PAUL SCHERRER INSTITUT PSI

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Time resolved diagnostics: TDS, TDC, TCAV…

WP13 EuPRAXIA electron and photon diagnostics, EPFL, 12.06.2023

Outline

– Motivations for high-resolution time-resolved diagnostic

– TDS as diagnostic tools

– Novel Concept with Variable Polarization – The PolariX TDS

- ❖ Results obtained at DESY

– Overview of the LPS measurements in SwissFEL

- ❖ C-band TDS system

– Post-undulator PolariX TDS for ATHOS

- ❖ Specifications and commissioning
- ❖ Results

– Summary and conclusion

Motivations for high-resolution time-resolved diagnostics

Ongoing Tendency of Getting Shorter and shorter Electron Bunches

- FEL science (user): novel coherent diffractive imaging techniques and timing of ultrafast process require shorter (sub-fs/as) FEL X-ray pulses, i.e., observation of atomic and molecular process occurring at attosecond timescale
  - Femtosecond-level temporal resolution are required for optimisation of these ultra-short bunches
  - Single-shot characterization of the longitudinal phase space of the beam allows for single-shot reconstruction of the X-rays pulses as well
- Novel high-gradient acceleration techniques: Laser Wakefield Plasma Acceleration – LWFA, Beam Driven Plasma Acceleration –PWFA, THz driven Acceleration, Dielectric Laser Driven Acceleration - DLA) are characterized by short period of accelerating field and therefore naturally produce or accelerate fs long beams
  - The focusing gradients inherent to these novel high-gradient accelerator concepts require high-quality, axially-symmetric beams
  - Longitudinal characterization of the driver and witness electron beams is essential for characterizing and optimizing the acceleration channel

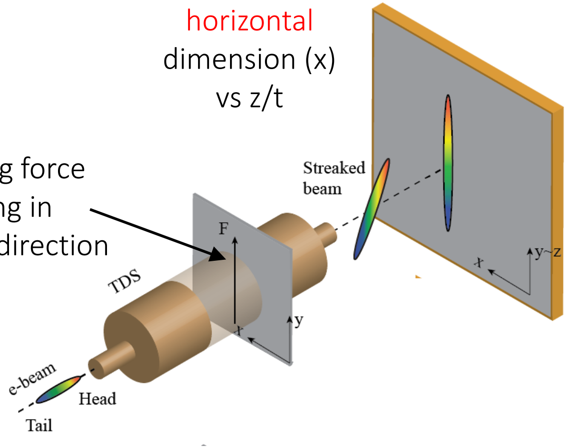
Transverse Deflecting Structures – What's next?

TDS are RF-based devices used for the manipulation and/or the diagnostics of charged particle beams to retrieve longitudinal/temporal proprieties

Conventional TDS: streaking in a fixed polarization (i. e. vertical or horizontal)

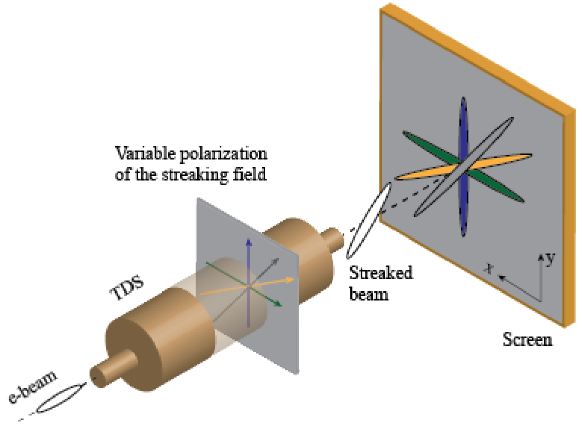
horizontal dimension (x) vs z/t

Streaking force oscillating in vertical direction



The longitudinal distribution of the e-bunch is mapped into the transverse one thanks to the time dependent transversely deflecting field

POLARIzable X-band Transverse Deflection Structure – **POLARIX TDS**



Diagnose multidimensional phase space of electron bunches to investigage complex beam dynamics (e.g. collective effects, beam correlations, slice emittance..)

TDS as diagnostic tools – capabilities

– Bunch length measurement and longitudinal charge profile measurement (1D)

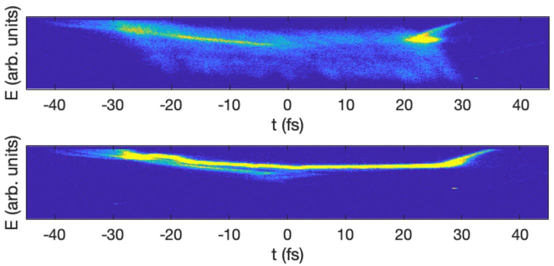
– Combined with dipole → longitudinal phase space measurement

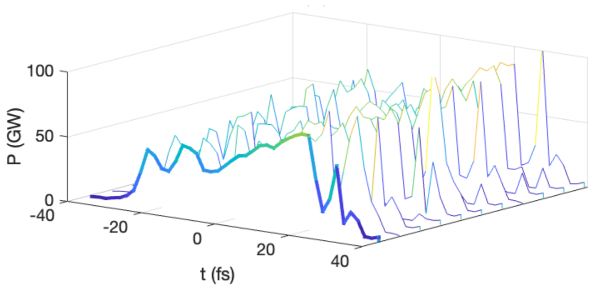
– Combined with quadrupole scan or multi-screen lattice → slice emittance measurement on the plane perpendicular to the streaking direction, slice transverse phase space reconstruction - **slice emittance on different transverse planes**

– Measure of the FEL-induced lasing effects imprinted on the electron beam longitudinal phase space: first reference C. Behrens et al., Nat. Comm. 5, 3762 (2014)

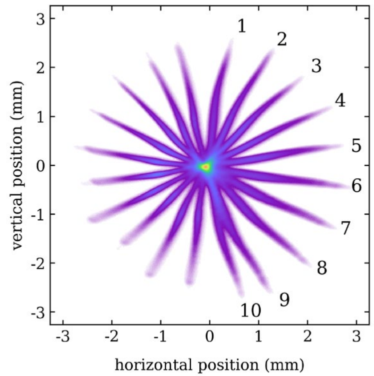
– 5D/6D phase-space characterization becomes possible by different streaking planes and using tomographic methods

– Reconstruction of the 3D charge density





Example from SwissFEL/Athos



B. Marchetti et al., Sci. Rep., 2021

TDS as a diagnostic tool – time resolution

Longitudinal resolution is limited by the vertical beam size and the streak parameter S:

$$\sigma_{t,R} \geq \frac{\sigma_{y0}}{S} = \sqrt{\frac{\boxed{\varepsilon_{N,y}}}{\boxed{\gamma}\boxed{\beta_d}}}\,\frac{\boxed{pc}}{\boxed{eV_\perp\; ck_{rf}}}\,\frac{1}{\boxed{\sin(\Delta\psi_{ds})}}$$

Electron bunch: ✓ Given by the project
- beam energy
- normalized emittance $\varepsilon_{N,y}$ (screen resolution!!)

Optics:
- phase advance, $\sin(\Delta\psi_{ds})$
- beta function at TDS, β_d

✓ Optic design of the diagnostic beam line
✓ $\sin(\Delta\psi_{ds}) \sim 1$
✓ High-beta function at TDS

RF structure:
- wave number $k_{rf} = w_{rf}/c$
- Integrated deflecting voltage $V_\perp = K \cdot L \cdot \sqrt{P_{RF}}$

✓ X-band frequency allows having higher resolution due a smaller wave number than S-band (x4) and C-band (x2) frequencies
✓ Shorter structure with large kick, i.e., K = 4 and 11 MV/ (m·√MW) for C-band and X-band structures

TDS as a diagnostic tool – some remarks

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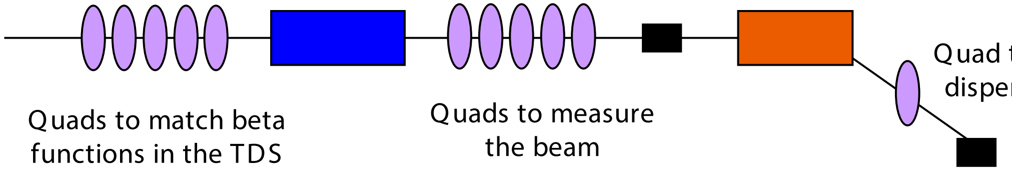
General measurement concept



TDS system needs space for the installation of all components!

