Passive Streaking Using Transverse Wakefield for Ultrashort Bunch Diagnostics

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Talk outline

- Longitudinal beam profile measurement: why?
- Wakefield: a brief recall
- SwissFEL and SwissFEL Injector Test Facility (SITF)
- Passive streaker model and wake potentials
  - Formulas to calculate the beam longitudinal profile at the screen
  - Algorithm to time-resolve the electron beam profile
  - Example of reconstruction from numerical simulations
- Proof-of-principle experiment at SITF
  - Example of reconstruction from experimental data
- Next steps at SwissFEL and at other labs
- Conclusions
Longitudinal beam profile diagnostics

X-band transverse cavity very valuable instrument to:

- Optimize the lasing along the bunch
- Directly observe the microbunching instability and its mitigation

[Ref. 1] C. Behrens et al.
[Ref. 2] D. Ratner et al.

BUT:

- Expensive manufacture
- Operation costs (powering, maintenance)
- It may suffer from jitter issues
Wakefields: from problems...

**Longitudinal**
- z-dependent energy loss

**Transverse**
- z-dependent deflection

**SHORT-RANGE:**
- Wakefield persists only for the duration of a bunch passage
- Particles in the tail can interact with wakes due to particles in the head
- **Single bunch** instabilities can be triggered → projected emittance growth

**LONG-RANGE:**
- The wakefield lasts longer than the time between bunches
- Trailing bunches can interact with wakes from leading bunches to generate **multi-bunch** instabilities → beam breakup
LINEARIZER
Linearize the beam longitudinal phase space (equivalent to a high harmonic cavity or non-linear bunch compressor)

DECHIRPER
Remove the residual correlated energy spread residual from the compression

BEAM TRAIN GENERATION
Modulation of the current profile for THz sources or multi-color operation in FELs or wakefield acceleration schemes

[Ref. 6] P. Craievich
First observation of passive streaking

→ Slice Energy Spread at the FERMI@Trieste spectrometer with BC1+BC2 ($\sigma_t \approx 1\text{ps}$)
  (...while waiting for High Energy RF Deflector at the end of 2011)
→ Sending the beam off-axis in Linac 4 (high-impedance accelerating structures), used the transverse wakes to create a time-energy correlation

![Diagram of electron beam and energy spread](image)

- e\(^-\)
- HERFDy
- dipole
- to transfer line
- screens
- DBD

![Energy distribution graph](image)

- $\sigma_E \approx 150\text{keV}$
- DBD head
- spot
SwissFEL

Construction started in 2013
Commissioning started in Jul 2016
Lasing at 24.0 nm (Dec 2016), at 4.1 nm (May 2017)
Aramis pilot experiment planned in Dec 2017
Athos user operation planned in 2021

Electron source
RF gun with CaF$_2$ laser driven with Cs$_2$Te photocathode

Undulator beamlines
1. **Aramis**: hard X-ray FEL (1-7 Å). In-vacuum, planar undulators with variable gap, period = 15 mm
2. **Athos**: soft X-ray FEL (6.5-50 Å). Undulators with variable gap and full polarization control, period = 38 mm

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Wavelength</td>
<td>1 - 50 Å</td>
</tr>
<tr>
<td>Pulse duration rms</td>
<td>3 – 30 fs</td>
</tr>
<tr>
<td>Maximum e- beam energy</td>
<td>5.8 GeV</td>
</tr>
<tr>
<td>e- beam charge</td>
<td>10 – 200 pC</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Slice emittance (design)</td>
<td>40-150 nm</td>
</tr>
<tr>
<td>Slice emittance (expected)</td>
<td>100-300 nm</td>
</tr>
<tr>
<td>Slice energy spread</td>
<td>250-350 keV</td>
</tr>
<tr>
<td>Saturation length</td>
<td>&lt; 50 m</td>
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</table>
Missions

- Benchmark the simulation expectations and prove the feasibility of SwissFEL
- Develop and test components/systems and optimization procedures in SwissFEL

Commissioning phases

**Phase 1:** Electron source and diagnostics (2010)

**Phase 2:** Phase 1 + two S-band stations (2010-2011)

**Phase 3:** Machine in full configuration: all RF structures operational and bunch compressor installed (2012-2013)

**Phase 4:** Undulator installed for several weeks (2014)

**Phase 4+:** PSI gun installed (Oct 2014)

**Shut-down:** Oct 2014
The method to time-resolve the longitudinal profile is based on the self-transverse-wakefield generation.

