High time resolution & robust longitudinal diagnostics for CLIC

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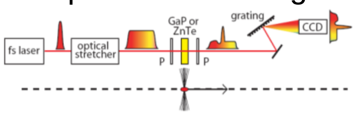
- Electro-optic Transposition (with $\chi^{(2)}$ interaction)
    - Concept & motivation
    - Experimental conformation of sub systems
- An alignment & tolerance effect in EO systems
- EO-Transposition demonstration & benchmarking @ FLASH
- TFISH - THz Field Induced Second Harmonic generation
    - $\chi^{(3)}$ analogue to EO detection
    - Surface effect on Au   - no phase matching but weak!

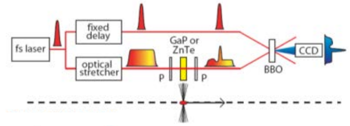
Electro-optic longitudinal diagnostics for CLIC

Existing systems

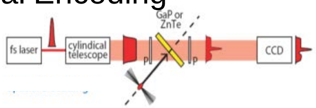
Spectral Decoding



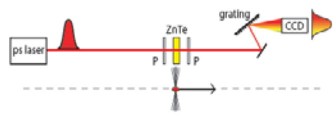
Temporal Decoding



Spatial Encoding



Spectral upconversion**



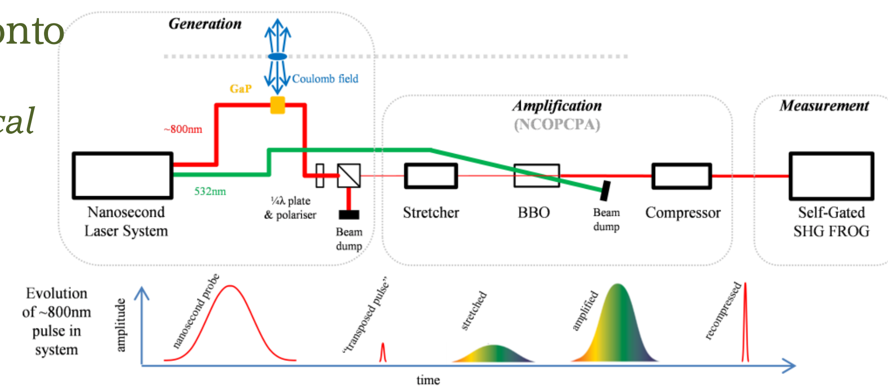
- Optical capability limited to >50fs
- Nonlinear/material limited to >60fs
- “Experimental” in implementation

EO Optical Transposition

femtosecond diagnostics without a fs laser

- Target of ~20 fs rms resolution
- Non-destructive
- Instrumentation capability

- Temporal structure of Coulomb field imposed onto ‘industrial’ nanosecond laser probe
  spectral structure of Coulomb field upshifted to optical
- All optical amplification of signal
- “FROG” for self-referenced <10fs rms optical characterisation
- Material developments



Electro-optic longitudinal diagnostics for CLIC

Coulomb spectrum shifted to optical region

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

Coulomb pulse replicated in optical pulse

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

Monochromatic probe

$$\tilde{E}^{\rm opt}(\omega) \to \tilde{E}_0\delta(\omega = \omega_0)$$

$$\tilde{E}^{\rm opt}(\omega) = \tilde{E}_0\tilde{E}^{\rm Coul}(\omega-\omega_0)\tilde{R}(\omega-\omega_0) + \tilde{E}_0\delta(\omega_0)$$

$$E^{\rm opt}(t) \sim \left\{E^{\rm Coul}(t) * R(t)\right\}\cos(\omega_0 t) + \sin(\omega_0 t)$$

Measure spectrum of optical sidebands

$$\left|\tilde{E}^{\rm THz}(\omega)\right|^2$$

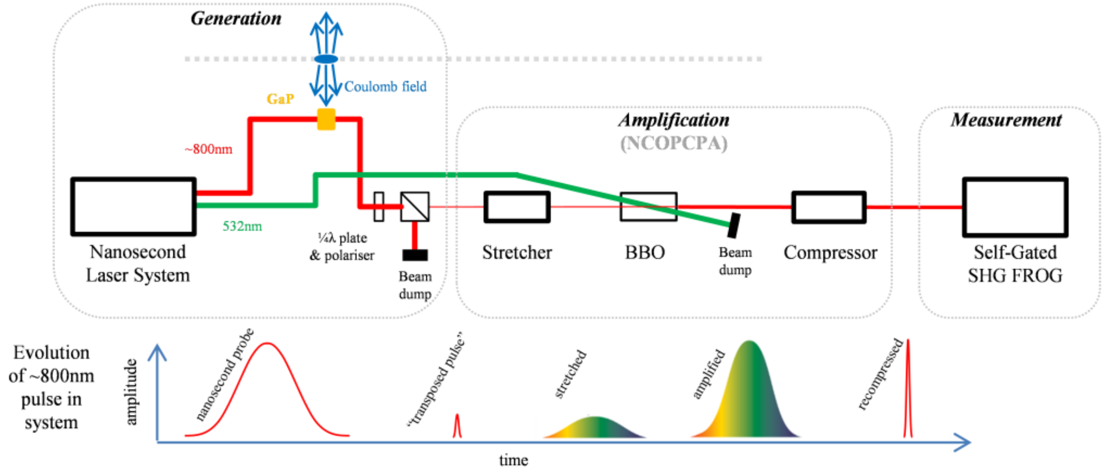
- Positive and negative sidebands must be same $\tilde{E}^{\rm THz}(-\omega) = \tilde{E}^{\rm THz\,*}(\omega)$ (some small changes in material response)
- Provides option for intermediate diagnostic (feedback ?)
- test of optics for temporal system & response function

Measure optical pulse envelope in time

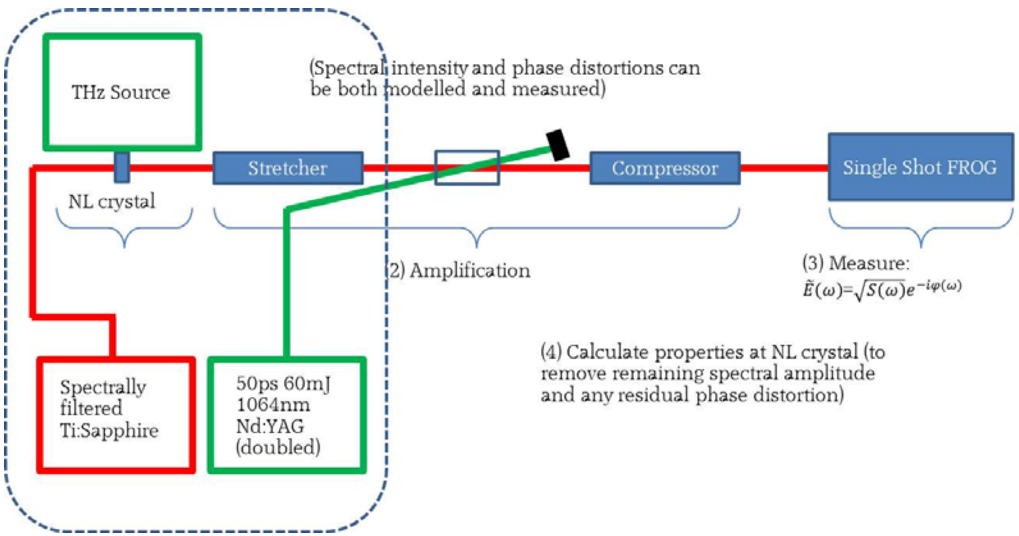
$$\left\{\, E^{\rm Coul}(t) * R(t)\,\right\}^2$$

- FROG diagnostic allows field envelope retrieval $E^{\rm Coul}(t) * R(t)$
- Phase of Coulomb converted to envelope of optical
  bypass FROG carrier-envelope ambiguity

Final system : single laser delivering ~10ns probe and ~10ns OPA pump

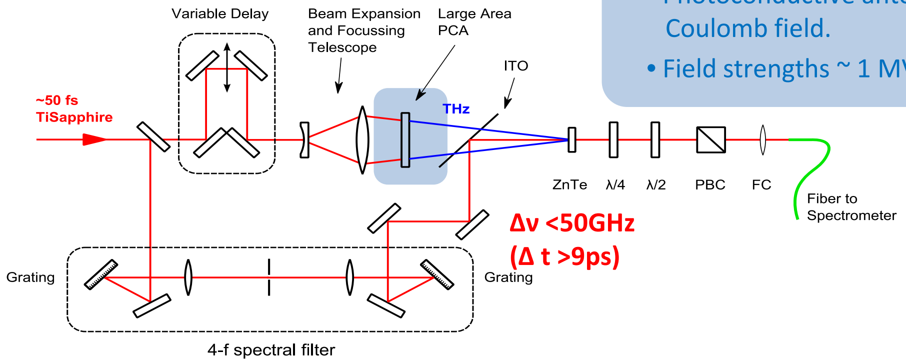


For testing and specification development



- Ti:S excited THz source
- spectrally filtered TiS for probe,
- synchronized 50ps YAG for OPA pump

Laser-lab test-bed



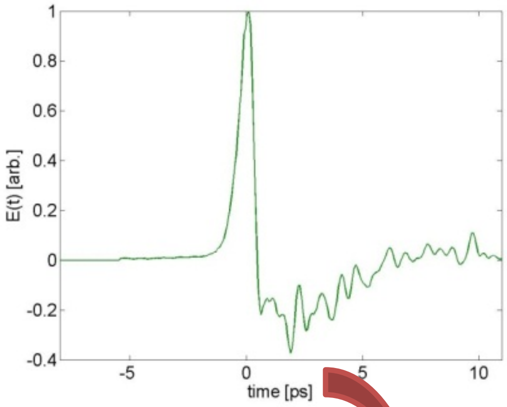
- Photoconductive antenna THz source mimics Coulomb field.
- Field strengths ~ 1 MV/m.

