Electro-Optic development for short bunch length monitoring

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Outline of Talk

- Requirement/Aims
- EO Techniques
- Our new technique: EO Transposition
- System Design and Testing
  - Predicting EOT signal level
  - Status of EOT monitor construction
  - EOT + FROG results!
- Resolution (Materials)

Requirement and Aims

CLIC project targets

- Non-invasive
- Single shot
- Diagnostic target resolution ~20fs rms (Bunches ~150fs rms)

EO diagnostics: (encoding of Coulomb field into a laser field)

Advantages

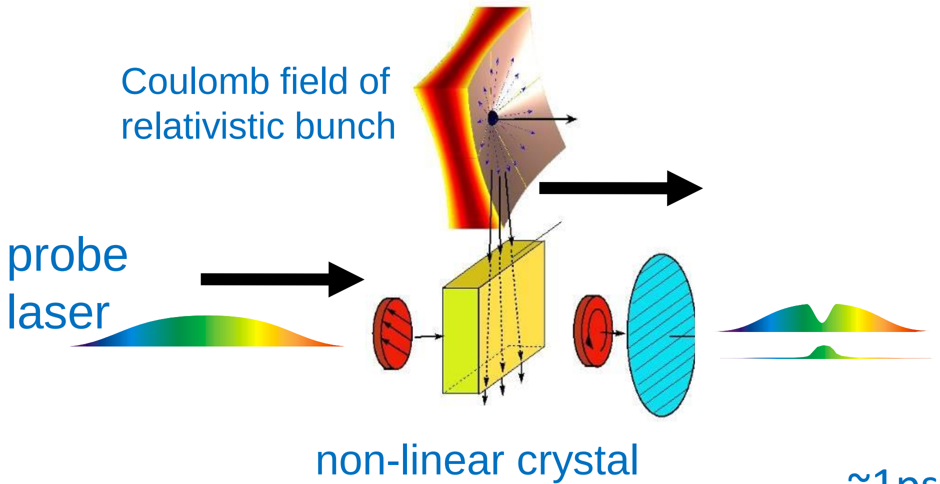
- Scales well with high beam energy
  - Particle methods get impractical (size, beam dumps)
- Non-destructive
  - Bunches can still be used
  - Live feedback

Challenges

- Unreliability, maintenance and cost of suitable ultrashort pulse laser systems
- Temporal resolution

We aim to improve on the **resolution** and the **robustness** of EO diagnostics

Current EO Techniques

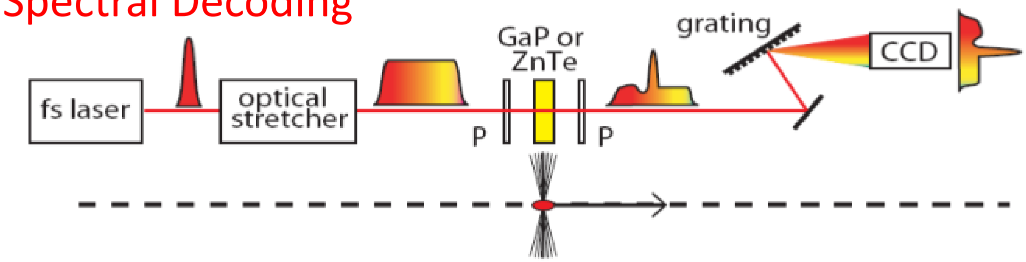


Standard Description

- Coulomb field flattens transversely, and defines charge distribution
- Pockels effect induces polarization ellipticity
- Technique borrowed from THz electro-optic sampling where ($t_{probe} << t_{THz}$)

