Longitudinal Phase-Space Diagnostics using Passive Streakers at FELs

Sergey Tomin

Philipp Dijkstal (PSI), Max Kellermeier (DESY)

Whistler, 1.09.2026

IBIC 2026

15TH INTERNATIONAL BEAM INSTRUMENTATION CONFERENCE

European XFEL

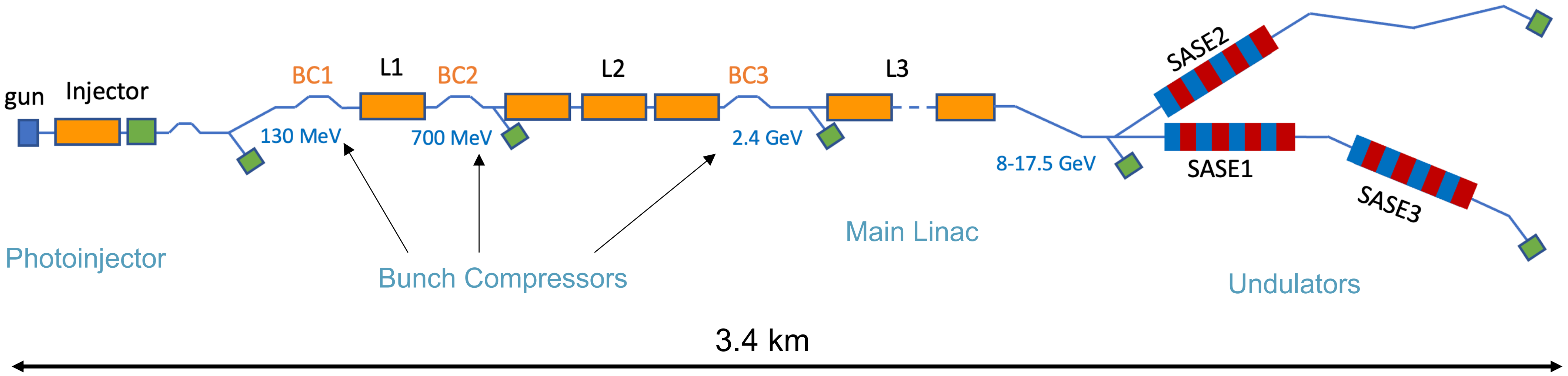
DESY.

HELMHOLTZ

Part I. Why do we care about longitudinal diagnostics?

- FELs require high brightness beams $B_{6D} \equiv \frac{2I_p}{\sigma_\gamma \epsilon_{Nx} \epsilon_{Ny}}$

The European XFEL



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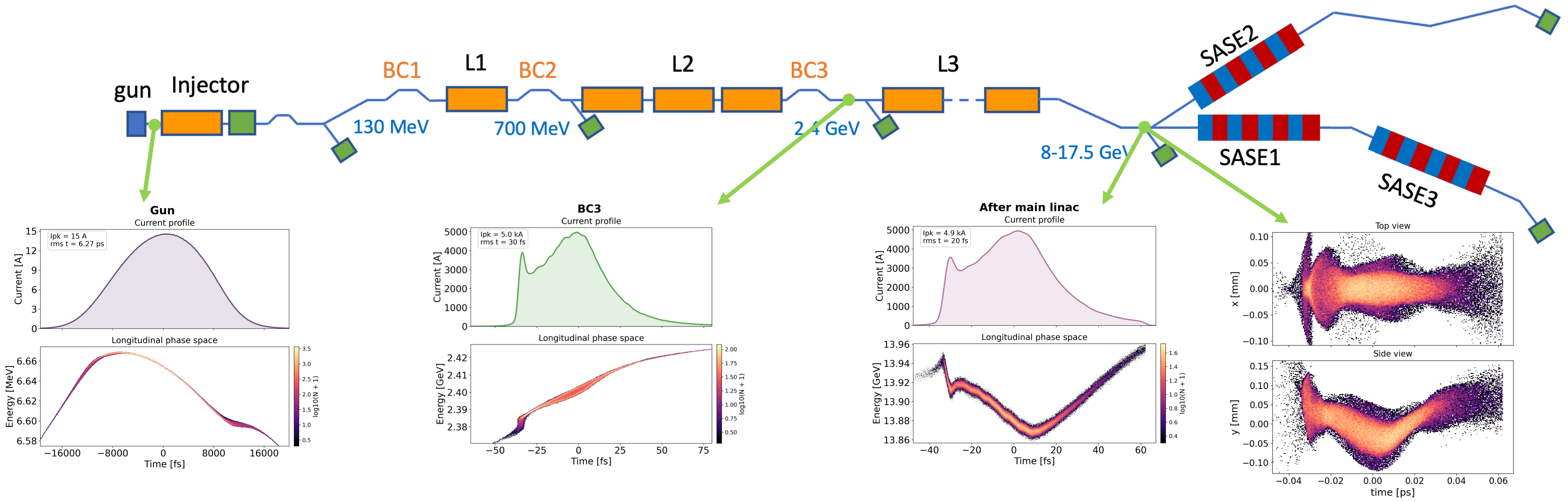
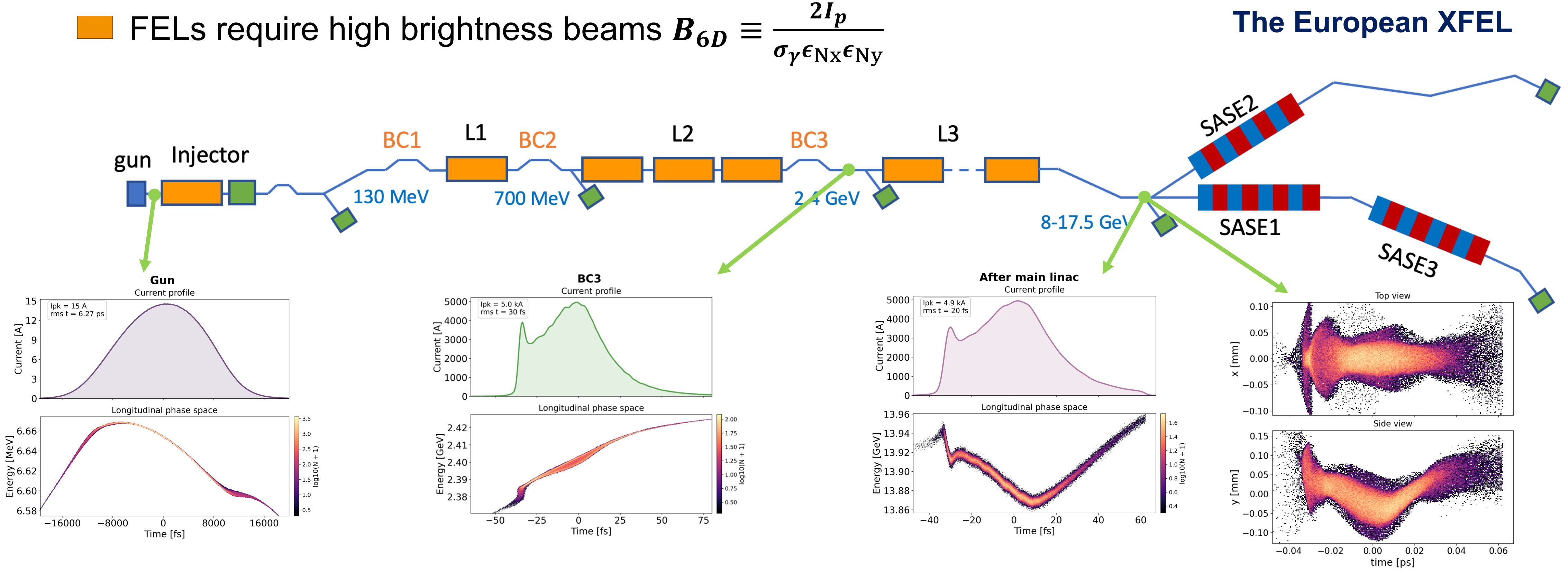


- Photoinjectors
  - $\epsilon_N \sim 0.5$ mm·mrad
  - $I_p \sim 10$ A
- Bunch Compressors
  - $\sim$tens A $\rightarrow$ $\sim$kiloampers
- Main Linac
  - Accelerates beams to multi-GeV energies and may provide hard X-ray photon energies up to 30 keV.

Part I. Why do we care about longitudinal diagnostics?

- FELs require high brightness beams $B_{6D} \equiv \frac{2I_p}{\sigma_\gamma \epsilon_{\mathrm{Nx}} \epsilon_{\mathrm{Ny}}}$

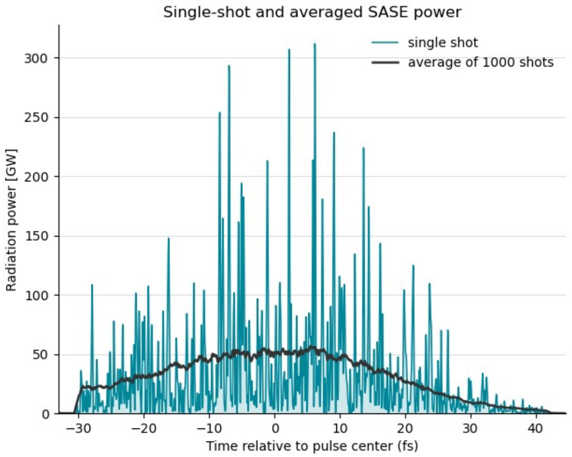


- The final 6D beam distribution is not determined by the RF settings alone: collective effects can distort the longitudinal phase space and cause slice-to-slice transverse misalignment

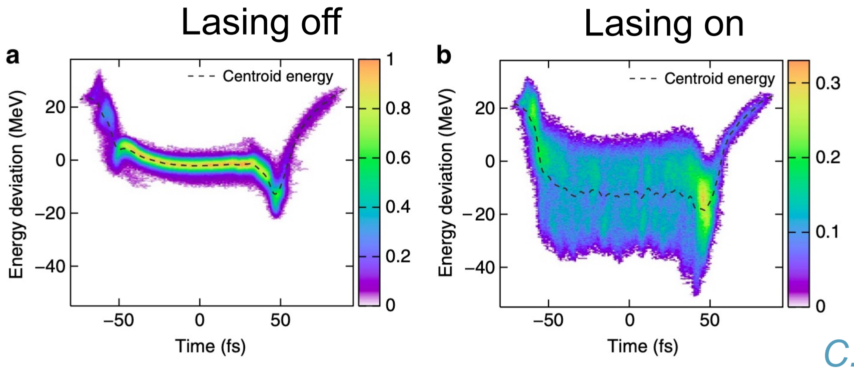
Part I. Why do we care about longitudinal diagnostics?

- The FEL interaction is longitudinally local
  - Electrons interact collectively only over a short longitudinal scale — the cooperation length $L_c \sim \frac{\lambda_r}{4\pi\rho}$.
  - Long bunch $\gg L_c \rightarrow$ many weakly correlated SASE regions.

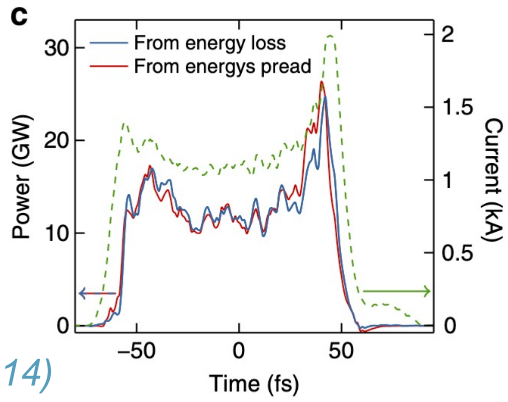
FEL performance depends on **slice beam properties**



- If LPS diagnostic is installed after an undulator it is able to measure **lasing power profile** $\boldsymbol{P_{rad}(t)}$



$$P_\Delta = I(t)(E_{\text{off}} - E_{\text{on}})$$
$$P_\sigma = I^{2/3}(t)(\sigma_{\text{on}}^2 - \sigma_{\text{off}}^2)$$



C. Behrens et al., Nat. Commun. **5,** 3762 (2014)

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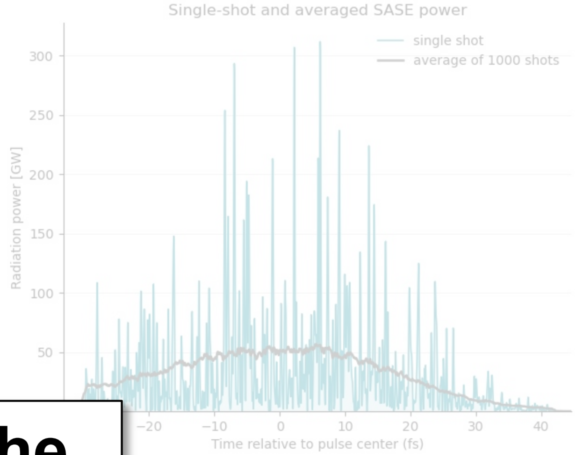
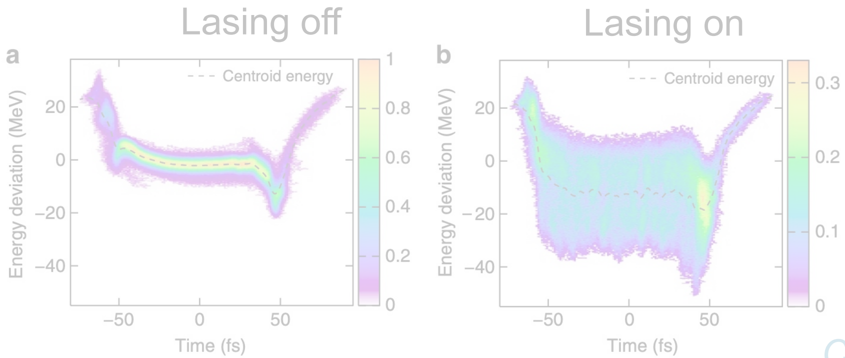


RF transverse deflecting structures: the established reference method

- If LPS diagnostic ... measure **lasing power profile** $P_{rad}(t)$



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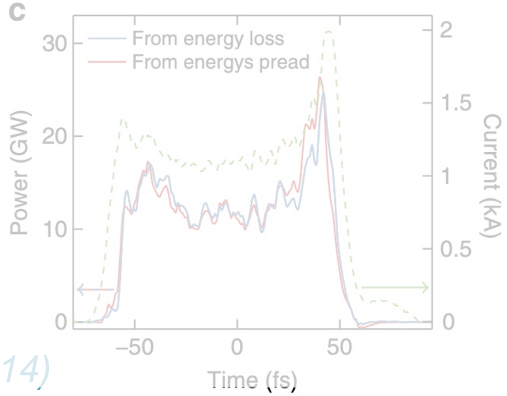
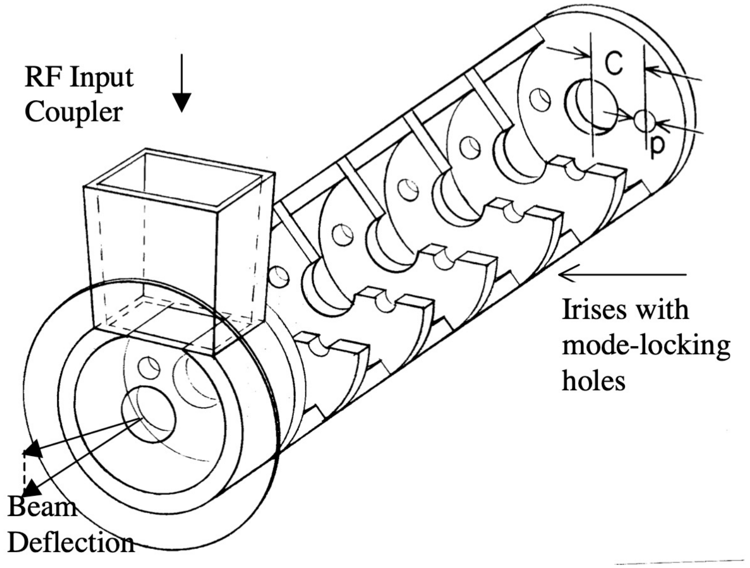
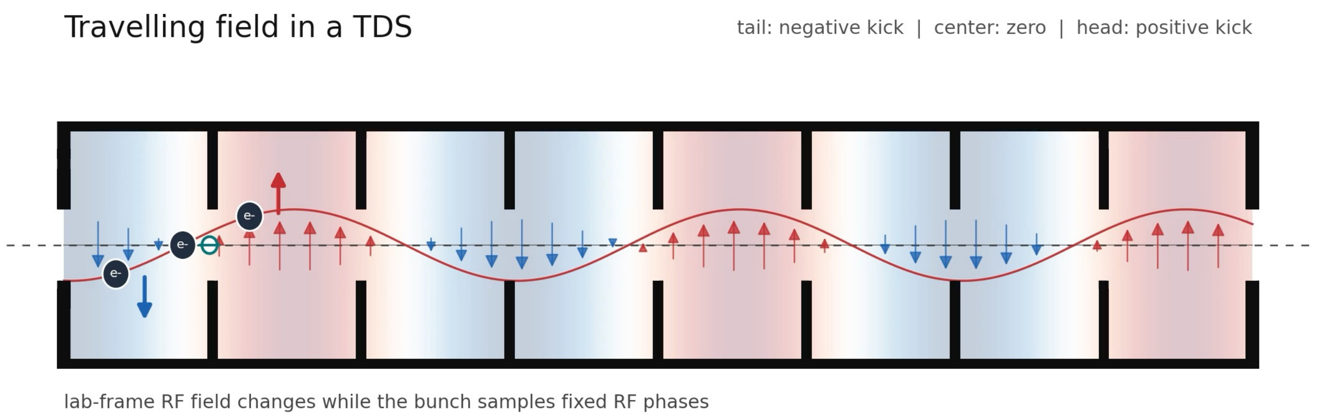


