WP: CTC-006 - beam instrumentation task3

CLIC Electro-Optic Bunch Temporal Profile Monitor

Allan Gillespie[1] , David Walsh[1,2], Steve Jamison[2], Rui Pan[1, 3], Thibaut Lefevre[3]

[1] Carnegie Laboratory of Physics, University of Dundee, Dundee DD1 4HN, UK

[2] Accelerator Science & Technology Centre (ASTeC), STFC Daresbury Laboratory, Warrington WA4 4AD, UK

[3] Beam Department, CERN, CH-1211 Geneva 23, Switzerland

Synopsis:

1. Activities at CLIC CALIFES
2. Activities at STFC Daresbury Laboratory
3. Activities at the University of Dundee
4. Planned group activities over next year

1. CALIFES Electro-Optic Bunch Profile Monitor

Development & commissioning of single-shot EO bunch profile monitor – low time resolution system (~1ps)

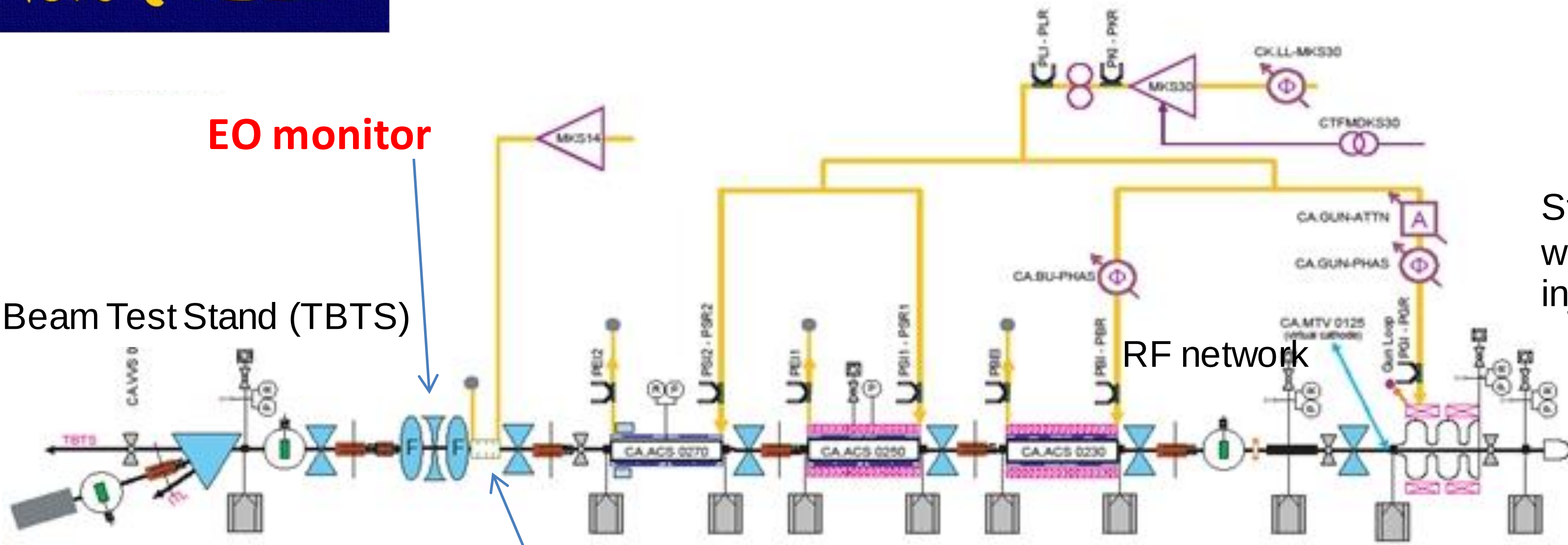
Progress update (Rui Pan)

1. Planned EO monitor simulated and resolution calculated
2. Overall EO system for CTF3 designed
3. Laser system designed and purchased
4. Laser system and ancillary optics arrived
5. Control system design completed
6. All cables and optical fibres installed
7. Optical synchronization system designed
8. Transfer lines for laser and OTR photons designed
9. Laser laboratory under preparation
10. Camera and motors are being delivered
11. Two monitor vacuum chambers are being designed
12. Preliminary work completed for beam profile measurement

CALIFES

EO monitor

to Two Beam Test Stand (TBTS)



Standing-wave photo-injector

RF network

Complete set of diagnostics

3 travelling-wave structures (LIL)

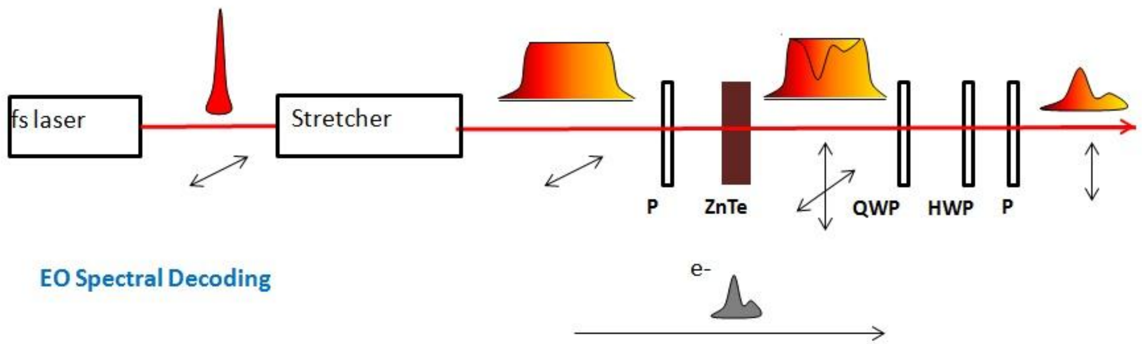
Energy	**200 MeV**
Energy spread	1% (FWHM)
Pulse length	0.6–150 ns
Bunch frequency	1.5 GHz
Bunch length	1.4 ps
Bunch charge	0.085–0.6 nC
Intensity	
- short pulse	1 A
- long pulse	0.13 A
Repetition rate	0.833 – 5 Hz

