Electro-Optic Transposition Bunch Length Monitor – Project Overview

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Project Gaols

CLIC EO diagnostic project targets

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

Electro-Optic diagnostics: (encoding of Coulomb field into a laser intensity)

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**

Central project goals:

- Improve on the **time resolution**
- Establish **robustness** of EO diagnostics

Project Deliverables

1.1 Design report for the prototype of EO system optical system

Submitted 6/11/2014 without cost estimates/drawings/vendors as agreed. Will be included in the final report (1.3) after the full system has been characterised and tested.

Will complete when performance of final system is characterised – including an injection seeded OPO for probe generation - to ensure correct parts are included.

1.2 Technical report on EO materials

Nanomaterials have exhibited optical nonlinearities (SHG) but no THz interaction seen, nor any theoretical understanding gained of how to create a significant response. Alternative resolution enhancing scheme – ”multi-crystal spectral-composition” chosen (planned decision point).
Testing the multi crystal scheme requires a source of a high energy, broad band, THz-band radiation; *THz source developed in independent project, but applied to CLIC EO.*

Technical report on materials to be completed Feb 2017

1.3 Technical Report on the performance of this prototype and its implementation for CLIC.

Performance data derived from laser based tests. Demonstration of EOT prototype with electron bunches delayed until post CLARA switch-on. All the core concepts (EOT) and components have been proven. *Technical report on performance to be delivered March 2017.*

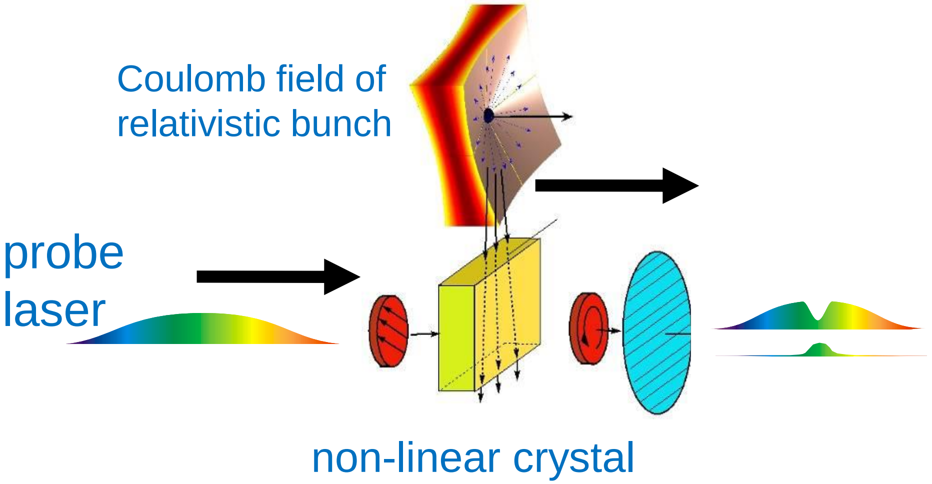
1.4 Design report for an “intra-macrobunch” profile evolution 31/12/16

A multiple bunch profile evolution monitor using a spectrometer and streak camera was envisaged. Further system characterisation and OPO development have been re-prioritised over this (with agreement).

1.1 & 1.3 System Design and Characterisation

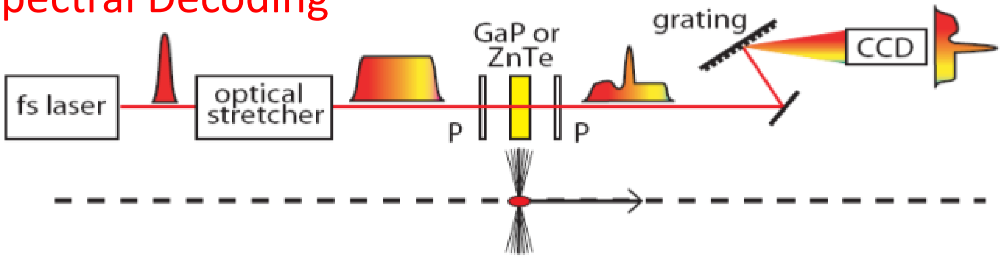
Design and testing of system components and principles

‘Standard’ EO Techniques



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

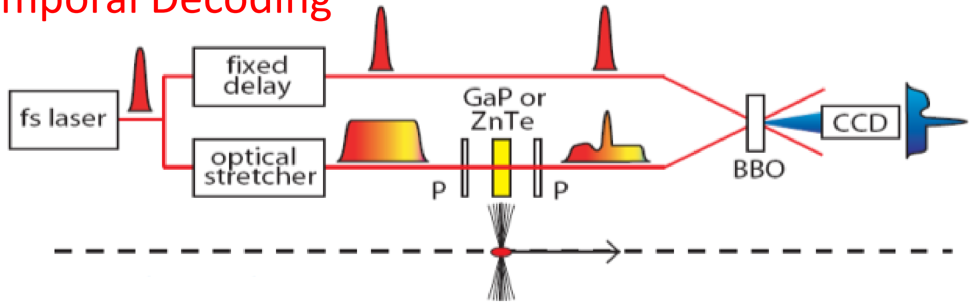
Spectral Decoding



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

~1ps

Temporal Decoding



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

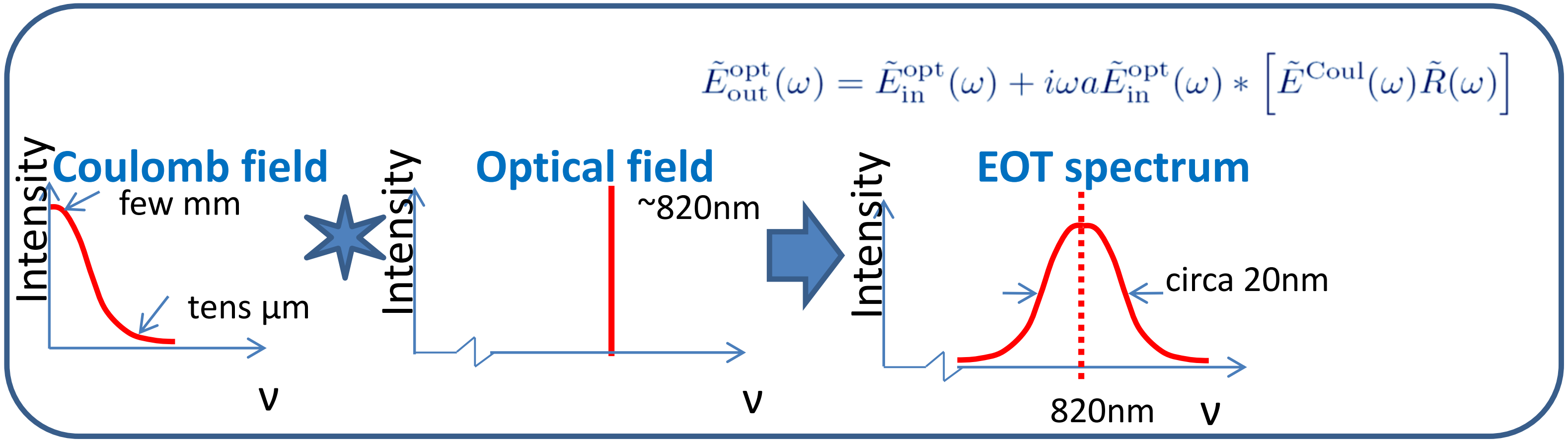
Concept of EO Transposition

Narrow bandwidth probe laser interacting with Coulomb field

Bunch spectrum faithfully upshifted to optical region.

- *Octave spanning 0-20THz bandwidth converted to 10% bandwidth (375THz +/- 20THz)*
- *Readout with commercial cameras & spectrometers*

Frequency Domain

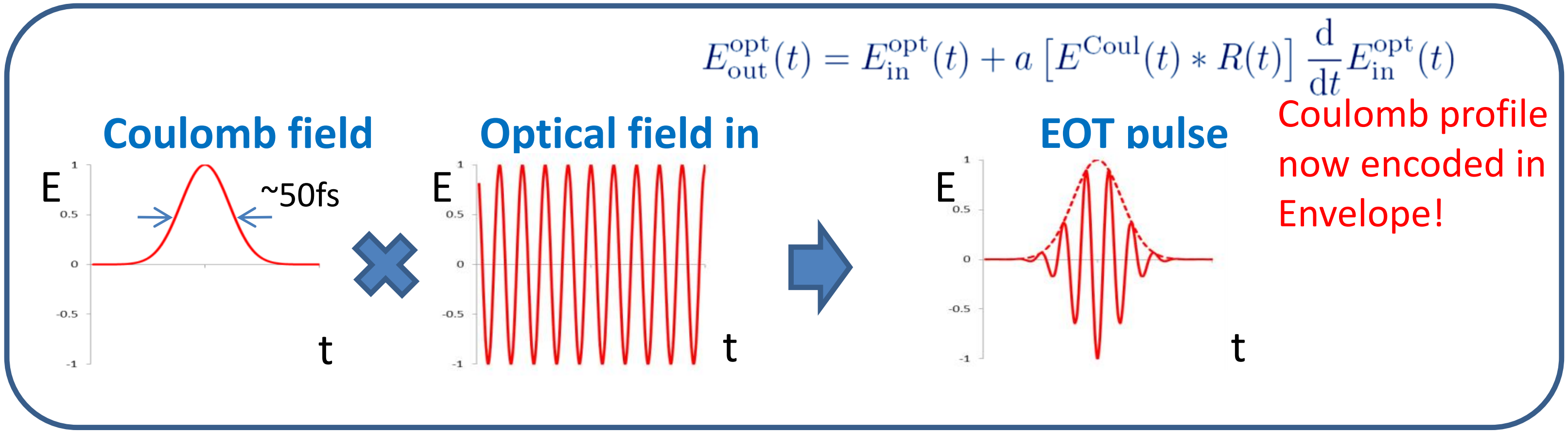


$$\tilde{E}^{\rm opt}_{\rm out}(\omega) = \tilde{E}^{\rm opt}_{\rm in}(\omega) + i\omega a\tilde{E}^{\rm opt}_{\rm in}(\omega) * \left[\tilde{E}^{\rm Coul}(\omega)\tilde{R}(\omega)\right]$$

Bunch electric field E(t) converted to optical intensity envelope .

- *Established (& commercial) ultrafast laser measurement system applicable (Frequency Resolved Optical Gating – FROG)*

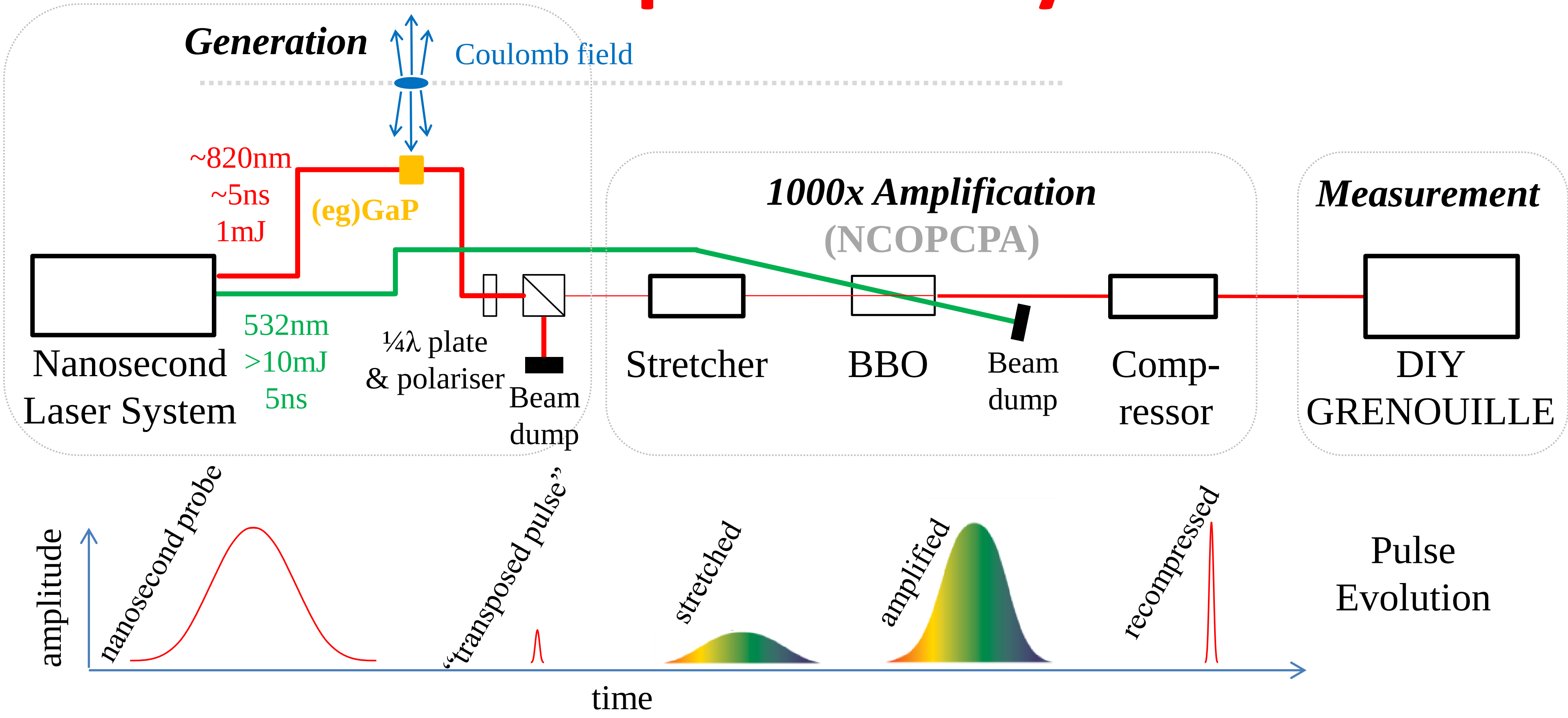
Time Domain



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

Coulomb profile now encoded in Envelope!