C. Behrens et al., Nat. Commun. **5,** 3762 (2014)

Part II
RF transverse deflecting structures



Example of an RF transverse deflecting structure operating in the TM_{110} -like deflecting mode



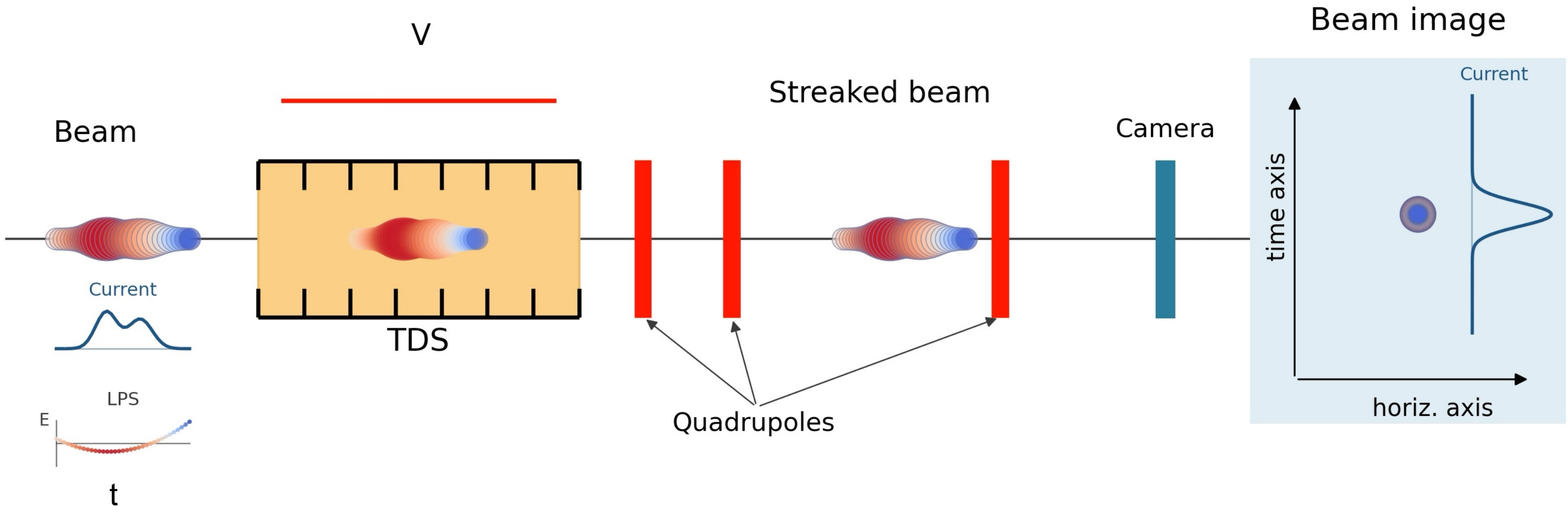
- *G. A. Loew & O. H. Altenmueller, SLAC-PUB-135 (Frascati, Italy, 1965)*
- *R. L. Sheffield et al, IEEE J. Quant. Electron. QE-21, 895–903 (1985).*
- *Wang, X.-J. PAC 229–233 (IEEE, New York, USA, 1999)*
- *P. Emma et al, P. A. SLAC LCLS Technical Report No.LCLS-TN-00-12 (2000)*

RF transverse deflecting structures

- **How does it work?**
  - Screen in a **straight** section

- What can be measured?
  - Current profile
  - Slice emittance (in a plane orthogonal to streaking direction)
  - Beam tilt

Scan TDS voltage

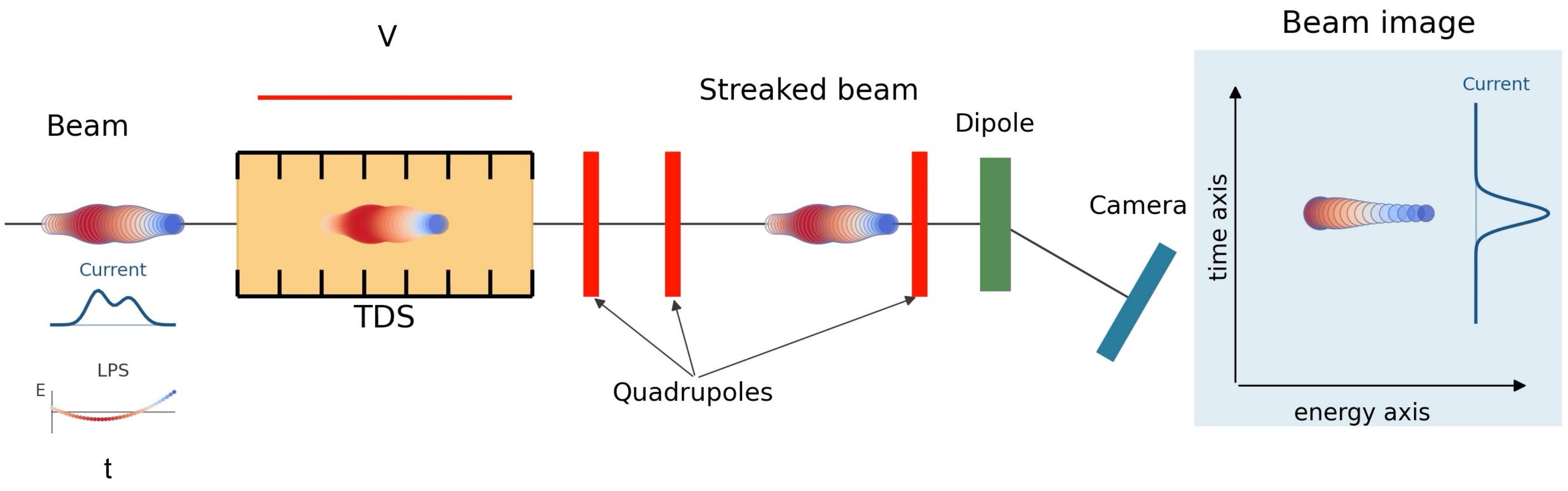


RF transverse deflecting structures

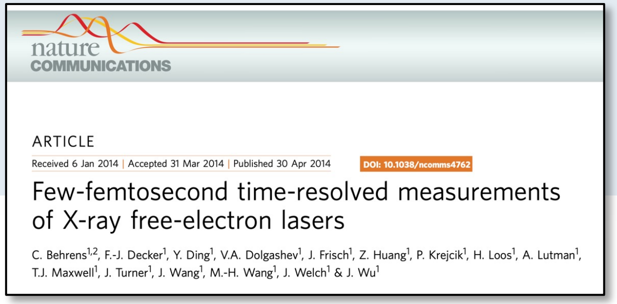
- **How does it work?**
  - Screen in a **dispersive** section

Scan TDS voltage

- What can be measured?
  - Current profile
  - Longitudinal phase space
  - FEL power profile, when the TDS is installed downstream of the undulator



RF transverse deflecting structures

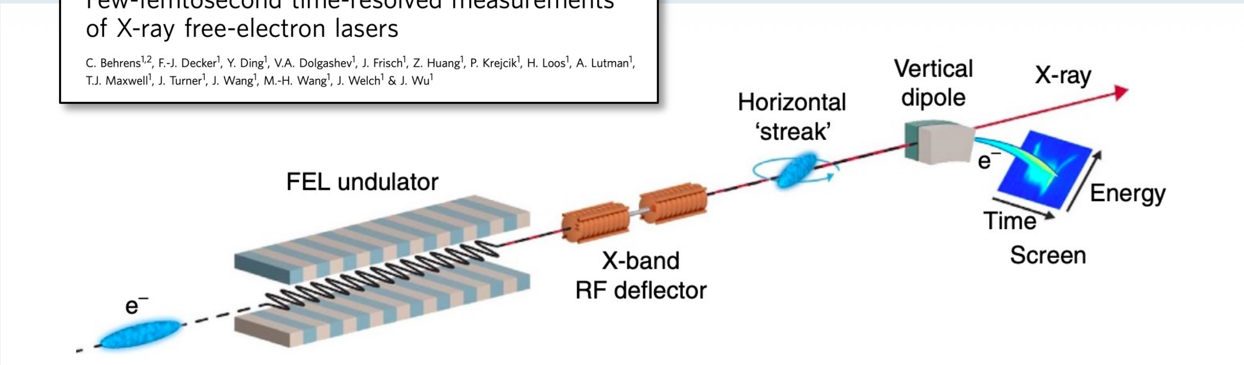

nature COMMUNICATIONS

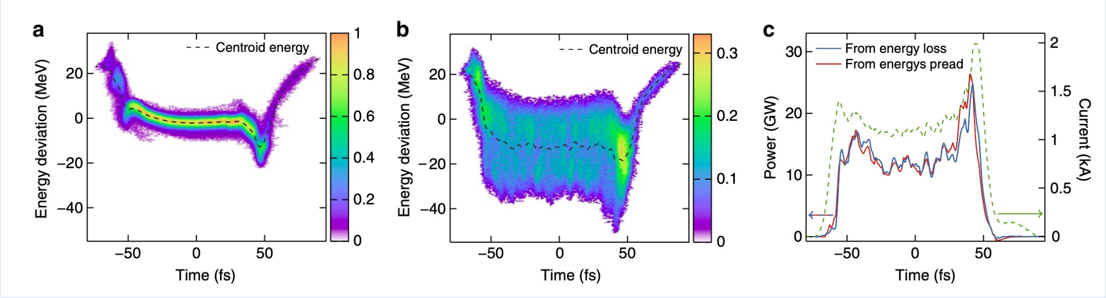
ARTICLE

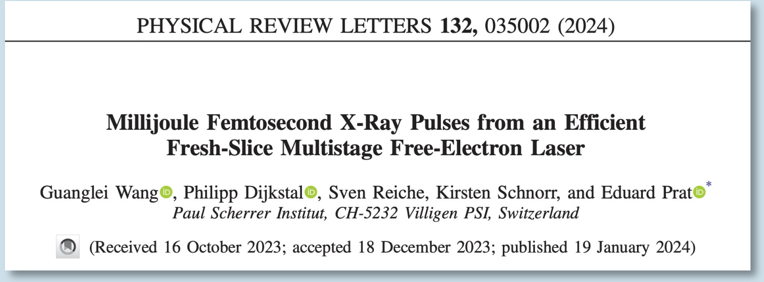
Received 6 Jan 2014 | Accepted 31 Mar 2014 | Published 30 Apr 2014 DOI: 10.1038/ncomms4762

Few-femtosecond time-resolved measurements of X-ray free-electron lasers

C. Behrens[1,2], F.-J. Decker[1], Y. Ding[1], V.A. Dolgashev[1], J. Frisch[1], Z. Huang[1], P. Krejcik[1], H. Loos[1], A. Lutman[1], T.J. Maxwell[1], J. Turner[1], J. Wang[1], M.-H. Wang[1], J. Welch[1] & J. Wu[1]



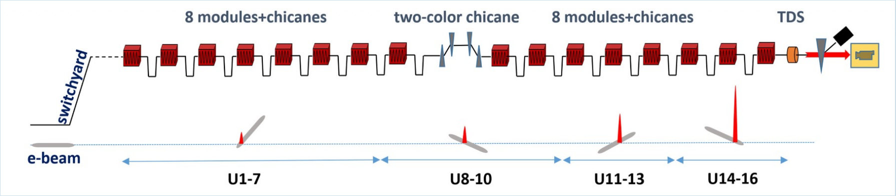


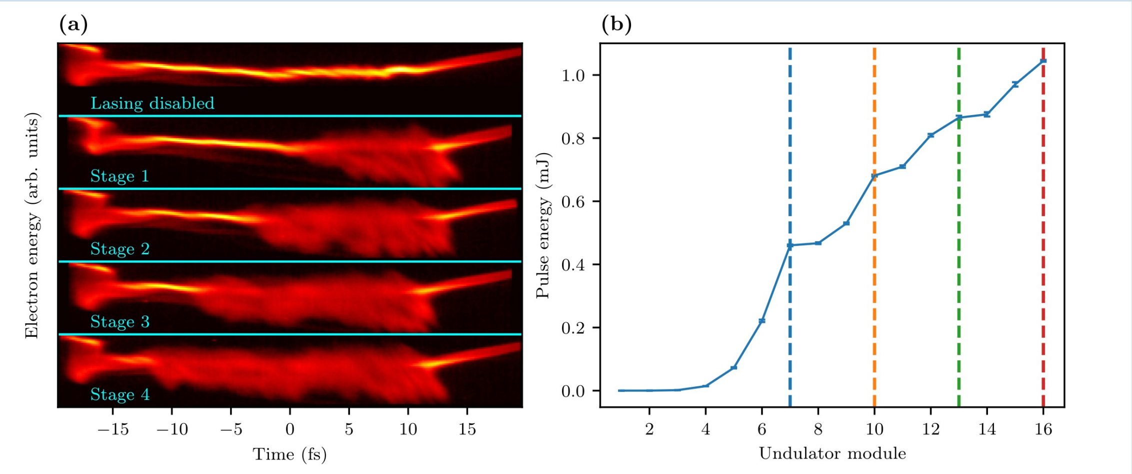

PHYSICAL REVIEW LETTERS 132, 035002 (2024)

Millijoule Femtosecond X-Ray Pulses from an Efficient Fresh-Slice Multistage Free-Electron Laser

Guanglei Wang, Philipp Dijkstal, Sven Reiche, Kirsten Schnorr, and Eduard Prat*
Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

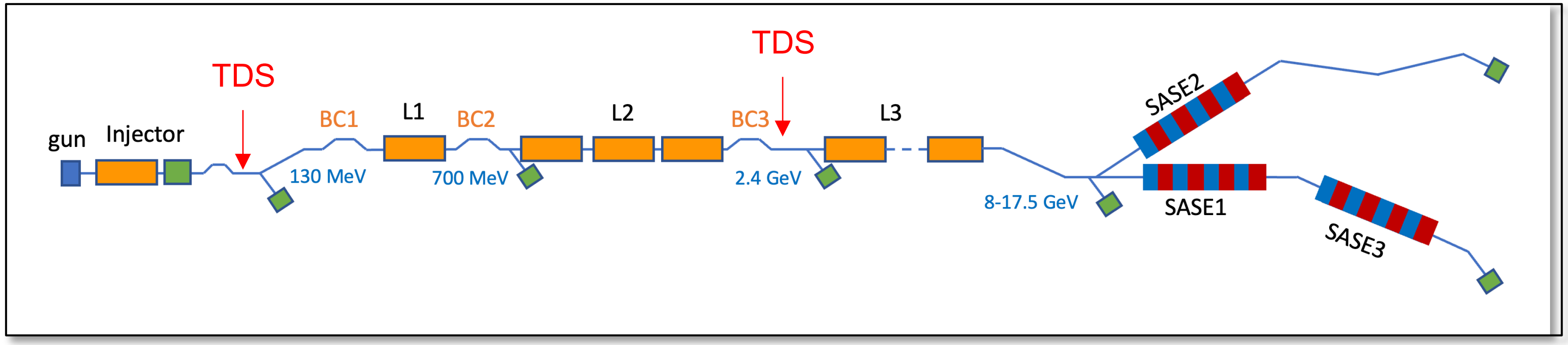
(Received 16 October 2023; accepted 18 December 2023; published 19 January 2024)





RF transverse deflecting structures

- **Large and complex infrastructure**
  - RF power sources: klystrons and modulators
  - Waveguides, low-level RF, and timing systems
  - Cooling-water and temperature-stabilization systems
- **High cost**
  - Structure fabrication
  - RF system
  - Installation and commissioning
- **Synchronization and stability**
  - RF phase jitter directly affects arrival-time measurements
  - Amplitude jitter affects calibration and resolution
  - High-resolution measurements require tight phase stability
- Space in the accelerator tunnel



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- **Large and complex infrastructure**
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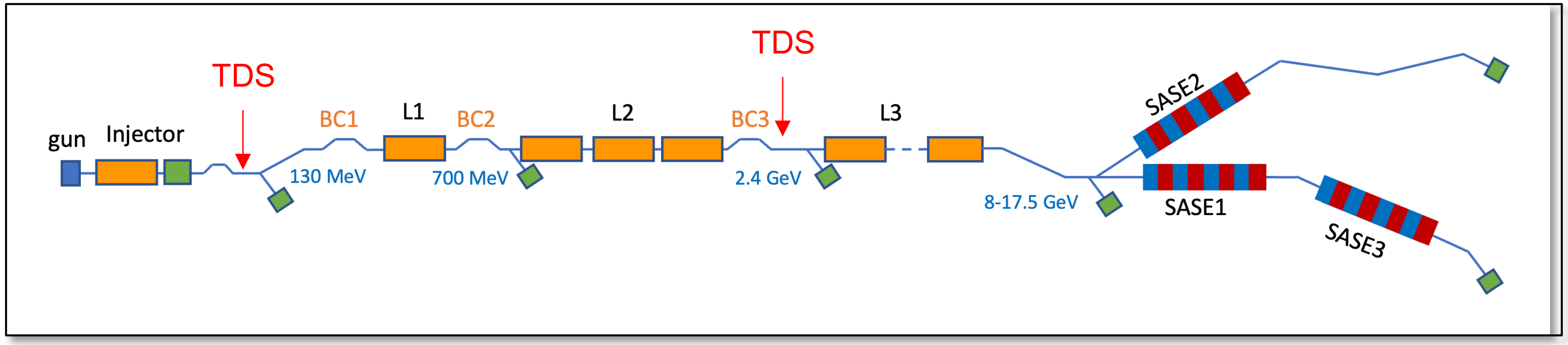
Higher beam energy → more powerful, complicated and expensive RF system

