# Femtosecond resolution bunch profile diagnostics

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# Femtosecond longitudinal diagnostics

**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

## 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***

# Two distinct classes of diagnostics

## Grouped by similar physics and capabilities/limitations

### Direct Particle Techniques

$\rho(t) \rightarrow \rho(x)$
$\rightarrow$ transverse imaging

- Transverse deflecting cavities
  $\rho(t) \rightarrow \rho(x') \rightarrow \rho(x)$
- RF zero-phasing
  $\rho(t) \rightarrow \rho(\gamma) \rightarrow \rho(x)$

### "Radiative" Techniques

$\rho(t) \rightarrow \mathrm{E}(t)$ ....propagating & non-propagating

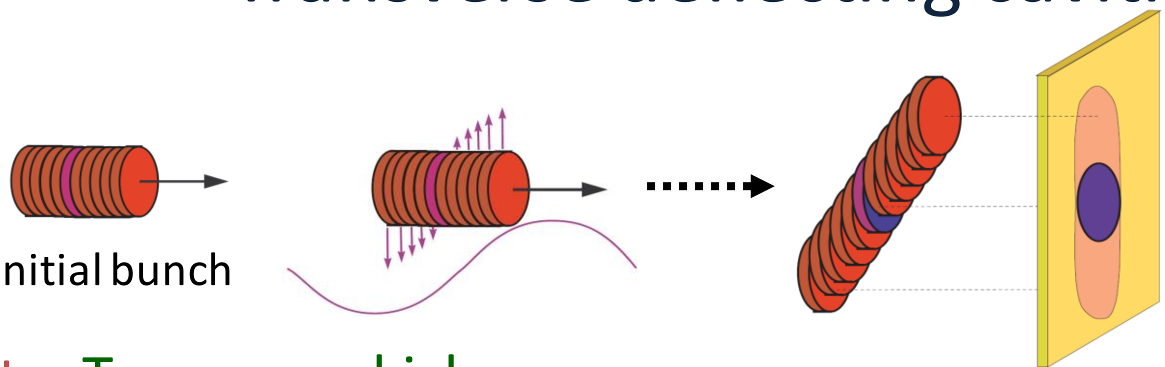
#### Spectral domain

- CTR, CDR, CSR (spectral characterisation)
- Smith Purcell
- Electro-optic

#### Time domain

- Electro-optic
- optical replica
- CTR, CDR (autocorrelation)

# Transverse deflecting cavities




Cavity: Transverse kick

$$\Delta y'_{\mathrm{cav}}(z) = \frac{eV}{pc}\sin\left(\frac{2\pi z}{\lambda_{\mathrm{cav}}} + \phi\right)$$

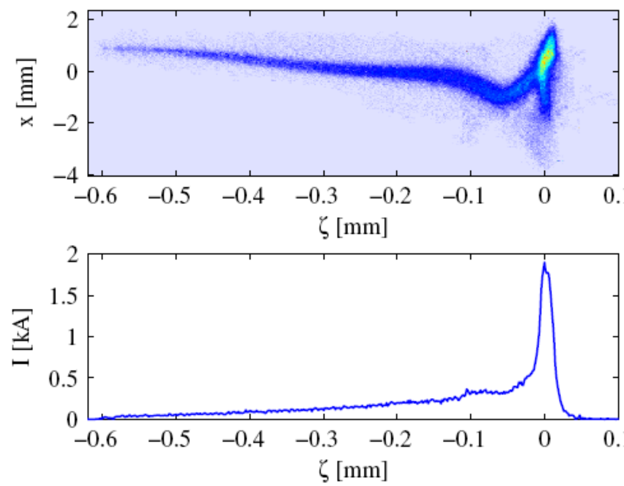
beam optics : Transverse streak

$$\Delta y_{\mathrm{screen}}(z) = \left\{\sqrt{\beta_c \beta_s}\,\sin(\Delta\psi)\right\}\,\Delta y'_{\mathrm{cav}}(z)$$

Time resolution scaling

$\alpha$ { deflection gradient, $\gamma^{-1/2}$ }

Diagnostic capabilities linked to beam optics

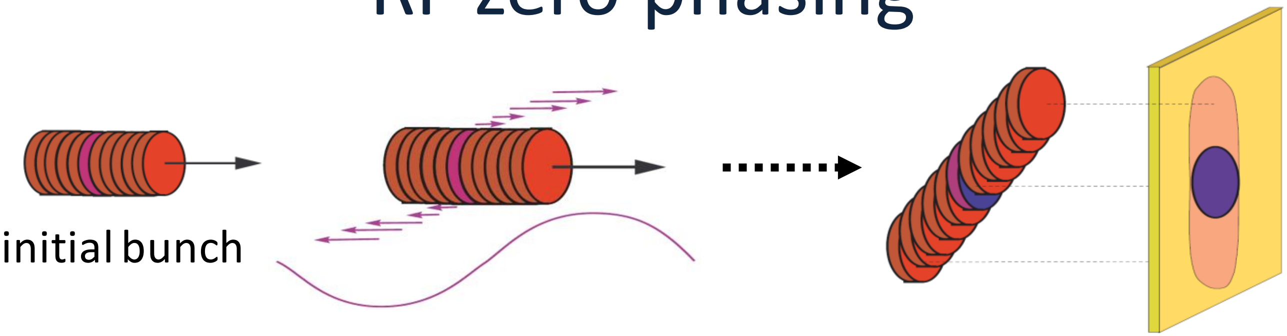



FLASH :

27 fs resolution

Rohrs et al. Phys Rev ST (2009)

# RF zero phasing




screen
transverse
profile

cavity
z-dependent acceleration

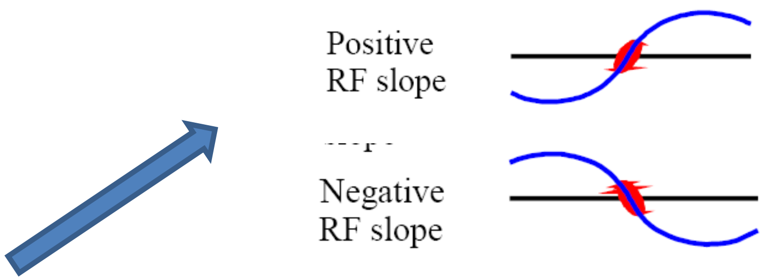
beam optics
energy dispersion

- Introduce energy chirp to beam
- Measure energy spread $\Rightarrow$ infer initial bunch profile

time resolution dependent on

- gradient of energy gain
- dispersion of spectrometer
- initial energy spread

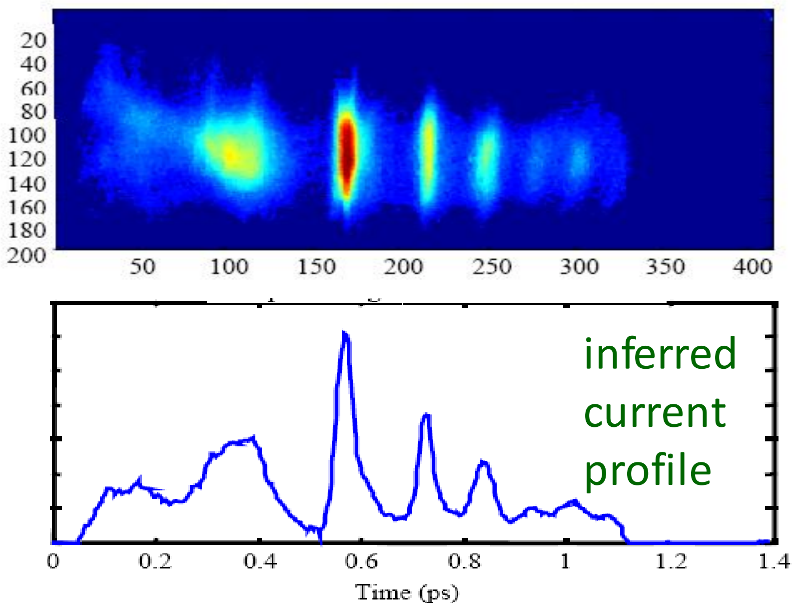
initial $\gamma$–z correlation?



# RF zero-phasing examples

## DUV-FEL: 75 MeV

energy (time )

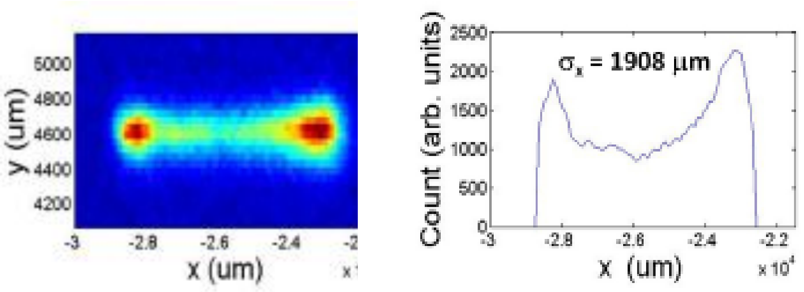


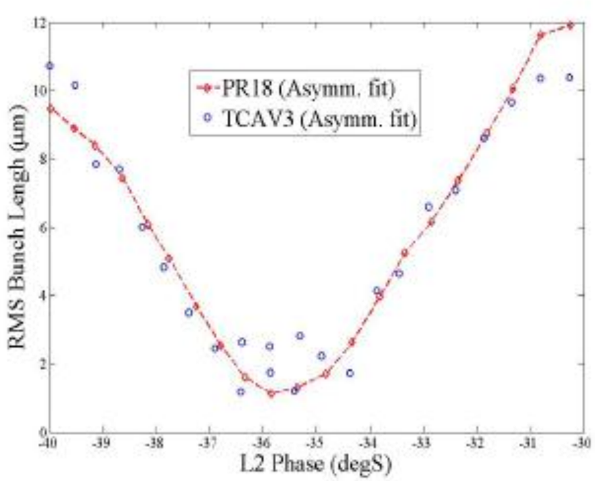

**time resolution of 8 fs**

Graves et al. PAC'01

## LCLS, at ~ 9 GeV

- 550m of linac at RF zero crossing!
- 6m dispersion




**1um = 3 fs rms bunch length**

Huang et al PAC 2011

# "Radiative" techniques

## Cause bunch to radiate coherently

$$\rho(t, x_0) \longrightarrow E_{\rm rad}(t, x_0)$$

- emission response
- phase matching

`Propagate' to observation position $\longrightarrow E_{\rm rad}(t, x)$

- Dispersion
- Attenuation
- Diffraction…

Measure spectrum, intensity time profile

$|\tilde{E}_{\rm rad}(\omega, x)|^2$

$E^2_{\rm env}(t, x)$

$E_{\rm rad}(t, x)$

- detector response
- missing phase information

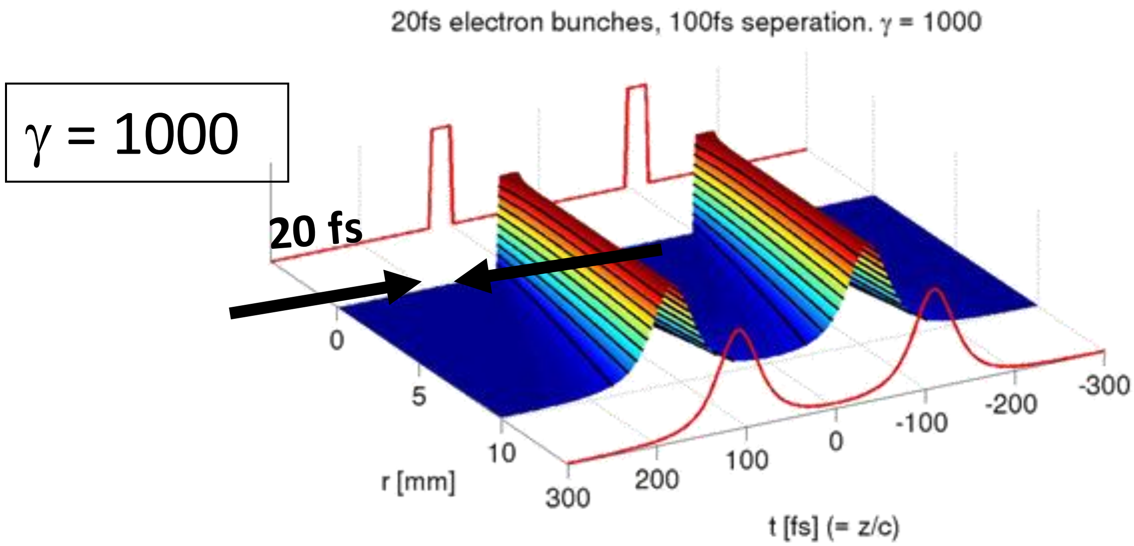
**Infer back to charge density**

## Techniques & limitations

| | |
|---|---|
| CSR/CTR : | propagation effects; detector response; missing phase |
| CDR : | as for CSR/CTR; plus emission response |
| Optical Replica: | emission response (? Radiating undulator) |
| Electro-optic: | detector response |

