Ultrafast lasers & THz Radiation
for
Accelerator Diagnostics & Beam Manipulation

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Electro-optic diagnostics

- Established capabilities & limits
- Spectral upconversion
- FROGs & fs diagnostics without a fs laser

Lasers and distributed fs timing

- Optical clocks and RF reference
- Distributing clocks
- Optical beam arrival monitors

THz driven modulation of electron beam

(some) Diagnostics for CLARA & VELA

- Transverse deflecting cavity
- Ultrafast Photon diagnostics

Femtosecond longitudinal diagnostics

Target applications & requirements

Light sources: Free electron Lasers

kA peak currents required for collective gain

- 200fs FWHM, 200pC (…2008 standard)
- <10fs FWHM , 10pC (2008… increasing interest)

Particle physics: Linear colliders (CLIC, ILC)

Short bunches, high charge, high quality, for luminosity

- ~300fs rms, ~1nC
- stable, known (smooth?) longitudinal profile

Laser-plasma: Acceleration physics

Diagnostics needed for…

- Verification of optics
- Machine tune up
- Machine longitudinal feedback (non invasive)

Significant influence on bunch profile from

Wakefields, space charge, CSR, collective instabilities…

Machine stability & drift $\Rightarrow$ ***must be single shot diagnostic***

Electro-optic diagnostics

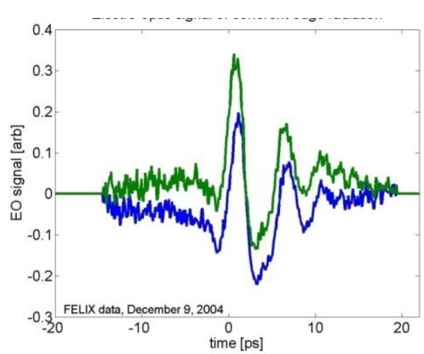
Encoding electric field temporal profiles into optical probe intensity variations

Many *demonstrations*...

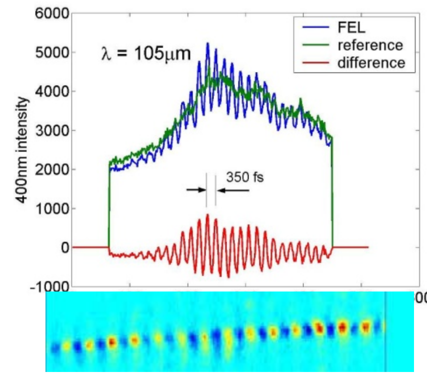
Accelerator Bunch profile -	FLASH, FELIX, SLAC, SLS, ALICE, FERMI ....
Laser Wakefield experiments -	CLF, MPQ, Jena, Berkley, ...
Emitted EM (CSR, CTR, FEL) -	FLASH, FELIX, SLS, ...

Temporal Decoding @FLASH

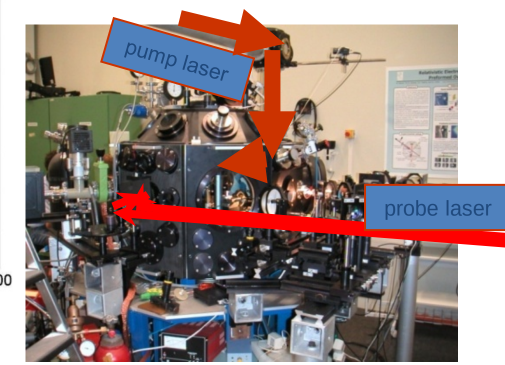
CSR @FELIX



Mid-IRFEL lasing @FELIX



Laser Wakefield
@ Max Planck Garching



Few facility implementations: remaining as experimental / demonstration systems

- Complex & temperamental laser systems
- Time resolution “stalled” at ~100 fs FWHM

Phys Rev Lett **99** 164801 (2007)
Phys. Rev. ST, **12** 032802 (2009)

EO Current status, future requirements

Low time resolution (>1ps structure)

- spectral decoding offers explicit temporal characterisation
- robust laser systems available
- diagnostic rep rate only limited by optical cameras

High time resolution (>60 fs rms structure)

- proven capability
- significant issues with laser complexity / robustness

Very higher time resolution (<60 fs rms structure)

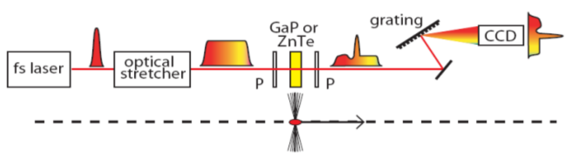
Limited by
- EO material properties (phase matching, GVD, crystal reflection)
- Laser pulse duration (TD gate, SE probe)

Accelerator wish list - Missing capabilities

- o Higher time resolution (20fs rms for light sources, CLIC)
- o Higher reliability, lower cost (high resolution systems)
- o Solution for feedback.

Electro-Optic temporal profile monitors

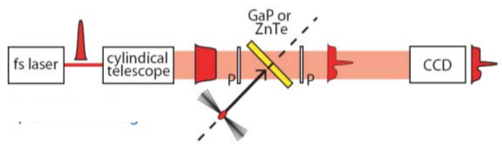
Spectral Decoding



- o Chirped optical input
- o Spectral readout
- o Use time-wavelength relationship
- o >1ps limited (?)

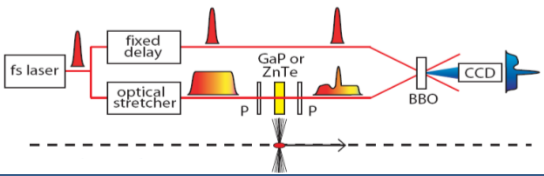
- Deconvolution for ~100fs resolution
- In beamline BAMs

Spatial Encoding



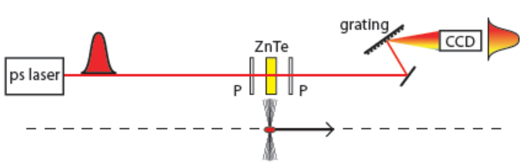
- o Ultrashort optical input
- o Spatial readout (EO crystal)
- o Use time-space relationship

Temporal Decoding



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

Spectral upconversion**

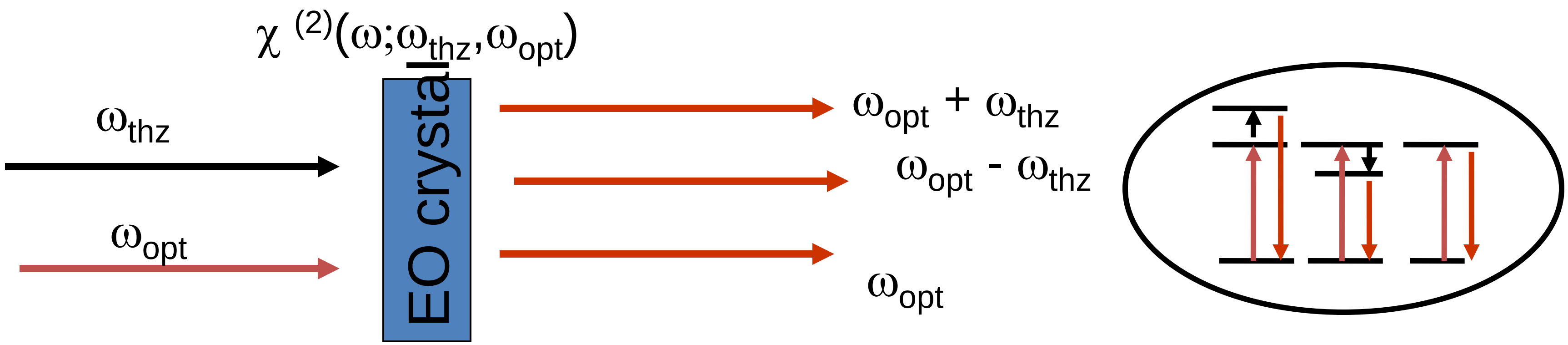


- o monochomatic optical input (long pulse)
- o Spectral readout
- o ***Implicit time domain information only*

- Robust EO systems (no fs lasers required!)
- Extension to time domain readout (FROG)

Electro-optic detection

description of EO detection as sum- and difference-frequency mixing



$$\tilde{E}^{probe}_{out}(\omega) \sim \tilde{E}^{probe}_{in}(\omega) + i\chi^{(2)}\int_{-\infty}^{\infty}\tilde{R}(\Omega)\tilde{E}^{THz}(\Omega)\tilde{E}^{probe}_{in}(\omega-\Omega)\mathrm{d}\Omega$$

geometry dependent (repeat for each principle axis)

convolution over all combinations of optical and Coulomb frequencies

propagation & nonlinear efficiency

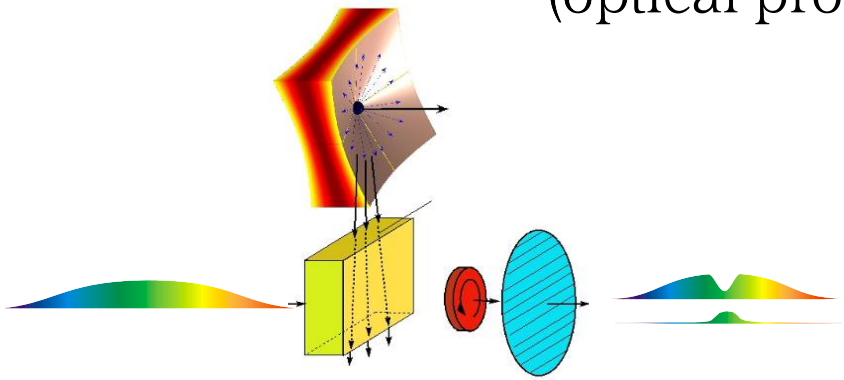
THz spectrum (complex)

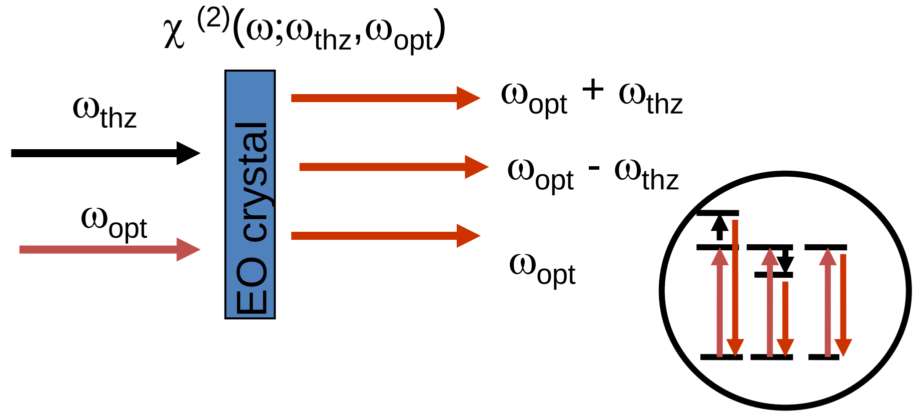
optical probe spectrum (complex)

This is "Small signal" solution. High field effects c.f. Jamison Appl Phys B 91 241 (2008)

Electro-optic process

sum & difference frequency mixing
(optical probe & coulomb field)





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$$\widetilde{A}(\omega, z) = \widetilde{A}_0(\omega)e^{-z\beta_{opt}} + \frac{i}{2c\eta}e^{-z\beta_{opt}}\omega \int d\omega' \widetilde{A}^{THz}_{eff}(\omega-\omega')\widetilde{A}(\omega'),$$

DC "THz" field....

$$\tilde{A}(\omega, z) \rightarrow \tilde{A}_0(\omega)\left[1 + i\alpha A_{DC} z\right]$$
$$\rightarrow \tilde{A}_0(\omega)e^{i\alpha A_{DC} z}$$

phase shift (pockels cell)

Delta-Fnc ultrafast pulse...

$$\tilde{A}_0(\omega) \rightarrow A_0 e^{i\omega\tau}$$

$$\int A_0 \tilde{A}^{THz}_{eff}(\omega - \omega')e^{i\omega\tau} \longrightarrow A_0 A^{THz}_{eff}(t-\tau)$$

temporal sampling of THz field

Monochromatic THz & optical

$$\tilde{A}_{THz}(\Omega), \tilde{A}_0(\omega_0)$$

$$\tilde{A}_0(\omega_0) + i\alpha\tilde{A}_0(\omega_0 - \Omega) + i\alpha\tilde{A}_0(\omega_0 + \Omega)$$

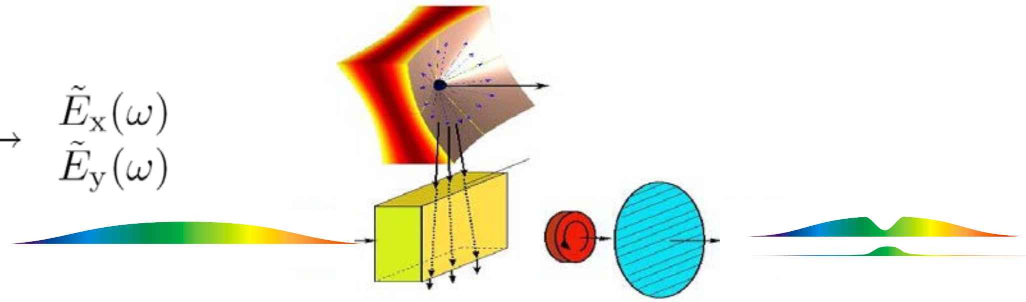
optical sidebands

Chirped optical

Parameter dependent results

Spectral or temporal measurements

$$\begin{matrix} E_\mathrm{x}(t) \\ E_\mathrm{y}(t) \end{matrix} \rightarrow \begin{matrix} \tilde{E}_\mathrm{x}(\omega) \\ \tilde{E}_\mathrm{y}(\omega) \end{matrix}$$



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

Coulomb spectrum shifted to optical region

$$E^{\mathrm{opt}}_{\mathrm{out}}(t) = E^{\mathrm{opt}}_{\mathrm{in}}(t) + a\left[E^{\mathrm{Coul}}(t) * R(t)\right]\frac{\mathrm{d}}{\mathrm{d}t}E^{\mathrm{opt}}_{\mathrm{in}}(t)$$

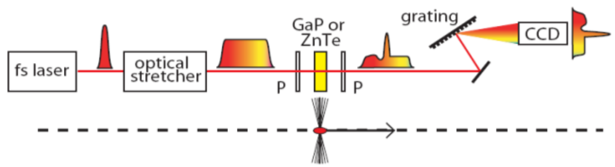
Coulomb pulse replicated in optical pulse

envelope — optical field

- Measuring optical spectrum straightforward
- measuring a femtosecond scale time profile more complex
- *...ultimately, time domain is what is wanted*

Spectral decoding as optical Fourier transform

The spectrum can have functional form of time profile



Consider (positive) optical frequencies from mixing

$$\tilde{M}(\omega) = \int_{-\infty}^{\infty} \mathrm{d}\Omega \tilde{E}_{\mathrm{opt}}(\omega - \Omega)\tilde{E}_{THz}(\Omega)$$

Positive and negative Coulomb (THz) frequencies; sum and diff mixing

Linear chirped pulse: $\tilde{E}_{\mathrm{opt}}(\omega) = A(\omega)\exp(-i\beta(\omega-\omega_0)^2)\exp(-i\omega t_0)$

$$\tilde{M}(\omega) = \exp(-i\beta(\omega-\omega_0)^2)A(\omega)\int \exp(-i\beta\Omega^2)\tilde{E}_{THz}(\Omega)\mathrm{e}^{i\Omega(\tau-t_0)}$$

Fourier transform form

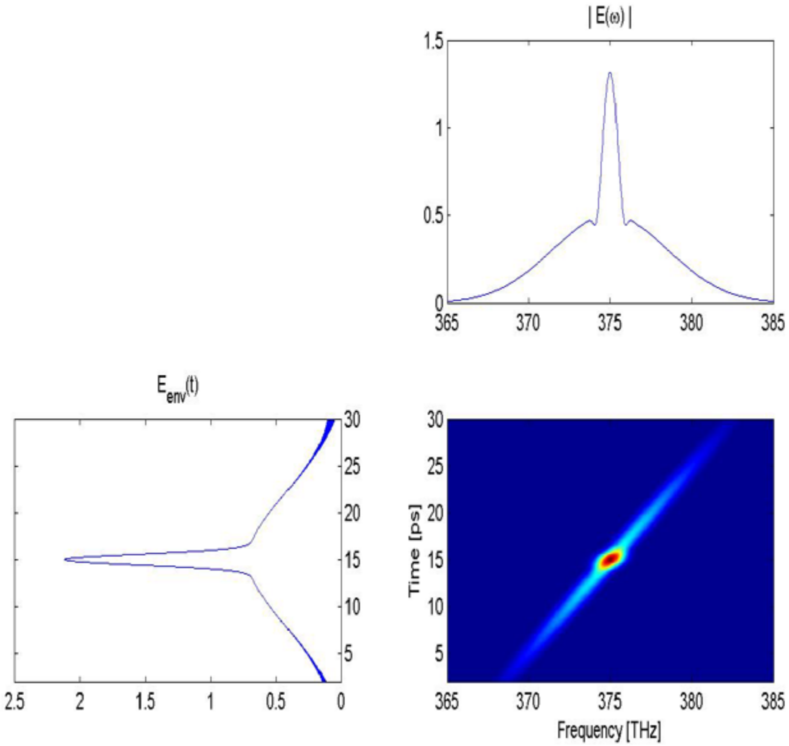
$$\tau \equiv \beta(\omega - \omega_0)$$

$$\sqrt{\frac{\pi}{\beta}}\exp\left(\frac{i\tau^2}{4\beta} - \frac{i\pi}{4}\right) * E_{THz}(\tau - t_0)$$

Convolution function limits time resolution…

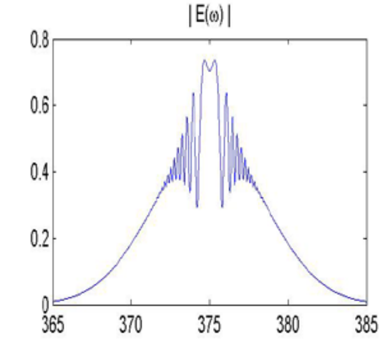
… but will aid in identifying the arrival time

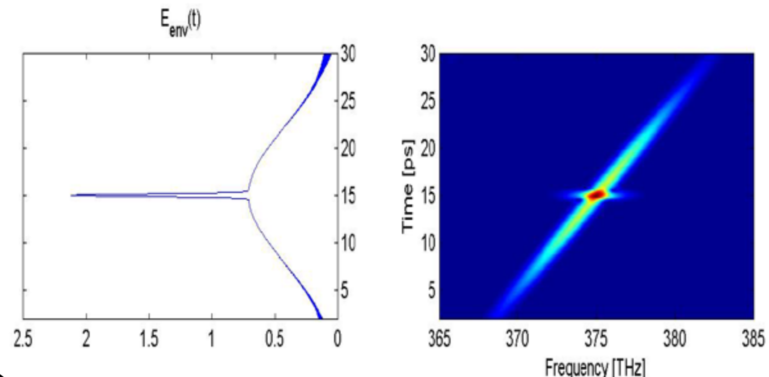
long bunch modulation : spectrum gives time profile



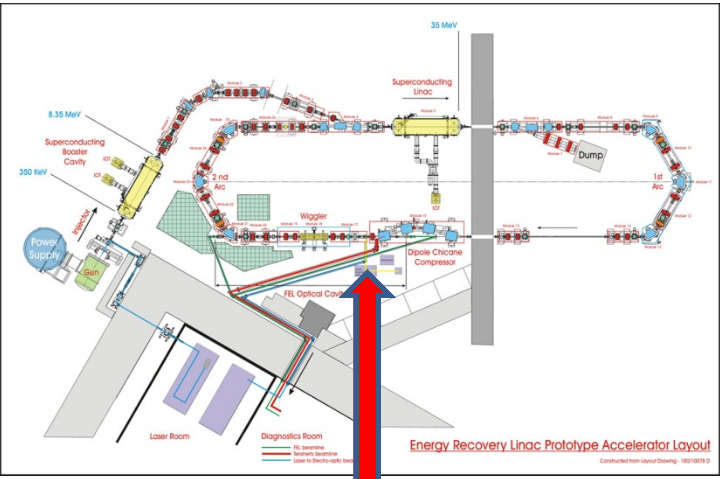
Short bunch modulation : Spectral interpretation fails

