# Electro-optic time arrival diagnostic for AWAKE

## & other potential EO diagnostics

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# Electro-optic capabilities

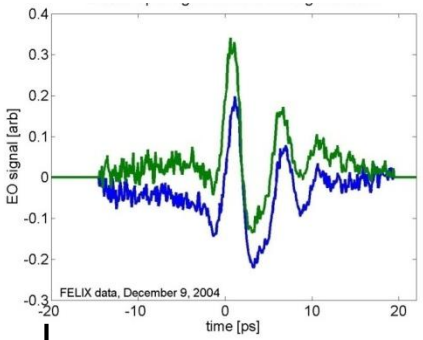
## Many *demonstrations*...

Accelerator Bunch profile - FLASH, FELIX, SLAC, SLS, ALICE, FERMI ....
Laser Wakefield experiments - CLF, MPQ, Jena, Berkley, ...
Emitted EM (CSR, CTR, FEL) - FLASH, FELIX, SLS, ...

Temporal Decoding @FLASH

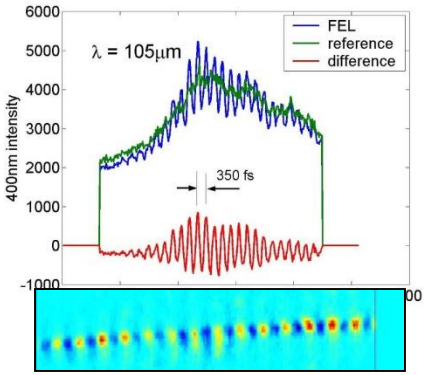
High-time resolution,
'Temporal decoding'

CSR @FELIX



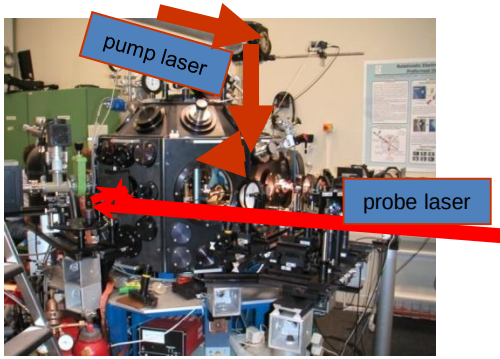

Low-time resolution
Spectral decoding

Mid-IRFEL lasing @FELIX




Temporal modulation,
measured in time domain

Laser Wakefield
@ Max Planck Garching

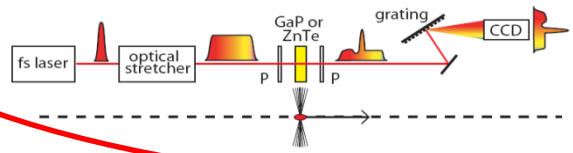



Measurements in presence
of TW laser and plasma 'scatter'

# Electro-Optic Techniques…

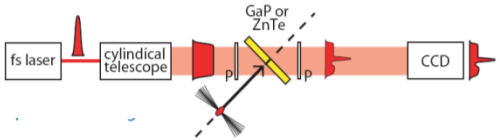
## Variations in read-out of optical temporal signal

### Spectral Decoding



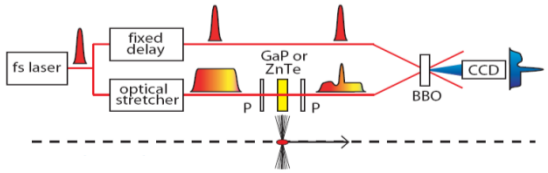

- Chirped optical input
- Spectral readout
- Use time-wavelength relationship

### Spatial Encoding



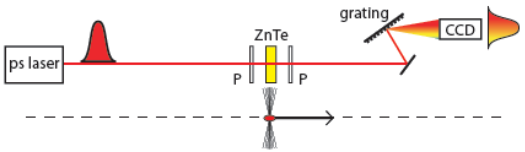

- Ultrashort optical input
- Spatial readout (EO crystal)
- Use time-space relationship

