# Beam Diagnostics using Lasers II

# *Electro-Optic Longitudinal Profile Diagnostics*

## *Current Status & Future Directions*

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# Collaborators in this research:

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# Femtosecond resolution bunch profile diagnostics

**(predominantly for electrons)**

**Menu:**

- The need for longitudinal (temporal) bunch diagnostics
- Two distinct classes of temporal diagnostics:
  direct particle & radiative techniques
- Transverse deflecting cavities
- Spectral domain techniques
- Electro-optic techniques

# The need for femtosecond longitudinal diagnostics

**1. Advanced Light Sources: 4th generation**

Free-Electron Lasers kA peak currents required for collective gain

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

**2. Particle Physics:** Linear Colliders (CLIC, ILC) $e^+$-$e^-$ and others

Short bunches, high charge, high quality, for *luminosity*

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

**3. LPWAs:** Laser-plasma accelerators produce ultra-short electron bunches!

- 1-5 fs FWHM , ~ 20pC (and perhaps even smaller in future)

## Diagnostics needed for…

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

Significant influence on bunch profile from

wakefields, space charge, CSR, collective instabilities…

machine stability & drift

⇒ ***must have a single-shot diagnostic***

# Two distinct classes of diagnostics

Grouped by similar physics and capabilities/limitations

## *Direct Particle Techniques*

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

longitudinal → 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*

$\rho(t) \rightarrow E(t)$ …. propagating &
non-propagating

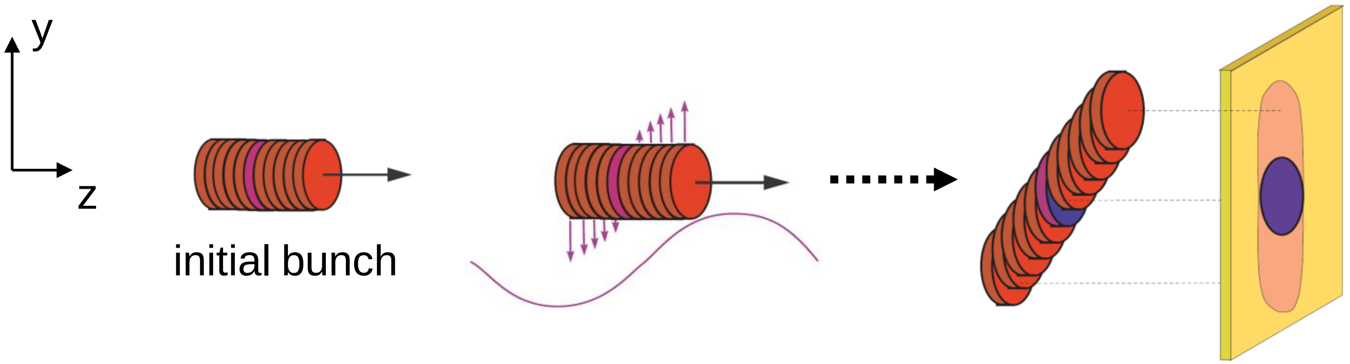
### Spectral domain:

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

### Time domain:

- Electro-Optic
- Optical Replica
- CTR, CDR (autocorrelation)

# Transverse deflecting cavities (TDC)



cavity: transverse kick

beam optics : transverse streak

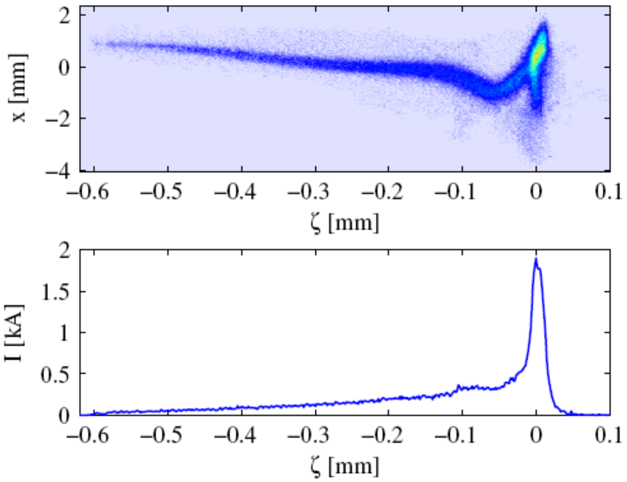
$$\Delta y'_{\mathrm{cav}}(z) = \frac{eV}{pc}\sin\left(\frac{2\pi z}{\lambda_{\mathrm{cav}}} + \phi\right)$$

$$\Delta y_{\mathrm{screen}}(z) = \left\{\sqrt{\beta_{\mathrm{c}}\beta_{\mathrm{s}}}\sin(\Delta\psi)\right\}\Delta y'_{\mathrm{cav}}(z)$$

Time resolution scaling

$$\alpha \left\{ \begin{array}{l} \text{deflection gradient} \\ \gamma^{-1/2} \end{array} \right.$$

Diagnostic capabilities linked to beam optics

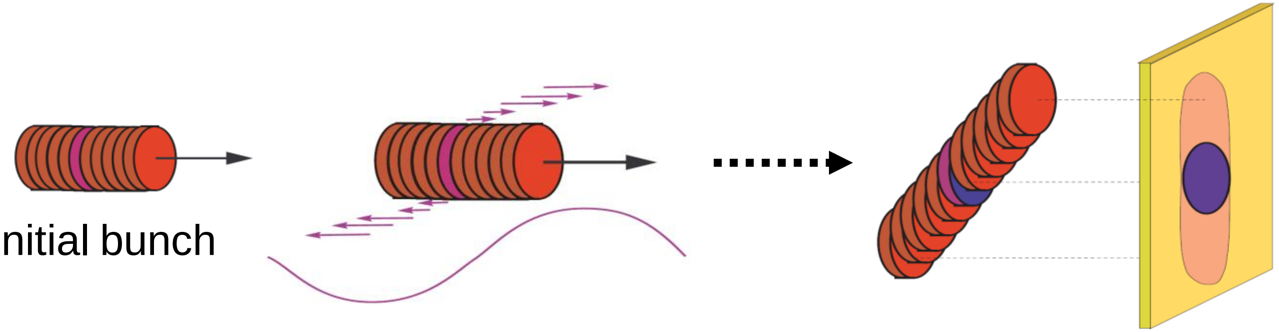


FLASH :

27 fs resolution

*Rohrs et al. Phys Rev ST (2009)*

# RF zero phasing



initial bunch

screen
transverse
profile

cavity:
z-dependent acceleration

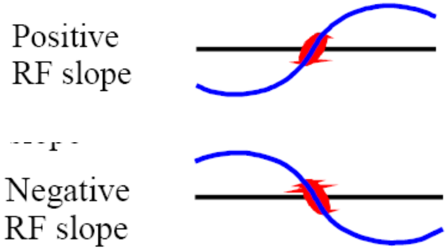
beam optics:
energy dispersion

- Introduce energy chirp to beam via “linear” near-zero crossover of RF
- Measure energy spread with downstream spectrometer ⇒ <u>infer</u> initial bunch profile

## time resolution dependent on:

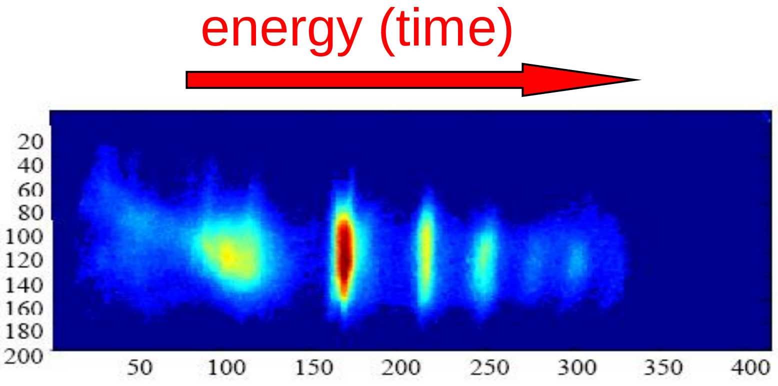
- gradient of energy gain
- dispersion of spectrometer
- initial energy spread

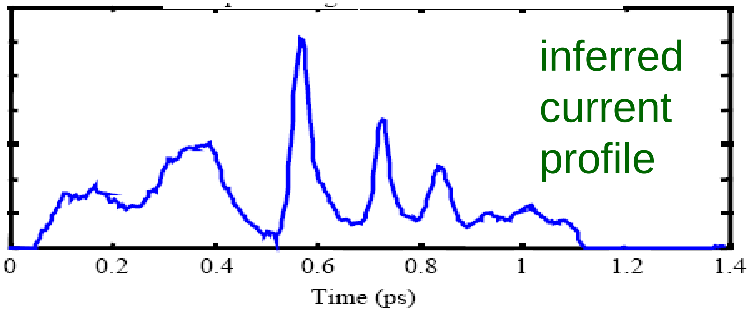
initial $\gamma$–z correlation ?



