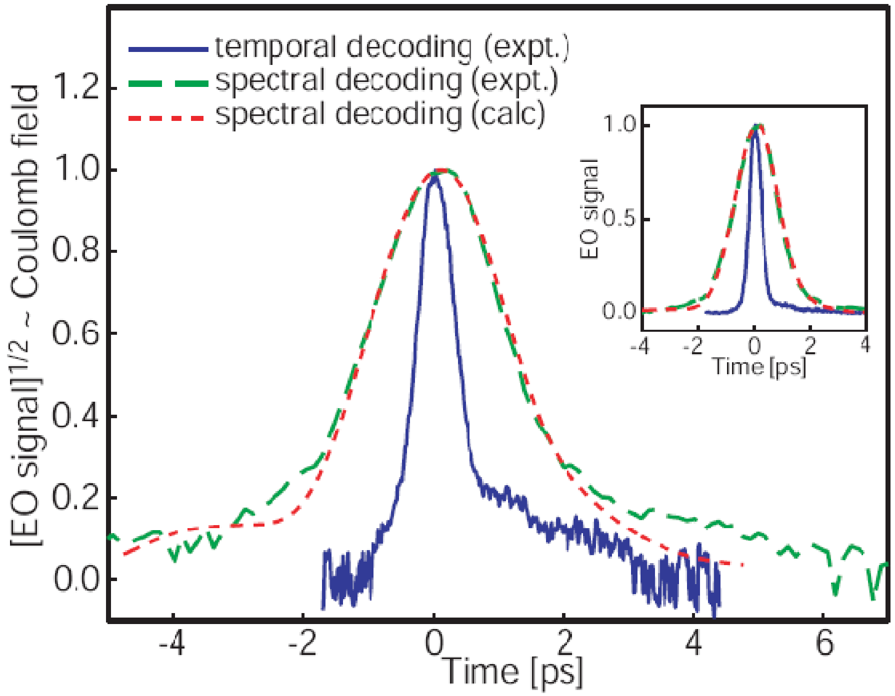
FELIX Electro-optic experiments

bunch profile from
Temporal Decoding



(at that time)

