PSI Center for Accelerator Science and Engineering

Transverse Deflecting Structures (TDS) as a diagnostic tool

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Content

- Introduction to the TDS as diagnostic tool: capabilities and figures of merit

1. Longitudinal Phase Space (LPS) reconstruction down to sub-fs resolution at SwissFEL (PSI)
2. Next generation TDSs: the PolariX TDS
   - 5D phase space reconstruction at FLASHForward (DESY) and SwissFEL (PSI)

- Conclusion and outlook

Motivations for high-resolution time-resolved diagnostics

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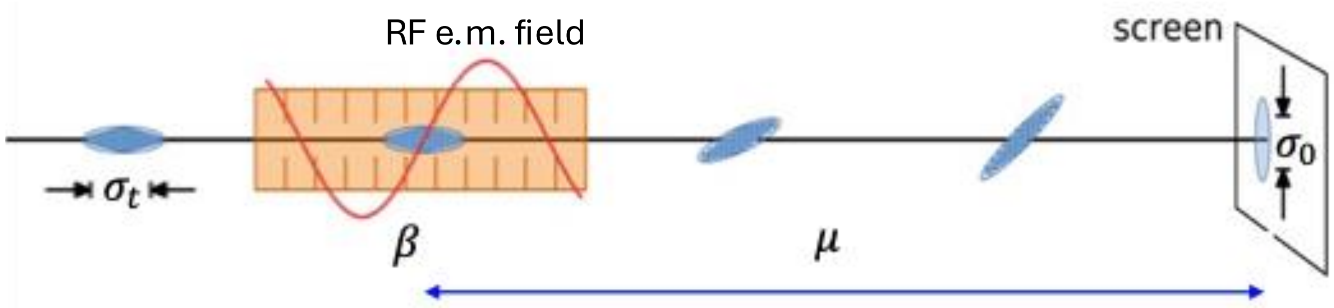
- Measuring the temporal properties of electron beams is of fundamental importance in particle accelerators.
- Here we focus on **X-ray free-electron lasers (FELs),** tools that produce short pulses (fs or below) to study matter with time and spatial resolution at the atomic level.
- FEL performance is determined by the electron bunch duration and the time-resolved properties of the electron beam (e.g. peak current and emittance).
- Time-resolved measurements of electron and photon beams are fundamental in X-ray free-electron laser facilities, ideally with sub-femtosecond resolution.
- Novel high-gradient acceleration techniques, e.g. plasma-based FELs, are characterized by short period of accelerating field and **therefore naturally produce or accelerate fs long bunches (and sometime at lower charge).**

Measurement methods using transverse streaking

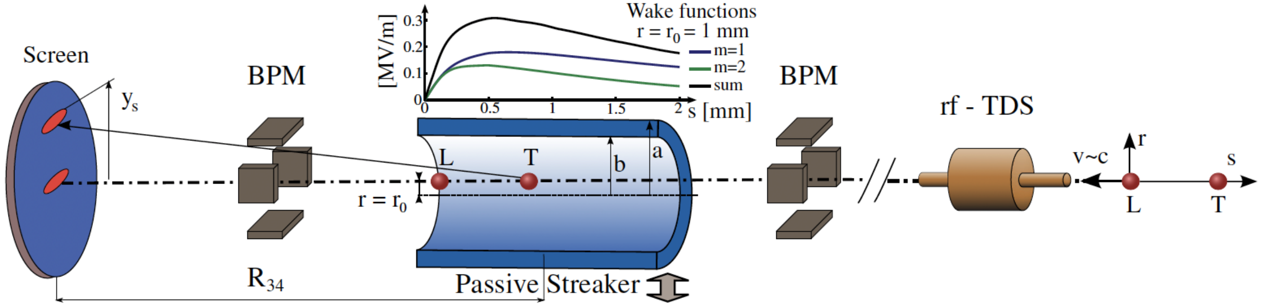
Streaking is the standard way to access the time-resolved properties of **electron beams**:

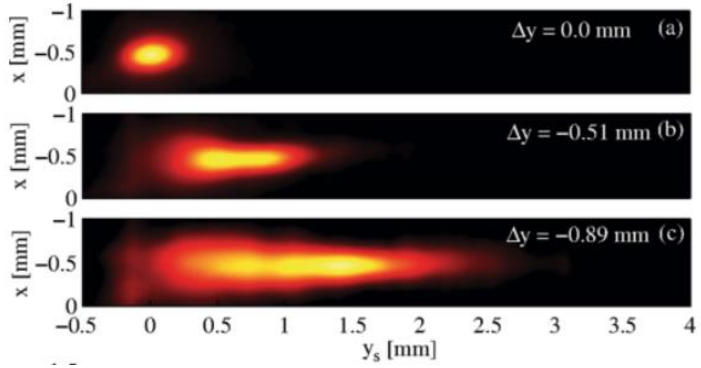
- With **RF deflectors:** Transverse Deflection Structure (TDS) are RF-based devices used for the manipulation and/or the diagnostics of charged particle beams to retrieve longitudinal/temporal proprieties.



- With **dispersion:** elegant but only suitable for specific FEL operation modes, showed ~ fs resolution [*E. Prat et al, PRR 4, L022025, 2022*]

- With **wakefields** ("passive" streaking): An electron beam traveling off-axis through such a device excites transverse wakefields, resulting in a non-linear time-dependent kick that streaks the electron beam.

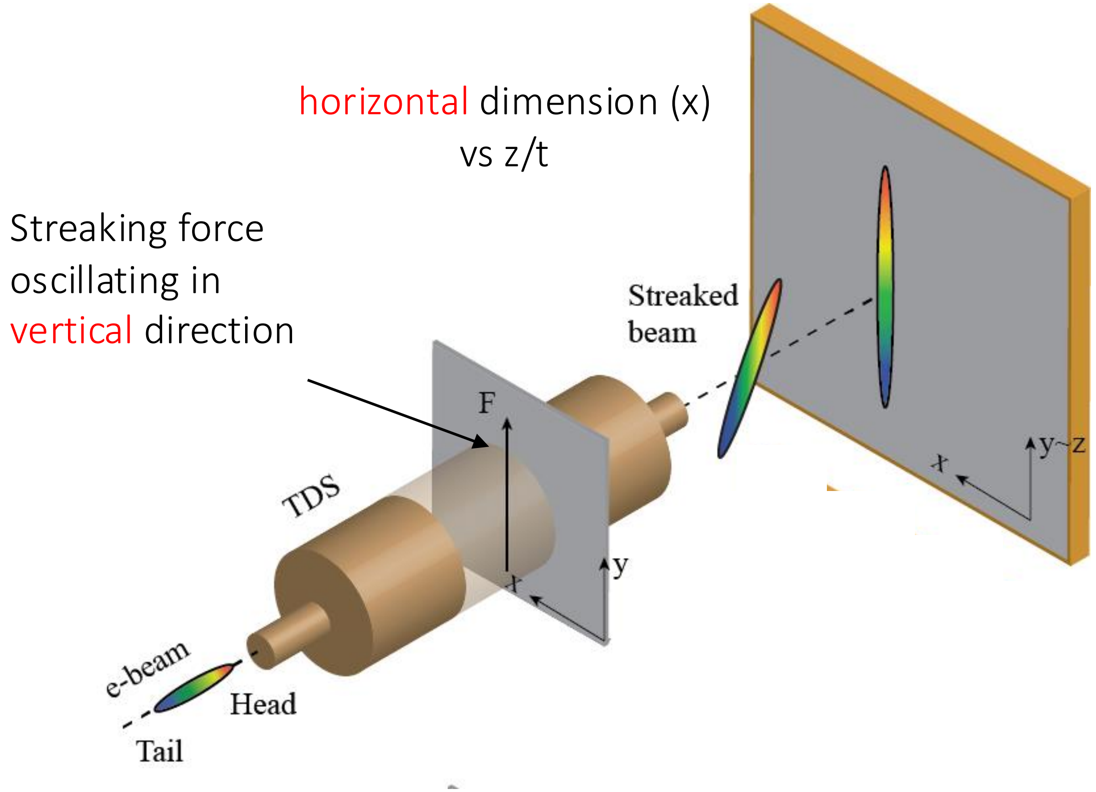




S. Bettoni et al., PR AB 19, 021304 (2016)

TDS as a diagnostic tool for linacs – capabilities (1/2)

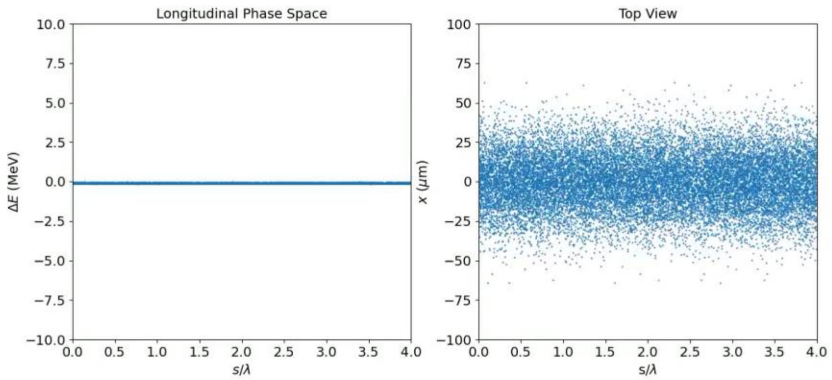
Conventional TDS: streaking in a fixed polarization (i. e. vertical or horizontal).



- Bunch length measurement – already proposed in the 1960s, H. Miller (SLAC), R. Chehab (LAL, Orsay).
- Then it was proposed again in 2000, LCLS-TN-00-12
- Longitudinal charge profile measurements, combined with dipole → longitudinal phase space (LPS) measurement.
- Combined with quadrupole scan or multi-screen lattice → slice emittance measurement on the plane perpendicular to the streaking direction

TDS as a diagnostic tool for linacs – capabilities (2/2)

Measurement of the FEL-induced lasing effects imprinted on the electron beam longitudinal phase space: first references *Y. Ding et al., PRST-AB 14, 120701 (2011), C. Behrens et al., Nat. Comm. 5, 3762 (2014).*



Steady-state Genesis 1.3 simulation (courtesy of S. Reiche)

If streaking is done after the undulator → FEL power profile measurement can be obtained from the time-resolved energy loss and energy spread increase of the electron beam imprinted by the lasing on and off conditions

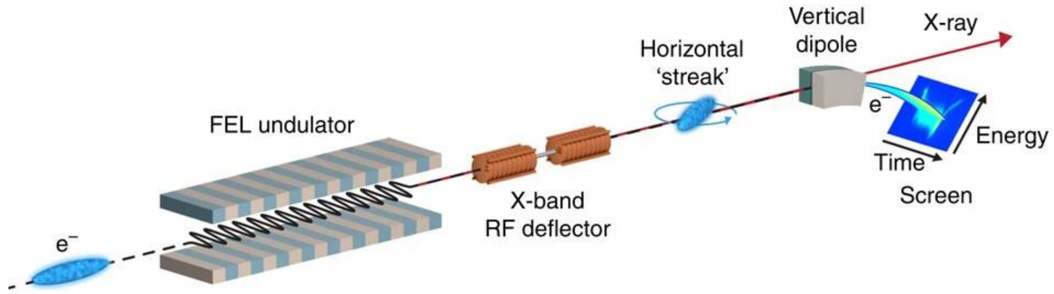
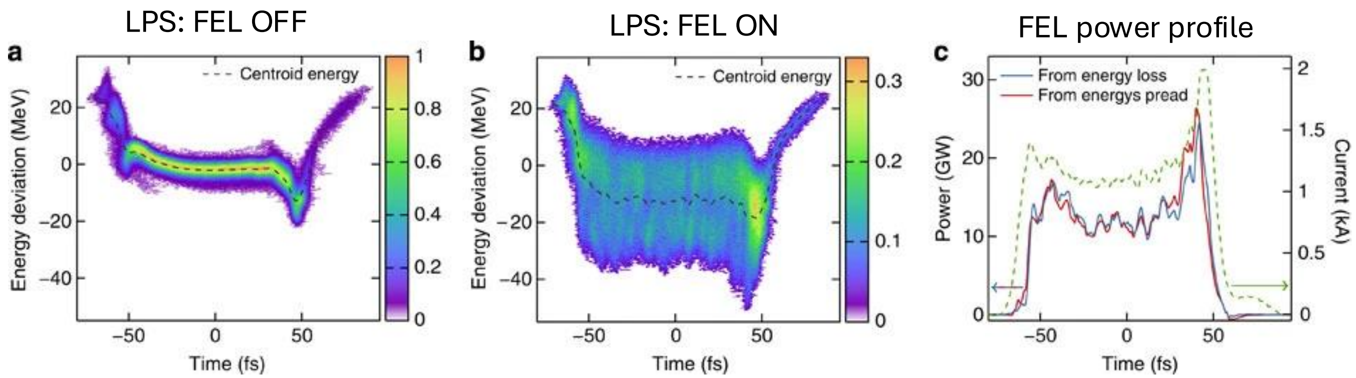


