Electro-optic Longitudinal Profile Diagnostics

current status & future directions

S P Jamison
Accelerator Science and Technology Centre, STFC Daresbury Laboratory

Collaborators:

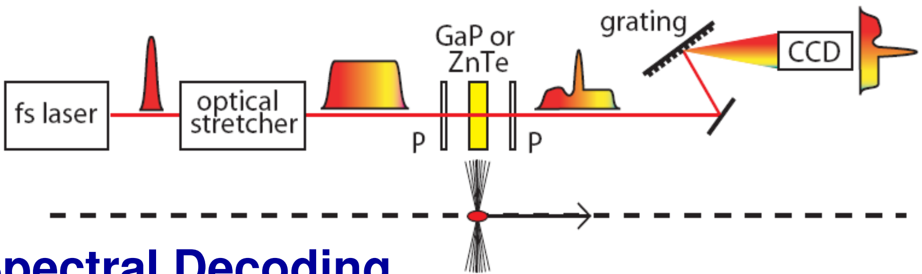
W.A. Gillespie *University of Dundee*

A.M. MacLeod, *University of Abertay Dundee*

G. Berden, B. Redlich, A.F.G. van der Meer *(FELIX)*

B. Steffen, E.-A. Knabbe, H. Schlarb, B. Schmidt, P. Schmüser *(DESY)*

Electro-optic techniques...

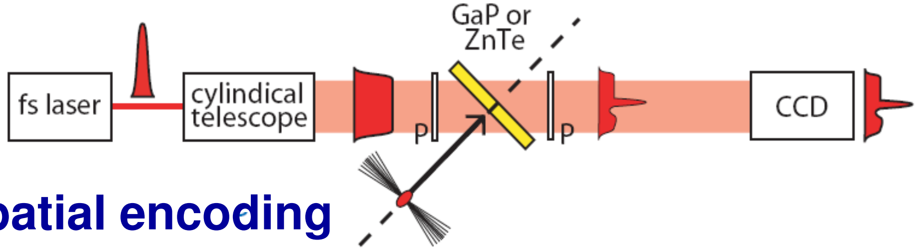


Spectral Decoding

FELIX
DESY
BNL
...

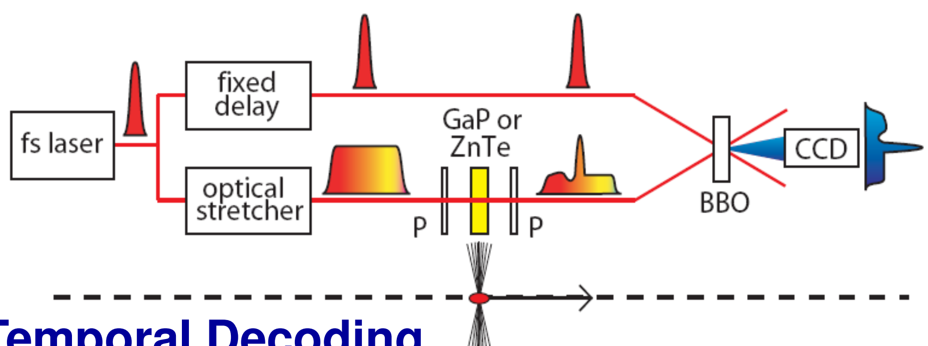
complexity

demonstrated
time resolution



Spatial encoding

SLAC
DESY

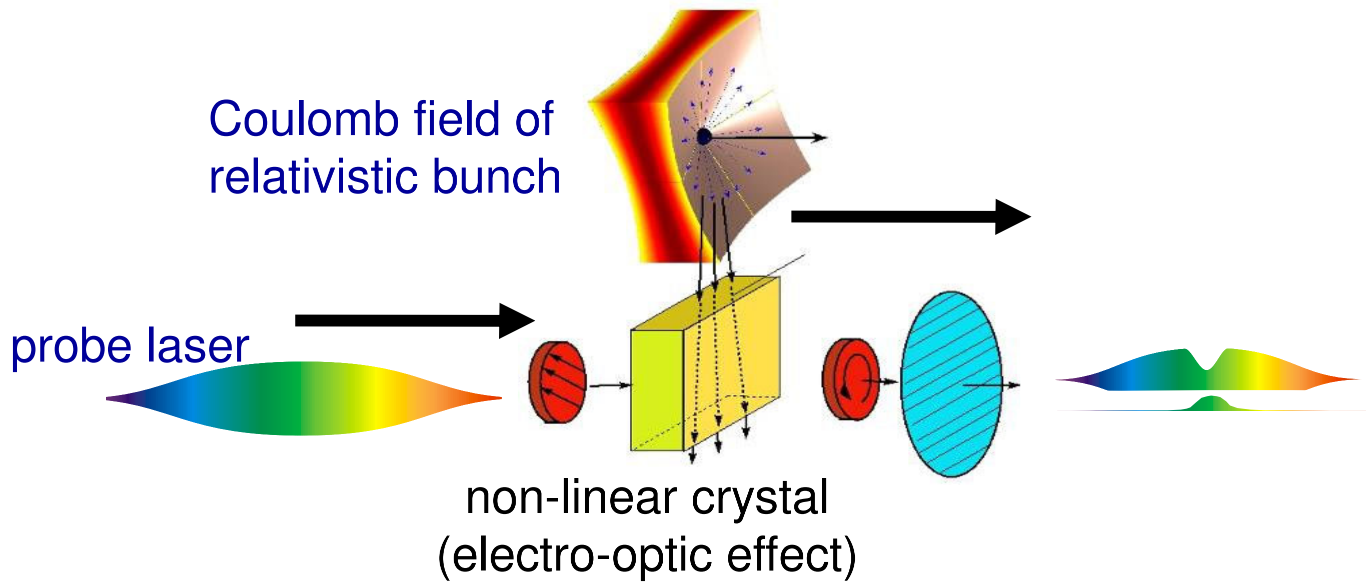


Temporal Decoding

FELIX
DESY
RAL(CLF)
MPQ
Jena

Concept of electro optic profile diagnostic

all-optical intra-beamline pickup of bunch Coulomb field



Decoding
of information
from laser pulse

Encoding

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

Decoding

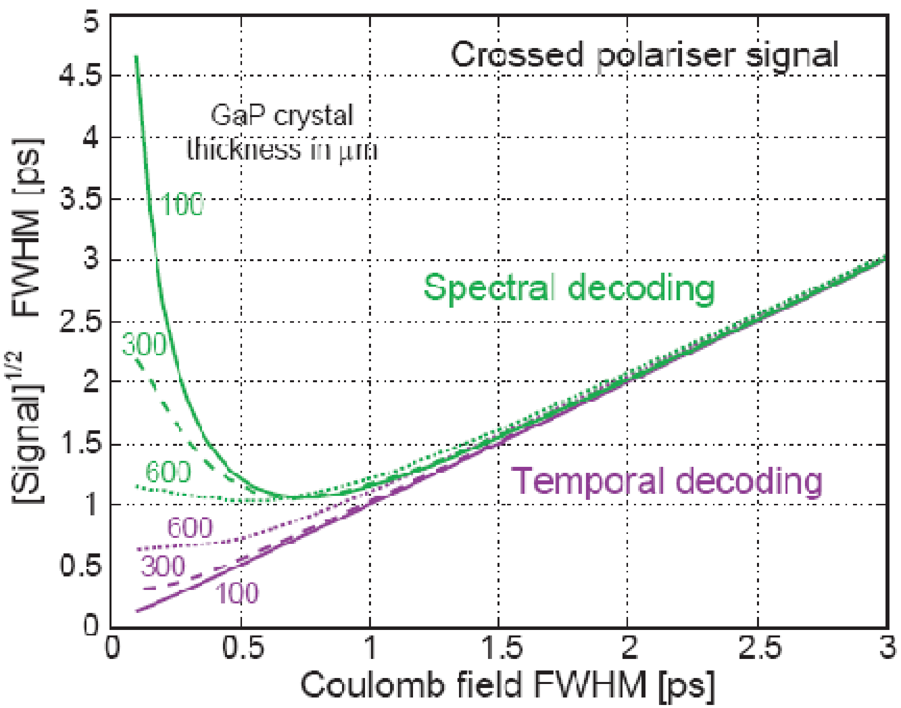
- choices for complexity
- limiting factor for spectral decoding

Spectral decoding 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…

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



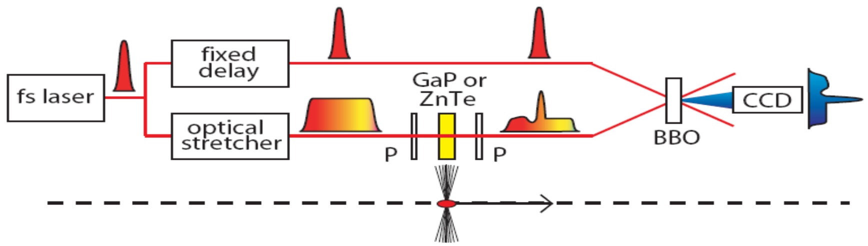
Unlikely to get better than 1.0 ps (FWHM) with spectral decoding

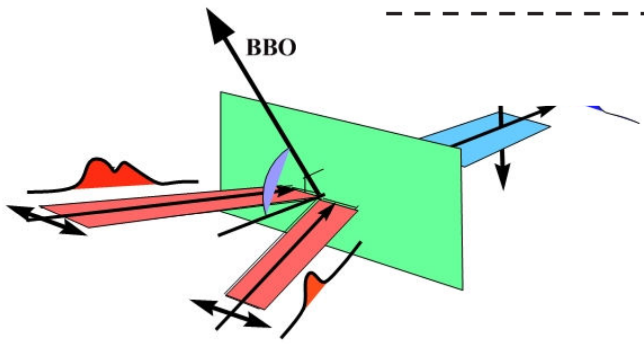
However, still attractive as simplest technique.