### Temporal Decoding




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

### Spectral upconversion**




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

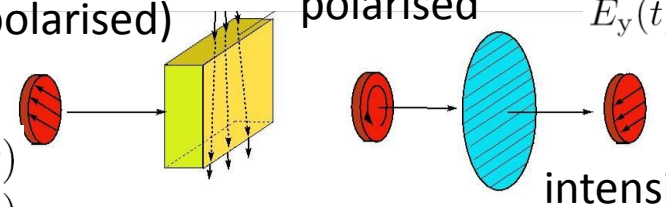
# Spectral decoding limitation

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

laser pulse (linear polarised)

elliptically polarised

$$E_{\mathrm{x}}(t) \sim E_{\mathrm{x}}(t)\exp(i\omega t - i\eta_x \omega z/c)$$
$$E_{\mathrm{y}}(t) \sim E_{\mathrm{y}}(t)\exp(i\omega t - i\eta_y \omega z/c)$$

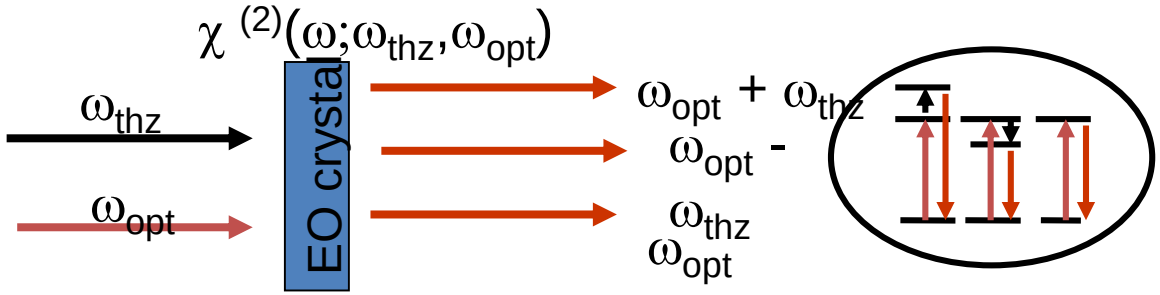


$E_{\mathrm{x}}(t)$
$E_{\mathrm{y}}(t)$

$$\eta_{\mathrm{x}} = \eta_0 + \alpha_{\mathrm{x}} E_{\mathrm{DC}}$$
$$\eta_{\mathrm{y}} = \eta_0 + \alpha_{\mathrm{y}} E_{\mathrm{DC}}$$

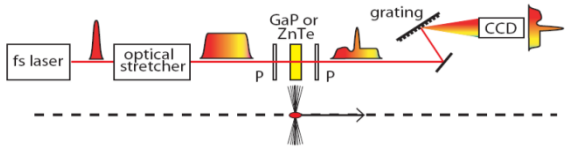
intensity dependent on 'DC' field strength

EO detection as sum- and difference-frequency mixing




Fast modulation produces new frequencies that disrupts time-frequency chirp

# Spectral decoding…

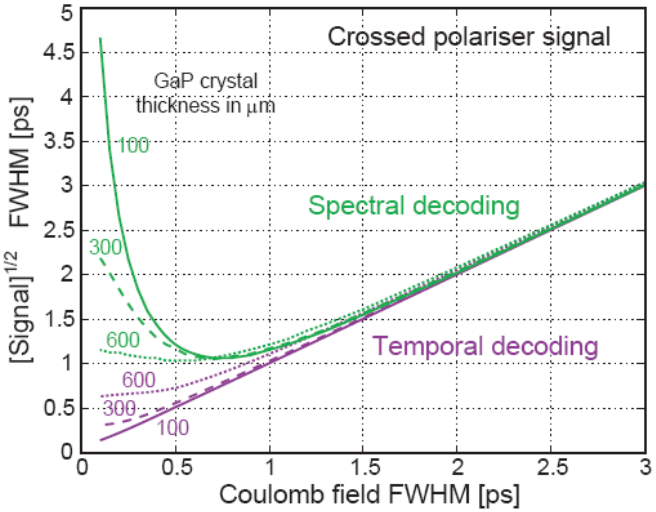



Attractive for technical simplicity, cost.
High rep-rate, low pulse energy lasers suitable
Synchronisation requirements relaxed