# RF zero-phasing examples

## DUV-FEL: at 75 MeV





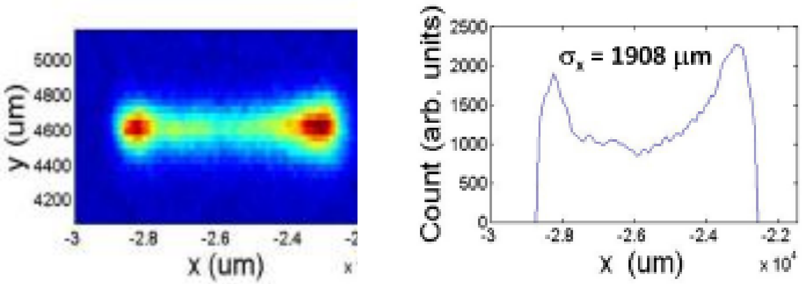
inferred current profile

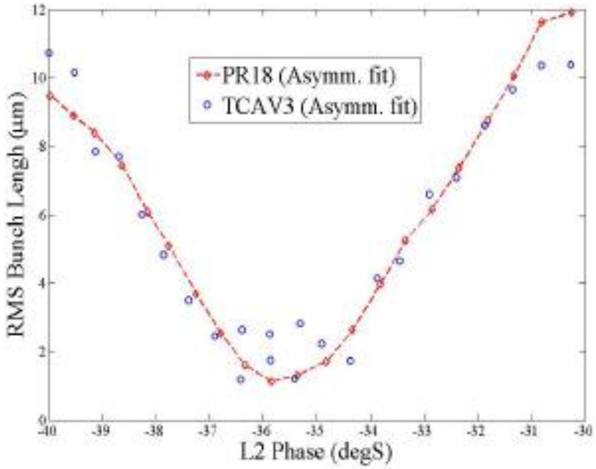
**time resolution of ~50 fs**

*Graves et al. PAC 2001*

## LCLS: at ~ 9 GeV

- 550m of linac at RF zero crossing!
- 6m dispersion on A-line spectrometer



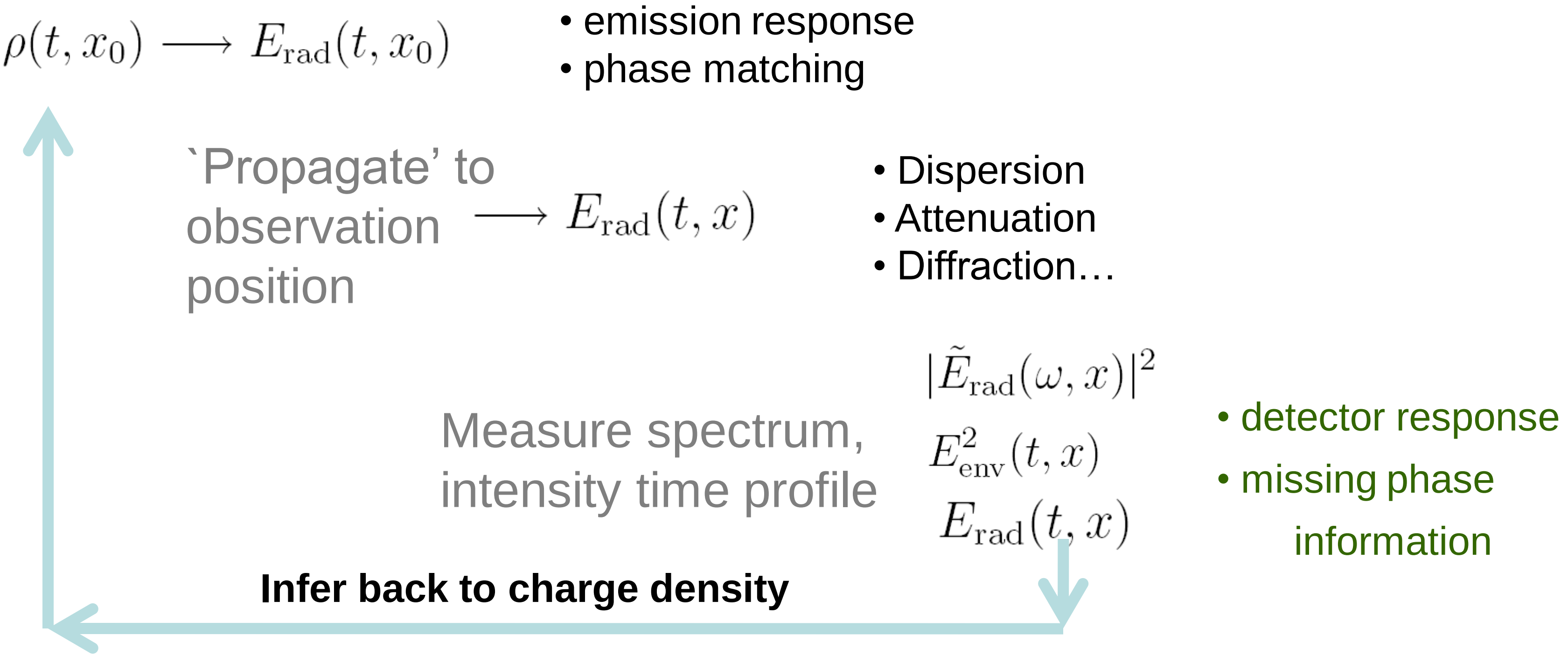


**1μm = 3 fs rms bunch length**

*Huang et al. PAC 2011*

# “Radiative” Techniques

Cause bunch to radiate coherently



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

- emission response
- phase matching

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

- Dispersion
- Attenuation
- Diffraction…

Measure spectrum, intensity time profile

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

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

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

- detector response
- missing phase information

**Infer back to charge density**

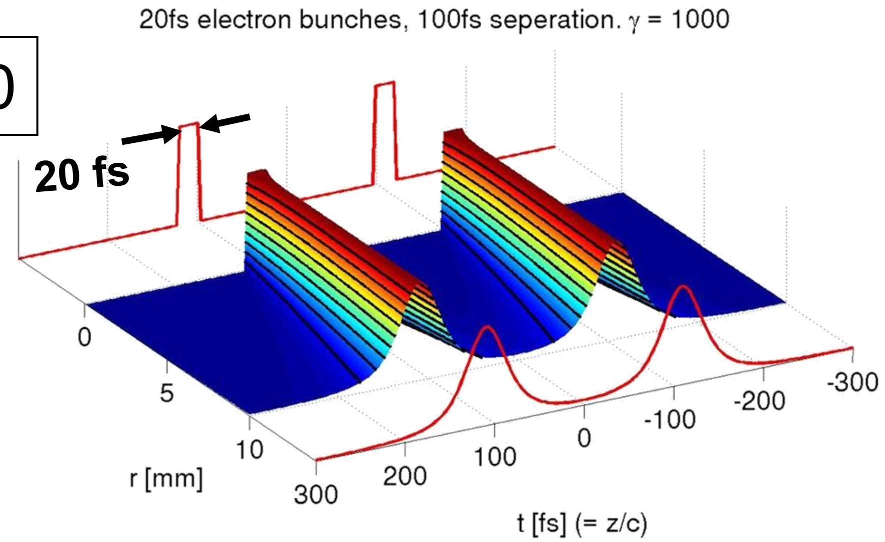
## Techniques & limitations:

| | |
|---|---|
| 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 |

# Common Problem - Field at Source

Field radiated or probed is related to Coulomb field near electron bunch

$\gamma = 1000$



Time response & spectrum of field dependent on spatial position, R:

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

$\Rightarrow$ ultrafast time resolution needs close proximity to bunch

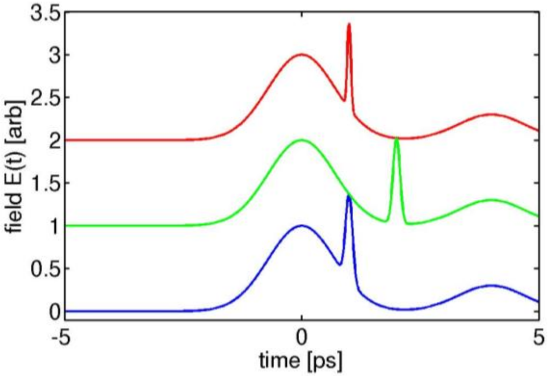
(N.B. equally true of CDR, Smith-Purcell, Electro-optic, etc)

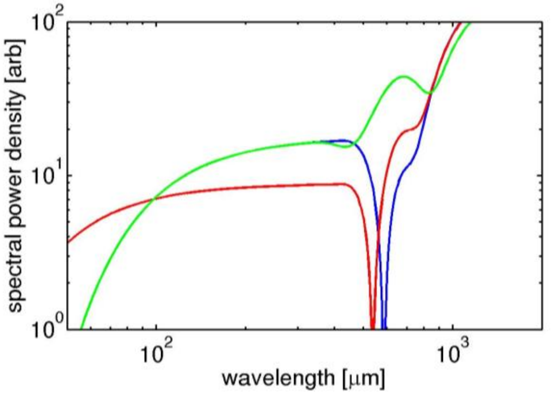
# Spectral domain techniques

Bunch form factor ⇒

**Coherent diffraction radiation**
**Coherent transition radiation**
**Coherent synchrotron radiation**
**Smith-Purcell radiation**

⇒ far-IR/mid-IR spectrum





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

For:

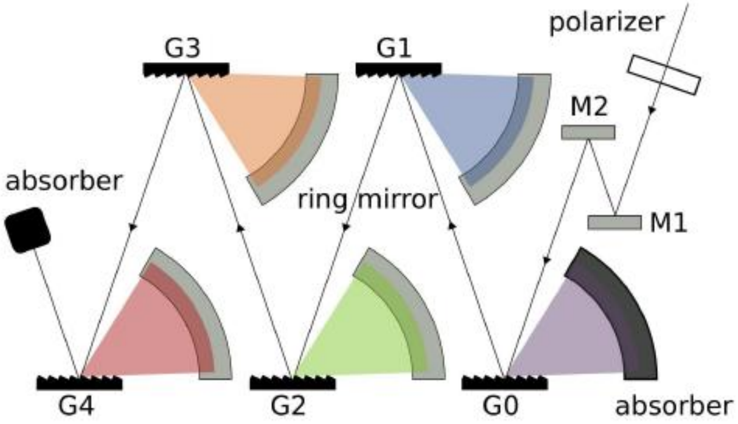
Simplicity (not always!)
Empirical machine information, real time
Information on fast and slow structure

Against:

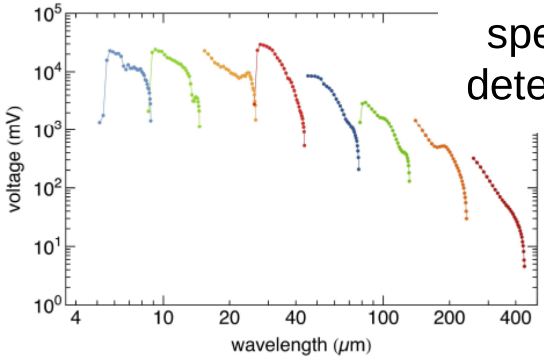
No explicit time profile
(but reconstruction *may* be possible)
Significant calibration issues

# example: single shot CTR spectrometer at FLASH

cascaded dispersive grating elements, and pyroelectric detector arrays

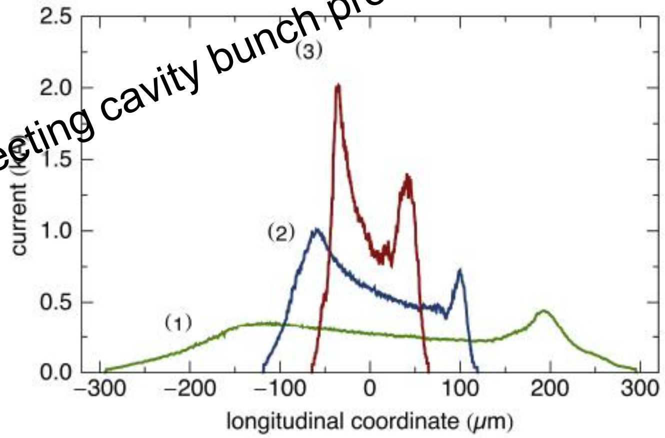


*Wesch, Schmidt, FEL 2010*

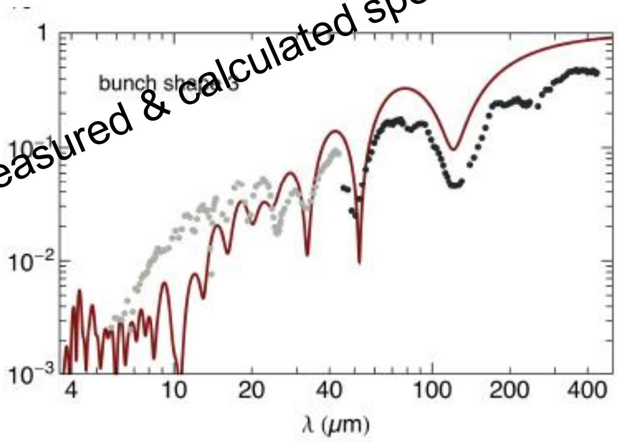


spectrometer &
detector response

Deflecting cavity bunch profiles



Measured & calculated spectra

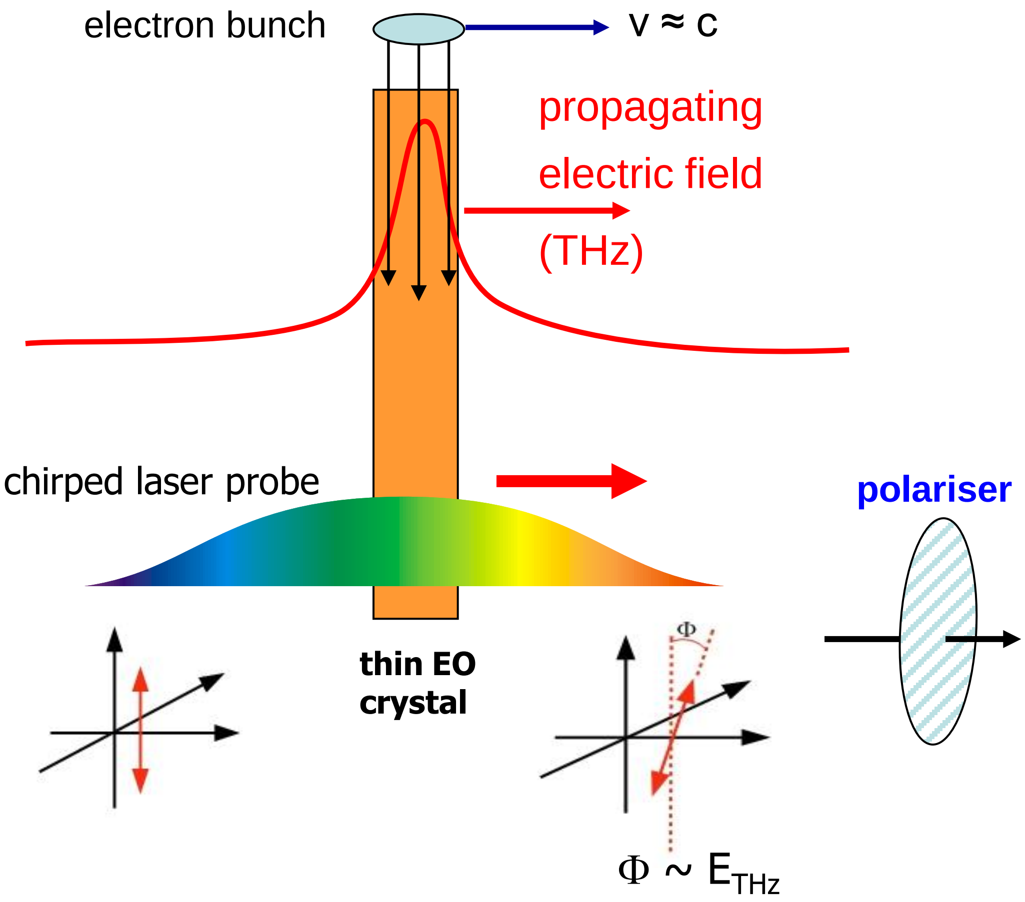


# Concept of electro-optic profile diagnostic

*( all-optical intra-beamline pickup of relativistic bunch Coulomb field )*

Principle: Convert Coulomb field of e-bunch into an optical intensity variation

Encode Coulomb field on to an optical probe pulse - from Ti:Sa or fibre laser



electron bunch

$v \approx c$

propagating electric field (THz)

chirped laser probe

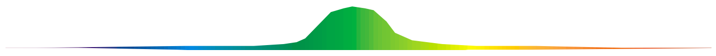
**thin EO crystal**

**polariser**

$\Phi \sim E_{THz}$

Decoding: of temporal intensity variations in single laser pulse via single-shot cross correlation in a BBO crystal

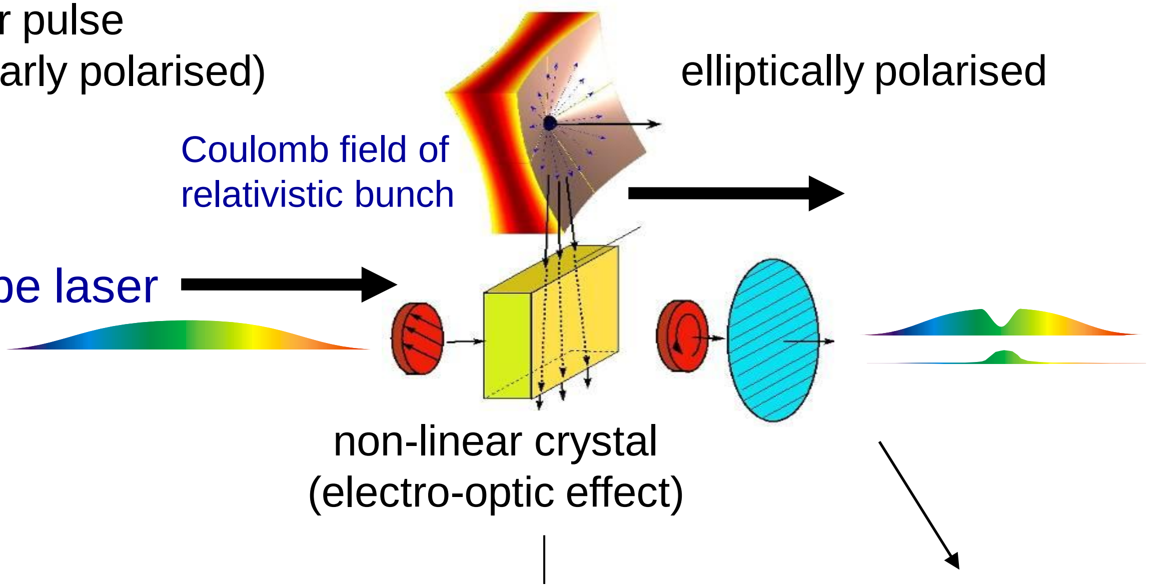
yields the temporal intensity variations in a single laser pulse



Detect polarisation rotation proportional to E or $E^2$, depending on set-up

# Physics of EO encoding ... standard description

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



laser pulse
(linearly polarised)

elliptically polarised

intensity dependent
on 'DC' field strength

Coulomb field of
relativistic bunch

probe laser

non-linear crystal
(electro-optic effect)

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

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

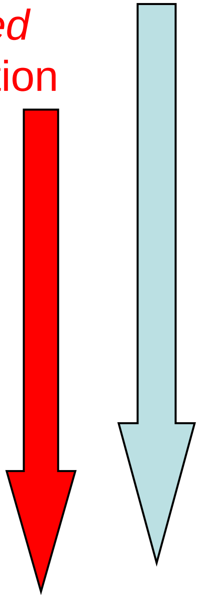
(basis for Pockels cells, sampling electro-optic THz detection, ...)

