Femtosecond resolution bunch profile diagnostics

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Femtosecond longitudinal diagnostics

Target applications & requirements

Light sources: Free electron Lasers

kA peak currents required for collective gain

- 200fs FWHM, 200pC (…2008 standard)
- <10fs FWHM , 10pC (2008… increasing interest)

Particle physics: Linear colliders (CLIC, ILC)

Short bunches, high charge, high quality, for luminosity

- ~300fs rms, ~1nC
- stable, known (smooth?) longitudinal profile

Laser-plasma: Acceleration physics

Diagnostics needed for…

- Verification of optics
- Machine tune up
- Machine longitudinal feedback (non invasive)

Significant influence on bunch profile from

Wakefields, space charge, CSR, collective instabilities…

Machine stability & drift $\Rightarrow$ ***must be single shot diagnostic***

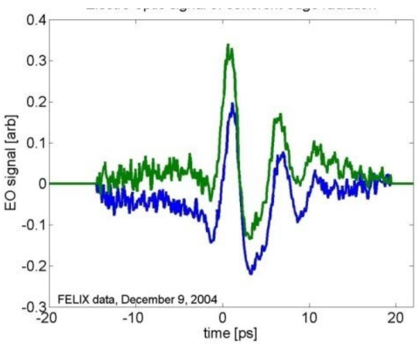
General status of electro-optic...

Many *demonstrations*...

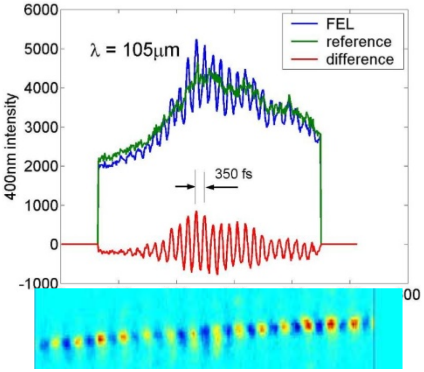
Accelerator Bunch profile - FLASH, FELIX, SLAC, SLS, ALICE, FERMI ....
Laser Wakefield experiments - CLF, MPQ, Jena, Berkley, ...
Emitted EM (CSR, CTR, FEL) - FLASH, FELIX, SLS, ...

Temporal Decoding @FLASH

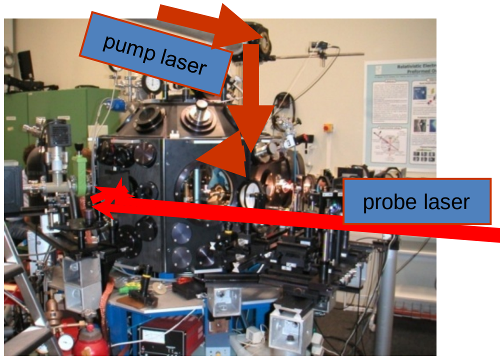
CSR @FELIX



Mid-IRFEL lasing @FELIX



Laser Wakefield
@ Max Planck Garching



Few facility implementations: remaining as experimental / demonstration systems

- Complex & temperamental laser systems
- Time resolution "stalled" at ~100fs Phys Rev Lett **99** 164801 (2007)
  Phys. Rev. ST, **12** 032802 (2009)

EO Current status, future improvements

Low time resolution (>1ps structure)

- spectral decoding offers explicit temporal characterisation
- 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 (phase matching, GVD, crystal reflection)
- Laser pulse duration (TD gate, SE probe)

Accelerator wish list - Missing capabilities

- o Higher time resolution (20fs rms for light sources, CLIC)
- o Higher reliability, lower cost (high resolution systems)
- o Solution for feedback.

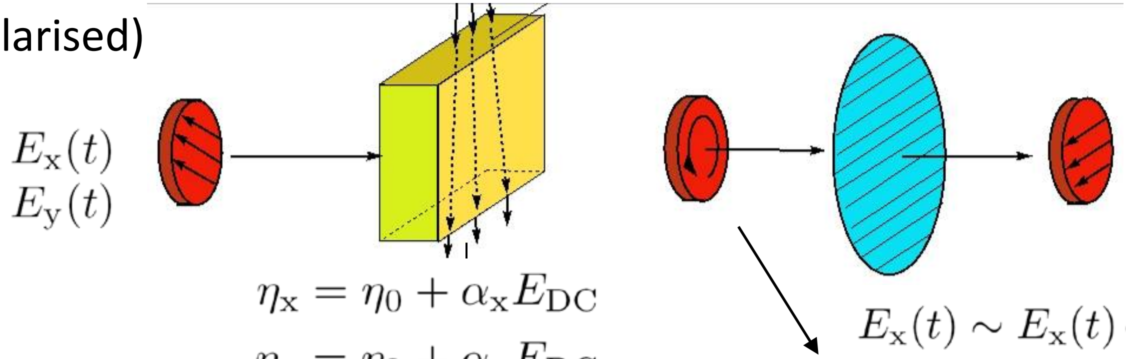
Concept of Electro-optic detection..

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

laser pulse
(linear polarised)

elliptically
polarised

intensity dependent
on ‘DC’ field strength



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

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

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

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

This doesn’t describe chirped pulse interaction with ultra-short THz pulses...

Wave equation for $\chi^{(2)}$ frequency mixing

non-linear properties

$$\left[\frac{\partial}{\partial z} + \beta^{\mathrm{opt}}(\omega)\right]\widetilde{A}(\omega, z) = \frac{\mathrm{i}\omega}{2c\eta} \times \int_{-\infty}^{\infty} \mathrm{d}\Omega\, \chi^{(2)}(\omega; \Omega, \omega - \Omega) \times \underbrace{\exp[\mathrm{i}\Delta k(\Omega, \omega)z - \beta^{\mathrm{THz}}(\Omega)z]}_{\text{linear material properties}}\widetilde{A}_{\mathrm{THz}}(\Omega)\widetilde{A}(\omega - \Omega, z)\,.$$

sum & difference mixing included

Coulomb / THz field

input optical field

Simple solution within small signal approximation...

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

where material properties define an “effective” THz field....