Spectral Decoding

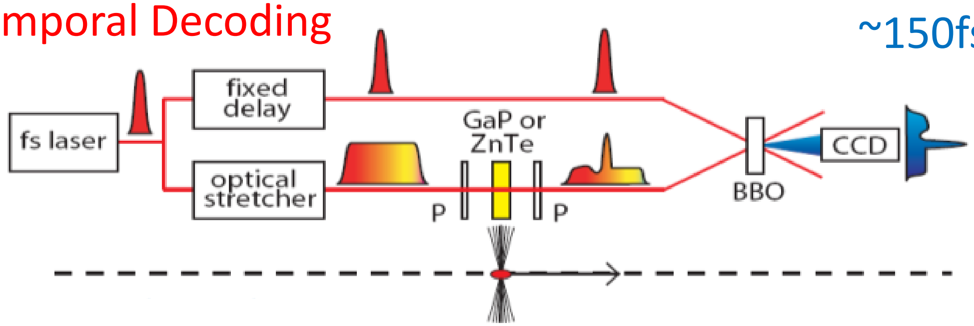
~1ps



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

Temporal Decoding

~150fs



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

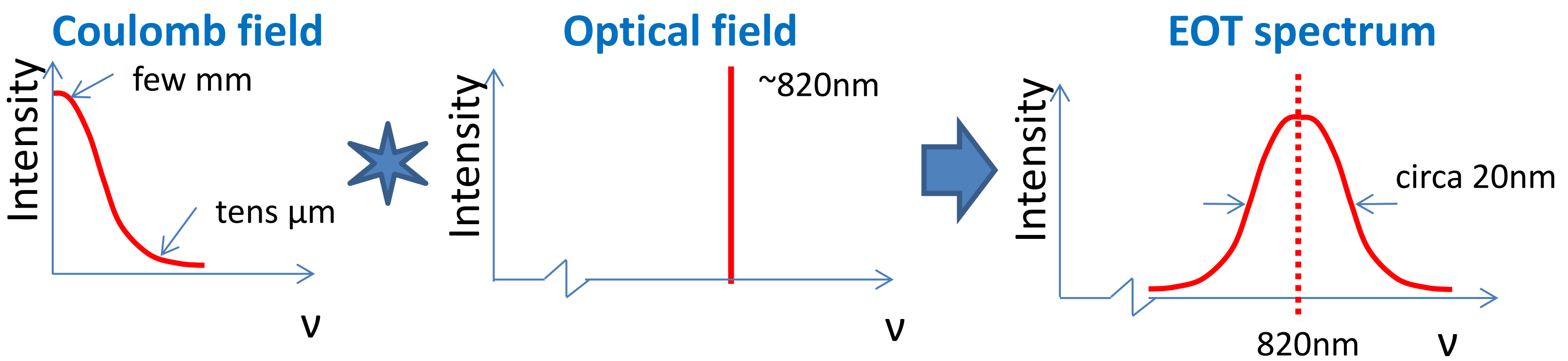
Physics of EO Transposition

More Rigorous Description – nonlinear frequency mixing

S.P. Jamison Opt. Lett. v**31** no.11 p1753

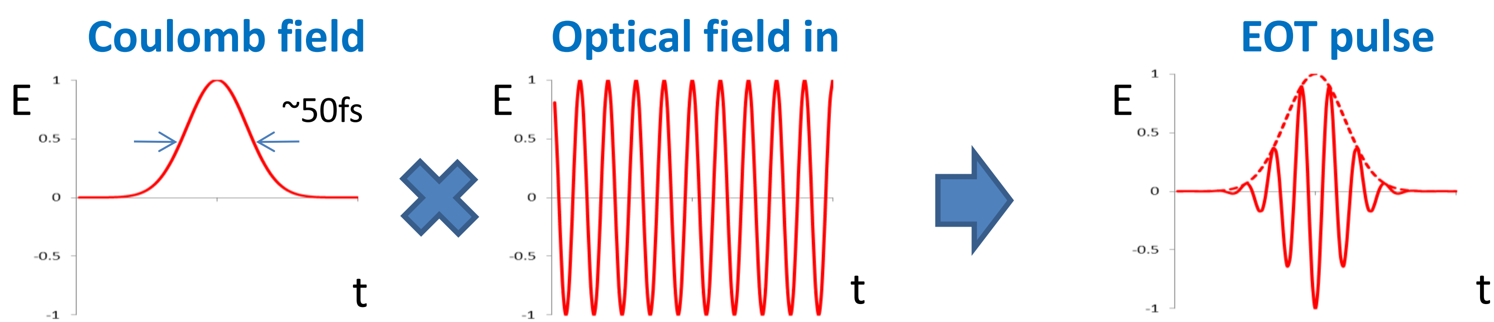
Frequency Domain

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



Time Domain

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



Characterisation of Transposed Pulse

Considerations:
* needs to be single shot
* autocorrelation not unambiguous – no shorter reference pulse available
* low pulse energy

Solution: Grenouille (frequency resolved optical gating), a **Standard and robust** optical diagnostic.

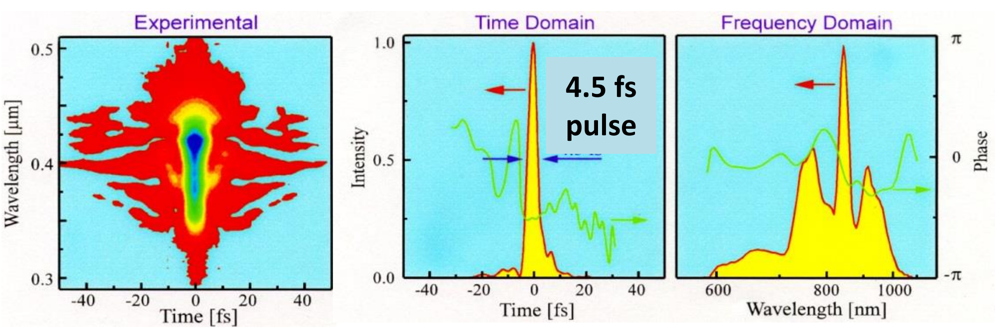
Retrieves spectral intensity and phase from spectrally resolved autocorrelation.

What we want to know → $E(t) = Re\left(\sqrt{I(t)}e^{i(\omega_o t - \phi(t))}\right)$ <-Fourier-> $\tilde{E}(\omega)=\sqrt{S(\omega)}e^{-i\varphi(\omega)}$

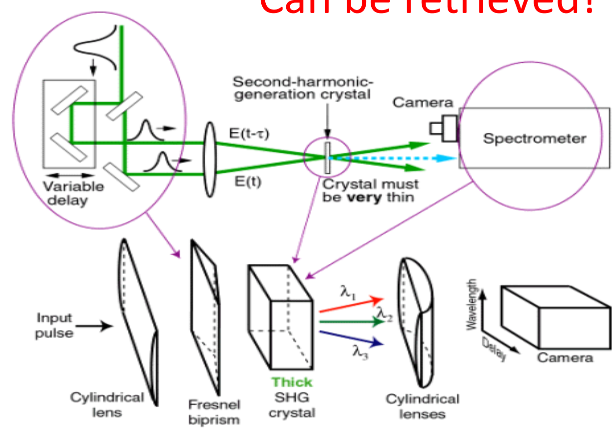
"Carrier" frequency — Can't measure — Spectrum — Spectral Phase

Can be retrieved!

$$I(\omega,t) \propto \left|\int E(t)\,E(t-\tau)e^{-i\omega t}dt\right|^2$$

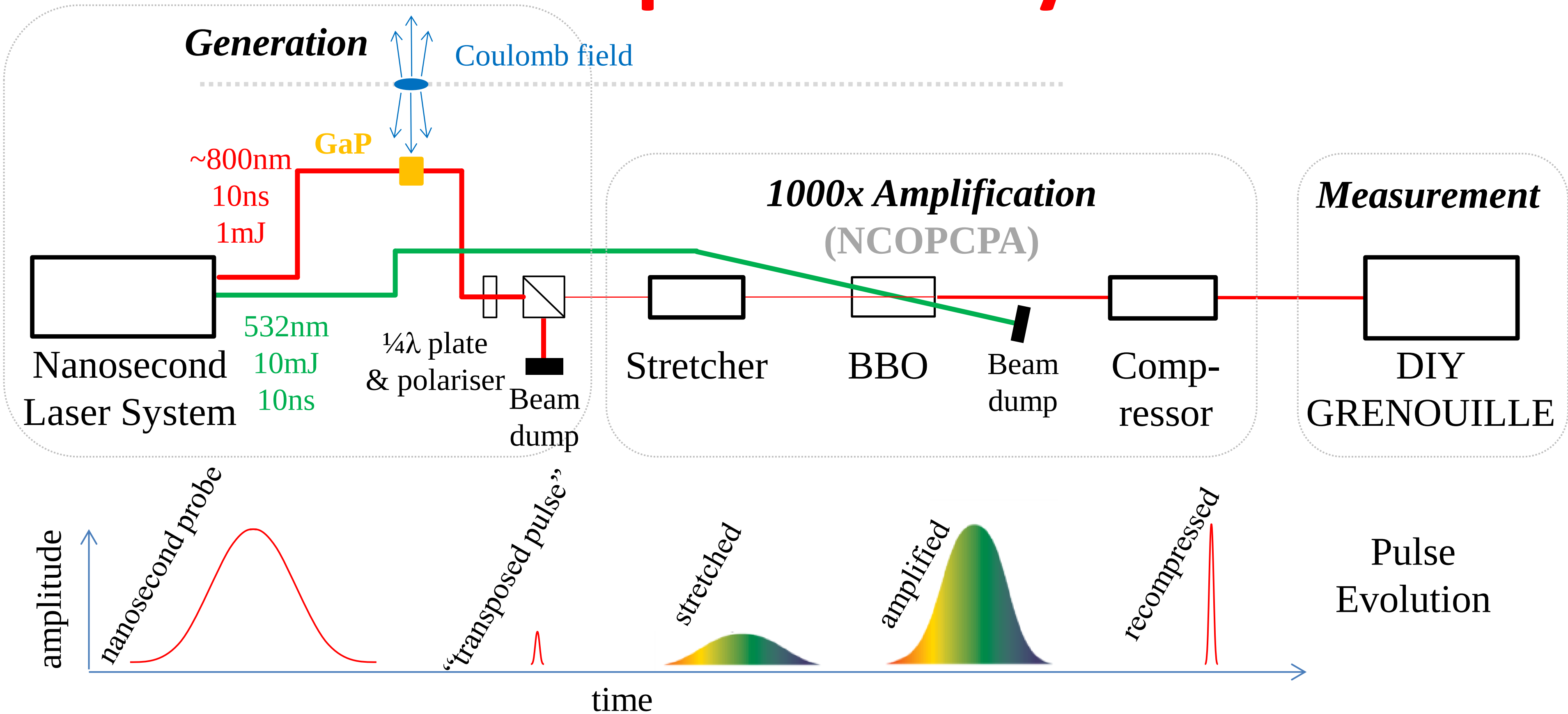


Baltuska, Pshenichnikov, and Weirsma, J. Quant. Electron., 35, 459 (1999).



