

Laser and THz techniques for
wakefield & bunch characterisation
and for
bunch phase-space manipulation

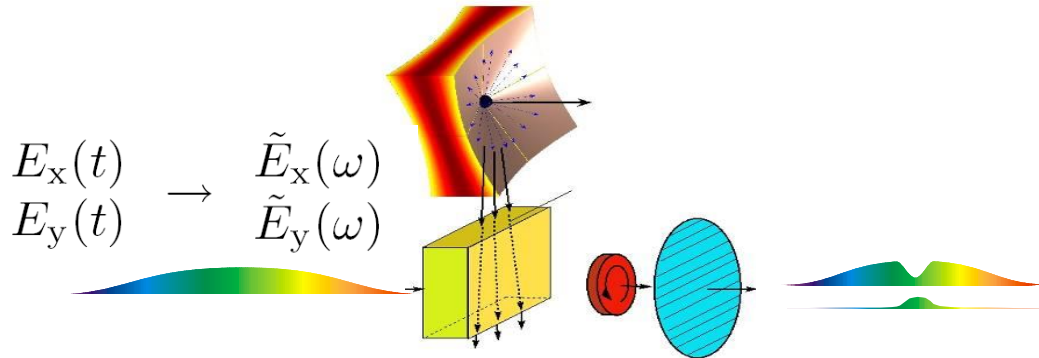
Steven Jamison

STFC Daresbury National Laboratory
& Cockcroft Institute for Accelerator Science

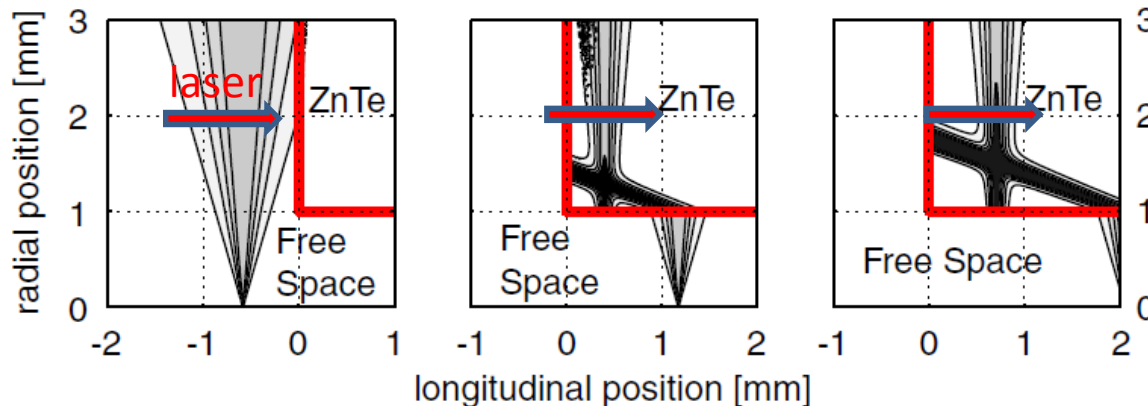
Longitudinal profile via laser probe of Coulomb field

Electro-optic detection

- Time varying electric field induced birefringence in material
- Observation by polarisation change in probe laser

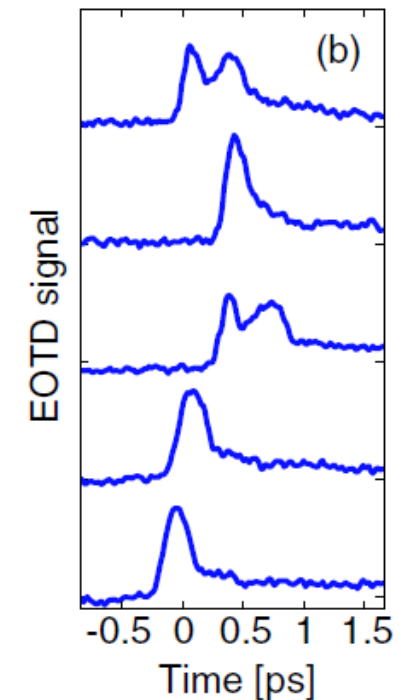


Coulomb field appears as single-cycle THz pulse



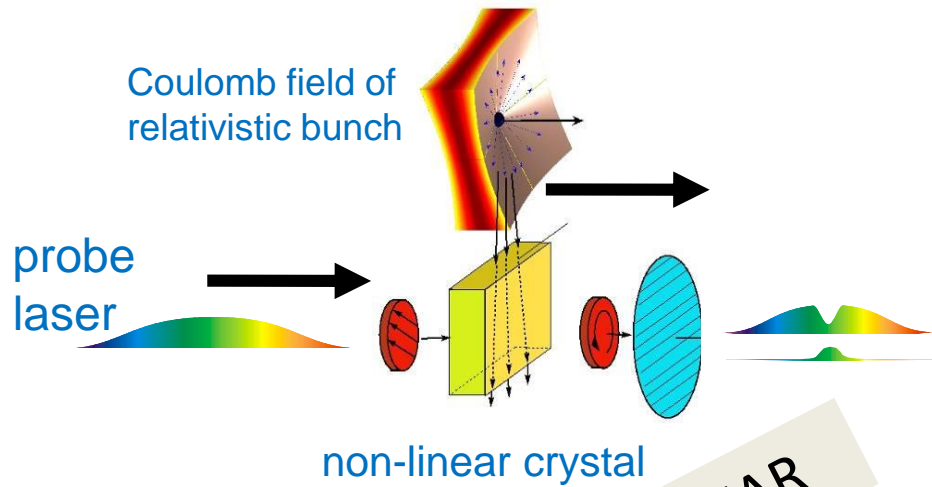
Single-shot required

- laser-bunch jitter
- bunch profile jitter



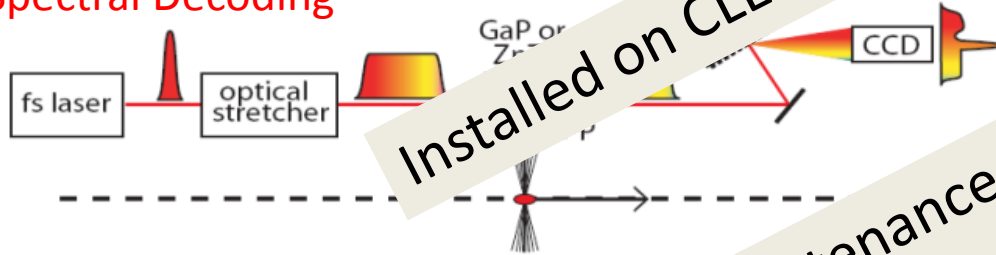
Phys Rev Lett 9 164801 (2007)

