Single-shot electro-optic longitudinal profile of sub-ps bunches

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- Single-shot electro-optic detection of ultra-short bunches
    - spectral-decoding
    - temporal decoding

- FELIX electron bunch measurements

    real time bunch profile adjustment

    bunch timing jitter

    charge dependence

- Sub-100fs bunch diagnostic ?

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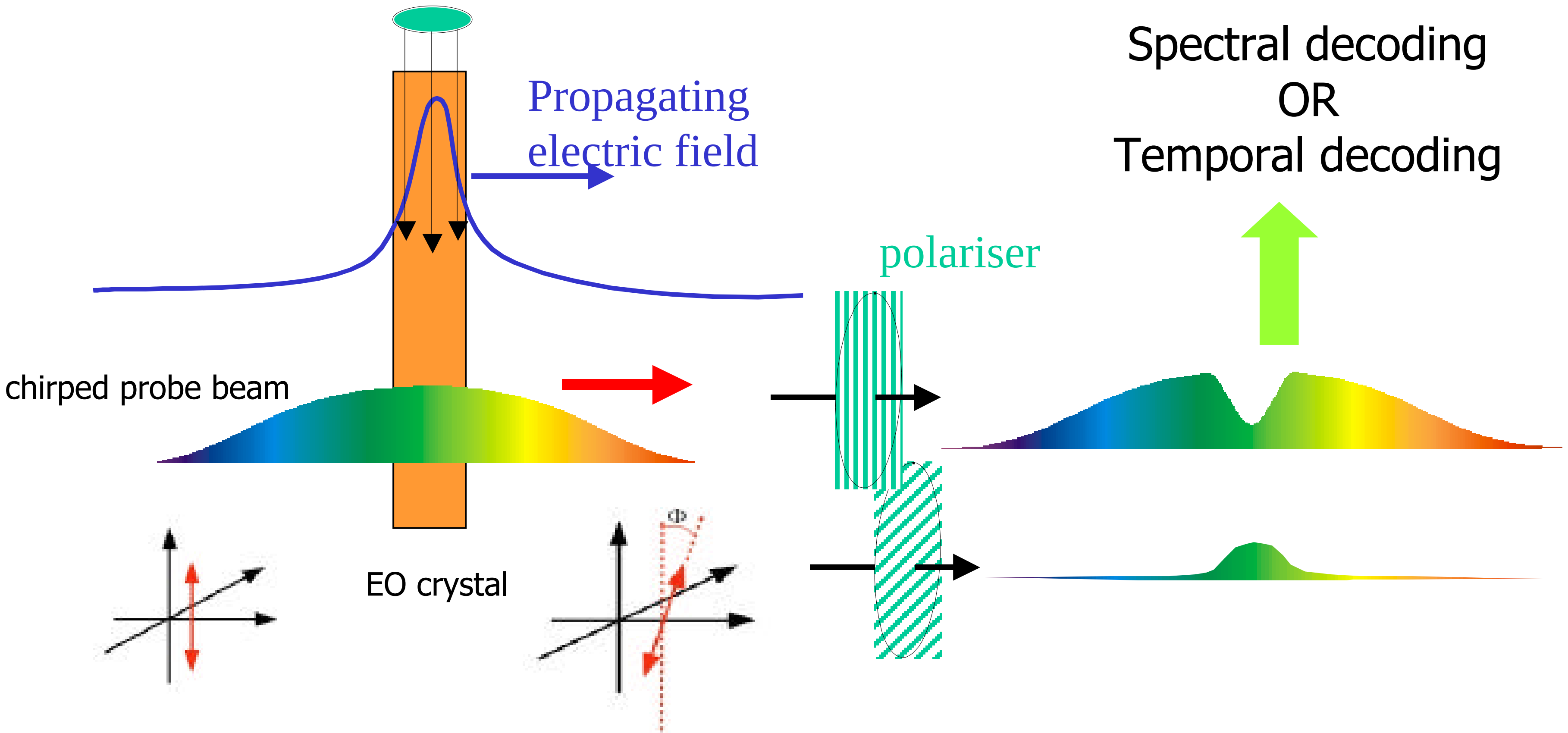
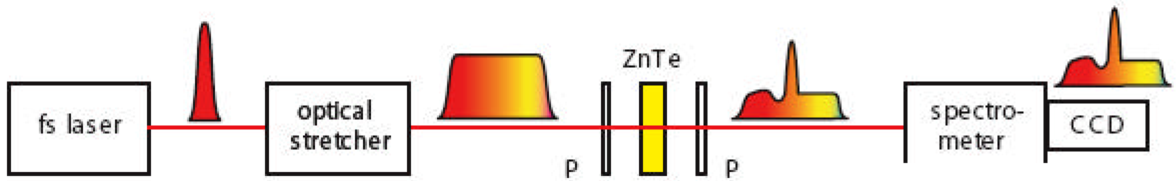
Single-shot EO measurement of Coulomb field

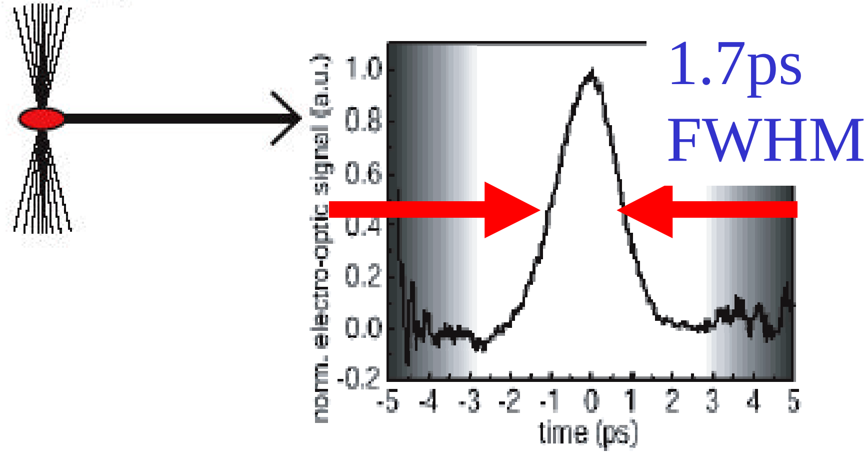


Effective polarisation rotation
proportional to coulomb field

Electro-optic detection of the Coulomb field: 'Spectrometer method'

(Spectral decoding)





- Measure probe intensity I(λ)
- known (initial) λ(t)
  infer I(t)

Not suitable for ultra short electron bunches
(i.e. bunches <500fs FWHM)

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

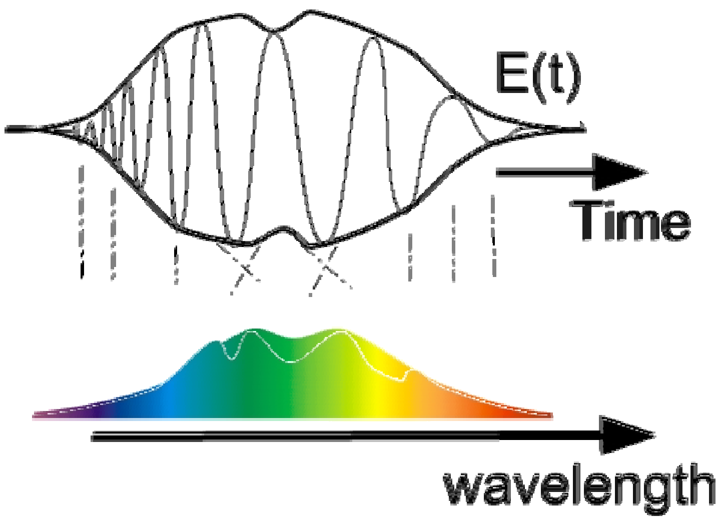
Time-resolution of spectral decoding.