EO Transposition System



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

Characterisation of modulated optical probe

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

$$E(t) = Re\left(\sqrt{I(t)}\,e^{i(\omega_o t-\phi(t))}\right)$$

"Carrier" frequency

Can't measure

<-Fourier->

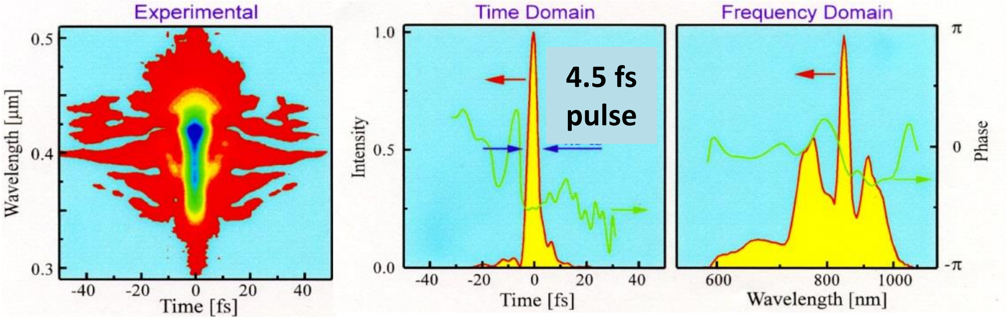
$$\tilde{E}(\omega)=\sqrt{S(\omega)}\,e^{-i\varphi(\omega)}$$

Spectrum

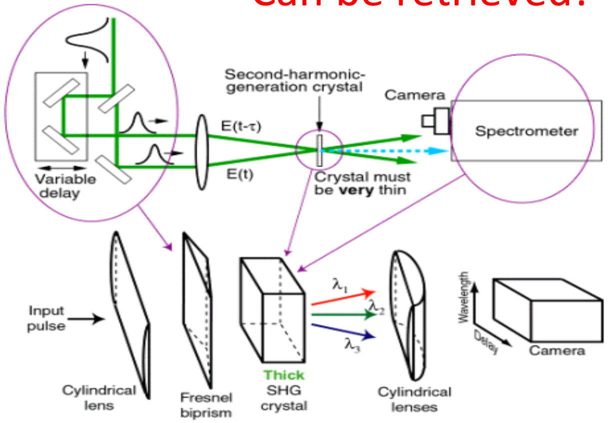
Spectral Phase

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).



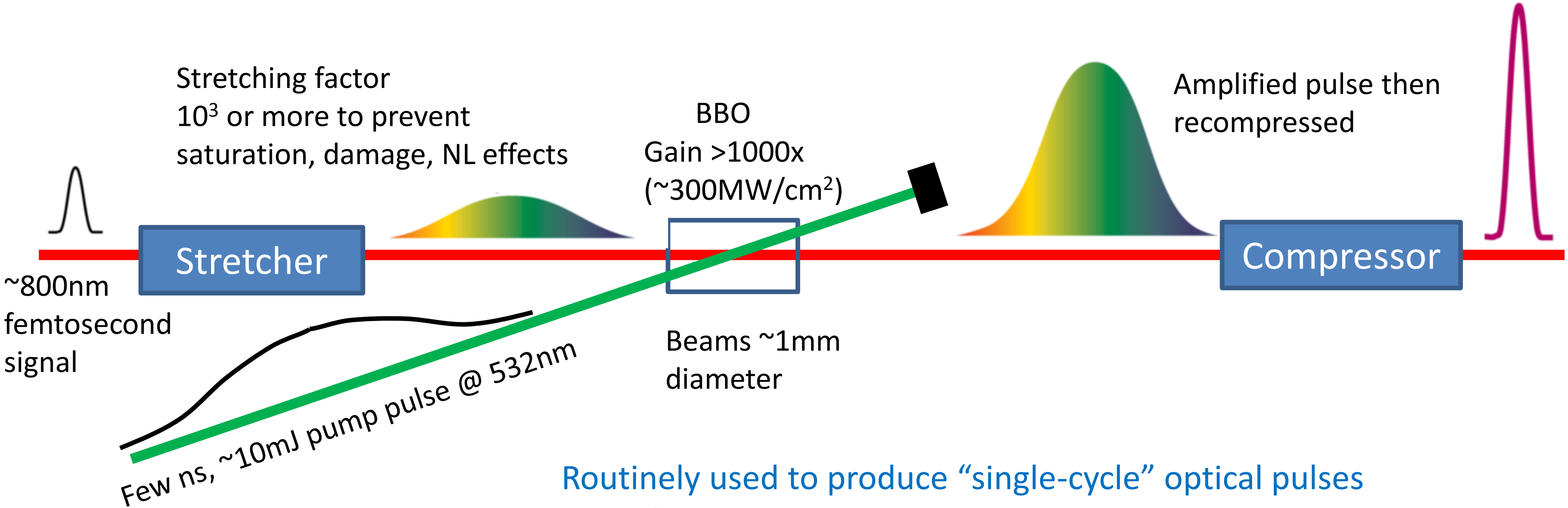
- The most sensitive "auto gating" measurement
- Self-gating avoids timing issues (no need for a fs laser)
- ***Requires minimum pulse energy of ~1 µJ***

Enabling single-shot measurement

‘Non-collinear Chirped Pulse Amplification’ of optical signal

Problem: Up-conversion is relatively weak – our calculations suggest energies of a few nJ.
Signal needs amplifying without loss of information.

Solution: Non-collinear Chirped Pulse Amplification (NCPA)



Stretching factor 10^3 or more to prevent saturation, damage, NL effects

BBO
Gain >1000x
(~300MW/cm^2)

Amplified pulse then recompressed

~800nm femtosecond signal

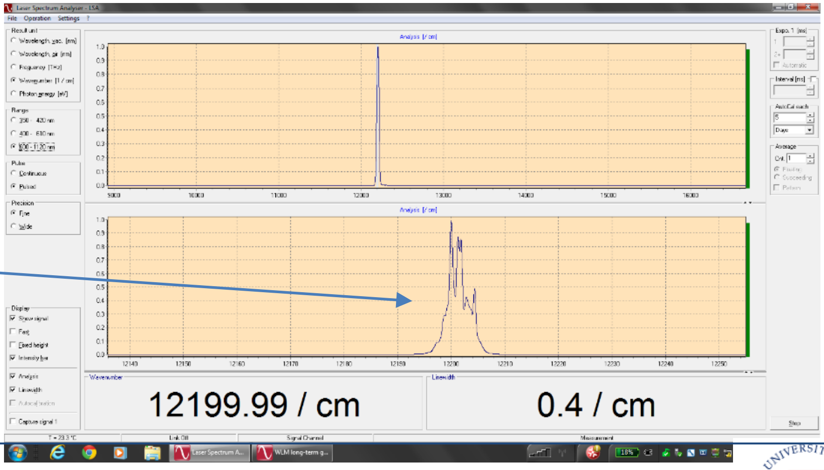
Beams ~1mm diameter

- Routinely used to produce “single-cycle” optical pulses
- Amplification with robust nanosecond-pulse lasers
- High **gains of 10^7** or more
- Gain **bandwidths >100 nm (50 THz)**
- **Preservation of phase information** of pulse
  (low conversion efficiency and/or phasematched)

Laser Systems

- Design requires >10mJ, 10ns 532nm light for OPO pump, and ~1mJ for probe at ~820nm
- Aimed to use commercial Q-Switched Nd:YAG and OPO
  - ‘standard’ commercially available OPOs do not have suitable bandwidth
  - Commercial suppliers offering custom modifications to satisfy specifications….
  - Chosen supplier extremely late and did not deliver to specification! No confidence in vendor OPO designs
- New system procured with dye laser for probe
- Primary laser systems finally delivered Nov 2014
  - Had ~3 months before fully commissioned due to faulty driver unit which was replaced
- Dye laser not proposed for the final design – building a seeded OPO

Multi longitudinal mode (causes strong temporal intensity modulations) operation of OPO that failed specification tests



Laser Spectrum Analyser - LSA

Result unit: ● Wavenumber [1 / cm]

Range: ● 600 - 1120 nm

Pulse: ● Pulsed

Precision: ● Fine

Display: ☑ Show signal ☐ Fast ☐ Fixed height ☑ Intensity bar ☑ Analysis ☑ Linewidth ☐ Autocalibration ☐ Capture signal 1

AutoCal each: 5 Days

Average: Cnt. 1

Wavenumber: 12199.99 / cm

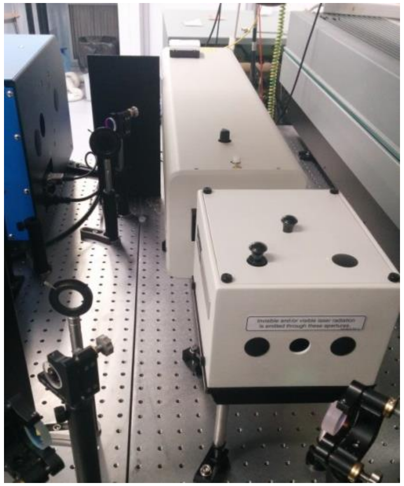
Linewidth: 0.4 / cm

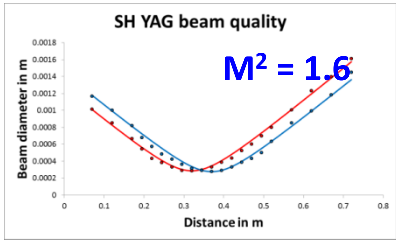
T = 23.3 °C

Characterisation of Laser Systems

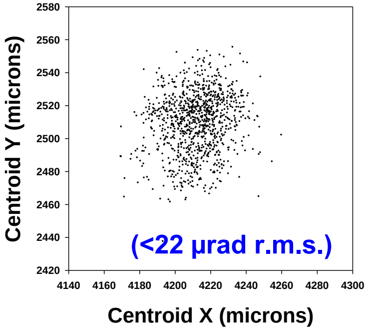
Continuum Surelite YAG

150 mJ, seeded for SLM operation



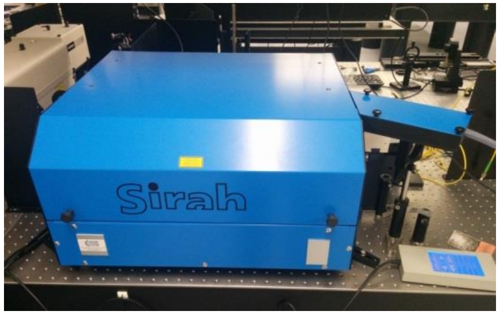


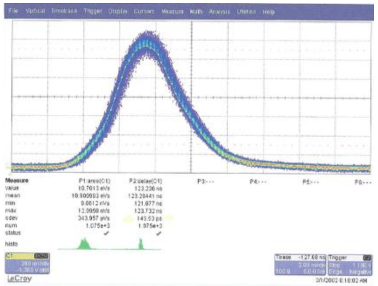
Beam Pointing Stability



Sirah Cobra Dye laser

6 ns, 3 mJ, SLM





~4.5 ns

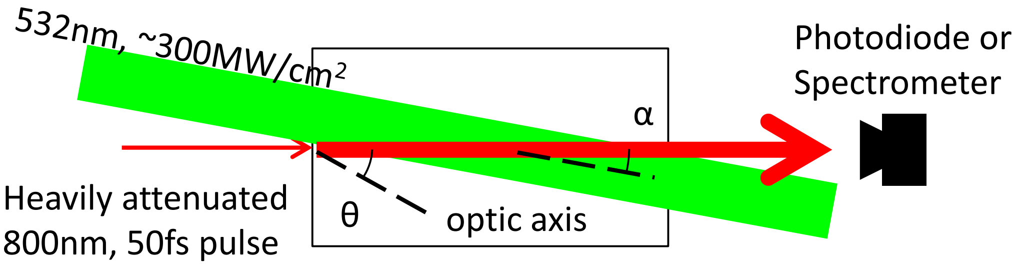
Arrival jitter <0.3 ns r.m.s.

