Ultrafast lasers & THz Radiation for Accelerator Diagnostics & Beam Manipulation

S.P. Jamison
Accelerator Science and Technology Centre,
STFC Daresbury Laboratory
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 ⇒ must be single shot diagnostic
Electro-optic diagnostics

Encoding electric field temporal profiles into optical probe intensity variations

Many demonstrations...

- Accelerator Bunch profile
- Laser Wakefield experiments
- Emitted EM (CSR, CTR, FEL)

FLASH, FELIX, SLAC, SLS, ALICE, FERMI, ...
CLF, MPQ, Jena, Berkley, ...
FLASH, FELIX, SLS, ...

Few facility implementations: remaining as experimental / demonstration systems

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

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
- Higher time resolution (20fs rms for light sources, CLIC)
- Higher reliability, lower cost (high resolution systems)
- Solution for feedback.
**Electro-Optic temporal profile monitors**

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

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

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

### Spectral upconversion**
- Monochromatic optical input (long pulse)
- Spectral readout
- **Implicit time domain information only**

- Deconvolution for ~100fs resolution
- In beamline BAMs
- 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

\[ \chi^{(2)}(\omega; \omega_{\text{thz}}, \omega_{\text{opt}}) \]

\[ \omega_{\text{thz}} \rightarrow \omega_{\text{opt}} \rightarrow \omega_{\text{opt}} + \omega_{\text{thz}} \]
\[ \omega_{\text{opt}} - \omega_{\text{thz}} \]
\[ \omega_{\text{opt}} \]

\[ \widetilde{E}_{\text{out}}(\omega) \sim \widetilde{E}_{\text{in}}^{\text{probe}}(\omega) + i\chi^{(2)} \int_{-\infty}^{\infty} \widetilde{R}(\Omega)\widetilde{E}_{\text{THz}}(\omega - \Omega) \widetilde{E}_{\text{in}}^{\text{probe}}(\omega - \Omega) d\Omega \]

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)

\[ \chi^{(2)}(\omega; \omega_{\text{thz}}, \omega_{\text{opt}}) \]

\[ \omega_{\text{opt}} + \omega_{\text{thz}} \]
\[ \omega_{\text{opt}} - \omega_{\text{thz}} \]
\[ \omega_{\text{opt}} \]

EO crystal

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

This is “Small signal” solution. High field effects c.f. Jamison Appl Phys B 91 241 (2008)
\[ \tilde{A}(\omega, z) = \tilde{A}_0(\omega) e^{-z \beta_{\text{opt}}} + \frac{i}{2c\eta} e^{-z \beta_{\text{opt}}} \omega \int d\omega' A_{\text{eff}}^{\text{THz}}(\omega - \omega') \tilde{A}(\omega') , \]

**DC “THz” field...**

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

\[ \rightarrow \tilde{A}_0(\omega) e^{i\alpha A_{DC} z} \]

**phase shift (pockels cell)**

**Delta-Fnc ultrafast pulse...**

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

**temporal sampling of THz field**

\[ \int A_0 \tilde{A}_{\text{eff}}^{\text{THz}}(\omega - \omega') e^{i\omega \tau} \rightarrow A_0 A_{\text{eff}}^{\text{THz}}(t - \tau) \]

**Monochromatic THz & optical**

\[ \tilde{A}_{\text{THz}}(\Omega), \tilde{A}_0(\omega_0) \]

**optical sidebands**

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

\[ + i\alpha \tilde{A}_0(\omega_0 + \Omega) \]

**Chirped optical**

**Parameter dependent results**
Spectral or temporal measurements

\[ E_x(t) \rightarrow \tilde{E}_x(\omega) \]
\[ E_y(t) \rightarrow \tilde{E}_y(\omega) \]

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

\[ E_{\text{out}}^{\text{opt}}(t) = E_{\text{in}}^{\text{opt}}(t) + a \left[ E^{\text{Coul}}(t) * R(t) \right] \frac{d}{dt} E_{\text{in}}^{\text{opt}}(t) \]

Coulomb spectrum shifted to optical region

Coulomb pulse replicated in optical pulse

\[ \text{envelope} \quad \text{optical field} \]

- Measuring optical spectrum straightforward
- Measuring a femtosecond scale time profile more complex
- \textit{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

\[ \tilde{M}(\omega) = \int_{-\infty}^{\infty} d\Omega \tilde{E}_{\text{opt}}(\omega - \Omega) \tilde{E}_{THz}(\Omega) \]

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

Linear chirped pulse:

\[ \tilde{E}_{\text{opt}}(\omega) = A(\omega) \exp(-i\beta(\omega - \omega_0)^2) \exp(-i\omega t_0) \]

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

\[ \tau \equiv \beta(\omega - \omega_0) \]

Fourier transform form

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

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”

χ(2) optical pulse interferes with input probe (phase information retained)

\[ S_{BD}^{(\omega)} = I_{opt}^{in(\omega)} - I_{opt}^{in(\omega)} \]

\[ \propto I_{opt}^{in(\omega)} \left\{ E_{Coul}(\tau + t_0) \cdot \cos \left( \frac{\tau^2}{4\beta} - \frac{\pi}{4} \right) \right\}. \]

Deconvolution possible.

