Investigating longitudinal bunch structure - developments at FLASH

Bernhard Schmidt, DESY-FLA
fingerprints of longitudinal structure

\begin{align*}
\text{direct} & \quad \text{charge distribution} \quad \rho(z) \\
& \quad \text{coulomb field} \quad E_r(z) \\
\text{indirect} & \quad \text{coherent radiation} \quad P(\lambda)
\end{align*}

\{ \text{time domain} \}

\{ \text{wavelength domain} \}
fingerprints of longitudinal structure

direct
charge distribution \( \rho(z) \)
coulomb field \( E_r(z) \)

indirect
coherent radiation \( P(\lambda) \)

\{ \text{time domain} \}
\{ \text{wavelength domain} \}

fluctuations from shot to shot

single shot methods preferential
charge distribution: transverse deflecting structures (TDS)

**principle of operation**

\[ \Delta y = S \cdot \Delta \zeta \]

\[ \sigma_y \Rightarrow \sigma \zeta = \frac{\sigma_y}{S} \]
some FLASH results, E~800 MeV

+ dipol magnet: long. phase space

Typical Resolution: 20-50 fs

all data courtesy M. Röhrs
TDS: formulas

\[
\sigma_y = \sqrt{\sigma_{y0}^2 + \left(2 \beta c \beta_p \frac{2\pi e V_0}{\lambda E_0} \sin \Delta \psi_y \cos \varphi \right)^2}
\]

\[
\langle S_y \rangle = \frac{e V_0}{E_0} \sqrt{\beta c \beta_p} \sin \Delta \psi_y \sin \varphi , \quad V_0 \approx \left(1.6 \text{ MV/m/MW}^{1/2}\right) L \sqrt{P_0}
\]

~ 10 m \quad \leq 1

beam energy
TDS : formulas

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\( \sim 10 \text{ m} \quad \leq 1 \)

beam energy

\( \sigma_\zeta \sim 1 \text{ mm} \)

\( S_y(s_1) \cdot \sigma_\zeta > \sqrt{\varepsilon_y \cdot \beta_y(s_1)} \)

\[ L \sqrt{P_0} > 1000 \text{ m}\sqrt{\text{MW}} \]

not usable at 450 GeV/ c !
Coulomb field: electro-optic modulation

Intra-beamline measurement of the bunch Coulomb field

- Field induced refractive index change
- Polarization-modulation of probing laser
- Temporal structure of Coulomb field → impressed to ellipticity of optical pulse
Coulomb field: electro-optic modulation

Intra-beamline measurement of the bunch Coulomb field

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signal \( \sim E_r(t) \)

for \( \gamma >> 1 \)

\[
E_r(t) = \frac{\lambda(t)}{2\pi b \varepsilon_0} = \frac{I(t)}{2\pi b \varepsilon_0 c}
\]

\( \lambda(t) \) linecharge

\( I(t) \) current

independent of \( \gamma \)!
EO: detection methods

not single shot

Scanning Delay Sampling

EO-SD

less complex
limited resolution

single shot

Spectral Decoding

EO-TD

quite complex
ultimate resolution

Temporal Decoding
courtesy S. Jamison
EO spectral decoding: sample results

- Camera background
- Background at θ = 0
- Background at θ = 2°
- Signal at θ = 2°

GaP 175 μm, σ₀ = 7 fs, σ_c = 1.5 ps

σ = 230 fs

All data courtesy B. Steffen
EO techniques, compared

Expected regime

All data courtesy B. Steffen
EO: limits of temporal resolution

crystal response functions

for $\lambda_p = 1$ mm ($f = 0.3$ THz): both crystals are fine, thick crystals preferential
ZnTe: smaller EO coefficient, pure quality
GaP: smaller EO coefficient, good quality
EO: spectral decoding

\[ \sigma_t \approx 1.1 \sqrt{T_0 T_c} \]

- \( T_0 \) compressed length
- \( T_c \) chirped length

<table>
<thead>
<tr>
<th>( \lambda_p )</th>
<th>( T_{\text{per}} )</th>
<th>( T_c )</th>
<th>( T_0 )</th>
<th>( \sigma/\lambda_p )</th>
</tr>
</thead>
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<tr>
<td>1mm</td>
<td>3 ps</td>
<td>6 ps</td>
<td>15 fs</td>
<td>0.11</td>
</tr>
<tr>
<td>1mm</td>
<td>3 ps</td>
<td>6 ps</td>
<td>35 fs</td>
<td>0.17</td>
</tr>
<tr>
<td>1mm</td>
<td>3 ps</td>
<td>15 ps</td>
<td>35 fs</td>
<td>0.26</td>
</tr>
</tbody>
</table>

- Only few periods can be covered with reasonable resolution
- Measure "modulation distribution" along bunch
- Stable synchronization (< 1 ps) required

Tough!
more rigorous simulation

$16 \text{nC with } 400 \text{ ps } \sigma_t$

$T_0 = 60 \text{ fs, } \lambda=1030 \text{ nm}$

\[ I_{\text{det}}(\theta, 0, \Gamma) = \frac{I_{\text{laser}}}{2} \left[ 1 - \cos(\Gamma + 4\theta) \right] \]

courtesy L. Wißmann

- realistic chirp
- crystal effects
- detection

• no need for thin crystals (resolution)
• thick crystals allow to detect partial modulation
EO-SD set up : what is needed?