Image taken from *[C. Behrens et al, Nat. Comm. 5, 3762 (2014)]*



$$P_1 = I(t)\left[E_{off}(t) - E_{on}(t)\right]$$

$$P_2 \propto I^{2/3}(t)\left[\sigma_{E,on}^2(t) - \sigma_{E,off}^2(t)\right]$$

TDS as a diagnostic tool – time resolution

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The resolution r_t is defined as the measured unstreaked beam size $\sigma_{x,\mathrm{eff}}$ (including screen resolution) over the time calibration *dx/dt*

The **calibration** factor *dx/dt* between the transverse coordinate on the screen and the time coordinate is obtained by measuring the transverse centroid variation as a function of the RF phase.

$$r_t(t) = \frac{\sigma_{x,\mathrm{eff}}}{\mathrm{d}x/\mathrm{d}t} = \frac{mc^2\sqrt{\epsilon_n\gamma\beta_{\mathrm{scr}} + \sigma_{\mathrm{scr}}^2\gamma^2}}{eV\omega\sqrt{\beta_{\mathrm{TDS}}\beta_{\mathrm{scr}}}\sin\mu}$$

with beam properties $E = \gamma mc^2$, ϵ_n
with hardware properties σ_{scr}, ω, V
with lattice properties β_{TDS}, β_{scr}, $\sin\mu$

- Energy and emittance are given by the project but smaller energy and emittance improve the resolution.
- Lattice proprieties: high-beta function at TDS, phase advance between TDS and screen 90/270 deg.
- Hardware proprieties (RF and screen): Maximize V, build TDS with higher RF frequency and shorter structures with larger kick.
- Max deflection voltage and thus time resolution may be limited by the centroid jitter induced by the TDS itself due to RF phase and arrival time jitter.

TDS as a diagnostic tool – energy resolution

PSI

Off-axis particles are also accelerated Vz(y) = k*y*V0 and 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)

The **energy resolution r_E** is the natural beam size in the dispersive plane over the dispersion *D*. Large dispersions, small beta functions, and good screen resolutions are desired

$$r_E = \frac{E\sigma_{y,\mathrm{eff}}}{D} = \frac{mc^2\sqrt{\epsilon_n \gamma \beta_{\mathrm{scr}} + \sigma_{\mathrm{scr}}^2 \gamma^2}}{D}$$

with beam properties ***E* =γ**mc^2, $\boldsymbol{\varepsilon_n}$
with hardware property $\boldsymbol{\sigma_{scr}}$
with lattice properties $\boldsymbol{\beta_{scr}}$, ***D***

Effect of resolution

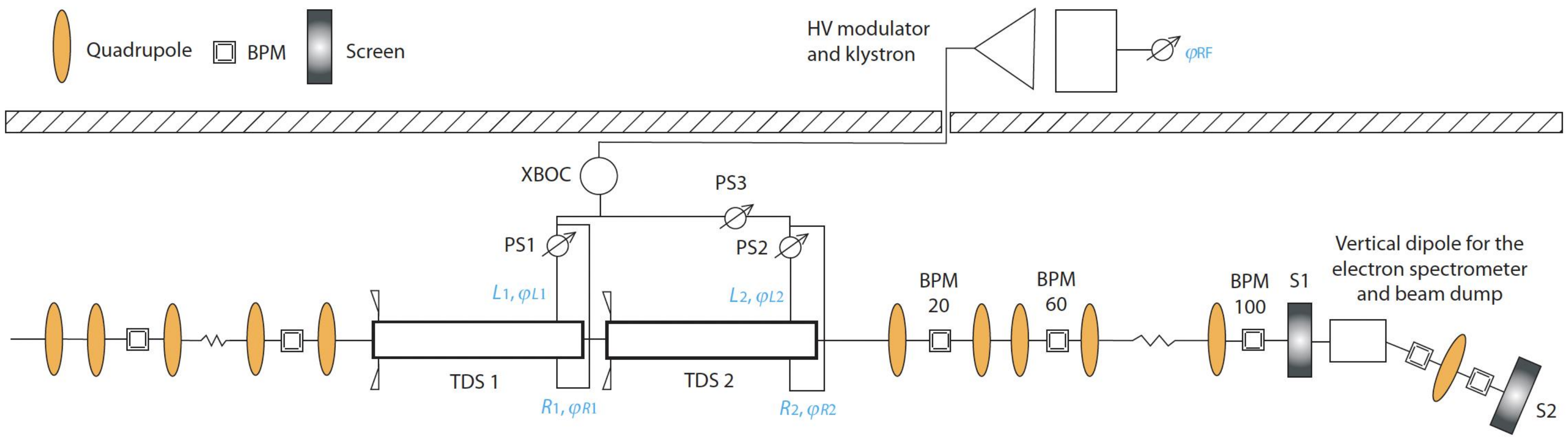
In a measurement, resolution adds in quadrature to true beam properties.

For example, rms FEL pulse duration:

$$\sigma_{\mathrm{FEL,meas}} = \sqrt{\sigma_{\mathrm{FEL}}^2 + r_t^2}$$

Consequence: $\sigma_{\mathrm{FEL,\,meas}}$ is also an upper limit of r_t.

TDS as a diagnostic tool – General measurement concept



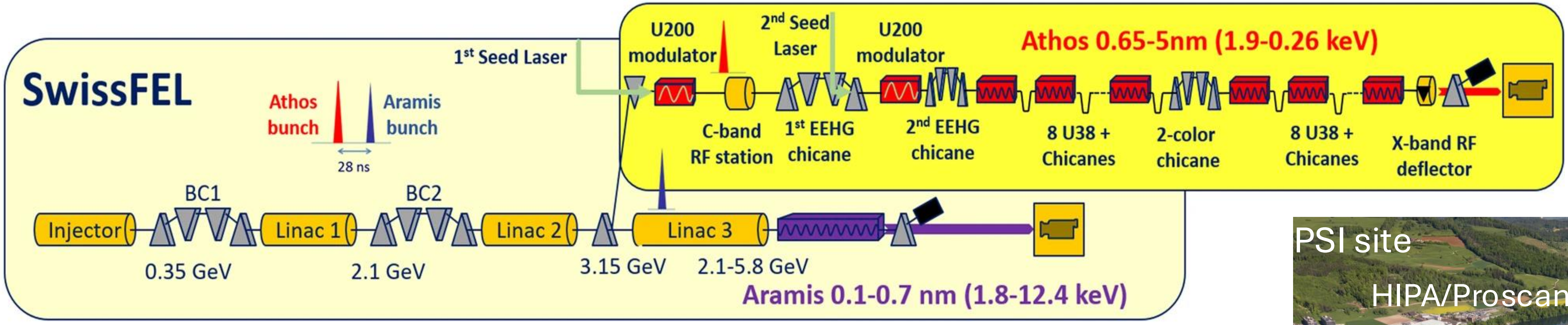
In each measurement location:

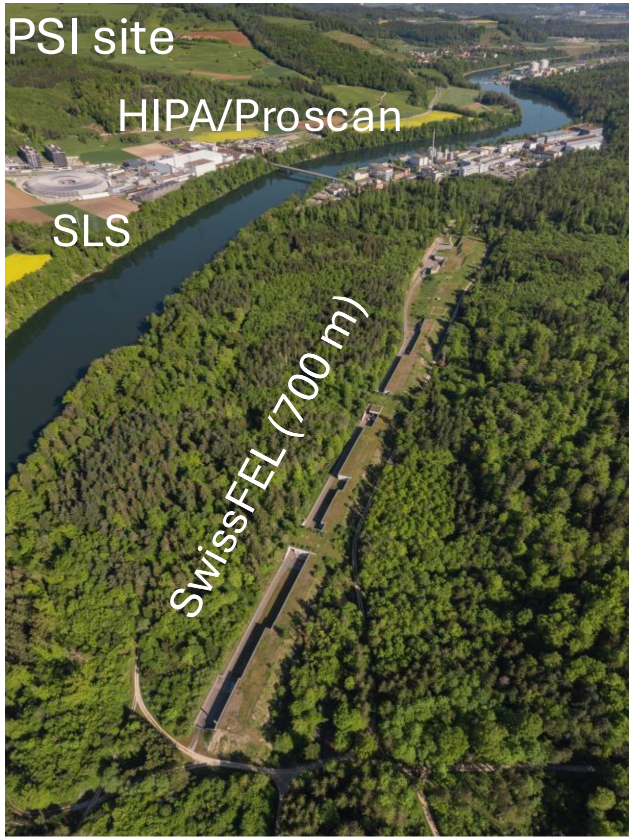
- There are few quadrupoles before the TDSs the match the beta function at the TDSs
- Few quadrupoles after the TDSs to measure the beam at the screen (current profile and slide emittance)
- One screen in dispersive location to also measure LPS
- Quadrupoles to set optics for optimum resolutions (and to scan phase advance for emittance measurements)

→ TDS system needs space for the installation of all components!

SwissFEL and Electron beam LPS measurements

SwissFEL overview





Main parameters:

Photon wavelength: 0.1–5 nm

Photon energy : 0.2–12 keV

Pulse duration : 1–20 fs

Electron energy : up to 6 GeV

Electron bunch charge: 10–200 pC

Repetition rate: 100 Hz (2-bunches)

Aramis:

Hard X-ray FEL, λ=0.1–0.7 nm

Linear polarization, in-vacuum undulators

First users 2018

Athos:

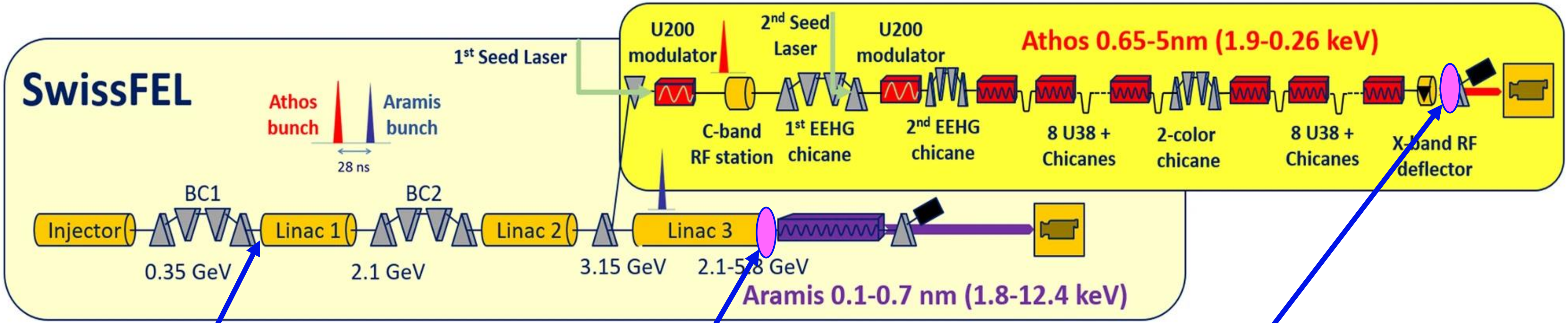
Soft X-ray FEL, λ=0.65–5.0 nm

Variable polarization, Apple-X undulators

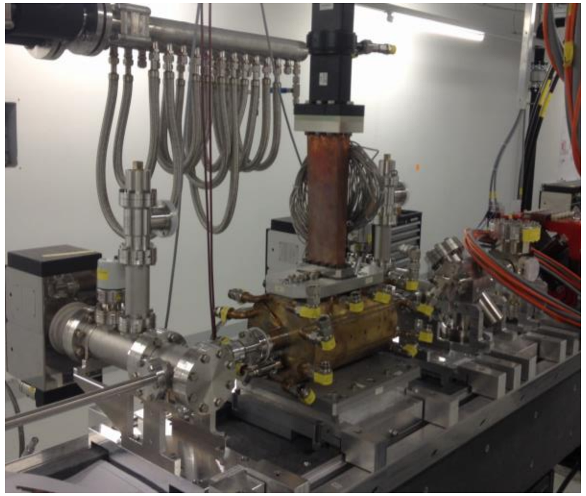
First users 2021

SwissFEL: LPS measurement locations

PSI

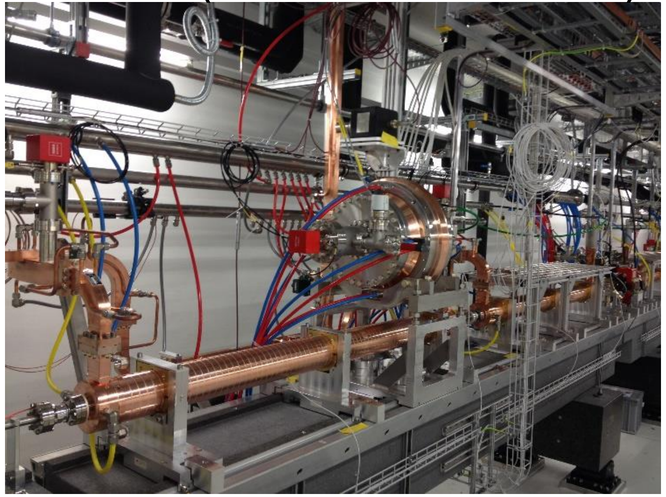


S-band (vertical deflection)



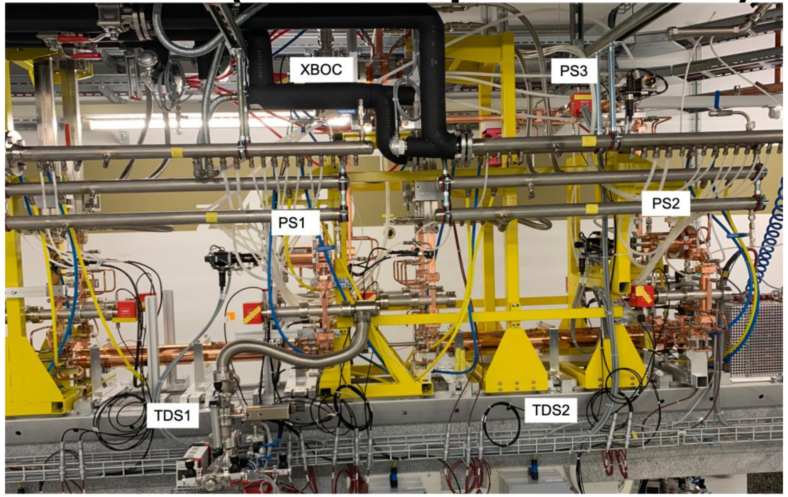
$V_{max} \sim 5$ MV, R ~10 fs

C-band (vertical deflection)



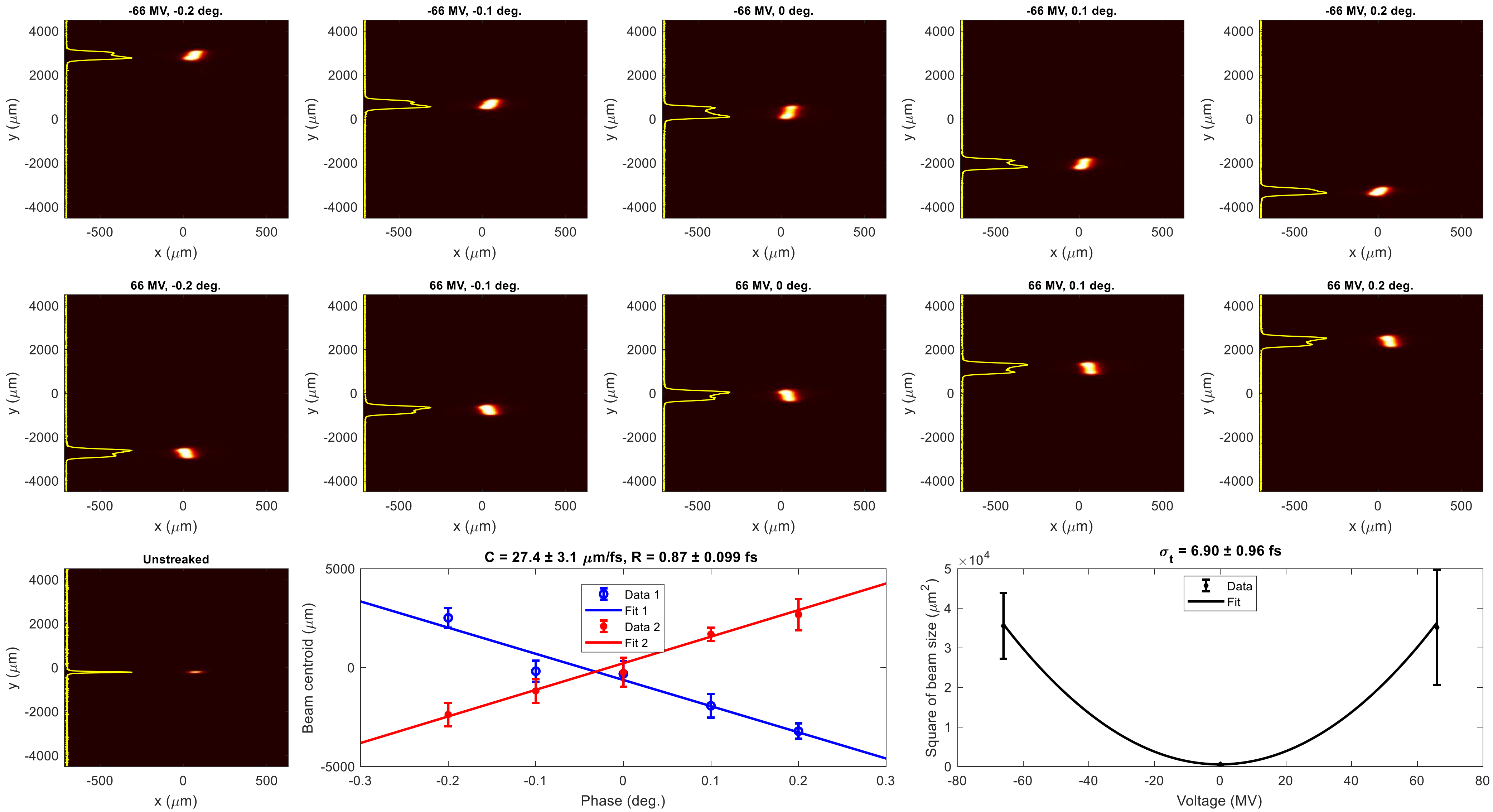
$V_{max} \sim 70$ MV, R < 1 fs

X-band (variable polarization)



$V_{max} \sim 85$ MV, R < 1 fs

C-band measurements (I): sub-fs resolution



E = 5.2 GeV

V = 66 MV

C = 27.4 ± 3.1 μm/fs

σ_0 = 23.8 ± 0.3 μm

σ_t = 6.90 ± 0.96 fs

R = 0.87 ± 0.10 fs

C_{calc} = 26.4 μm/fs

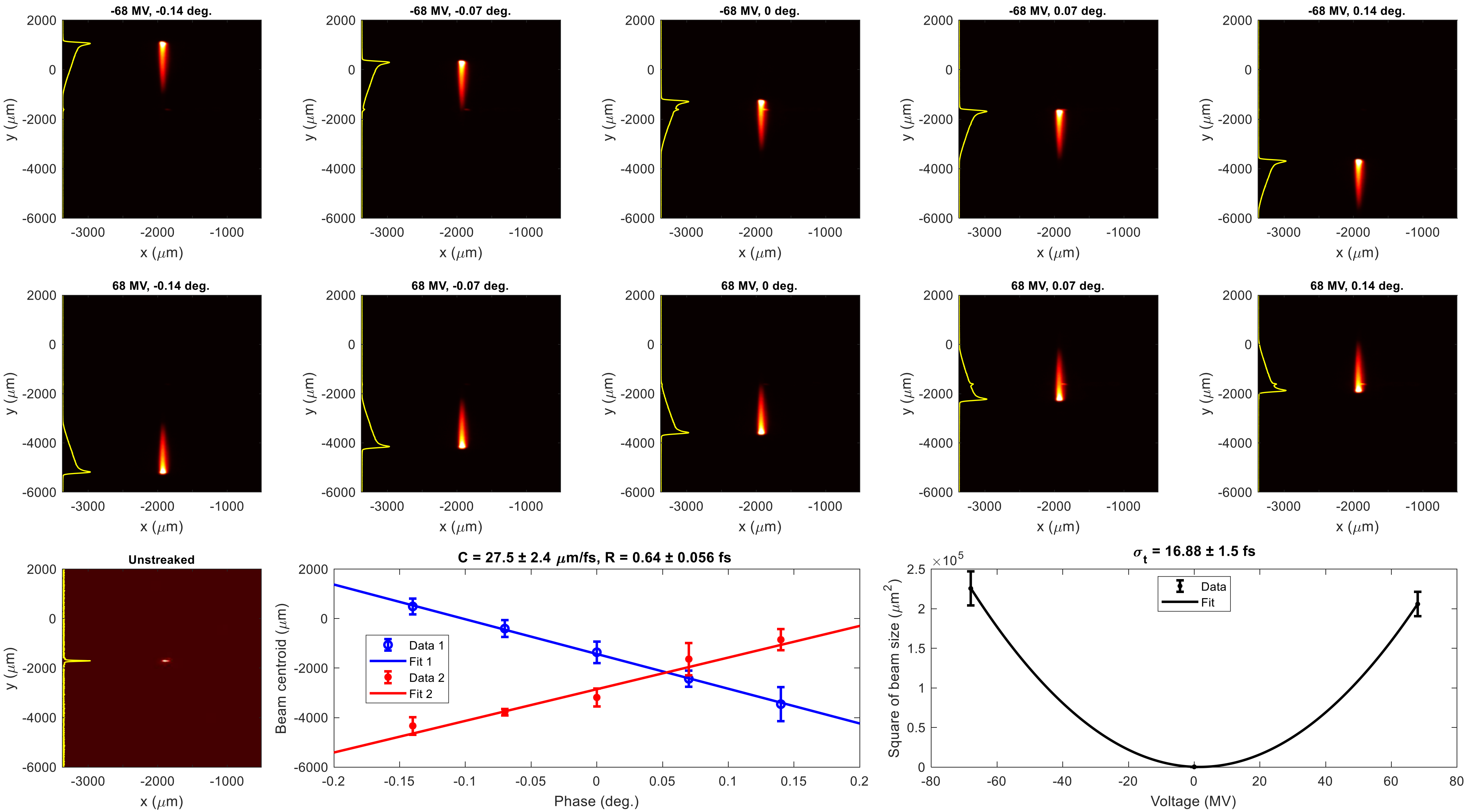
$\sigma_{0,calc}$ = 20.4 μm

R_{calc} = 0.77 fs

(assuming 75 nm emittance)

