UNIVERSITY of ABERTAY DUNDEE

DESY

Science & Technology Facilities Council

Measurement of Femtosecond Electron Bunches

Allan Gillespie

Carnegie Laboratory of Physics
University of Dundee

FOM-Instituut voor Plasmafysica Rijnhuizen

University of Edinburgh, 7 December 2007

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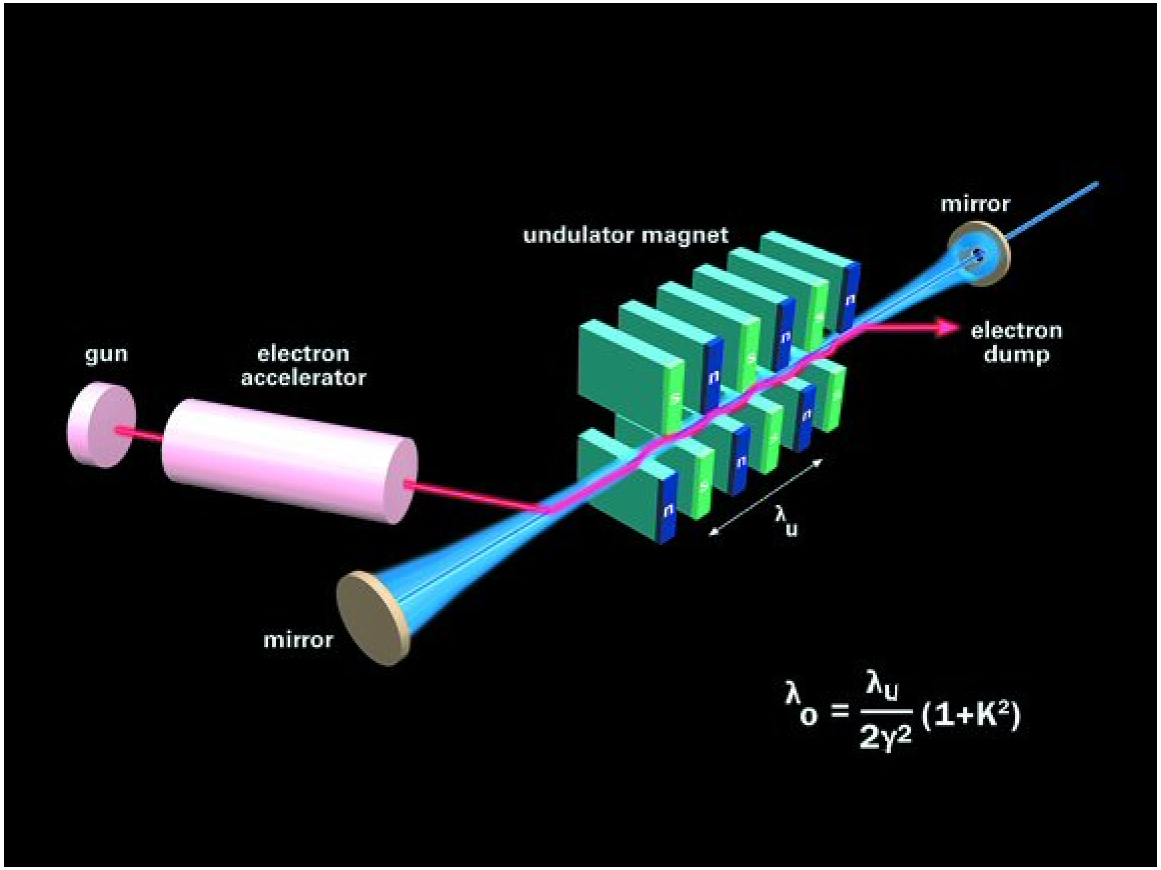
Plan of Talk

- Introduction and Motivation
- Free-Electron Lasers and Advanced Light Sources (FELIX)
- ILC and related projects (DESY)
- Plasma-wakefield accelerators (Strathclyde)
- The future (?)

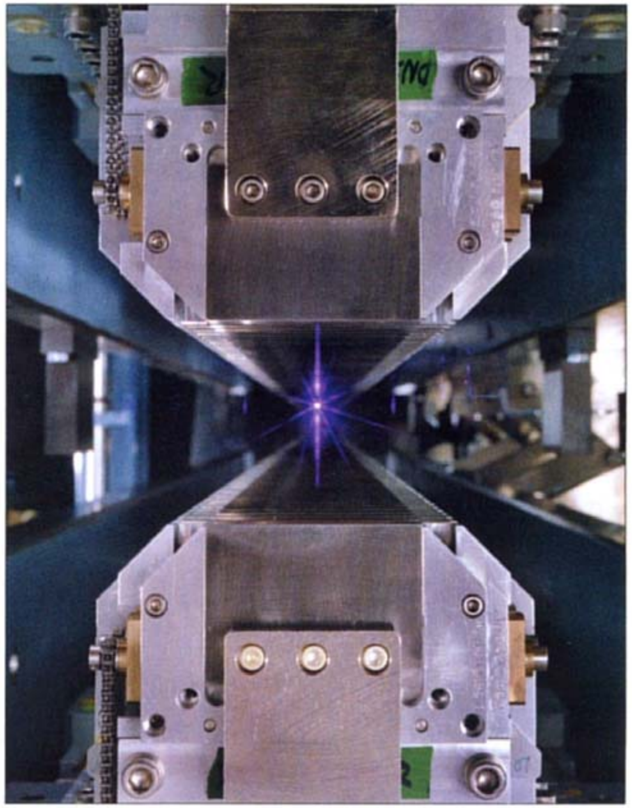
Introduction & Motivation

- Originally from free-electron laser research
- UK and Dutch FEL projects – FEL oscillators

- "Large" FELs – SASE devices (e.g. DESY FLASH)
- Need ultrashort (<100fs) electron bunch structure
- Large electron-positron colliders like ILC don't need such short bunches, BUT may want good (~10%) time resolution within, say, bunch length of $150\mu\text{m} \equiv 500$ fs



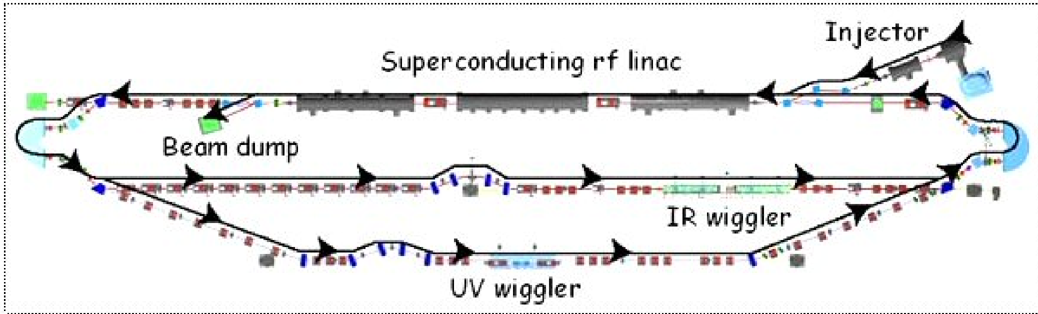
Principle of FEL oscillator



Undulator at ALS Argonne

Undulator radiation can be incoherent ("long" bunches) or coherent ("short" bunches)

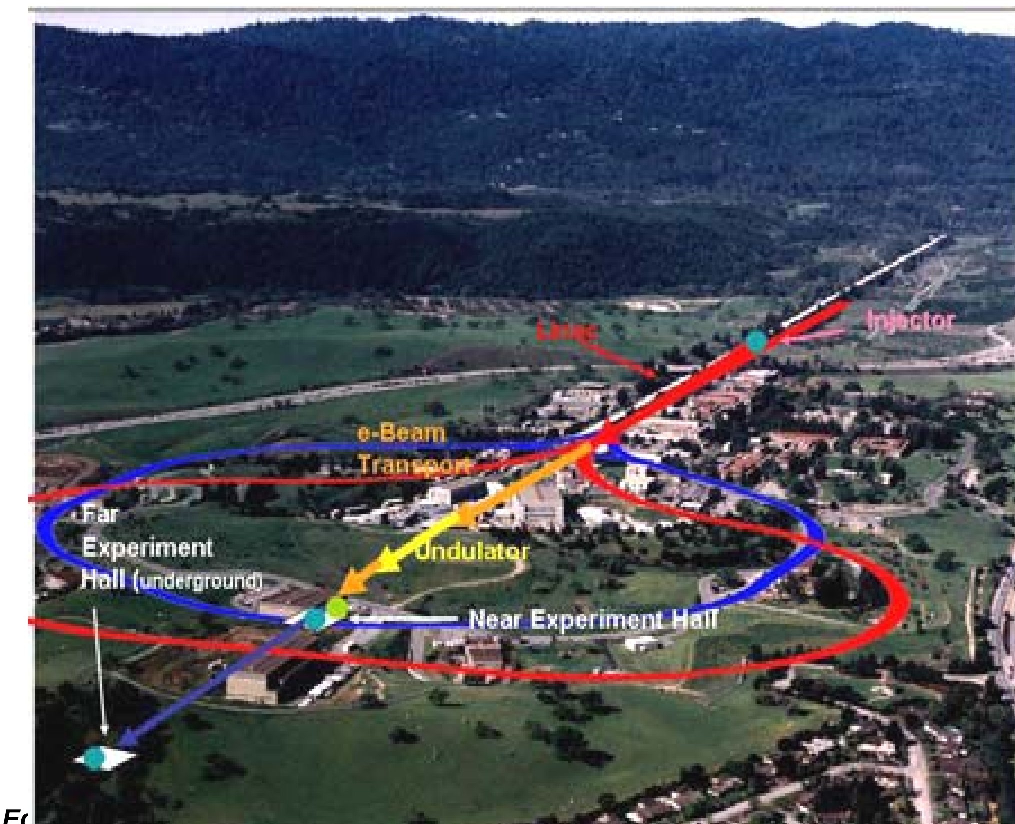
FEL oscillator recycles photons in resonant optical cavity to give gain



Jefferson Lab FEL Output Light Parameters

	IR Branch	UV Branch
Wavelength range (microns)	1.5 - 14	0.25 - 1
Bunch Length (FWHM psec)	0.2 - 2	0.2 - 2
Laser power / pulse (microJoulesJ)	100 - 300	25
Laser power (kW)	> 10	> 1
Repetition Rate (cw operation, MHz)	4.7 - 75	4.7 - 75

SLAC LCLS

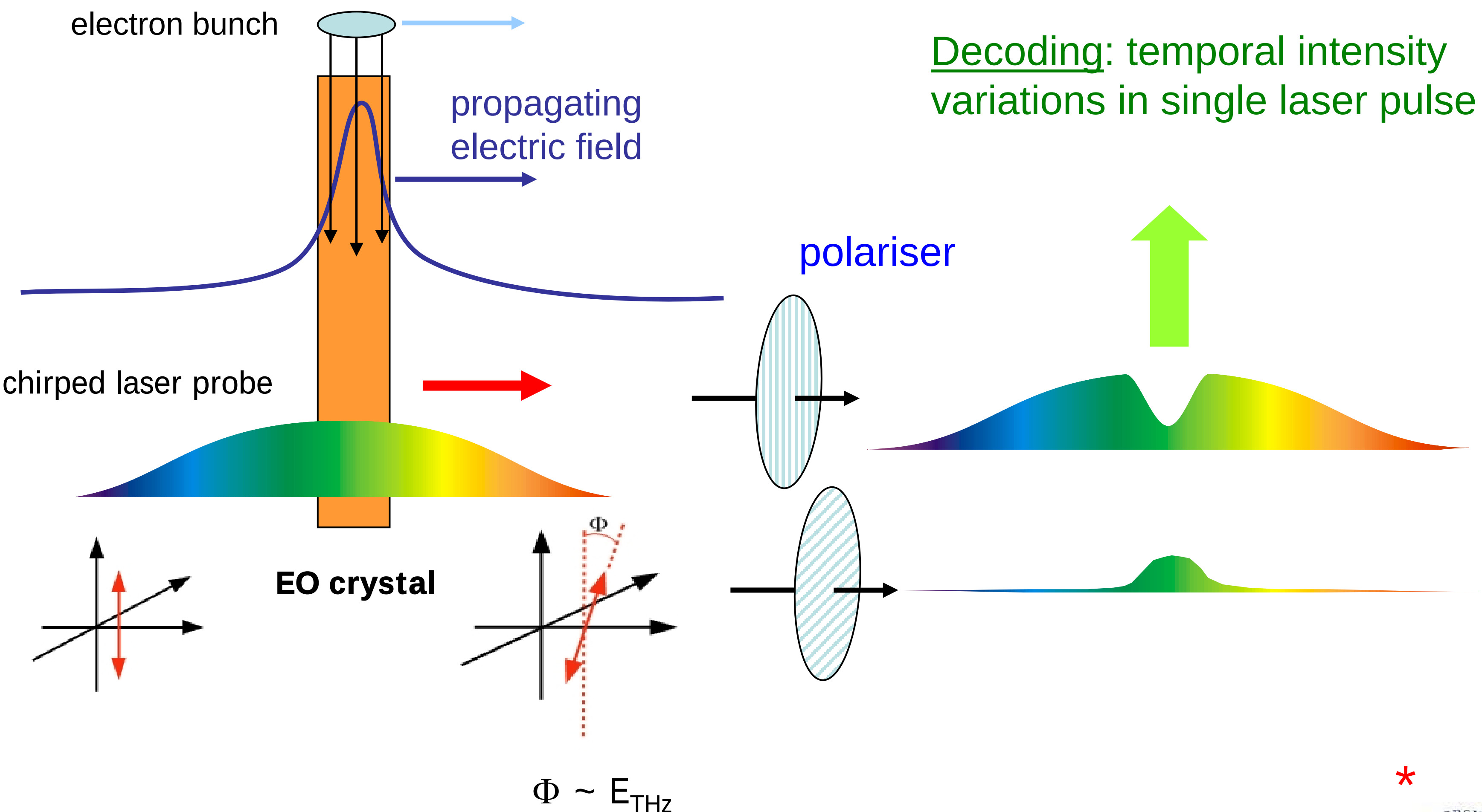


SLAC aerial view and Endstation A

E-O longitudinal bunch profile measurements

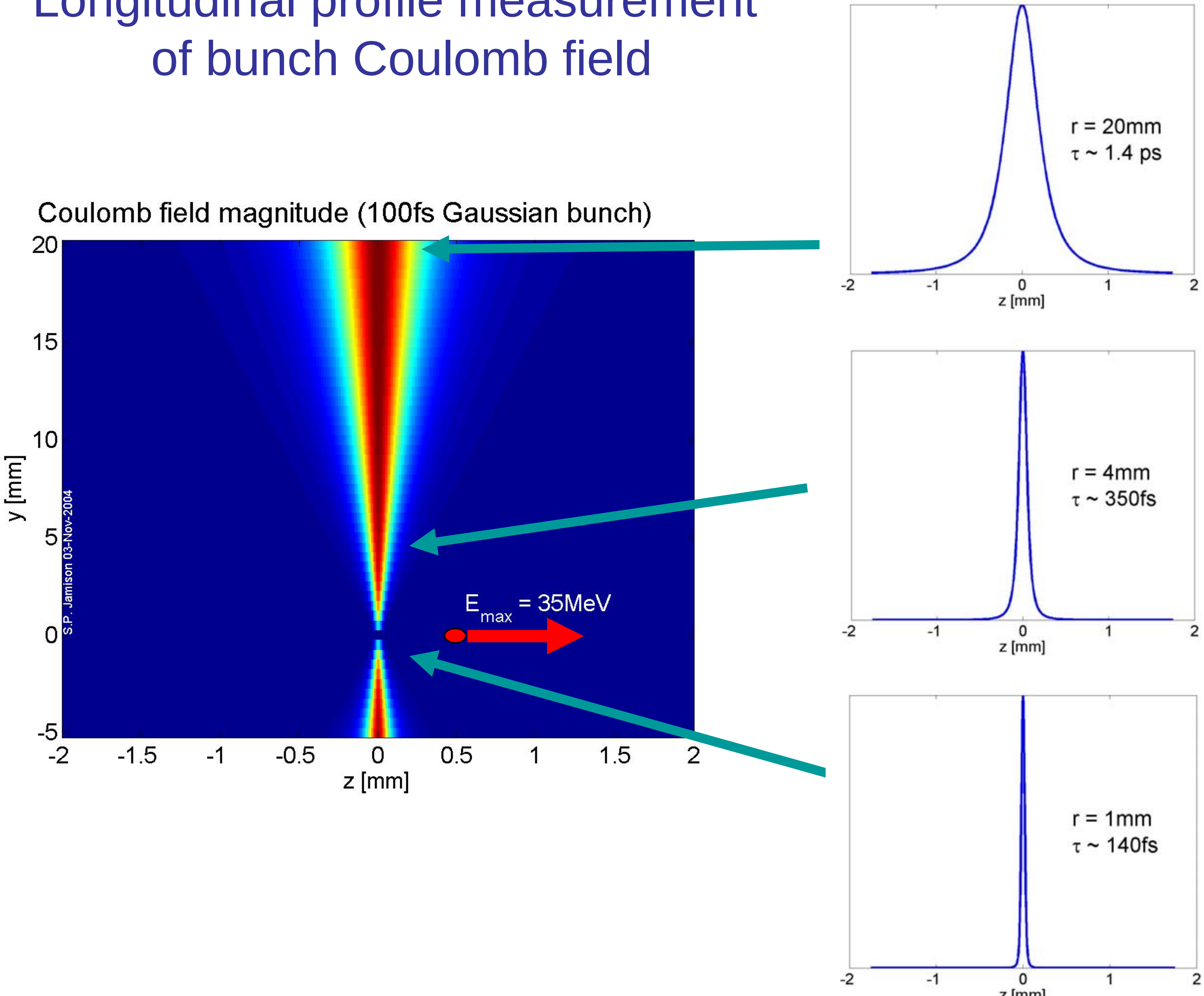
Principle: Convert bunch Coulomb field into optical intensity variation