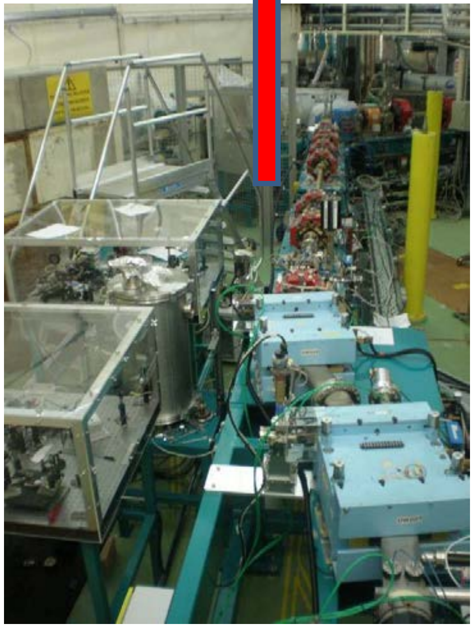
Bandwidth of short modulation larger than ‘local’ bandwidth of input probe





ALICE Electro-optic experiments

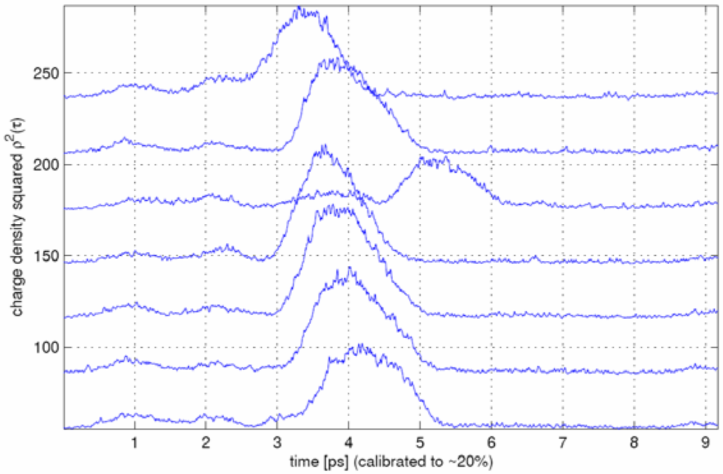




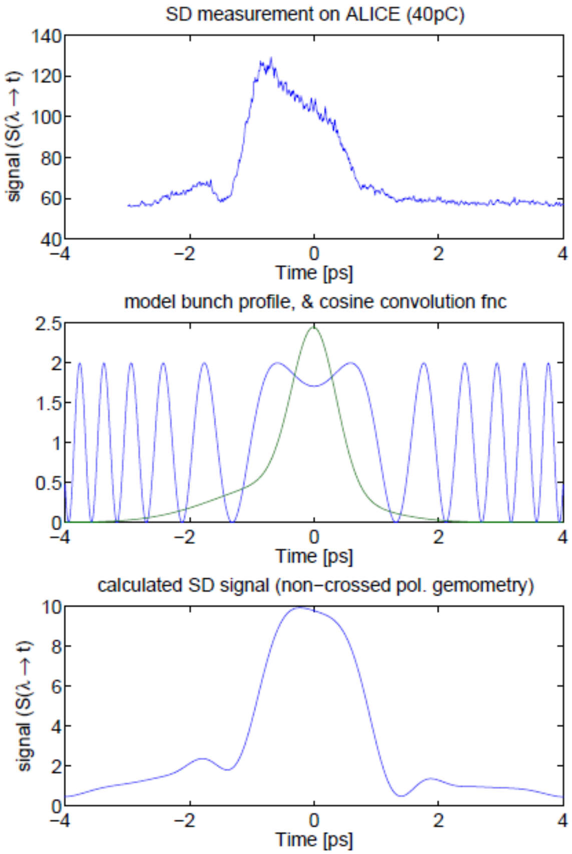
- Energy recovery test-accelerator
  intratrain diagnostics must be non-invasive
- low charge, high repetition rate operation
  typically 40pC, 81MHz trains for 100us

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 deconvolution



"Balanced detection"

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

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

Deconvolution possible.

"Crossed polariser detection"

input probe extinguished...phase information lost

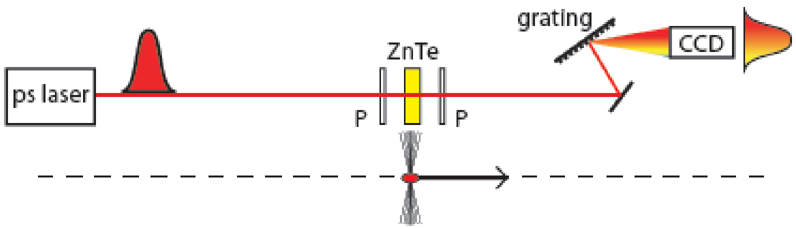
$$S(\omega)^{CP} \propto I^{\rm in}_{\rm opt}(\omega)\left\{\left[E_{\rm Coul}(\tau+t_0) * \cos\left(\frac{\tau^2}{4\beta} - \frac{\pi}{4}\right)\right]^2 + \left[E_{\rm Coul}(\tau+t_0) * \sin\left(\frac{\tau^2}{4\beta} - \frac{\pi}{4}\right)\right]^2\right\} \quad (2)$$

Deconvolution not possible [Kramers-Kronig(?)]

Oscillations from interference with probe bandwidth
$\Rightarrow$ resolution limited to probe duration

Spectral upconversion diagnostic

measure the bunch Fourier spectrum...



... accepting loss of phase information & explicit temporal information

... gaining potential for determining information on even shorter structure

... gaining measurement simplicity

Long pulse, narrow bandwidth, probe laser

$$\tilde{E}^{\mathrm{opt}}_{\mathrm{out}}(\omega) = \underbrace{\tilde{E}^{\mathrm{opt}}_{\mathrm{in}}(\omega)}_{\to\ \delta\text{-function}} + i\omega a \underbrace{\tilde{E}^{\mathrm{opt}}_{\mathrm{in}}(\omega)}_{} * \left[\tilde{E}^{\mathrm{Coul}}(\omega)\tilde{R}(\omega)\right]$$

same physics as "standard" EO

$$\tilde{E}(\omega_0+\Omega) = \tilde{E}(\omega_0) + i\omega a\tilde{E}(\omega_0)\left[\tilde{E}^{\mathrm{Coul}}(\Omega)\tilde{R}(\Omega)\right]$$

$(\Omega \text{ can be } < 0)$

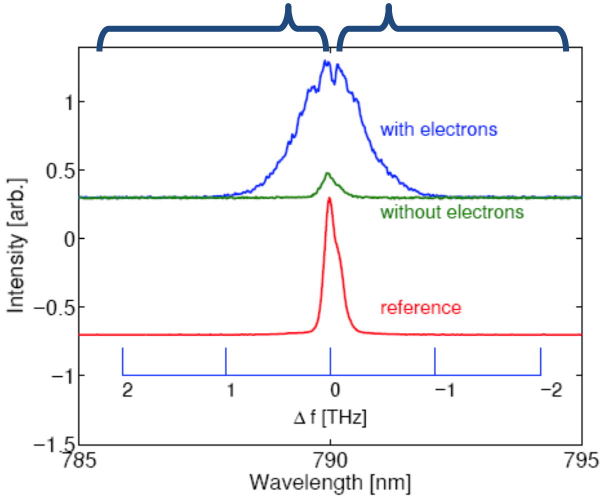
different observational outcome

NOTE: the long probe is still converted to optical replica

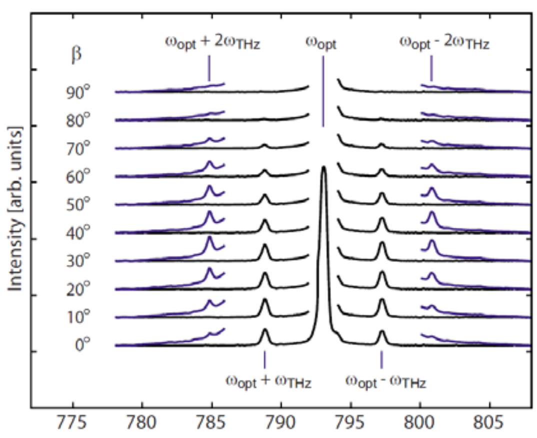
Spectral upconversion

- Femtosecond diagnostic without femtosecond laser
- Capability for <20fs resolution

sum frequency mixing | difference frequency mixing



FELIX FEL expt App Phys Lett (2010)

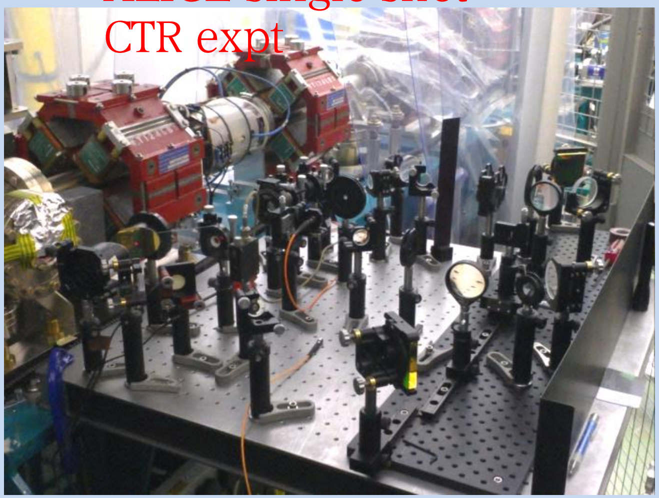


Sidebands generated by 2.0THz FEL output

Spectral sidebands contain the temporal (phase) information

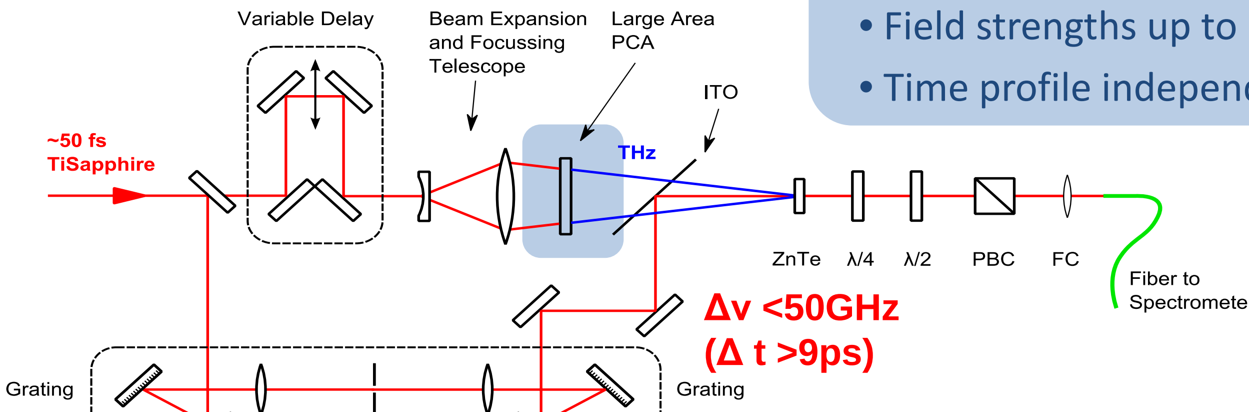
- Measure octave spanning THz spectrum in single optical spectrometer
  0-10 THz (λ= mm – 30um) → 800nm □20nm
- Add temporal readout as extension. (FROG, SPIDER)

ALICE single shot CTR expt



Laser based test-bed

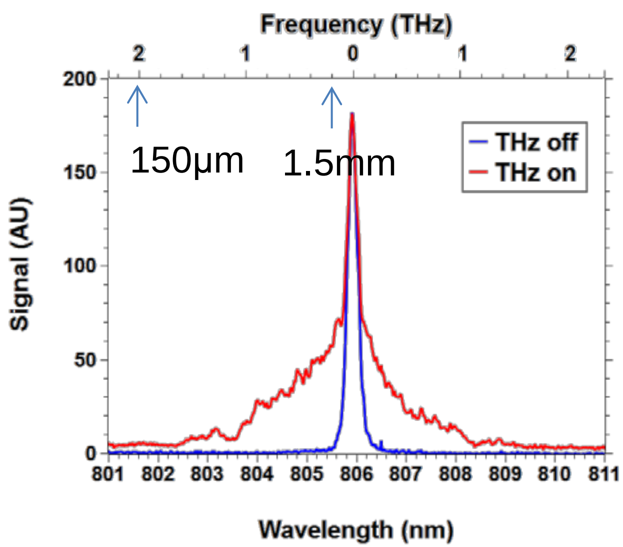
- Photoconductive antenna THz source mimics Coulomb field.
- Field strengths up to 1 MV/m.
- Time profile independently measurable



4-f spectral filter

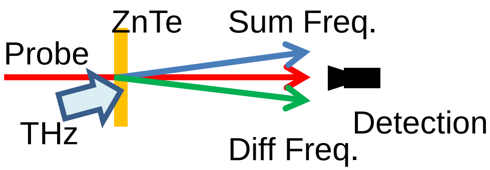
Followed to by NC-CPOPA & FROG

Femtosecond laser pulse spectrally filtered to produce narrow bandwidth probe



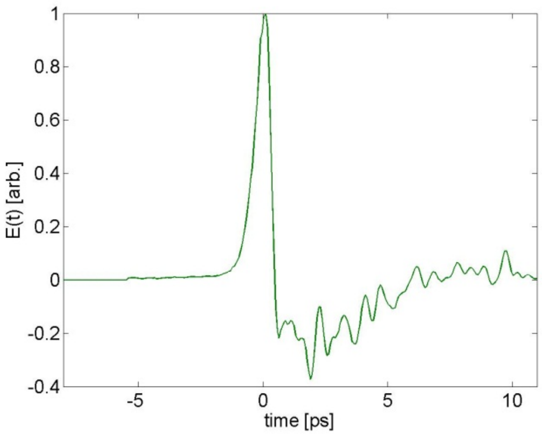
Asymmetry in sum and difference spectra
- not explainable by (co-linear) phase matching

Due angular separation of sum & difference waves
- general implications for THz-TDS and EO diagnostics

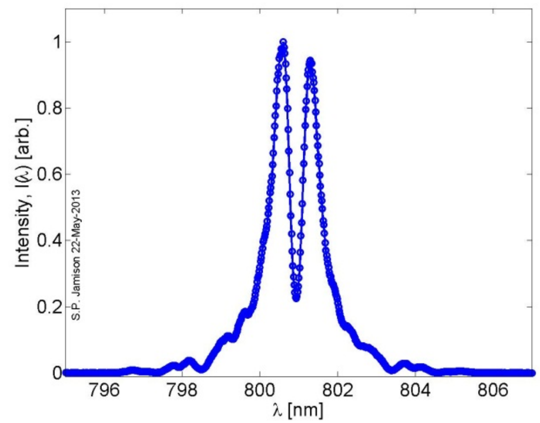


Upconversion of laser driven THz source

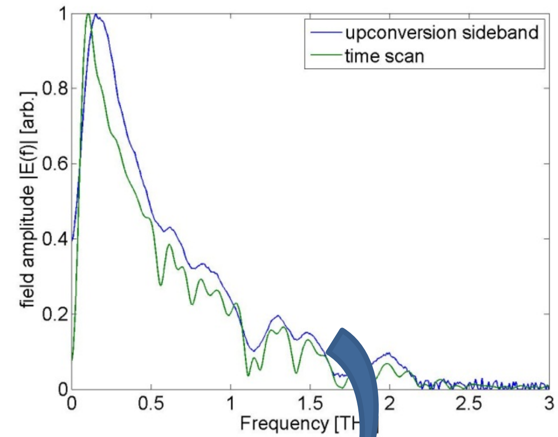
Electric field time profile



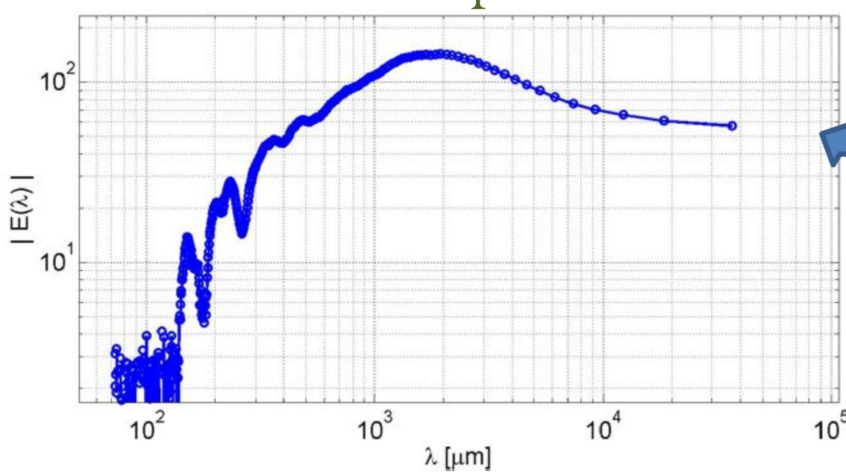
Upconversion spectrum (optical)



Inferred Far-IR spectra



Far-IR spectrum



2-decades
in wavelength
measured in single
optical spectrum

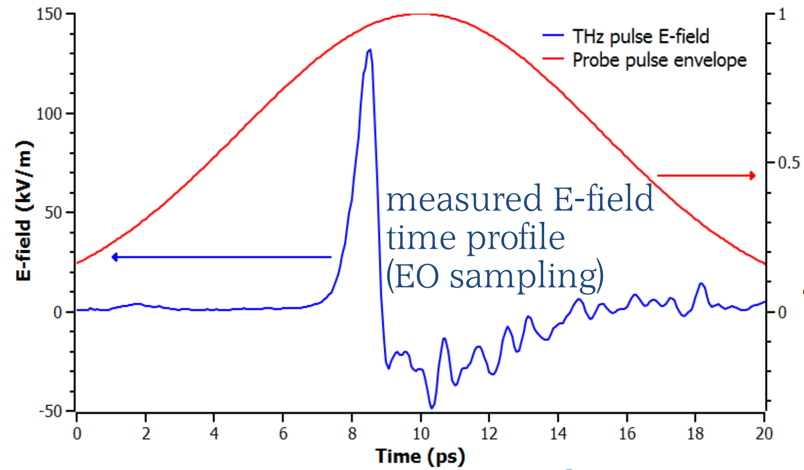
In accelerator system, do not propagate the far-IR
Conversion to optical *in situ*,
in beam line

Same spectrum
$f \rightarrow \lambda$

Signal levels, measurability & scaling

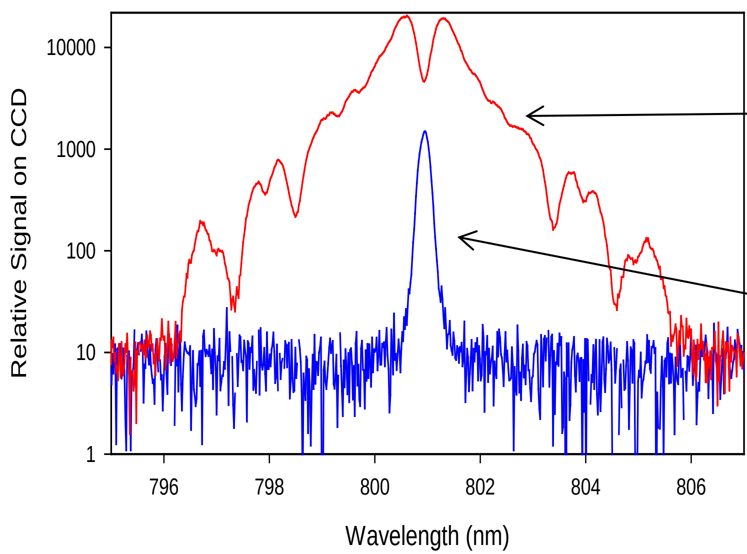
Input pulse characteristics

- Optical probe length $\Delta t \sim 10$ ps
- Optical probe energy $S \sim 28$ nJ
- THz field strength max $E \sim 132$ kV/m



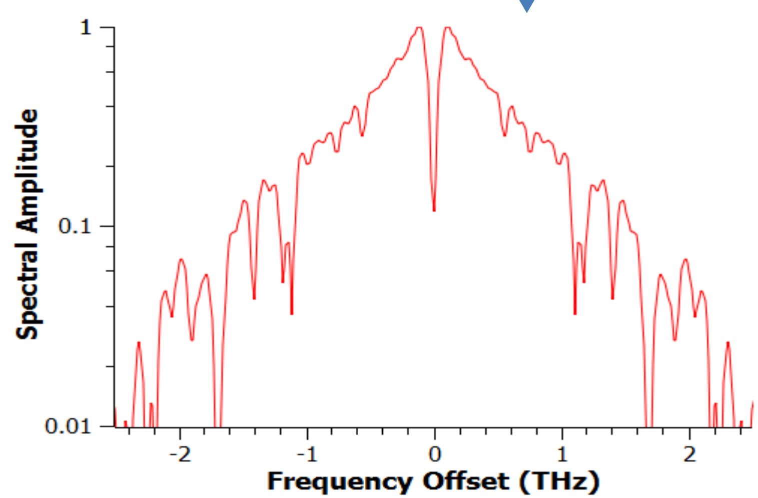
FFT

Upconversion spectrum (4 mm ZnTe)



Up-conversion
~470pJ

Leaking probe



Signal levels, measurability & scaling

Scaling factors

$$\boldsymbol{Energy_{upconv} \propto Power_{probe} \times (E_{field} \times l \times r)^2}$$

$\boldsymbol{l}$ is the EO crystal length, $\boldsymbol{r}$ is the nonlinear coefficient

Example:

"Typical" nanosecond pulse laser as probe

- Pulse energy 1mJ
- Pulse duration 10ns

$Power_{probe} \sim$ 100kW

Coulomb field for target CLIC bunch parameters (CDR)

- Bunch length 44μm
- Bunch charge 0.6pC

$Efield \sim \frac{2Q}{4\pi\varepsilon_0 R l_b} =$ 24.5MV/m

Property	Factor of improvement
$Power_{probe}$	x36
l	$\div 100^2$
r	$\div 2^2$
$Efield$	$\times 186^2$
Overall	**x31**

Pulse energy of ~15nJ is produced

1μJ required for single-shot FROG

pulse needs amplifying ~100x

An achievable goal!