Existing bunch profile monitors:

- RF deflecting cavity
- Bunch length measurement with 12 GHz high gradient acceleration structure (2 beam test stand)

Electro-Optical Spectral Decoding

Simulations of bunch-induced polarisation change and non-linear interaction



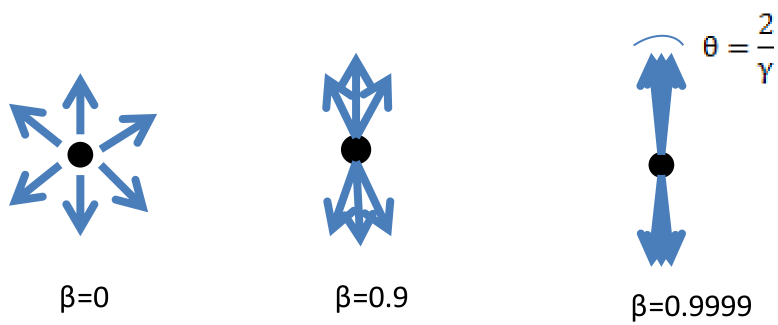
Spectral Decoding (EOSD): The Coulomb field temporal profile of the e-bunch is encoded on to a *time-wavelength correlated* optical probe pulse. The profile is read-out through the *spectrum* of the probe pulse.

$$E_{\mathrm{Out}}(\omega) = \begin{bmatrix} 0 & 1 \end{bmatrix} R(\varphi)\, M_{\mathrm{H}} R(-\varphi)\, R(\alpha)\, M_{\mathrm{Q}} R(-\alpha)\, R(\theta)\, M_{\mathrm{EO}} R(-\theta) \begin{bmatrix} E^{\mathrm{Chirp}}_{\mathrm{Laser}}(\omega) \\ 0 \end{bmatrix}$$

Where, $$M_{\mathrm{EO}} = \begin{bmatrix} \left(1 + \frac{i\omega}{2nc} \cdot \widetilde{E}^{Eff}_{\mathrm{Coul}} *\right) & 0 \\ 0 & \left(1 - \frac{i\omega}{2nc} \cdot \widetilde{E}^{Eff}_{\mathrm{Coul}} *\right) \end{bmatrix}$$

Where, $$\widetilde{E}^{Eff}_{\mathrm{Coul}}(0,\Omega) = \chi^{(2)}_{Eff} \left[\frac{e^{i\Delta k(\omega,\Omega) z} - 1}{i\Delta k(\omega,\Omega)} \right] \cdot \widetilde{E}_{\mathrm{Coul}}(0,\Omega)$$

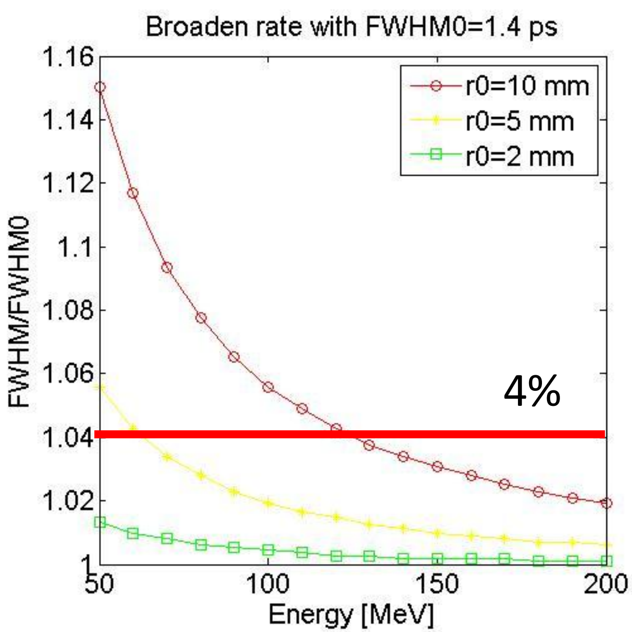
Simulation: Coulomb field of e-bunch and broadening



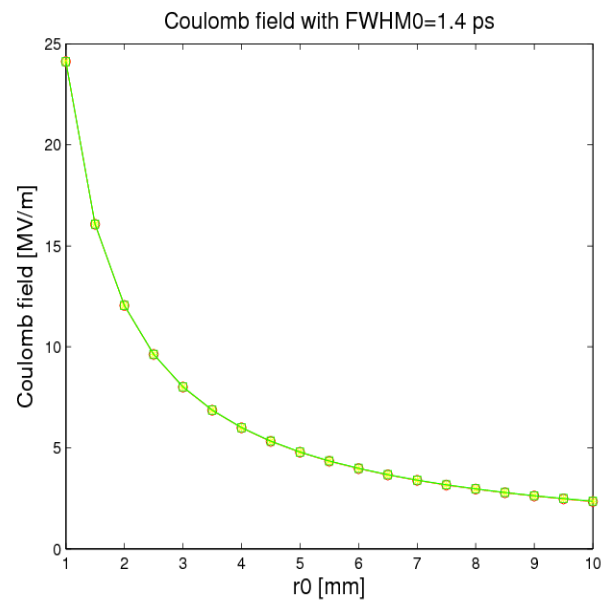
- At high energies , the Coulomb field temporal profile is approximately the bunch temporal profile