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

C-band measurements (II): better resolution



Best resolution thanks to improved screen resolution

E = 5.7 GeV

V = 68 MV

C = 27.5 ± 2.4 μm/fs

σ_0 = 17.6 ± 0.2 μm

σ_t = 16.9 ± 1.5 fs

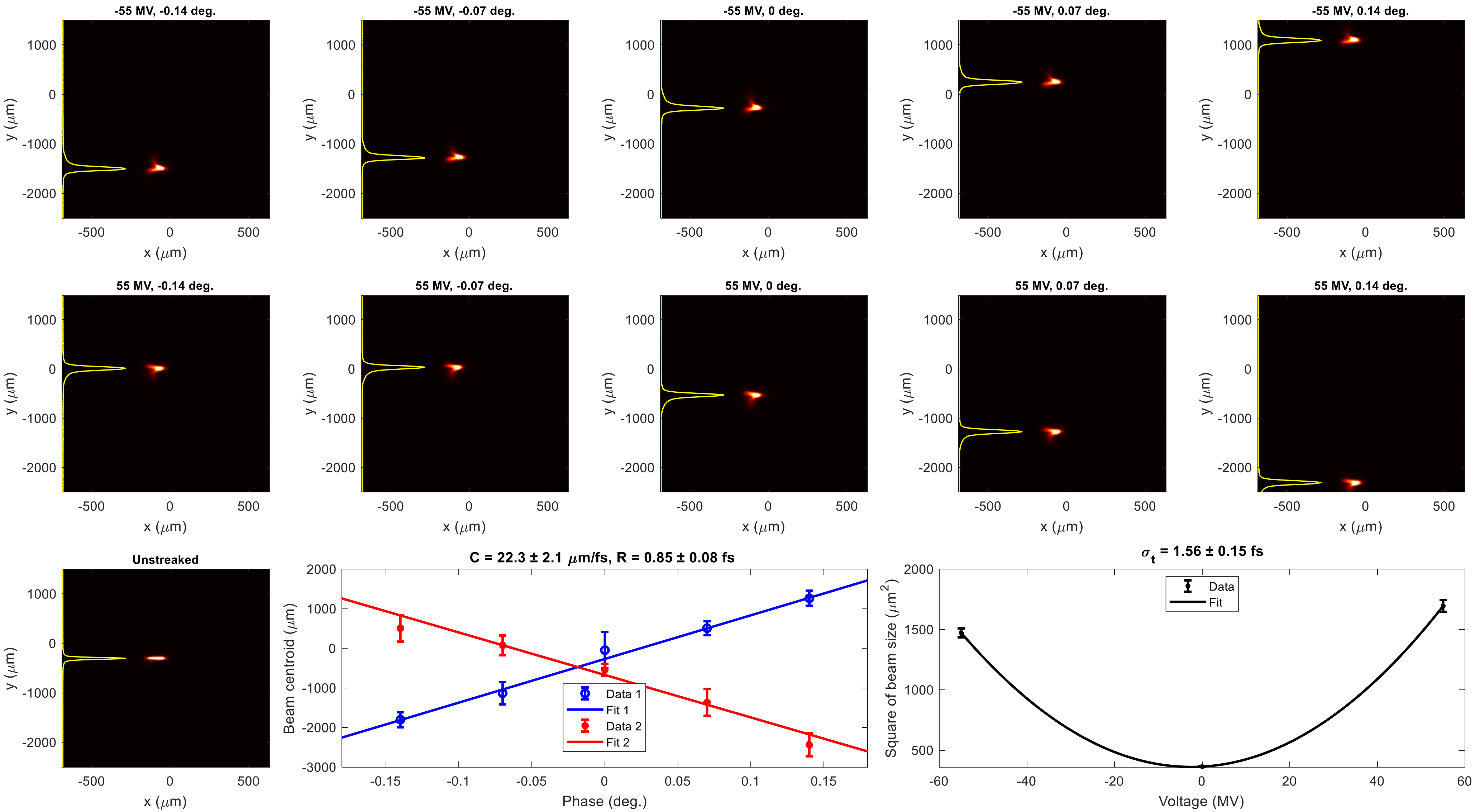
R = 0.64 ± 0.06 fs

C_{calc} = 25.0 μm/fs

$\sigma_{0,calc}$ = 19.5 μm

R_{calc} = 0.78 fs

C-band measurements (III): ~1 fs bunch duration



Shortest electron bunch duration

E = 5.8 GeV

V = 55 MV

C = 22.3 ± 2.1 μm/fs

σ_0 = 19.0 ± 0.4 μm

σ_t = 1.56 ± 0.15 fs

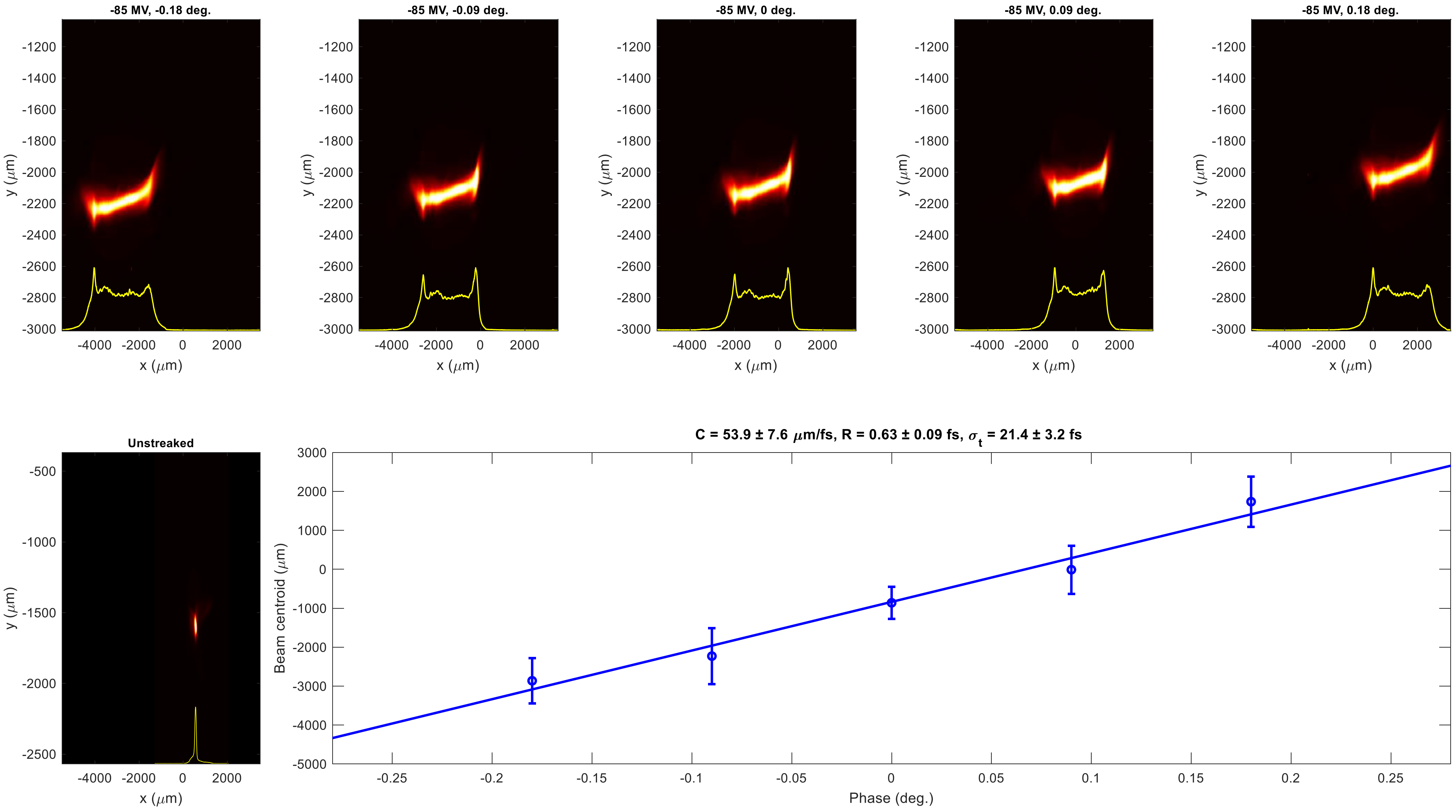
R **= 0.85 ± 0.08 fs**

C_{calc} = 19.7 μm/fs

$\sigma_{0,calc}$ = 19.2 μm

R_{calc} **= 0.98 fs**

X-band measurements (I): sub-fs resolution



E = 3.2 GeV

V = 84 MV

C = 53.9 ± 7.6 μm/fs

σ_0 = 33.8 ± 0.7 μm

σ_t = 21.4 ± 3.2 fs

R = 0.63 ± 0.09 fs

C_{calc} = 51.6 μm/fs

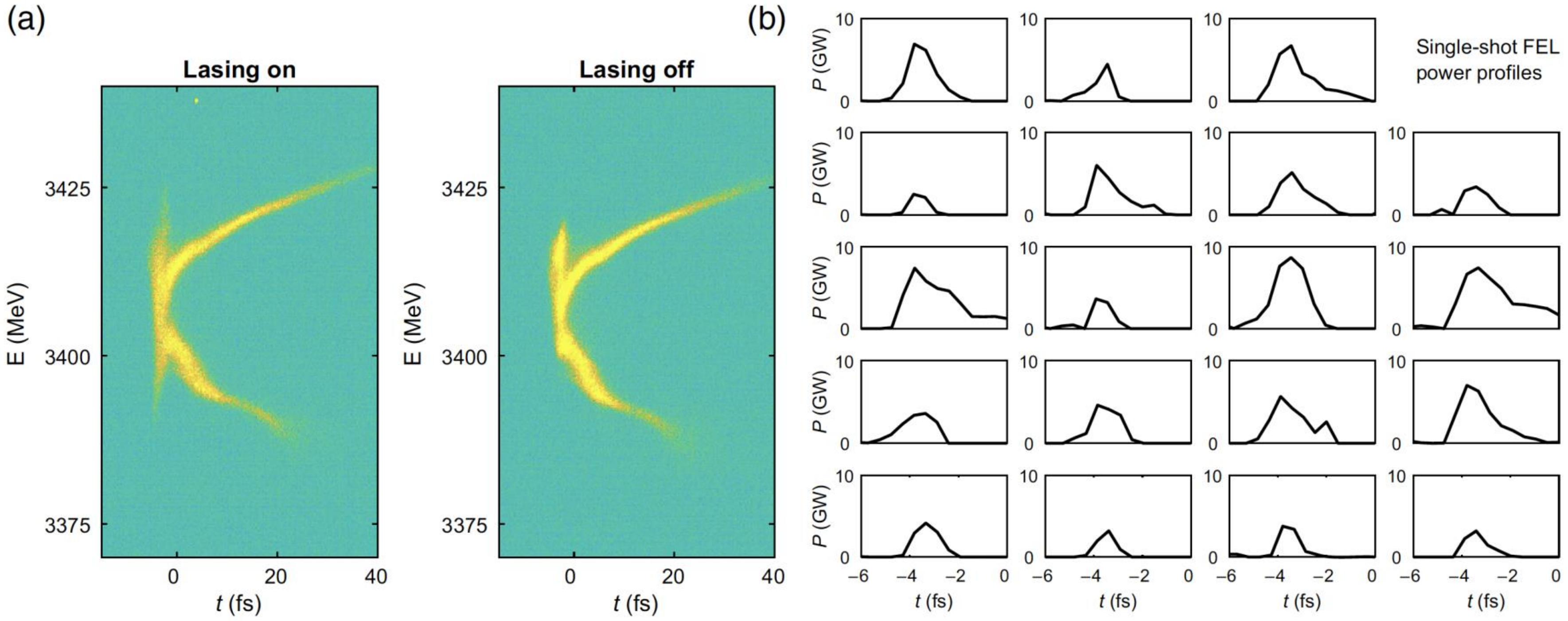
$\sigma_{0,calc}$ = 30.6 μm

R_{calc} = 0.59 fs

(assuming 400 nm emittance)