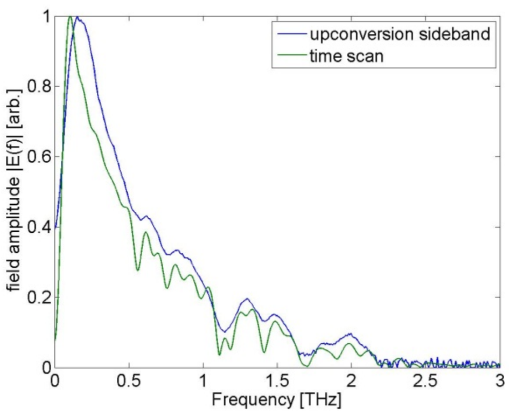
Kramers-Kronig phase retrieval

Measure spectral intensity ⇒ phase not known
phase required for temporal reconstruction

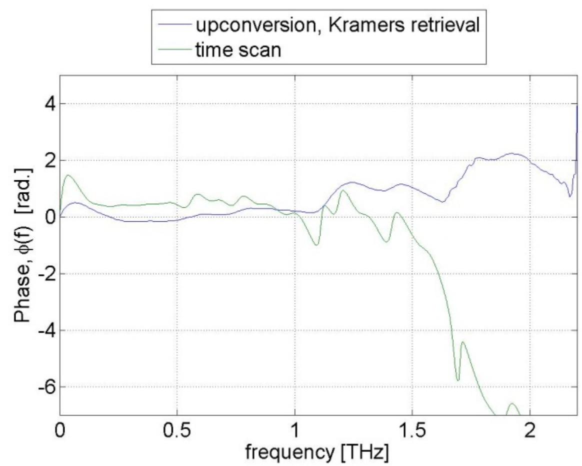
For *analytic* spectrum (electric field), real and imaginary parts related

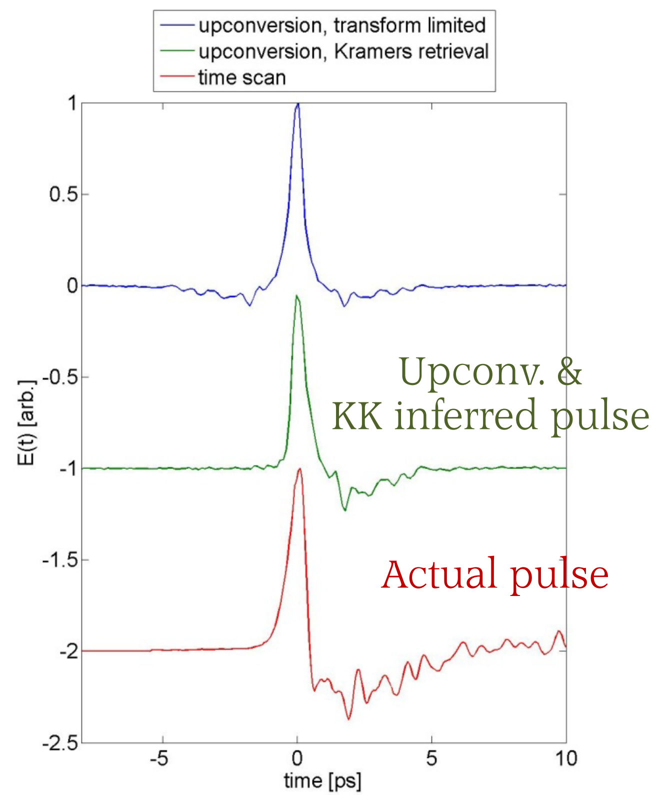
$$\phi(\omega_0) = \frac{2\omega_0}{\pi}\int \frac{\ln\{|E(\omega)|/|E(\omega_0)|\}}{\omega_o^2 - \omega^2}\mathrm{d}\omega$$

Measured field-amplitude spectrum



Phase inferred through Kramers-Kronig





K-K works partially

- Retrieves trailing dip
- Incorrect sharping of leading edge

Temporal measurement of Spectral upconversion

Unconverted optical probe retains temporal profile information

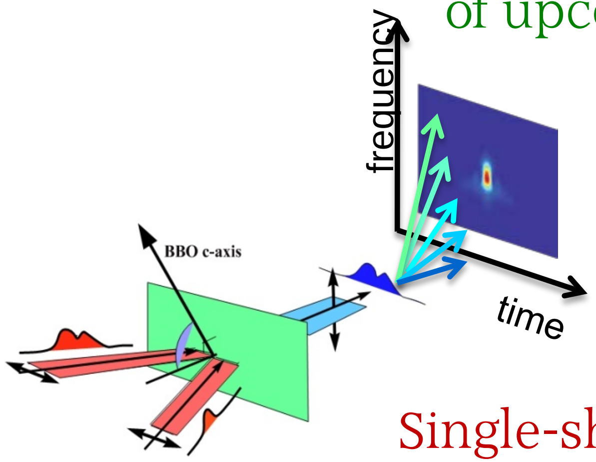
$$E^{\mathrm{opt}}_{\mathrm{out}}(t) = E^{\mathrm{opt}}_{\mathrm{in}}(t) + a\left[E^{\mathrm{Coul}}(t) * R(t)\right] \frac{\mathrm{d}}{\mathrm{d}t} E^{\mathrm{opt}}_{\mathrm{in}}(t)$$

Bunch profile determines envelope

Quasi-CW beam

Self-referencing measurement of temporal profile

"Frequency resolved optical gating" FROG of upconversion optical pulse...



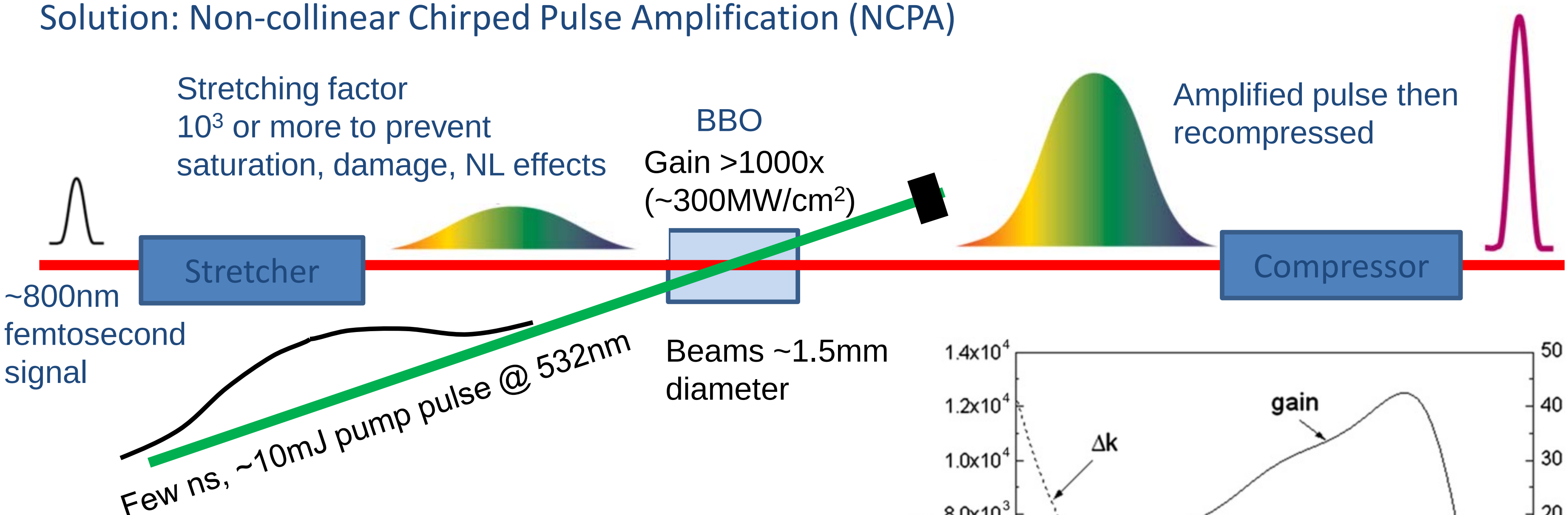
- Autocorrelation PLUS spectral information
- Sub-pulse time resolution retrievable from additional spectral information

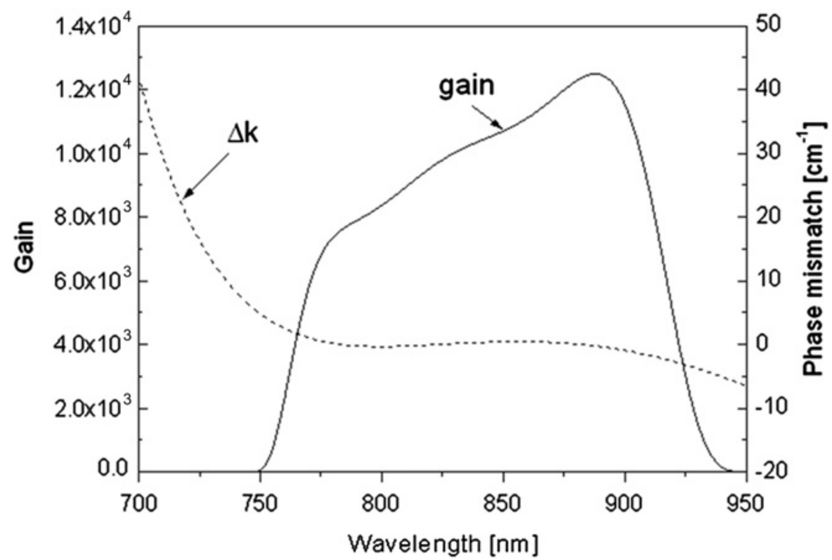
Single-shot FROG requires more intensity than feasible with EO material limitations...

Spectral upconversion & FROG extension
fs time domain diagnostic without fs laser

Problem: Up-conversion is relatively weak – our calculations suggest energies of a few nJ. Signal needs amplifying without loss of information.

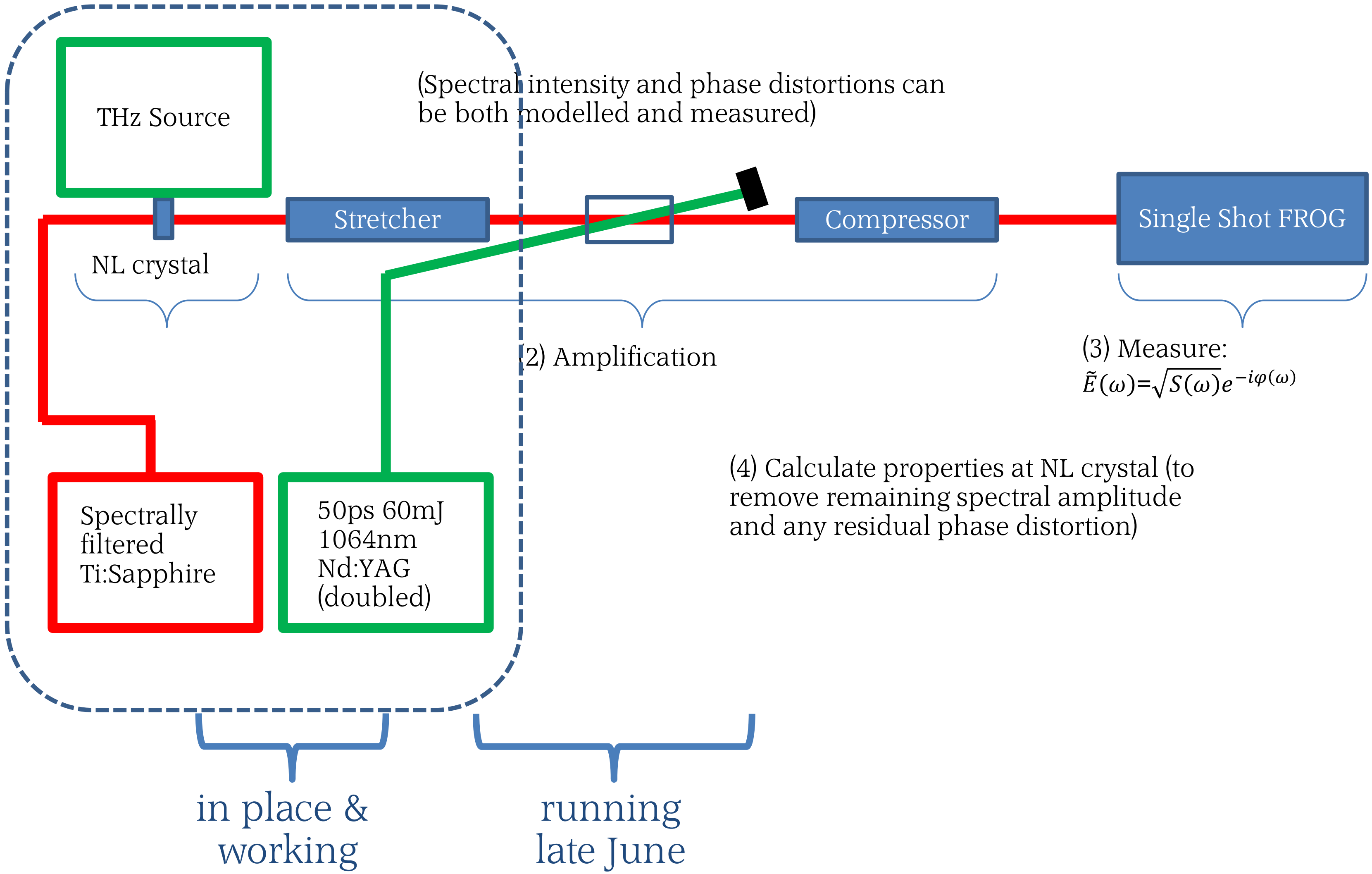
Solution: Non-collinear Chirped Pulse Amplification (NCPA)



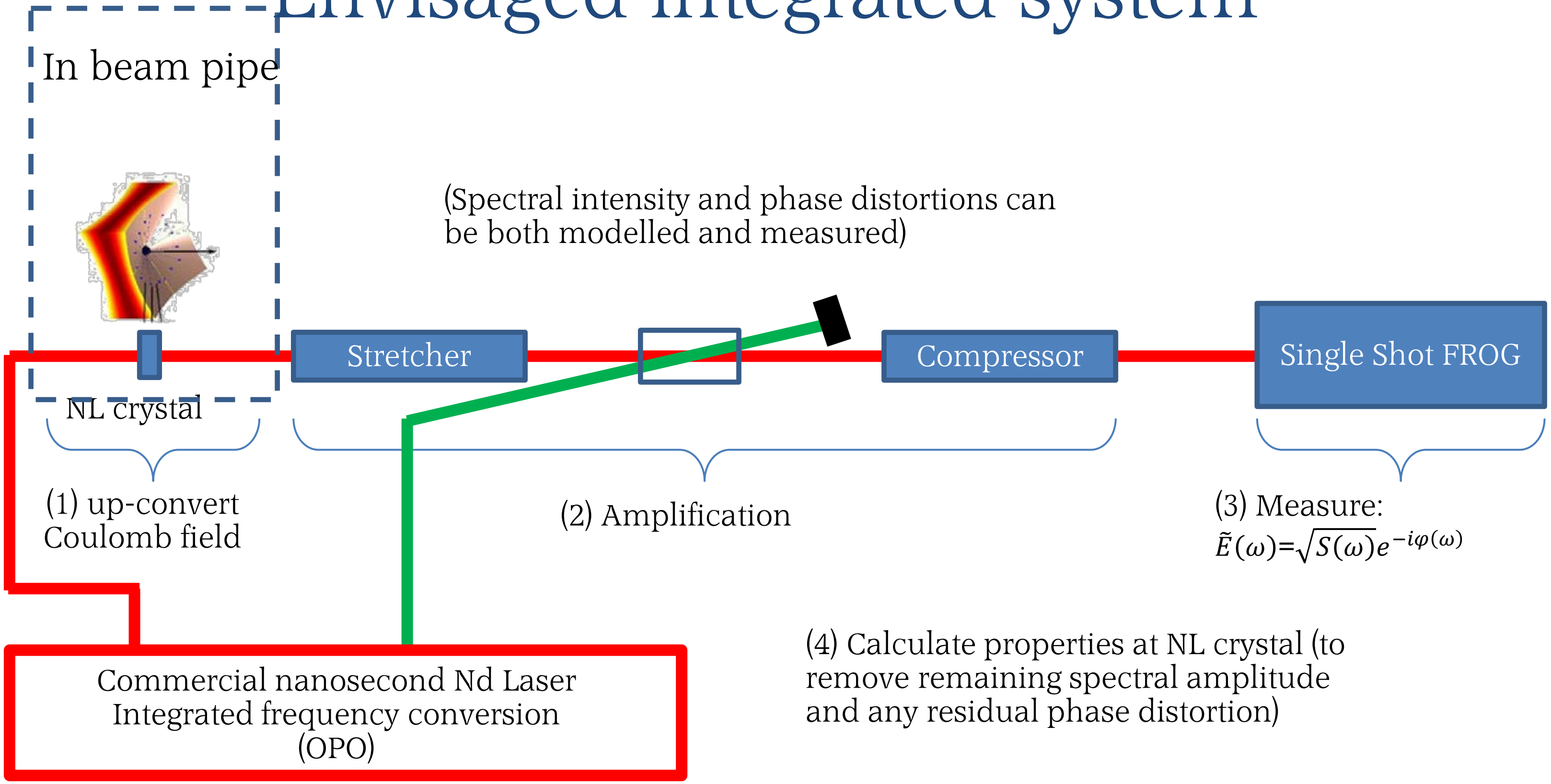


Routinely used to produce "single-cycle" optical pulses
Amplification with robust nanosecond pulse lasers
High **gains of 10^7** or more
Gain **bandwidths >100nm (50THz)**
Preservation of phase of pulse is possible

Laser-lab development system

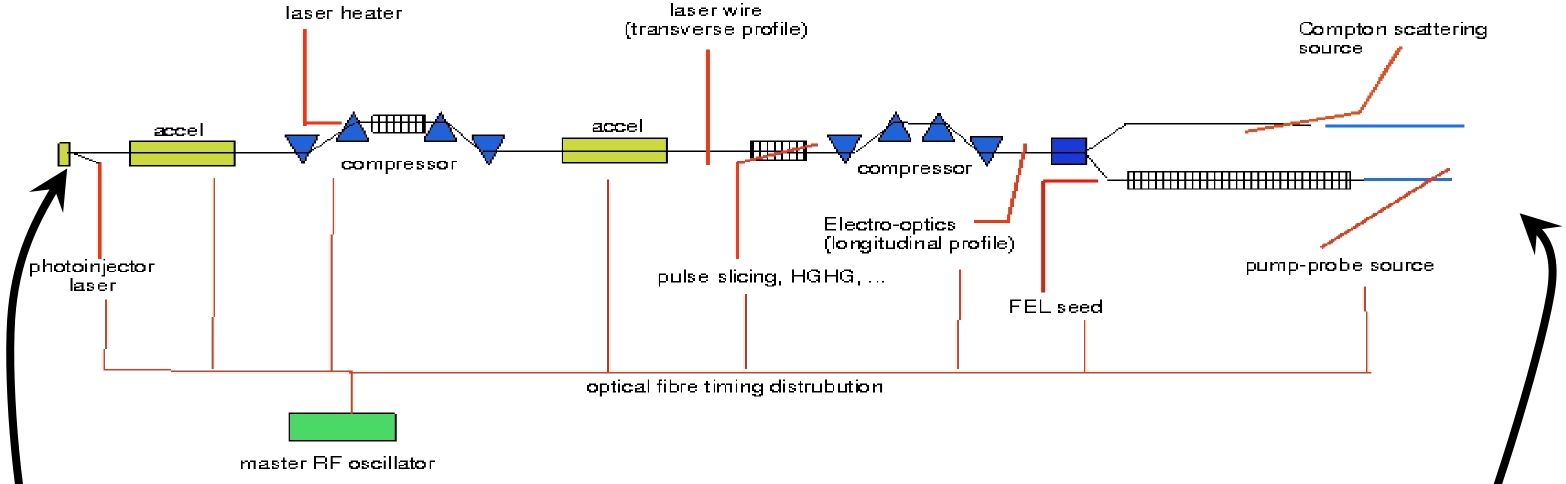


Envisaged integrated system



- Confirmation of amplification parameters June/July
- Commercial "turn-key" laser procurement July-Sept
- Accelerator tests… early 2014(?)