- Broadening of profile from transverse parameters:

$$\Delta t \sim \frac{2r}{\gamma}$$



For high energy beam (>150 MeV), resolution broadening is < 4% @ 10 mm

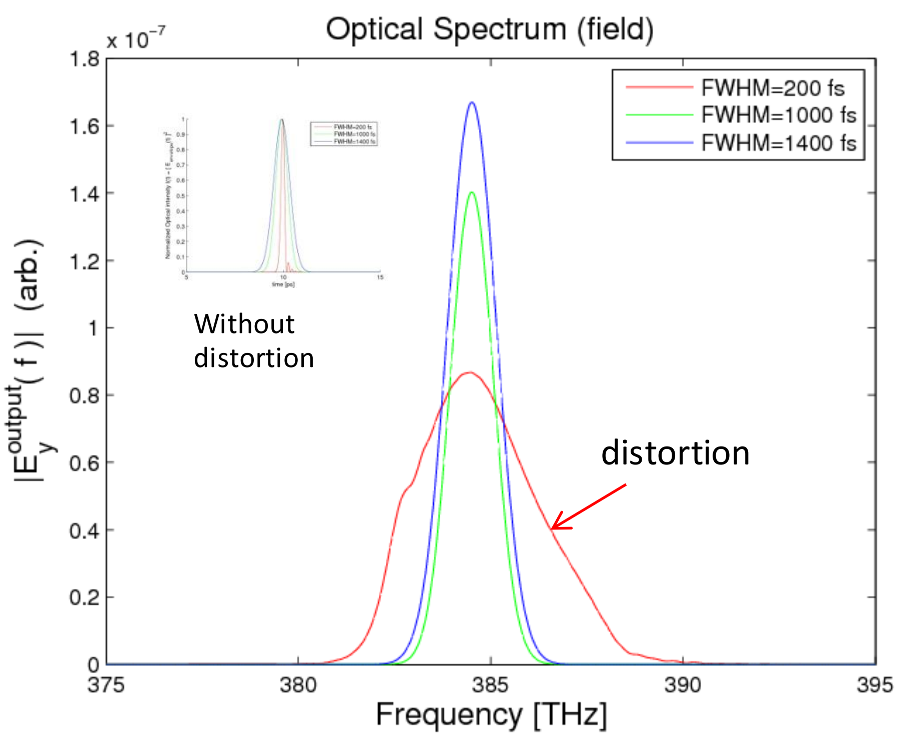


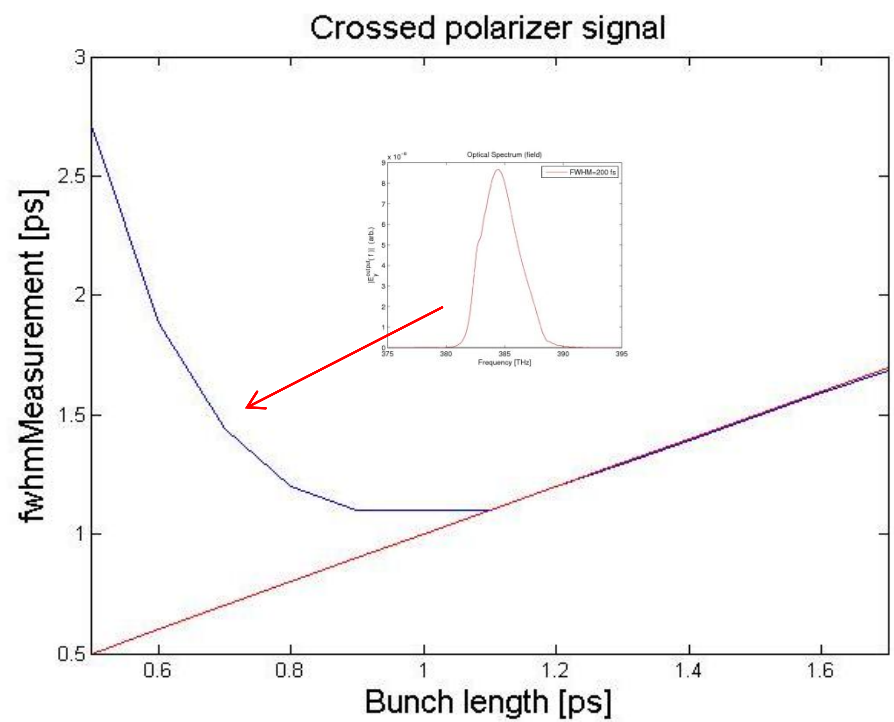
r_0 = transverse separation from e-bunch