Fourier transform

$E_{Opt}(t) \longrightarrow E_{Opt}(t)[1 + E_{Coul}(t)]$ Time domain

$\bar{E}_{Opt}(\omega) \longrightarrow \bar{E}_{Opt}(\omega) + \bar{E}_{Opt}(\omega) \ \bar{E}_{Opt}(\omega)$ Frequency domain

Mixing of optical spectrum with neighbouring frequencies
optical spectral modulation unreliable with resolution greater than modulation bandwidth



approximate temporal resolution based on bandwidth

$\Delta\tau > (t_o t_{chirped})^{1/2}$

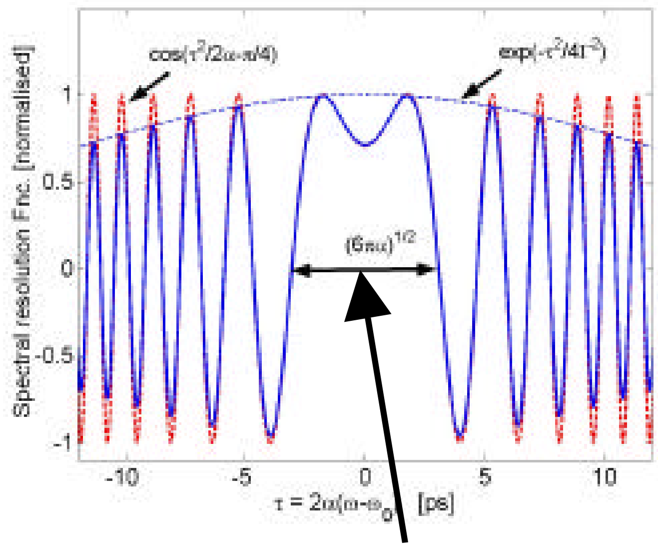
Time-resolution function NOT a smoothing function.
Can cause artifacts!!
CANNOT BE TREATED AS RMS TIME-RESOLUTION
Should be considered as temporal *limitation*

e.g balanced detection: measure change in probe spectrum…

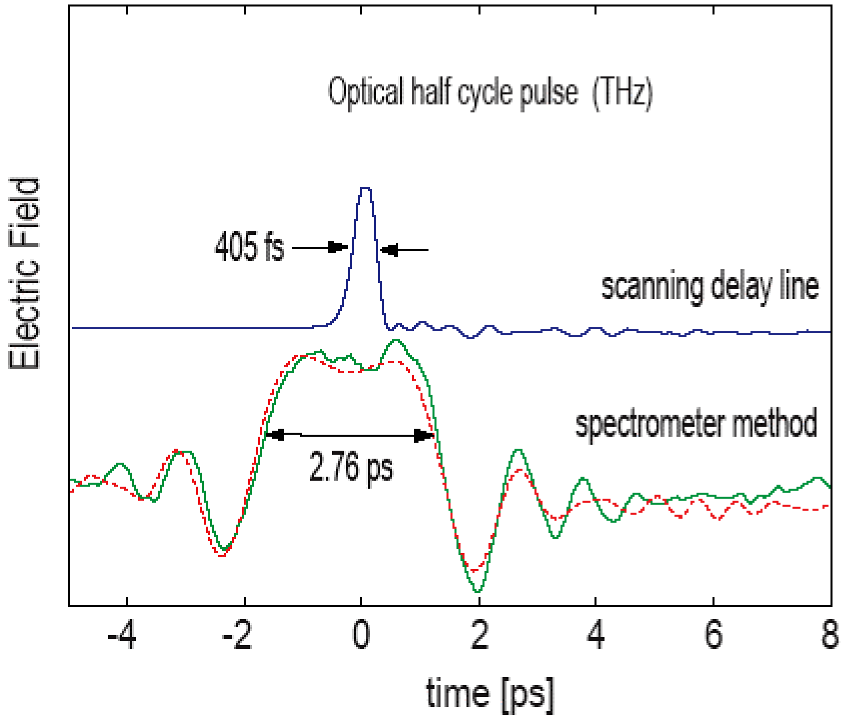
$$S(\omega) = \left|\bar{E}_{opt}(\omega)\right|^2 - \left|\bar{E}_{opt}(\omega)\ \bar{E}_{Coul}(\omega)\right|^2$$

$$\left|\bar{E}_{opt}(\omega)\right|^2 \left(E_{Coul}(\tau + t_0)\ \cos(\tau^2/\alpha - \pi/4)\right)$$

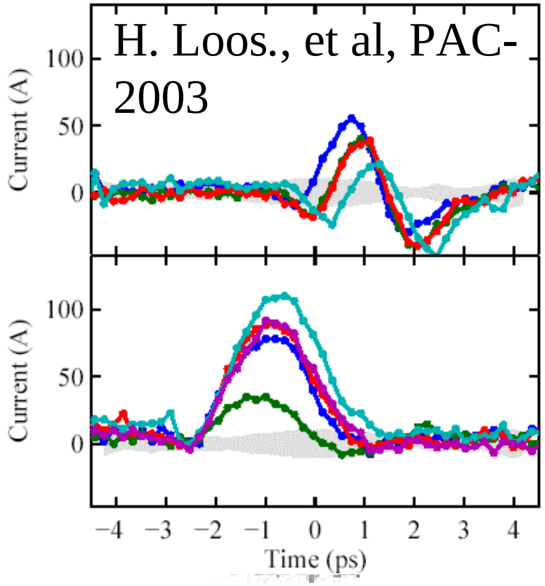
where $\tau = 2\alpha(\omega - \omega_0)$



$t_{res} \sim (t_0 t_{chirped})^{1/2}$



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

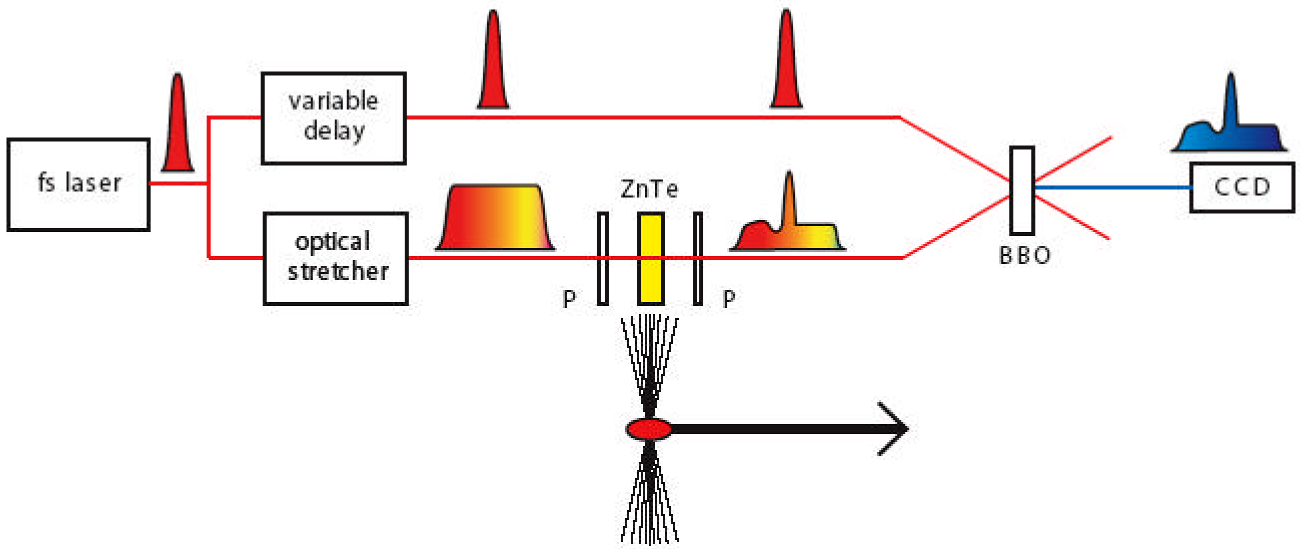


Oscillations due to spectral-encoding artifact?

Observe oscillating features on shorter time scale than usual "time resolution"

(Temporal decoding)

Electro-optic detection of Coulomb field: 'Cross correlation method'

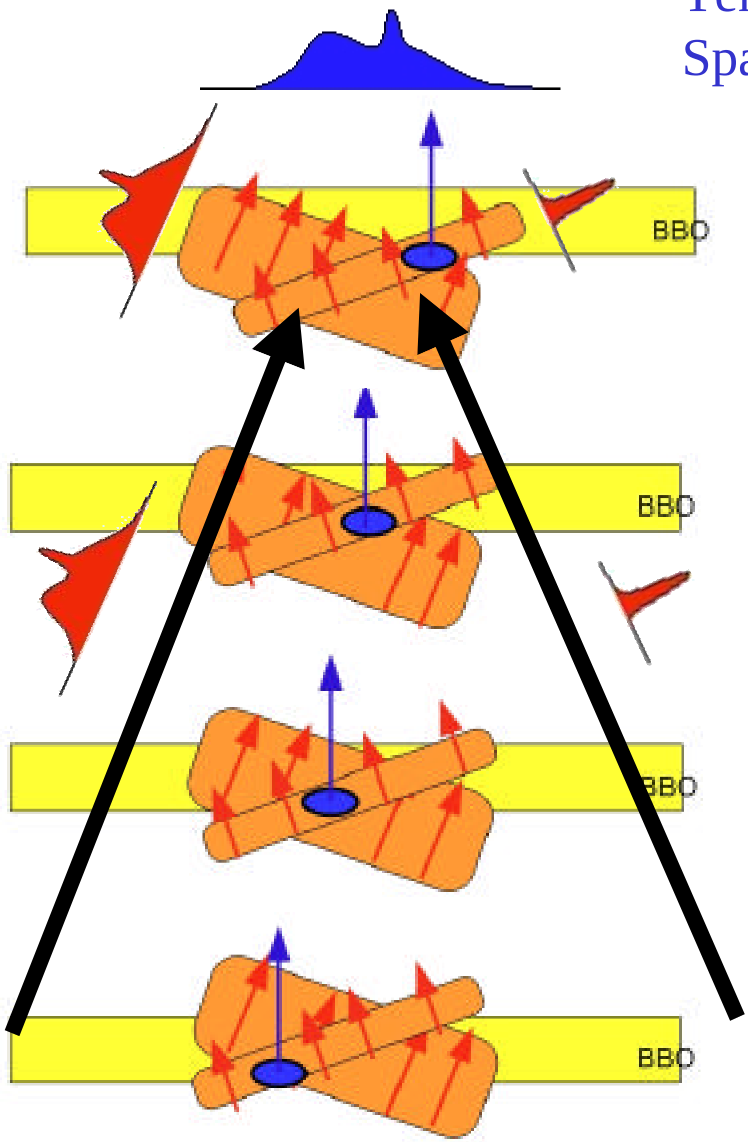


Temporal to spatial mapping of optical probe pulse

- Avoids problems of inseparability of frequency-time
- *Decoding* time-resolution ~ 30fs

