Electro-optic techniques for bunch-length monitoring and synchronisation

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Structure of talk:

- Brief summary of techniques
- Experiments at FELIX and FLASH
- Limitations and potential
- Other group activities
- Immediate future plans

Dundee-Daresbury Diagnostic Group

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Collaborators:

G. Berden, B. Redlich, A.F.G. van der Meer (FELIX)

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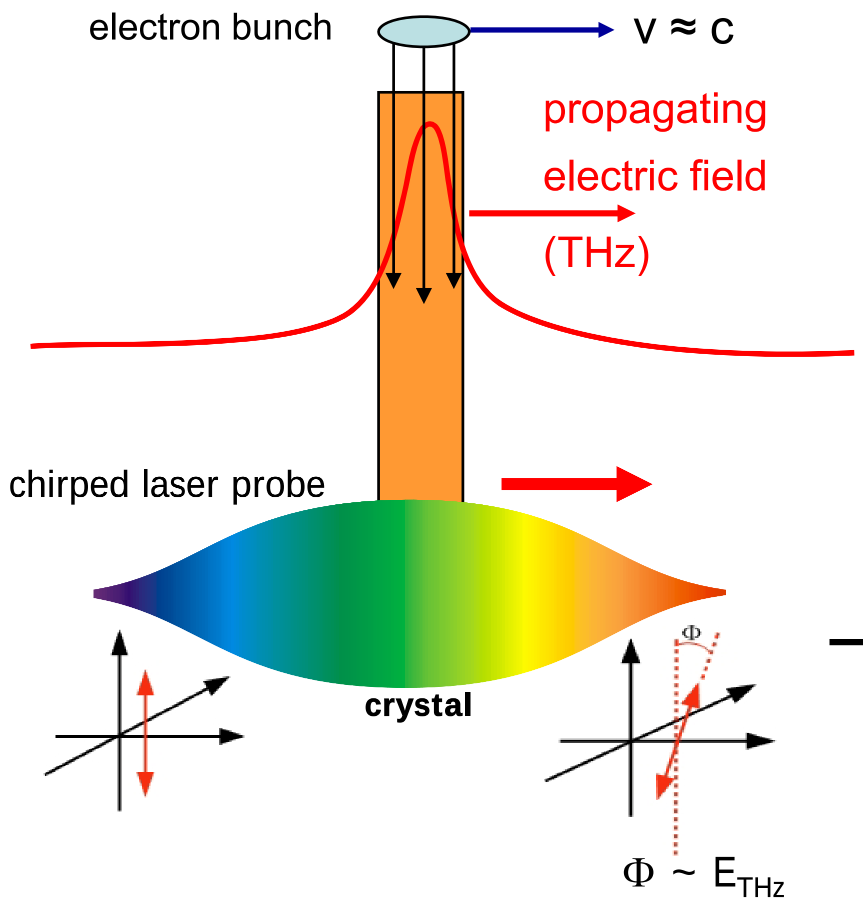
E-O longitudinal bunch profile measurements

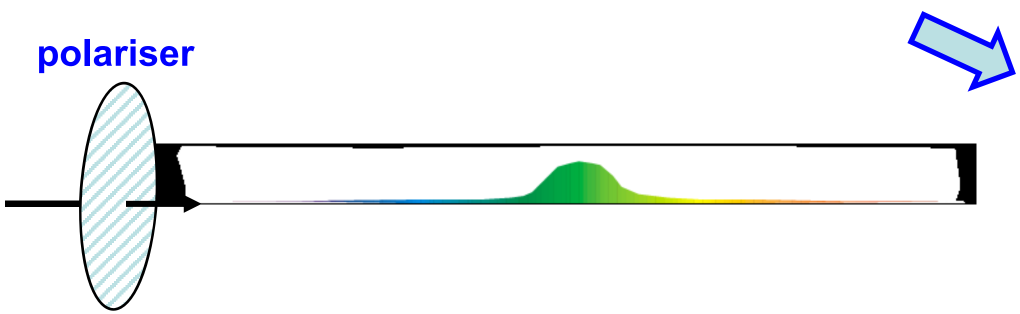
Principle: Convert Coulomb field of e-bunch into an optical intensity variation

Encode Coulomb field on to an optical probe pulse - from Ti:Sa or fibre laser



Decoding: via single-shot cross correlation in a BBO crystal

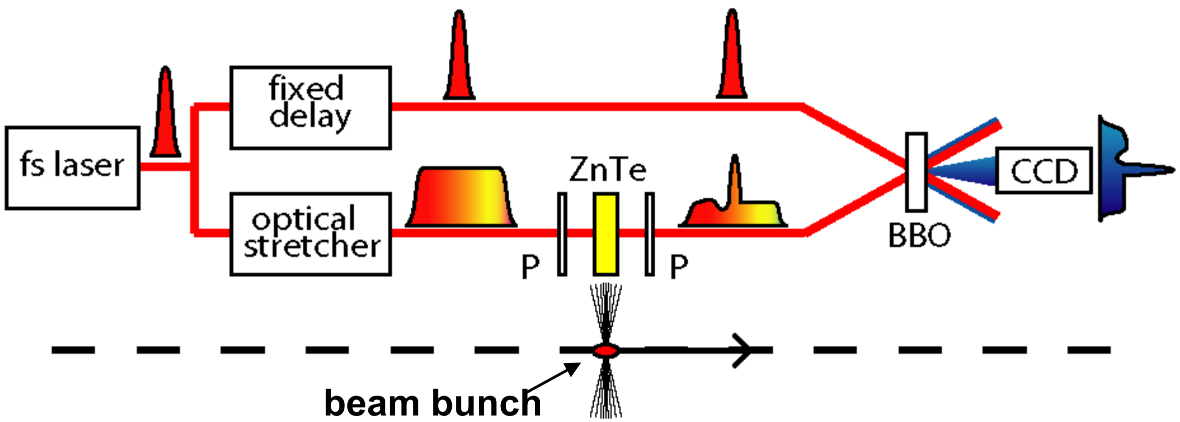
yields the temporal intensity variations in a single laser pulse



(FELIX & FLASH)

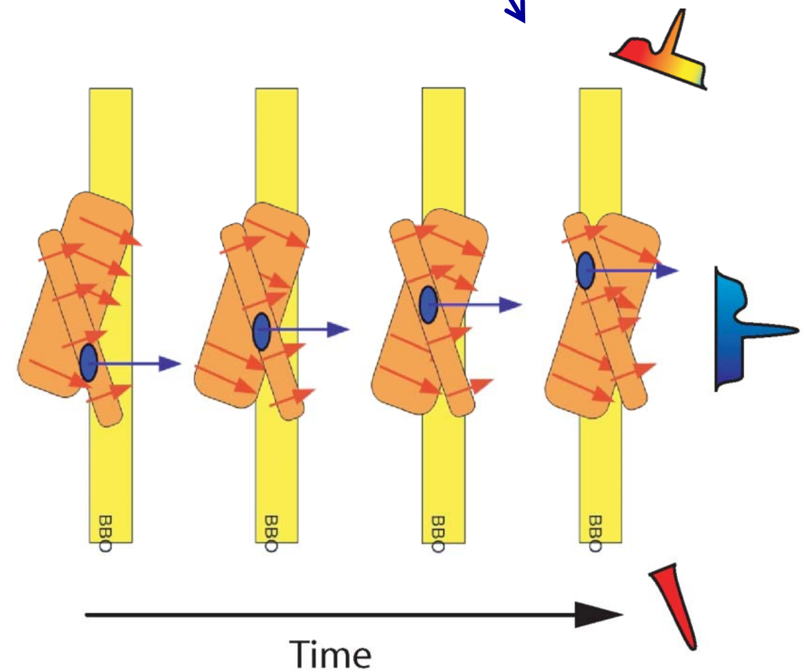
Detect polarisation rotation proportional to E or E^2, depending on set-up

Single-shot Temporal Decoding (EOTD) (gives best time resolution)



Temporal profile of probe pulse →

Spatial image of SHG pulse



- *stretched & chirped* laser pulse leaving EO crystal assembly measured by short laser pulse via single-shot cross correlation in BBO
- ~1mJ laser pulse energy required (Ti:Sa amplifier)

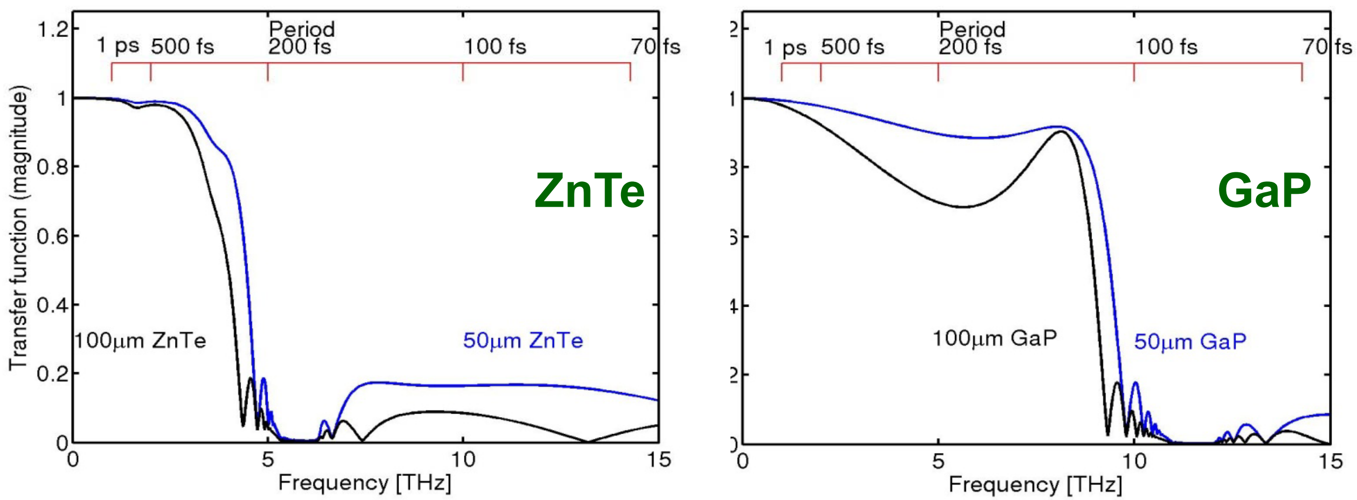
Or Spectral Decoding (simpler)