Coulomb field encoded on to optical probe

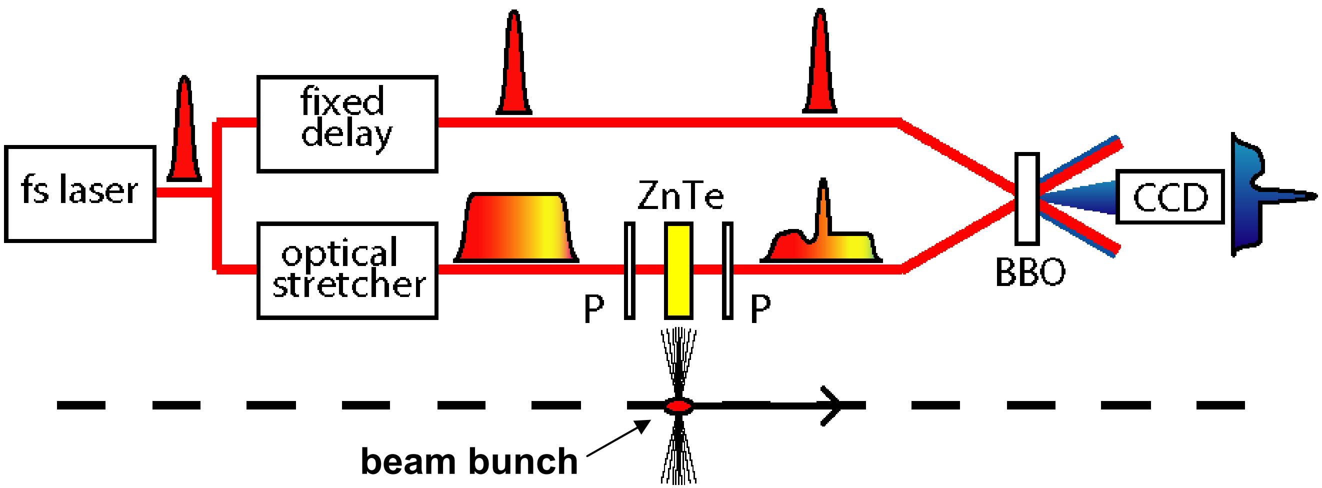


Effective polarisation rotation proportional to Coulomb field

Longitudinal profile measurement of bunch Coulomb field



Temporal Decoding



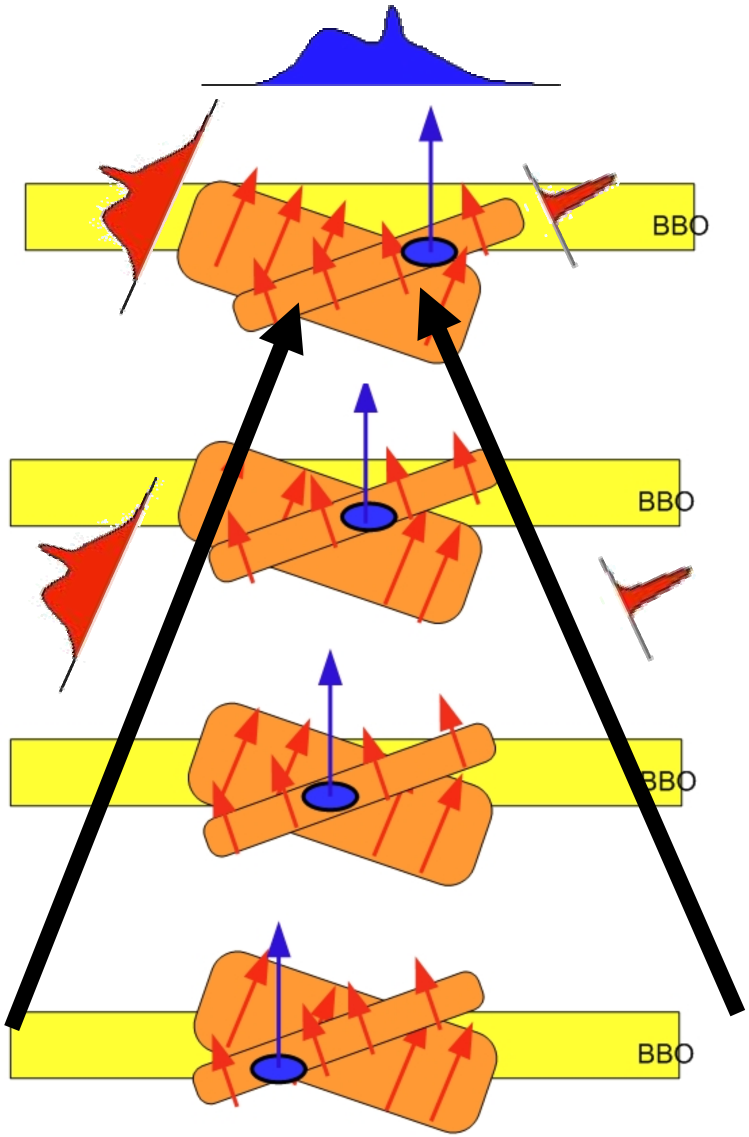
- the chirped laser pulse behind the EO crystal is measured by a short laser pulse with a single-shot cross correlation technique
- approx. **1mJ** of laser pulse energy is required

Spectral Decoding

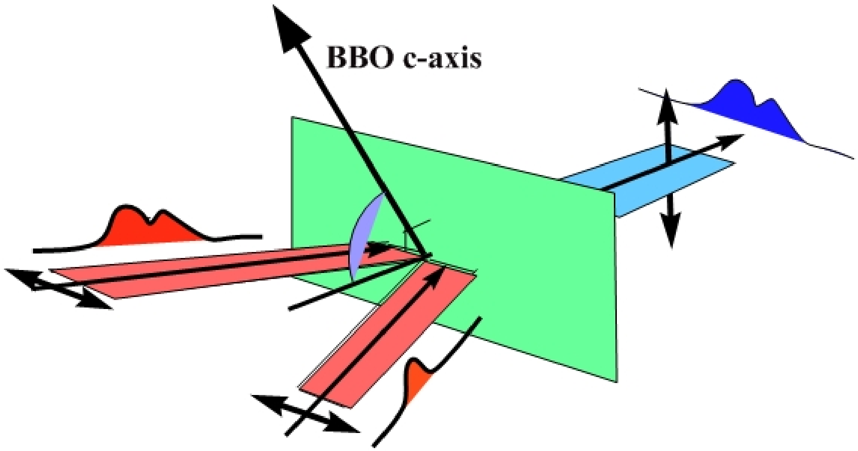
- simpler, but suffers from artefacts at high frequencies

*

Single-shot Temporal Decoding of optical probe



Temporal profile of probe pulse
→ Spatial image of SHG



Symmetric crystal geometry:
400nm "walk-off" orthogonal to time-axis

*

FELIX Experiments

Allan Gillespie, Jonathan Phillips, Steve Jamison, Allan MacLeod

Dundee – Daresbury Group

Giel Berden, Britta Redlich, Lex van der Meer, Guido Knippels

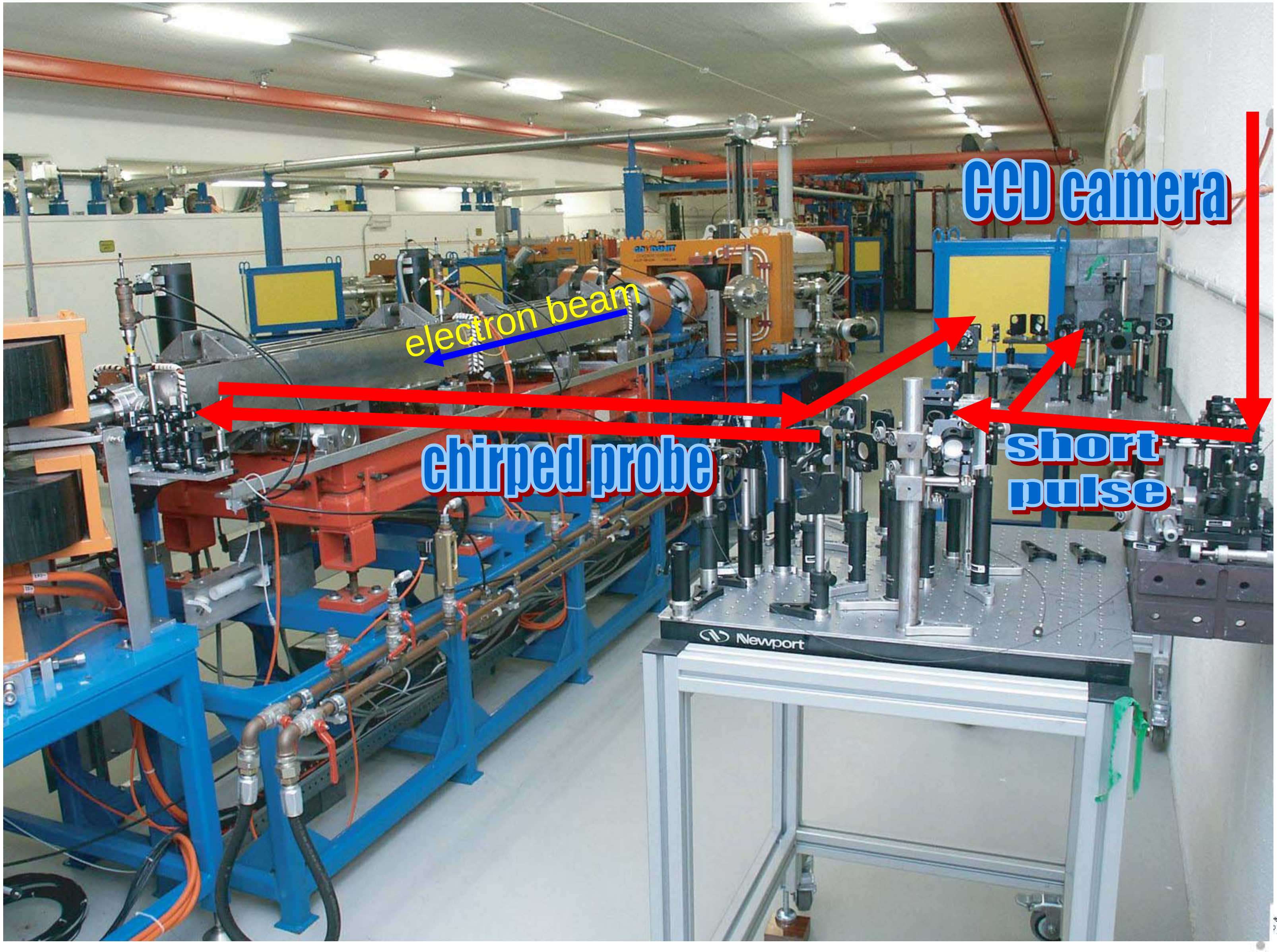
FOM Institute for Plasma Physics “Rijnhuizen”, Nieuwegein, The Netherlands

Ingrid Wilke

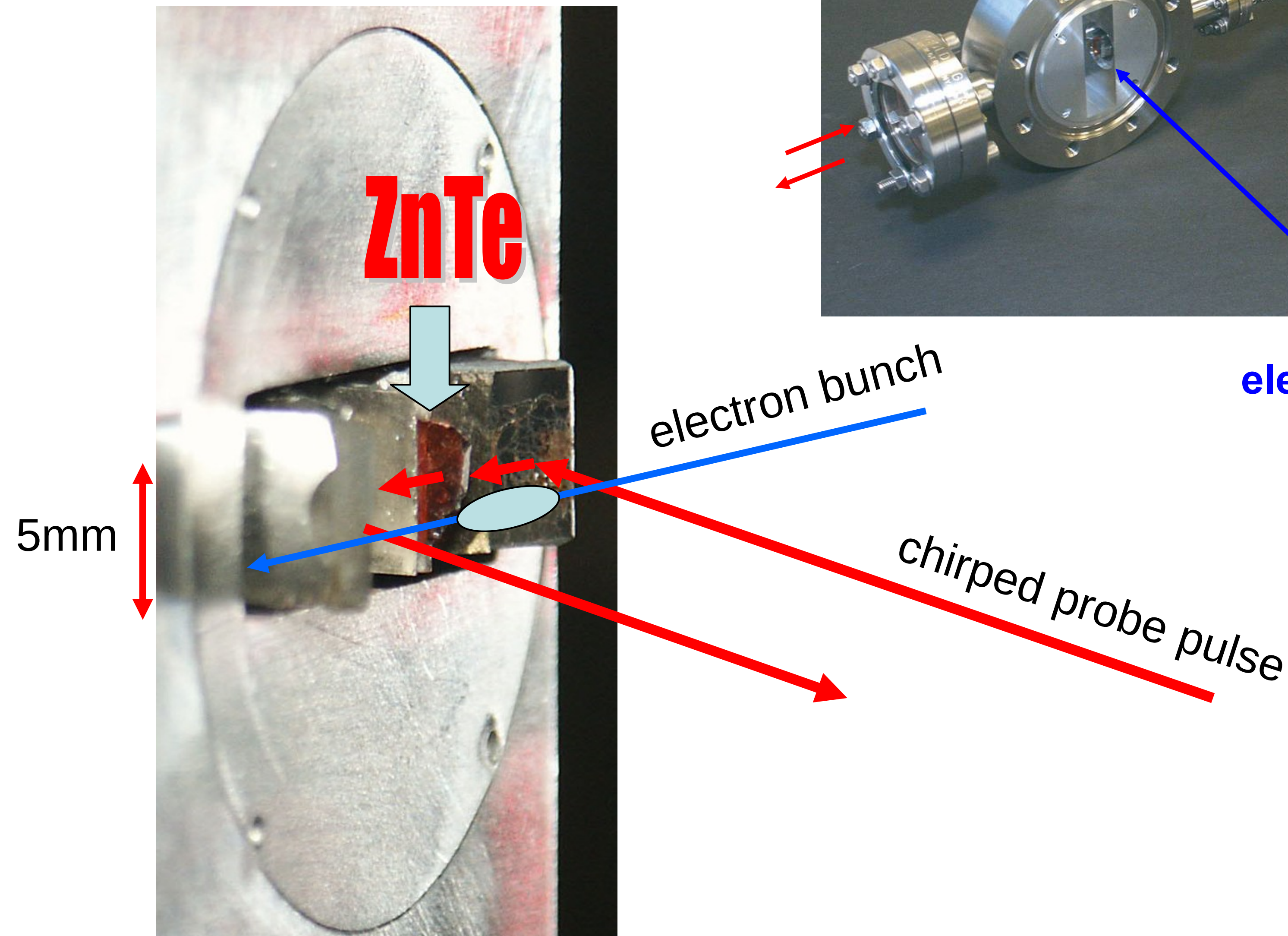
University of Hamburg, Germany

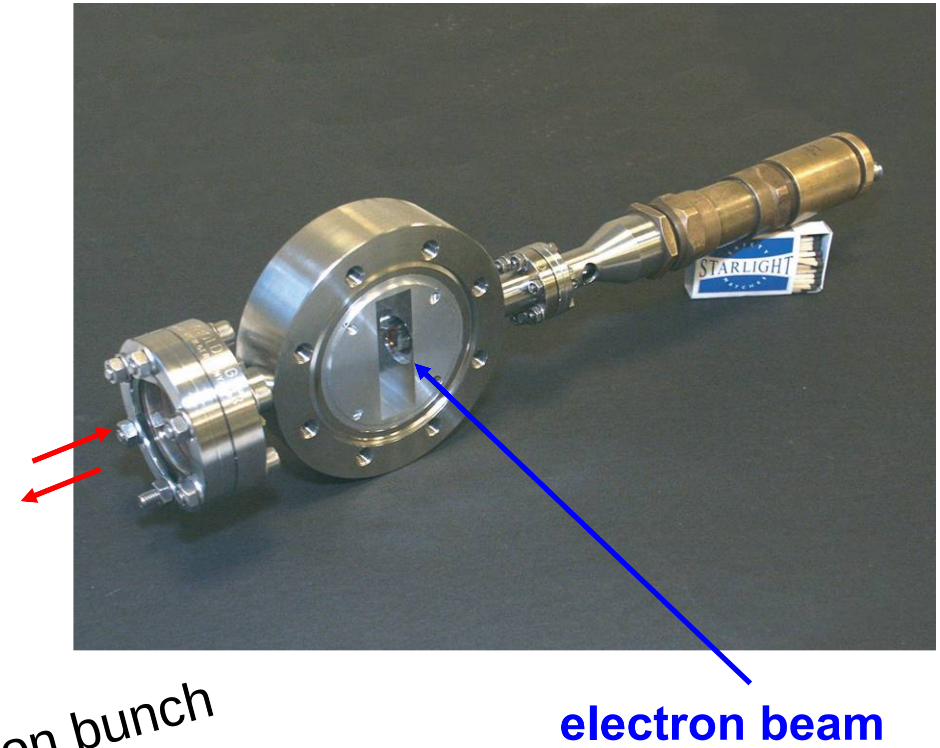
University of Edinburgh, 7 December 2007