Lasers for accelerator timing distribution...



How to compare
timing here..

... with here,
with 10fs precision & stability

10 femtoseconds:

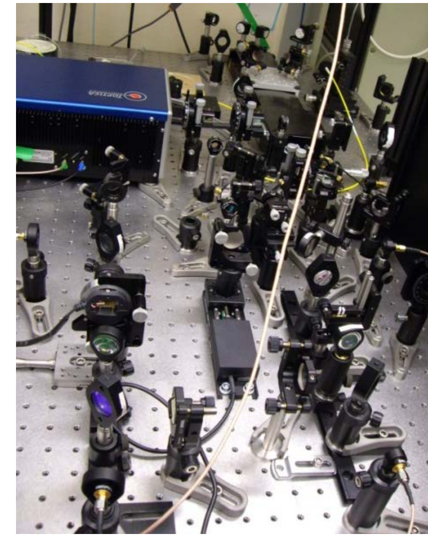
Propagation at c	3mm path length stability
RF phase	$\Delta\phi = 8\text{x}10^{-5}$ rad. phase stability at 1.3GHz
Aluminium thermal expansion ($23\text{x}10^{-6}$ / deg)	$\Delta T < 0.1^{o}C$ per meter

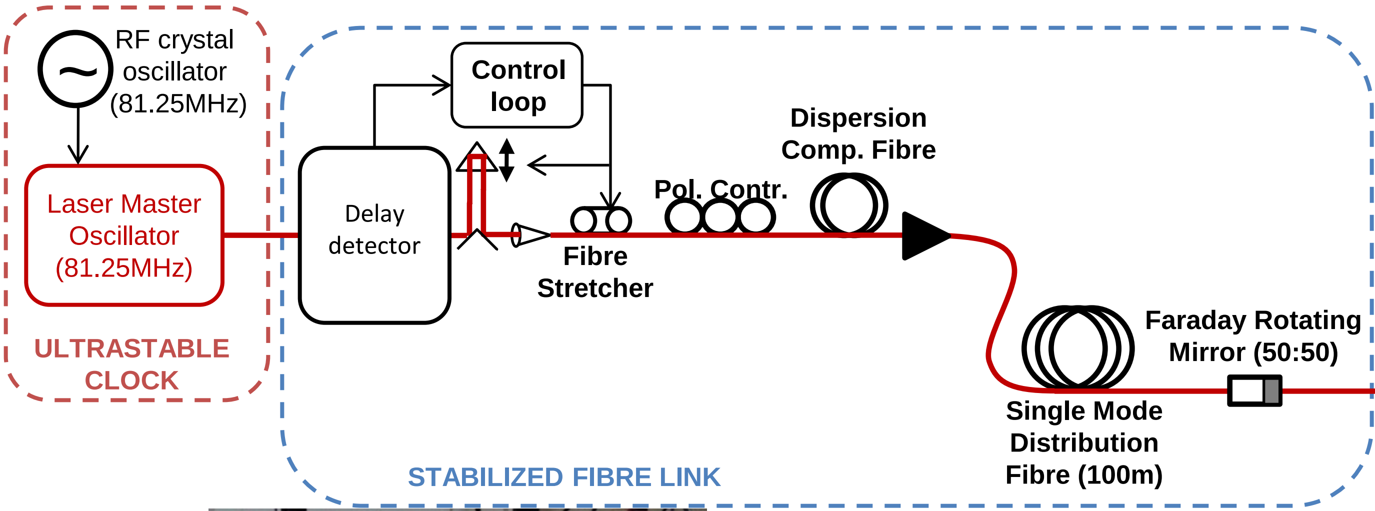
Optical Clocks, Distribution & Bunch measurement

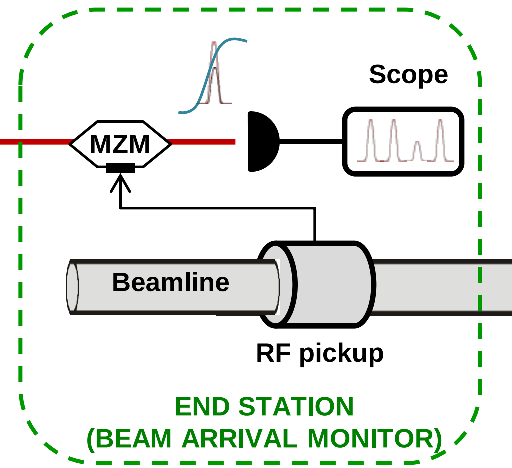
Timing system consists of 3 sub-systems

- Generation of the ultrastable clock,
- The stabilized fibre link for delivery of the clock
- An end station, such as a beam arrival monitor.

Delivered clock stability target at the few femtosecond level.





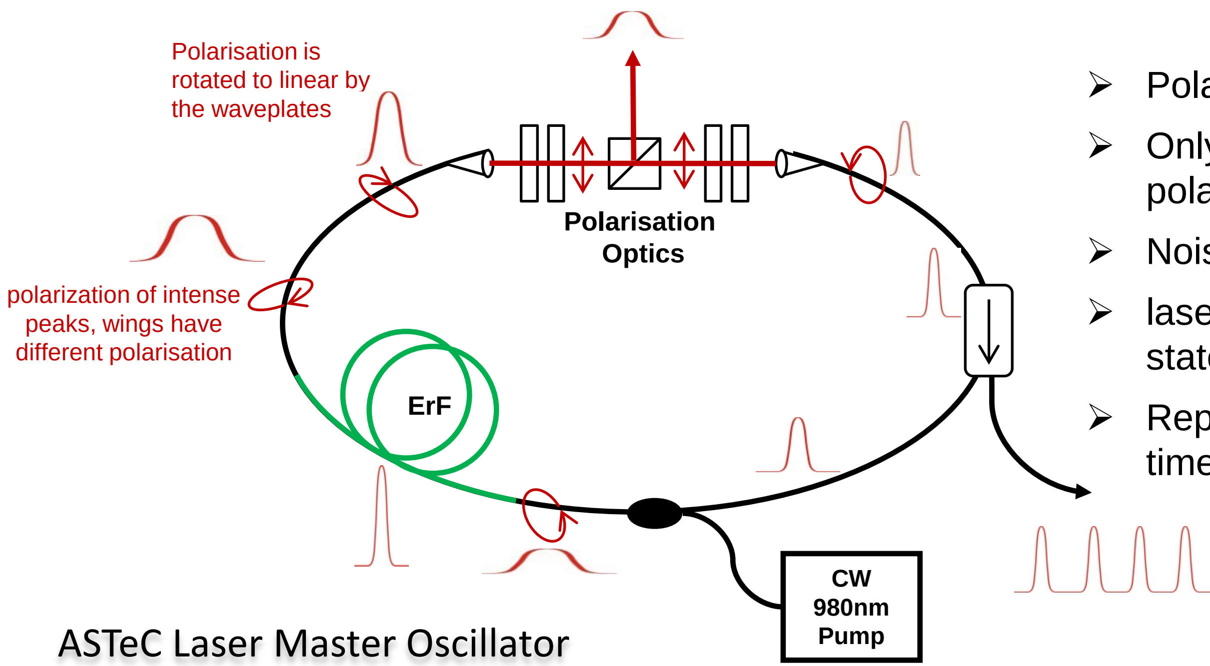


Systems installed on ALICE & Daresbury:

- timing system development
- accelerator/FEL physics

Ultrastable clocks

Stretched-pulse fibre ring lasers

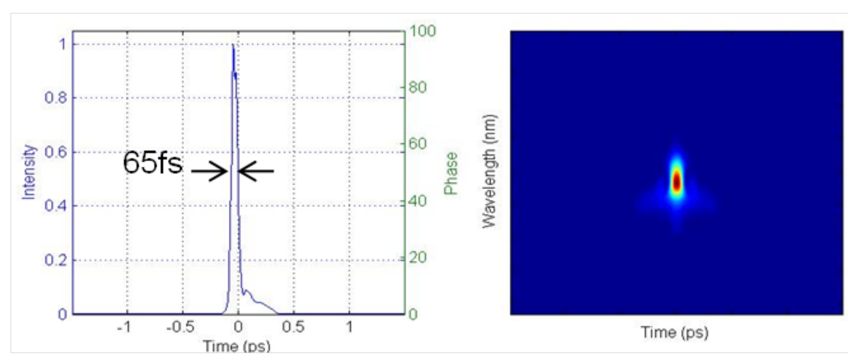


ASTeC Laser Master Oscillator

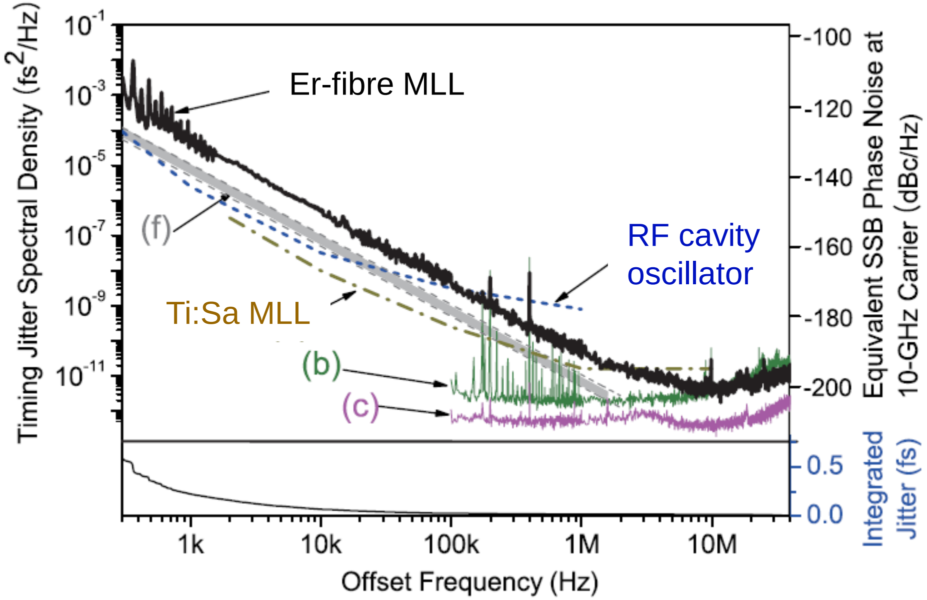
Pulsed operation starts from random noise

- Polarisation rotation is intensity dependent
- Only the intense peaks have the correct polarisation to pass through the polariser
- Noise and pedestal is rejected
- laser converges to single pulse steady state
- Repetition rate is determined by ring transit time

- Mode-locked stretched-pulsed Eribum fibre ring laser from Toptica Photonics
- The oscillator output is amplified in an EDFA and recompressed in free space
- Output pulses are transform limited at 65fs long and has a bandwidth >80nm

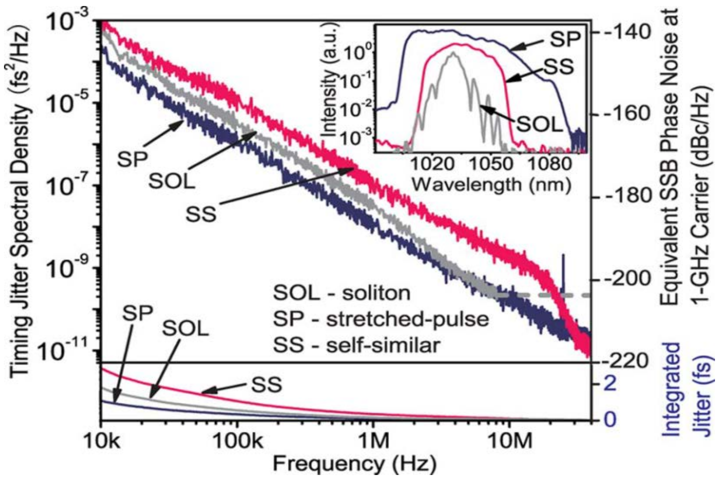


Ultrastable clocks

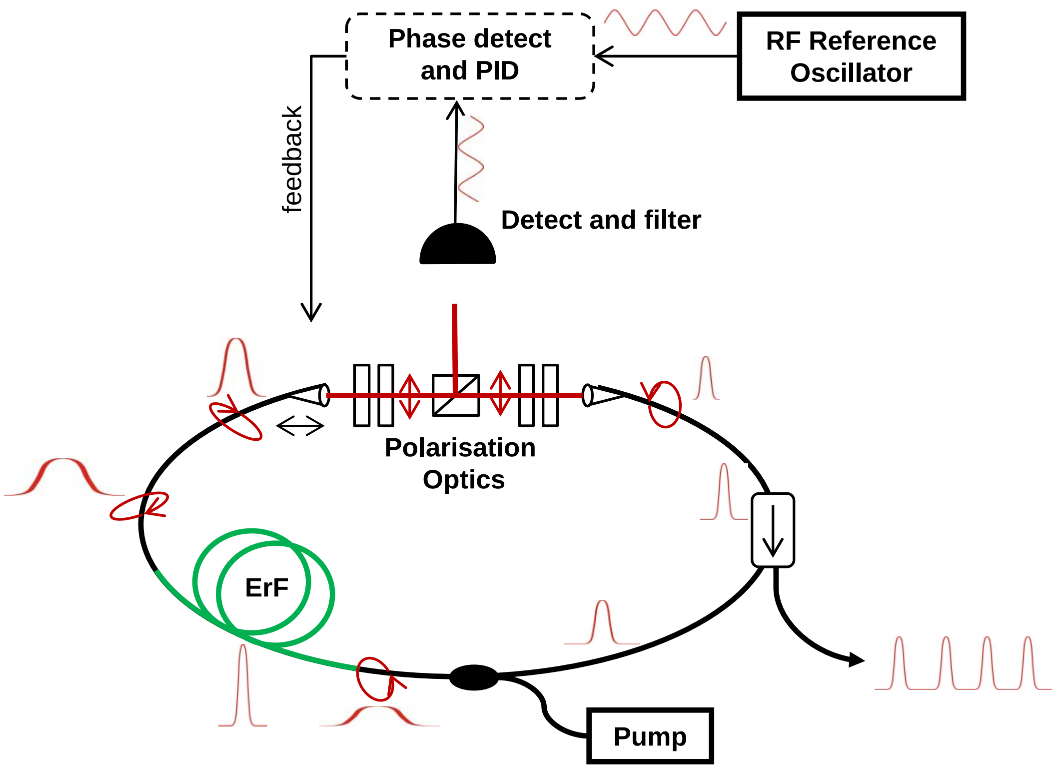


- Passively mode-locked lasers (MLL) are quieter at high frequencies than microwave oscillators
- Ti:Sa oscillators are some of the quietest clocks currently available

- Fibre lasers at telecommunications wavelengths are particularly suitable for distribution
  - Low loss
  - mature components
  - high bandwidth components



Ultrastable clocks

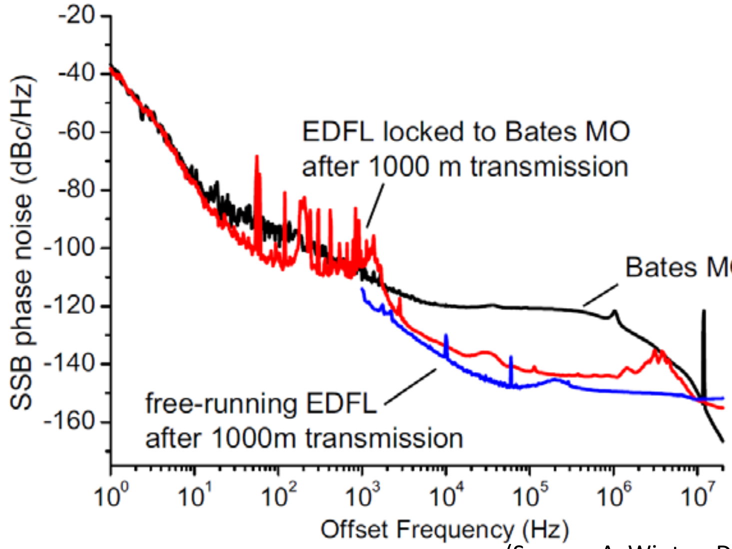


2.637... m cavity length -> 81,250,000 Hz
add **28 nm** -> 81,250,001 Hz

Cavity length susceptible to low frequency noise/drifts...