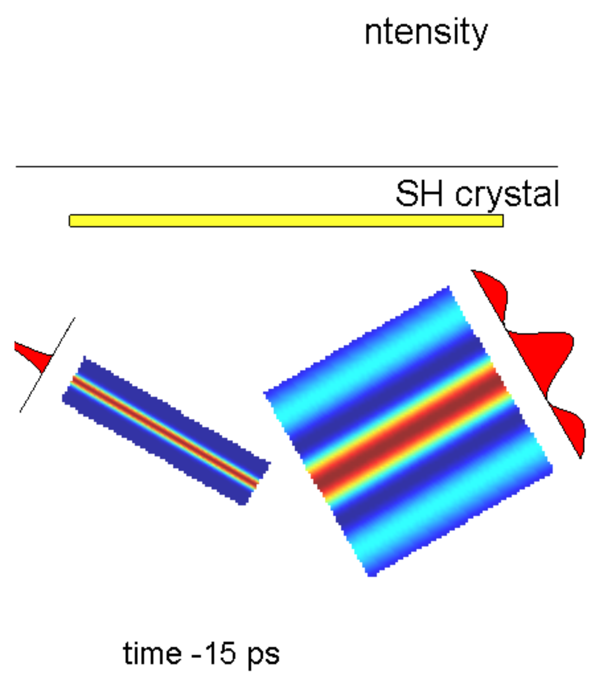
Routinely used for finding signal for higher time resolution techniques

Temporal decoding...

temporal-spatial mapping in 2nd Harmonic Generation







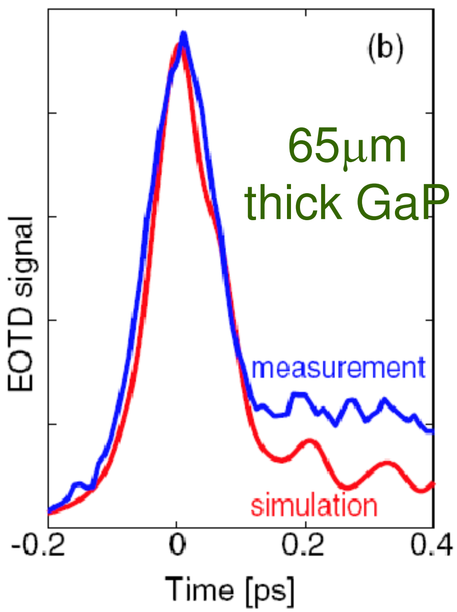
Temporal profile of probe pulse

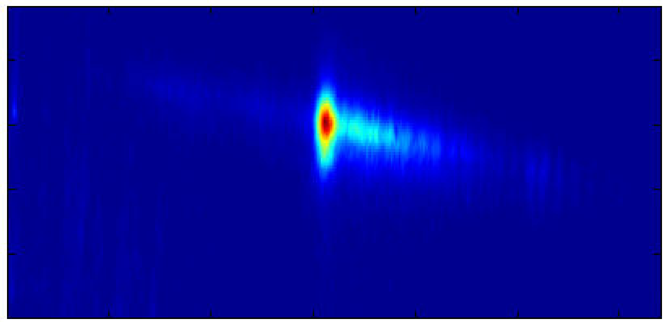
$\Rightarrow$ Spatial image of 2nd harmonic

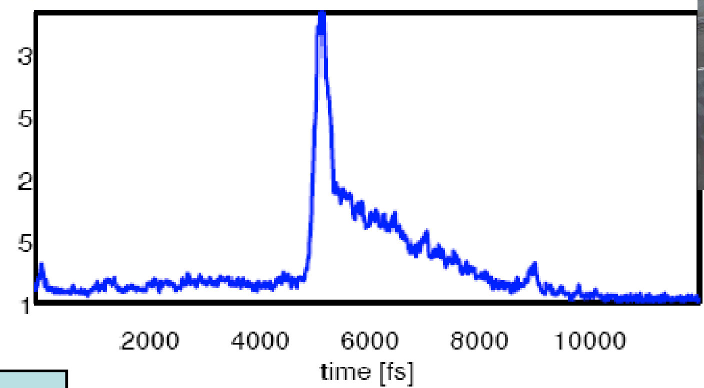
Time resolution set by gate pulse duration (typically <50fs)

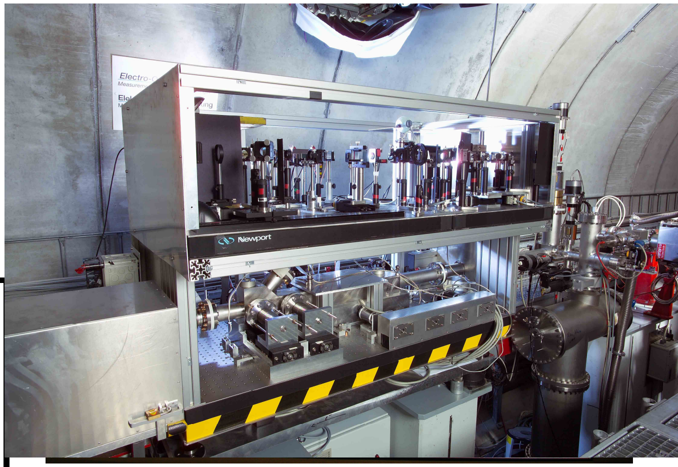
High Time Resolution...

currently the highest time-resolution
non-destructive diagnostic demonstrated







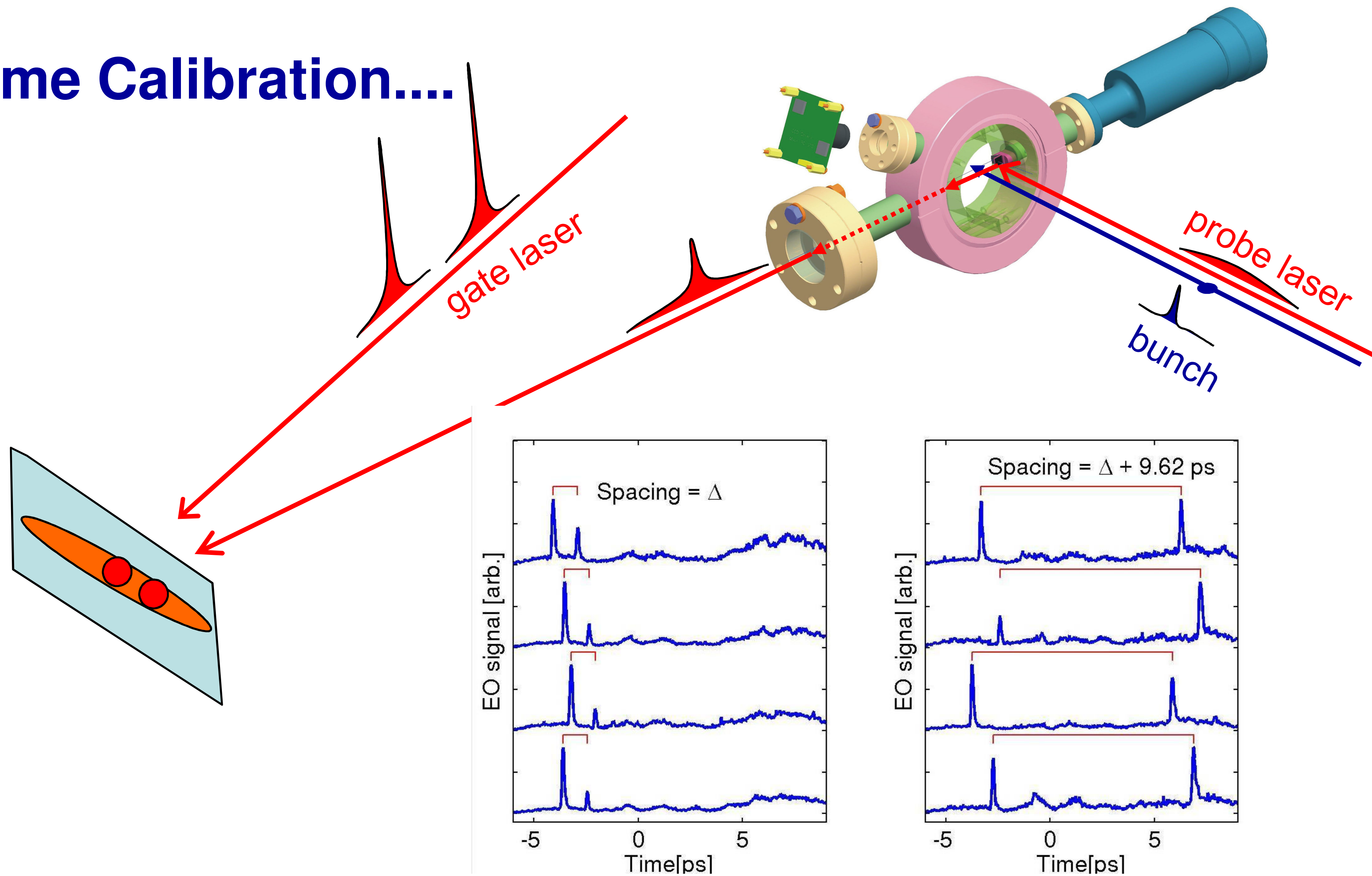


"Time resolution"

σ_z ~ 90fs (rms)

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

Time Calibration....