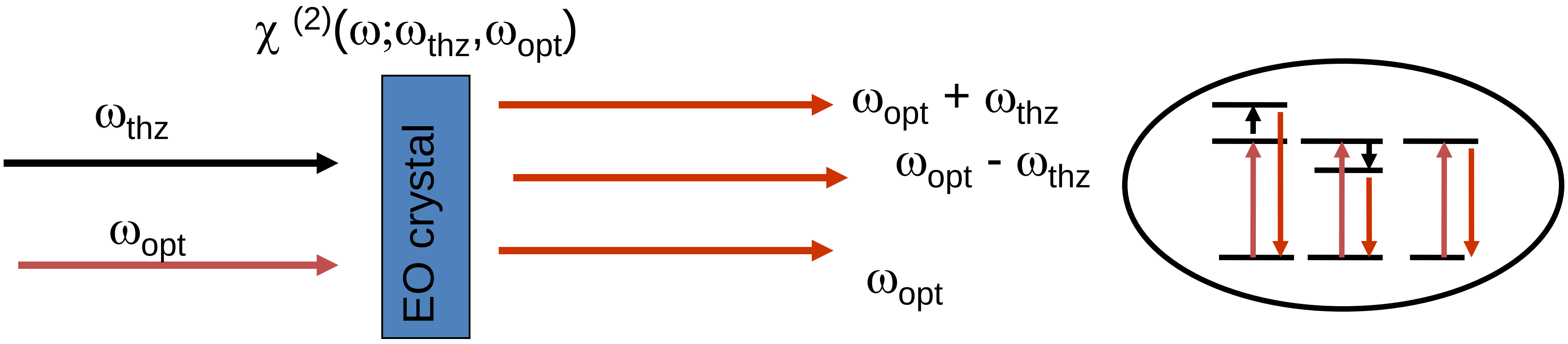
$$\widetilde{A}^{\mathrm{THz}}_{\mathrm{eff}}(\omega) \equiv \widetilde{A}^{\mathrm{THz}}(\omega)\chi^{(2)}(\omega)\left[\frac{\exp(\mathrm{i}\Delta\widetilde{k}(\omega, \omega^{\mathrm{opt}})z) - 1}{i\Delta\widetilde{k}(\omega, \omega^{\mathrm{opt}})}\right]$$

Very general... describes CW, ultrafast transform limited and arbitrarily chirped pulses

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

Electro-optic detection bandwidth

description of EO detection as sum- and difference-frequency mixing



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

ω_{thz}

ω_{opt}

EO crystal

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

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

ω_{opt}

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

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)

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

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

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...

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

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

temporal
sampling
of THz field

Monochromatic
THz & optical

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

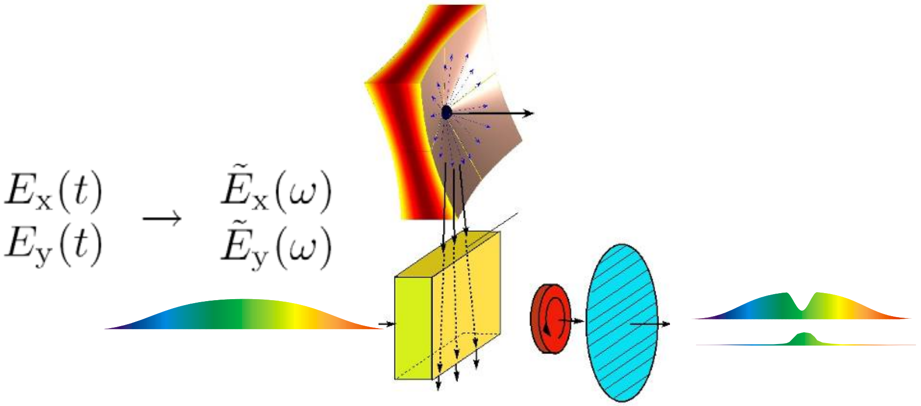
$$\tilde{A}_0(\omega_0) + i\alpha\tilde{A}_0(\omega_0 - \Omega) + i\alpha\tilde{A}_0(\omega_0 + \Omega)$$

optical
sidebands

Chirped optical

Parameter dependent results

Limitations of measurement interpretation



Polarisation rotation

- Phase shift from addition of probe and $\chi^{(2)}$ generated wave
- Rotation from distinct phase shift in differing probe components

Polarisation Interpretation assumes Coulomb field shorter than probe pulse (τ_{coulomb} > 50fs)

... Solution is in attention to interpretation

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

Coulomb spectrum shifted to optical region

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

Coulomb pulse replicated in optical pulse

Limitations of materials

Laser co-propagating with Coulomb pulse

Free-space

Electro-optic crystal

Movie (maybe!)

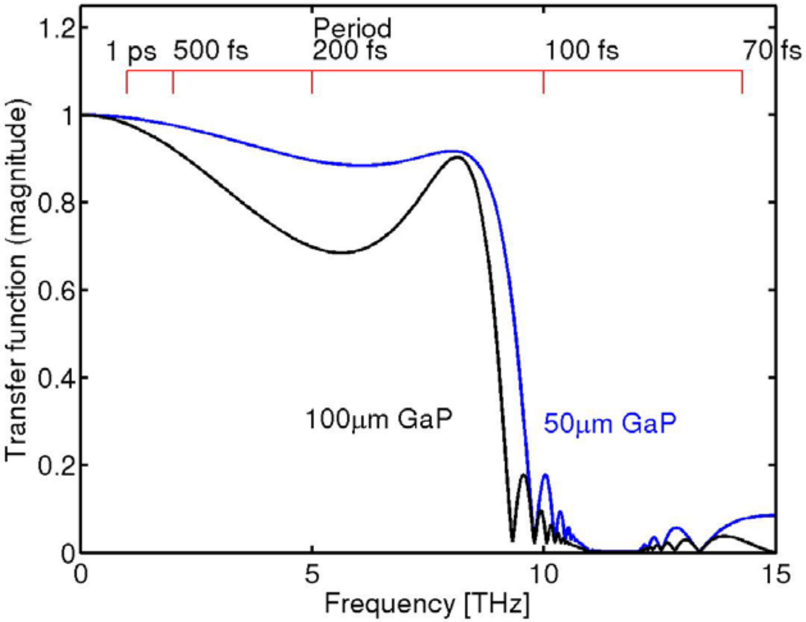
300 um

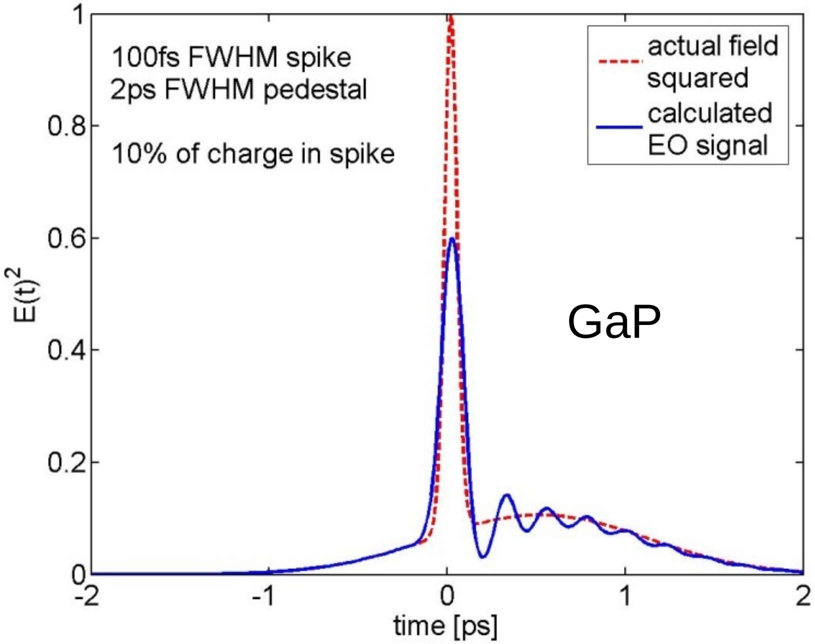
Longitudinal Position, z

Encoding issues…

- Coupling of Coulomb pulse into non-linear material
- Distortion of Coulomb pulse as it propagates in material
- slippage between Coulomb pulse and optical replica
- Bandwidth of upconversion to optical

…Limitations of materials





“Standard” materials (ZnTe, GaP,...) bandwidth limited to <10 THz

[$t_{coulomb} > 100\text{fs}$]

Crystal limits come from unavoidable phone bands

- 5 – 15 THz
- crystal specific

THz - optical phase matching possible because of these bands!