Followed to by NC-CPOPA & FROG

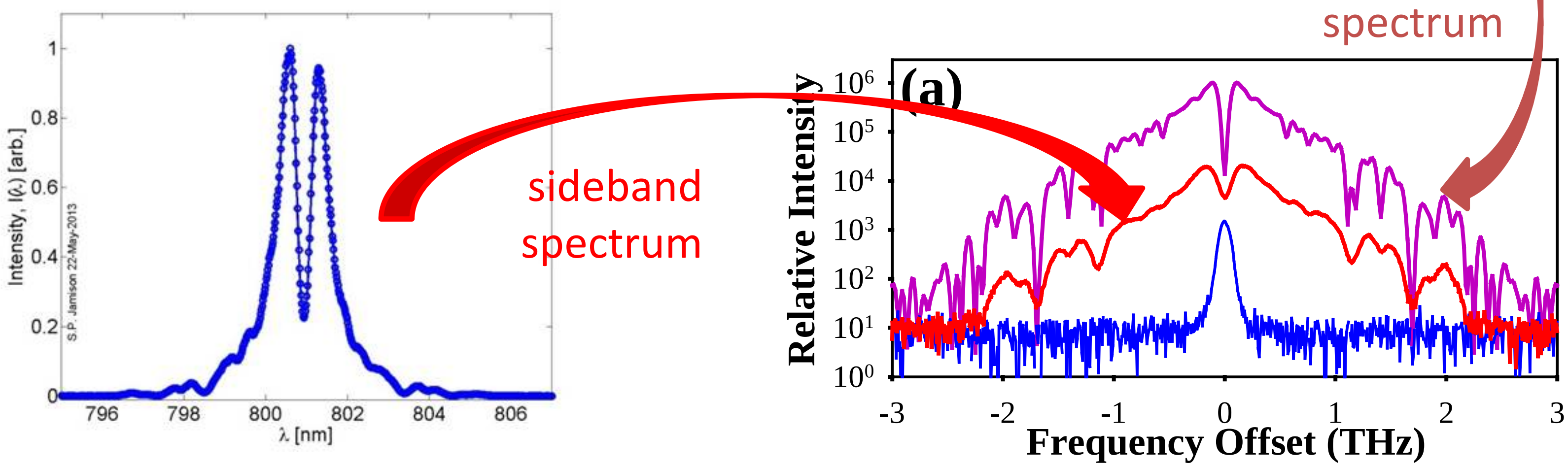
Δν <50GHz (Δ t >9ps)

Femtosecond laser pulse spectrally filtered to produce narrow bandwidth probe

THz pulse as bunch mimic
- Measured by scanning EO sampling (THz-TDS)



Measured optical sidebands



Signal levels, measurability & scaling

Scaling factors

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

$\boldsymbol{l}$ is the EO crystal length, $\boldsymbol{r}$ is the nonlinear coefficient

Example:

"Typical" nanosecond pulse laser as probe

- Pulse energy 1mJ
- Pulse duration 10ns

$Power_{probe} \sim$ 100kW

Coulomb field for target CLIC bunch parameters (CDR)

- Bunch length 44µm
- Bunch charge 0.6pC

$Efield \sim \frac{2Q}{4\pi\varepsilon_0 R l_b} =$ 24.5MV/m

Property	Factor of improvement Darsbury -> CLIC
$Power_{probe}$	x36
l	$\div 100^2$
r	$\div 2^2$
$Efield$	$\times 186^2$
Overall	**x31**

Pulse energy of ~15nJ is produced

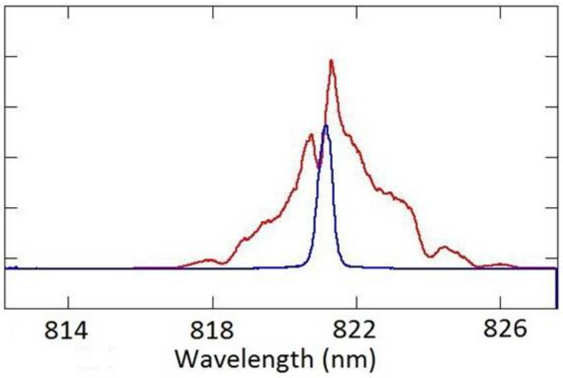
1µJ required for single-shot FROG

pulse needs amplifying ~100x

An achievable goal!

Alignment sensitivity & asymmetry in sidebands

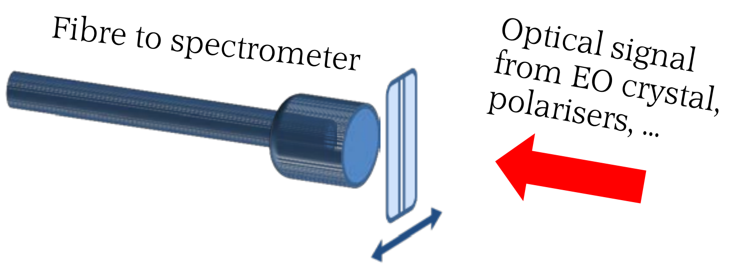
Expect sidebands to be symmetric,
but often not….

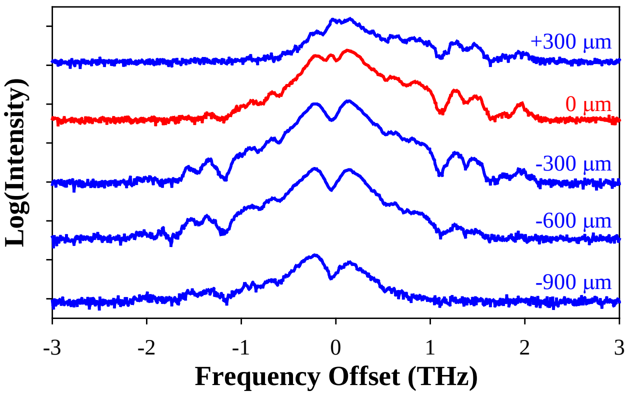


Angular separation of sidebands

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

Aperture on coupling into fibre



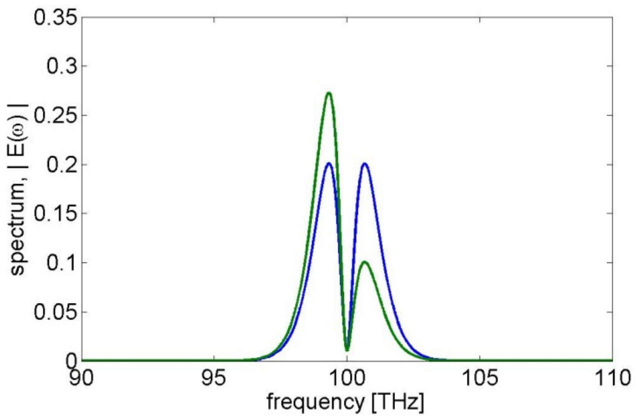


- explanation of signal stability / reliability in many previous EO implementations ??
- Mechanism now understood; mitigations through optical design

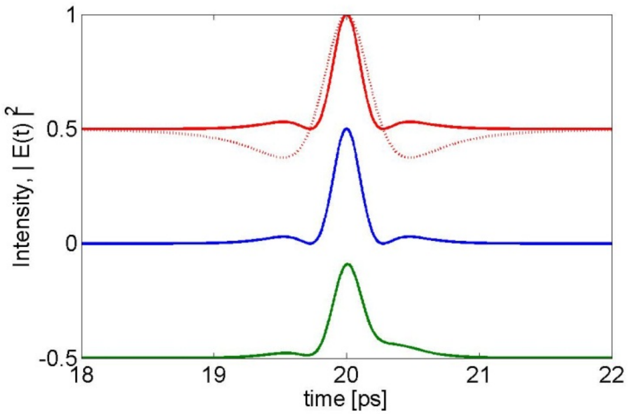
Sideband asymmetry in the time domain

Symmetry intrinsic to temporal envelope interpretation

applies to all EO systems, not just narrowband probes



- Symmetric sidebands spectrum from THz modulation
- Modified spectrum ; phase and amplitude for causality