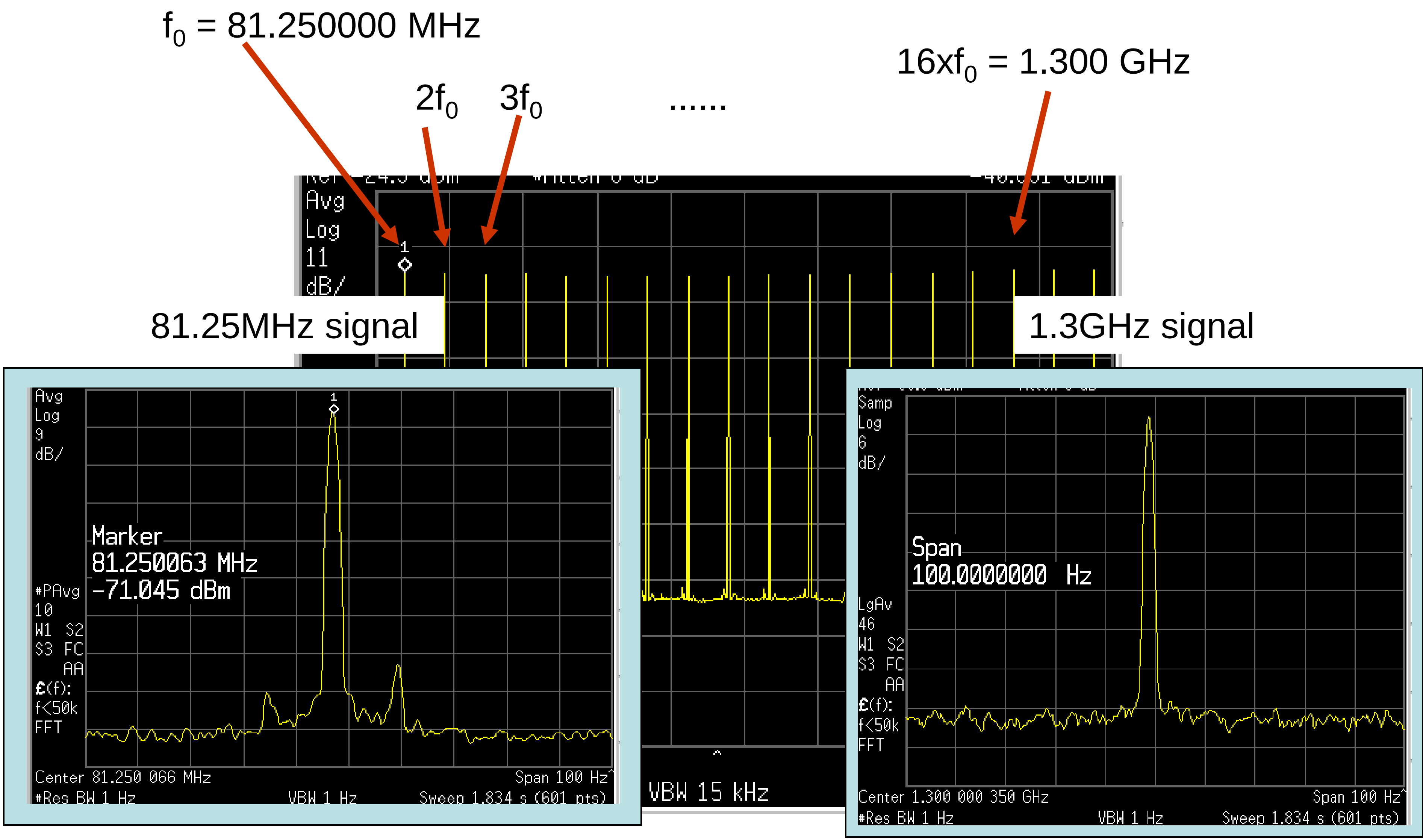
- Fibre length changes are detected through phase comparison to RF
- Feedback signal compensates for changes in path length

but very low noise at high frequencies



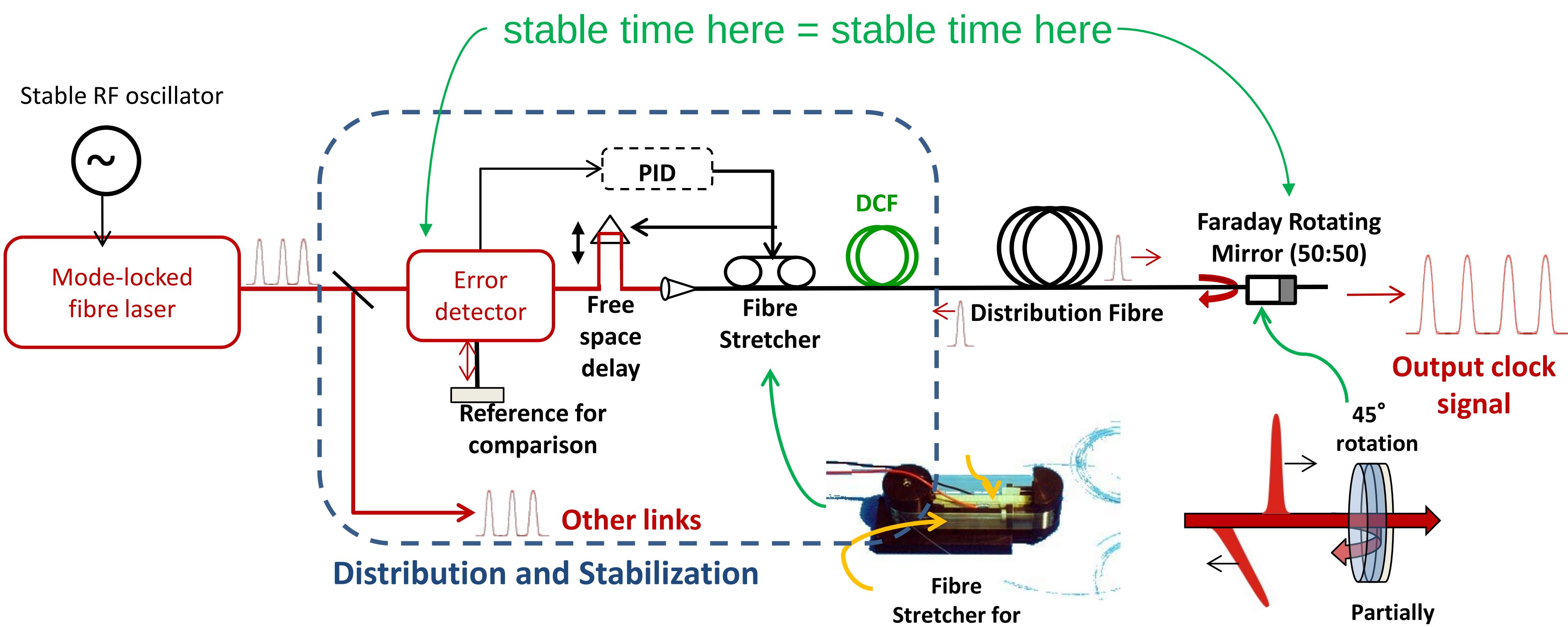
(Source: A. Winter, DESY)

RF spectrum of photodiode output....



Distribution : optical path length stabilization

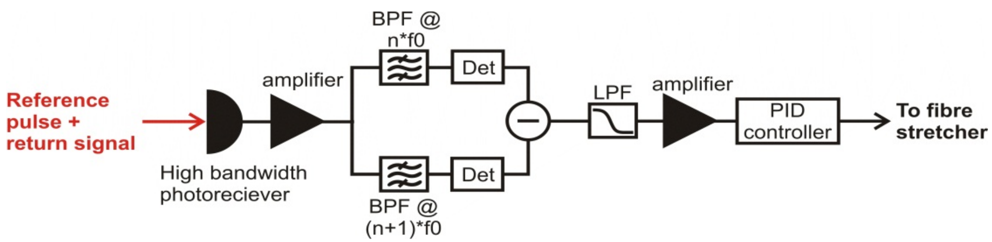
- Detect round trip travel time & compensate for length changes
  Compare reflected signals with reference
- Compensation based on 'same return path' assumption
- Transit time maintained with delay line and fibre stretcher

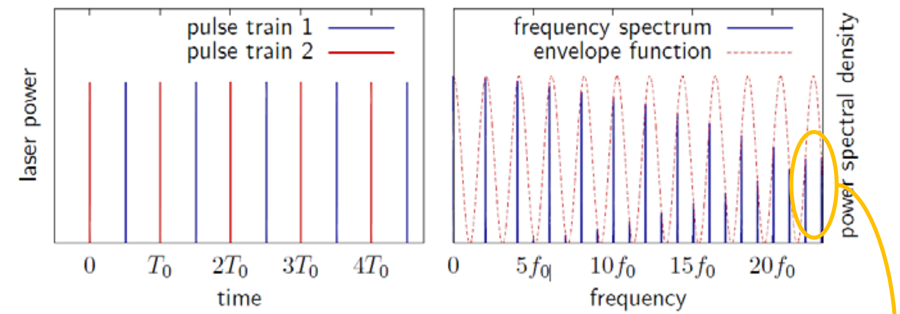


RF harmonic Delay Detection

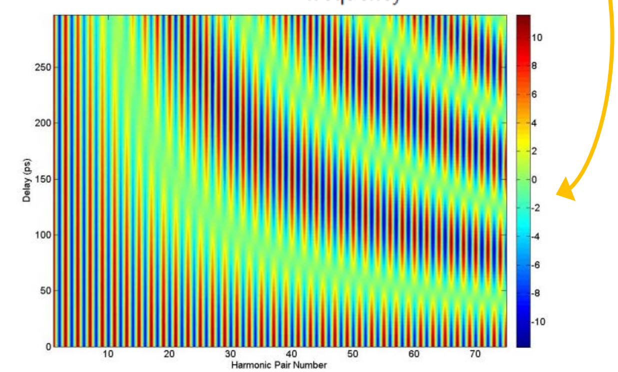
(Source: F. Loehl, DESY)

- **Harmonic comparison**





- Power of adjacent harmonics as monitor of relative train 1 – train 2 delay
- The power of the harmonics increase/decrease together in the case of amplitude fluctuation
- Higher harmonics have greater time-sensitivity, but limited by the photodiode bandwidth

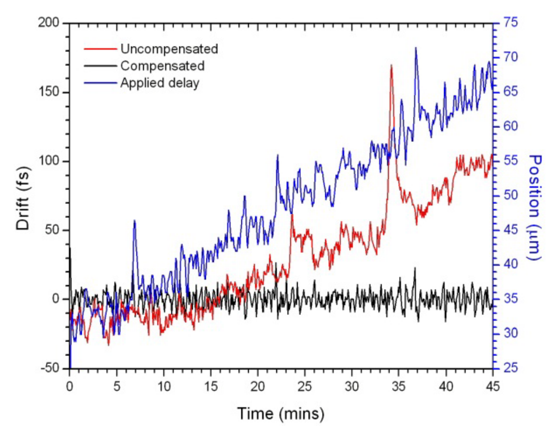


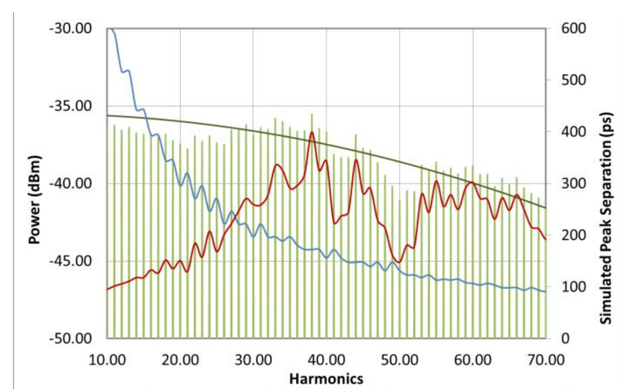
Adjacent harmonic differences (H_n-H_{n-1}) of detected pulses as a function of delay.

ASTeC system

- use the 42nd and 43rd harmonics of our 81.25MHz signal
- The measured signal used in a control loop to compensate for any measured drift in the link.
- We obtained 4 ps/mV sensitivity and a 150 ps maximum range.

Drift compensation over 45 mins

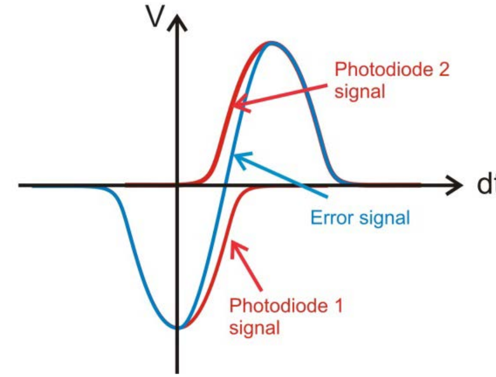


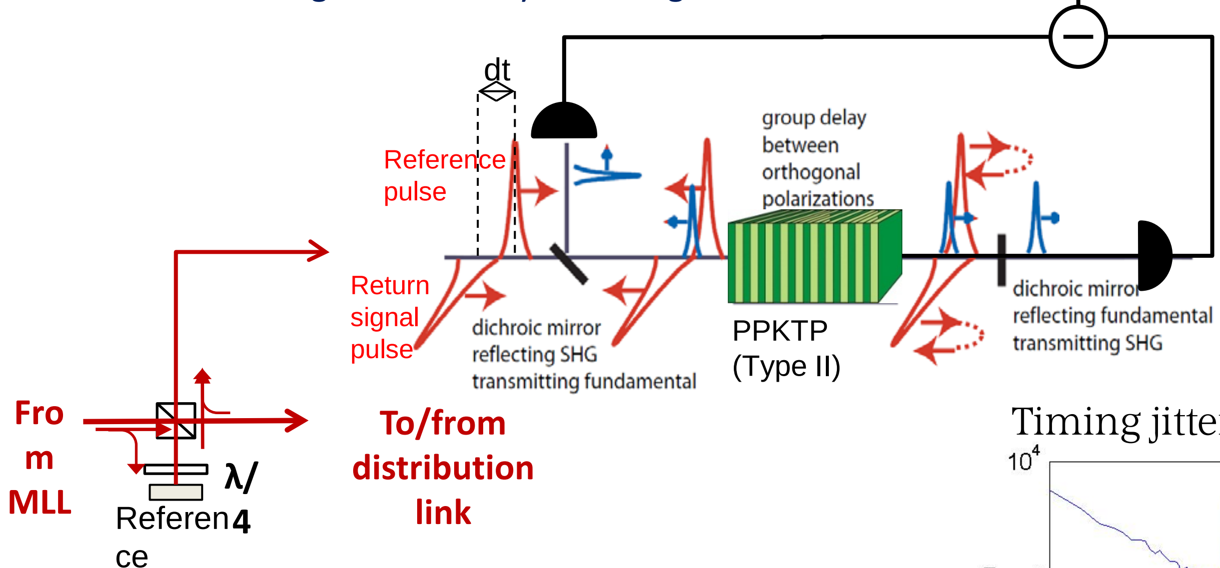


Comparison of photodiode power against peak separation

Optical cross-correlator delay detection

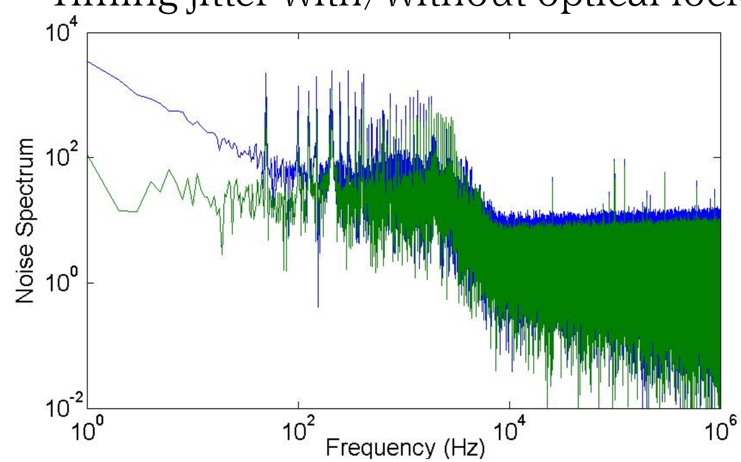
- Dichroic mirrors select out the SFG and from the fundamental to enable double pass configuration.
- PPKTP uses quasi-phase matching to get high SHG conversion efficiency
- The type-II is cut for phase matching of orthogonal polarisations, which eliminates the background signal associated with each pulse's own SHG and generates only the SFG generated





- Balanced configuration increases sensitivity and reduces amplitude dependence of error signal.

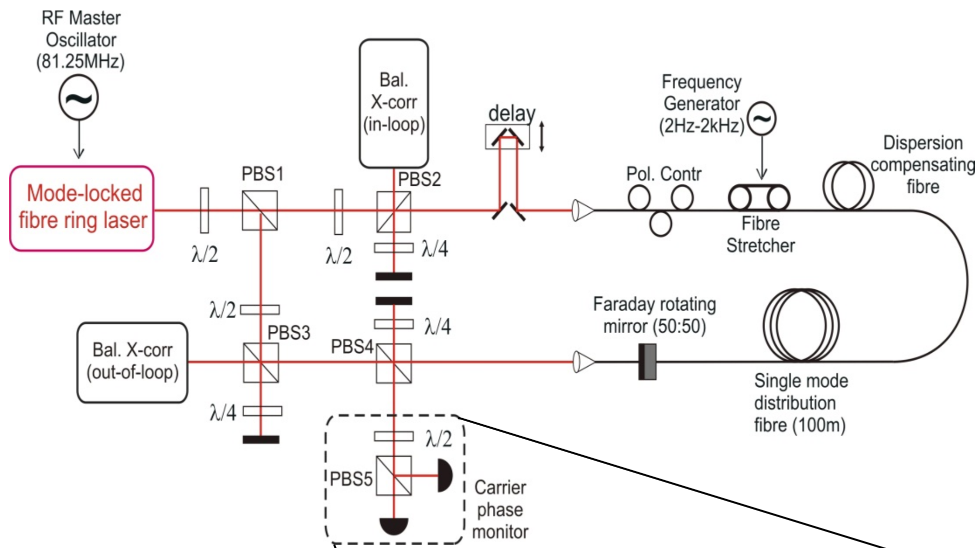
Timing jitter with/without optical lock

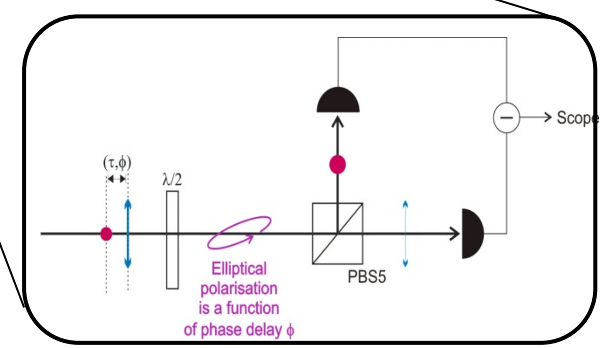


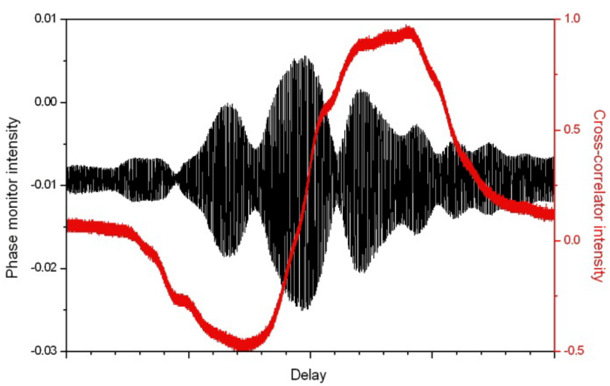
ASTeC / ALICE link has been stabilized to 8 fs rms measured out-of-loop using a second balanced cross-correlator

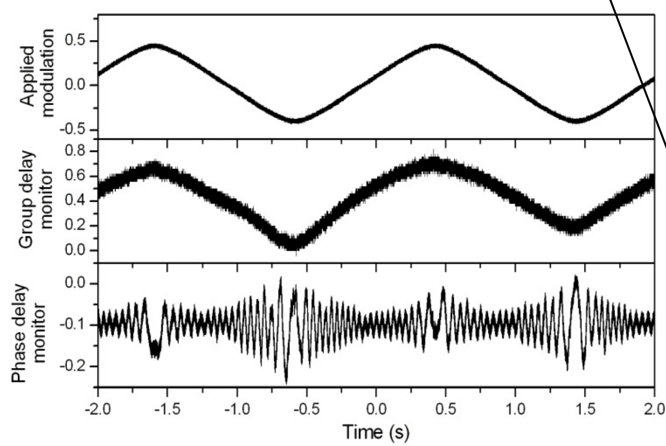
Carrier interferometry for <1 fs lock

- Monitoring effect of fibre stretching on changes in carrier phase offset
- Deliberate stretching of fibre enable studies of fibre response at different frequencies
- Feasibility study on locking both group and phase velocity in distribution link.
- Pulsed interferometric system can potentially give higher locking resolution while maintaining short pulse delivery.









Electron bunch arrival-time diagnostics

High bandwidth (>10GHz) RF pick-up on electron beam line

e.g. button pickups in Beam Position Monitor.