…Limitations of materials

Potential solution to *bandwidth* problem in multiple crystal detection

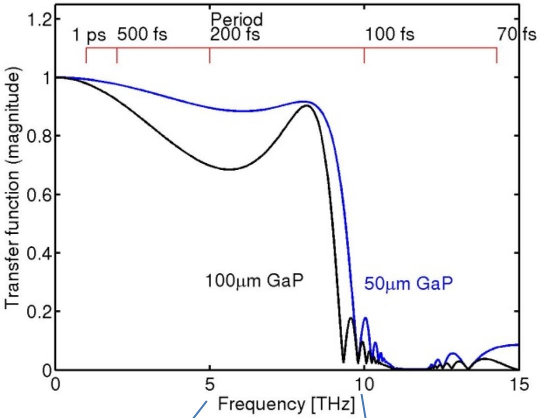
1ps 100 fs 20 fs 5 fs

GaP "standard"

Plus

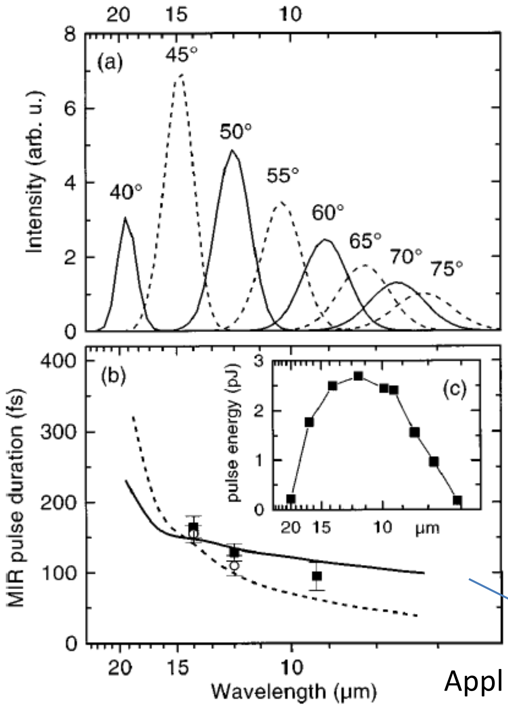
GaSe,
angle tuned response

Plus



60 um

30 um



BBO, KTP, ...
standard
mid-IR / near IR
laser characterisation

from Kaindl et al,
Appl Phys Lett **75** 1060 (1999)
[THz generation is
inverse of THz detection.]

Multiple crystal detection

Significant implementation and interpretation issues

Implementation

- Distinct crystal detection in parallel
  (stacking of crystals = distortion of Coulomb)
- Multiple laser beams and laser detection...

complexity increase

Complexity can be addressed for frequency domain techniques
(spectral upconversion)
Unclear feasibility for explicit time-domain techniques

Interpretation - splicing of data ?

- Frequency domain straightforward
- Explicit time domain ??

Novel materials

Polymer materials: Known electro-optic materials with

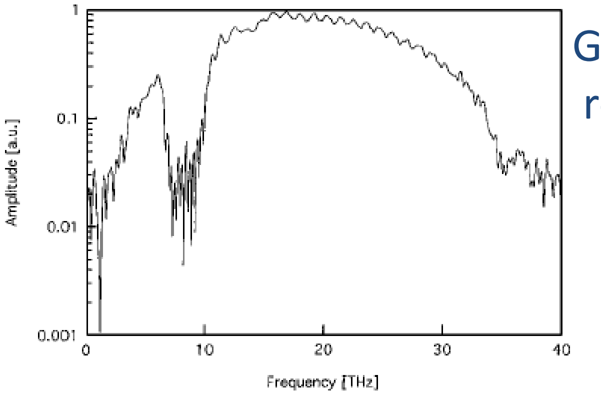
- extremely broad bandwidth
- absence of phonon- resonance cutoffs

Unexplored in accelerator context:

Radiation stability concerns not tested....worthy of investigation

(is there an electro-optic equivalent of Kapton?)

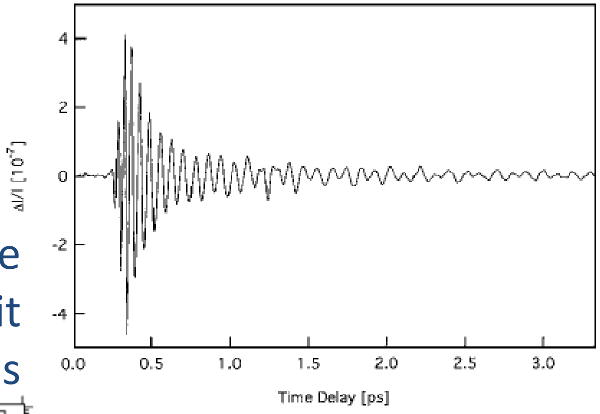
Response for poled “MA9”
Cao et al. Opt Lett (2002)



Good frequency response possible

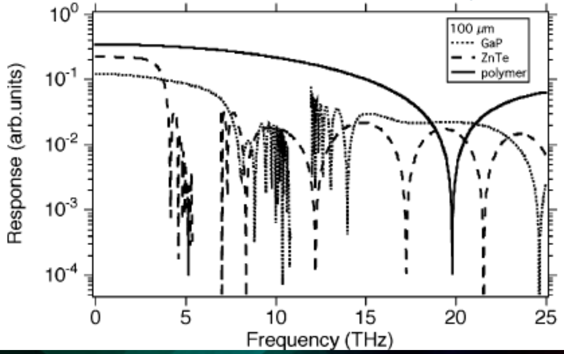
BUT...