Comparison of Temporal &
Spectral decoding

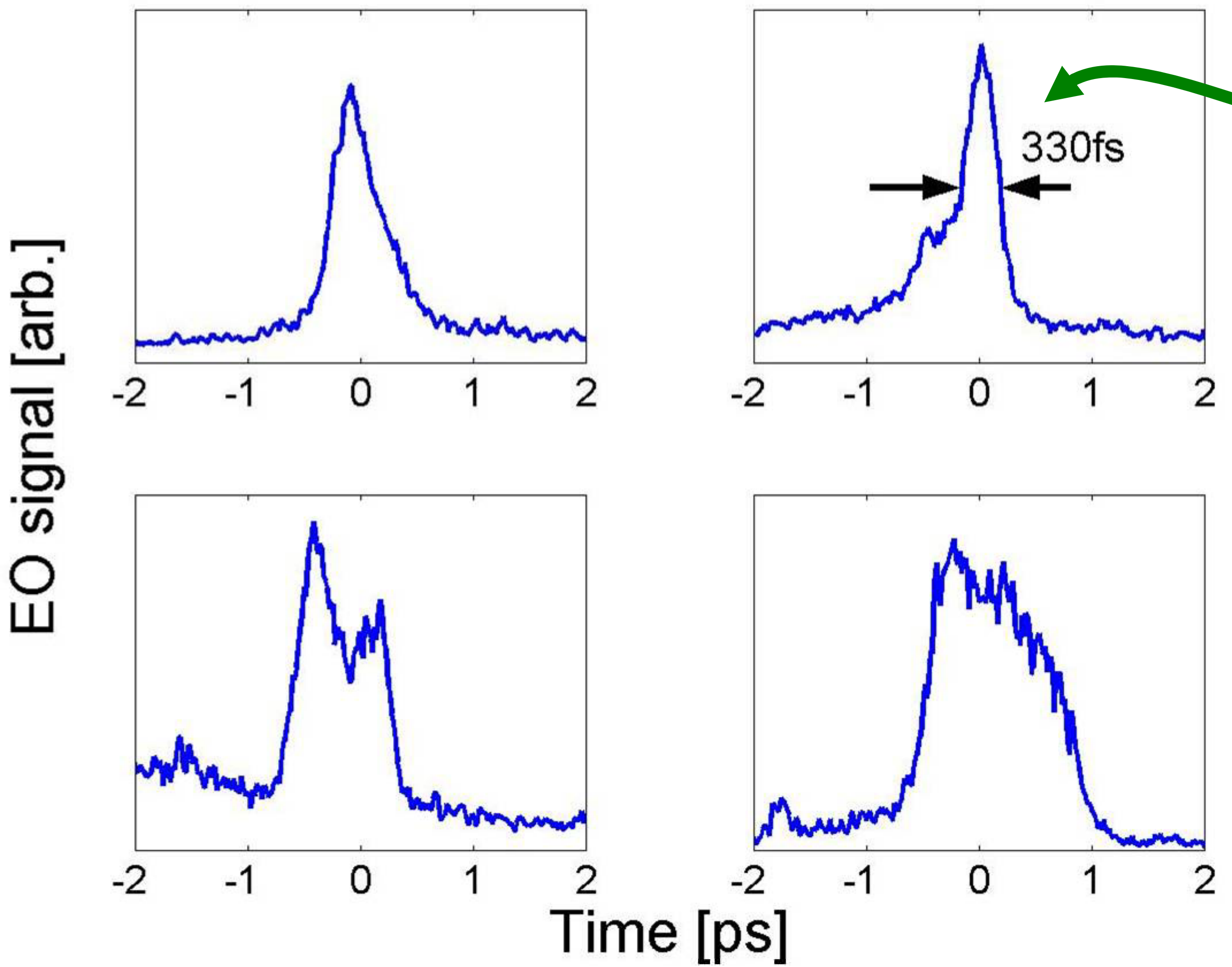


Berden, Jamison et al.
Phys. Rev. Lett. **93**, 114802 (2004)

Highest resolution bunch profile obtained by EO techniques

measurement showing actual bunch profile

Real time monitoring and bunch profile modification…



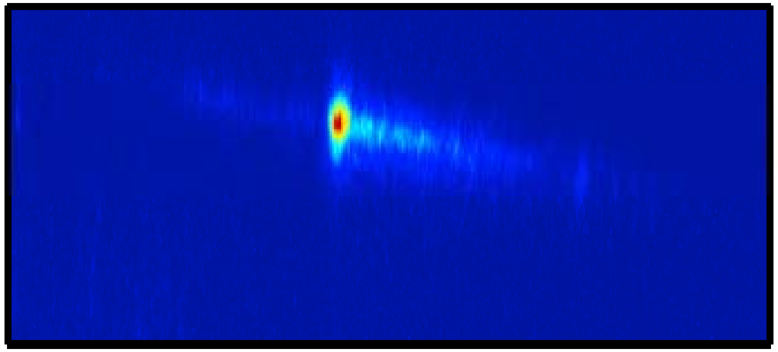
. ≅ 450 fs FWHM Coulomb field on sub peak

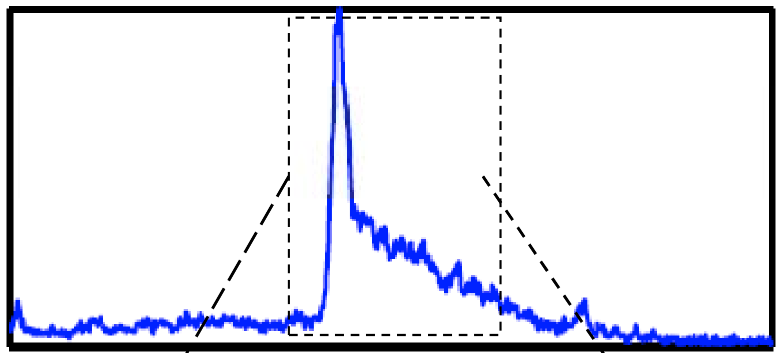
Bunch profile modified by changing the buncher and accelerator phase.

