Longitudinal Diagnostics for FELs
Rasmus Ischebeck, Paul Scherrer Institut
Longitudinal Diagnostics for Free Electron Lasers

> **Time Domain Methods**
  > Conversion to electrical signals
  > Cross-correlation with external laser in medium
  > Streak Cameras

> **Spectral Methods**
  > Spectrometers with 1,4…N channels
  > Autocorrelation of the radiation (Fourier transform spectroscopy)

> **More Methods**
  > Optical Replica Synthesizer
  > Measurement of multiple ionization ratio
  > Correlation in the spectral content of incoherent radiation
  > FROG of visible radiation
Use the Coulomb Field of the Bunches

> Ultra-relativistic bunches have a field that is purely transverse to the direction of motion
> The field can be probed besides the beam axis
  > Electrical pickup
  > Direct pickup
Generate Radiation from the Bunches

> Transition radiation

> Diffraction radiation

> Synchrotron / edge radiation

> Undulator / FEL radiation
Wakefields

> Signal picked up near a beam in a storage ring

-4° angle of λ/2-plate
5.3 mm distance from beam

16% modulation in peak

wake fields

bunch

Very high single bunch current for ANKA 2.97 mA = 1.1 nC

16% modulation in peak

Time delay controlled with a vector modulator in steps of 500 fs
Wakefields

> Improved setting of waveplates

14–Mar–2013 03:40:17 – 1.3 GeV – 2.36 mA
Radiation Generated by the Bunches

> Coherent <-> incoherent radiation

As electron bunches collide with a metallic foil, optical transition radiation is emitted. Looking at the spectral content of this radiation we can determine bunch length.

- Bunch length measurement
  - possible in coherent and incoherent domain

Bunch length measurement using visible OTR

- OTR Spectrum
  - Invariant coherent spectrum
  - Variant incoherent spectrum

\[
N = 6.25 \cdot 10^7 \text{electrons}
\]
**Measurement of Electrical Signals**

> Measurement at the PSI Proton Cyclotron

> Time-to-amplitude converters good for time resolution down to about 30 ps
Cross–Correlation Techniques

> Cross–correlation with an external laser pulse
  > Pockels effect allows to cross–correlate coherent THz fields with laser
  > Reflectivity change allows to cross–correlate X–rays with laser

> Measure:
  > Bunch arrival time
  > Bunch length
Pockels Effect

> Also known as “Electro–optical effect”
> Electric field induces birefringence in crystal
> Birefringence can be probed with a polarized laser
> Pockels Effect can probe down to time scales of 10…100 fs
> Effect is totally reversible
> Possible materials
  > ZnTe
  > LiNb
  > GaP
X-Ray Induced Reflectivity Change

> Index of refraction is changed by X-rays

Sundaram and Mazur Nat. Mat. 1 217 (2002)
Measurement of Bunch Arrival Time

> Arrival time signal generated at pickup is transferred onto an electro-optical modulator

![Diagram of bunch arrival time measurement system]
Measurement of Longitudinal Bunch Profile

- Need a faster pickup (~THz)
- Direct sampling of transverse fields
- Coherent edge / synchrotron radiation (CSR)
Measurement of Longitudinal Bunch Profile
Measurement of Longitudinal Bunch Profile

![Graph showing EO Signal vs. Time with various settings and options for camera, motor, VM & timing, laser status, background, and reference.]

- **Data Path**: /afs/psi.ch/intranet/FIN/Data/FIN250-Phase3X/201
- **Time Steps**: 1
- **Samples / Time Step**: 10
- **Step Size**: 1
- **Start Position of**: -2312
- **Current Position**: -2312
- **100% Start/Save**
- **Abort**

**Region of Interest**
- **100**
- **450**
- **Start Position of**: -2392
- **n VM**: 20
- **d VM**: 30

**Calibrated**
- **r.m.s fit**: 1.9975 ps
- **FWHM**: 4.854 ps

**Status and Error Messages**
- No Error

- **Charge**: 172.5171pC
- **Orbit X**: 0.009mm
- **Orbit Y**: 0.1355mm
- **Crystal in (40.5mm)**

![Control panel with liveview settings, x-axis and y-axis controls, current axis mode, and additional options for background and reference.]
Measurement of Arrival Time