As r_0 increases, Coulomb field decreases

Simulation: limitations of EOSD

Interleaving bandwidth conflict for optical probe and bunch spectra





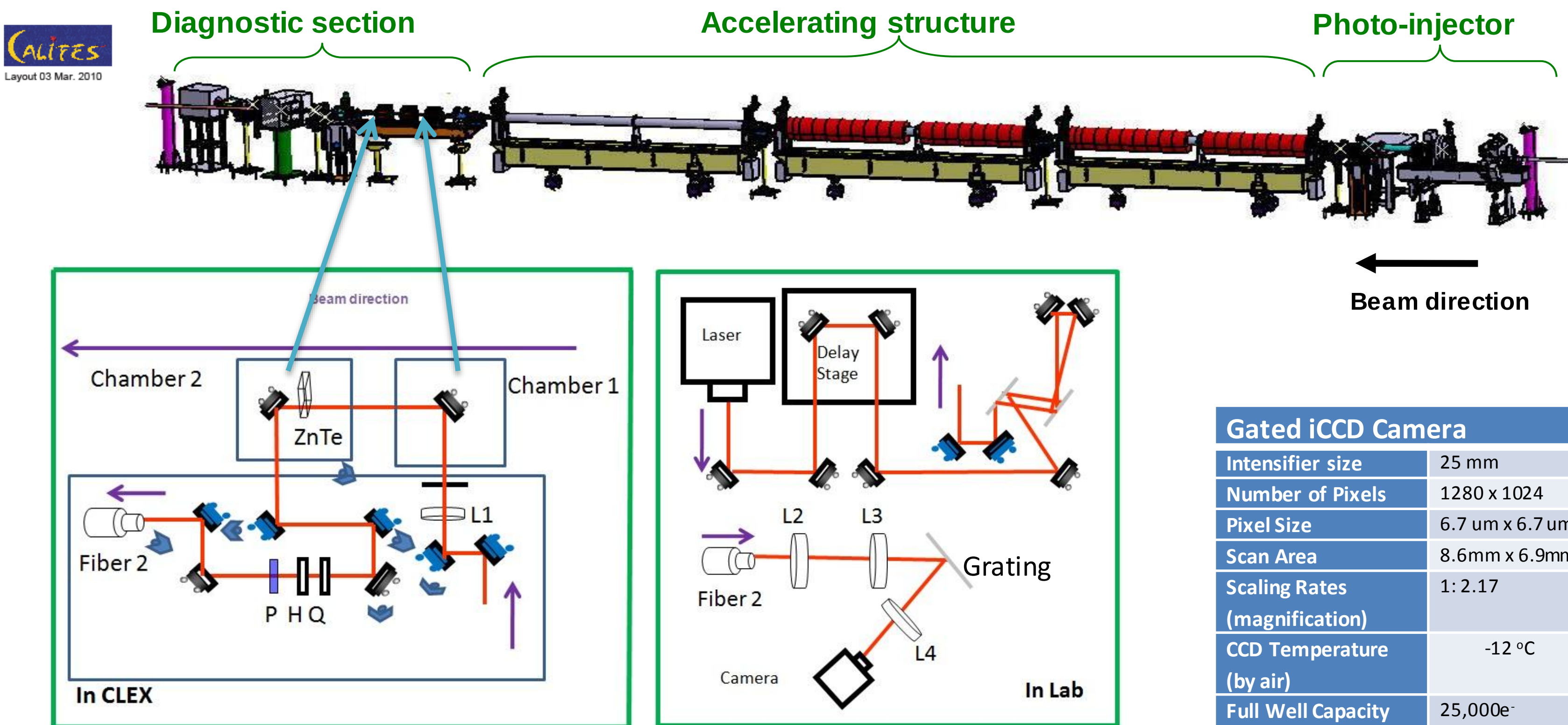
Other parameters:
Laser wavelength: 780nm
Laser pulse energy: 1.5nJ
Pulse duration: 150fs

Crystal thickness: 500µm
Crystal separation: 5mm

Result is distortion for bunch lengths < 1 ps

Reason:
Short bunch induces fast temporal modulation, which modifies spectral content and thus distorts $t \leftrightarrow \lambda$ mapping

Implementation of the EO monitor at CALIFES



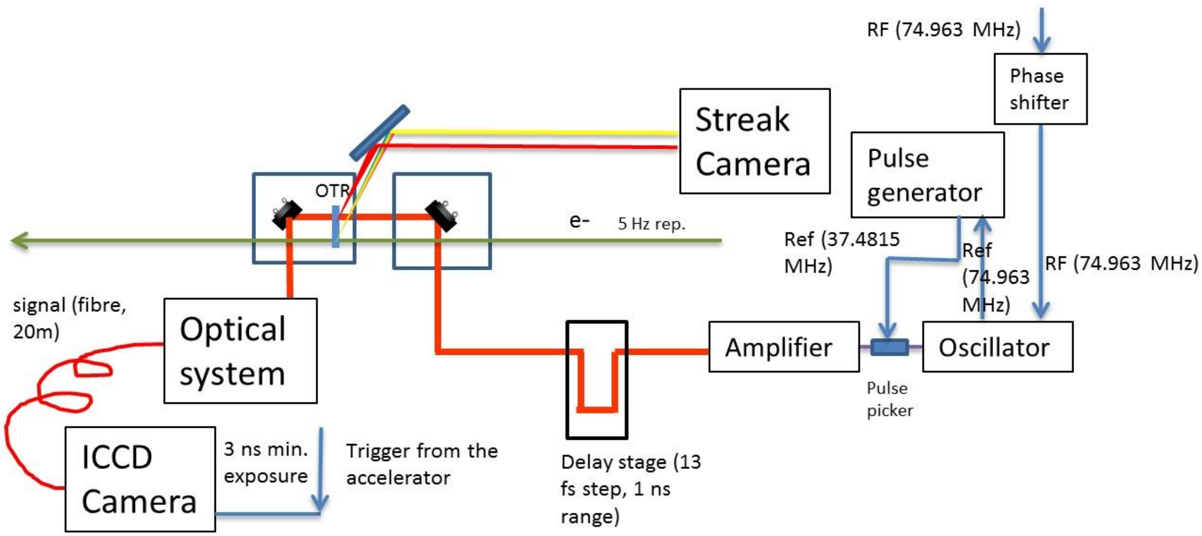
P: Polarizer **H**: Half wave plate
Q: Quarter wave plate
: Mirror with actuators
: Finger camera