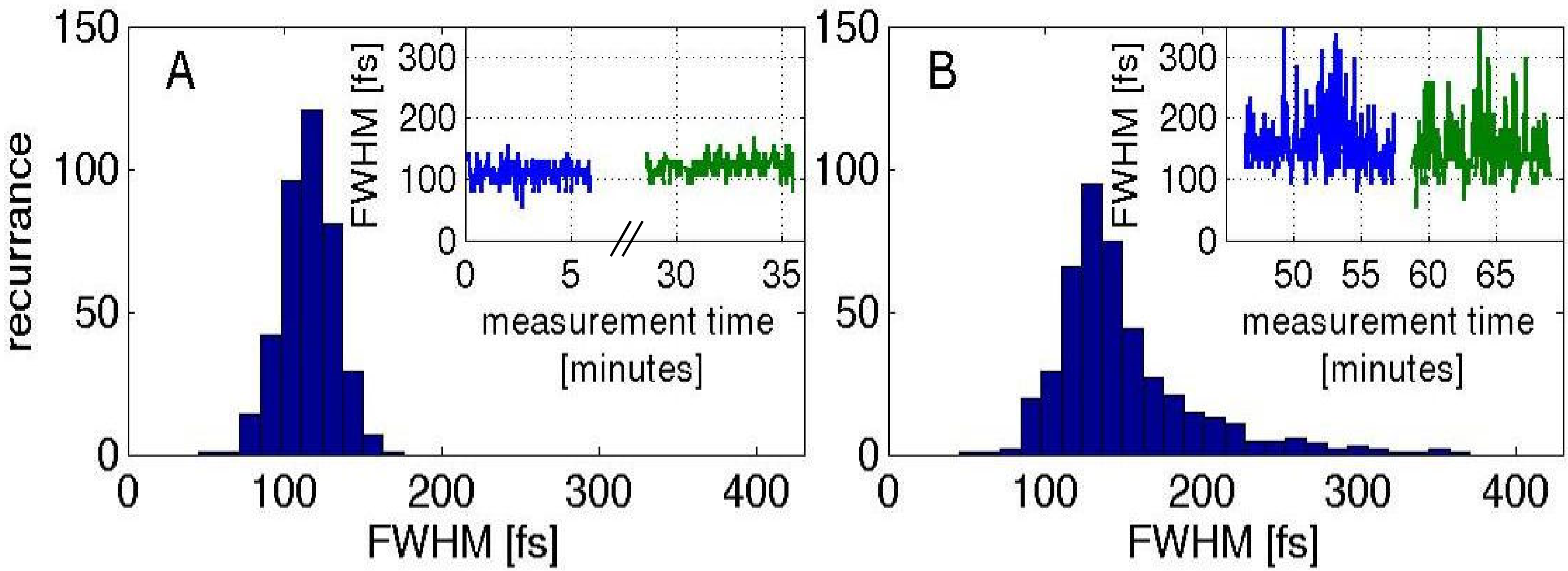


Concept could be used for checking CLIC/CTF3 bunch stacking?

EO confirmation of CDR feedback systems

single shot capability reveals stabilising effect of slow feedback

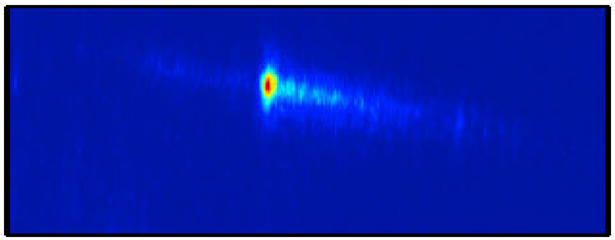
CDR feedback on **CDR feedback off**

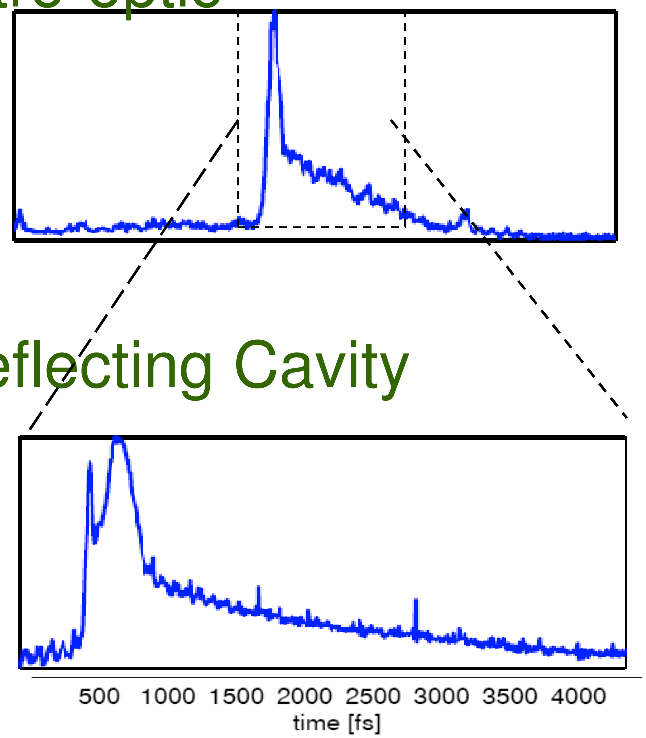


Benchmarking of EO diagnostics

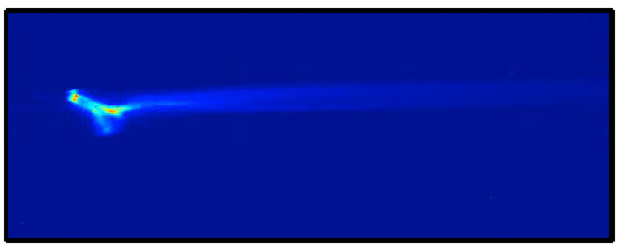
comparison with transverse deflecting cavity

Electro-optic

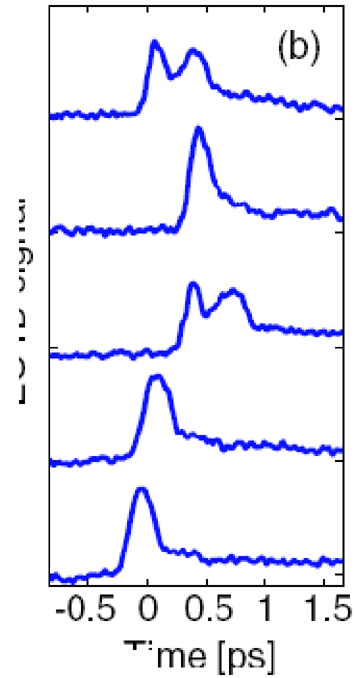




Transverse Deflecting Cavity



shot-shot variations



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, 2009***

So are all 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*

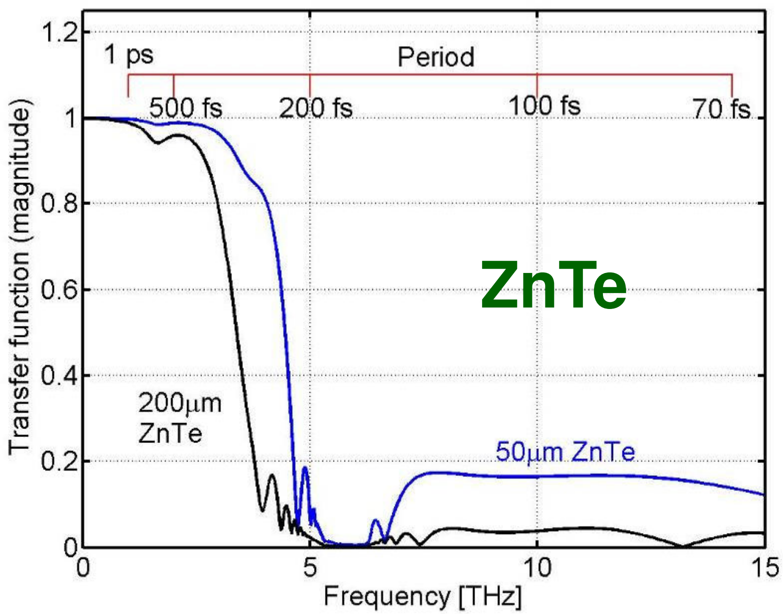
Very higher time resolution (<60 fs rms structure)