Intention was for integrated solid-state λ = 800nm generator:

Commercial suppliers unable to satisfy specs (despite claims)

Optical Parametric Amplifier Design

- Very small Phase and Amplitude distortions can be calculated (and so can be removed)
- Bandwidth calculated to be very broad **>50THz**
- Early testing used stand-ins for pump and signal in absence of nanosecond laser systems – amplified picosecond laser system and Ti:Sapphire laser

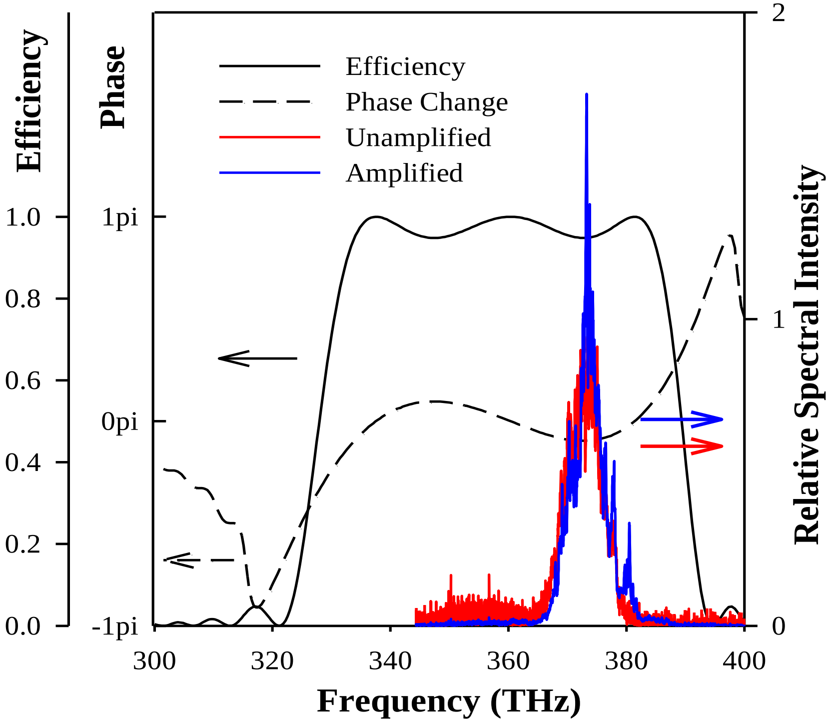


Pump derived from 50ps pulse laser

Photodiode or Spectrometer

Heavily attenuated 800nm, 50fs pulse

20mm BBO
θ = 23.81
α = 2.25

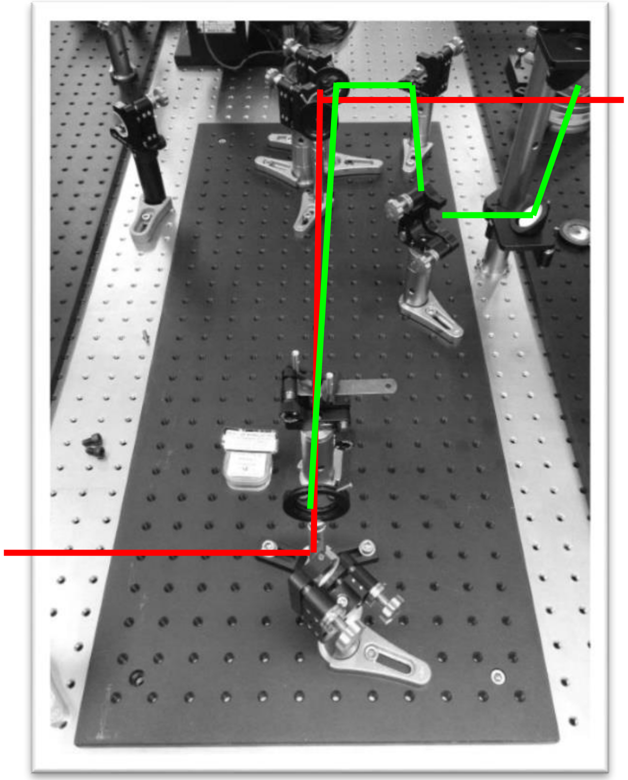


Gain of >1000x verified

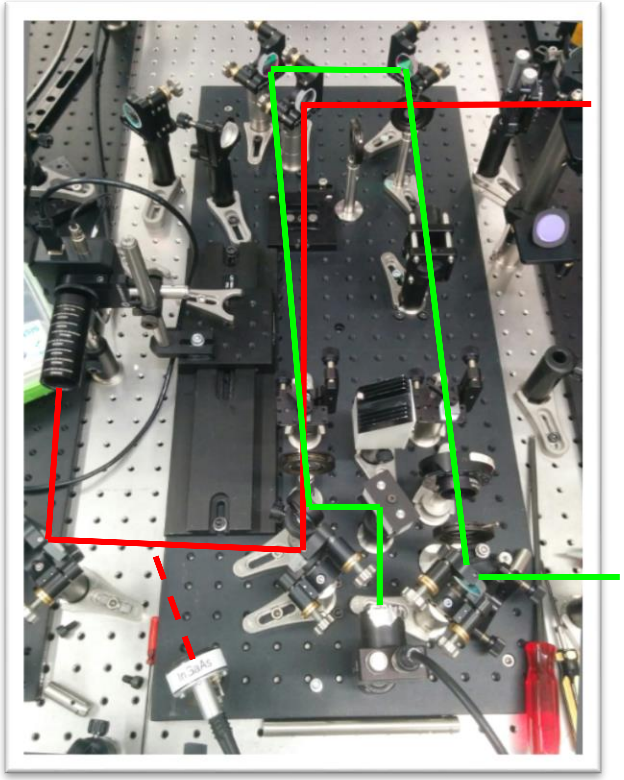
Pulse spectrum maintained

Recent OPA Progress

- Nanosecond Pulse Pump and Stretcher in Use



Layout for early testing



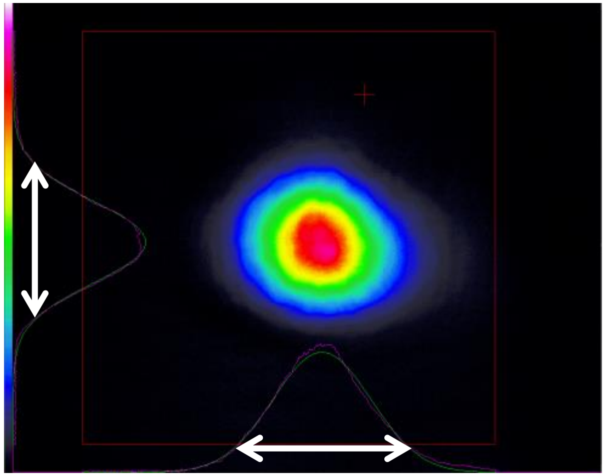
Development of amplifier – easier alignment and increased gain potential.

- More alignment points
- Beam profiling stage for collimation and quality
- Pump power adjustment
- Pulse arrival monitoring

Recent OPA Progress

- Gain of 1000x achieved at pump intensity of 360 MW/cm^2 (calculated 200 MW/cm^2)
- New design permits >1.7 GW/cm^2 i.e. gain of 6x10^9!
- **However** - damage of BBO is in range 1 - 10 GW/cm^2 , so gain maximum is ~ 10^6 !

Amplified Pulse Beam Profile

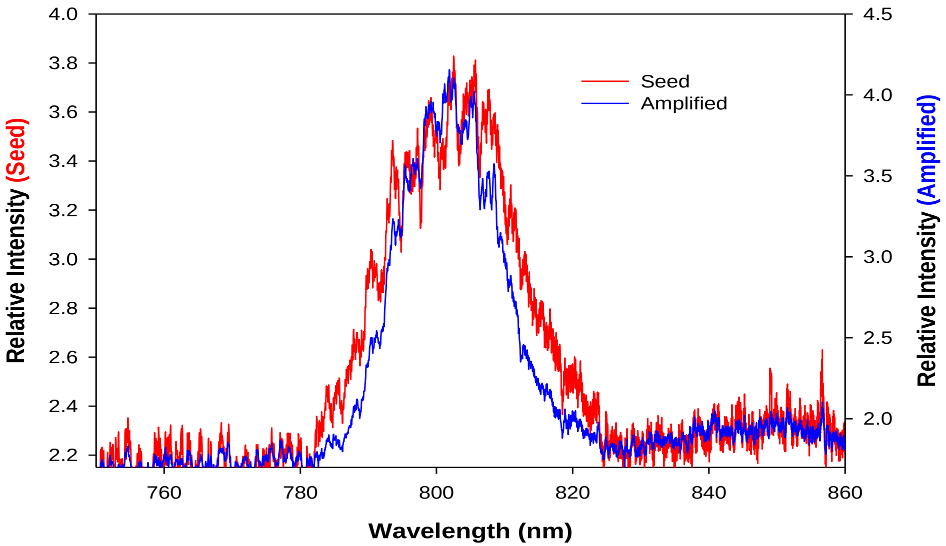


1.2mm @ e^{-2}

1.4mm @ e^{-2}

Amplified pulse has an excellent spatial profile – required for GRENOUILLE

Amplified vs Seed Spectrum Comparison



Amplified spectrum is marginally narrower than seed spectrum.Tuning shifts and widens spectrum it, but requiring some further optical optimisation

Stretcher and Compressor Design

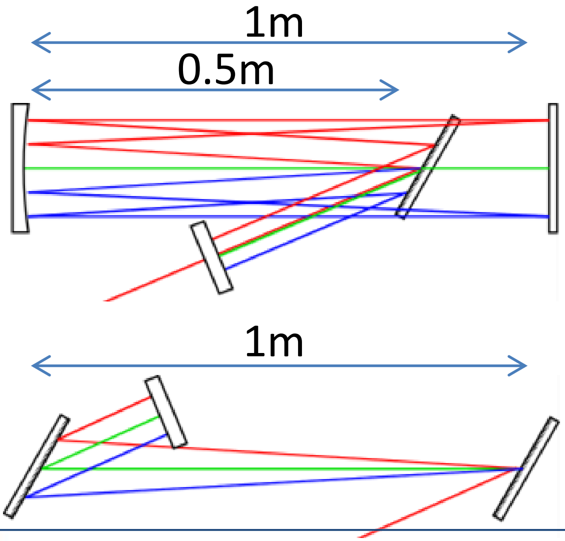
Peak power in amplified EOT pulse must not deplete pump (i.e. must have significantly lower peak power)
- Readily achieved via pulse stretching

Pulse	Properties	Peak Power
532nm Pump	10mJ, 10ns Gaussian temporal profile	1x10^6 W
800nm EO Transposition Signal	Amplified signal energy > 1 μJ, ~50 fs	20x10^6 W
As above but stretched GVD = 5.6x10^6 fs^2	> 1 μJ, ~310 ps	3.2x10^3 W

>Pump! Not possible

OK, will not distort

Conjugate Stretcher and Compressor designs perfectly cancel



GVD = 5.6x10^6 fs^2

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

Calculations show that the 0.3 ns rms timing jitter of the ~4.5 ns pump pulse duration has no significant effect on the amplification.