- The most sensitive "auto gating" measurement
- Self-gating avoids timing issues (no need for a fs laser)
- Requires minimum pulse energy of ~1 μJ

EO Transposition System



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
5. Coulomb field, and hence bunch profile, calculated via time-reversed propagation of pulse

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EOT System Build Status

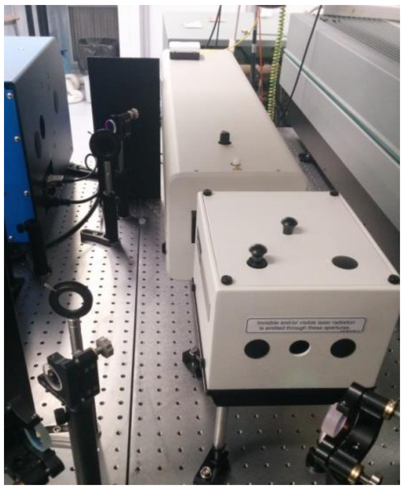
Primary laser systems finally delivered end of Nov 2014– Characterisation largely complete

All other components ready (except camera for FROG) and can now be integrated, characterised, and made robust

Dye laser not proposed for the final design – possibility of building a seeded OPO

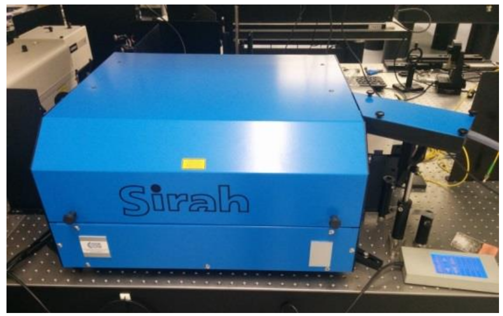
Continuum Surelite YAG

~ 4.5 ns, 150 mJ, seeded

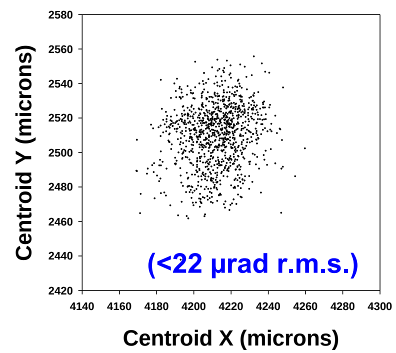


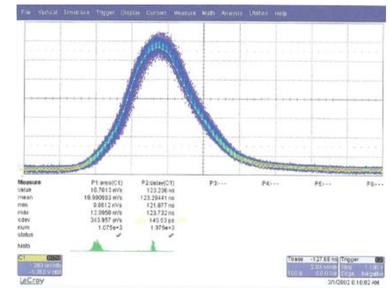
Sirah Cobra Dye laser

6 ns, 3 mJ, linewidth < 2 GHz

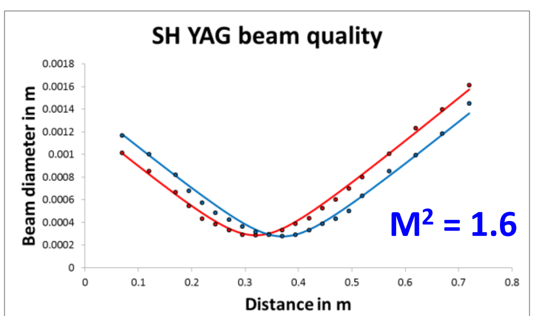


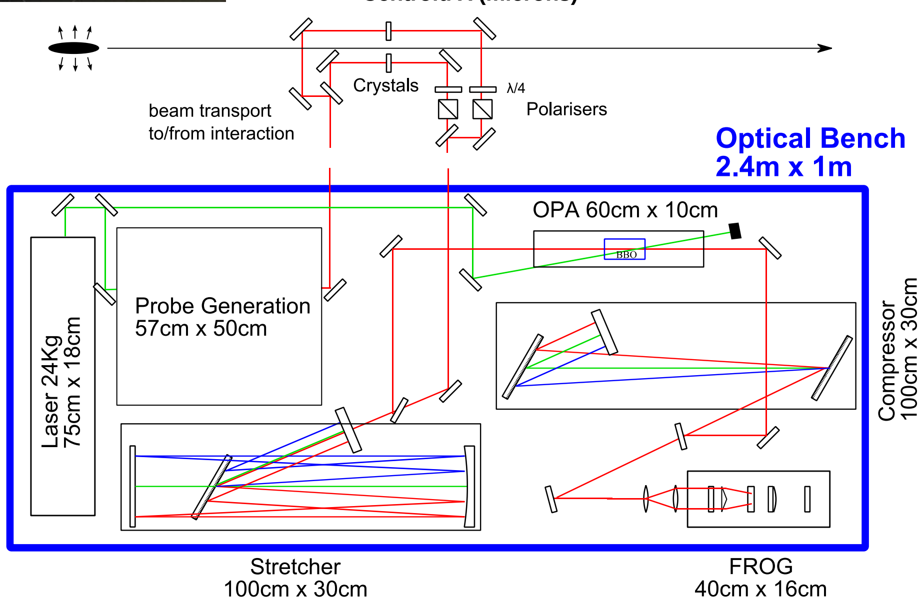
Beam Pointing Stability





Jitter < 0.3 ns r.m.s.