“Crossed polariser detection”

input probe extinguished...phase information lost

\[ S(\omega)^{CP} \propto I_{opt}^{in(\omega)} \left\{ \left[ E_{Coul}(\tau + t_0) \cdot \cos \left( \frac{\tau^2}{4\beta} - \frac{\pi}{4} \right) \right]^2 + \left[ E_{Coul}(\tau + t_0) \cdot \sin \left( \frac{\tau^2}{4\beta} - \frac{\pi}{4} \right) \right]^2 \right\}. \]

Deconvolution not possible [ Kramers-Kronig(?)]

Oscillations from interference with probe bandwidth ⇒ 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

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

\[ \rightarrow \delta\text{-function} \]

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

(\(\Omega\) can be < 0)

**NOTE:** the long probe is still converted to optical replica
Spectral upconversion

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

**Spectral sidebands contain the temporal (phase) information**

- Measure octave spanning THz spectrum in single optical spectrometer
  \[ 0-10 \text{ THz (} \lambda = \text{mm} - 30\mu\text{m}) \rightarrow 800\text{nm} \pm 20\text{nm} \]
- Add temporal readout as extension. (FROG, SPIDER)

**Sidebands generated by 2.0THz FEL output**

**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

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

Femtosecond laser pulse spectrally filtered to produce narrow bandwidth probe

\[ \Delta v < 50 \text{GHz} \]
\[ (\Delta t > 9 \text{ps}) \]

Followed to by NC-CPOPA & FROG

\[ \text{S.P. Jamison / JAI, Oxford, May 23, 2013} \]
Upconversion of laser driven THz source

Electric field time profile

Upconversion spectrum (optical)

Inferred Far-IR spectra

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

Far-IR spectrum

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

Upconversion spectrum (4 mm ZnTe)

Leaking probe

Up-conversion
$\sim 470$ pJ

measured E-field time profile (EO sampling)

FFT

Scaling factors

\[ \text{Energy}_{\text{upconv}} \propto \text{Power}_{\text{probe}} \times (E_{\text{field}} \times l \times r)^2 \]

\( l \) is the EO crystal length, \( r \) is the nonlinear coefficient

Example:

“Typical” nanosecond pulse laser as probe

<table>
<thead>
<tr>
<th>Property</th>
<th>Factor of improvement</th>
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</thead>
<tbody>
<tr>
<td>( \text{Power}_{\text{probe}} )</td>
<td>x36</td>
</tr>
<tr>
<td>( l )</td>
<td>( \div 100^2 )</td>
</tr>
<tr>
<td>( r )</td>
<td>( \div 2^2 )</td>
</tr>
<tr>
<td>( E_{\text{field}} )</td>
<td>x186²</td>
</tr>
<tr>
<td>Overall</td>
<td>x31</td>
</tr>
</tbody>
</table>

Pulse energy of \(~15\text{nJ}\) is produced \(1\mu\text{J}\) required for single-shot FROG pulse needs amplifying \(~100\times\) 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

\[ \phi(\omega_0) = \frac{2\omega_0}{\pi} \int \frac{\ln\{|E(\omega)|/|E(\omega_0)|\}}{\omega_0^2 - \omega^2} \, d\omega \]

Measured field-amplitude spectrum

Phase inferred through Kramers-Kronig

K-K works partially
- Retrieves trailing dip
- Incorrect sharpening of leading edge

Upconv. & KK inferred pulse
Actual pulse
Temporal measurement of Spectral upconversion

Unconverted optical probe retains temporal profile information

\[ E_{\text{out}}^{\text{opt}}(t) = E_{\text{in}}^{\text{opt}}(t) + a \left[ E_{\text{Coul}}^{\text{opt}}(t) \ast R(t) \right] \frac{d}{dt} E_{\text{in}}^{\text{opt}}(t) \]

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...