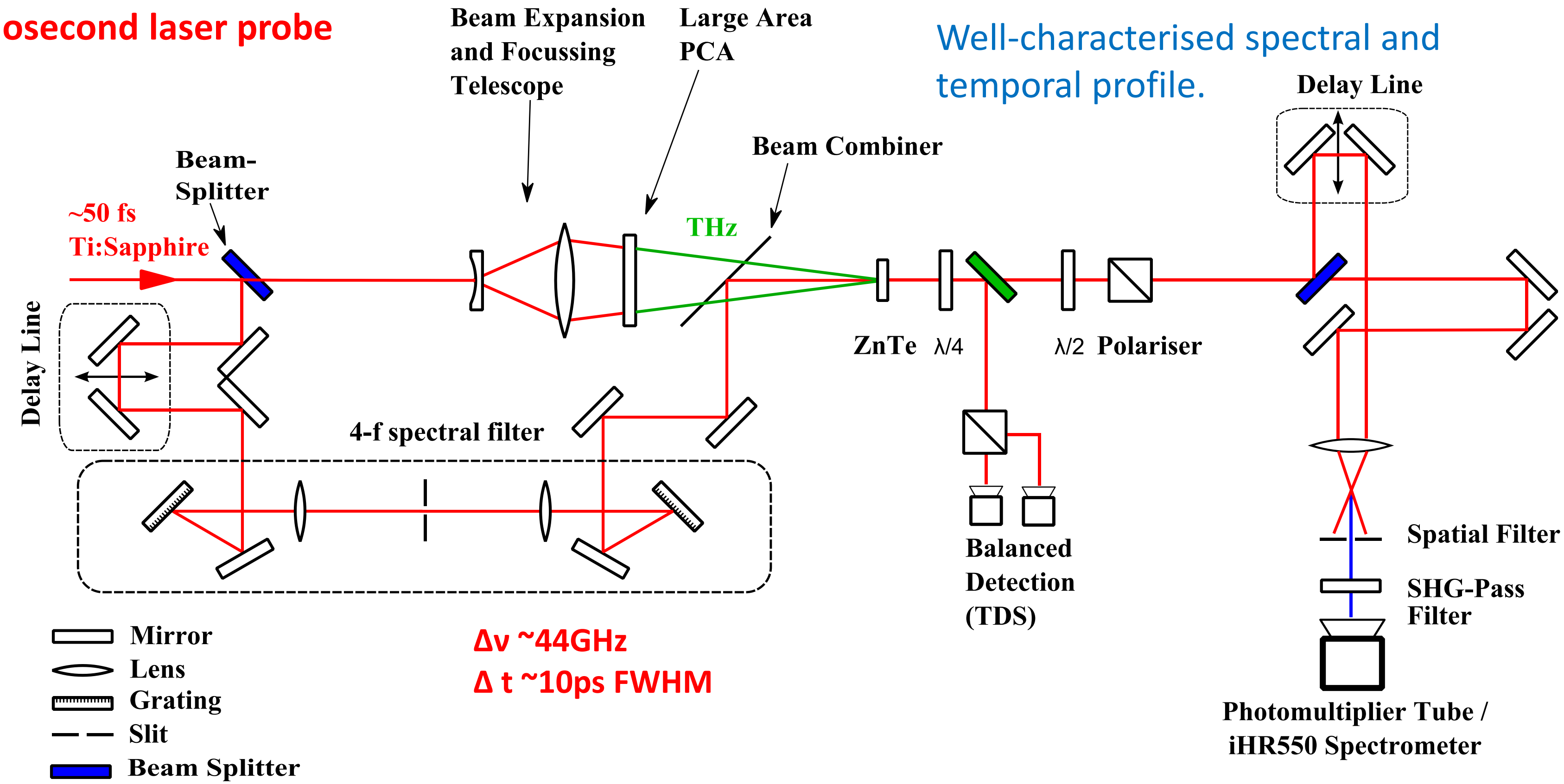
Demonstration and Characterisation of EO Transposition

Femtosecond laser-based test bed

Enabled progress despite lack of a nanosecond laser probe

Auston switch THz source mimics Coulomb field.

Well-characterised spectral and temporal profile.

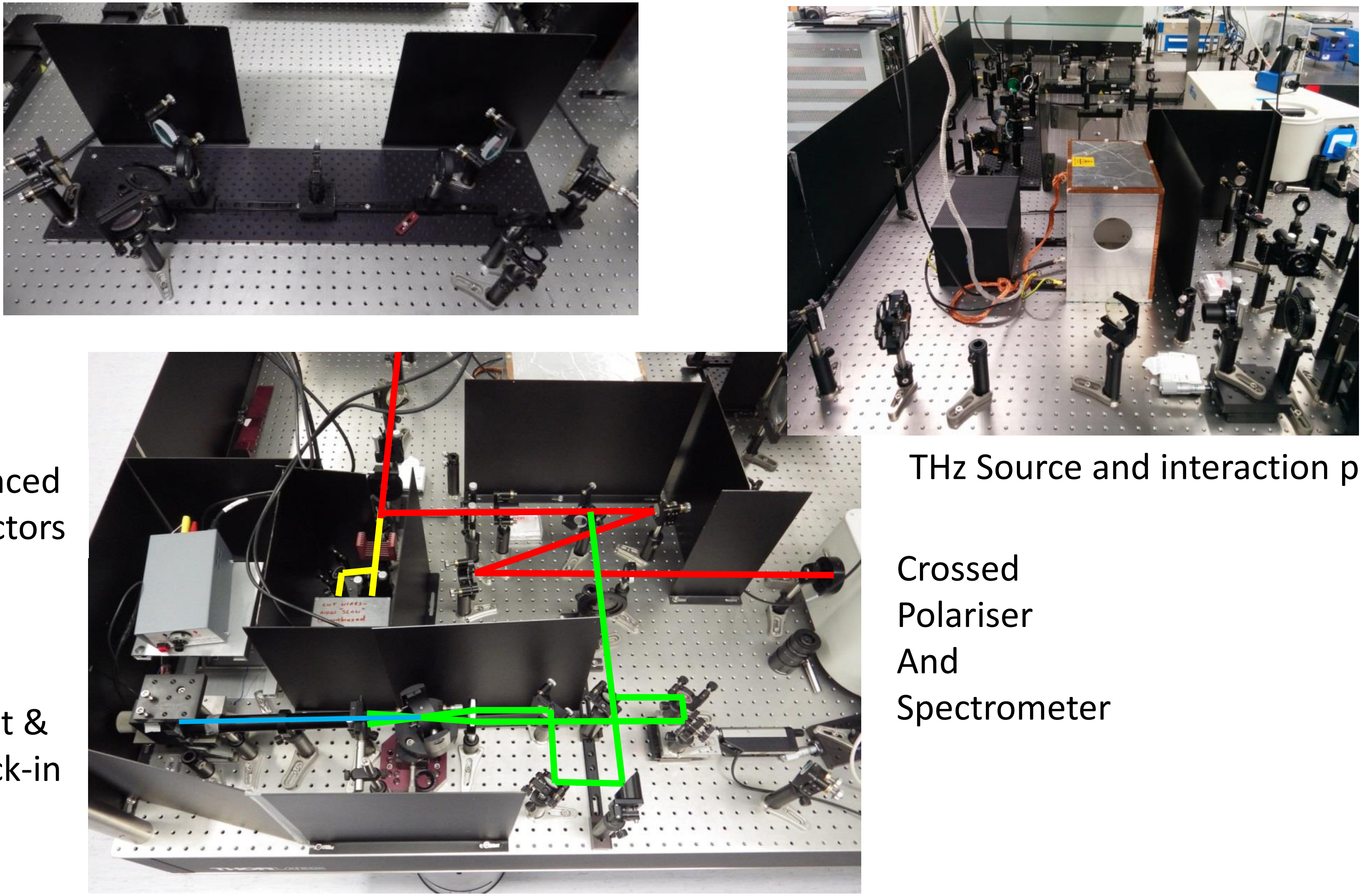


Δν ~44GHz
Δ t ~10ps FWHM

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

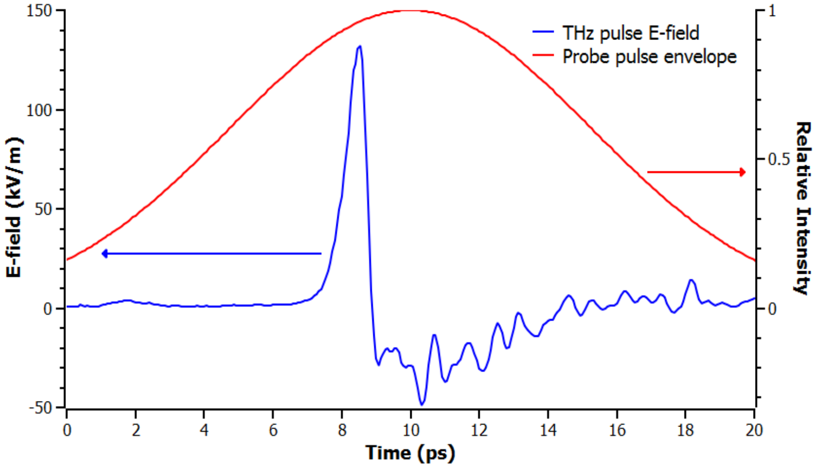
Autocorrelator

Measurement of Transposed Spectrum

Input pulse characteristics

(transform limited)

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

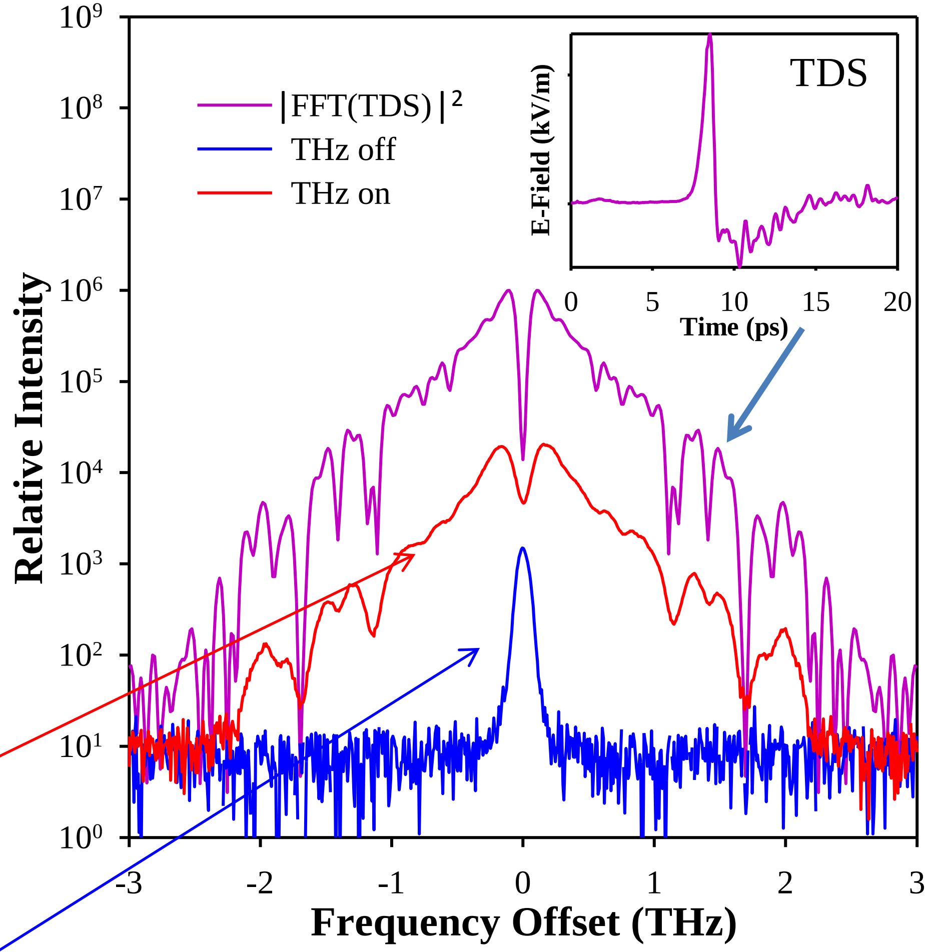


Total energy ~470pJ

Spectrum measured via iHR550

Leaking probe

Output characteristics (4mm ZnTe)



Up conversion of spectrum verified

Extrapolation to bunch parameters

Scaling factors

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

$\boldsymbol{l}$ is the EO crystal length, $\boldsymbol{r}$ 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 @1 cm

Property	**Factor of improvement**
$Power_{probe}$	x36
Δt	x0.7
l	÷100^2
r	÷2^2
$Efield$	x186^2
Overall	**x22**

Pulse energy of ~10nJ is predicted.

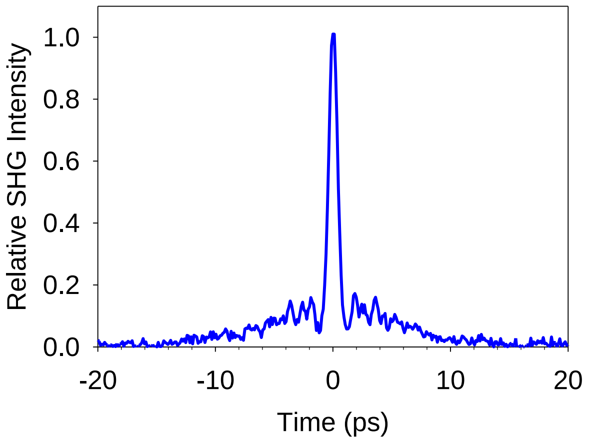
1µJ required for the commercial single-shot FROG, "Grenouille".

OPA design easily adequate.

Method can be used to estimate applicability to other beams

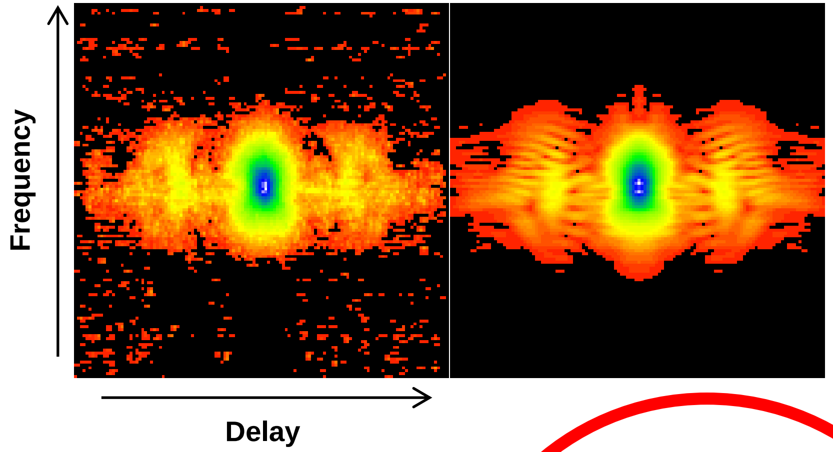
FROG Measurement
- Proof of EOT Principle

Autocorrelation of <0.5nJ EOT pulse!