Energy resolution

Off-axis particles are also accelerated $V_z(y) = k*y*V_0$

This results in a relation of time and energy resolution:

$\delta_E \sigma_z = \varepsilon$ (C. Behrens and C. Gerth, DIPAC09)

$$\sigma_{\Delta Eind} = \frac{E_0 \cdot \varepsilon_N}{c \cdot \sigma_{t,res}}$$

More info:
E. Prat et al. PR AB 23, 090701 (2020)

Non linearities in RF fields

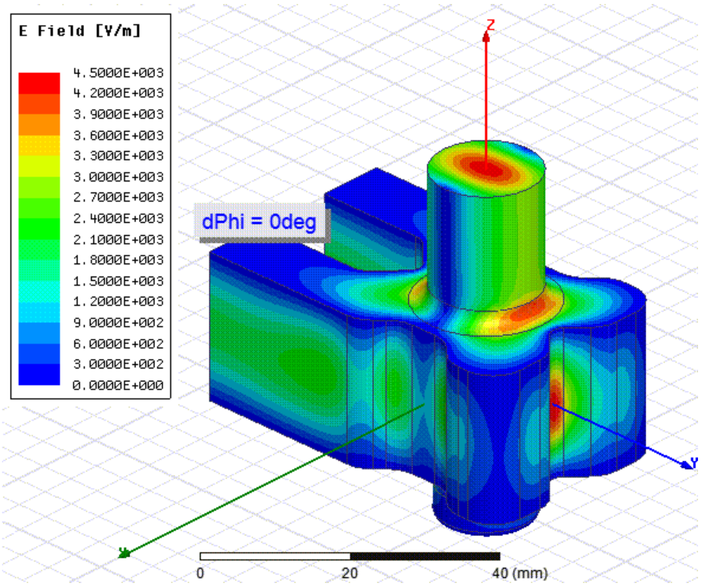
To first order the streaking field is independent from transverse offset, **BUT** this depending on the beam size and iris diameter. In additon there are RF input/output couplers that can give non linearities in the RF field.

TDS system used at lower energy **MUST HAVE** very low residual non linearities in order to:

- perform high precison mesurements
- emittance preservation at phase space manipulations
- avoid optics matching issue even without RF TDS

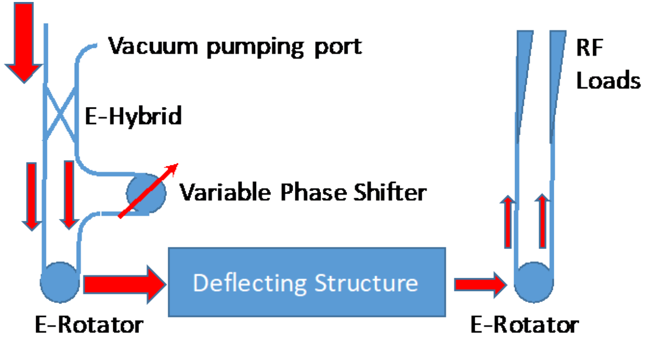
Novel Concept with Variable Polarization – X band

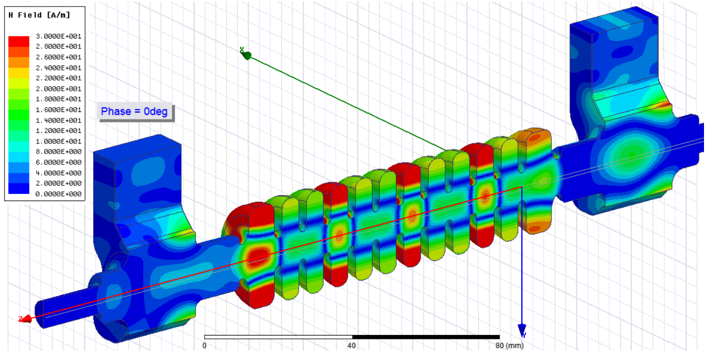
Variable polarization circular TE11 mode launcher: E-rotator



Phase difference between port 1 and port 2:

- 0 degree -> vertical polarization
- 180 degree -> horizontal polarization





References:
Grudiev, CLIC-Note-1067, 2016
P. Craievich et al., Phys. Rev. Accel. Beams, 2020
B. Marchetti et al., Sci. Rep., 2021

DESY-CERN-PSI Collaboration

History of the Collaboration, including the main Milestones of the Project

The RF design of the TDS has been done at CERN (with support from PSI)

Common Mechanical Design of the structure fulfilling the requirements of the different experiments.

The mechanical design of the prototype has been done at PSI. The prototype as well as the series structures has been/ will be manufactured using the PSI tuning free assembly procedure.

CERN performed the high-power test of the prototype.

DESY installed the prototype structure and appropriate RF-source in the FLASHForward beamline for first test of the structure with electron-beam → this lead to first measurements in September 2019!

2x TDSs installed in FLASH II and in operation

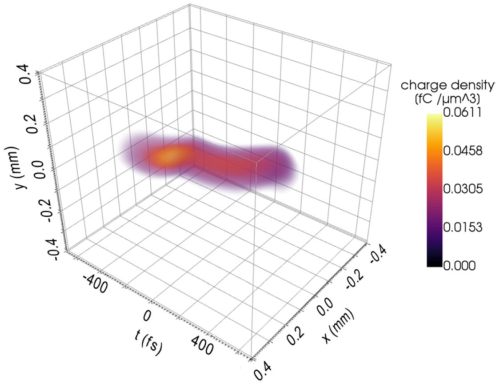
2x TDS installed in SINBAD-ARES (DESY) – they will start the RF conditioning soon

2x TDSs installed in SwissFEL Athos

Variable streaking angle enables new tomographic methods

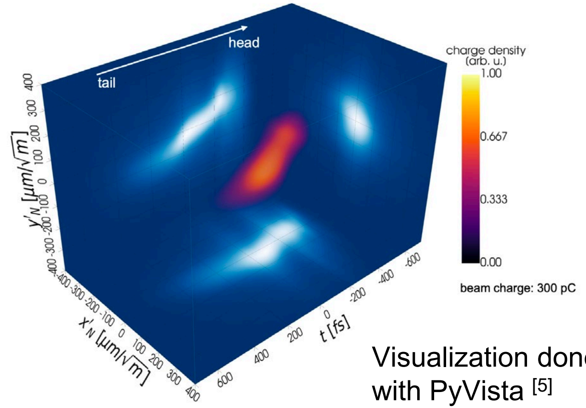
To obtain the full 5-dimensional (x, x′, y, y′, t) phase space of bunches

Experimental reconstruction of 3D charge density [1, 2] at FLASHForward:



Successful reconstruction of the 5D phase-space distribution

3D visualization of the (x'_N, y'_N, t) phase space



Visualization done with PyVista [5]

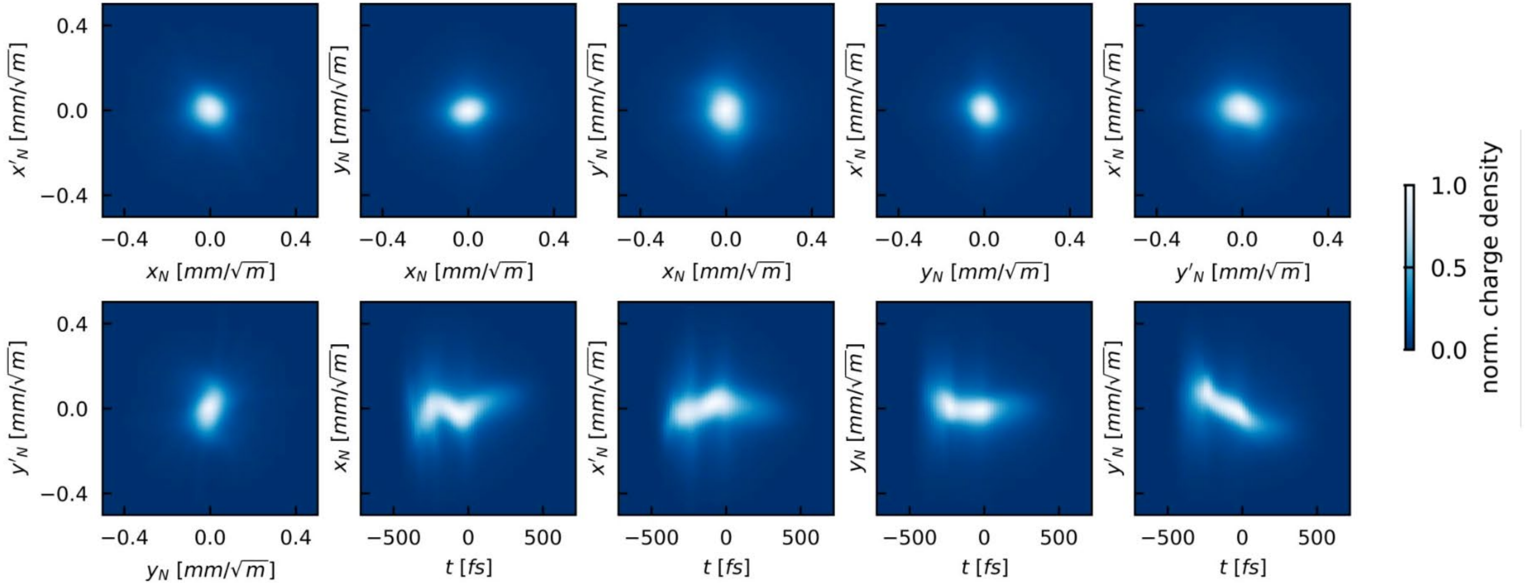
- 5D tomography:
  Quadrupole-based transverse phase-space tomography + streaking along various angles with PolariX TDS.
- Excellent performance shown in simulations [3, 4].
- Experimentally demonstrated (Sonja Jaster-Merz, IPAC’23, WEODB2)