Proc. SPIE 12581, doi: 10.1117/12.2665447

X-band measurements (II): sub-fs FEL pulse



E = 3.4 GeV

V = 85 MV

C = 55.0 ± 4.3 μm/fs

σ_0 = 46.5 μm

$\boldsymbol{R}$ **= 0.85 ± 0.07 fs**

Photon energy 665 eV

FEL peak power average: 5.1 ± 1.8 GW

Average rms pulse duration: $\boldsymbol{\sigma_{FEL}}$ = *0.57 ± 0.22 fs*

Minimum reconstructed rms photon pulse duration is 0.29 fs

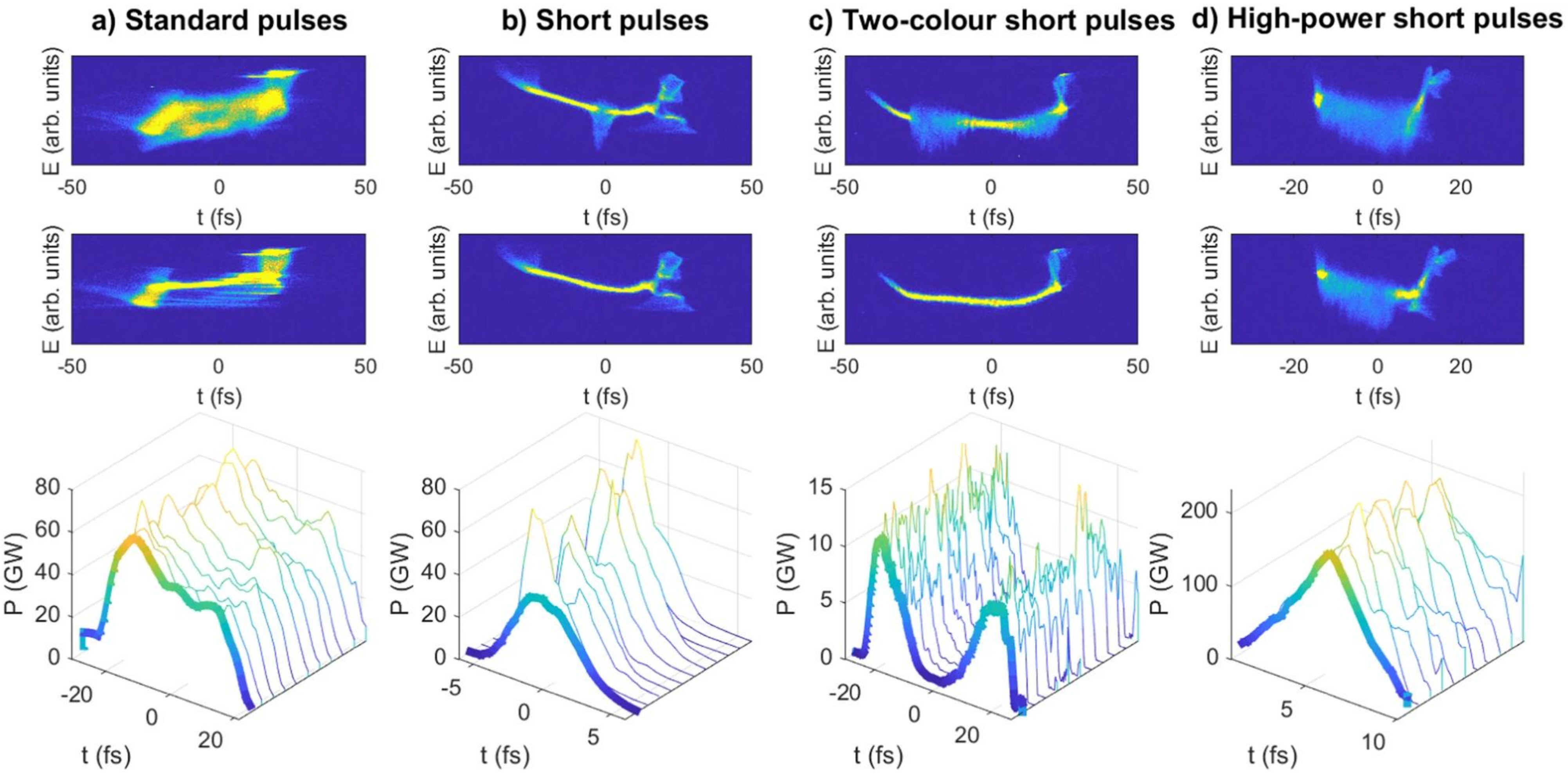
06.05.2025 • Large research facilities • 8 min

World record attosecond measurement at SwissFEL

using electron-beam streaking.

Advanced Photonics, 2025, 7 (2): 026002
APL Photonics 8, 111302, 2023

X-band measurements (III): versatile tool for many modes



σ_{FEL} = 15.6 ± 0.9 fs

σ_{FEL} = 1.4 ± 0.1 fs

σ_{FEL1} = 5.1 ± 0.7 fs

σ_{FEL2} = 4.5 ± 0.4 fs

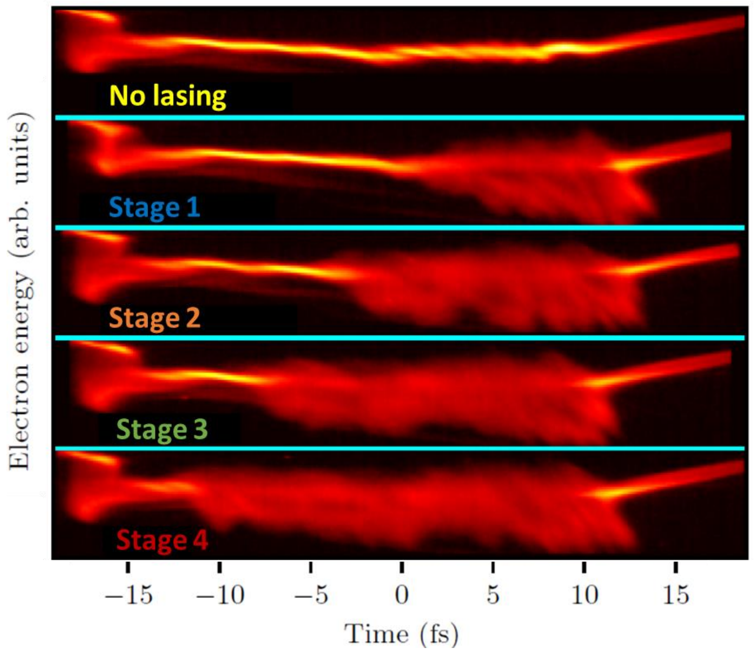
σ_{FEL} = 2.0 ± 0.3 fs

Extremely useful device to setup and optimize FEL for standard and special operation modes

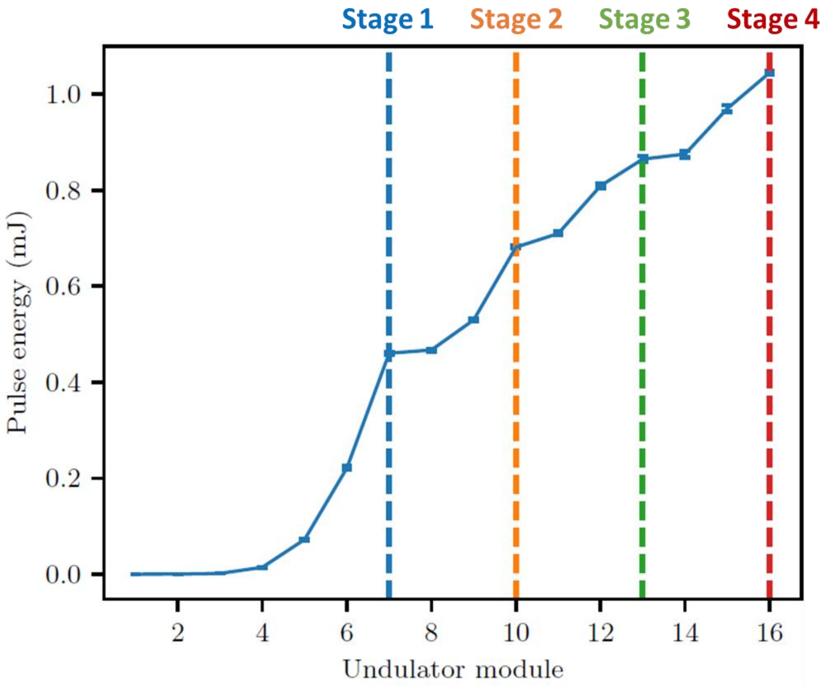
E. Prat et al., Nature Communications, (2023)14:5069

X-band measurements (IV): multi-stage amplification

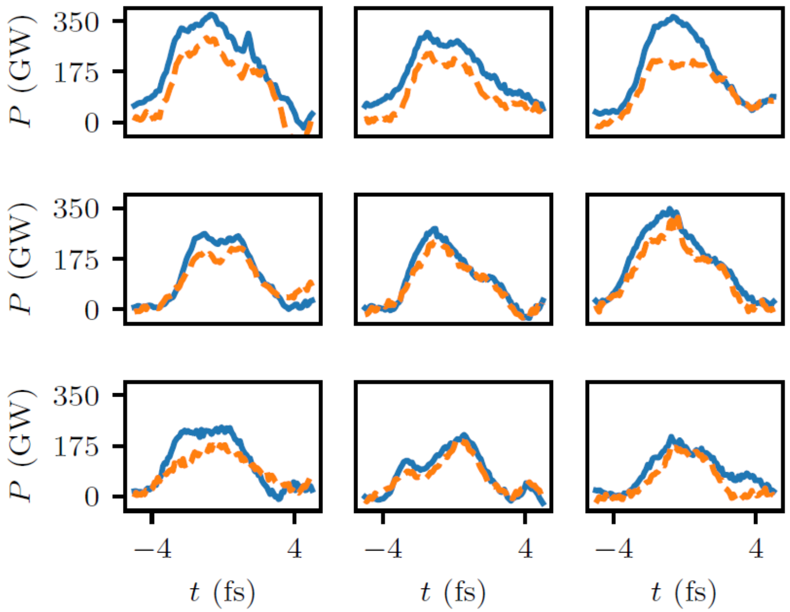
LPS measurements



FEL Pulse Energy along Undulator



FEL Pulse Reconstruction



Double streaking (RF deflector + dispersion)

Calibration measured from chicane delays

C = 92 ± 7 μm/fs

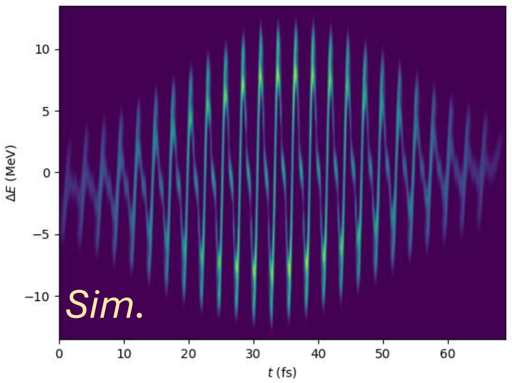
σ_0 unmeasured

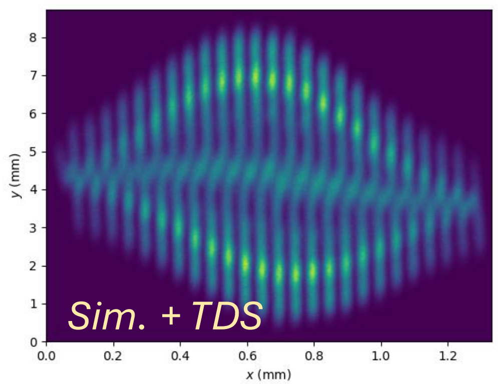
Resolution expected to be **less than 0.5 fs**

