Electro-Optic Longitudinal Profile Diagnostics

Current Status & Future Directions

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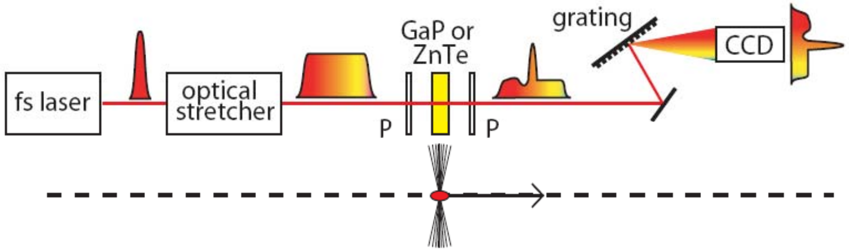
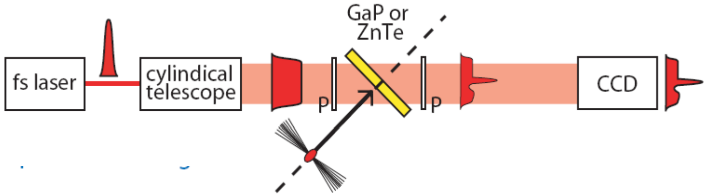
Electro-Optic Techniques…

1. Spectral Decoding



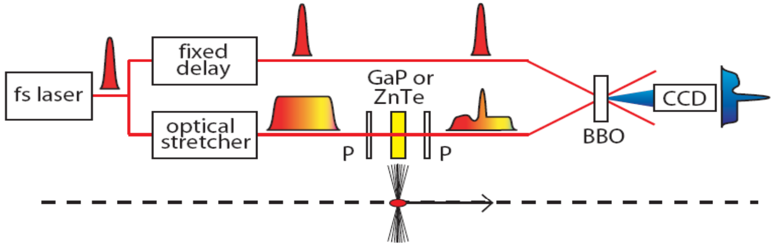
FELIX
DESY
LBNL
…

2. Spatial Encoding



SLAC
DESY
LBNL, …

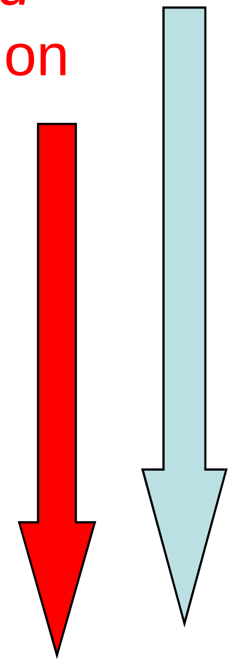
3. Temporal Decoding



FELIX
DESY
RAL(CLF)
MPQ
Jena, …

complexity

demonstrated
time resolution



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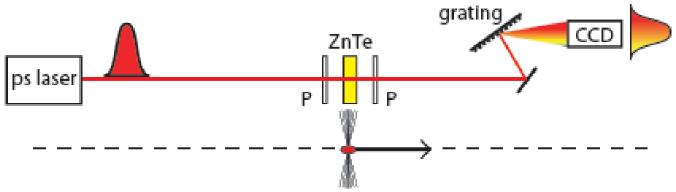
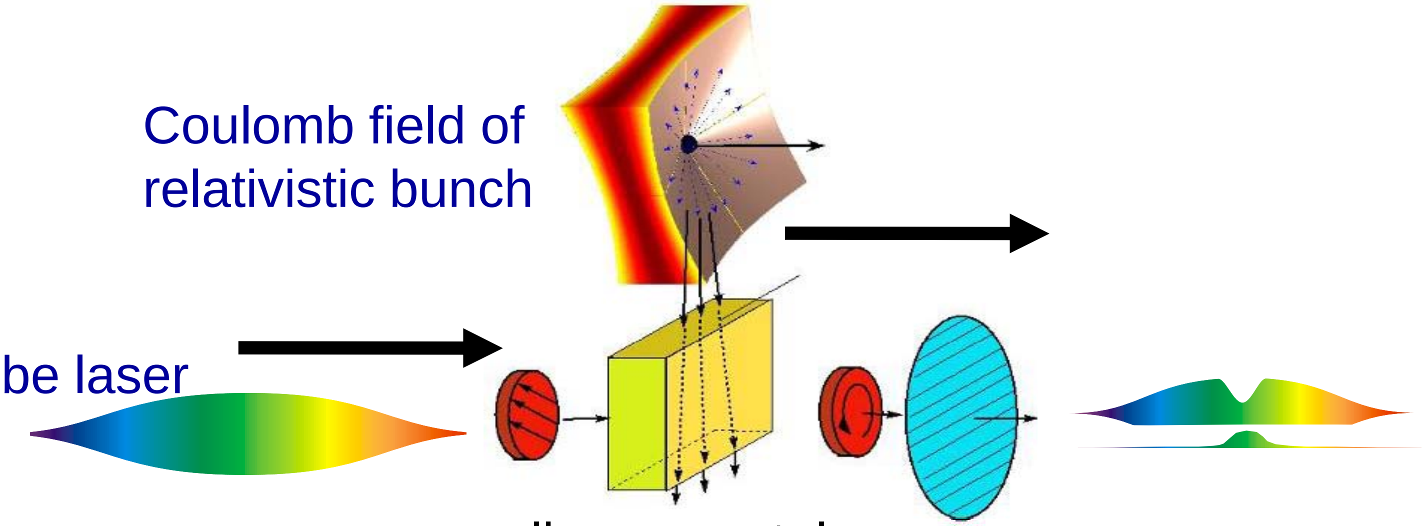
4. Spectral Upconversion



Concept of electro-optic profile diagnostic

all-optical intra-beamline pickup of relativistic bunch Coulomb field



Coulomb field of relativistic bunch

probe laser

non-linear crystal
(electro-optic effect)

Decoding
of information
from laser pulse

Encoding

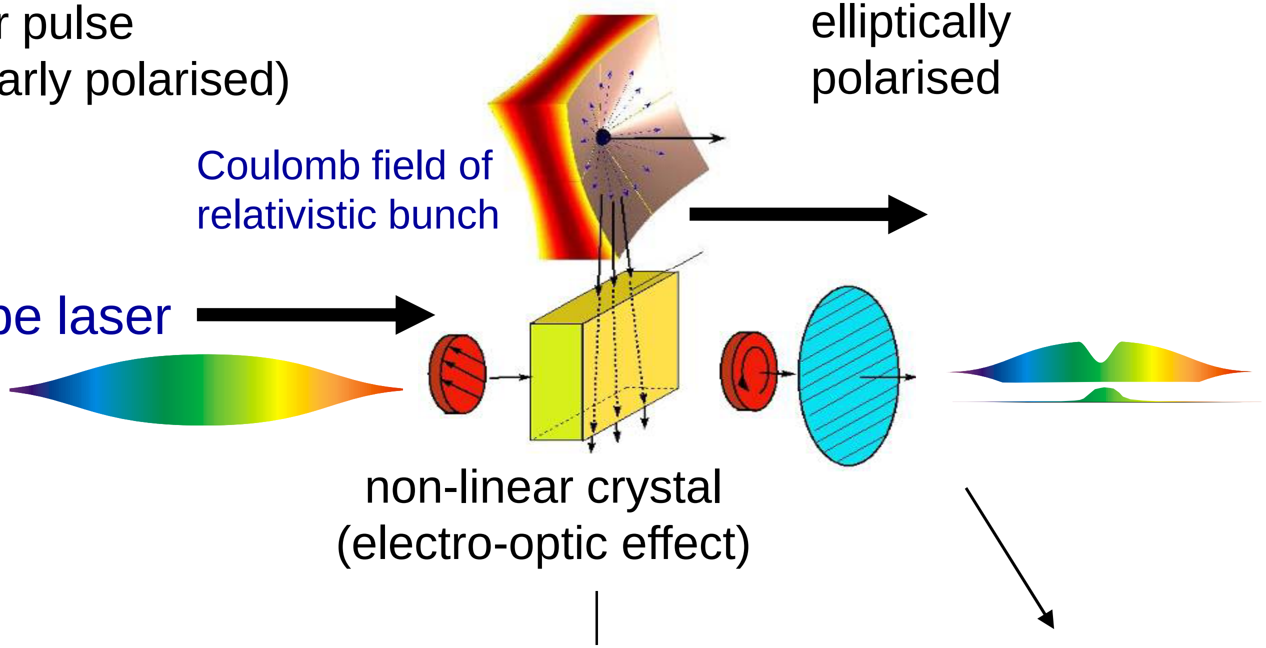
- same for all techniques
- limiting factor for high time resolution techniques

Decoding

- choices for complexity
- limiting factor for spectral decoding

Physics of EO encoding ... standard description

Refractive index modified by external (quasi)-DC electric field



laser pulse
(linearly polarised)

