Diagnostics for X- and XUV-FELs

- diagnostics specific for single pass FEL
- especially demanding areas, new developments

- no photon diagnostics
- personal perspective

Bernhard Schmidt
The case for diagnostics

FEL power depends **exponentially** on beam parameters (peak current, emittance...)

Measure, control and stabilize beam parameters such that optimum FEL performance is achieved

“a single pass FEL is a non-forgiving machine” (S.R.)

Slow : human experience
Fast : intra-bunch feedback for SC machines
Bunch compression for high peak currents has non-linear components → complex phase space distributions

Very demanding parameter control!

Phases < 0.01°
Fields < 10⁻⁴ ....

Expected long. Bunch shape at LCLS, ‘double horn’ due to wake fields

Only fraction of the total charge will ‘lase’, diagnostic has to be sensitive to this fraction

Courtesy: Paul Emma

Courtesy: M. Dohlus
Including coherent effects: CSR & space charge

FLASH, nonlinear compression
S2e simulations, Martin Dohlus, Thorsten Limberg

Projected parameters are of limited use!
Diagnostics has to reveal details of the bunch structure...
slice emittance, bunch profile, slice energy spread, bunch position
The ideal diagnostics

- ultimate resolution
- comprehensive
- immediate feedback on single bunch
- non-invasive

.. will remain a dream

Status and perspectives of a few key technologies
Warm sections - Cold sections (XFEL) - Undulators

Resolution:

- 10 µm, resonant stripline, button
- "workhorse"
- << 1 µm for 1 Å

Similar developments in Italy (ELLETRA) (P. Craievich et al., THPPH025) and Japan (Spring8) (T. Shintake, MOBAU05)

Cavity BPM's

**LCLS (SLAC, ANL)**
- 8.26 GHz, X-band
- Goal: < 100 nm/nC
- H. D. Nuhn et al
  - THBAU02

**XFEL (PSI, DESY)**
- 4.38 GHz, C-band
- Goal: << 1 µm/nC
- D. Noelle et al
  - THPPH014

Challenge: design, fast signal processing, mechanical precision, alignment and stability..
BPM-2, specialities

Beam induced HOM in SC cavities for BPM

Complex ‘spectrum’ of different modes depends on beam position and angle

Expected: resolution ~1 µm

System Test at FLASH (J. Frisch, N. Baboi, M. Ross,..)

Achieved ~ 7 µm res.

+ beam angle + timing

Large aperture BPM inside BC chicane

Example:
ΔE: 10^{-4}
Δx: 35 µm
Δt: 60 fs

Energy feedback needed

Resolution required
Δx: ~ 5 µm
Δt: ~ 15 fs

Optical detection seems feasible

Courtesy: K. Hacker (DESY)

TUPPH054

Alternative: image SR in the UV range from chicane dipole (C. Gerth, THPPH011)
Arrival time monitors

Pick up (ring electrode)

Resolution
direct electrical mixing: ~ 300 fs
Electro-optic: ~ 30 fs demonstrated (EPAC, talk by F. Löhl)

Caveat: center of charge!

Flash, 30 bunch trains

First bunch
Last bunch

2% ACC1 power

Courtesy: F. Löhl (DESY)
Transverse deflecting cavities (TCAV)

• Adds z-position dependent transverse kick to bunch
• Phase advance to screen $\rightarrow$ vertical streak of longitudinal bunch structure

![Diagram of TCAV](image)

adding fast horizontal kicker $\rightarrow$ streak image on off-axis screen

- single bunch capable
- not multi-bunch capable
- ‘semi-parasitic’ (sacrifice 1 bunch)
- slow read out (imaging)

Resolution depends on cavity power, beam energy and machine optics
TCAV installation at FLASH

- $E_0 = 600 \text{ MeV}$
- $\sqrt{\beta_c \beta_s} = 50 \text{ m}$
- $\Delta \psi = 18^\circ$