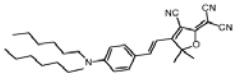
dispersion still an issue for temporal explicit techniques



...as examples of achievable response, rather than proposed samples

Sinyukov et al.
J. Chem Phys B (2004)





DCDHF-6-V
μ = 12.7 Debye,
FOM = 1.7 x Lemke

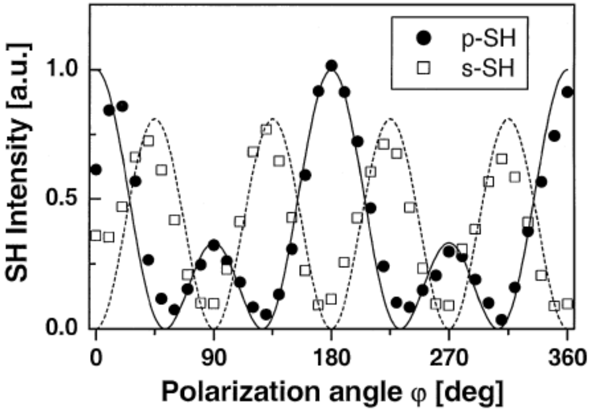
Novel materials

Surface layers

Avoiding propagation /phase matching issues

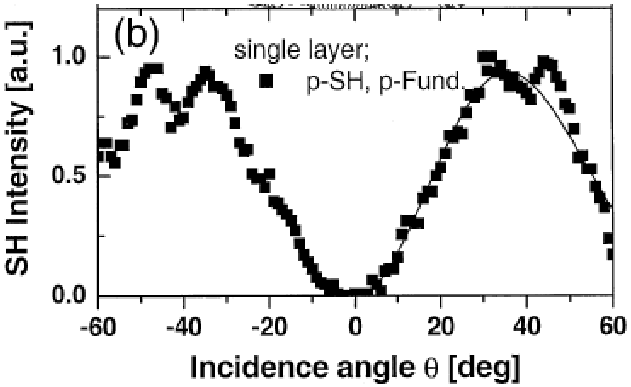
Candidate system: Surface Ellipsoidal nano-particles in dielectric surface

Second harmonic generation
=> $\chi^{(2)}$ active



From Podliensky et al
Opt Lett (2003)

But not suitable for normal incidence
(OK for spatial encoding)



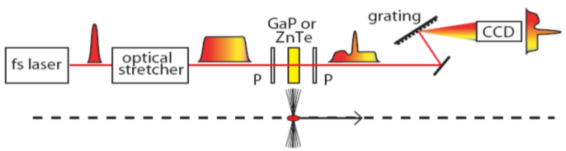
Speculative – THz mediated second harmonic $\chi^{(3)}$
2xoptical + THz -> optical

- o sample preparation at University of Dundee,
  (Maps, material processing group)
- o Laser-lab based Electro-Optic characterisation at Daresbury

Electro-Optic Techniques...

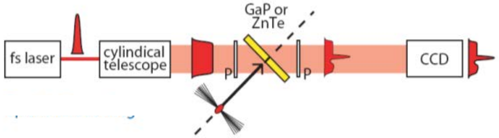
Variations in read-out of optical temporal signal

Spectral Decoding



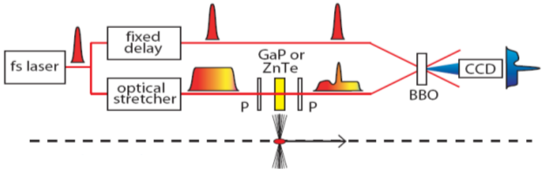
o Chirped optical input
o Spectral readout
o Use time-wavelength relationship

Spatial Encoding



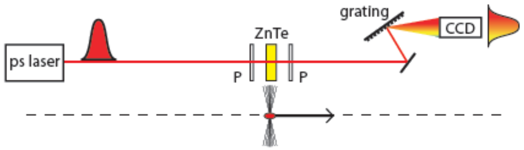
o Ultrashort optical input
o Spatial readout (EO crystal)
o Use time-space relationship

Temporal Decoding



o Long pulse + ultrashort pulse gate
o Spatial readout (cross-correlator crystal)
o Use time-space relationship

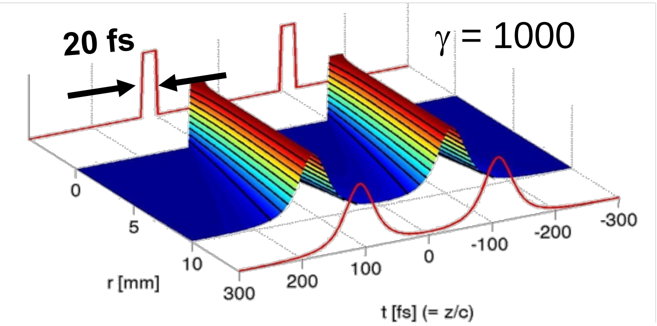
Spectral upconversion**

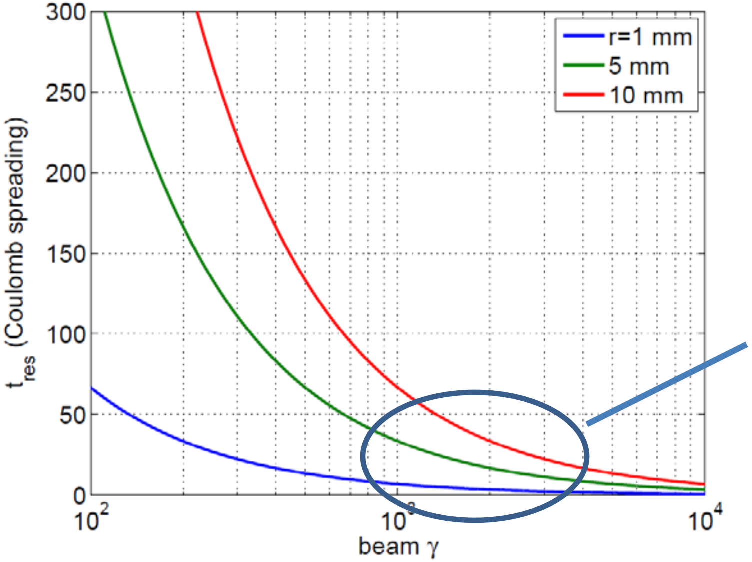


o monochomatic optical input (long pulse)
o Spectral readout
o ***Implicit time domain information only*

Non-invasive 20fs resolution ?

Field radiated or probed related to Coulomb field near electron bunch





20fs resolution
only obtainable
For >1GeV beams

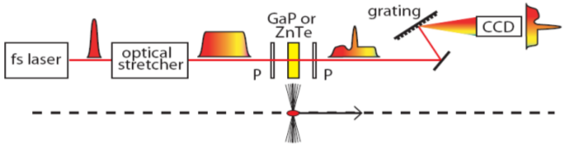
Time response & Spectrum of field dependent on spatial position:

$\delta t \sim 2R/c\gamma$

Ultrafast time resolution needs close proximity to bunch

(equally true of CDR, Smith-Purcell, Electro-optic etc)