Berden, Jamison, et al Phys Rev Lett (2004)

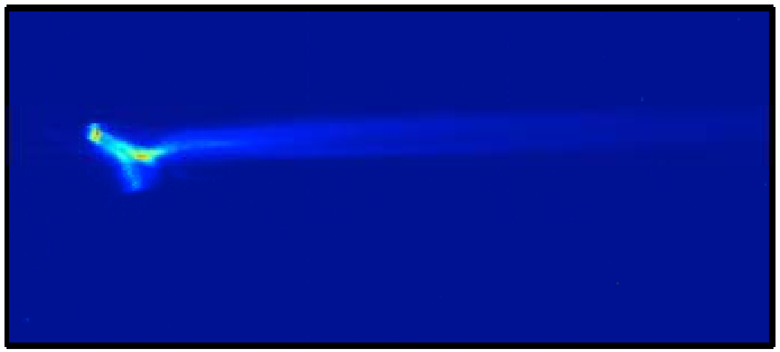
Measurements at FLASH...

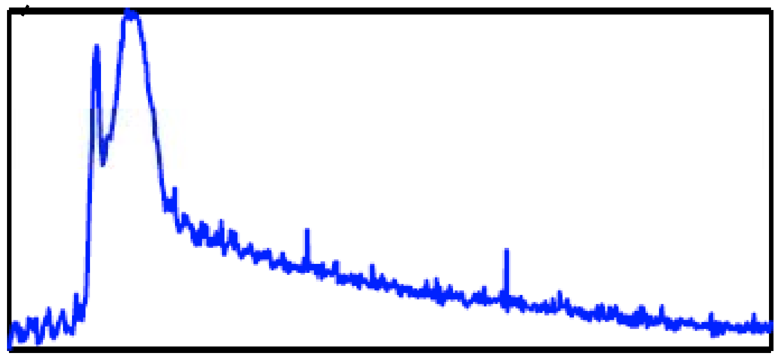
Electro-optic bunch profile





Transverse Deflecting Cavity bunch profile





Phys Rev Lett 2007
Phys Rev ST 2009

Can we achieve even better resolution ...?

Encoding

Detector Material:

- GaP
- Move to new material? (phase matching, $\chi^{(2)}$ considerations)
- Could use GaSe, DAST, MBANP ..... or poled organic polymers?
- use multiple crystals, **and reconstruction process**

Decoding

Gate pulse width ~ 50 fs

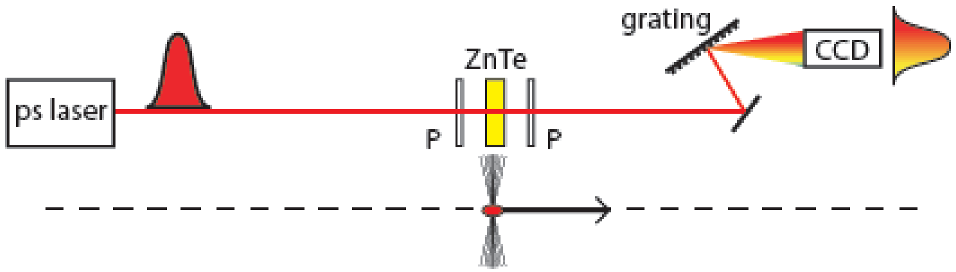
- Introduce shorter pulse
- Use (linear) spectral interferometry
- Use FROG Measurement (initially attempted at FELIX, 2004)

or Alternative techniques: spectral upconversion

If drop requirement for explicit time information at high frequencies, other options also become available

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

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

same physics
as "standard" EO

→ δ-function

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

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

different observational
outcome

- ***laser complexity reduced, reliability increased***
- ***laser transport becomes trivial (fibre)***