50 MeV electron beam measurements (2001-2004)
FELIX FEL facility, The Netherlands



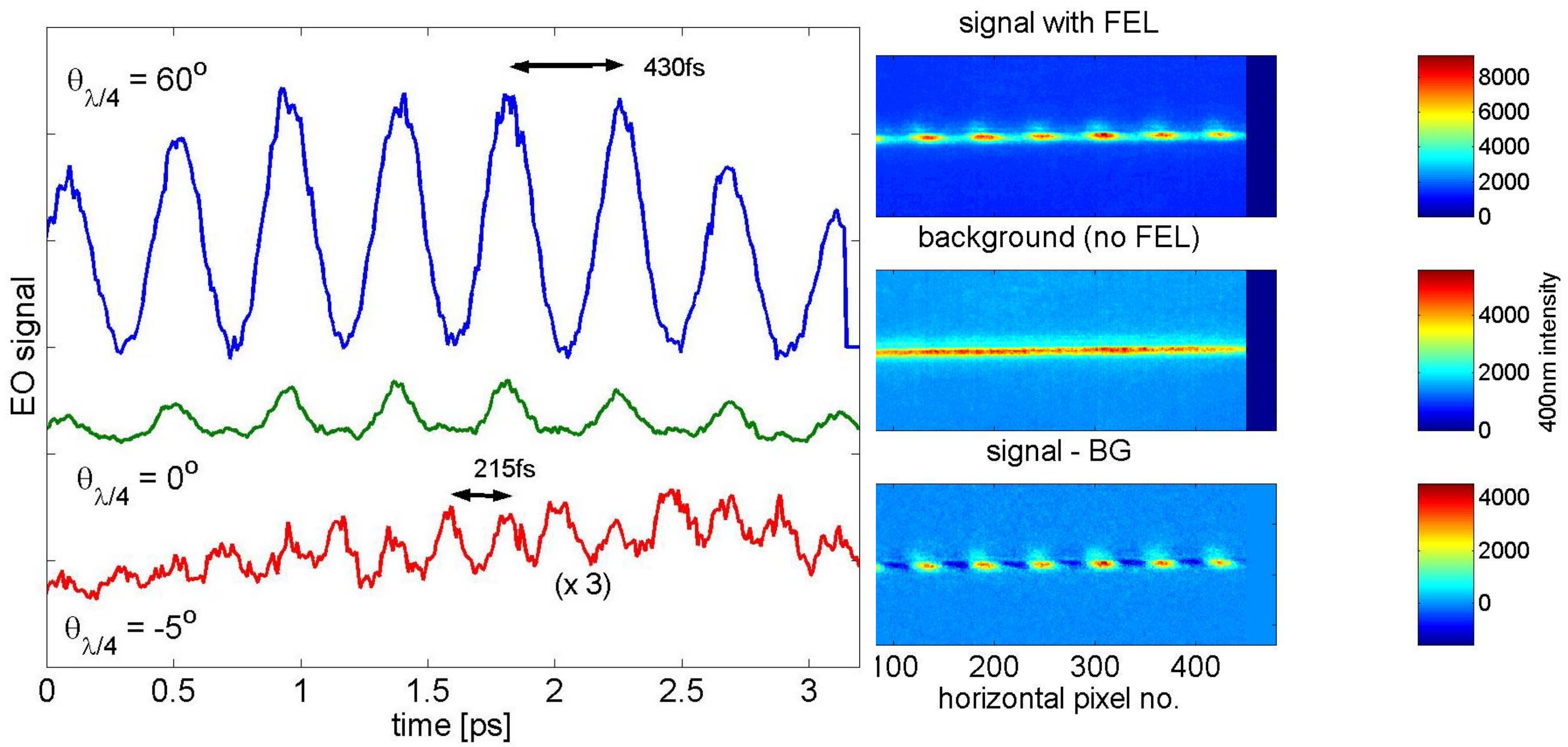
Probe Head (FELIX)





Potential for single-shot THz time-domain spectroscopy …

Example of single-shot measurement of FEL radiation



Experiments at DESY FLASH accelerator

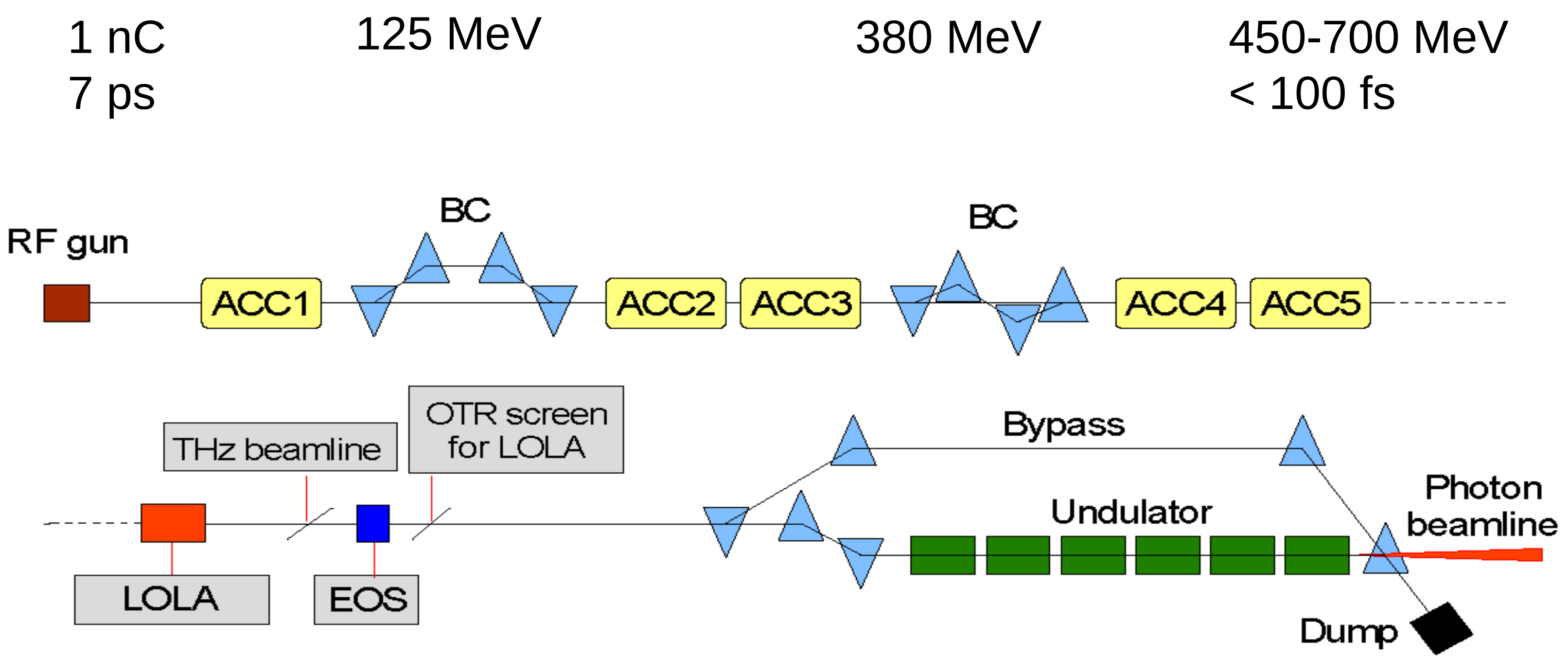
LC-ABD

W.A. Gillespie, P.J. Phillips - *University of Dundee*
S.P. Jamison - *ASTeC, Daresbury Laboratory*
A.M. Macleod - *University of Abertay*

Collaborators

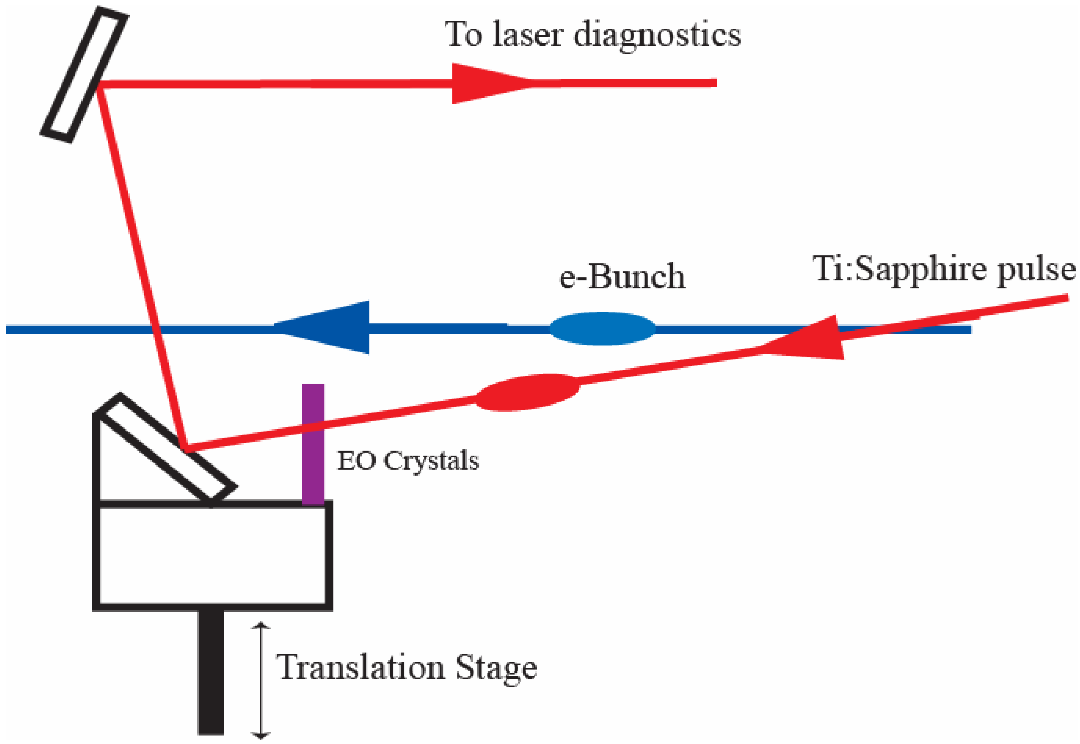
G. Berden, A.F.G. van der Meer – *FELIX (Utrecht)*
B. Steffen, E.-A. Knabbe, H. Schlarb, B. Schmidt, P. Schmüser – *DESY FLASH (Hamburg)*

FLASH accelerator at DESY



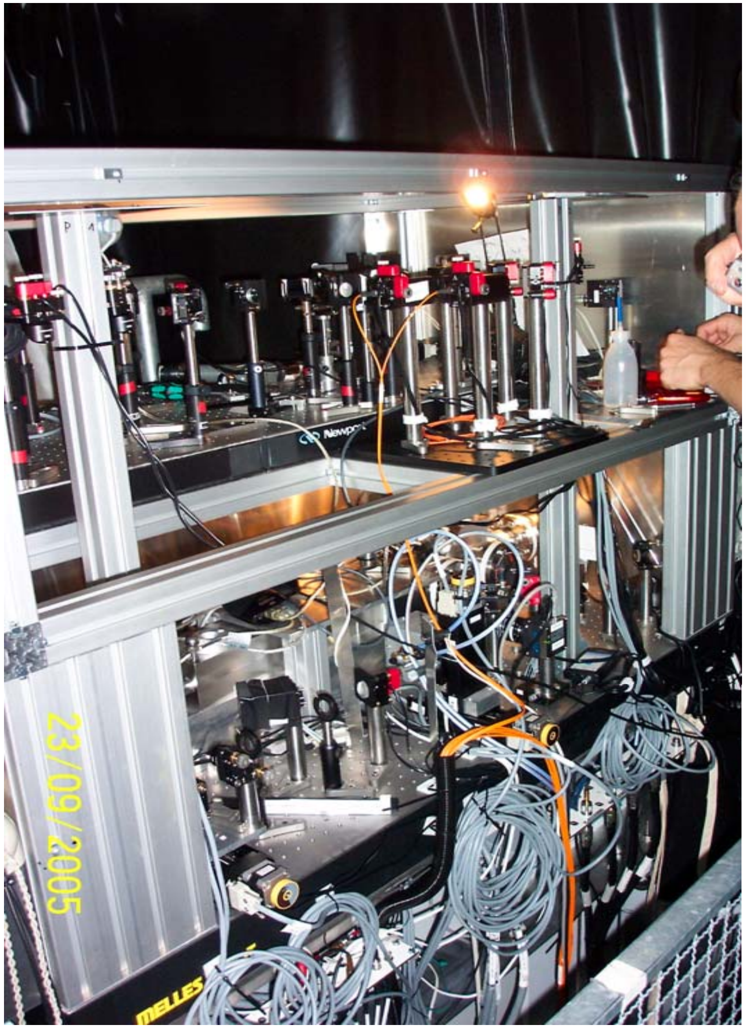
Resulting e-bunches at 450 MeV with 200 pC in a < 100 fs spike during VUV FEL operation at 32 nm.

