Comparative Measurements between CRISP and LOLA-TDS at 13SMATCH.

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on behalf of

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Overview.

> Introduction CRISP
> Coherent Radiation Diagnostics
  • Frequency domain
  • Reconstruction into time domain
> Transverse Deflecting Structure
  • Two Point Tomography
> Comparison at FLASH1
  • Experimental setup
  • Data analysis
  • Measurements
> Other and new CRISP stations
> Summary
> Idea
  • Reflective blazed gratings
  • Strong polarization dependency in first and zeroth order
  • Acts as low-pass and dispersive element simultaneously

→ Staging to increase band width
→ Broadband single shot spectra

→ 2-stage prototype by Hossein
→ 4-stage „user“ spectrometer
Coherent Radiation Intensity SPectrometer.  

→ Major design finished in 2010  
→ Minor changes over last 8 years  

> Specs  
  • in vacuum  
  • 2 grating sets  
    4 – 40 um  
    40 – 450 um  
  • focusing ring mirrors  
  • broadband pyro-electric sensors  
  • 120 channels  
  • fast readout on 1 us level
Coherent Radiation Diagnostic.

- Radiation emitted by electron bunch
  - Synchrotron, Transition, Diffraction, ...
  - Broadband spectrum, deep UV to far infrared / THz
  - Small opening angle $\sim 1/\gamma$

$\lambda \ll \sigma_z$
$E \propto \sqrt{N}$
$I \propto N$

fully incoherent (random interference)

$\lambda \gg \sigma_z$
$E \propto N$
$I \propto N^2$

fully coherent (constructive interference)

$\rightarrow$ Increase of radiated intensity by number of electron in bunch ($N \sim 10^9$)
$\rightarrow$ Frequency dependent
Coherent Radiation Diagnostic.

> Radiated spectral intensity

\[
\frac{dU_{coh}}{d\lambda} \approx \frac{dU_{sing}}{d\lambda} \cdot N^2 \cdot |F_{long}(\lambda)|^2
\]

> Form factor == Fourier transform (transition between extreme cases)

\[
F_{long}(k) = \int \rho_{long}(z) \exp(-ik \cdot z) \, dz
\]

But phase information is lost!

\[
F_{long}(k) = |F_{long}(k)| \exp(i\Phi(k))
\]

→ Get modulus of the form factor by measuring the spectral intensity
Coherent Radiation Diagnostic.

> Example: Gaussian and rectangular profiles with same RMS lengths

→ Resolvable with a spectral measurement
Coherent Radiation Diagnostic.

> Example: I. Zagorodnov, FLASH beam dynamic simulations (www.desy.de/fel-beam/s2e/)

→ Form factor modulus is a unfamiliar quantity
Profile Reconstruction.

Reconstruction out of the form factor modulus

\[ \rho(z) = \int F(k) \exp(ik \cdot z) \, dk = \int |F(k)| \exp(ik \cdot z + \Phi(k)) \, dk \]

> Reconstruction out of the form factor modulus

- Mathematical statement in 1D

1. No unique retrieval of the phase information out of the form factor modulus. It is lost!
2. Reconstructed profiles are ambiguous and reflects only one potential solution

- General constraints
  Insensitive on absolute arrival time
  Insensitive on time reversal (bunch tail → head)
Profile Reconstruction.

> Example: “Akuto”


\[
\begin{align*}
  f_1(t) &= e^{-\beta t} \\
  f_2(t) &= e^{-\beta t} \left(1 + \frac{4\beta^2(1 - \cos(\alpha t))}{\alpha^2} - \frac{4\beta \sin(\alpha t)}{\alpha}\right)
\end{align*}
\]

\[|\mathcal{F}_1(\omega)| = |\mathcal{F}_2(\omega)| = \frac{1}{\sqrt{\beta^2 + \omega^2}}\]

→ No chance to distinguish between these profiles by measuring |F|
Kramers-Kronig Reconstruction.

* Causal functions
  - Profile / function \( f \rightarrow f(t_0 < 0) = 0 \)
  - Explicit **analytical** relation

* Adaption to \( |F| \)
  - KK phase by using
  
  \[
  \ln F(\omega) = \ln |F(\omega)| + i \Phi(\omega)
  \]
  - Solving the principle value in complex plane
    R. Lai, U. Happek, and A.J. Sievers,
  - \( |F| \) may have zeros in the upper half plane
    W. Blaschke, Berichte Math.-Phys.,
    Kl. Sächs. Gesell. der Wiss. Leipzig, 67 (1915), 194-200
  - Contribution of “Blaschke Phase” **inaccessible**

  \[\begin{align*}
  \Re(\tilde{f}(\omega_0)) &= \frac{1}{\pi} \int \frac{\Im(\tilde{f}(\omega))}{\omega - \omega_0} d\omega \\
  \Im(\tilde{f}(\omega_0)) &= -\frac{1}{\pi} \int \frac{\Re(\tilde{f}(\omega))}{\omega - \omega_0} d\omega
  \end{align*}\]

  \[\Phi_{\text{KK}}(\omega) = \frac{2\omega}{\pi} \mathcal{P} \int_0^\infty \frac{\ln(|\mathcal{F}(\omega')|) - \ln(|\mathcal{F}(\omega)|)}{\omega^2 - \omega'^2} d\omega'\]

  → **Perfect reconstruction only if the form factor has no complex zeros**
Kramers-Kronig Reconstruction.