A correlation between temporal position of the particle along the bunch and transverse position at a downstream screen is introduced.

The beam passes off-axis through a structure capable of generating a strong monotonic transverse wakefield along the full bunch length.

Cylindrical or planar, corrugated or dielectric-lined geometries may be used without altering the principle.

Potentially sub-fs resolutions achievable.
Suitable wakefield sources

- Several sources can be used to do such measurements. The requirements are:
  - Function monotone along the full bunch length
  - Amplitude of the wakefield enough to limit the length of the device to a reasonable value (~few meters)

**Passive streaker**
- C-band
- S-band
- X-band

**Corrugated Dielectric Lined-Waveguide**
- Conductor
  - $g < 1$ mm
  - $h \sim 100 \mu$m
  - $L_x < 1$ cm

**Flat Round**
- More typically corrugated
  - Easily tunable
  - Reduced amplitude (by $\pi^2/16$)

- More difficult to tune
  - Maximum amplitude

**Dielectric**
- Inner diameter < 1-2 mm
- Outer diameter < 2-4 mm
Wakefield point charge is a linear combination of several sinusoidal functions:

$$w_{r,m}(s, r, r_0, \varphi, \varphi_0) = \frac{Z_0 c}{4\pi a^2} \left( \frac{r}{a} \right)^{m-1} \left( \frac{r_0}{a} \right)^m \sum_{i=1}^{\infty} A_{m,i} \sin(k_{m,i} s) \cos[m(\varphi - \varphi_0)]$$

[Ref. 3] K. Y. Ng

$$w_{\varphi,m}(s, r, r_0, \varphi, \varphi_0) = \frac{Z_0 c}{4\pi a^2} \left( \frac{r}{a} \right)^{m-1} \left( \frac{r_0}{a} \right)^m \sum_{i=1}^{\infty} A_{m,i} \sin(k_{m,i} s) \sin[m(\varphi - \varphi_0)]$$

The different modes build up increasing the effect

- Transient effect at the entrance of the tube neglected
- Wake functions were also verified with ImpedanceWake2D code
From the passive streaker to the screen

From the charge conservation:

\[ \rho_y \, dy = \rho_L \, ds \]

\[ \rho_y = \rho_L \, \frac{ds}{dy} \equiv \rho_L \, s' \]

**Transverse displacement at the screen**

\[ y_s(s) \approx \frac{QL_p R_{34}}{E} \left[ W_{r,1}(r_0, s) + W_{r,2}(r, r_0, s) \right] \]

Wake potentials when the transverse size is much smaller than the offset along the streaker:

\[ W_{r,m}(r, s; r_0) = \int_{-\infty}^{s} w_r(r, r_0, s') \rho_l(r_0, s - s') \, ds \]

**Finite beam size**

- The beam size is not negligible
- The profile at the screen, \( \rho_{T,y} \), is evaluated as:

\[ \rho_{T,y} = \rho_y \otimes \tilde{\rho}_{0,y} \]

**Assumptions**

- The transverse beam parameters are independent of the longitudinal coordinate
- The optics between the tube and the screen is linear
Time-resolving algorithm

The algorithm minimizes the cost function (neglecting the finite transverse beam size at the passive streaker):

\[
\text{cost function} = |\rho_y - \tilde{\rho}_y|
\]

changing \( \tilde{\rho}_L \), modeled as a piecewise cubic polynomial

\[ \rho_L \] Charge distribution at the streaker
\[ \rho_y \] Transverse charge distribution at the screen (off-axis in the streaker) from \( \rho_L \)
\[ \tilde{\rho}_L \] Trial charge distribution at the streaker
\[ \tilde{\rho}_y \] Calculated transverse charge distribution at the screen (off-axis in the streaker) from \( \tilde{\rho}_L \)

Including the beam transverse size \( \rho_{T,y} \) is used in the optimization
Numerical simulations

- Simulated in Elegant [Ref. 4] a wakefield source monotonic along the full bunch length
- Double horn current profile (LCLS undulator like)

Only the dipole included
Beam at the head poorly streaked
Transverse size is a small fraction of the streaked image