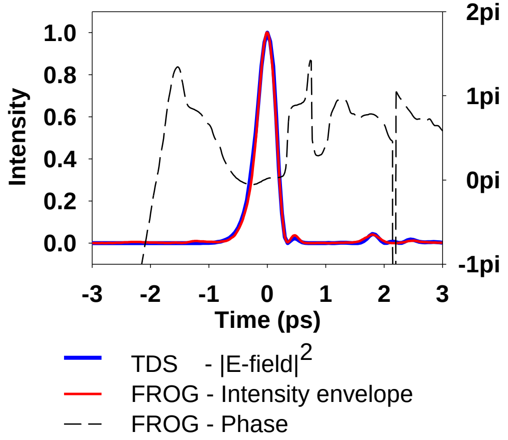
Experimental Spectrogram

Recovered Spectrogram

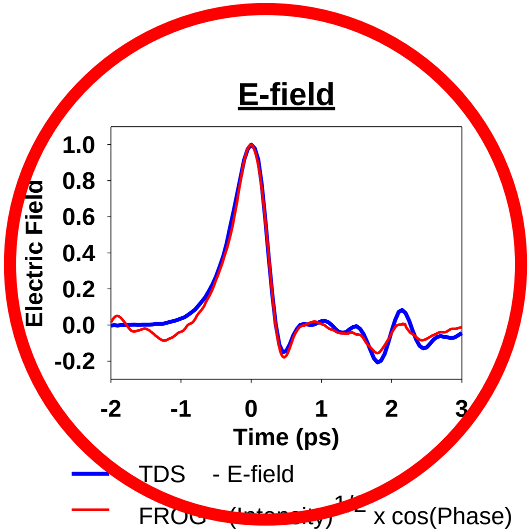


PCO dicam pro
ICCD camera
256x frame integration
30x software averaging

Intensity



E-field



0.55 ps pulse measured with a 10 ps, transform limited, probe!

App. Phys. Lett. 106(18), 181109 (2015)

1.2 EO Materials (or, how to reach 20 fs rms resolution)

Approaches, experimental testing and numerical examples

Temporal Resolution

EO transposition scheme is now limited by materials:

- Phase matching and absorption bands in ZnTe/GaP distort spectrum.
- 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.

A key property of the EO Transposition scheme may be exploited

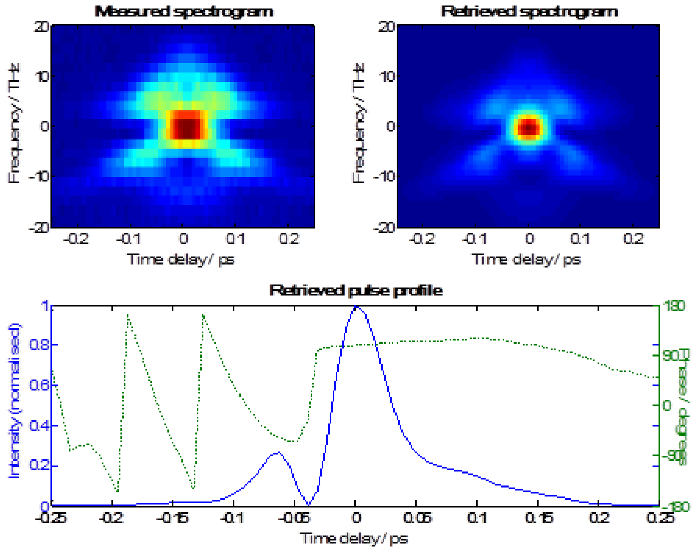
- FROG (Grenouille) retrieves the spectral amplitude and phase
- At frequencies away from absorptions etc. the spectrum should still be faithfully retrieved
- Potential to run two, "tried and tested", crystals with complementary response functions side by side and recompose the FULL spectral information!

Novel Electro-optic material

- Metal-Glass Nanocomposite material suppled by MAPS group, University of Dundee
- Microscopic metal spheres embedded in glass and laser processed to distort shapes – generates polarisation sensitivity
- Exhibits Chi(2) nonlinear response from symmetry break as sphere density changes
- Field enhancement due to surface plasmon resonances lowers thresholds, but <u>efficiency still low</u>

Joint Daresbury-Dundee experiments

- Successful demonstration of an SHG FROG measurement using MGNs
- no observable signal for THz interaction; resonant enhancement insufficient with THz=optical combination



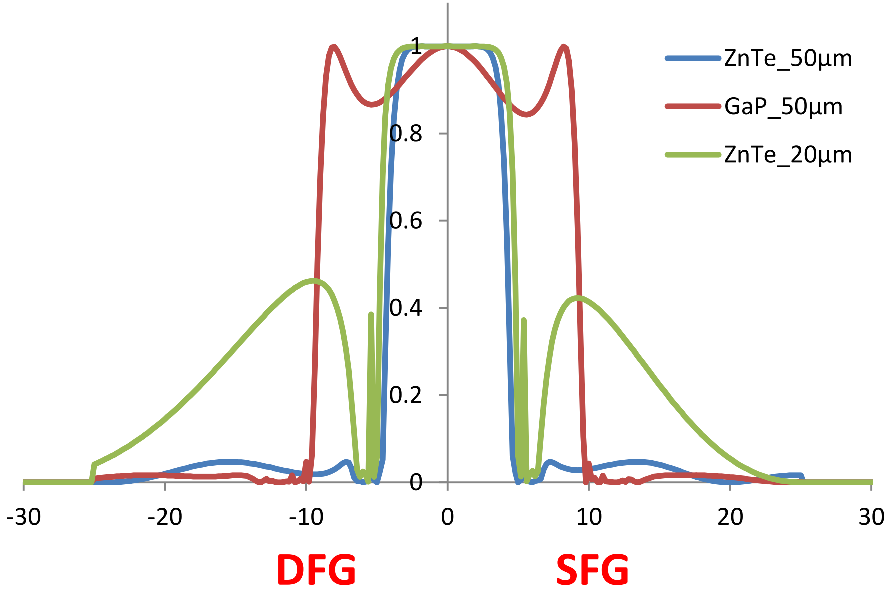
Multi Crystal Approach

Methodology

1. Capture data using complementary crystals – ZnTe and GaP
2. Align and Normalise amplitude and relative phase where data overlaps
3. Patch GaP captured spectrum with ZnTe data

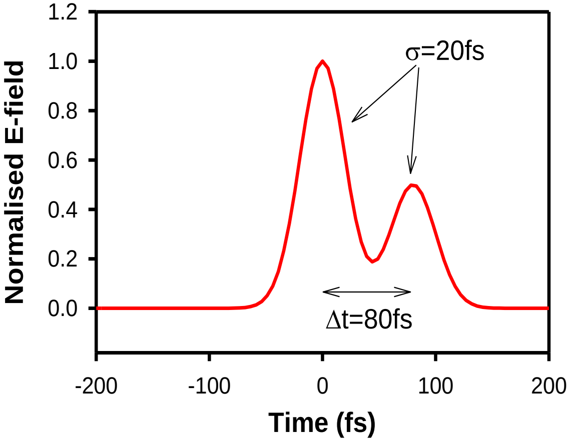
Initial numerical simulations very promising!

Phasematching response comparison

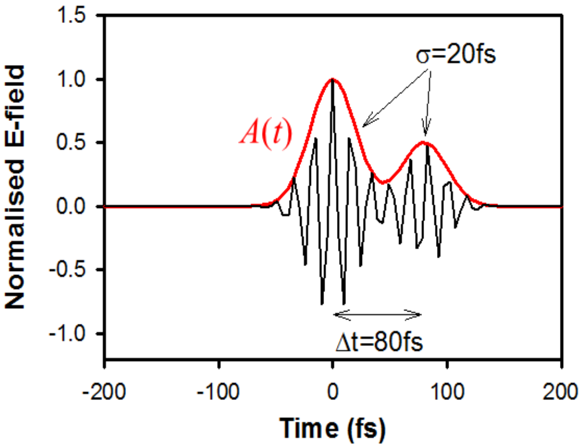


ZnTe and GaP "chips" procured for testing

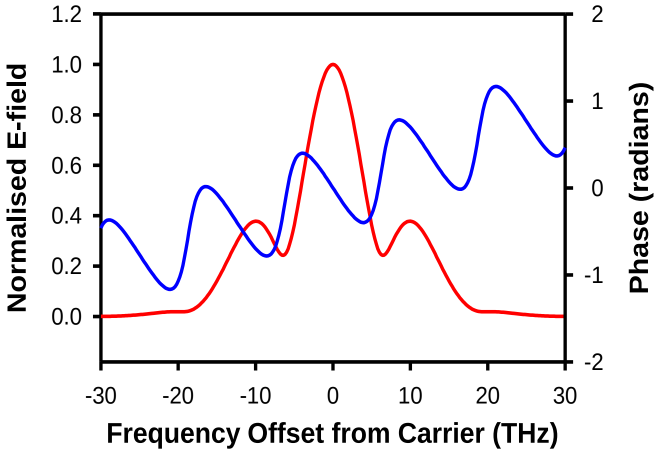
A Numerical Example



Starting with a Coulomb field consisting of two Gaussians



Mixing with an optical field to generate the “EOT pulse” (no phasematching considered here)

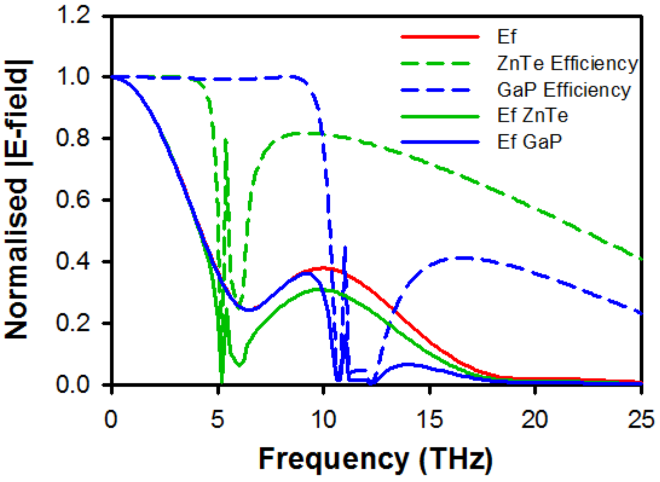


Fourier transformed to show spectral amplitude and phase

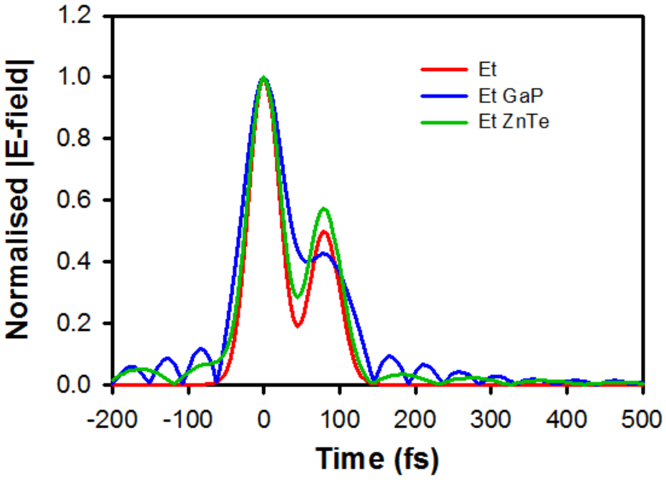
- Absolute phase not relevant - phase at 0THz set to be 0
- Linear slope component indicates offset of pulse in time window

A Numerical Example

- Will now consider the phasematching efficiency
- Non-physical as absorption and dispersion affect efficiency and phase, but also in a calculable way



Phasematching Efficiency for 10 micron thicknesses

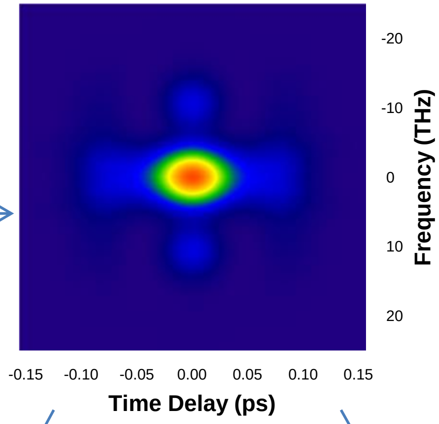


Effect on temporal profiles after application of efficiency in frequency domain

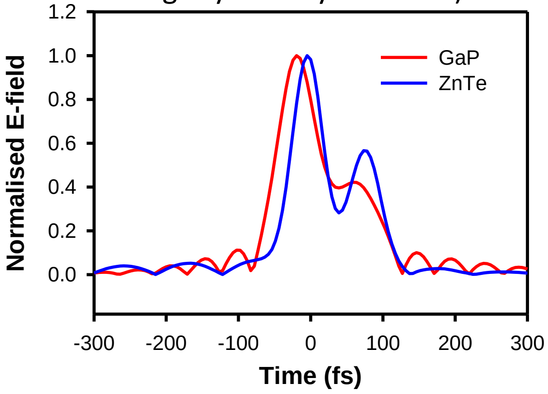
FROG Retrieval

FROG traces computed using numerically transposed pulses, with a 0.1% intensity noise added