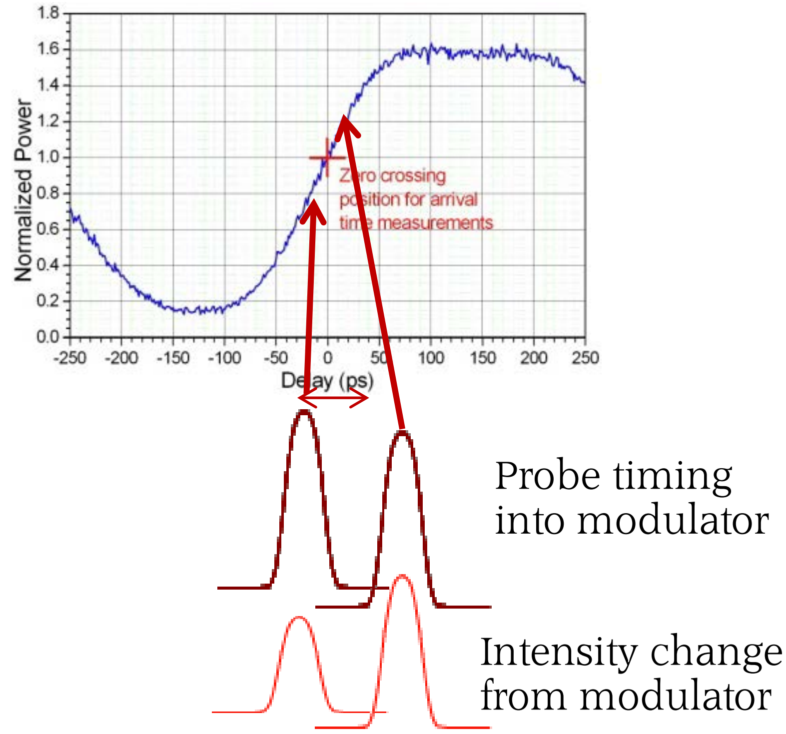
RF signal feed into fibre-optic electro-optic modulator

- Highly developed telecoms devices
- Converts input RF waveform into intensity modulation of transmitted optical signal.
- >40GHz bandwidth systems available

Ultrafast (~100fs) optical pulse probes the RF waveform

- Optical pulses from timing distribution (much shorter than telecoms applications)
- Effectivly time sampling of waveform

BAM characteristic

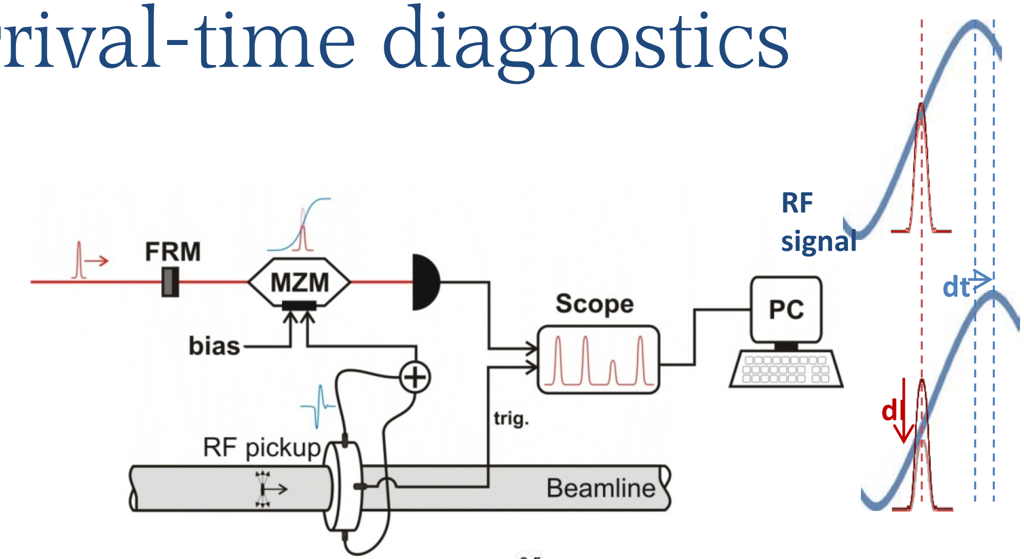


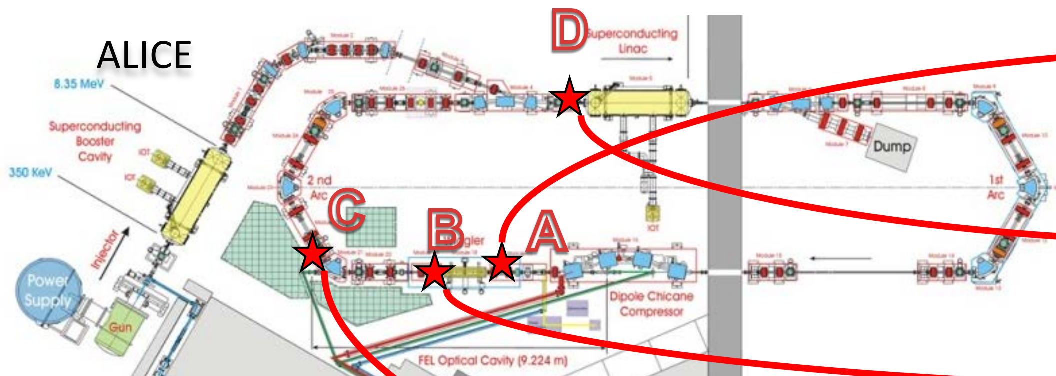
Provides sub-100fs level timing information on electron bunches

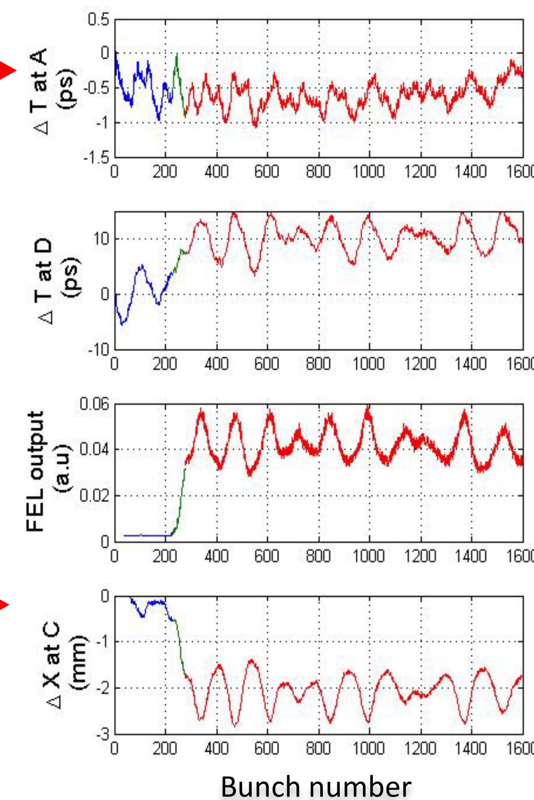
Feedback; machine stability studies; time stamping (user experiments)

Electron bunch arrival-time diagnostics

- The BAM uses an optical pulse train which is synchronised to the accelerator clock.
- Arrival time of electron bunches is sampled optical pulses in a Mach-Zehnder modulator to gate them
- Gate signals driven by pickup in the beamline.



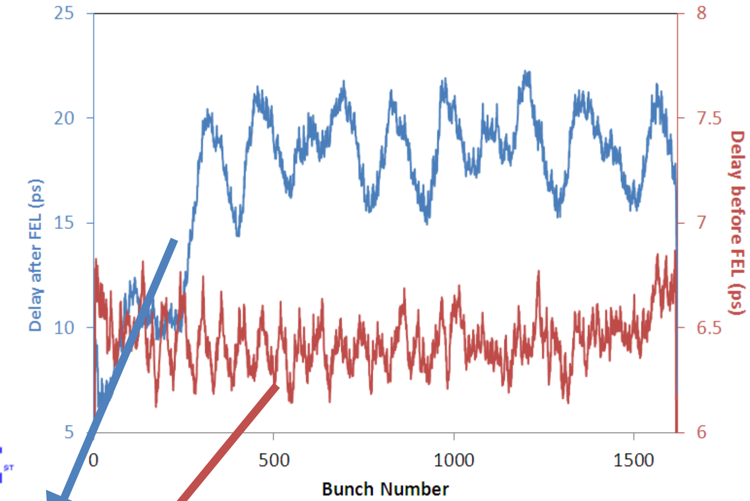


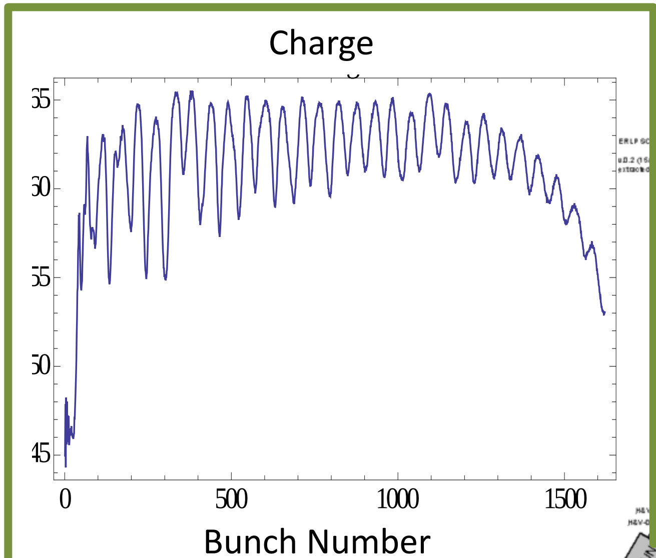


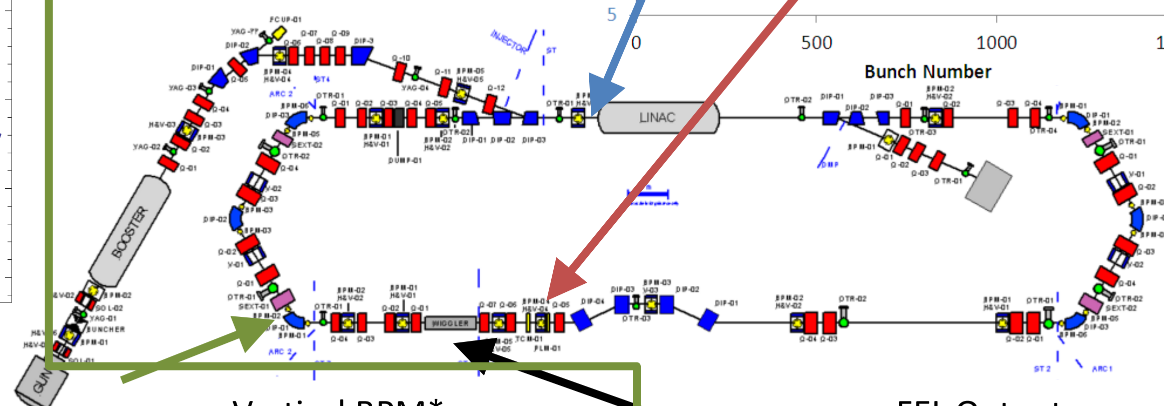
A combined experiment using multiple diagnostics was performed to study instabilities in the FEL and ALICE as a whole.

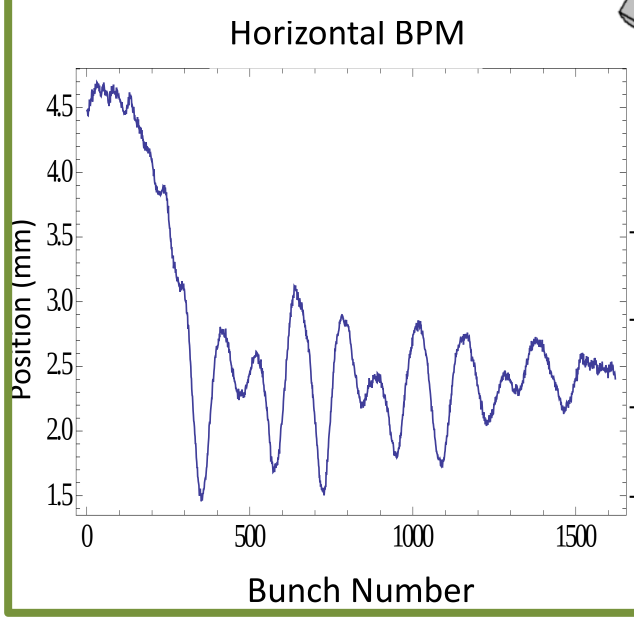
- Synchronised measurements of two BAMs, a BPM and the FEL output
- We were able to do bunch-by-bunch tracking of individual bunches and their photon output along a 100µs macropulse across all the diagnostics.
- Analogue triggers and time-stamping in EPICS were used to synchronise all the diagnostics together.

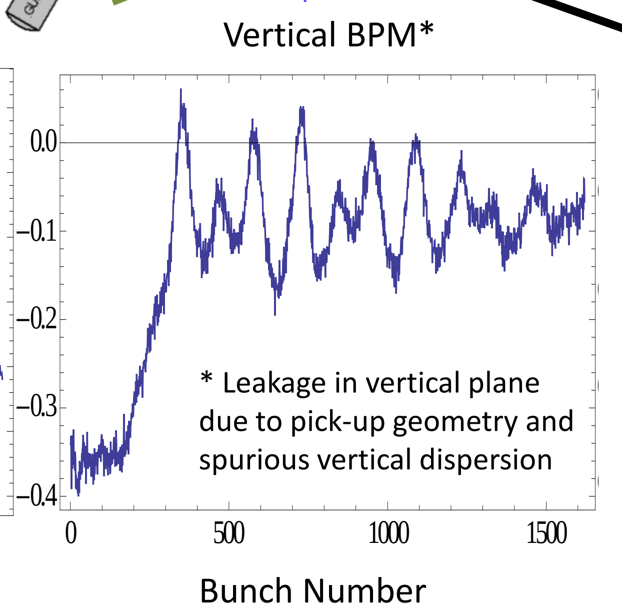
Combined BPM/BAM/FEL Diagnostics at ALICE

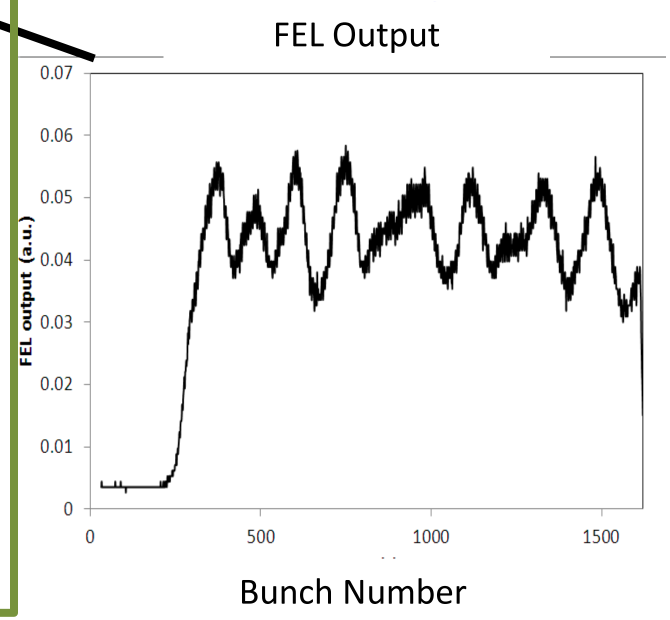






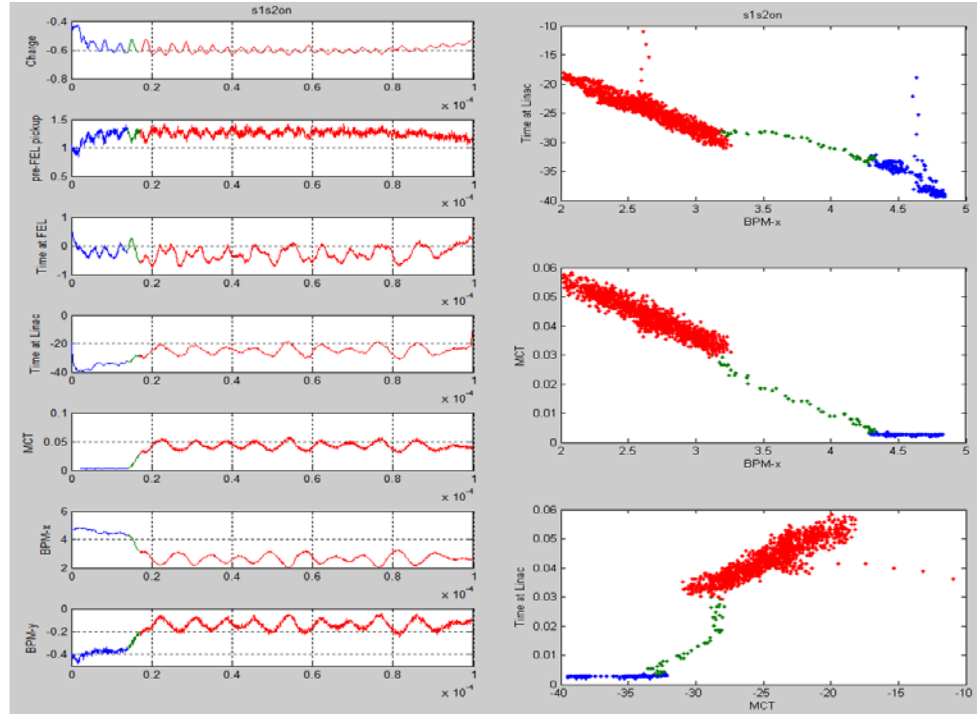




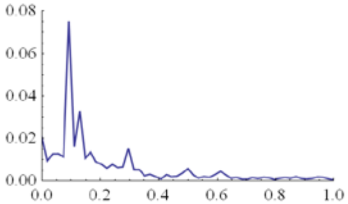


Study of FEL with combined diagnostics

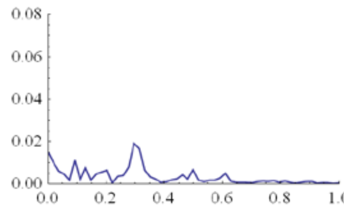
- Combine with fast FEL detector and BAM measurements, similar instabilities observed
- Correlations of diagnostics give information about Arc 2
- Tracing of trends though pre-lasing and lasing parts of pulse train.



position

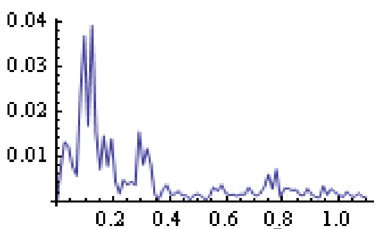


charge

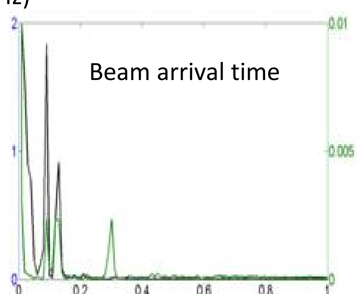


Frequency (MHz)

FEL pulse energy



Beam arrival time



Frequency (MHz)

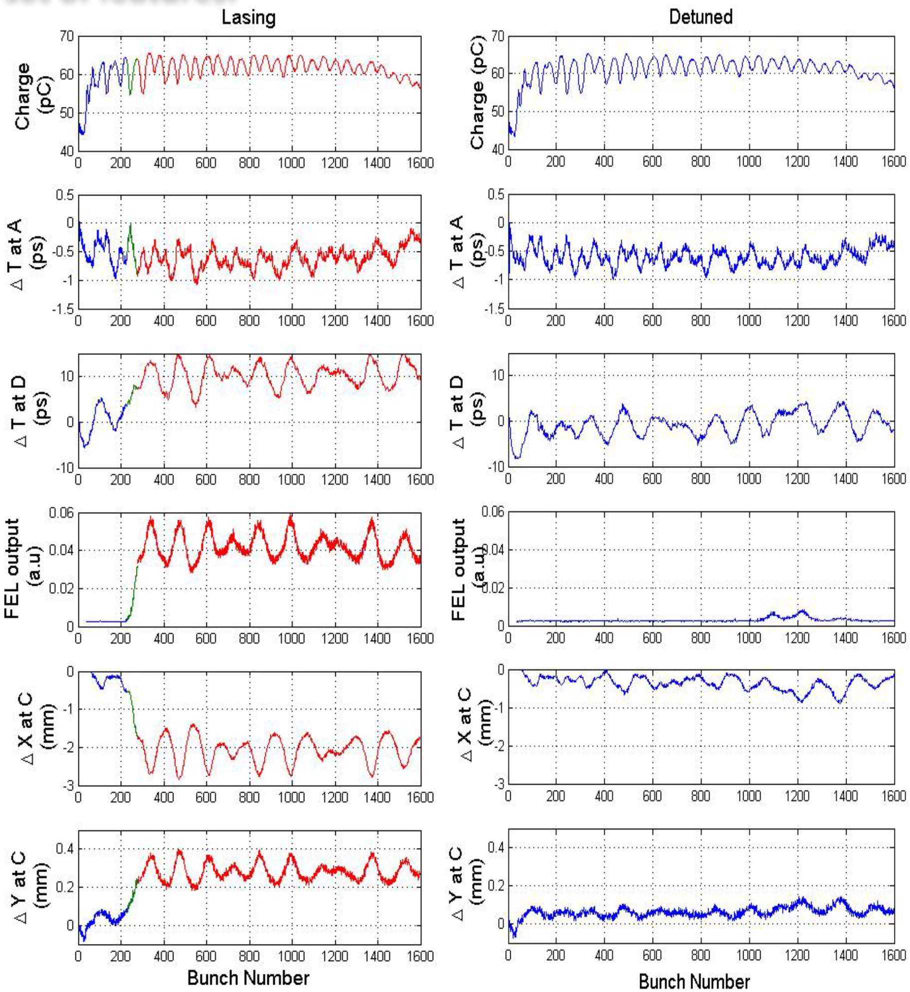
- Several instabilities observed in beam by fast BPM system
  - 100 kHz bunch position oscillation
  - 300 kHz charge oscillation. Confirmed in faraday cup and PI laser power
- On-going investigation into laser position stability

courtesy F. Jackson

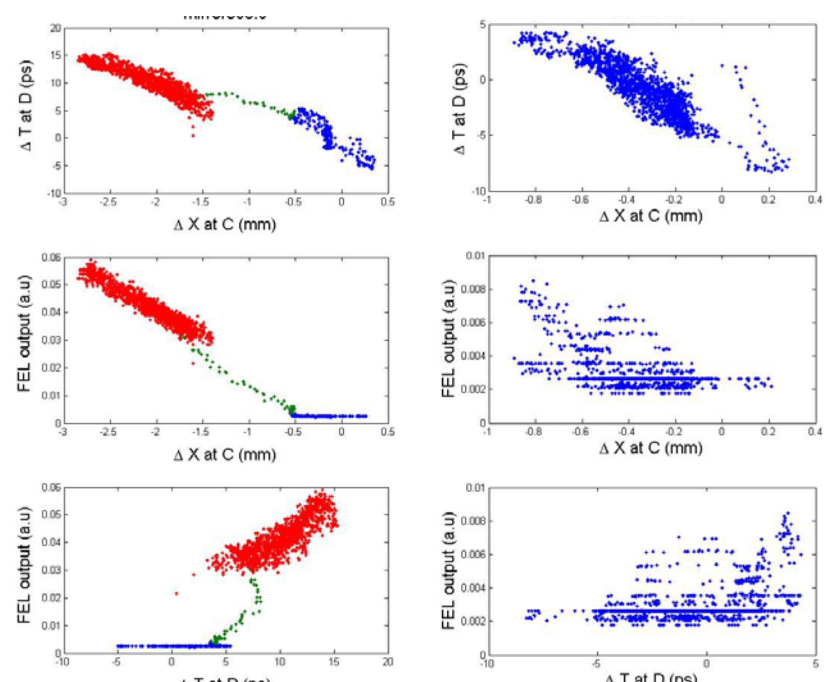
Analysis of correlations

Developing bunch-by-bunch understanding of how beam affects FEL and how FEL affects beam

The arrival time at energy recovery, FEL output and beam position in Arc 2 are highly correlated and show the same set of features.