# Field at Source

Field radiated or probed related to Coulomb field near electron bunch



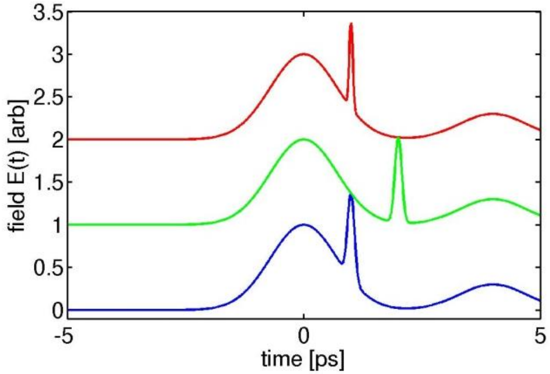

Time response & Spectrum of field dependent on spatial position:
$\delta t \sim 2R/c\gamma$

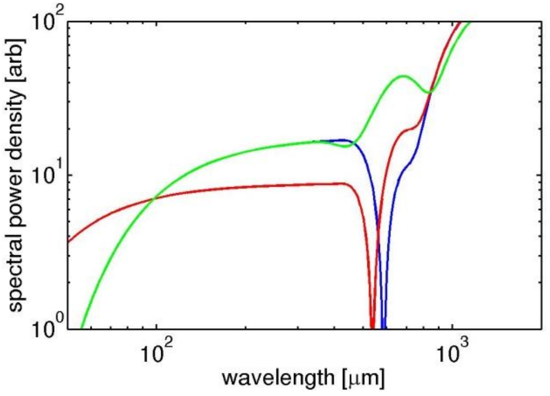
Ultrafast time resolution needs close proximity to bunch

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

# Spectral domain techniques

Bunch form factor ⇒ Coherent diffraction radiation
Coherent transition radiation
Coherent synchrotron radiation
Smith-Purcell radiation ⇒ Far-IR/mid-IR spectrum



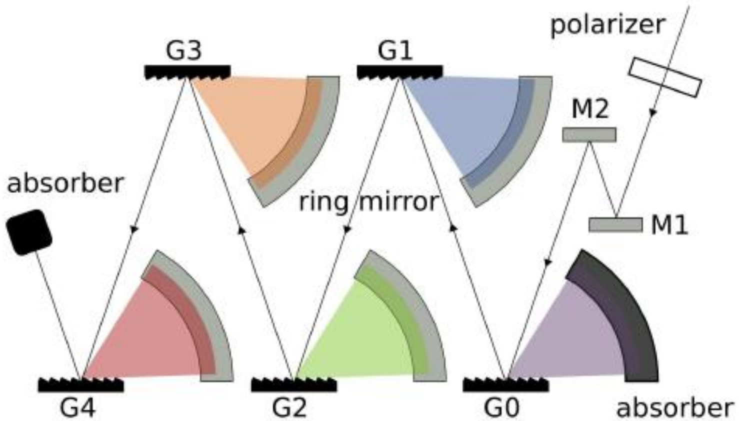

- More than octave spanning in frequency
- Short wavelengths describe the fast structure
- long wavelengths needed for bunch reconstruction

For:
Simplicity (not always!)
Empirical machine information, real time
Information on fast and slow structure

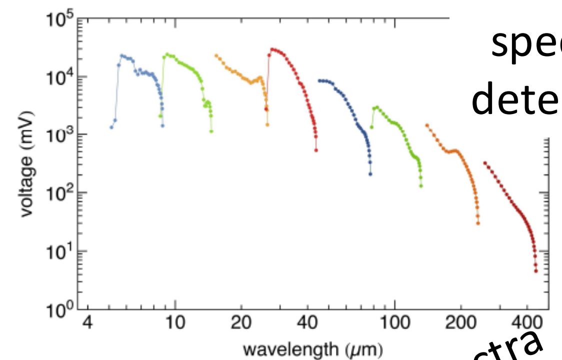
Against:
No explicit time profile
(but reconstruction *may* be possible)
Significant calibration issues

# example: single shot CTR spectrometer at FLASH

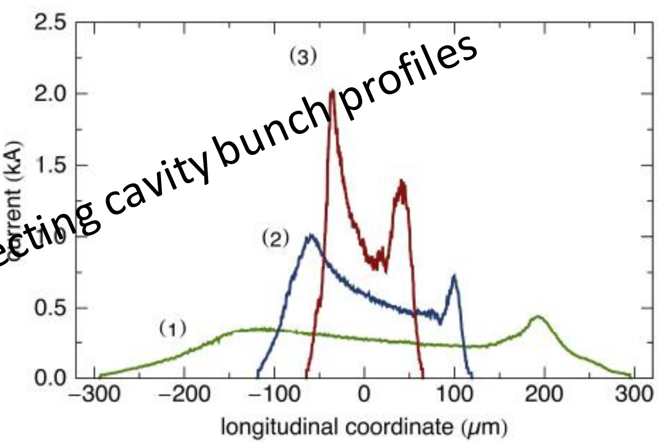
cascaded dispersive grating elements, and pyroelectric detector arrays



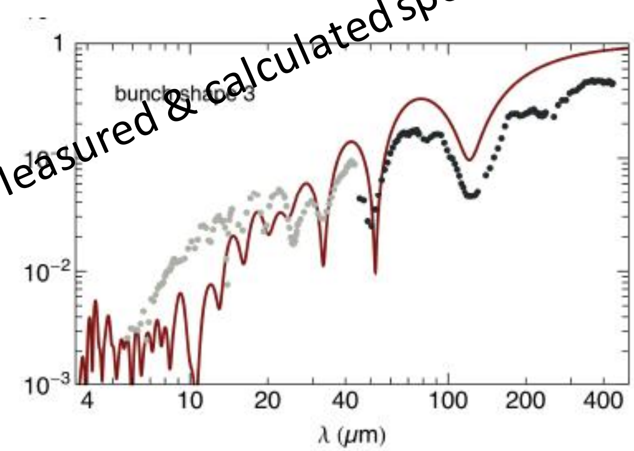

Wesch, Schmidt, FEL 2010




spectrometer & detector response




Deflecting cavity bunch profiles




Measured & calculated spectra

# Time domain Reconstruction….missing phase

$$|\tilde{E}_{\mathrm{det}}(\omega)|^2 \propto |\tilde{E}_{\mathrm{source}}(\omega)|^2 T(\omega, \gamma, \cdots)$$

Transfer function must be known (from calculation or experiment)

phase to be inferred (via K-K relations)

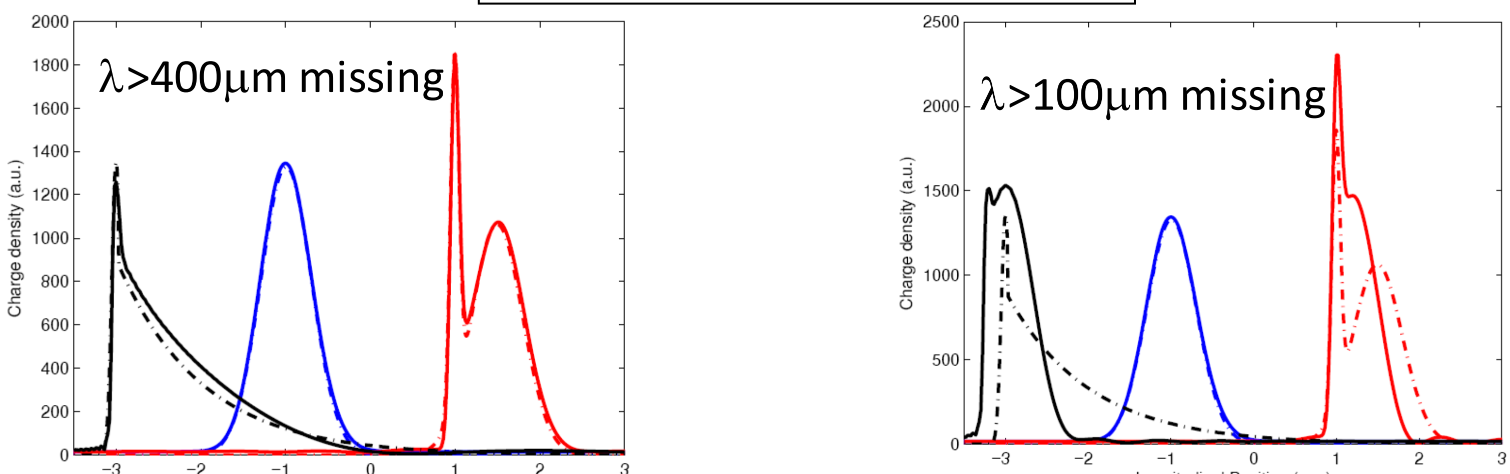
$$\tilde{E}_{\mathrm{source}}(\omega, \underline{\boldsymbol{x}}) \propto \int \rho(t, \underline{\boldsymbol{x}}) \mathrm{e}^{i\omega t} \mathrm{d}t$$

Form factor is analytic => real and imaginary parts linked (Kramers-Kronig relations)
Inversion is possible*, but requires… full spectral information*

*… absence of zeros in spectrum…*

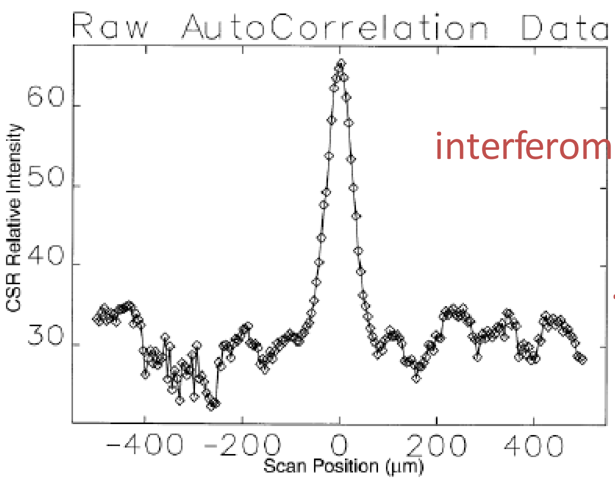
– · – · – original
—— reconstructed

O. Grimm Tesla-Fel 2006-04



# Kramers-Kronig Phase Reconstruction...

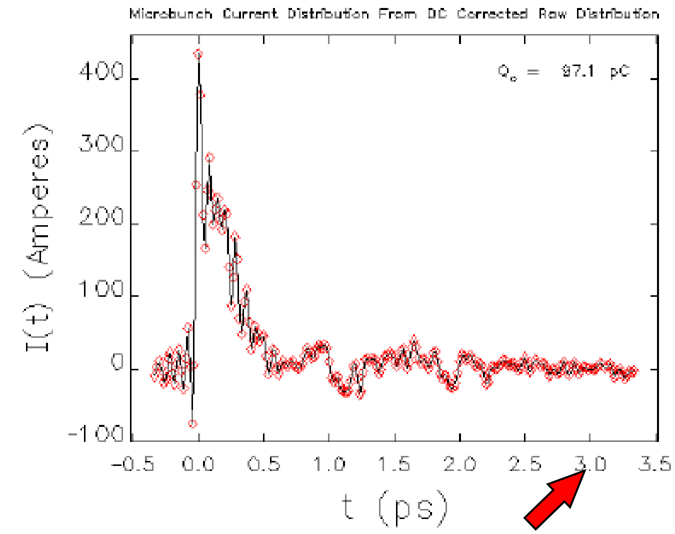
An example from APS... Lumpkin et al, FEL 2005




interferometer data...