Established EO Techniques



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

Spectral Decoding



Installed on CLEAR

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

~1ps

Temporal Decoding

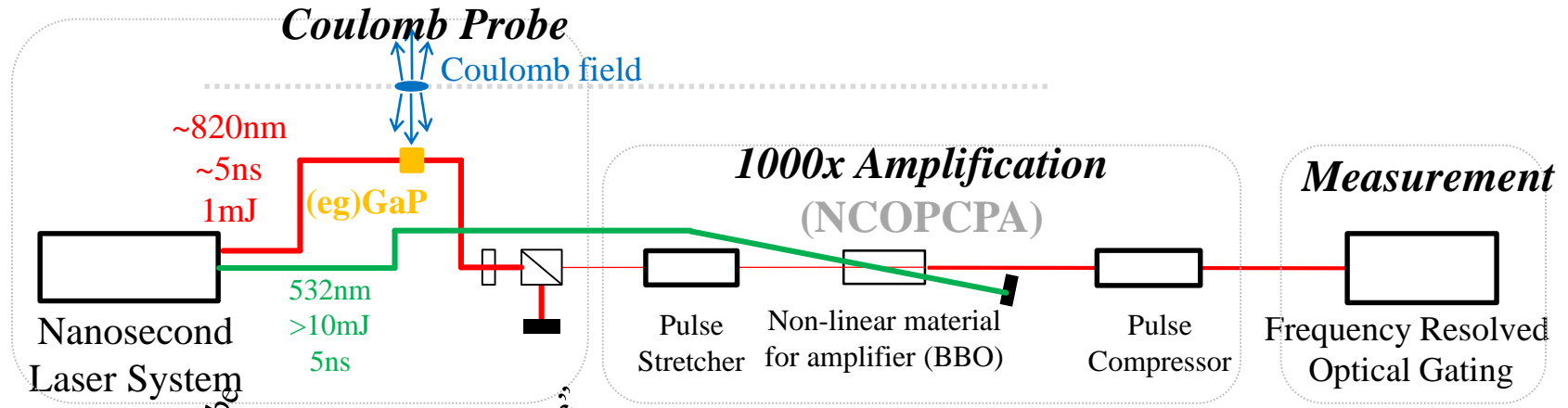


complex, high-maintenance amplified fs lasers

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

EO Transposition System – CLIC development

Femtosecond measurement without a femtosecond laser



‘Pulse carve’ Bunch profile into nanosecond probe generating sub-ps optical probe

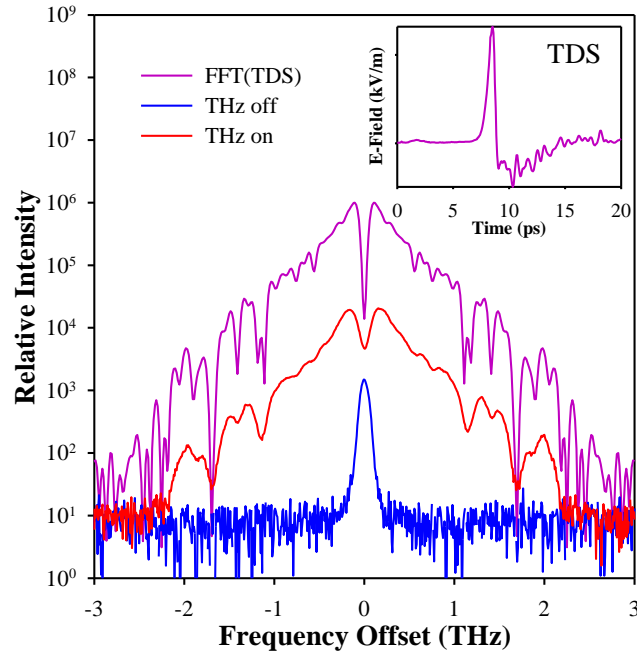
All-optical amplification of probe retaining optical time-structure

All-optical self-referenced measurement of optical profile ‘standard’ laser technique, 10fs resolution

- 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

EO-Transposition

Probe spectrum



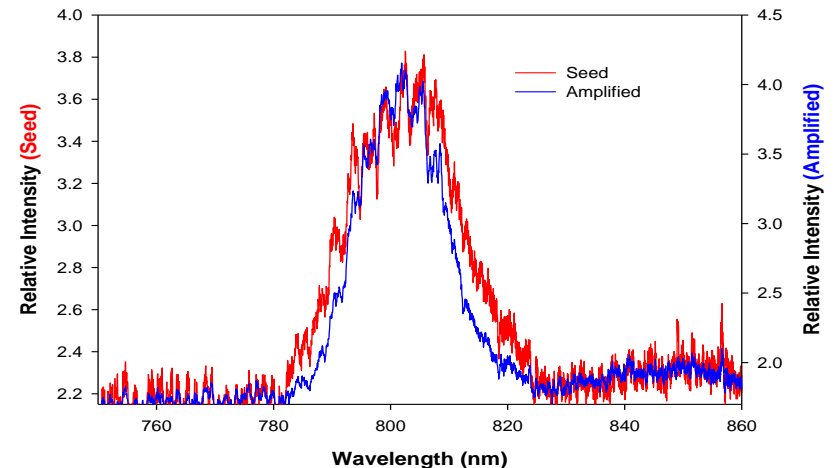
Probe Amplification

- Gain of 10^3 @ pump intensity 360 MW/cm^2
- New design permits $>1.7 \text{ GW/cm}^2$ pump i.e. *gain of 6×10^9 !*
- Restricted by optic damage threshold..., **realisable probe gain maximum is $\sim 10^6$**

Gain of 10^3 achieved

Gain approaching 10^6 possible

Bandwidth supports $<40\text{fs}$ FWHM probe



Input probe

'Coulomb' spectrum
from optical probe
Pulse energy $\sim 470\text{pJ}$

Independent measured
pulse profile & spectrum

FROG measurement of probe : demonstrated

EO material bandwidth : multiple crystal solution. To be demonstrated 2017

EO spectral decoding on CLEAR

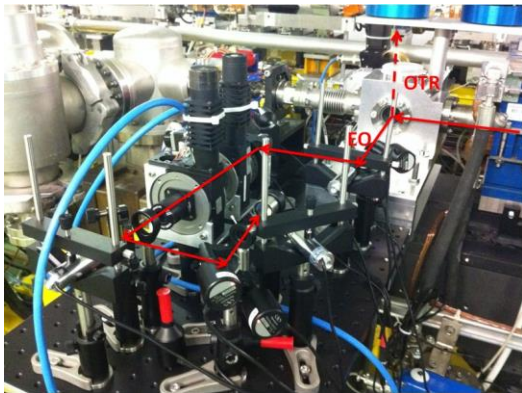
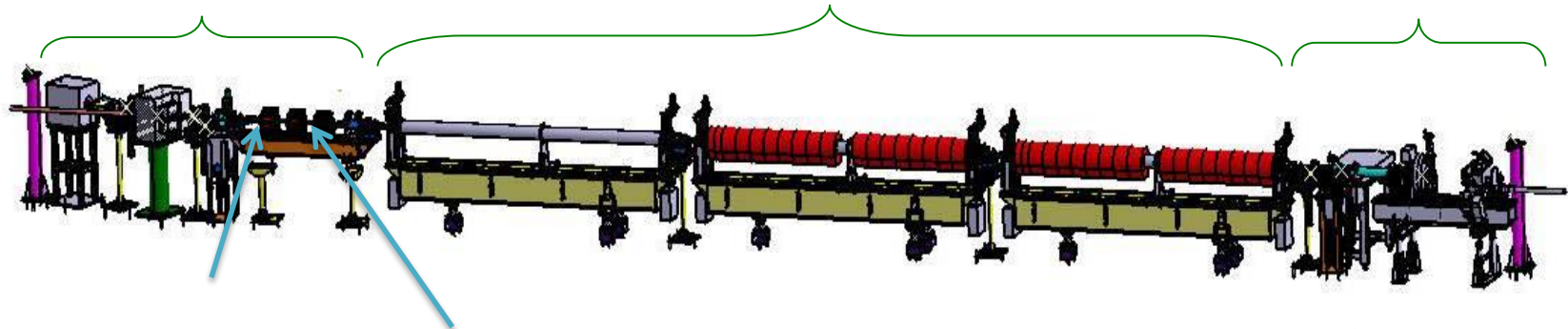