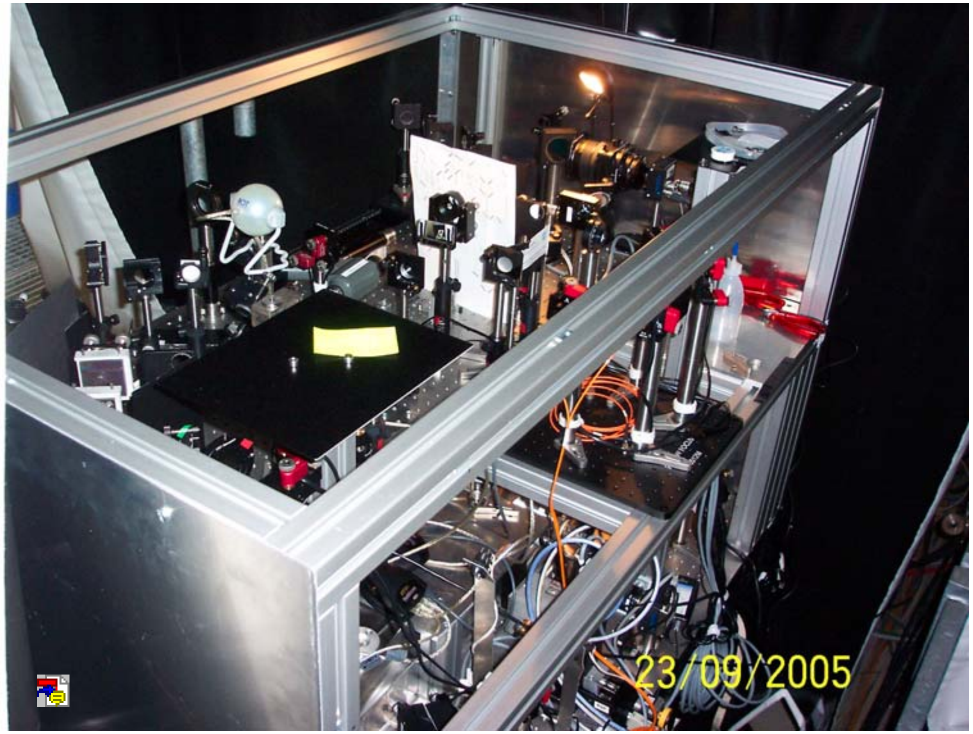
Experimental setup at DESY FLASH



- Laser system is housed outside the accelerator tunnel including
  - 4 nJ, 15 fs Ti:Sa oscillator
  - 1 mJ, 30 fs Ti:Sa amplifier
- Beam is transported via a 20m vacuum transfer line
- Set-up allows sampling, spectral and temporal decoding
- Currently ZnTe (185µm) and GaP (65µm) crystals mounted

EO Setup at FLASH

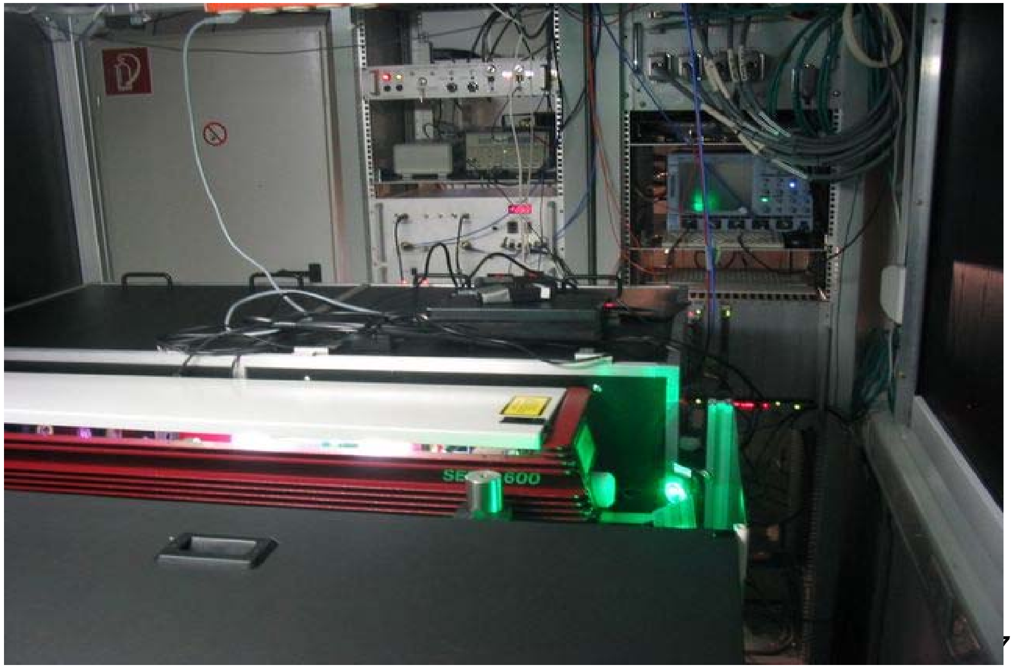




- situated at 140m point on FLASH
- beam energy 450 MeV
- adjacent to LOLA transverse deflection cavity
- adjacent to CTR/CDR screen

EO Setup at FLASH

in accelerator tunnel

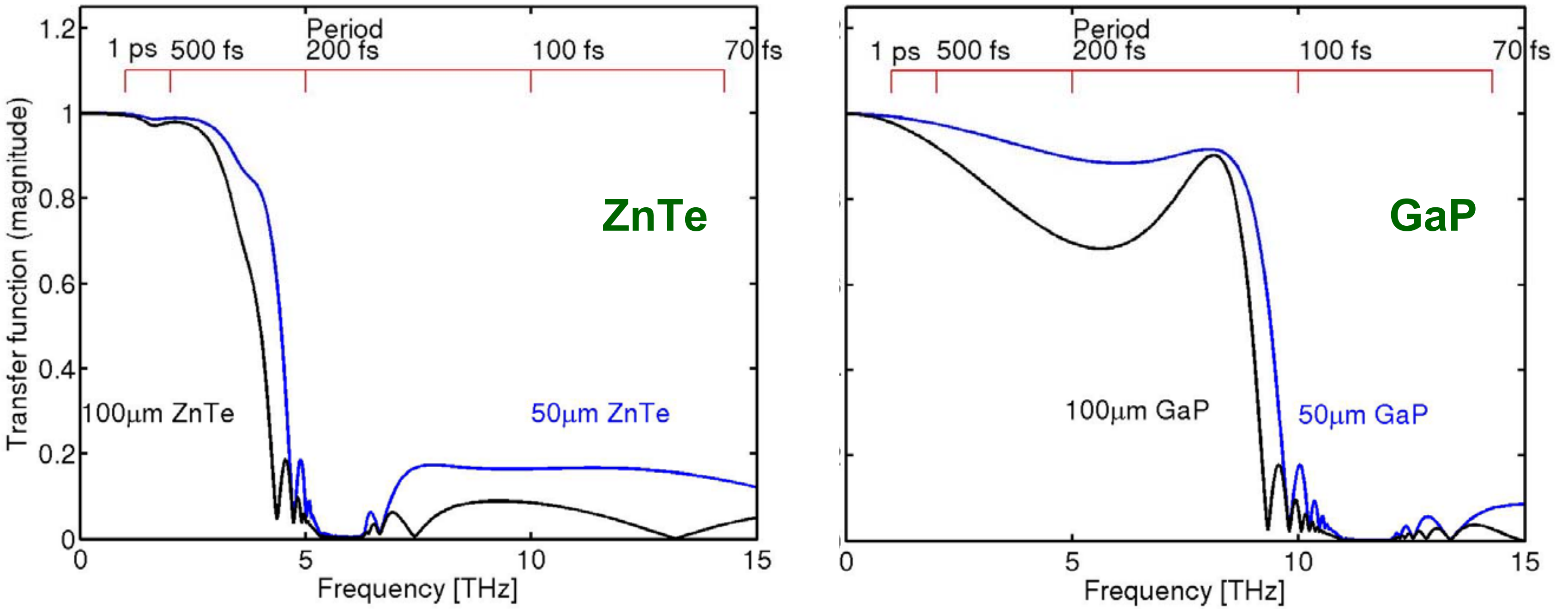


in laser hut
above ground

Improved time resolution

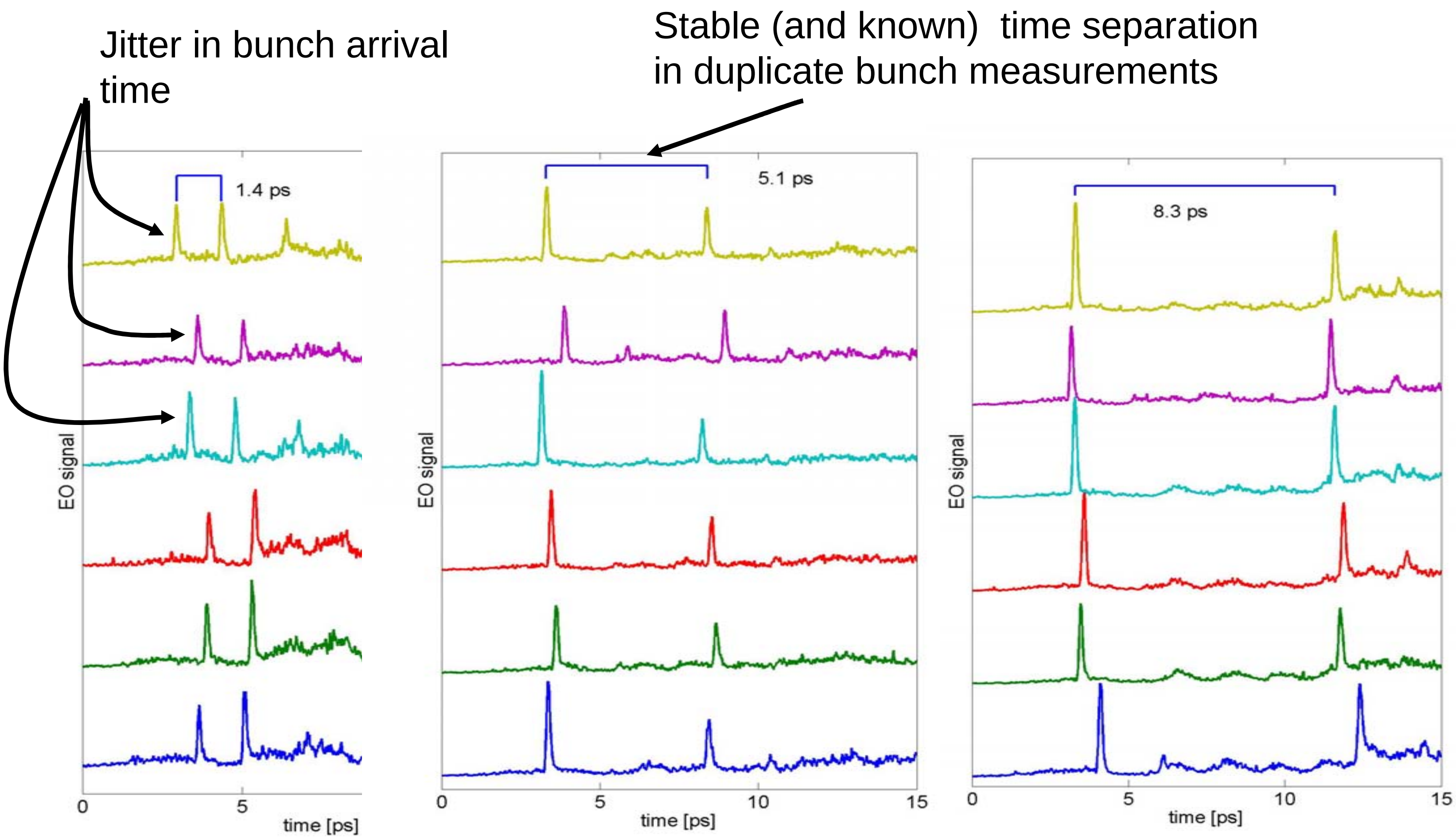
Original measurements used ZnTe as E-O crystal

Latest DESY measurements used GaP crystal



Time calibration…new approach

Simultaneously measure same bunch twice,
with known time separation between measurements



Benchmarking of diagnostic ..

Calibration of EO crystals..

1. EO coefficient frequency dependence , $\chi^{(2)}(\omega)$

   Requires known source of ultrafast THz …

   … no such source available for <100fs pulses

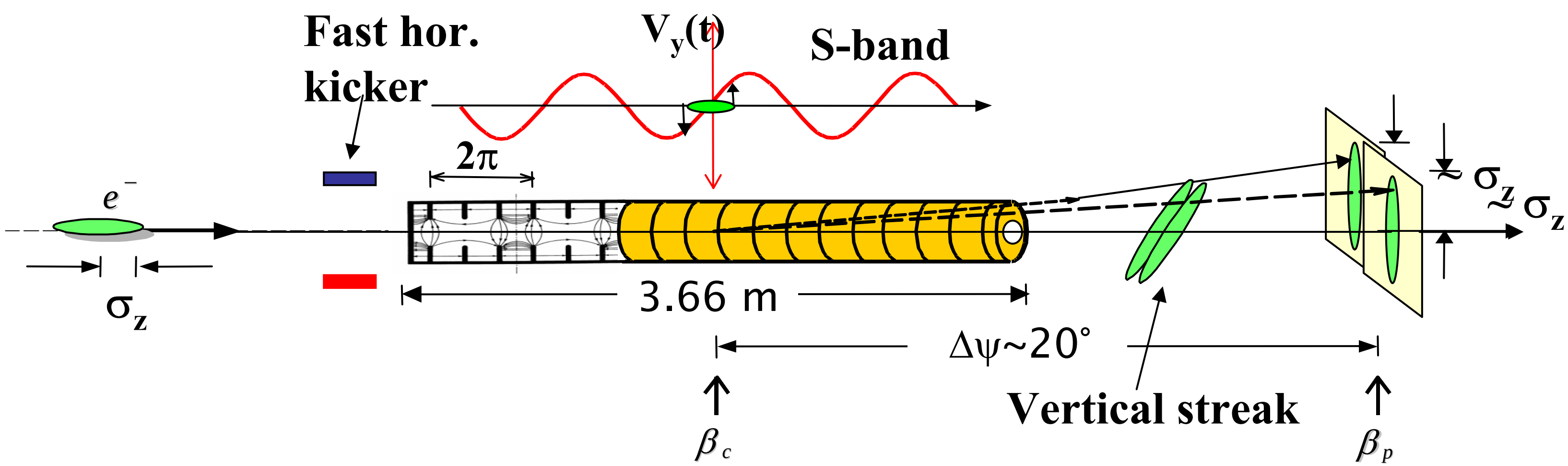
2. Calibration through CSR spectrum? (not unique)

3. Calibration with transverse deflecting cavity?

   - In situ initial calibration
   - calibration can reliably be extrapolated to shorter time scales

Benchmarking EO by LOLA cavity (TDC)

LOLA: Transverse Deflecting Cavity = fast electron oscilloscope

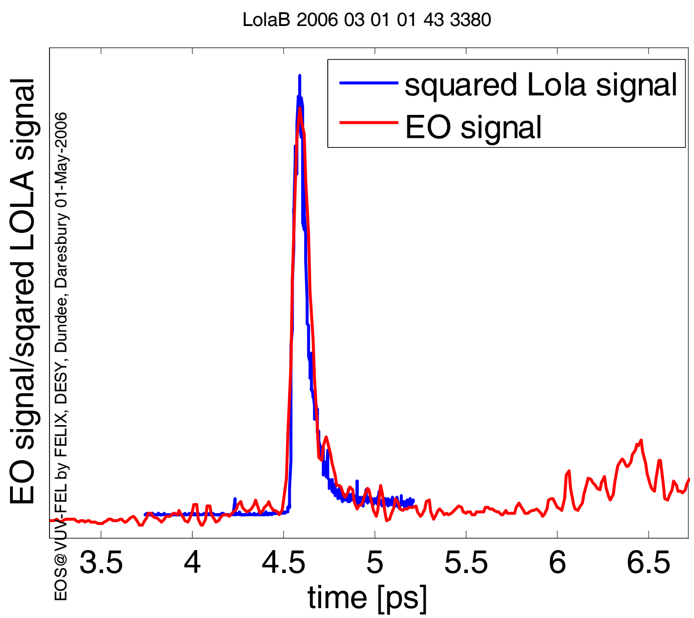


Resolution: 100fs (20fs with special optics)