## temporal resolution limits…

In general spectral decoding limited by chirp $\tau_{\mathrm{lim}} = \sqrt{12\pi\beta}$

For specific laser profiles, can relate to FWHM durations…



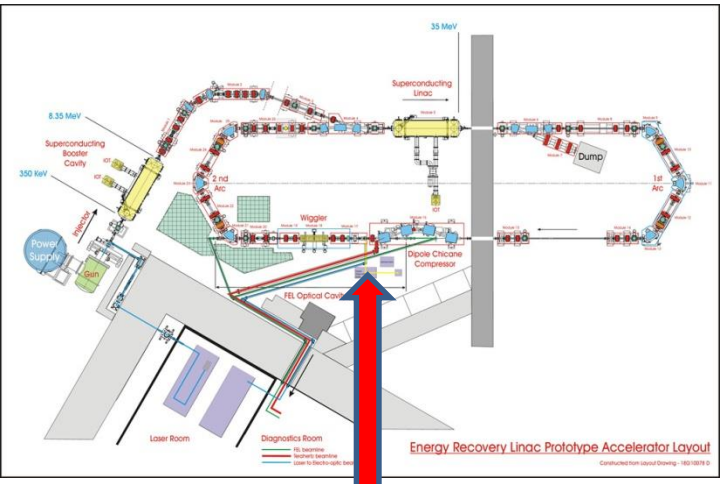

$$\tau_{\mathrm{lim}} = 2.61\sqrt{T_0 T_c} \quad ; \text{for a Gaussian pulse}$$

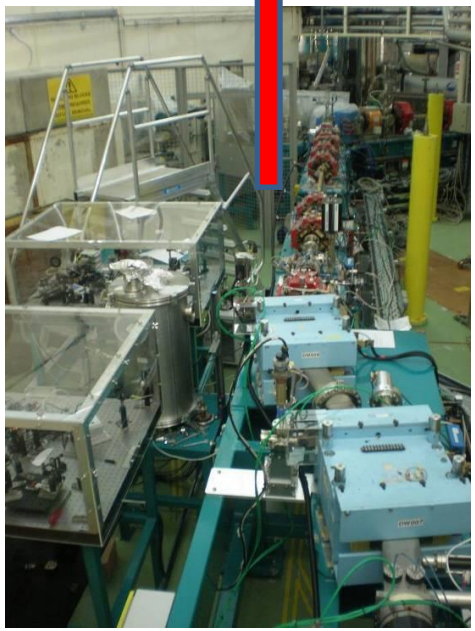
Can resolution limits be overcome?

$$S^{BD}(\omega) \equiv I^{\mathrm{in}}_{\mathrm{opt}}(\omega) - I^{\mathrm{in}}_{\mathrm{opt}}(\omega)$$
$$\propto I^{\mathrm{in}}_{\mathrm{opt}}(\omega)\left\{E_{\mathrm{Coul}}(\tau + t_0) * \cos\left(\frac{\tau^2}{4\beta} - \frac{\pi}{4}\right)\right\}.$$