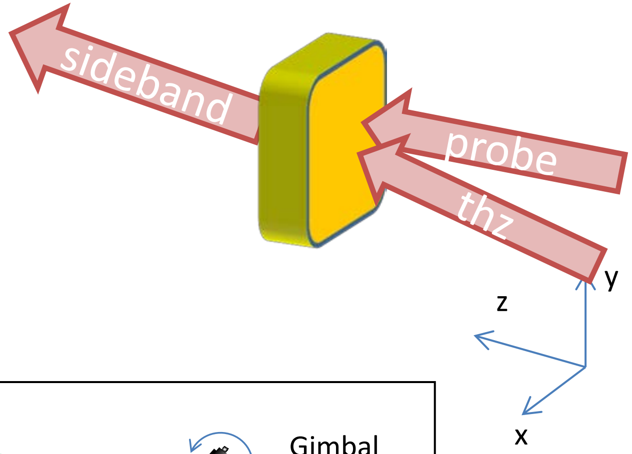


- Time profile (squared) of modulation
- Symmetric sidebands spectrum from THz modulation
- Modified spectrum ; phase and amplitude for causality

Sideband asymmetry – phase matching with misalignments

For non-collinear THz and probe,
positive and negative sidebands diverge

$$\eta_{Intensity} \propto \underbrace{\exp\left(-\frac{1}{2}w^2\left(\Delta k_x{}^2+\Delta k_y{}^2\right)\right)}_{\text{Dominant term for angle}} \mathrm{sinc}^2\left(\frac{\Delta k_z L}{2}\right)$$

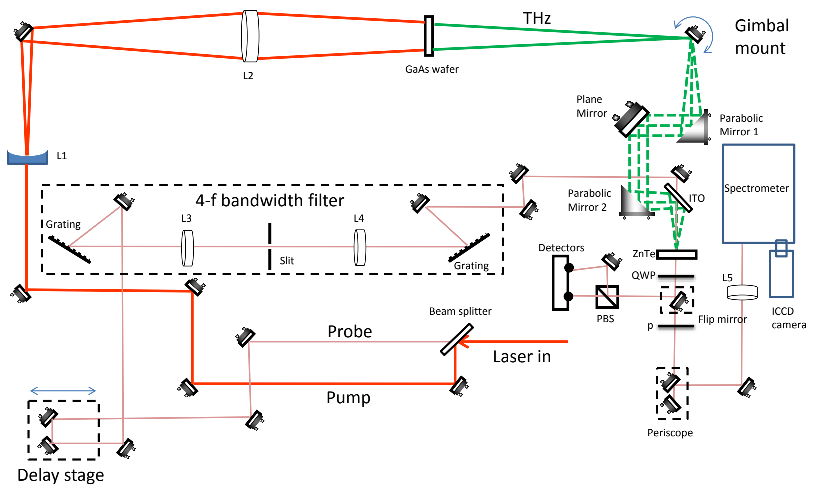


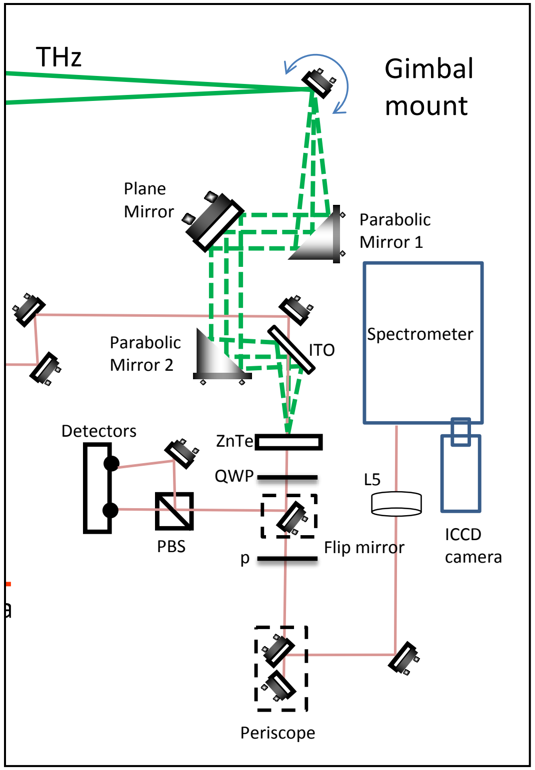
Angles involved are small but

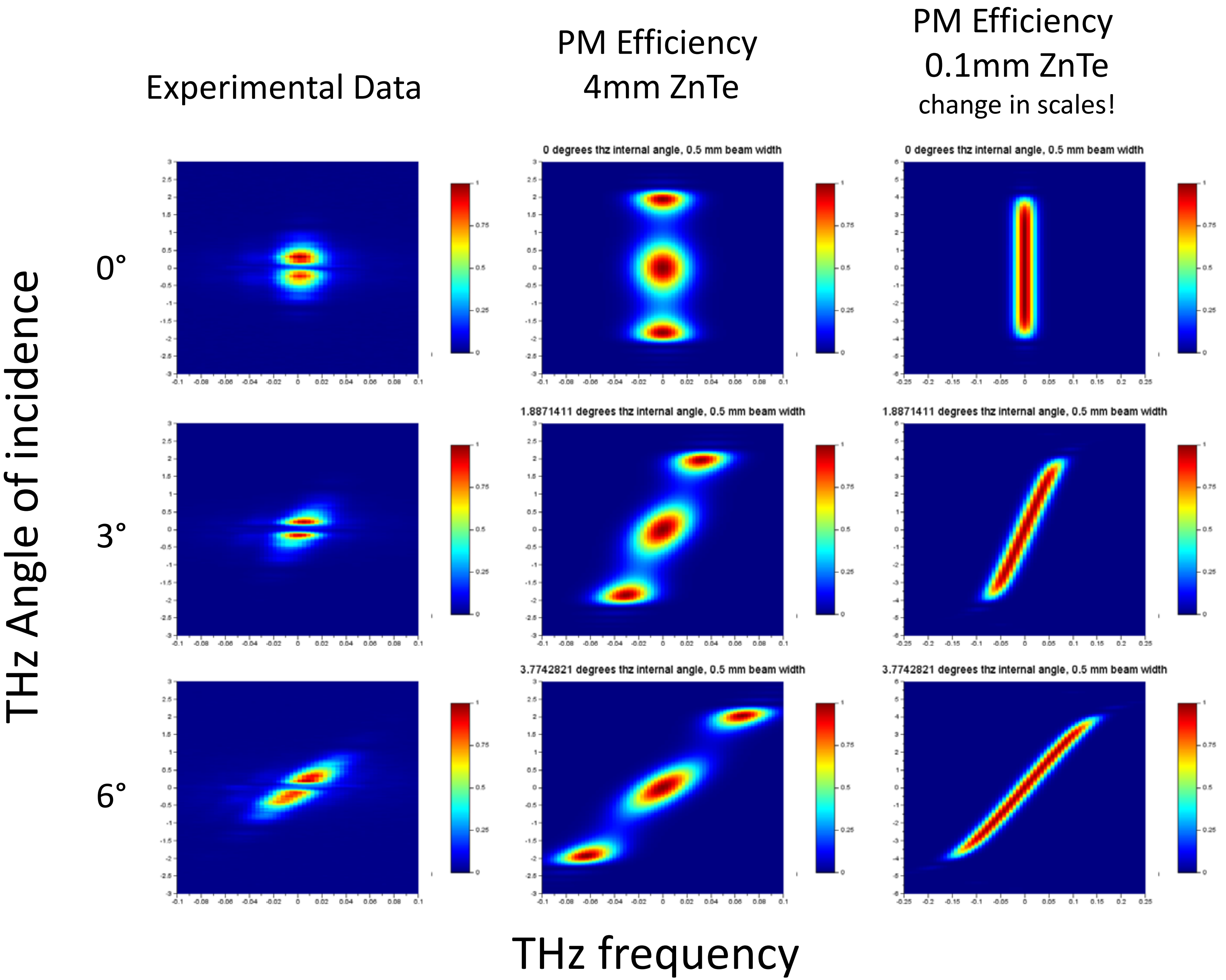
- Measurable (<0.1deg for ZnTe)
- potentially distorting on EO
- Dependent on transverse probe dimensions