Layout 03 Mar. 2010

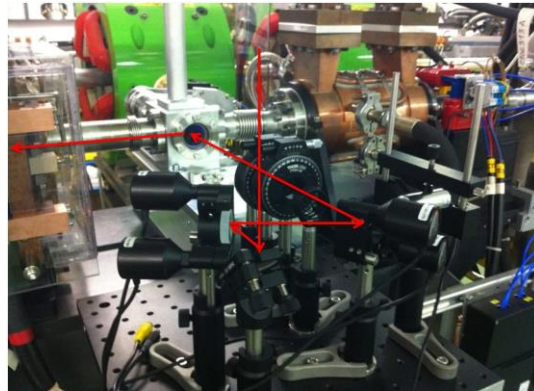
Diagnostic section

Accelerating structure

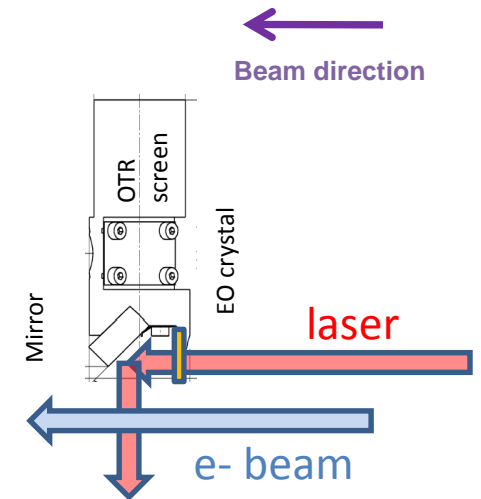
Photo-injector



Laser extracted & sent to remote spectrometer by fibre optic

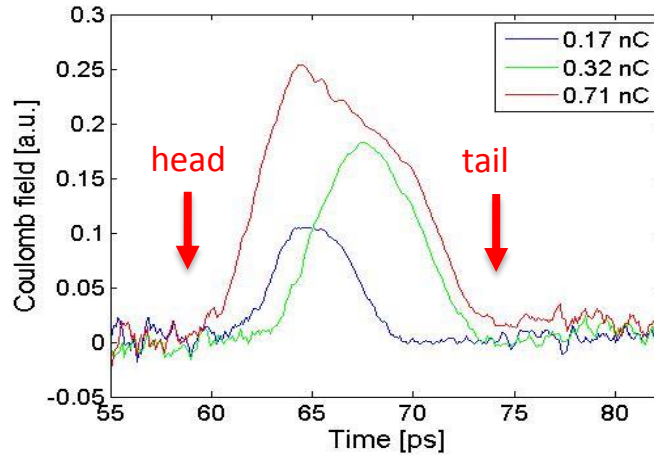


Laser injected into beamline



EO spectral-decoding on CLEAR

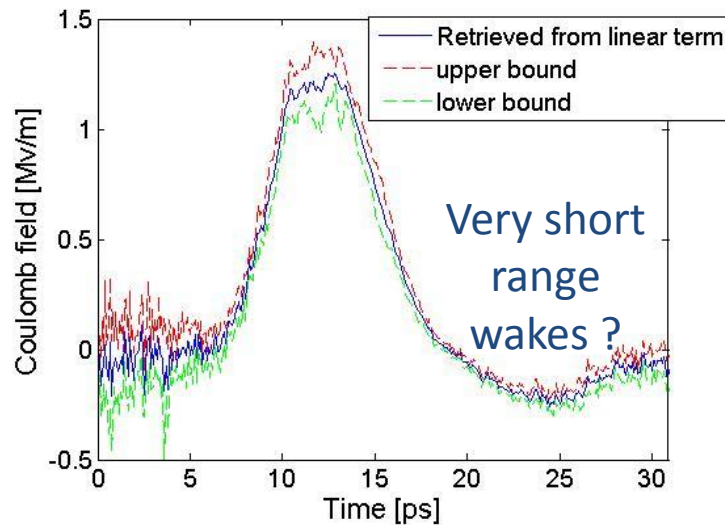
Bunch profile
as function of
charge



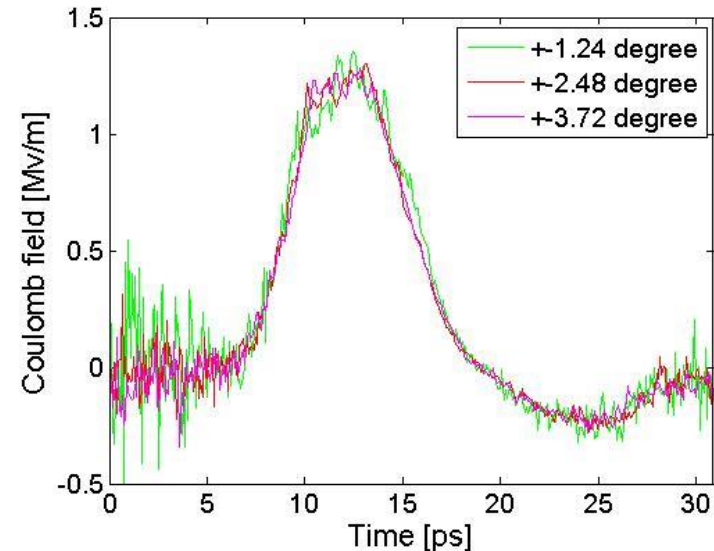
Courtesy Rui Pan

Absolute field strength

Multi-measurement calibration



'2-shot' calibration



Electro-optic diagnostics

Widely used for measurement of ultra short longitudinal profiling of beams, and accelerator radiation sources

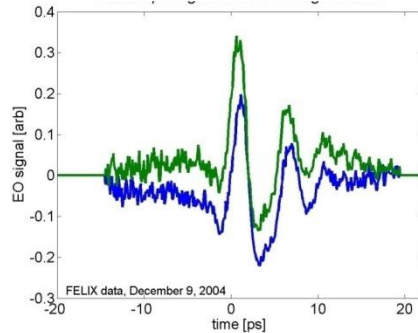
Many demonstrations...

