Ultra-short electron bunch instrumentation

Current Status & Future Directions

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Femtosecond resolution bunch profile diagnostics

(selective discussion due to time constraints – and predominantly for electrons)

Menu:

- The need for longitudinal (temporal) bunch diagnostics
- Two distinct classes of temporal diagnostics:

  direct particle & radiative techniques

- Examples: Transverse deflecting cavities

  RF zero crossing techniques

  Spectral domain techniques

  Electro-optic techniques

The need for femtosecond longitudinal diagnostics

1. **Advanced Light Sources:** **4th - 5th generation**

Free-Electron Lasers kA peak currents required for collective gain

τ = 200fs FWHM, 200pC (<2008, standard) $\Rightarrow$ 10fs FWHM,10pC (>2008, increasing interest)

Low-emittance storage rings *τ = 10-200 ps rms, ε_H = 150-300 pm.rad (MAX-IV, ESRF II)*

2. **Particle Physics:** Linear Colliders (ILC, CLIC) e^+-e^- and others
short bunches, high charge, high quality - for *luminosity*
   - *~300fs rms, ~1nC stable, known (smooth?) longitudinal profiles*

3. **LPWAs:** Laser-plasma accelerators produce ultra-short electron bunches!
   - *1-5 fs FWHM (and perhaps even shorter in future), ~20pC + future FELs*

Diagnostics needed for…

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

Significant influence on bunch profile from
wakefields, space charge, CSR, collective instabilities… machine stability & drift
$\Rightarrow$ ***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

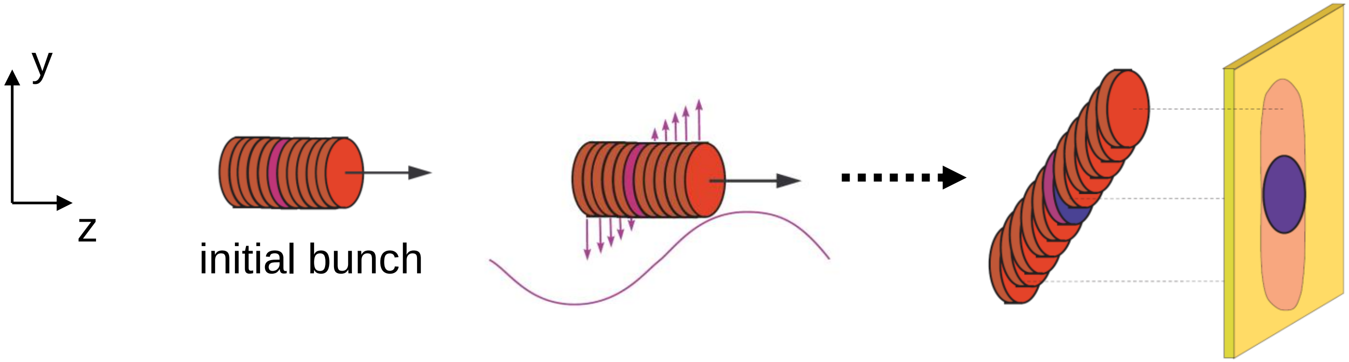
Spectral domain:

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

Time domain:

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

Transverse Deflecting Cavities (TDC)



cavity: transverse kick

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

beam optics : transverse streak

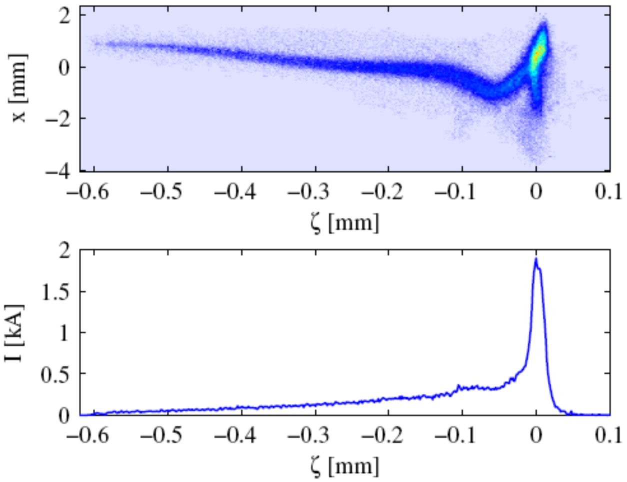
$$\Delta y_{\text{screen}}(z) = \left\{\sqrt{\beta_{\text{c}}\beta_{\text{s}}}\,\sin(\Delta\psi)\right\}\,\Delta y'_{\text{cav}}(z)$$

Time resolution scaling

$$\alpha \begin{cases} \text{deflection gradient} \\ \gamma^{-1/2} \end{cases}$$

Diagnostic capabilities linked to beam optics

Disadvantage - destructive to beam



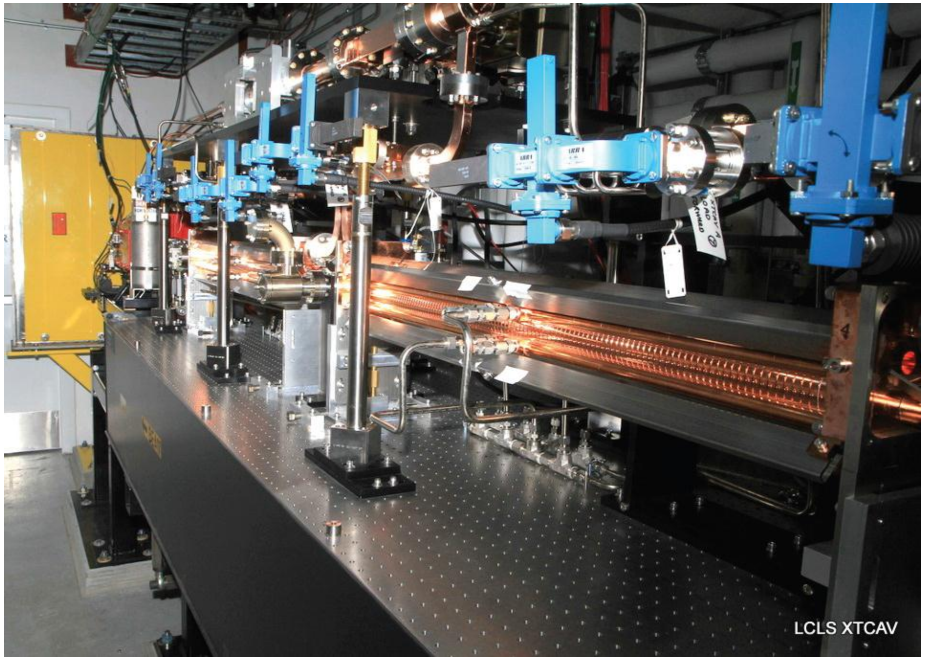
FLASH :

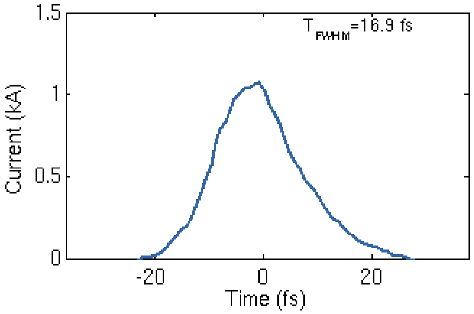
27 fs resolution

Rohrs et al. Phys Rev ST (2009)

LCLS XTCAV X-band transverse deflecting cavity

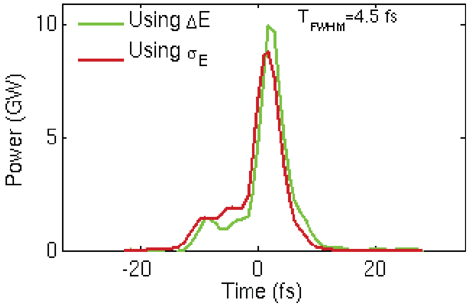
(Y. Ding et al, FEL 2013, NYC)





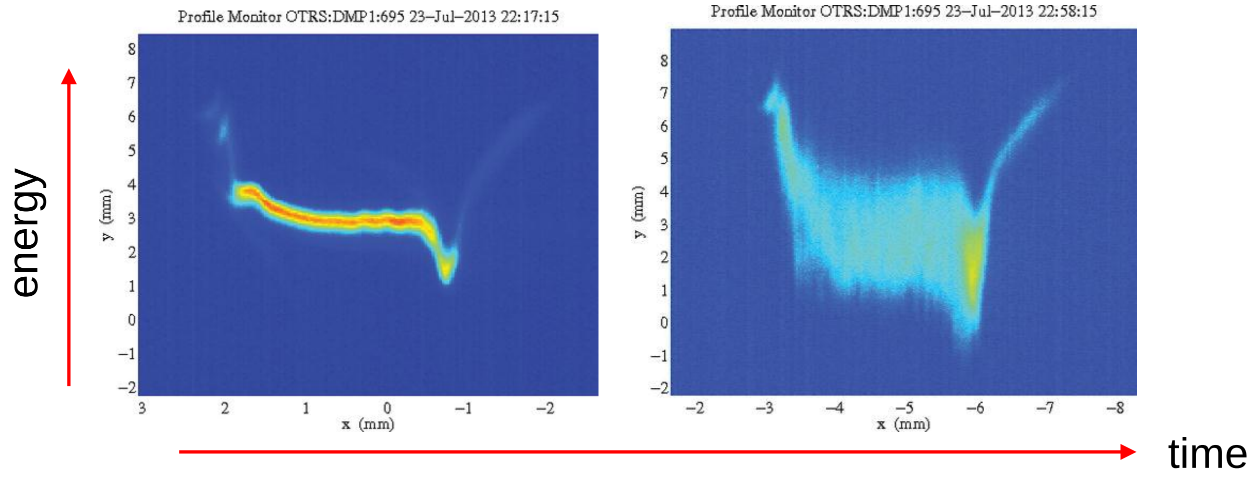
20pC, 1keV examples

Electrons



X-rays

Bunch head on the left

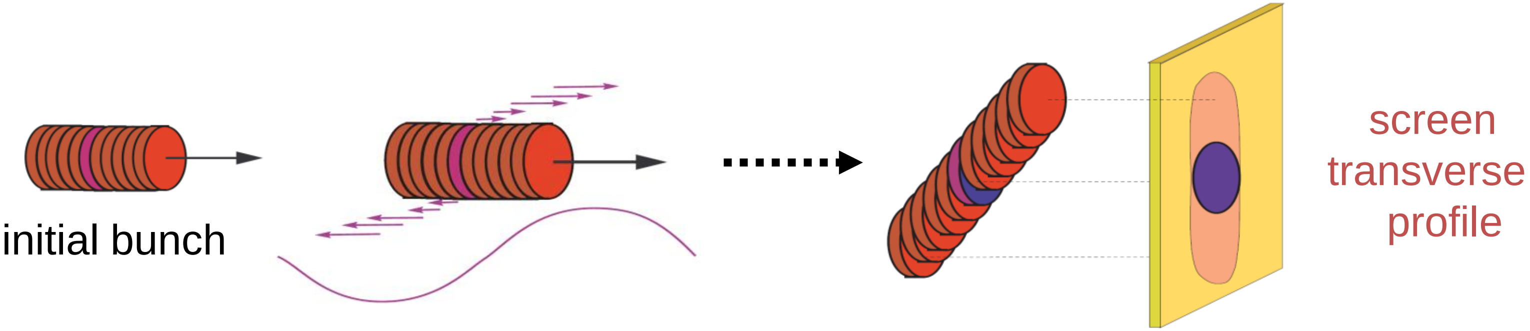


FEL-OFF

FEL-ON

(~1mJ pulse energy)

