Coherent Radiation Diagnostics for Short Bunches

Bunch length measurement in the frequency domain

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The **longitudinal charge distribution** is an important parameter for machine operation...

...and difficult to measure (non-destructively) for short and/or complicated bunches.

**Example for CRD at FLASH (FEL at DESY)**

...also used at ALS, ANKA, BESSY, JAERI, NewSubaru, LCLS, SLS, UVSOR-II, ...
Illustration of basic principle of CRD

Single electron synchrotron radiation spectrum

Circular motion, 130 MeV, R=1.6 m
Gaussian (line) bunch

FWHM = 350 µm

Charge 1 nC
**Spiked bunch**

FWHM = 70 µm
Spiked bunch
FWHM=40 μm

Normalized charge density
Basic relation of CRD

Emission spectrum depends on *longitudinal* charge distribution.

Transverse effects exist, not covered

**Double Gaussian Bunch**

FWHM=350 µm, Δ=600 µm

\[
\frac{dU}{d\lambda} = \left( \frac{dU}{d\lambda} \right)_1 \left( N + N(N-1)|F(\lambda)|^2 \right)
\]

\[
F(\lambda) = \int S(z) e^{\frac{2\pi iz}{\lambda}} \, dz
\]
Bunch compression monitor

Transition/Diffraction Radiator

Electron beam

Infrared radiation

Detector

Phase/compression scan

Graph showing detector signal (a.u.) vs. Phase (deg):
- Synchrotron radiation
- Transition radiation

Graph showing detector signal (a.u.):
- 'Maximum compression'
- 'Initial width'
- 'Operating point Feedback'

Accelerating module

Gun

Bunch compressor
Compression monitor feedback on phase

SASE intensity
Diode detector as bunch compression monitor

Ceramic gap

Phase scan

**Phase Ramp (degrees)**

- **100GHz A**
- **100GHz B**
- **23GHz**

**BLU signal**

**Courtesy J. Frisch, SLAC**

**VDI Model: WR3-AZBD**

- tunerless design
- no bias required
- NEP: 1E-10 W/Hz^0.5 (typ.)
- TSS: 44 dBm (typ.)
- TSS measured with 20 kHz video bandwidth

Contact VDI today for specifications and quotation details.
Pyroelectric detector

--- room-temperature ---

Absorption of radiation

\[ \rightarrow \text{Conversion into temperature variation} \]

\[ \rightarrow \text{Conversion into polarization (pyroelectric effect)} \]

\[ \rightarrow \text{Detection of charge/current/voltage} \]

\[ I(t) \]

\[ U(t) \]

\[ J(t) \]

\[ \approx 2 \text{ mm} \]

\[ \approx 20-100 \mu \text{m} \]

Piezoelectric vibrations

Frequency depends on crystal size

Etalon interferences

Fit: \( d_{\text{LiTaO}_3} = 98.5 \mu \text{m} \)

\( d_{\text{Chrome}} = 13.7 \text{ nm} \)

Responsivity (V/\( \mu \text{J} \))

Wavelength (\( \mu \text{m} \))
Pyros are intrinsically fast

Heating of pyro
($\tau_{\text{thermal}} \approx 100 \text{ ms}$)

...even very fast!


600 bunches at FLASH
Pyrocam

Transition radiation at FLASH

Spiricon pyroelectric camera (LiTaO$_3$)
124x124 pixels, 100 μm pitch
7 nJ per pixel noise limit
Fast superconducting hot-electron bolometer

Log-spiral antenna receiver

Approximately 10 μm

Resistance

Normal state

Superconducting state

Resistive transition region

Temperature

Gain [rel. units]

Wavelength [μm]

Photoresponse signal (mV)

Simulation

Main pulse

First reflection

Initial rising edge (arbitrary units)

Time (100 ps/div)

Courtesy H.-W. Hübers, DLR Berlin
FLASH synchrotron radiation beamline

For experimental studies, an accessible laboratory outside of the accelerator confinement is mandatory.
Bunch reconstruction

through inversion of

\[
\frac{dU}{d\nu} = \left( \frac{dU}{d\nu} \right)_1 \left( N + N(N-1)|F(\nu)|^2 \right) F(\nu) = \int S(t)e^{2\pi i\nu t} dt
\]

 Courtesy L. Fröhlich, DESY
The reconstruction procedure

\[
\left( \frac{dU}{d\nu} \right)_{\text{measured}} \Rightarrow \frac{dU}{d\nu} \Rightarrow |F(\nu)| \Rightarrow F(\nu) \Rightarrow S(z)
\]