- **High cost**
  - Structure fabrication
  - RF system
  - Installation and commissioning



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  - High-resolution measurements require tight

- Space in the accelerator tunnel

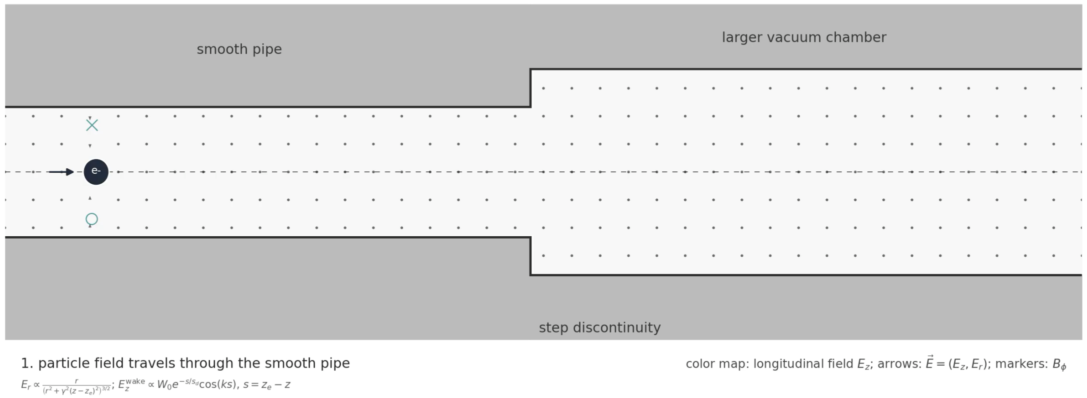
Cost example: EuXFEL X-band TDS

- Two TDS systems after SASE2 and SASE3, and a test stand
- Estimated total project cost: order of €10 million
- Including RF infrastructure, diagnostics, installation, and integration

Part III
Passive deflectors

- RF TDSs provide powerful, well-established LPS diagnostics, but they are expensive and difficult to deploy
- Can the beam generate its own streaking field?
- Wakefields are well known for their detrimental effects on the beam — but can we use them to our advantage?

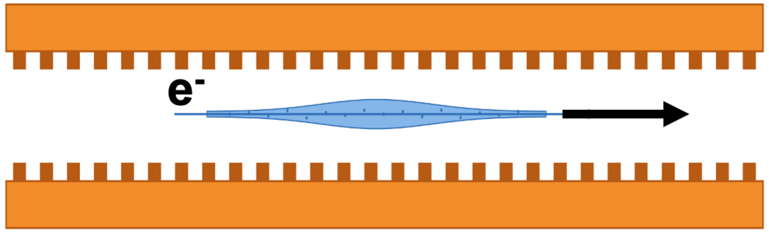
Illustrative analytical model



- In a smooth pipe, the electromagnetic field travels with the relativistic particle.
- A change in boundary conditions excites fields that remain behind the particle — the wakefield

Corrugated structures as passive dechirpers

- The bunch head excites longitudinal wakefields
- The tail loses more energy than the head → correlated energy chirp can be reduced
- But the same structure also produces transverse wakes when the beam is off axis



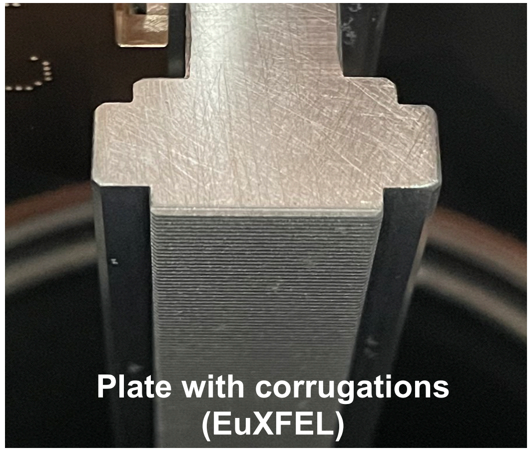
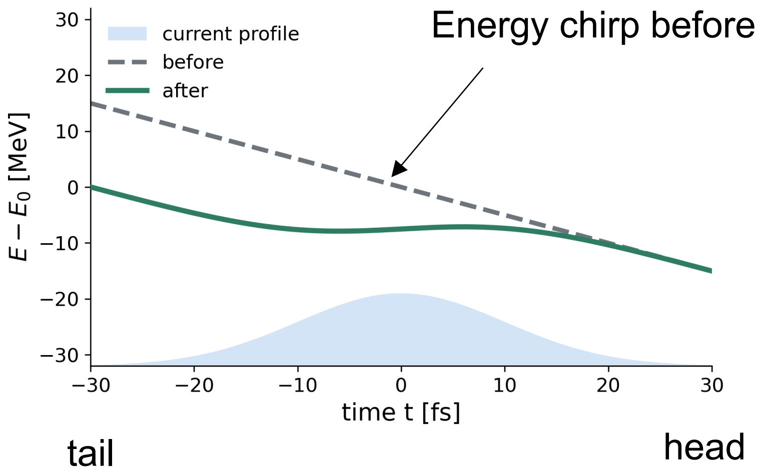


Plate with corrugations (EuXFEL)

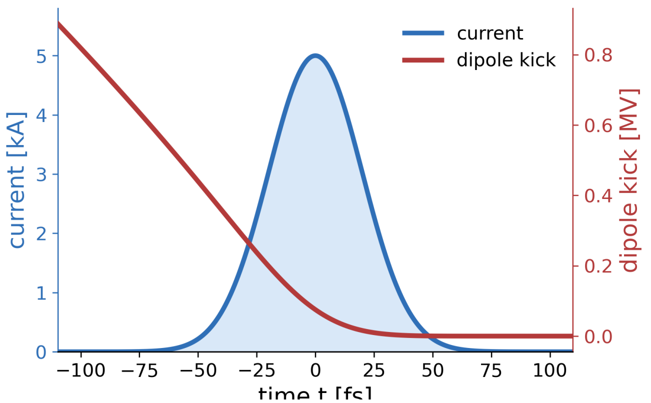


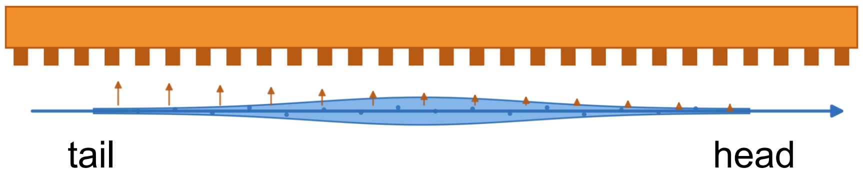
- K. Bane & G. Stupakov, NIM A 690 (2012) 106–110
- P.Emma et al, PRL 112, 034801 (2014)
- K. Bane & G. Stupakov, NIM A 820 (2016) 156–163

Corrugated structures as deflectors

- An off-axis beam excites transverse wakefields in a corrugated structure
- Different longitudinal slices experience different transverse kicks
- In 2015, Novokhatski* proposed using corrugated structures as passive deflectors

**A. Novokhatski, PRAB 18, 104402 (2015)*





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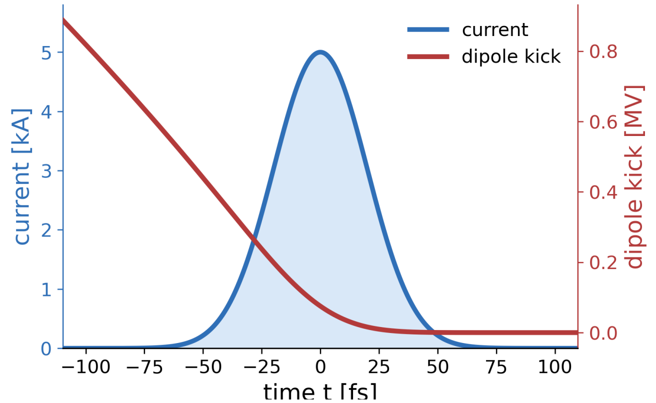
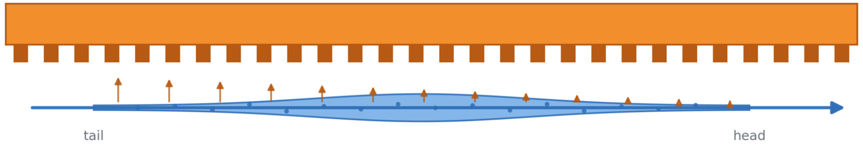
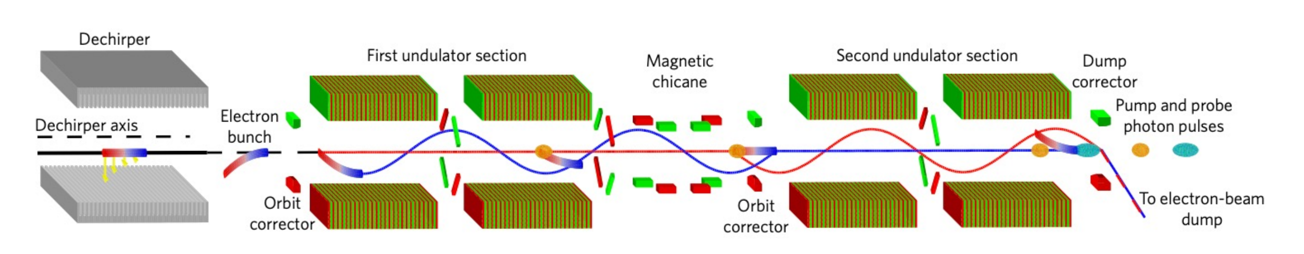


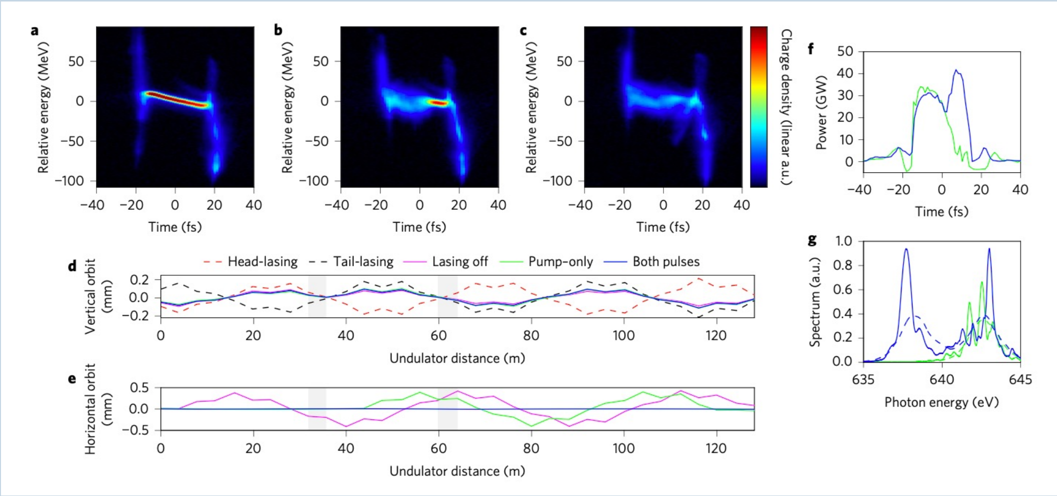



nature photonics
ARTICLES
PUBLISHED ONLINE: 24 OCTOBER 2016 | DOI: 10.1038/NPHOTON.2016.201

Fresh-slice multicolour X-ray free-electron lasers

Alberto A. Lutman[1]*, Timothy J. Maxwell[1], James P. MacArthur[1], Marc W. Guetg[1], Nora Berrah[2], Ryan N. Coffee[1,3], Yuantao Ding[1], Zhirong Huang[1,3], Agostino Marinelli[1], Stefan Moeller[1] and Johann C. U. Zemella[1,4]