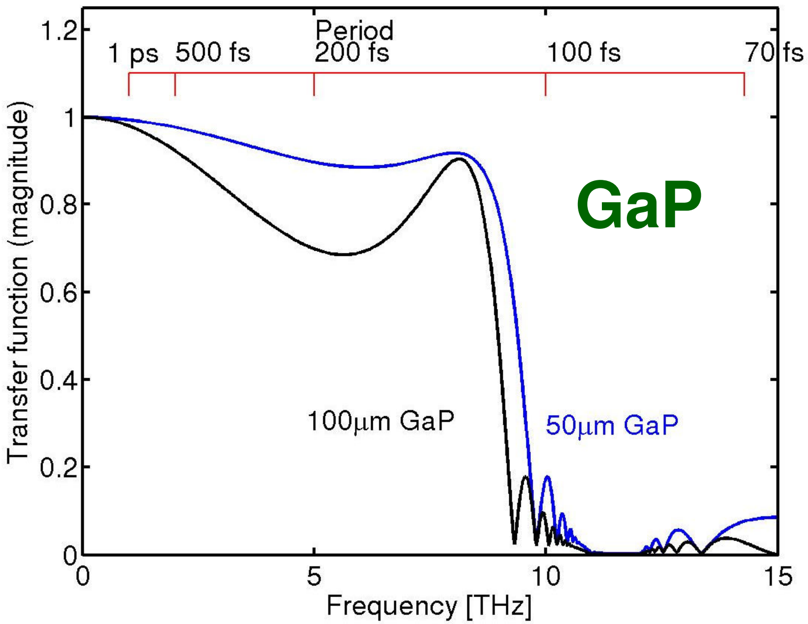
- *limited by EO material properties (& laser)*

Encoding Time Resolution...

material response, R(ω)

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

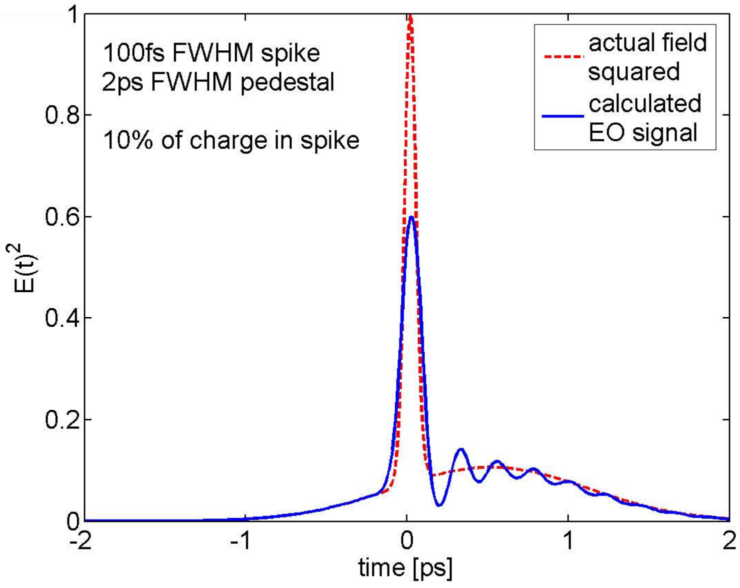


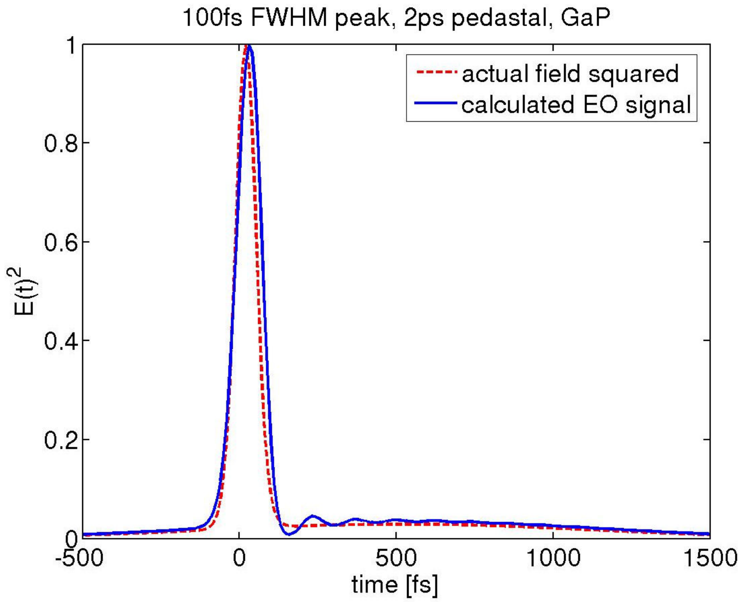


Time resolution from frequency response

- **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 spectral interferometry
- Use FROG Measurement (initially attempted at FELIX, 2004)

or Alternative techniques: spectral upconversion

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

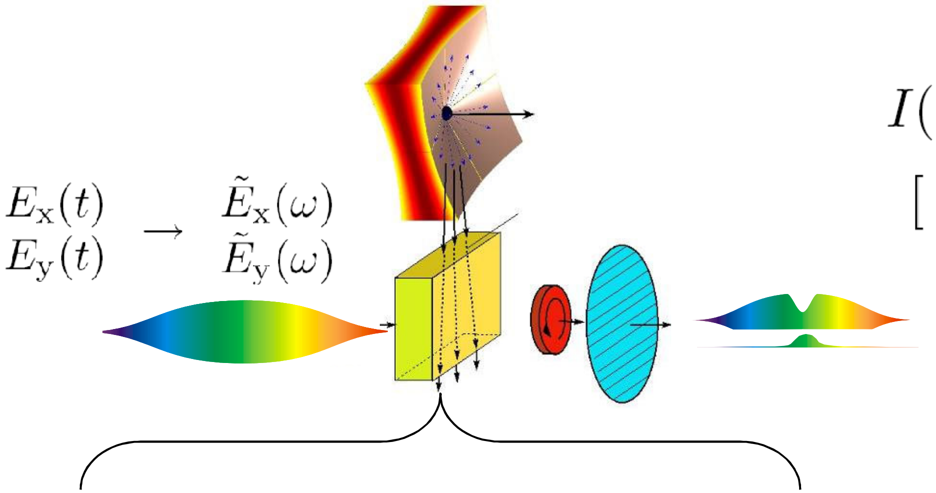
Spectral upconversion diagnostic

Physics of EO encoding...

- shifting Coulomb spectrum to optical region

OR

- creating an optical “replica” of Coulomb field



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

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

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

Coulomb spectrum shifted to optical region

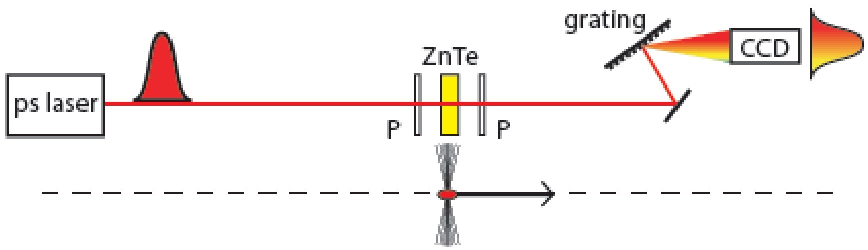
$$E^{\rm opt}_{\rm out}(t) = E^{\rm opt}_{\rm in}(t) + a\left[E^{\rm Coul}(t) * R(t)\right]\frac{\rm d}{{\rm d}t}E^{\rm opt}_{\rm in}(t)$$