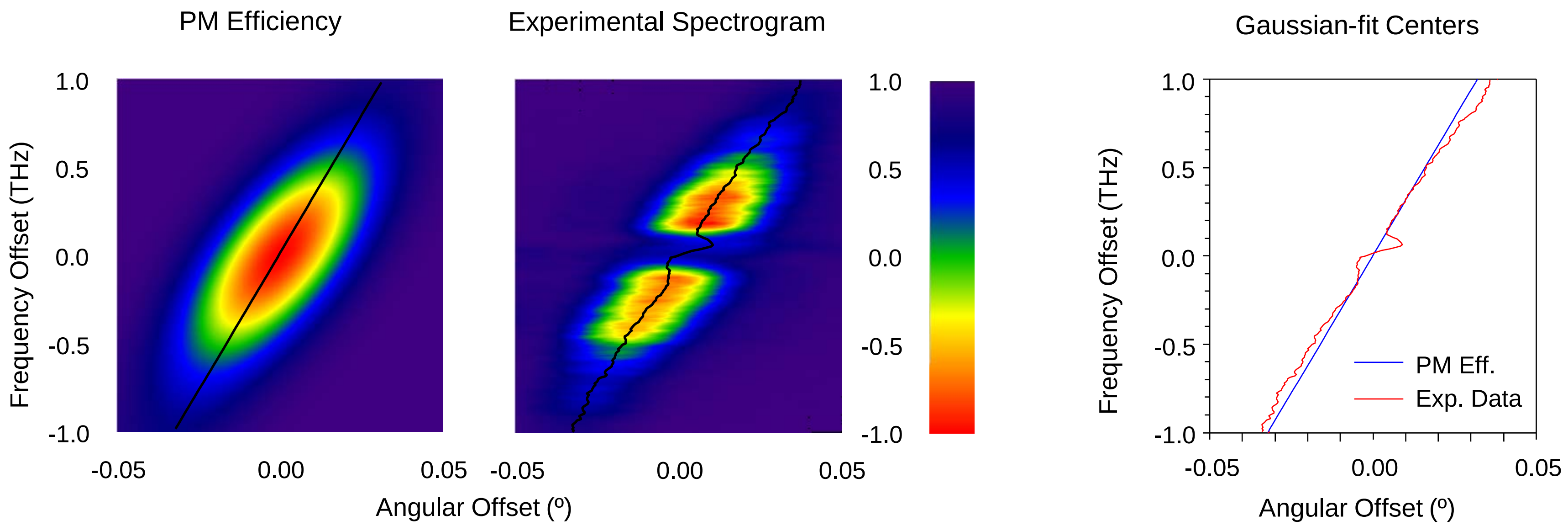
Quantitative characterisation

- imaging spectrometer for sideband angle
- THz angle-only variation






Experimental Data
PM Efficiency
4mm ZnTe
PM Efficiency
0.1mm ZnTe
change in scales!
THz Angle of incidence
0°
3°
6°
0 degrees thz internal angle, 0.5 mm beam width
1.8871411 degrees thz internal angle, 0.5 mm beam width
3.7742821 degrees thz internal angle, 0.5 mm beam width
THz frequency

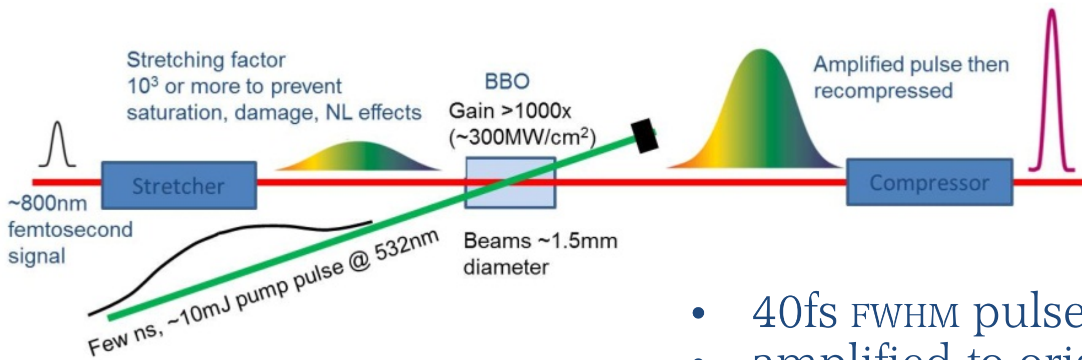


PM Eff. linear fit gradient = 30.26 ± 0.04 THz/°
Exp. Data linear fit gradient = 28.08 ± 0.10 THz/°

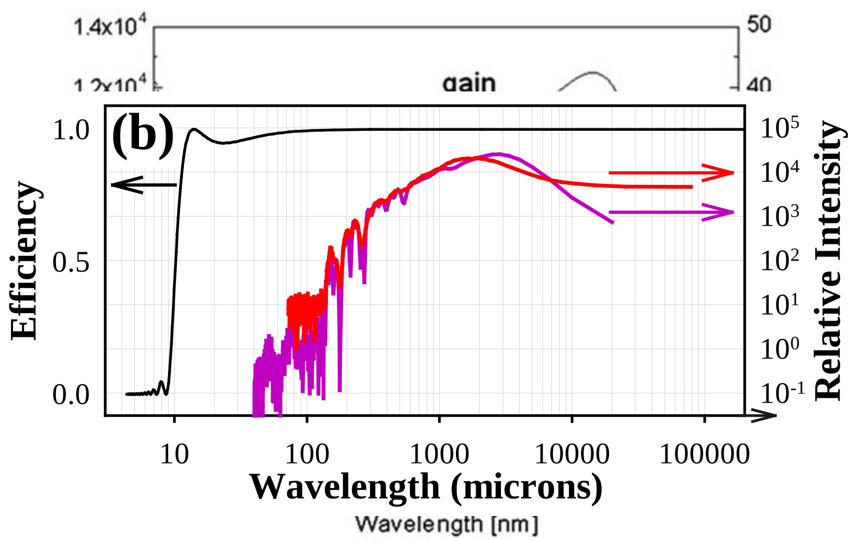
Discrepancy attributed to potential errors in the positioning of the 20cm angle-position mapping lens and in the position of camera.

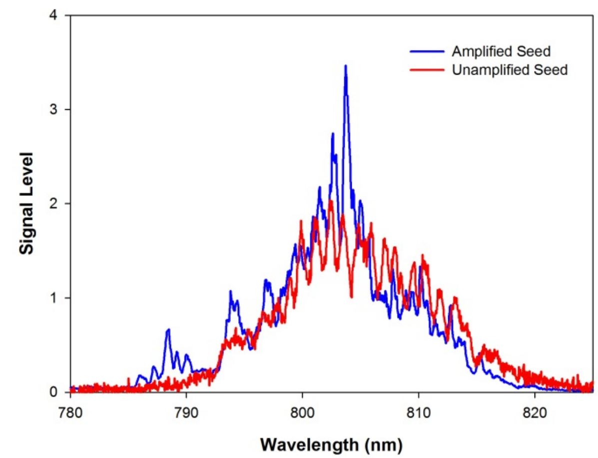
Amplification of post-interaction probe

- Amplification required to allow for FROG characterisation of carved pulse
- NCOPA design demonstrated. 10^3 gain, and sub<20fs rms bandwidth confirmed.
  (using existing 60 ps YAG pump laser with <ps synchronisation to e-bunch mimic



- 40fs FWHM pulse attenuated by x10^3
- amplified to original pulse energy





Preserved bandwidth of 40fs pulse

System integration

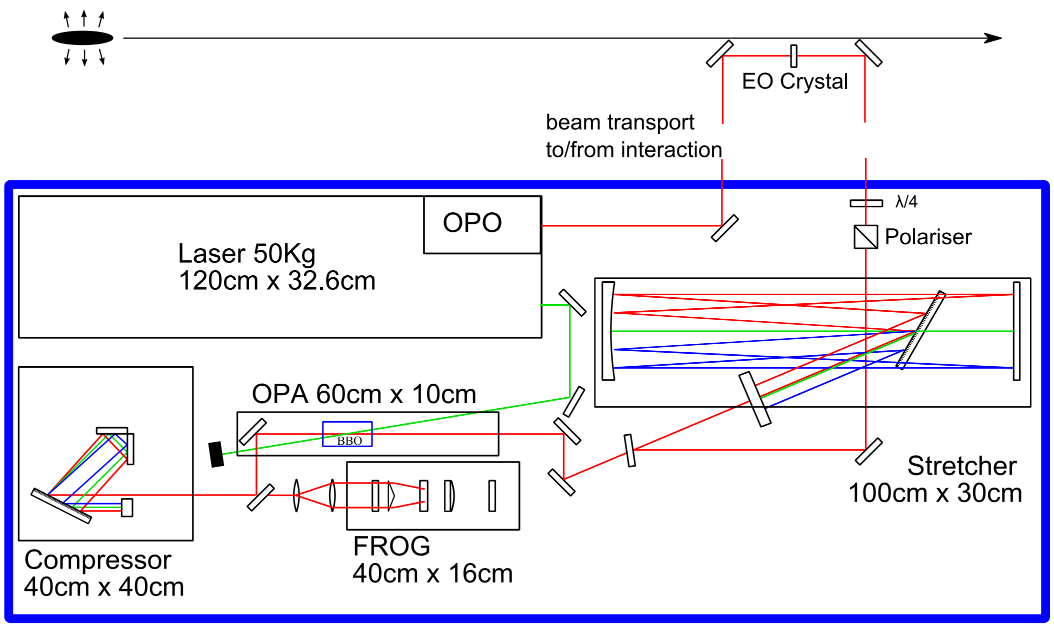
Commercial ‘one-package’ laser on order - late January 2014 delivery (Litron)

- 10mJ, 10ns , seeded single mode 1062nm + 532nm
- integrated OPA for 750-850nm probe
- Probe bandwidth < 30 GHz

Stretcher/compressor design in-hand

Modular layout for experimental location flexibility

- double layer for compactness? Needed?