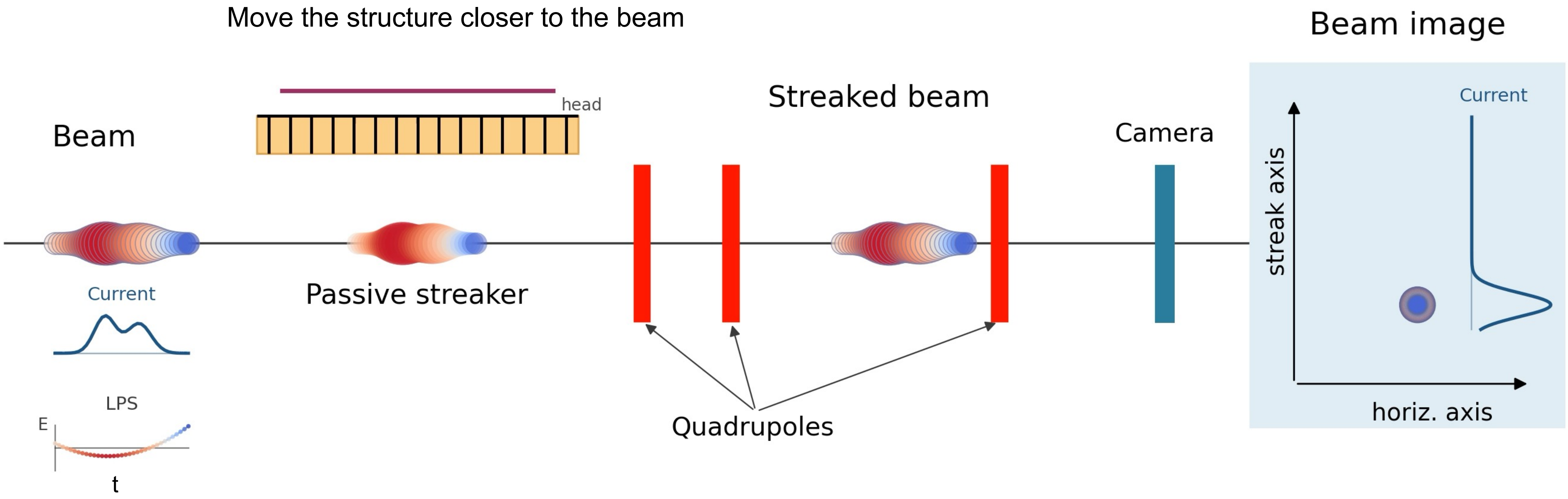


First FEL application: wakefield-induced beam tilt for fresh-slice operation

Passive deflector for LPS diagnostics

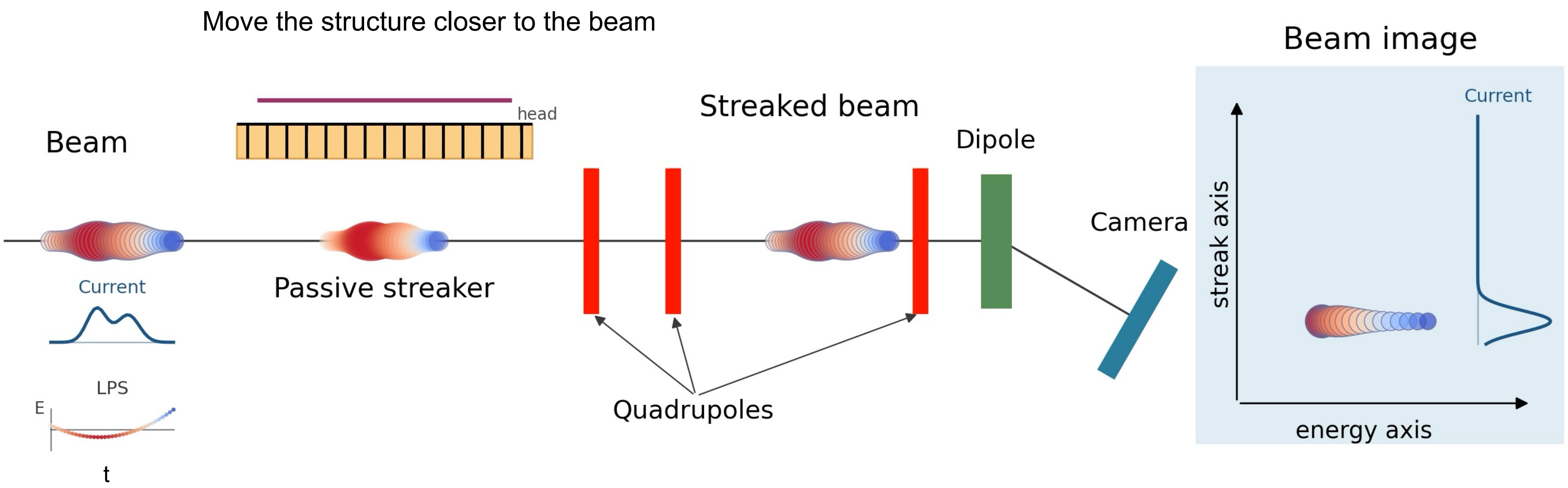
- Screen in a straight section

Move the structure closer to the beam



Passive deflector for LPS diagnostics

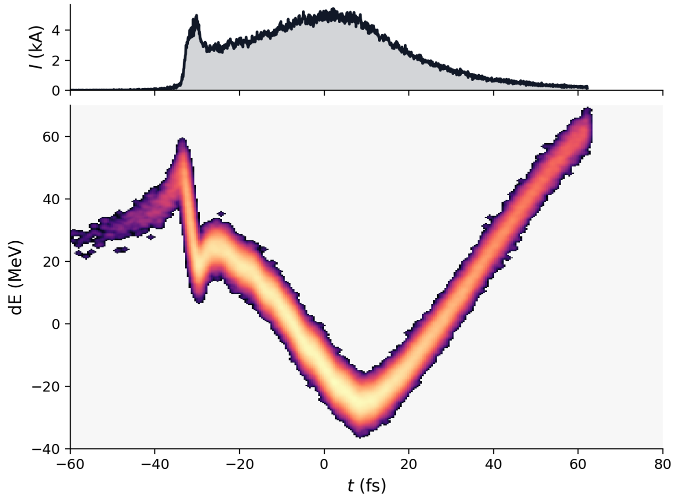
- Screen in a dispersive section

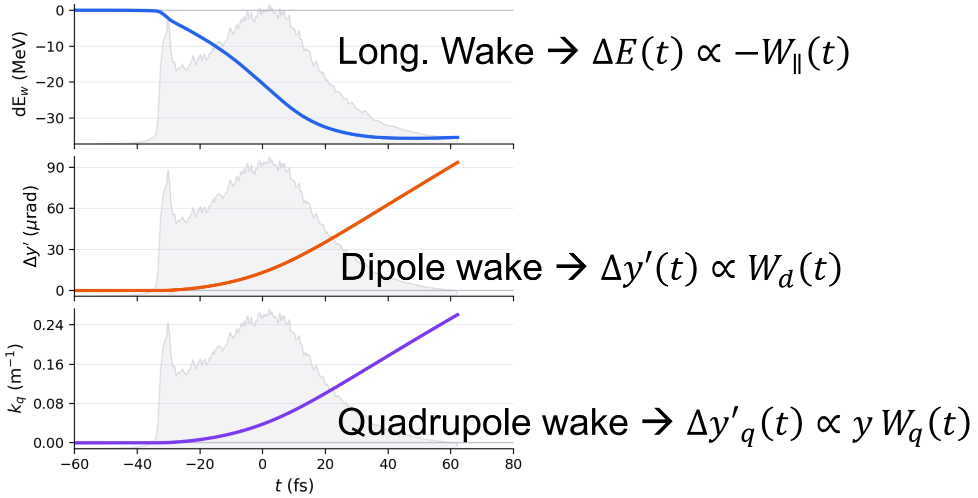


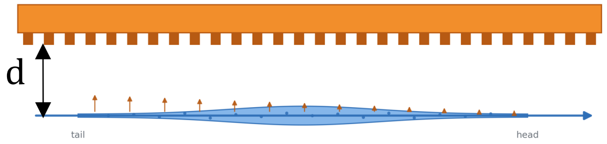
- Reconstruction is required
- Longitudinal and Quadrupole wakes must be taken into account

Wakefields in a flat corrugated structure

Initial beam distribution and wakes

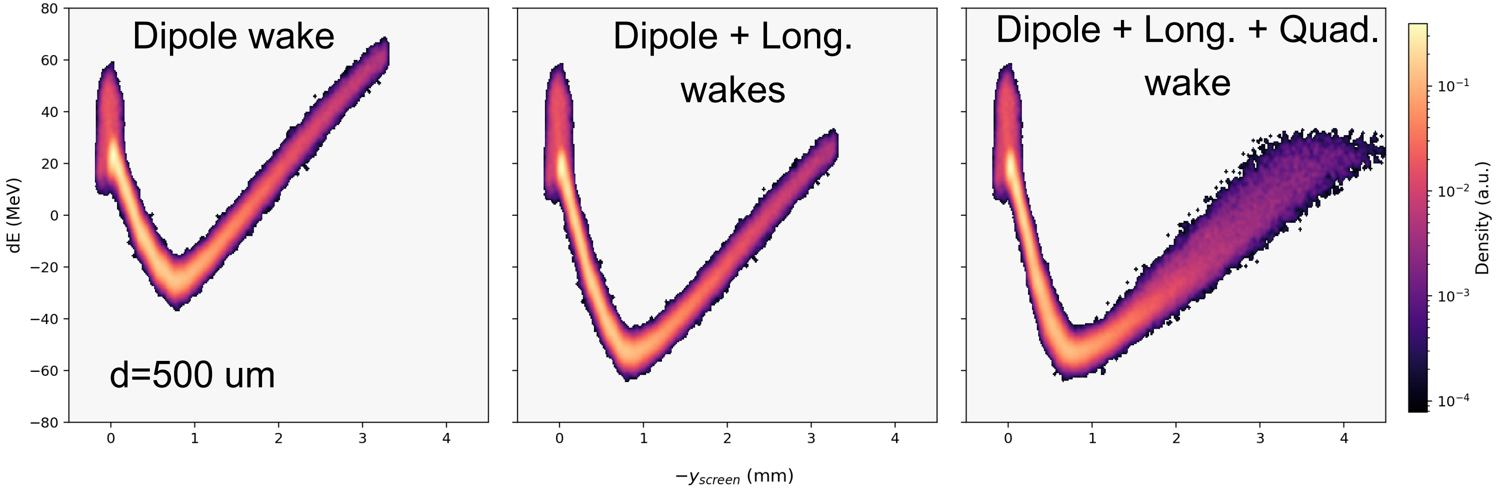






$W_{\|} \sim d^{-2}, \quad W_d \sim d^{-3}, \quad W_q \sim d^{-4}$

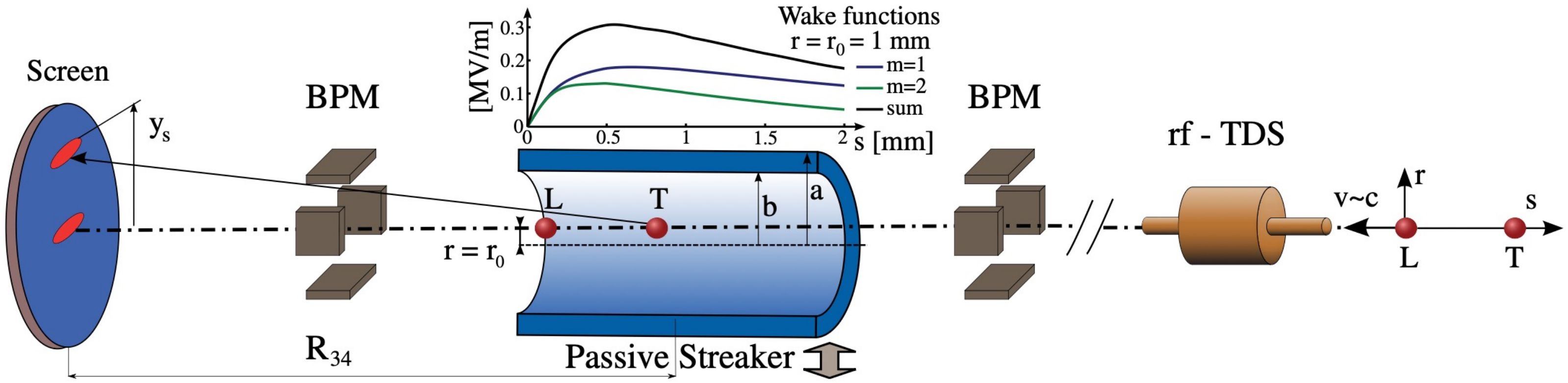
LPS after passive streaker

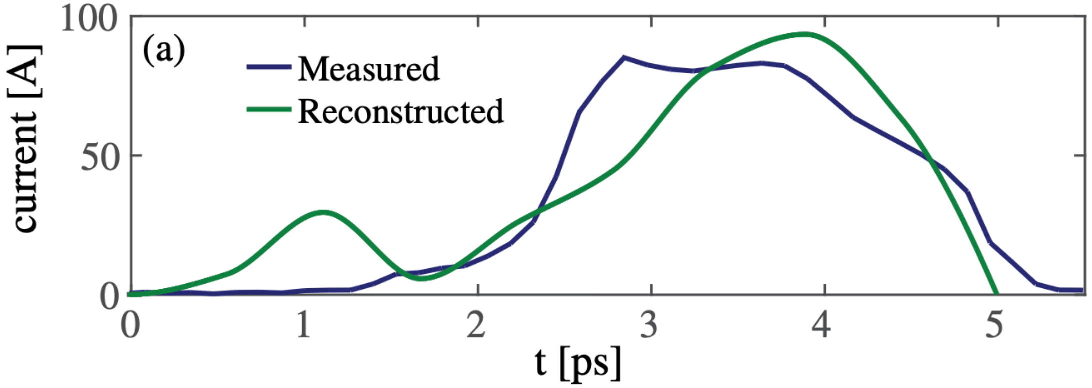


Bane, Stupakov & Zagorodnov, PRAB 19, 084401 (2016)

Passive deflector for LPS diagnostics

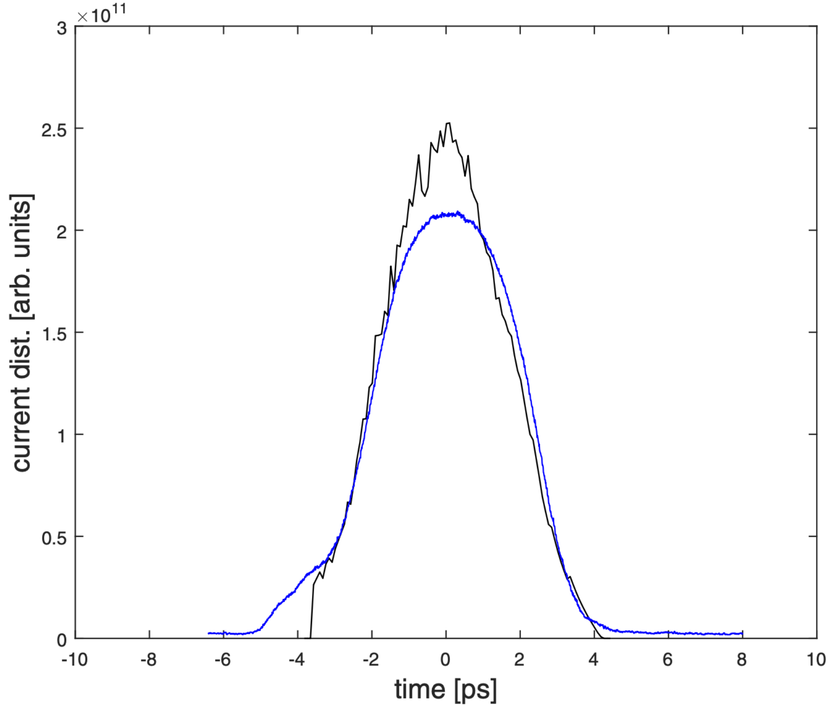
- S. Bettoni et al PRAB 19, 021304 (2016)
  - First current profile measurement with a dielectric tube at the SwissFEL injector

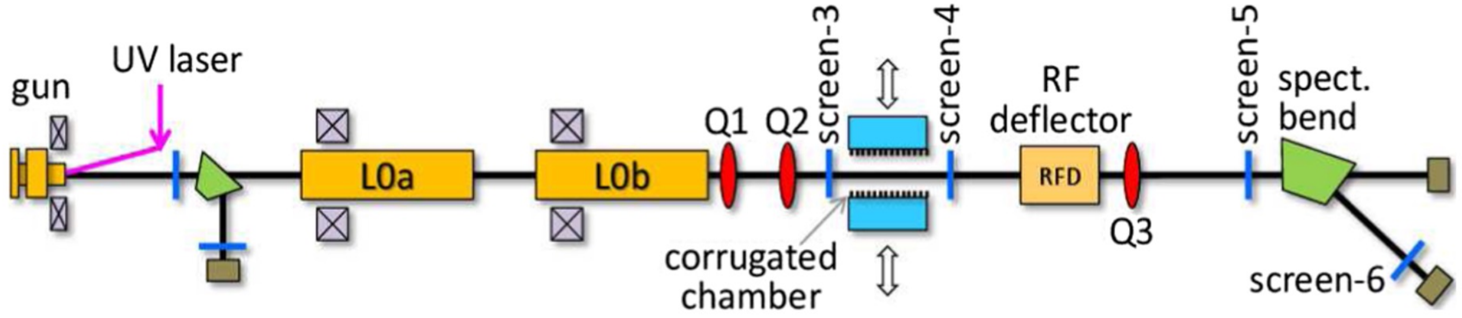




Passive deflector for LPS diagnostics

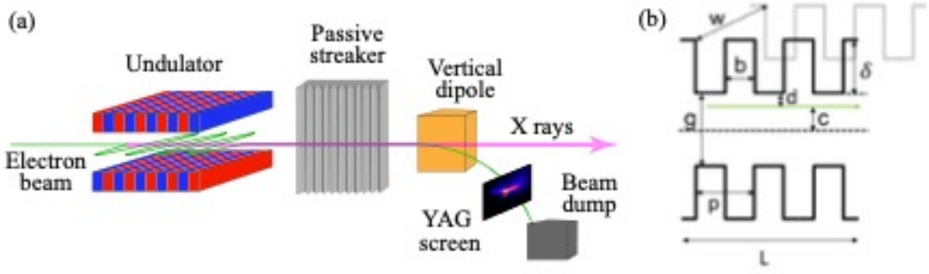
- S. Bettoni et al PRAB 19, 021304 (2016)
  - First current profile measurement with a dielectric tube at the SwissFEL injector
- J. Seok et al, PRAB 21, 022801 (2018)
  - Current profile reconstruction using a double-sided, movable corrugated structure at PAL-XFEL injector test facility.





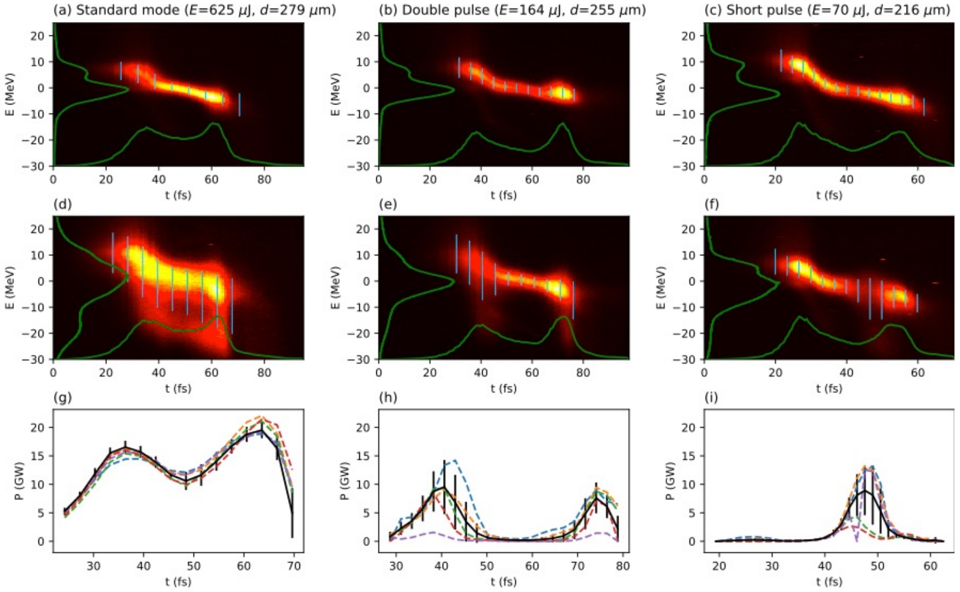
- Iterative procedures for current profile reconstruction
- Long beams and low beam energy
- Not used as actual diagnostics

Passive deflector for LPS diagnostics

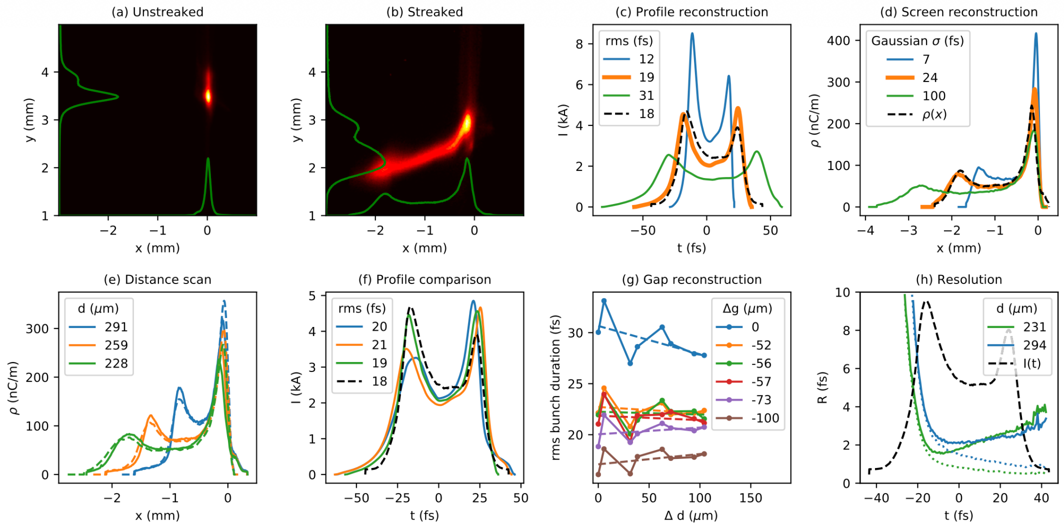


- P. Dijkstal et al, Phys. Rev. Research 4, 013017 (2022)
  - First passive streaker after an undulator