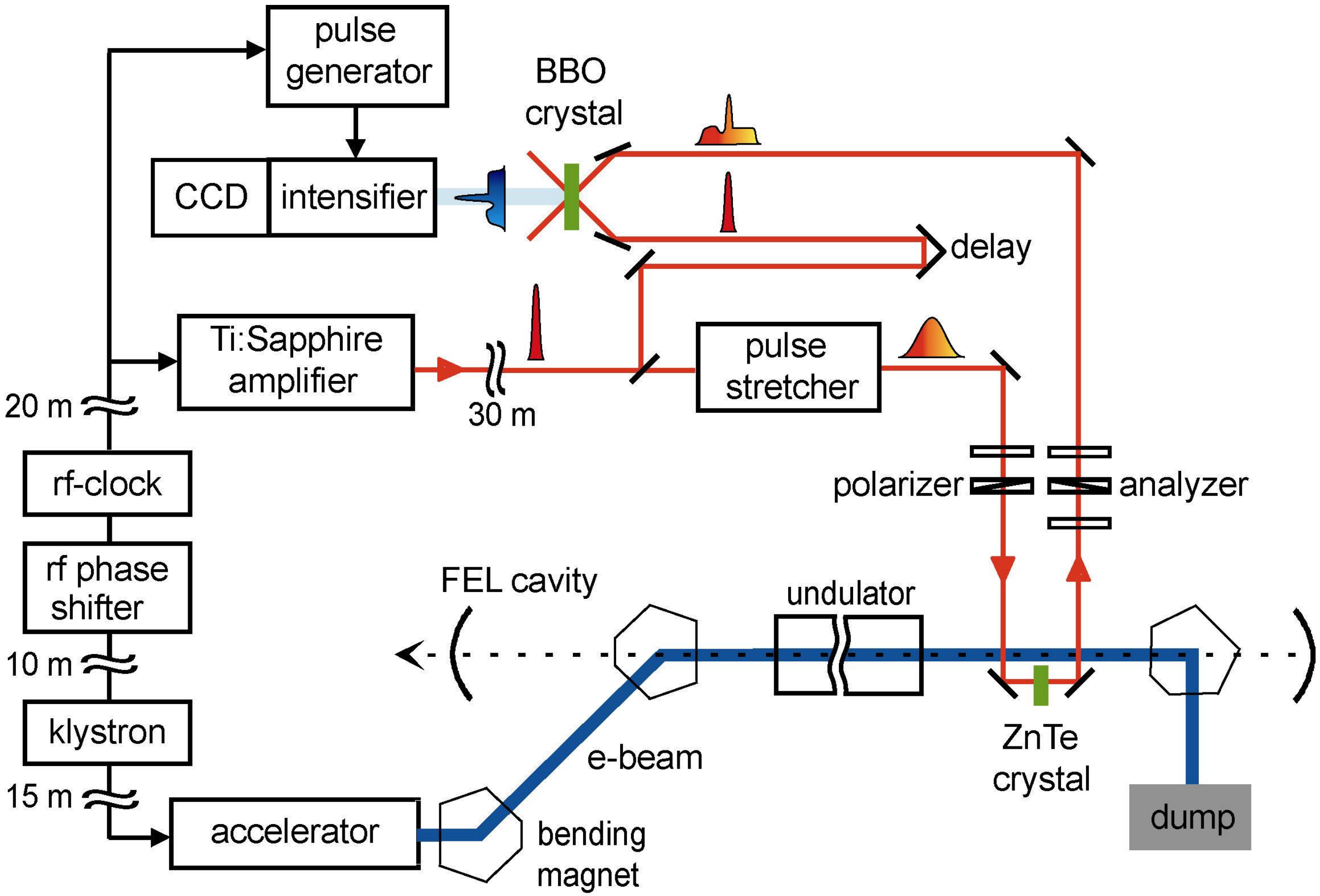
Single-shot “temporal decoding” of optical probe