RF zero phasing



cavity:
z-dependent accel/deceleration

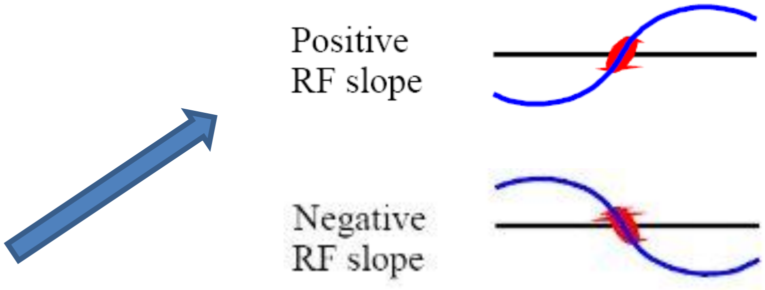
beam optics:
energy dispersion

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

time resolution dependent on:

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

initial γ–z correlation ?

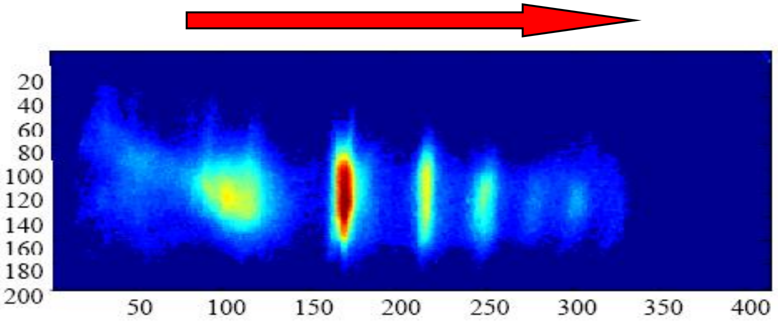


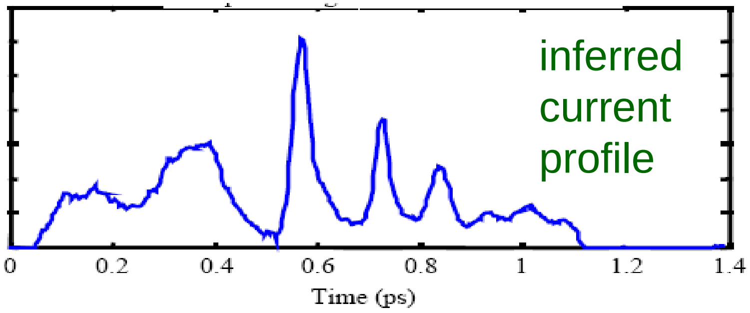
Disadvantage - destructive to beam

RF zero-phasing examples

DUV-FEL: at 75 MeV

energy (time)





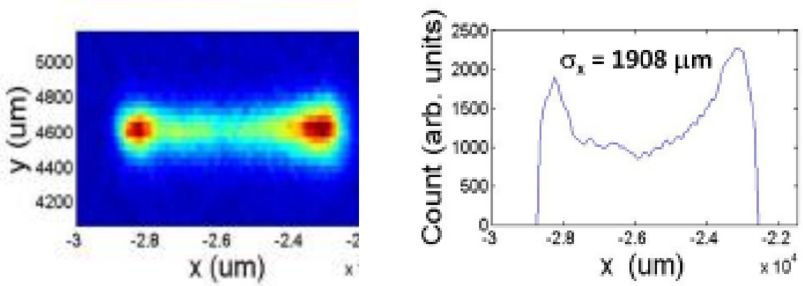
inferred current profile

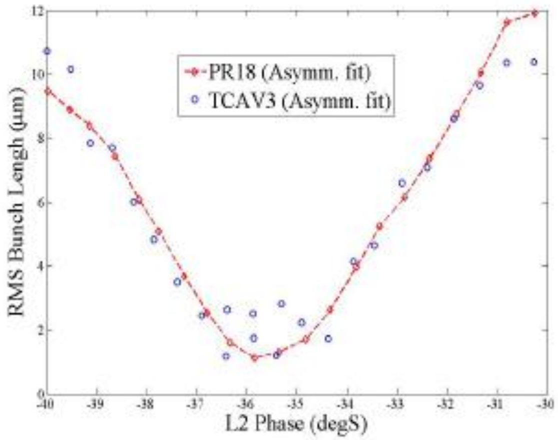
time resolution of ~50 fs

Graves et al. PAC 2001

SLAC LCLS: at 4.3 &14 GeV

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





XTCAV

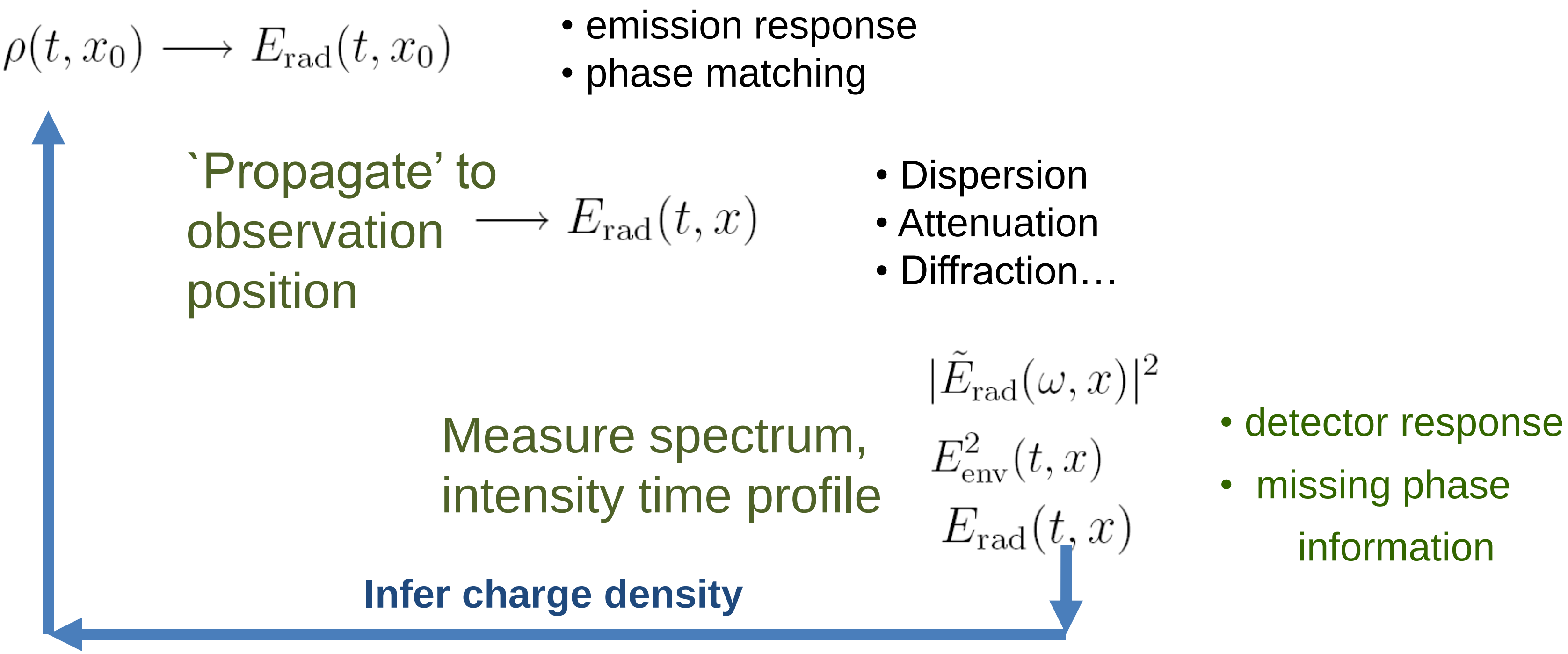
~ 3 fs rms bunch length at 14 GeV

~ 1 fs rms bunch length at 4.3 GeV

Huang et al. PAC 2011, FEL2013

“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 charge density

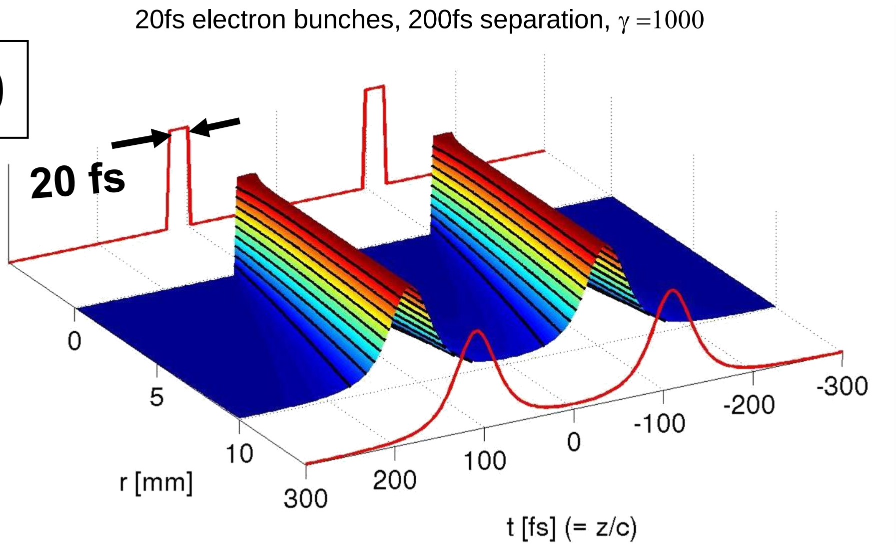
Techniques & limitations:

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

$\gamma = 1000$



γ

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

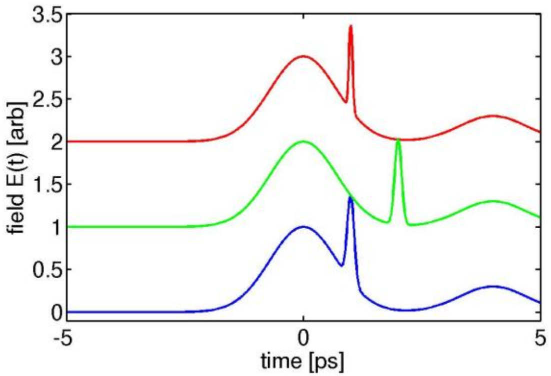
(N.B. equally true of CTR, CDR, Smith-Purcell, Electro-Optic, etc.)