...intensity spectrum...

...Kramer-Kronig phase retrieval...




...inferred bunch profile.

Personal view

Reconstruction can work

*but...*

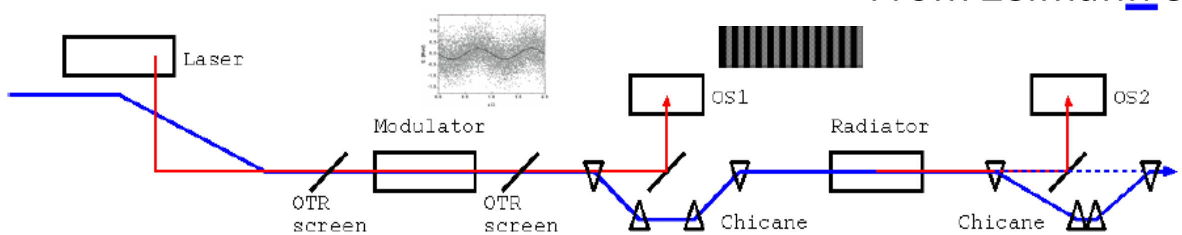
Can be very sensitive to data

- Extrapolations to low frequency (lost through propagation)
- Detector response errors

# Optical Replica Synthesiser

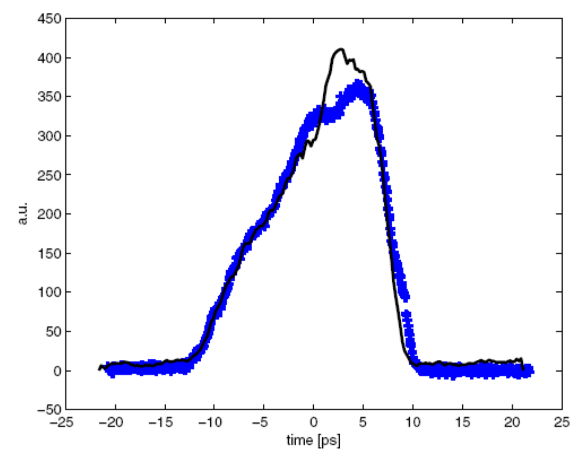
- Superimpose optical wavelength structure on bunch
  Laser driven I-FEL interaction + R56
- Generate optical radiation in few-period radiating undulator
- Ultrafast laser diagnostics for optical temporal characterisation (autocorrelation, FROG, SPIDER, …)

From Zeimann et al, PRST 2009



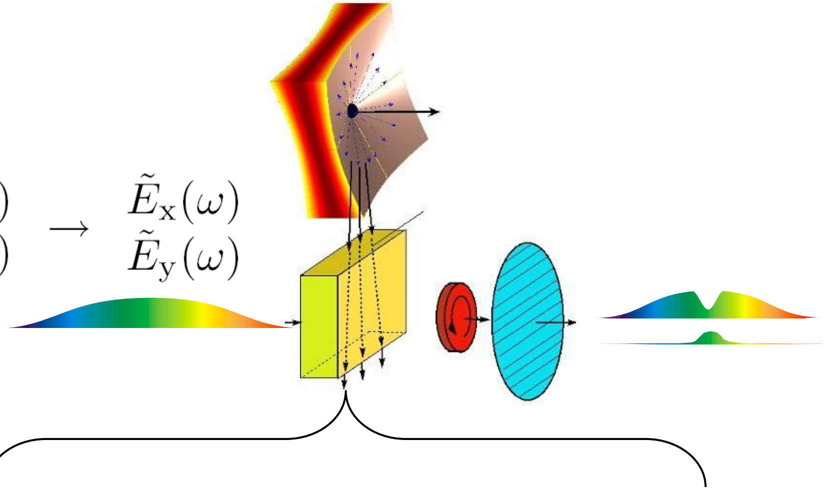

## FLASH experiments

- Observed time-scanned signal
  [Angelova et al, PRST-AB 11, 070702 (2008) ]
- Obtained FROG signals
-…. Single shot temporal profiles..?




Temporal resolution will be limited by number of radiator periods ( N= 5 -> 12fs)

# Electro-optic diagnostics



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

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

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

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

Coulomb spectrum shifted to optical region

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

Coulomb pulse replicated in optical pulse

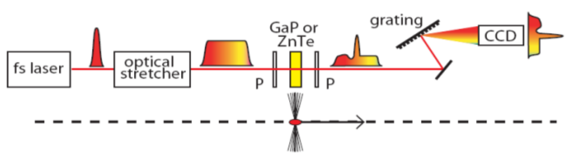
**envelope** **optical field**

Time domain or spectral domain versions….
….same underlying physics, but different practicalities

# Electro-Optic Techniques…

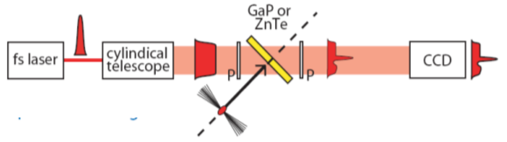
## Variations in read-out of optical temporal signal

**Spectral Decoding**



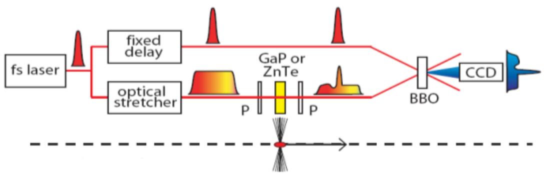

- Chirped optical input
- Spectral readout
- Use time-wavelength relationship

**Spatial Encoding**



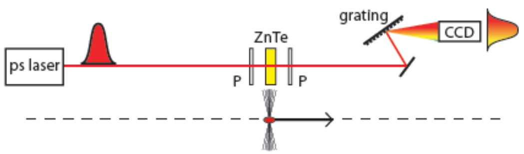

- Ultrashort optical input
- Spatial readout (EO crystal)
- Use time-space relationship

**Temporal Decoding**




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

**Spectral upconversion****

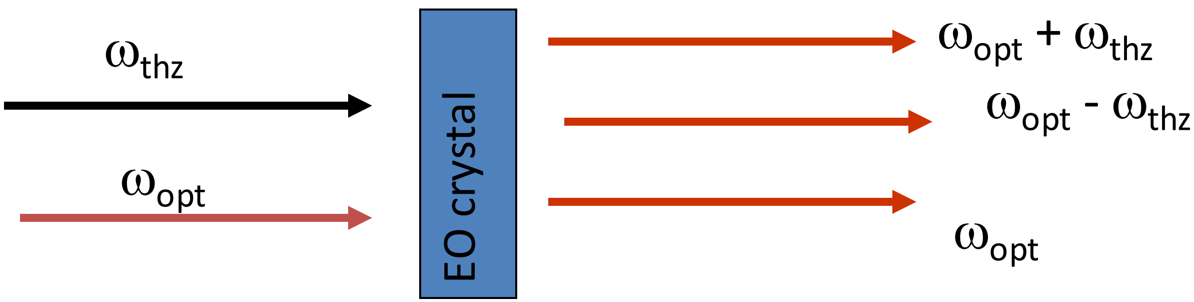



- monochomatic optical input (long pulse)
- Spectral readout
- ***Implicit time domain information only*

# Electro-optic detection bandwidth

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

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




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

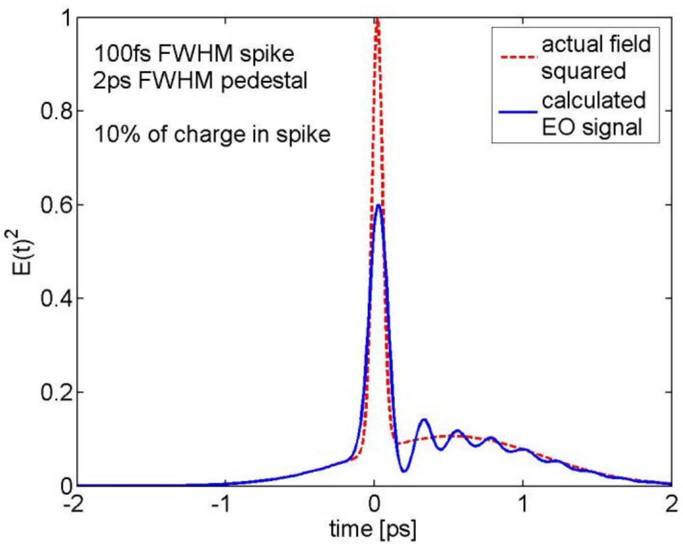
- geometry dependent (repeat for each principle axis)
- convolution over all combinations of optical and Coulomb frequencies
- propagation & nonlinear efficiency
- THz spectrum (complex)
- optical probe spectrum (complex)

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

# Time domain electro-optic diagnostics
## Generating an optical replica of a Coulomb field pulse…

Laser co-propagating with Coulomb pulse

Free-space | Electro-optic crystal




300 um

Longitudinal Position, z

### Encoding issues…

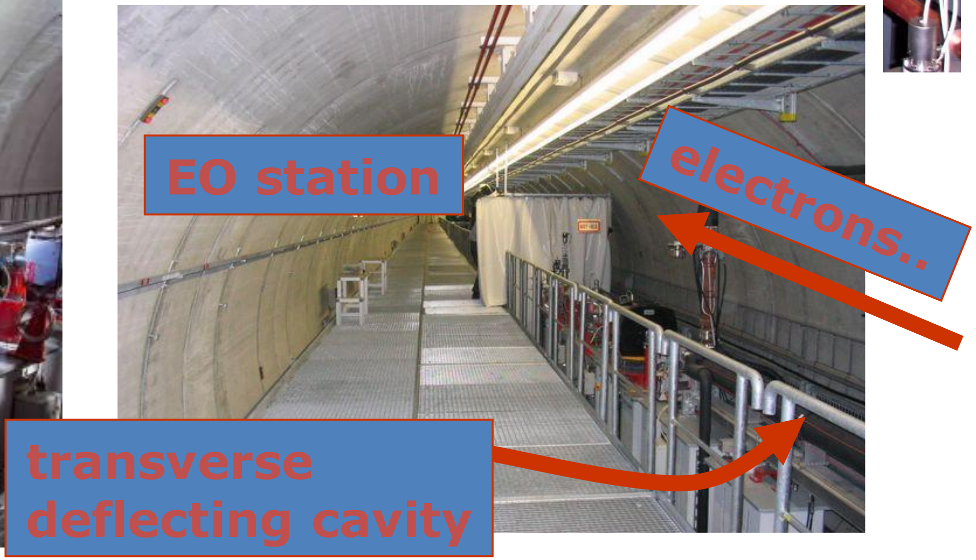
- Coupling of Coulomb pulse into non-linear material
- Distortion of Coulomb pulse as it propagates in material
- slippage between Coulomb pulse and optical replica
- Bandwidth of upconversion to optical