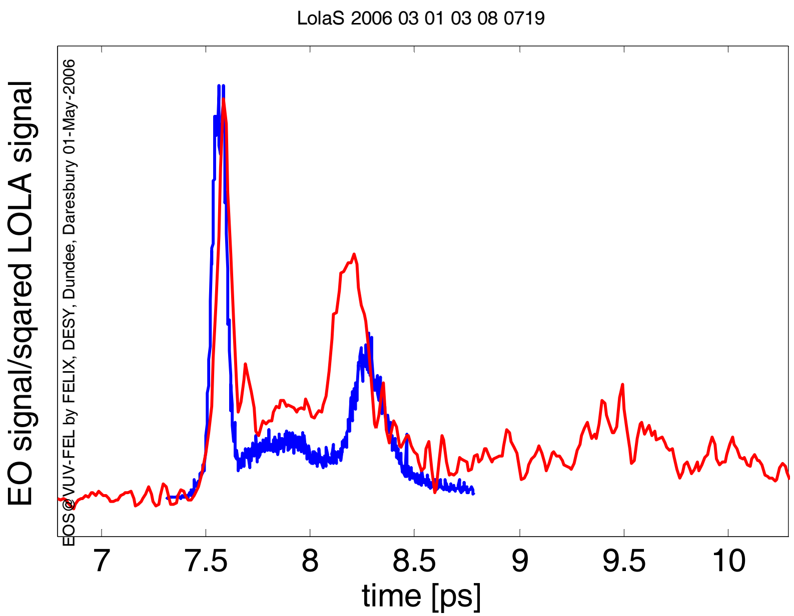
Disadvantages: no absolute timing (high time jitter)

no SASE signal from the measured bunch, since destructive diagnostic

Comparison of EO and LOLA signals



SASE conditions

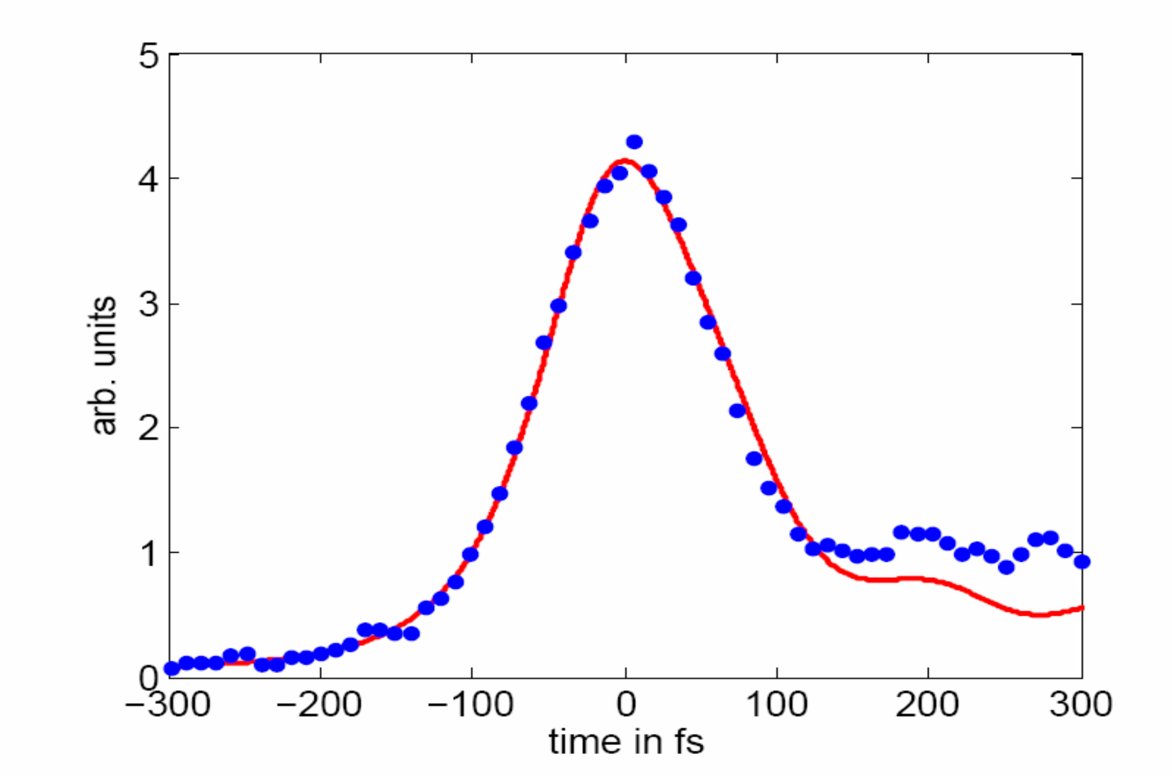


ACC1 phase 3° overcompression

EO at <u>first</u> bunch, LOLA at <u>second</u> bunch in the <u>same</u> bunch train

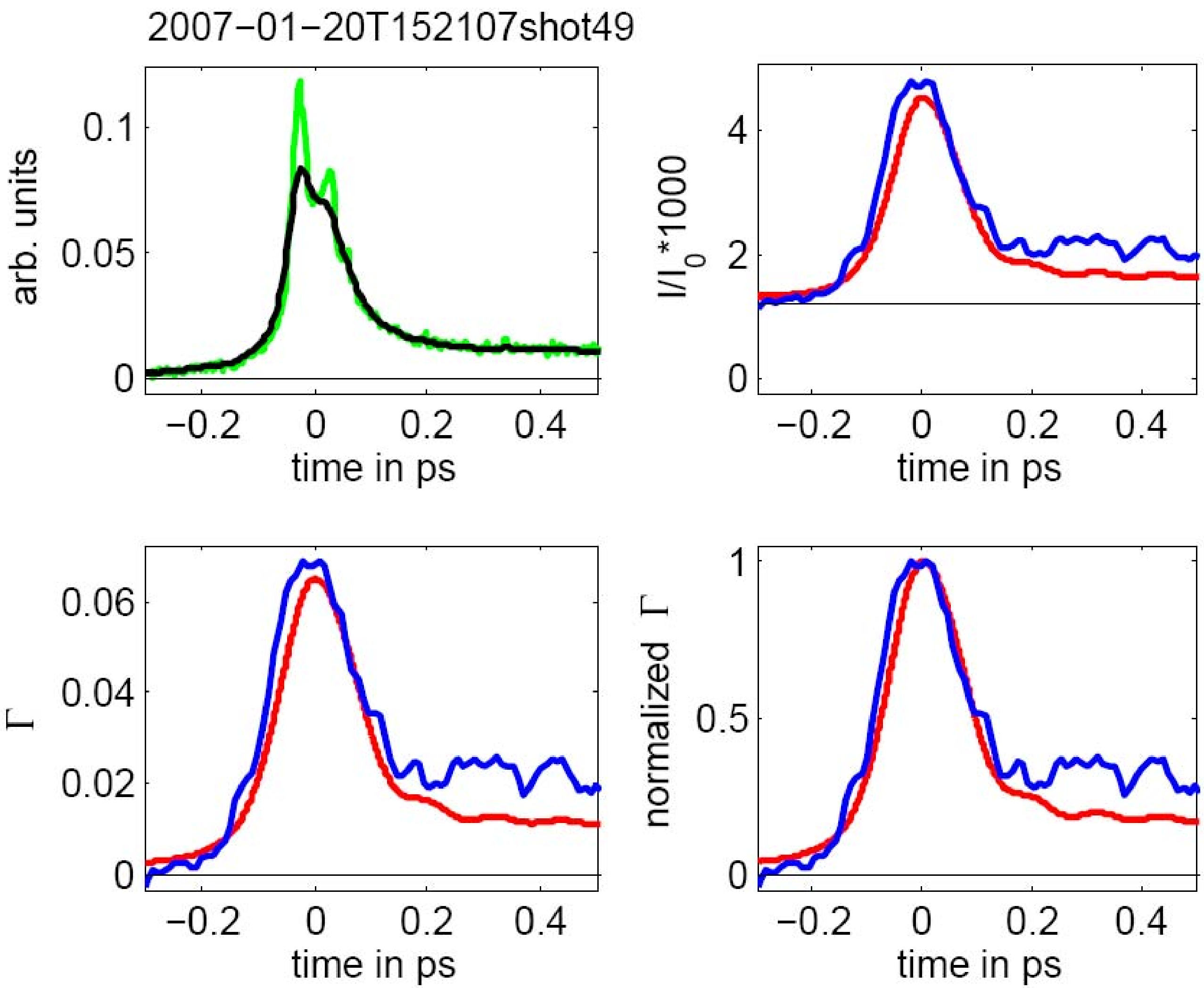
Narrow bunches measured at FLASH

For a fitted Gaussian curve we get a sigma of 79.3 ± 7.5 fs



FLASH data – Jan 2007

Data taken with gap (175 um), Q=0.84 nC, r = 3.8 mm; LOLA Res 3.2 fs /pix



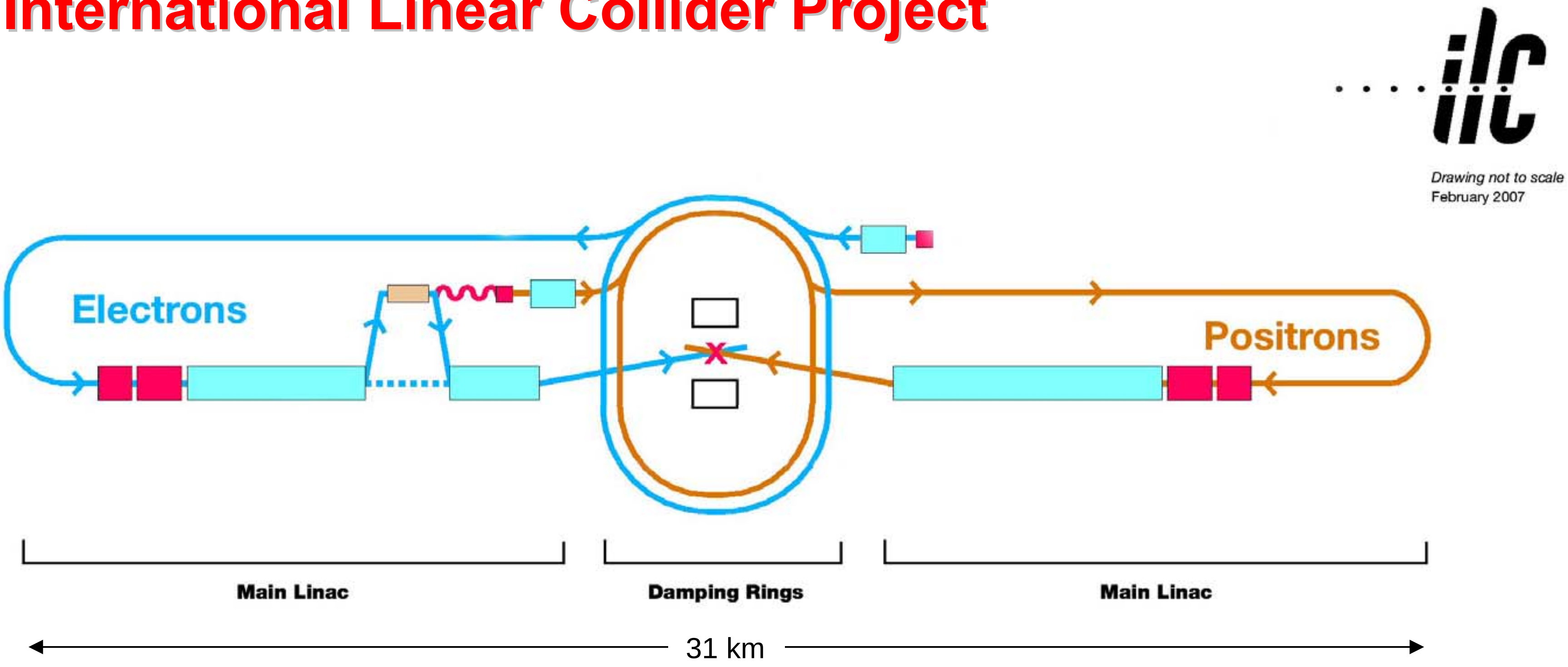
Green line LOLA trace

Black line calculated electric field

Red line simulated EO signal / phase retardation

Blue line the measured retardation

International Linear Collider Project



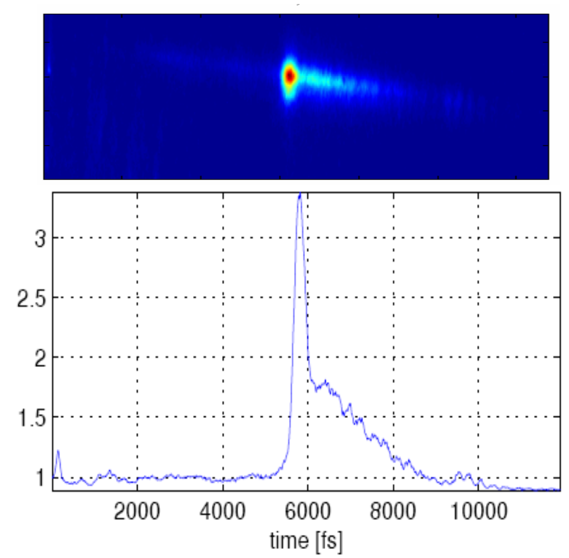
Energy: 500 GeV (upgrade to 1 TeV)

Bunch length: 150μm ≡ 500 fs

ILC Project: LC-ABD 1

2004 - 2007

WP 2.2   Advanced diagnostics:
Electro-optic longitudinal beam profiling



Tasks:

prototype system installed at FELIX	600fs FWHM beams measured at FELIX Published Phys. Rev Lett (2004)
FROG system installed	with SLAC collaboration (P. Bolton)
Tests with “ILC-like” bunches at DESY (higher E/shorter duration)	extensive set of DESY experiments. ~100fs FWHM measured.

ILC Project: LC-ABD Group

Why do we need an ILC ultrafast beam diagnostic?

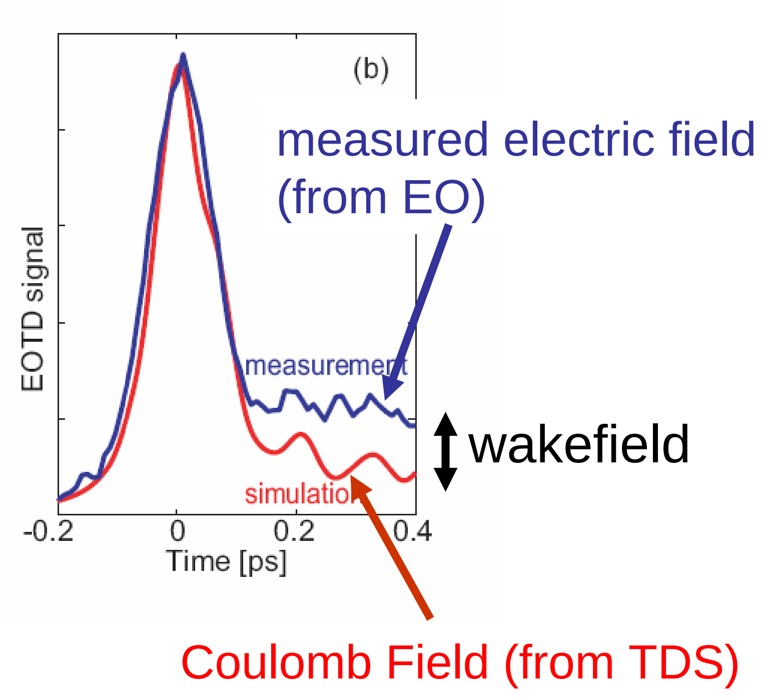
Machine operation has high influence on beam shape:

- Wakefields

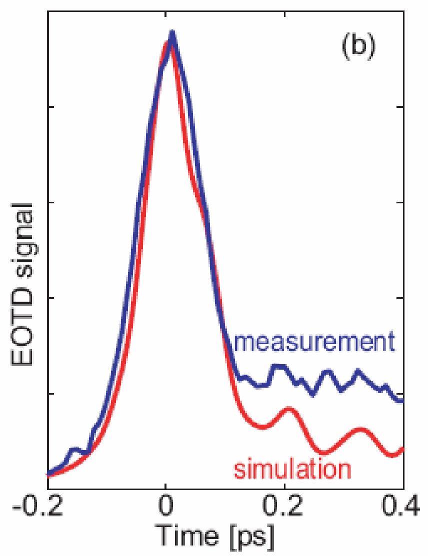
  (Important in ILC)

- Synchrotron radiation

- Beam – Beam interaction

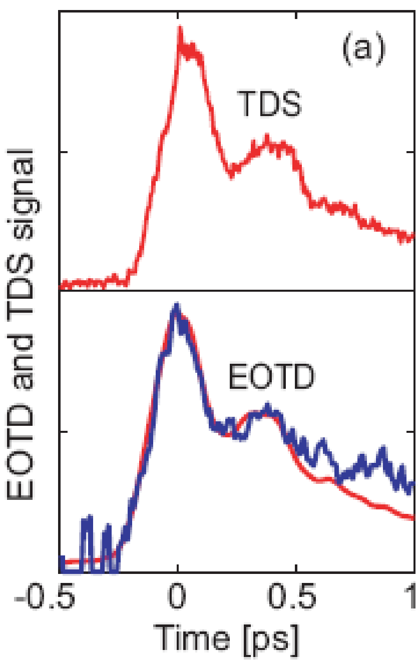


WP 2.2 Highlights



* Demonstrated capability of resolving σ ~ 60 fs structure

* "Non-destructive" capability tested
- SASE lasing at FLASH unperturbed



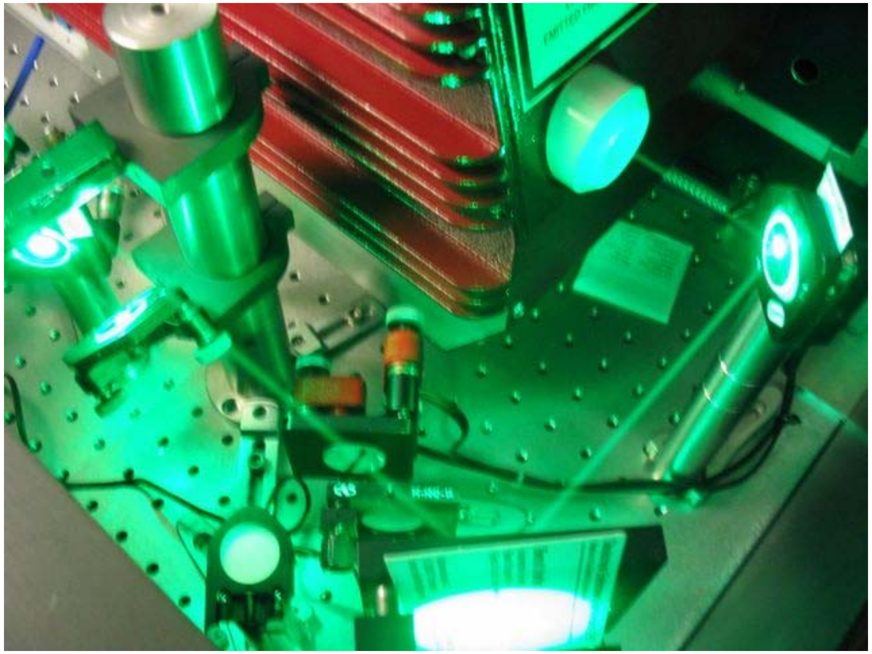
Deflecting cavity (destructive)