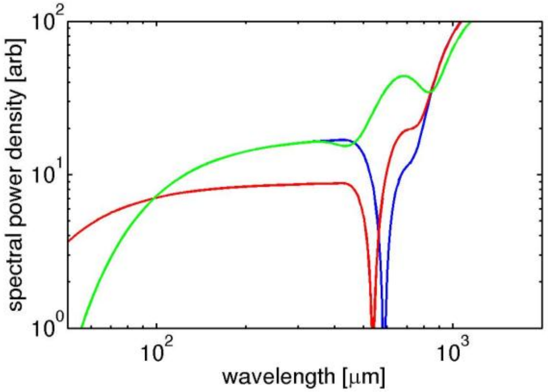
Spectral domain radiative techniques

Bunch form factor ⇒

Coherent transition radiation (CTR)
Coherent diffraction radiation (CDR)
Coherent synchrotron radiation (CSR)
Smith-Purcell radiation (SP)

⇒ far-IR / mid-IR spectrum





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

For:

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

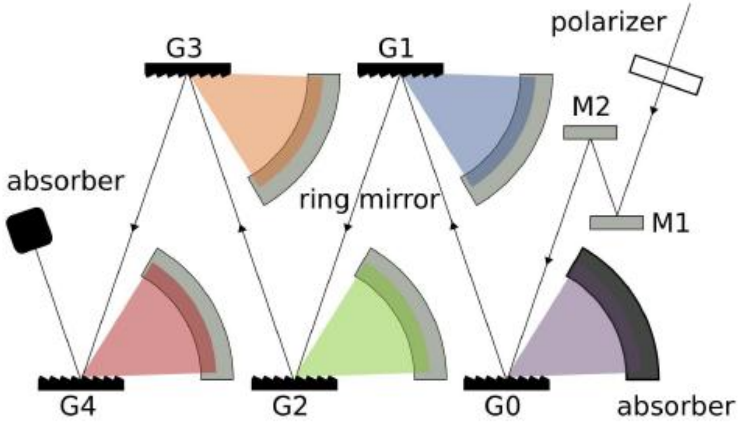
Against:

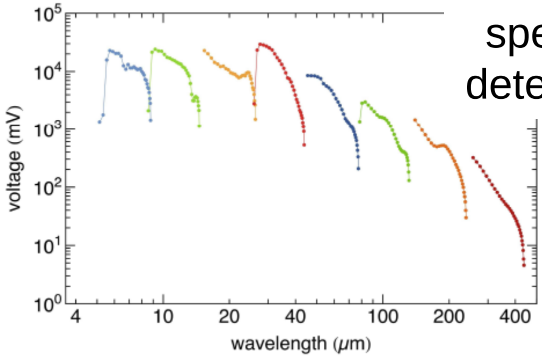
No explicit time profile
 (but reconstruction *may* be possible)
Significant calibration issues

Good example: single shot CTR spectrometer at FLASH

cascaded dispersive grating elements, and pyroelectric detector arrays

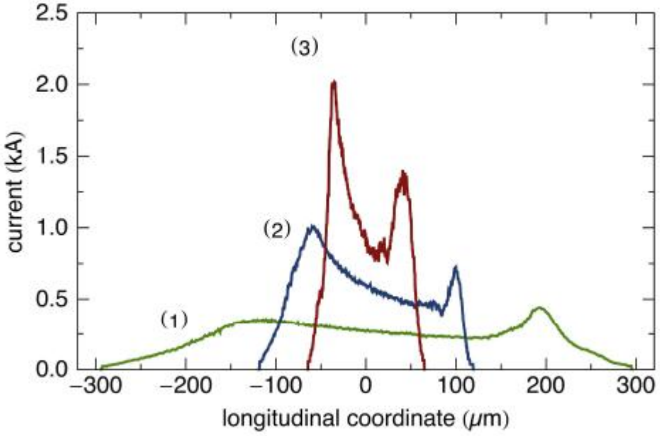
E. Hass et al., Proc. SPIE 8778, May 2013



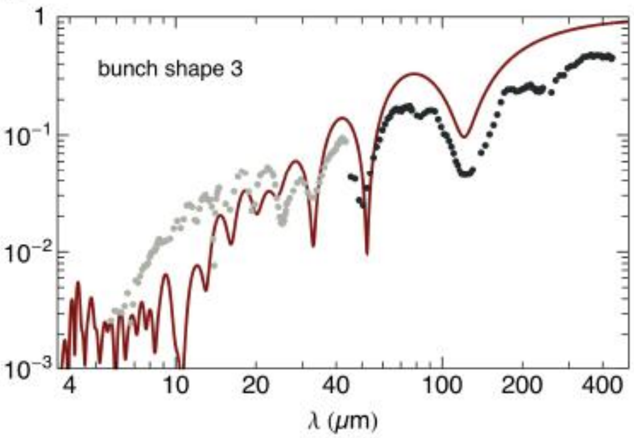


spectrometer & detector response

Deflecting cavity bunch profiles



Measured & calculated spectra



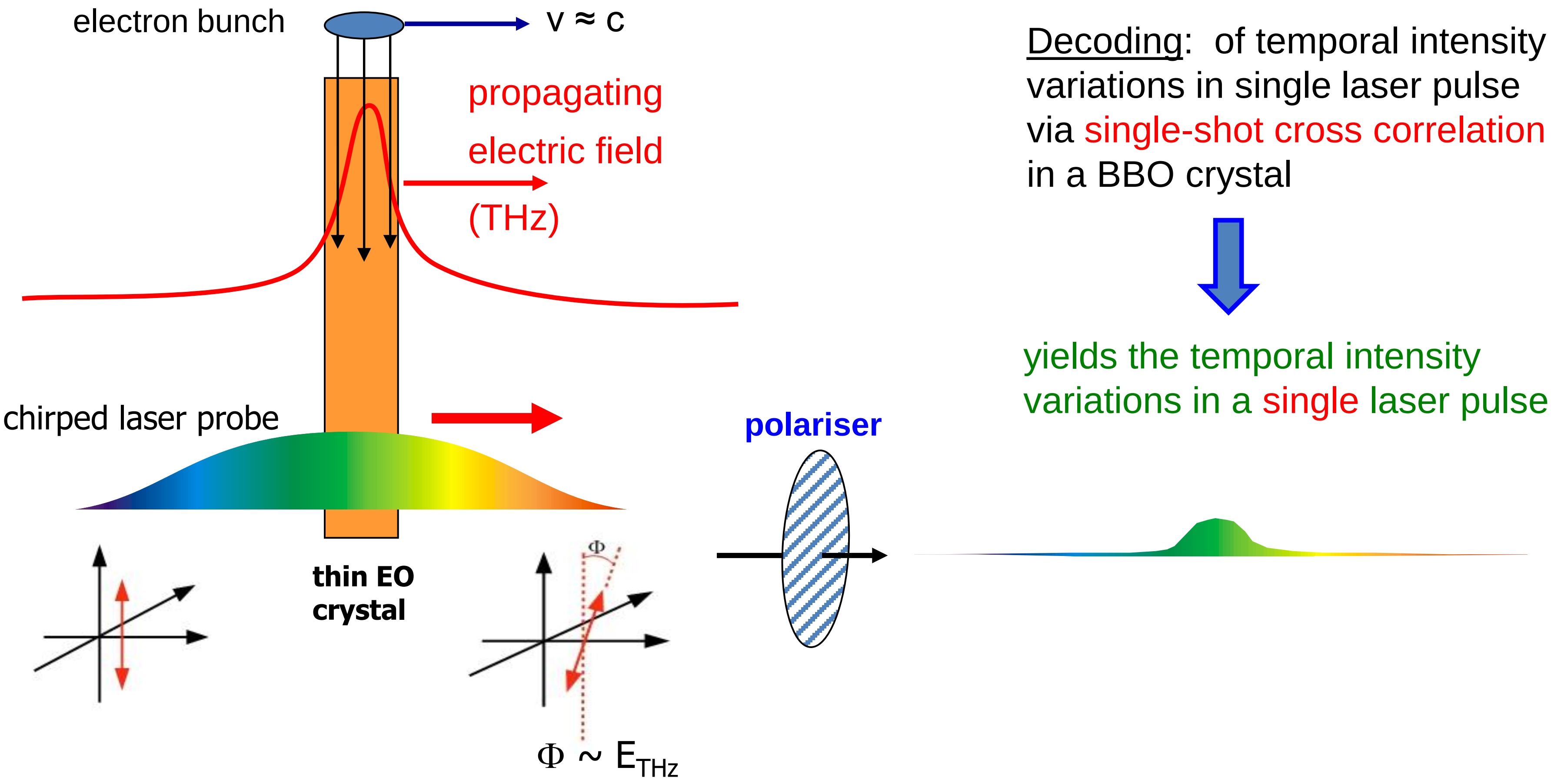
Similar concepts applied at HZDR ELBE facility (O. Zarini et al, LA^{3}NET workshop, Dresden, April 2014) and at SLAC LCLS (T. J. Maxwell et al, PRL 111, 184801, 2013)

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

Φ

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

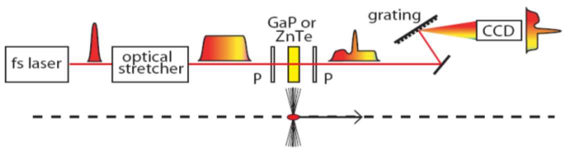
Detect polarisation rotation proportional to E or E^2, depending on set-up