... but suffers from artefacts at high frequencies

Improved time resolution

Originally used ZnTe as E-O crystal – Latest FLASH measurements used GaP

Possible improvements using different inorganic/organic materials .... ?



electro-optic crystal response function

$$G(f,d)=\frac{2/d}{1+n(f)+ik(f)}\int_0^d \exp\left(i2\pi fz\left(\frac{1}{V_{ph}(f)}-\frac{1}{v_g}\right)\right)dz$$

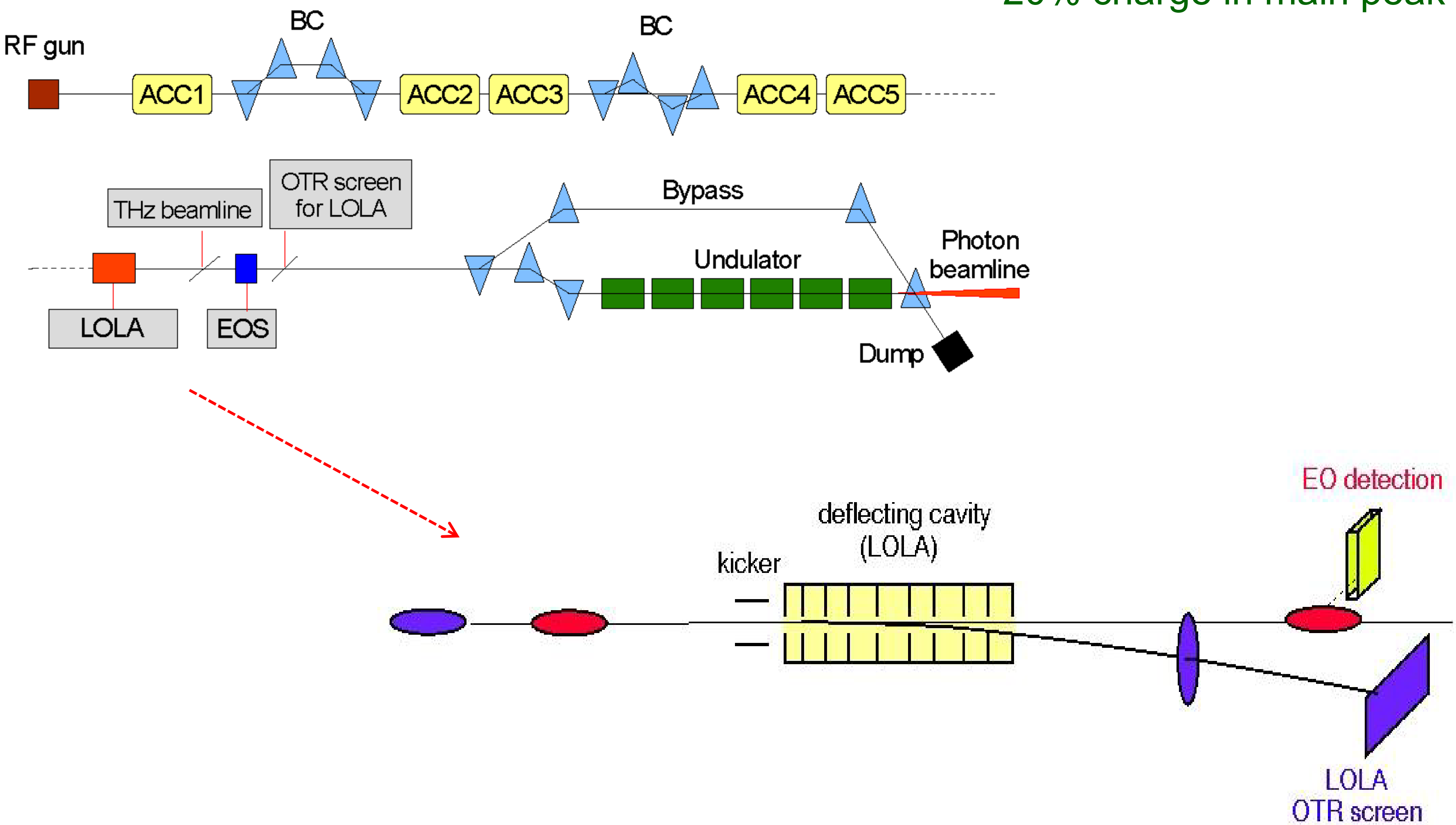
Temporal resolution fundamentally limited by :

- crystal phonon resonance(s)
- crystal dispersion
- phase mismatch

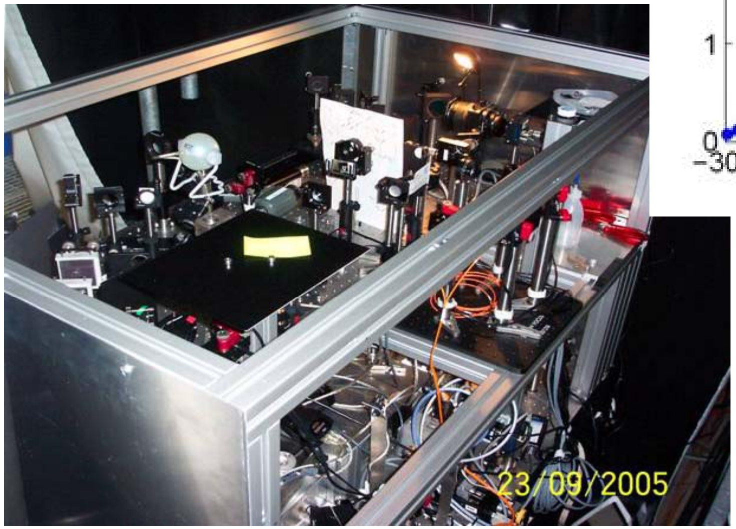
$\Big\}$ between Coulomb (THz) and laser (optical) fields

Benchmarking EO at FLASH against TDS (LOLA) cavity

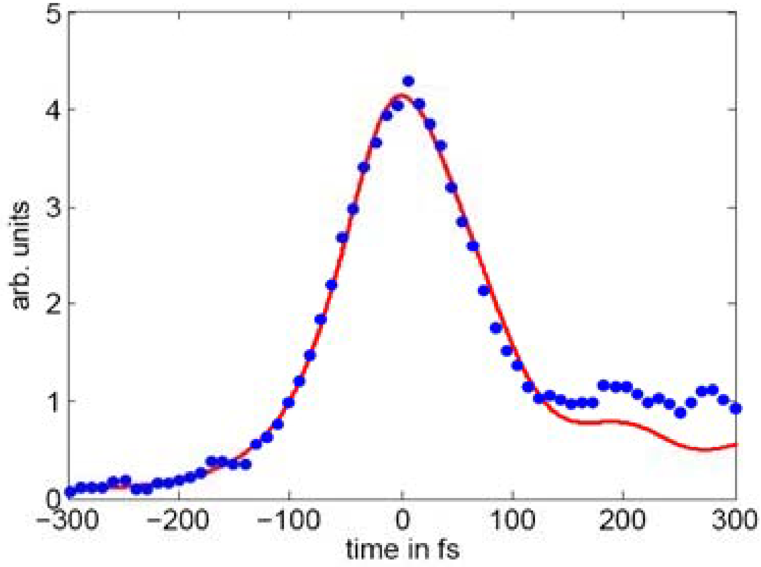
E = 450 MeV, q = 1nC
~20% charge in main peak