NOTE: the long probe is still converted to optical replica

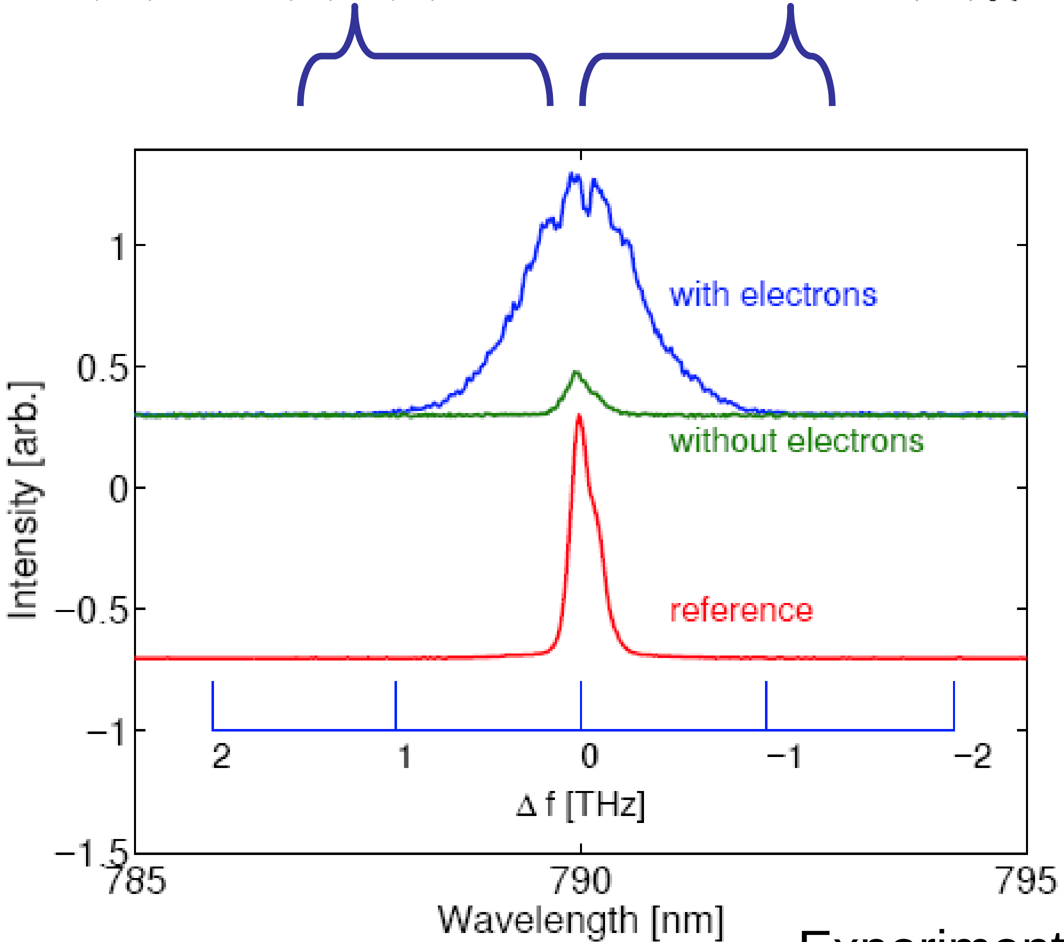
Spectral upconversion diagnostic

sum
frequency mixing

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

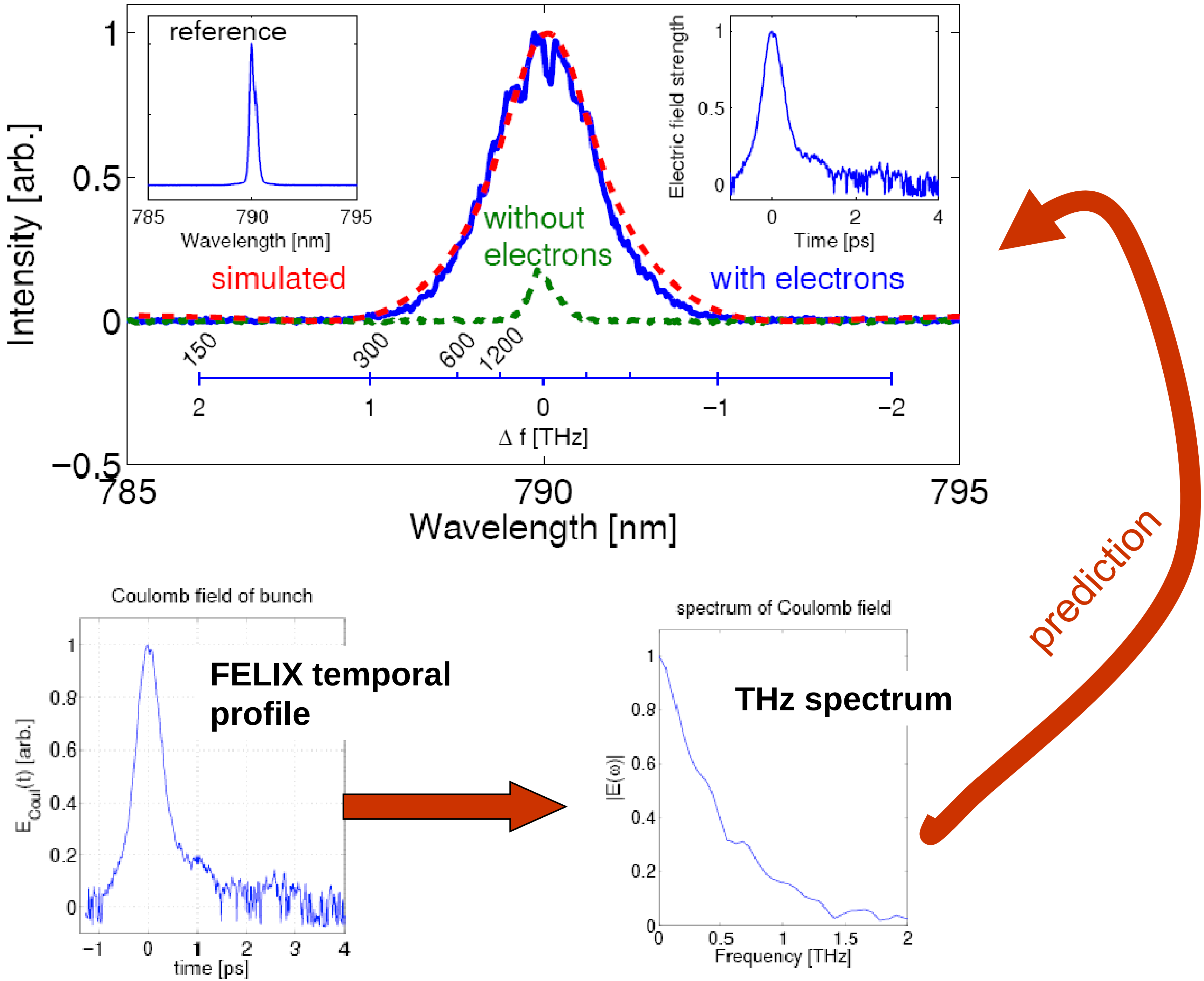
difference
frequency mixing

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



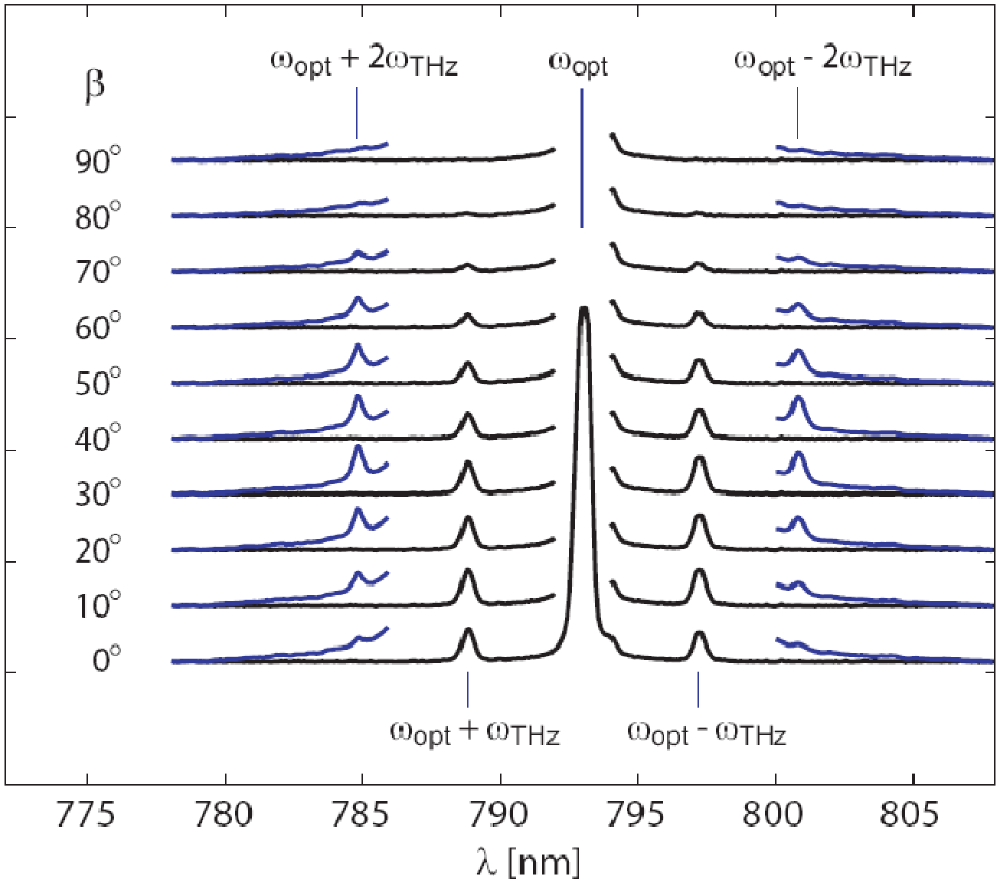