FROG trace for pulse
Transposed in ZnTe, GaP not shown

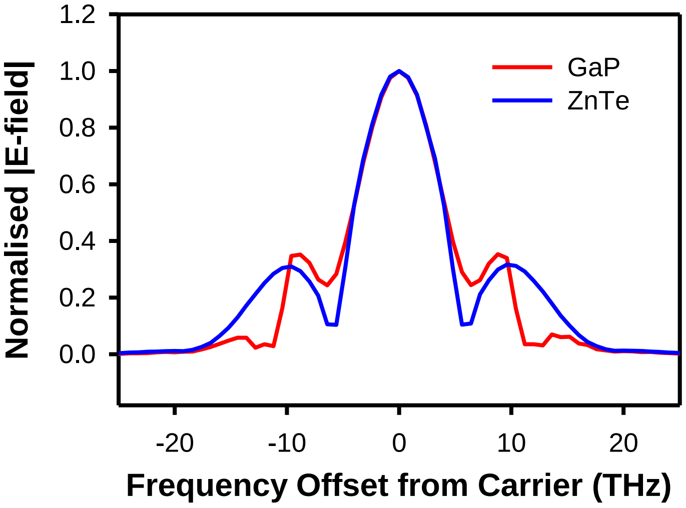


Retrieved temporal traces
(temporal offset due to absolute time ambiguity – easily removed)

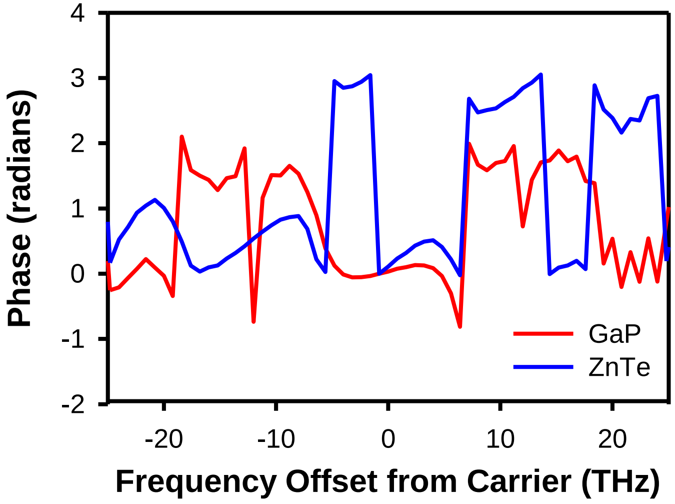


Good similarity to EOT pulse inputs

Retrieved Spectral Amplitude
(central 0 – 4 THz spectral amplitudes normalised)



Retrieved Spectral Phase
(phase has been set to zero at 0 THz for both)



Result

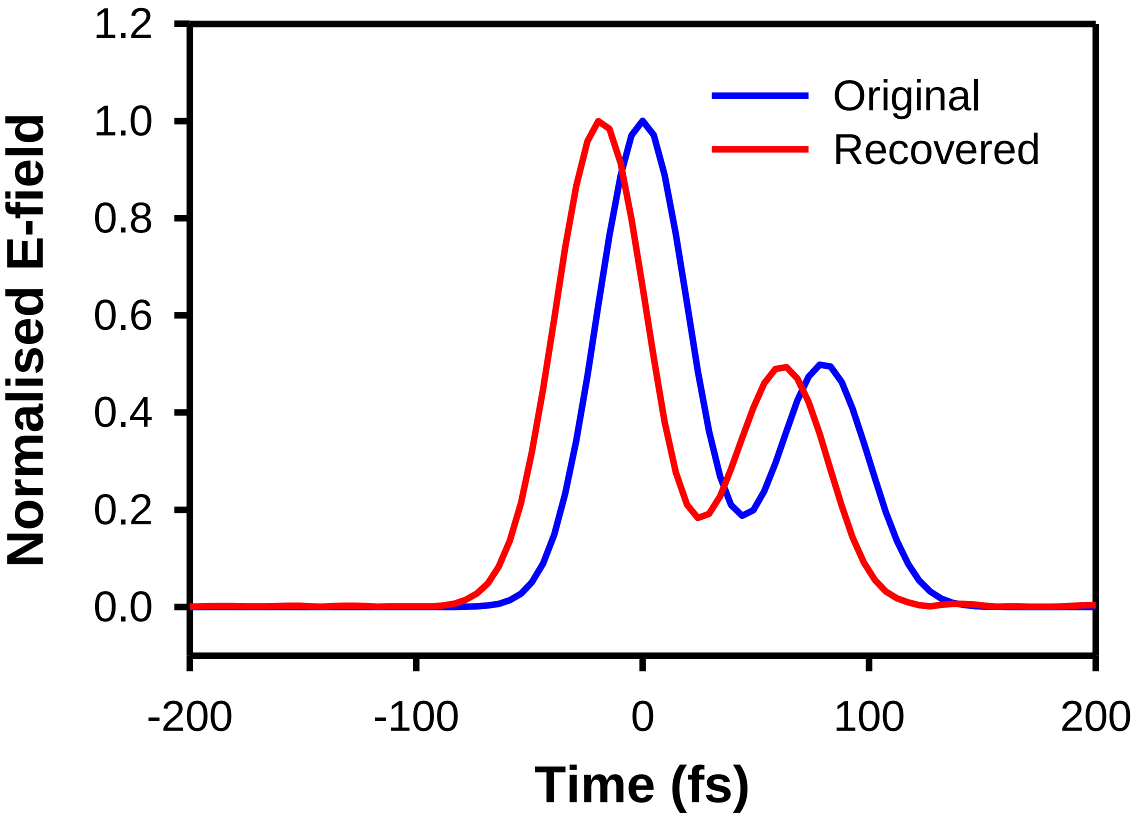
Profiles match excellently

Temporal offset an ambiguity but an **unimportant** one

Need to investigate effects of higher levels of noise in FROG trace

Need to develop a robust, automatic, spectrum patching algorithm

Requires a second amplifier and GRENOUILLE pair



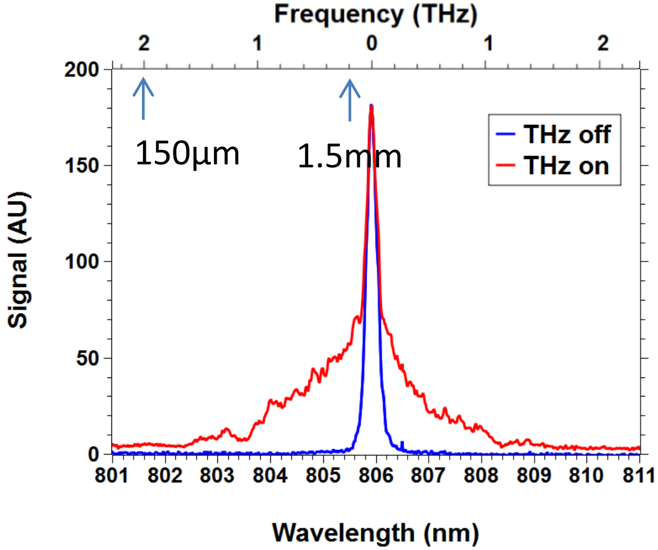
<u>Work so far written up in updated report for 1.1</u>

additional outcomes & system understanding

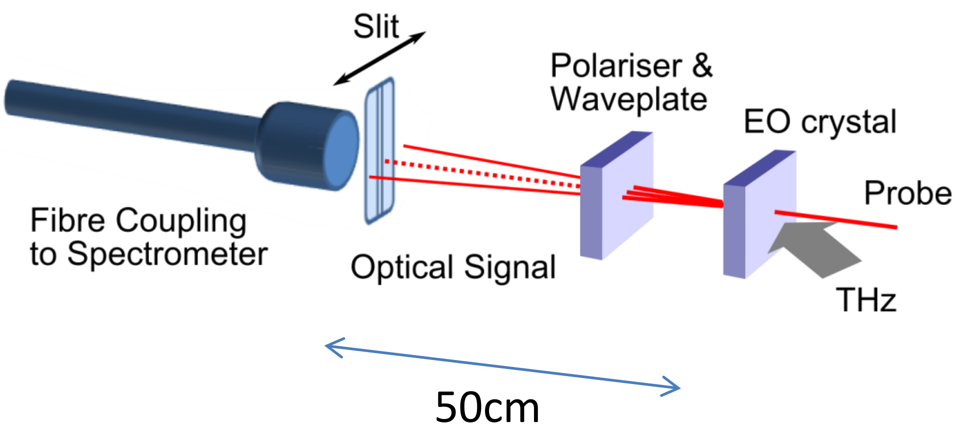
EO system design considerations, new FROG method for THz/Coulomb field measurements

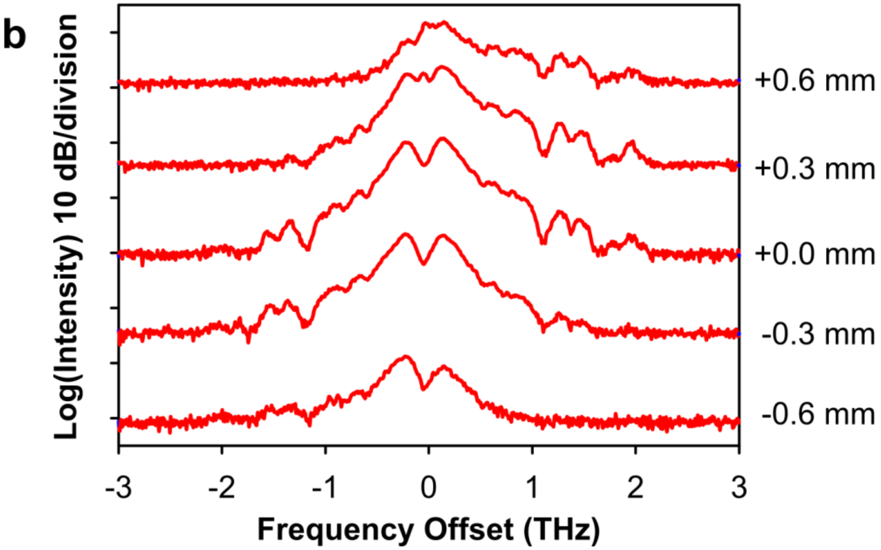
Alignment Issues

Early measurements of up conversion spectra often asymmetric and weak/unobservable



Adjustment of the THz/optical alignment could modify the observed spectral sidebands!

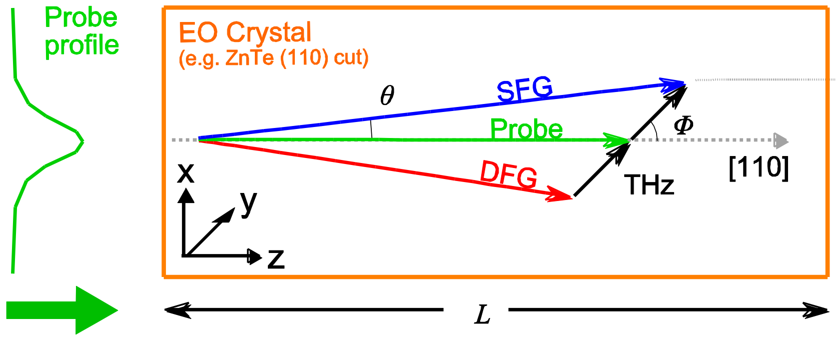


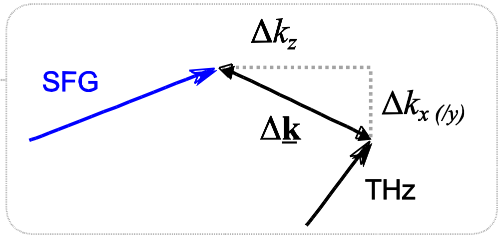


Understanding this effect is crucial to correctly performing any EO measurement!

Non-collinear Phase Matching

A natural consequence of considering nonlinear processes is that phase matching must be considered!