EOTD experimental setup at DESY FLASH and some results

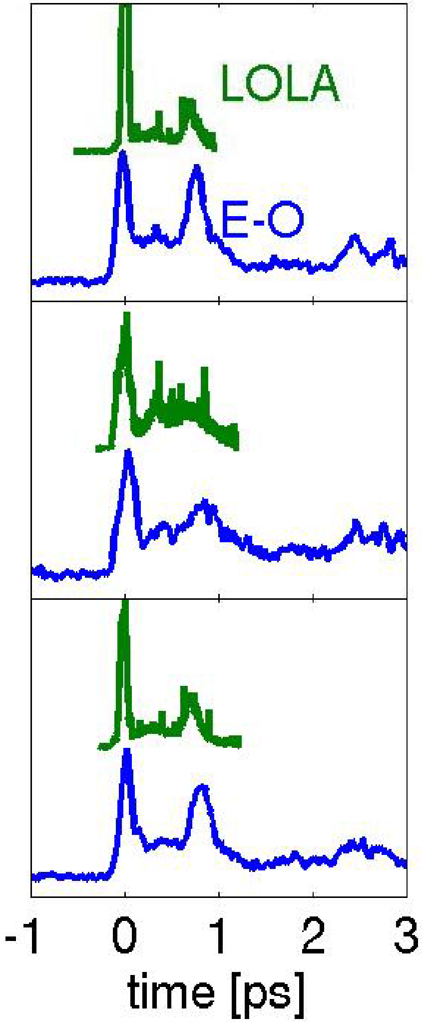


Optimum compression
Fitted Gaussian curve
sigma = 79.3 ± 7.5 fs



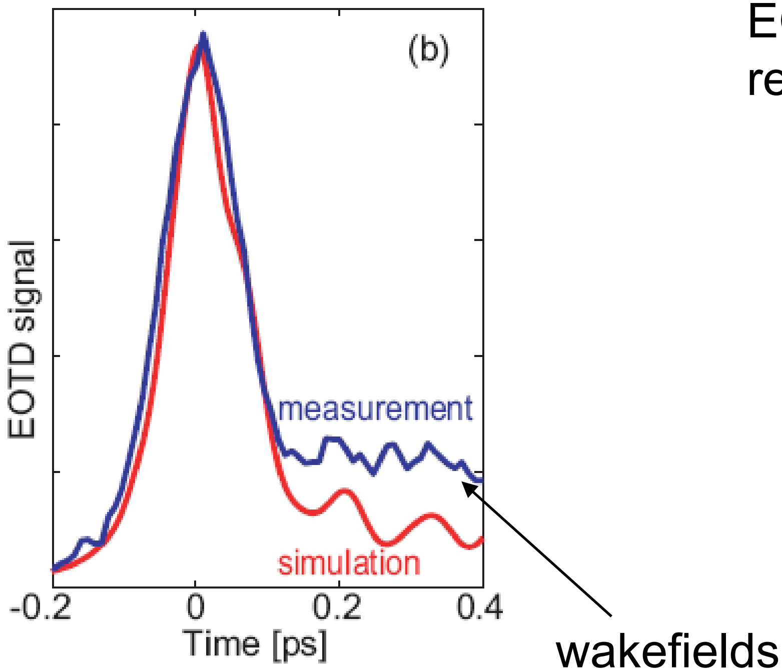
- 140m point on FLASH
- beam energy 450 MeV
- <u>after</u> LOLA TDC

with FLASH bunch compressors detuned

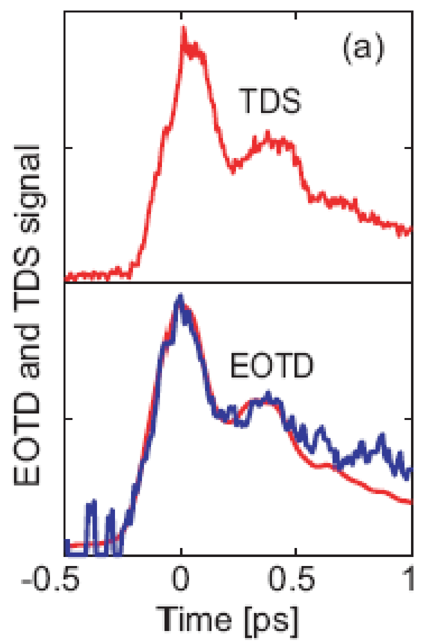


Physical Review Special Topics - Accelerators and Beams 12, 032802 (2009)

[Major review of the field with colleagues at FLASH and FELIX]



EO measurements of longitudinal bunch profile resolving σ_z ~ 60 fs (rms) bunch structure



Transverse deflecting cavity (destructive)

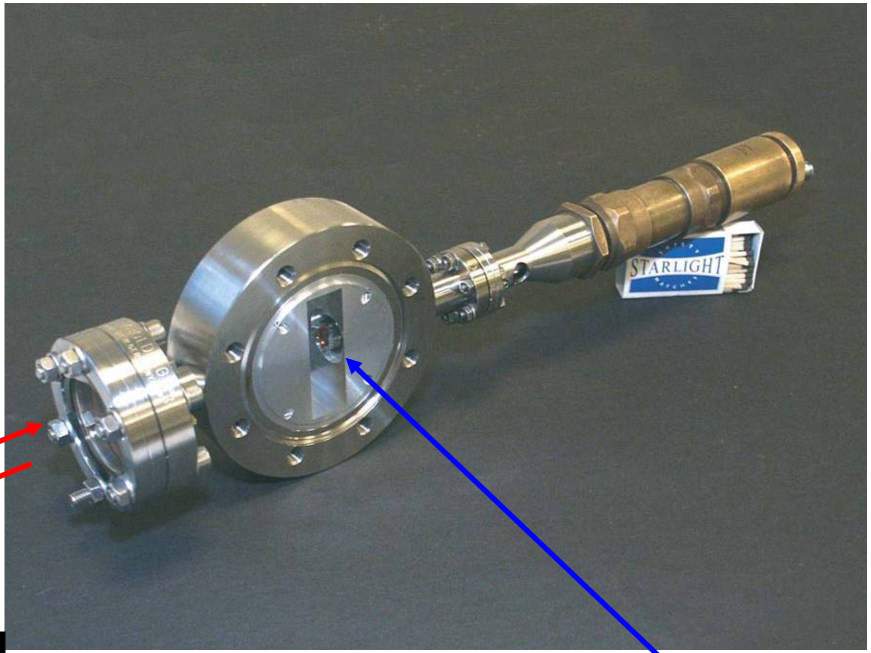
EO temporal decoding (non-destructive)

First ever detailed benchmarking (PRL 2007) of EO against a Transverse Deflecting System (TDS)

EO compact probe head (FELIX)

EO Technique is non-destructive and compact

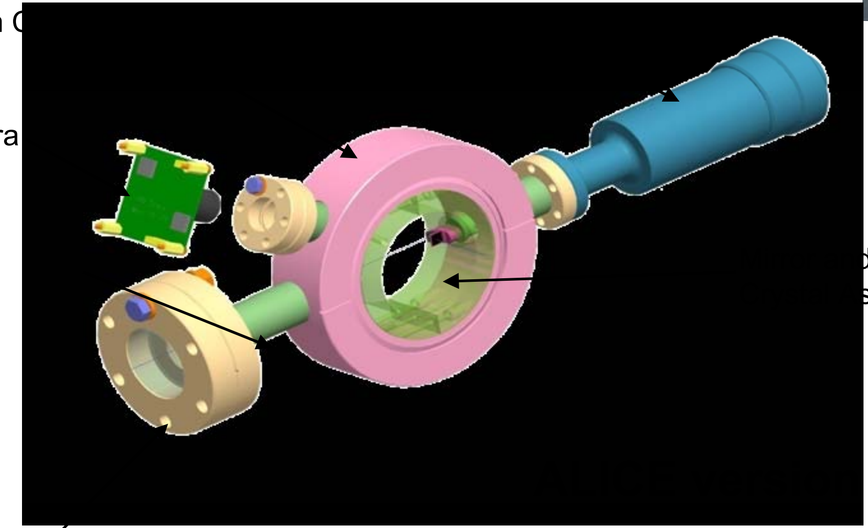
(requires 50 - 200 mm longitudinal space)



electron beam

Vacuum C

Camera



d

ssy

(Daresbury Laboratory, UK)

Laser Exit Port

Range of Facilities used in EO measurements

FELIX : **FOM Institute 'Rijnhuizen', The Netherlands**

- Coulomb field characterisation [PRL 2004]
- Diagnostic capability tests using FEL radiation
- single-shot EO measurements of CSR time profile
- Experimental EO Techniques

FLASH : **DESY, Hamburg**

- Coulomb field characterisation of electron bunches
- First benchmarking against TDS (LOLA cavity)

ALICE : **Daresbury, UK**

- Coulomb field measurement / diagnostics development

Alpha-X : **Strathclyde University, Glasgow, UK**

- Plasma Wakefield electron energy measurements, plus EO

Laser Wakefield:

- Max Planck Institute for Quantum Optics, Garching
- University of Jena
- Central Laser Facility, Rutherford-Appleton Laboratory

Can we achieve even better resolution ...?

- Coulomb angle limitation: $1/\gamma \sim 50$ fs for $\gamma \sim 1000$

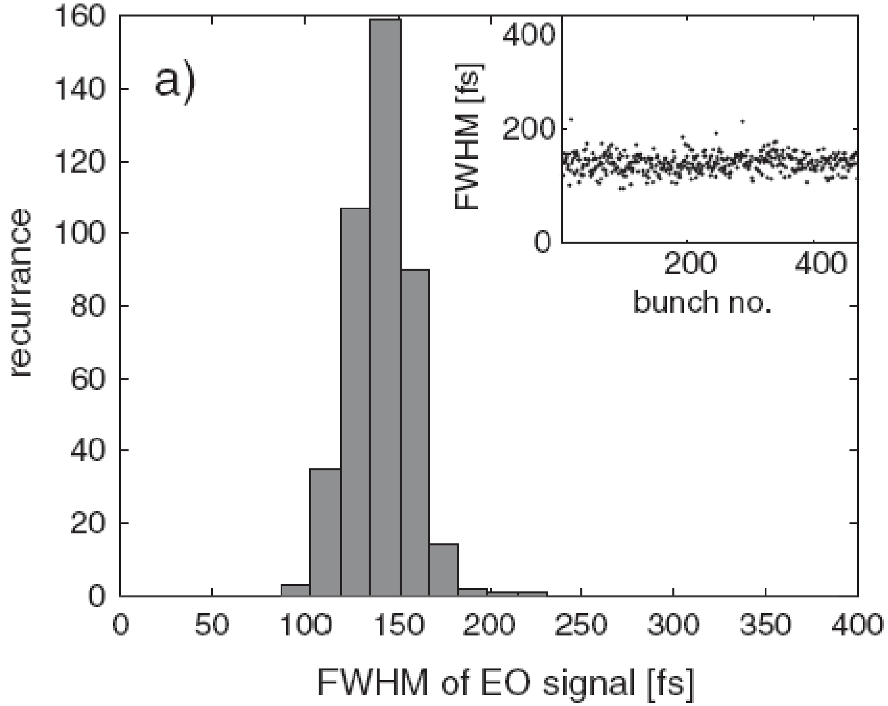
- Detector Material:
  - GaP $\geq 80\, fs(rms)$
  - Move to new material? (phase matching, $\chi^{(2)}$ considerations)
  - Could use GaSe, DAST, MBANP ..... or poled organic polymers?