Temporal profile of probe pulse _
Spatial image of SHG



30-50MeV electron beam measurements

FELIX FEL facility, Rijnhuizen, Netherlands



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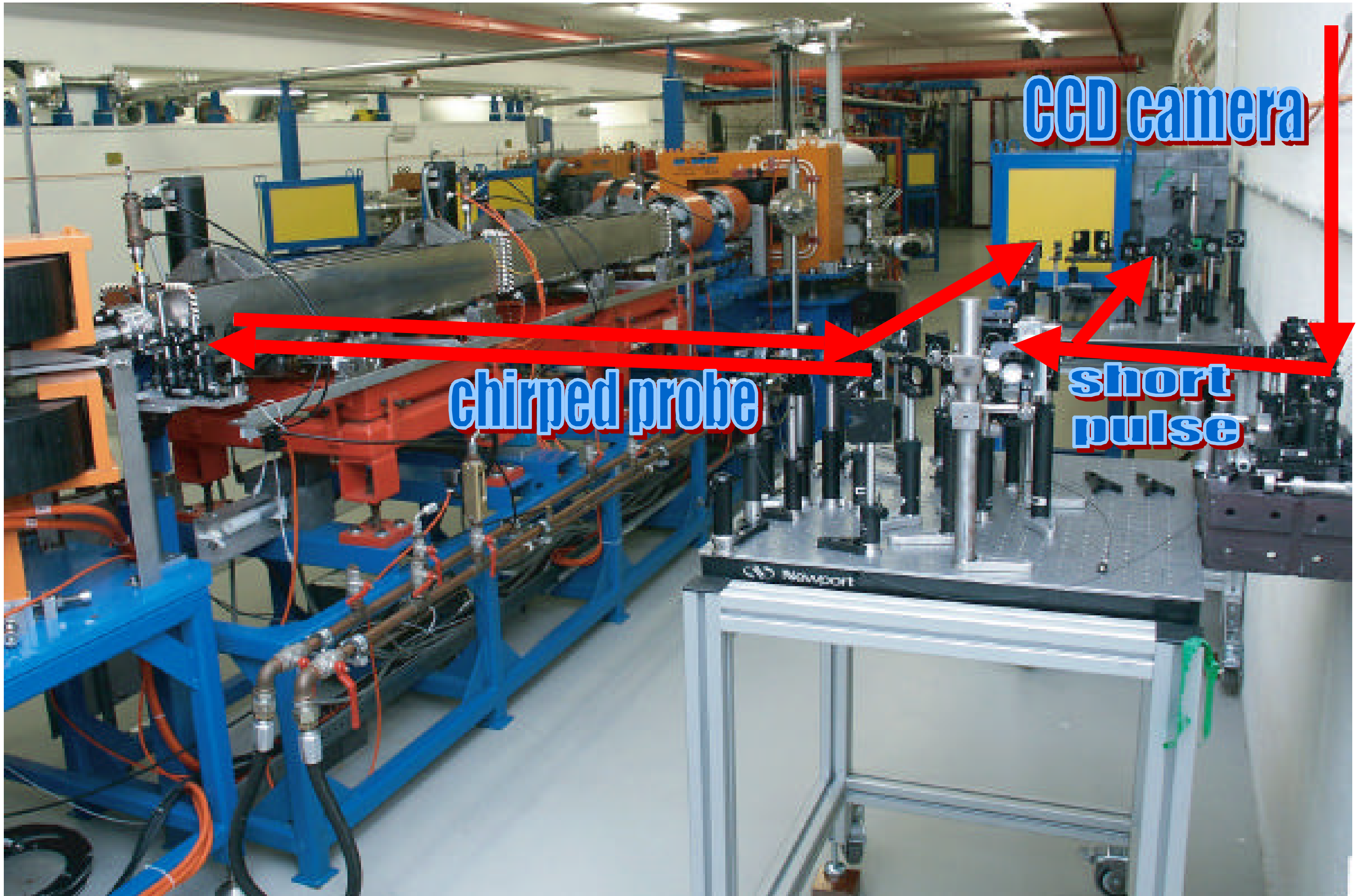
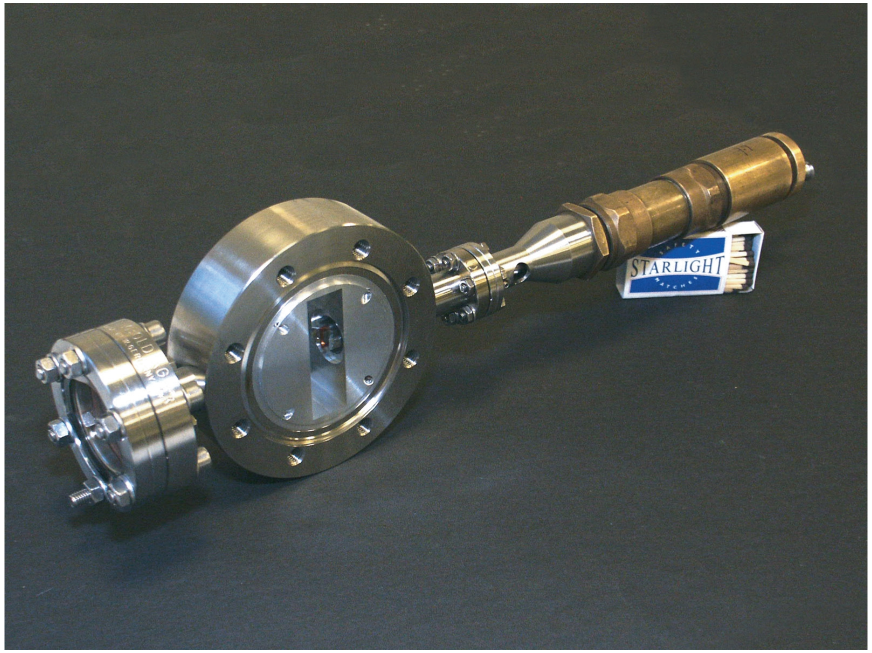
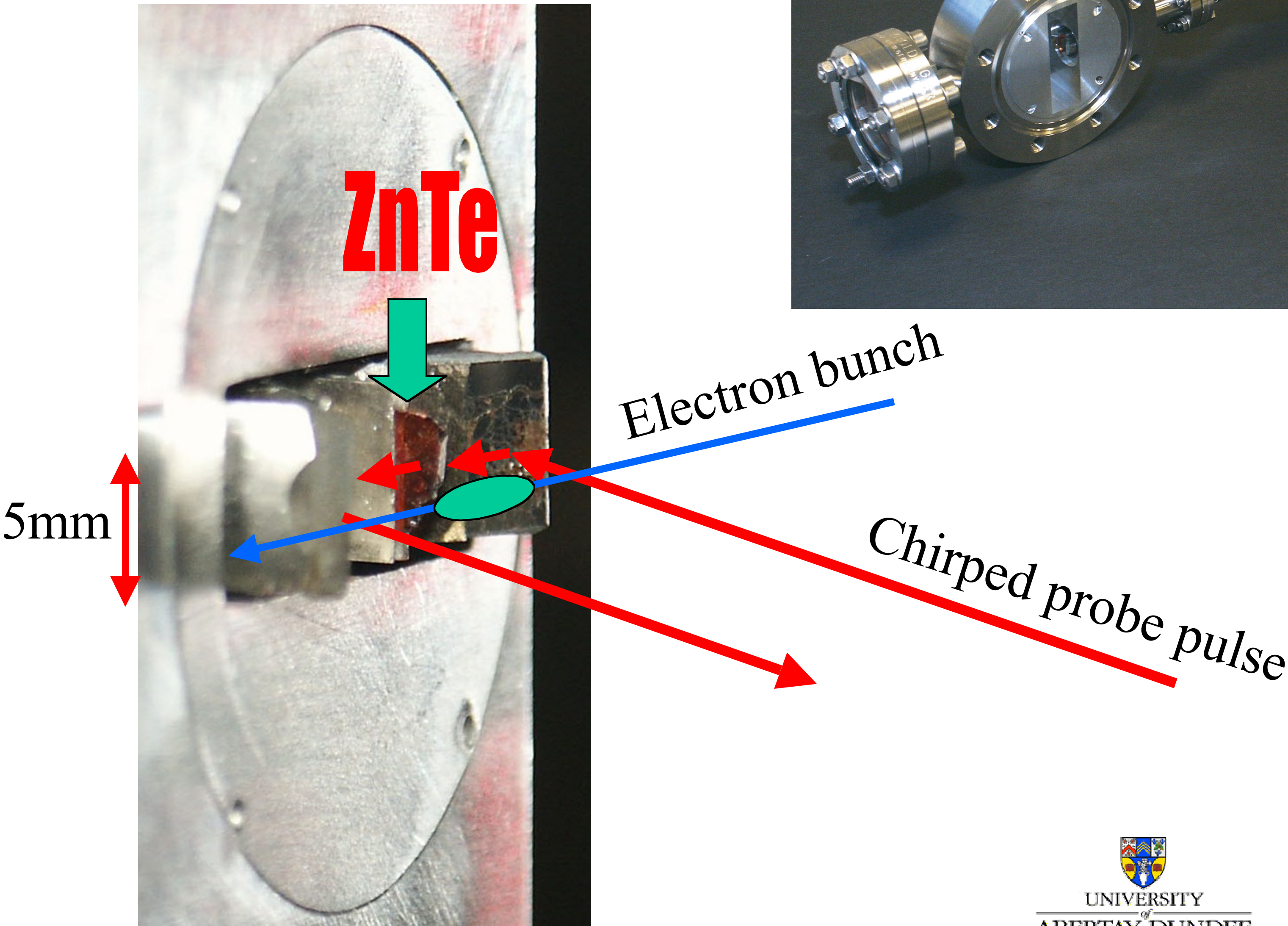
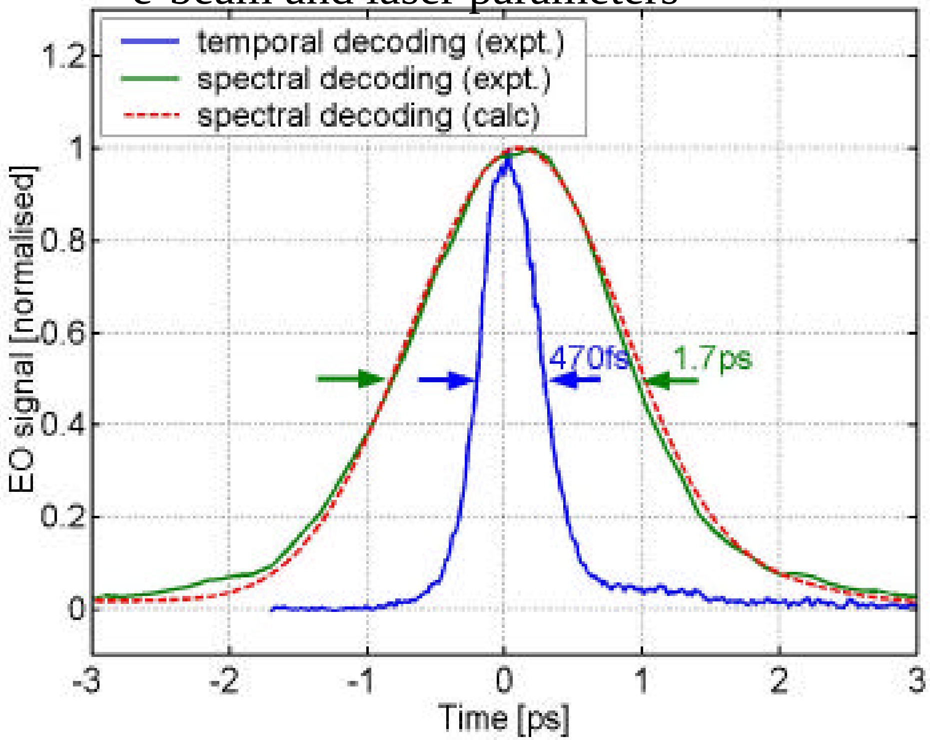





ZnTe
5mm
Electron bunch
Chirped probe pulse

Comparison of temporal and spectral decoding at FELIX

contemporaneous measurements with identical e-beam and laser parameters



(Data from December 2003)

Confirms time resolution improvements of TD technique

Degradation of SD signal in excellent agreement with calculation

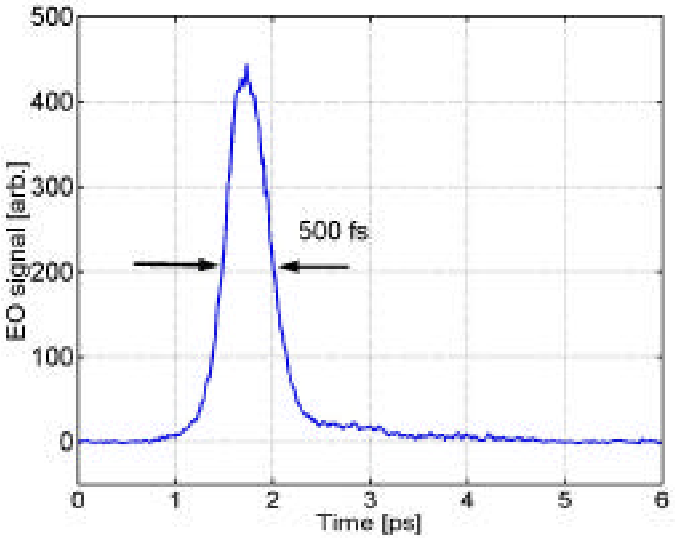
NO free parameters in SD calculation – based on bunch profile inferred from TD and measured laser parameters.