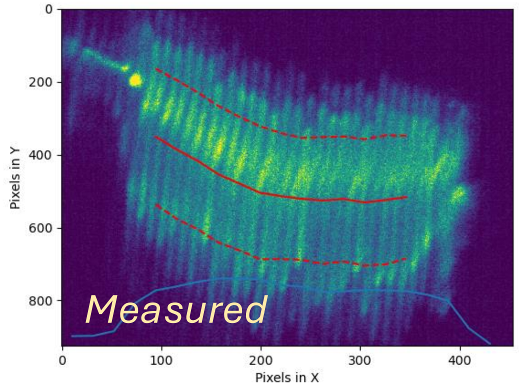
σ_{FEL} = 1.9 ± 0.2 fs

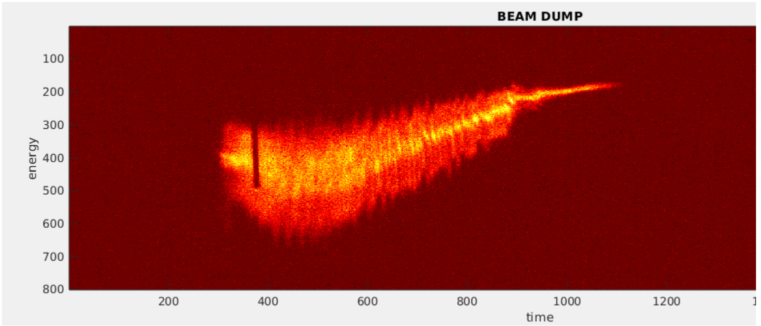
G. Wang et al, PRL 132, 035002, 2024

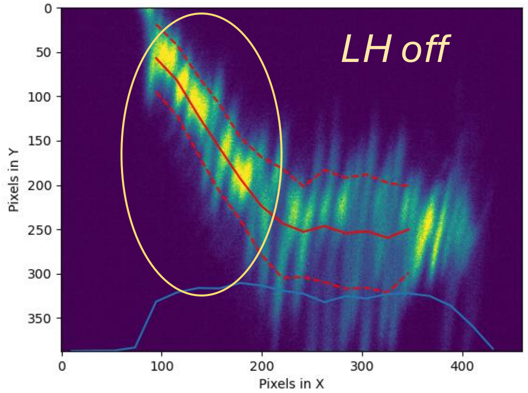
X-band measurements (V): Seeding FEL at SwissFEL

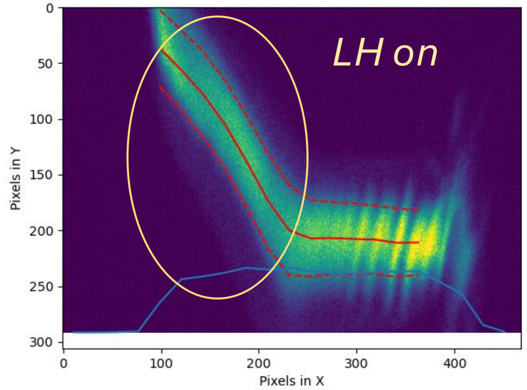


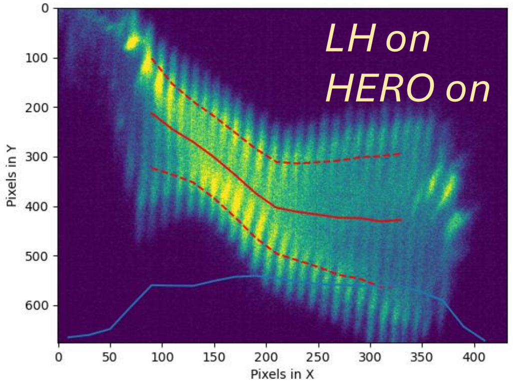










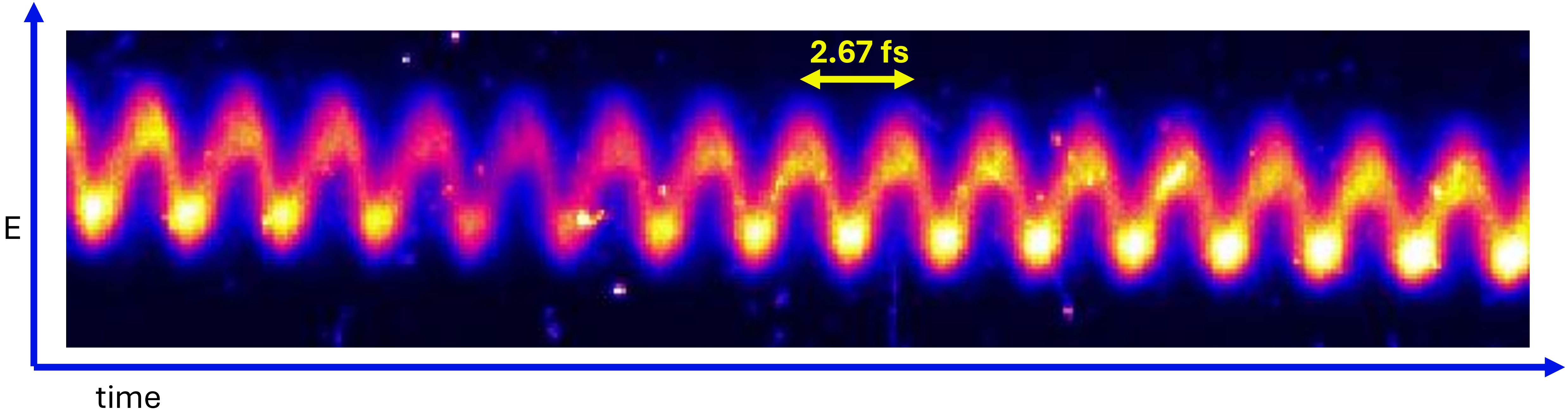


Effect of the laser heater used to damp microbunching instability in ESASE

Courtesy of S. Reiche

X-band measurements (V): femtosecond-scale energy modulation

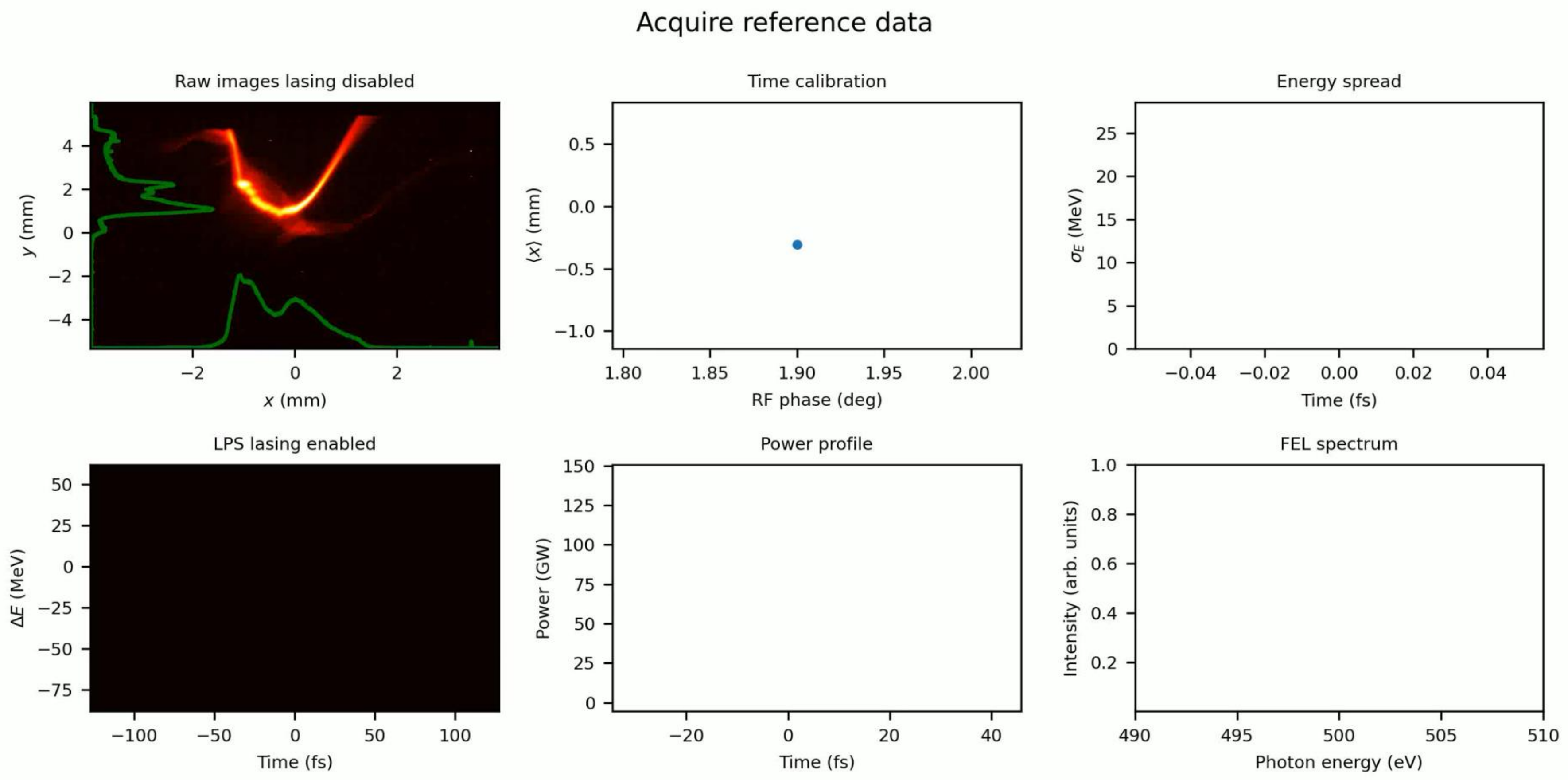
- ESASE: Energy modulation generated in a modulator with a laser with a period of 800 nm (2.67 fs)



- Measurement indicates sub-fs resolution (more accurate?)

Courtesy of E. Prat

Live reconstruction of FEL power profile with PolariX (demo)



OUTLOOK

- SwissFEL's maximum rep rate of 100 Hz in principle allows to measure each bunch.
- The PolariX is currently limited to 10 Hz of continuous operation due to dose rate limits.
- The „bsread" DAQ system allows to synchronously acquire other data such as FEL spectrum.

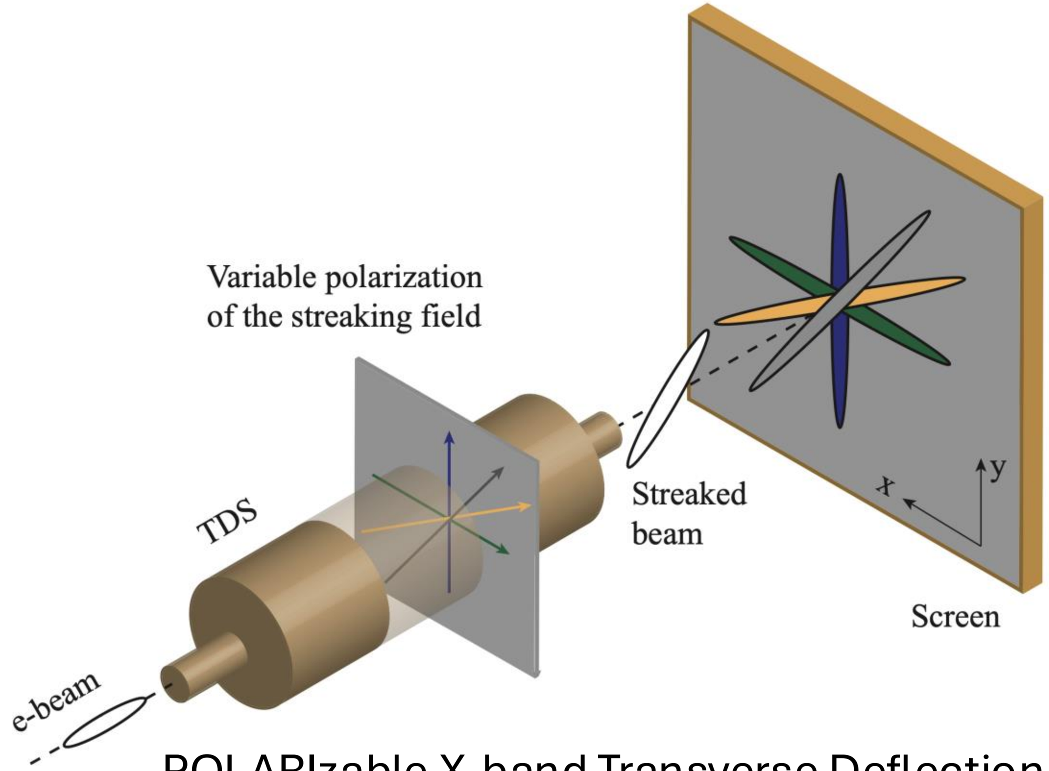
Slide courtesy of the P. Dijkstal (PSI)