- Gate pulse width ~ 50 fs
  - Introduce shorter pulse
  - Use spectral interferometry
  - Use FROG Measurement (initially attempted at FELIX, 2004)

- These methods will be tried on ALICE at Daresbury and other suitable facilities ...

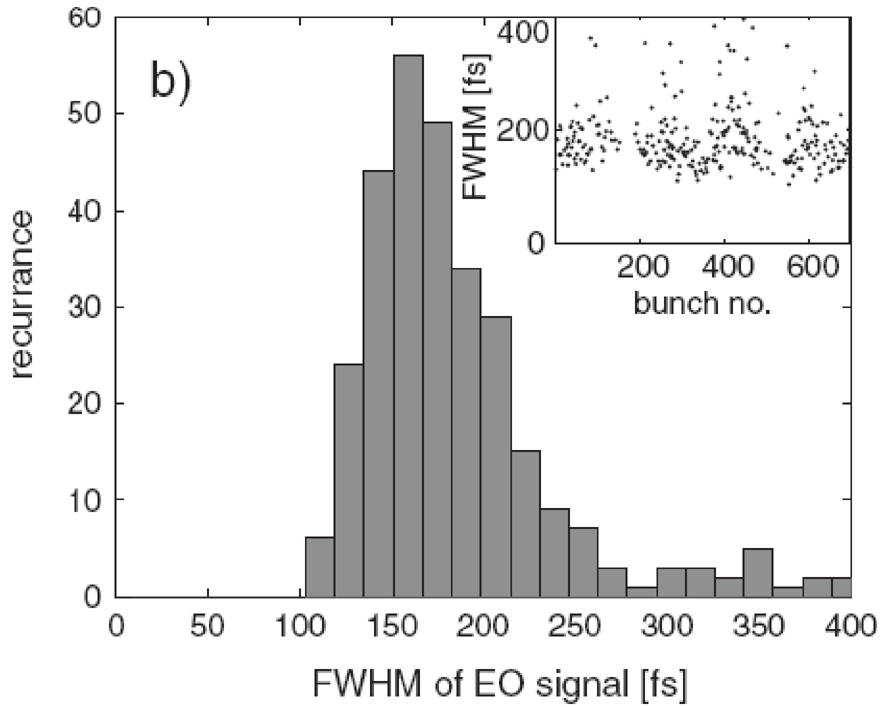
Monitoring performance of bunch compression feedback system at FLASH

Bunch compression switched on:



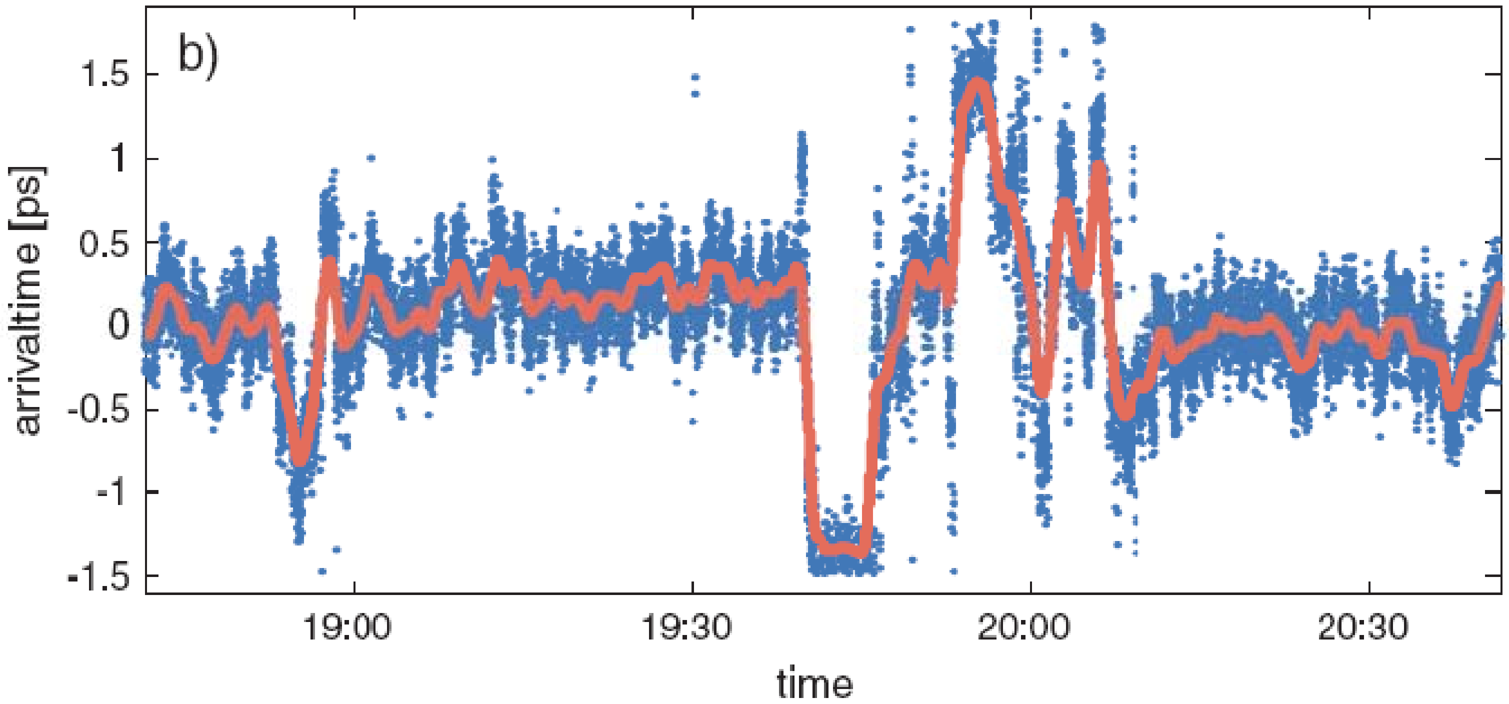
Width of EOTD signal was 158 ± 15 fs (fwhm)

Bunch compression switched off:



Width was 181 ± 34 fs (fwhm)

Bunch arrival time monitoring at FLASH using EO setup



Data taken with EO spectral decoding showing the arrival time of the electron bunch at the EO monitor station during SASE tuning in which the SASE output is optimised by changing the phase of the accelerator

Group planned use of Fibre Lasers in an Accelerator Environment

- Fibre @ 1.55μm via SHG can generate 0.775 μm for seeding with Ti:Sa amplifier. Inherently low noise
- Multiple fibre wavelengths allow experiments to be synchronised to accelerators. Clock distributed through stabilised fibres[1]
- Measurement of arrival time of electron bunch with EO techniques → bunch arrival time monitors (BAM @ FLASH)[2]
- Synchronisation to experiments in future accelerators – current state-of-art is ~30 fs over several hundred metres[3]
- Developing EO Fibre laser prototype with time resolution < 50 fs

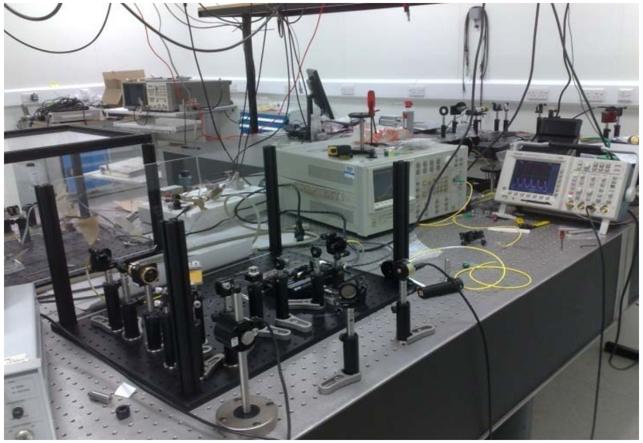
1 FEL 2004 J. Kim et al
2 EPAC 2006 F. Loehl et al
3 EPAC 2006 A. Winter et al

Rationale for migration of EO capability to fibre laser technology…

- Robustness & reliability
- Potential integration into accelerator timing system
- Arrival time information for photon sources

Erbium doped systems: 1.55 μm; likely timing distribution system. frequency doubled to 770nm => similar to Ti:Sa