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

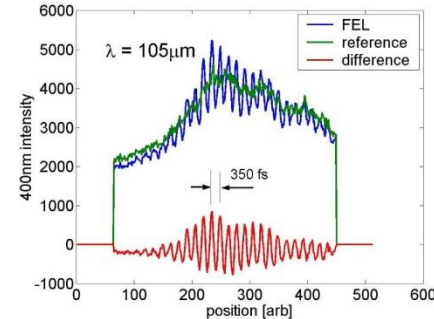
Temporal Decoding @FLASH



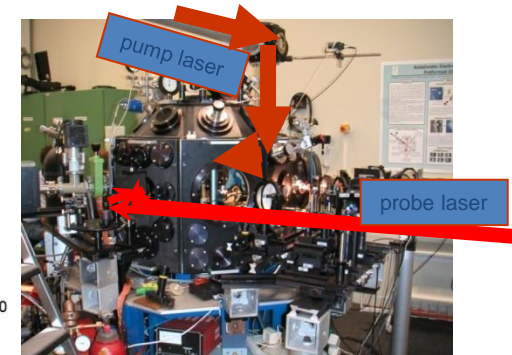
CSR @FELIX



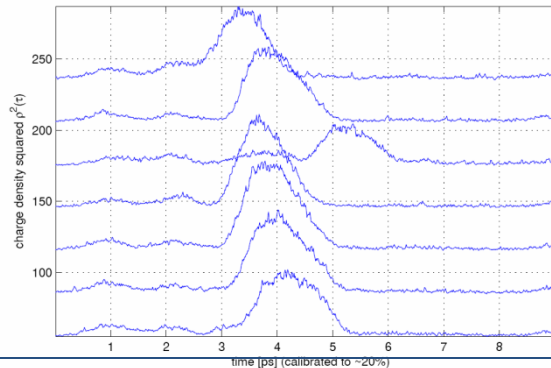
Mid-IRFEL lasing @FELIX



Laser Wakefield @ Max Planck Garching



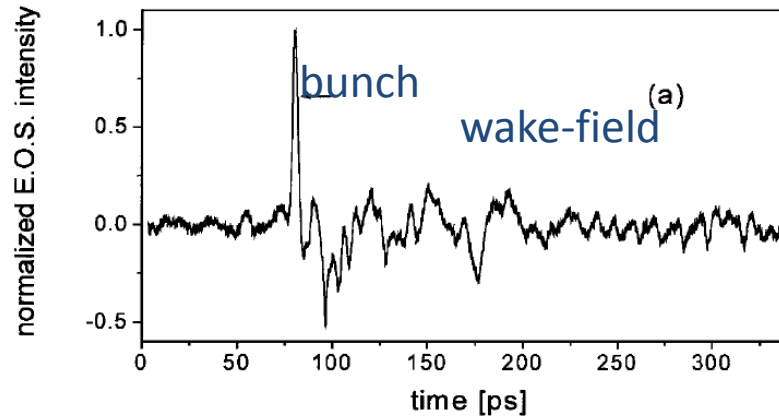
Spectral Decoding @ ALICE / STFC



Electro-optic diagnostics for wake-field characterisation

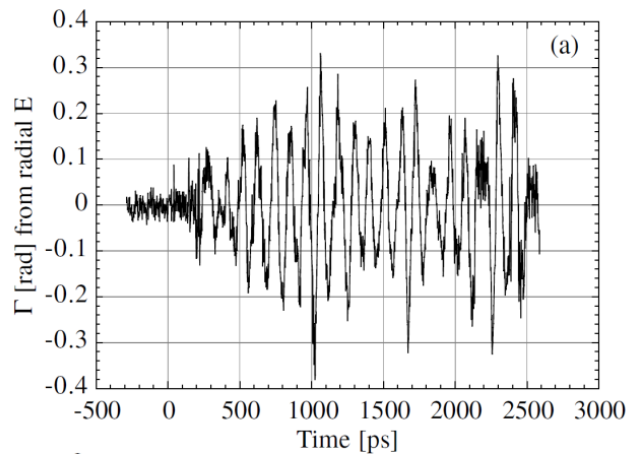
Not a new idea

Yan, Phys. Rev. Lett. (2000)

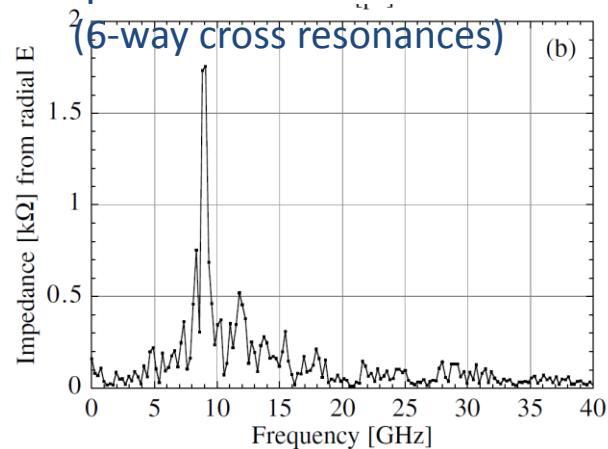


Scanning laser-bunch timing

Fitch, Phys. Rev. Lett. (2001)

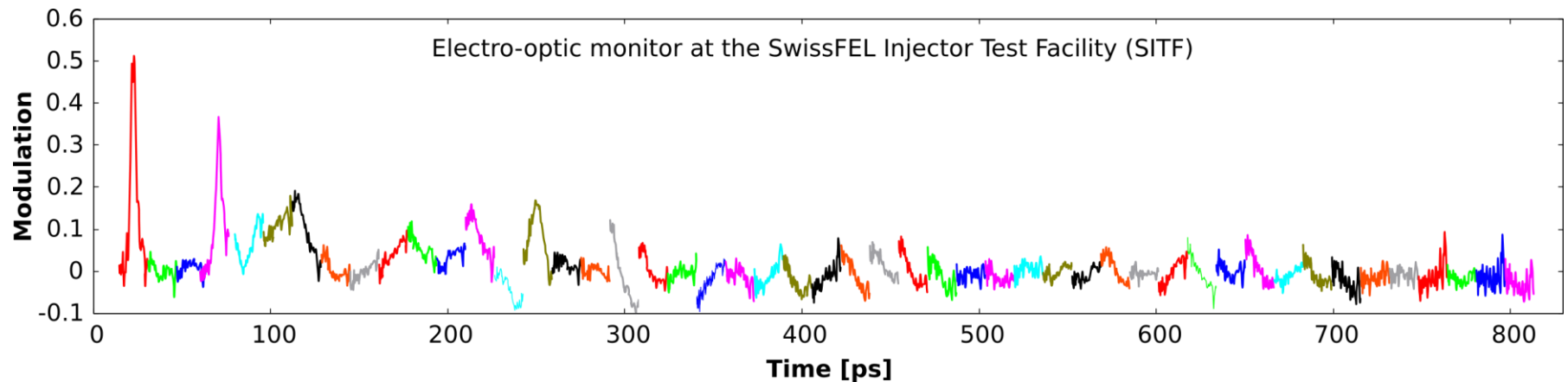


Spectrum from transform



EO measurement of wake fields in Swiss Injector test facility

EO spectral decoding, stepped in time to give longer range wakes



Courtesy Yevgeniy Ivanisenko, PSI

Presented at PSI workshop on Longitudinal diagnostics, Jan 2015

From time-resolved electric field to wakefield impedance

EO detection is polarisation sensitive:

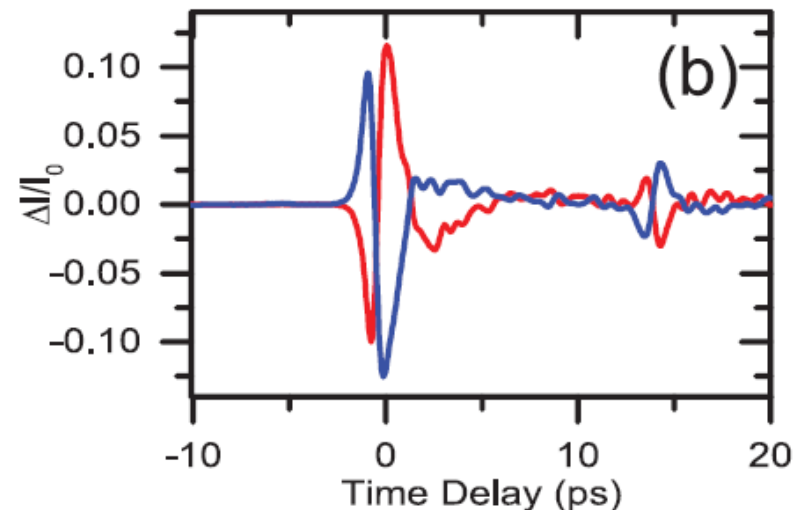
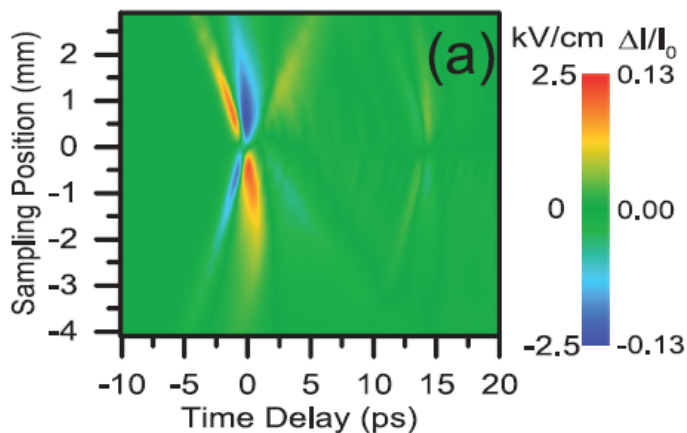
- Most commonly sampling transverse field near wall
 - Longitudinal field can be (has been) measured with suitable optics/crystals
 - Magnetic field can be sampled in similar manner (different crystals)
-
- Sample transverse and longitudinal fields at wall, & infer field on-axis (approach of Fitch et al)
 - Directly measure the field distribution – EO imaging
 - positioning of EO detector within beam pipe
 - imaging of ‘reflected’ wake fields (OTR screen)

Transverse profile and field-polarisation

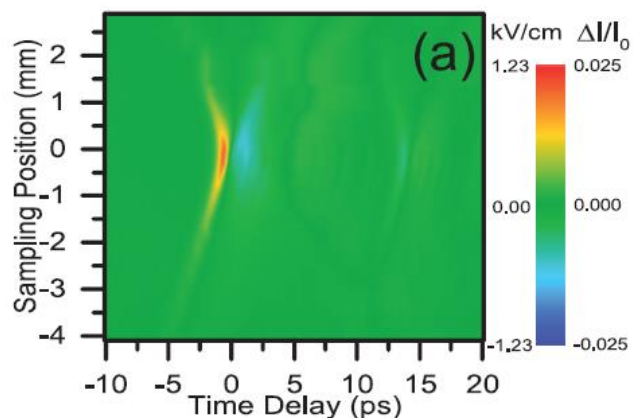
EO characterisation of TEM₁₀-like mode from radial antenna

Appl Phys Lett 105, 191112 (2014)

Transverse field



Longitudinal field



- Imaging is possible single shot, but challenges in signal-noise
- Multi-shot imaging possible on CLEAR (time resolution limited by synchronisation)

In summary

- Electro-optic spectral decoding system in place on CLEAR
- Potential to measure wake fields directly, with picosecond resolution
- EO spectral upconversion able to measure spectral information directly
- Nanosecond laser developments for CLIC 'EO-Transposition' could enable single-shot long-range (100's ps) Wakefield spectra measurement
- 3D EO imaging demonstrated in lab – potential for application on CLEAR

High gradient acceleration or manipulation using laser and beam generated THz fields

Very high fields strength possible

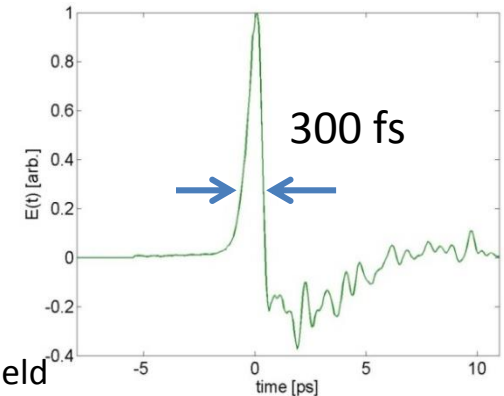
- > 100 MV/m achievable with 'standard' techniques
- 5GV/m reported (Paul Scherer Institute)

Direct control of electric field profile

standard laser temporal shaping → frequency / phase control of THz field

Picosecond period well matched to accelerating of <100 fs bunches

standard laser temporal shaping → frequency / phase control of THz field



Typical measured $E(t)$

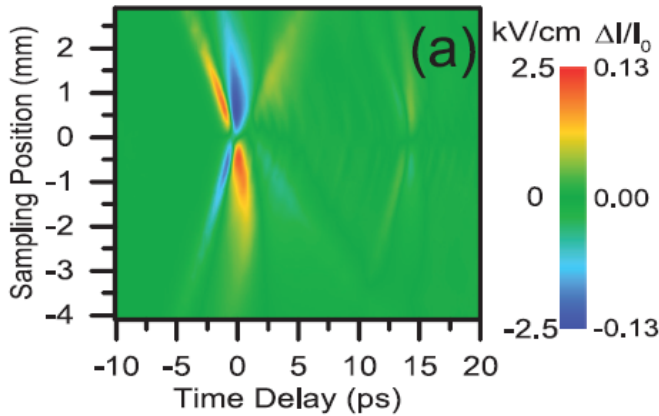
Challenges

- Generation & coupling of accelerating (transverse) mode
- Managing broadband pulses,
dispersion control; velocity matching of THz to particle: $V_{\phi} = \beta$
- **Wakefields, beam-loading,**

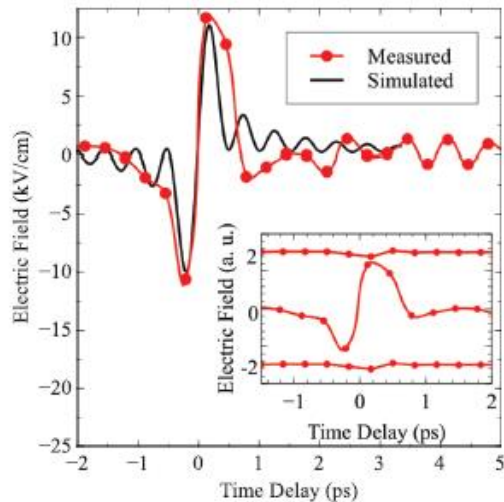
Demonstrations and experiments needed with relativistic beams