Examples

→ "Blaschke Phase" is not accessible
Iterative Reconstruction.

> Gerchberg-Saxton algorithm

\[
g_n(t) \xrightarrow{\text{FFT}} \mathcal{G}_n(\omega) = G_n(\omega) \exp(i\varphi_n(\omega)) \xrightarrow{\text{satisfy Fourier constraints}} \mathcal{G}_n'(\omega) = F(\omega) \exp(i\varphi_n(\omega)) \xrightarrow{\text{IFFT}} g_n'(t)
\]

R.W. Gerchberg and W.O. Saxton, „A practical algorithm for the determination of phase from image and diffraction plane pictures”, Optik 35, 227 (1972)

> Start phase
  • random

> Applied constrains
  • Charge density > 0
  • Bunch profile is localized

> Stop criterion
  • Fix number of iterations
  • Convergence of profile

→ Run multiple times with different starting parameters ...
Iterative Reconstruction.

Example: Convergence

Example: “Akuto“ and Gaussian Profile

mean profile + error band
Shift Motivation.

“Comparative Measurements between CRISP and LOLA-TDS at 13SMATCH“

- Test reconstruction methods on real FLASH beam profiles
- Reliable bunch profile measurements by CRISP?
- Measure shortest bunches down to 50 fs rms
Transverse Deflecting Structure.

\[ V_0 \cos \left( \frac{2\pi}{c} f_{\text{TDS}} z + \varphi_{\text{TDS}} \right) \]

\[ \sigma_z \]

\[ \sigma_y \]

\[ \beta_y(s_0) \]

\[ \Delta \psi_y(s, s_0) \]

\[ \beta_y(s) \]

**Offset in zero-crossing**

\[ y = y_0 + S \cdot z \]

**Streak** given by optics and TDS

\[ S = R_{34}(s, s_0) k = \sqrt{\beta_y(s) \beta_y(s_0)} \sin \Delta \psi_y(s, s_0) \frac{2\pi e}{c^2} V_0 f \]

**Resolution** given by bunch properties

\[ R_z = \frac{\sigma_{y0}}{S} = \sqrt{\frac{\epsilon_{n,y}}{\beta_y(s_0)} \frac{1}{\sin \Delta \psi_y(s, s_0)} \frac{mc^3}{2\pi e} \sqrt{\gamma - 1/\gamma}} \frac{V_0 f}{V_0 f} \]

→ LOLA-TDS available at FLASH
Two Point Tomography.

> Intrinsic centroid correlation \( \langle y \rangle_\pm (z) \)

\[
f_\pm (z) = \langle y \rangle_\pm (z) = f_0(z) + S_\pm z
\]

• Accumulated charge

\[
q_\pm (y) = \int_{-\infty}^{y} \rho_\pm (y^*) \, dy^*
\]

\[
q_- (y) = \int_{y}^{\infty} \rho_- (y^*) \, dy^*
\]

• Map

\[
z(q) = \frac{y_+ (q) - y_- (q)}{S_+ - S_-}
\]

→ Reconstruction of correlation and profile

\[
f_0(q) = \frac{S_+ y_-(q) - S_- y_+(q)}{S_+ - S_-}
\]

\[
\rho_{z,x}(z) = \frac{d}{dz} q(z)
\]
Two Point Tomography.

Example: I. Zagorodnov

→ Successful with sufficient streak
CRISP@FLASH

CRISP@202m (@FL1)
- inside tunnel
- delays: BLM masking, kicker, screen, detectors, ...
- exchange complete spectrometer in 2015

CRISP@141m (@LINAC)
- beamline to external lab 28g
- commissioning of the 1st CRISP
- first comparisons with LOLA-TDS

CRISP@FL2
- inside FLASH2 tunnel
- later in this talk ...

Diagram showing various components of FLASH, including RF Stations, Accelerating Structures, Bunch Compressors, RF Gun, Lasers, Fixed Gap, Undulators, Photon Diagnostics, THz, FEL Experiments, and sFLASH.
Experimental Setup SDUMP/SMATCH.