[1] D. Marx et al., Journal of Physics: Conference Series, vol. 874, 2017,
[2] B. Marchetti et al., Sci. Rep., 2021 ,
[3] S. Jaster-Merz et al., JACoW IPAC2022 MOPOPT021, 2022 ,
[4] S. Jaster-Merz et al., JACoW LINAC2022 MOPORI10, 2022,
[5] Sullivan and Kaszynski, Journal of Open Source Software, 2019

Slide courtesy of S. Jaster-Merz

Reconstructed 5D phase space enables new insights

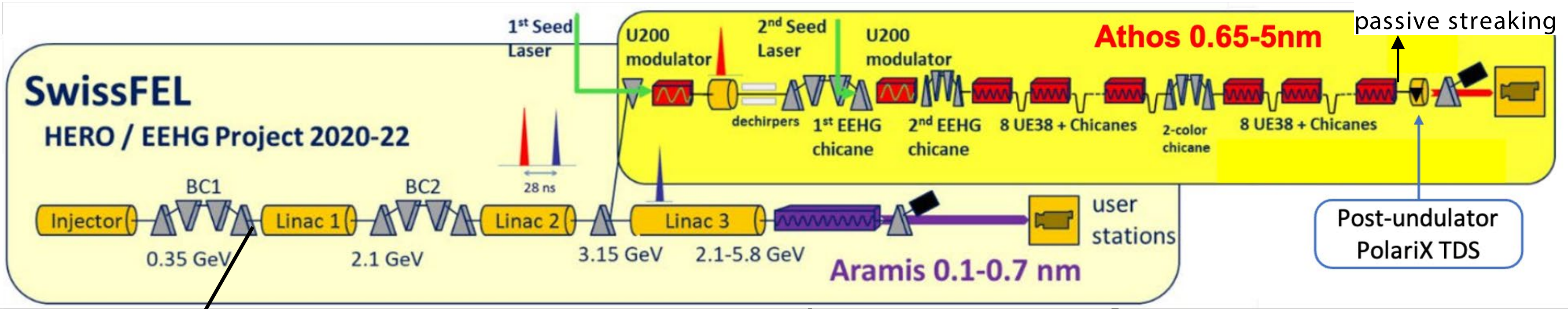
5D phase-space reconstruction of an electron beam - WEODB2 | Sonja Jaster-Merz, IPAC'23



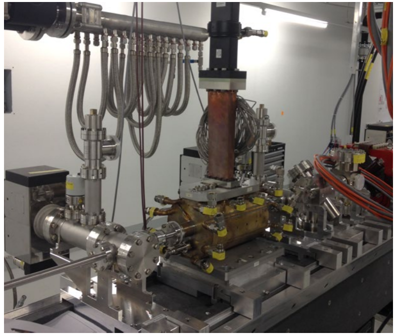
- **All 2D projections** of the 5D phase space, and **sliced** 4D emittance.
- **Full 5D** phase-space distribution enables improved modelling of accelerators, benchmarking of simulation codes.

Overview of the LPS measurements in SwissFEL

Post-undulator passive streaking

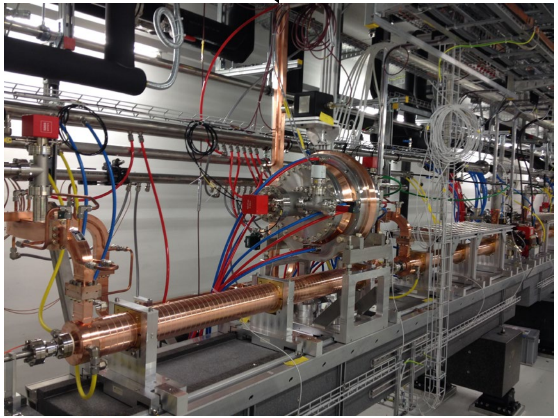


S-band TDS (5-cell SPARC/FERMI type)



Max integrated Deflecting voltage 5 MV, beam energy 300 MeV, Resolution ~10 fs

C-band TDS

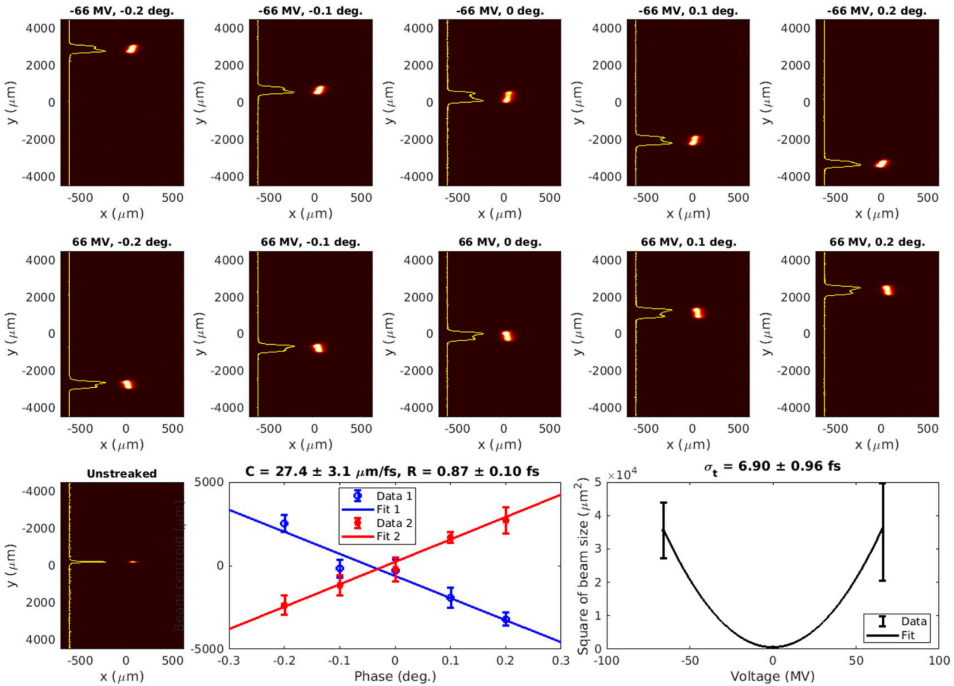


Post-undulator passive streaking

C-band TDS system

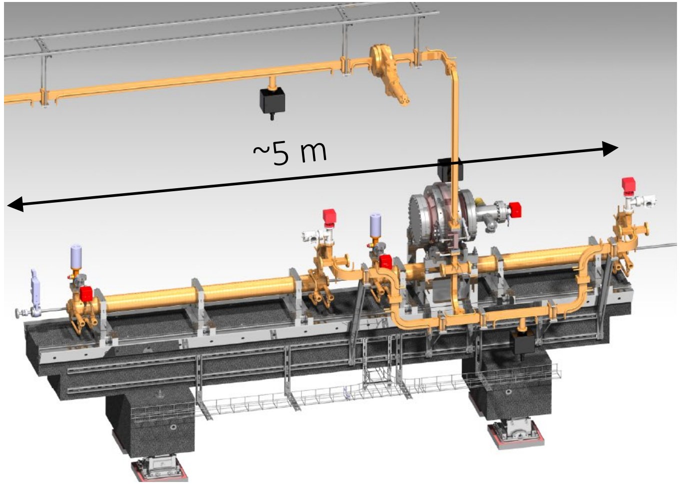
Temporal resolution 0.87 ± 0.10 fs (bunch length 6.90 fs)

with ε=76 nm, *E*=5.2GeV, β=60m, *V* =66MV



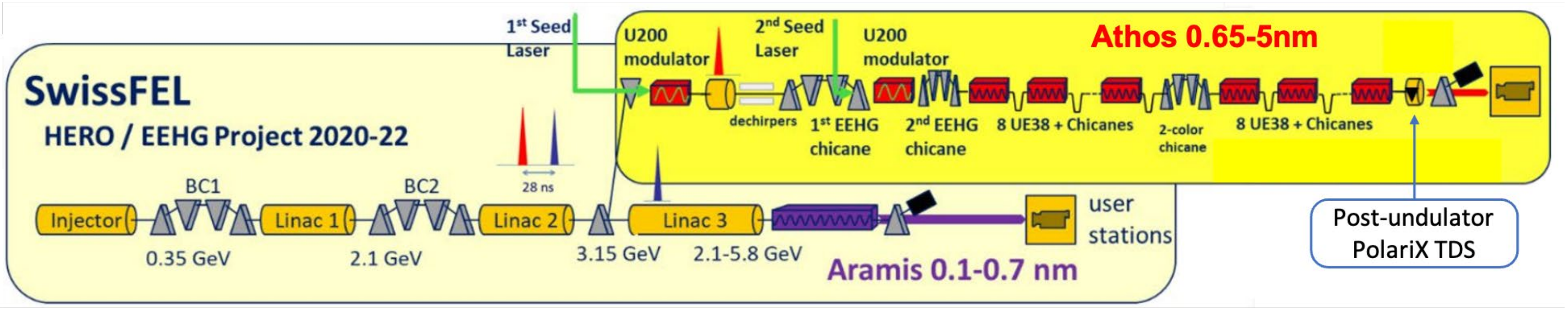
RF system

2x TDSs + BOC		
BOC Q_0	216 000	
BOC β	10	
RF pulse length	3	μs
Power-to-voltage	15.42	MV/MW$^{0.5}$