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

# Electro-Optic Techniques

o

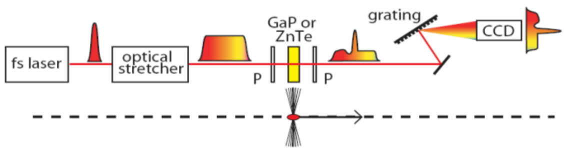
## Variations in read-out of optical temporal signal



complexity

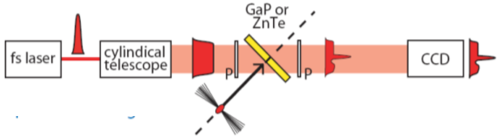
*demonstrated* time resolution

### Spectral Decoding



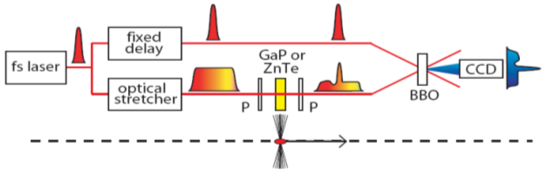
- Chirped optical input
- Spectral readout
- Use time-wavelength relationship

### Spatial Encoding



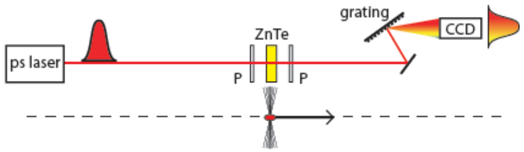
- Ultrashort optical input
- Spatial readout (EO crystal)
- Use time-space relationship

### Temporal Decoding



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

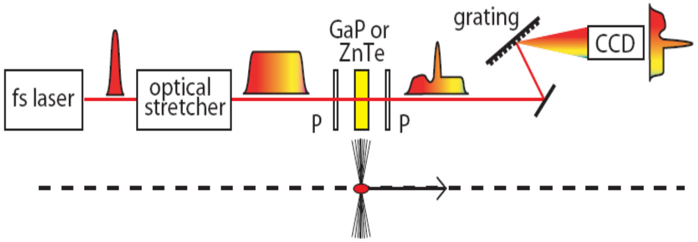
### Spectral upconversion**



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

# 1. Spectral Decoding

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

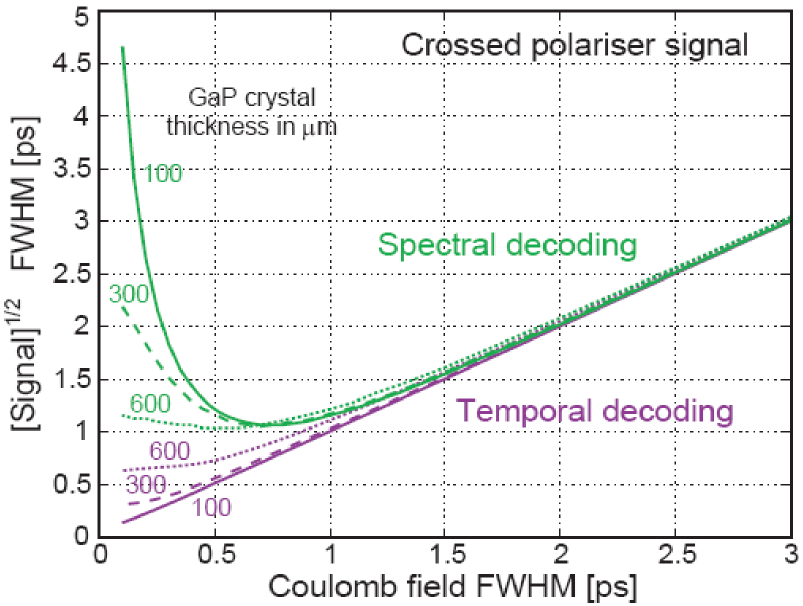


***Rely on t-$\lambda$ relationship of input pulse for interpreting output optical spectrum. Resolution limits come from the fact that the EO-generated optical field doesn't have the same t-$\lambda$ relationship***

## 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…



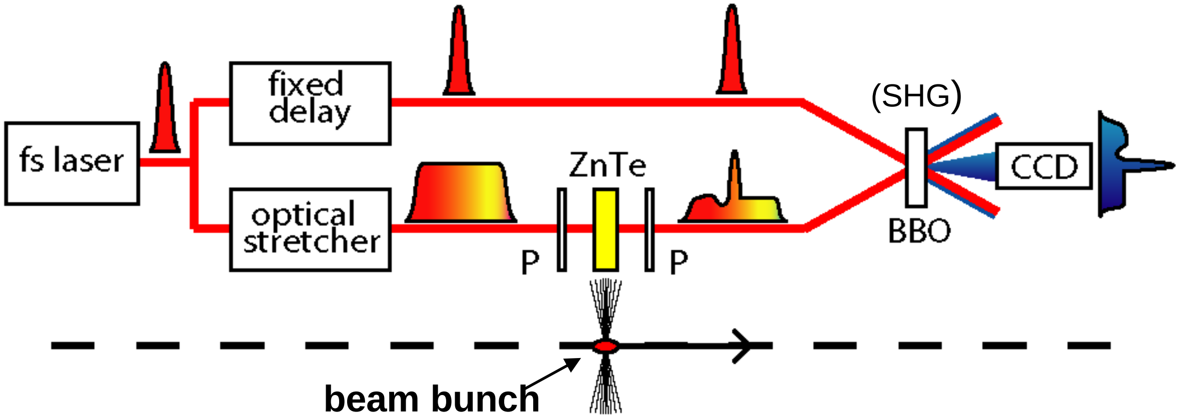
$$\tau_{\mathrm{lim}} = 2.61\sqrt{T_0 T_c} \quad ; \text{ for a Gaussian pulse}$$

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. Single-shot Temporal Decoding (EOTD)

(gives best time resolution at present)



**Temporal profile of probe pulse**

**→ Spatial image of SHG pulse**

Rely on EO crystal (ZnTe) producing a *optical temporal replica* of Coulomb field

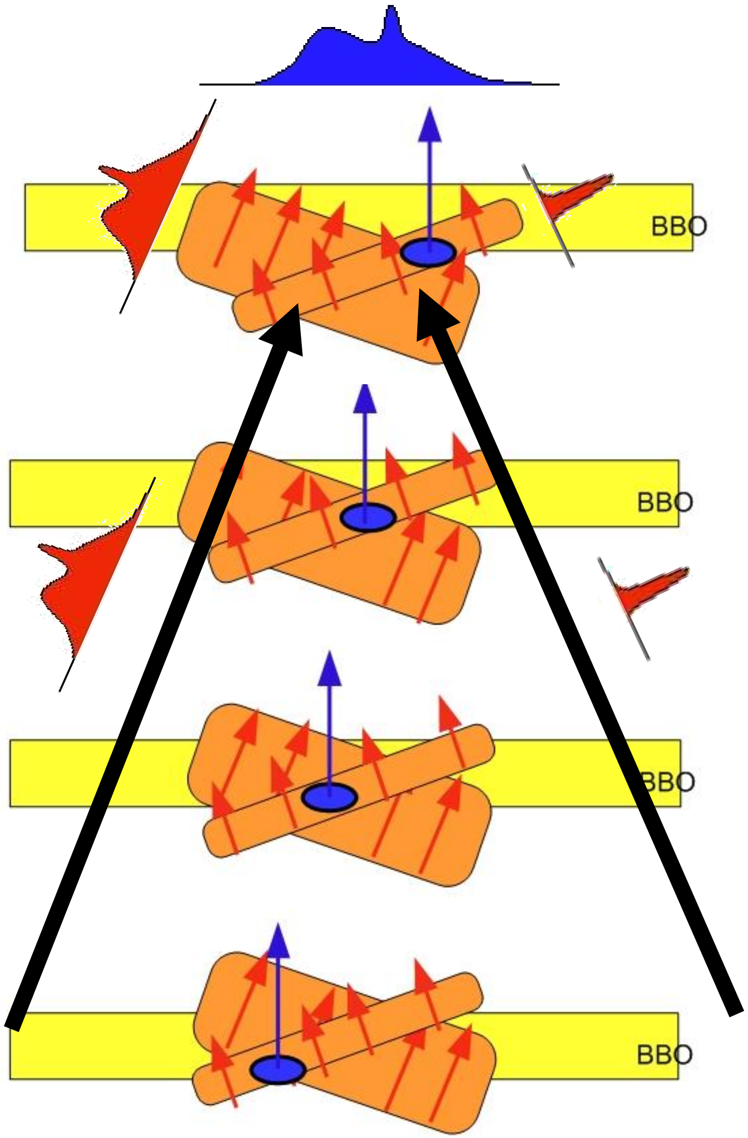
Measure optical replica with *t-x* mapping in $2^{nd}$ Harmonic Generation (SHG)

- *stretched & chirped* laser pulse leaving EO crystal assembly measured by short laser pulse via single-shot cross correlation in BBO
- large (~1mJ) laser pulse energy required ( via Ti:Sa amplifier)

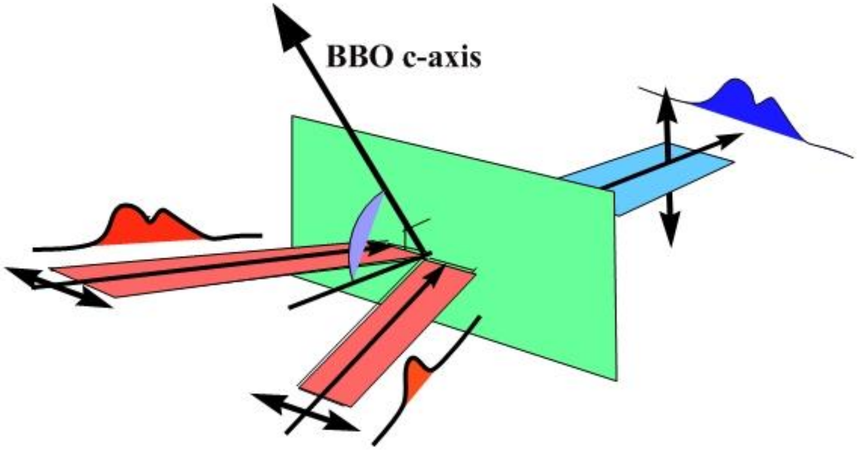
Technique limited by
- gate pulse duration (although FROG, etc. could improve)
- EO encoding efficiency, phase matching

*Practical limitations: complexity of laser systems involved*
*transporting short-pulse laser (gate pulse only)*

# Single-shot Temporal Decoding of optical probe



**Temporal profile of probe pulse**
**→ Spatial image of SHG**



Symmetric crystal geometry:
400nm “walk-off” orthogonal to time-axis

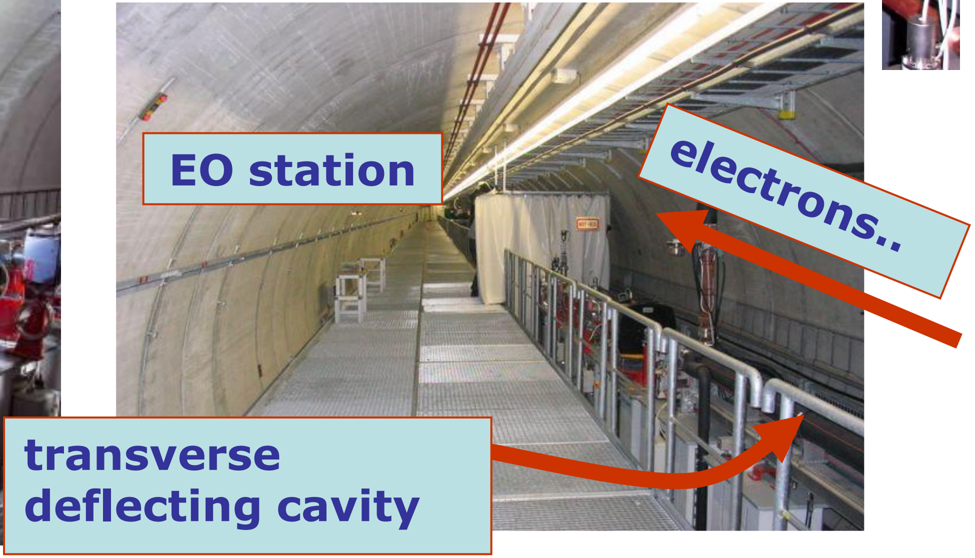
# Electro-optic diagnostics at FLASH

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

- ○ temporal decoding
- ○ spectral decoding
- ○ benchmarking against deflecting cavities

- 450 MeV, $\gamma$ ~1000
- bunches with peak + pedestal structure
- 20% charge in ~100 fs spike