*For arrival time, frequency mixing enables time resolution to be maintained*

# ALICE Electro-optic experiments

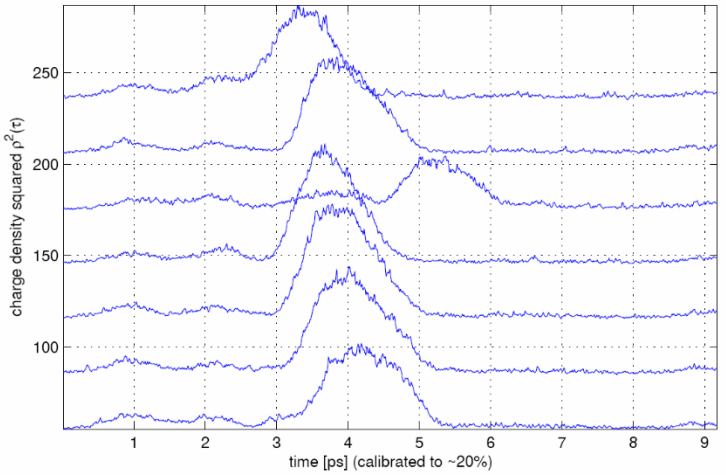


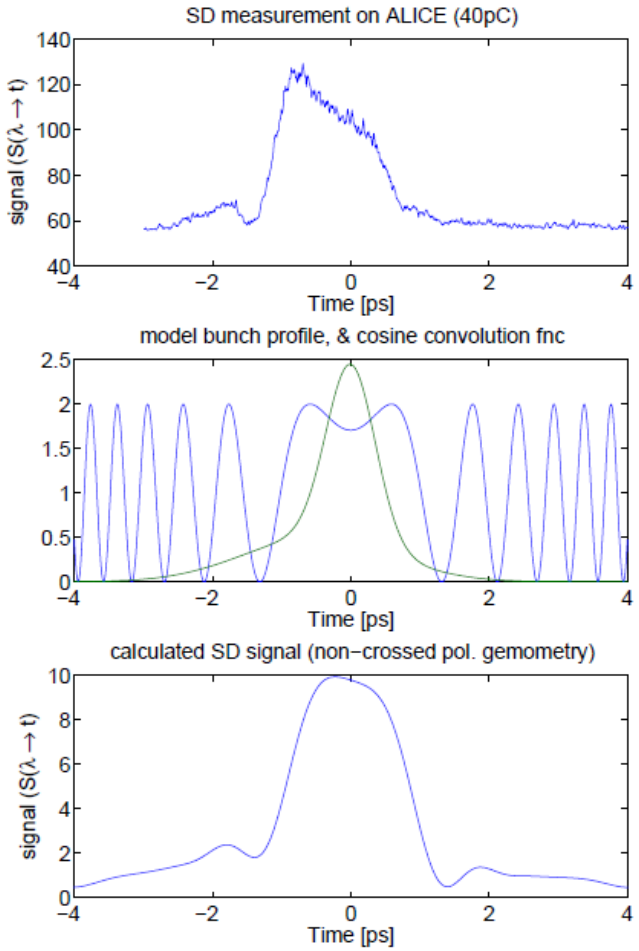
- Energy recovery test-accelerator
  - *intratrain diagnostics must be non-invasive*
- low charge, high repition rate operation
  - *typically 40pC, 81MHz trains for 100us*

## Spectral decoding results for 40pC bunch

- *confirming compression for FEL commissioning*
- *examine compression and arrival timing along train*
- *demonstrated significant reduction in charge requirements*



# Spectral decoding frequency mixing limits




## "Balanced detection"

$\chi^{(2)}$ optical pulse intefers with input probe (phase information retained)

$$S^{BD}(\omega) \equiv I^{\text{in}}_{\text{opt}}(\omega) - I^{\text{in}}_{\text{opt}}(\omega)$$
$$\propto I^{\text{in}}_{\text{opt}}(\omega)\left\{E_{\text{Coul}}(\tau + t_0) * \cos(\frac{\tau^2}{4\beta} - \frac{\pi}{4})\right\}.$$

Deconvolution possible.

## "Crossed polariser detection"

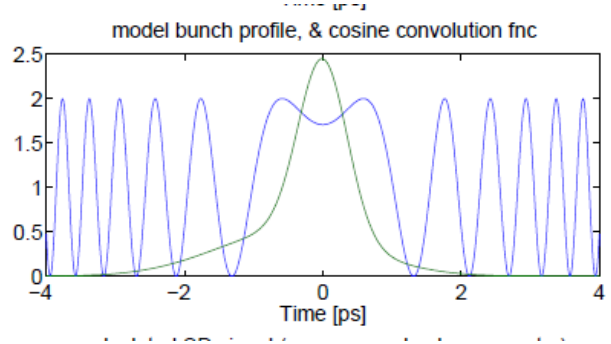
input probe extinguished...phase information lost