Coulomb field of
relativistic bunch

elliptically
polarised

intensity dependent
on ‘DC’ field strength

probe laser

Decoding
of information
from laser pulse

non-linear crystal
(electro-optic effect)

$$E_{\mathrm{x}}(t) \qquad \eta_{\mathrm{x}} = \eta_0 + \alpha_{\mathrm{x}} E_{\mathrm{DC}} \qquad E_{\mathrm{x}}(t) \sim E_{\mathrm{x}}(t)\exp(i\omega t - i\eta_x \omega z/c)$$

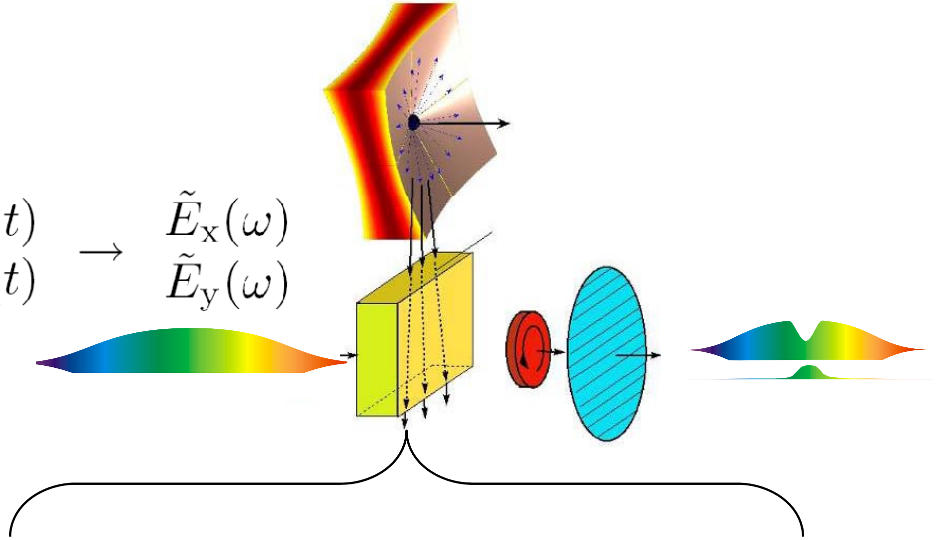
$$E_{\mathrm{y}}(t) \qquad \eta_{\mathrm{y}} = \eta_0 + \alpha_{\mathrm{y}} E_{\mathrm{DC}} \qquad E_{\mathrm{y}}(t) \sim E_{\mathrm{y}}(t)\exp(i\omega t - i\eta_y \omega z/c)$$

quasi-DC description ok if $\tau_{\mathrm{laser}} \ll$ time scale of E_{DC} variations

(basis for Pockels cells, sampling electro-optic THz detection, ...)

N.B. Time-varying refractive index is a restricted approximation to the physics
(albeit a very useful and applicable formalism for majority of situations)

Physics of EO encoding...



$$\begin{matrix} E_{\mathrm{x}}(t) \\ E_{\mathrm{y}}(t) \end{matrix} \;\rightarrow\; \begin{matrix} \tilde{E}_{\mathrm{x}}(\omega) \\ \tilde{E}_{\mathrm{y}}(\omega) \end{matrix}$$

$$I(t) \propto E_{\mathrm{Coul}}(t)$$

$$[\ \text{or} \quad \propto E^2_{\mathrm{Coul}}(t) \quad]$$

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

Coulomb spectrum shifted to optical region

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

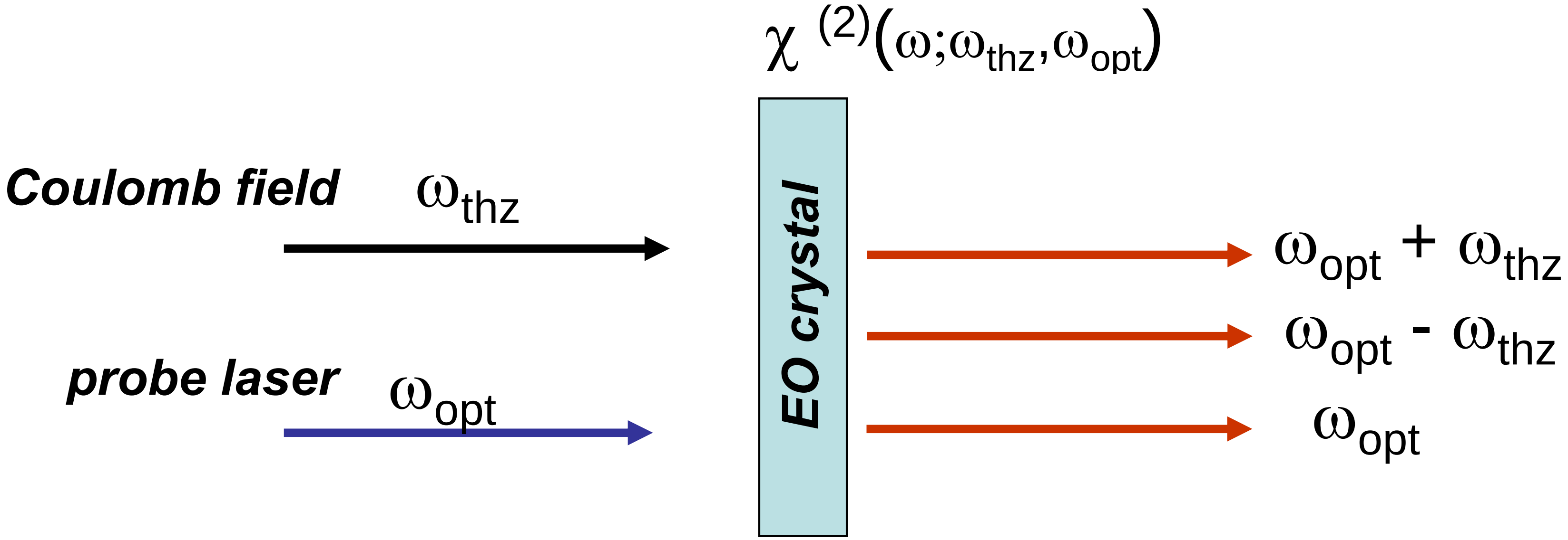
Coulomb pulse replicated in optical pulse

New concepts & understanding of very high time resolution techniques come from generality of frequency mixing physics description

Jamison et al. Opt. Lett **31** 1753 (2006)

Frequency domain description of EO detection...

Electro-optic encoding is a consequence of sum- and difference-frequency mixing



$\chi^{(2)}(\omega;\omega_{thz},\omega_{opt})$

Coulomb field ω_{thz}

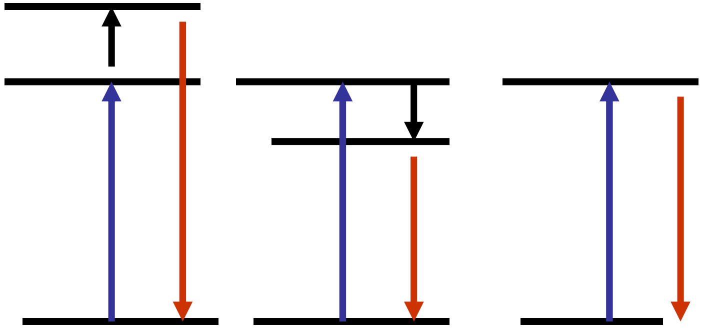
probe laser ω_{opt}

EO crystal

$\omega_{opt} + \omega_{thz}$

$\omega_{opt} - \omega_{thz}$

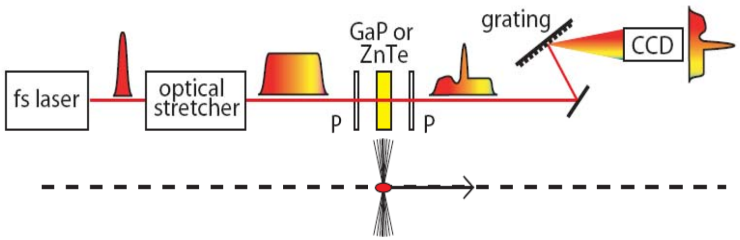
ω_{opt}



for arbitrary probe and Coulomb pulses...