- Timing fluctuations at D are not much larger when the FEL is lasing compared to when it is not.
- When detuned, the BAM and BPM measurements are completely decorrelated from the FEL output, but are still correlated to each other.
- Implies some energy fluctuations before entry to FEL, and are correlated to the FEL pulse energy through its coupled time and position changes.
- Only the 100 kHz oscillation in arrival time into the FEL shows up as a oscillation in the output. The 300 kHz oscillation is not seen.



EMMA BPM Diagnostics
(EMMA BPMs used for ALICE stability expts)

EMMA was constructed for study of non-scaling FFAG acceleration

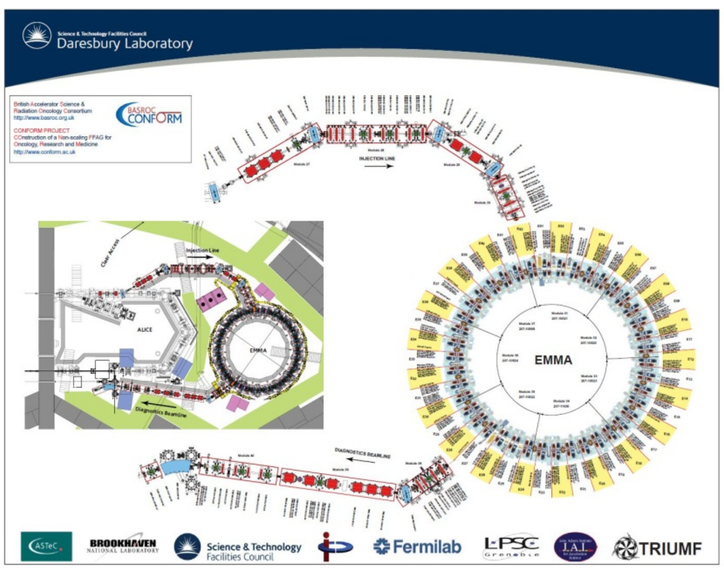
rapid serpentine acceleration with large tune variation.

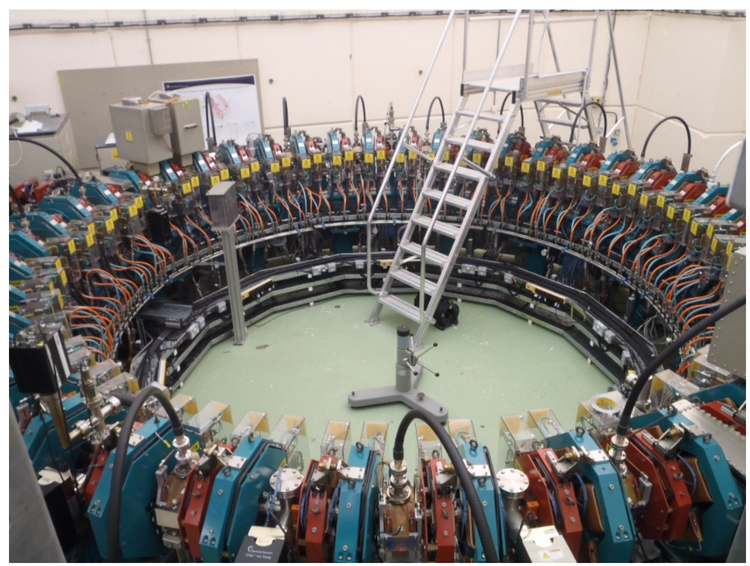
During accelerating the bunch executes up to ten turns

- Expanding trajectory sweeps about a half of the pickup aperture.
- For machine tuning, the bunch can be kept circulating >1000turns.
- Revolution period is *T*=55.2ns,
- bunch charge is up to 30pC, the bunch length is about 10ps.

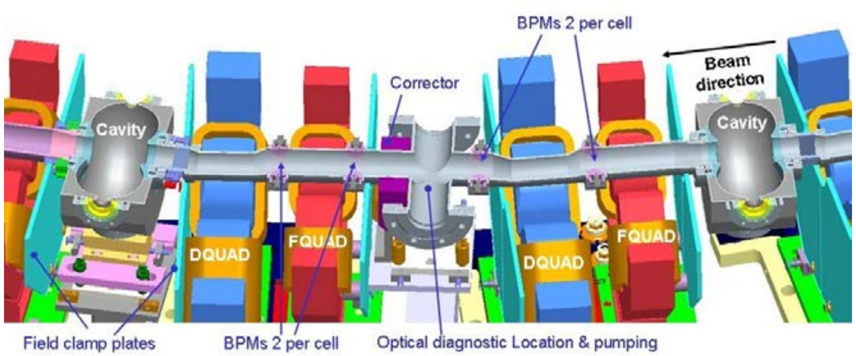
The rapid dynamics needs advanced diagnostics.

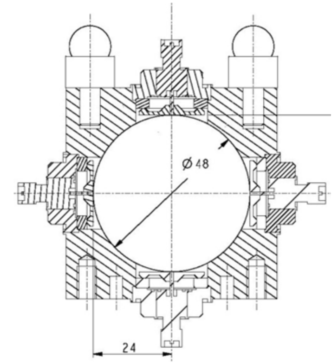
The trajectory should be measured on each turn, in each of 42 F-D cells.





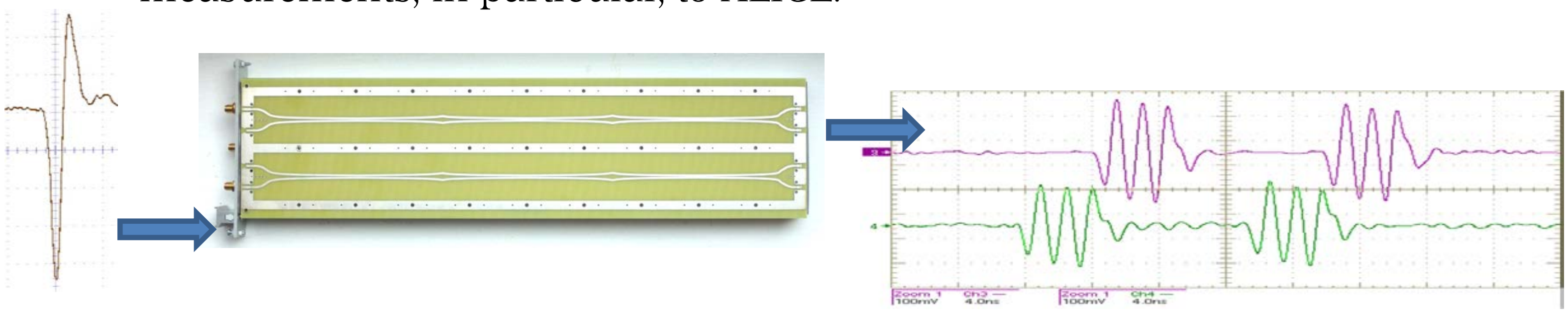
EMMA Beam Position Monitor System





High rep-rate BPM system, ASTeC designed, built and commissioned

The system is applicable to ERL machines for bunch-by-bunch-in-train measurements, in particular, to ALICE.



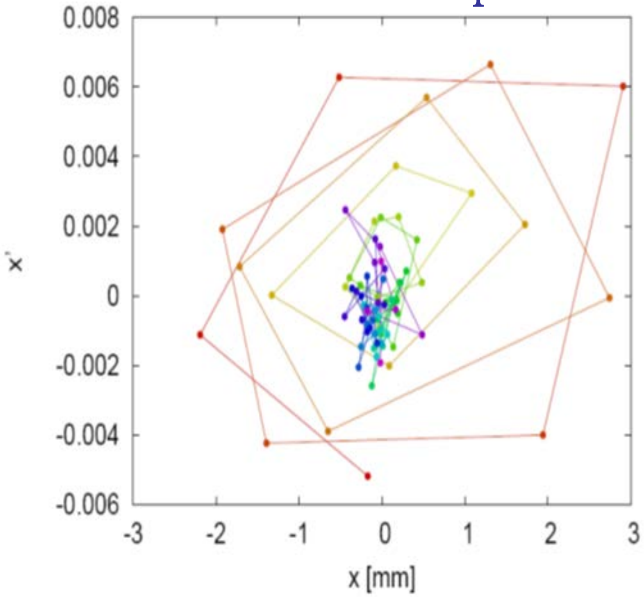
Developed concept of BPM self-synchronisation with beam,

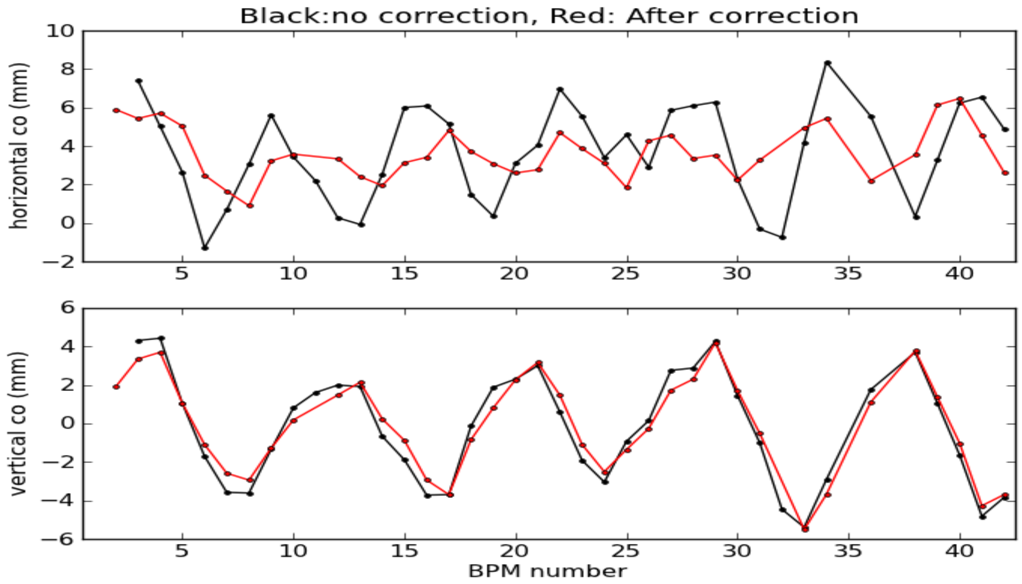
- the BPM detector reference signals and the ADC clock are manufactured from the BPM input signal - automatically synchronous with the beam signal.
- pipe-line-type ADC chip for single bunch/train measurements

- The EMMA system comprises total 53 of BPMs, approx 400 boards & cards.
- Functional architecture, solutions and design of electronics was done by ASTeC.
- In-house EPICS implementation
- In collaboration, a VME interface and its firmware was designed by WareWorks Ltd (UK).

Board/card fabrication was done by UK Electronics Ltd.
Components & fabrication cost is about 150kGBP.

Poincare map.





Laser driven THz sources for electron-beam manipulation

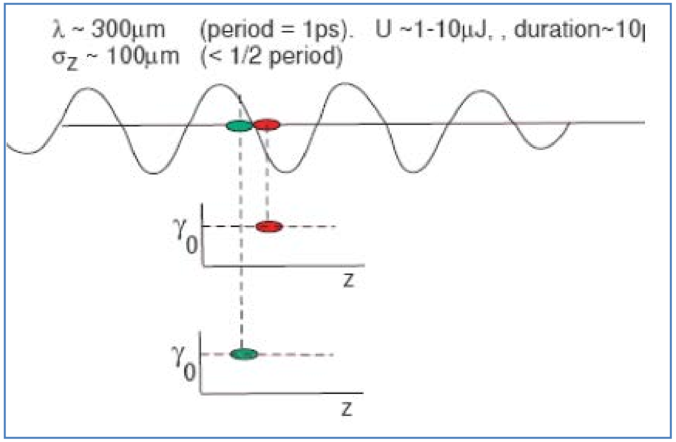
Picosecond periods match time scale of compressed bunches lengths in conventional accelerators.

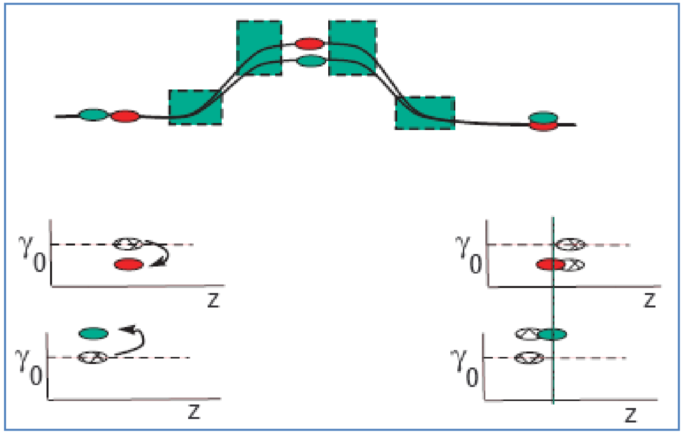
- No oscillatory smearing as in optical bunch slicing
- Controllable field profile on sub-ps time scale.
- Octave spanning spectrum possible

Terahertz carrier-phase is synchronised to laser pulse envelope

- Potential for the whole bunch to be "resynchronised" or compressed (in contrast to the selection/tagging from within the bunch)

LASER DRIVEN SYNCHRONISATION ?





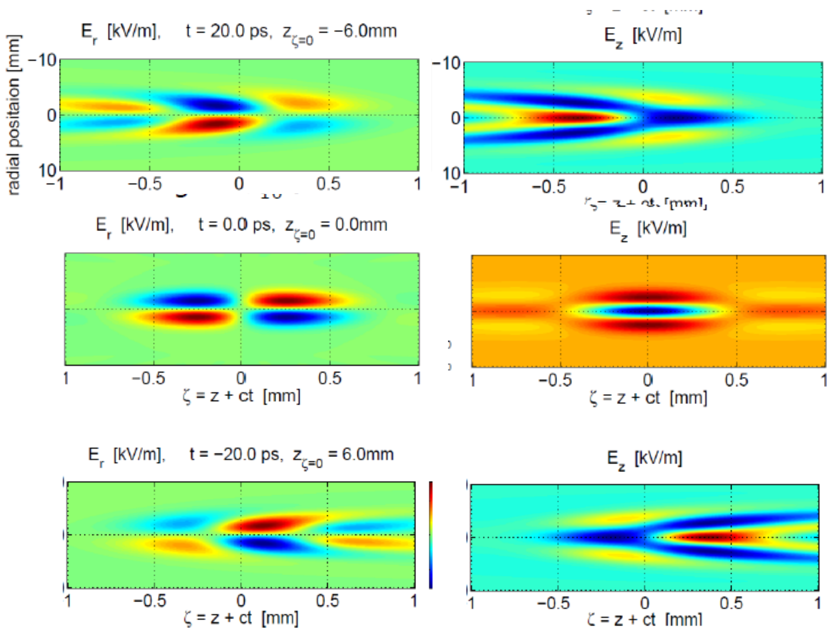
AEMITR

ALICE Energy Modulation by Interaction with THz Radiation

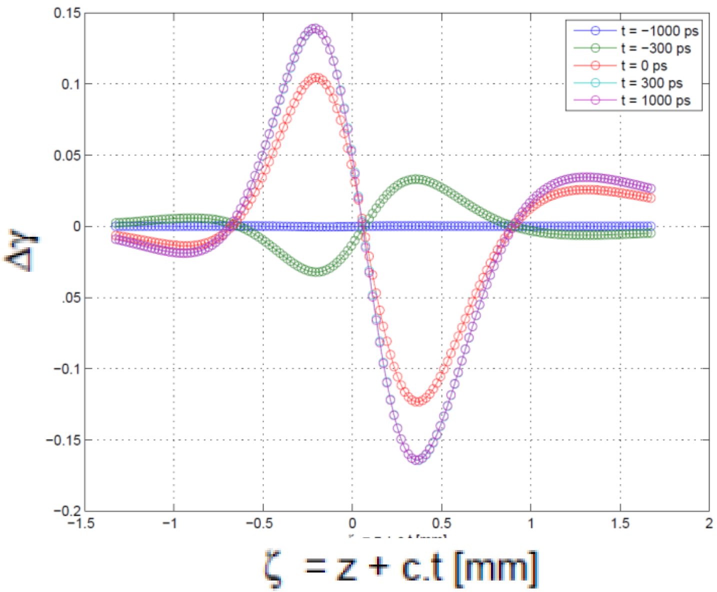
Vacuum acceleration of bunch with TEM_{10}-like single-cycle THz pulses

- >> 1 MV/m fields achievable
- long slippage period ~1 m for 20 MeV ($\beta = 1 - 10^{-3}$)