# Electro-optic diagnostics in practice

Many experiments on FLASH – one of first of short bunch machines

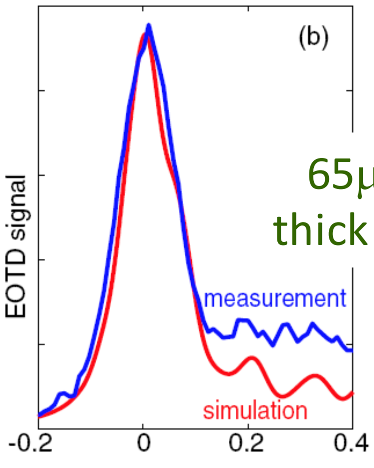
- Temporal decoding
- Spectral decoding
- Spatial encoding
- benchmarking against deflecting cavities

**Temporal Decoding Diagnostic**

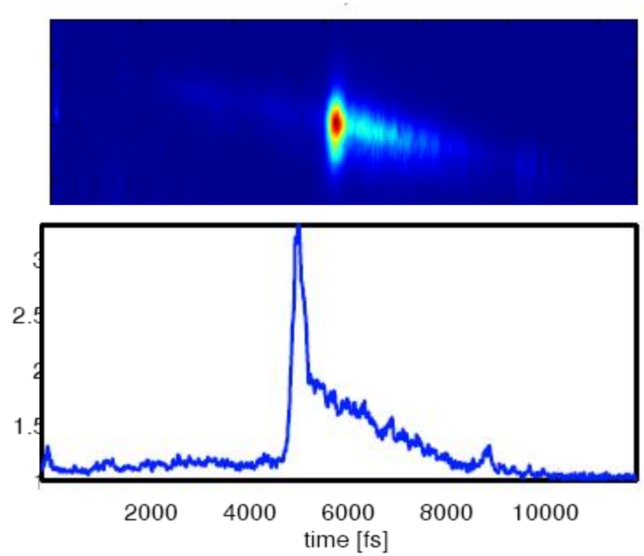


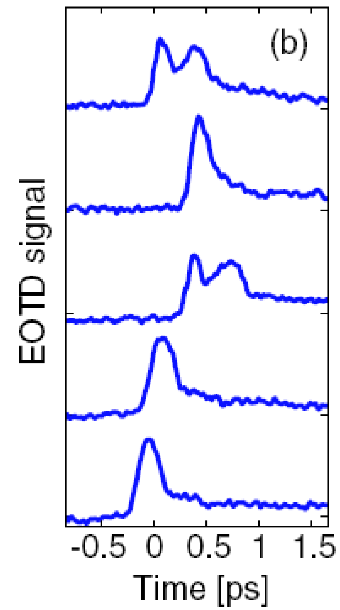
# High Time resolution...

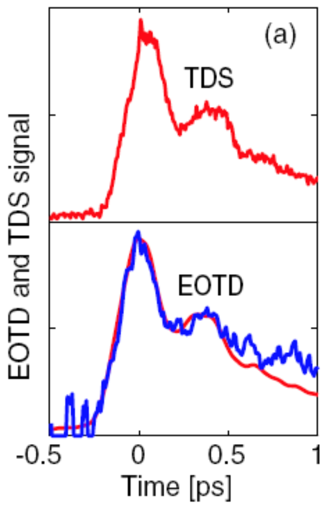
currently the highest time-resolution
non-destructive diagnostic demonstrated




65µm
thick GaP



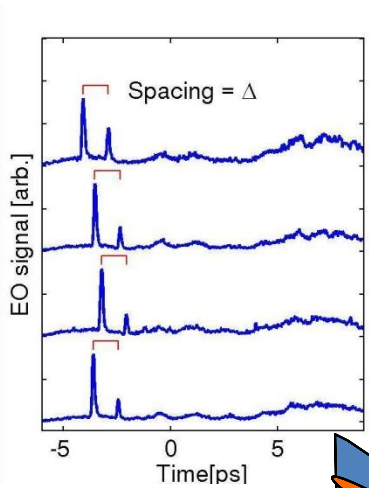

Benchmarked against a destructive
RF diagnostic technique

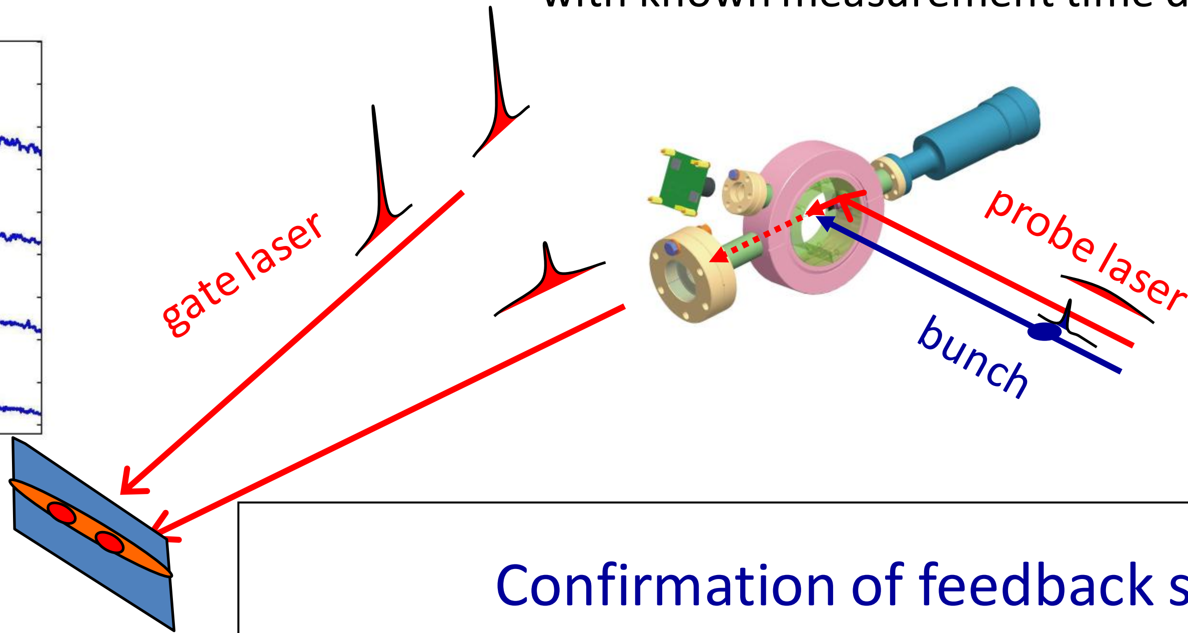
- provides a *unique* "calibrated" THz source...
- agreement confirms understanding of material properties

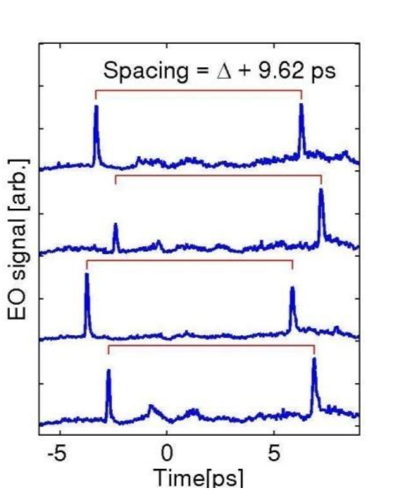
Berden et al. Phys Rev Lett. **99** (2007)

# Time Calibration....

measure the same electron bunch twice
with known measurement time delay

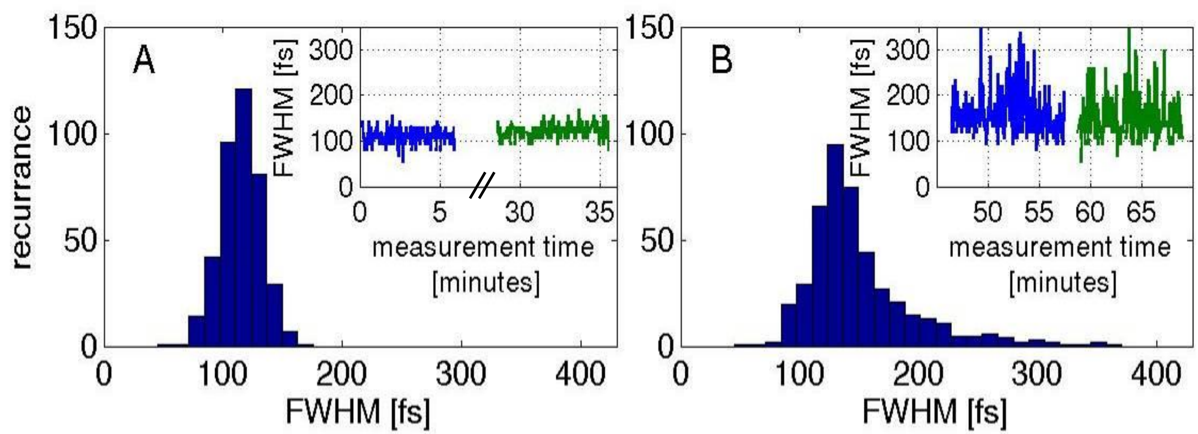


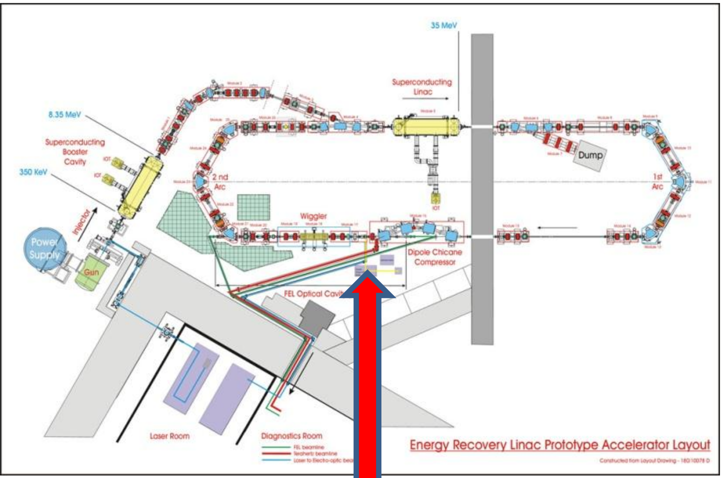



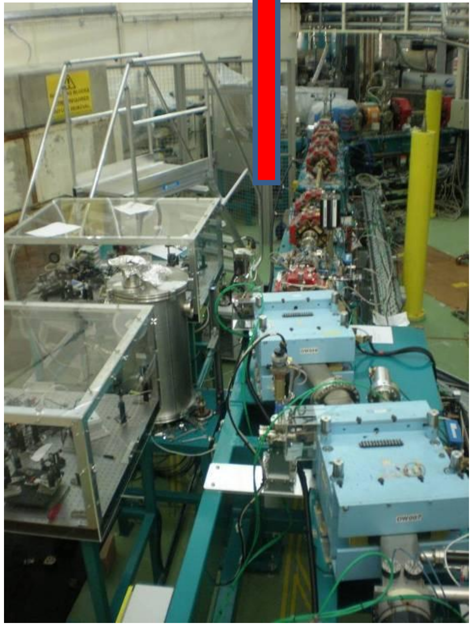

## Confirmation of feedback systems

**CDR feedback on** **CDR feedback off**



# ALICE Electro-optic experiments

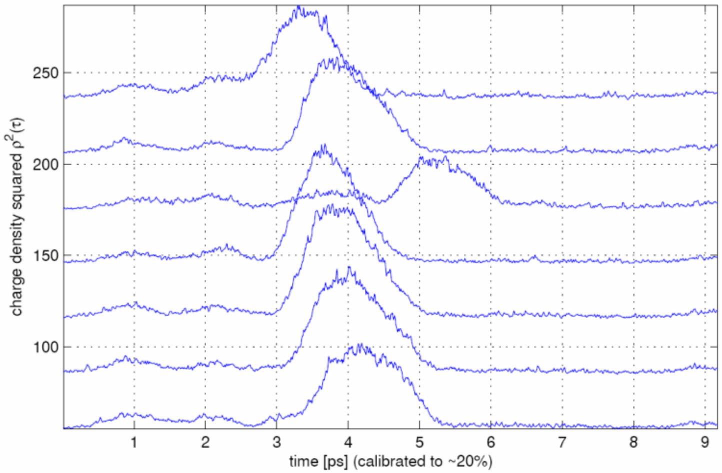


- Energy recovery test-accelerator
  - *intratrain diagnostics must be non-invasive*
- low charge, high repition rate operation
  - *typically 40pC, 81MHz trains for 100us*