- convolve over <u>all</u> combinations of optical and Coulomb frequencies.
- includes field phase (chirp), general phase matching, optical GVD, etc

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



1. Spectral Decoding

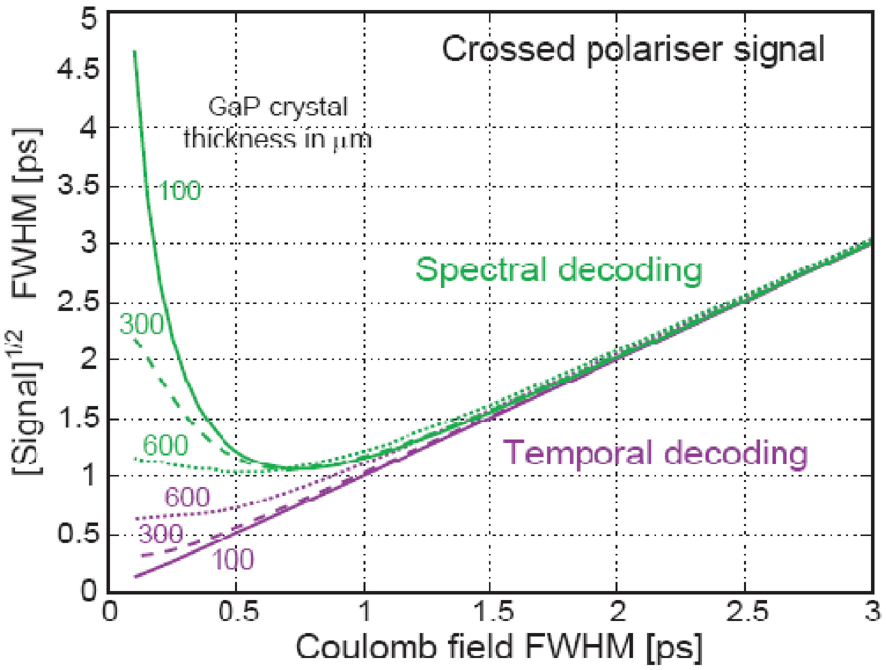
Attractive simplicity for low time resolution measurements e.g. injector diagnostics

Rely on t-λ relationship of input pulse for interpreting output optical spectrum
Resolution limits come from the fact that the EO-generated optical field doesn't have the same t-λ relationship

temporal resolution limits…

In general spectral decoding limited by chirp $\tau_{\text{lim}} = \sqrt{12\pi\beta}$

For specific laser profiles, can relate to FWHM durations…

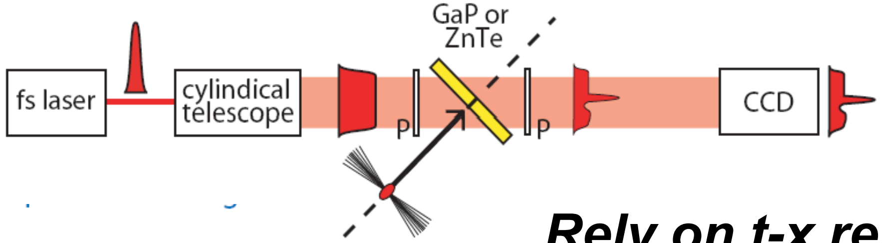


$\tau_{\text{lim}} = 2.61\sqrt{T_0 T_c}$; for a Gaussian pulse

Unlikely to get better than 1.0 ps (FWHM) with spectral decoding

Concepts based on T_c <20 fs pulses must address extra problems of optical GVD (not clear these can be overcome without significant complication)

2. Spatial Encoding



Rely on t-x relationship between laser and Coulomb field

EO encoding (almost) same as before - Same t-x relationship

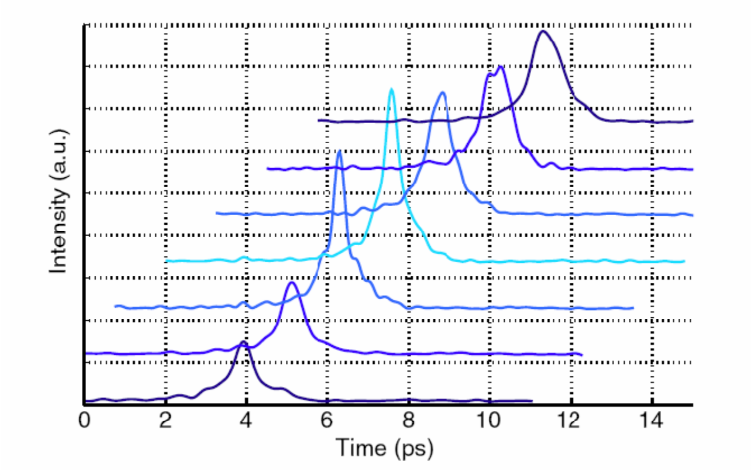
In principle: expect same/similar capabilities as TD

<u>Caveat:</u> non-collinear geometry alters EO *tensor* response

less widely demonstrated:

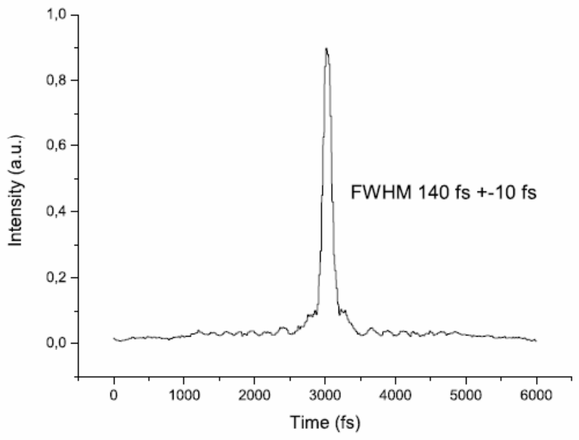
SLAC and DESY expts had significant additional complications of long transport in fibre...

SPPS (SLAC) measurements



from Cavalieri et al. PRL 2005

FLASH (DESY) measurements



from A. Azima et. al EPAC06

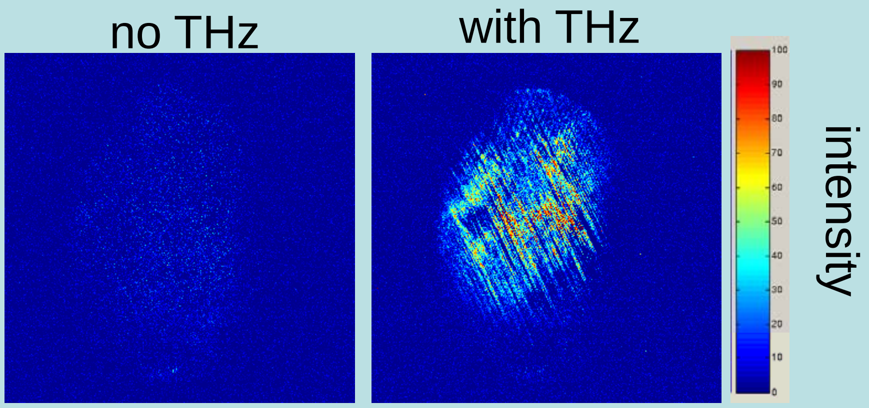
Spatial Encoding...

Questions / concerns on practical implementation

(from someone who hasn’t performed a spatial encoding diagnostic expt!)

EO crystal quality...is this an issue?

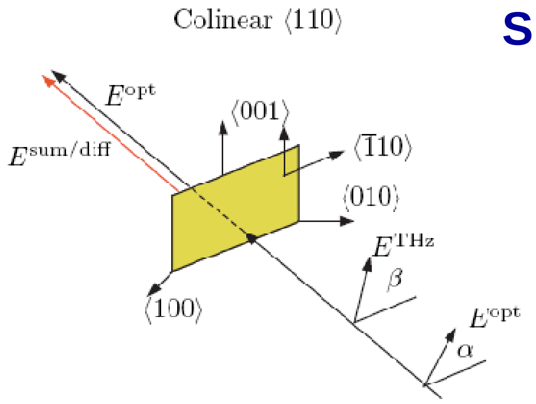
imaging of EO crystal and probe laser
(similar to spatial encoding)



striations in signal
from crystal inhomogeneity

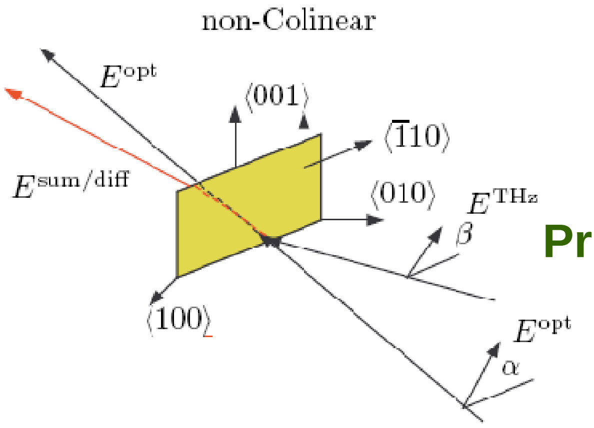
(tests using laser-driven THz source)

special properties of Collinear <110> geometry



SD or TD arrangement

sum frequency
optical field
remains
collinear to input
field

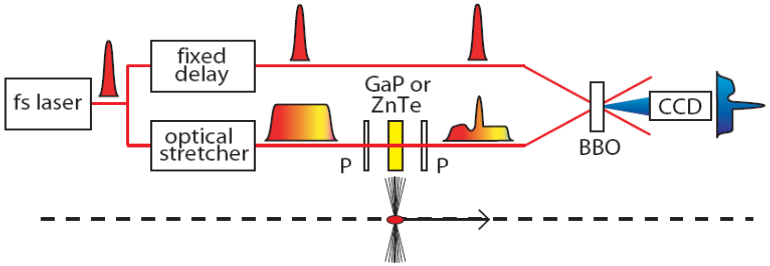


SE arrangement

sum frequency
propagation
direction differs.

Problem or advantage?