Laser:
Wavelength: 780 nm Duration: 100 fs
Repetition: 37.4815 MHz Pulse energy: 2.7 nJ
Crystal: Thickness: 1mm Separation: 5-10 mm

In CLEX		In Lab	
10 Actuators 3 Rotation motors 6 Finger cameras	7 Plane mirrors 2 Polarizers 2 Wave plates 1 Lens 1 Fibre head	1 Laser 1 ICCD Camera 1 Motor stage	10 Plane mirrors 3 Gratings 3 Lenses 1 Fibre head

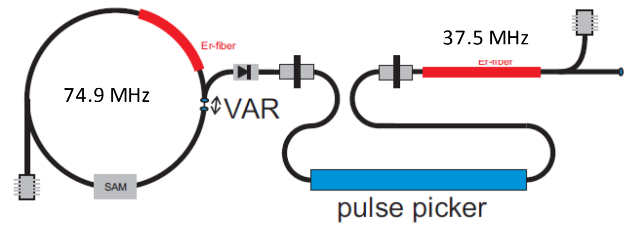
Gated iCCD Camera	
Intensifier size	25 mm
Number of Pixels	1280 x 1024
Pixel Size	6.7 um x 6.7 um
Scan Area	8.6mm x 6.9mm
Scaling Rates (magnification)	1: 2.17
CCD Temperature (by air)	-12 °C
Full Well Capacity (Image pixel well depth)	25,000e$^-$
Readout Noise	7…8e$^-$ @12.5MHz
A/D convertor	12 bit
A/D conversion factor (Sensitivity)	5 e$^-$/count
Average Dark Charge (Equivalent Background Illuminance)	<0.1 e$^-$/pixel sec
Readout Time (Full frame)	8 fps
Min gating time	3 ns
QE	~25%

Laser ↔ e-bunch synchronization



Non-standard design, providing higher pulse energy

Laser



(1) Synchronization between laser pulse and e-bunch

- **Laser synchronised to accelerator RF (75MHz) at <200fs level.**
- **OTR light transported to laser lab, providing beam arrival time monitor**
- **Laser transported from same screen**
- **Streak camera monitors few ps beam-laser synchronisation.**
- **Optical delay for sub-ps to ns timing adjustments**

Laser parameters

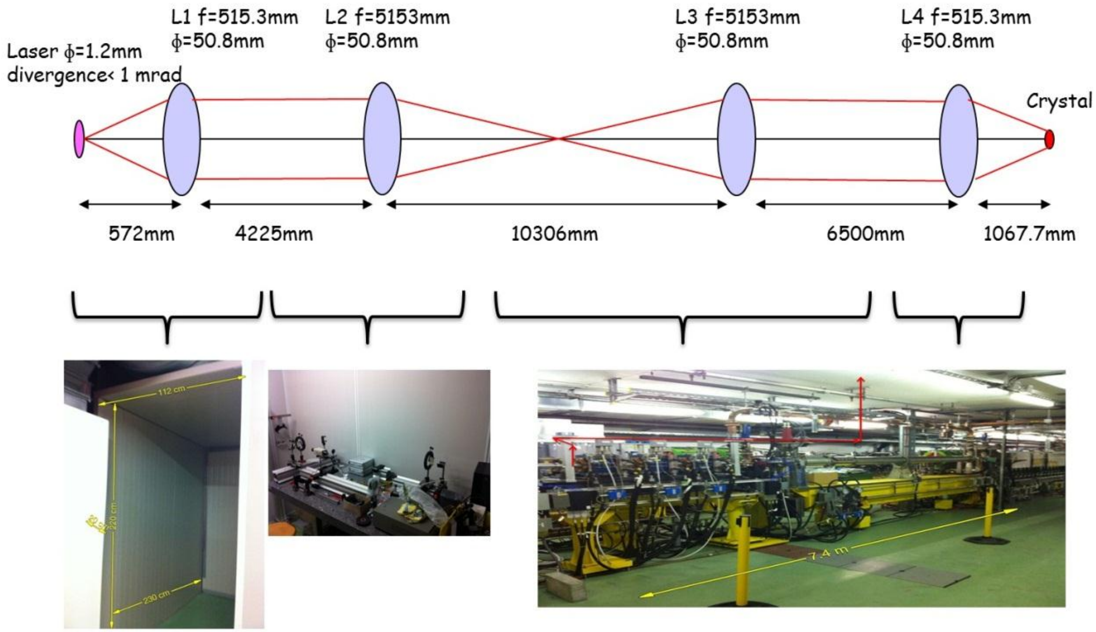
Wavelength: 780 nm & 1560 nm
Duration: <120 fs
Repetition: 74.9 MHz @ 1560 nm
37.5 MHz @ 780 nm
Pulse energy: 4.4 nJ @ 1560 nm
2.7 nJ @ 780 nm

(2) Spectral characterisation of the post-interaction laser pulse

A low jitter (<1ns) signal triggers the iCCD camera, gating a single laser pulse => can choose which electron bunch to characterise