Range of Electro-Optic Techniques

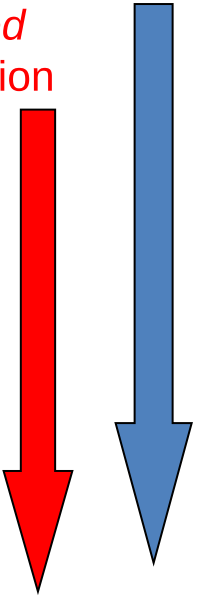
Variations in read-out of optical temporal signal

o

Spectral Decoding



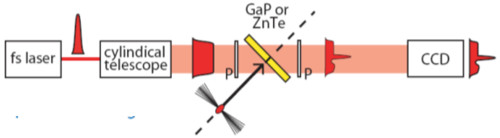
- Chirped optical input
- Spectral readout
- Use time-wavelength relationship



demonstrated
time resolution

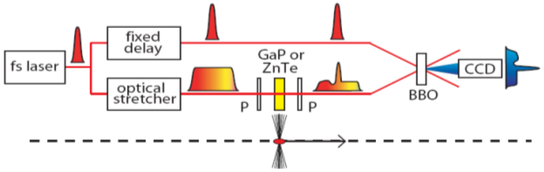
complexity

Spatial Encoding



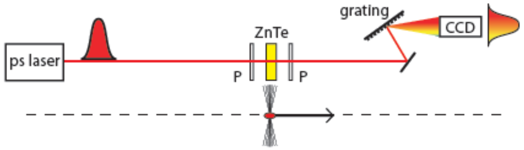
- Ultrashort optical input
- Spatial readout (EO crystal)
- Use time-space relationship

Temporal Decoding

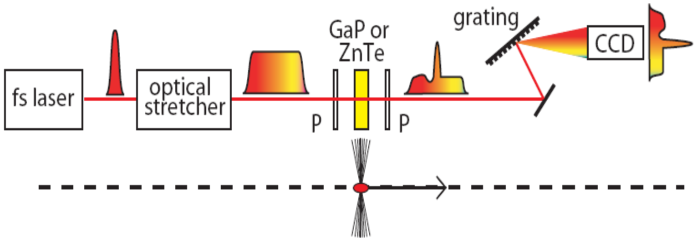


- Long pulse + ultrashort pulse gate
- Spatial readout (cross-correlator crystal)
- Use time-space relationship

Spectral Upconversion/ EO Transposition



- quasi-monochomatic optical input (long pulse)
- Spectral readout
- Uses FROG-related techniques to recover bunch info

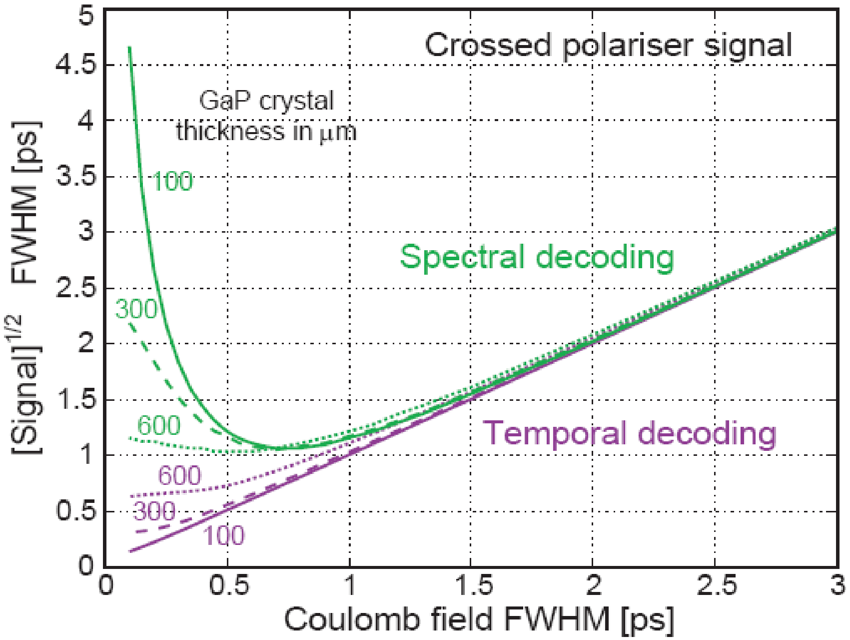


1. Spectral Decoding (EOSD)

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

Rely on t-λ relationship of input pulse for interpreting output optical spectrum.

Resolution limits come from the fact that the EO-generated optical field doesn't have the same t-λ relationship



temporal resolution limits:

EOSD limited by chirp

Can relate to FWHM durations…

$$\tau_{\lim} = \sqrt{12\pi\beta}$$

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

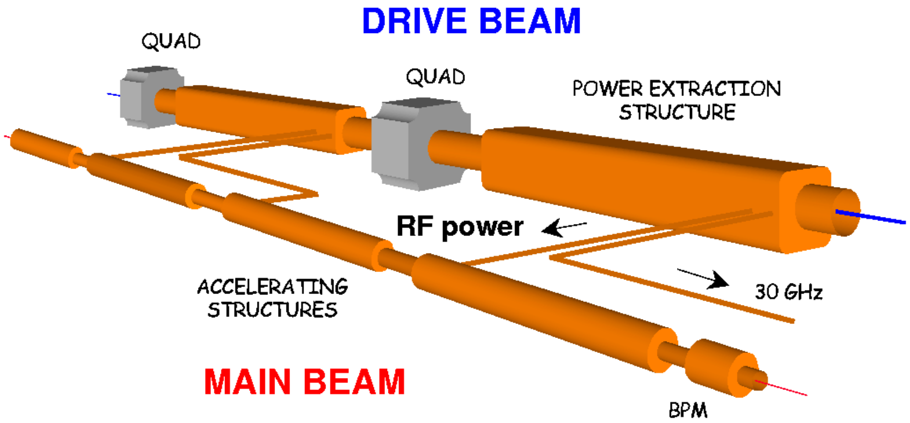
Conclusion:
Unlikely to get better than 1.0 ps (FWHM) with Spectral Decoding

Collaboration with CLIC Project at CERN

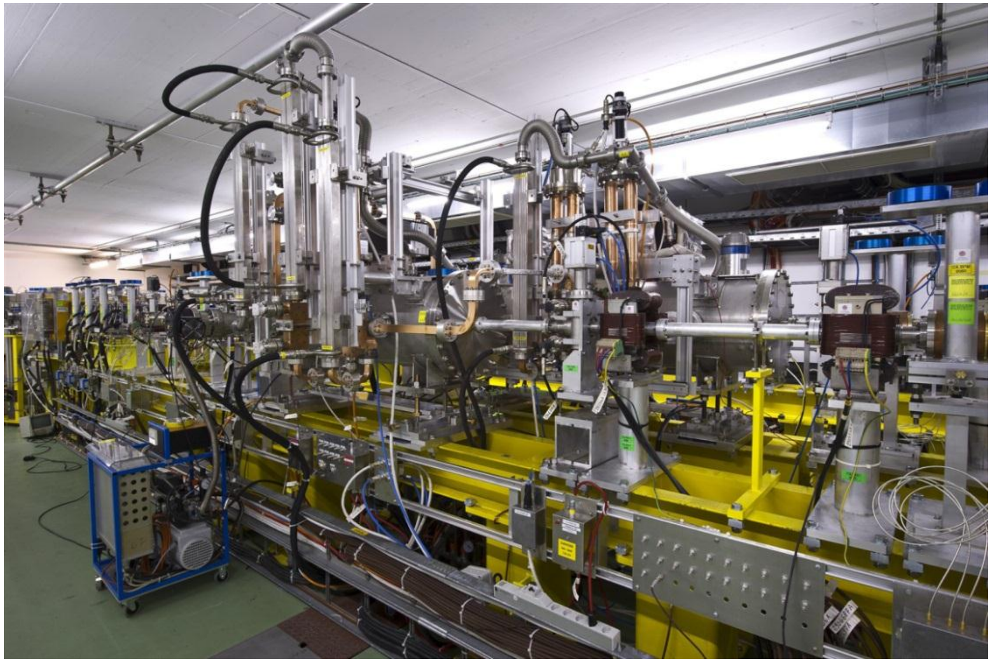
Feasibility study for 3 TeV electron-positron collider

UK collaboration with CLIC 2010-2017

Main Beam Instrumentation for CLIC



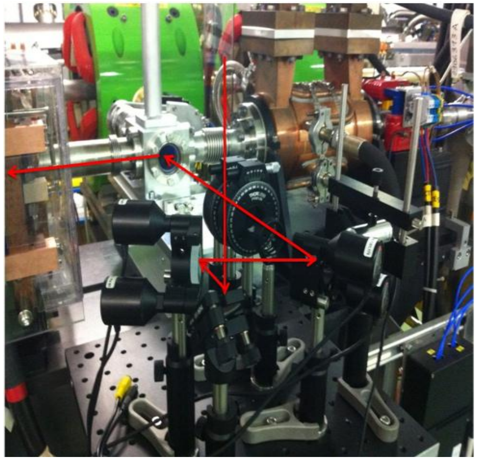
CTF3 two-beam test stand



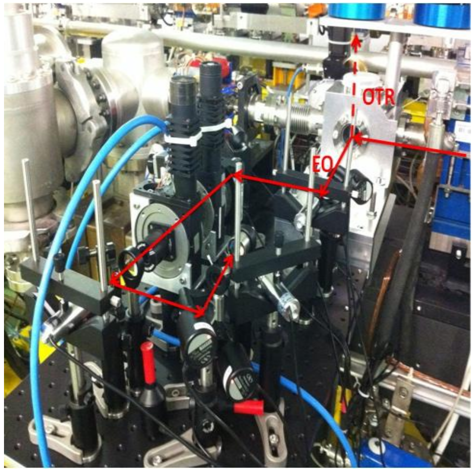
EO Project at Dundee & Daresbury:

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

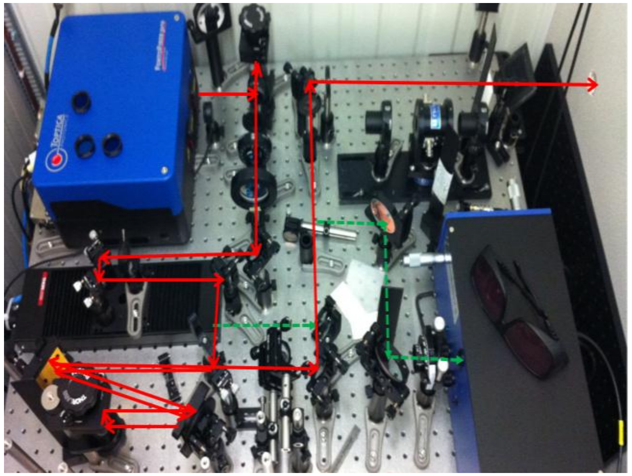
CLIC CTF3 Electro-Optic Bunch Temporal Profile Monitor



Stage 1 & Chamber 1



Stage 2 & Chamber 2



Optics in laser lab

Progress:

(1) Timing overlap E-bunch and laser pulse measured by streak camera

(2) First EO signal measured by a photomultiplier

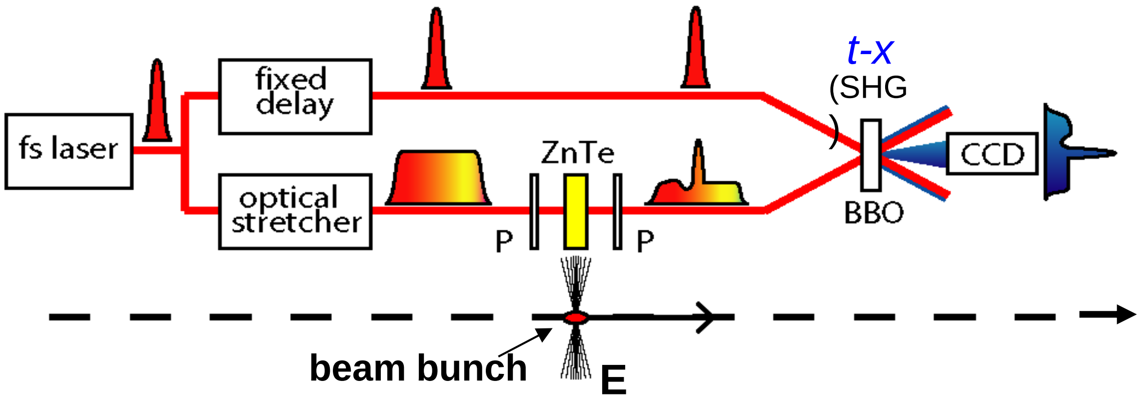
Resolution improvements may include:

-- Thinner crystal
-- Fibre instead of optical transfer line
-- New algorithm (data acquisition and processing)
-- New materials replacing EO crystal

R. Pan et al. CERN CLIC workshop, Feb 2014

2. Single-shot Temporal Decoding (EOTD)

(currently gives best time resolution)



Temporal profile of probe pulse

→ **Spatial image of SHG pulse**

<u>Thin</u> EO crystal (ZnTe or GaP) produces a *optical temporal replica* of Coulomb field

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

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

Technique limited by

- gate pulse duration (~50 fs, although FROG, etc. could improve)
- EO encoding efficiency, phase matching

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

EOTD Electro-optic diagnostics at FLASH

- temporal decoding
- spectral decoding
- benchmarking against TDC

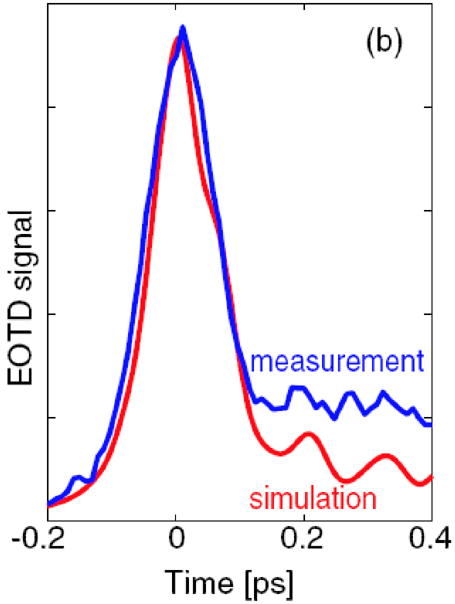
- 450 MeV, γ ~1000
- bunches with peak + pedestal structure
- 20% charge in ~100 fs spike

Time resolution σ_z ~ 90fs (rms)

Temporal Decoding Diagnostic

60 – 200µm thick GaP detector

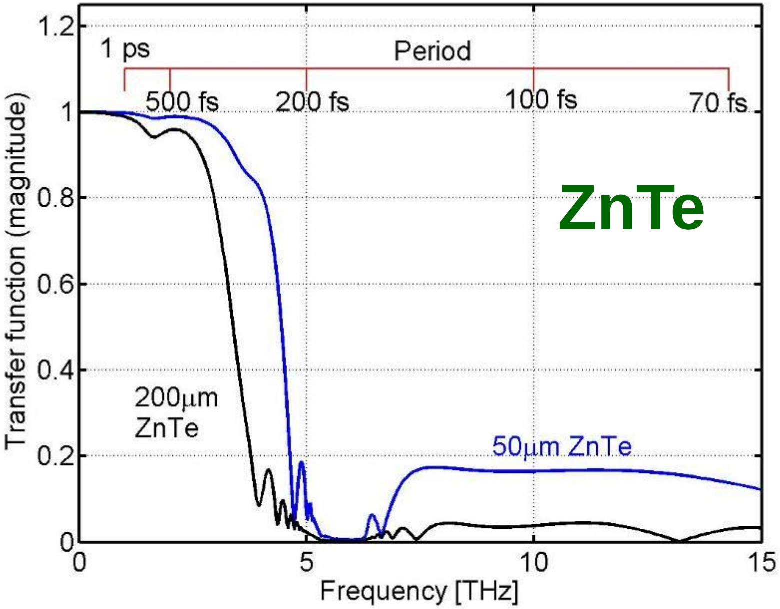
23/09/2005



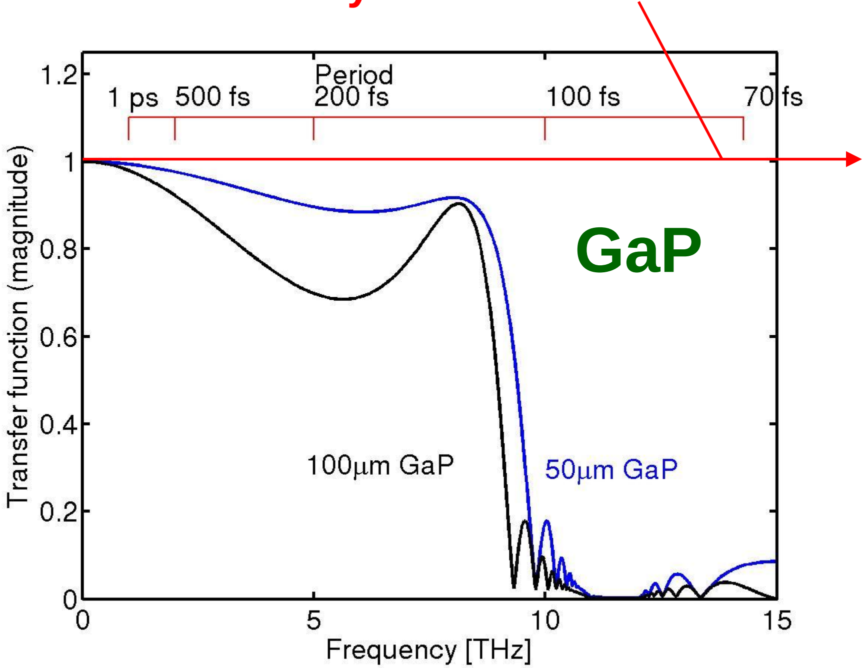
Fundamental Problem: Encoding Time Resolution

material frequency response, R(ω)

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



ideally we would like!



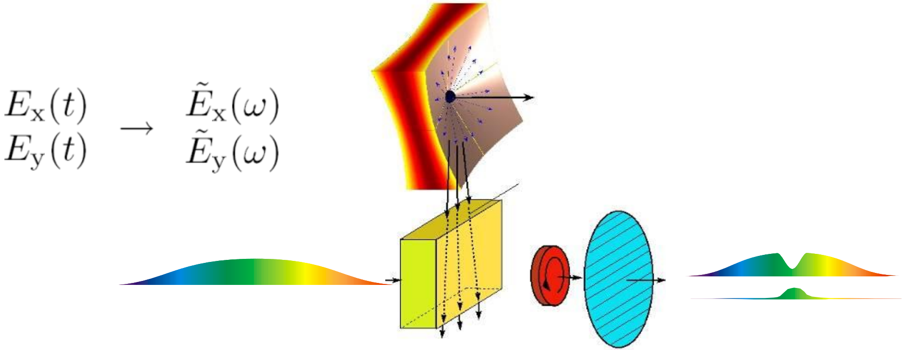
May be soluble by:

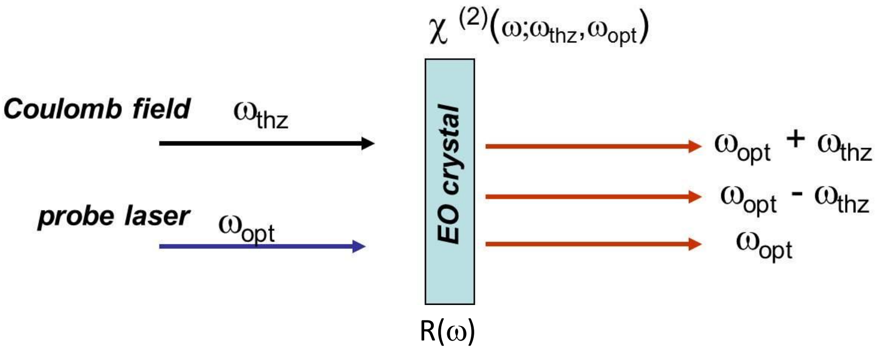
1. Organic crystals (e.g. DAST, DSTMS, OH1) or poled polymeric materials
2. Artificially-created “metamaterials” under development at Dundee

“silver-glass nanocomposites”

Back to the physics of EO encoding...