FEL power profile measurements

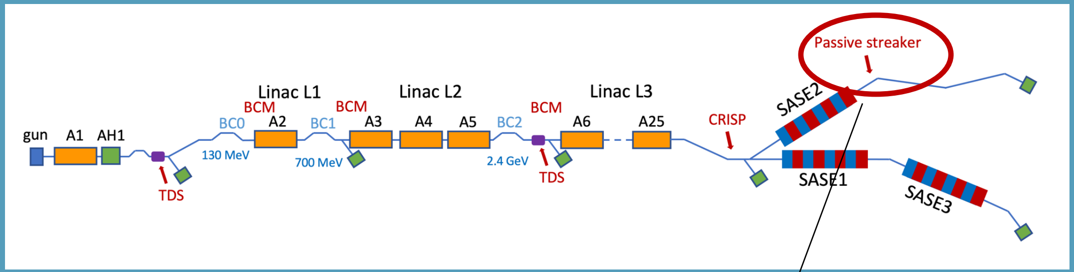


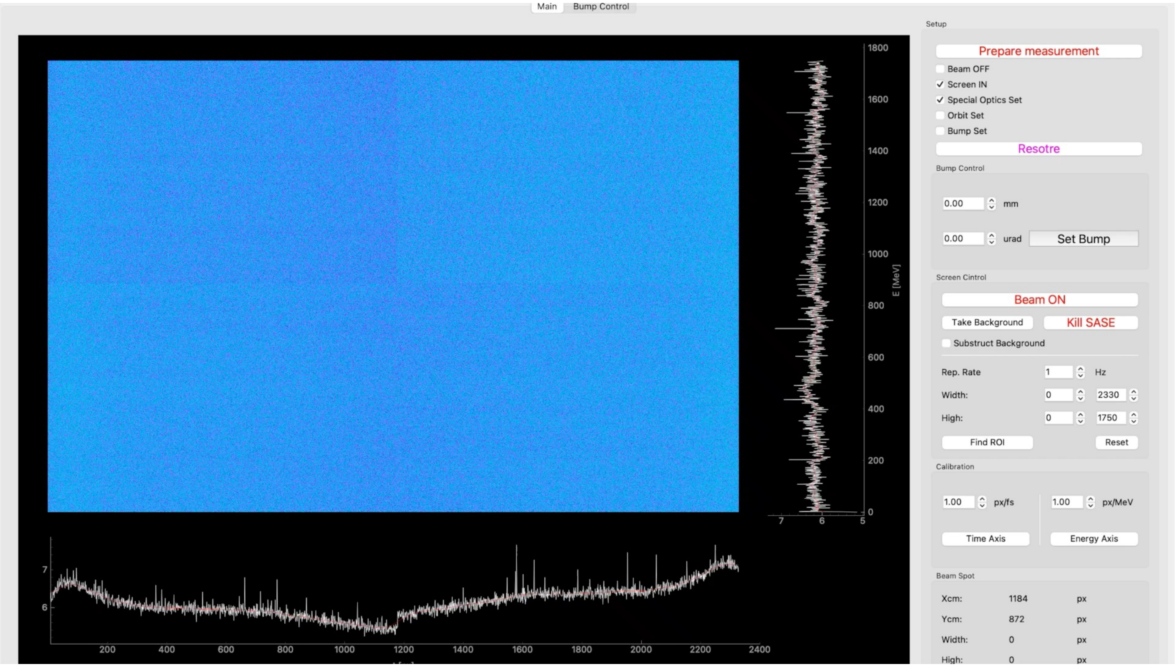
Self-consistent current profile reconstruction algorithm

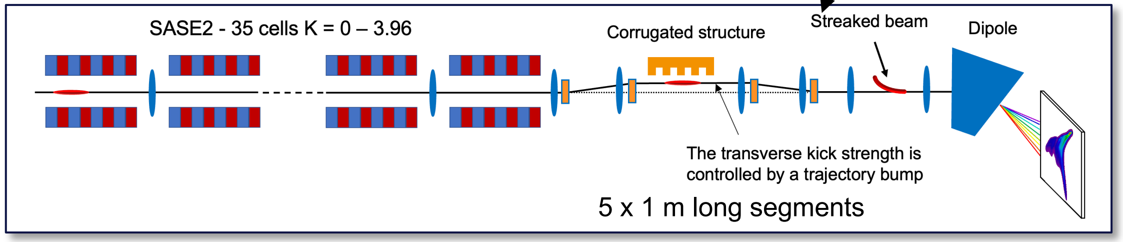


- Summer 2020 DESY colleagues visited PSI and observed passive streaker in action

Part IV
Passive streaker in the EuXFEL







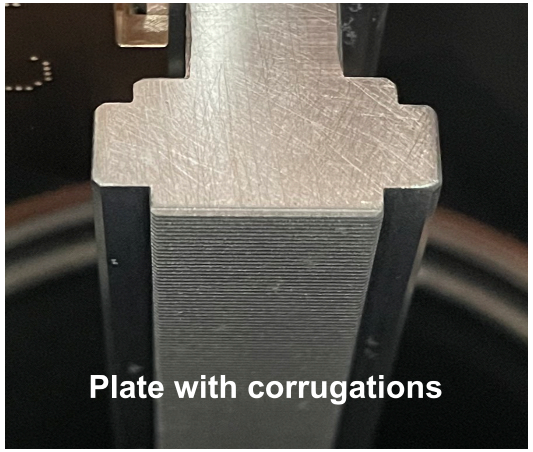
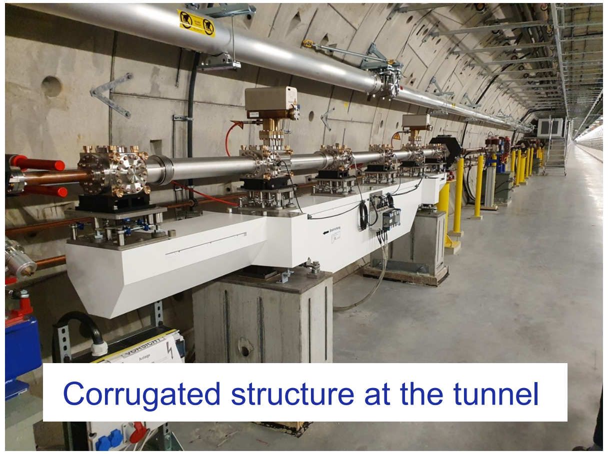


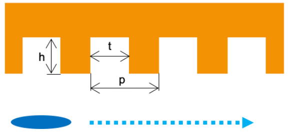
Plate with corrugations


Corrugated structure at the tunnel

- A very first video during commissioning

S. Tomin et al., Proc. IPAC 2022, https://doi.org/10.18429/JACoW-IPAC2022-MOPOPT020

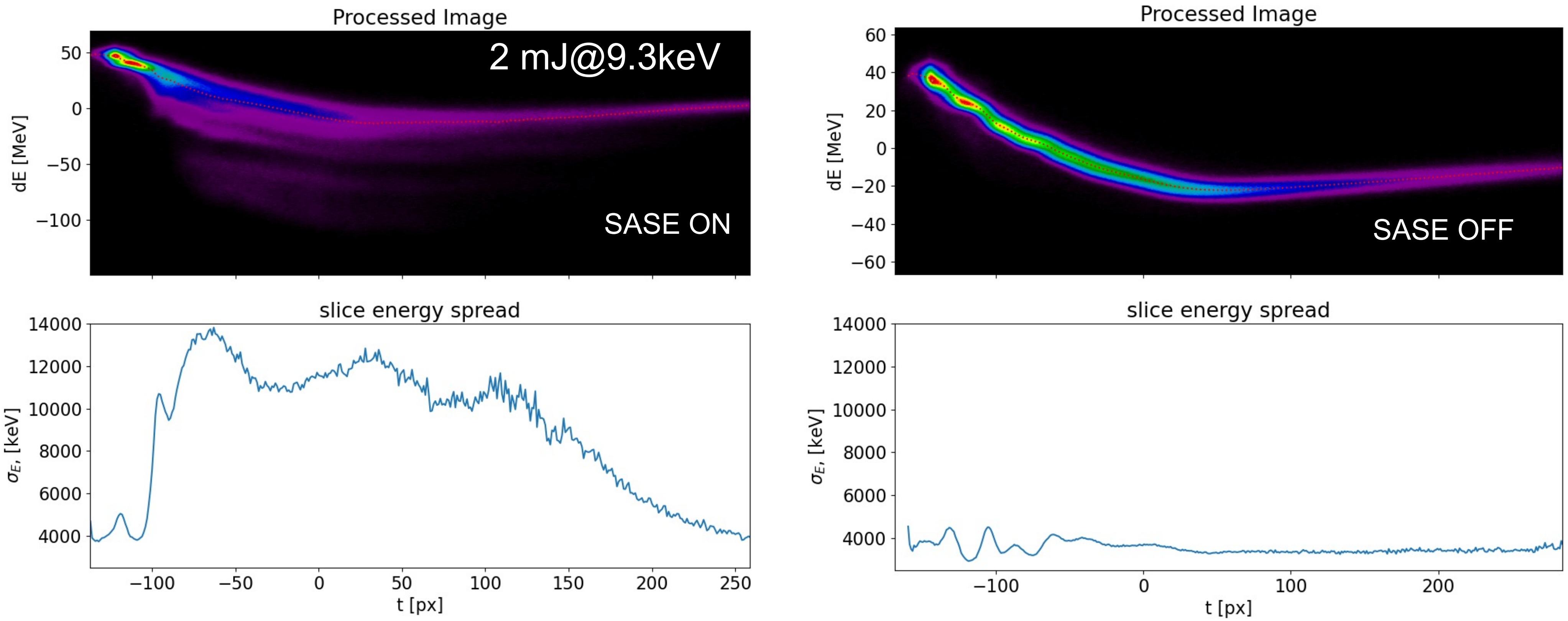
- Design report: October 2020
- Installation: December 2021
- Commissioning: 27 and 30 January 2022



h [mm]	t [mm]	p [mm]
0.5	0.25	0.5

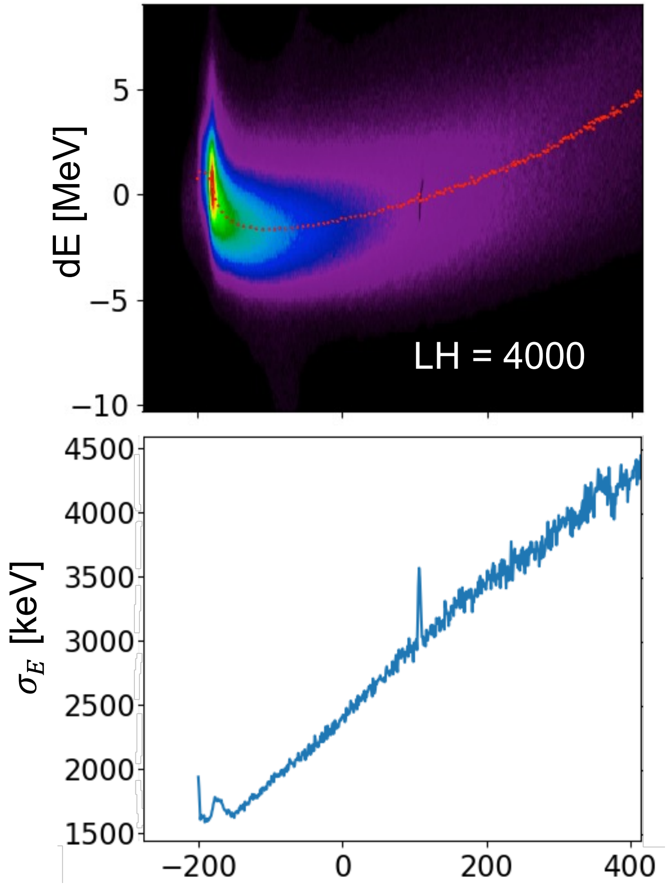
LPS measurements with the passive streaker

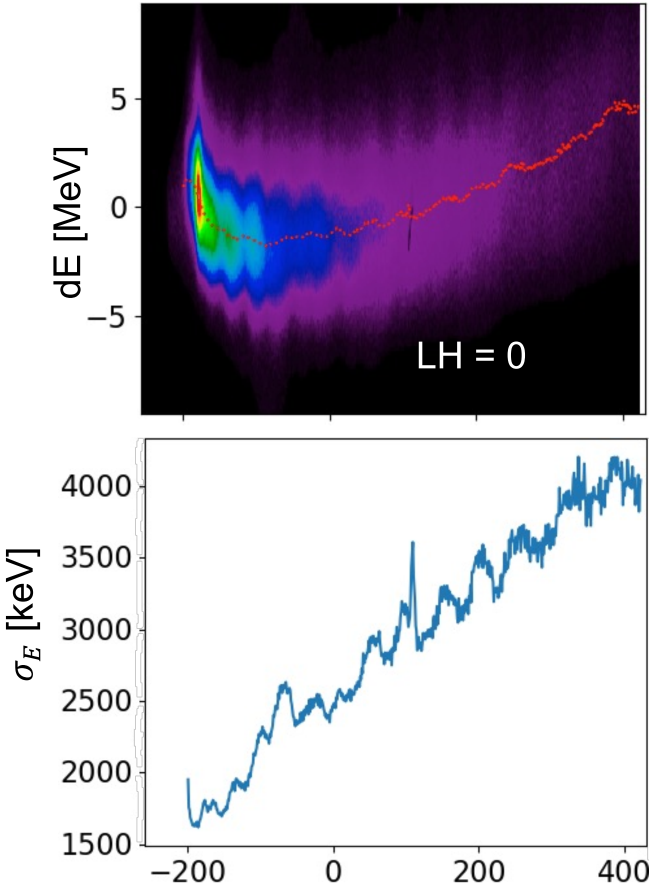
- Once installed after the undulator, the passive streaker becomes a compact longitudinal diagnostic for FEL operation.



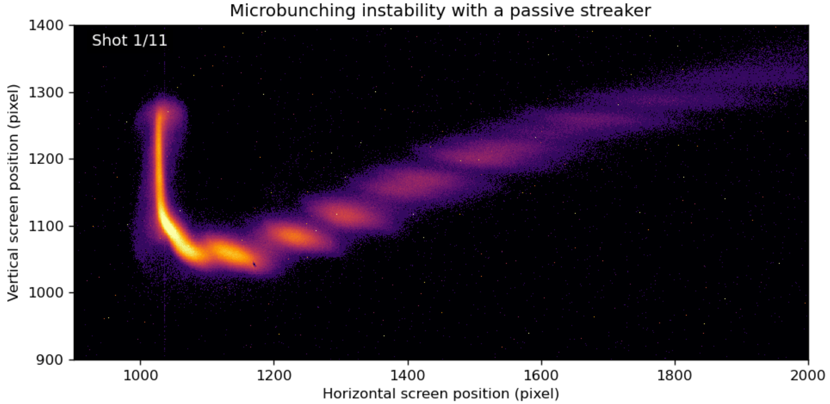
Observation of microbunching instability

- Lower beam current





- Nominal beam current LH is OFF

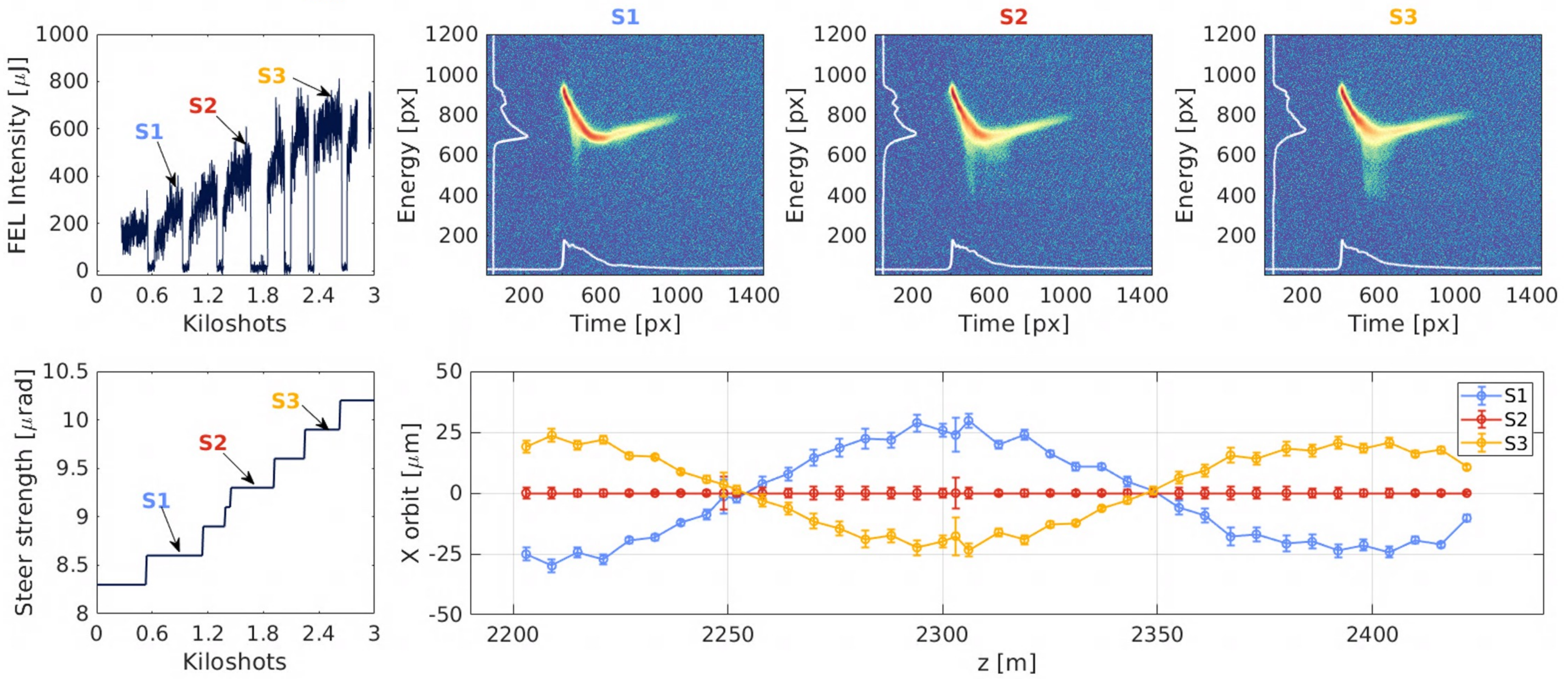


- LH - Laser Heater attenuation

PostSA2 diagnostic passive streaker

PostSA2 diagnostic passive streaker: Lasing slice control by launching orbit

14.02.2022, 9keV, full lasing 2 mJ



European XFEL

Courtesy of W.Qin

DESY.