Optical Transfer Line

(1) Laser transfer line: from the laser lab to CLEX



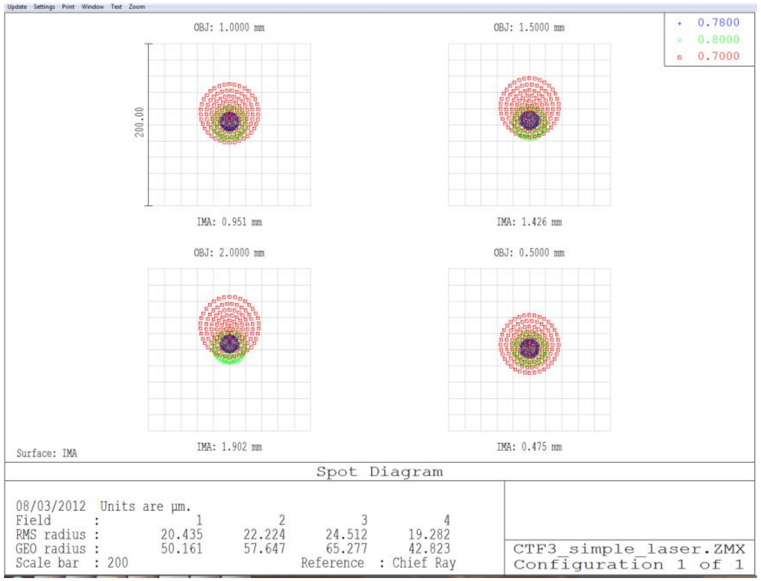
Laser lab

Camera lab

CLEX

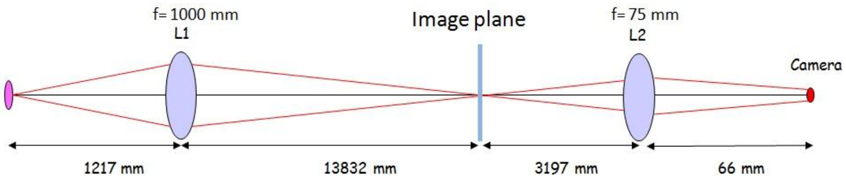
Transfer the laser to the machine. The measured signal will be transferred back to the lab by optical fibre.

Relay lenses stabilise optical transport



ZEMAX simulation
(purple dots are the centre wavelength)

(2) OTR photons transfer line: from CLEX to the camera lab

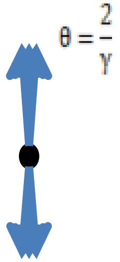


Transfer OTR photons and laser photons to a streak camera for synchronization

Contributions to System Time Resolution

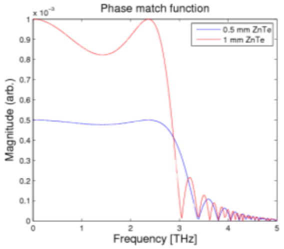
1. Distance between crystal and e-beam

$$\Delta t \sim \frac{2r}{\gamma}$$ ~10 fs at r=5 mm



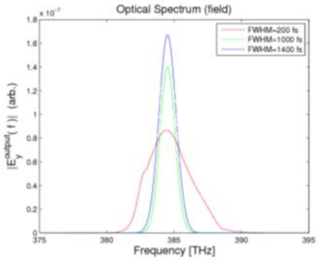
2. The frequency response of crystal (material and thickness)

for 1 mm ZnTe: ~333 fs ~1/(3THz)

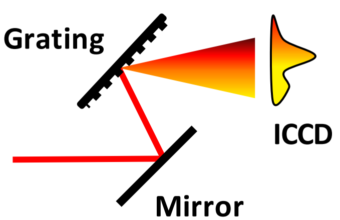


3. EOSD limitation (Laser pulse duration and chirped duration)

$$\tau_{\lim} = \sqrt{\tau_0^{FWHM} \tau_c^{FWHM}}$$ ~550 fs (for 100 fs pulse chirped to 3ps)



4. Resolution of spectrometer and iCCD ~3 fs



2. Activities at STFC Daresbury Laboratory

Testing optical requirements for ultimate time resolution monitor

Spectral Upconversion Techniques

Convert the far-IR – mid-IR spectrum to an optical spectrum

Offers potential for simple & robust bunch form factor measurements

- Bandwidth reduction 1mm - 10μm → 800nm – 740nm
- Simple CW lasers (?)

2011/12 experiments at Daresbury (Manchester University also collaborating)

Shooting for ultimate aim of CW laser probe:

- Simple 200mW diode laser, ALICE macrobunch CSR
  wavelength drift believed to be obscuring the very small signal

- 2 Watt single mode (MHz linewidth) laser installed
  (loan through University of Manchester collaboration)
  Continuing absence of signal attributed to long bunch, low CSR energy, & radiation transport losses.

Change of approach....

Use laser-generated THz for initial parameter setting experiments

Laser-generated THz pulses as mimic of electron bunch

MV/m sub-ps source available with independent EO characterisation

(separate project in high power THz generation for bunch manipulation)

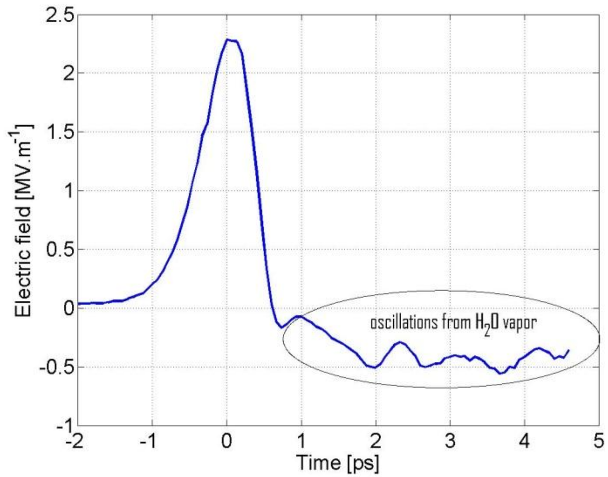
→ Still failed to observe signal using single-mode laser