Spectral decoding…

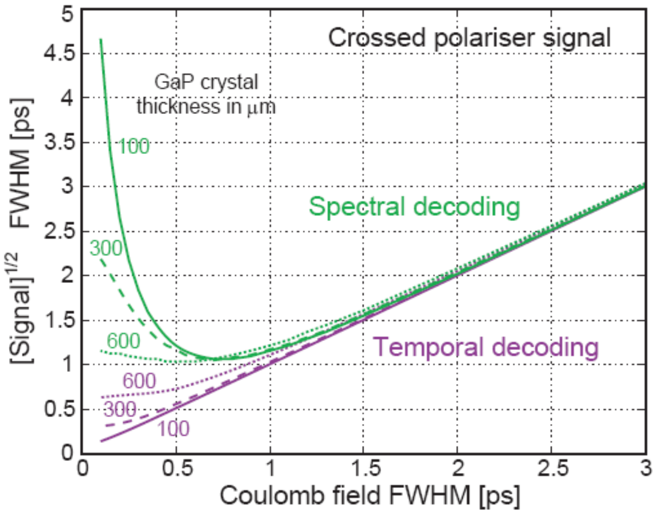


Attractive for technical simplicity, cost.
High rep-rate, low pulse energy lasers suitable
Synchronisation requirements relaxed

temporal resolution limits…

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

For specific laser profiles, can relate to FWHM durations…

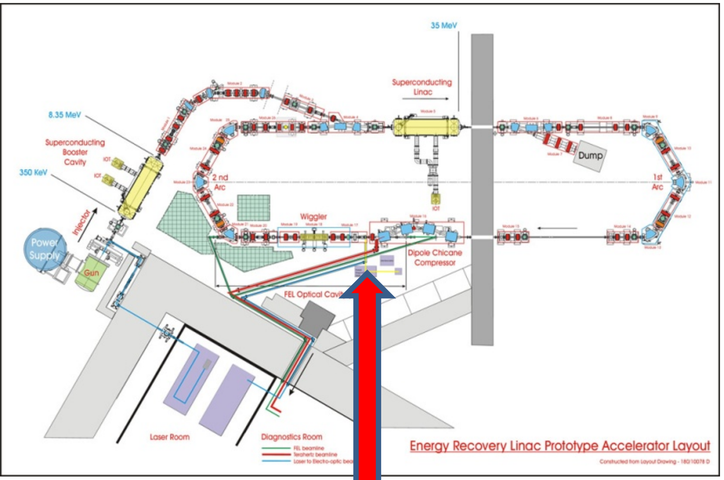


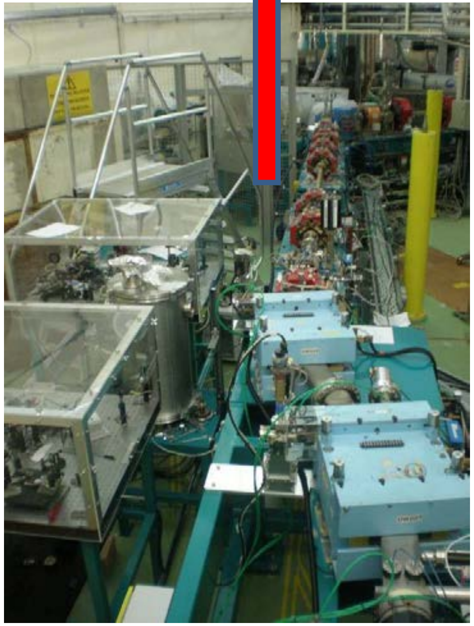
$$\tau_{\mathrm{lim}} = 2.61\sqrt{T_0 T_c} \quad ; \text{ for a Gaussian pulse}$$

Can resolution limits be overcome?

$$\begin{aligned} S^{BD}(\omega) &\equiv I^{\mathrm{in}}_{\mathrm{opt}}(\omega) - I^{\mathrm{in}}_{\mathrm{opt}}(\omega) \\ &\propto I^{\mathrm{in}}_{\mathrm{opt}}(\omega)\left\{E_{\mathrm{Coul}}(\tau + t_0) * \cos\left(\frac{\tau^2}{4\beta} - \frac{\pi}{4}\right)\right\}. \end{aligned}$$

ALICE Electro-optic experiments





- Energy recovery test-accelerator

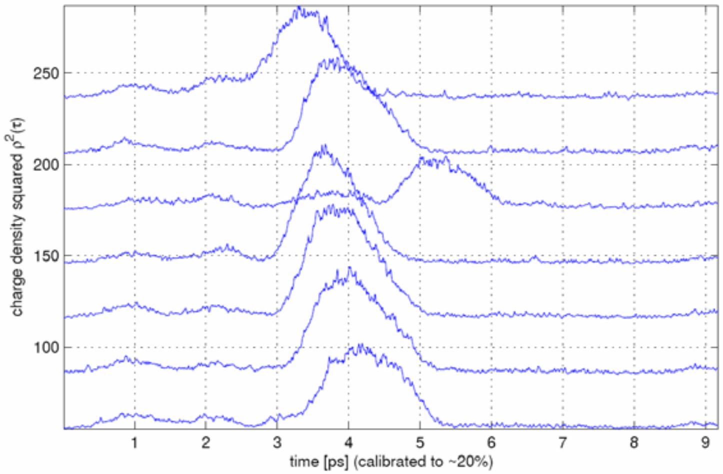
  intratrain diagnostics must be non-invasive

- low charge, high repition rate operation

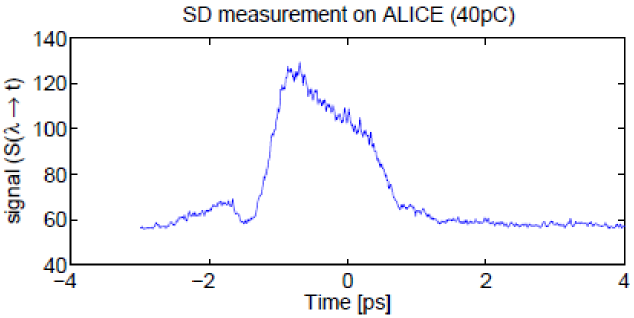
  typically 40pC, 81MHz trains for 100us

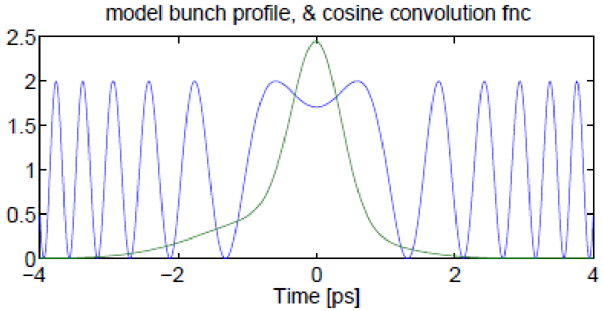
Spectral decoding results for 40pC bunch

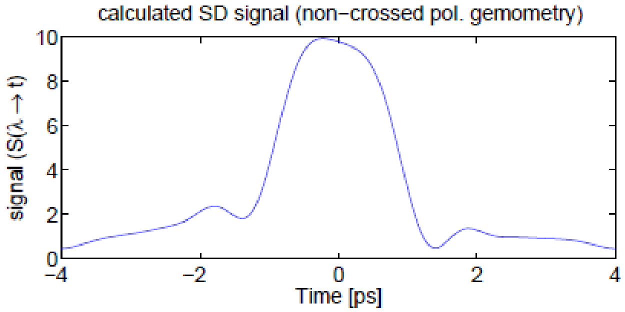
- *confirming compression for FEL commissioning*
- *examine compression and arrival timing along train*
- *demonstrated significant reduction in charge requirements*



Spectral decoding deconvolution







"Balanced detection"

$\chi^{(2)}$ optical pulse intefers with input probe (phase information retained)

$$\begin{aligned} S^{BD}(\omega) &\equiv I^{\rm in}_{\rm opt}(\omega) - I^{\rm in}_{\rm opt}(\omega) \\ &\propto I^{\rm in}_{\rm opt}(\omega)\left\{E_{\rm Coul}(\tau+t_0) * \cos(\frac{\tau^2}{4\beta}-\frac{\pi}{4})\right\}. \end{aligned}$$

Deconvolution possible.