Primary components drawn in boxes

Boxes are drawn to scale

Components can be rearranged to fit

Power Supply
for Laser

14U rack
20A single phase
220-240Vac 50Hz
70cm x 60.5cm

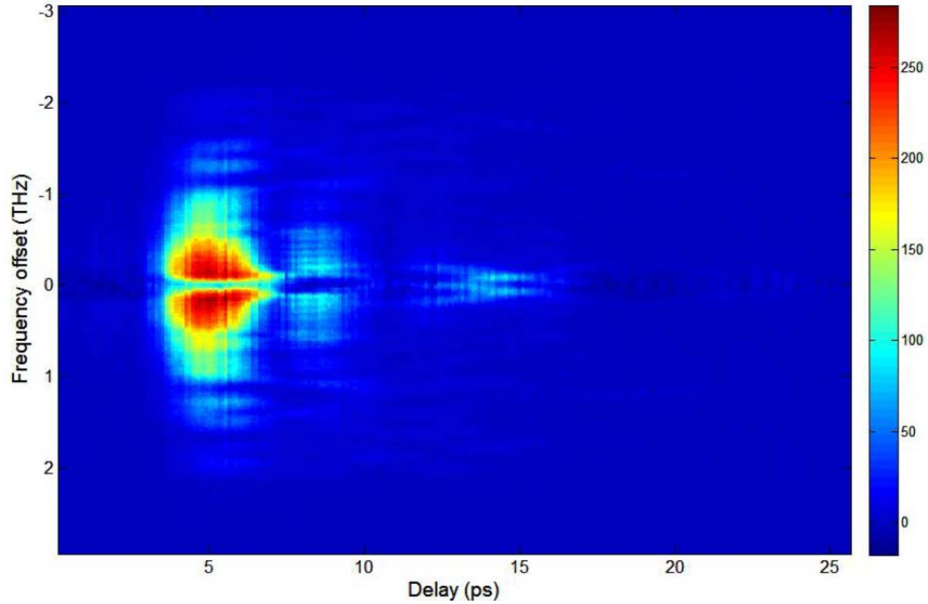
3m umbilical

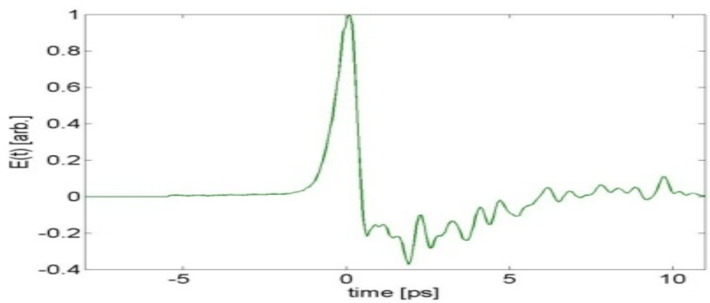
Optical Bench
2.4m x 1m

Upconversion spectrogram – a direct X-FROG measurement ?

Sideband spectra as function of THz-probe delay

probe ~5ps duration





FROG - spectrally resolved autocorrelation

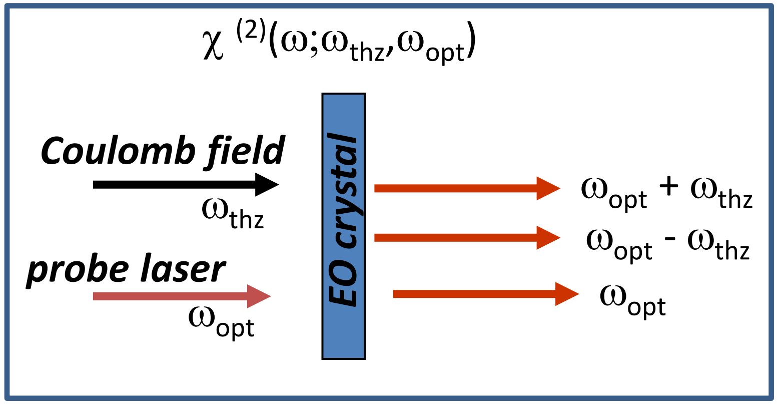
- *self-referenced* retrieval of temporal profile
- retrieves *envelope* phase within the pulse
- ambiguity remain on carrier-envelope phase. *Significant for single-cycle optical pulses*

- THz-optical X-FROG: *THz carrier phase ambiguous*
- upconversion-FROG: *THz carrier phase converted to optical envelope – ambiguity removed*

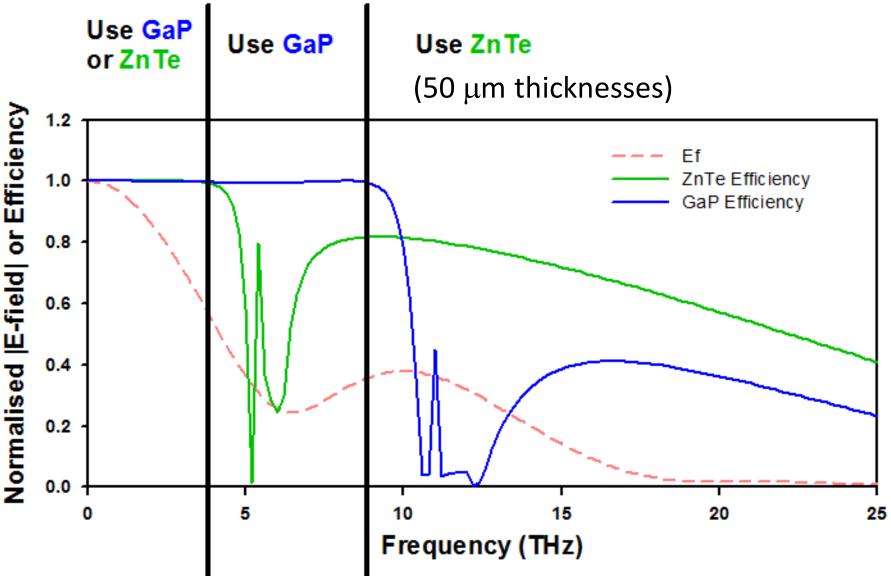
Material bandwidth limits:
Spectral Compositing of Multiple Crystals

Physics : Frequency mixing between Coulomb field (or CSR, CTR,FEL ...) pulse and probe laser

Phase propagation mismatch limits bandwidth of materials



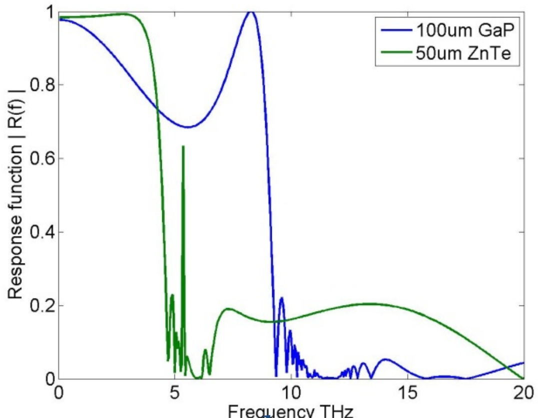
Material frequency response

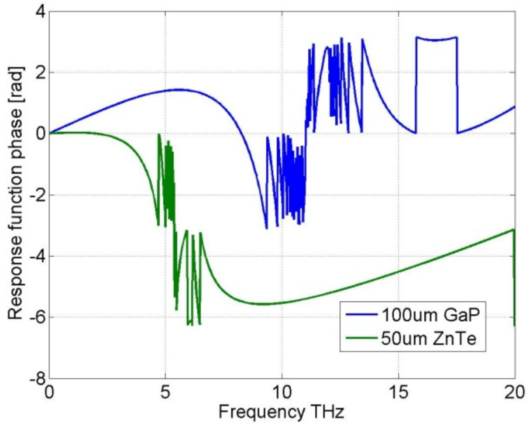


Missing response due to phonon resonance
High frequency response limited to thin crystals & small signal

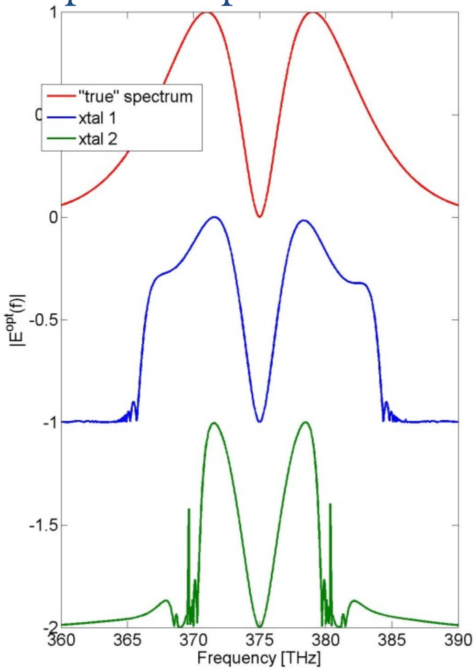
- Laser simplicity allows for multiple probes & crystals
- Amplification allows for thin, <50um (?) active thickness crystals
- FROG retrieval of phase information allows for "splicing" of response function