- EO crystal in movable mount, close to beam
- short pulse laser, $T_0 < 50$ fs
- laser synchronization to beam
- pulse stretcher, conventional optics, polarizers etc.
- commercial spectrometer
- gated read-out system (ICCD or optical gating)

**typical laser system :**
TiSa oscillator, 800 nm

**new developments (DESY, PSI ..) :**
Yb fibre laser, 1030 nm

other EO methods ?
more resolution (not needed) but MUCH more complex
coherent radiation: spectrum reveals form factor

\[
\frac{dU}{d\omega} = C \ N^2 |F_{\text{long}}(\omega)|^2 T(\omega, \gamma, \theta, \text{source})
\]

\[
F_{\text{long}}(\omega) = \int_{-\infty}^{\infty} \hat{\rho}(t) \exp(-i\omega t) dt
\]

integral and indirect information on charge density

N number of particles \hspace{1cm} \text{source characteristics}

unstructured bunch with ~nsec length: no coherent radiation (f > GHz)

detection of "integral intensity" in THz regime: substructure, no further information (spike, periodic modulation, non-statistic ripples..)

spectrally resolved measurement: type of structure, but still integral

if wavelength unknown, broadband or variable: need broadband single shot spectrometer
coherent transition radiation

problems:
- long wavelength, diffraction limited
- needs „large“ optics and detectors
- dispersive elements (gratings) cover small $\Delta \lambda$
coherent transition radiation

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$\lambda = 1\text{mm}$
DESY staged grating spectrometer

5 µm < λ < 450 µm

principle

engineering

reality
DESY staged grating spectrometer - detectors

**electronics**

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**Pyroelektrischer Detektor**

Sensorzelle zur THz- und mm-Wellenlängen-Detektion

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**InfraTec**

**DESY staged grating spectrometer**

**Detectors**

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**CTR pulse**

- $\tau_r = 7$ ns
- $\tau_d = 140$ µs
- $g_1 = 1.4$ V/pC
- $g_1 = 5$ µs

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**Commercial hybrids by**

**CREMAT, Inc.**

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**Cremat’s radiation detector electronics can be used with a wide range of detectors, including semiconductor solid state detectors, scintillation detectors, avalanche photodiodes, photomultiplier tubes (PMTs), monochromatic pile detectors, and gaseous detectors (e.g., proportional counters).**

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**LiTaO$_3$ detector**

- Pre-amplifier
- Amplifier
- Shaping amplifier
- ADC
- PC

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**Workshop on Proton driven Plasma Accelerators - CERN 17./18.12.2009 Bernhard Schmidt**
DESY staged grating spectrometer - status

- extensive experience with two stage prototype
- two four stage devices set up
- few test runs with one device, summer 2009
- two will be operational after FLASH shut-down

Graph: 2nd grating combination
- data from test Sep. 09
- Intens [arb. units] vs. Wavelength [um]
DESY staged grating spectrometer - status

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existing spectrometer optimized for $\lambda < 400 \ \mu$m
change gratings, but „tight“ for $\lambda \sim \text{mm}$
? use „old“ prototype version with 1 - 2 stages ? (2x larger)
form factor modulated bunch

sensitivity of pyroelectric sensors: \( \sim 3 \text{ mV/nJ} \)
noise level: \(< 1 \text{ mV} \) (depending on integration time)
detectable: \(< 1 \text{ nJ} \) (with 4 \( \mu \text{s} \) shaping)
form factor modulated bunch

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model bunch:
long sequence of \( m \) Gaussian bunches, width \( \sigma_b \), separation \( t_p \)

\[
F^2 = e^{-4 \pi^2 f^2 \sigma_b^2} \frac{(\cos(2 \pi f (m + 1) t_p) - 1)}{(m + 1)^2 (\cos(2 \pi f t_p) - 1)}
\]

additionally:
„T-function“ for CTR, two mirrors, detector focussing

total charge 16 nC, \( t_p = 3 \text{ ps} \), \( m = 100 \), \( \sigma_{x,y} = 1mm \), \( \gamma = 450 \)
radiation intensity at detector (CTR, mirrors etc.)

strong modulation, 100 periods

enormous signal at fundamental!

if wavelength known, single stage might be enough
radiation intensity at detector - II

**strong modulation, 10 periods**

![Graph showing strong modulation with 10 periods.](image1)

**weak modulation, 100 periods**

![Graph showing weak modulation with 100 periods.](image2)
the combined approach: EO-THz-spectrometer

- use long (~100 ps) Fourier limited laser
- interaction with THz pulse in EO material
- up-convert THz frequency to optical
- use high resolution **optical** spectrometer
- side bands reveal periodic bunch structure


**FIGURE 2** Optical spectra following the interaction with a quasi-mono-chromatic $\omega = 1.5 \text{THz}$ pulse, with a peak field strength of $5 \times 10^5 \text{V m}^{-1}$, and for interaction lengths of 1 mm and 3 mm: (a) and (c) assume perfect phase matching, while (b) and (d) include phase matching as expected for ZnTe material properties. In each plot, the **dotted line** is the input optical spectrum.
EO-THz-spectrometer demonstrated

could be simple and reliable set-up
no "close to beam" crystal, could use focused CTR
no short-pulse laser required
especially suited for periodic signals
summary

- the problem to detect the mm substructure is solvable
- different experimental techniques applicable
- nothing from the shelf, may be OTR + streak camera?
- no „obvious show-stoppers“ expected

Thanks for attention
The Flash: Rebirth

2010

The Mystery of the Seventh Miracle

DC

First Issue

S. FLUSH

3.9 GHz

Bernhard Schmidt