## Spectral decoding results for 40pC bunch

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



# 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)

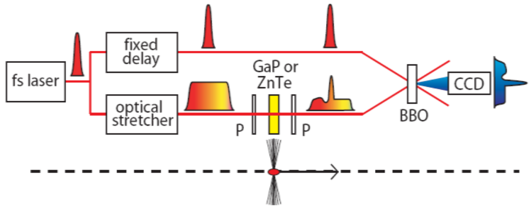
- proven capability
- significant issues with laser complexity / robustness

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)

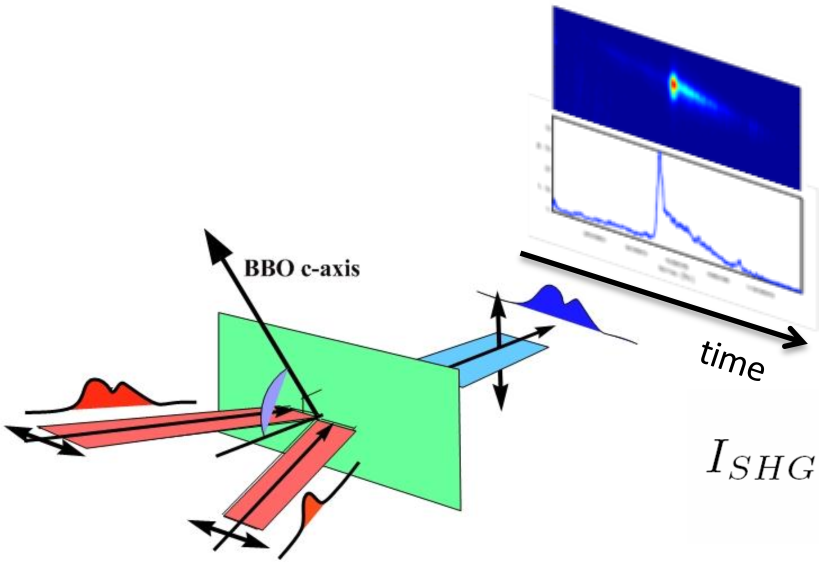
**Accelerator wish list - Missing capabilities**

- Higher time resolution (20fs rms for CLIC)
- Higher reliability, lower cost (high resolution systems)
- solution for feedback.




# Temporal Limitations of Electro-optic

## Cross-correlation method




- Optical probe with electron bunch info
- ultrafast "gate" for time->space readout

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

- Resolution is limited by gate duration (+phase matching)

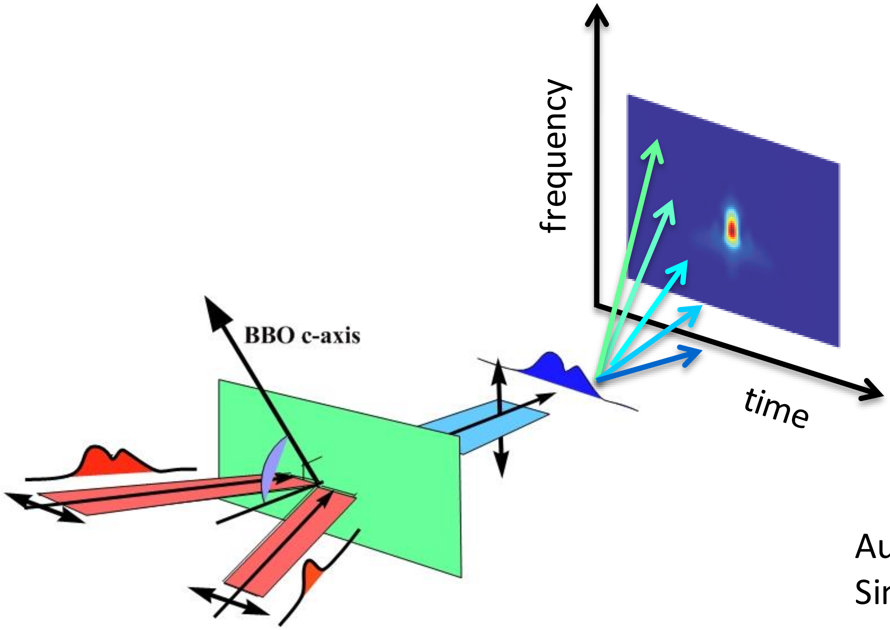
Practical implementation limits gate to >40fs fwhm
( laser transport, cross-correlator phase matching/signal levels )

- Weak probe due to EO material damage limits…
- Compensated by intense gate

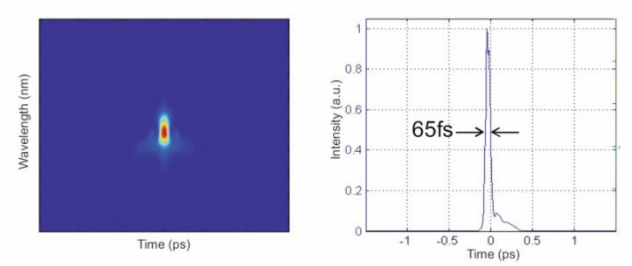
Signal/noise issues from this mismatch in intensities

# 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)

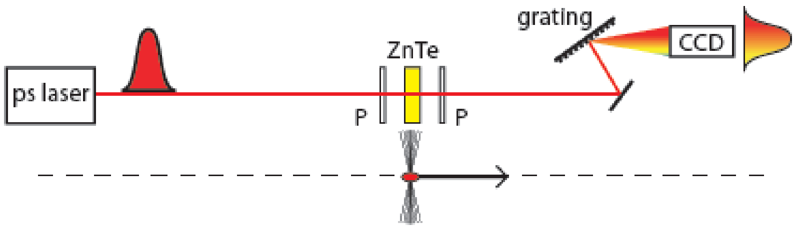
Auto-correlation, not cross correlation
Single shot requires more intensity than reasonable from EO material limitation