Electro-optic (non-destructive)

** First ever benchmarking of EO technique against Transverse Deflecting (LOLA) cavities

* Single-shot calibration technique developed

*



Key papers: Dundee Group

- NIM. Phys. Res. A429 (1999) 7- 9
- PRL 85 (2000) 3404-7
- PRL 88 (2002) 124801/1-4
- Opt. Lett. 28 (2003) 1710
- PRL 93 (2004) 114802/1-4
- Opt. Lett. 31 (2006) 1753-55
- PRL 93 (2007) 114802/1-4

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LC-ABD2: WP8.2 EO forward plans (from April 2007)

1. integrate techniques into fibre laser timing distribution
2. investigate the capabilities as feedback diagnostics
3. significantly increase repetition rate capabilities
4. address the laser requirements of technique:

   - **seek large reductions in laser pulse energy**
   - **migrate to reliable/stable fibre laser system**

1. Integration of EO techniques into fibre systems, including timing distribution systems

why?:
- dual purpose in arrival time monitor
- use of existing systems and infrastructure
- improved stability & reliability

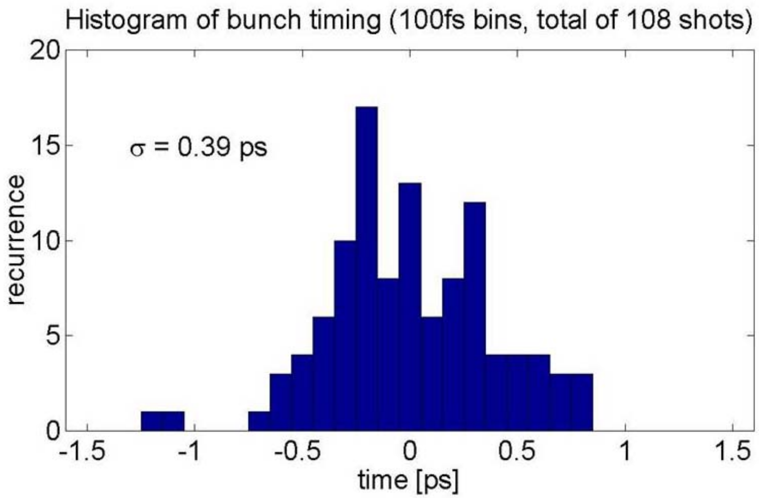
what?: hybrid Ti:S + low power Er-fibre (existing lasers)

- provides timing info, but no saving on infrastructure
- maintains our proven high time resolution capabilities
- tests will be carried out on ERLP at Daresbury Lab

Synchronisation and bunch timing jitter

Probe laser synchronised to RF

- ~100fs laser-RF synchronisation
- Jitter measurement also subject to laser beamline path length changes
  (active stabilisation?)

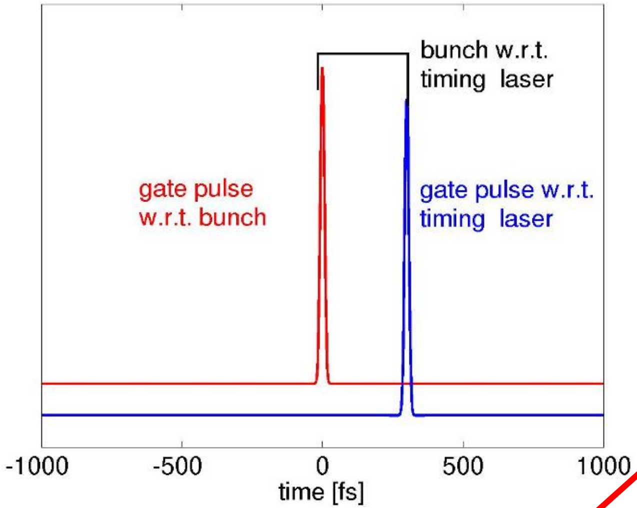


Bunch sampling rate < 1 kHz

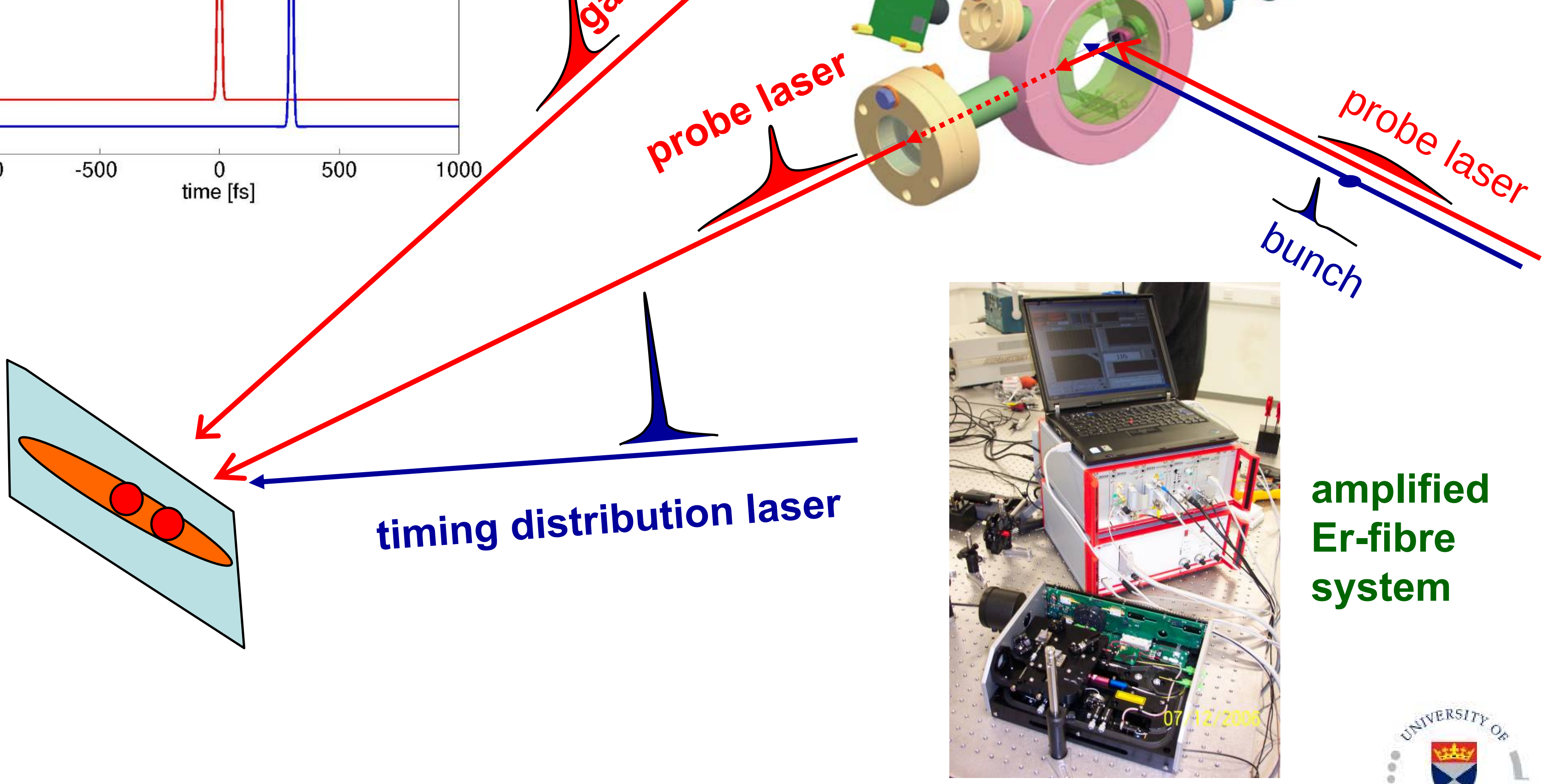
(could envisage ways for rapid sampling of a pair of bunches)

Additional timing jitter measurement (or synchronisation?) between photoinjector laser and EO probe laser?

Integration with timing distribution systems...

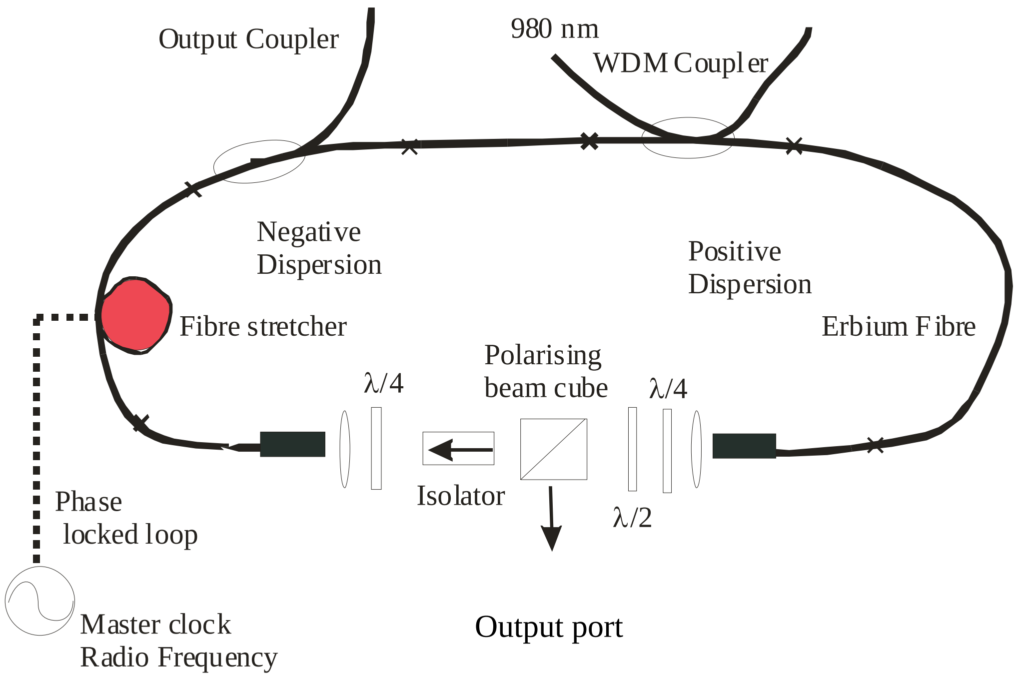


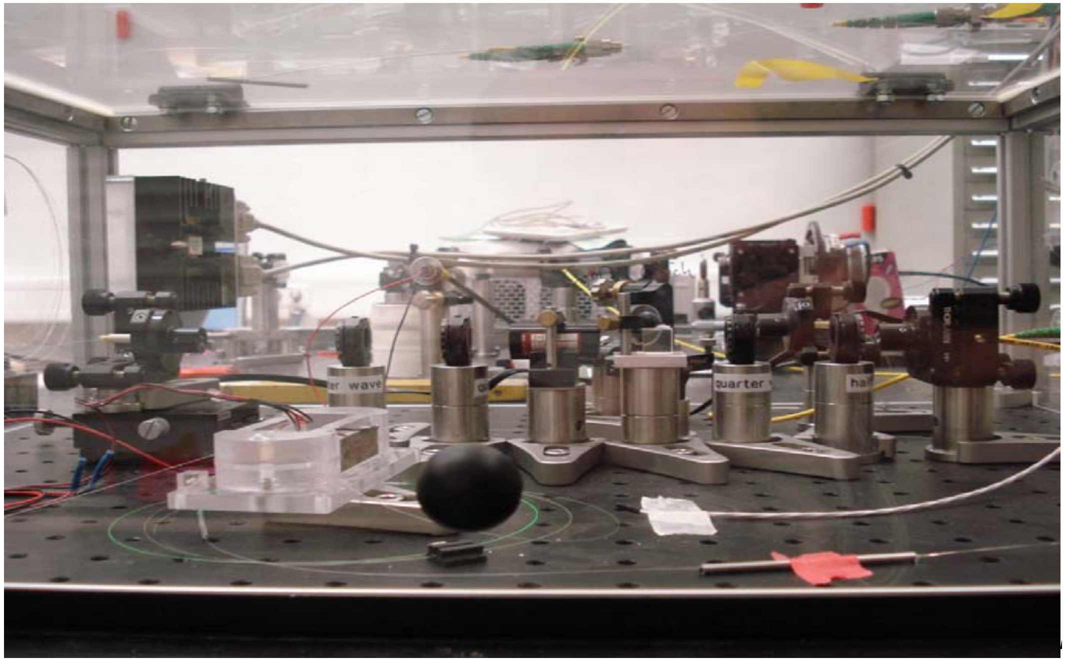
to be tested on ERLP



amplified Er-fibre system

Erbium-doped fibre laser layout





Fibre Laser at DESY

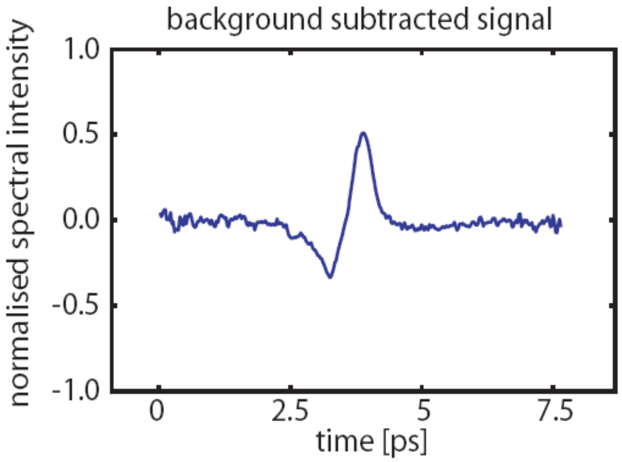
Planning integration of diagnostics into ILC baseline ….

- optimal / available location of monitors ?

ring to main linac

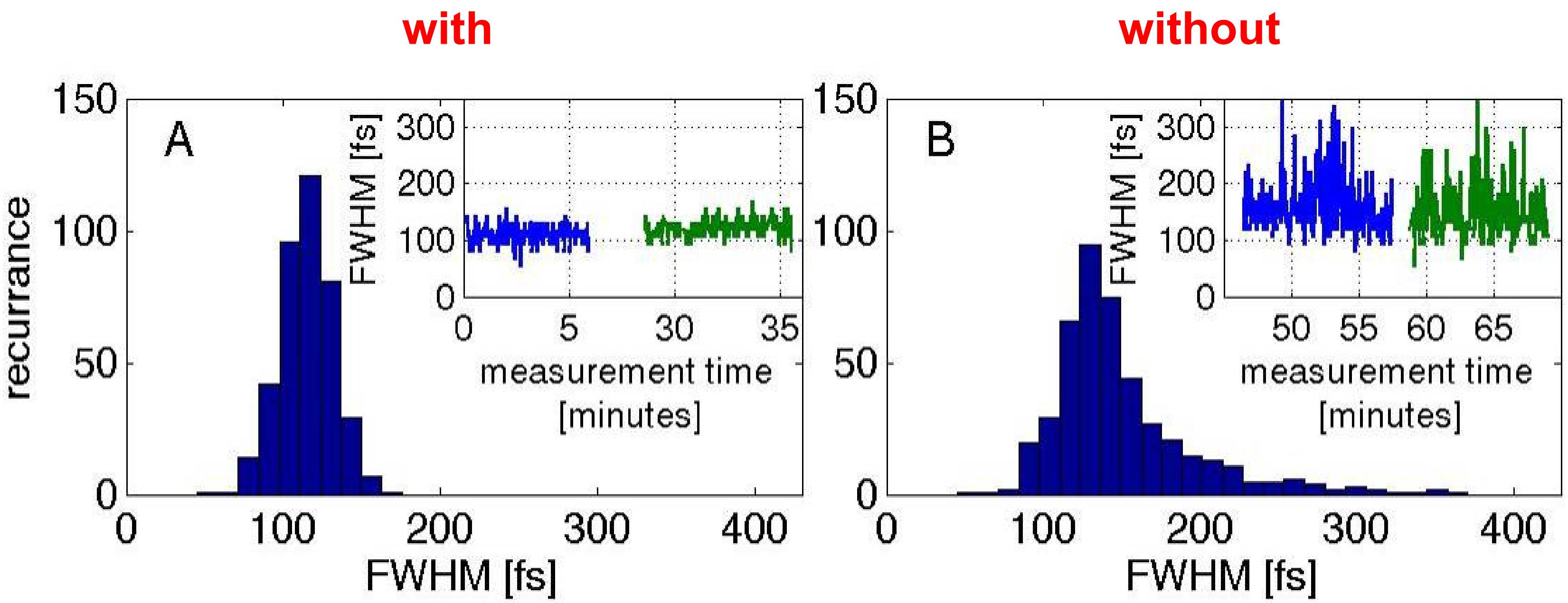
- BC1 long diagnostic section ?
- BC2 long diagnostic section: σ_z = 0.3mm / 0.15mm
  (simultaneous high res profile +
  high res arrival timing)

- invasiveness in real machine ?
- capabilities of CSR/CDR monitoring ?