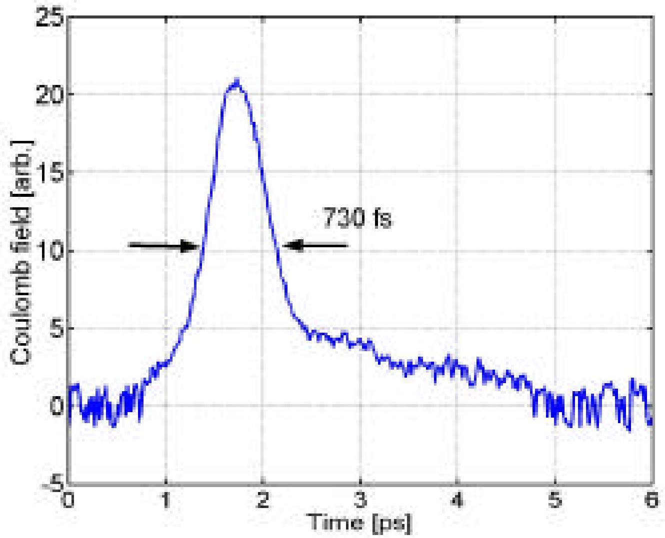
Determining Coulomb field from EO signal

Using "crossed-polariser" configuration

EO signal α [Coulomb Field]^2

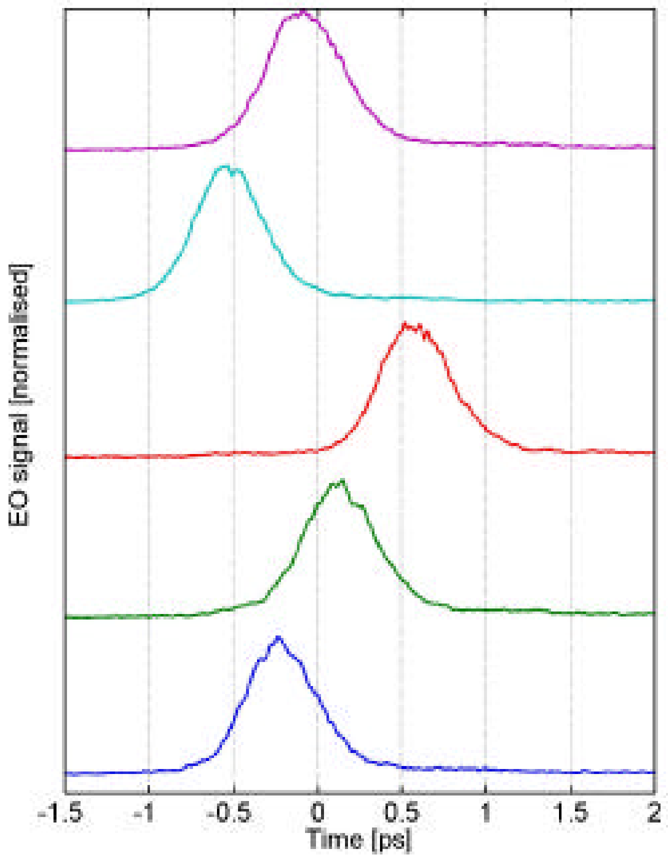
$E_{coulomb}$ = [EO signal]$^{1/2}$

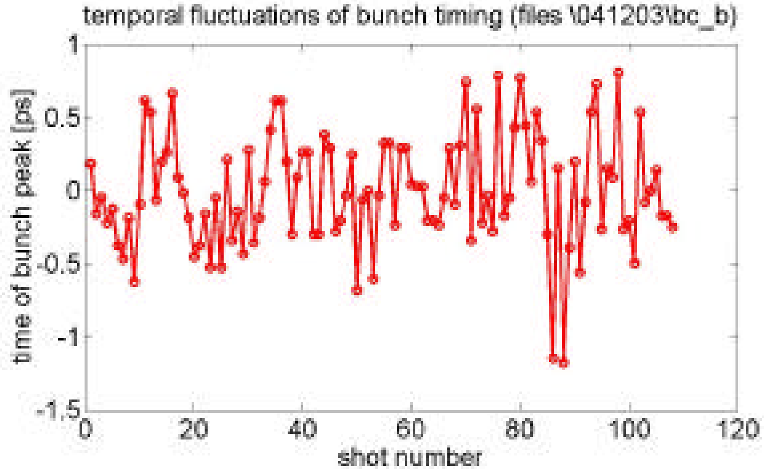


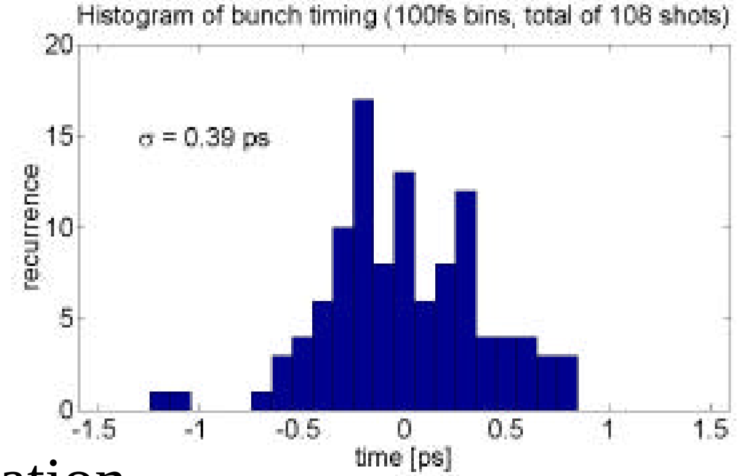


Quadratic dependence of EO signal on field confirmed by varying bunch charge (EO signal α Q^2)

EO measurement of bunch timing jitter
(FELIX, December 2003)



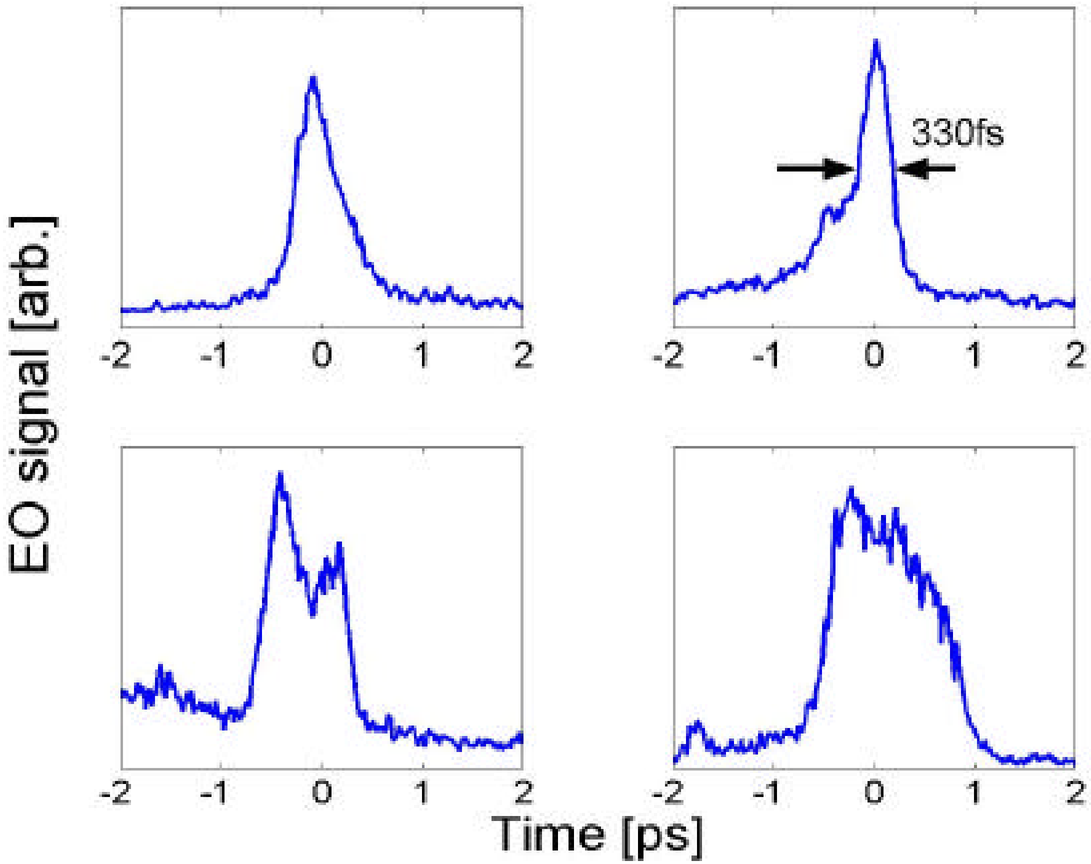




Bunch timing jitter ~ bunch duration

Real time monitoring and bunch profile modification…

(FELIX, December 2003)



Bunch profile modified by changing the buncher and accelerator phase.