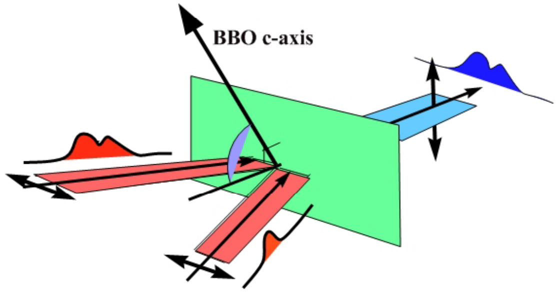
not addressed in current models

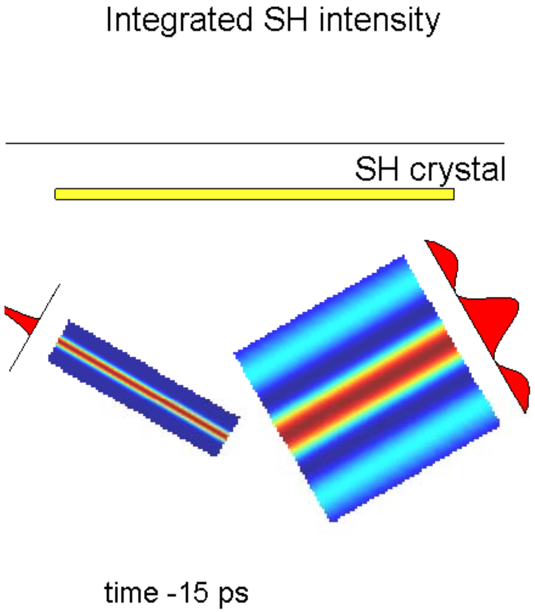


3. Temporal Decoding

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

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





Temporal profile of probe pulse

⇒ Spatial image of 2nd harmonic

limited by

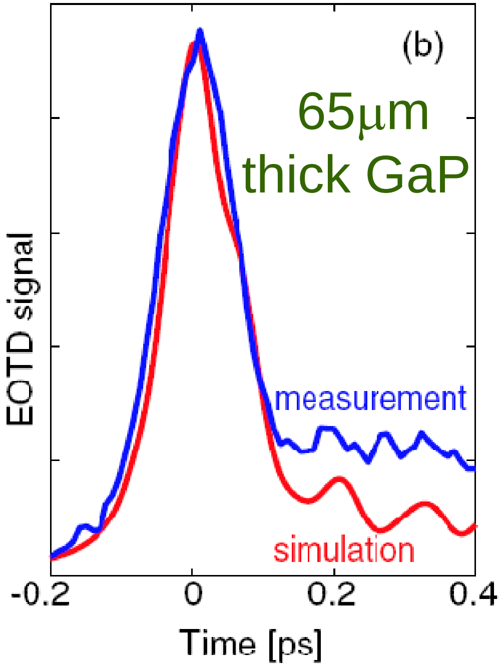
- gate pulse duration (although FROG etc could improve)
- EO encoding efficiency, phase matching

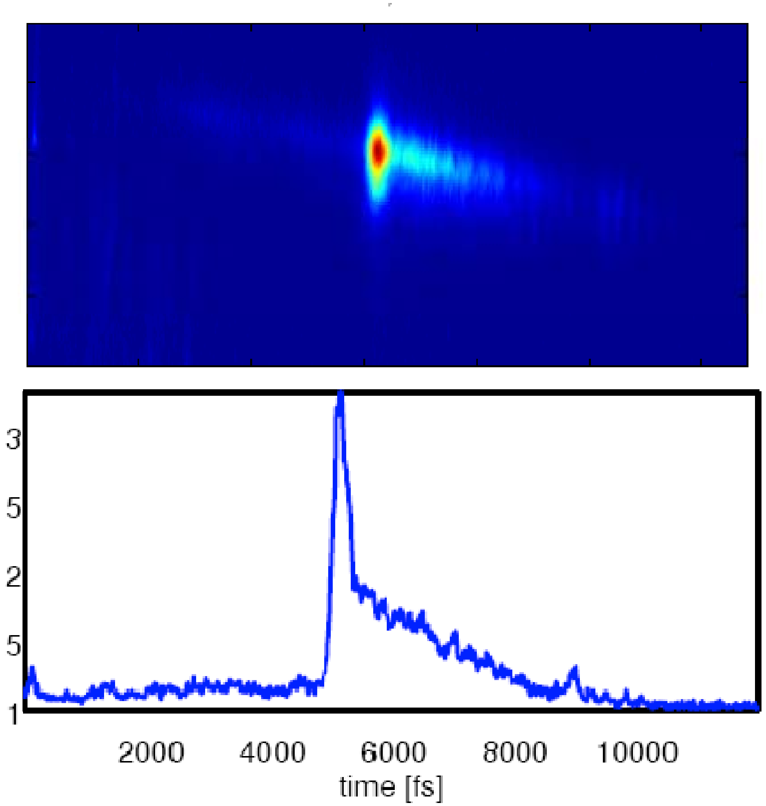
Practical limitations: ***complexity of laser systems***

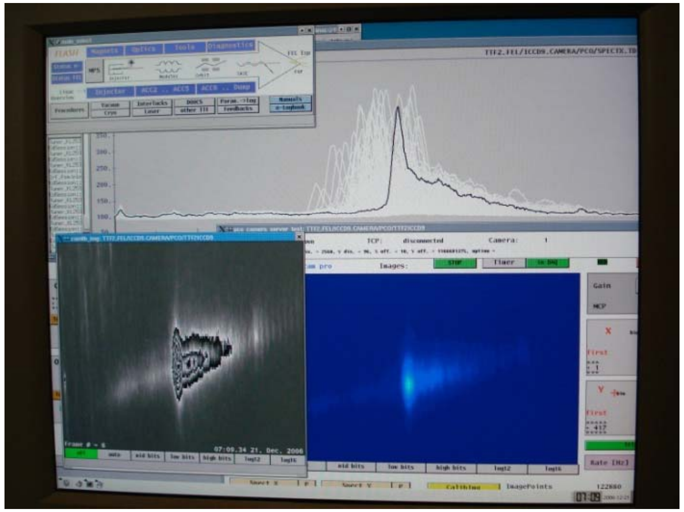
transporting short pulse laser (gate pulse only)

temporal decoding in practice..

currently the highest time-resolution
non-destructive diagnostic demonstrated







“Time resolution”

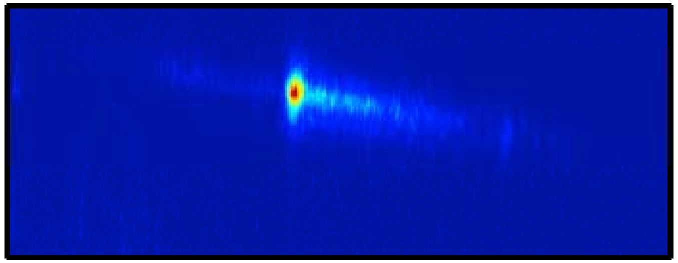
σ_z ~ 90fs (rms)

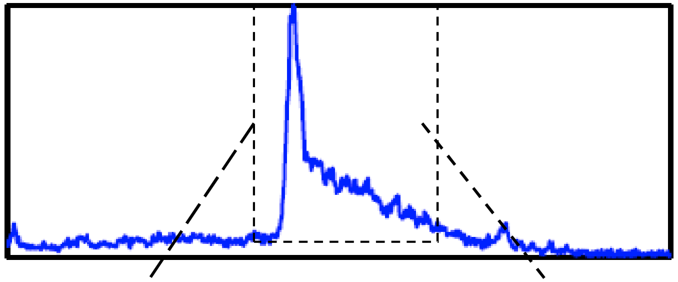
σ_z^{actual} ~ 30fs $\Rightarrow$ $\sigma_z^{measured}$ ~55 fs
σ_z^{actual} ~ 90fs $\Rightarrow$ $\sigma_z^{measured}$ ~90 fs

Benchmarking of EO diagnostics

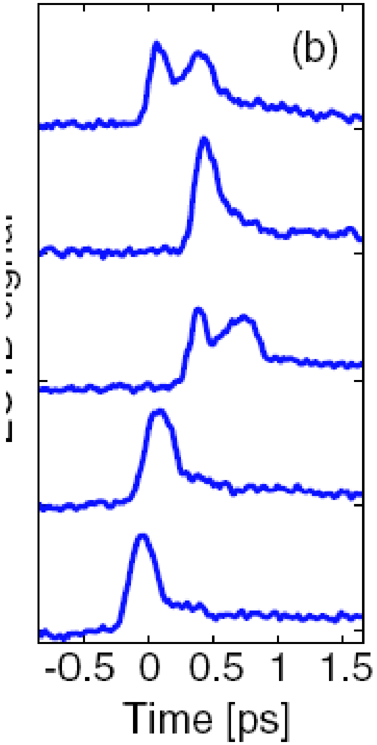
comparison with transverse deflecting *(LOLA)* cavity