R&D goals

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

# 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

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

$\rightarrow$ ***δ-function***

same physics as "standard" EO

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

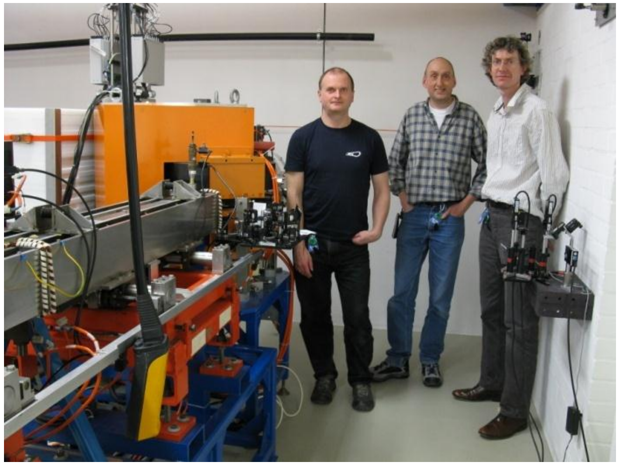
$(\Omega \text{ can be } < 0)$

different observational outcome

***NOTE: the long probe is still converted to optical replica***

# Spectral upconversion diagnostic

## First demonstration experiments at FELIX

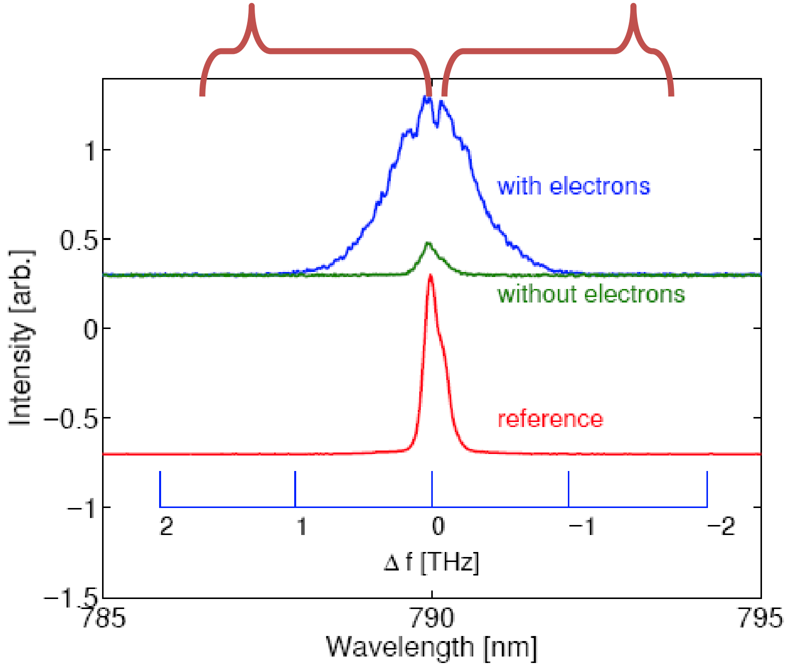


**sum frequency mixing**

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

**difference frequency mixing**

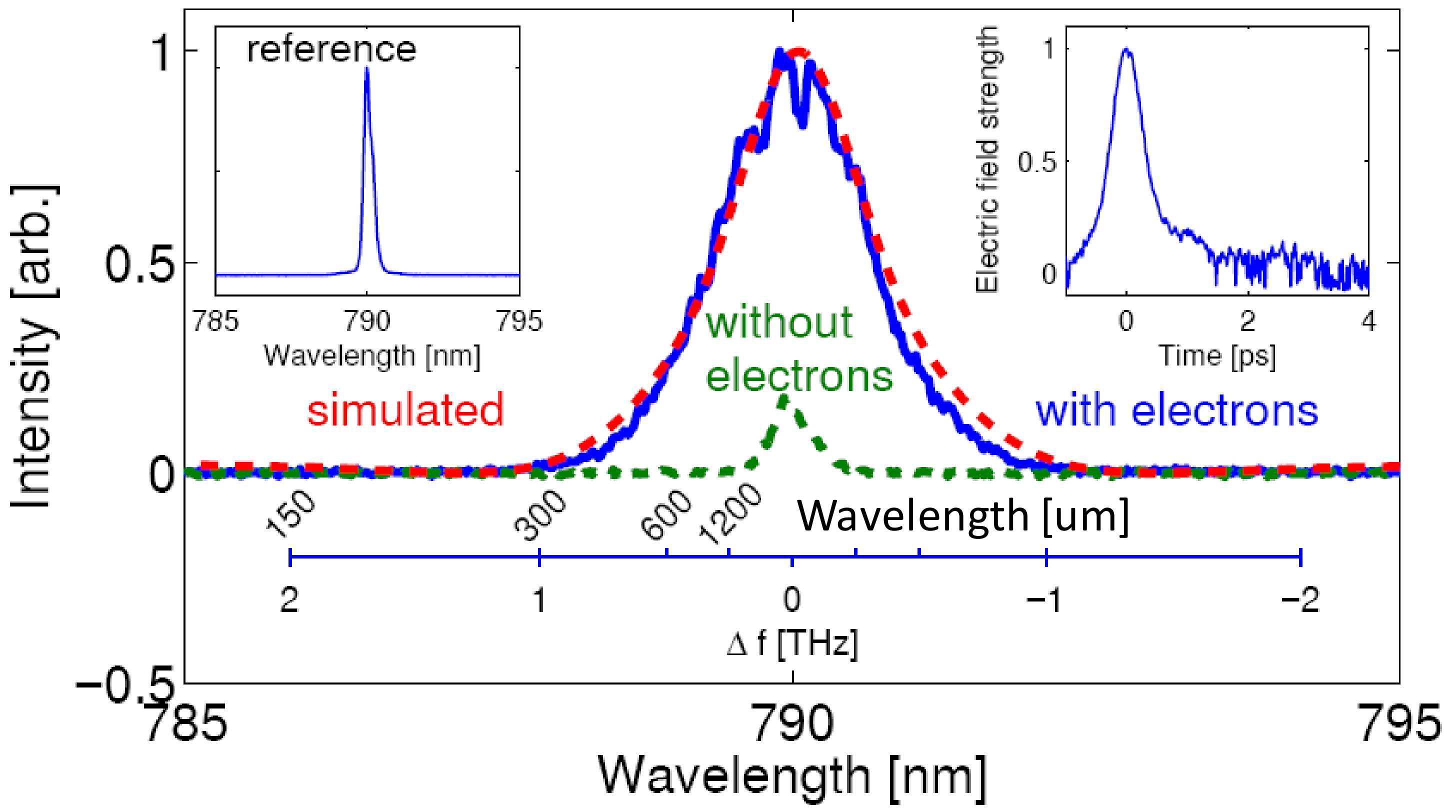
$$\tilde{E}(\omega_0 - \Omega) = i\omega a \tilde{E}(\omega_0)[\{\tilde{E}^{\mathrm{Coul}}(\Omega)\}^* \tilde{R}^*(\Omega)]$$




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

# Measures long wavelength components

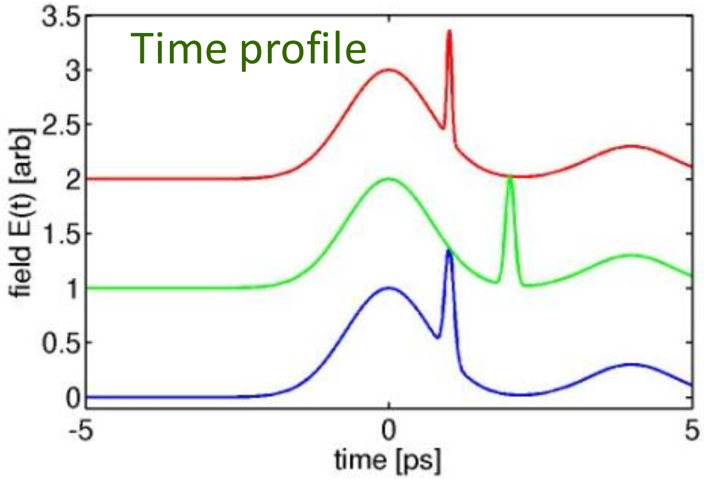
non-propagating *spectral components which are not accessible to radiative techniques (CSR/CTR/SP)*

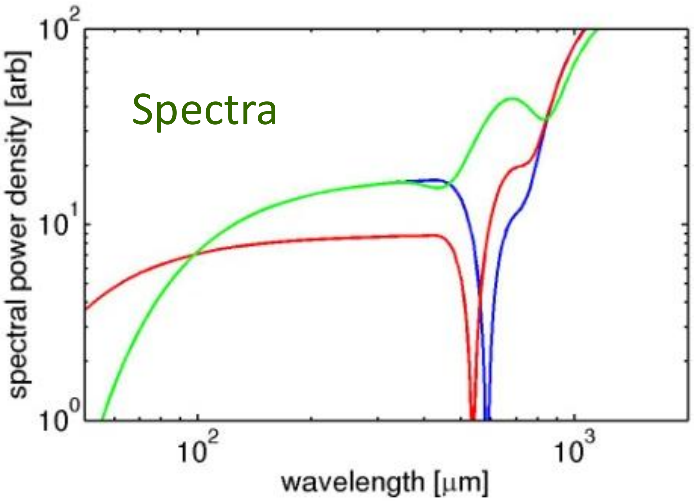



These experiments had less than ideal laser: ~5ps, not very narrow spectrum

# Time resolution & bandwidth

- 20 fs time resolution…
  Implies 20-30 THz detection bandwidth
- Uniform (or known) response function required
  over full bandwidth



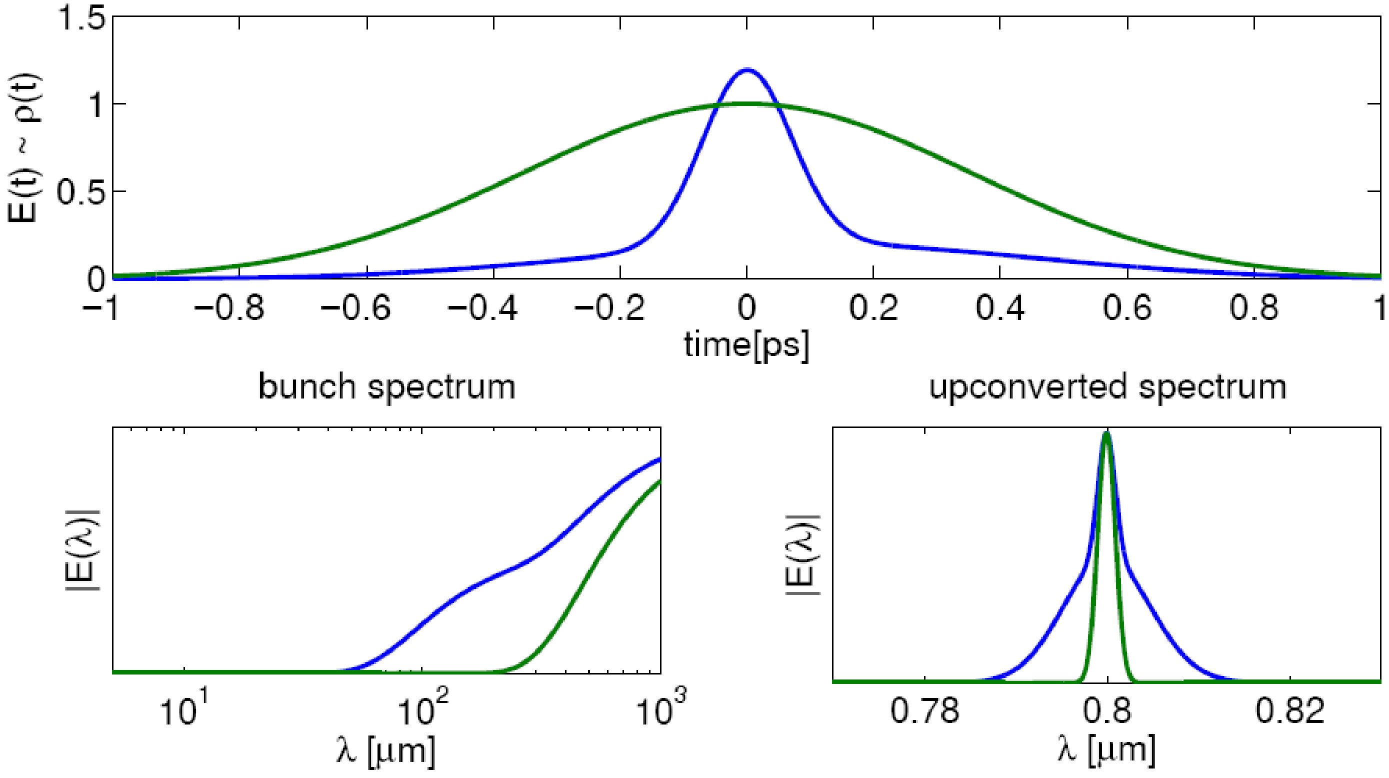




Coulomb field …. 0.1 – 20 THz (octave spanning bandwidth)

Convert to optical field …. 300 THz +/- 20THz (10% bandwidth

- Manageable relative bandwidth
- could exploit ultrafast laser diagnostic techniques

# Ideal: narrow band laser, short pulses.



# Summary

- Deflection cavity / zero crossing
  - 10fs resolution capability
  - Huge infrastructure for high energies
  - Destructive

- Radiative spectral techniques
  - Demonstrated with extremely broadband & single shot capability
  - Empirical tuneup, stabilisation

- Electro-optic temporal techniques
  - Limited by materials and optical characterisation
  - Solution in multiple crystal detectors /alternative materials (?) in "FROG" like techniques

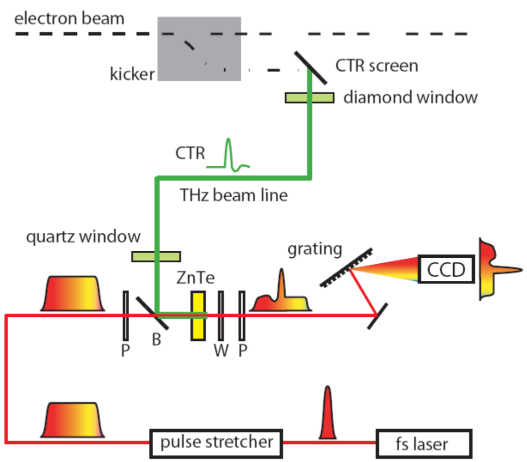
- Electro-optic upconversion
  - Converts extreme broadband signal into manageable optical signal
  - Strong potential for empirical feedback system

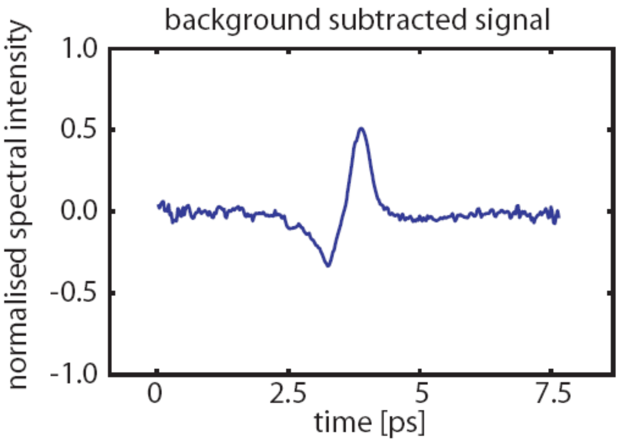
# Electro-optic Longitudinal Profile Diagnostics For CLIC