- Beam line transmission, instrument response
- Single-electron spectrum, bunch charge
- Phase reconstruction
- Inverse Fourier transform

Complex form factor \[ F(\nu) = |F(\nu)|e^{i\Theta(\nu)} \]

Kramers - Kronig relation (phase retrieval) \[ \Theta(\nu) \geq \frac{2\nu}{\pi} \int_{0}^{\frac{\nu}{\sqrt{\nu^2 - \nu'^2}}} \ln \left( \frac{|F(\nu')|}{|F(\nu)|} \right) d\nu' \]
Synchrotron radiation is a complex source...

Measurement ($\lambda=155 \mu m$)

Simulation using UTD

Uniform Theory of Diffraction = geometrical optics + diffraction

• Edge effects
• Shielding

Poster Friday: FRPMN015

Courtesy A. Paech, TU Darmstadt
FLASH transition radiation beamline

Diamond window

CTR screen

M1

M2

18.6 m

M3

M4

Final focus

(flat mirrors not shown)

---

Advantage of vacuum+diamond

Transmission (calculated)

Frequency (THz)

300 GHz/1 mm

Experimental data

Signal

Wavelength (μm)

quartz window & 1.5 m air

x 10

Courtesy B. Schmidt, DESY
Single shot grating spectrometer

Based on staged blazed gratings

Efficiencies
(from GSolver, vertical polarization)

Zeroth order
First order

Courtesy H. Delsim-Hashemi, DESY
Phase scan

Good starting point for SASE tuning

Courtesy
H. Delsim-Hashemi, DESY
Correlations

Fluctuations over 50 seconds of stable SASE run

Anti-correlation!

Courtesy H. Delsim-Hashemi, DESY
Spatial Electro-Optical Auto-Correlation Interferometer (PSI)

- Interferometer images coherent transition radiation onto electro-optic crystal
- Spatial auto-correlation pattern read out by Nd:YAG laser using cross polarizer scheme and linear image sensor
- Single shot bunch length monitor providing ~200 fs resolution

![Diagram of Spatial Electro-Optical Auto-Correlation Interferometer](image)

**Measurement at SLS pre-injector LINAC**

- [Graph showing bunch length vs. pre-buncher phase](image)

Courtesy V. Schlott, PSI
**FLASH infrared undulator**

Electromagnetic undulator, tuneable 1-200 µm (at 500 MeV)

The same bunches generate SASE and infrared radiation (naturally synchronized)
Smith-Purcell radiation measurements

Results of a run at 28.5 GeV from SLAC are currently being analyzed.

see PRST 9,092801 (2006)

Courtesy G. Doucas, V. Blackmore, Oxford
Summary

- **Longitudinal bunch shape investigations** using coherent radiation are a *standard tool* for all machines operating with short bunches or bunch features (slicing).

- **Standard tools** employ *non-calibrated* devices.

- Full longitudinal charge profile reconstruction is a *specialist application* (thesis level…).

- Additional benefit from *wide wavelength coverage* in a *single-shot manner* — comes at the price of higher *hardware complexity* (vacuum, diamond window, optics).

*Thanks very much for the kind help of many colleagues who provided material (of which I could not cover everything, sorry!) or advise!*
Phase retrieval – Kramers-Kronig relations

Generally, Kramers-Kronig relations result from an expression

\[ \text{Response} = \text{Stimulus} \times \text{Response function} \]

and connect the real and imaginary part of the response function.*

--- Formal relation ---

\[
\langle E(\nu) \rangle = E_1(\nu) \left( \sum e^{2\pi i \nu \Delta t} \right)
\]

\[
= E_1(\nu) \int NS(z) e^{\frac{2\pi i \nu z}{c}} \, dz
\]

\[
= N F(\nu) E_1(\nu)
\]

--- Conceptual picture ---

(for synchrotron radiation)

Laboratory system

Bunch moves through static magnetic field

Bunch emits coherent synchrotron radiation

Co-moving system

Bunch irradiated with electromagnetic wave

Bunch responds according to its response function

Check concept with Lorentz-Transformation of static field etc.

Where is the connection between phase and magnitude?

**Original time dependent signal**

(=0 for t<0)

**One Fourier component**

**Signal if this component is removed**

(≠0 for t<0)

**Conclusion:** The phases must be automatically adjusted (e.g. by a filter) such that signal=0 for t<0.

From: John S. Toll,