"Crossed polariser detection"

input probe extinguished...phase information lost

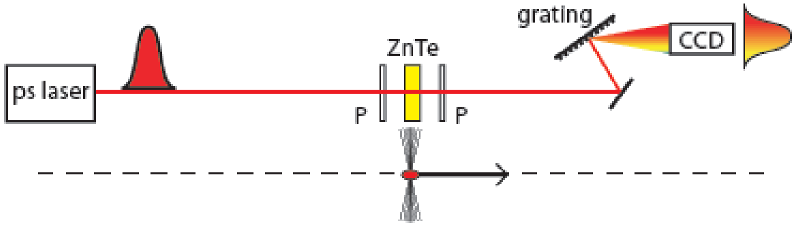
$$S(\omega)^{CP} \propto I^{\rm in}_{\rm opt}(\omega)\left\{\left[E_{\rm Coul}(\tau+t_0) * \cos\left(\frac{\tau^2}{4\beta}-\frac{\pi}{4}\right)\right]^2 + \left[E_{\rm Coul}(\tau+t_0) * \sin\left(\frac{\tau^2}{4\beta}-\frac{\pi}{4}\right)\right]^2\right\} \tag{2}$$

Deconvolution not possible [Kramers-Kronig(?)]

Oscillations from interference with probe bandwidth
⇒ resolution limited to probe duration