Need even better time-resolution….
(measuring sub-200fs bunches) .

Optical spectrum-envelope interdependence
>300fs bunch duration limitation
Solved by envelope-cross-correlation
~30-50fs possible (?)

EO phase matching
>200fs limitation for undistorted measurement
Rigorous retrieval of true field possible

EO crystal absorption
Alternative EO materials. (GaP, GaSe, DAST…)
Approximate interpolation…
~30fs possible (?)

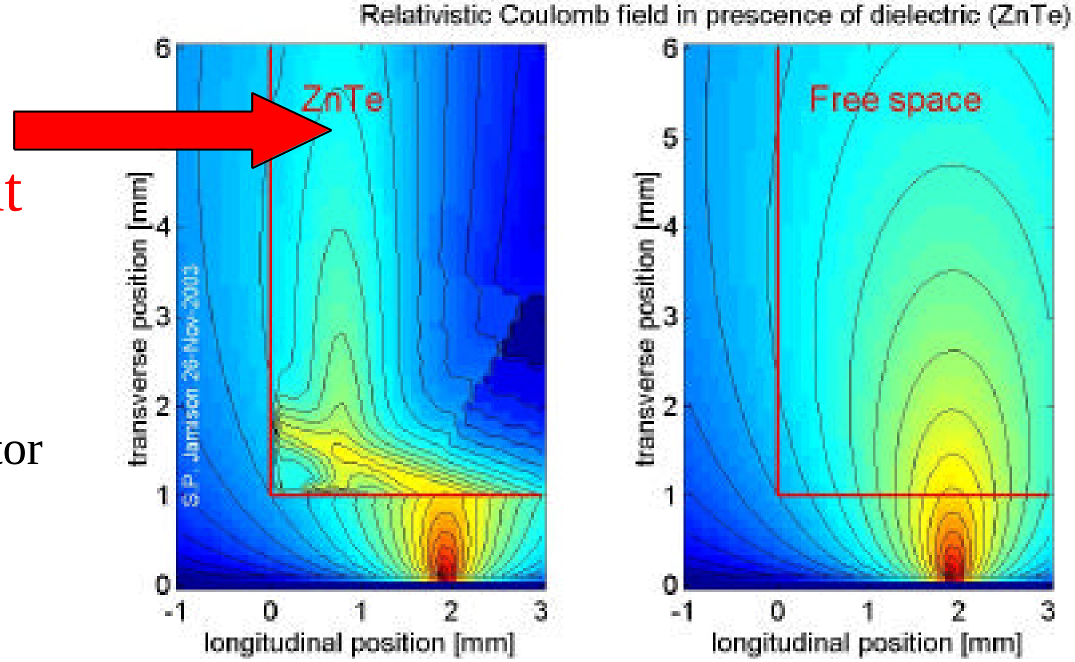
Coulomb field angle
100 MeV electrons ~ 30 fs @ 1 mm distance
Improves with higher energy beams

Optical bandwidth
Time resolution approx. optical pulse duration.
~30 fs. Improvements through X-FROG, ….?

Inclusion of perturbing effect of dielectric crystal

"slowed down" Coulomb field is what we wish to measure

the probe pulse velocity is reduced by a very similar factor

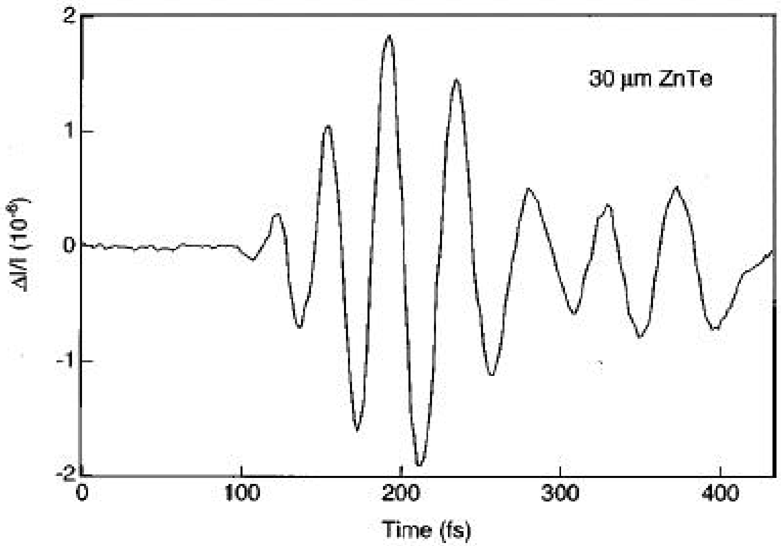


Calculation only applied to region inside the crystal.

The fields outside the crystal are the "freespace" Coulomb Fields, and only shown to provide an indication of the relative position of the electron.

EO Phase matching limitations

Able to measure fast oscillations ….



~30fs oscillations measured with E.O. effect in ZnTe EO crystal

Q. Wu, X.-C. Zhang Appl. Phys. Lett **71** 1285 (1997)

But…
Different frequency components measured with different efficiency and different phase

$$S(t) \quad \int E_{THz}(\Omega)\, f(\Omega)\, \mathrm{e}^{\mathrm{i}\Omega t}\, \mathrm{d}\Omega$$

where

$$f(\Omega) \quad \frac{\exp(i\omega(n_{opt}-n_{THz})L/c)-1}{i\omega(n_{opt}-n_{THz})/c}$$

Raw measurement does not correspond to Coulomb field

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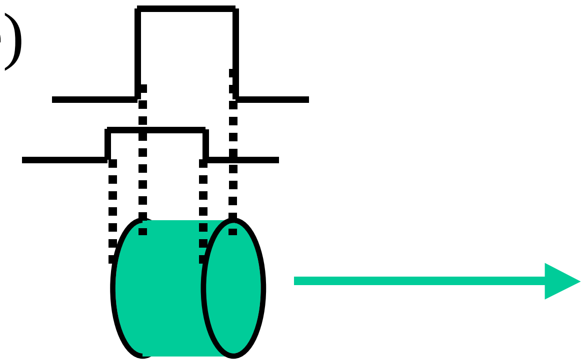
Summary…..

- Demonstrated non-destructive longitudinal profile measurement with 650fs FWHM bunches.
- Estimated bunch time resolution ~200fs
- Real-time bunch shape monitoring and adjustment
- Challenges remain in getting sub-100fs resolution (materials, data deconvolution, optical bandwidth, ...)

What next?….. (wish list)

- Testing of diagnostic on shorter bunches (and higher energy)
- Bench marking of diagnostic
- Combined transverse & longitudinal profile (single shot, non-destructive)



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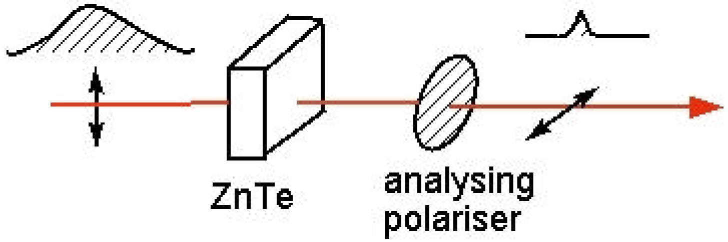
FOM-Instituut voor Plasmafysica Rijnhuizen

Giel Berden
Britta Redlich
Lex van der Meer

Bunch profile from EO signal…

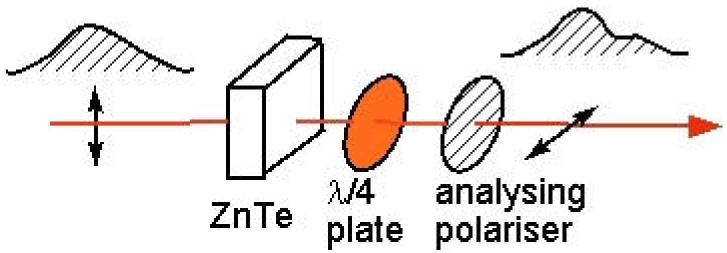
"Crossed-polarisers"