Generation of single-cycle TEM₁₀ modes

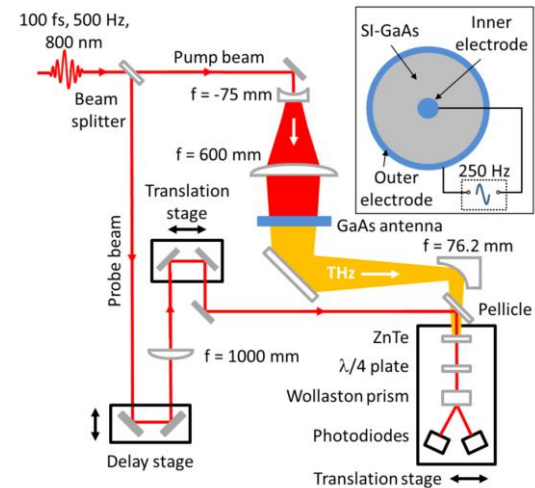
Transverse field



Longitudinal field

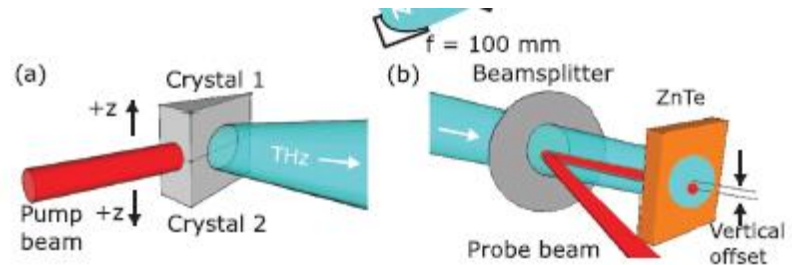


Laser excited antenna approach



Appl Phys Lett 105, 191112 (2014)

Non-linear optics approach



Appl Phys Lett 108, 221102 (2016)

Waveguide coupling

Design, simulation for coupling and velocity matching THz source

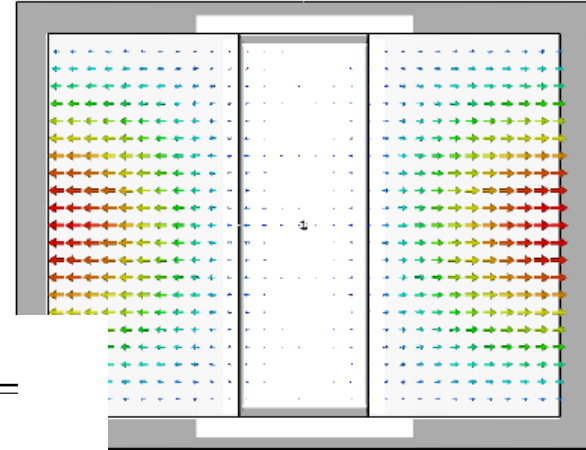
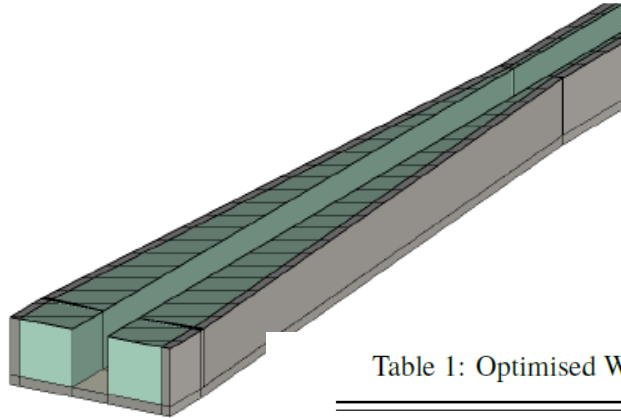


Table 1: Optimised Waveguide Parameters

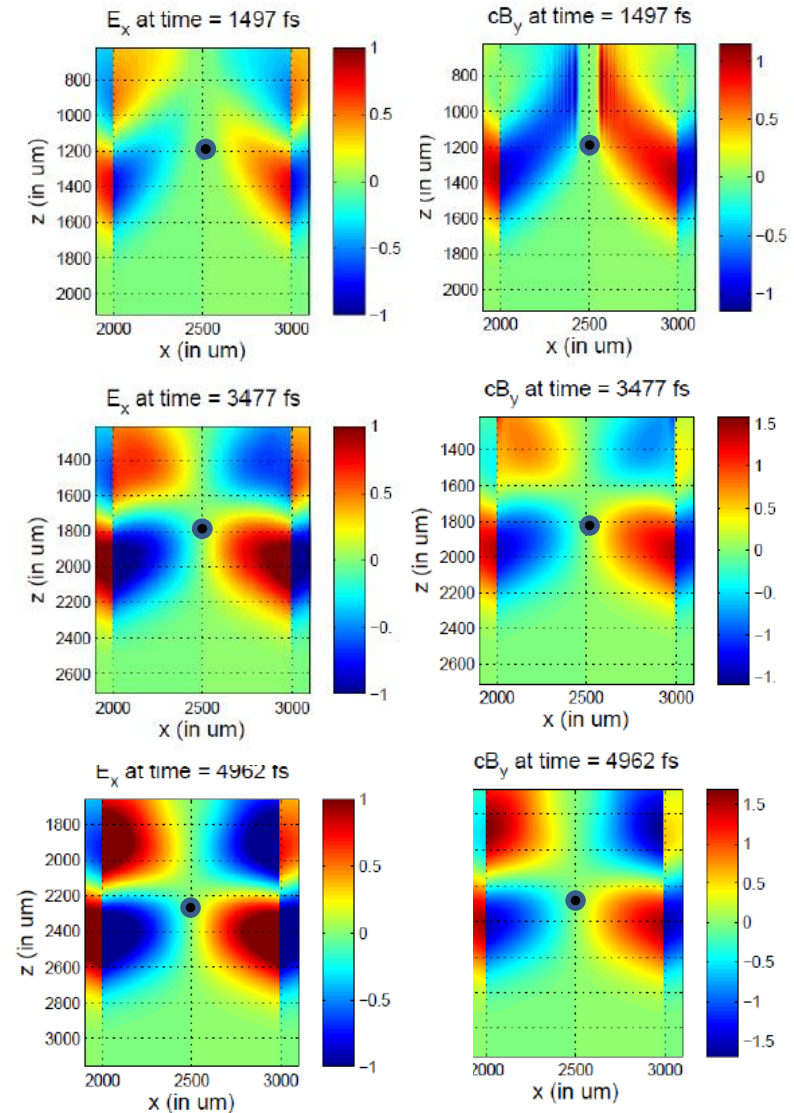
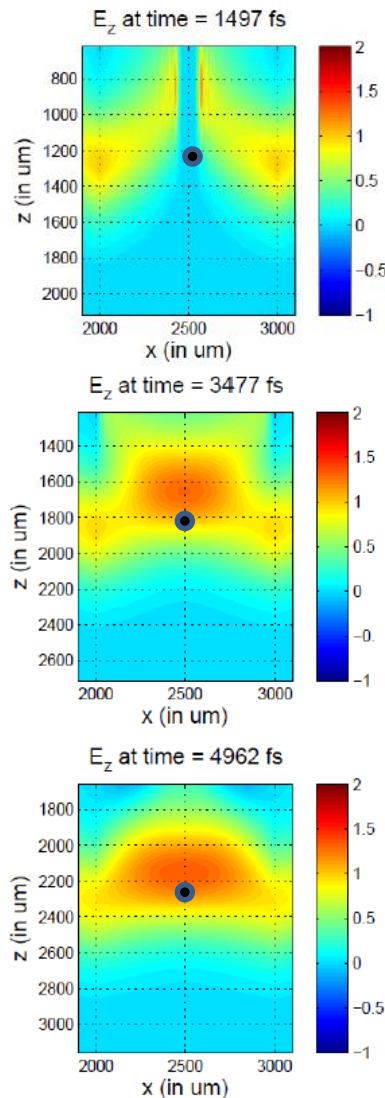
Operating frequency, f_{op}	0.784 THz
Dielectric slab separation, $2a$	$200 \mu\text{m}$
Width, w	$600 \mu\text{m}$
Dielectric slab thickness, t	$30 \mu\text{m}$
v_p/c	1
v_g/c	0.4
r_s	$167 \text{ M}\Omega \text{ m}^{-1}$
r_s/Q	3.28
Δf	5.8 GHz