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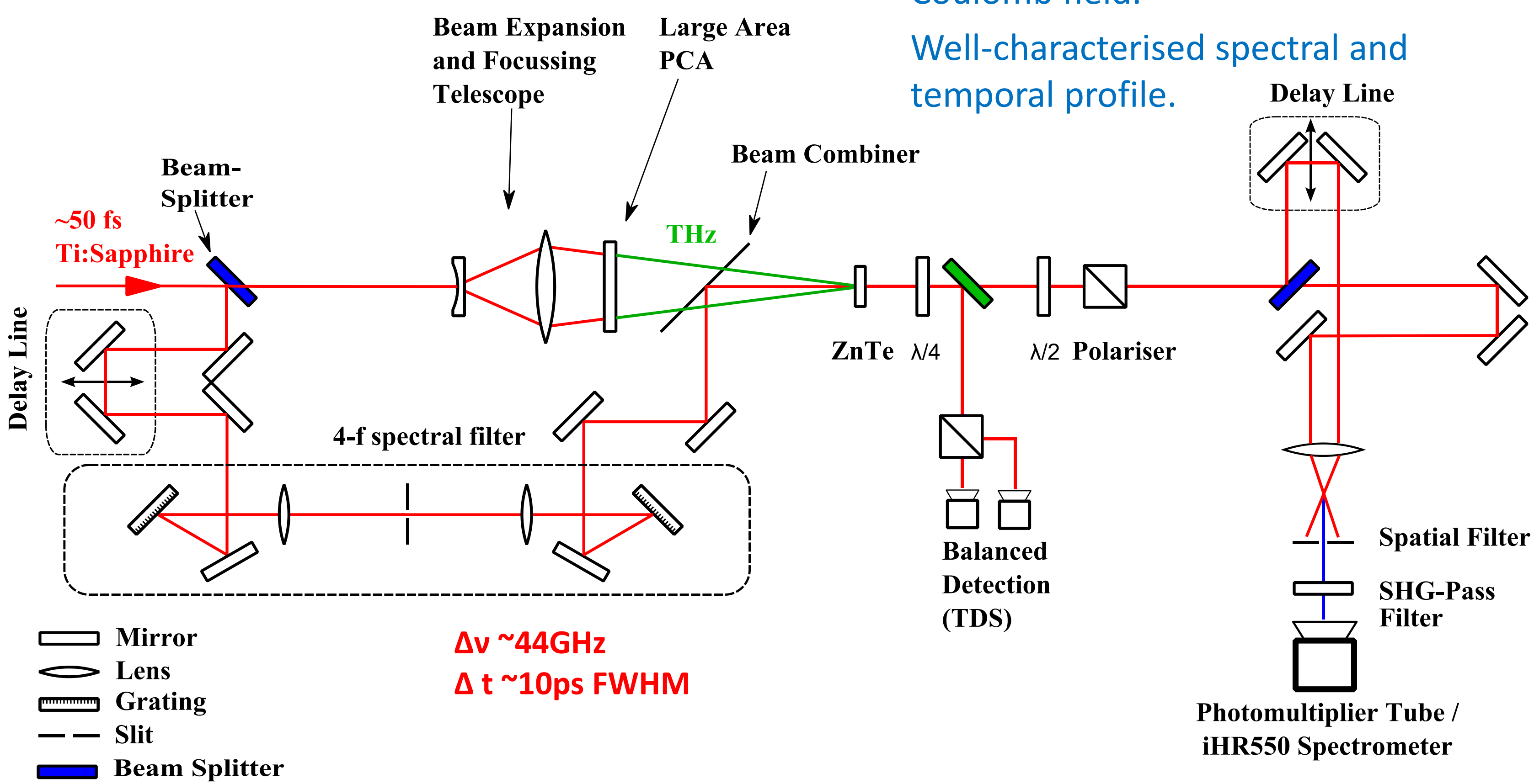
Characterisation of EO Transposition

Femtosecond laser-based test bed

Auston switch THz source mimics Coulomb field.

Well-characterised spectral and temporal profile.



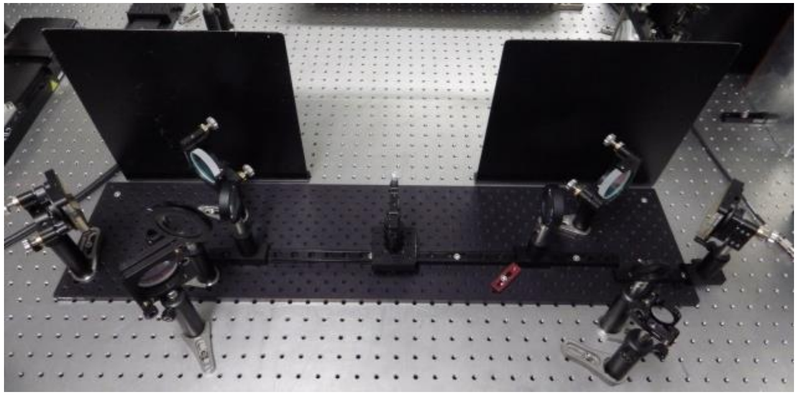
Δν ~44GHz
Δ t ~10ps FWHM

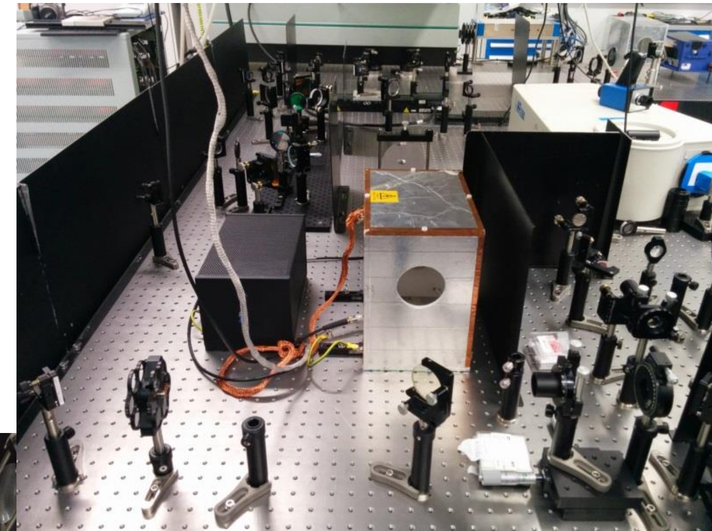
Femtosecond laser pulse spectrally filtered to produce narrow bandwidth probe

Switchable diagnostics – Balanced sampling, Crossed Sampling, and **Autocorrelation** (spectrally resolved!)

Experimental System

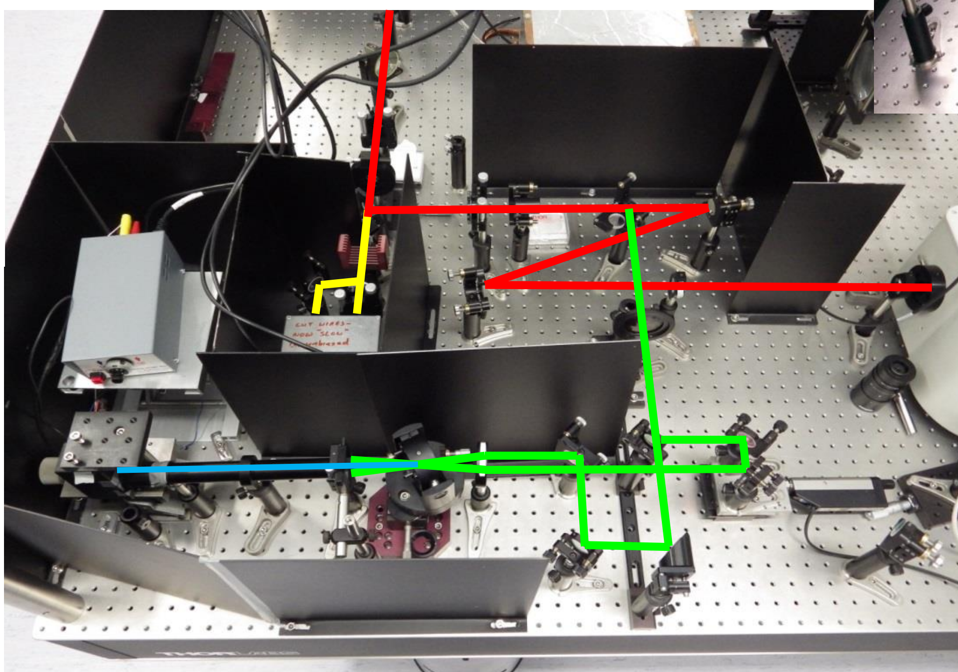
4-f filter





THz Source and interaction point

Balanced detectors



Crossed
Polariser
And
Spectrometer

Pmt &
Lock-in

Autocorrelator

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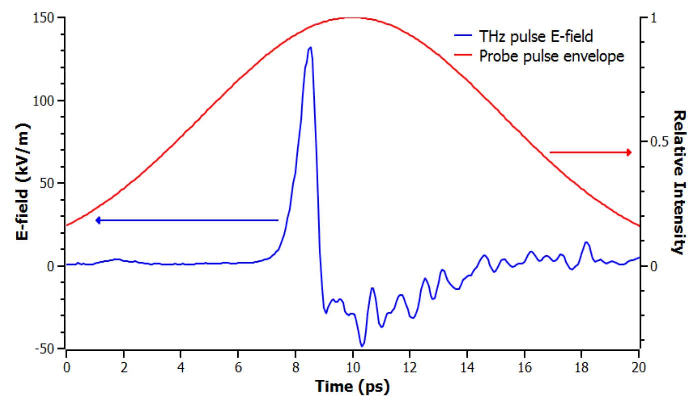
Transposed Pulse Measurements