- $\nu_{HF} = 2.856 \text{ GHz}$
- $\lambda_{HF} = 105 \text{ mm}$
- $L = 3.66 \text{ m}$
- $V_{eff} = 25 \text{ MV}$
- $P_{HF} = 18 \text{ MW}$

Bunch head distorted by space charge & CSR effects

Typical Resolution: 20-50 fs

$Q_{\text{spike}} = 0.230 \pm 0.016 \text{ nC}$

$\Delta t_{\text{spike}} = 132.8 \pm 8.3 \text{ fs (FWHM)}$
TCAV for slice emittance and slice energy spread

- Longitudinal slices of 250um or 154fs

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- Horizontal emittance

(apparently too large for lasing !!)

slicing >> width of spike(s) ➔ “projected” emittance

courtesy: M. Röhrs
Electro - Optic (EO) Techniques

Intra-beamline measurement of the bunch Coulomb field

- Field induced refractive index change
- Polarization-modulation of probing laser
- Temporal structure of Coulomb field \(\Rightarrow\) impressed to ellipticity of optical pulse

Limitations:
- high frequency cut-off due to finite distance to beam
- velocity mismatch of FIR and optical propagation in EO crystal
- phonon resonances of EO material
Limiting factors

High frequencies get close to beam, especially for low energy beams.

High frequencies thin GaP crystals small signals.

Graphs showing the relative field strength for different crystal thicknesses and frequencies.
Decoding the probing laser pulse

- Scanning Delay Sampling
- Spectral Decoding
- Spatial Decoding
- Temporal Decoding

scanning technique NOT single shot inadequate if jitter \( \geq \) pulse lengths

different complexity and resolution

Courtesy: Giel Berden (FELIX), Bernd Steffen (DESY)
Spectral decoding

Optical pulse:
\( \Delta \lambda \) 60-80 nm, chirped to 1-2 ps
nJ energy (oscillator)

Read out:
Polarizer + gated CCD camera
Rep. Rate: Hz

Structures ~ 300 fs
Centroid of spike ~ 50 fs

pro:
Relatively simple set up
No high power laser

contra:
Resolution intrinsically limited due to frequency mixing between FIR (E-field) and Optical (probe pulse) fields
Broadening & artificial structures

Application:
Spike arrival time, coarse features

Future developments:
multi - bunch capability with fast read out (line detector)
Online monitor with simplified robust laser system (fibre laser)
Optical pulse:
$\Delta \lambda$ 60-80 nm, SHORT
nJ energy (oscillator)

Read out:
Polarizer + gated camera
Rep. Rate Hz

pro:
Moderate laser power
No methodical limitations

contra:
Relies on spatially uniform EO material
Needs complex optics and imaging system inside accelerator

Data from
SLAC-FFT (A. Cavalieri et al.)

fwhm ~270 fs

Similar experiment at FLASH with GaP, ~100 fs resol. achieved
(Armin Azima et al.)
Optical pulses:
$\Delta \lambda$ 60-80 nm, stretched to few ps, nJ energy
+ short pulse, several $\mu$J energy
Read out:
Optical SH generation in non-colinear geometry
Imaging with intensified CCD
Rep. Rate Hz

pro:
No methodical limitations
Superior resolution demonstrated (so far)
contra:
High power laser system (amplifier)
Needs complex optics and imaging system inside accelerator

Data from: FLASH
Giel Berden (FELIX)
Steve Jamison (Daresbury)
Jonathan Philips (Aberdeen Dundee)
Bernd Steffen (DESY)
et al.
EO-TD online, raw data
Optimal SASE compression

- time jitter not removed

EO-TD compared with TCAV data
(jitter removed off-line)
Over-compressed beam

DESY - FLASH, Courtesy Bernd Steffen et al.