- believe currently just below signal-noise of detection systems
  EO crystal efficiency, ITO dichroic losses,
  shorter pulse/larger bandwidth => smaller $I(\lambda)$ *per nm*

...returning to understanding of signal-noise levels with "quasi-CW" laser

- kW equivalent laser power trivially available
  (~50ps 1064nm system to be used initially).
- small increase in complexity through synchronisation

Sub-picosecond pulse generation and detection in ASTeC laser lab



Upconversion of CTR on ALICE

Experiments for May 2012 delayed due to unscheduled cathode replacement (underway now)

3. Activities at the University of Dundee

Development of alterative higher bandwidth non-linear materials

EO Detection solution in thin films & 2D structures

- to bypass propagation effects

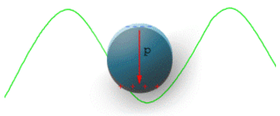
Thin film polymers

- Demonstrated broadband EO response
- Sufficient EO efficiency
- ?? Accelerator environment, material stability ??

Nano-structured materials

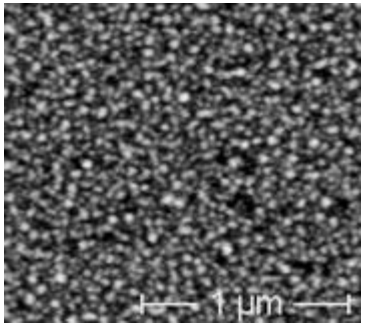
- Electro-optic effect from short-range structure.
- ... limited experimental demonstrations

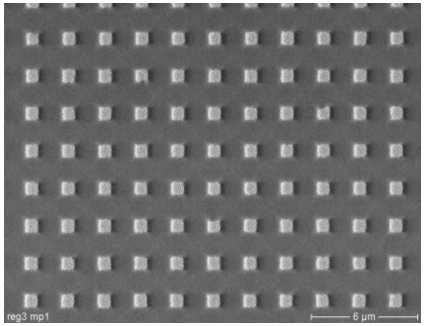
Materials, Photonics & Smart Systems (MAPS) Group at Dundee



Fabrication & Applications of Nanocomposites

Dundee group expertise: DC electric field-assisted selective dissolution of nanoparticles in nanocomposites (patented technology)





Overall R&D goals

- Fabricate percolation films and metal-dielectric nanocomposite films at Dundee University
  → a type of "metamaterial" - utilising electric field & laser processing of materials
- Test these films for the required E-O properties at Daresbury Laboratory
- Incorporate materials into set-ups at PSI and CLIC

Progress

3 nanosecond laser systems (at wavelengths 355, 532 and 1064 nm) in place during 2011 for materials processing (£180,000 investment)

Picosecond (Coherent Talisker ULTRA 355-04) system being installed (May 2012)
Operates at same 3 wavelengths (£240,000 investment)

Talisker pulsewidth <15ps with an average power of up to 4W at 355nm, 8W at 532nm, and 16W at 1064nm.

First tests on new system planned for early June 2012

Summary

- CALIFES preparations progressing well
- Vacuum chambers to be installed during next shutdown (June 2012)
- Laser laboratory under preparation, laser systems being installed May 2012

- Daresbury experiments on spectral upconversion beginning to show results
- Separate ASTeC project underway in high power THz generation for bunch manipulation

- Dundee laser systems for processing alterative higher bandwidth non-linear materials are now in place, and will soon be available for regular use
- Preparation and testing of silver & gold metal-dielectric nanocomposites (MDNs) are planned for near future

Planned activities for year 2 of project

- Optical synchronization system implemented at CALIFES, and transfer lines installed for laser and OTR photons.
- Laser and control systems completed and tested
- First beam tests at CALIFES
- “Conventional” E-O materials (organic crystals, thin film polymers, etc) tested and characterised at Daresbury
- First MDN metamaterials produced at Dundee and evaluated at Daresbury
- Arrangements put in place to test first high-resolution prototype system at PSI test facility

END

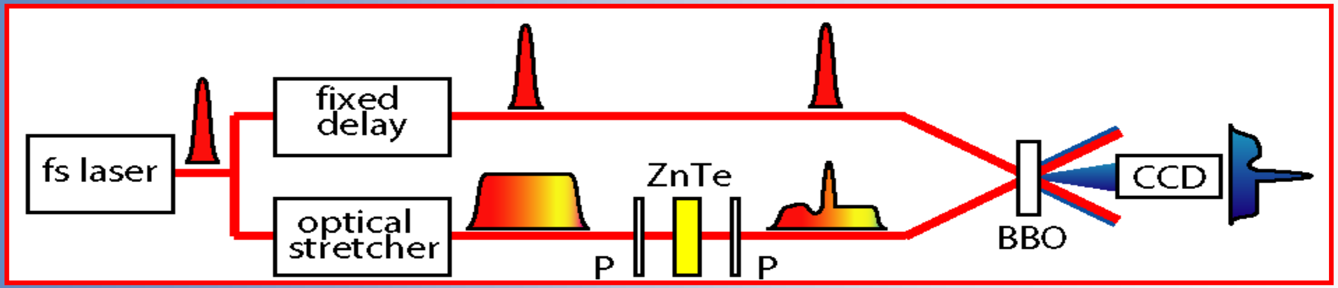
UK CLIC collaboration over three years (April 2011 to March 2014)