Electro-Optic

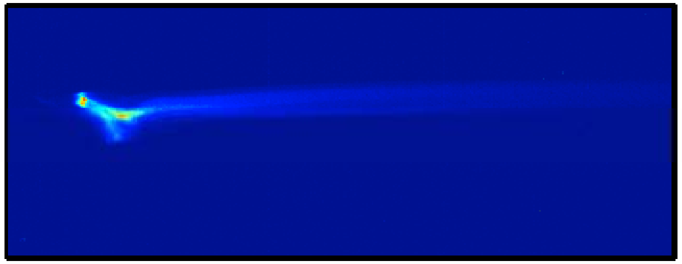


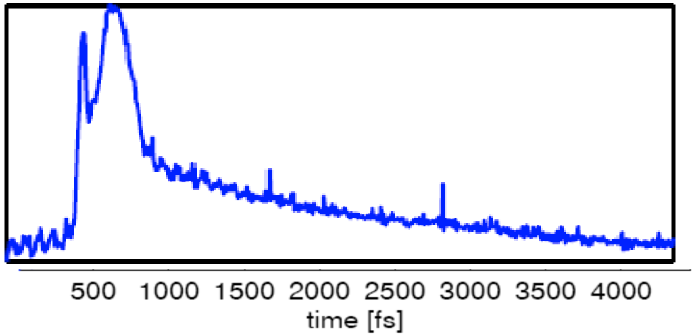


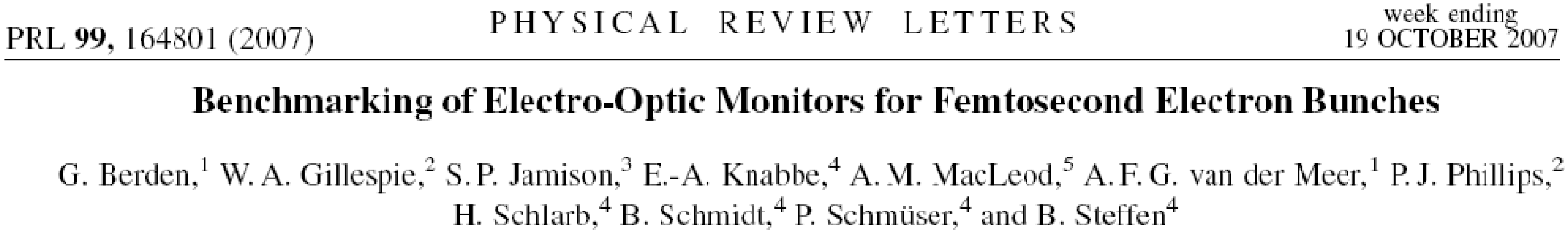
shot-shot variations



Transverse Deflecting Cavity







PRL **99,** 164801 (2007) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2007

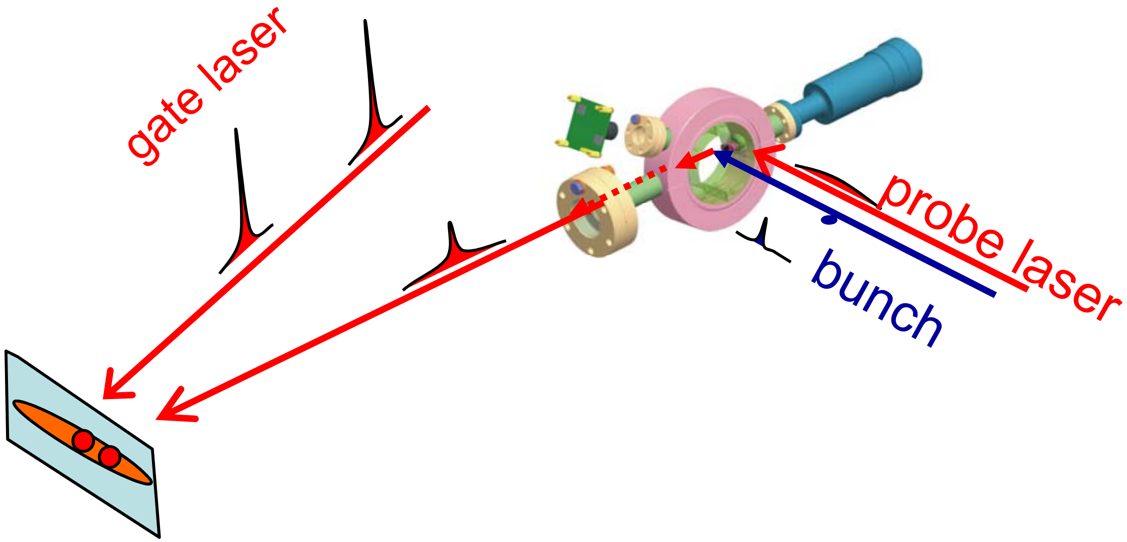
Benchmarking of Electro-Optic Monitors for Femtosecond Electron Bunches

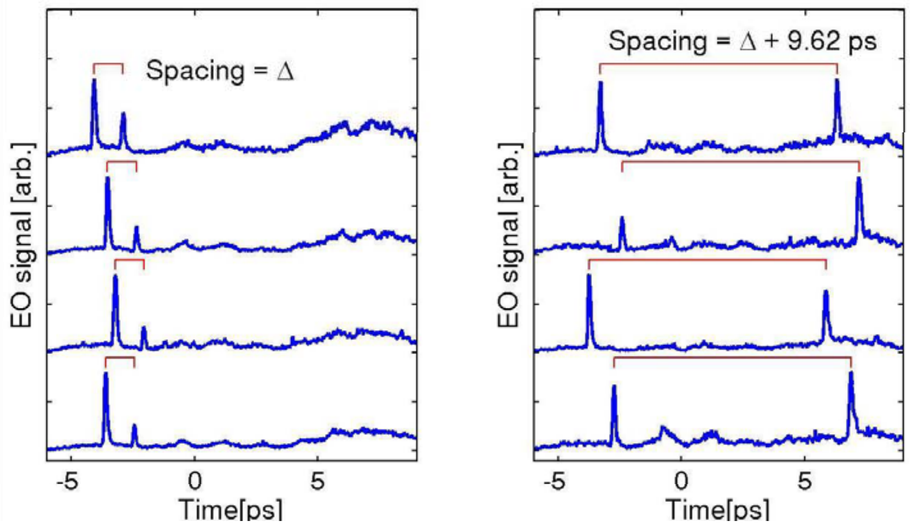
G. Berden,[1] W. A. Gillespie,[2] S. P. Jamison,[3] E.-A. Knabbe,[4] A. M. MacLeod,[5] A. F. G. van der Meer,[1] P. J. Phillips,[2]
H. Schlarb,[4] B. Schmidt,[4] P. Schmüser,[4] and B. Steffen[4]

plus ***Phys. Rev. ST,*** *12 032802* ***2009***

Temporal decoding extras:
EO confirmation of CDR feedback systems

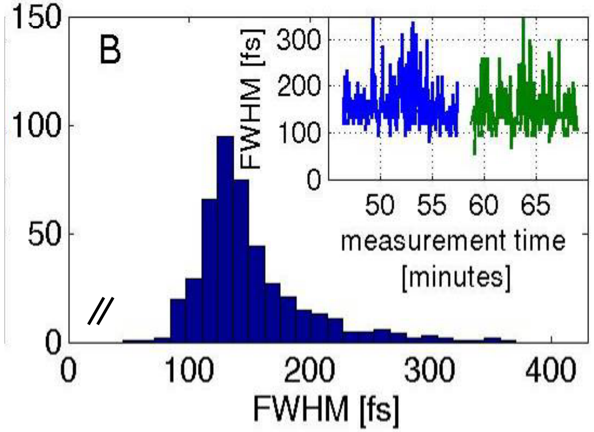
Time Calibration....



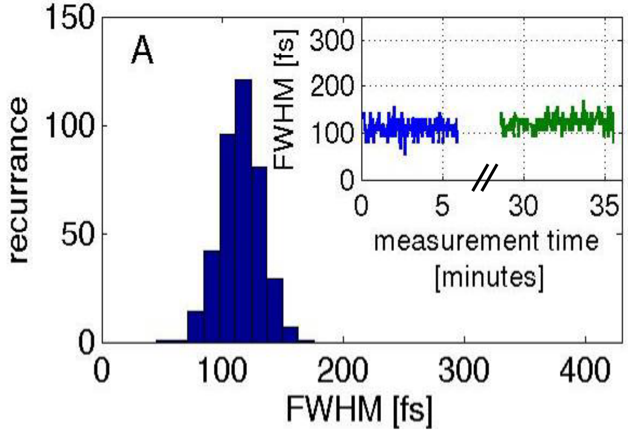


single shot capability (FLASH) reveals stabilising effect of slow feedback

CDR feedback off



CDR feedback on



So are all the problems solved...?