Response function for standard crystals





Short-pulse up-converted spectra



- Measure $\left\{ E^{\mathrm{Coul}}(t) * R(t) \right\}^2$

  Requires amplification

- FROG retrieval of $E^{\mathrm{Coul}}(t) * R(t)$
- Evaluate and splice $\tilde{E^{\mathrm{Coul}}}(\omega)$

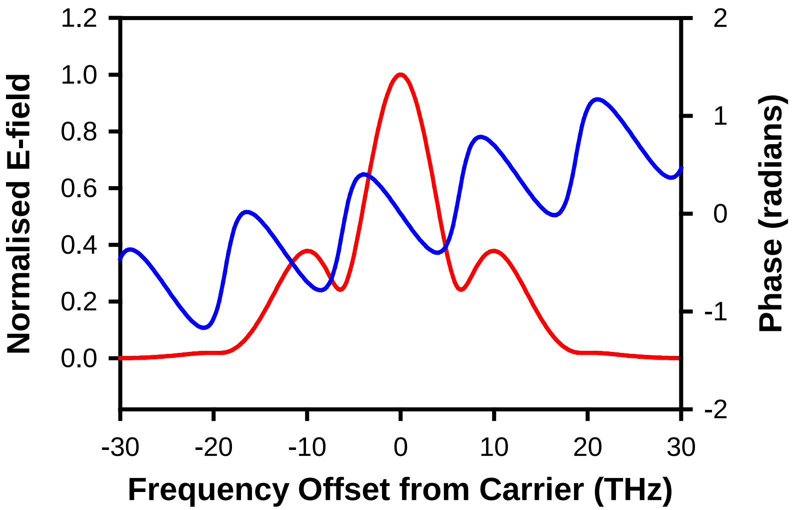
Currently do not have very short test pulses
- will demonstrate FROG on single xtal output

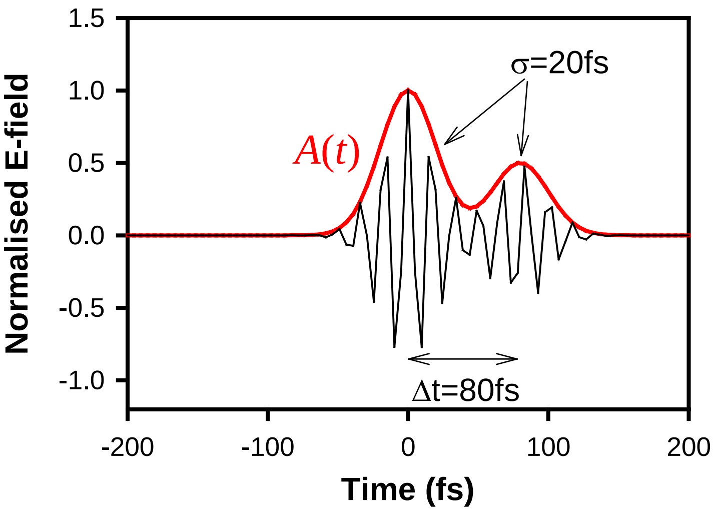
+ GaSe for shorter pulses; BBO in extreme case (? on validity in extreme)

Spectral Transposition

Ideally, nonlinear $\chi^{(2)}$ frequency mixing transposes complex amplitude to the optical regime.

Coulomb field now represented by pulse envelope $E(t) = A(t)\cos(\omega t)$



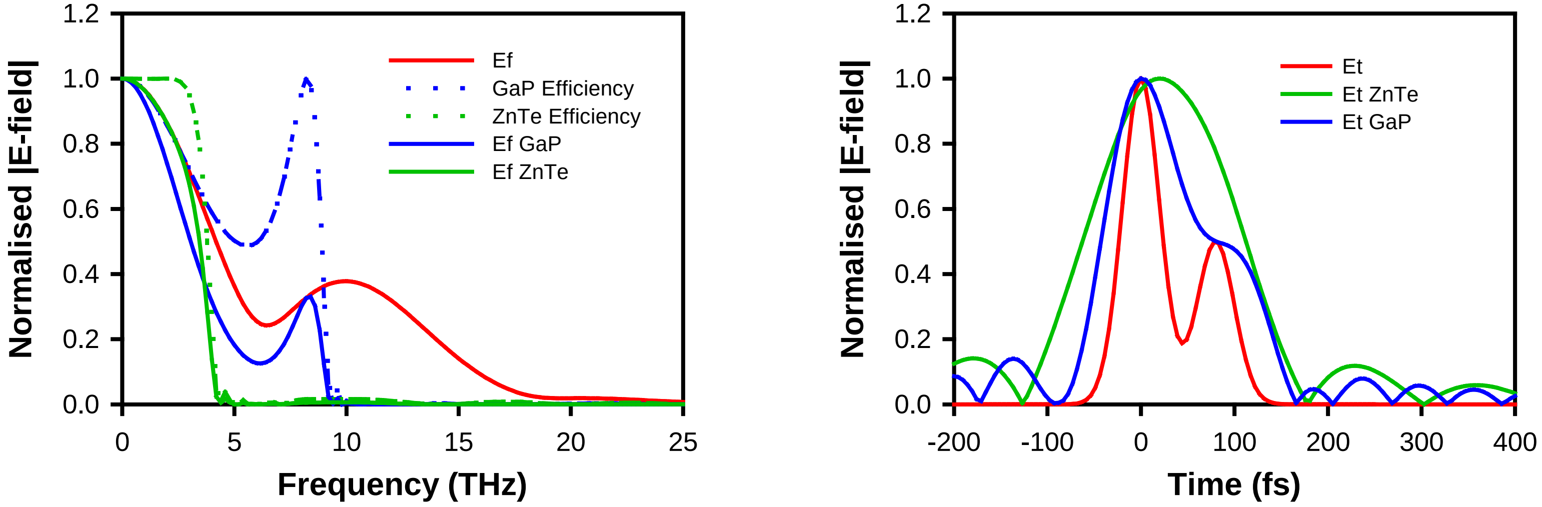


Optical measurement techniques such as **FROG** can be used to retrieve full spectral **amplitude** and **phase**.

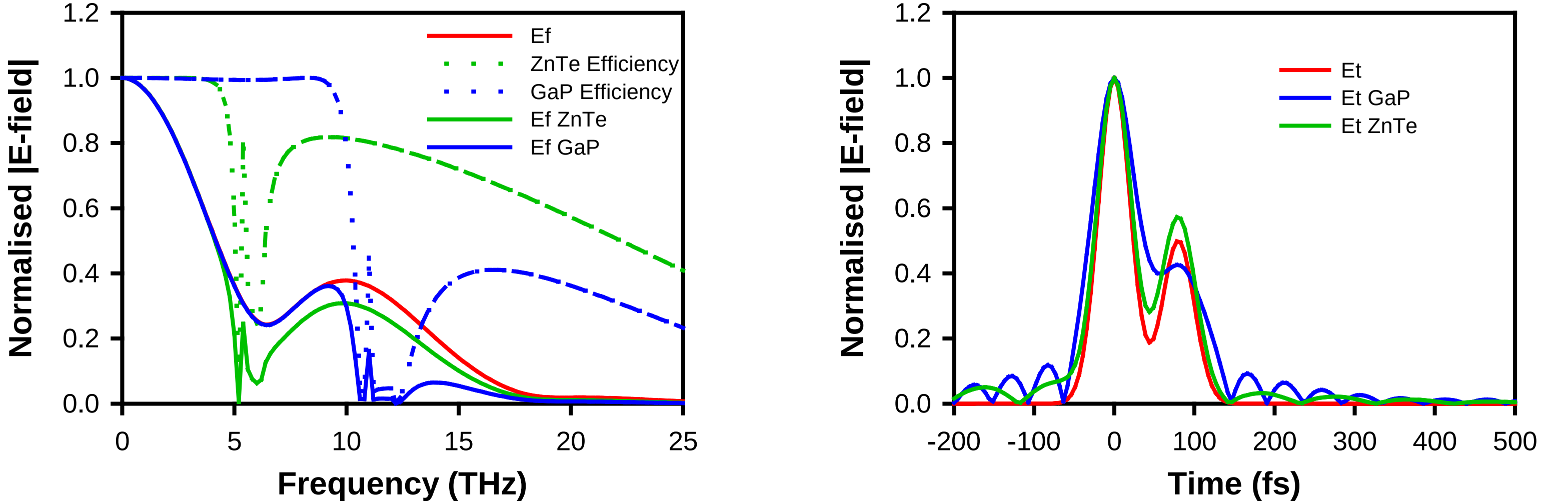
However, material response induces distortions and limits bandwidth