Phase mismatch

Polarisation field set up by probe and THz (Coulomb) field:

$$\tilde{P}(\omega_3,\underline{\mathbf{r}}) = \chi^{(2)}\tilde{E}^{\mathrm{opt}}(\omega_1,\underline{\mathbf{r}})\tilde{E}^{\mathrm{THz}}(\omega_2,\underline{\mathbf{r}})$$

Expand fields into envelope and carrier:

$$\tilde{P}(\omega_3,\underline{\mathbf{r}}) = \chi^{(2)}\tilde{A}_1(\omega_1,\underline{\mathbf{r}})\tilde{A}_2(\omega_2,\underline{\mathbf{r}})\exp\left(i(\underline{\mathbf{k}}_1+\underline{\mathbf{k}}_2)\cdot\underline{\mathbf{r}}\right)$$

Then solve paraxial wave equation using Gaussian transverse profiles:

$$Eff(\omega_3,\theta,\varphi) = \exp\left(-\frac{1}{2}\left(\sigma_{\mathrm{x}}^2\Delta k_{\mathrm{x}}^2+\sigma_{\mathrm{y}}^2\Delta k_{\mathrm{y}}^2\right)\right)\frac{\exp(i\Delta k_z L)-1}{\Delta k_z L}$$

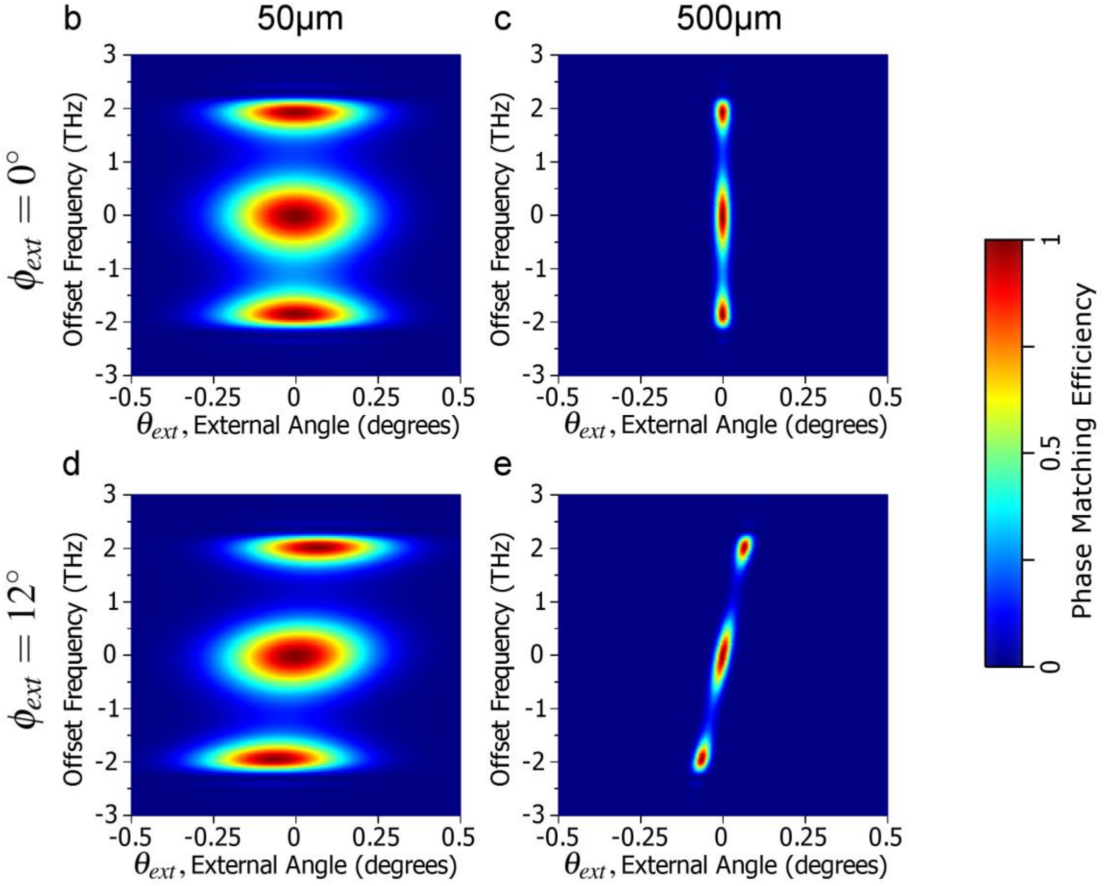
Same form as derived in NLO literature

Predictions and Validation

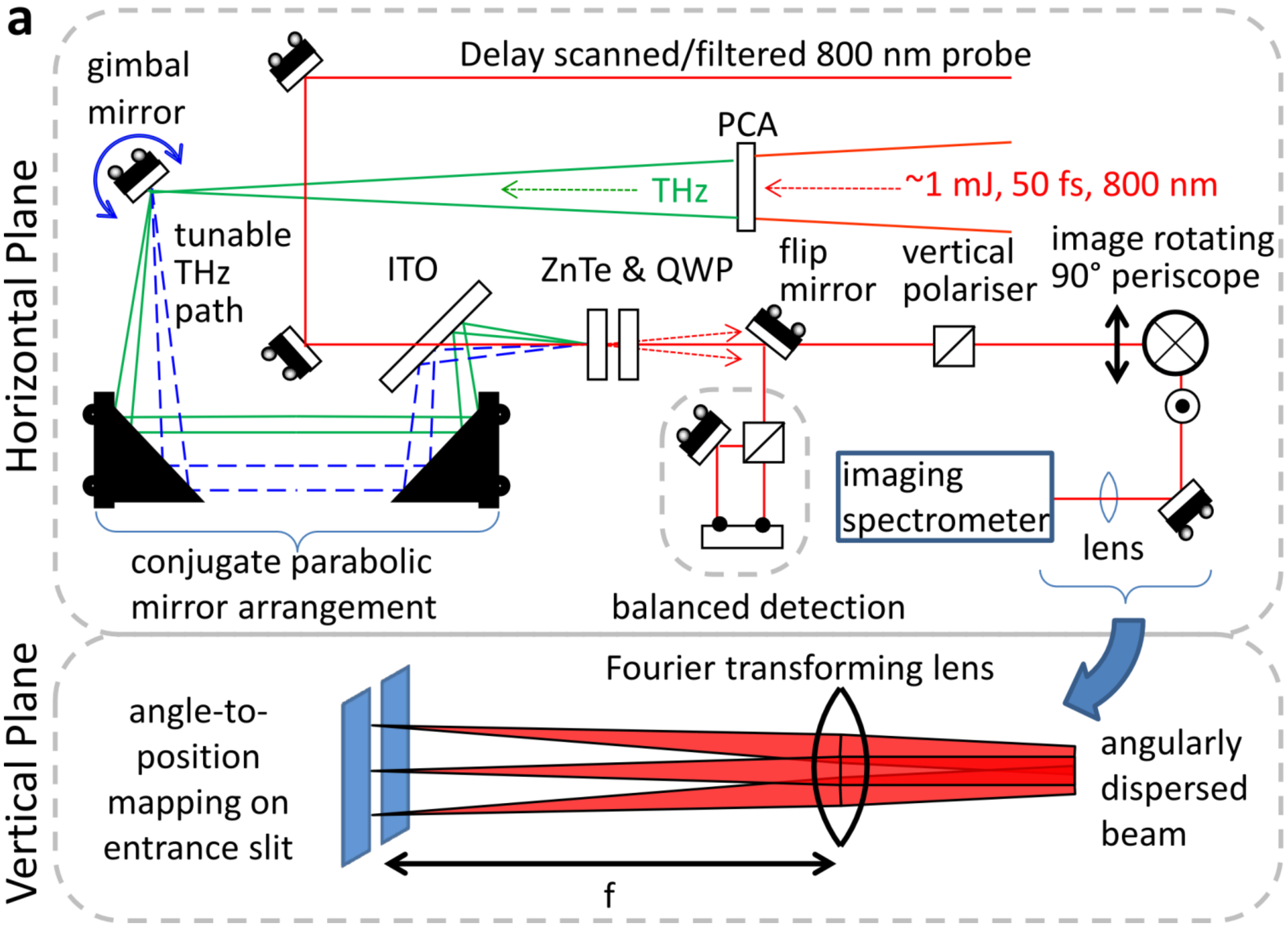
Phase matching efficiencies calculated in Matlab

Code iterates through THz frequencies and calculates the efficiency for a range of upconversion directions

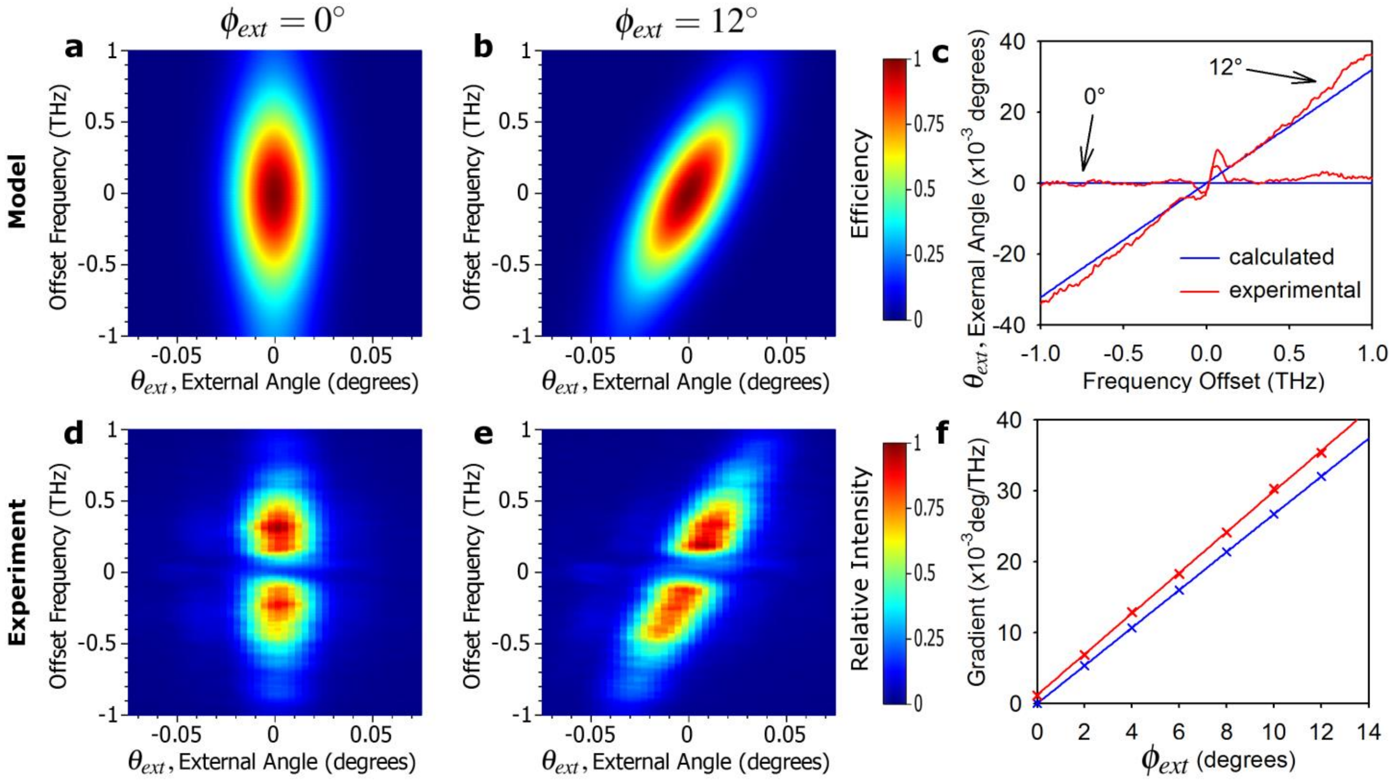
$$\exp\left(-\frac{1}{2}\left(\sigma_x^2\Delta k_x^2+\sigma_y^2\Delta k_y^2\right)\right)\frac{\exp(i\Delta k_z L)-1}{\Delta k_z L}$$



Experimental System



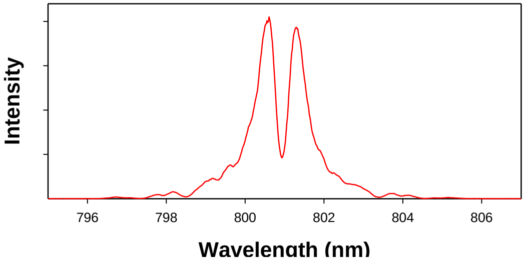
Results

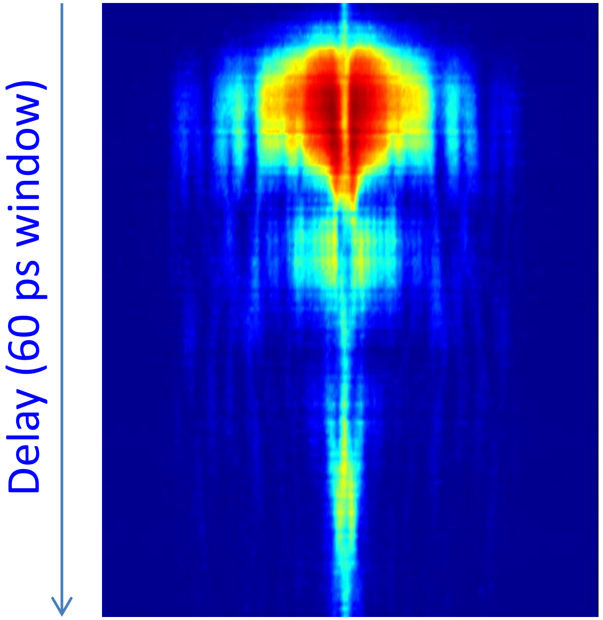


- Confirmed predictions of model.
- Enabled us to produce rule-of-thumb guides.