E. Prat, A. Malyzhenkov and P. Craievich, Rev. Sci. Instrum. **94**, 043103 (2023)

ATHOS: the Soft X-rays beamline in SwissFEL



Relevant hardware:

- 8x2 undulator APPLE-X modules: variable field, variable polarization, Transverse-Gradient Undulator (TGU)
- Inter-undulator Chicanes for High power and Improved Coherence (CHIC): R56 + delay
- 2-color chicane
- 2 x (laser + modulator + chicane)
- Temporal diagnostics :
  - Post-undulator X-Band RF system (PolariX-TDS)
  - Post-undulator passive streaker

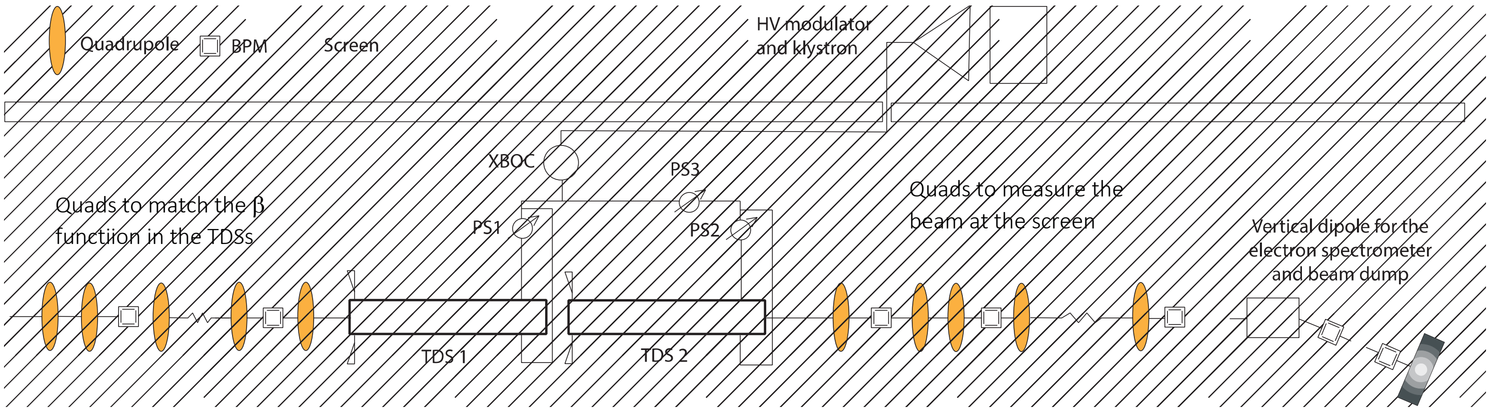
– For SASE process:

- Reduction of the saturation length, variable polarization, higher peak power and shorter pulse durations with increasing longitudinal coherence and bandwidth: High-Brightness SASE (HB SASE), large bandwidth. Fresh-slice multi-stage amplification
- Widely tunable two-color pulses

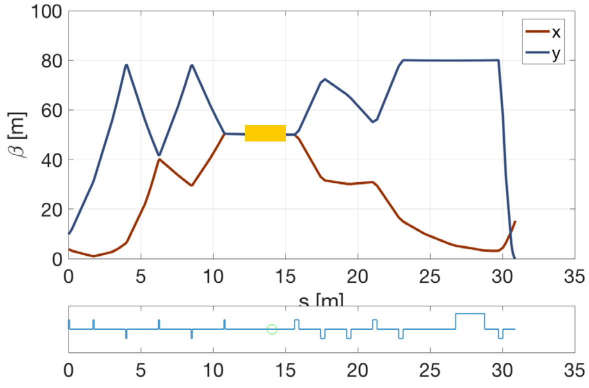
– With optical lasers for external seeding:

- Production of trains of attosecond pulses with the Enhanced SASE (ESASE) mechanism
- Phase-locked pulses
- Echo-Enabled Harmonic Generation (EEHG)

PolariX TDS diagnostic beamline @3GeV



$\beta_x = \beta_y = 50$ m → **optics for both polarizations**

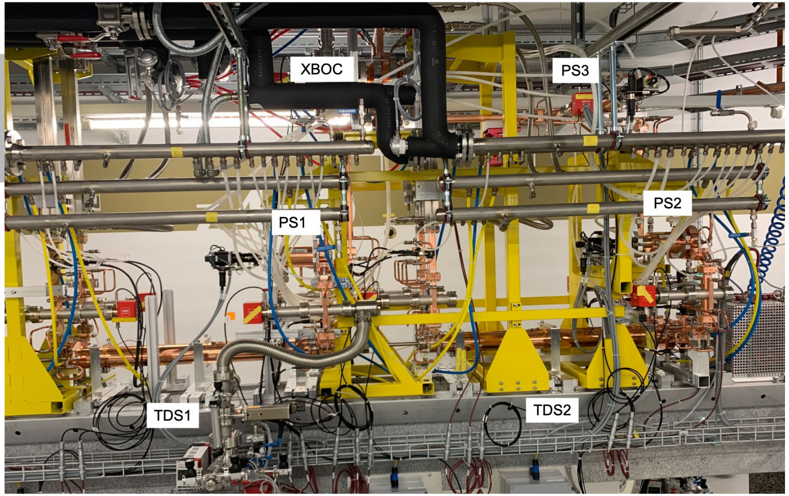


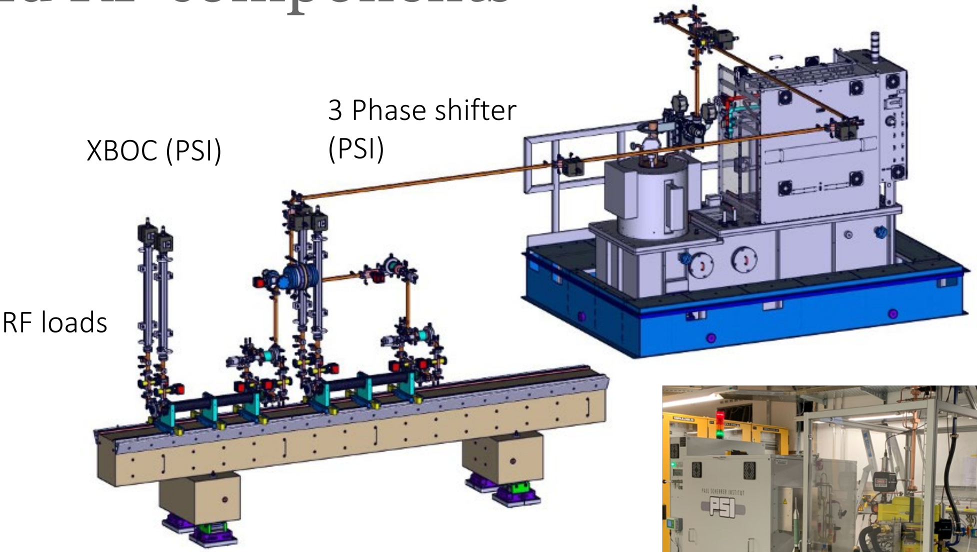
Plot by E. Prat

Beam measurements:

- ❖ Projected and slice emittance on different planes
- ❖ Electron pulse length and charge density profile (sub-fs resolution)
- ❖ Energy spread induced by FEL process (photon pulse length)

X-band TDS and RF components





All waveguide RF components including the XBOC and phase shifters were designed and built at PSI, Klystron: CPI VKK-8311 50 MW X-band

PSI HV modulator: develop and built in-house (400 kV, 3 ms)

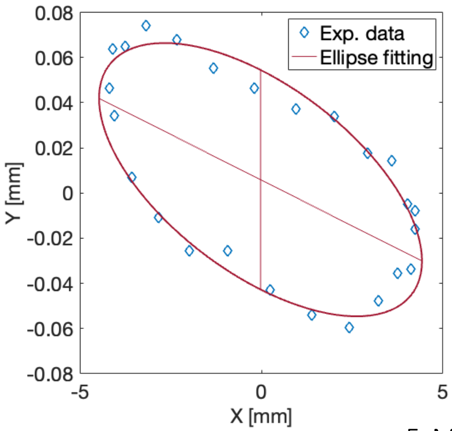
After about three weeks of integrated conditioning time, a peak power from the klystron of 30 MW with a total RF pulse length of 1 μs was achieved, now we can run the station with 35 MW with 1.2 us → deflecting voltage higher than 90 MV (specification was higher than 60 MV)

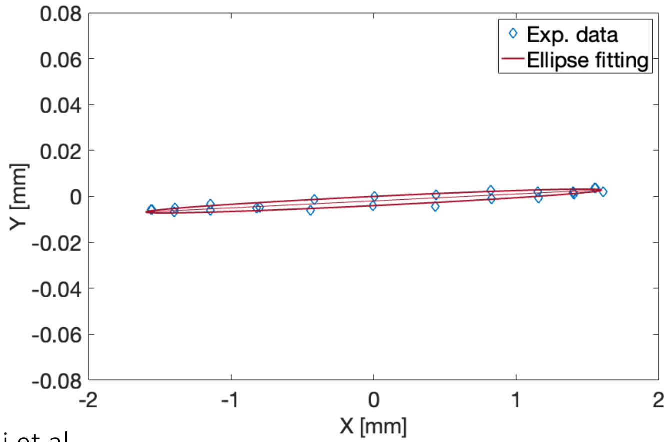
RF setup and commissioning with beam

$$\vec{V}_{+} = L\cos(\varphi_{\mathrm{RF}} + \varphi_L + \varphi_{\mathrm{PS}})\hat{x} + L\sin(\varphi_{\mathrm{RF}} + \varphi_L + \varphi_{\mathrm{PS}})\hat{y},$$
$$\vec{V}_{-} = R\cos(\varphi_{\mathrm{RF}} + \varphi_R)\hat{x} - R\sin(\varphi_{\mathrm{RF}} + \varphi_R)\hat{y}$$

Deflecting field is the sum of two rotating modes, one clockwise and the other counter clockwise

Wrong setting of the PSs and/or the amplitudes are unbalanced then the superposition of the two rotating modes results in an elliptically polarized mode, whose effect is to provide a kick in the plane orthogonal to the streaking plane (we will call this effect a *residual kick*).