**Temporal Decoding Diagnostic**

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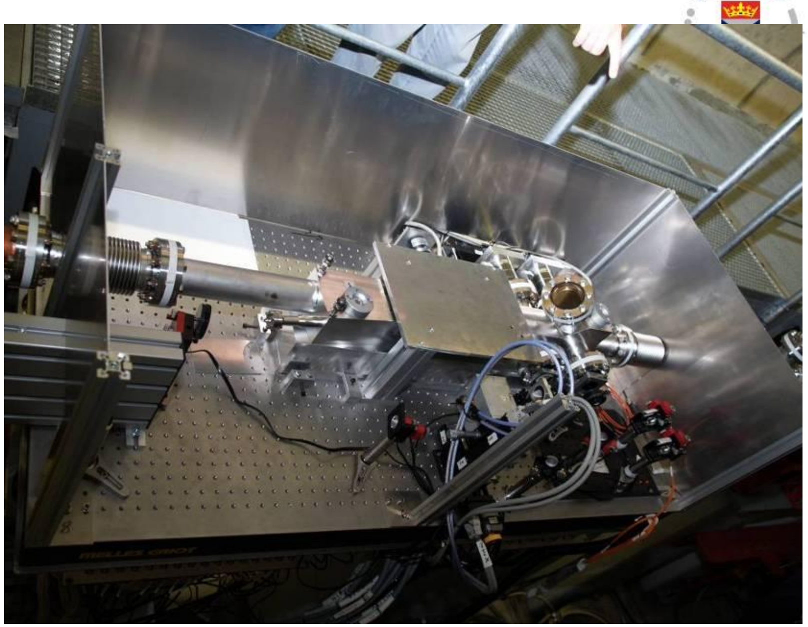

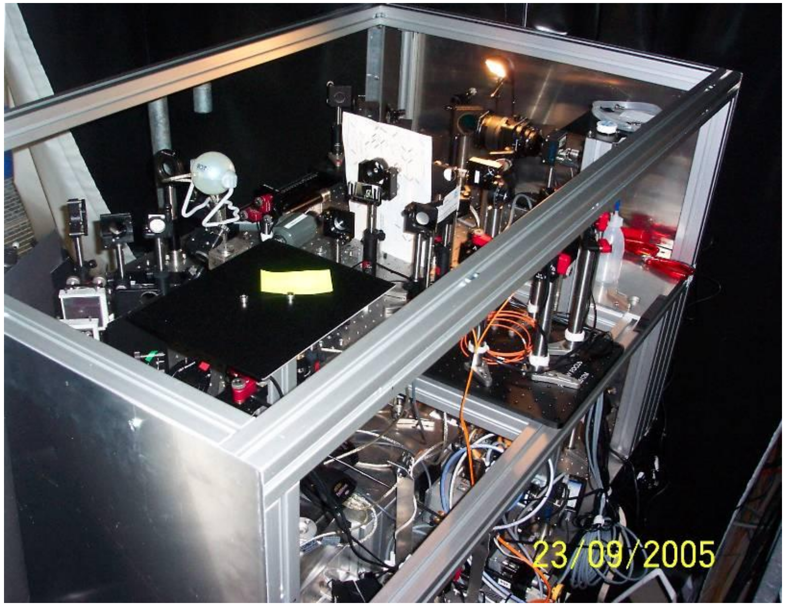
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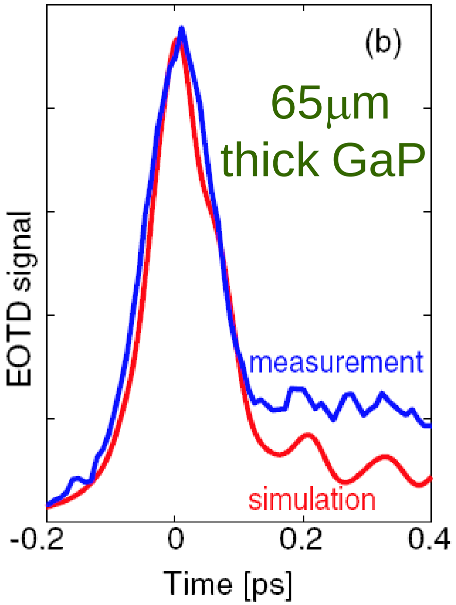
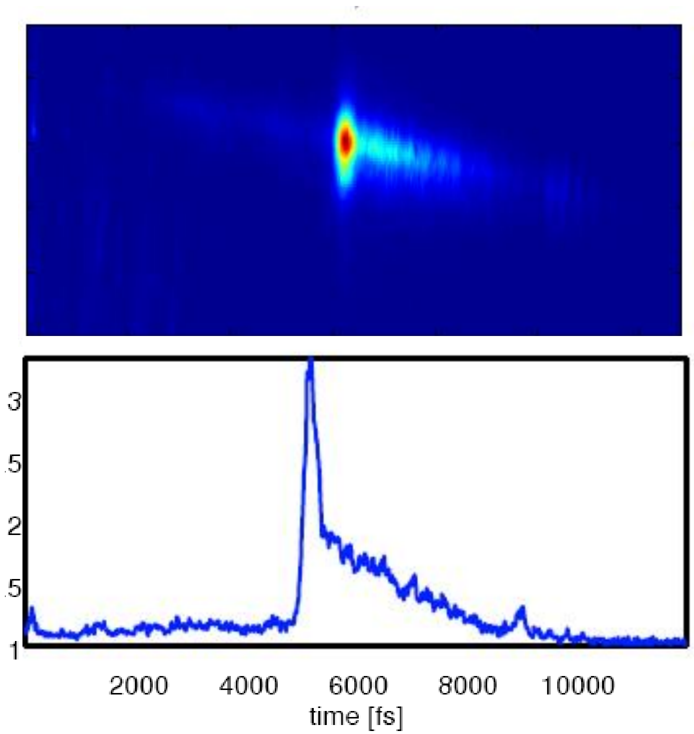
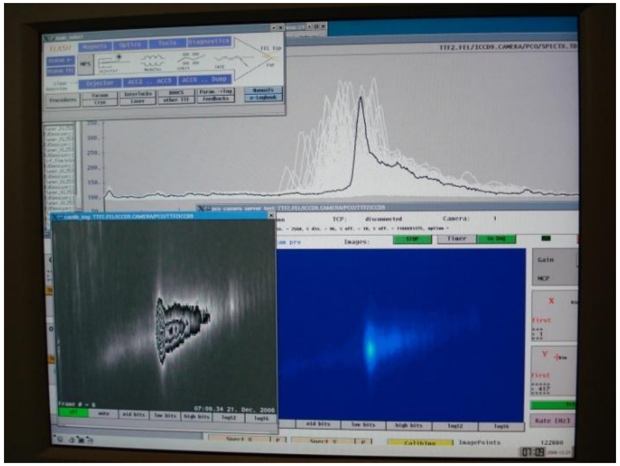
# temporal decoding in practice..

currently the highest time-resolution non-destructive diagnostic demonstrated (at DESY FLASH)





60 – 200µm thick GaP



“Time resolution”

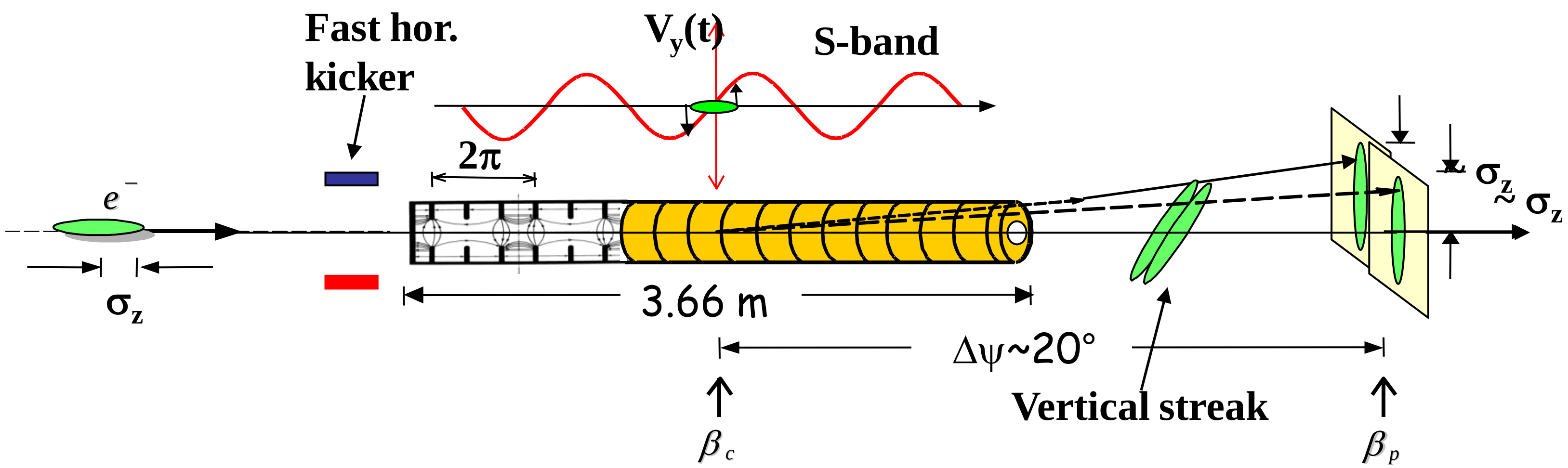
$\sigma_z$ ~ 90fs (rms)

$\sigma_z^{actual} \sim 30fs \Rightarrow \sigma_z^{measured} \sim 55\ fs$

$\sigma_z^{actual} \sim 90fs \Rightarrow \sigma_z^{measured} \sim 90\ fs$

# Benchmarking EO by LOLA cavity (TDC)

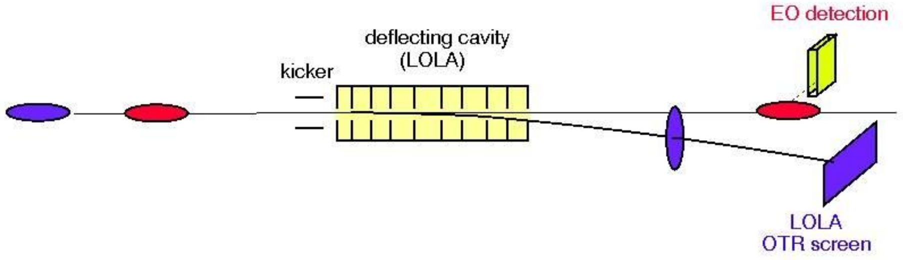
LOLA: Transverse Deflecting Cavity = fast electron oscilloscope



**Resolution:** 100fs (20fs with special beam optics)

**Disadvantages:** no absolute timing (high time jitter)

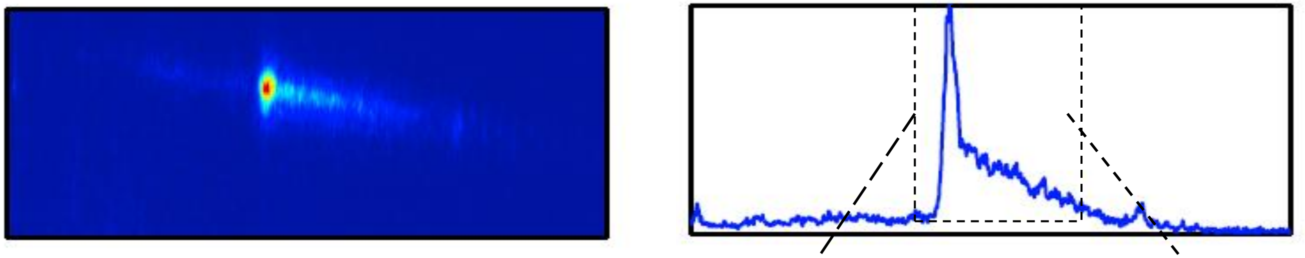
destructive diagnostic



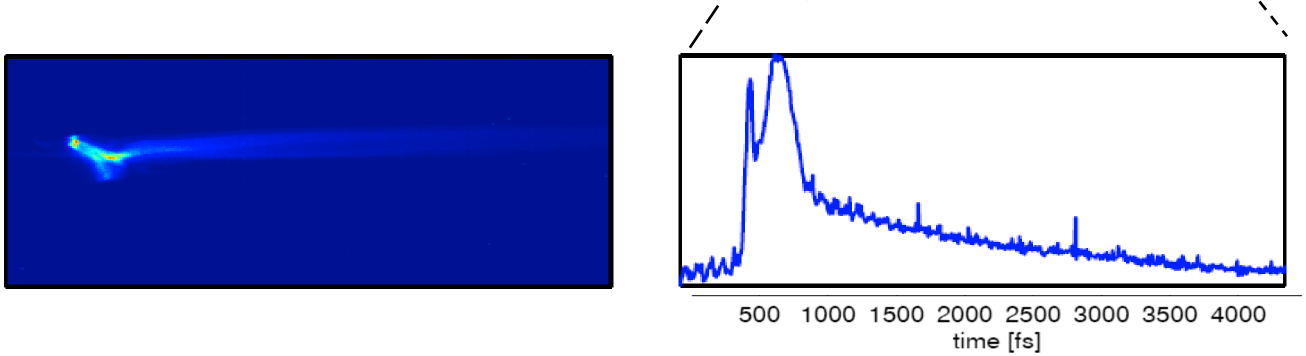
Transverse deflecting cavity
(1960’s cavity from SLAC)
located next to EO diagnostic