Coulomb pulse replicated in optical pulse

envelope **optical field**

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

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

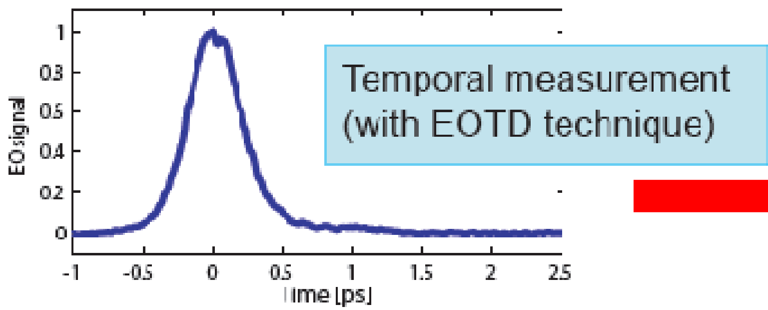
$\rightarrow$ ***δ-function***

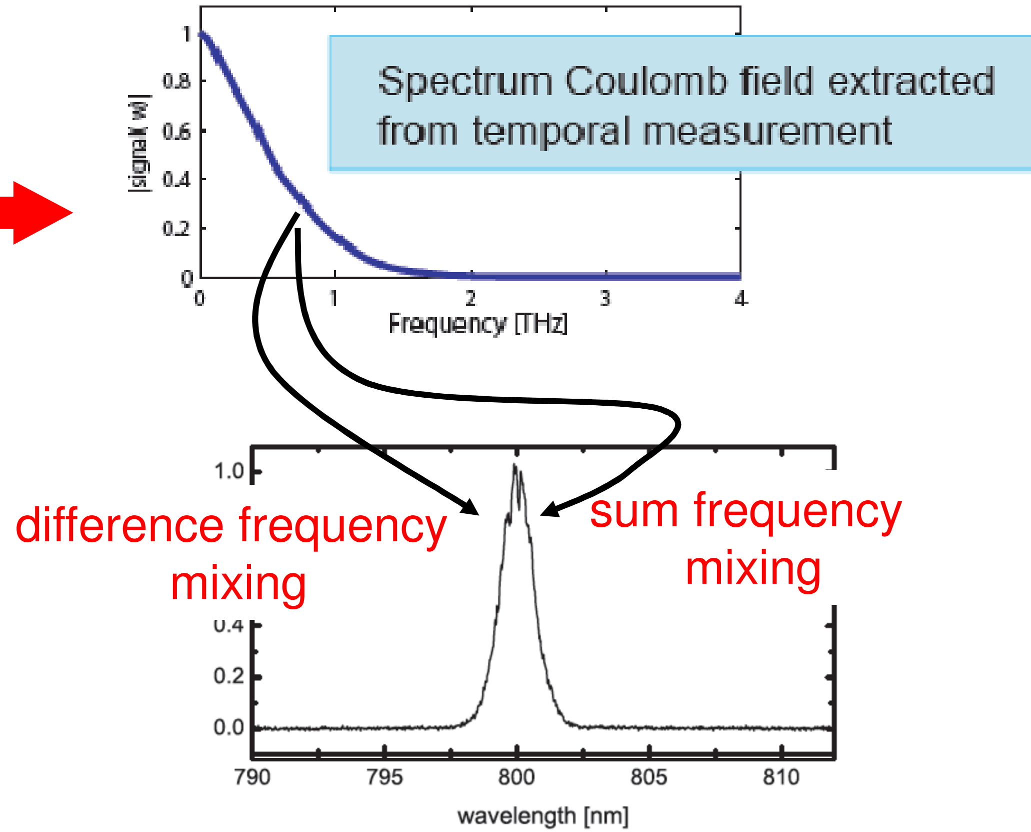
- ***laser complexity reduced, reliability increased***
- ***laser transport becomes trivial (fibre)***
- ***problematic artifacts of spectral decoding become solution***

NOTE: the long probe is still converted to optical replica

Spectral upconversion diagnostic

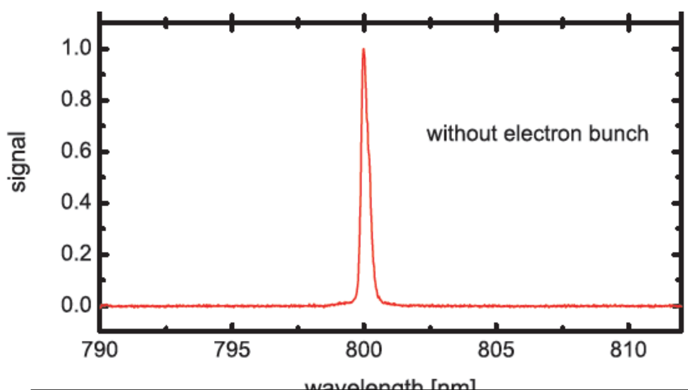
Results from experiments at FELIX (Feb 2009)





with electron interaction

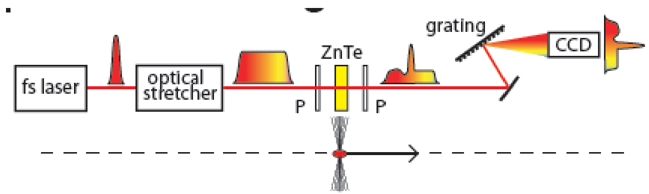
sprectral upconversion

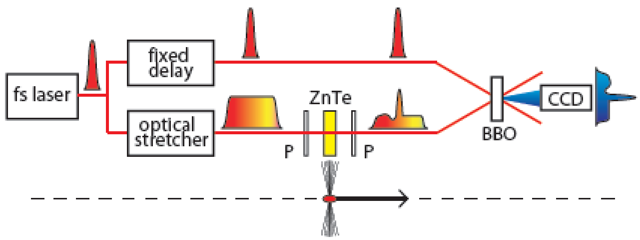


Input narrow band optical probe

and optical replica present if choose to measure it

What's different...?

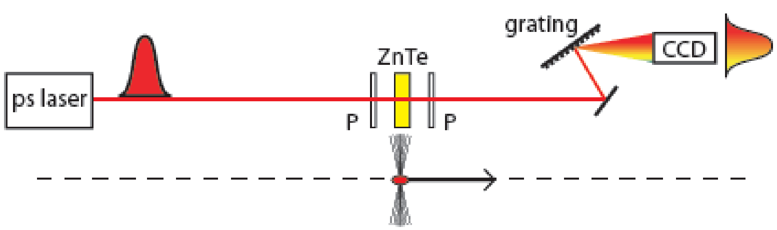




Spectral decoding & Temporal decoding

laser bandwidth >> bunch spectral extent

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



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

Spectral upconversion

laser bandwidth << bunch spectral extent

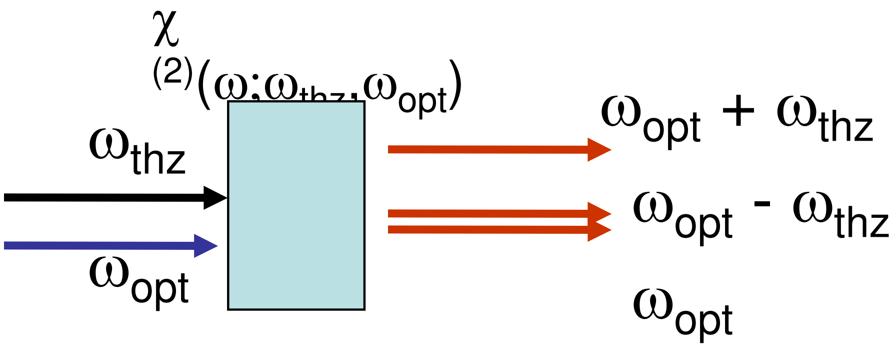
low power, 'simple' lasers OK
fibre transport now an option
simple – linear – spectral detection
without artefacts of spectral decoding

In Summary ...

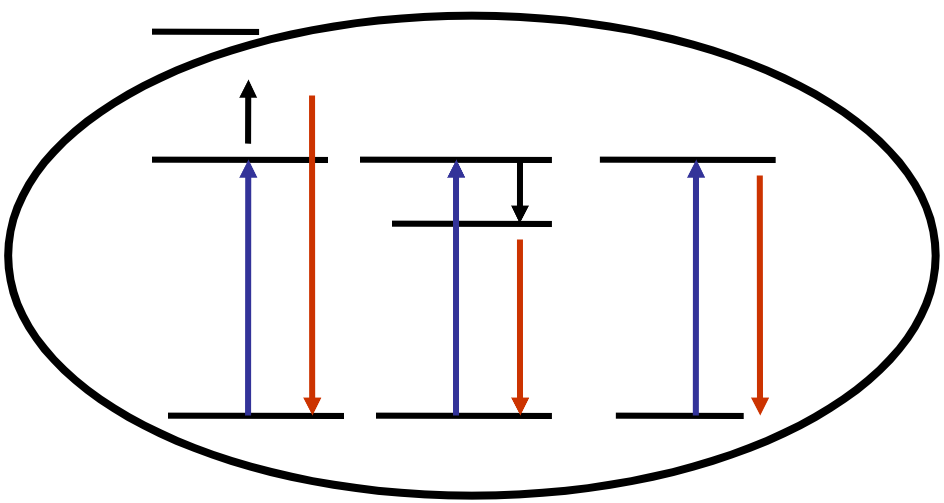
- Proven capability for explicit temporal chractrisation up to ~100 fs RMS electron bunch structure
- high time resolution techniques have problems with reliability & necessary infrastructure...
- ...*but* avenues available for improving time resolution & robustness (dependent on beam diagnostic requirements)
- For high time resolution, both alternative materials & spectral upconversion under investigation

EO Formalism:

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



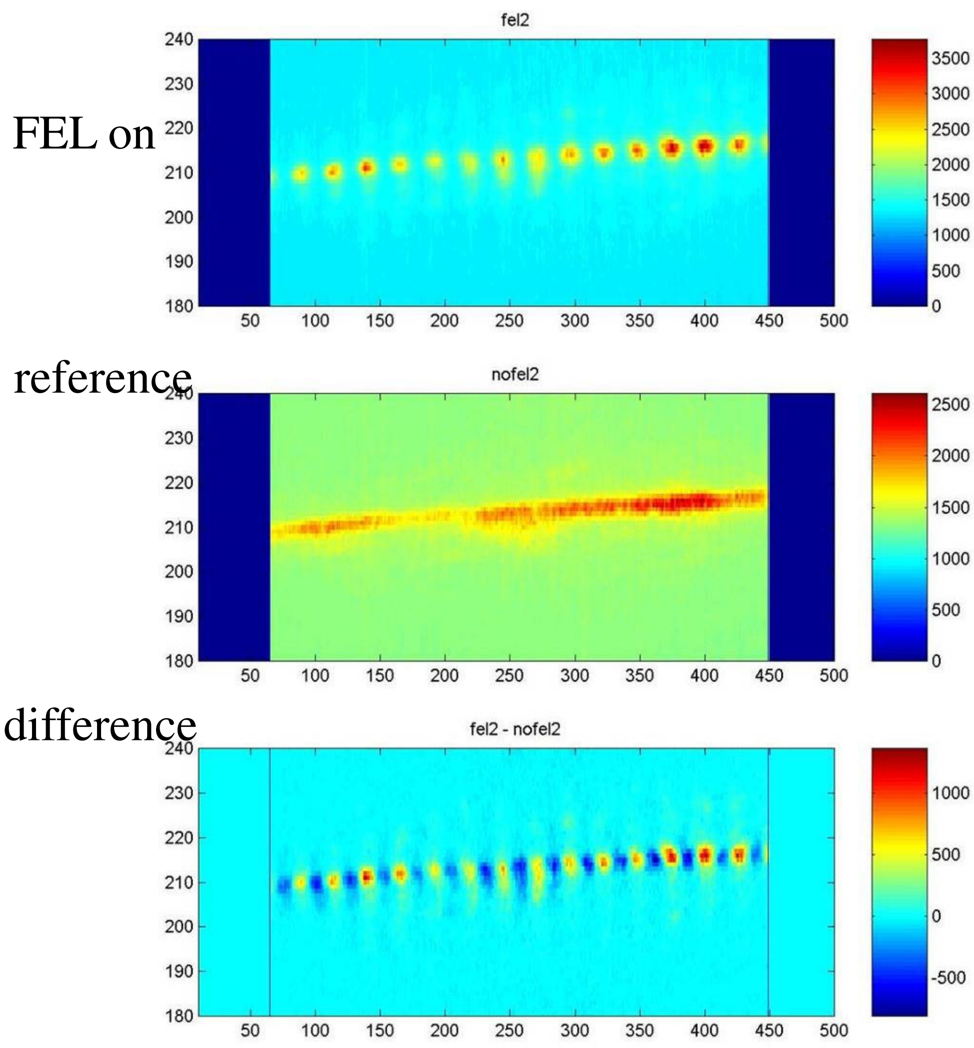
frequency domain description of EO detection...

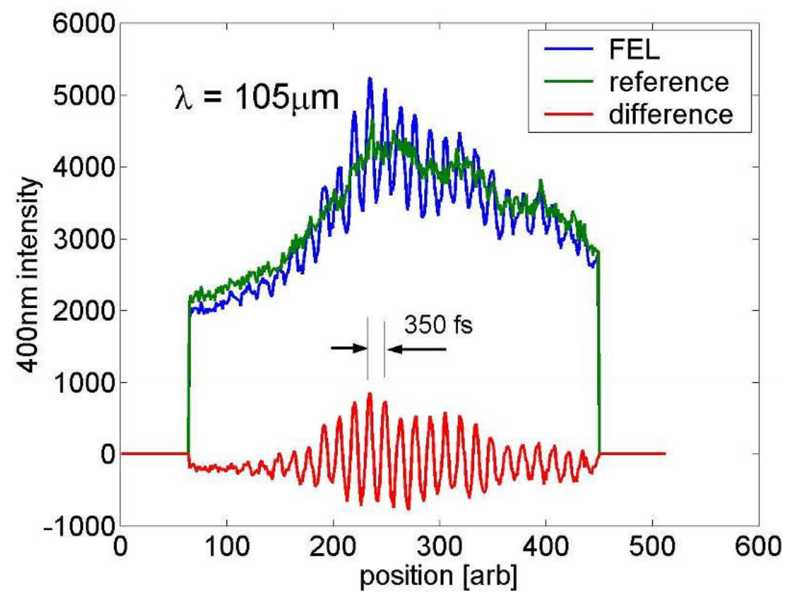


convolved over all combinations of optical and Coulomb frequencies

Electro-optic measurements of FEL radiation

single-shot measurement of THz electric field oscillations



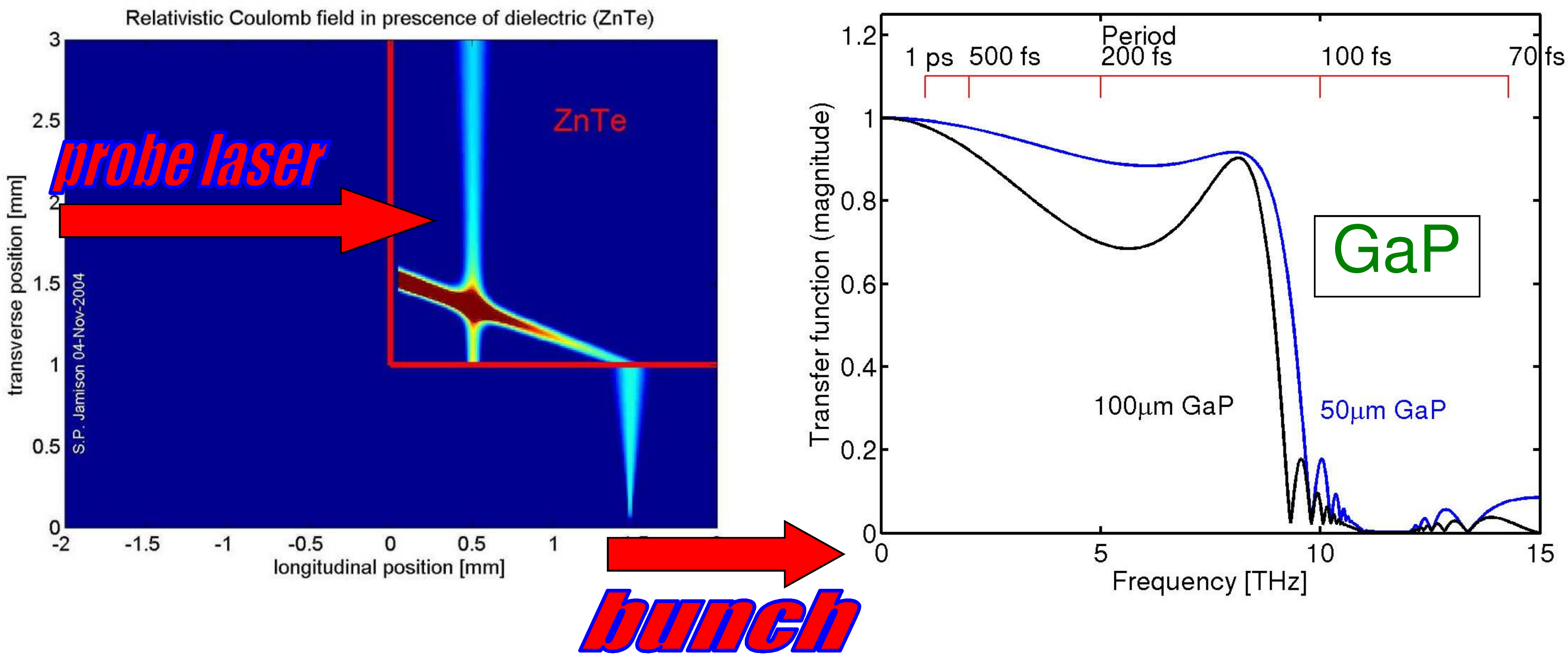


observed down to λ~60μm

opens possibility for
time domain THz spectroscopy
on light accelerator sources.

Encoping Time Resolution...

material response, R(ω)