Input pulses

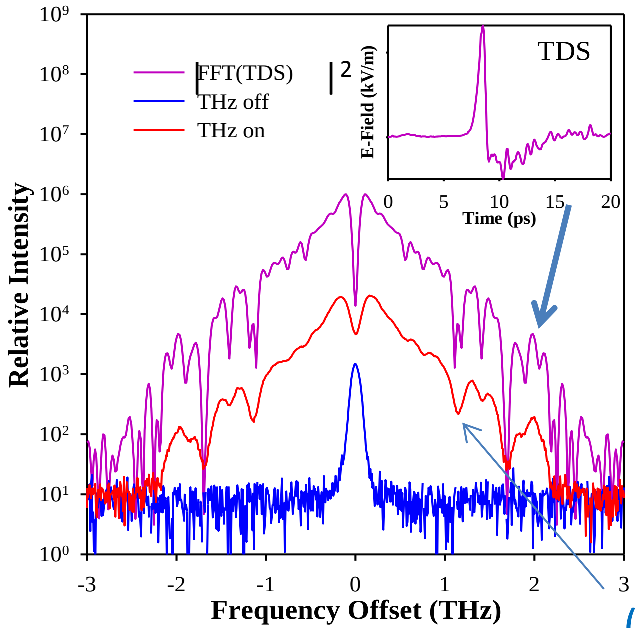
Optical probe length Δt ~ 10 ps

Optical probe energy S ~ 28 nJ

THz field strength E ~ 132 kV/m

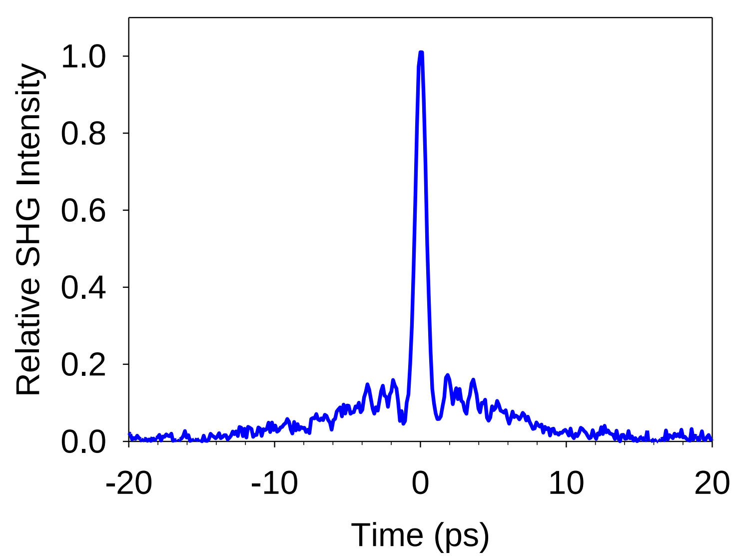


Spectral Measurement



(<0.5 nJ)

Autocorrelation



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Extrapolation to bunch parameters

Scaling factors

$$Energy_{upconv} \propto Power_{probe} \times (Efield \times l \times r)^2$$

l is the EO crystal length, r is the nonlinear coefficient

CLIC Example:

Total energy in EOT Pulse ~470pJ

"Typical" nanosecond pulse laser as probe — Pulse energy 1mJ, Pulse duration 10ns — $Power_{probe} \sim$ 100 kW

Coulomb field for target CLIC bunch parameters (CDR) — Bunch length 44µm, Bunch charge 0.6pC — $Efield \sim =$ 24.5 MV/m

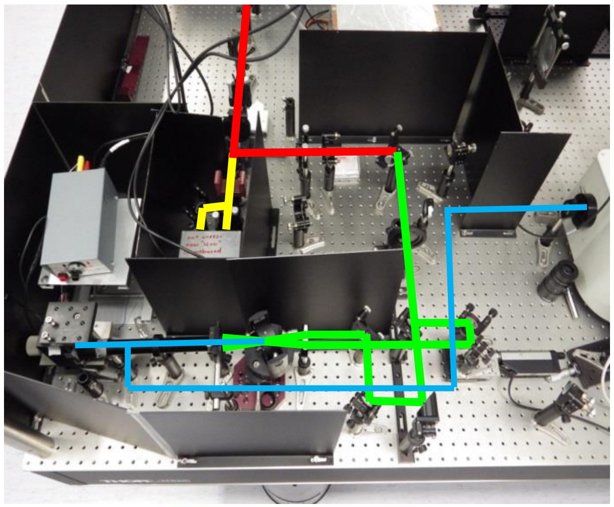
Property	Factor of improvement
$Power_{probe}$	x36
l	÷100^2
r	÷2^2
$Efield$	x186^2
Overall	**x31**

Pulse energy of ~15nJ is predicted.

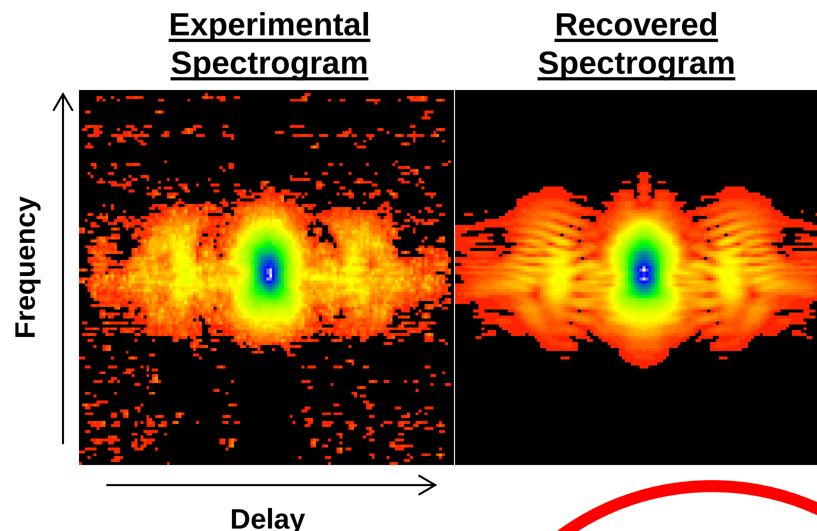
1µJ required for the commercial single-shot FROG, "Grenouille".

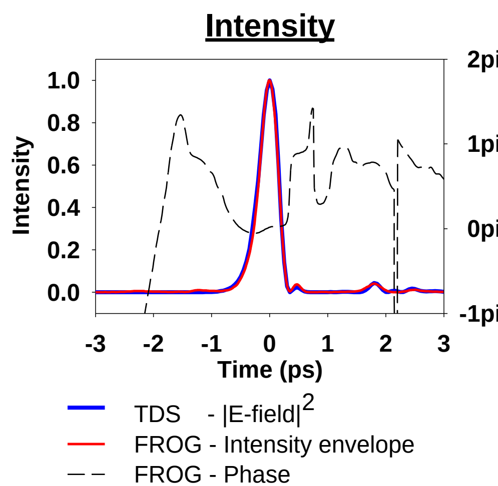
Method can be used to estimate applicability to other beams – left as an exercise for the listener!