# Benchmarking of EO against LOLA TDC

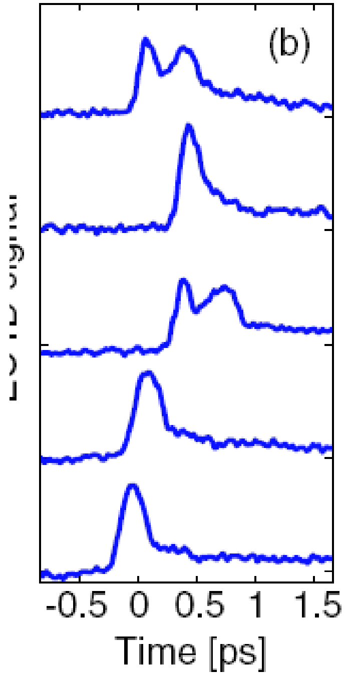
**Electro-Optic**

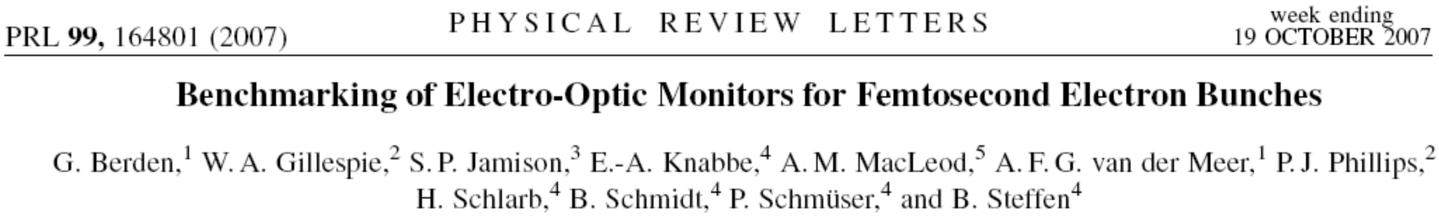


**Transverse Deflecting Cavity**



***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***

# 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)*

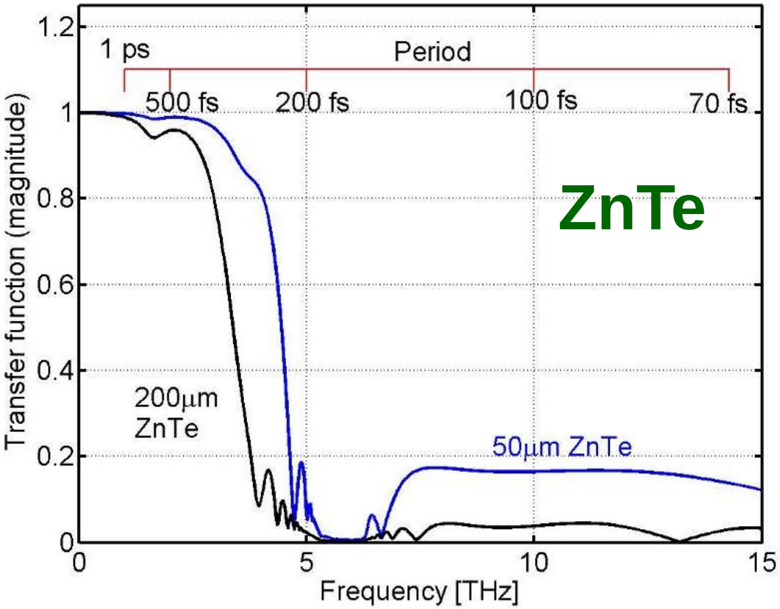
***limited by***

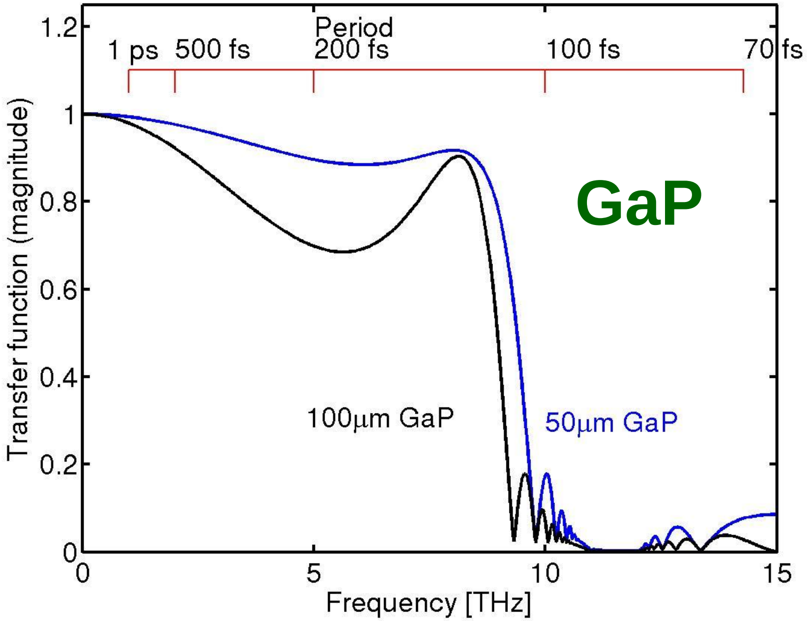
- ***EO material properties (phase matching, GVD, crystal reflection)***
- ***laser pulse duration (TD gate, SE probe)***

# Encoding Time Resolution...

## material frequency response, R(ω)

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





# 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**
- possibility of artificially-produced “metamaterials”

***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*

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

*All (inorganic) 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*

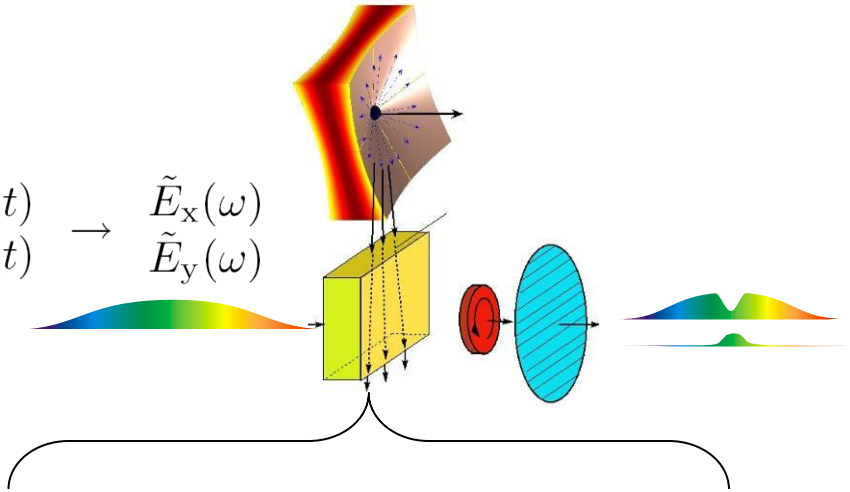
*If reconstruction needed anyway, reconsider spectral techniques ...*
*BUT traditional spectral techniques have difficulties :*

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

*A possible solution : Electro-optic spectral upconversion*

# Back to the physics of EO encoding...

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



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

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

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

Coulomb spectrum shifted to optical region

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

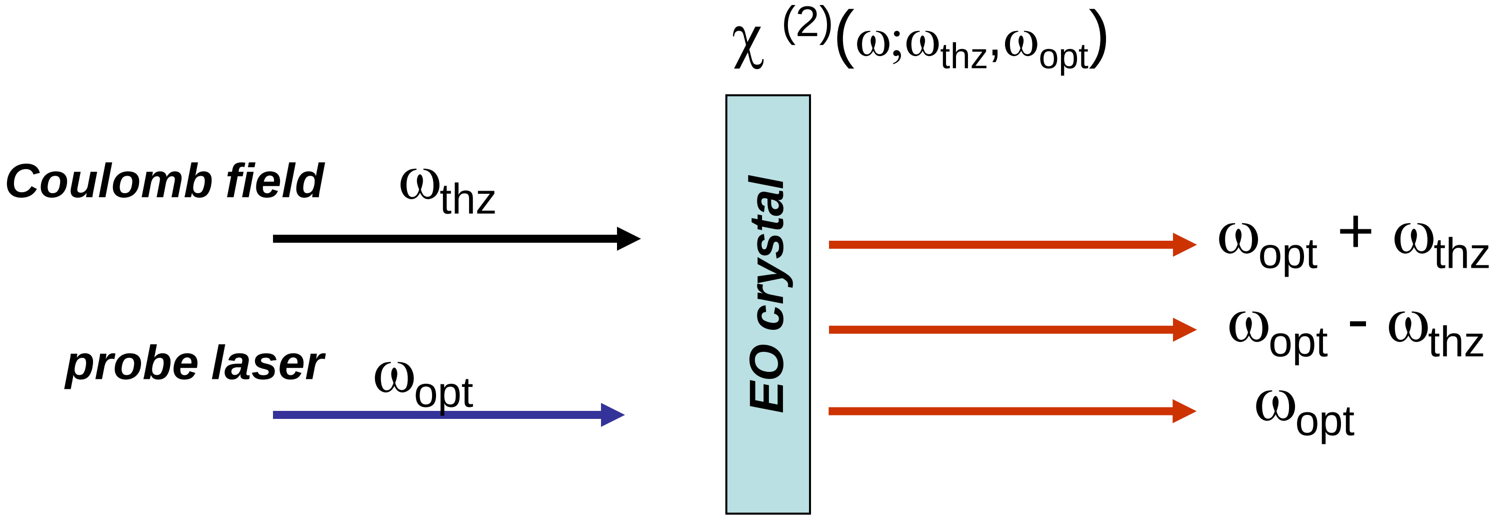
Coulomb pulse replicated in optical pulse

***New concepts & understanding of very high time resolution techniques come from a 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*** $\omega_{thz}$

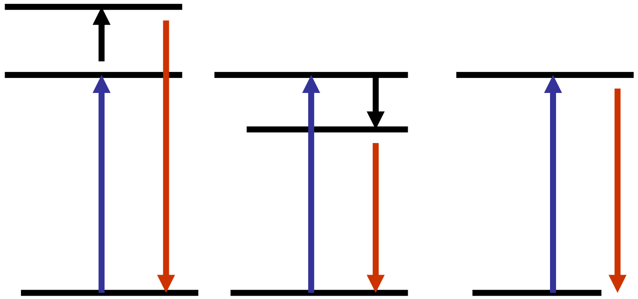
***probe laser*** $\omega_{opt}$

***EO crystal***

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

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

$\omega_{opt}$



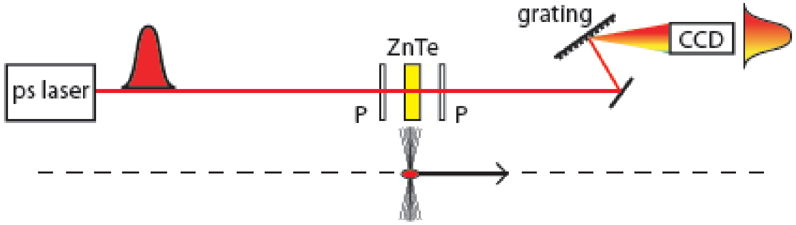
***for arbitrary probe and Coulomb pulses...***

- 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 )***

# 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

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

→ *δ-function*

same physics
as “standard” EO

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

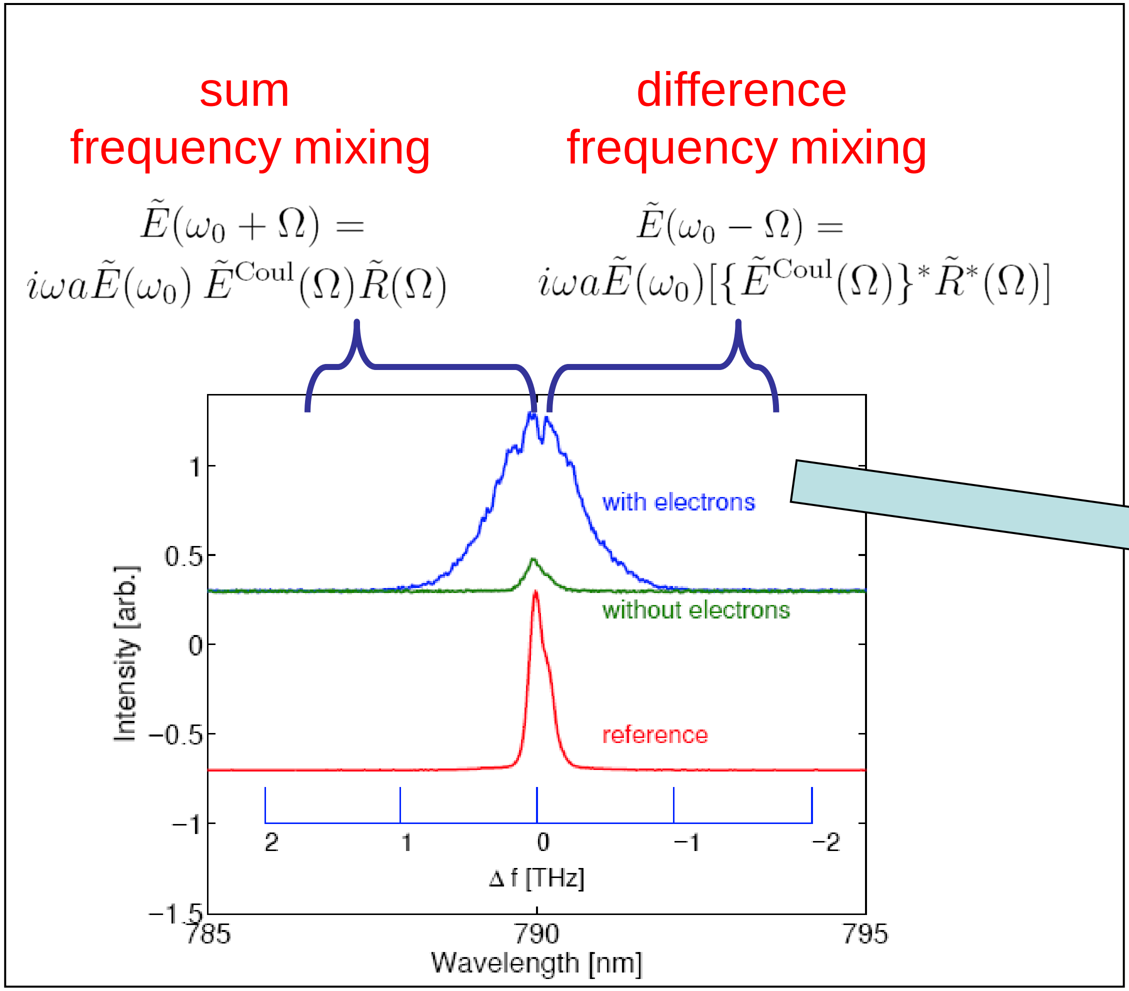
($\Omega$ can be $<0$)