Material Limits

100 μm ZnTe and GaP

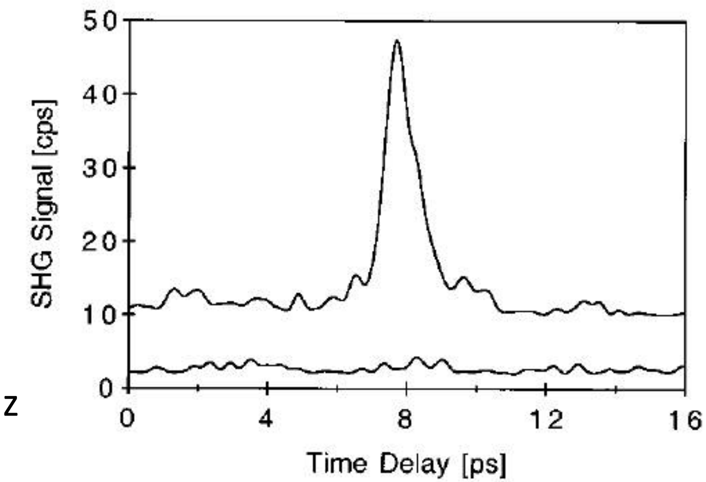


10 μm ZnTe and GaP



Higher bandwidth materials - TFISH

THz Field Induced Second Harmonic Generation

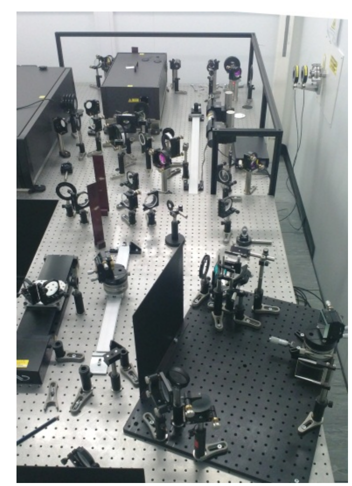


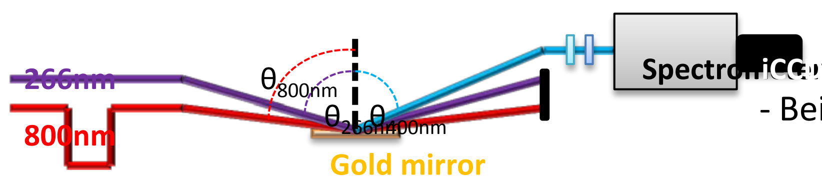
From Nataha et al.

- THz characterisation on metal surface demonstrated
  e.g. Nataha (1999)
  - limited examples, efficiency needs characterisation
  - will need (extra) amplification

- separate ASTeC project in gold surface DFG for UV characterisation
  - being adapted for TFISH tests with laser generated THz

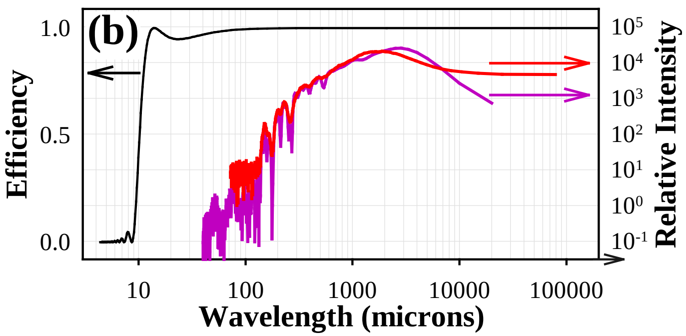
- Enhancement of interaction: known enhancement of SHG with nanoparticle metals.
  - Dundee producing samples, Daresbury characterisation
    Marie Curie student (Mateusz Tyrk);
  - Silver-in-glass MDNs generated by field-assisted ion exchange
    (30nm dia nanoclusters)
  - Nanoparticles re-shaped to ellipsoidal shape using
    polarised ps laser fluence

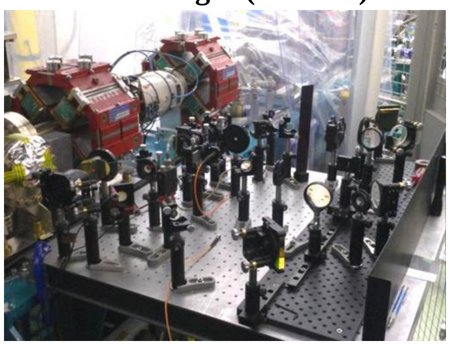




Metal SHG set-up
- Being adapted for CLIC TFISH

Accelerator tests, and benchmarking with short pulses





CTR pulse carving experiments
(ALICE, Daresbury lab.)

Laser lab tests limited by THz source

- Bandwidth <6THz
- Calibrated spectrum & temporal profile missing
  characterised by EO; circular "benchmarking

CTR experiments at ALICE (unsuccessful)

- no CTR transport system,
- without amplification
- v. low CTR pulse energy (25MeV, 60pC)

Proposal: Benchmarking against FLASH transported CTR

- Cross check against calibrated CTR spectrometer
  - Individual crystals for selected bandwidth regions
  - Direct spectrum comparison
- Evaluate temporal retrieval with realistic field
  - Compare with expected bunch profile & CTR propagation?
  - *Icing:* compare with 'simultaneous' TDC measurements

Proposal: Benchmarking against FLASH transported CTR

Optical arrangement

- Compact layout ~ 1.3x1.0m (stacking)
- Open layout 2.4 x 1.0 m
- Optical window access for probe to CTR
- *Focal spot for CTR (within CTR spectrometer?)*
- *Optical flipping between spectrometer / EO measurements*

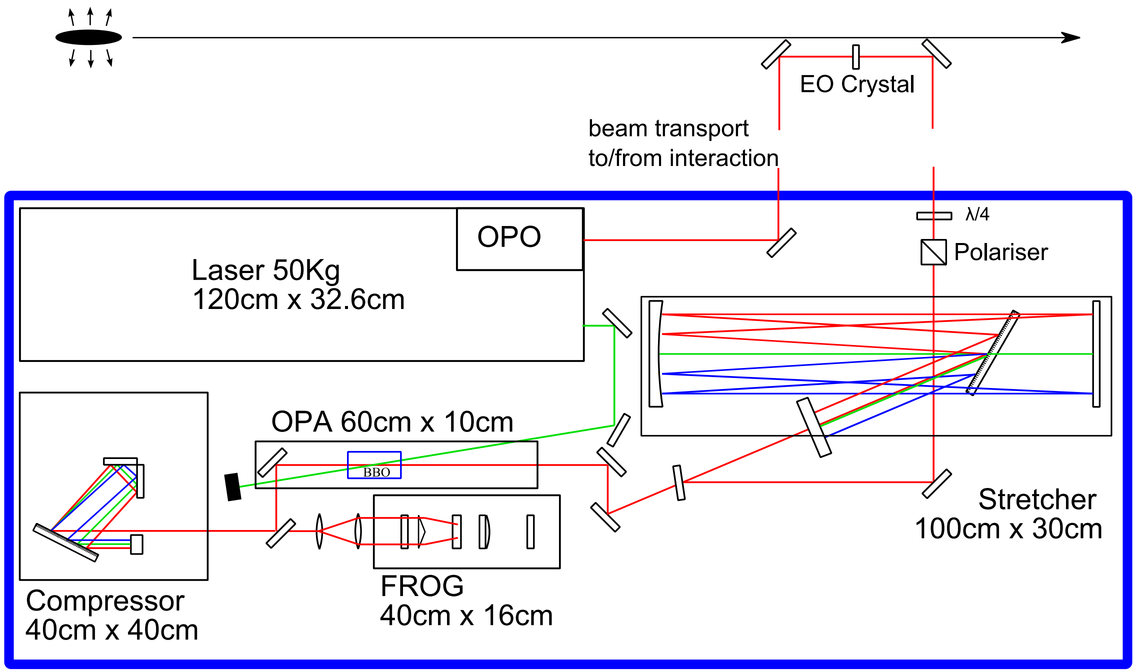
Installation and build-up

- Daresbury/Dundee provide system on breadboard
- David Walsh available for extended periods setup and experiment
- Additional Daresbury people available for 1-2 week experiment runs

- CTR spectrometer and TDC for experiments

- Laser expected late January 2014; system build by end March
  (linked to laser lab relocation schedule)
- Available for DESY/FLASH experiments ~June 2014

Optical arrangement – "open layout"