Ytterbium doped systems: 1030 nm: phase matched with GaP EO material

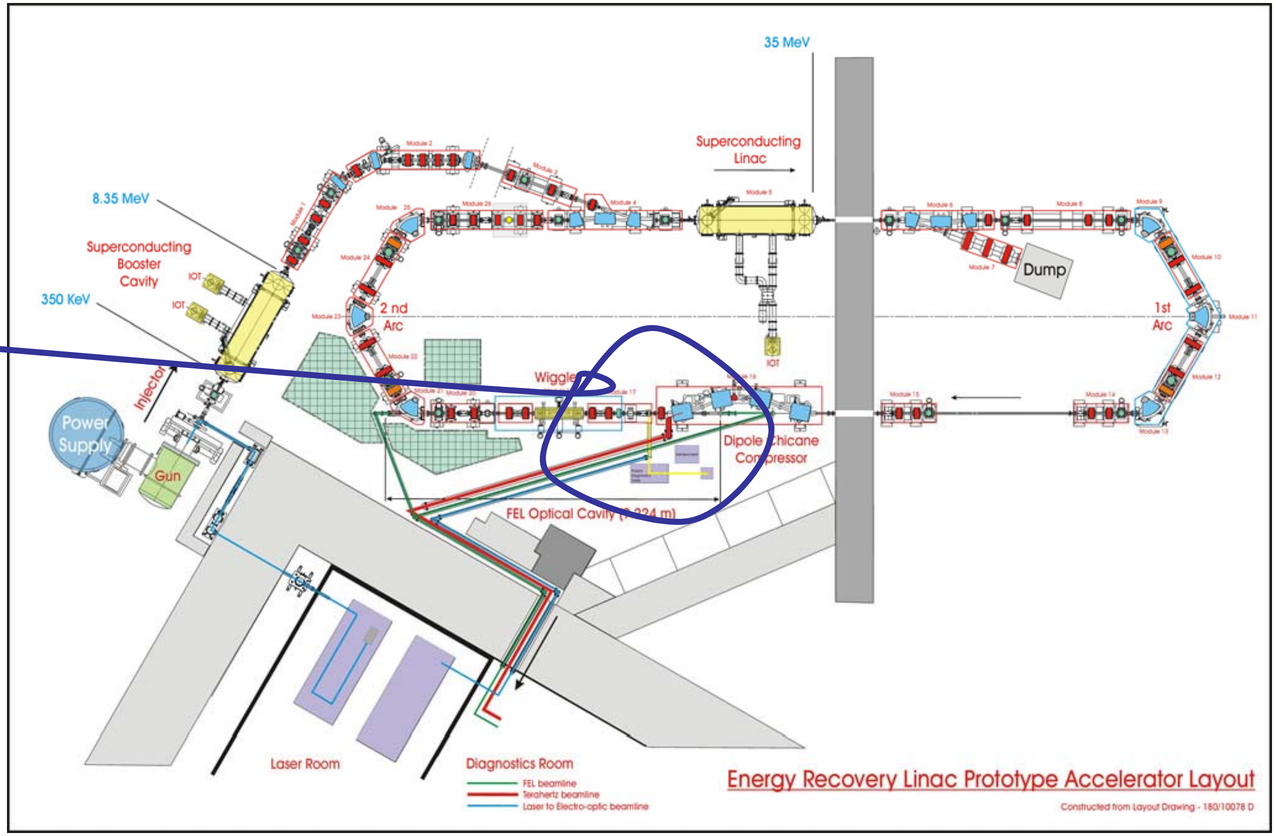


Er system under construction at Daresbury

Corresponding Yb system

ALICE - Accelerators and Lasers in Combined Experiments

EO diagnostic test-station



... aiming for EO station up and running in July 2009

Experiments in progress / planned on ALICE

Commissioning ALICE EO test-bed with Ti:S systems

- temporal decoding ... signal-to-noise; pulse energy, ...
- spectral decoding ... modified concepts for feedback
- peak bunch current arrival-time monitoring (following FLASH)

Tests of fibre EO system on ALICE

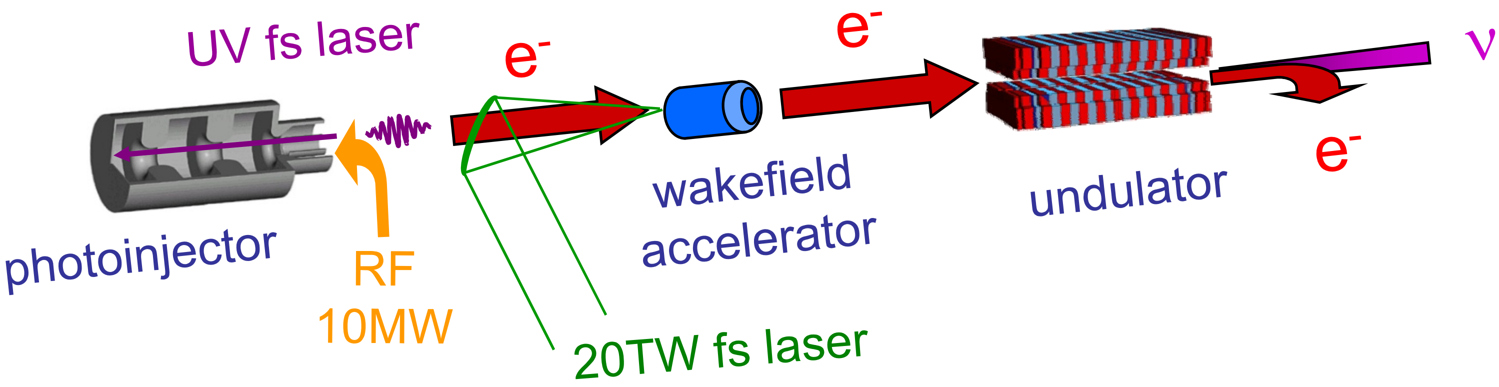
- phase-matching
- signal-noise
- integration with fibre-laser timing distribution system

Future Measurements

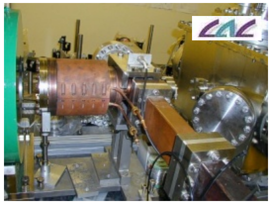
- Synchronise fibre laser to ALICE RF
- Phase noise measurements
- Phase matching of Yb fibre with NL crystals
- Optical bunch arrival time monitor

Other Group Activities

ALPHA-X Plasma Wakefield Project – Strathclyde University, Glasgow

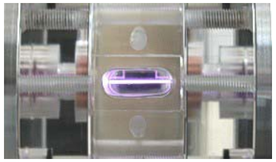


- RF Photoinjector
  electron bunch production
  6.3 MeV, 100 fs, 100 pC



Brookhaven N.L.
T.U. Eindhoven
LAL Orsay (Terry Garvey)

- Wakefield Accelerator
  e.g. capillary discharge waveguide
  up to 1 GeV electrons



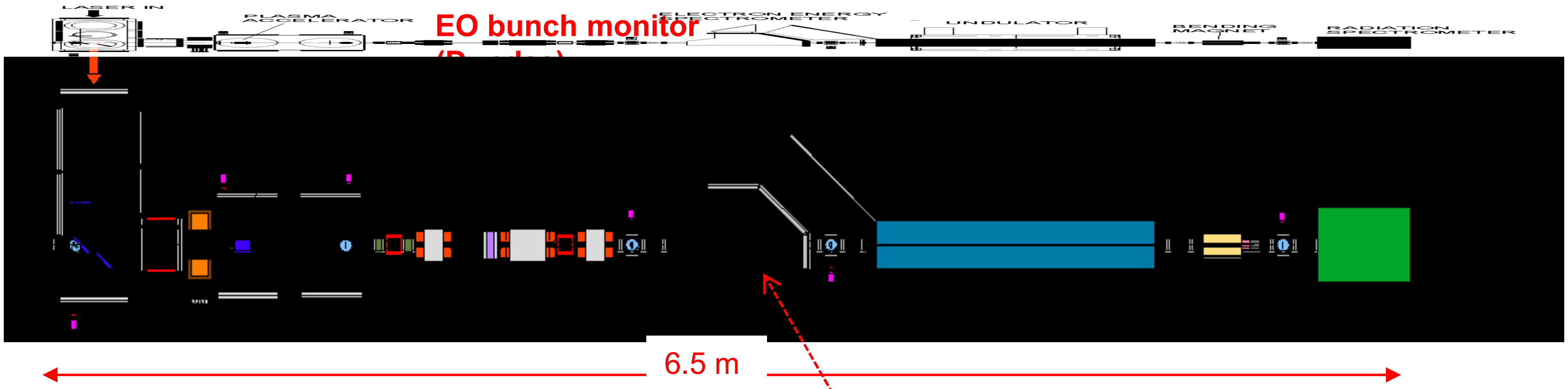
U. Oxford
(Simon Hooker)

- Undulator
  coherent radiation pulses
  λ down to ~ 2 nm

Daresbury Lab: ASTeC
(Jim Clarke,
Ben Shepherd)