Schorb et al., App. Phys. Lett. in production
Encoding Techniques

> Spatial encoding
  + Easy to set up
  - Need imaging setup

> Spectral encoding
  + Easy to set up
  + Insensitive to transverse inhomogeneities and jitter
  - Resolution limited by Fourier limit

> Temporal encoding
  + Very high resolution possible
  - Complex setup
  - Need high laser power
Streak Camera

> Radiation generates photoelectrons from a photocathode
> Accelerated electrons are swept transversely by sweep electrodes
> Detection of photoelectrons with a 2-dimensional sensor
> Achievable resolution: ~300 fs FWHM
Streak Camera

- Bunch length at BC2 was measured.
- BC3 was bypassed.
- S-band phase was shifted to change the bunch length.
- Each figure shows 50-shot integrated image.
- Bunch length of < 1 ps (FWHM) was obtained.
Examples of Synchroscan Streak Camera Measurements (by M. Ferianis, ELETTRA)

Four Bunch Mode – Stable Beam

Multi-Bunch Mode – Stable Beam

Four Bunch Mode – Unstable Beam

Multi-Bunch Mode – Unstable Beam
Terahertz Streak Camera

- THz pulse generated in LiNO₃ by tilted wavefront method
- THz pulse characterized on-target using EOS
- EOS also establishes spatial and temporal overlap of THz pulse with NIR probe
- Use NIR probe to find coarse temporal overlap with XUV
- Block probe and use THz pulse to streak XUV induced photoemission
• All single-shots displayed for timescan #56
• Interaction in Helium (isolated line)
• 0.3nC bunches; ~260eV; ~10µJ/pulse
Direct Streaking of the Electron Beam

- Requires integrated transverse field of several MV
- Use transverse deflecting RF structure, powered by klystron
- Two-dimensional measurements possible

![Image of electron streaking apparatus with label 10 ps]
2-Dimensional Measurements

> More examples of 2-dimensional measurements

## Comparison of Time Domain Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Bunch length</th>
<th>Arrival time</th>
<th>Limitation</th>
<th>Invasiveness</th>
<th>Additional Advantages</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Signals</td>
<td>≳ 30 ps</td>
<td>≳ 30 ps</td>
<td>Pickups, cables</td>
<td>: — )</td>
<td>2–d measurements</td>
<td>[1]</td>
</tr>
<tr>
<td>Cross-Correlation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>THz / Pockels effect</td>
<td>≳ 30 fs</td>
<td>≳ 5 fs</td>
<td>Absorption in crystal</td>
<td>: — )</td>
<td></td>
<td>[2]</td>
</tr>
<tr>
<td>X–rays / reflectivity</td>
<td>—</td>
<td>≳ 10 fs</td>
<td>Thermal processes</td>
<td>: — )</td>
<td></td>
<td>[3]</td>
</tr>
<tr>
<td>Streak Cameras</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GHz streaking (cathode)</td>
<td>≳ 300 fs</td>
<td>≳ 1 ps</td>
<td>Streak frequency</td>
<td>: — )</td>
<td></td>
<td>[4]</td>
</tr>
<tr>
<td>THz streaking (gas)</td>
<td>≳ 35 fs</td>
<td>≳ 5 fs</td>
<td>Gas target</td>
<td>: —</td>
<td></td>
<td>[5]</td>
</tr>
<tr>
<td>Direct streaking</td>
<td>≳ 8 fs</td>
<td>≳ 100 fs</td>
<td>Streak field, Profile monitor</td>
<td>: — (</td>
<td>2–d measurements</td>
<td>[6]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>resolution, Optics</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Spectral Methods

> Spectrum is the Fourier transform of the longitudinal form factor
  > Measurement of the spectrum can be used to infer bunch length
> But: typically, phase information is lost
  > Reconstruction possible if the complete spectrum is measured
  > Use as relative monitor

> Varying complexity:
  > Single channel
  > 3 channels
  > 5 channels
  > 120 channels
1-Channel “Spectrometer”

- Need shot to shot non-invasive bunch length monitor.
- Diffraction aperture and broadband (pyroelectric) detector.
1-Channel “Spectrometer”

Relative Bunch Length Monitor

Pyroelectric detector good from 100GHz to light (response is not flat)

Si window transmits from mm-wave to ~1 micron.

Can also use mm-wave diodes for BC1 (< 1 THz)
The bunch length observed with the CSR monitor was calibrated by using the RF-deflector’s data.