EO movies

Two adjacent bunches!
Make the electrons radiate ... coherently

**spectral energy density**

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

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

- integral intensity
  - 'compression factor', effective bunch length
- spectral resolved intensity
  - + bunch structure, 'longitudinal fingerprint'

source characteristics (CSR,CTR,CER,CDR,SP..)
Wavelength range of relevance

Experimental data

Depending on compression scheme, 1 - 200 µm
Coherent effects create spectral substructure
Micro-bunching can produce ~ few µm coherent radiation

Technical implications

• CDR problematic at low beam energies, short wavelength cut off
• CVD diamond windows to accelerator vacuum
• NO radiation transport in (humid) air
• Broad wavelength range to cover, SINGLE SHOT
Bunch compression monitors

The ‘classical’ compression monitor

- integral intensity, > 100 µm
- overall compression strength
- robust, simple, workhorse

The ‘advanced’ compression monitor (EPAC, H.Delsim-Hashemi)

- wavelength specific intensity (bands)
- reveals ‘long. features’ of the bunch
- complex, still experimental

ABCM phase scan (FLASH), CTR
single bunch kicked from train

Cryst. Quartz
Classical: Michelson type interferometers
- scanning devices, no single shot
- complex unfolding procedure (autocorrelation function)

Single shot spectrometers:
dispersive elements & multichannel detector

Transmission Gratings
- can have large free spectral range (1 decade)
- limited to $\lambda > 50$ $\mu$m
- poor dispersion efficiency (~15%)

Reflective Gratings
- small free spectral range (< 1 octave)
+ any $\lambda$
+ high dispersion efficiency (> 90%)
Single shot multichannel detectors?

Requirements:

- fast, 200 ns for XFEL bunch spacing
- uniform spectral response
- broadband (1 µm - 1mm)
- robust?

Recent development at DESY

Pyro-electric line detector
- + 30 channels
- + room temperature
- + no window, works in vacuum
- + fast read out
- + sensitivity ~ 300 pJ (S/N=5)
- + smooth response function (suppressed resonances)

Various new ideas, benefit from IR-astronomy

HgCdTe array?

Hot electron bolometer array?

+ commercial
+ fast
+ sensitiv
- cryogenic
device
- very expensive

Courtesy: QMC Inc.
Single Shot CTR spectra - transmission gratings

1 bunch from 30 bunch train
kicked to off-axis screen

Small fluctuations
Strongly peaked at short wavelengths

700 single shot spectra, 50 - 350 µm

Two gratings cover 40 µm - 1.5 mm range

H. Delsim-Hashemi et al. THPH018
Single shot spectra - reflective gratings - short wavelengths

Scanning ACC1 phase, 5 - 8 µm

More structure, more fluctuations
NO distinct phase regimes
No clear spectral shape, spikes
More compression - more spikes
Microbunching of bunch structure
produce CTR @ ~ 20 µm

Short wavelength single shot spectra: "fingerprint" of bunch structure
Corresponds to ~70 fs spike length

S&E simulation M. Dohlus

preliminary very recent stuff
outlook: the optical replica system

Proposed by Saldin, Schneidmiller, Yurkov: NIM A 539 (2005) 499

“seed” the bunch with optical wavelength
cause coherent emission of light pulse in radiator that mimics the longitudinal shape of the electron bunch (optical replica)
analyse the optical pulse by FROG system (fs resolution)

+ powerful diagnostic instruments exist for optical pulses (FROGS, Grenouilles ..)
  + direct ‘image’ of longitudinal structure with fs resolution
- needs “heavy” infrastructure (high power laser two undulators, beam transport..)
  - tricky spatial - temporal alignment of laser pulse and bunch

Installation at FLASH in 2007
DESY - Univ. Stockholm - UU/ISV collaboration
N. Javahiraly et al. TUBAU05

FIR Undulator VUV Undulator Off-axis screen Radiator Modulator Laser
Grenouille Chicane for ORS and tagging
Summary?

Diagnostic at the fs / μm scale is a challenging and fascinating business

Thanks to all who have contributed material and other input to this talk..