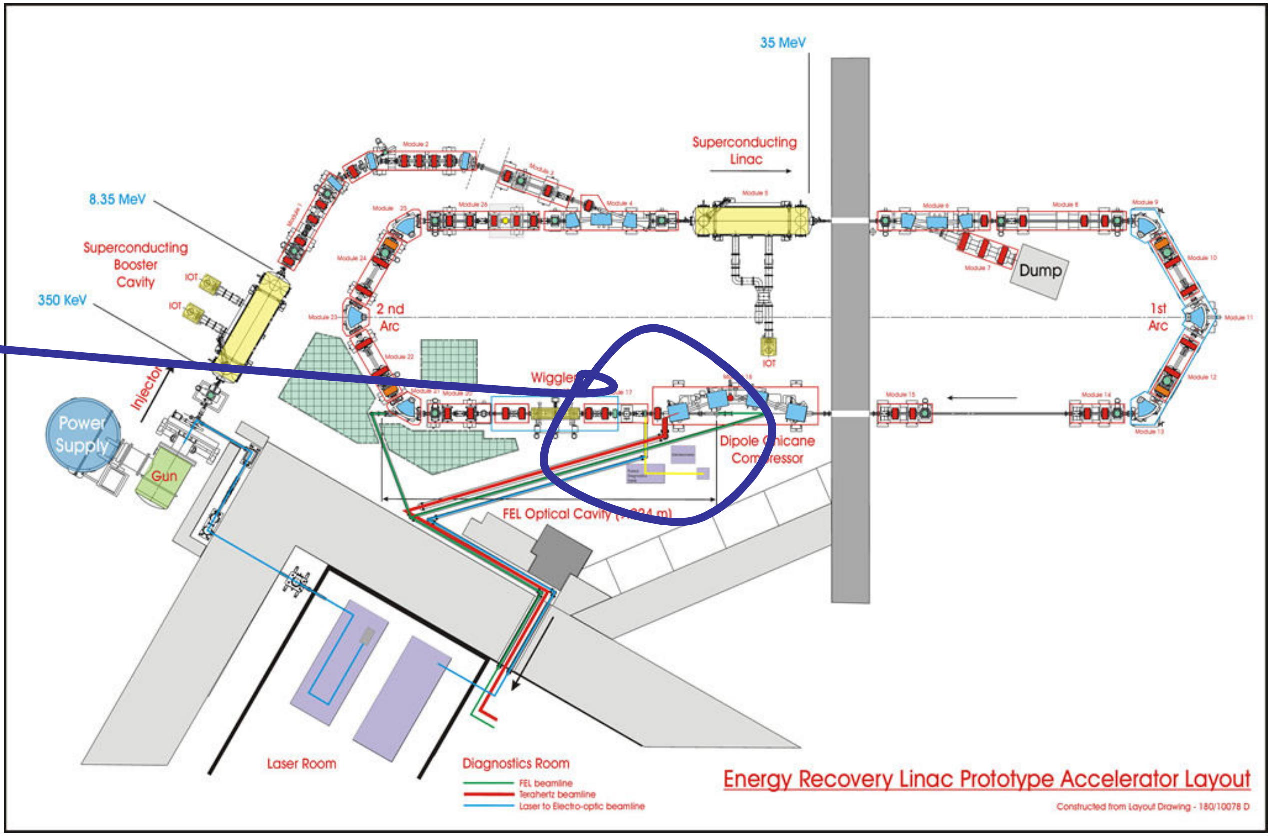
Uniform response <8THz (λ >40 μm)

⇒ Faithful reproduction of > 150 fs (FWHM) bunches

ALICE.... (formerly ERLP)

Accelerator and Lasers in Combined Experiments

Electro-optic diagnostic test-station



Recent progress (last Thursday):

First beam acceleration through the superconducting booster

- expect rapid commissioning of accelerator to follow..
- aiming for EO station up and running in December

High field effects…

"Standard" theory of EO measurement does
not apply for very strong fields

Standard description…

Coulomb field induces refractive index change

$$\eta_{\mathrm{x}}(t) = \eta_0(t) + \alpha_{\mathrm{x}} E_{\mathrm{Coul}}(t)$$

phase retardation

$$E_{\mathrm{x}}(t) \sim E_{\mathrm{x}}(t) \exp(i\omega t - i\eta\omega z/c)$$

Our "standard" description

Frequency mixing of coulomb field

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

new optical field

Both descriptions include assumption of small-signal limit…

(does the "new optical field" itself undergo an EO interaction..?)

High field effects…

Extension to high field considered necessary for ILC...

$$E_{\mathrm{Coul}} \approx \frac{Q}{\sqrt{2\pi}\ \epsilon_0\, r\, \sigma_z} \quad \sim 100\,\mathrm{MV.m}^{-1}$$

fields of this magnitude imply significant retardation .... potentially > π

retardation treatment becomes liable to breakdown

SPPS (SLAC): expect "over-rotation" but not observed

PRL **94,** 114801 (2005) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2005

Clocking Femtosecond X Rays

A. L. Cavalieri,[1] D. M. Fritz,[1] S. H. Lee,[1] P. H. Bucksbaum,[1] D. A. Reis,[1] J. Rudati,[2] D. M. Mills,[2] P. H. Fuoss,[3] G. B. Stephenson,[3] C. C. Kao,[4] D. P. Siddons,[4] D. P. Lowney,[5] A. G. MacPhee,[5] D. Weinstein,[5] R. W. Falcone,[5] R. Pahl,[6]

EO breakdown observed with intense CTR pulses

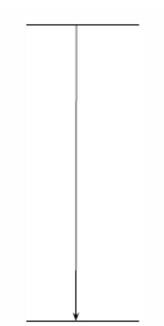
PRL **99,** 043901 (2007) PHYSICAL REVIEW LETTERS week ending 27 JULY 2007

Nonlinear Cross-Phase Modulation with Intense Single-Cycle Terahertz Pulses

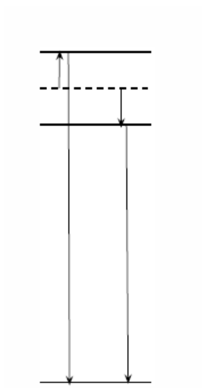
Y. Shen,[1] T. Watanabe,[1] D. A. Arena,[1] C.-C. Kao,[1] J. B. Murphy,[1] T. Y. Tsang,[2] X. J. Wang,[1] and G. L. Carr[1]
[1]*National Synchrotron Light Source, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*
[2]*Instrumentation Division, Brookhaven National Laboratory, Upton, New York 11973-5000, USA*
(Received 27 December 2006; published 23 July 2007)

Development of high-field/large-signal EO theory

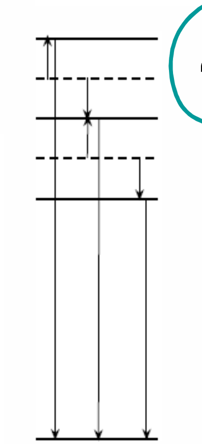
starting point... wave equation with co-propagating non-linear source



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

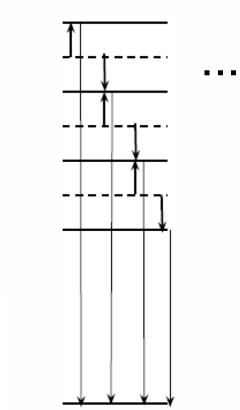


optical “sidebands” in small signal theory



“sidebands” on sidebands

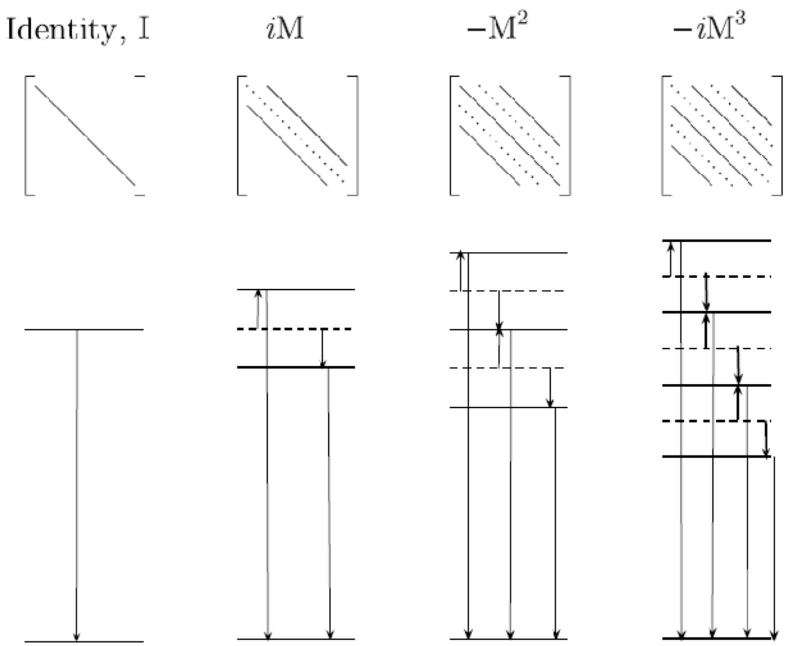
describes probe depletion



...on sidebands

......

...high-field/large-signal EO theory



.....

can associate EO interaction with matrix operation on input probe spectrum

$$\underline{\boldsymbol{A}}(z) = \exp\left[-z\underline{\underline{\beta}}^{\mathrm{opt}} + \frac{\mathrm{i}}{2c\eta}\underline{\underline{\boldsymbol{T}}}(z)\right]\underline{A}_0 \,,$$