ALPHA-X Beam Line Components

6.3MeV, 100-300fs bunches from gun

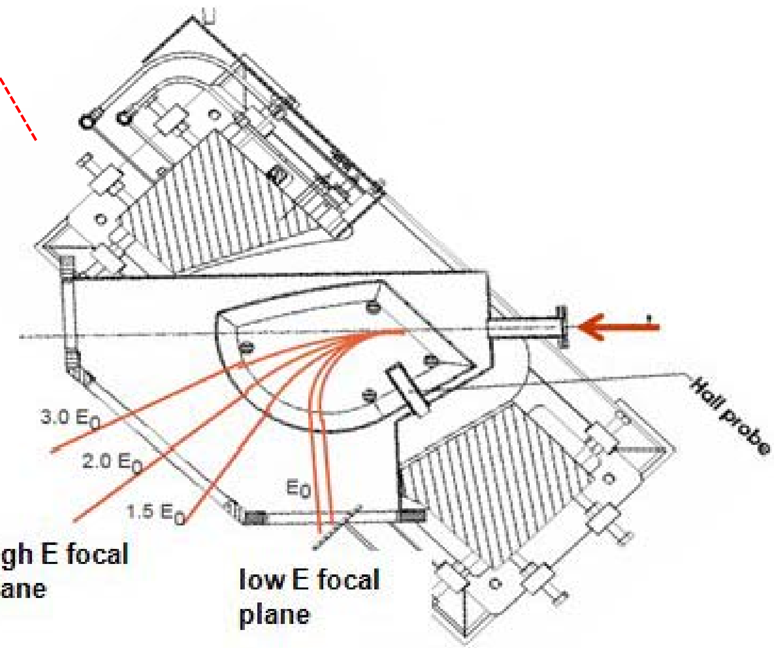


electrons

high E focal plane

low E focal plane

YAG(Ce) screens



Broadband Electron Spectrometer

(Dundee group)

Selected References:

Free-electron laser pulse shape measurements with 100fs temporal resolution using a 10fs Ti:sapphire laser and differential optical gating
X.Yan, A.M. MacLeod, W.A.Gillespie et al.
Nucl. Instr. Meths. Phys.Res. Vol A429 (1999) 7- 9

Sub-picosecond electro-optic measurement of relativistic electron pulses
X. Yan, A.M. MacLeod, W.A. Gillespie, G.M.H. Knippels, D. Oepts, A.F.G. van der Meer.
Physical Review Letters 85 (2000) 3404-7

Single-shot electron bunch length measurements
I. Wilke, A.M. MacLeod, W.A. Gillespie, G. Berden, G.M.H. Knippels, A.F.G. van der Meer
Phys. Rev. Lett. 88 No 12 (2002) 124801/1-4

Real-time, non-destructive, single-shot electron bunch-length measurements
G. Berden, S.P. Jamison, A.M .MacLeod, W.A. Gillespie, B. Redlich and A.F.G. van der Meer
*Physical Review Letters **93** (2004) 114802*

Temporally resolved electro-optic effect
S.P.Jamison, A.M. Macleod, G. Berden, D.A. Jaroszynski and W.A. Gillespie
*Optics Letters **31**, 11 (2006) 1753-55*

Benchmarking of Electro-Optic monitors for Femtosecond electron bunches
G. Berden, W.A.Gillespie, S.P. Jamison, B. Steffen, V. Arsov, A.M. MacLeod, A.F.G. van der Meer, P.J. Phillips, H. Schlarb, B. Schmitt, and P. Schmüser
Phys. Rev. Lett. 99 043901 (2007)

Electro-optic time profile monitors for femtosecond electron bunches at the soft X-ray free-electron laser FLASH
B. Steffen, V. Arsov, G. Berden, W.A. Gillespie, S.P. Jamison, A.M. MacLeod, A.F.G. van der Meer, P.J. Phillips, H. Schlarb, B. Schmitt, and P. Schmüser
Physical Review Special Topics – Accelerators and Beams 12 032802 (2009)

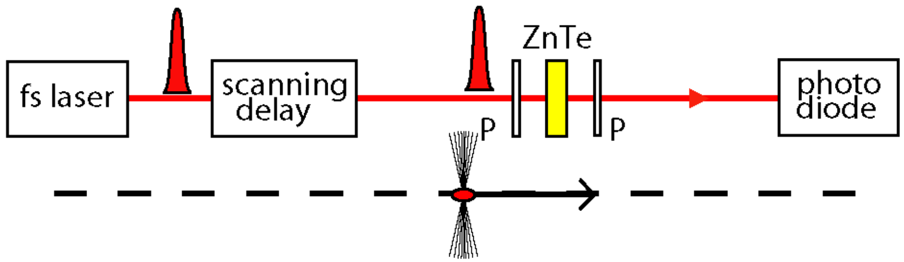
In Summary ...

- EO longitudinal profile capabilities approaching expected requirements
- Has proven capability at **~60fs rms** at ~450MeV
- Capability is maintained (and even improved) as energy increases

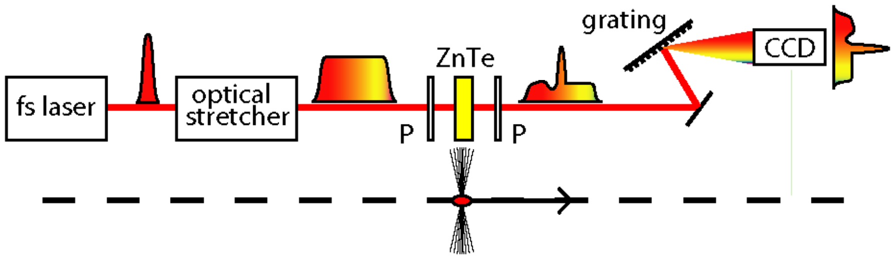
  (potentially surpassing TDCav at higher energies)
- Limited by non-linear optical effects
- <u>But</u> no time-slice information
- Now addressing issues of robustness & reliability …

End

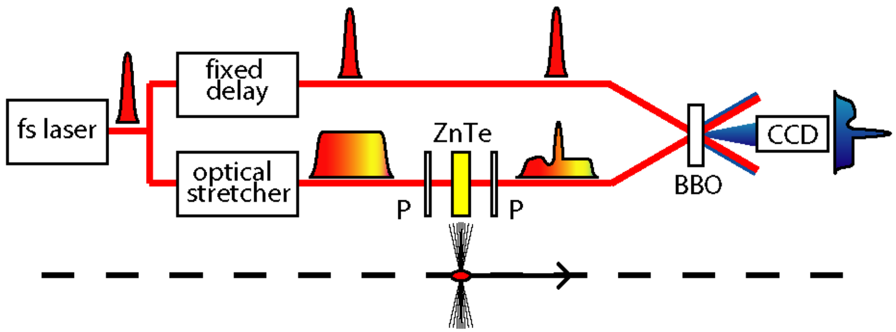
Electro-optic Sampling :
+ simple (laser) system
+ arbitrary time window
- no single bunch
- time jitter

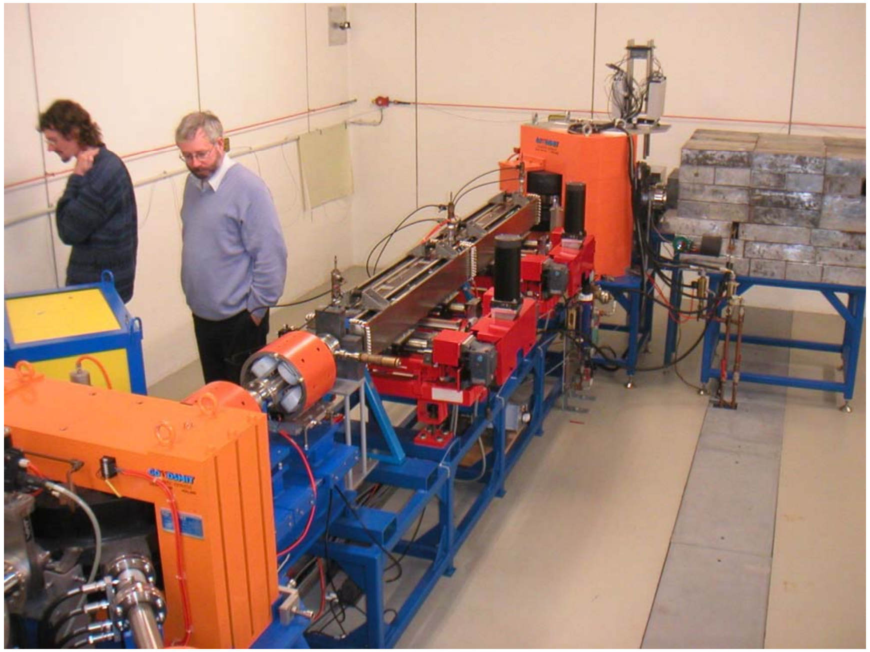


Spectral Decoding:
+ simple (laser) system
+ high repetition rate
(400fs measured at FLASH)
- distorted signal for
e-bunches < 200fs