Low time resolution (>1ps structure)

- *spectral decoding offers explicit temporal characterisation*
- *relatively robust laser systems available*
- *diagnostic rep rate only limited by optical cameras*

High time resolution (>60 fs rms structure)

- *proven capability*
- *significant issues with laser complexity / robustness*

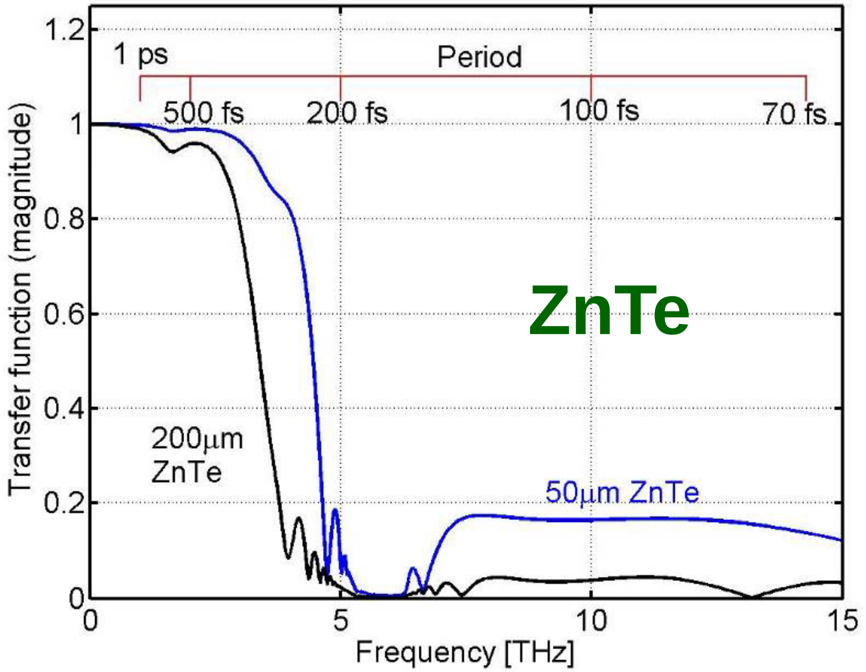
Very high time resolution (<60 fs rms structure)

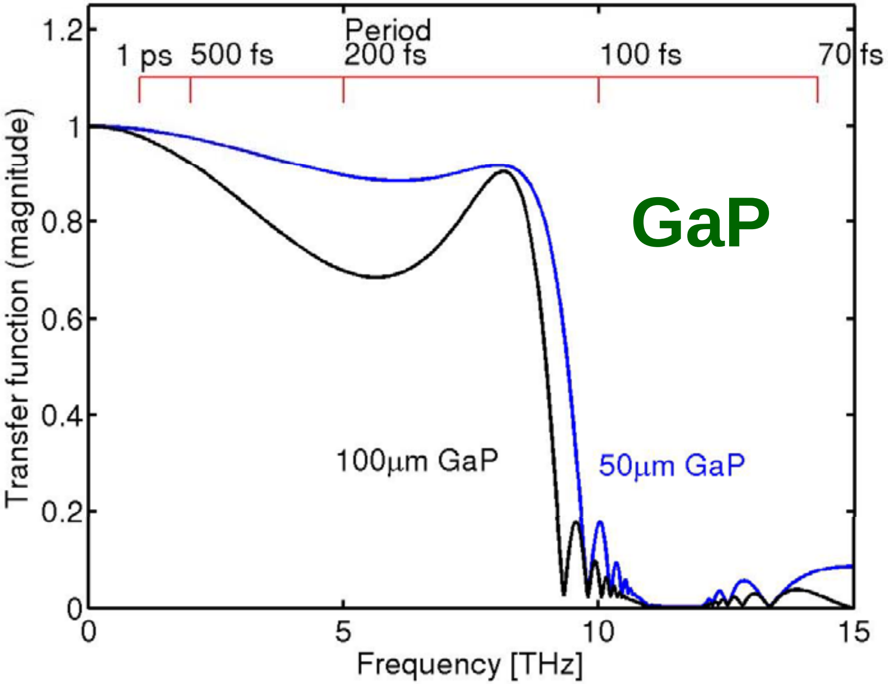
- *limited by EO material properties (& laser)*

Encoding Time Resolution...

material frequency response, $R(\omega)$

- velocity mismatch of Coulomb field and probe laser
- frequency mixing efficiency, $\chi^{(2)}(\omega)$

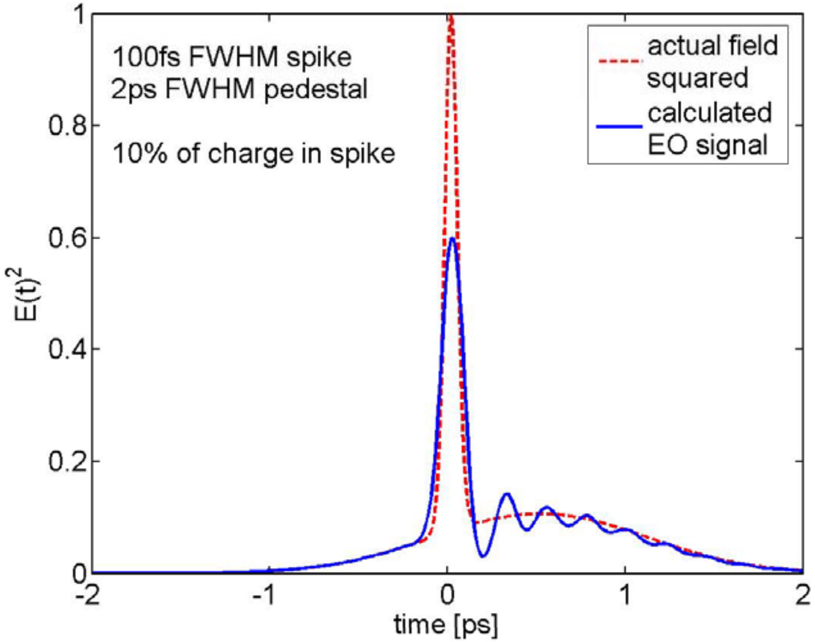


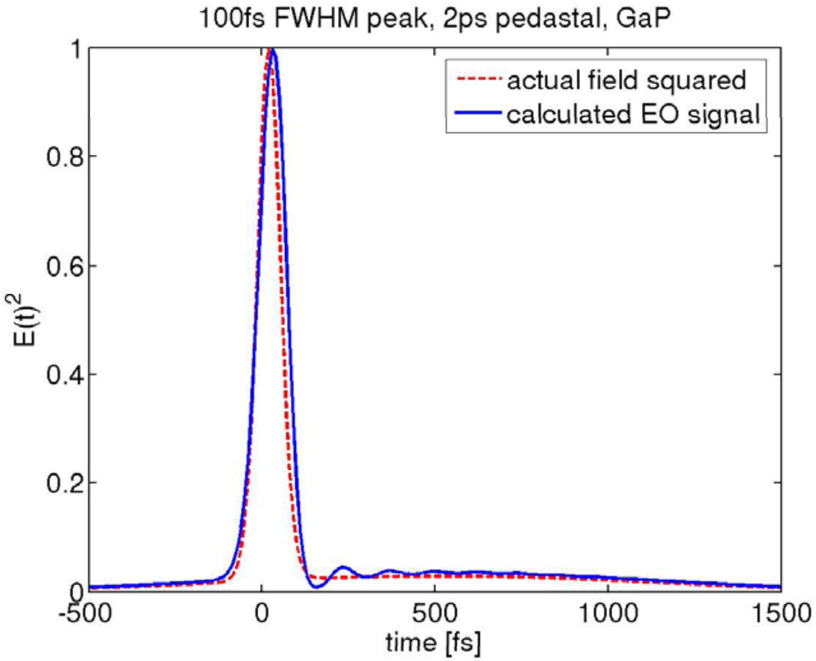


Time resolution from frequency response

- **Encoding "time resolution" not a RMS measure...**
- **Better described as "temporal limitation"**

- ***structure on longer time scale recorded faithfully***
- ***short time scale structure not observed, PLUS ringing artefacts***





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 ...

alternative ways forward...