- Zero background signal
- Signal ~ E^2



"balanced detection"

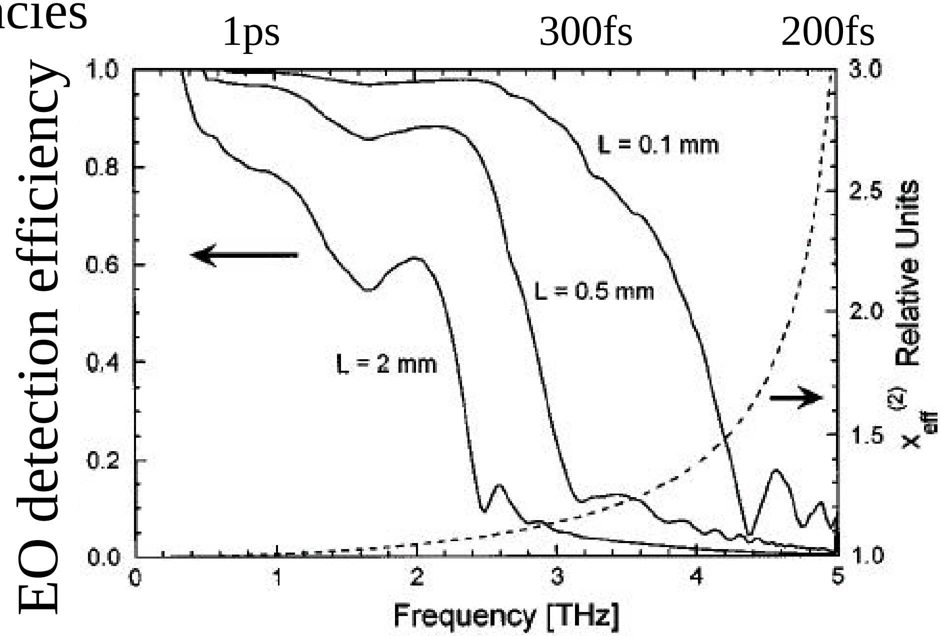
- Small modulation on large background
- Signal ~ E



for thin crystals, EO detection efficiency ~ constant over all frequencies

➡ Direct measurement accurately represents Coulomb field

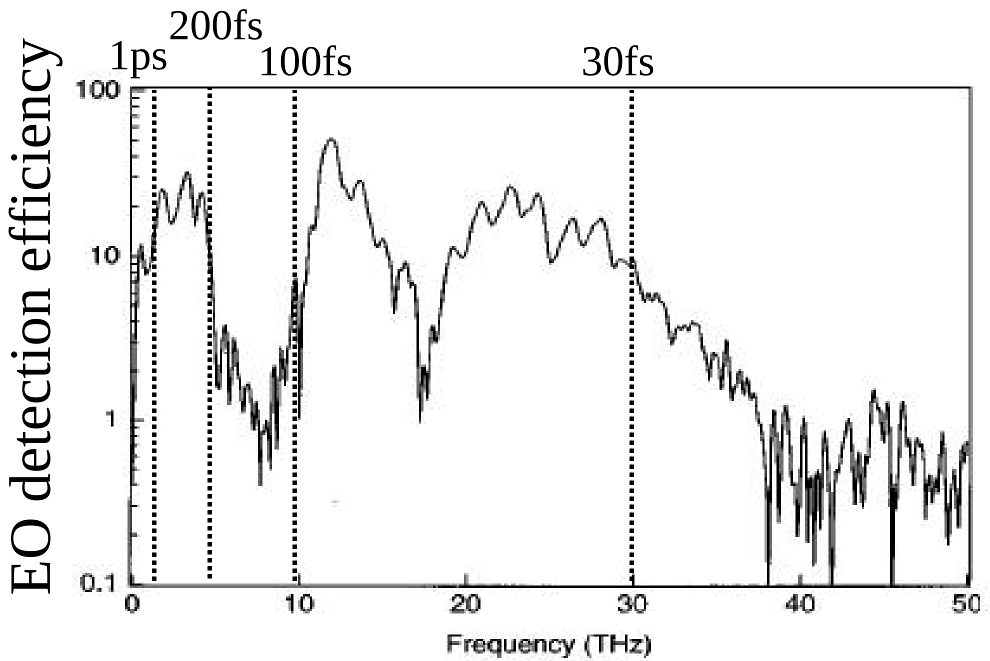
Typically use 0.5mm thick ZnTe $\Delta\tau$~300fs



G. Gallot et al. App. Phys. Lett. **74** 3450 (1999)

for faster field oscillations, can formally deconvolve the material response, and obtain the true electric field profile

EO absorption… missing data



Appl. Phys. Lett, Q. Wu, X-C Zhang **71** 1285 (1997)

Limits ability to recover true electric field.

- different materials (GaP, GeSe,…)
- Interpolation of data through missing region

Spectral bandwidth limitations

- Amplitude modulation of carrier wave implicitly creates "side-band" frequencies

$$\overline{E}_{Opt}(\omega)\ \overline{E_{Coul}(\omega)} = \int_0^\infty d\Omega \left[\overline{E}_{Opt}(\omega+\Omega)\overline{E^*_{Coul}(\Omega)} + \overline{E}_{Opt}(\omega-\Omega)\overline{E_{Coul}(\Omega)}\right] \quad ;\text{for} \quad \omega > 0;$$

Mixing of optical spectrum with neighbouring frequencies $\omega \mp \Omega$
optical spectral modulation unreliable with resolution greater than modulation bandwidth

approximate temporal resolution based on bandwidth $\Delta\tau > (t_o t_{chirped})^{1/2}$

Optical bandwidth limitations

EO effect as retardation based on sum and frequency mixing between optical and THz frequencies.

Breakdown in use of polarisation rotation as diagnostic when modulation bandwidth>> optical bandwidth

Cross-correlator time resolution limited by transform limited optical pulse

Frequency resolved optical gating (FROG) techniques ?

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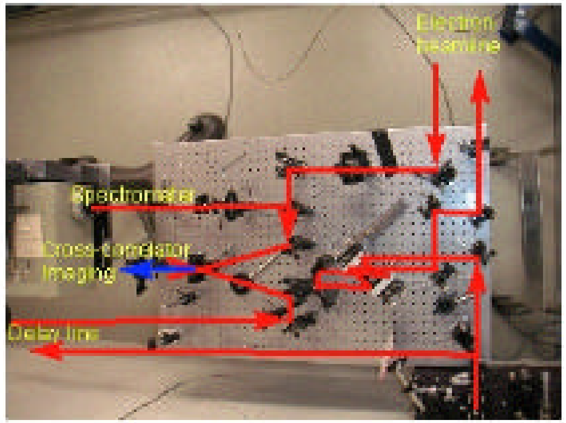
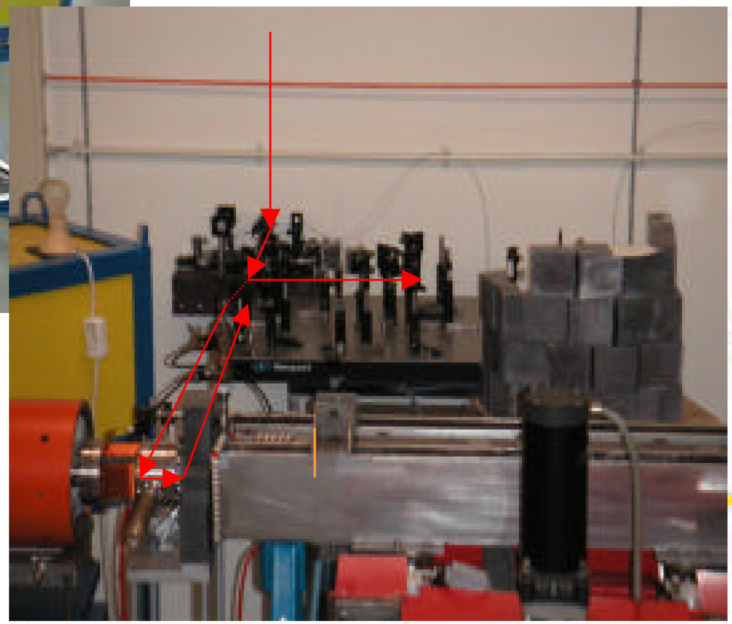
30-50MeV electron beam measurements