Calibration factor:
\[ S = \frac{dy_s}{ds} \]

Resolution:
\[ \sigma_{s,\text{res}} = \frac{\tilde{\rho}_{0,\text{scr}}}{S} \]
Beam compressed to have a length compatible with a monotonic wakefield point charge

Limited space for the streaker \((L_p = 9.5 \, \text{cm})\)

Lowered the beam energy to enhance the effect \((y_s(s) \propto \frac{1}{E})\)

Phase advance in the vertical plane between the streaker and the screen to maximize the resolution \((270 \, \text{deg})\)
- Shifted the position of the tube
- Measured the centroid of the beam on a downstream screen
- Centroid kick calculated
Measurements at SITF

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- Centroid kick calculated

The kick factor can be expressed as:

$$K = C_1 \Delta y + C_3 \Delta y^3$$

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<thead>
<tr>
<th></th>
<th>Model</th>
<th>Measured</th>
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<tbody>
<tr>
<td>$C_1$ [MV/(nC·m·mm)]</td>
<td>0.62</td>
<td>0.63</td>
</tr>
<tr>
<td>$C_3$ [MV/(nC·m·mm³)]</td>
<td>0.52</td>
<td>0.43</td>
</tr>
</tbody>
</table>

- Quadrupole effect not negligible for $\Delta y > 0.3$ mm
Defocusing due to the quadrupole

- More important if the beam size is large compared to the aperture of the device or the beam is more off-centered
- The charge distribution at the screen used for the convolution, to include the defocusing effects for a transverse beam distribution at the streaker is given by the expression:

$$\rho_{\text{screen}}(y_s) = \int \rho_{\text{screen}}(\tilde{y}_s) \rho(\Delta) \frac{\Delta y(y_s - \tilde{y}_s)}{y_{sq}(\tilde{y}_s)} \frac{\Delta y}{y_{sq}(\tilde{y}_s)} d\tilde{y}_s$$

- $y_{sq}$ is the transverse displacement of the beam at the screen due to the quadrupole wake only, for a particle at offset $\Delta y$ at the passive streaker, and that is deflected to the coordinate $y_s$ at the screen
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\rho_{\text{screen}}(y_s) = \int \rho_{\text{screen}}(\tilde{y}_s) \rho_{\tau} \left[ \frac{\Delta y(y_s - \tilde{y}_s)}{y_{sq}(\tilde{y}_s)} \right] \frac{\Delta y}{y_{sq}(\tilde{y}_s)} d\tilde{y}_s
\]

- \(y_{sq}\) is the transverse displacement of the beam at the screen due to the quadrupole wake only, for a particle at offset \(\Delta y\) at the passive streaker, and that is deflected to the coordinate \(y_s\) at the screen.

- Green: convolution with dipole and quadrupole wake functions, defocusing effect due to quad and finite emittance

- Blue: measured transverse profile at the screen
Experimental reconstruction

- The method demonstrated to be able to reconstruct the FWHM of the beam experimentally with a limited 9.5 cm length device (space limitations at SITF)

- The resolution of the method is determined by the wakefield source, and the beam size along the streaker:
  - is poor at the head of the beam (no streaking)
  - depends on the quadrupole effect going from the head towards the tail
Resolution optimization

Scan of the phase advance between the passive streaker and the profile monitor may be an efficient way to optimize the resolution of the measurement.

[Ref. 5] P. Craievich, A. A. Lutmann
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Scan of the phase advance between the passive streaker and the profile monitor may be an efficient way to optimize the resolution of the measurement.
Next steps at SwissFEL: beam manipulation
Installation of two passive structures 1 m length each upstream of BC1 to:

- Measure the wakefield in view of the dechirper installation for Athos: $\lambda \sim 2$ mm
- Alternatively linearize (following idea in [Ref. 6]): $\lambda \sim 6$ mm
- Test the two-color generation via wakefield excitation [Ref. 7]: $\lambda \sim 1$ mm

Continue the streaking and reconstruction experience with a longer device with corrugated surface, equivalent to the dielectric line waveguide in terms of beam dynamics.
Next steps at SwissFEL: high energy activity
Next steps at SwissFEL: high energy activity