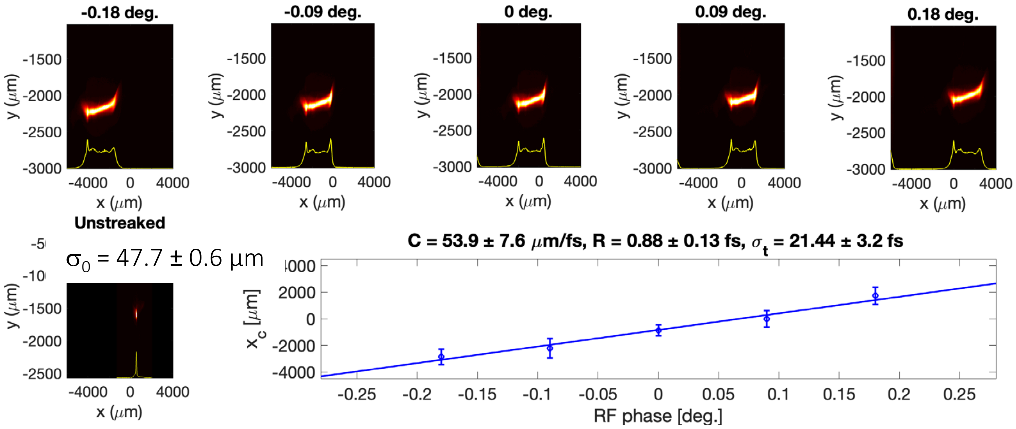




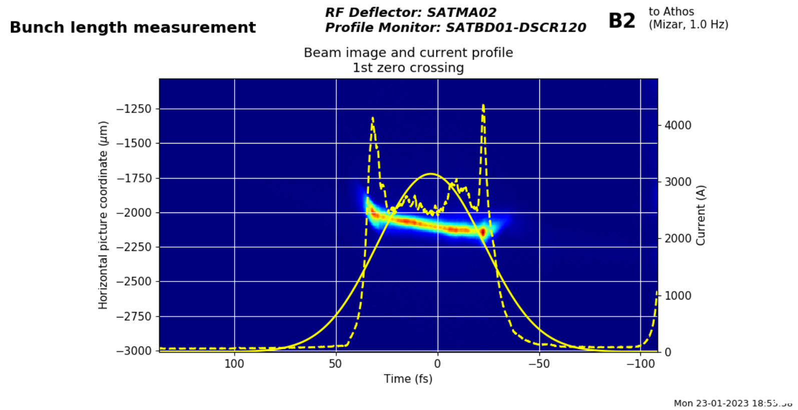
F. Marcellini et al.

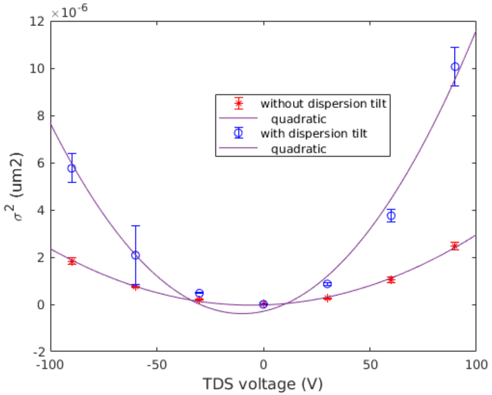
Calibration, resolution and bunch length

- The absolute calibration factor C between the transverse coordinate on a screen and the time coordinates within the electron bunch is obtained by measuring the dependence of the transverse position of the centroid of the streaked beam on the RF phase
- Time coordinates are obtained by dividing the transverse coordinates on the screen by the calibration
- Bunch length is simply obtained as the streaked beam size divided by the calibration factor C
- Resolution R= s_0/C



Deflecting voltage 85 MV, s_0 = 47.7 ± 0.6 μm





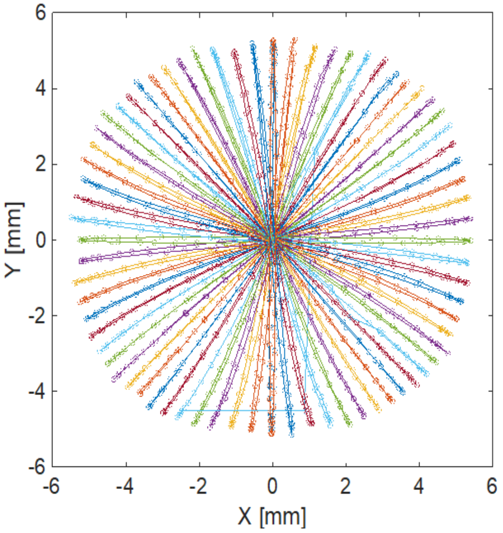
Preliminary resolution studies of X-band TDS combined with dispersive tilt

TDS adds up to the incoming tilt so that the final streaking becomes larger.

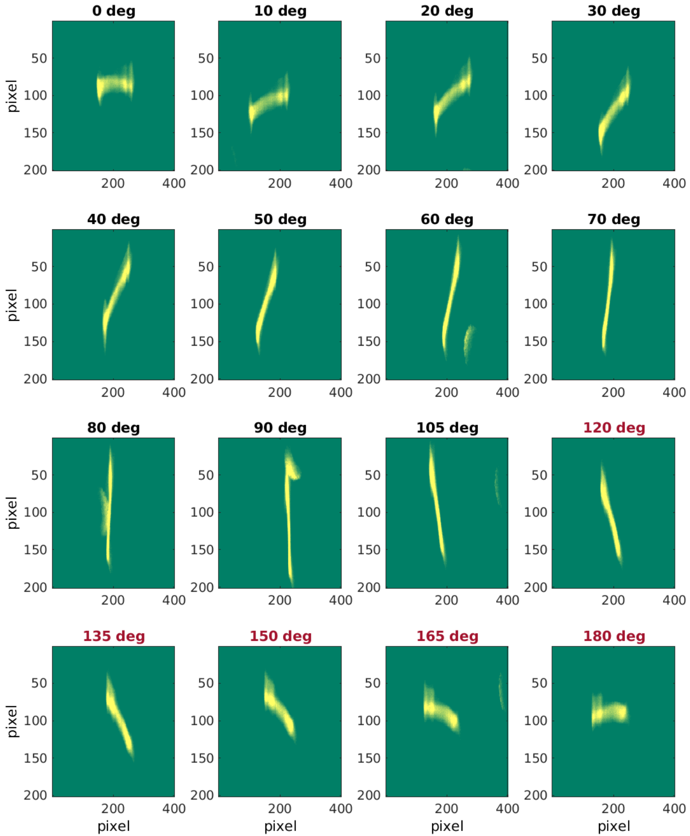
Assuming that the calibration factor does not change with respect to the standard case without initial beam tilt

Variable polarization – first measurements

Bunch centroid on a BPM after TDSs as a function of the global RF phase. Polarisation variation of 5 deg.

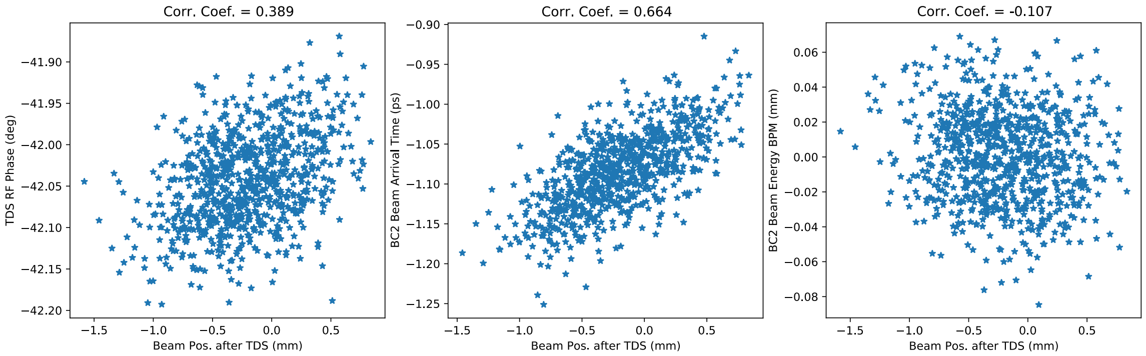


Right plots: Images on screen before dipole as a function of polarization angle. Dark polarization angles: 85 MW, red polarization angles: 72.8 MV.