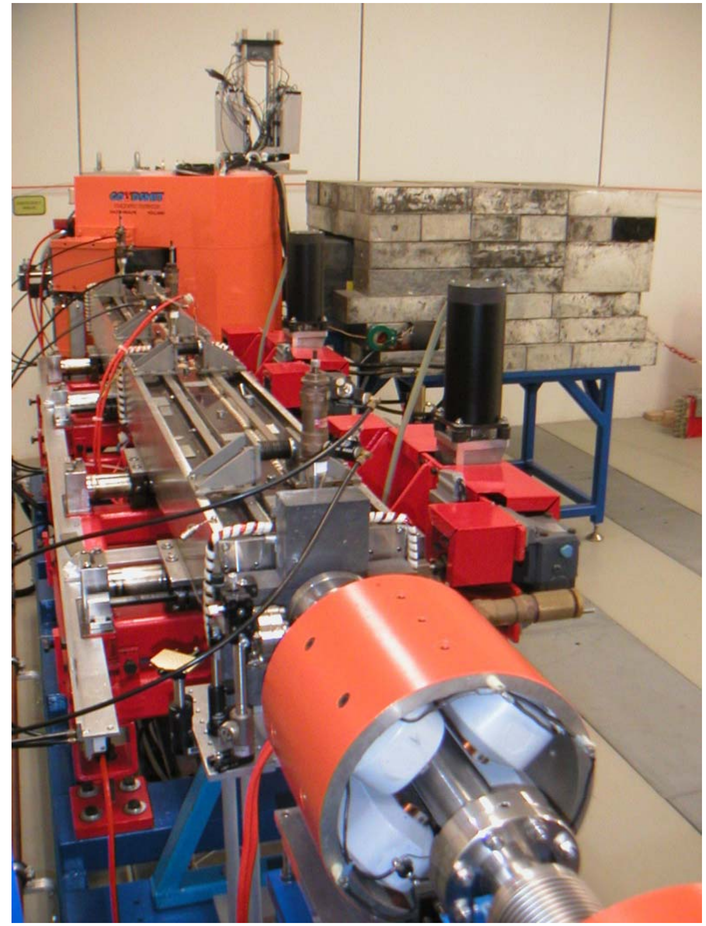


Temporal Decoding:
+ large time window
+ high resolution: ‹100 fs
(**80 fs** measured at FLASH)
- mJ laser pulse energy
- low repetition rate