Optical Bench
2.4m x 1m

Primary components drawn in boxes

Boxes are drawn to scale

Components can be rearranged to fit

Power Supply
for Laser

14U rack
20A single phase
220-240Vac 50Hz
70cm x 60.5cm

3m umbilical

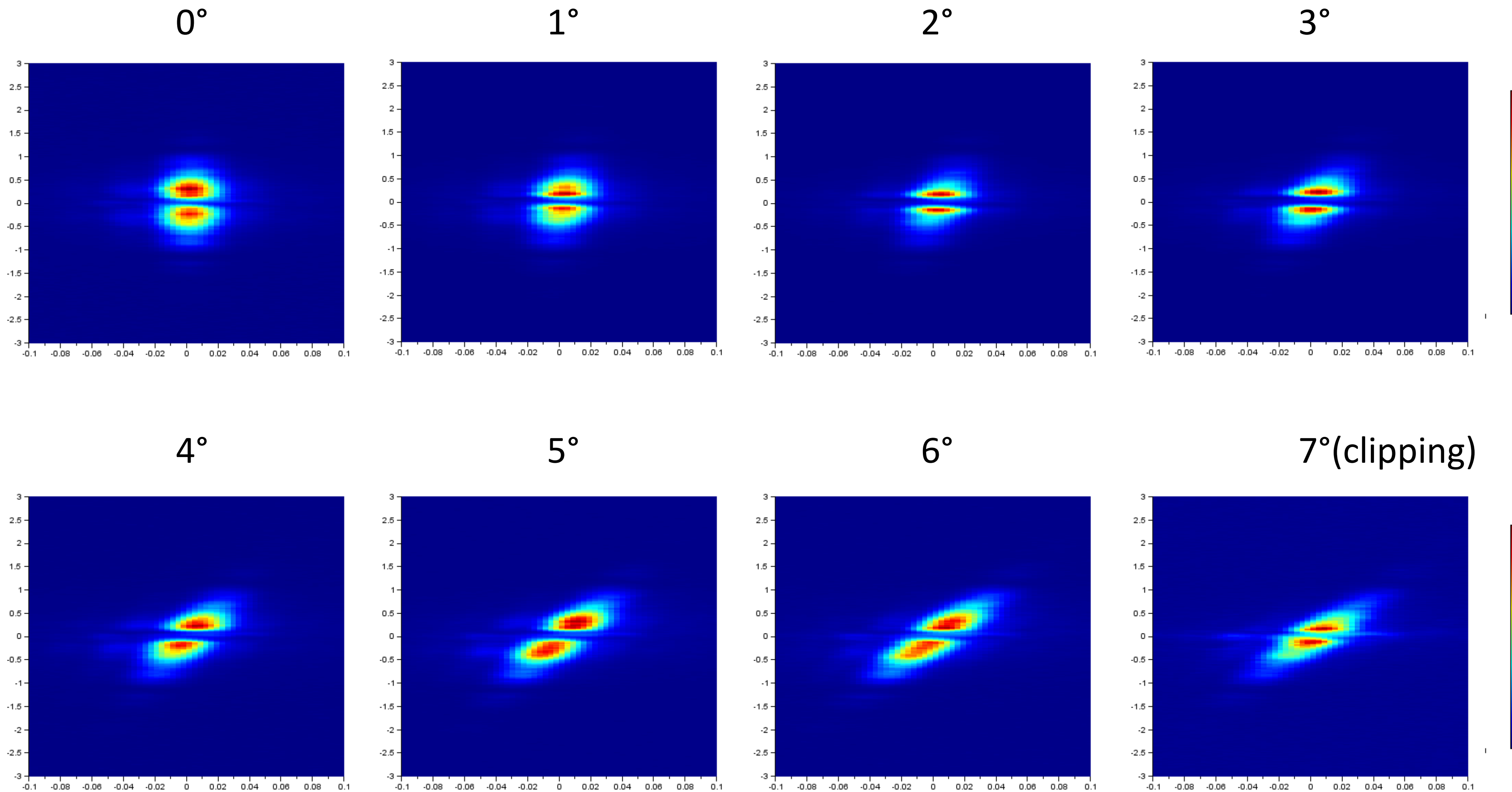
+ air cooled chillier

In conclusion

- Electro-optic transposition scheme being developed for CLIC
  - fs resolution without fs laser
  - Concept allows multiple crystal detectors
- Component systems tested
- Integrated ‘one-laser’ system ready ~march 2014
- Separate project on TFISH surface effects
- On-going materials development at Dundee, non-linear testing at Daresbury started

Thank you.

Experimental spectrograms showing angular dispersion of sidebands at several THz input angles of incidence

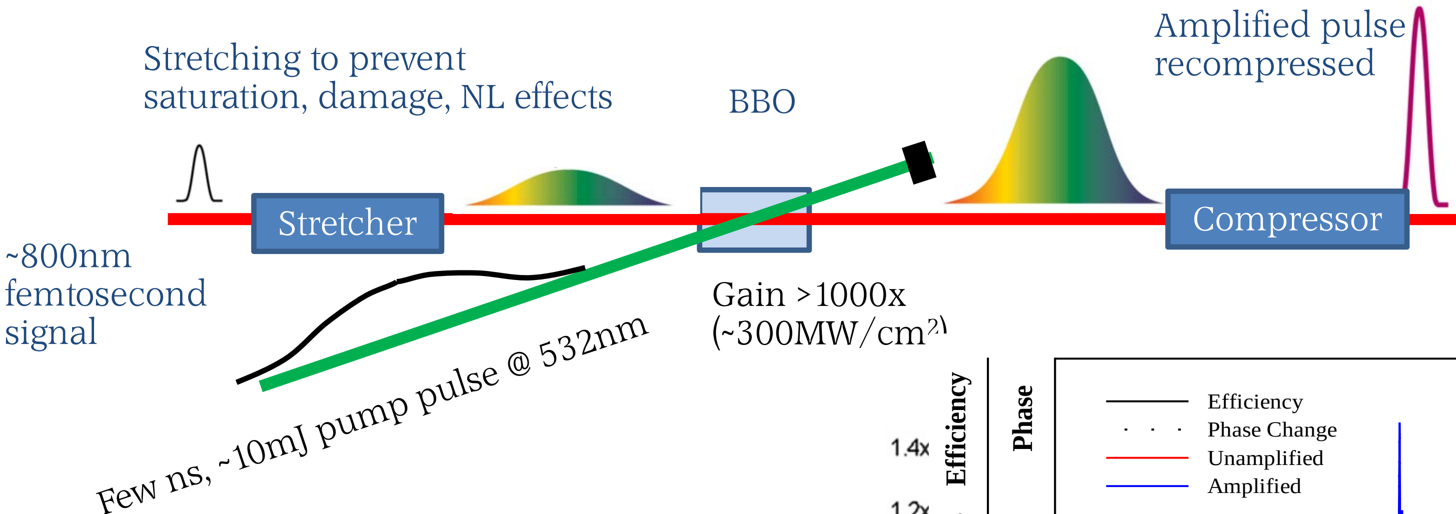


Frequency resolved optical gating (FROG)

Ultrafast laser technique, self referenced characterisation of pulse at <10fs res.

Upconverted optical pulse is too weak for FROG   few nJ available, uJ required.

Solution: Non-collinear Chirped Pulse Amplification (NCPA)



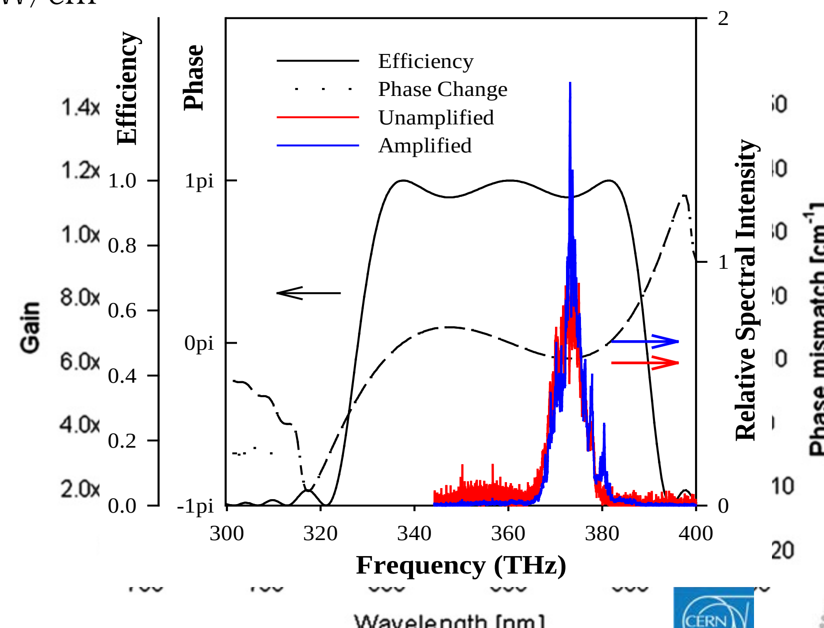
Routinely used to produce “single-cycle” optical pulses

Amplification with robust nanosecond pulse lasers

High **gains of 10^7** or more

Gain **bandwidths >100nm (50THz)**

Preservation of phase of pulse is possible



Commercial packaged laser specification