different observational
outcome

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

# Spectral upconversion diagnostic

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



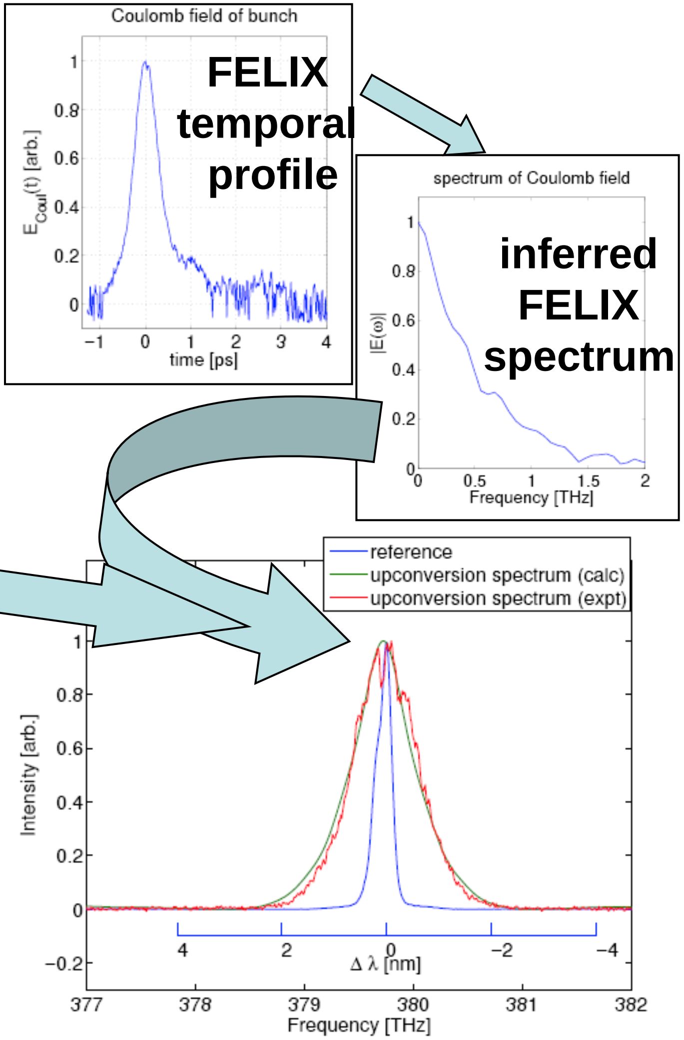
sum
frequency mixing

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

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**

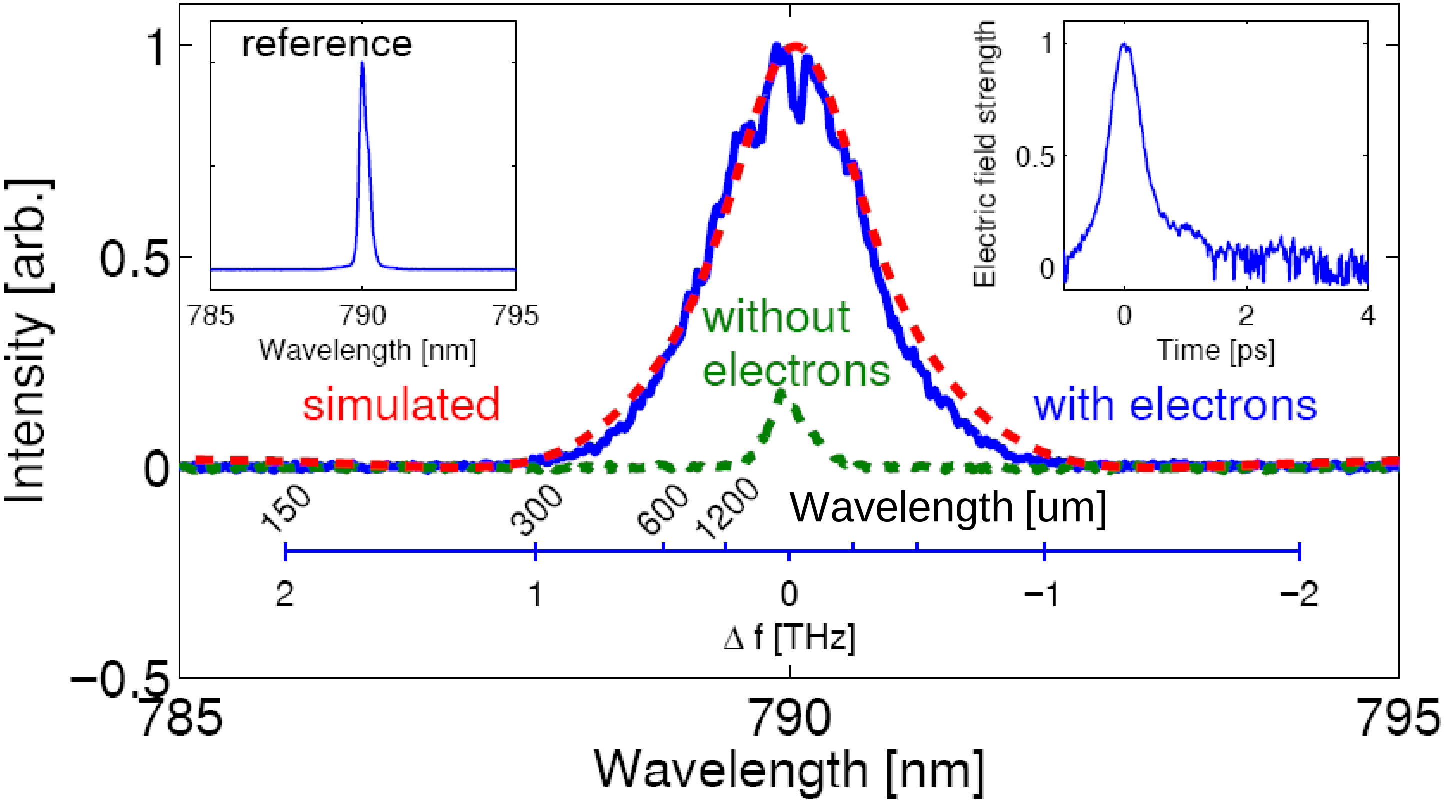


**FELIX temporal profile**

**inferred FELIX spectrum**

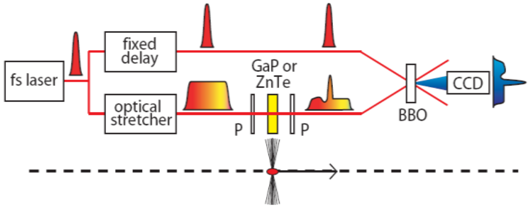
# SU measures long wavelength components

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

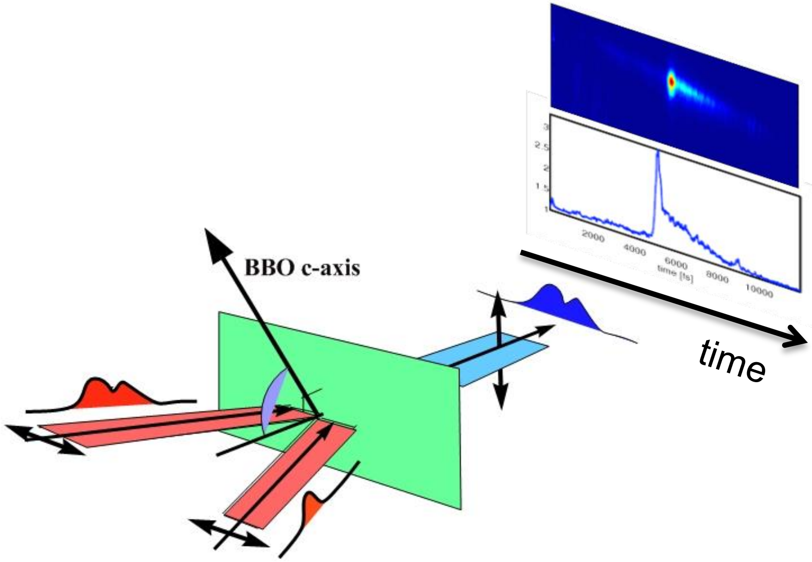


These experiments had a less than ideal laser: ~5ps, not very narrow spectrum

# Temporal Limitations of EOTD



## 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 )

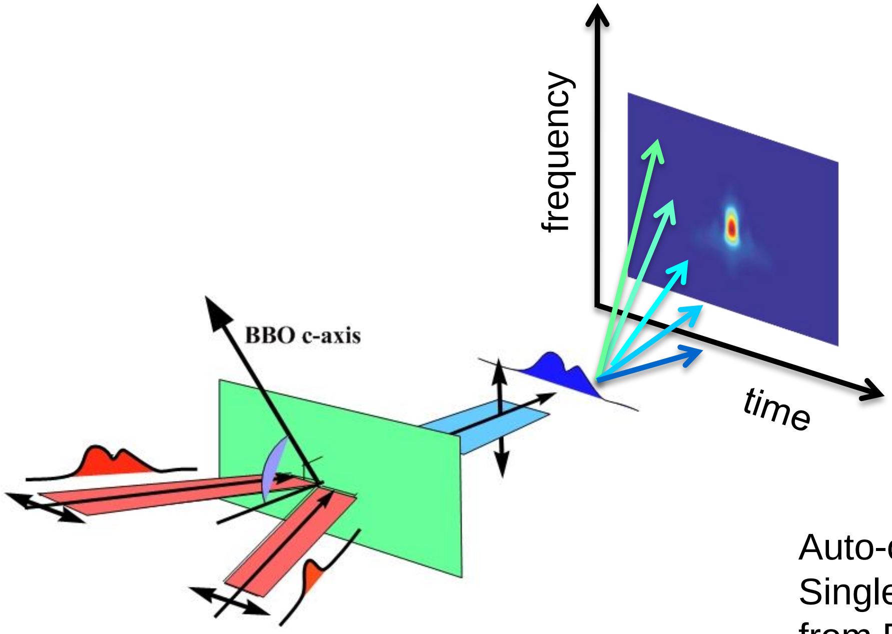
- Weak probe due to EO material damage limits…
- Compensated by intense gate pulse

  Signal/noise issues from this mismatch in intensities

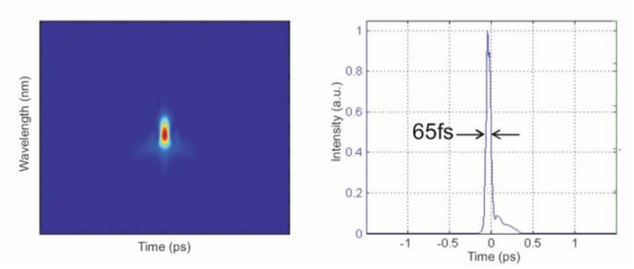
# Higher resolution through “X-FROG”

## 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 Thakker)

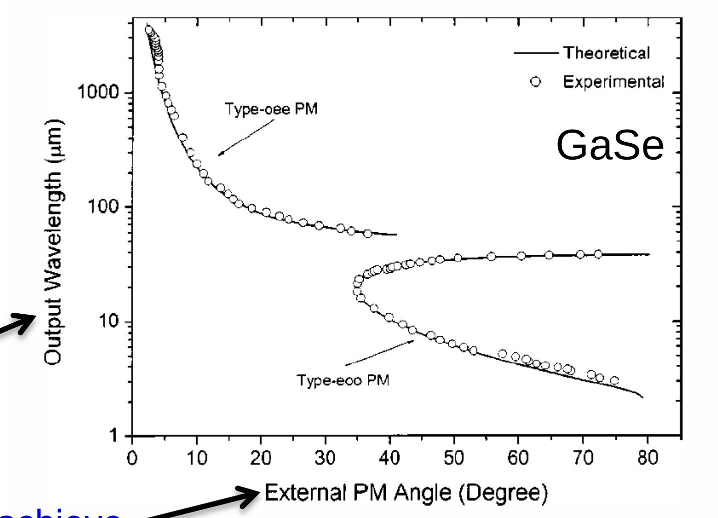
Auto-correlation, not cross correlation
Single-shot requires more intensity than reasonable
from EO material limitation

**R&D goals:**

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

# Solution in multiple crystals and crystal orientations…

Tuneable phase matching of laser and THz pulse…



Many candidate crystals

Coulomb spectral component to be measured…

… crystal angle to achieve phase matching

From Shi et al. Appl. Phys. Lett 2004

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 a known ultrashort source

# Femtosecond longitudinal diagnostics

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

Targeting 20fs rms resolution with Electro-optic diagnostics

## Current limitations of electro-optic detection:

Time resolution restricted by - materials phase matching
- probe laser duration (~40-80 fs)

Implementation limited by - femtosecond laser complexity

## Solutions?

**Spectral upconversion** – quasi CW laser probes beam with EO effect

**All-optical parametric amplification of probe signal**

**Frequency Resolved Optical Gating (FROG)**
for sub-pulse femtosecond characterisation of amplified optical probe

**Nano-structured materials**
for bypassing of EO phase-matching constraints

**Fibre laser spectral decoding**
(low power fs lasers), and temporal retrieval algorithms

# Summary

- Deflection cavity / zero crossing
  - 10fs resolution capability, in principle
  - huge infrastructure for high energies
  - destructive technique