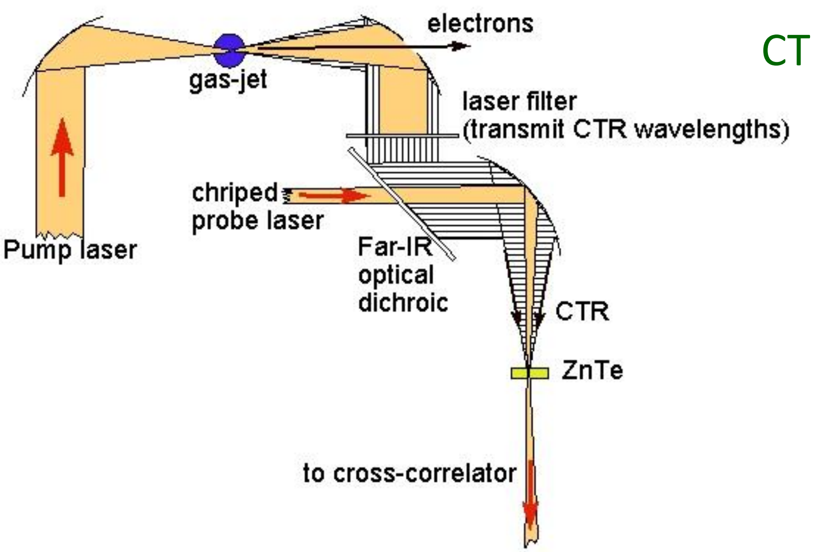
S P Jamison,
Accelerator Science and Technology Centre,
STFC Daresbury Laboratory

W.A. Gillespie
School of Engineering, Physics and Mathematics,
University of Dundee

# Electro-optic measurements of CTR

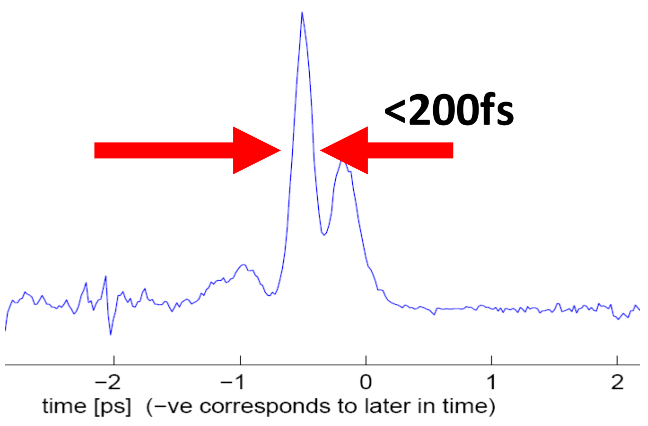


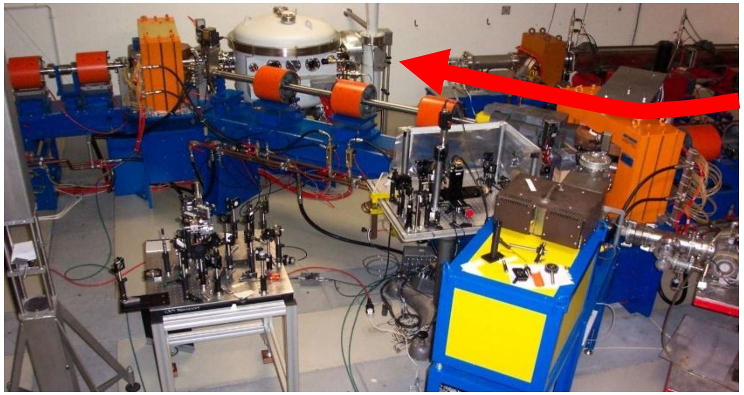



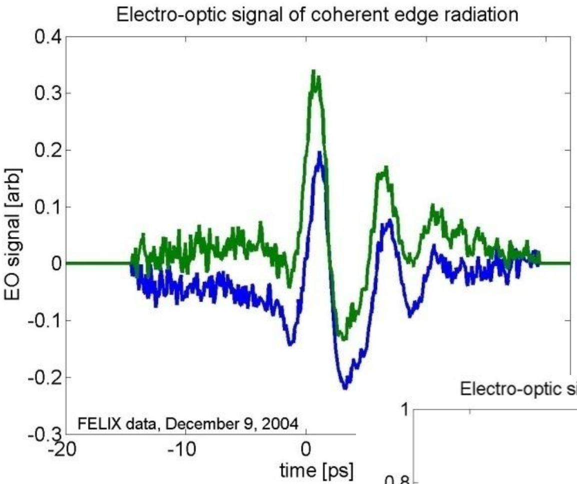

CTR from laser wakefield acceleration expts.

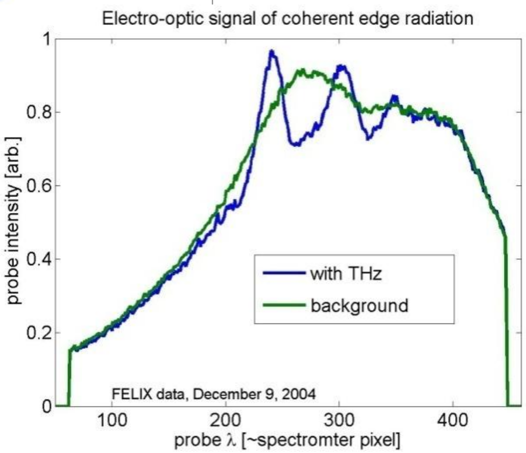
(Central laser facility, RAL)

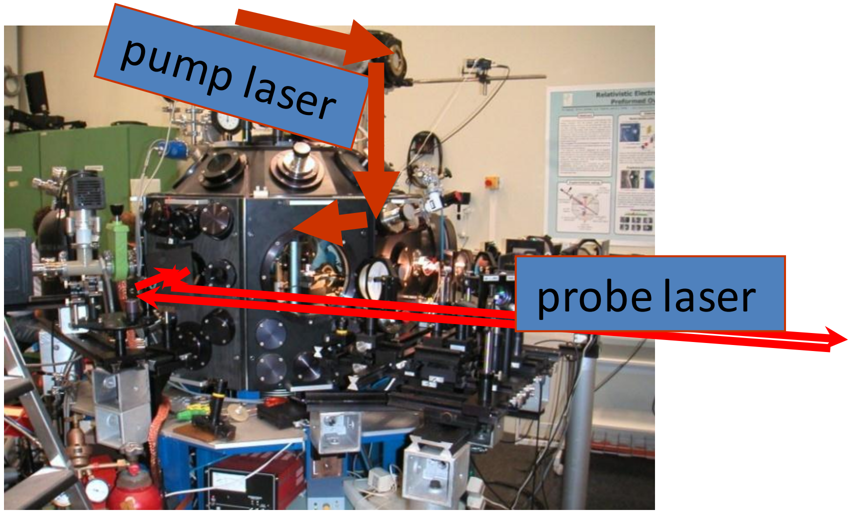


# Electro-optic detection of edge radiation..





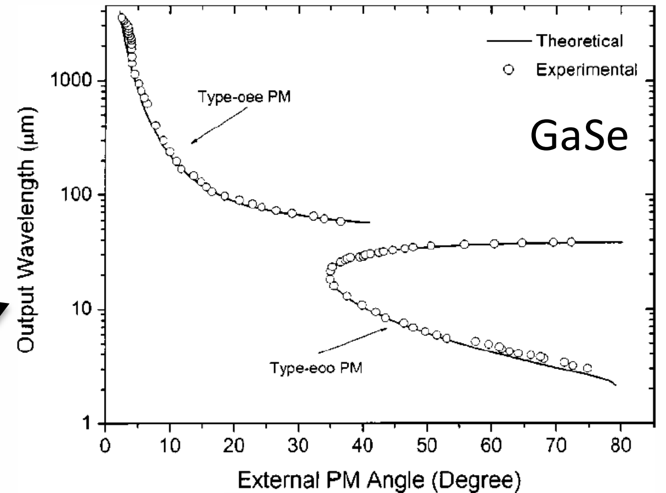




Electro-optic detection of laser-wakefield accelerated electrons

# Solution in multiple crystals and crystal orientations…

Tuneable phase matching of laser and THz pulse…




From Shi et al. Appl. Phys. Lett 2004

Many candidate crystals

Coulomb spectral component to be measured…

… crystal angle to achieve phase matching

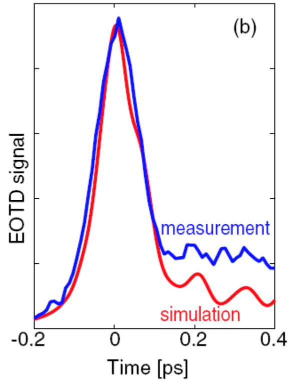
Questions on how to "splice" data.

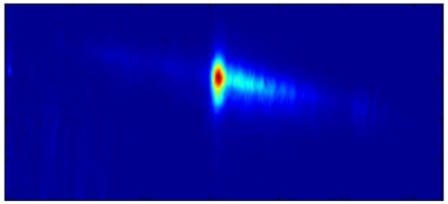
- Response amplitude can be measured from detection of tuneable THz source
- Spectral complex response can be measured from THz-TDS from linear THz-TDS … if we have known ultrashort source

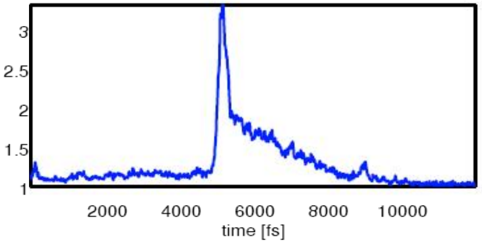
# …Time resolution

Current best resolution achieved: ~120fs FWHM (~60fs rms)

Require Improvements in






- Materials for upshifting to optical.
  Currently limited to <8THz (GaP, bulk)

  -multiple crystal detectors: will investigate patchwork deconvolution capabilities
  - Will investigate alternative 2D materials
    Solves propagation limits. Efficiency ?)

- Single-shot optical characterisation
  currently limited to ~40-80 fs by input probe duration

  Sub-pulse resolution available through "FROG" schemes but Intensity requirements conflict with EO materials.