RF setup and commissioning with beam

RF Phase and beam arrival time jitter can be limiting factors in achieving higher resolution



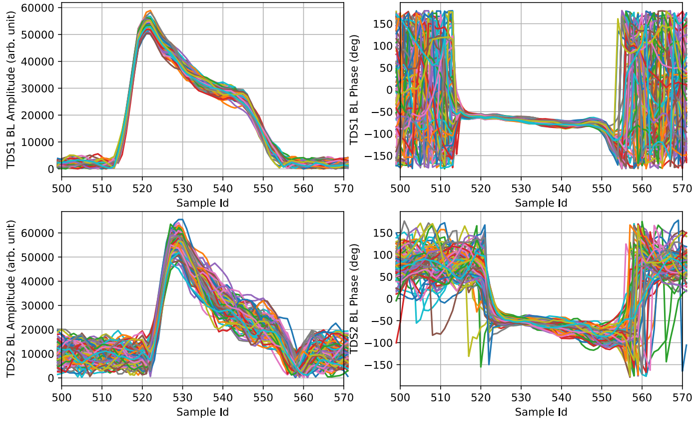
Correlations between streaked beam centroid measured on the BPMs after the TDSs and RF phase (left), beam arrival time (middle) and mean energy (right) in BC2

Calibrated time jitter on the screen ~10 fs

Beam loading amplitude and phase

TDS 1

TDS 2

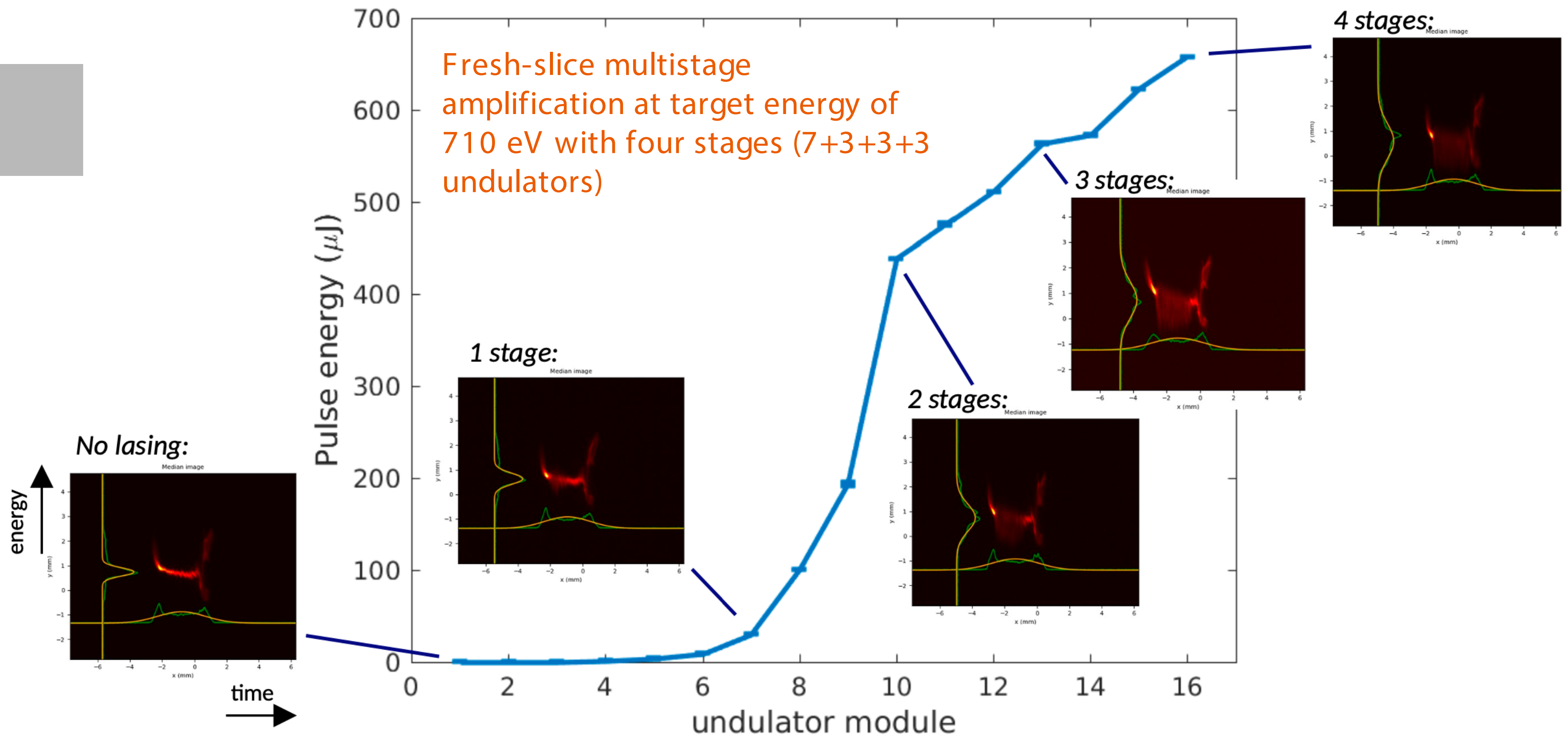


The beam-loading phase of TDS2 fluctuates more than twice in magnitude compared to TDS1 → this could be caused by an initial angle when the beam enters in TDS2 (due to an angle in the beam orbit itself), or by transverse wakefield effects in TDS1.

Use a proper signal (beam loading) to be used for RF feedbacks could improve the RF phase jitter

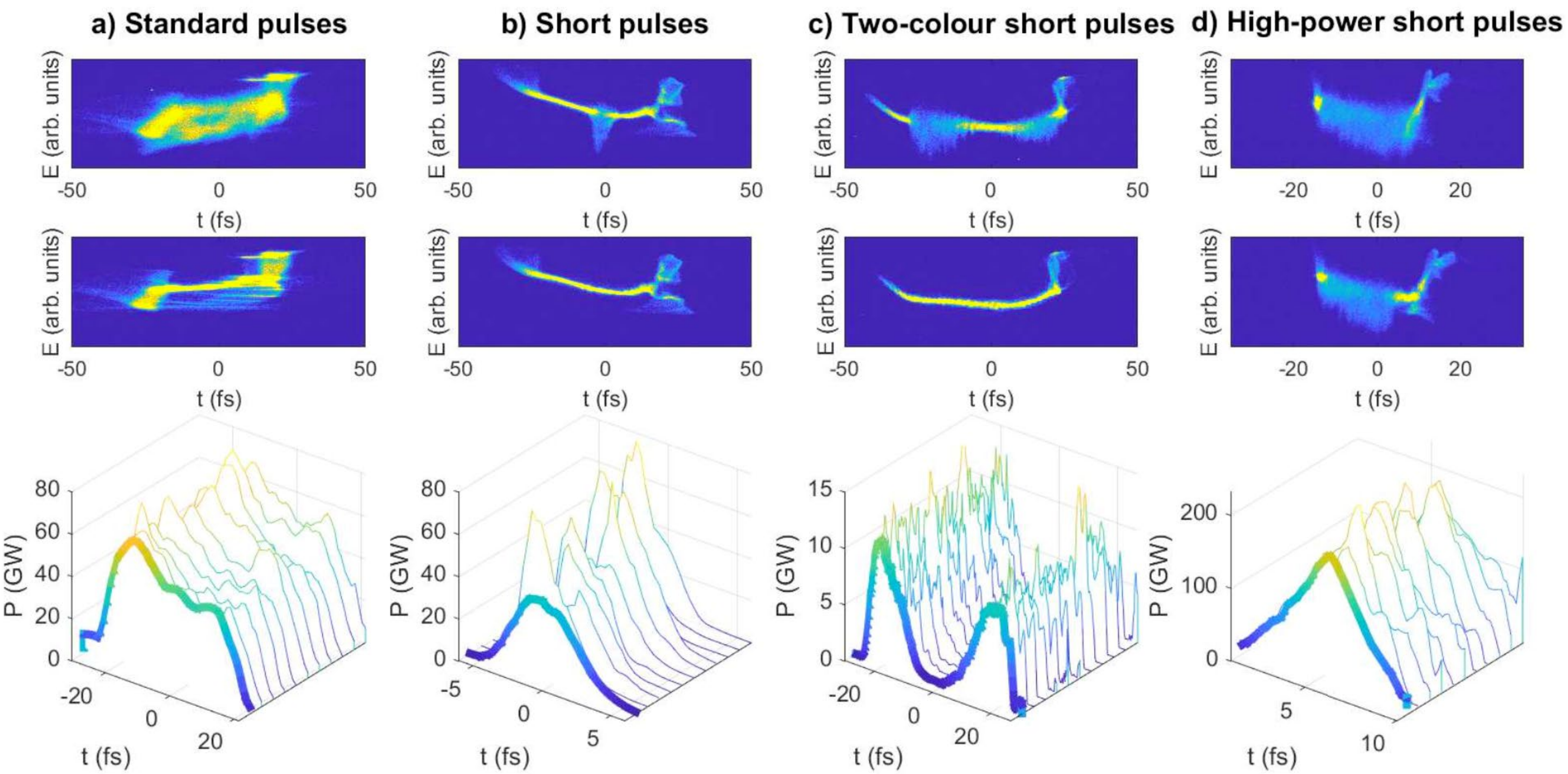
Plots by Z. Geng

Example of Athos setup (beam dump screen)