Spectral upconversion diagnostic

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

Long pulse, narrow bandwidth, probe laser

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

$\rightarrow \delta$***-function***

same physics
as "standard" EO

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

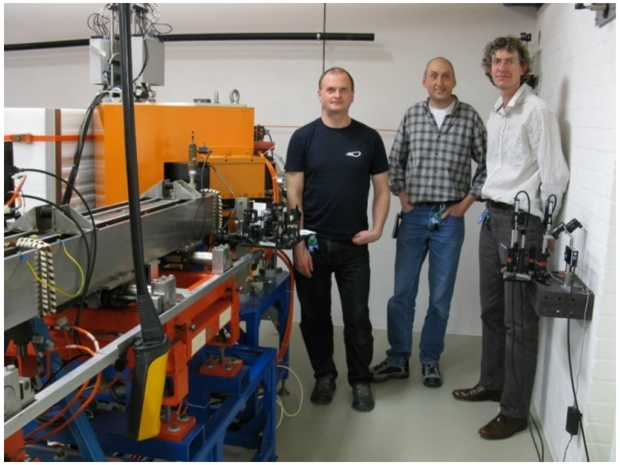
$(\Omega \text{ can be } < 0)$

different observational
outcome

NOTE: the long probe is still converted to optical replica

Spectral upconversion diagnostic

First demonstration experiments at FELIX

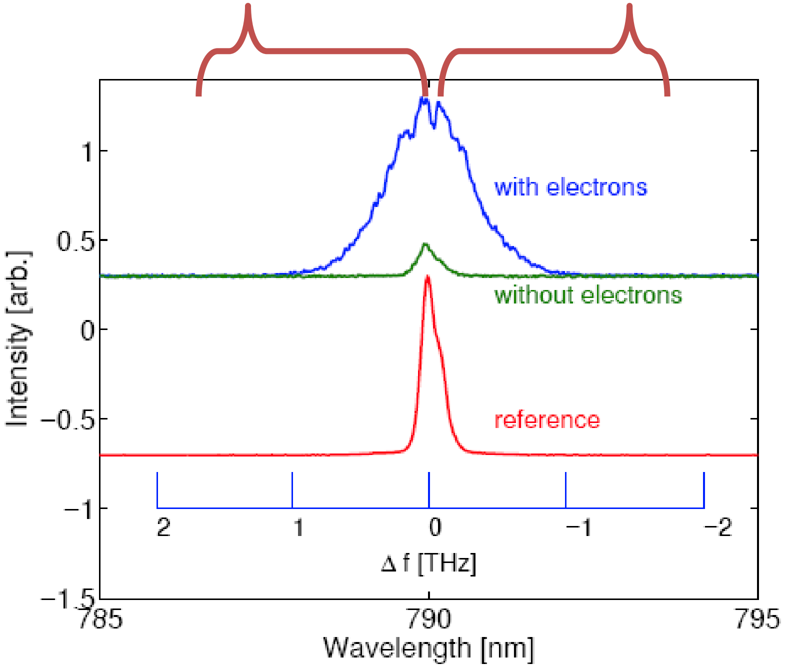


sum
frequency mixing

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

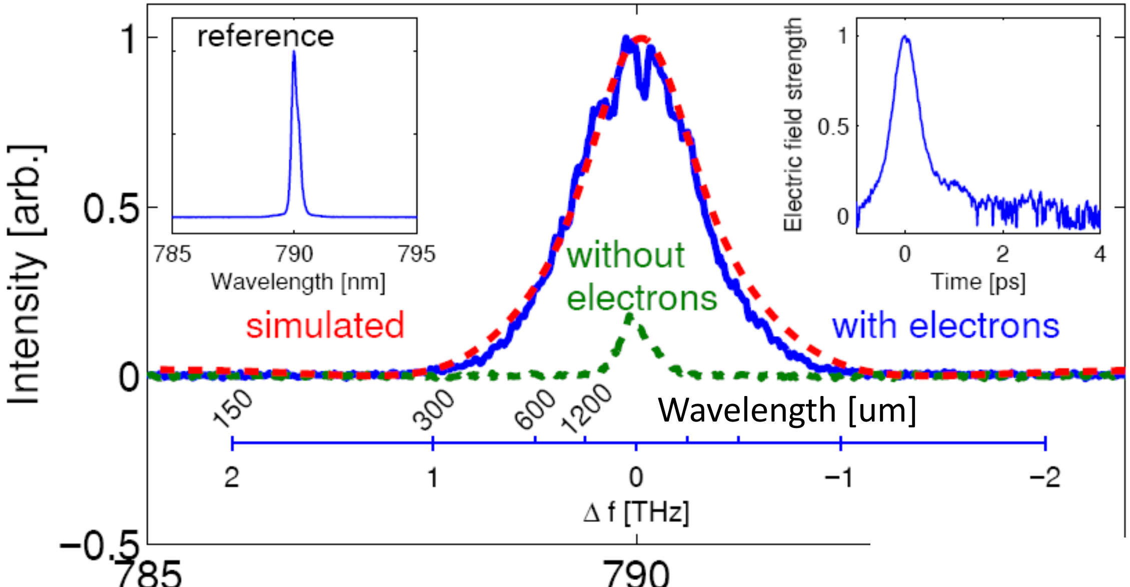
difference
frequency mixing

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



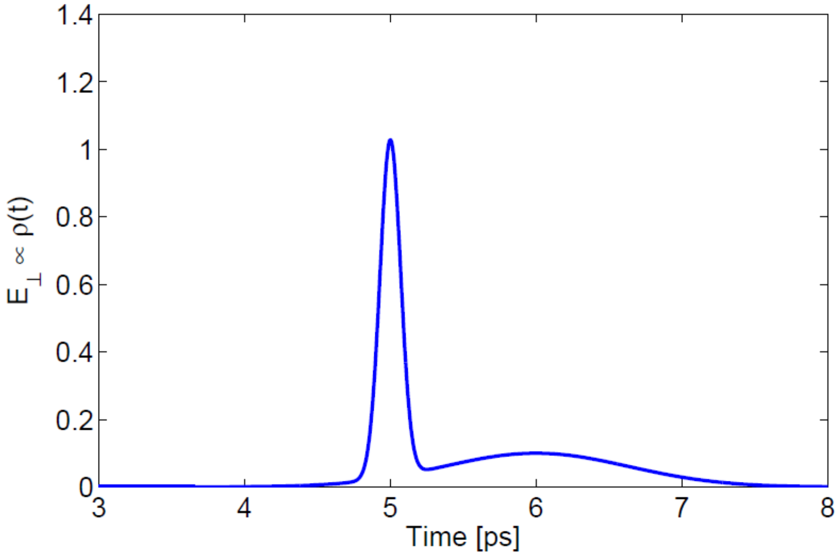
Applied Physics Letters, **96** 231114 (2010)

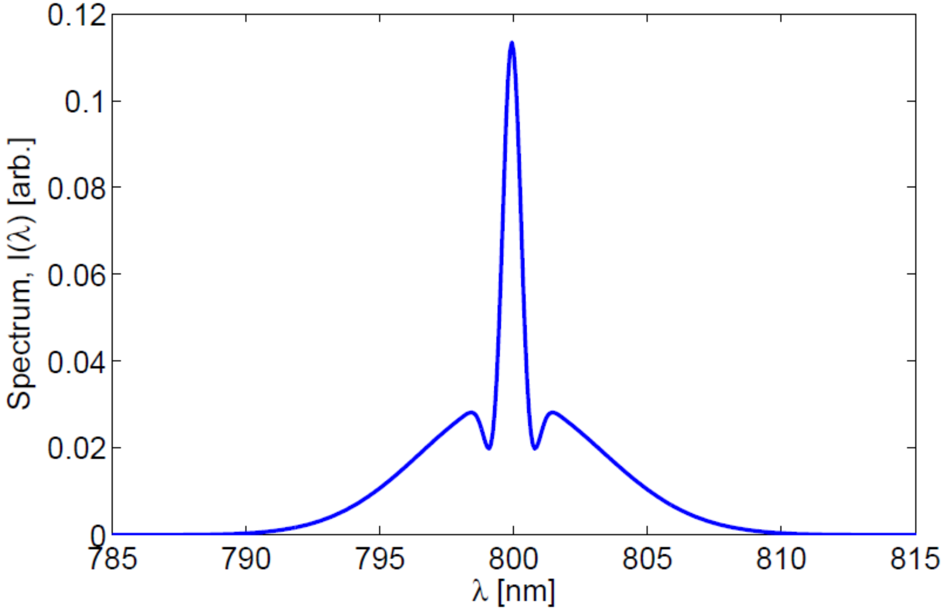
Spectral upconversion



Observe non-propagating *spectral components which are not accessible to radiative techniques (CSR/CTR/SP)*

Ti:S probe, ~5ps duration, transform limited.





Spectral upconversion diagnostic…

CW laser probe & monochromatic THz upconversion demonstrated

Wijnen et al. **18** 26517 Opt Express (2010)

Offers potential for simple, robust laser diagnostic

Recent experiments at Daresbury with CW laser...

- CSR source on ALICE,
- laser-generated "coulomb field mimic"

..not successful.

Broadband spectrum suppresses signal

- CW probe "photons per picosecond" insufficient

Will repeat with 50ps Nd:YAG system in coming weeks...

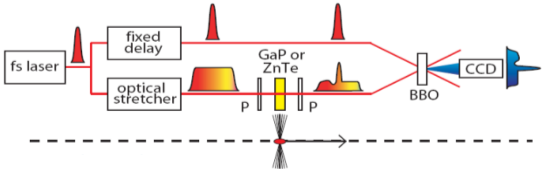
>10^4 increased signal with even 1uJ pulse energy (50mJ available!)

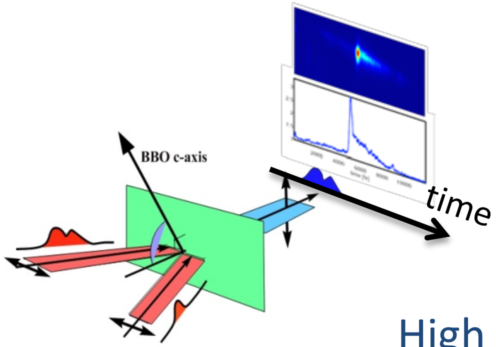
Goals

- Explore signal-noise and laser requirements
- Determine feasibility for using "cheap-robust" ns, uJ lasers
- Detector requirements (InGaAs arrays?)

Explicit time-domain detection

Temporal decoding method



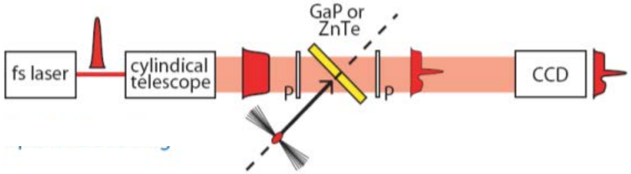


- long optical probe with electron bunch info
- ultrafast “gate” for time->space readout

$$I_{SHG}(x \leftarrow t) \propto \int I_{probe}(\tau) I_{gate}(t-\tau) \mathrm{d}\tau$$

High pulse energy required (~20-100uJ)

Spatial encoding method



- Short optical probe with electron bunch info
- short probe acts also acts as ultrafast “gate” for time->space readout

Low pulse energy required (~2nJ demonstrated)

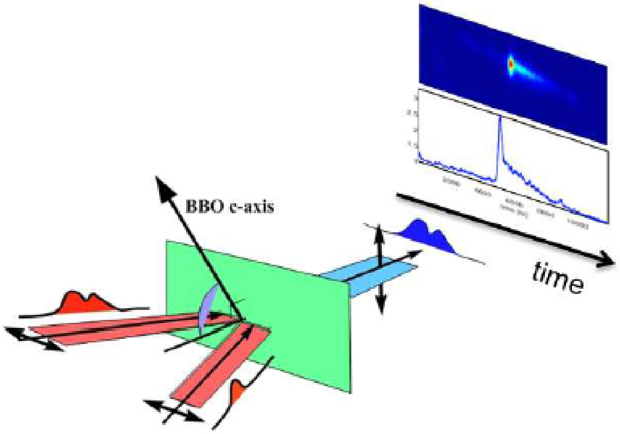
Both cases: Resolution is limited by gate duration (+phase matching)