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





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

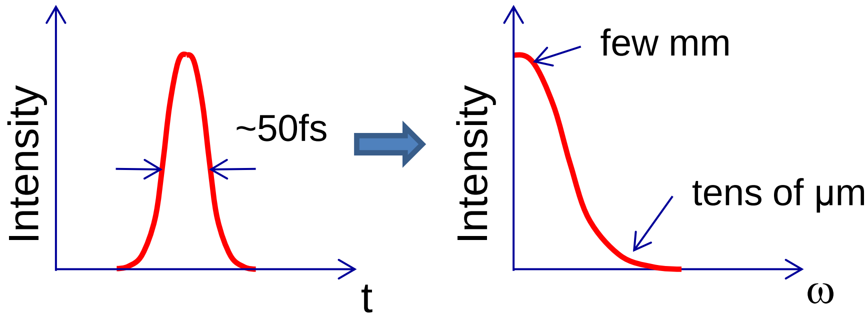
$$E^{\mathrm{opt}}_{\mathrm{out}}(t) = E^{\mathrm{opt}}_{\mathrm{in}}(t) + a \underbrace{\left[E^{\mathrm{Coul}}(t) * R(t)\right]}_{\text{envelope}} \underbrace{\frac{\mathrm{d}}{\mathrm{d}t} E^{\mathrm{opt}}_{\mathrm{in}}(t)}_{\text{optical field}}$$

Coulomb spectrum shifted to optical region

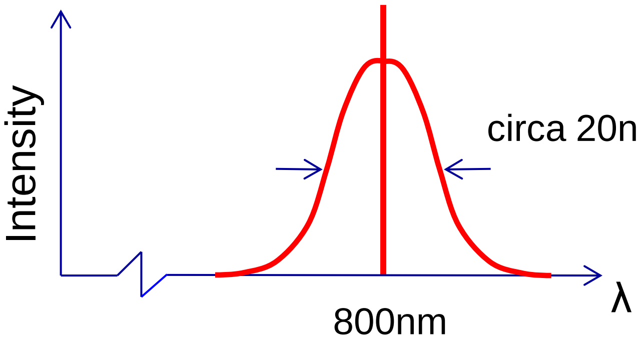
Coulomb pulse temporally replicated in optical pulse

Consider a single-frequency probe and short Coulomb field “pulse”

Coulomb field

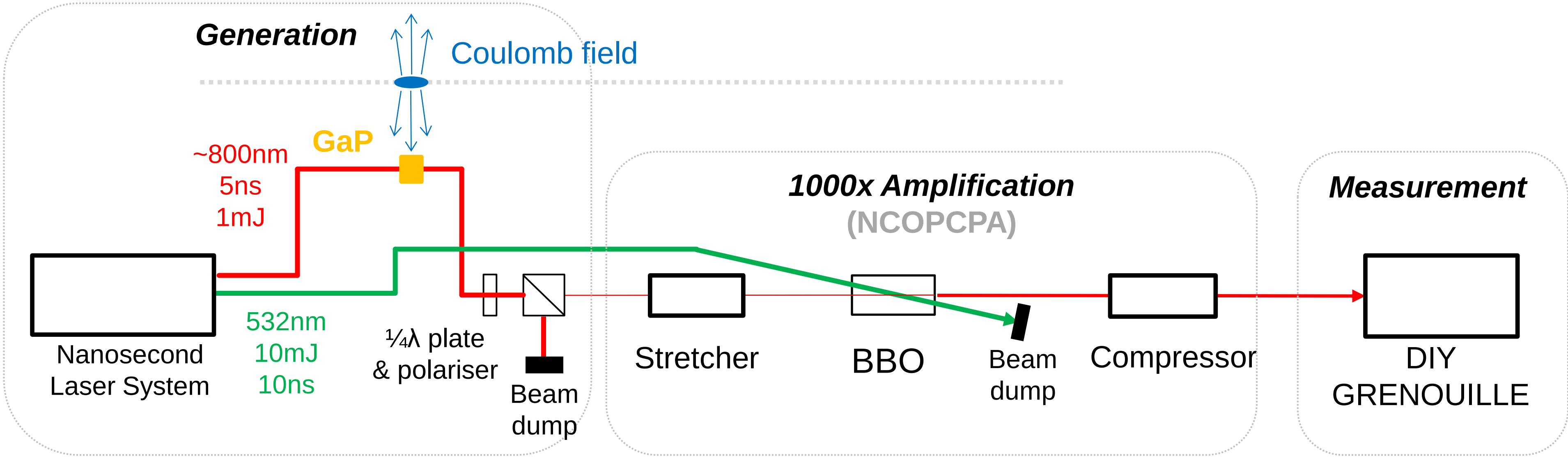


Optical field



EO Transposition System

D. A. Walsh et al, Proc. IBIC 2013, Oxford UK, 474-477



Generation

Coulomb field

GaP

~800nm
5ns
1mJ

532nm
10mJ
10ns

Nanosecond
Laser System

¼λ plate
& polariser

Beam
dump

1000x Amplification
(NCOPCPA)

Stretcher

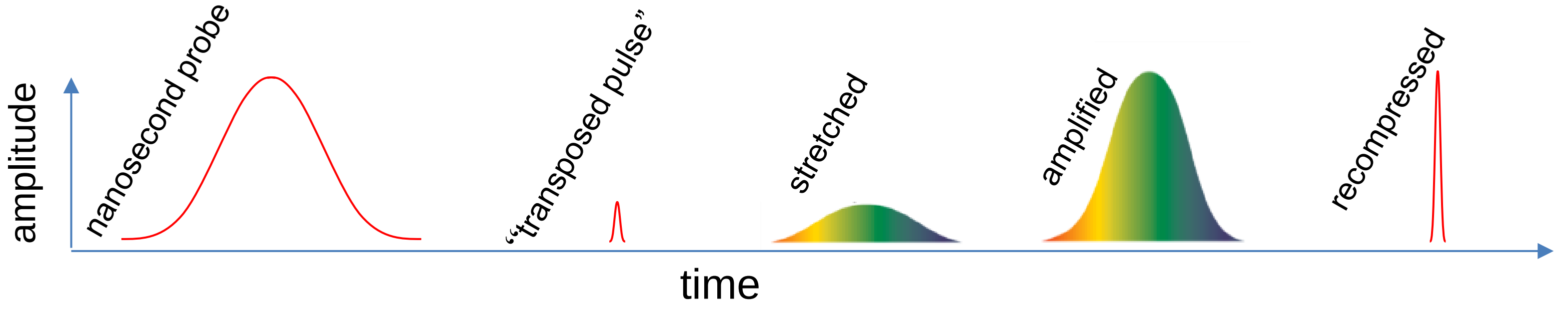
BBO

Beam
dump

Compressor

Measurement

DIY
GRENOUILLE

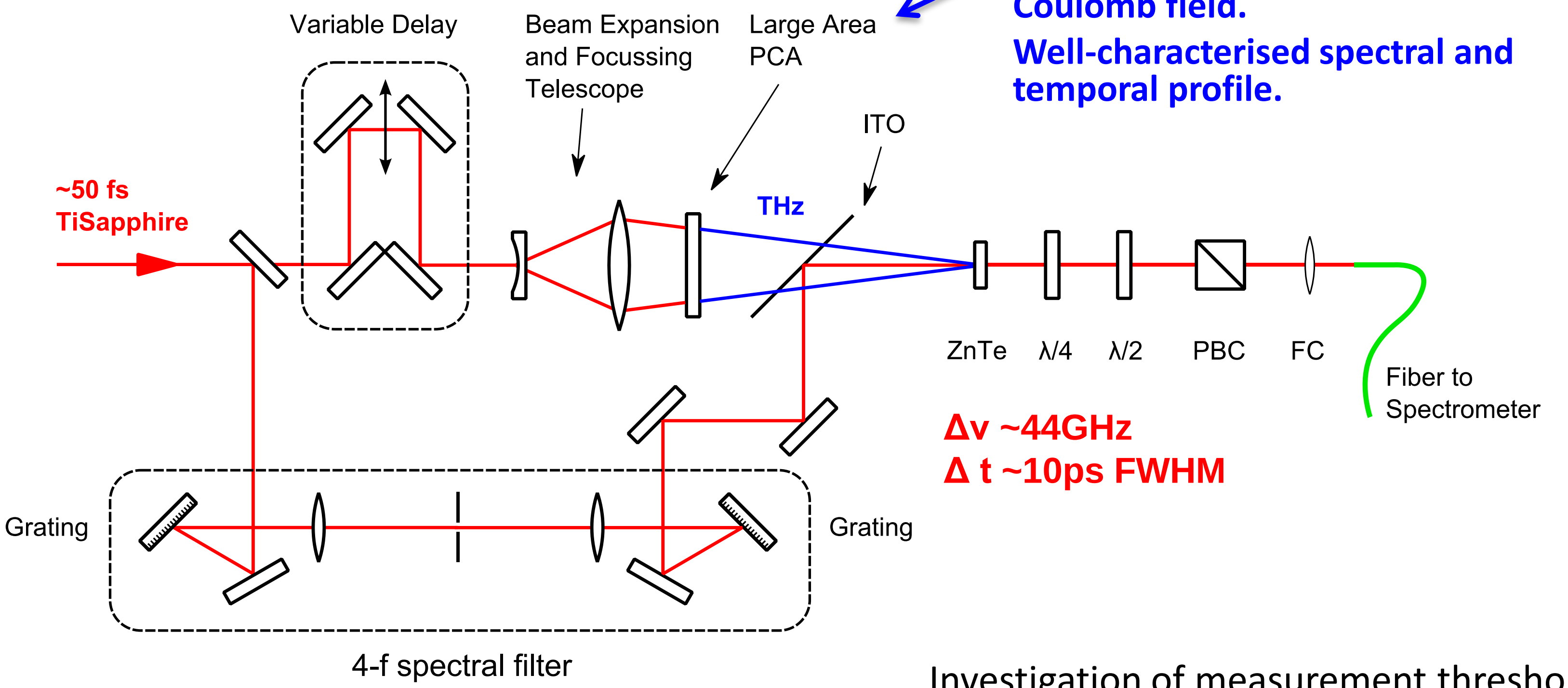


Pulse
Evolution

1. Nanosecond laser-derived single-frequency probe brings reliability
2. "Electro-Optic Transposition" of probe encodes temporal profile
3. Non-collinear optical parametric chirped pulse amplification (NCOPCPA) amplifies signal
4. Full spectral amplitude and phase measured via FROG / Grenouille technique
5. Coulomb field (bunch profile) calculated via time-reversed propagation of pulse

Benchmarking & Validation 1

Femtosecond laser-based test bed (STFC Daresbury Laboratory)



Auston switch THz source mimics Coulomb field.