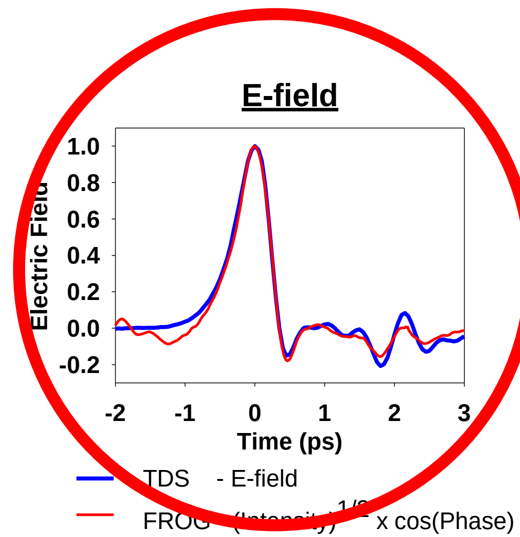
FROG Measurement



PCO dicam pro
ICCD camera
256x frame integration
30x software averaging







<u>0.55 ps</u> pulse measured with a <u>10 ps</u>, transform limited, probe!

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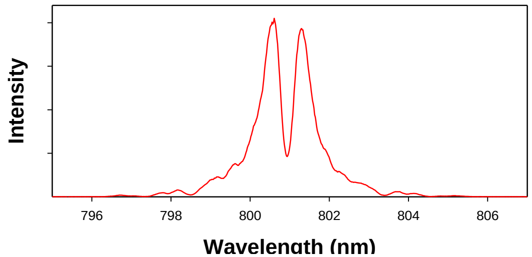
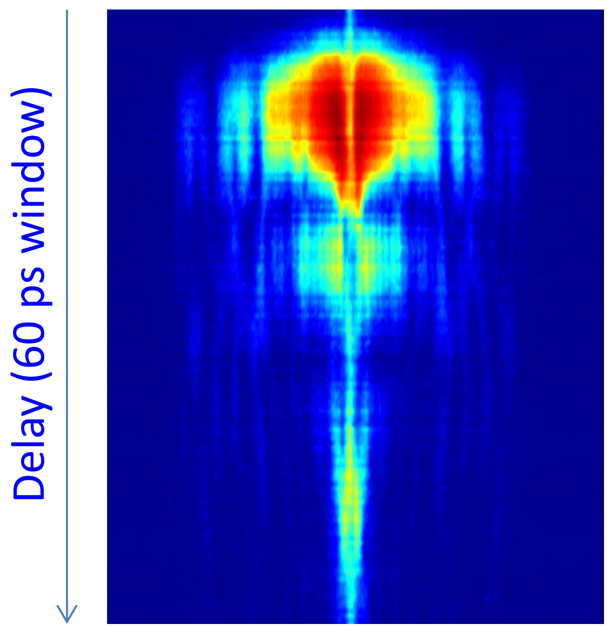
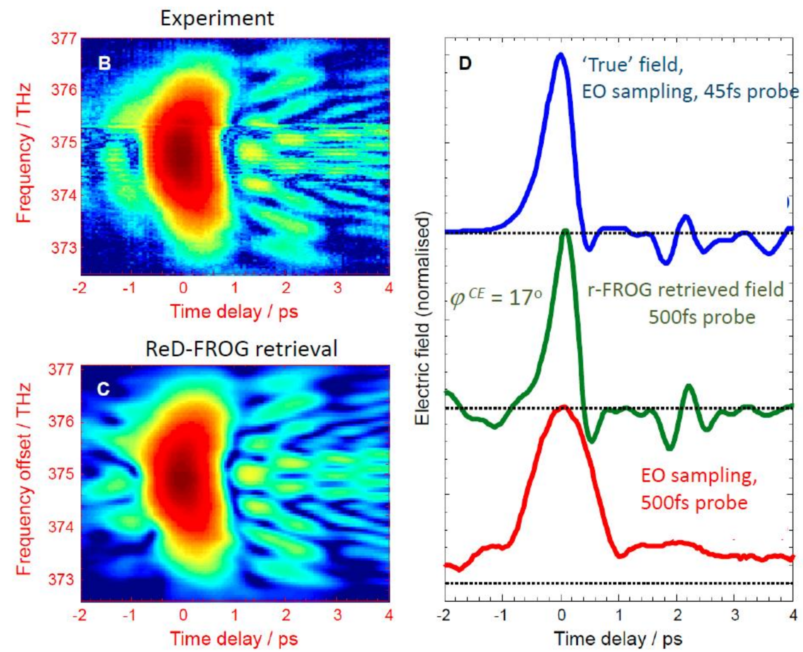
New THz Measurement Scheme
(an absolute phase FROG!)





This looks like a spectrogram!

This is a FROG where both SFG and DFG mechanisms are present and spectrally overlap, a FROG algorithm was modified to account for this.
Essentially, the interference pattern between SFG and DFG in the trace reveals the absolute phase.



Theory extended to optical pulses and is being published (on Arxiv now)
arXiv:1501.04864 [physics.optics]

Temporal Resolution

EO transposition scheme is now limited by materials:

- **Phase matching and absorption bands in ZnTe/GaP.**
- **Other materials are of interest, such as DAST or poled polymers, but there are questions over the lifetime in accelerator environments.**

Collaborative effort with MAPS group at the 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 TFISH enhancement being investigated.**
- **Surface nonlinear effects…**

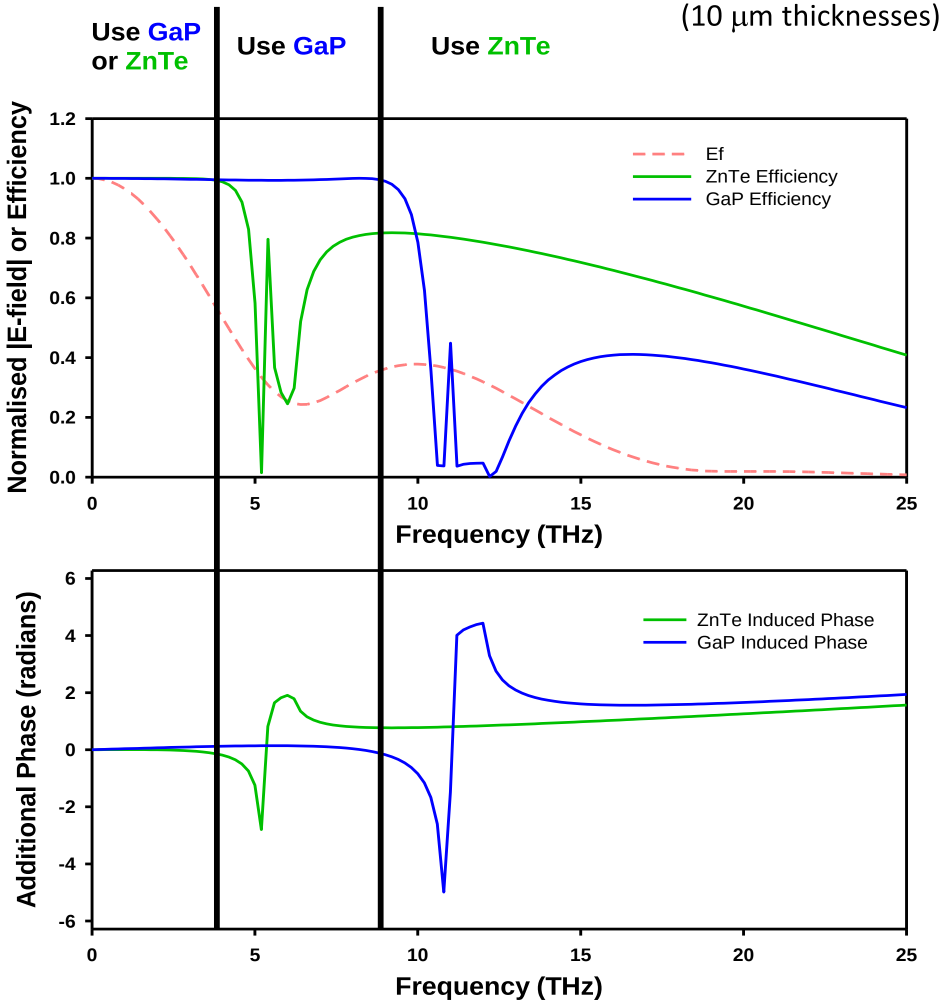
A key property of the EO Transposition scheme may be exploited