where

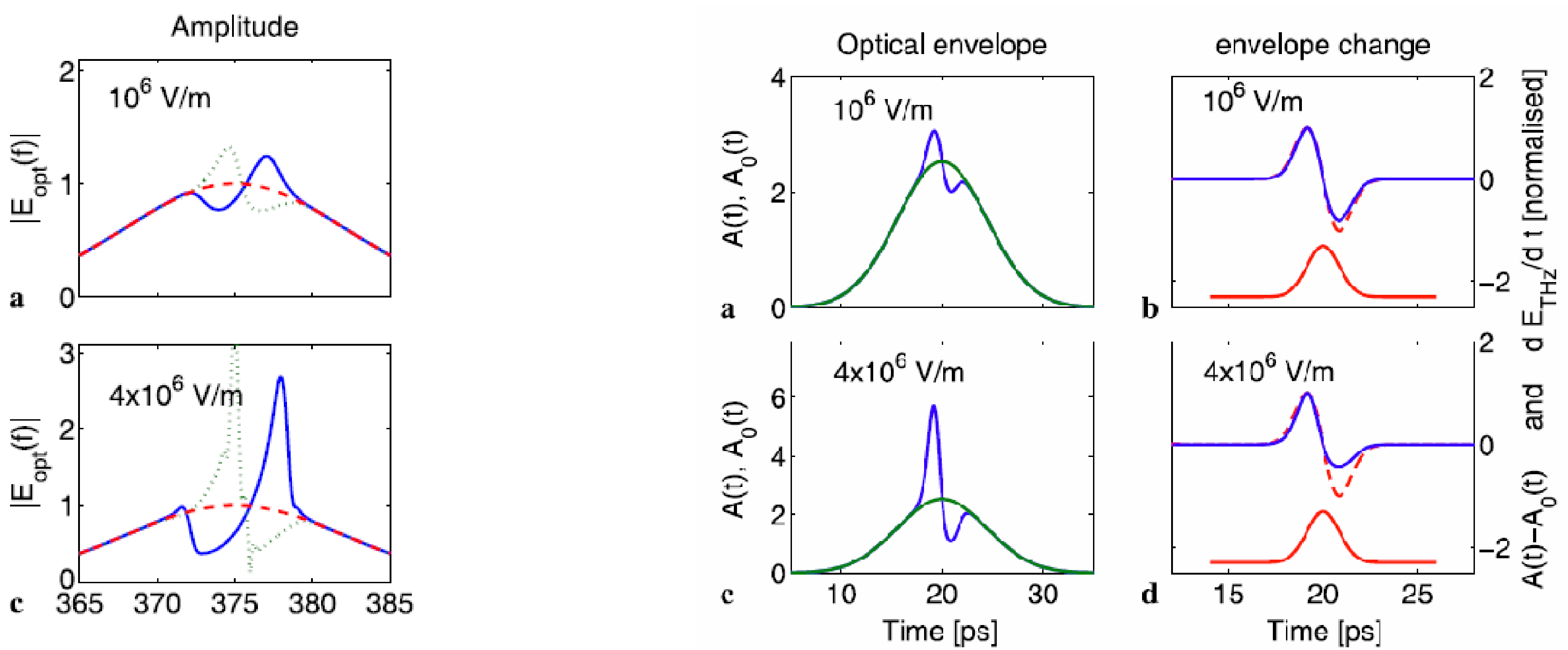
$$\underline{\underline{\boldsymbol{T}}}(z) = \{T_{mn}\} \equiv \left\{M_{mn}^{(0)}\left[\frac{\exp(\mathrm{i}\Delta\widetilde{k}_{(m-n),m}z) - 1}{\mathrm{i}\Delta\widetilde{k}_{(m-n),m}}\right]\right\}$$
$$= \left\{\delta\omega_m\,\chi_{m-n}^{(2)}\,A_{m-n}^{\mathrm{THz}}\left[\frac{\exp(\mathrm{i}\Delta\widetilde{k}_{(m-n),m}z) - 1}{\mathrm{i}\Delta\widetilde{k}_{(m-n),m}}\right]\right\}.$$

End result....

- “simple” matrix exponential solution to probe spectrum
- Fourier transform to get time domain solution

S.P. Jamison. Appl. Phys. B **91,** 241-247, (2008)

Example of high field short-pulse simulation...

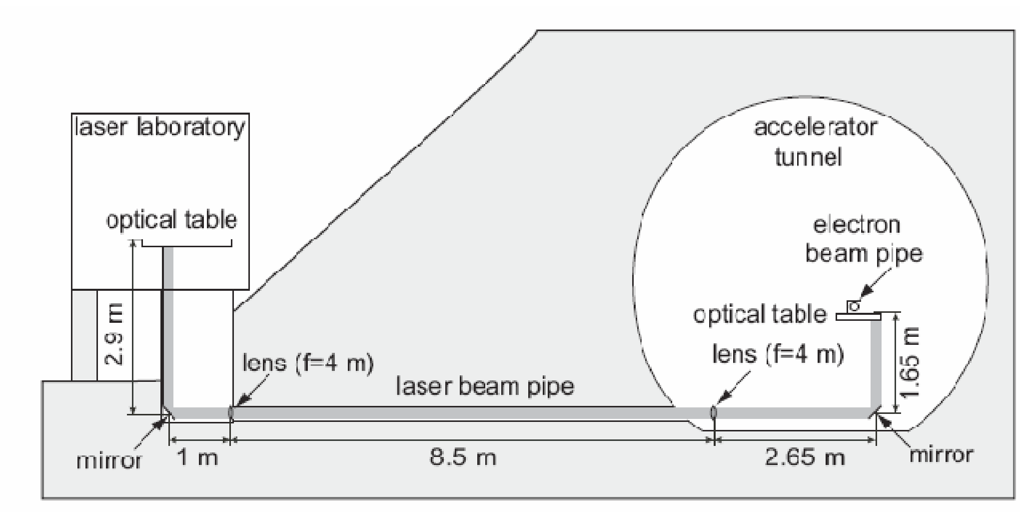


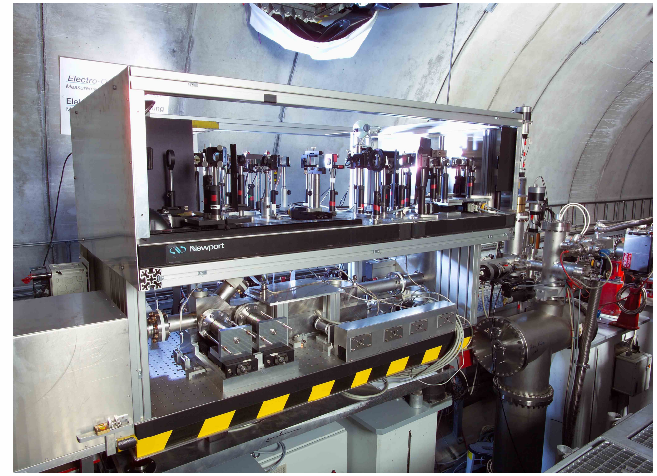
"simple" matrix exponential solution...

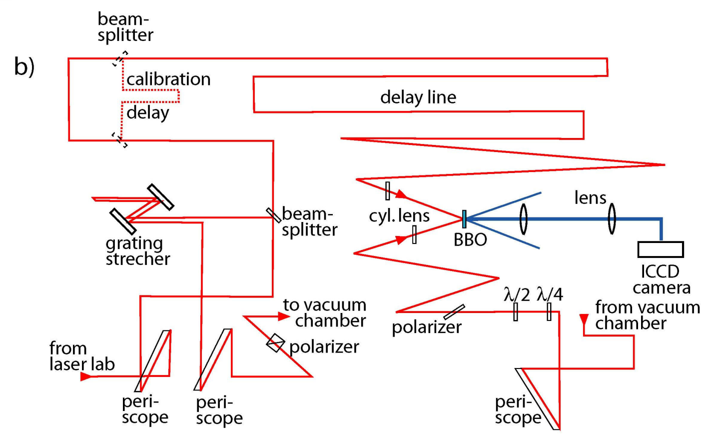
care needed for e.g. 4000x4000 matrix as in above simulation

Laser transport... in FLASH experiments

EO Temporal decoding setup







More complicated setup
Less access to setup in accelerator

- Vacuum laser transport from laser "hut" to tunnel.
- Some relay lenses in transport
- Remote adjustments on many mirrors

Selected References:

Free-electron laser pulse shape measurements with 100fs temporal resolution using a 10fs Ti:sapphire laser and differential optical gating
X.Yan, A.M. MacLeod, W.A.Gillespie et al.
Nucl. Instr. Meths. Phys.Res. Vol A429 (1999) 7- 9

Sub-picosecond electro-optic measurement of relativistic electron pulses
X. Yan, A.M. MacLeod, W.A. Gillespie, G.M.H. Knippels, D. Oepts, A.F.G. van der Meer.
Physical Review Letters 85 (2000) 3404-7

Single-shot electron bunch length measurements
I. Wilke, A.M. MacLeod, W.A. Gillespie, G. Berden, G.M.H. Knippels, A.F.G. van der Meer
Phys. Rev. Lett. 88 No 12 (2002) 124801/1-4

Real-time, non-destructive, single-shot electron bunch-length measurements
G. Berden, S.P. Jamison, A.M .MacLeod, W.A. Gillespie, B. Redlich and A.F.G. van der Meer
Physical Review Letters ***93*** *(2004) 114802*

Temporally resolved electro-optic effect
S.P.Jamison, A.M. Macleod, G. Berden, D.A. Jaroszynski and W.A. Gillespie
Optics Letters ***31****, 11 (2006) 1753-55*

Benchmarking of Electro-Optic monitors for Femtosecond electron bunches
G. Berden, W.A.Gillespie, S.P. Jamison, B. Steffen, V. Arsov, A.M. MacLeod, A.F.G. van der Meer, P.J. Phillips, H. Schlarb, B. Schmitt, and P. Schmüser
Phys. Rev. Lett. 99 043901 (2007)

Electro-optic time profile monitors for femtosecond electron bunches at the soft X-ray free-electron laser FLASH
B. Steffen, V. Arsov, G. Berden, W.A. Gillespie, S.P. Jamison, A.M. MacLeod, A.F.G. van der Meer, P.J. Phillips, H. Schlarb, B. Schmitt, and P. Schmüser
Physical Review Special Topics – Accelerators and Beams 12 032802 (2009)