Next steps... manufacture
laser-lab testing of coupling & propagation
with-beam testing

2D FDTD simulation of field evolution

Accelerating fields

Deflecting fields



Time

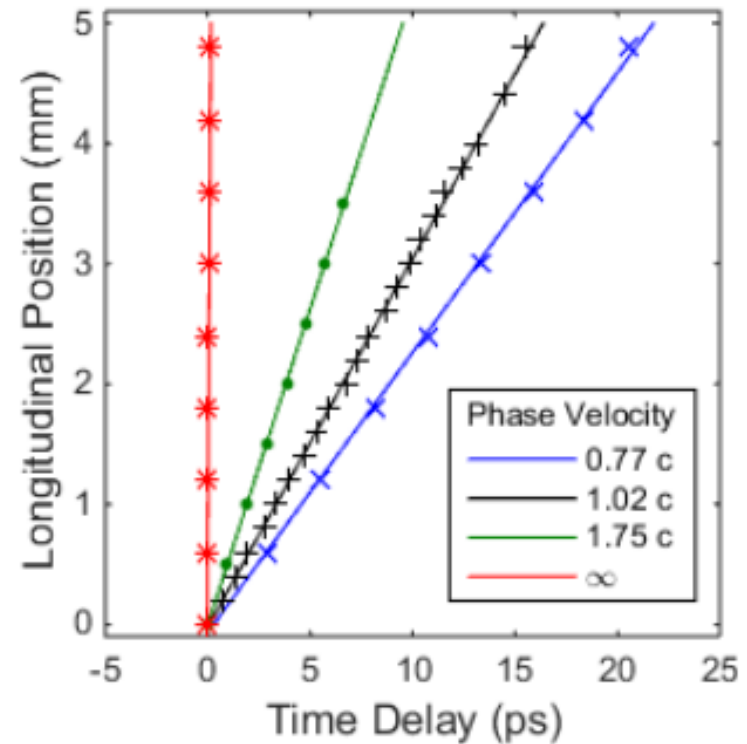
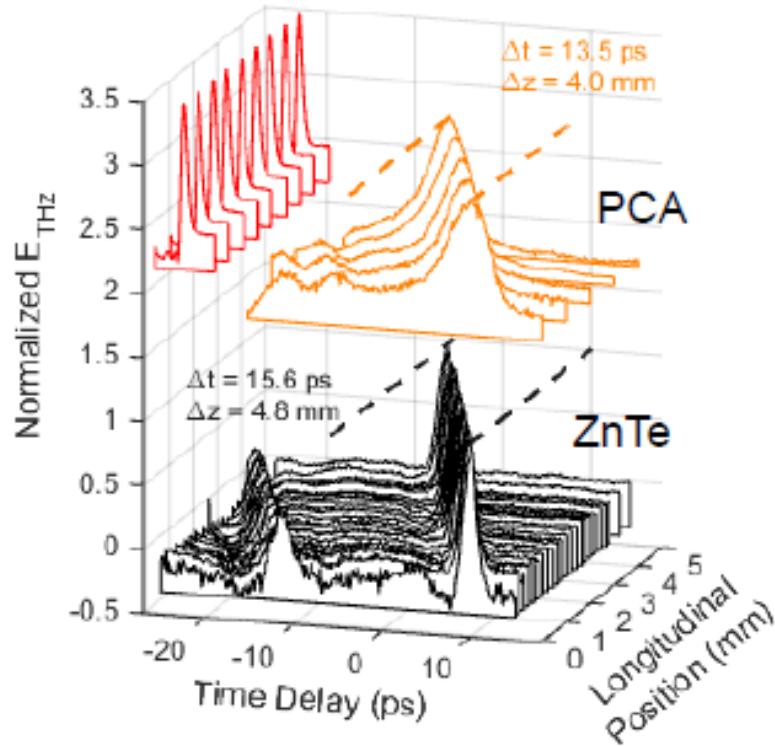
$\beta_{\text{frame}} = c$



THz 'Travelling source'

High gradient acceleration 0.1-1 GV/m
Compact transverse deflection structures

Measurement



THz 'Travelling source' Deflector

20 fs resolution with 1cm structure

Simulation based on laser-lab demonstrated source/structure

10MV/m THz source, travelling wave configuration
200MeV electron beam
1cm interaction, 1 metre drift

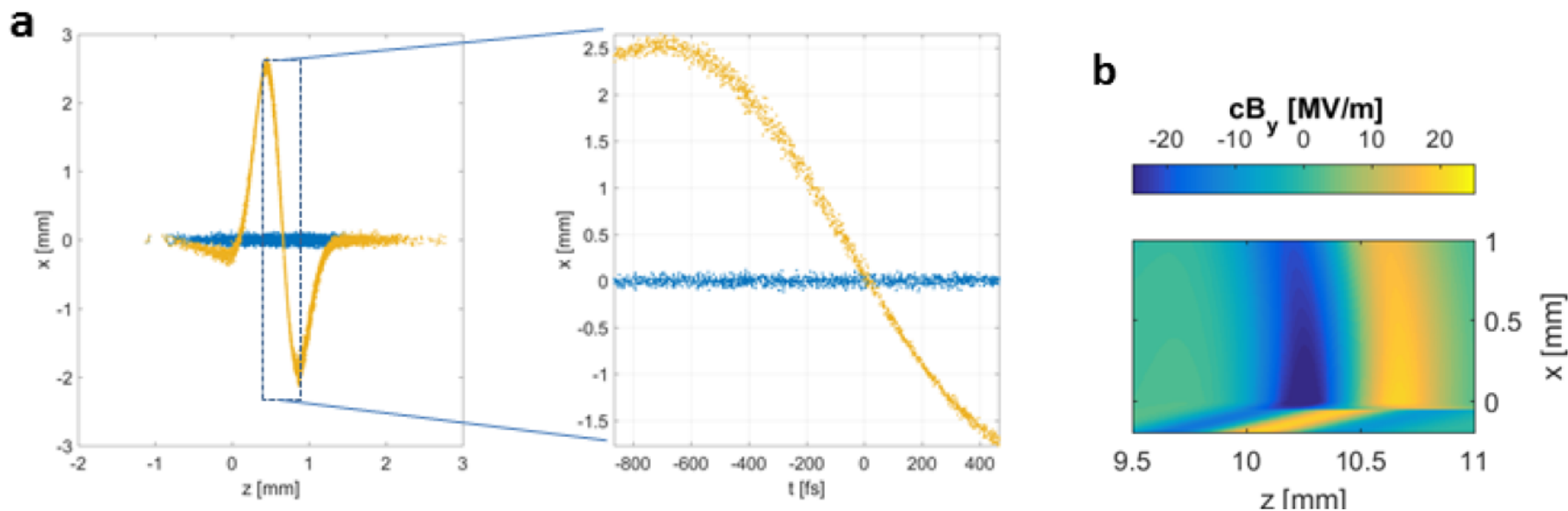


Figure 2: (a) simulated deflection imposed on a 200 MeV, $\varepsilon = 0.3$ mm.mrad beam with a 1 cm interaction region and a 1 metre drift. Blue: without THz pulse. Orange: with a 10 MV/m THz source driving the interaction. (b) FDTD simulations of the magnetic field produced in the vacuum region by a travelling wave THz source.