Electric field of a focussing TEM_{10}^{*} terahertz pulse



Energy gain for 20 MeV beam

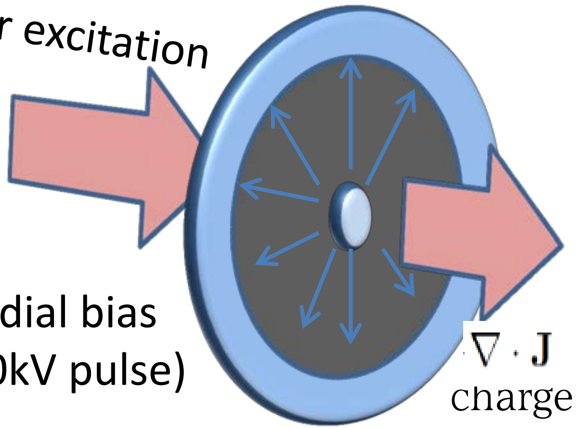


Longitudinal polarised THz pulses from Photoconductive antenna

Simple & efficient

but Lacks temporal shaping capability

Laser excitation



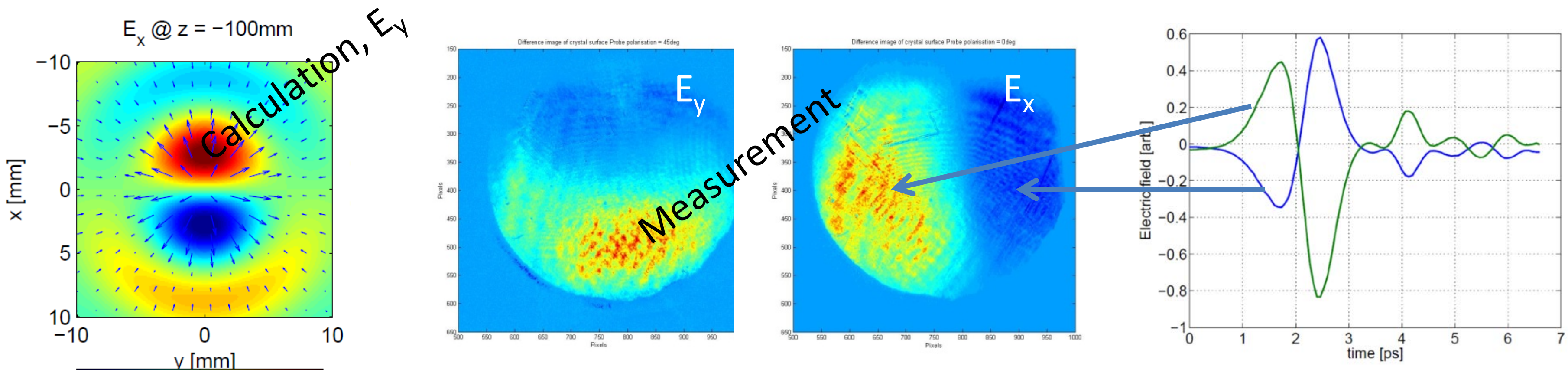
Radial bias (120kV pulse)

$$\mathbf{E}(\mathbf{x},t) = \frac{1}{4\pi\epsilon_0}\int d^3\mathbf{x}'\,\frac{1}{R}\left[\nabla'\rho - \frac{1}{c^2}\frac{\partial \mathbf{J}}{\partial t}\right]_{\rm ret}$$

$\nabla\cdot\mathbf{J}$ generates charge separation → origin of longitudinal field

Transverse field from current surge

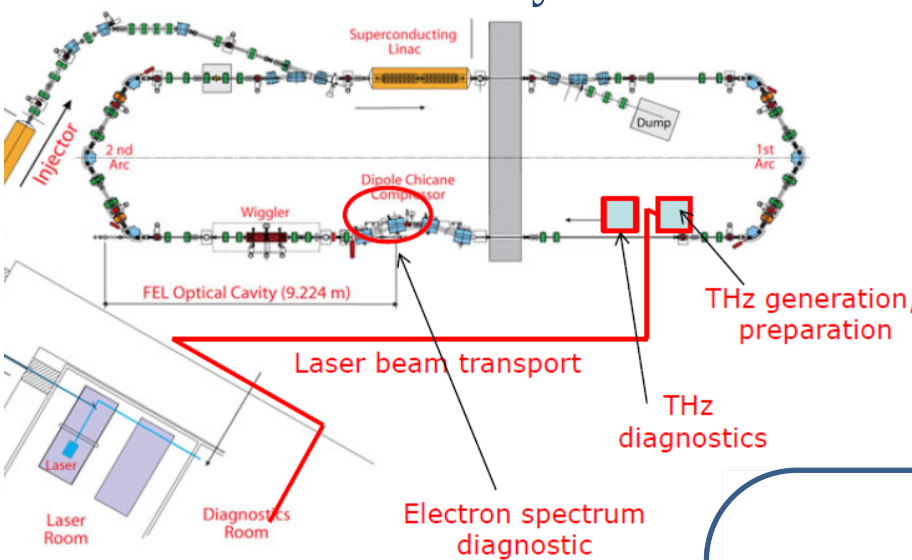
Longitudinal field implicit from $\nabla\cdot E = 0$



now working on nonlinear generation of longitudinal beams

temporal shaping capability

AEMITR layout



Energy spread diagnostic

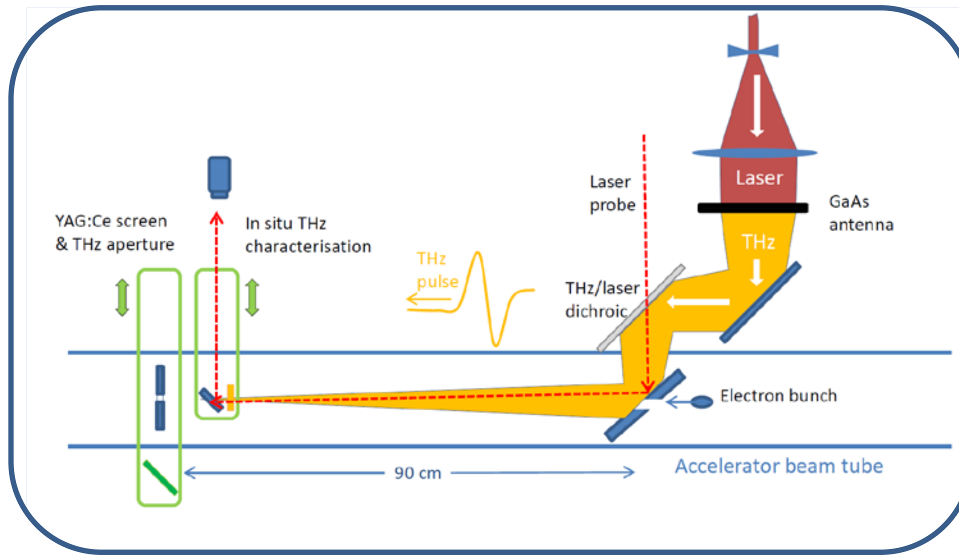
- Two-bunch train, separation
- 790ns (reference & modulated)
- YAG:Ce screen (t~100ns)
- Double shutter gated camera, measuring both reference & modulated bunches

Electron beam parameters

- 20MeV, 20pC
- Minimising projected energy spread "on-crest" acceleration. <50keV spread

THz generation

- THz generation adjacent to accelerator f~1.5 m
- <2 mJ, 50 fs TiS & photoconductive antenna



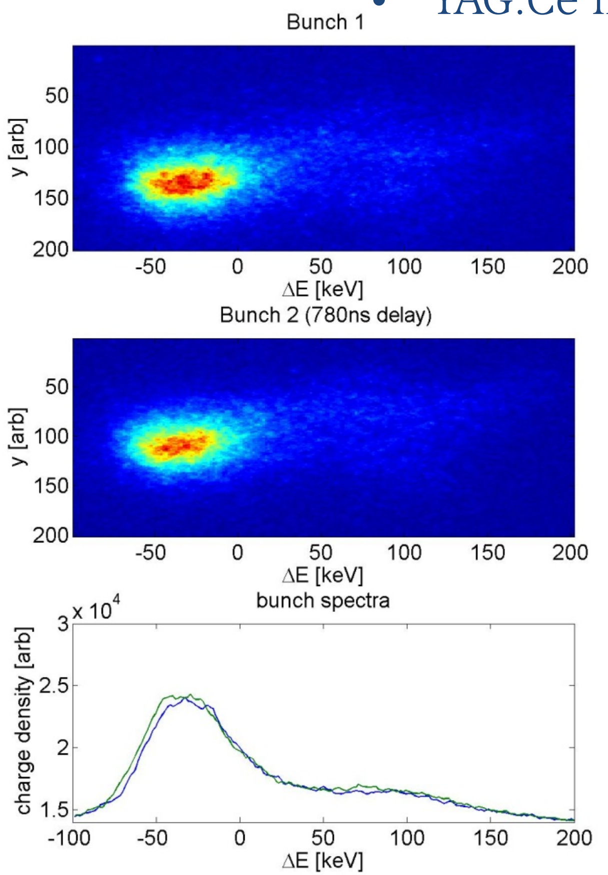
Two experimental periods completed, no acceleration observed yet

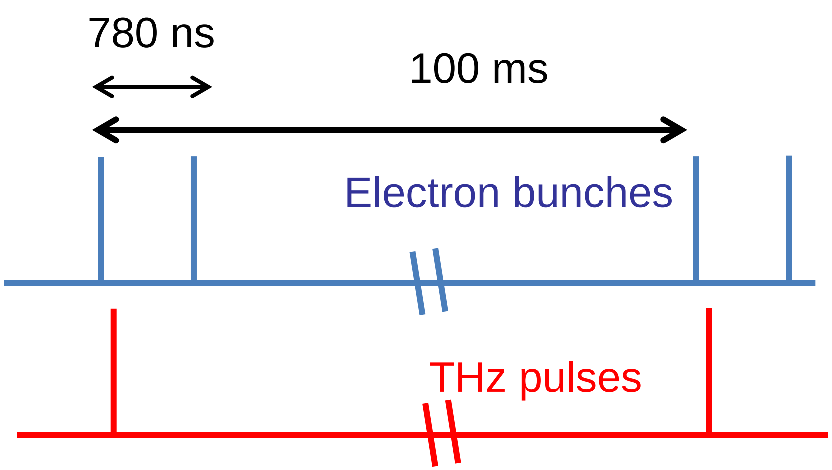
- Many issues resolved, improvement made
- Synchronisation significant remaining issue

Coping with ALICE energy jitter

Expecting small change in projected energy spread
Energy and energy spread jitter

- large between macro-bunches
- lower jitter on short time scales
- YAG:Ce lifetime ~100ns…… observe bunches 780ns apart





Single gated/intensified camera captures both bunch spectra

- 100ns exposure
- 780ns delay

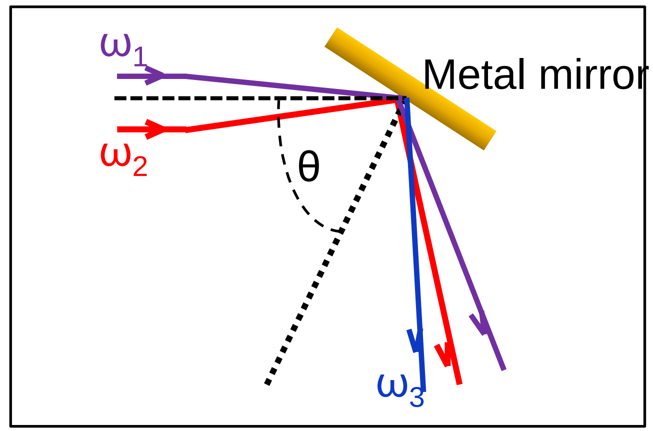
CLARA FEL Photon diagnostics

Photon temporal characterisation for evaluating FEL schemes

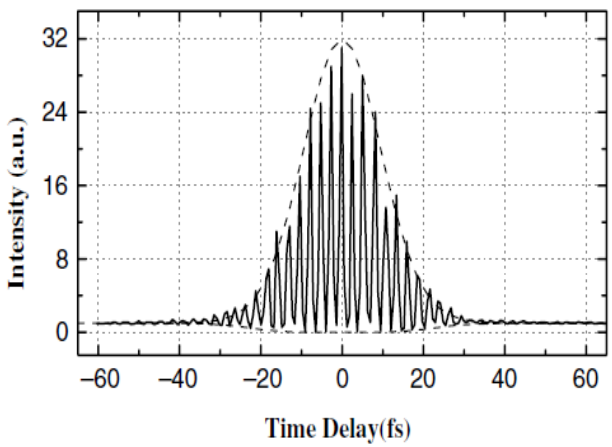
Expected FEL output from CLARA: 100nm-250 nm, <10 fs pulse duration.

Challenges in bandwidth, phase-matching, absorption

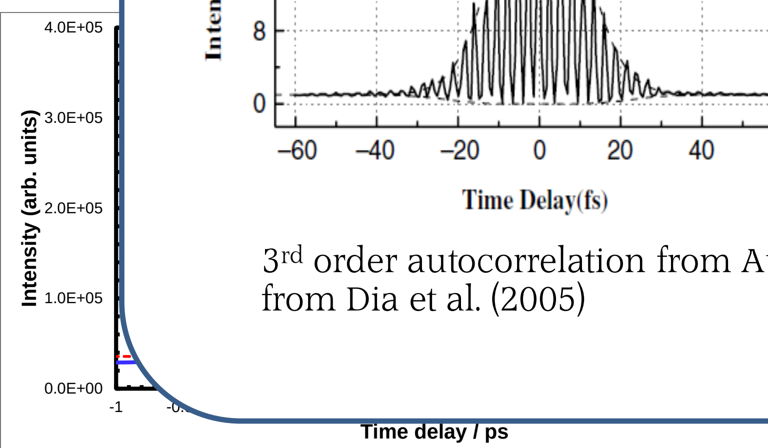
Chosen solution: surface sum/difference frequency generation



Schematic of SDFG setup



3rd order autocorrelation from Au, from Dia et al. (2005)

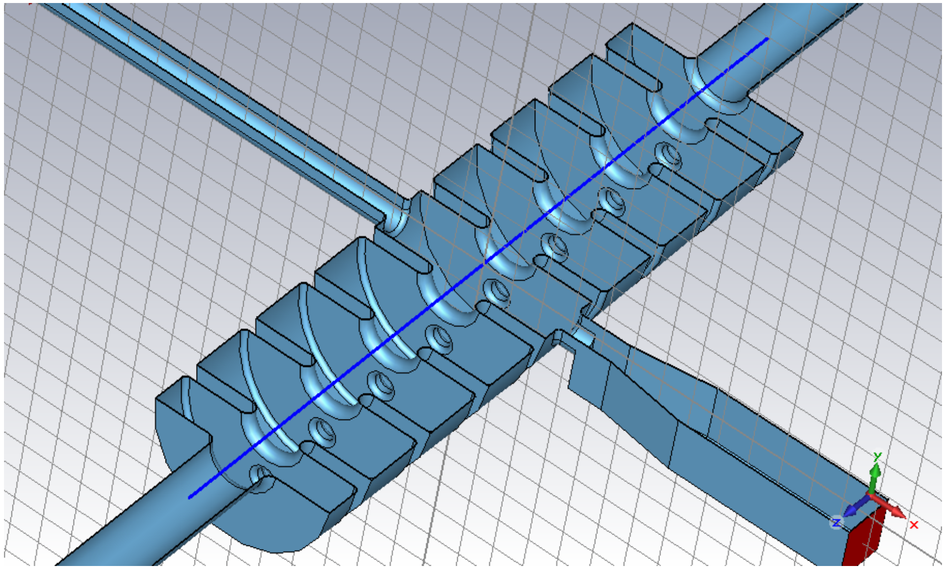


stem under development:

- characterisation of EBTF photo-injector 266 nm, ~180 fs
- e-shot amplitude/phase characterisation using)G, BBO crystal.
- acement of BBO crystal with gold mirror, repeat XFROG haracterisation.

Transverse Deflecting Cavity for VELA & CLARA

- TDC required for bunch profile measurement (40fs bunches)
- Central coupler greater ‘near mode’ separation
- Dummy port used for field symmetry and possible vacuum port
- CST used for cavity design
- Prototype developed to reduce project risk



Operating Frequency	2.9985	GHz
Bunch energy	5-6	MeV
Time resolution	10	fs
Phase stability required	0.1	deg
Operating mode	TM110-like	
Nearest mode separation	>5	MHz
Available RF power	5*	MW
Pulse length	3	μs
Repetition rate	10	Hz
Average RF power loss	<150	W

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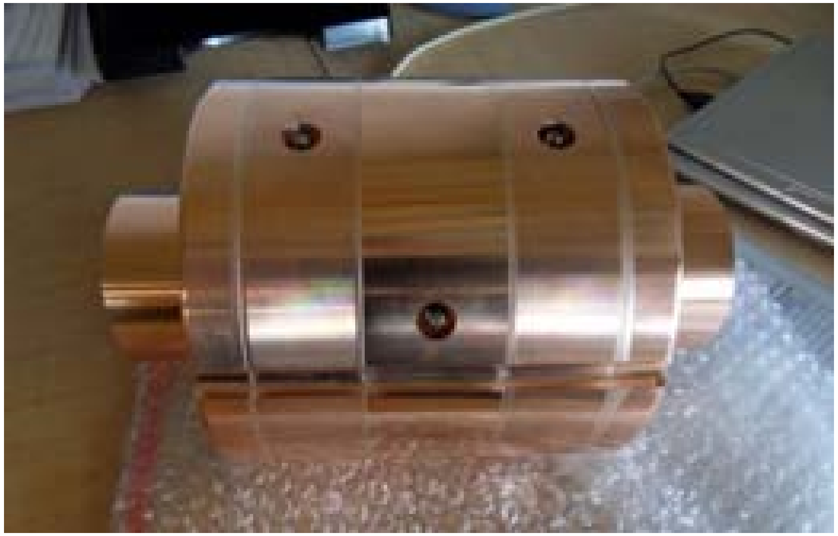
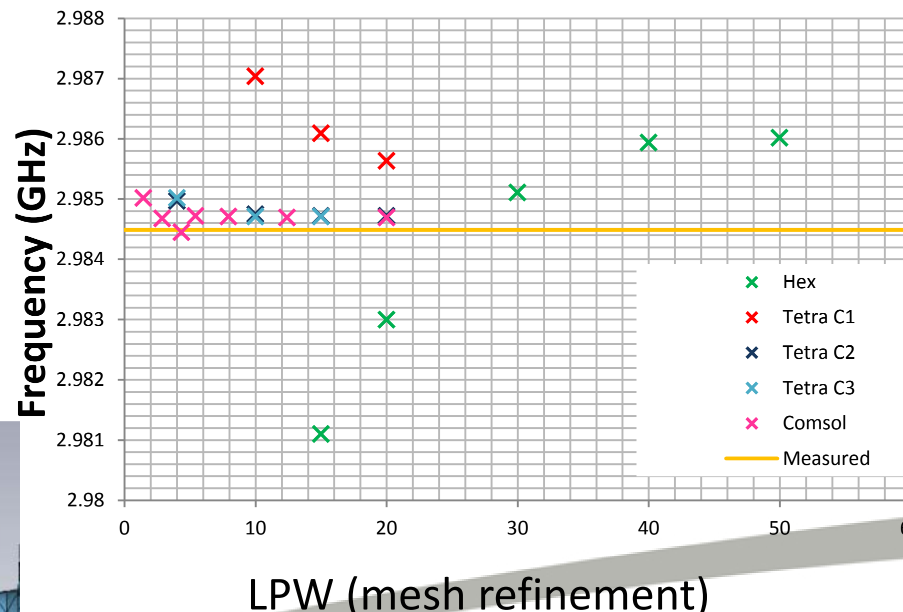
TDC Prototype Development

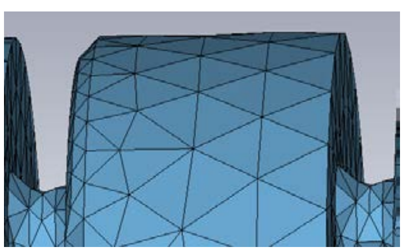
- Built by Research Instruments GmbH
- To confirm simulation technique
- To confirm braze technique/deformation
- Field flatness tuning system analysis
- Test results not as expected



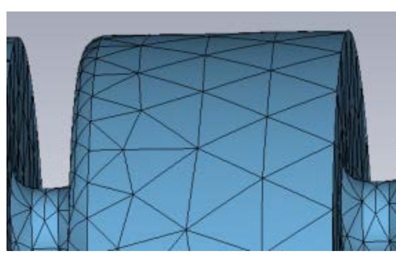
TDC Simulation Discrepancy

- Prototype cavity measured to be 2.65 MHz from simulated results
- Cut open prototype and confirmed dimensions with design
- Discovered inaccuracy using Hexahedral mesh
- CST analysis - Tetrahedral mesh 2nd order or better should be used
- Cavity was re-designed, and is currently being manufactured





First order curvature



Second order curvature

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Acknowledgments

Trina Thakker Alexander Kalinin David Dunning	Timing, Beam arrival monitors, ALICE beam correlation experiments
Stephen Buckley Philippe Goudket	Deflecting cavity
David Walsh Matt Cliffe	Spectral upconversion, amplification AEMITR & THz sources
Ed Snedden	DFG, photon diagnostics