- **truly non-invasive EO monitor CSR from chicanes**
- **continuous monitoring potential → feedback**

2. Capabilities as feedback diagnostics



Bunch profile FWHM at FLASH, with and without feedback system (CDR) running as measured by Dundee EO system

3. Repetition rate, laser requirements ...

Proposal: moderate power Yb laser (microJoule), 50fs

phase 1: standalone bunch “length” using *spectral decoding*

reliability, bunch length (+ higher moments) at high rep rate

phase 2: optimisation / minimisation of laser power requirements for temporal decoding

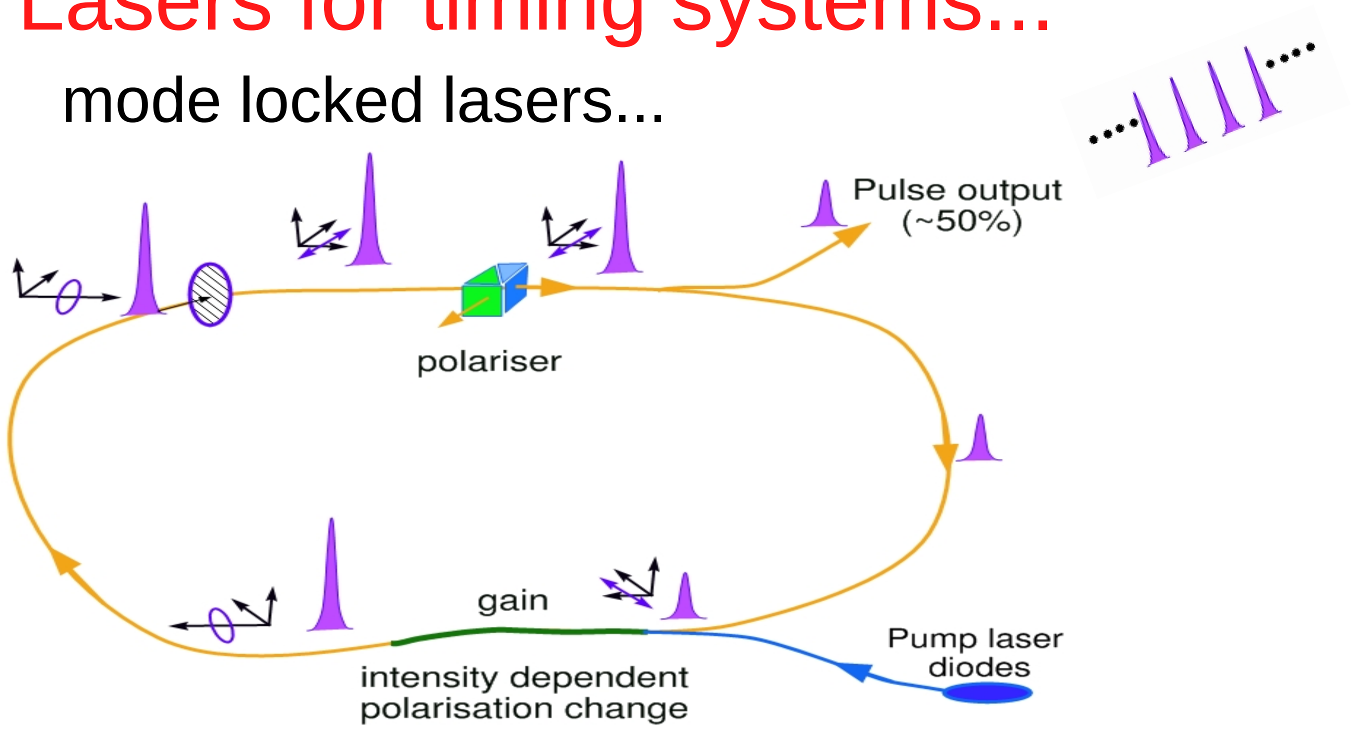
currently ~100 μJ, Ti:S

aim for 10 μJ => migrate away from complicated Ti:S systems
=> higher rep rate possible at lower pulse energy

end

Lasers for timing systems...

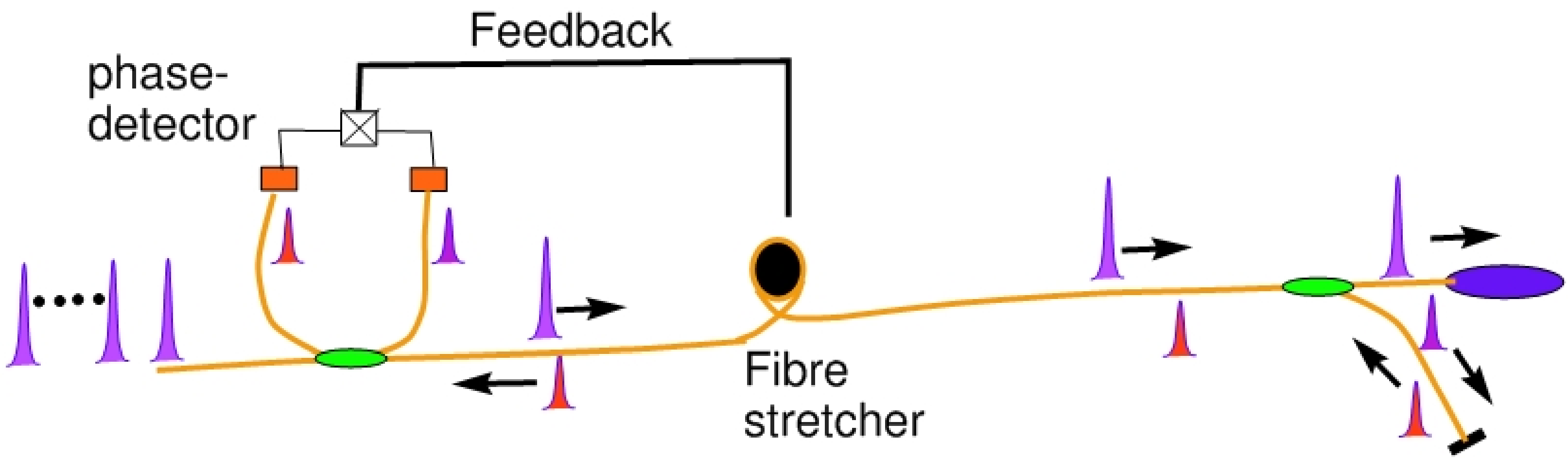
mode locked lasers...



- intensity peaks suffer lower loss (in polariser)
- gain medium further enhances intense peak
- gain medium “robbed” intense peaks (suppresses CW gain)

- pulsed operation starts from random fluctuations...
- self organises into intense (short) pulse circulation

Lasers for timing distribution...

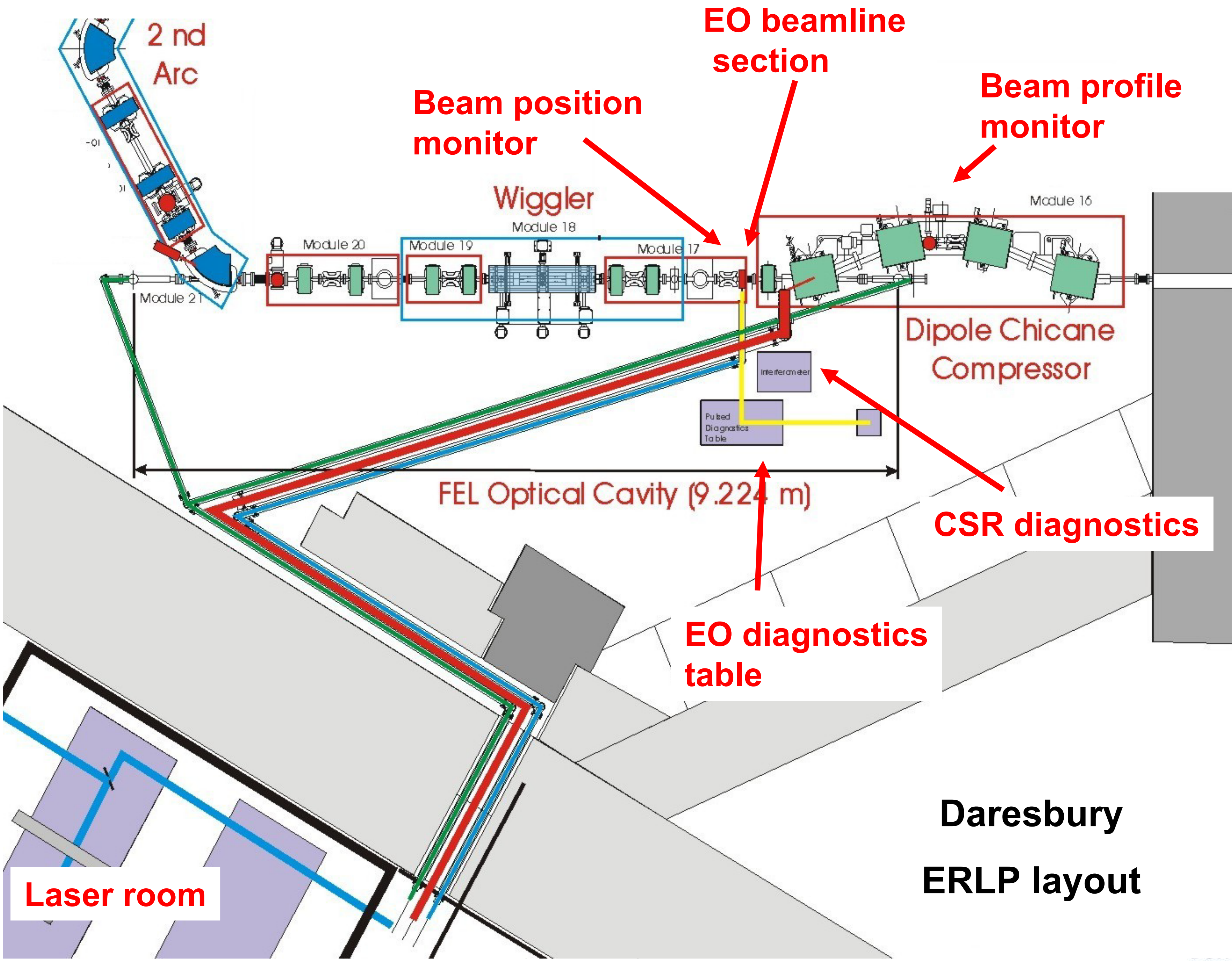


Compare arrival time of outgoing and round trip pulses
- RF phase detection ~20fs sensitivity
- optical cross-correlation ~1fs (?)

Active stabilisation of fibre length

Can we get even better time resolution ?

- LOLA measurement: Actual bunch profile (10 fs resolution)
- Coulomb angle $1/\gamma$ ~ 50 fs for γ ~ 1000
- Material
  - GaP
  - New material (phase matching, χ^2 considerations)
- Gate pulse width ~ 50 fs
  - Introduce shorter pulse
  - Spectral interferometry
  - FROG Measurement
  - Try these methods on Daresbury ERLP



Daresbury

ERLP layout

ALPHA-X

ALPHA-X Project, Strathclyde - Overview

Advanced Laser Plasma High-energy Accelerators towards X-rays

Consortium of U.K. research teams (phase 2)

U. Strathclyde
D. Jaroszynski
B. Bingham
K. Ledingham
P. McKenna

U. St. Andrews
A. Cairns

U. Dundee
A. Gillespie
J. Phillips
S. Jamison

U. Abertay-Dundee
A. MacLeod

Imperial College
S. Rose

Cockcroft Institute
M. Poole → Science & Technology Facilities Council ASTeC
R. Tucker → LANCASTER UNIVERSITY

Partners – T. Mendonca (IST), B. Cros (UPS - LPGP), W. Leemans (LBNL),
B. van der Geer (Pulsar Phys), G. Shvets (UTA), J. Zhang (CAS)

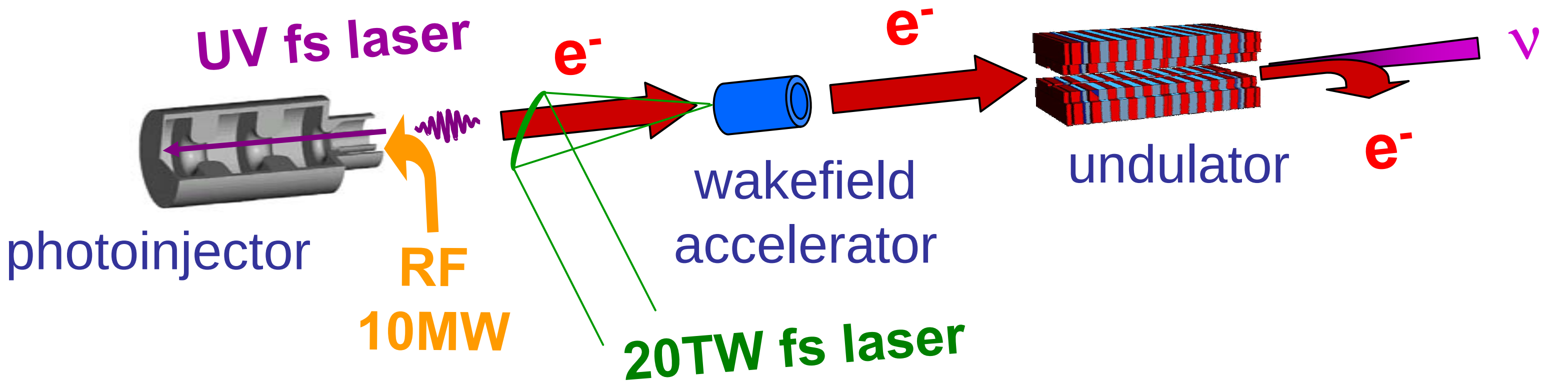
Project Goals

- A programme to investigate laser-plasma acceleration of electrons.
- A source of ultra-short, coherent, short-wavelength pulses of radiation.
- Allows high-resolution time-resolved experiments in physics, chemistry and biology.

Motivated by…

- Very large acceleration gradients in wakefield accelerators (1 GeV/cm).
- Conventional RF accelerators (1 MeV/cm).
- Potential for compact, high-energy electron (and other particle) sources and short-wavelength radiation sources → Revolutionary technique & much cheaper!