Well-characterised spectral and temporal profile.

Δv ~44GHz
Δ t ~10ps FWHM

Femtosecond laser pulse spectrally filtered to produce narrow bandwidth probe

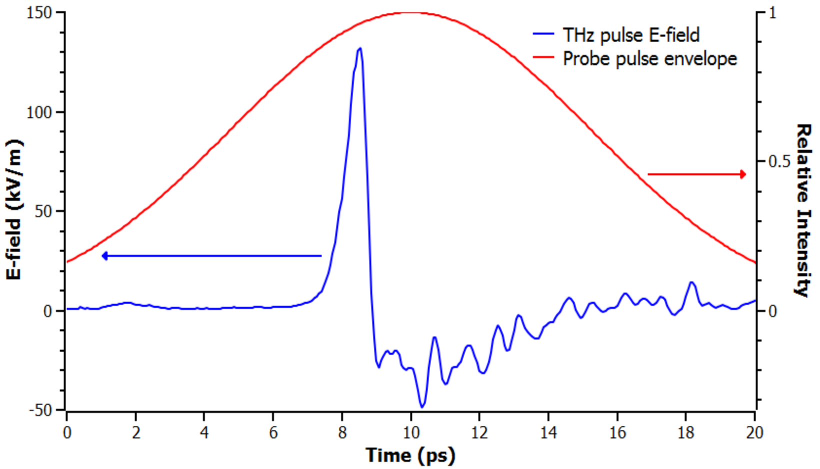
Investigation of measurement thresholds / signal-to-noise ratios

Important for defining system requirements

Benchmarking & Validation 2

Input pulse characteristics

Optical probe length	Δt ~ 10 ps
Optical probe energy	S ~ 28 nJ
THz field strength max	E ~ 132 kV/m

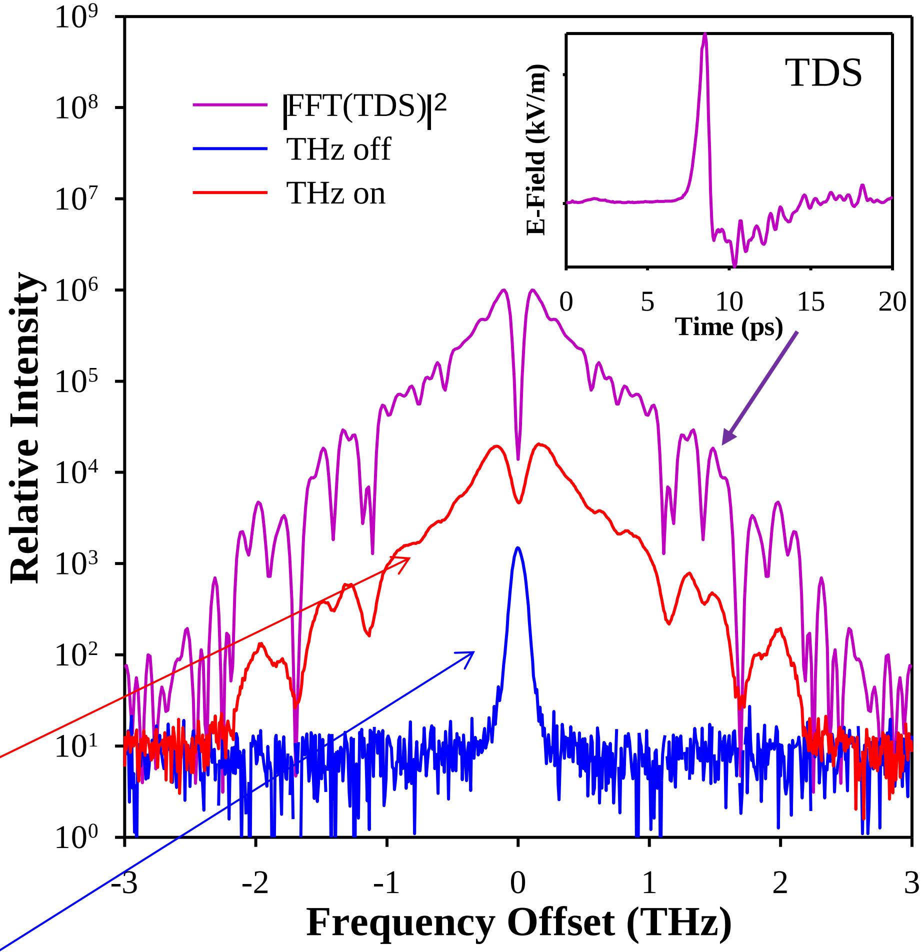


Total energy ~470pJ

Leaking probe

Output characteristics (4mm ZnTe)

TDS = time-domain spectroscopy



EOT Temporal Resolution

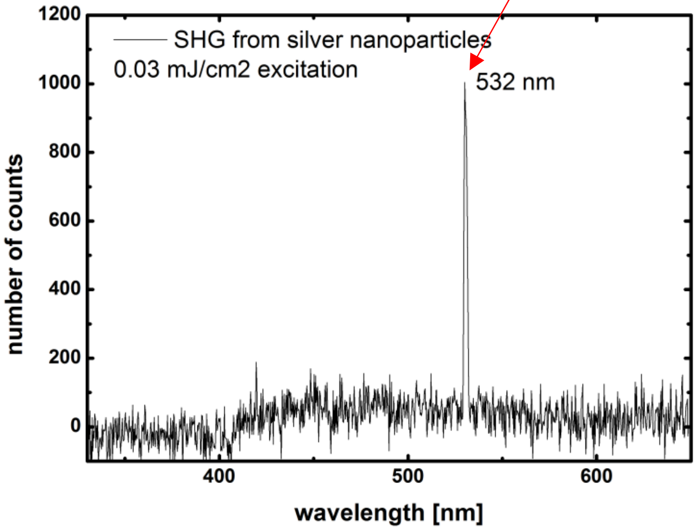
EO transposition scheme is now limited by materials:

phase matching, absorption, stability

Collaboration with MAPS group, University of Dundee on development of novel EO materials

- Potential to produce an enhancement of nonlinear processes through metallic nanoparticles
- THz field-induced second harmonic enhancement under investigation

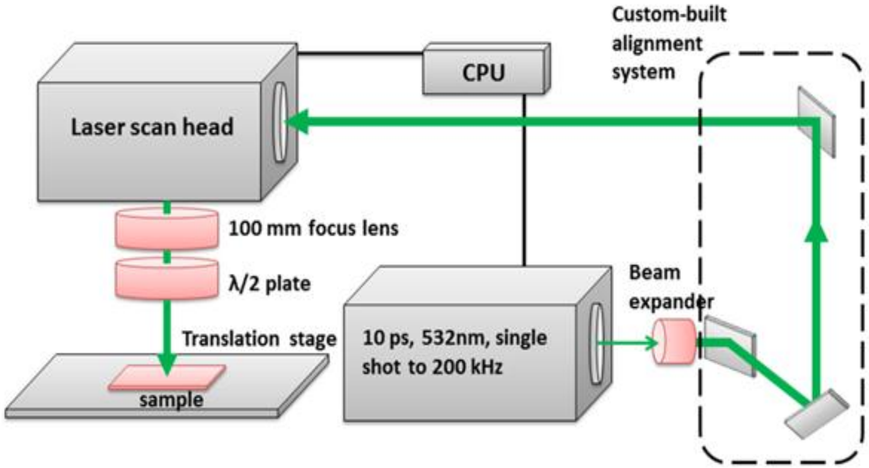
SH of 1024 nm at 532 nm



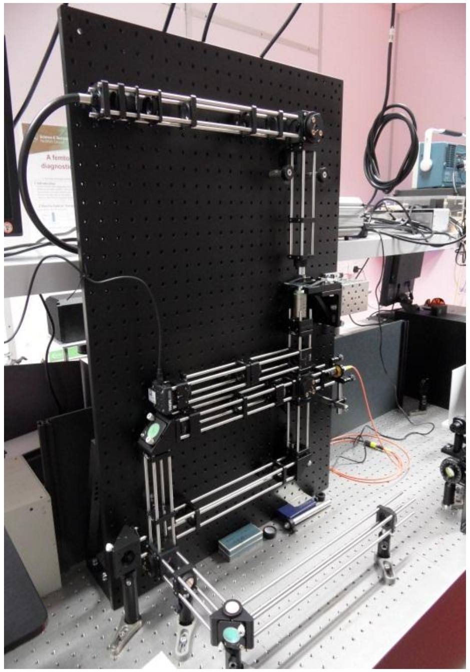
A key property of the EO Transposition scheme may be exploited

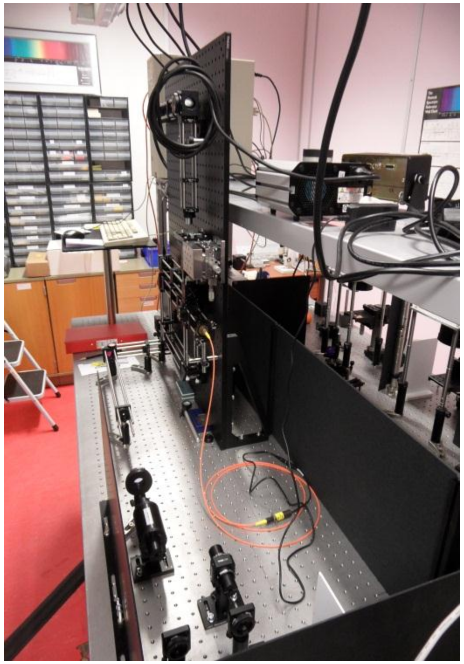
- FROG (Grenouille) retrieves the spectral amplitude and phase
- At frequencies away from absorptions, etc., the spectrum should still be faithfully retrieved
- Potential to run <u>two</u> “tried and tested” crystals with complementary response functions side-by-side to record FULL spectral information!

Picosecond laser X-Y scanning optics



Ultrashort laser configuration for EO materials processing





inverted microscope set-up to measure second-harmonic generation from metamaterial samples (Talisker picosecond laser off to right of photos).