Material | Fused silica
---|---
Dielectric constant | 4.8
Internal diameter | 160 μm
External diameter | 200 μm
Length | 20 cm
Beam Q | 200 pC
Beam energy | 3 GeV
Bunch length | 80 fs FWHM

AT THE EXIT OF THE TUBE
(offset = 10 μm)

few tens of slices streaking
Passive streaking at PAL

A longitudinal phase space measurement by corrugated structure


$e^-$ beam:

$E = 85$ MeV

$\sigma_z = 0.45$ mm

$Q = 200$ pC
Passive streaking at PAL

A longitudinal phase space measurement by corrugated structure


\[ e^- \text{ beam:} \]
\[ E = 85 \text{ MeV} \]
\[ \sigma_z = 0.45 \text{ mm} \]
\[ Q = 200 \text{ pC} \]

Dechirper gap 28 mm (OUT), deflector OFF

Dechirper OUT, deflector ON

Dechirper gap 8 mm, offset 2 mm, deflector OFF

Dechirper gap 6 mm, offset 1 mm, deflector OFF
Passive streaking at LCLS

**Measurement**

LCLS Dechirper by RadiaBeam System

- \( E \) 13.3 GeV
- \( \sigma_t \) 50 fs (FWHM)
- \( Q \) 185 pC

[Ref. 10] Slac team

**Simulation**

- \( E \) 4 GeV
- \( \sigma_t \) 10 fs (rms)
- \( Q \) 100 pC
- Gap 3 mm
- Offset 1 mm

From the wakefield point charge the bunch shape “can be reconstructed”

\[ \sigma_{t,\text{res}}(s) \approx 1 \text{ fs} \]

[Ref. 11] A. Novokhatski et al.
SLAC/FACET E204 experiments

Accelerating structure at 100 GHz

Beam parameters at FACET
- beam energy $E = 20.35$ GeV
- bunch charge $q = 3.2$ nC
- bunch length $\sigma_z = 50$ μm

Deviation of the tail is $\sim \pm 0.8$ mm

FERMI experiment

- SITF passive streaker and chamber shipped to Fermi for an experiment of beam manipulation carried on by Fermi team
- Fermi team built a second dedicated system to install 3 more passive streaker

- Small transverse beam size along the tube ($\sigma_x, \sigma_y < 150 \mu m$)
- No quadrupole component observed

G. Penco, P. Craievich, S. Bettoni, E. Ferrari, E. Roussel
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**TDC measurement**

- Intensity [arb. units]
- $t$ [ps]

**Traces on the screen**

- On-axis
- Off-axis
- Off-axis, shifted

G. Penco, P. Craievich, S. Bettoni, E. Ferrari, E. Roussel
Plasma-driven bunch diagnostics

A short-pulse laser drives a linear wakefield in a plasma target. The electron bunch is situated off-axis at the transverse maximum and longitudinal zero-crossing of the transverse fields.

[Ref. 13] I. Dornmair et al.

- Simulated resolution \(~0.1\) fs in the core of the beam
- Second order dependence of the electric field on the transverse coordinate degrade the resolution at the head and tail

- Plasma generation complex
- High power laser
- Synchronization with the beam

<table>
<thead>
<tr>
<th>Q</th>
<th>0.5 pC</th>
</tr>
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<tbody>
<tr>
<td>(\sigma_z)</td>
<td>7.5 fs (rms)</td>
</tr>
<tr>
<td>E</td>
<td>110 MeV</td>
</tr>
<tr>
<td>(\sigma_{\text{TRANSV}})</td>
<td>17 um</td>
</tr>
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</table>
Conclusions

- A *passive streaker* based on the self-transverse-wakefield can be used to effectively streak the electron beam.
- An algorithm to reconstruct the electron bunch longitudinal profile has been proposed and verified with simulations.
- A proof-of-principle experiment was performed at SITF.
- More activities are undergoing in several laboratories.
- Passive streaking presents pros and cons compared to a standard RF deflectors:

**Pros:**
- Single shot measurement
- Self-synchronized with the beam
- Cheaper to manufacture and operated (passive) compared to other existing devices
- Potentially fs or sub-fs resolutions achievable

**Cons:**
- Necessary to know beam energy, charge and optics
- Temporal resolution is not constant along the beam
- If relation between beam at the device and beam at the screen is non-linear, inversion requires more complicated computation

*More details in PR AB 19, 021304 (2016)*


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