5D phase space reconstruction using a next generation TDS

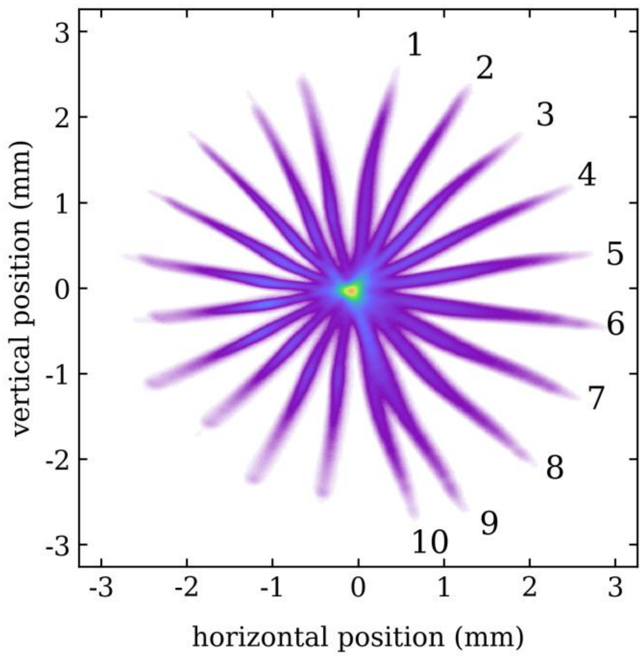
Transverse Deflecting Structures – What's next?

Diagnose multidimensional phase space of electron bunches to investigate complex beam dynamics (e.g. collective effects, beam correlations, slice emittance in different planes, etc..)

- 5D/6D phase-space characterization becomes possible by different streaking planes and using tomographic methods.
- Reconstruction of the 3D charge density.



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



B. Marchetti (2021)

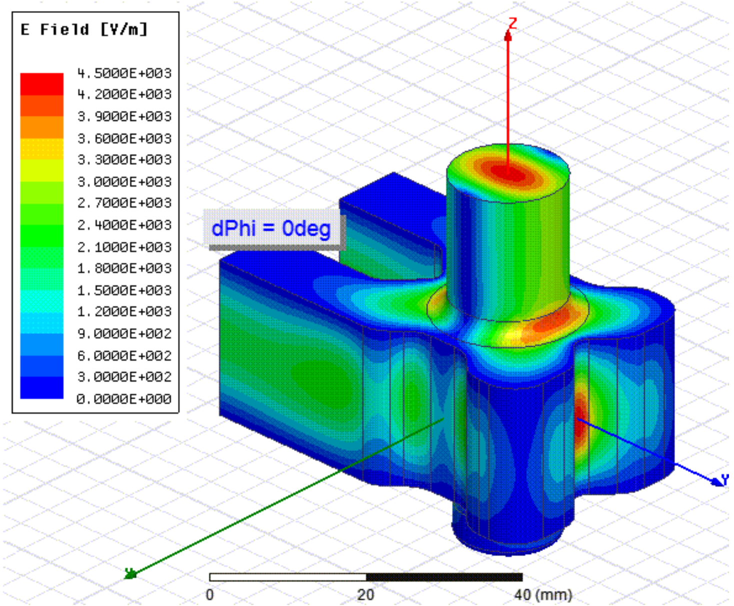
References:

Grudiev, CLIC-Note-1067, 2016
P. Craievich et al., Phys. Rev. Accel. Beams 23, 112001
B. Marchetti et al., Sci Rep 11, 3560 (2021)
P. González Caminal et al., Phys. Rev. Accel. Beams 27, 032801

Novel Concept with Variable Polarization (X band)

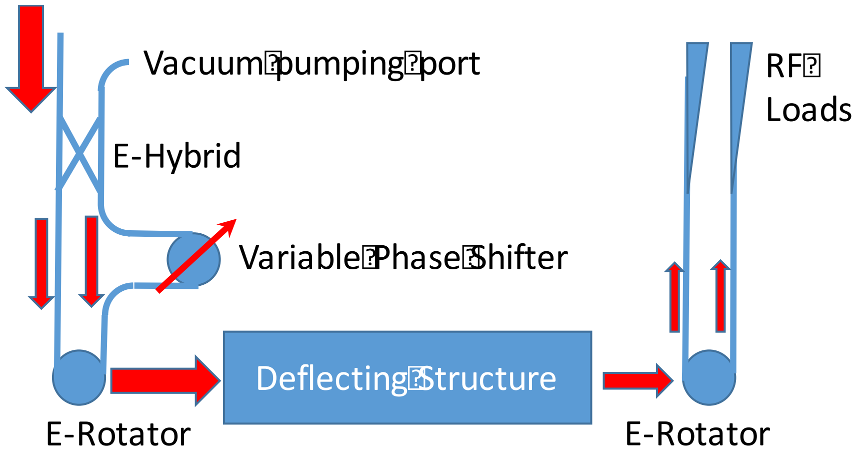
POLARIzable X-band Transverse Deflection Structure – **POLARIX TDS**

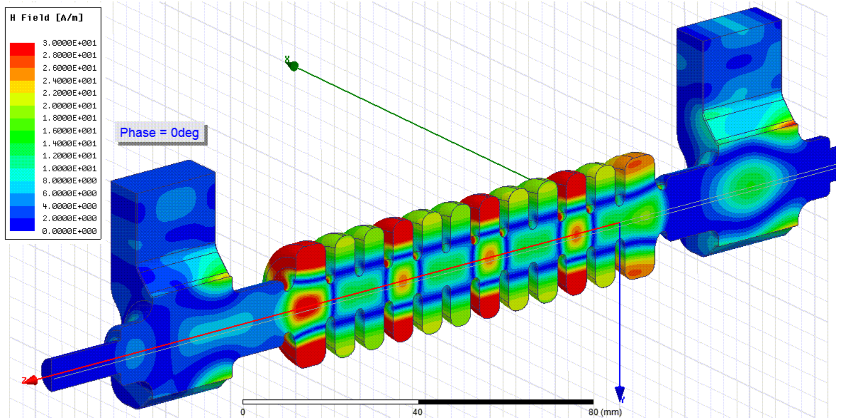
Variable polarization circular TE11 mode launcher:
E-rotator



Phase difference between port 1 and port 2:

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



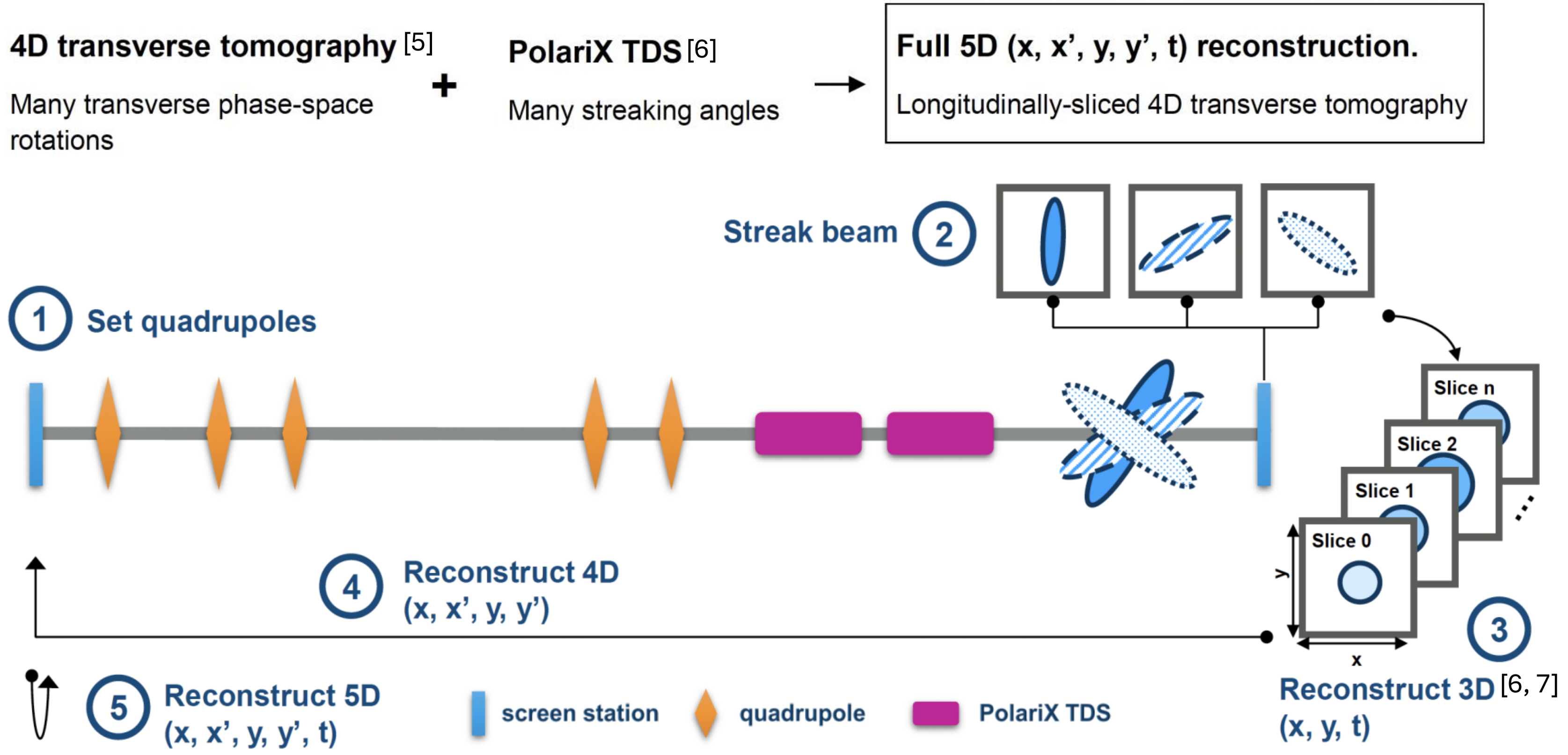


Designed in collaboration between CERN, PSI and DESY.
Installed at:

1x TDS FLASHForward (DESY)
2x TDSs FLASH II (DESY)
2x TDSs SINBAD-ARES (DESY)
2x TDSs SwissFEL Athos (PSI)

5D phase-space tomography – method[1-4]

Reconstructing the full transverse phase-space of each longitudinal slice



- **Two independent rotations,** via transverse optics (θ_x, θ_y) and TDS streak angles, enable mapping from 2D images to full 5D distribution.
- **Hierarchical reconstruction**: first resolve (x, y, t), then expand each time slice into full transverse phase space.
- **Resolution and accuracy are tunable** via beamline tuning (β-matching), TDS voltage, drift length, and number of projections.