- Radiative spectral techniques
  - demonstrated with extreme broadband & single shot capability
  - empirical tune-up, stabilisation

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

- Electro-optic upconversion
  - converts extreme broadband signal into manageable optical signal
  - strong potential for empirical feedback system

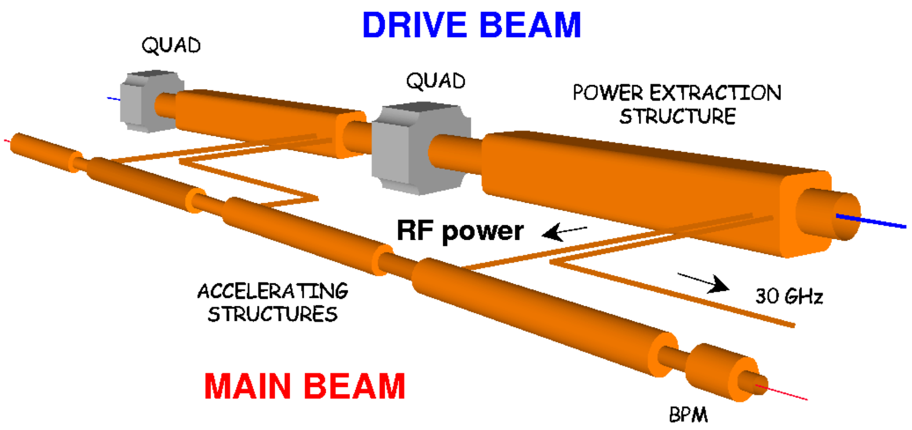
# CLIC Project at CERN (Compact Linear Collider)

Feasibility study for 3 Tev (c.o.m.) electron-positron collider

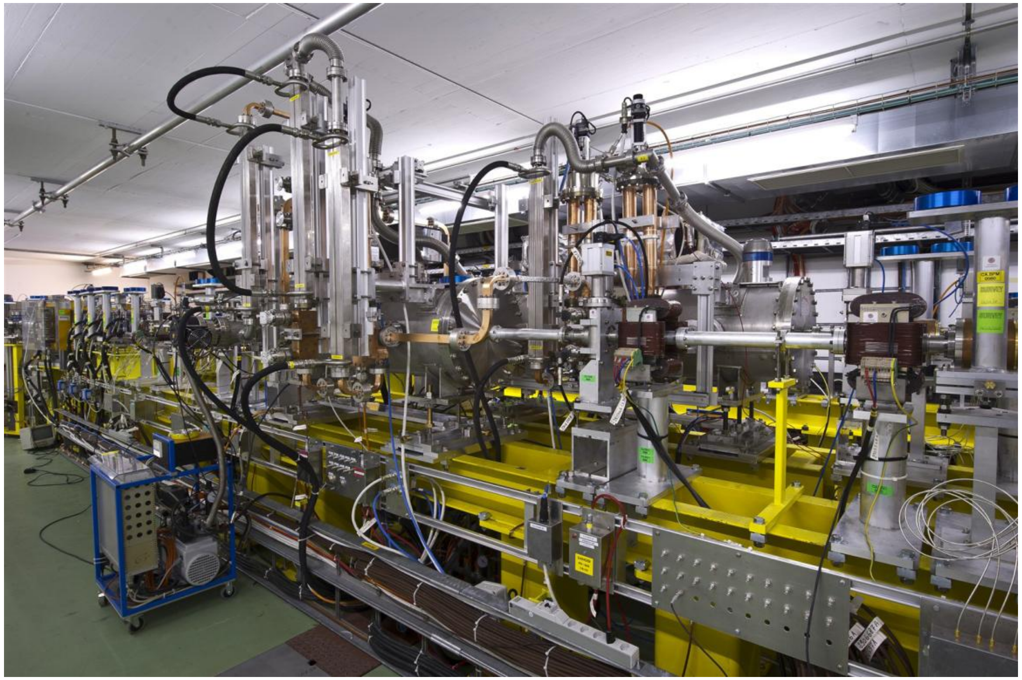
**UK collaboration with CLIC starting 2010**

5 UK Universities + Daresbury Laboratory

Main Beam Instrumentation for CLIC



**CTF3 two-beam test stand**



## EO Project at Dundee & Daresbury

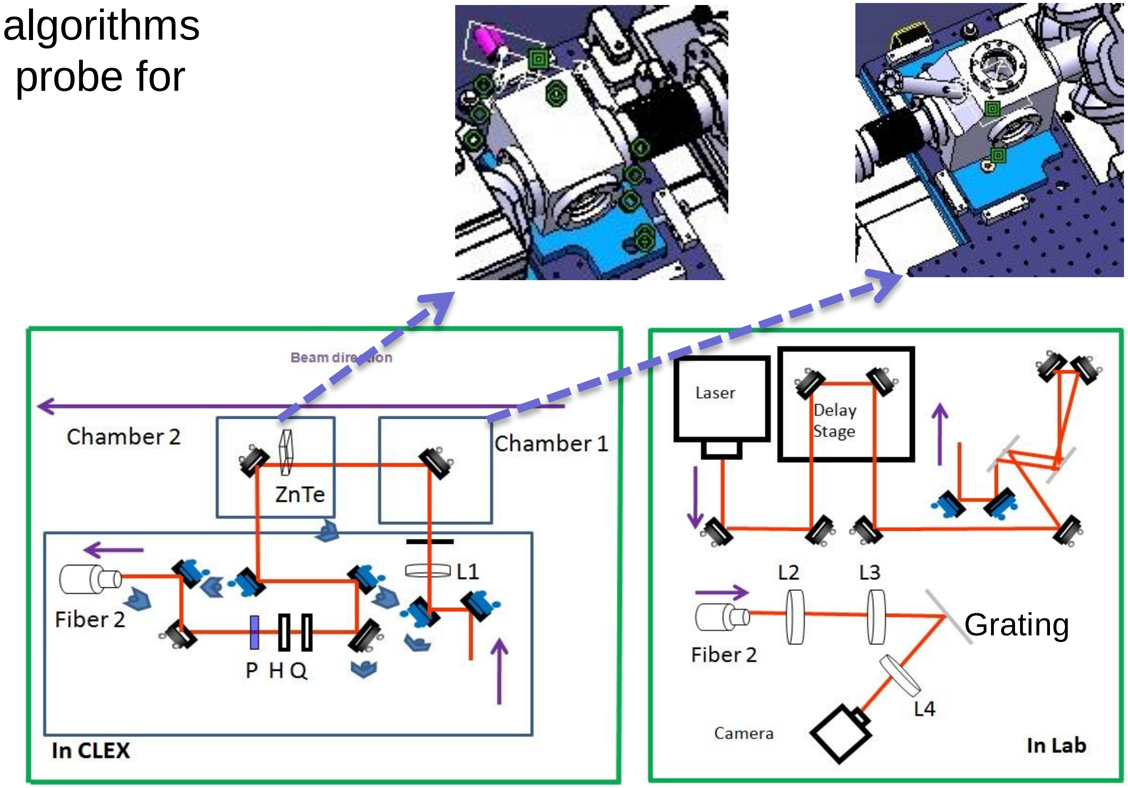
- Measure 150 fs electron bunches with a precision of <20 fs using EO techniques
- Provide EO spectral decoding bunch monitor for 200 MeV, 1.4 ps *CALIFES* beam at CLIC Test Facility

# CTF3 *Califes* Electro-Optic Bunch Temporal Profile Monitor

Robust (low power) fibre laser implementation of spectral decoding:
- usually only low time resolution capability

- examining temporal retrieval algorithms
- possible alternative front-end probe for optical amplification scheme

1. Laser laboratory completed
2. Laser & synchronization system installed and tested.
3. Control system design completed. All cables and optical fibres installed.
4. Transfer lines for laser and OTR installed in the accelerator.
5. Two monitor vacuum chambers are being assembled.



**P**: Polarizer **H**: Half wave plate **Q**: Quarter wave plate
◆ : Mirror with actuators
◀ : Finger camera

**Laser:**
Wavelength: 780 nm Duration: 100 fs
Repetition: 37.4815 MHz Pulse energy: 2.7 nJ
**Crystal:** Thickness: 1mm Separation: 5-10 mm

System expected to be installed in November 2012, with first measurement in December.

# Spectral upconversion diagnostics

## Optimising upconversion with narrow-bandwidth (long duration) optical probe

High-power laser-driven THz sources being used as electron beam mimic ....

- Ti:S probe, with tuneable bandwidth (spatial chirp compensated)
- known THz pulse - scanning time-domain THz techniques available
- using Ti:S-driven THz source with MV/cm fields

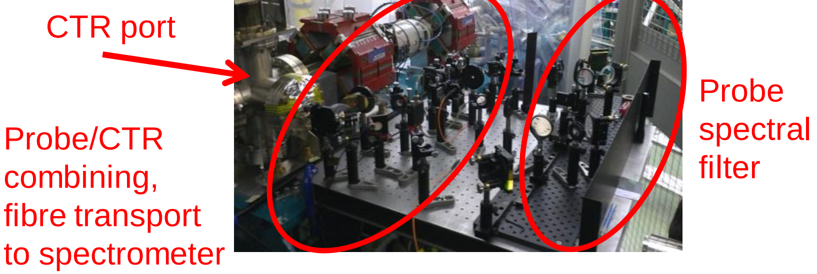
sum frequency mixing

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

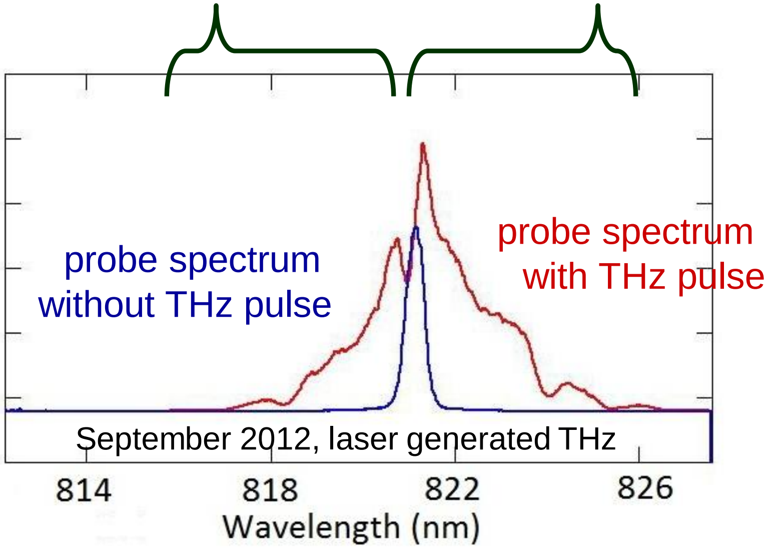
difference frequency mixing

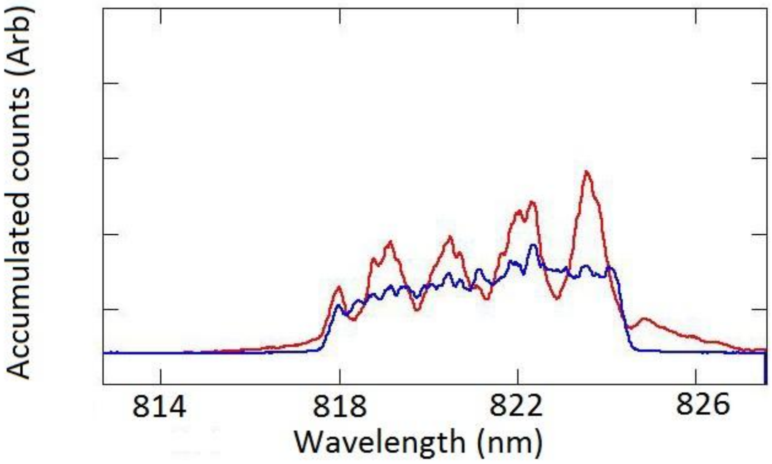
$$\tilde{E}(\omega_0-\Omega) = i\omega a\tilde{E}(\omega_0)[\{\tilde{E}^{\mathrm{Coul}}(\Omega)\}^*\tilde{R}^*(\Omega)]$$