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

Spectral Compositing of Multiple Crystals

- Phasematching not the whole story
  - Dips caused by absorption near phonons
  - Phase distortion near absorptions become very large
  - Distortions in $\chi^{(2)}$ near absorptions
- Discard data around the absorption lines
- Fill in the blanks with different crystals

Basic numerical study is promising. Not yet demonstrated for THz… (insufficient bandwidth)



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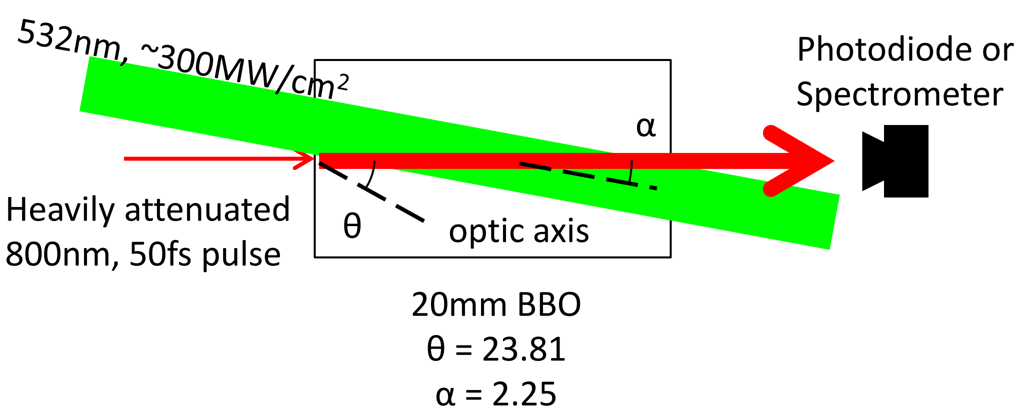
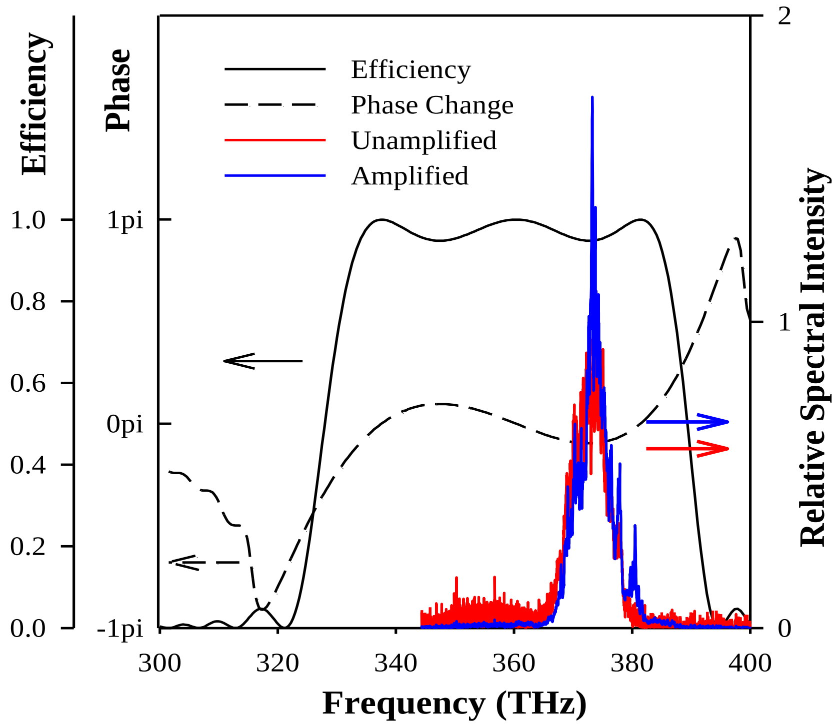
Thank you for your attention

Chirped Pulse Optical Parametric Amplification

- Very small Phase and Amplitude distortions can be calculated (and so can be removed)
- Bandwidth very broad >50THz
- Tested using stand-ins for pump and signal – picosecond laser system and Ti:Sapphire laser

Pulse spectrum maintained





Gain of >1000x verified

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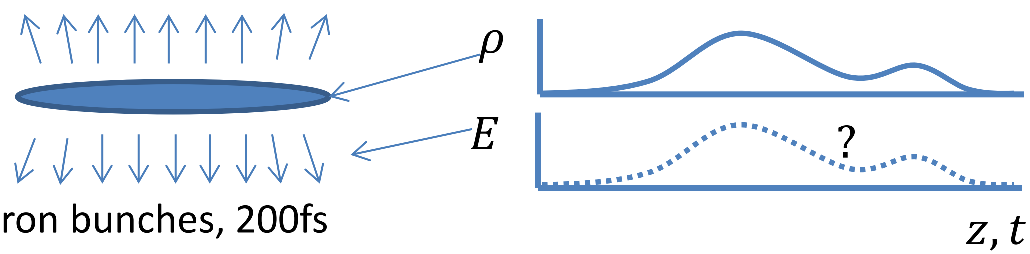
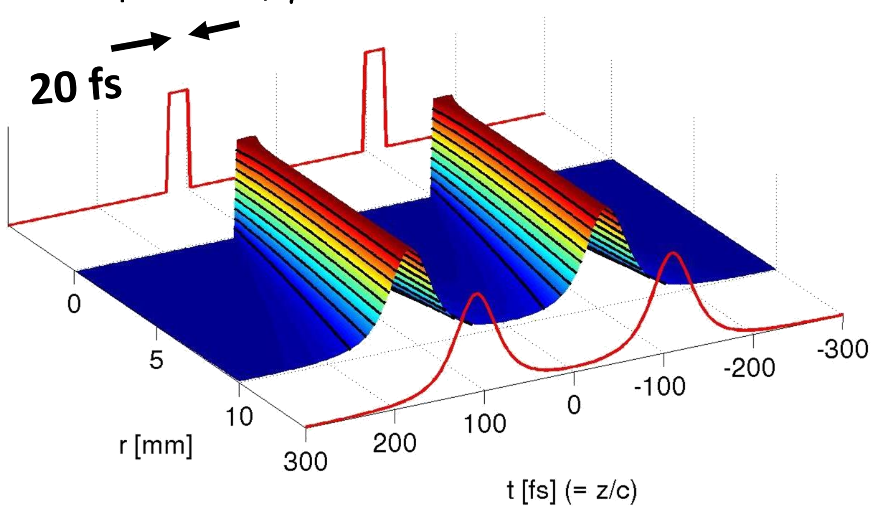
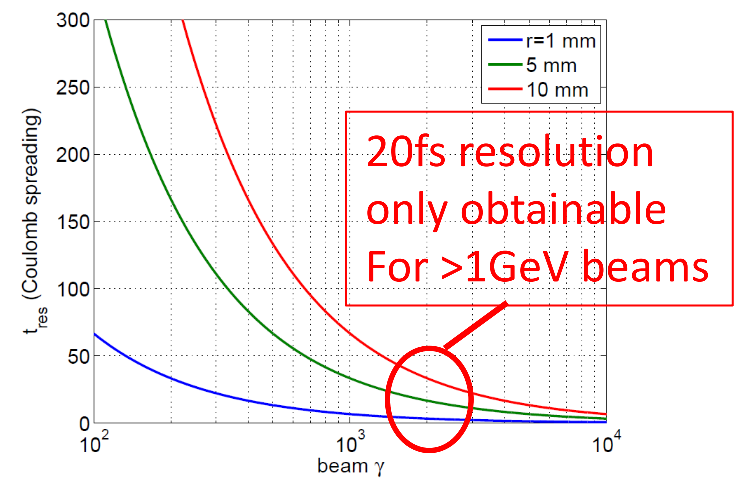
Common Problem - Field at Source