Slice Energy Spread measurements with passive streaker

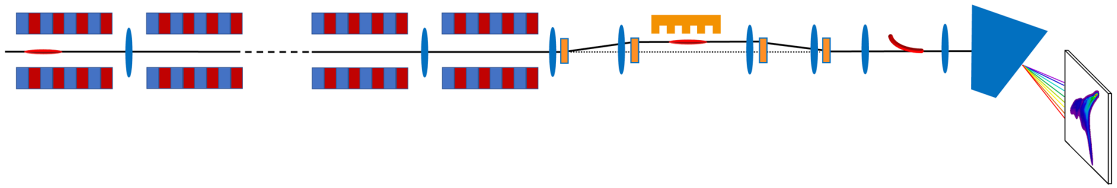
- A relativistic electron beam moving in a magnetic field emits radiation. Its mean energy decreases, and its energy spread increases due to quantum fluctuations of photon emission. The quantum diffusion effect is the energy diffusion in an electron beam due to quantum fluctuations
- Two measurements: dependence of energy diffusion on
  - the length of the undulator (total magnetic length 175 m)
  - the undulator K parameter

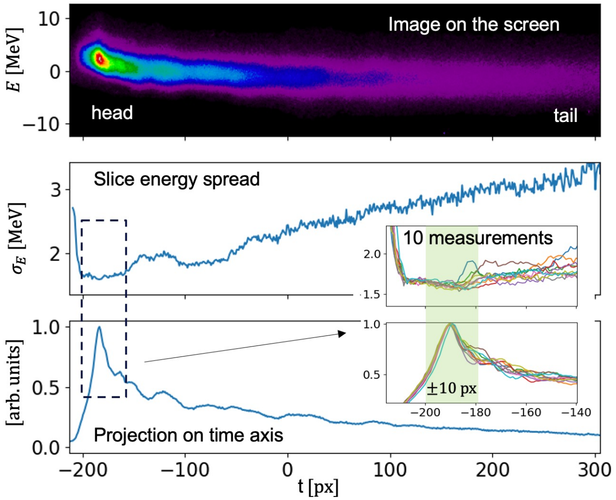
$$\frac{d\left\langle(\delta\gamma)^2\right\rangle}{dt} = \frac{7}{15} c \lambda_c r_e \gamma^4 k_w^3 K^2 F(K)$$

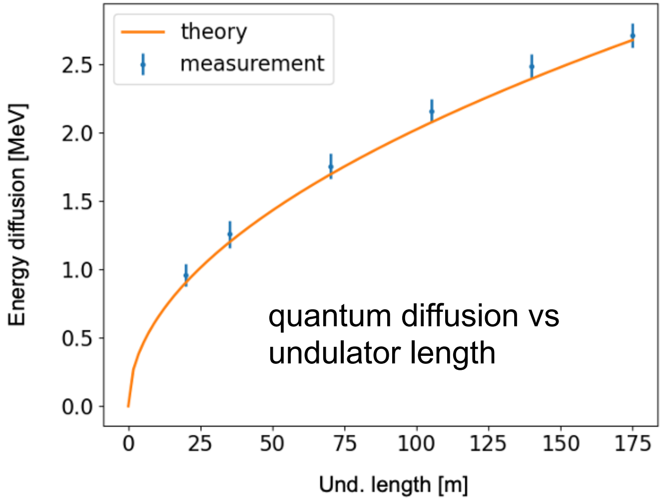
$$F(K) = 1.20K + \frac{1}{1 + 1.33K + 0.40K^2}$$

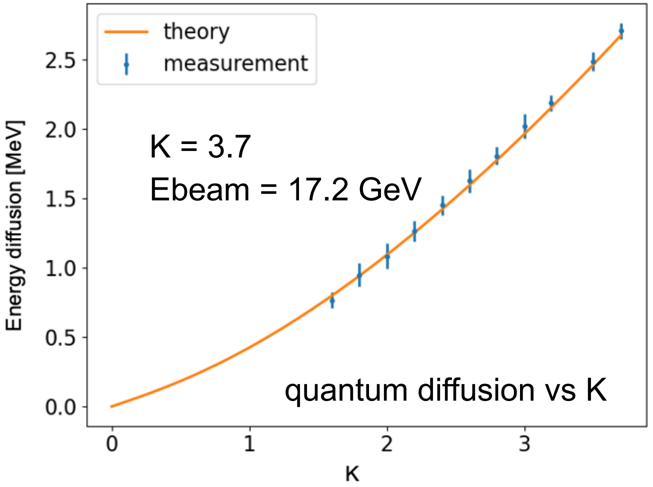
E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, NIM A 381 (1996) 545-547

SASE2 - 35 cells K = 0 – 3.96









S. Tomin, E. Schneidmiller & W. Decking, Scientific Reports 13, 1605 (2023)

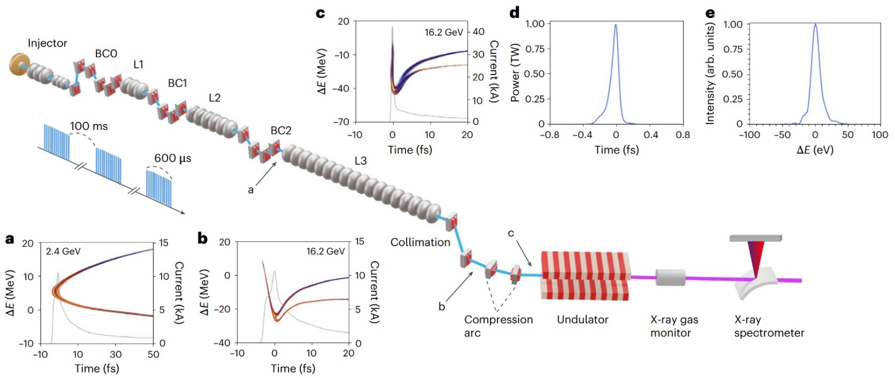
PostSA2 diagnostic passive streaker

Generation of high-power attosecond hard X-ray free-electron laser pulses

Jiawei Yan, XOPT2025, 22.04.2025

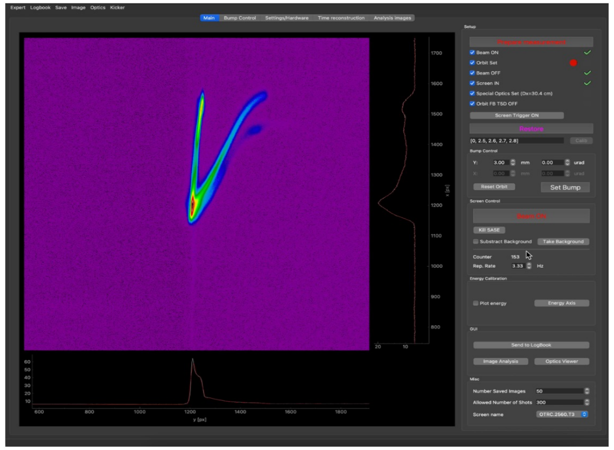
1

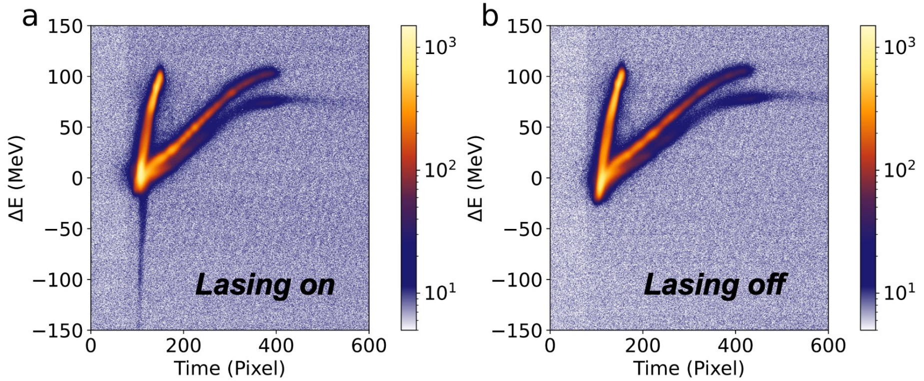
Dechirper for attosecond hard X-ray FEL development



Schematic of the self-chirping mode at European XFEL

Jiawei Yan, et al. Nature Photonics (2024)





European XFEL

- The dechirper and LPS reconstruction are critical tools for attosecond XFEL tuning.
- While the current spike is not fully resolved, LPS analysis still reveals potential over- or under-compression in the arc.
- Qualitative features of the LPS measurements are in good agreement with the simulations

Passive streaker LPS reconstruction

- The price of simplicity is a more involved reconstruction: the streaking field is generated by the beam itself, so the time-to-screen mapping depends on the unknown current profile.

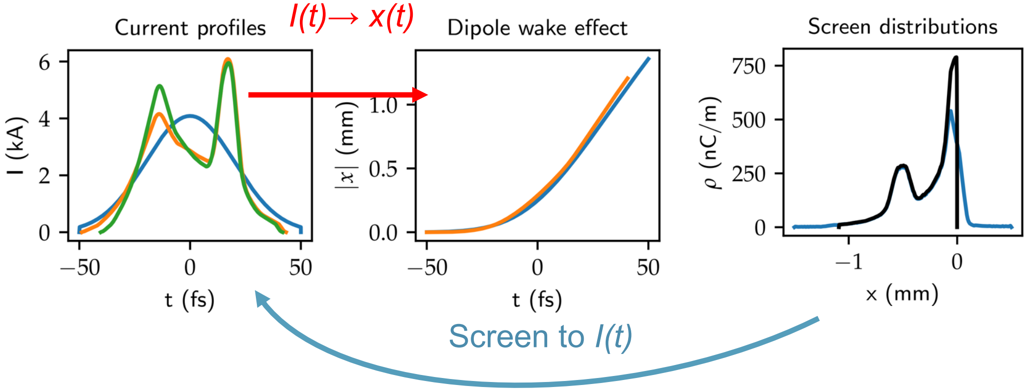
- **Bettoni et al., PRAB 19, 021304 (2016)**
  - Forward-fitting reconstruction of the measured screen profile

- **Seok et al., PRAB 21, 022801 (2018)**
  - Iterative inversion using the monotonic $t \leftrightarrow x$ mapping

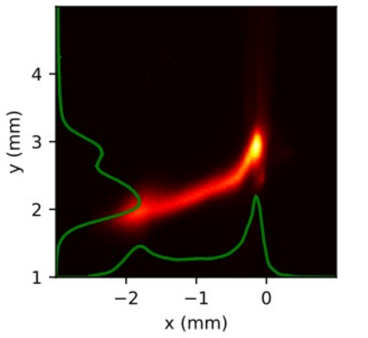
- **Dijkstal et al., PRR 4, 013017 (2022)**
  - Self-consistent current profile reconstruction algorithm

Self-consistent current profile reconstruction algorithm

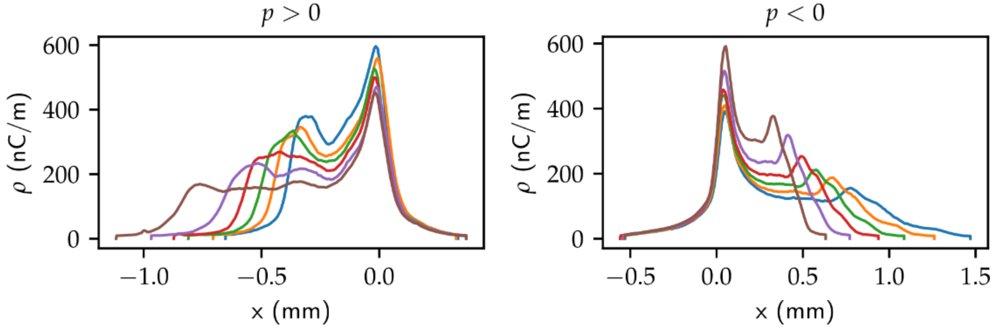
- The wake, and therefore the streaking, depends on the unknown current profile → an iterative reconstruction is needed.
- Main problem: A short bunch passing close to a plate is difficult to distinguish from a long bunch passing further from a plate.
- Idea: combine measurements performed with different distances (with known differences between them)
- Use measurements from both plates ($p>0$ and $p<0$) to **find self-consistent solution where all reconstructed current profiles are similar**