  Will develop suitable cross-correlation FROG (X-FROG)

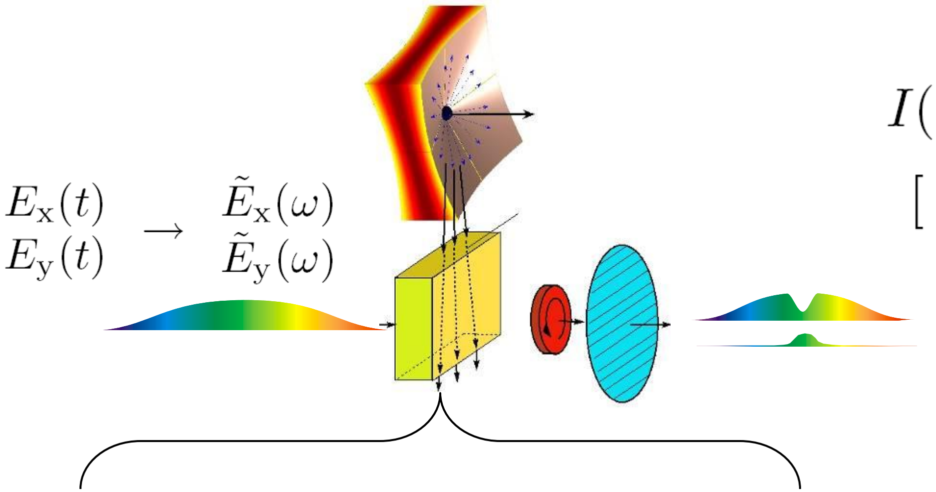
# 4. Spectral upconversion diagnostic

Physics of EO encoding…

- shifting Coulomb spectrum to optical region

OR

- creating an optical "replica" of Coulomb field




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

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

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

Coulomb spectrum shifted to optical region

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

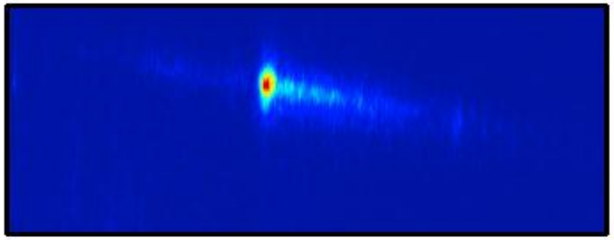
envelope — optical field

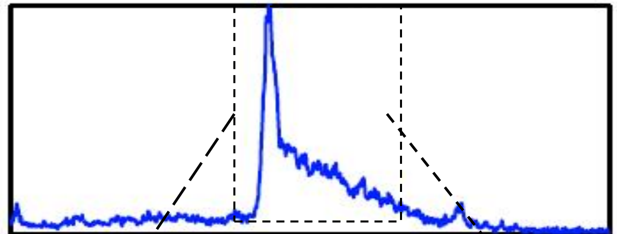
Coulomb pulse replicated in optical pulse

# Benchmarking of EO diagnostics

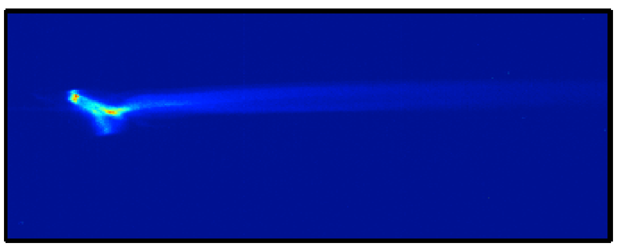
## comparison with transverse deflecting *(lola)* cavity

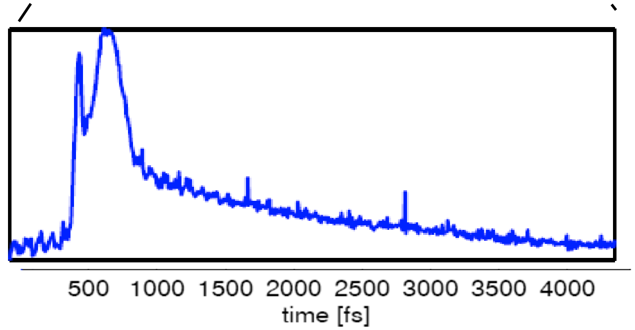
**Electro-optic**



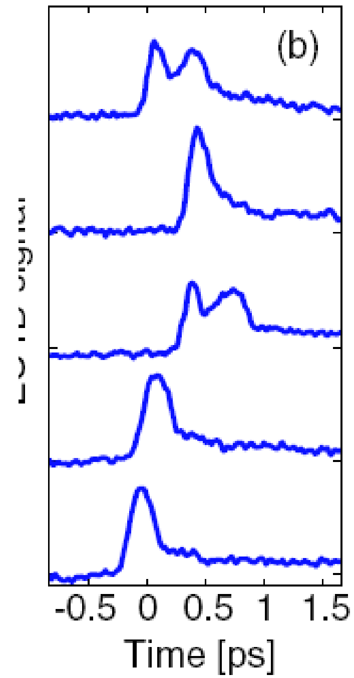


**Transverse Deflecting Cavity**






***shot-shot variations***




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

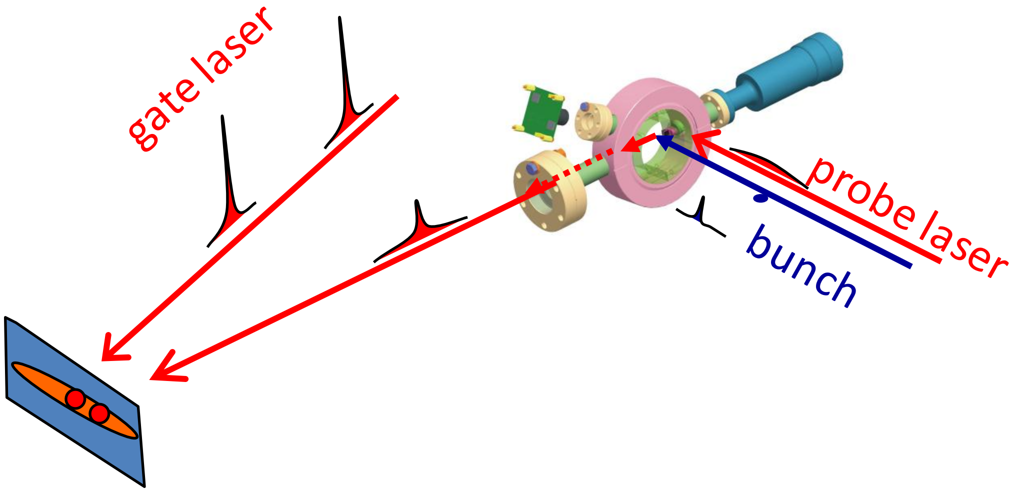
**Benchmarking of Electro-Optic Monitors for Femtosecond Electron Bunches**

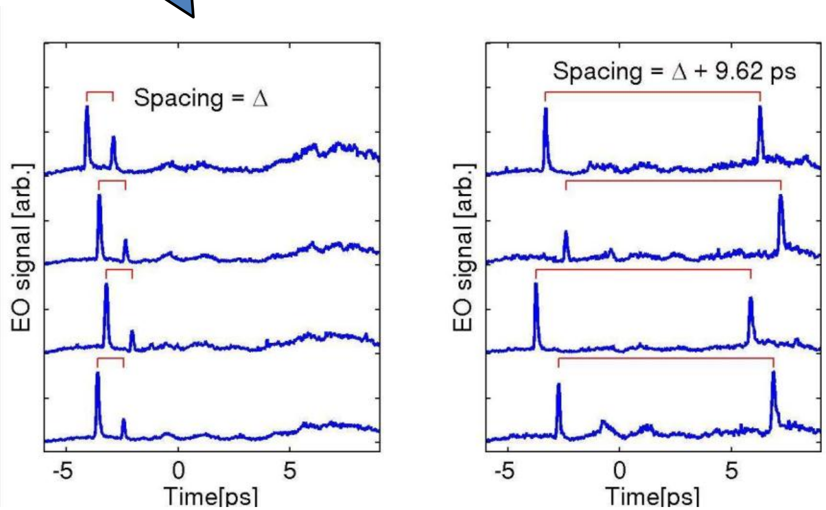
G. Berden,[1] W. A. Gillespie,[2] S. P. Jamison,[3] E.-A. Knabbe,[4] A. M. MacLeod,[5] A. F. G. van der Meer,[1] P. J. Phillips,[2] H. Schlarb,[4] B. Schmidt,[4] P. Schmüser,[4] and B. Steffen[4]

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

# Temporal decoding extras:
# EO confirmation of CDR feedback systems

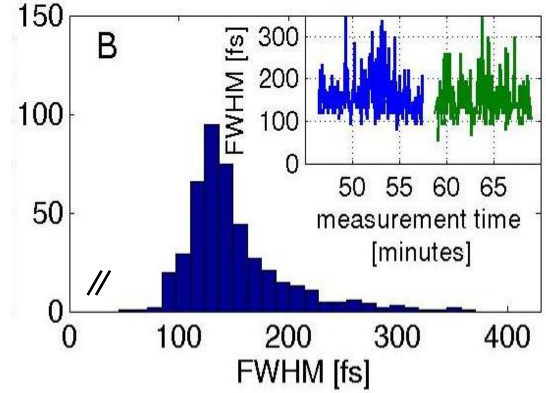
**Time Calibration….**



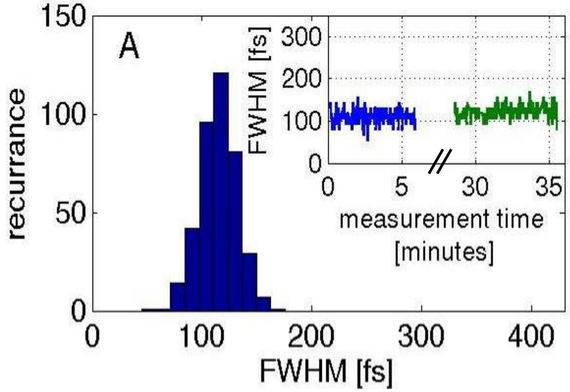



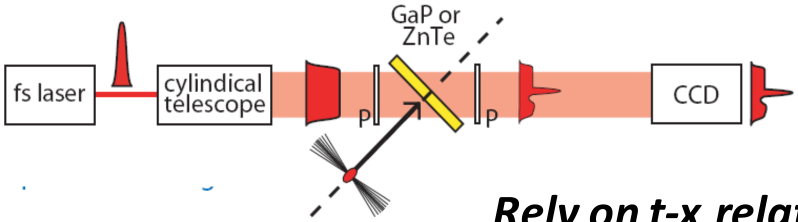

single shot capability reveals stabilising effect of slow feedback

CDR feedback off




CDR feedback on






# Spatial Encoding

***Rely on t-x relationship between laser and Coulomb field***

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

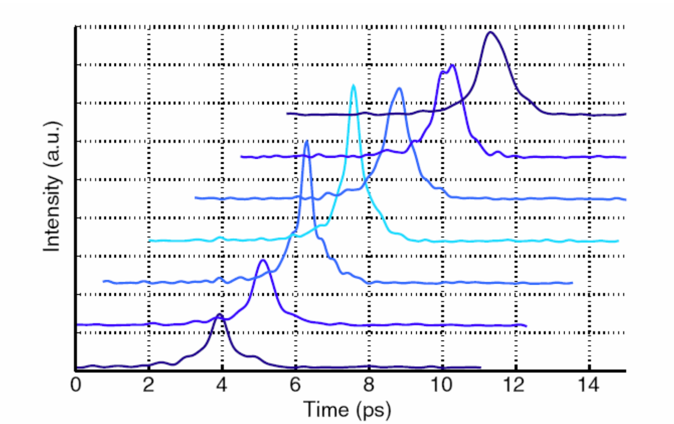
In principle: expect same/similar capabilities as TD

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

less widely demonstrated:

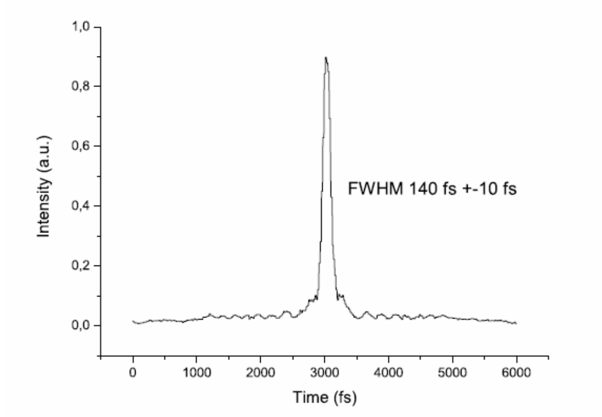
SLAC and DESY expts had significant additional complications of long transport in fibre...

SPPS (SLAC) measurements




from Cavaleria et al. PRL 2005

FLASH (DESY) measurements




from A. Azima et. al EPAC06