Experiments at FELIX

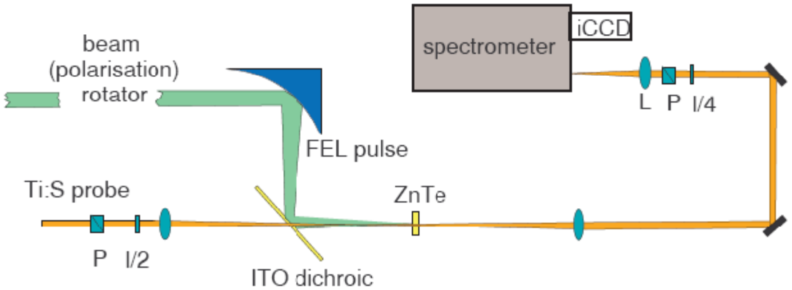
Appl. Phys. Lett. **96** 231114 (2010)



reference
Wavelength [nm]
Electric field strength
Time [ps]
Intensity [arb.]
simulated
without electrons
with electrons
Δ f [THz]
Wavelength [nm]
Coulomb field of bunch
FELIX temporal profile
time [ps]
spectrum of Coulomb field
THz spectrum
|E(ω)|
Frequency [THz]
prediction

Spectral upconversion diagnostic for FEL radiation...





optical side bands from λ=150μm FEL radiation

Summary

- Material effects (phonon resonances) significant issue at <100fs FWHM structure
- Spectral decoding good for >1ps pulse. Can have artifacts
- Temporal techniques reaching resolution limit from materials
- Spectral upconversion promising for higher time resolution & feedback applications