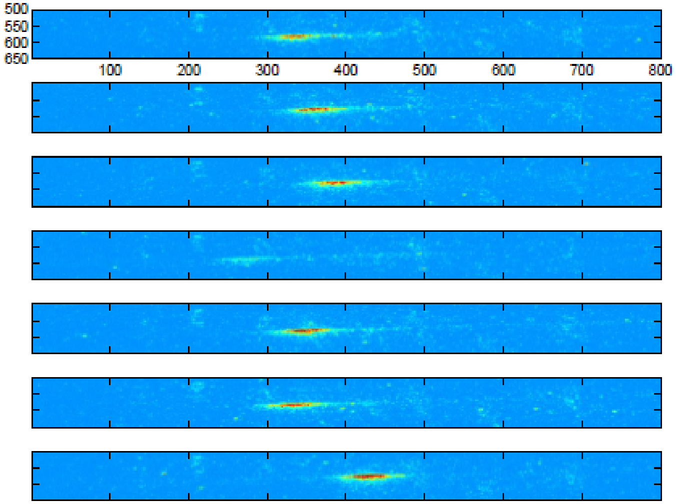
Practical implementation limits gate to >40fs fwhm

(laser transport, cross-correlator phase matching/signal levels)

Temporal decoding

Single shot optical characterisation of very weak optical signal



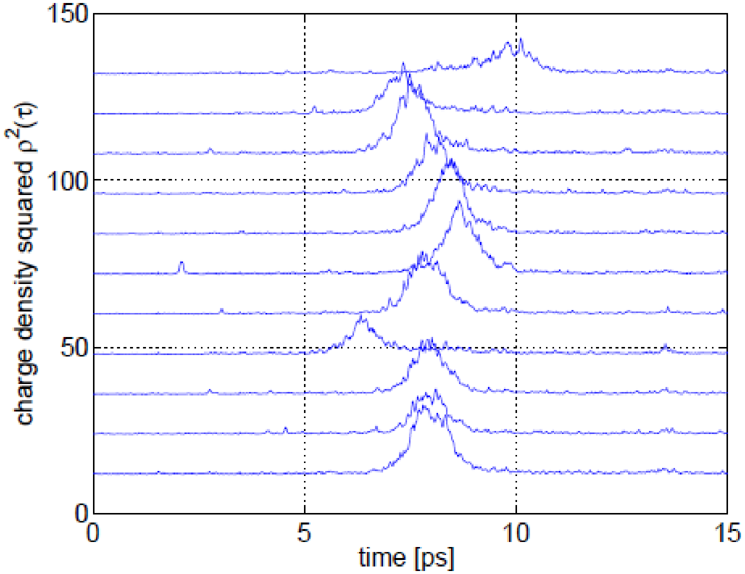


- Weak probe due to EO material damage limits…
  ~1uJ in 10ps *input* pulse energy
  < 1 nJ in 100fs *output* pulse energy

o Single shot autocorrelation not feasible

o Compensation by cross-correlation with strong (~50uJ) gate

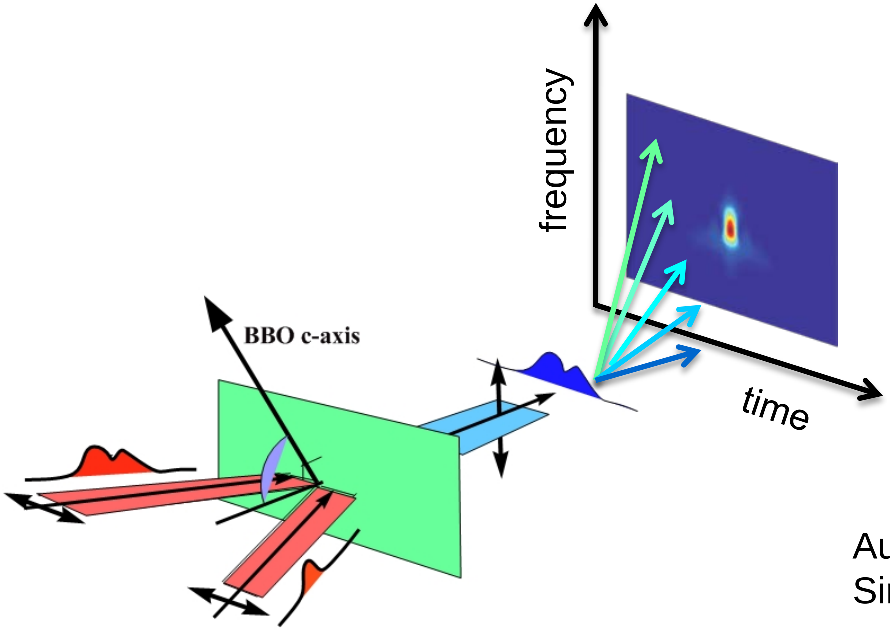
Signal/noise issues from this mismatch in intensities



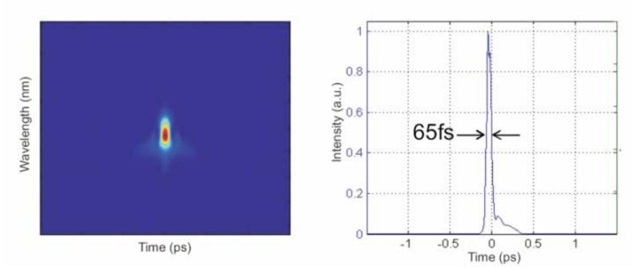
Higher resolution through "X-FROG "

cross-correlation, frequency resolved optical gating

- Obtain both time and spectral information
- Sub-pulse time resolution retrievable from additional information



standard FROG ultrafast
laser diagnostics



FROG measurements of
DL fibre laser (Trina Ng)

Auto-correlation, not cross correlation
Single shot requires more intensity than
reasonable from EO material limitation

R&D goals

- Develop XFROG with realistic EO intensities
  - signal/noise issues; non-degenerate wavelengths (?)
- Develop & demonstrate retrieval algorithms
  - including "spliced data"

Summary

- Electro-optic techniques available for different parameter regimes
- Significant effort needed to improve time resolution below 100fs
- Highest time resolution time-explicit techniques limited by
  - material properties
  - optical pulse duration
  - laser system robustness
- Multiple-crystal detectors being considered
- "FROG-TD" may solve laser pulse duration limitation
  - amplified laser essential
  - data-splicing procedure to be determined
- Spectral-upconversion offers solution for feedback & robust systems
  - with multiple-crystal arrangement for "high time resolution"