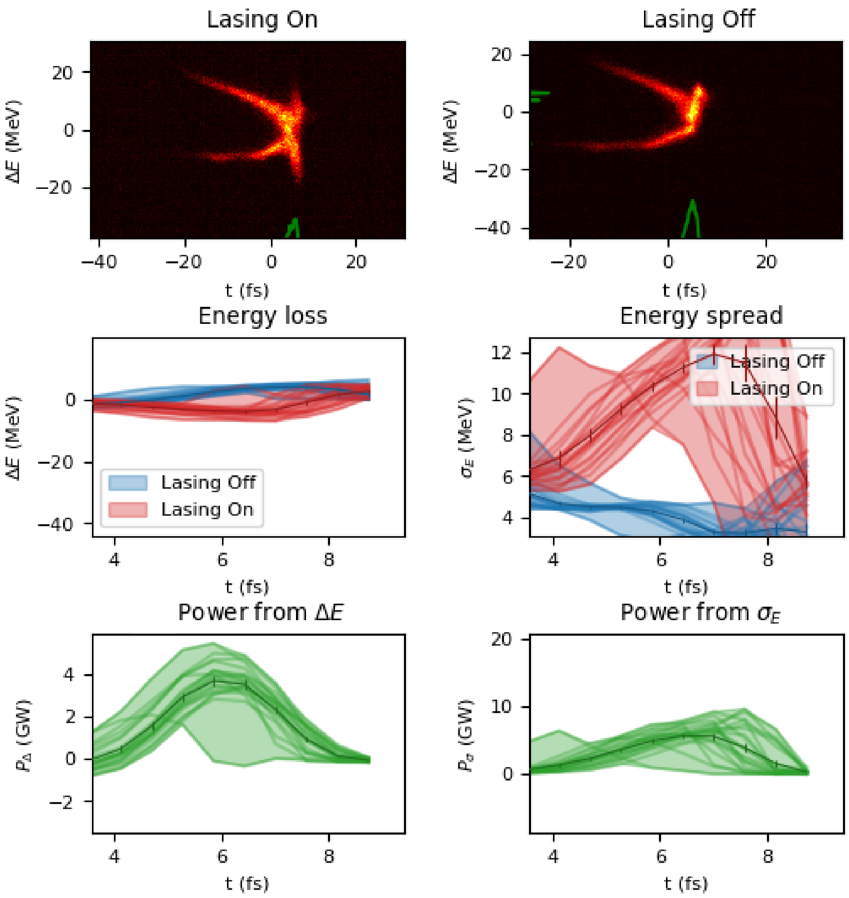
E. Prat, G. Wang,
T. Weilbach, Ch. Kittel

Setup of the FEL modes (beam dump screen)

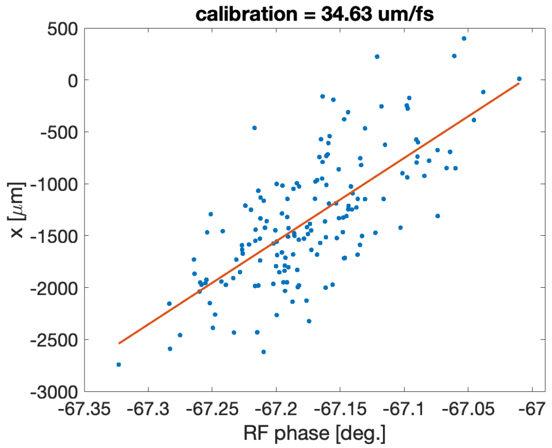


E. Prat et al., *An X-ray free-electron laser with a highly configurable undulator and integrated chicanes for tailored pulse properties*, submitted, 2023

Short pulse mode (10 pC) – and higher jitter



Plots by E. Prat

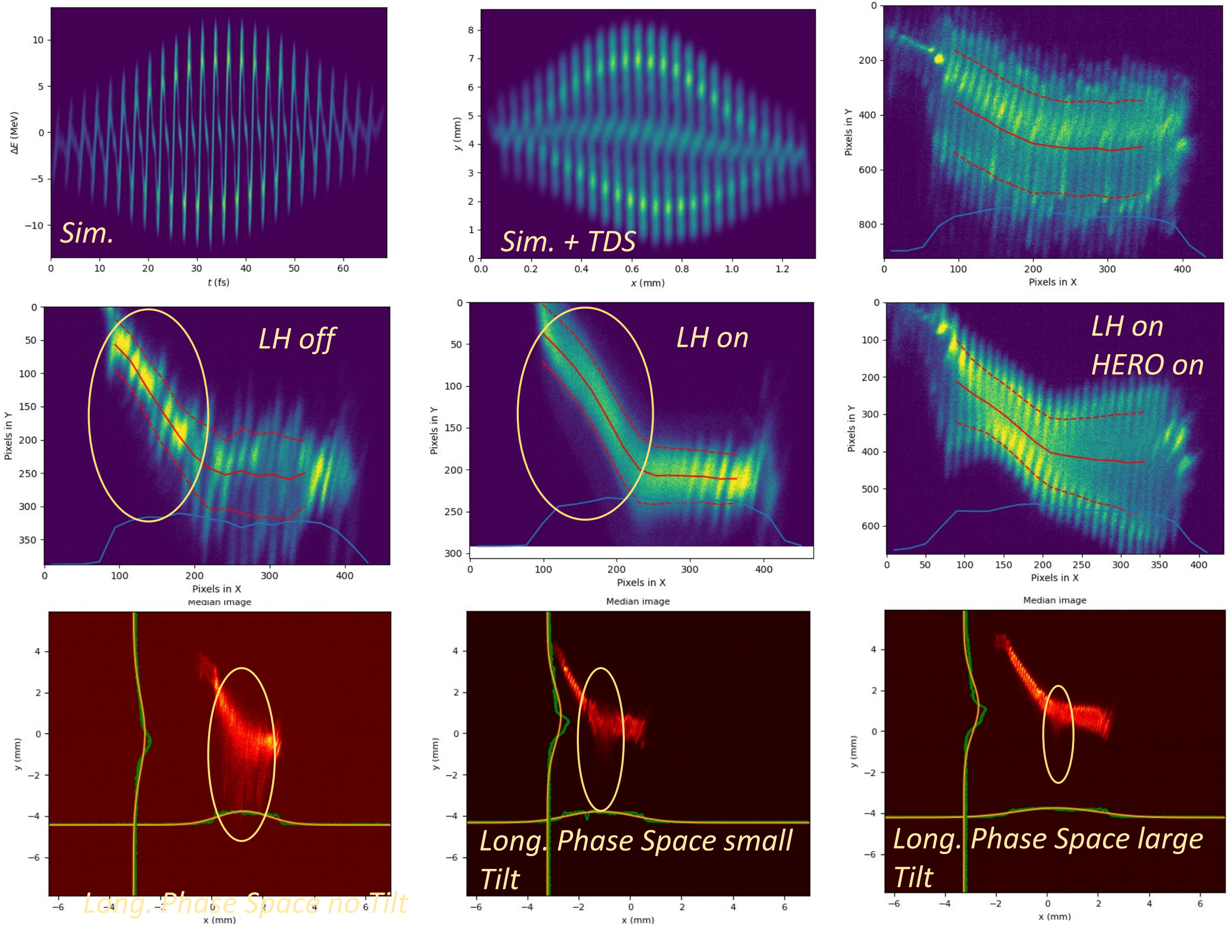


For some modes of operation, a jitter on the images was observed at the screen, which made the calibration of the TDS system difficult

— In order to perform the time calibration and bunch length measurement in the presence of jitter, we may exploit the jitter itself.

— the calibration coefficient can be estimated with reasonable accuracy by means of a linear regression between the values of the beam centroid at the screen and the RF phase jitter values.