- Electron beam was bypassed through BC3.

- Bunch length was changed by the RF phase of the S-band accelerating structures.

- Estimated bunch length measurement sensitivity is about 6% at a bunch length of 170fs.
CSR intensity was linearly changed by the RF phase of the C-band (5712 MHz) accelerating structure before BC3. Estimated bunch length measurement sensitivity is less than 0.1 deg., which is better than that of the RF deflector.
4-Channel ‘Spectrometer’
4-Channel ‘Spectrometer’

Normalized signals from pyros with different filters

Pyro signals compared to expected response
5–Channel Spectrometer

- Coherent transition radiation from a fluorescent screen is detected.
- By using a cut off of a rectangular waveguide, this works as a single-shot spectrometer.
- In the injector part, about 10 GHz rf signal is obtained.
  - Bunch length ~ 100 ps
5–Channel Spectrometer

Accelerating voltages of 238MHz sub-harmonic buncher cavity was scanned. (476 MHz booster was turned off.)

- The signal strength has a correlation with the bunch length.
  - Consistent with 1D simulation
  - Amplitude and phase of the sub-harmonic cavities can be determined
120–Channel Spectrometer

- Five consecutive gratings as prefilter and dispersive devices
- Wavelength coverage from 5.5 to 440 µm with two sets of gratings
  - Set one: 5.5 to 44 µm
  - Set two: 44 to 440 µm
- One order of magnitude in λ for four gratings
- Parallel readout of 120 channels for one set of gratings
120-Channel Spectrometer

- Formfactor with reconstructed temporal profile
- CRISP4

<table>
<thead>
<tr>
<th>Wavelength [µm]</th>
<th>Current [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRISP4 141m</td>
<td></td>
</tr>
<tr>
<td>CRISP4 202m</td>
<td></td>
</tr>
</tbody>
</table>

- Time [fs]
- Current [A]

- E.Hass (University of Hamburg)
Autocorrelation of the Radiation

> Autocorrelation is the Fourier transform of the form factor

\[ \sigma_z = 9 \ \mu m \]
Autocorrelation of the Radiation

Example of Martin-Puplett Interferometer (installed behind FLASH Synchrotron Radiation Beamline)

Example of Martin-Puplett Interferometer (installed behind FLASH Synchrotron Radiation Beamline)

- PG - polarizing grid
- BDG - beam splitter grid
- FRM - fixed roof mirror
- MRM - movable roof mirror
- PM2 - parabolic mirror
- AG - analyzing grid
- VDET - pyro-detector for vertical polarization
- HDET - pyro-detector for horiz. polarization

courtesy of Lars Fröhlich, DESY
Autocorrelation of the Radiation

SLS FEMTO Bunch Slicing - Turn-by-Turn Bunch Length Evolution III
Interferograms from 5 consecutive turns after slicing


Spectral Intensity of Turn 0 (Theory and Experimental Data)

Bunch Lengths Evolution after Slicing in SLS Storage Ring
## Temporal vs Spectral Methods

<table>
<thead>
<tr>
<th>Temporal Methods</th>
<th>Spectral Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute determination of bunch length and shape</td>
<td>Easy to set up</td>
</tr>
<tr>
<td>2-d measurements possible</td>
<td>Very sensitive to bunch length changes</td>
</tr>
<tr>
<td>Allow to measure arrival time</td>
<td>Robust setup allows for feedbacks</td>
</tr>
<tr>
<td>Require an external reference</td>
<td>Methods become easier for shorter bunches</td>
</tr>
<tr>
<td><strong>Temporal Methods</strong></td>
<td><strong>Spectral Methods</strong></td>
</tr>
<tr>
<td><strong>Spectral Methods</strong></td>
<td></td>
</tr>
<tr>
<td>Phase reconstruction methods require graduate students</td>
<td></td>
</tr>
</tbody>
</table>
Thank you for slides, graphics, photos and plots provided by:

- Vladimir Arsov
- Adrian Cavalieri
- Marta Divall
- Rudolf Dölling
- Joe Frisch
- Christopher Gerth
- Eugen Hass
- Nicole Hiller
- Hirokazu Maesaka
- Yuji Otake
- Peter Peier
- Eduard Prat
- Volker Schlott
- Bennie Smit

Slides available at: http://people.web.psi.ch/ischebeck