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)

- Stretching factor $10^3$ or more to prevent saturation, damage, NL effects
- BBO
  - Gain $>1000x$ ($\sim300\text{MW/cm}^2$)
- Amplified pulse then recompressed

Routinely used to produce “single-cycle” optical pulses
- Amplification with robust nanosecond pulse lasers
- High gains of $10^7$ or more
- Gain bandwidths $>100\text{nm}$ (50THz)
- Preservation of phase of pulse is possible
Laser-lab development system

(Spectral intensity and phase distortions can be both modelled and measured)

(2) Amplification

(3) Measure:
\[ \tilde{E}(\omega) = \sqrt{S(\omega)} e^{-i \varphi(\omega)} \]

(4) Calculate properties at NL crystal (to remove remaining spectral amplitude and any residual phase distortion)

in place & working

running late June

Envisaged integrated system

In beam pipe

- (1) up-convert Coulomb field
- (2) Amplification
- (3) Measure:
  \[ E(\omega) = \sqrt{S(\omega)}e^{-i\varphi(\omega)} \]
- (4) Calculate properties at NL crystal (to remove remaining spectral amplitude and any residual phase distortion)

- Commercial nanosecond Nd Laser
- Integrated frequency conversion (OPO)

- 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 $c$
- RF phase
- Aluminium thermal expansion ($23 \times 10^{-6} / \text{deg}$)

3mm path length stability

$\Delta \phi = 8 \times 10^{-5}$ rad. phase stability at 1.3GHz

$\Delta T < 0.1^\circ \text{C}$ 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

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

ASTeC Laser Master Oscillator
- 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

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

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

(Source: A. Winter, DESY)
RF spectrum of photodiode output...

$f_0 = 81.250000\text{ MHz}$

$2f_0 \quad 3f_0 \quad \ldots \quad 16f_0 = 1.300\text{ GHz}$

81.25MHz signal

1.3GHz signal

Marker
81.250063 MHz
-71.045 dBm

Span
100.000000 Hz
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

Stable RF oscillator

Mode-locked fibre laser

Error detector

PID

Free space delay

Fibre stretcher

DCF

Faraday Rotating Mirror (50:50)

Output clock signal

45° rotation

Partially reflecting Fibre Stretcher

45° rotation

Partially reflecting Fibre Stretcher for

Other links

Distribution and Stabilization

Reference for comparison

stable time here = stable time here

RF harmonic Delay Detection

**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

**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.
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.

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)
  - Effectively time sampling of waveform

Provides sub-100fs level timing information on electron bunches
  Feedback; machine stability studies; time stamping (user experiments)
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**

* Leakage in vertical plane due to pick-up geometry and spurious vertical dispersion

---

* Charge*  

* Horizontal BPM*  

* Vertical BPM*  

* FEL Output*  

---

* * Leakage in vertical plane due to pick-up geometry and spurious vertical dispersion*
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 through pre-lasing and lasing parts of pulse train.

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
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 >1000 turns.
- Revolution period is $T=55.2\text{ns}$,
- bunch charge is up to $30\text{pC}$, the bunch length is about $10\text{ps}$.

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 $\text{TEM}_{10}$-like single-cycle THz pulses

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

Electric field of a focussing $\text{TEM}_{10}$ terahertz pulse

Energy gain for 20 MeV beam
Longitudinal polarised THz pulses from Photoconductive antenna

Simple & efficient

but  Lacks temporal shaping capability

\[ \mathbf{E}(x, t) = \frac{1}{4\pi\varepsilon_0} \int d^3x' \frac{1}{R} \left[ \nabla' \rho - \frac{1}{c^2} \frac{\partial \mathbf{J}}{\partial t} \right]_{\text{ret}} \]

Transverse field from current surge

\[ \nabla \cdot \mathbf{J} \] generates charge separation

Longitudinal field implicit from \( \nabla \cdot \mathbf{E} = 0 \)

now working on nonlinear generation of longitudinal beams temporal shaping capability
AEMITR layout

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

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

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: 100 nm-250 nm, <10 fs pulse duration.

Challenges in bandwidth, phase-matching, absorption

Chosen solution: surface sum/difference frequency generation

Schematic of SDFG setup

System under development:
- Characterisation of EBTF photo-injector laser: 266 nm, ~180 fs
- Single-shot amplitude/phase characterisation using XFROG, BBO crystal.
- Replacement of BBO crystal with gold mirror, repeat XFROG characterisation.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Unit 1</th>
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<tbody>
<tr>
<td>Operating Frequency</td>
<td>2.9985</td>
<td>GHz</td>
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<tr>
<td>Bunch energy</td>
<td>5-6</td>
<td>MeV</td>
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<tr>
<td>Time resolution</td>
<td>10</td>
<td>fs</td>
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<td>Phase stability required</td>
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<tr>
<td>Nearest mode separation</td>
<td>&gt;5</td>
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<td>Available RF power</td>
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<tr>
<td>Pulse length</td>
<td>3</td>
<td>µs</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10</td>
<td>Hz</td>
</tr>
<tr>
<td>Average RF power loss</td>
<td>&lt;150</td>
<td>W</td>
</tr>
</tbody>
</table>
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

![Frequency GHz](image)
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