Current limitations are from material properties

Phonon-resonances at 3-15 THz (material dependent)

All materials will have some phonon resonance effects

Can we use a set of crystals to cover larger range?

requires (uncertain) reconstruction to find temporal profile
(relative phase shifts, phase matching, efficiency between crystals)

→ ***complication of system would multiply***

If reconstruction needed anyway, reconsider spectral techniques ...
BUT traditional spectral techniques have difficulties :

long-wavelength / DC-component transport
extreme ("100%") spectral bandwidths for detection

A solution : Electro-optic spectral upconversion

4. Spectral upconversion diagnostic

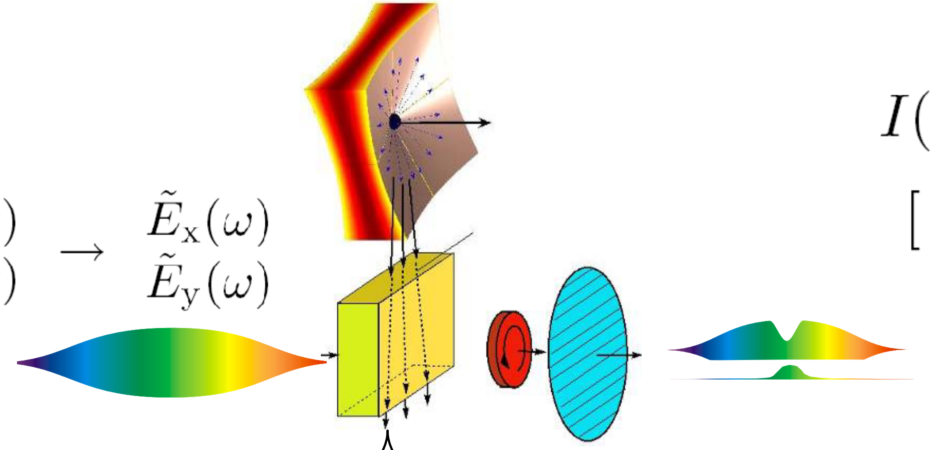
Physics of EO encoding…

- shifting Coulomb spectrum to optical region

OR

- creating an optical “replica” of Coulomb field

$$\begin{matrix} E_{\mathrm{x}}(t) \\ E_{\mathrm{y}}(t) \end{matrix} \rightarrow \begin{matrix} \tilde{E}_{\mathrm{x}}(\omega) \\ \tilde{E}_{\mathrm{y}}(\omega) \end{matrix}$$



$$I(t) \propto E_{\mathrm{Coul}}(t)$$

$$[\ \text{or} \quad \propto E^2_{\mathrm{Coul}}(t) \quad]$$

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

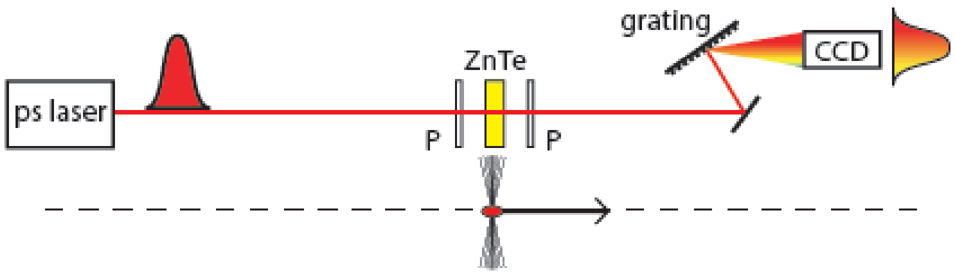
Coulomb spectrum shifted to optical region

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

Coulomb pulse replicated in optical pulse

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

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

same physics
as “standard” EO

$\rightarrow \delta$-function

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

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

different observational
outcome

- ***laser complexity reduced, reliability increased***
- ***laser transport becomes trivial (fibre)***
- ***problematic artefacts of spectral decoding become solution***

NOTE: the long probe is converted to optical replica

Spectral upconversion diagnostic

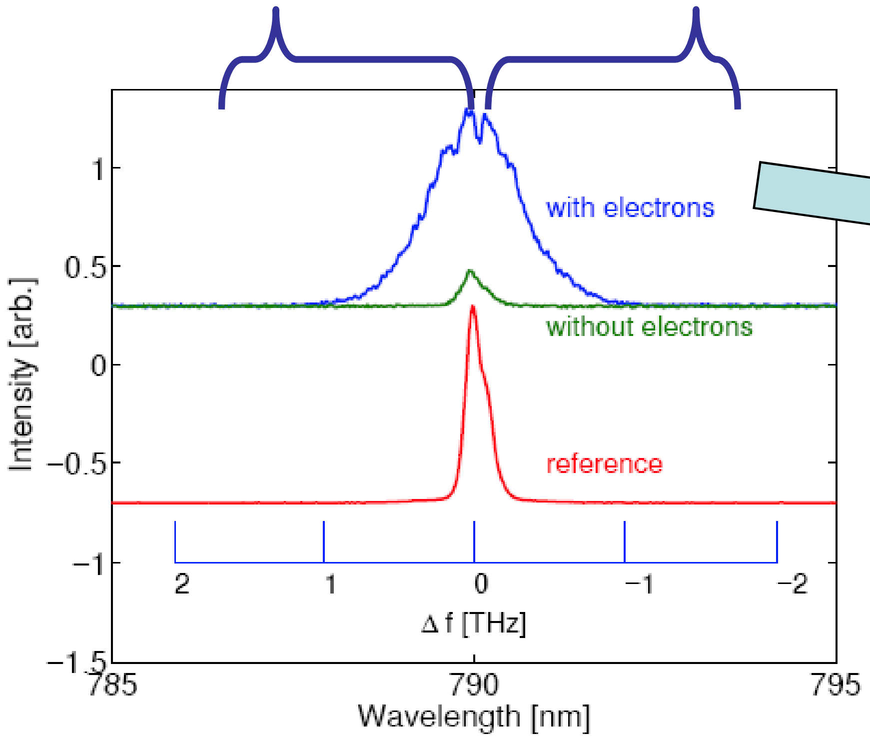
Results from experiments at FELIX (Feb 2009) in FEL'09; and ***Appl. Phys. Lett. 96, 231114 (2010)***

sum frequency mixing

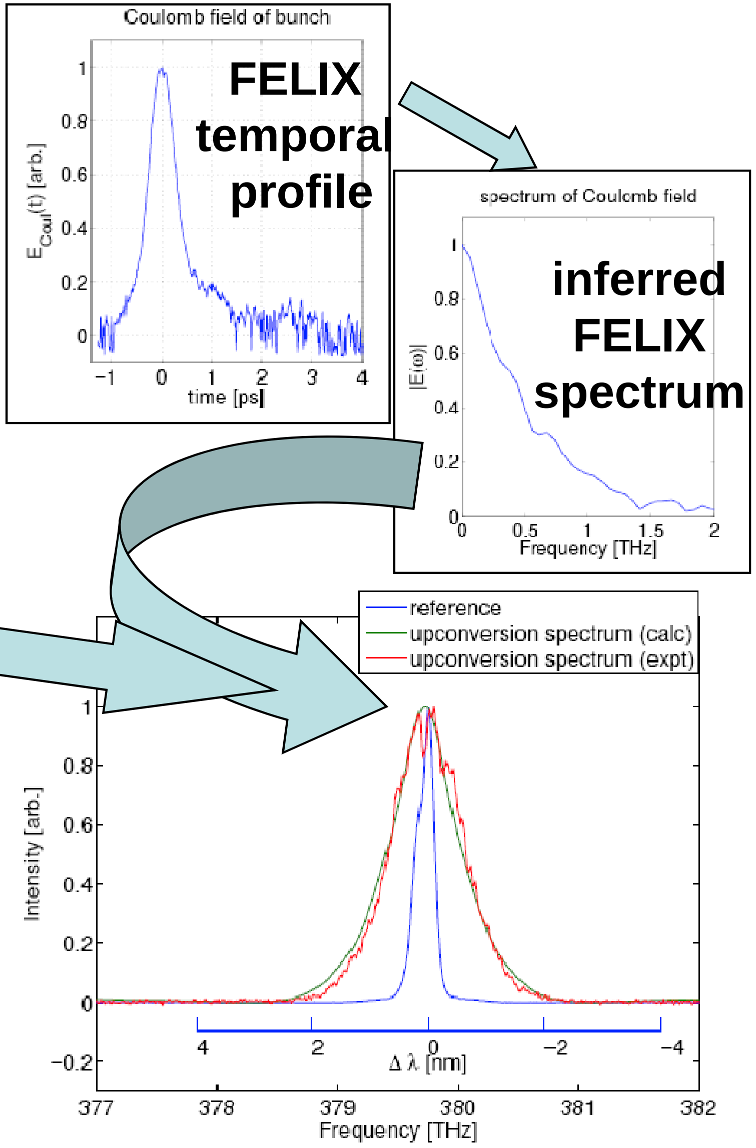
$$\tilde{E}(\omega_0+\Omega) = i\omega a\tilde{E}(\omega_0)\,\tilde{E}^{\mathrm{Coul}}(\Omega)\tilde{R}(\Omega)$$