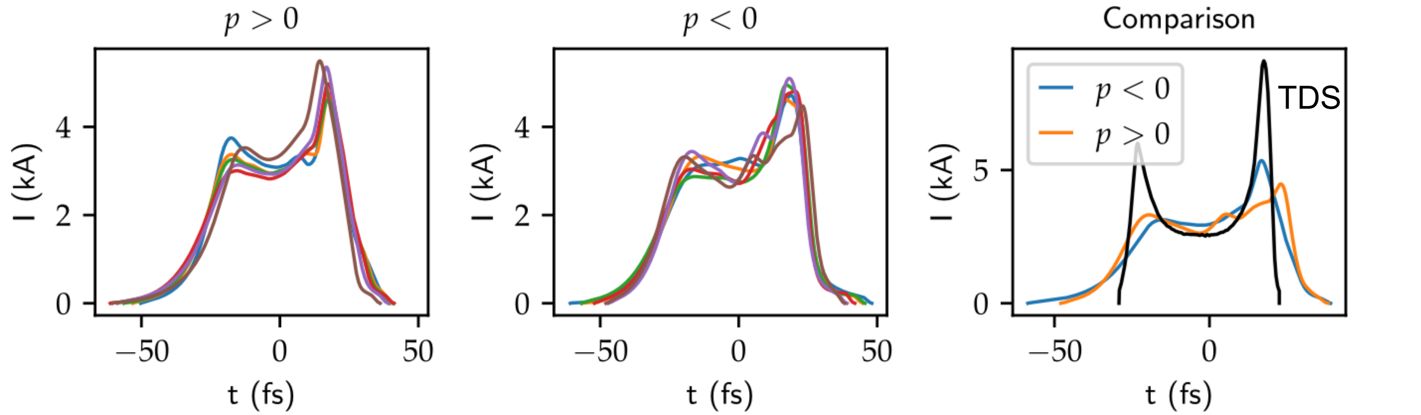
Single measurement



Measurements under variation of structure center position p



Final result of iterative procedure after optimizing assumed plate positions

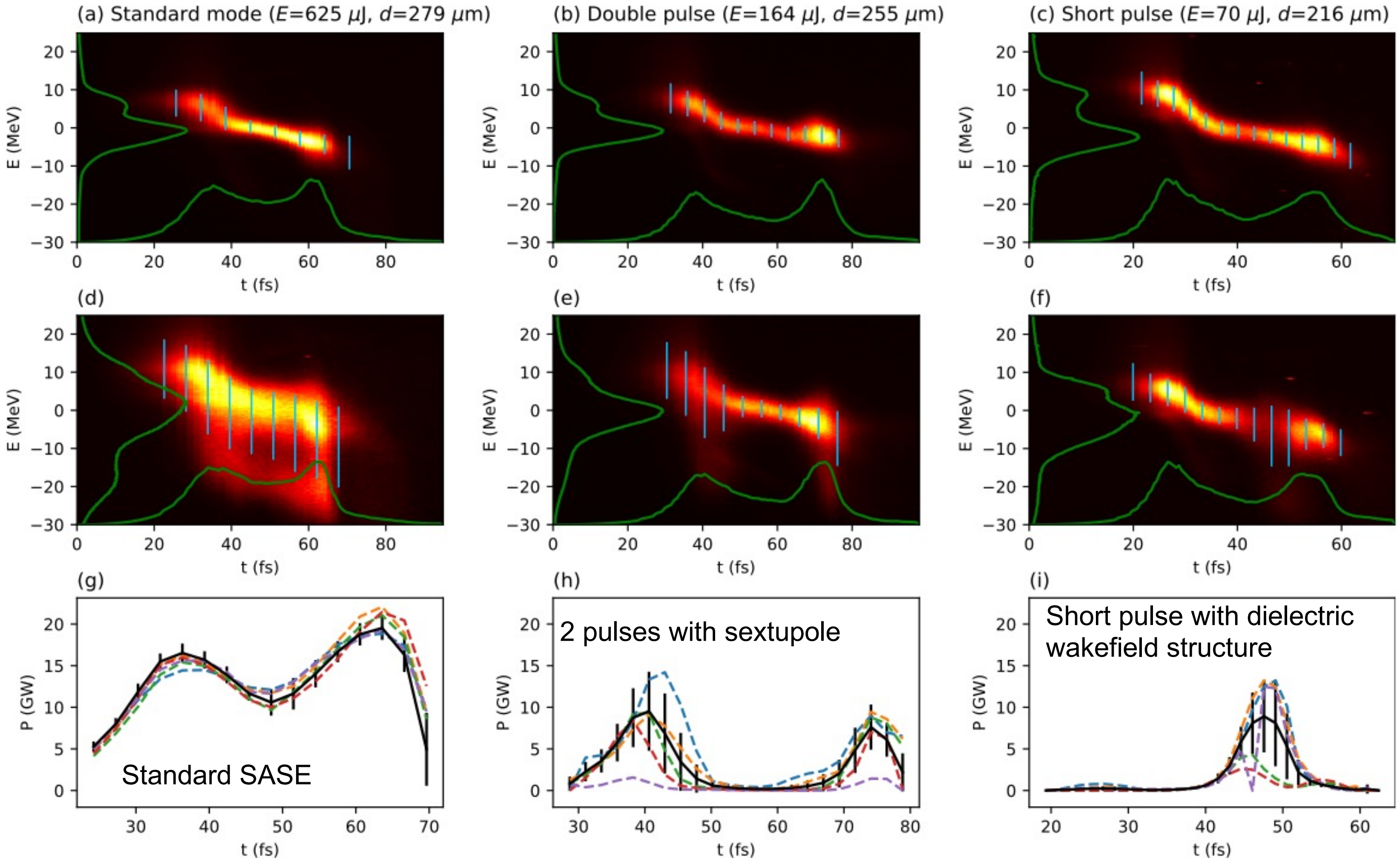


- similar to J. Seok et al., Phys. Rev. Accel. Beams **21**, 022801 (2018)

- *Dijkstal et al., PRR 4, 013017 (2022)*
- P. Dijkstal, PhD thesis, ETH Zurich (2022)

DESY.

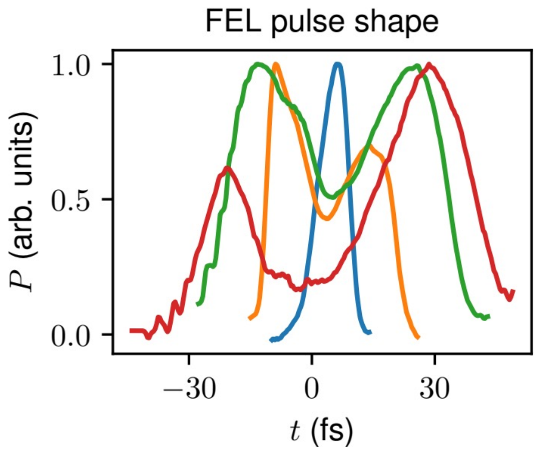
LPS and FEL power profile reconstruction

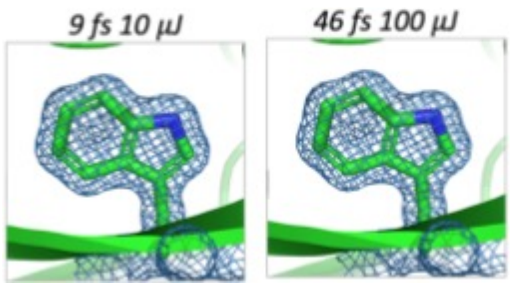


Dijkstal et al., PRR 4, 013017 (2022)

Pulse duration scan at SwissFEL

- Investigating "diffraction before destruction" at Cristallina-MX end station (SwissFEL)
- It was requested FEL pulses with durations between ~10 fs FWHM and the maximum possible.
- Pulse duration changed with bunch compression system between ~25 and 46 fs FWHM, and reduced from 25 to 8 fs with beam tilt from dielectric wakefield structure before Aramis
- FEL power profile measured with passive streaker

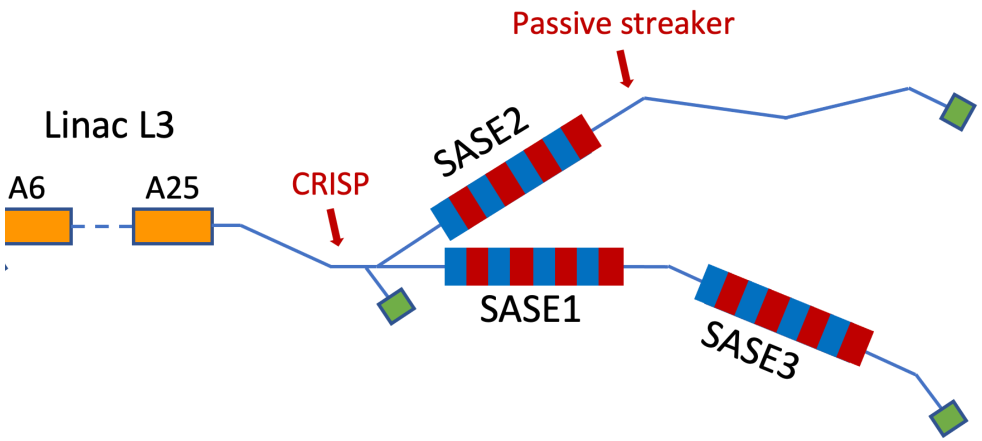




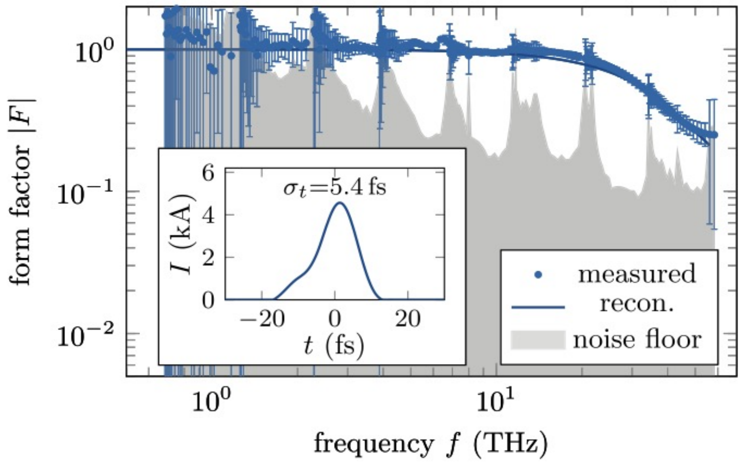
Williams et al., Damage before destruction? X-ray-induced changes in single-pulse serial femtosecond crystallography, IUCrJ ***12****, 358-371 (2025)*

This experimental capability is only possible because of the PS!

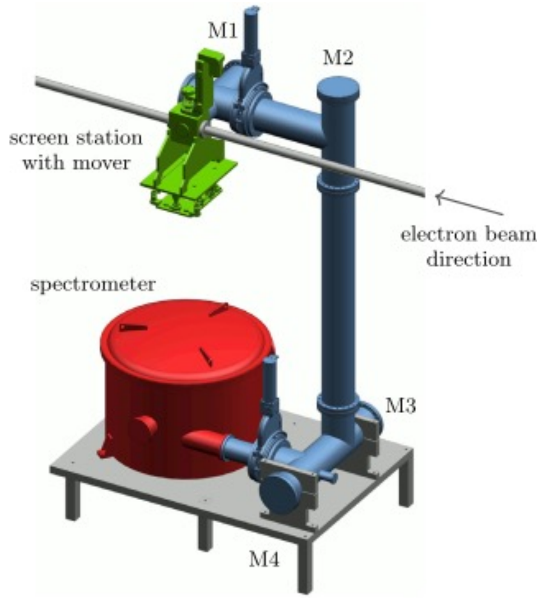
LPS reconstruction with known current profile



CRISP spectrum and reconstruction



Coherent radiation intensity spectrometer (CRISP)

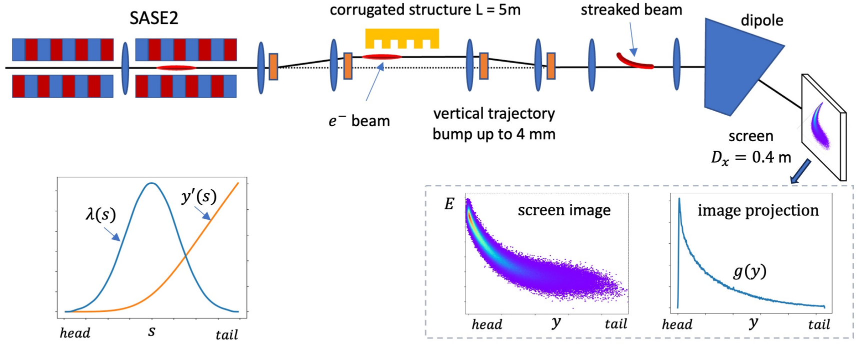


References

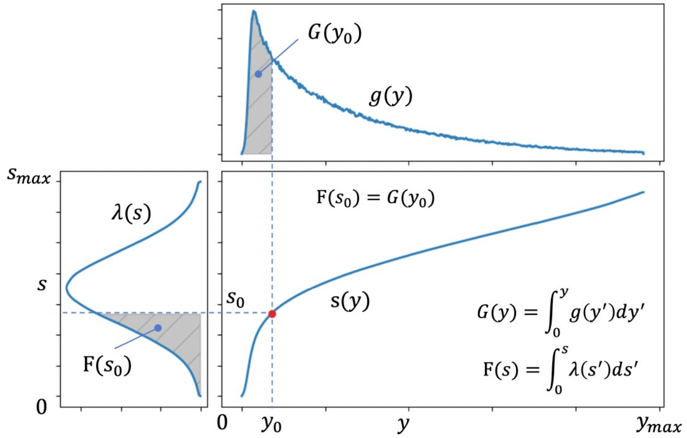
- S. Wesch et al., Nucl. Instr. and Meth. A, 655, 44 (2011), https://doi.org/10.1016/j.nima.2011.11.037
- B. Schmidt et al., https://doi.org/10.48550/arXiv.1803.00608 (2018)
- N. Lockmann et al., Phys. Rev. Accel. Beams 23, 112801, 112801 (2020) https://doi.org/10.1103/PhysRevAccelBeams.23.112801

LPS reconstruction with known current profile

- Developed new reconstruction method which uses beam current profile obtained from CRISP

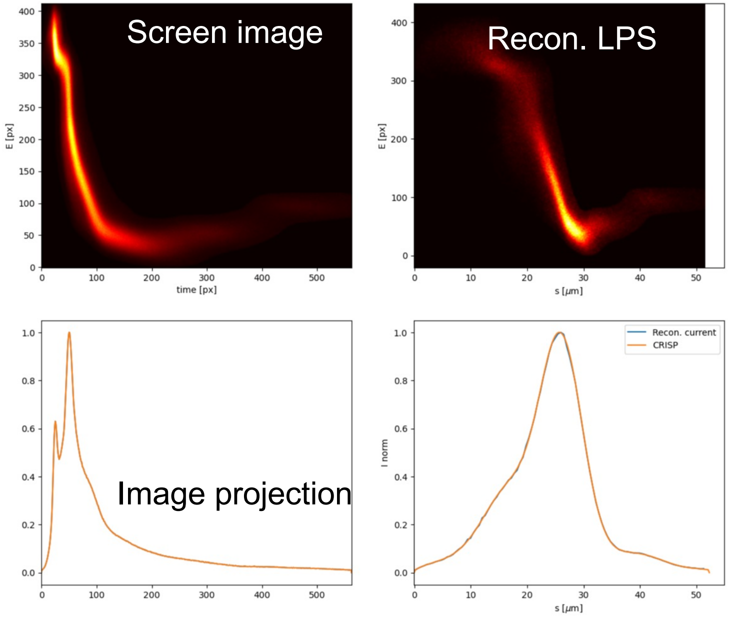


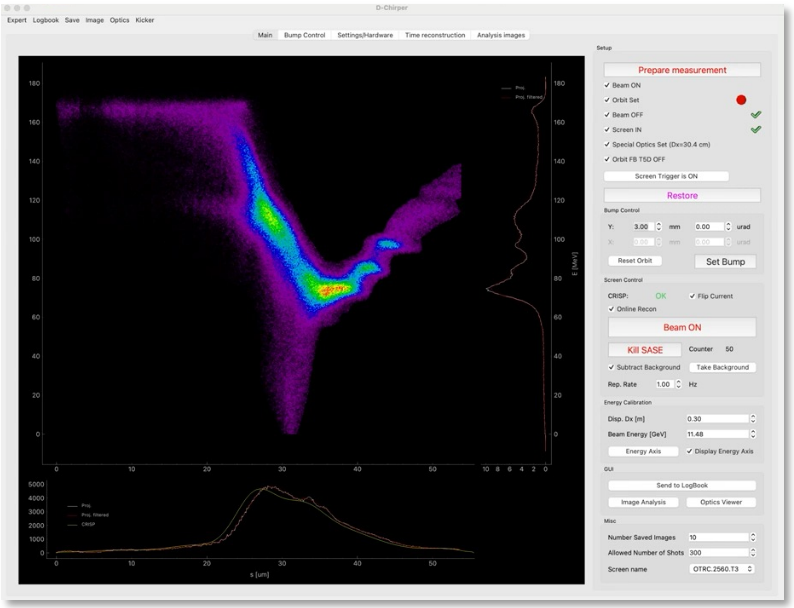
- **If current profile is known**



$$\int_0^{s_0} \lambda(s')ds' = \int_0^{y_0} g(y')dy'$$

- Lasing off





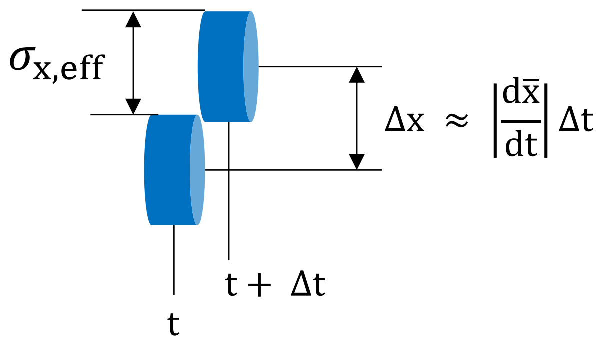
S. Tomin, I. Zagorodnov, A Method For Passive Streaker LPS Reconstruction, arXiv:2605.28541

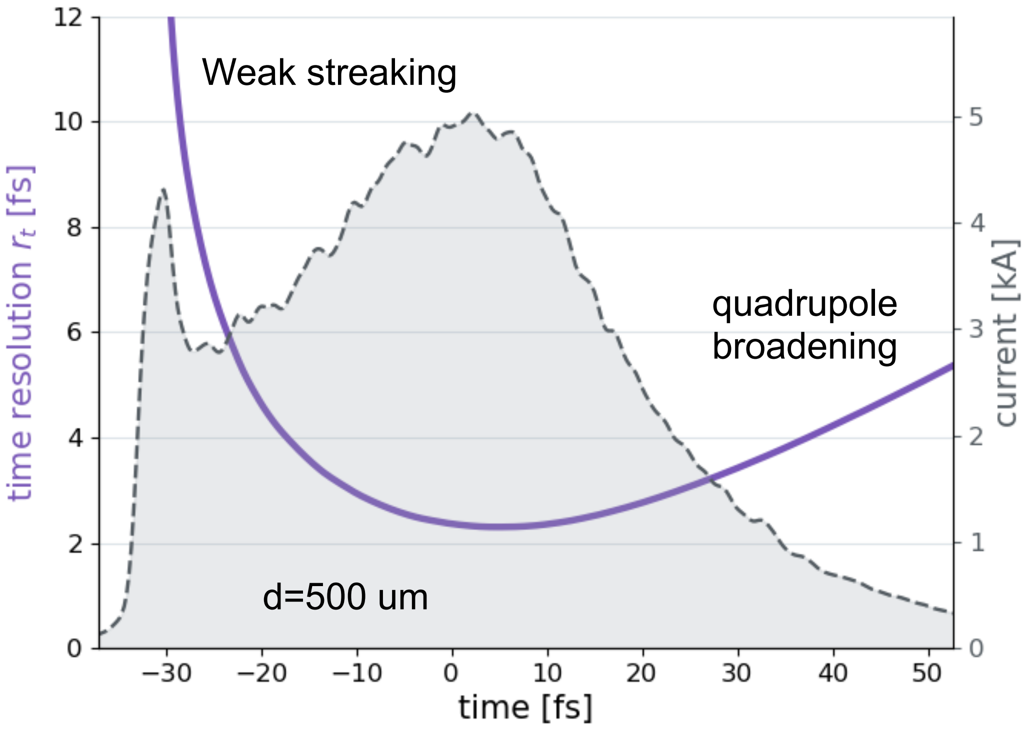
This is also the method used at SwissFEL, but with C-band TDS before undulators to measure the current profile. Much faster and more reliable method (but not self-consistent)

DESY.