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



20fs electron bunches, 200fs separation, $\gamma = 1000$





High γ is an advantage!

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.)

LATTE Lab

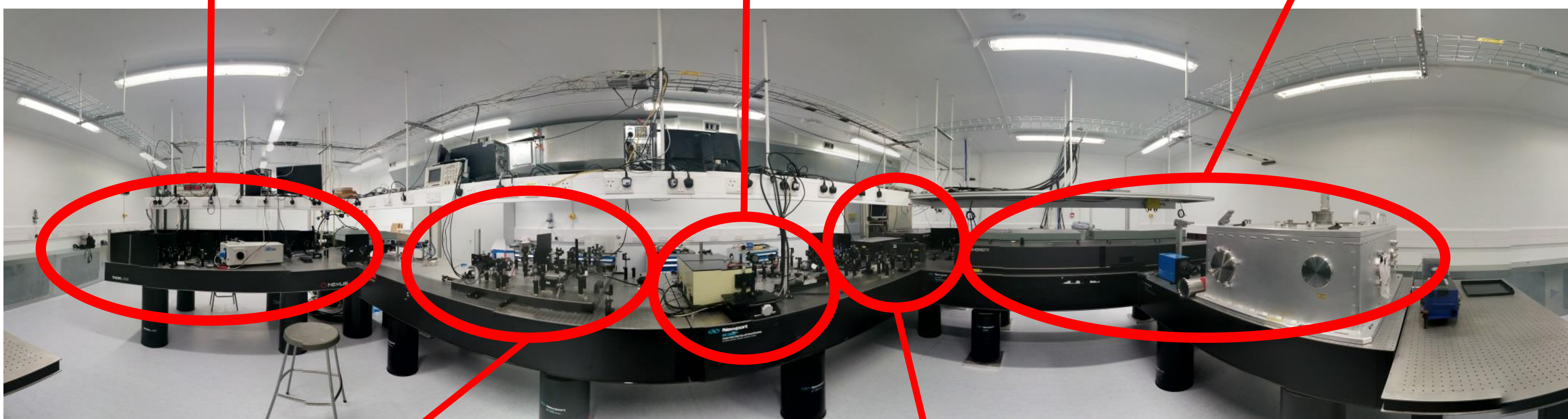
The Laboratory for
Laser, Terahertz and Terawatt Experiments
in accelerator applications

Lab overview

Longitudinal Profile Monitor CLIC-UK project

UV diagnostics and novel EO materials

TW laser system: to be commissioned. Output available in lab



High power, adjustable temporal profile and polarisation state THz sources >1 MV/m

Core laser sources (lockable to RF):
Ti:Sapphire - **81 MHz, <50 fs, 400 mW** or **1 kHz, <50 fs, >1 mJ**
OPA - **1 kHz, 570 nm to 12 µm, 1 µJ to 270µJ** (λ dependent)

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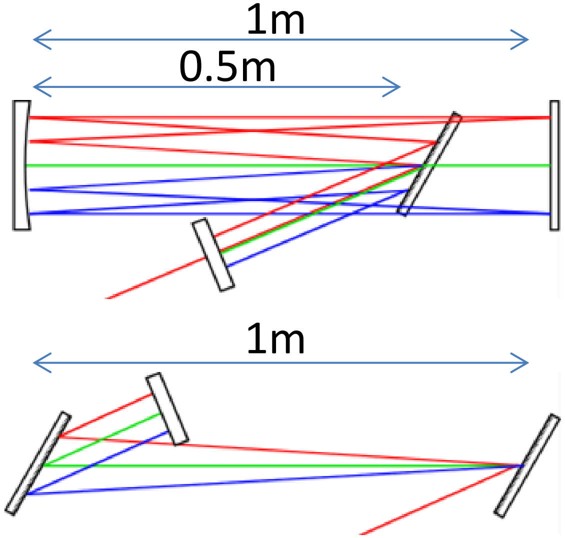
Stretcher and Compressor Design

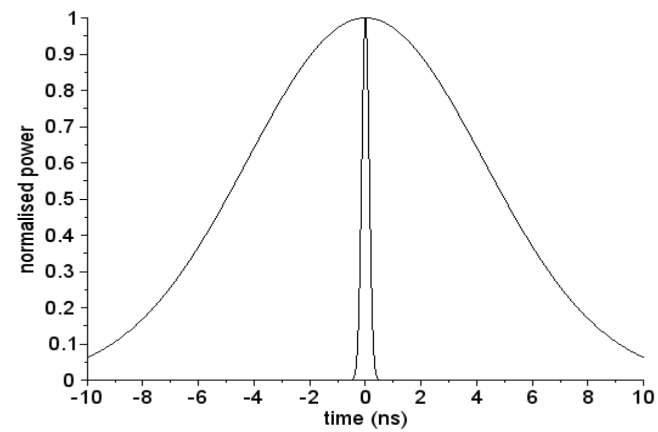
Pulse	Properties	Peak Power	
532nm Pump	10mJ, 10ns Gaussian temporal profile	$1x10^6$ W	
800nm EO Transpostion Signal	Amplified signal energy > 1 μJ, ~50 fs	$20x10^6$ W	>Pump! Not possible
As above but stretched GVD = $5.6x10^6$ fs^2	> 1 μJ, ~310 ps	$3.2x10^3$ W	OK, will not distort

Conjugate Stretcher and Compressor designs



GVD = $5.6x10^6$ fs^2

All gratings
G=1200 lines/mm
$\Theta_{deviation}$~15°



Calculations indicate nanosecond level jitter has negligible effect

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