→ Designed to compare both diagnostics
Experimental Setup SDUMP/SMATCH.

> SDUMP special optics
  - Based on FLASH1 theory optics
  - Streak in y:
    \[ \beta_{TDS} = 41 \text{ m}, \]
    \[ \beta_{SCR} = 4 \text{ m}, \]
    \[ \psi \sim \pi/2 \]
  - Energy x:
    \[ \beta = 0.54 \text{ m}, \]
    \[ \eta = 0.77 \text{ m} \]
  - Works for 13SMATCH as well

> Resolution
  (for 20 MV and 1 GeV/c, 1 um-rad)
  \[ S = 15 \]
  \[ R_z = 3 \text{ um (rms)} \]
  \[ R_\delta = 2 \times 10^{-4} \text{ (rms, dominated by TDS)} \]

→ Excellent time resolution (matched beam in SFUND needed)
Machine Setup.

> Check list: Machine
  - Virtual cathode
  - Phase scans
  - Set minimum energy spread downstream BC2
  - Match in DBC2 (4 screen method)
  - Set minimum energy spread downstream BC3
  - Close dispersion in dogleg
  - Match in SFUND (4 screen method)
  - Set special SDUMP optics

> Check list: Measurement
  - Set compression (sum voltage control, intuitive)
  - Measure longitudinal phase space with TDS
  - Switch to 13SMATCH (dark current tuning)
  - Measure spectra with CRISP
  - Switch back to 6SDUMP
  - Set new compression ...

> Spent a lot of time to prepare the machine

Optics in SFUND
  - Small beam sizes on screens
  - Weird beam shapes
  - Matching somehow random

Switching to 13OTRSMATCH
  - Upstream killer steerers
  - Attention to DC in undulators
TDS Measurement.

> Data taking for both zero-crossings
  • Time calibrations
  • Single image
  • 20 images

> Time calibration analysis (update)
  • Based on energy slices
  • Better understanding of resolution
TDS Measurement

> **Data taking for both zero-crossings**
  - Time calibrations
  - Single image
  - 20 images

> **Time calibration analysis** *(update)*
  - Based on energy slices
  - Better understanding of resolution

> **Image analysis**
  - Correct for center of mass shifts
  - Scale all profiles to the mean bunch length
  - Averaging profiles
  ... potentially wash out micro-structures
TDS Measurement.

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    … potentially wash out micro-structures

> Two point tomography
  - Most likely profile
  - Centroid shift
CRISP Measurement.

> **Data taken**
  - 200 shots
  - 2 grating sets

> **Measure form factor**
  - Average of all shots (for now)
  - Well calibrated device (source → electronics)
  - Characterization by response
    (infinitesimal short bunch)
  - ADC signal → form factor

\[
|F_i| = \left( \frac{\text{adc signal}[\text{V}]}{\text{charge}[\text{nC}]^2 \cdot \text{response}[\text{V}]} \right)^{1/2}
\]
CRISP Measurement.

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  • 200 shots
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\[ |F_i| = \left( \frac{\text{adc signal}[V]}{\text{charge}[nC]^2 \cdot \text{response}[V]} \right)^{1/2} \]

> Analyse form factor
  • Errors statistical
  • Sensitivity by ADC noise level
CRISP@FL2.

> Delays
  • Solved:
    - new uTCA electronics
    - over-heating of electronics
    - wrong THz beamline focussing mirror
    - no off-axis screen
  • Missing:
    - lead shielding for parallel operation

> Status
  • Beamline and spectrometer aligned
    (laser- and ebeam-based)
  • First bunch spectra by Tanish Satoor
    (summer student 2017)
  • Kicker characterization
  • Problems
    a.) extremely fluctuating signal on alignment pyros
    b.) other time consuming projects

→ Station is alive
→ Next measurements planned in Feb
CRISP@EuXFEL.

> **Setup**
  - In XTL at 1934 m (17.5 GeV = final energy)
  - Non-invasive diffraction radiator

> **Goals**
  - Monitoring all bunches simultaneously
  - Feedback on pulse-train bunch profiles

> **Status**
  - Installed
  - Technical commissioned
  - First spectra taken
  - First cross-checks with TDS
  - DOOCS server by O. Hensler

→ **PhD student Nils Lockmann**
  with C. Gerth and J. Röver (MSK)
> CRISP very well understood and characterized during the past years

> Comparisons with TDS show impressive agreements

> Stations at FLASH2 and EuXFEL

> Seamless integration into DOOCS has been started …

… CRISP as a regular bunch profiles monitor

> Further reading
  • PhD Thesis, DESY-THESIS-2012-052
  • 'CRISP', NIMA 665 (2011) 40–47
  • 'Reconstruction', DESY 18-027