Time resolution

- temporal resolution = transverse blur / local streaking slope
  - $r(t) \sim \dfrac{\sigma_{x,\mathrm{eff}}(t)}{\left|\frac{d\bar{x}(t)}{dt}\right|}$
- Why is it time dependent for a passive streaker?
  - $\dfrac{d\bar{x}(t)}{dt} = R_{12}\dfrac{d\widetilde{W}_d(t)}{dt}$
    - ▶ **Dipole wake $W_d(t)$:** nonlinear streaking → weak slope at the head
  - $\sigma^2_{x,\mathrm{eff}}(t) = \sigma_R^2 + \sigma_x^2(t)$
    - ▶ **Quadrupole wake** $W_q(t)$ **:** increases the slice width toward the tail

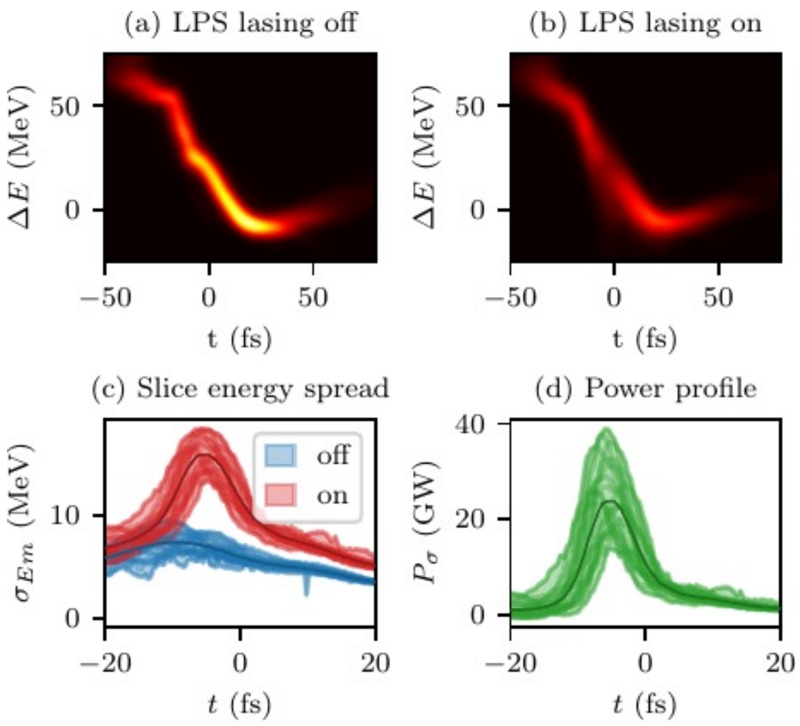




*P. Craievich and A. Lutman, NIM. A **865**, p. 55 (2017)*

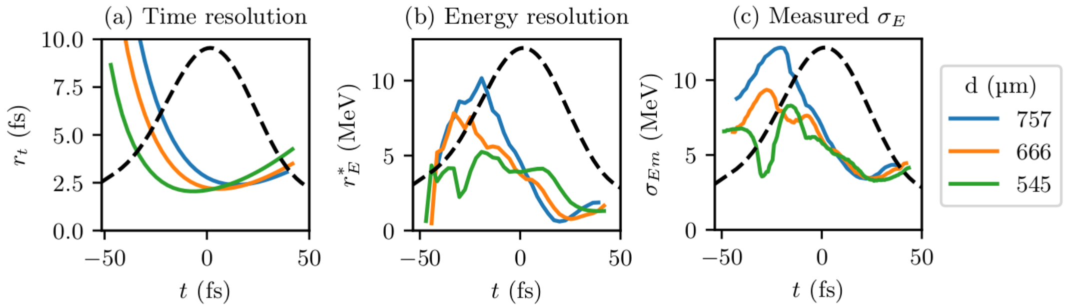
Energy resolution

FEL power profile measurement at EuXFEL



Observation: “Slice energy spread” obtained from σ/D is unrealistically high.

Finite time resolution causes additional measured slice energy spread in the presence of energy chirp.
The effect exists for RF TDS measurements but is stronger for passive streakers because the temporal resolution varies along the bunch.



$$r_E^*(t) = \sqrt{\left(\frac{E_0 \sigma_{x0}(t)}{D}\right)^2 + \Delta\sigma_E^2(t) + \left(r_t(t)\frac{\mathrm{d}E(t)}{\mathrm{d}t}\right)^2}$$

Dipole spectrometer resolution

PS-induced slice energy spread

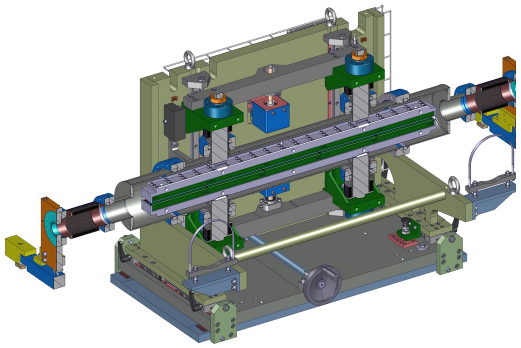
Temporal mixing due to finite time resolution

*P. Dijkstal et al., Phys. Rev. Accel. Beams **27**, 050702 (2024)*

Passive streaker design choice

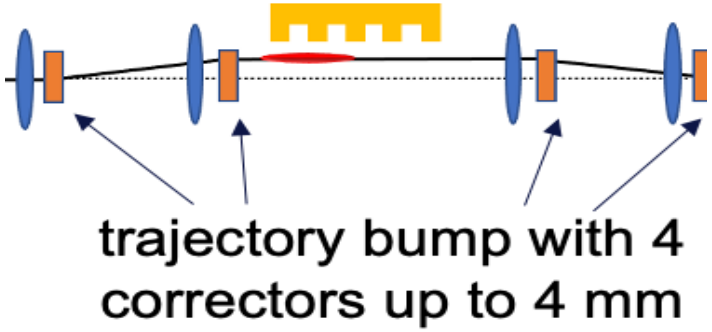
- Moveable structure
  - Precise distance scan
  - Provides reference (unstreaked) beam position
  - Mechanical complexity

- Double sided
  - Symmetric streaking, measures beam tilt/asymmetry
  - More complex



- Fixed structure
  - Simple, robust, vacuum-safe
  - Distance calibration required

- Single sided
  - Simplest implementation
  - Coupled transverse kicks and tilt cannot be separated



Final Part

Beam-driven TDS: can we combine advantages of both?

RF TDS

✅ Linear time-to-position mapping

✅ Direct LPS measurement

❌ External RF system

❌ Synchronization, klystrons, infrastructure

Passive streaker

✅ Compact and RF-free

✅ Self-synchronized

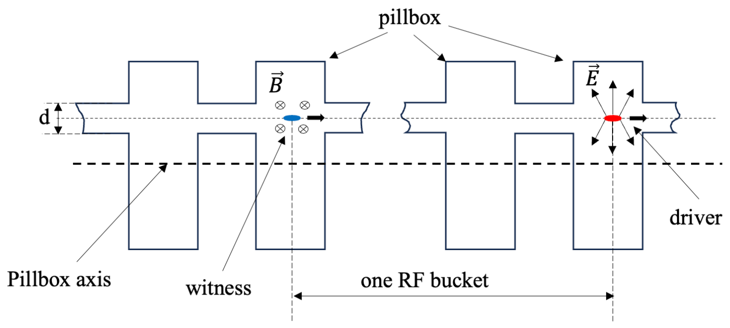
❌ Nonlinear streak

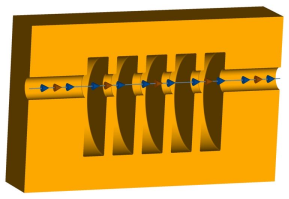
❌ Reconstruction required

Beam-Driven Transverse Deflecting Structure

- What if a driver bunch generates the streaking field?
  - At 1.3 GHz, driver and witness are separated by ~770 ps → a **long-lived wake** is required → **resonant structure**
  - The driver excites a broad spectrum of high-frequency transverse modes.
  - Their superposition produces a nearly linear wake around the zero crossing, where the witness bunch is placed

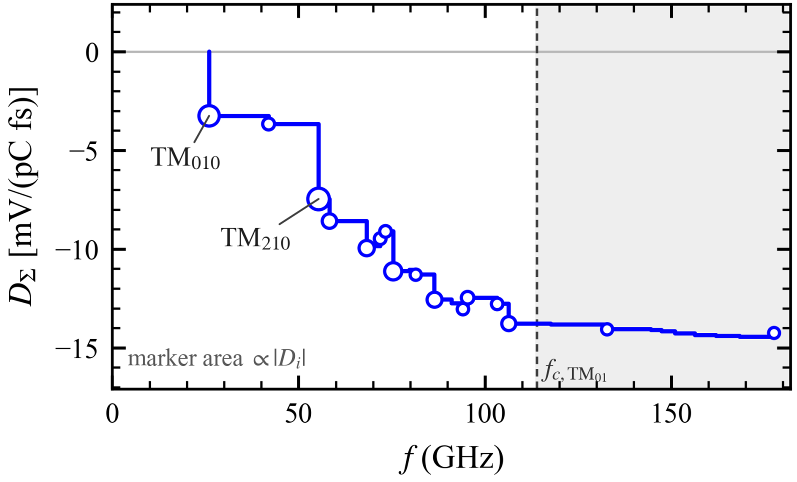
Pillbox cavity chain with an off-axis beam channel



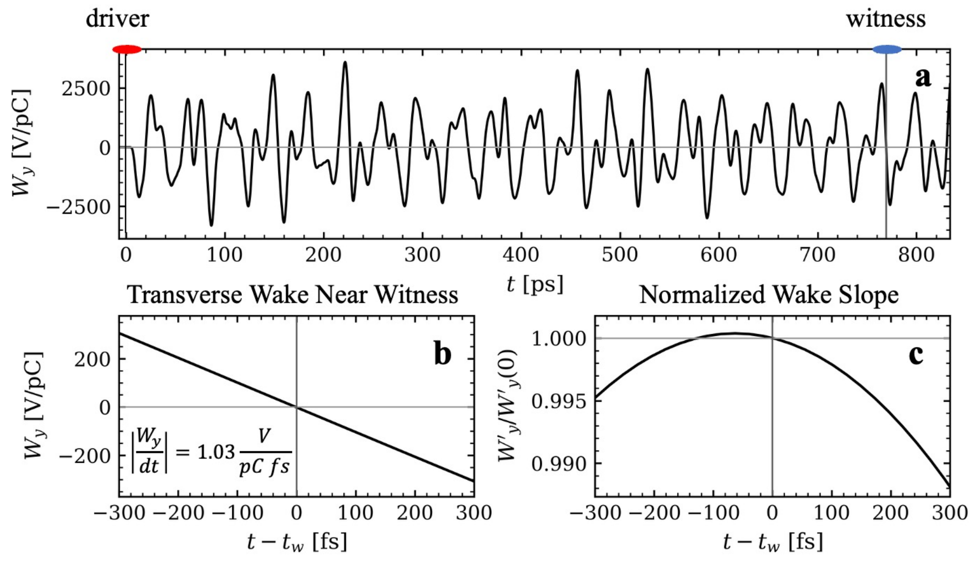


Half of the structure

Multimode spectrum of the beam-driven TDS



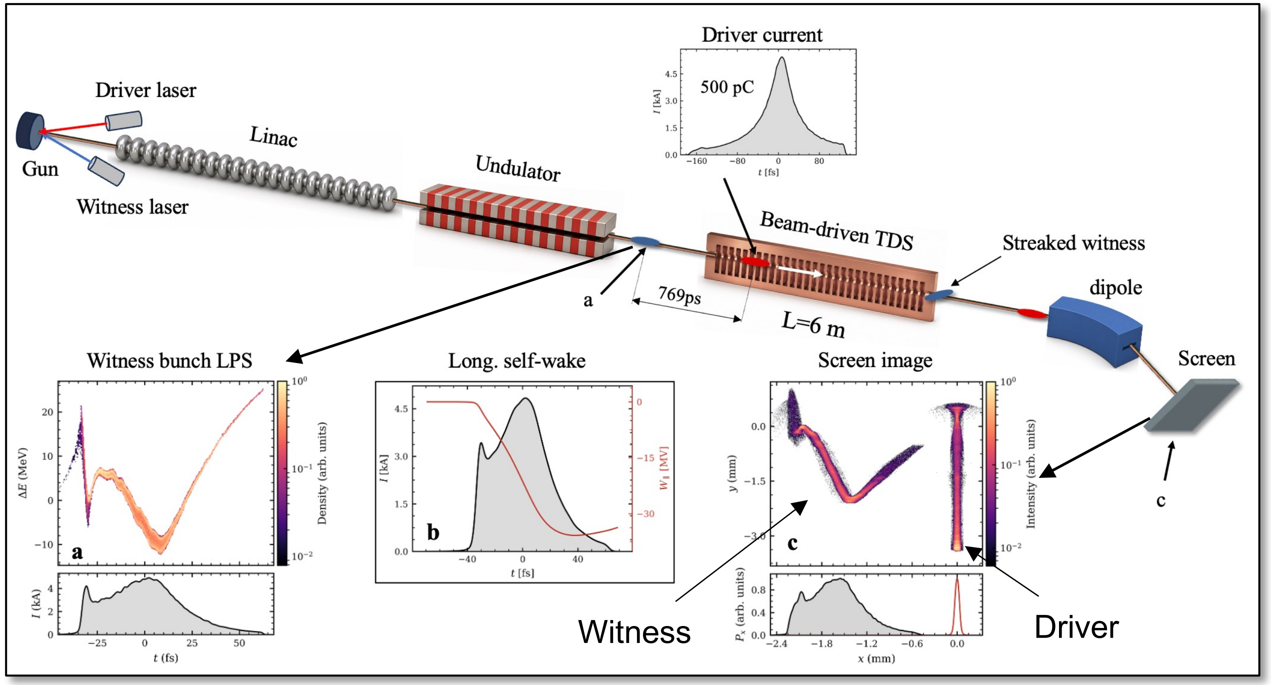
Transverse wake of a 1-m beam-driven TDS



S. Tomin et al, Beam-Driven Transverse Deflecting Structure for Femtosecond Electron-Beam Diagnostics, arXiv:2605.13752

Beam-Driven Transverse Deflecting Structure

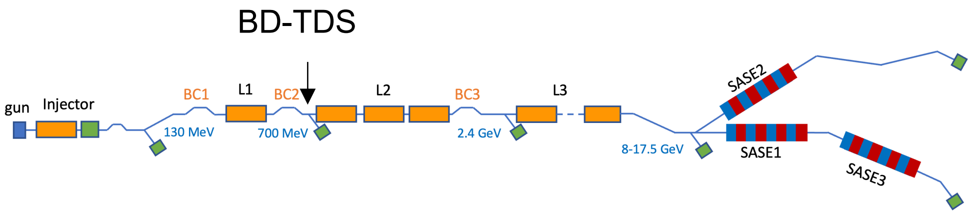
Replace the RF infrastructure with a driver bunch



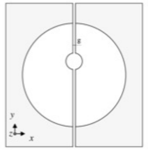
- Resolution: $\sigma_t \approx 1.6\,\mathrm{fs}$
- E_{beam} = 14 GeV, Q_{driver} = 500 pC
- **Trade off: second laser is required**

S. Tomin et al, Beam-Driven Transverse Deflecting Structure for Femtosecond Electron-Beam Diagnostics, arXiv:2605.13752

Experimental test in preparation at European XFEL



- Optimized resonant structure for the EuXFEL B1 section
  - Mechanical tolerance:
    - ► 10 µm fabrication errors preserve streaking performance
  - Temperature tuning:
    - ► wake phase shifts, slope remains stable
  - Split structure:
    - ► no RF contact between two halves required



D. Bazyl et al, Design criteria for a beam-driven resonant passive transverse deflector for longitudinal beam diagnostics, arXiv:2606.24594

Summary

- Passive wakefield streakers are now established tools for longitudinal diagnostics at FELs, with routine applications at SwissFEL and European XFEL.
- They provide current profile and LPS measurements without an RF deflector, but the beam-dependent nonlinear streak requires reconstruction and careful calibration
- Using an independently measured current profile can make LPS reconstruction potentially more precise and robust
- Beam-driven TDS concepts may ultimately combine the simplicity of passive devices with an RF-TDS-like quasi-linear mapping

- Next at EuXFEL:
  - post-SASE3 passive streaker - winter of 2026
  - Movable structure for precise beam-to-plate distance control
  - first Beam-Driven TDS test

Thank you for your attention