UK Laboratory	UK Laboratory representative	Task	UK responsible	CERN responsible	Reference	Collaboration Agreement Amount GBP	CERN Payment Profile 2011	2012	2013	2014	Total	
Dundee	A.Gillespie	Instrumentation: Electro-optic	A.Gillespie	T.Lefevre	KE1865	449,000	130	169	125	25	449	
ASTEC	J.Clarke	Quadrupoles	J.Clarke	M.Modena	KE1866	563,000	127.5	169.2	169.2	42.5	508.3	
		Crab cavity	P.McIntosh A.Dexter	A.Grudiev			13.3	18.3	18.3	5.0	55.0	
Lancaster	A. Dexter	Crab cavity	P.McIntosh A.Dexter	A.Grudiev	KE1867	130,000	39.3	40.3	46.5	4.0	130.0	note: 90k£/FTE in Lancaster
											0.0	
Manchester	R.Jones	Structures design	R.Jones	W.Wuensch	KE1868	422,000	3.0	148.0	149.0	122.3	422.3	
Oxford	P.Burrows	Feedback & control	P.Burrows	D.Schulte	KE1869	794,000	25.5	95.0	95.0	17.5	233.0	
		Phase Feedforward	P.Burrows	D.Schulte			45.5	155.0	200.0	39.5	440.0	
		Inst: Laserwire	G.Blair	T.Lefevre			9.0	112.0	0.0	0.0	121.0	
RHUL	G.Blair	Inst: Laserwire	G.Blair	T.Lefevre	KE1870	642,000	0.0	67.0	111.0	3.0	181.0	
		Instrum: Coherent bunch length	P.Karataev	T.Lefevre			15.0	39.7	68.3	0.0	123.0	
		Instrum: BPM	Boogert	T.Lefevre			9.0	87.0	80.0	0.0	176.0	
		RTML	S.Molloy	A.Latina			0.0	2.0	2.0	2.0	6.0	
		BDS integration	A.Seryi	R.Tomas			0.0	102.0	52.0	2.0	156.0	
Total			P.Burrows	H.Schmickler		3,000,000	417.1	1204.4	1116.3	262.8	3000.6	k£

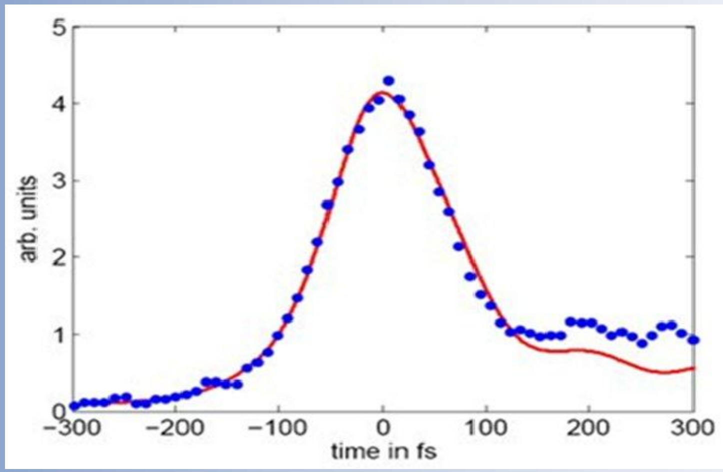
conversion using 1£ = 1.32 CHF (13.7.2011) 550.55 1589.83 1473.516 346.94 3960.836 kCHF

Plans for Longitudinal PM during the PPP

• R&D on Electro-optical techniques on single shot temporal decoding techniques



• Shortest measured electron bunch profile (at DESY FLASH) using 65um thick GaP crystal
The optimum fitted Gaussian curve sigma is 79.3 ± 7.5 fs

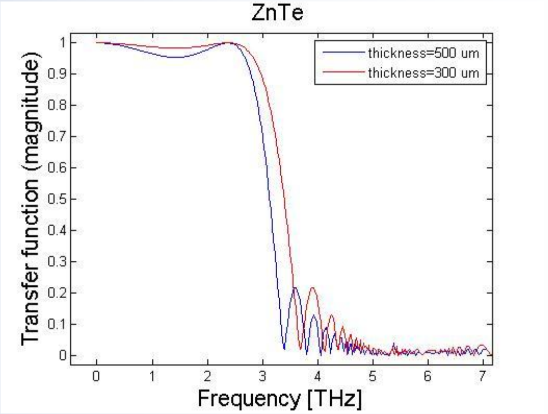


By S. Jamison and A. Gillespie

Plans for Longitudinal PM during the PPP

- Improving the encoding process

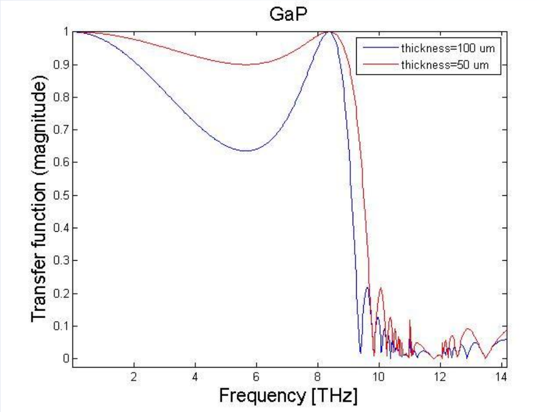
University of Dundee



- Investigation of new electro-optic materials for EO profile systems at CLIC

- Experimental characterisation of thin films and meta-materials as novel EO detectors.

- Demonstration of the concept of a multiple crystal detector spanning a wide optical bandwidth



- Improving the decoding process

- Demonstration of single-shot X-FROG measurements on a laser-generated THz source.
- Demonstration of X-FROG detection on an electron beam source.

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