Direct THz-optical FROG

Resolving carrier-envelope ambiguity in FROG

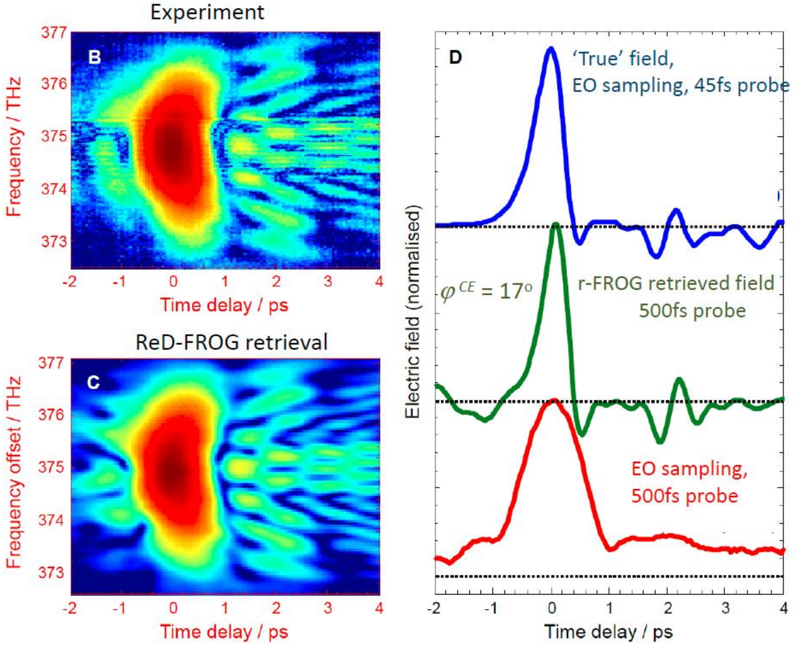




This looks like a spectrogram!

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 published.
Opt. Express 23(7), 8507–8518 (2015)

Future work

Replacement of system 'weak-link' in dye-laser for optical probe

- Build/development of solid-state Optical Parametric oscillator solution for probe; *outline design and hardware already in-hand*
- bypass commercial provider limitations

Completion March 2018:

- ***0.25 FT contribution from CERN requested***
- 0.25 FT contribution from ASTeC
  (Technician, engineering design, D Walsh)
- 10k consumables/equip contributed from ASTeC

Full system demonstration on short-bunch accelerator

- Demonstration and optimisation on CLARA in 2018
- <100fs duration bunches, at 50MeV

Schedule for 2018 operation

- ***0.25 FT contribution from CERN requested***
- 0.25 FT contribution from ASTeC
  (Technician, acclerator operation, D Walsh)
- 10k dedicated beamline equip contributed from ASTeC

Leading to

System design ready for implementation on other facilities:

- Wider CLEAR (Califes) programme and diagnostic development
- Direct wakefield measurement
- Bunch characterisation supporting wakefield experiments

Commercial OPO Systems

- Nanosecond solid *state* OPOs available for applications in
  - Laser induced fluorescence
  - Flash photolysis
  - Photobiology
  - Remote sensing
  - Time-resolved spectroscopy
  - Non-linear spectroscopy

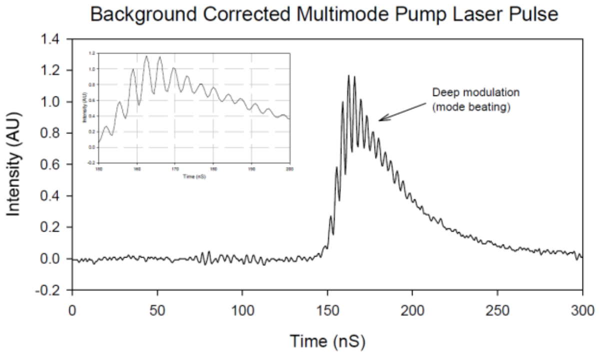
- Typically ~10cm^{-1}, "narrow" versions are ~5 cm^{-1}, thus multiple longitudinal modes

Gain has a bandwidth which encompasses many standing wave frequencies.

If 2 or more "lase" then modulation at the beat frequency is seen as sub-nanosecond, full amplitude, modulations.

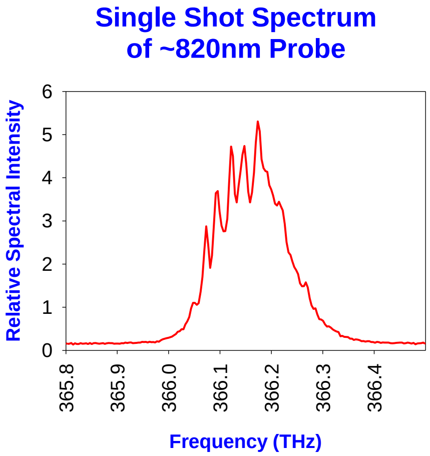
In a pulsed system the output builds from noise photons, so shot to shot different frequency components build up – beating is random and can mean no probe coincident with ultrashort Coulomb field

Example from 1064nm Nd:YAG laser with an intracavity etalon



Commercial OPO Systems

- Vendors offered bespoke systems but inadequate bandwidth narrowing


Single Shot Spectrum of ~820nm Probe

Acceptance testing of a vendor's line narrowed solution: ~30GHz beating existed (~30ps modulation)

Require <10GHz bandwidth and stable temporal intensity

Commercial Dye Lasers – project mitigation

Technology is much more developed in terms of linewidth.

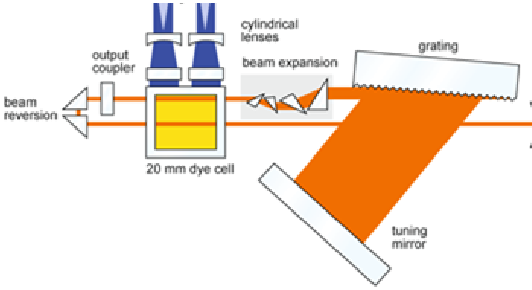
Downsides

Dye has limited lifespan and needs regular replacement

Spatial mode is poor (striated)

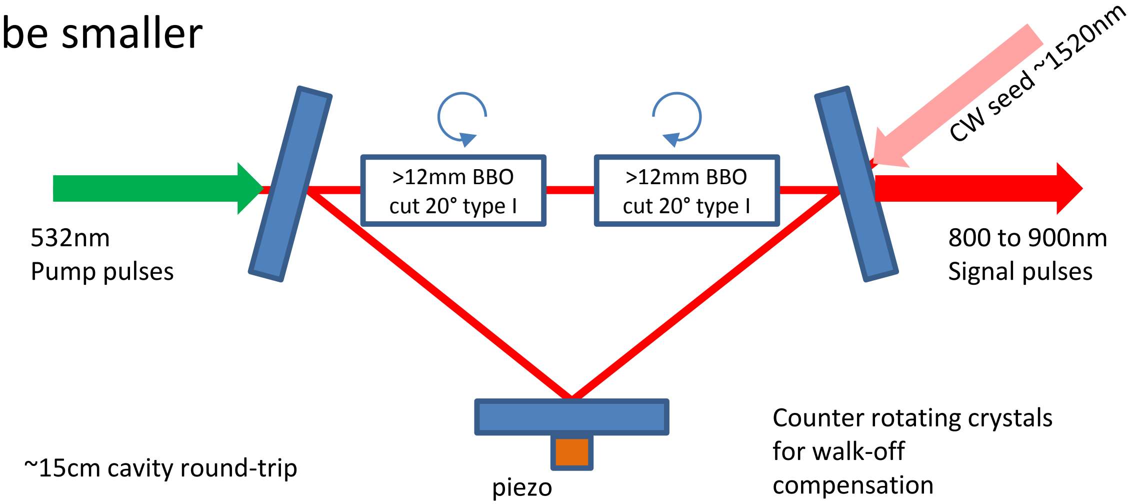
Not appropriate for accelerator environment

Sirah Cobra laser system currently being used



Bespoke OPO Design

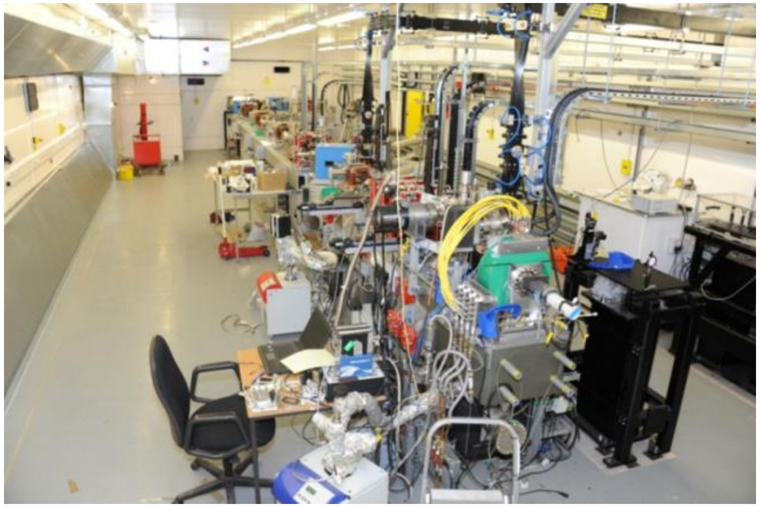
- All solid state construction allows greater reliability and much less maintenance
  - No dye to change
  - No pump to fail
- Can implement injection seeding to narrow linewidth – ensuring ALWAYS single longitudinal mode.
- Beam quality is excellent – divergence of output beam can be better than pump or seed when idler seeded.
- Can tune over greater range without the need to change dyes
- Potential to be smaller



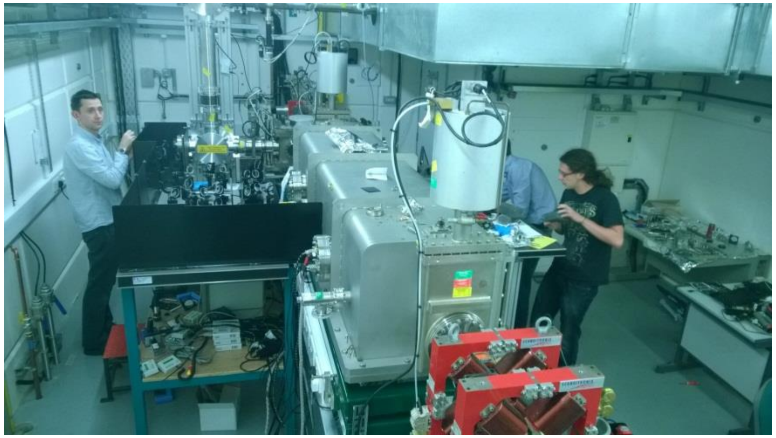
Facilities at Daresbury

From demonstration of source to demonstration of particle acceleration

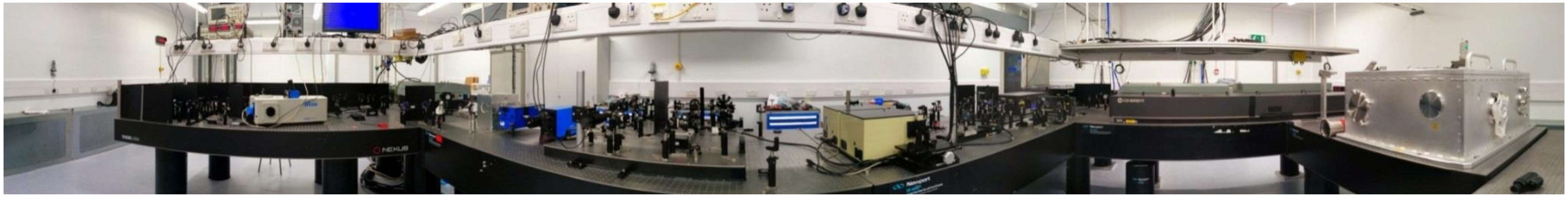
5MeV VELA injector & 50 MeV CLARA



Experimental station



laser lab, multiple lasers coupled to VELA & CLARA user station



Summary

- Core principle proven to work
  - Successful retrieval of an E-field profile via FROG analysis of an EOT pulse
- Lasers, amplifier and stretcher/compressor pair characterised and exceed requirements
- 20fs resolution in sight
  - Multi-Crystal approach passed in simulation; demonstration near (constrained by THz source availability)
- Ideally will complete an (accelerator based if possible) end to end test
- Project Deliverables
  - 1.1 System design complete and reported
  - 1.2 and 1.3 delayed, but on track for March 2017
- Proposing continue to accelerator test, and implementing all-solid state robust solution