Jan 2014

Summary of ultra-short bunch techniques

- Transverse deflection cavity / zero crossing
  - <10fs resolution capability, in principle
  - large infrastructure for high energies
  - destructive techniques

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

- 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 / transposition
  - converts extreme broadband signal into manageable optical signal
  - strong potential for empirical feedback system

Selected References

A femtosecond resolution electro-optic diagnostic using a nanosecond-pulse laser
D.A. Walsh, W.A. Gillespie, S.P. Jamison
TUPC41 Proceedings of IBIC2013, Oxford, UK
ISBN 978-3-95450-127-4, 474-477

Bunch length monitor using EO techniques
http://indico.cern.ch/event/275412/session/3/contribution/112
D A Walsh, S P Jamison, W A Gillespie, M A Tyrk, R Pan, T Lefevre
CLIC Workshop 2014, 3-7 Feb 2014, CERN, DESIGN & SYSTEM TEST activities
Contribution ID : 112

Coherent-Radiation Spectroscopy of Few-Femtosecond Electron Bunches Using a Middle-Infrared Prism Spectrometer
T. J. Maxwell, C. Behrens, Y. Ding, A. S. Fisher, J. Frisch, Z. Huang, and H. Loos
Phys. Rev. Lett. **111**, 184801, October 2013

The role of misalignment-induced angular chirp in the electro-optic detection of THz waves
D.A. Walsh, M.J. Cliffe, R. Pan, E.W. Snedden, D.M. Graham, W.A. Gillespie, S.P. Jamison
Optics Express, June 2014 (in press)

Thank you for your attention

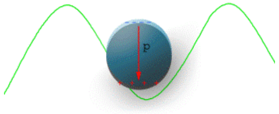
EO Detection solution in thin films & 2D structures

- to bypass propagation effects

Nano-structured materials

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

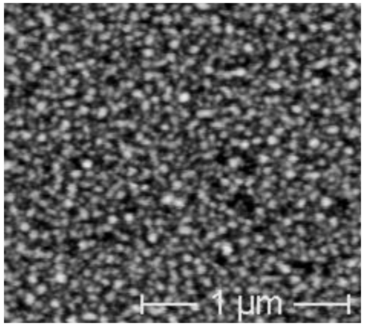
Materials and Photonic Systems (MAPS) Group

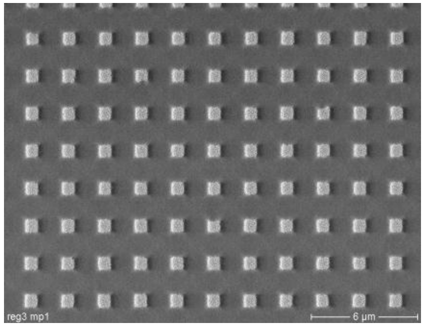


Fabrication & Applications of Nanocomposites

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



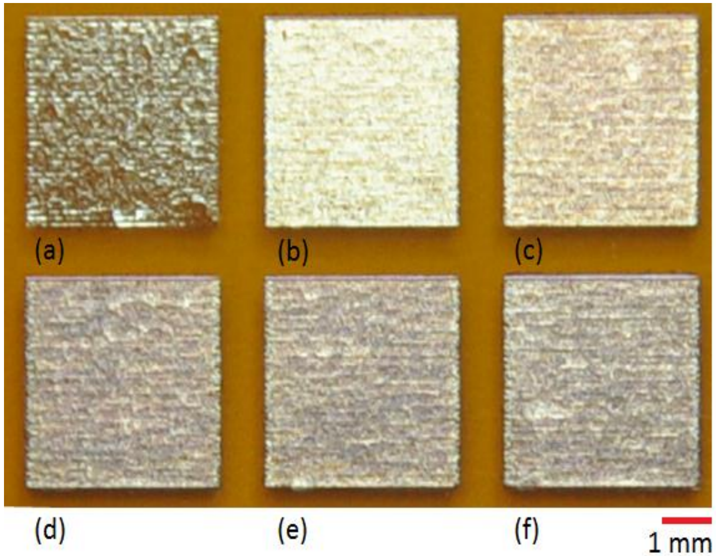


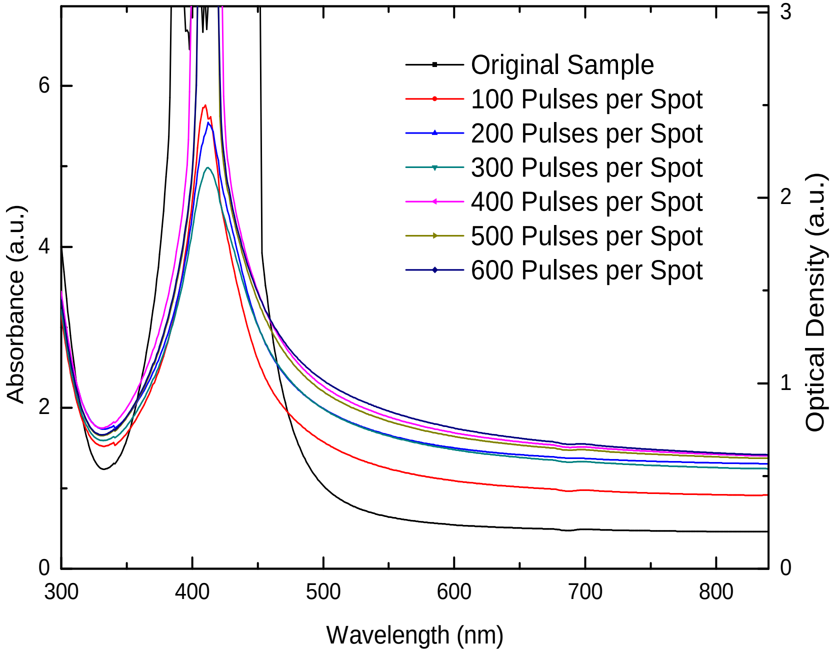
MAPS

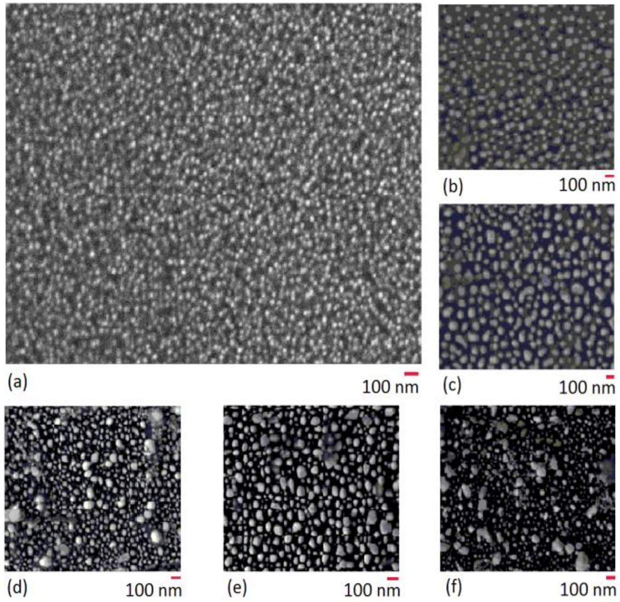
Nanosecond pulsed laser irradiation of glass with embedded metallic particles

Nanosecond laser irradiation of glass with embedded silver nanoparticles at 532 nm

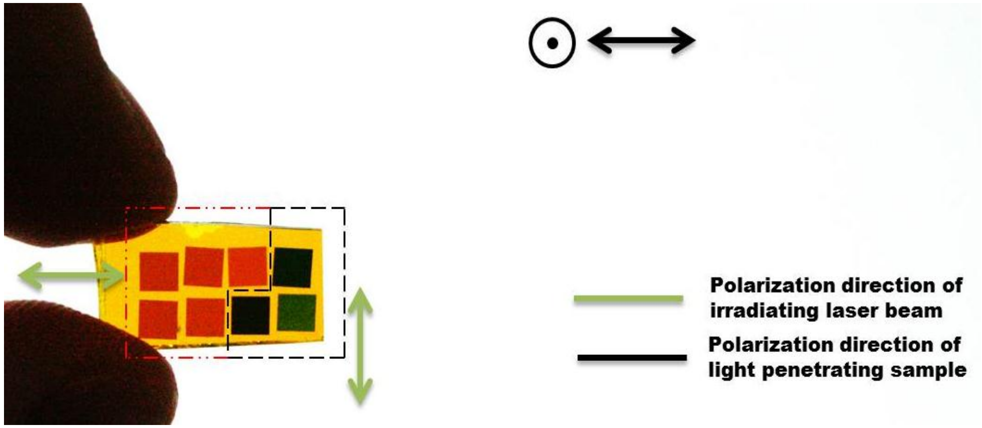
- Wavelength: **532 nm**
- Pulse length ~ **6 ns** at 50 kHz
- Laser fluence ~ 1.5 J/cm^2
- Beam spot diameter ~ 60 µm
- Writing speed: **10 mm/s**
- ~ 300 pulses per spot

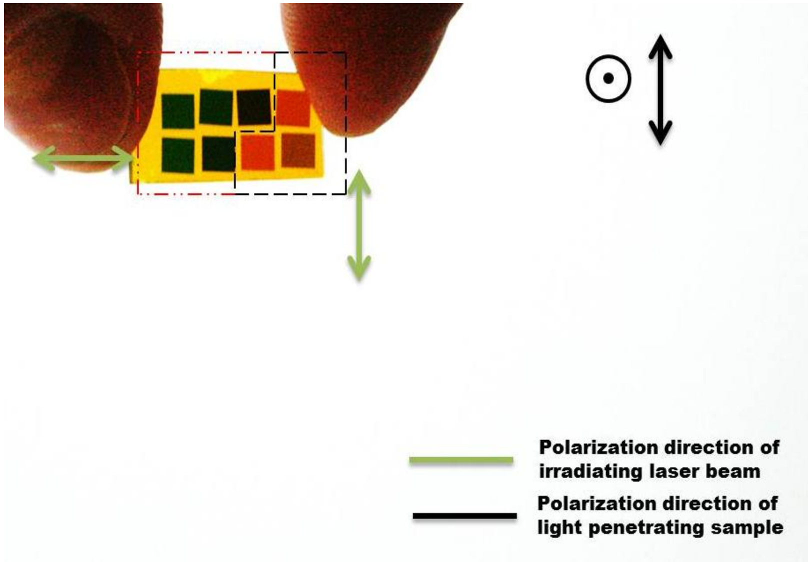






Picosecond laser irradiation of glass with embedded silver nanoparticles at 532 nm





- Wavelength: **532 nm**
- Pulse length ~ **6 ps**
- Laser fluence ≤ 0.3 J/cm^2
- Beam spot diameter ~ 15 µm
- **Top row** (left to right): 500, 300, 100, 200 pulses per spot
- **Bottom row** (left to right): 400, 200, 100,100 pulses per spot