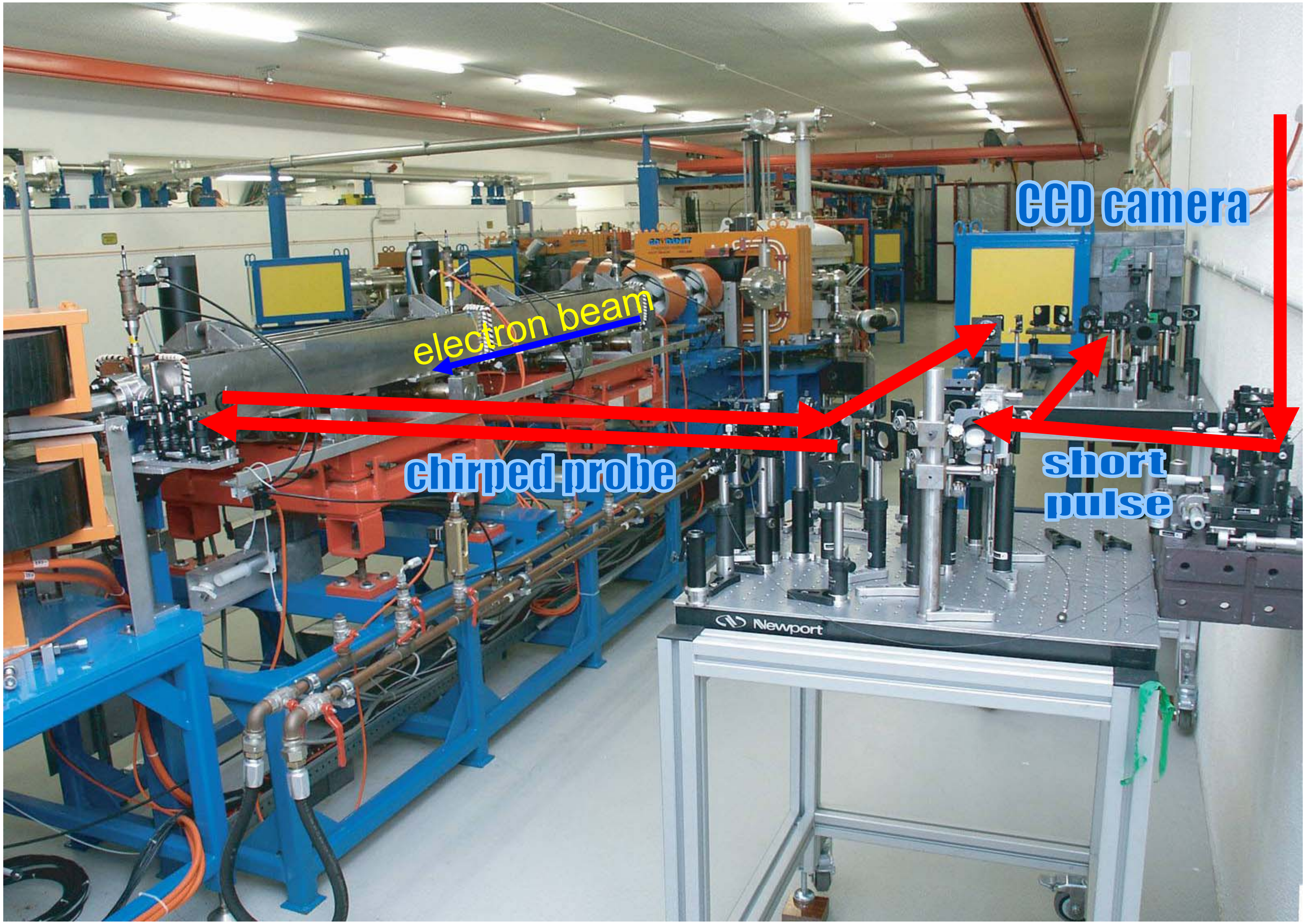




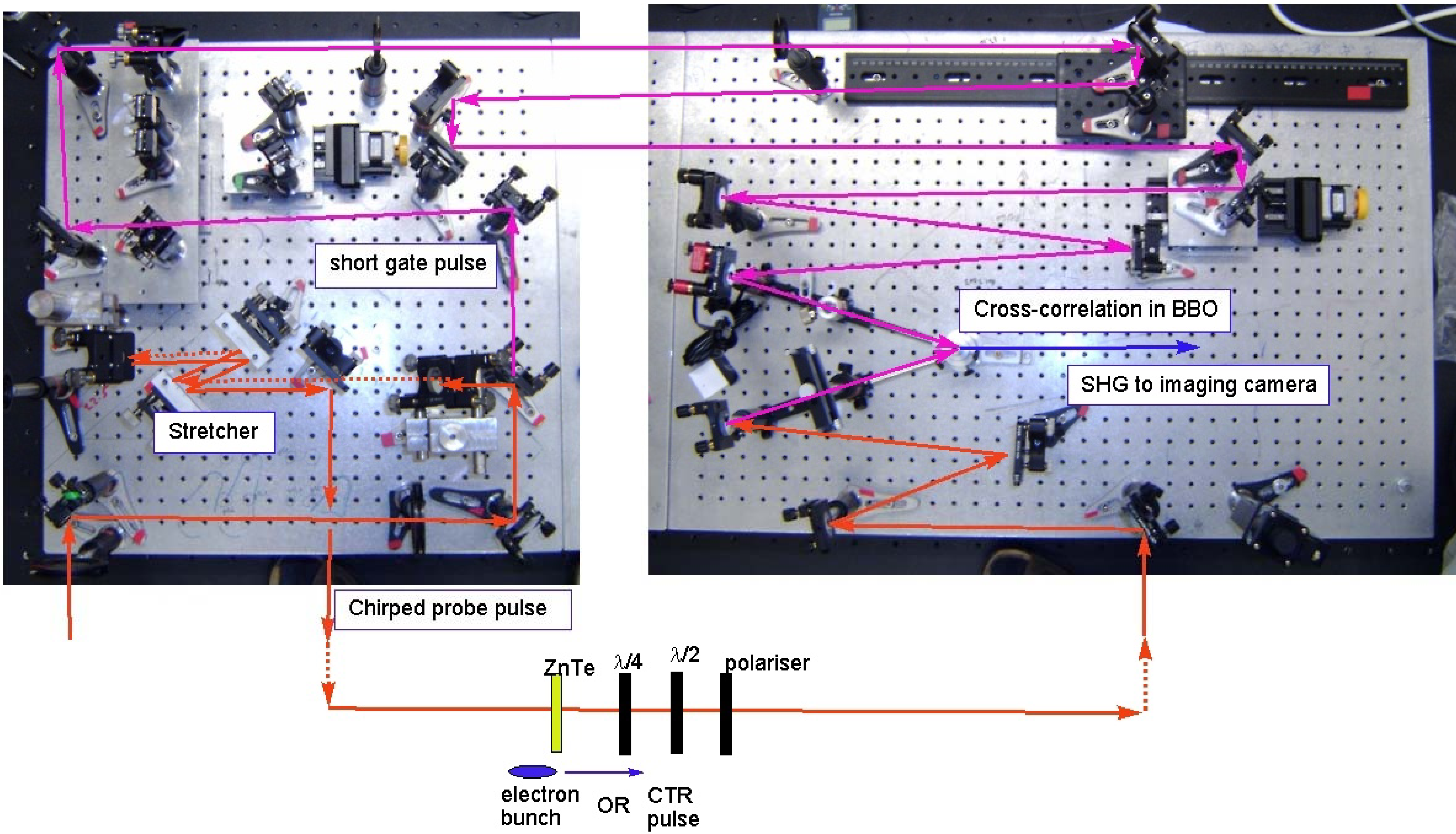
Experiments at FELIX



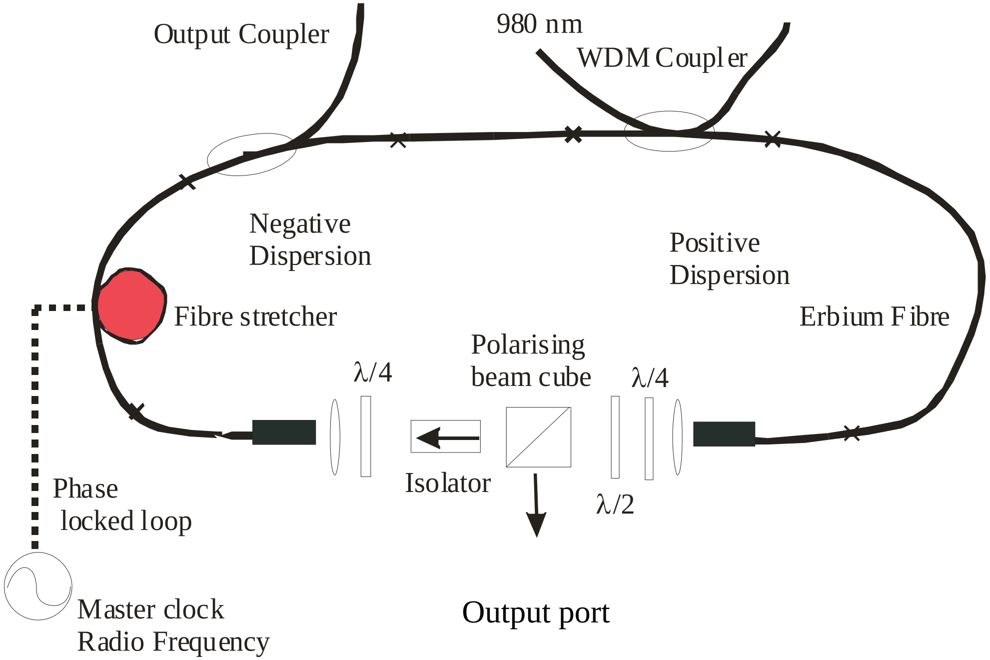
50 MeV electron beam measurements FELIX FEL facility, The Netherlands

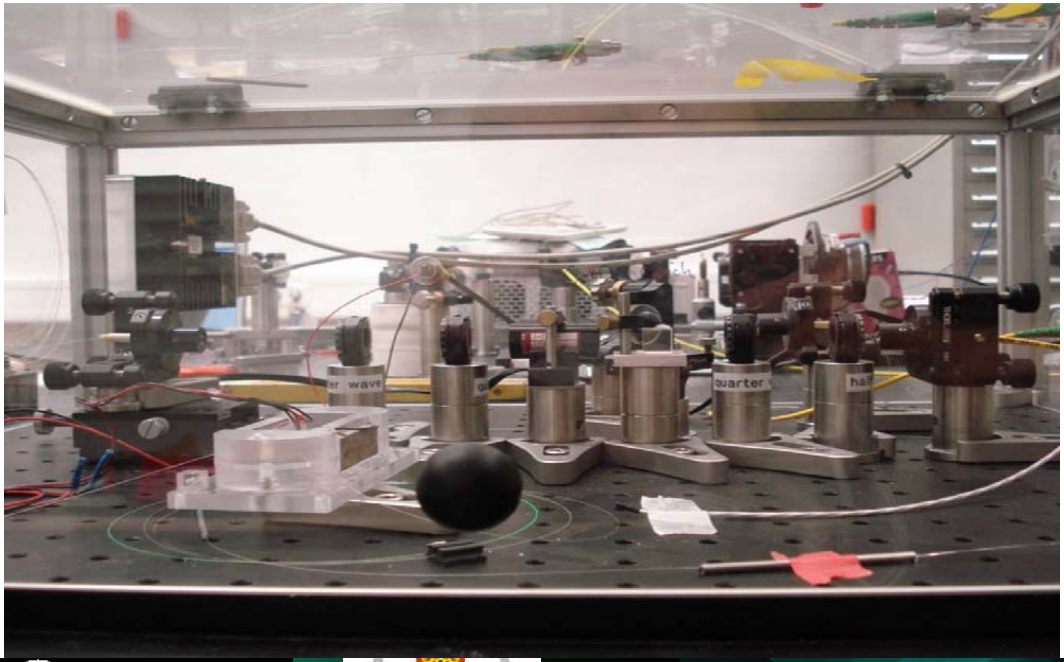


[Equipment from original UK FEL Project]


short gate pulse
Cross-correlation in BBO
SHG to imaging camera
Stretcher
Chirped probe pulse
ZnTe
λ/4
λ/2
polariser
electron bunch
OR
CTR pulse

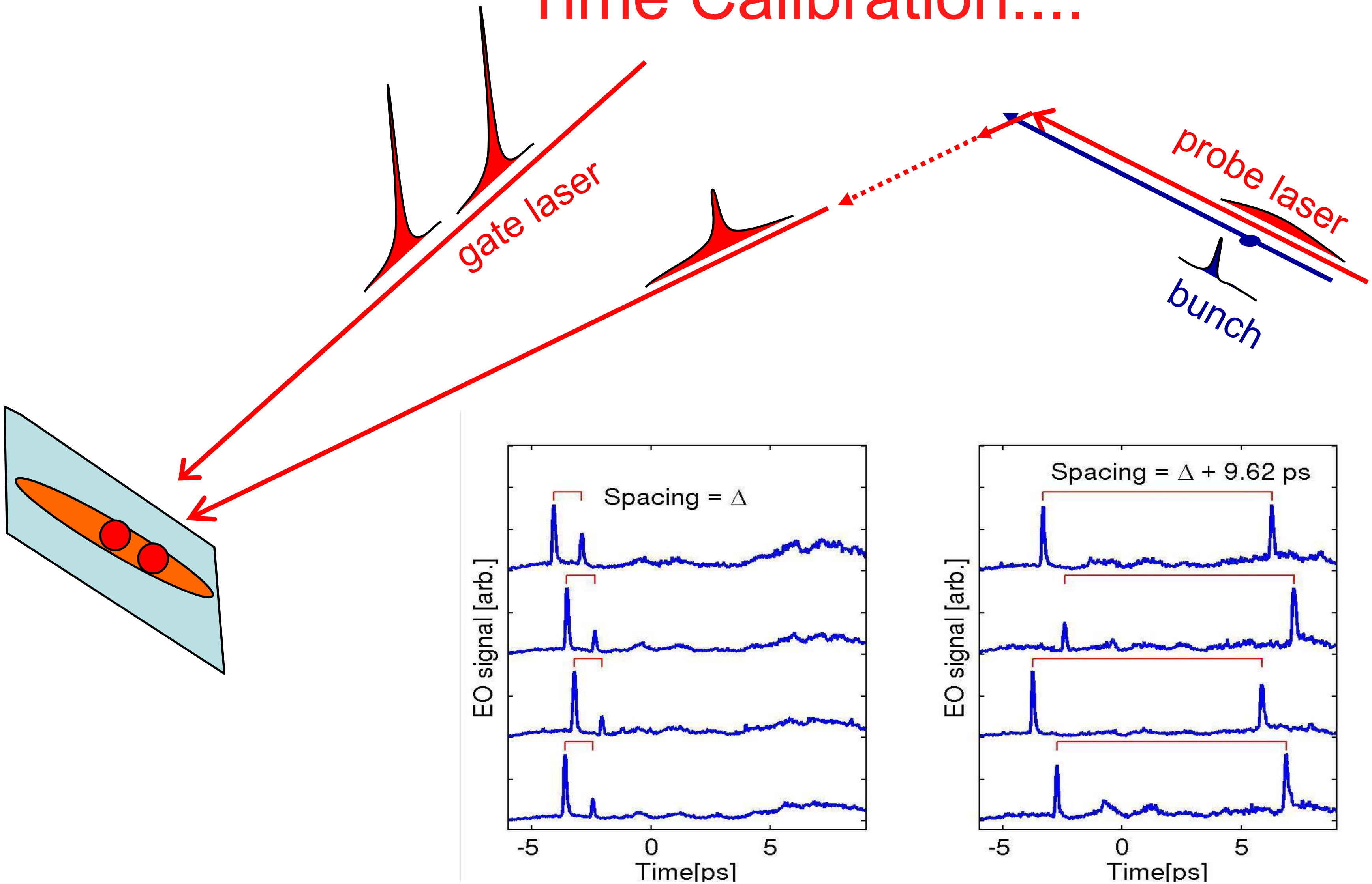
Erbium-doped fibre laser layout





Fibre Laser at DESY

Time Calibration....



Evolution of Electro-Optic diagnostic techniques:

Developed and demonstrated new approaches to EO bunch profile measurement

- “temporal decoding” technique developed to overcome known issues in previous approaches.
- improved time resolution by x10 over earlier techniques
- Very compact diagnostic ... < 0.2 m of beam line

Deployed our EO techniques at DESY FLASH

- demonstrated highest time resolution achieved anywhere, with ANY non-destructive bunch profile diagnostic
- demonstrated non-invasive characterisation at 500MeV, ~100fs (during SASE operation)
- Corroborated electro-optic profiles with simultaneous TDC (LOLA) measurements
- Direct observation of profile stabilisation in feedback system

Advanced the theoretical description of EO detection process

- corrected long-standing errors in theory
- improved understanding of limiting processes
- developing calibration processes for even higher time resolution measurements