difference frequency mixing

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

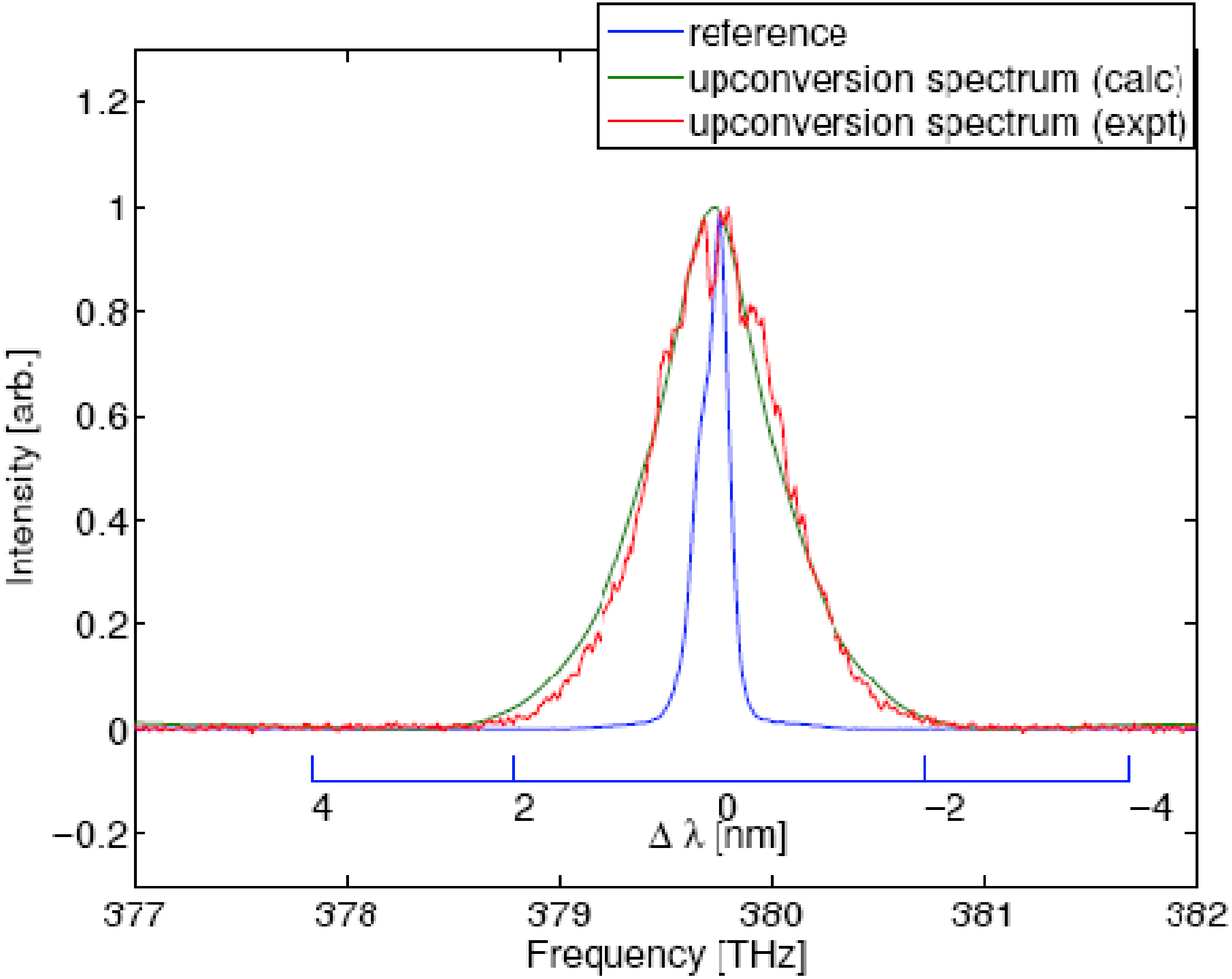


Theory / Expt. comparison

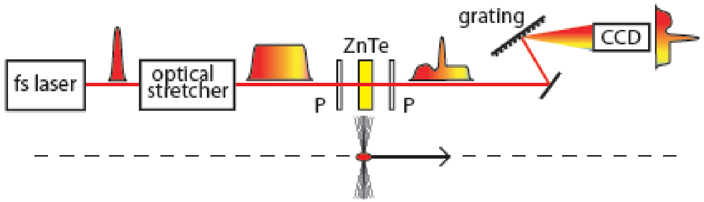


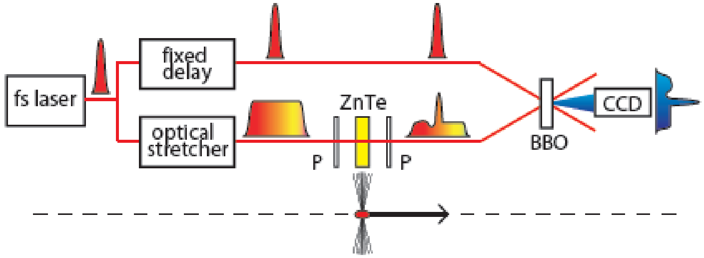
FELIX temporal profile

inferred FELIX spectrum


reference
upconversion spectrum (calc)
upconversion spectrum (expt)
Intensity [arb.]
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
4
2
0
−2
−4
Δ λ [nm]
377
378
379
380
381
382
Frequency [THz]

What's different...?



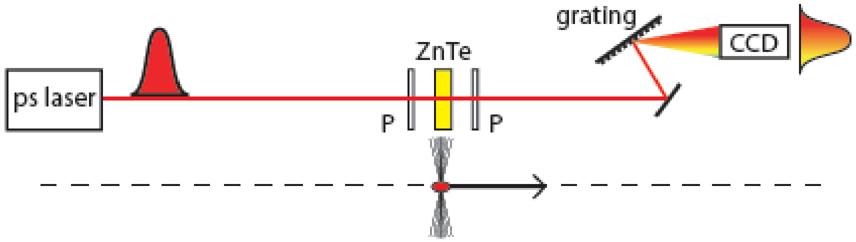


Spectral decoding & Temporal decoding

laser bandwidth >> bunch spectral extent

issues of

- laser transport
- laser complexity/expense/reliability
- material effects (e.g. group velocity dispersion)



Spectral upconversion

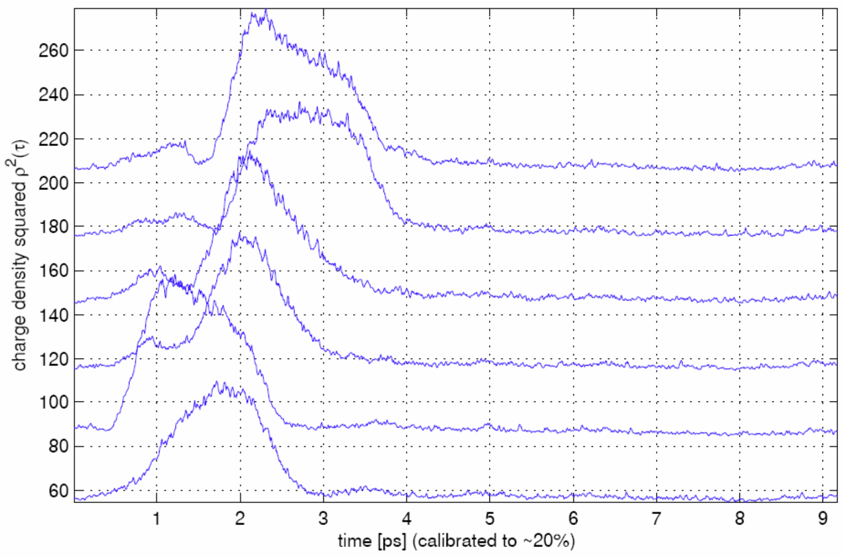
laser bandwidth << bunch spectral extent

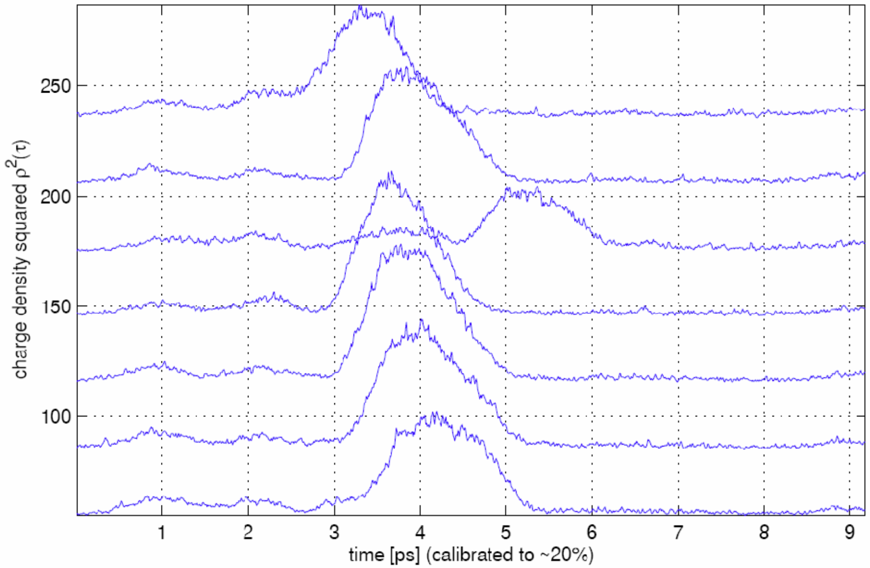
- low power, 'simple' lasers OK
- fibre transport now an option
- simple – linear – spectral detection

without artefacts of spectral decoding

Important: technique can measure non-propagating long-wavelength components not accessible to radiative techniques (CSR/CTR/S-P)

ALICE spectral decoding, 40pC, first results from last week....





In Summary ...

- Proven capability for explicit temporal characterisation up to ~100 fs rms electron bunch structure
- High time resolution techniques have problems with reliability & necessary infrastructure...
- ... *but* there exist avenues available for improving time resolution & robustness (depending on the beam diagnostics requirements)
- For high time resolution, alternative materials & spectral upconversion are both under investigation

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END