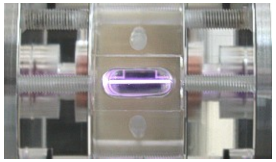
ALPHA-X Beam Line



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

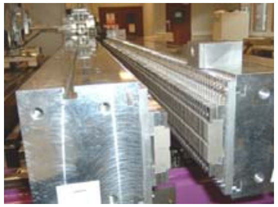
Brookhaven N.L.
T.U. Eindhoven
LAL Orsay (Terry Garvey)

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



U. Oxford
(Simon Hooker)

- **Undulator**
  - coherent radiation pulses
  - λ down to ~ 2nm

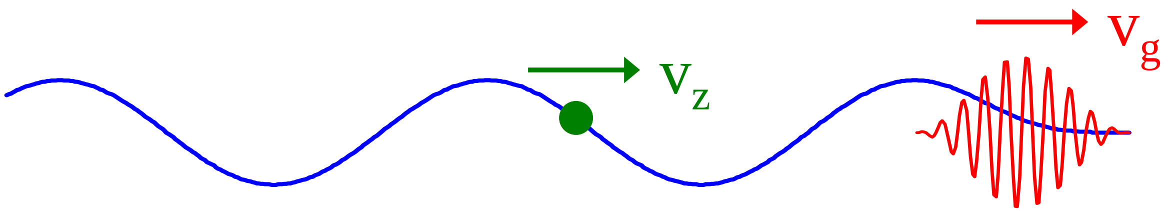


Daresbury: ASTeC
(Jim Clarke,
Ben Shepherd)

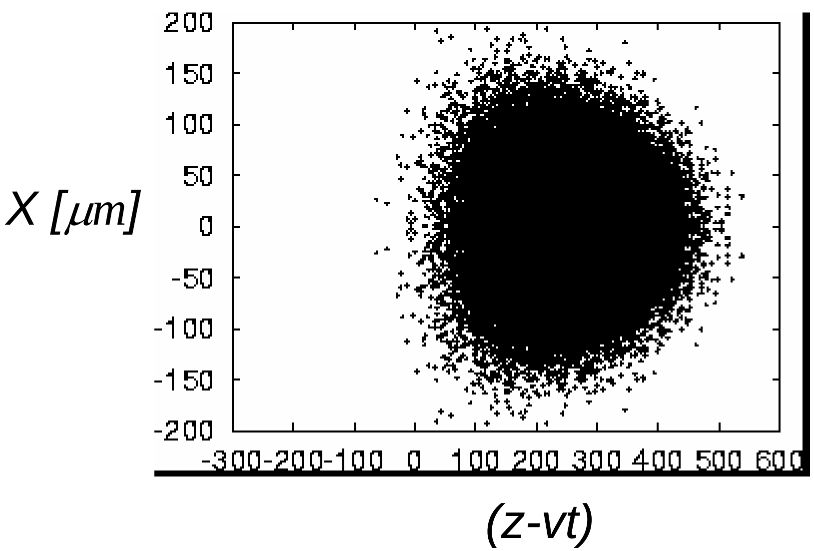
University of Dundee

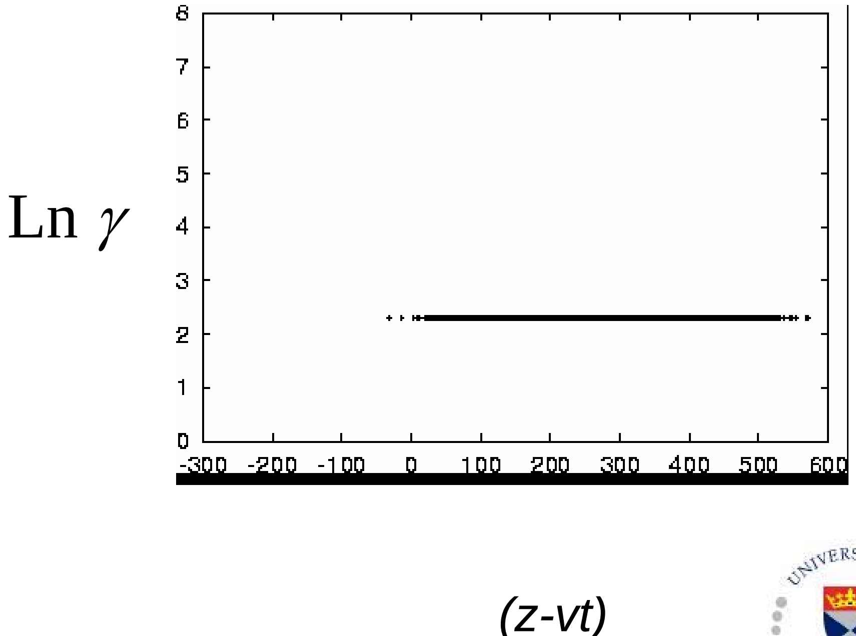
Laser Wakefield Acceleration

Electrons are <u>accelerated</u> in the wakefield if their initial velocity is sufficiently close to the phase velocity of the wakefield for <u>trapping</u> to occur

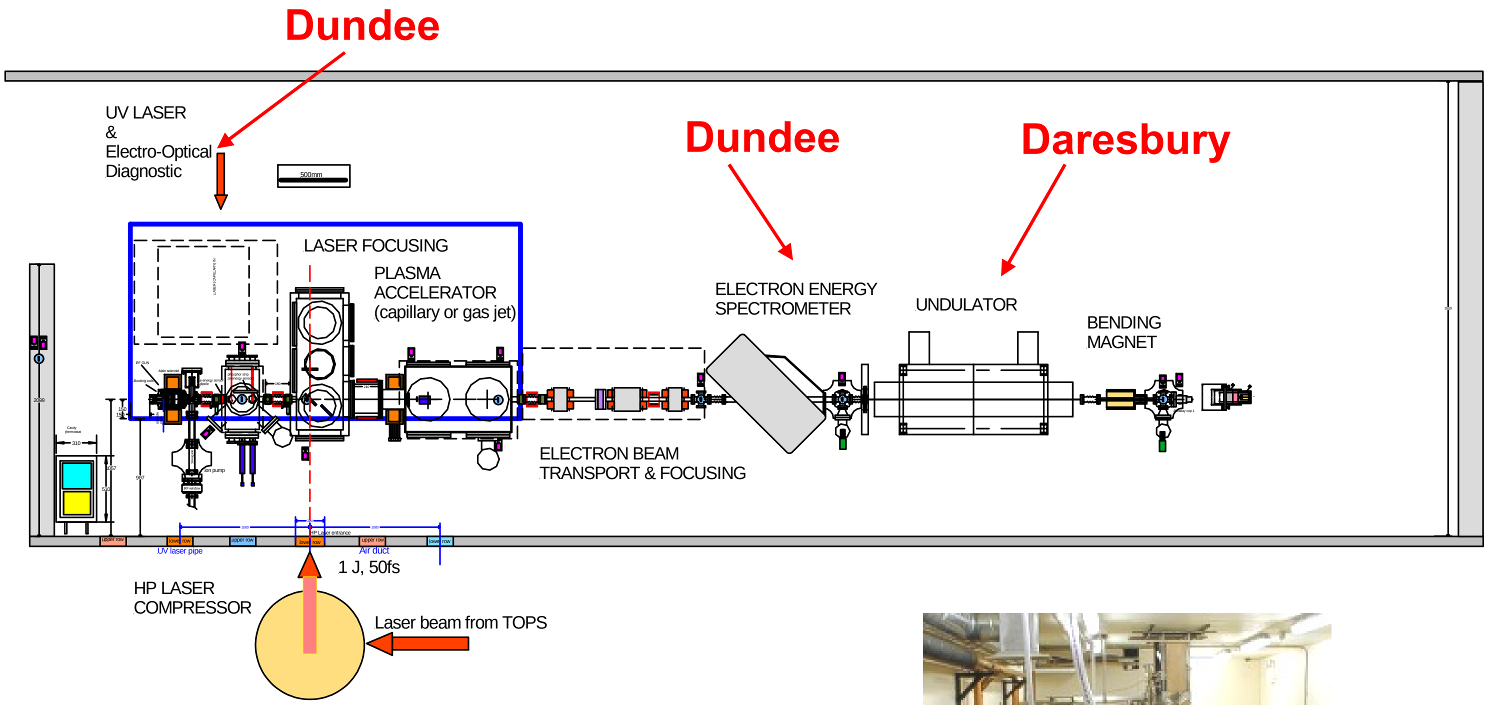


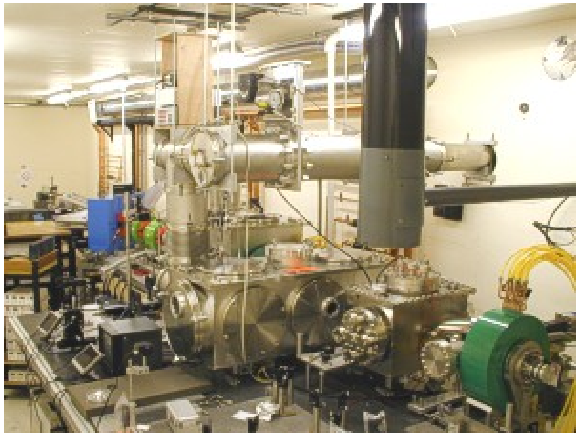
2-D example (A. Reitsma) e.g. PRL **94**, 085004 (2005).

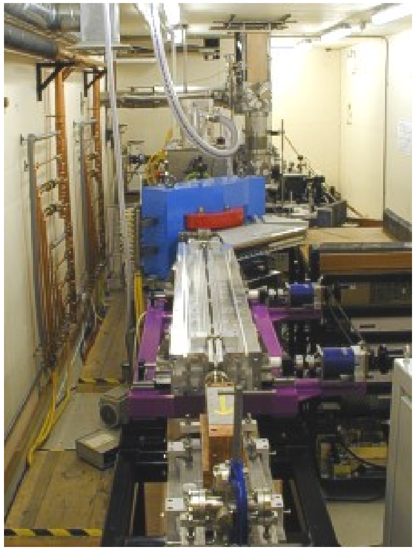




ALPHA-X Beam Line







Synchrotron Radiation Experiments

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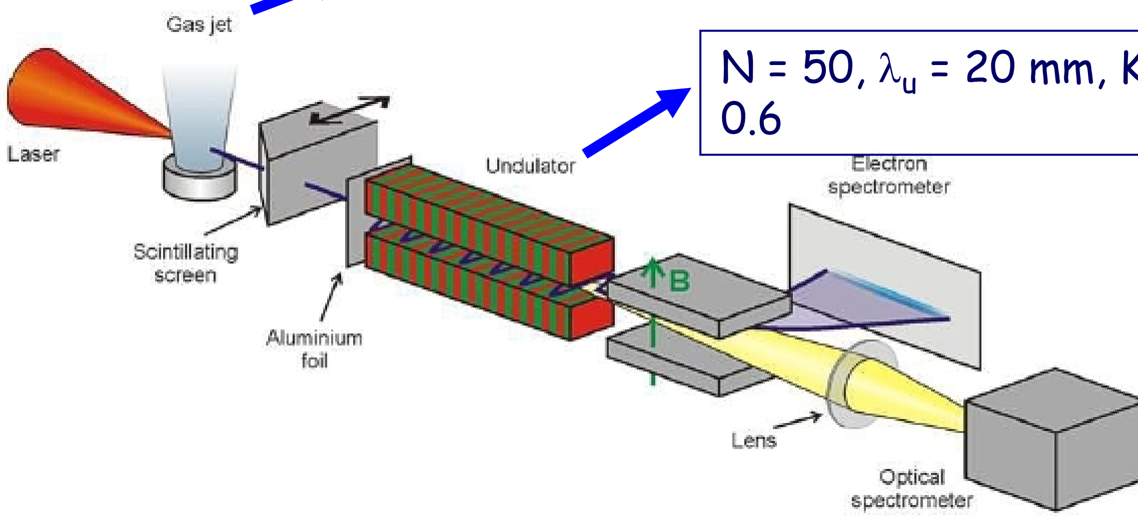
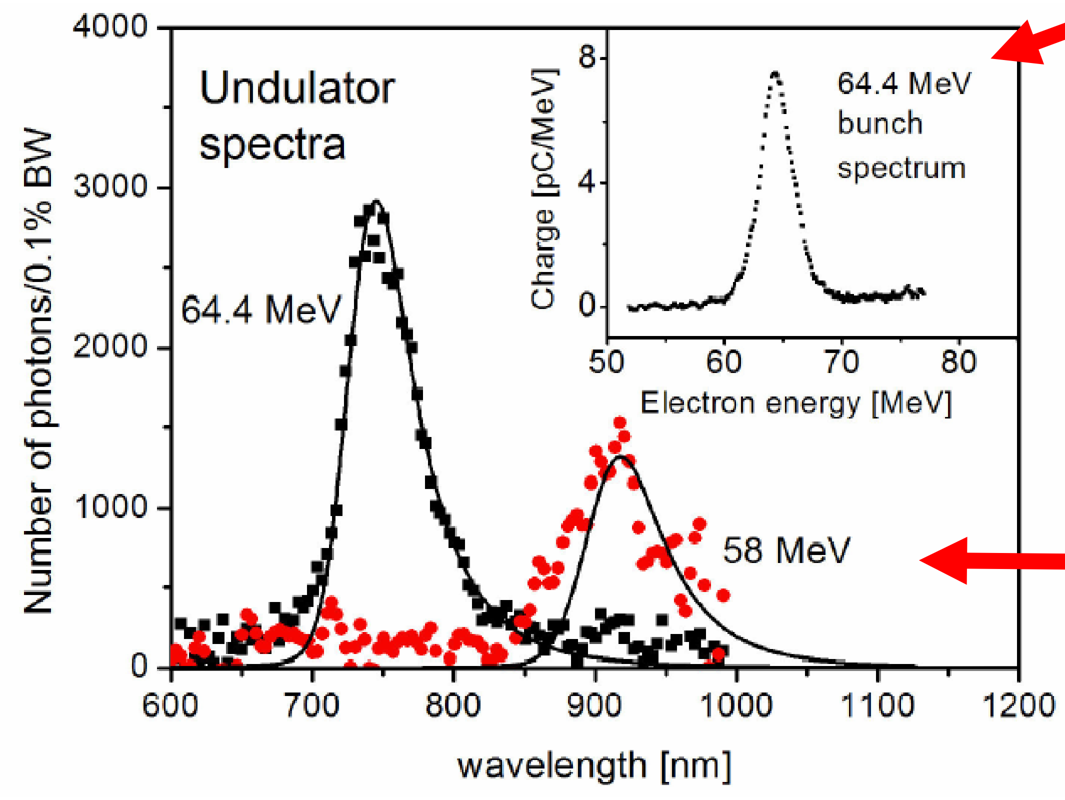
$n_e = 2 \times 10^{19}\ cm^{-3}$

$N = 50$, $\lambda_u = 20$ mm, $K = 0.6$

$E = 430$ mJ
$\tau = 85$ fs
$I = 5 \times 10^{18}$ W/cm^2
$a_0 = 1.5$



Observed Spectra



Electron Spectrum

- Monoenergetic electron bunches with peak E = 55-75 MeV.
- Bunch charge ~10-30 pC.
- Few % energy spread (δγ) close to spectrometer resolution.

Radiation Spectra

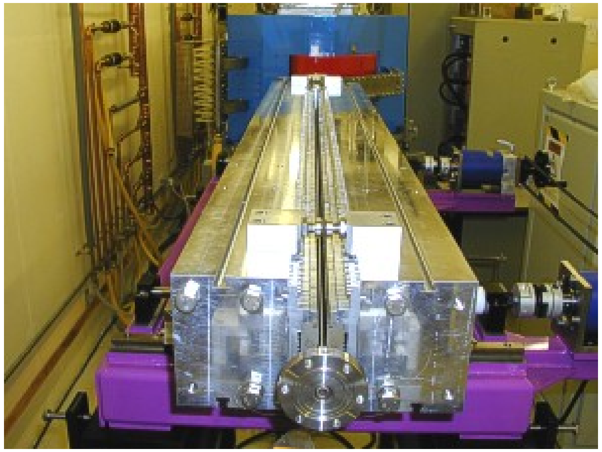
- Peak signal = 650-950 nm.
- Agreement with calculation (solid lines)

- Peak brilliance ~ 10^{16} photons/s /mrad²/mm²/0.1%BW (assuming τ ~ 10 fs)

Upcoming experiments

Generate radiation pulses on ALPHA-X Beam Line

ALPHA-X Undulator (part 1 of 2)



- Designed and built by ASTeC, Daresbury Lab
- N = 100 periods, period λ_u = 15 mm
- tunable gap with initial gap = 8.0 mm
- electron beam focusing / guiding up to ~ 100 MeV

E_e [MeV]	Radn λ [nm]
50	846
100	211
200	53
500	8
700	4

[λ_u = 15 mm, K = 0.38]

water window

Plasma Accelerator – Gas Jet

- Electron energy ~ 50-100 MeV
- Near IR to deep UV radiation pulses

Plasma Accelerator – Capillary Waveguide

- Electron energy ~ 100s of MeV
- VUV & EUV radiation pulses

→ UV wavelengths approaching X-rays

END