FELIX FEL facility, Rijnhuizen, Netherlands

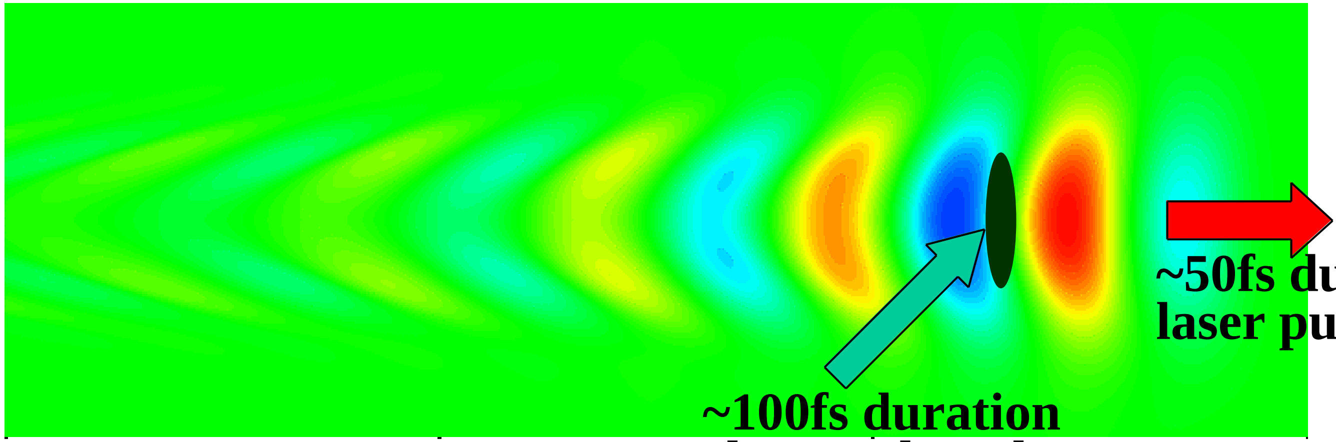




Why do we need an ultrafast electron bunch diagnostic?

Plasma wakefield acceleration

Injected bunch length < λ_{plasma}



How to measure bunch synchronism?
Bunch duration? Temporal profile?

What is temporal structure of both injected and accelerated beam?

Second-harmonic generation (single shot) cross-correlation

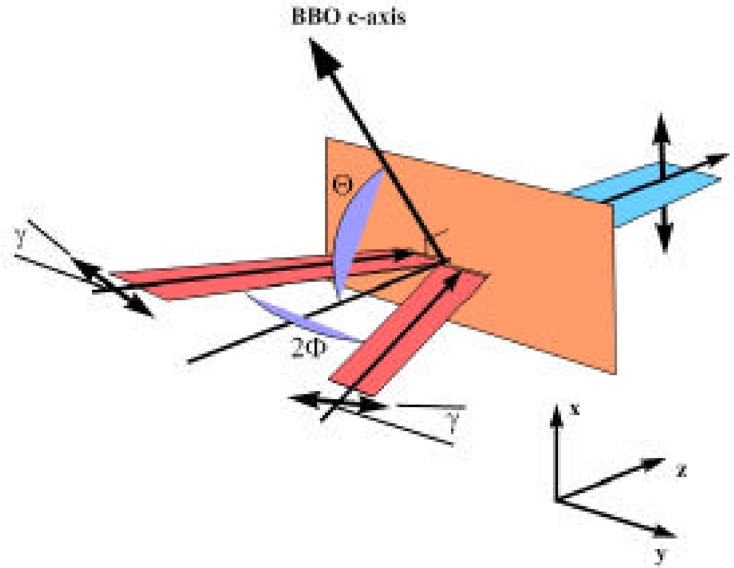
Time window, τ:

- Beam diameter, D
- Angle of incidence Φ

$$\boxed{\tau = 2D\sin(\Phi)/c}$$

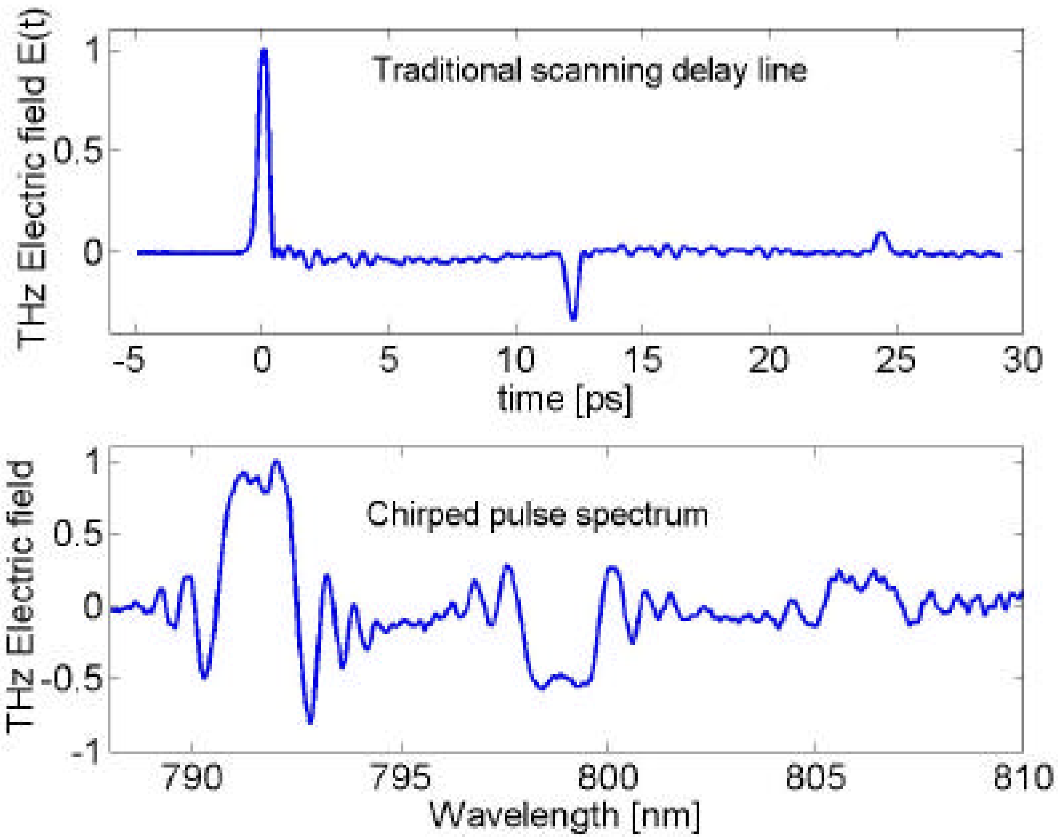
τ 9ps for D=5mm, Φ 15^{o}

Phase matching in BBO achievable for incident angles $\Phi < 33^{o}$

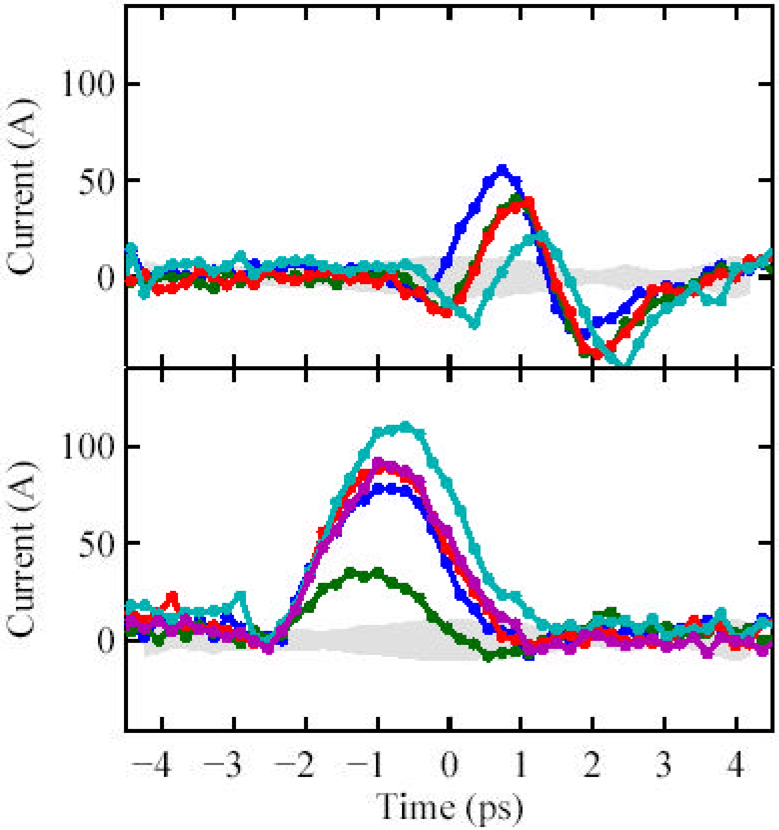


Non-standard crystal geometry

400nm "walk-off" orthogonal to time-axis


THz Electric field E(t)
Traditional scanning delay line
1
0.5
0
-5
0
5
10
15
20
25
30
time [ps]
THz Electric field
Chirped pulse spectrum
1
0.5
0
-0.5
-1
790
795
800
805
810
Wavelength [nm]

National Synchrotron Light Source at Brookhaven National Laboratory
(Source Development Laboratory)



H. Loos., et al, May 2003
Particle accelerator Conference
PAC-2003

Oscillations due to spectral-encoding artifact?

EO diagnostic being setup on TESLA test accelerator