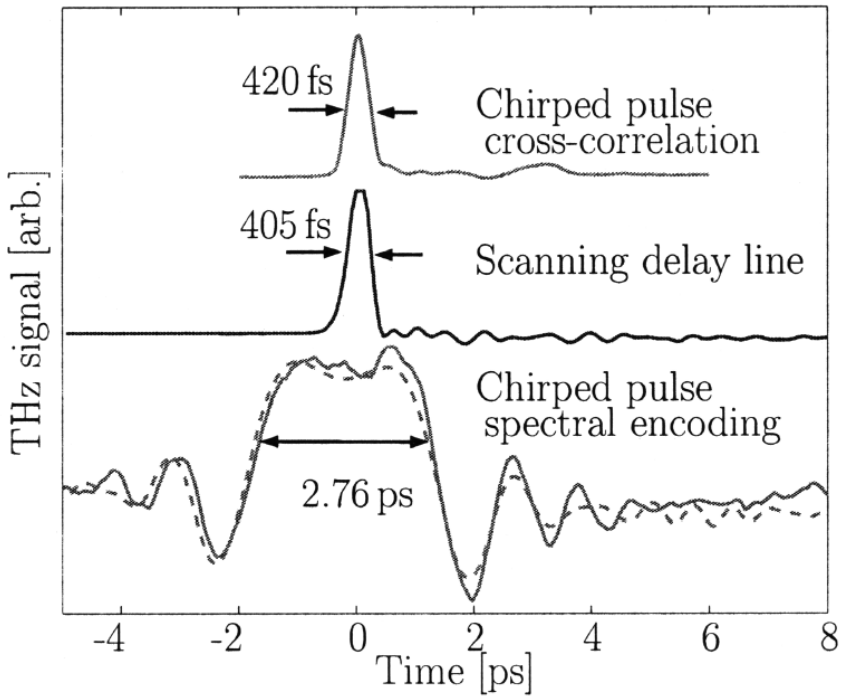
$$S(\omega)^{CP} \propto I^{\text{in}}_{\text{opt}}(\omega)\left\{\left[E_{\text{Coul}}(\tau + t_0) * \cos\left(\frac{\tau^2}{4\beta} - \frac{\pi}{4}\right)\right]^2 + \left[E_{\text{Coul}}(\tau + t_0) * \sin\left(\frac{\tau^2}{4\beta} - \frac{\pi}{4}\right)\right]^2\right\} \quad (2)$$

Oscillations from interference with probe bandwidth

$\Rightarrow$ resolution limited to probe duration

# Spectral decoding frequency mixing limits




Complicated temporal decoding, for high time resolution

Simple' spectral decoding, maintaining high time resolution in arrival time through oscillations

- Pickoff from plasma generation laser taken downstream to act as probe in spectral decoding diagnostic

- Probe chirp increased to give high-resolution arrival time of electron beam immediately prior to injection
  - sacrificing the e-beam profile accepted, or…
  - potential for deconvolution restoration of beam profile

Some numbers

- Crystal located ~ 2mm from electron beam;
- 10uJ laser energy, full bandwidth, chirped to >20ps
- 'Readout' is optical
- Expect time resolution ~50fs (material limited)

Ready to start developing:

12months Post-doc funding available in Lancaster, willing to direct to this and associated EO AWAKE schemes now. (UK based; potential testing at CLEAR?)

*on expectation that:*

- *will be implemented in some-form in AWAKE-II;*
- *& UK will provide further post-doc effort in 2020-2022 to implement in AWAKE-II (CERN based)*

Proposal 2a: proton beam modulation…

2b: …including electron/proton phasing

- Pickoff from plasma generation laser taken downstream to act as probe in spectral decoding OR temporal decoding diagnostic (10uJ or 1mJ laser)
- Detection at 1m at exit of plasma, modulation section or acceleration section. Potential for proton and electron simultaneous meaurement

Some numbers

- Crystal located ~ 2-4mm from electron beam;
- Proton beam divergence (plasma microbunching/defocusing 1.5mrad)
- Expect time resolution ~50fs for Temporal decoding

Ready to start developing:

12months Post-doc funding available in Lancaster now, willing to direct to this and associated EO AWAKE schemes. (UK based; potential testing at CLEAR?)

*on expectation that:*

- *will be implemented in some-form in AWAKE-II;*
- *& UK will provide further post-doc effort in 2020-2022 to implement in AWAKE-II (CERN based)*

Thank you.

Questions?