A potential CLEAR programme

Demonstration of high gradient Dielectric and THz acceleration & deflection

Includes both THz and dielectric laser acceleration schemes

Programme goals: Demonstration of MeV acceleration & > 10 MeV/m gradients
Wakefield measurement / benchmarking & mitigation
Understanding beam-loading in the new regime of few-cycle acceleration

Collaboration across Cockcroft Institute (STFC, Lancaster, Manchester, Liverpool Universities) & with University of Rome/ INFN and Paul Scherer Institute

2017/2018: THz driven deflector for ultrafast beam diagnostics

Experiment specific hardware

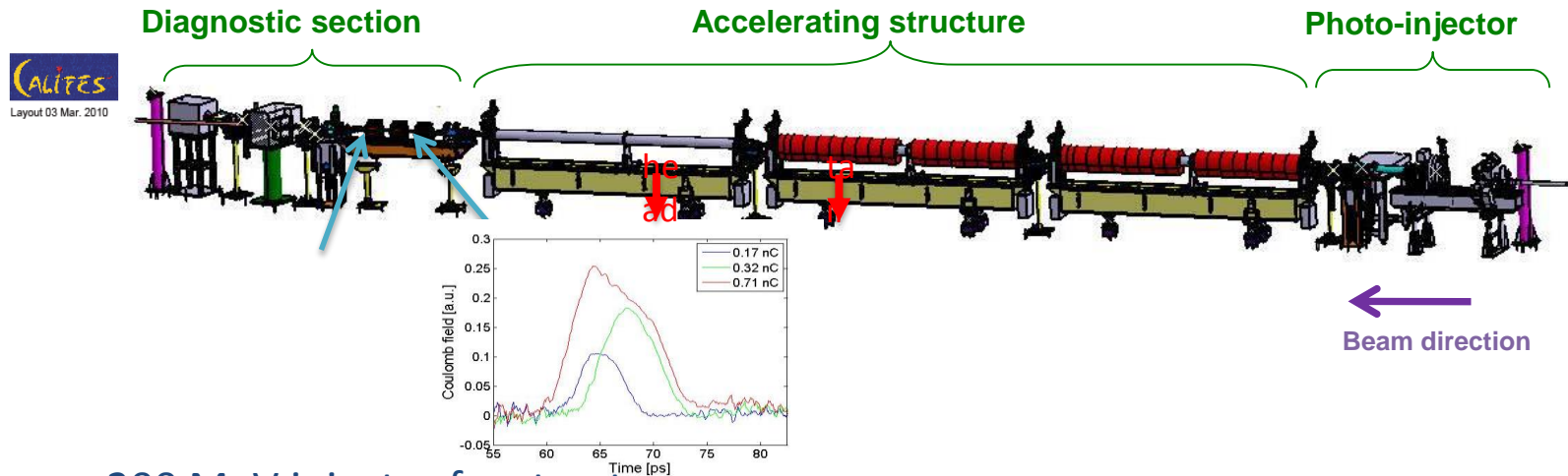
- design/build/test in UK, install for experimental runs
- additional diagnostics with potential use in wider wakefield projects

Immediate challenges: Establishing the few-mJ class laser at CLEAR

2017: collaboration with M Petrarca Uni Rome for THz CTR electro-optic characterisation (establishing synchronisation and THz detection systems)

2018: ready to install THz deflection experiment at CLEAR (*dependent on laser availability*)

What CLEAR has to offer



- 200 MeV injector for structures
- Existing few-ps bunch suitable
 - velocity bunching upgrade to <1ps desirable
- Suite of beam diagnostics – energy, charge, position, temporal diagnostics, ...

Additional infrastructure requirements

Laser (*modest - not a laser-plasma scale system: 2-20mJ, 100fs pulses*)

Laser transport

Interaction chamber / location

initiatives in similar concepts at PSI, KIT, DESY, ... potential for wider European testbed

In summary

- CLEAR excellent platform for laser & THz acceleration/deflection development.
- Additional infrastructure (laser) needed in place to begin in earnest
Alternative uses and users for laser sought.
Photoinjector developments? plasma ionisation?
- *Experimental systems being progressed at STFC Daresbury Lab and elsewhere; potential to install experiments at CLEAR 2018*

extras

Laser and THz acceleration for sub-ps beams

Radio frequency

- Frequency ≈ 3 GHz
period ≈ 300 ps,
- $\lambda \approx 10$ cm
Cavity aperture ~ 2 cm
- $E_{acc} \sim 10$ - 100 MV/m
- Pulse length: 5 ms (superconducting)
5 μ s (normal conducting)
- Energy to cavity: ~ 10 J

THz

- Frequency ≈ 1 THz
period ≈ 1 ps,
- $\lambda \approx 300$ μ m
Cavity aperture ≈ 1 mm
- $E_{acc} \approx 100$ MV/m to \gg GV/m
- Pulse length 1-5 ps
- Energy to 'cavity': ~ 10 -100 μ J

THz advantages:

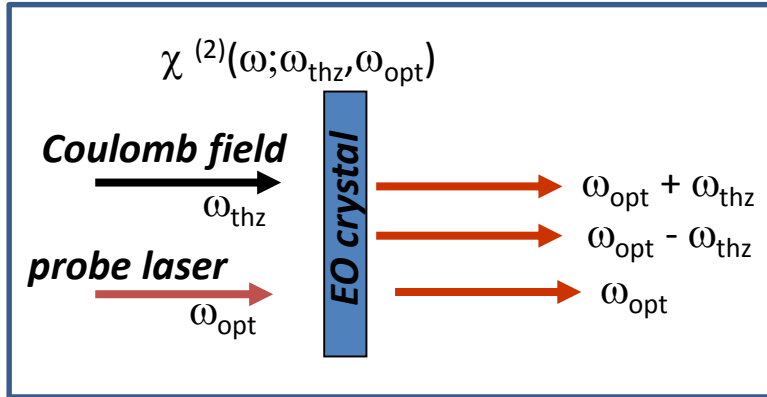
- pulse duration \sim bunch duration (energy efficiency)
- Very high field strengths possible (material breakdown); compact accelerators
- Oscillation period short, *but longer than desired pulses*

THz disadvantages:

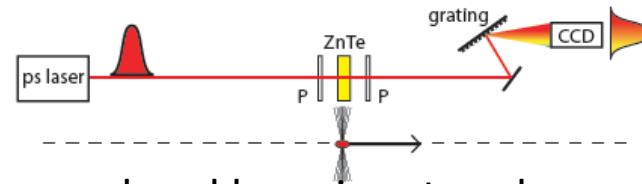
- Broadband pulses – controlling dispersion
- *Small apertures: wakefield perturbations on beam; injection & extraction beam transport*

Spectral upconversion

Direct measurement of spectral content



Spectral upconversion



Narrow band laser input probe:
spectrum of interacting field imposed onto laser

Creating optical pulse replicating wakefield

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

Wakefield oscillation replicated
in optical pulse

Equivalently...

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

wakefield spectrum shifted to optical region

Essentially heterodyne detection, but at higher frequency