Seeding at SwissFEL



ESASE: the periodicity of the modulation is 800 nm, corresponding to 2.66 fs. It shows that we have a resolution well be 1 fs

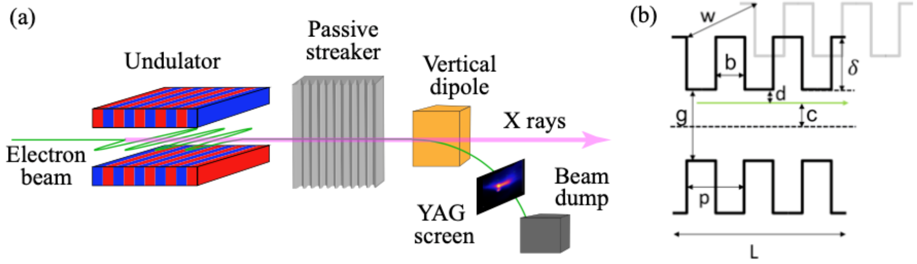
Effect of the laser Heater used to damp microbunching instability in ESASE

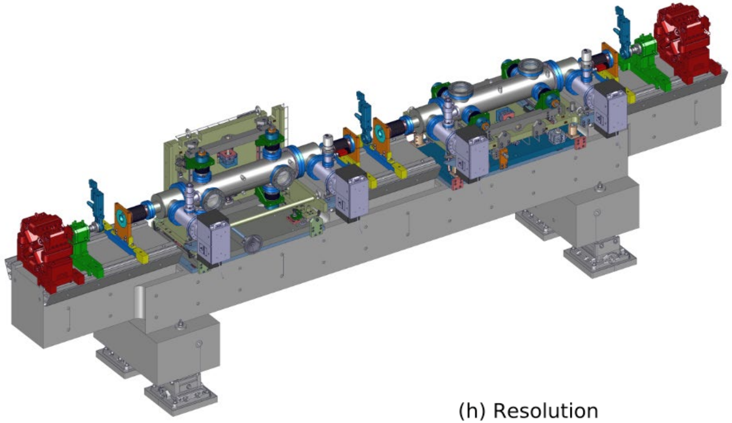
Controlling the Pulse Length with Tilts

Courtesy of S. Reiche

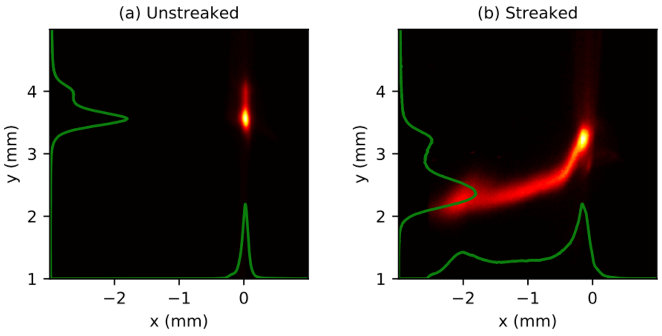
Post-undulator passive streaking (Aramis)

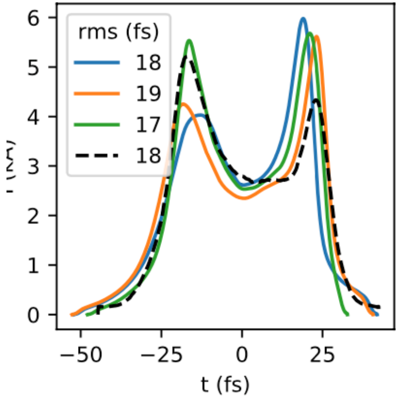
more information: P. Dijkstal et al., *PRR 2, 042018(R), 2020*)

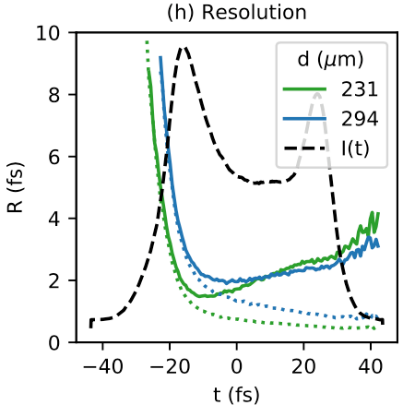




An electron beam traveling off-axis through such a device excites transverse wakefields, resulting in a time-dependent kick that streaks the electron beam.

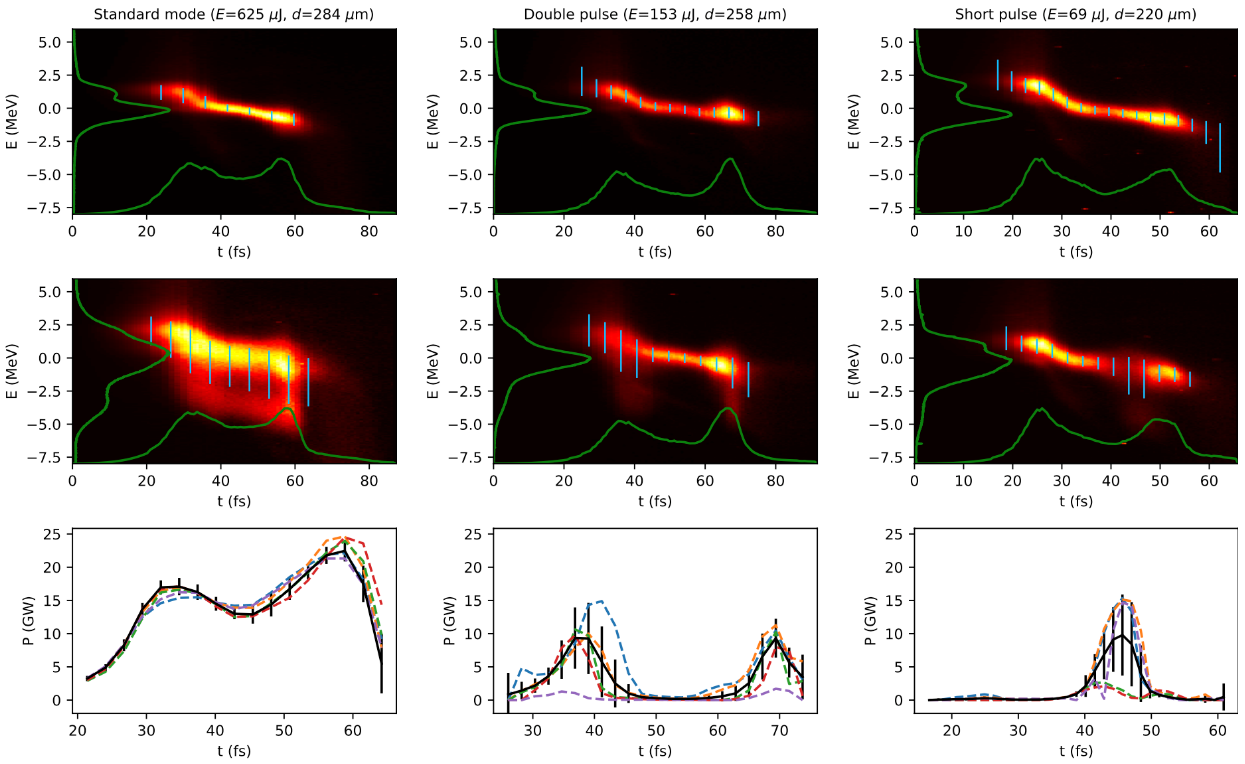






Post-undulator passive streaking – LPS

more information: P. Dijkstal et al., *PRR 2, 042018(R), 2020*)



Diagnostics of variable lasing modes at SwissFEL

Conclusion and outlook

– Conclusion

- ❖ TDS-based diagnostics systems are essential tools for the commissioning and optimisation of linac-based FELs (temporal resolution below 1 fs with C-band and X-band RF systems)
- ❖ They are also key devices for diagnosing the beam in new acceleration techniques (before and after acceleration). Here the sub-fs resolution is even more important!

– Outlook

- ❖ PolariX TDS: Try pushing the time resolution below 0.5 fs (in different streaking plane)
- ❖ Repetition rate up to 10 Hz, future operation up to 100 Hz (provide shot-to-shot photon pulse length to users)
- ❖ Slide emittance measurements in different deflecting planes
- ❖ Implement the measurement for a full 5-dimensional phase space
- ❖ Systematic comparison between the passive streaker and TDS

PAUL SCHERRER INSTITUT

Wir schaffen Wissen – heute für morgen

Credits

- To prepare my slides, I have especially used material from: E. Prat, F. Marcellini, S. Reiche, P. Dijkstal
- Thanks to my colleagues at PSI involved in the design, development and commissioning of the TDS systems
- Thanks also go to our colleagues at CERN and DESY involved in this collaboration for the useful discussions. Especially S. Jaster-Merz (DESY) for the slides related to activities at DESY
- Some more details for the PolariX TDS:

The PolariX TDS Project: a novel Polarizable X-Band Transverse Deflection Structure

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(Dated: June 28, 2020)

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Experimental demonstration of novel beam characterization using a polarizable X-band transverse deflection structure

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https://doi.org/10.1038/s41598-021-82687-2

SPIE.

P. Craievich, Z. Geng, F. Marcellini, C. Kittel, S. Reiche, T. Schietinger, G. Wang, E. Prat, "Post-undulator beam measurements with PolariX TDS in SwissFEL," Proc. SPIE 12581, X-Ray Free-Electron Lasers: Advances in Source Development and Instrumentation VI, 1258106 (9 June 2023); doi: 10.1117/12.2665447

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Sonja Jaster-Merz

WEODB2	5D phase-space reconstruction of an electron beam	4

The complete knowledge of electron bunch properties is of great interest to understand and optimize the performance of accelerators and their applications. A new tomographic beam diagnostics method to reconstruct the full 5-dimensional phase space (x, x', y, y', t) of bunches has recently been proposed. This method combines a quadrupole-based transverse phase-space tomography with the variable streaking angle of a polarizable X-band transverse deflection structure (PolariX TDS). In this contribution, we show preliminary data of the first experimental demonstration of the method including the reconstruction of the full 5-dimensional phase space distribution of an electron bunch at FLASHForward.

- **S. Jaster-Merz**
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