**Systems being implemented in tests on ALICE test accelerator at Daresbury**

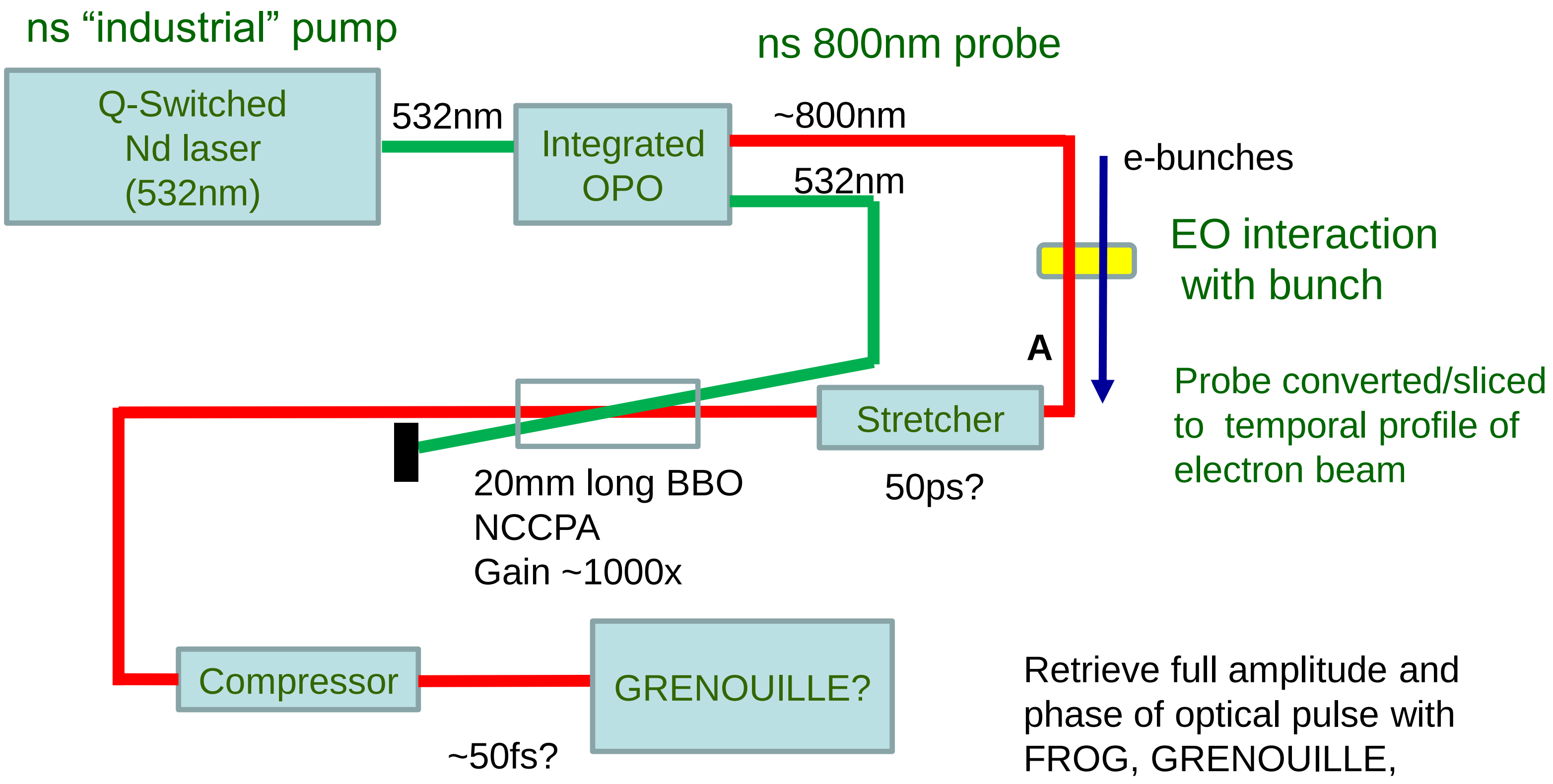


First experimental shifts Sept 2012, further shifts Oct/Nov 2012.





# Parametric amplification and nanosecond laser-driven femtosecond diagnostic



Probe converted/sliced to temporal profile of electron beam

Retrieve full amplitude and phase of optical pulse with FROG, GRENOUILLE,

- Probe non-collinear amplification stage largely designed
- Available 50ps Nd:YAG, synchronised to femtosecond Ti:S probe and THz source

Combined experiments with THz, 800nm probe and parametric optical amplification in early 2013.

# Activities at the University of Dundee

# EO Detection solution in thin films & 2D structures

- to bypass propagation effects

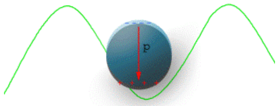
Thin film polymers

- Demonstrated broadband EO response
- Sufficient EO efficiency
- ?? Accelerator environment, material stability ??

Nano-structured materials

- Electro-optic effect from short-range structure.
- ... limited experimental demonstrations

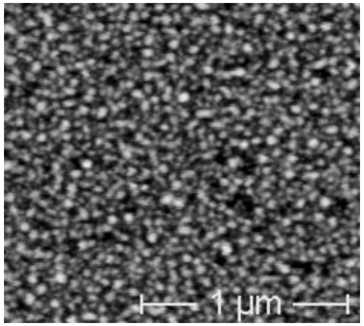
## Materials and Photonic Systems (MAPS) Group

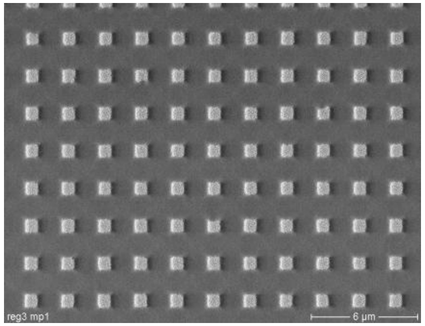


***Fabrication & Applications of Nanocomposites***

Dundee group expertise:

- ❖ Metal-dielectric nanocomposites (MDN) – Ag & Au
- ❖ DC electric field-assisted selective dissolution of nanoparticles in nanocomposites (patented technology)
- ❖ Laser structuring of metal surfaces





## Overall R&D goals

- Fabricate percolation films and metal-dielectric nanocomposites at Dundee U.

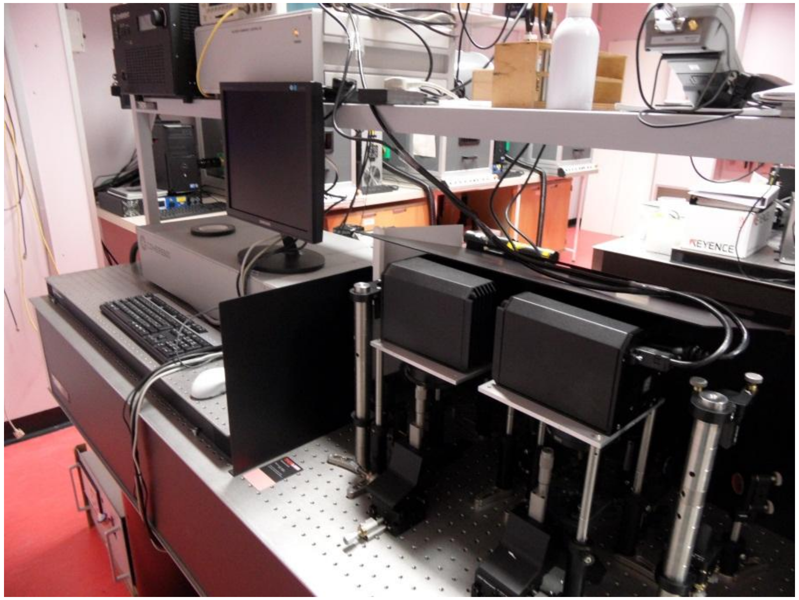
  → a type of “metamaterial” using electric field & laser processing
- Test these films for required E-O properties at Daresbury Laboratory
- Utilise films at CLIC and at the PSI XFEL test facility

## Progress

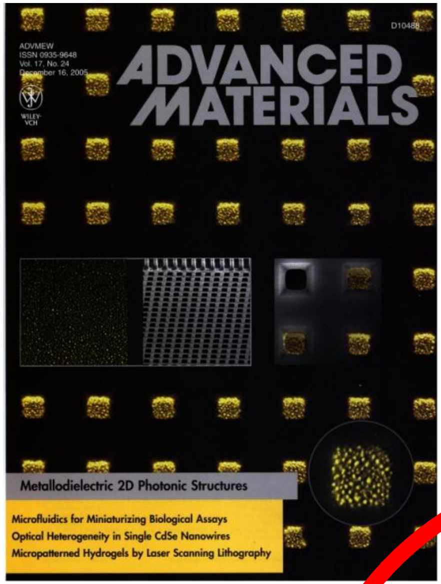
3 nanosecond scanning laser systems (wavelengths 355, 532 & 1064 nm) in place for materials processing, since 2011

pulsewidth <15ps, avge power up to 4W at 355nm, 8W at 532nm, 16W at 1064nm

Picosecond scanning system (Coherent Talisker ULTRA 355-04) installed May 2012.
Operates at same 3 wavelengths →



# Materials and Photonic Systems (MAPS) Group


ADVMEW
ISSN 0935-9648
Vol. 17, No. 24
December 16, 2005

D10488

ADVANCED MATERIALS

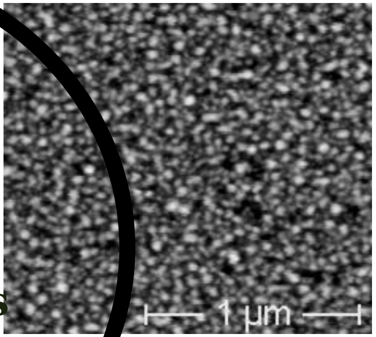
WILEY-VCH

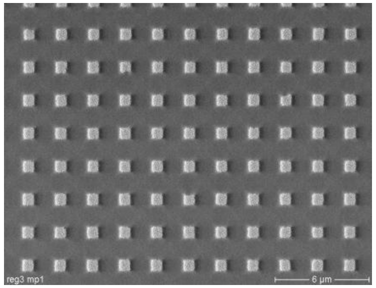
Metallodielectric 2D Photonic Structures

Microfluidics for Miniaturizing Biological Assays
Optical Heterogeneity in Single CdSe Nanowires
Micropatterned Hydrogels by Laser Scanning Lithography

**STRAND 1**

**Fabrication of Nanocomposites & Nanomaterials**



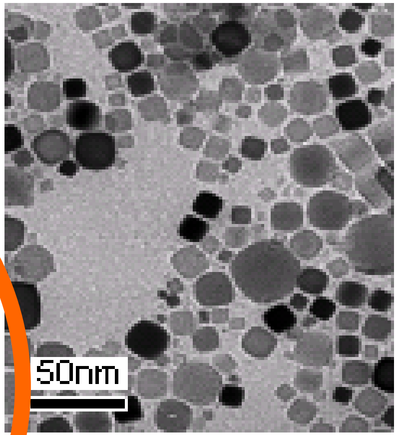


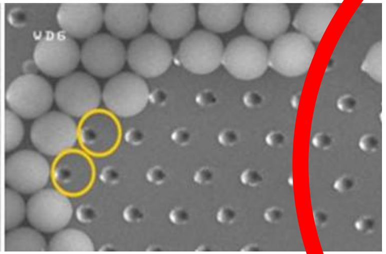
**STRAND 2**

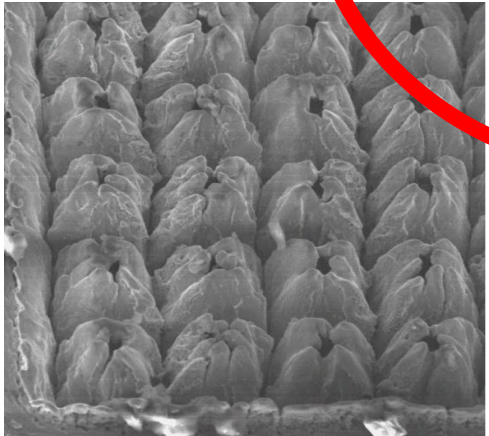
**Micro/Nano-Scale Engineering of Nanocomposites, composites & metals**

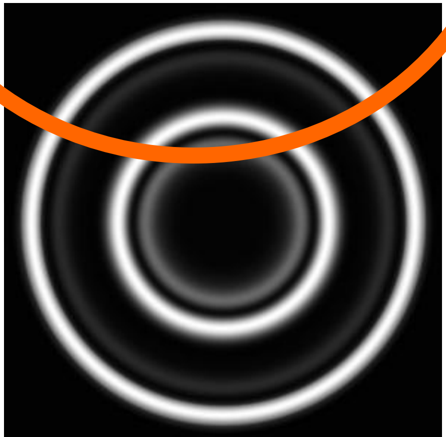
**STRAND 3**

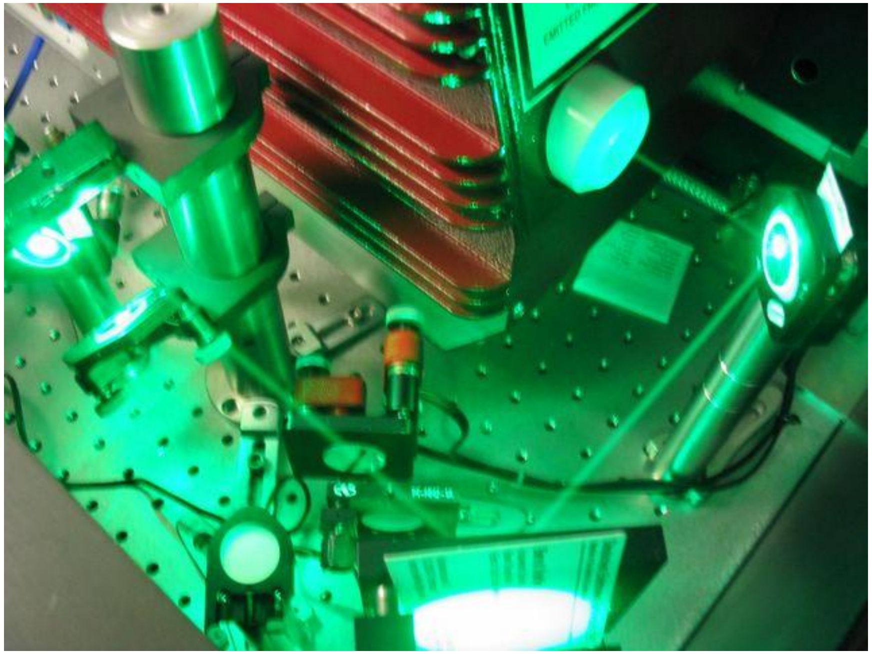
**Conical Diffraction Photonics**











## Key EO papers: Dundee Group

- NIM. Phys. Res. A429 (1999) 7- 9
- PRL 85 (2000) 3404-7
- PRL 88 (2002) 124801/1-4
- Opt. Lett. 28 (2003) 1710
- PRL 93 (2004) 114802/1-4
- Opt. Lett. 31 (2006) 1753-55
- PRL 93 (2007) 114802/1-4
- PRL 99 (2007) 164801/1-4
- App Phys B (2008) 91,2 241-247
- Phys Rev. (2009) ST, 12, 032802
- PRL (2010) 96, 231114

MAPS

END