[1] S. Jaster-Merz et al., Phys. Rev. Accel. Beams 27, 072801, 2024 - METHOD
[2] S. Jaster-Merz et al., https://doi.org/10.48550/arXiv.2505.13724, PROOF of PRINCIPLE
[3] S. Jaster-Merz et al ., *JACoW* LINAC2022 MOPORI10, 2022,
[4] S. Jaster-Merz et al ., *JACoW* IPAC2022 MOPOPT021, 2022
[5] K. Hock and A. Wolski, Nucl. Instrum. Methods Phys. Res. Sect. A, 2013,
[6] B. Marchetti et al., Sci. Rep., 2021
[7] D. Marx et al., Journal of Physics: Conference Series, vol. 874, 2017

Slide courtesy of S. Jaster-Merz
sonja.jaster-merz@desy.de

Excellent performance demonstrated in simulations

Proof-of-principle simulation studies with test distributions using the ARES beamline

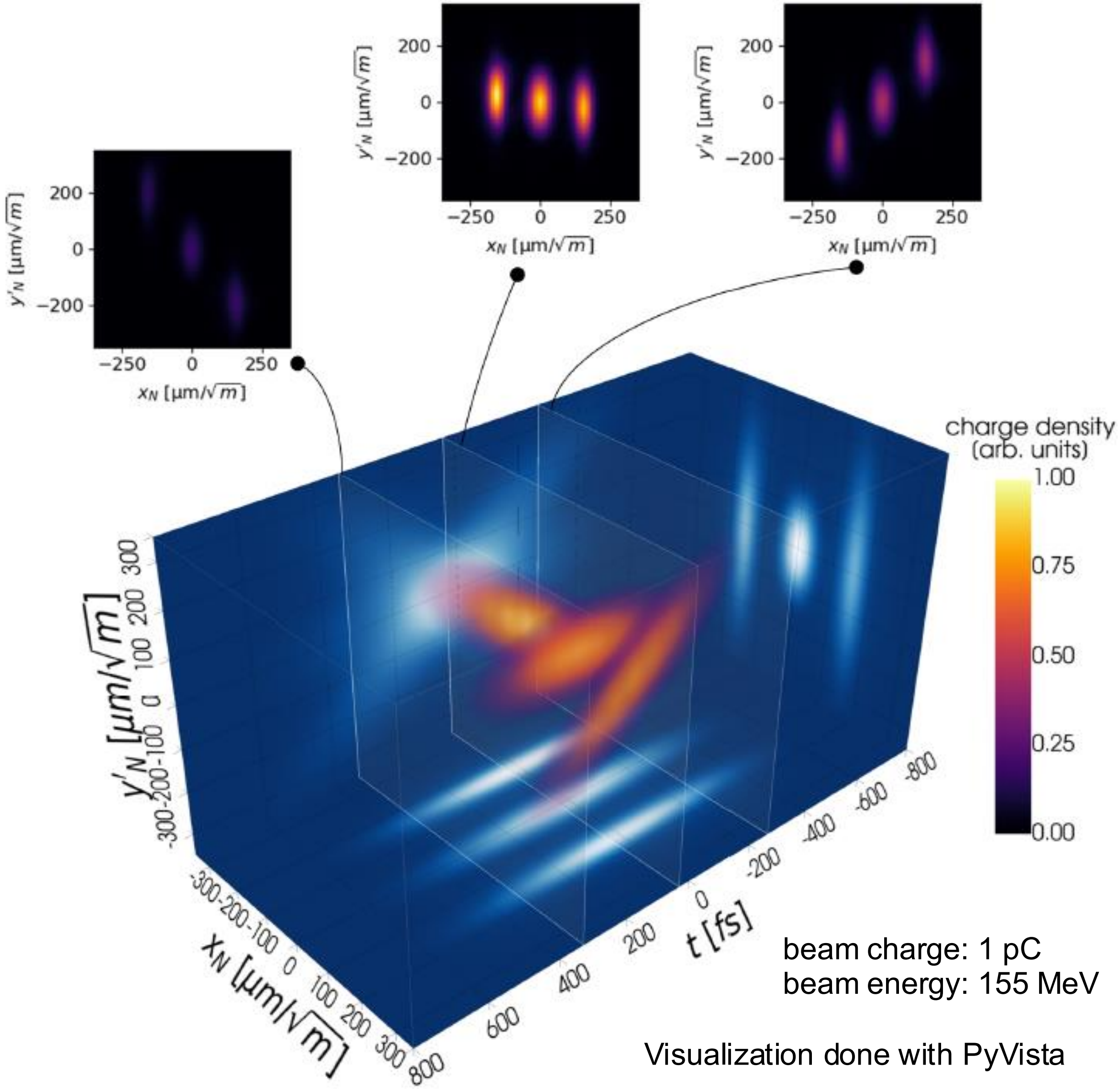
Full 5D reconstruction of Gaussian and highly complex phase spaces.

Beam parameters reconstructed with $\lesssim$ **5%** discrepancies.

Extraction of **sliced** beam parameters and the **4D slice emittance** possible.

$$\begin{pmatrix} x_N \\ x'_N \\ y_N \\ y'_N \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{\beta_x}} & 0 & 0 & 0 \\ \frac{\alpha_x}{\sqrt{\beta_x}} & \sqrt{\beta_x} & 0 & 0 \\ 0 & 0 & \frac{1}{\sqrt{\beta_y}} & 0 \\ 0 & 0 & \frac{\alpha_y}{\sqrt{\beta_y}} & \sqrt{\beta_y} \end{pmatrix} \begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix}$$

S. Jaster-Merz et al., Phys. Rev. Accel. Beams 27, 072801 (2024)



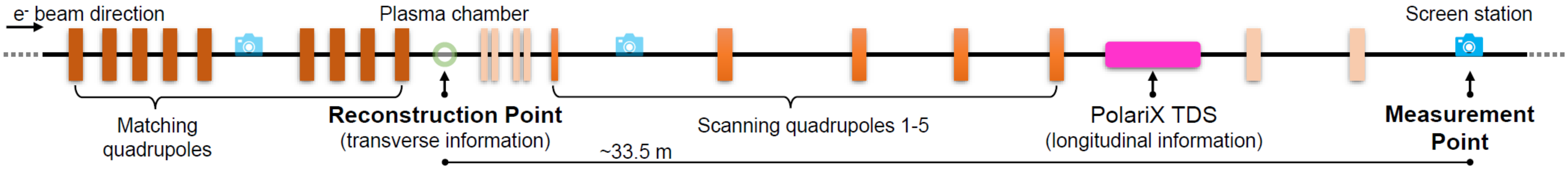
beam charge: 1 pC
beam energy: 155 MeV

Visualization done with PyVista

Experimental demonstration at FLASHForward

Fully commissioned PolariX TDS and flexible diagnostic beamline available

- Experimental facility dedicated to **beam driven plasma acceleration** experiments.
- Used up to 1.3 GeV electron beams from the **FLASH linac.**
- Measurement performed with 10 Hz **single bunch** operation, **~1.1 GeV** energy, **~0.3 nC** charge, and **~200 fs** RMS bunch duration.

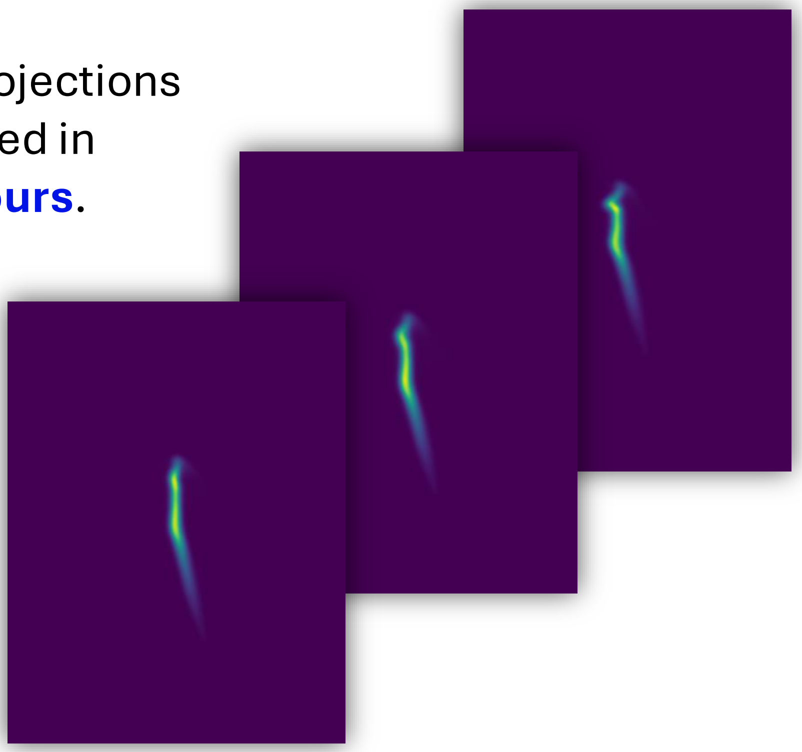


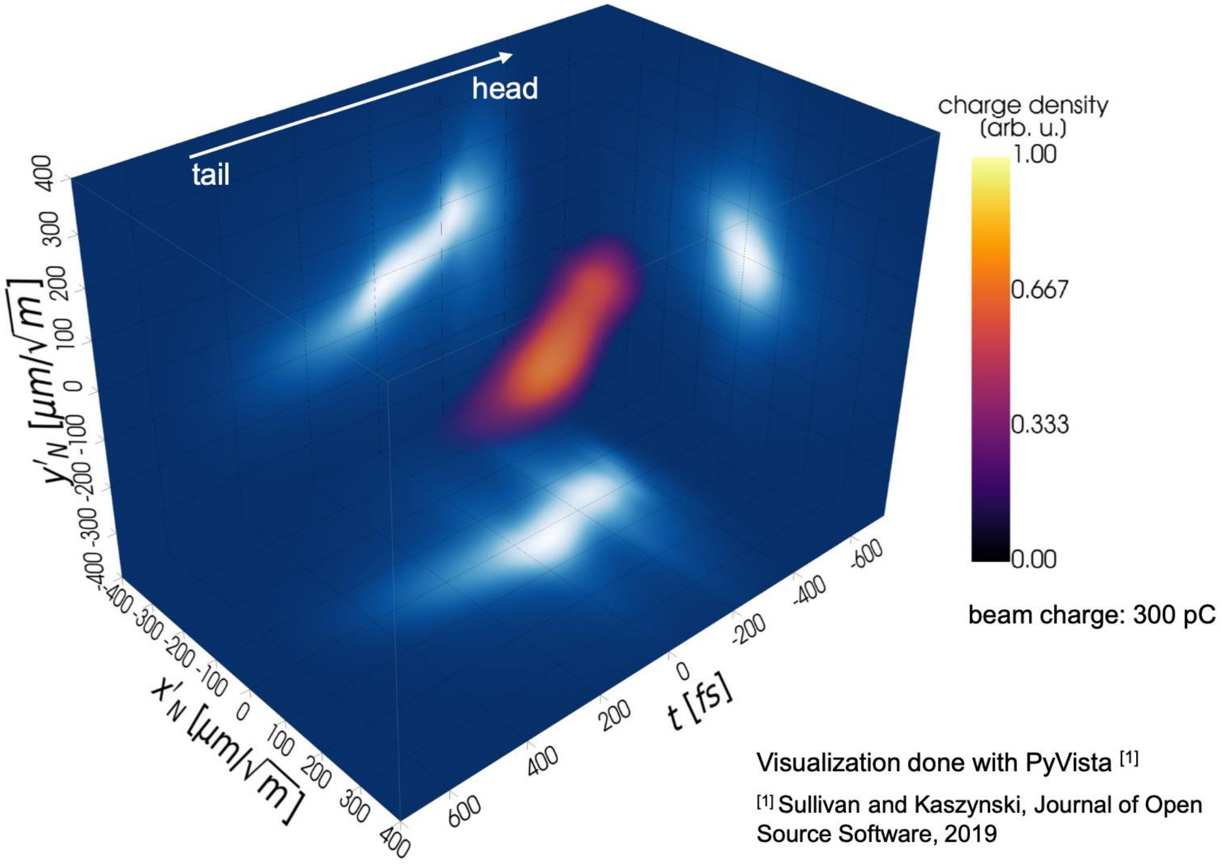
S. Jaster-Merz et al., Physical Review Research, accepted on 14 October 2025, also available here: https://doi.org/10.48550/arXiv.2505.13724

Successful reconstruction of the 5D phase-space distribution at DESY (first time!)

Feasibility of conducting a 5D tomography measurement is demonstrated for the first time

960 projections recorded in **~28 hours**.





[1] Sullivan and Kaszynski, Journal of Open Source Software, 2019

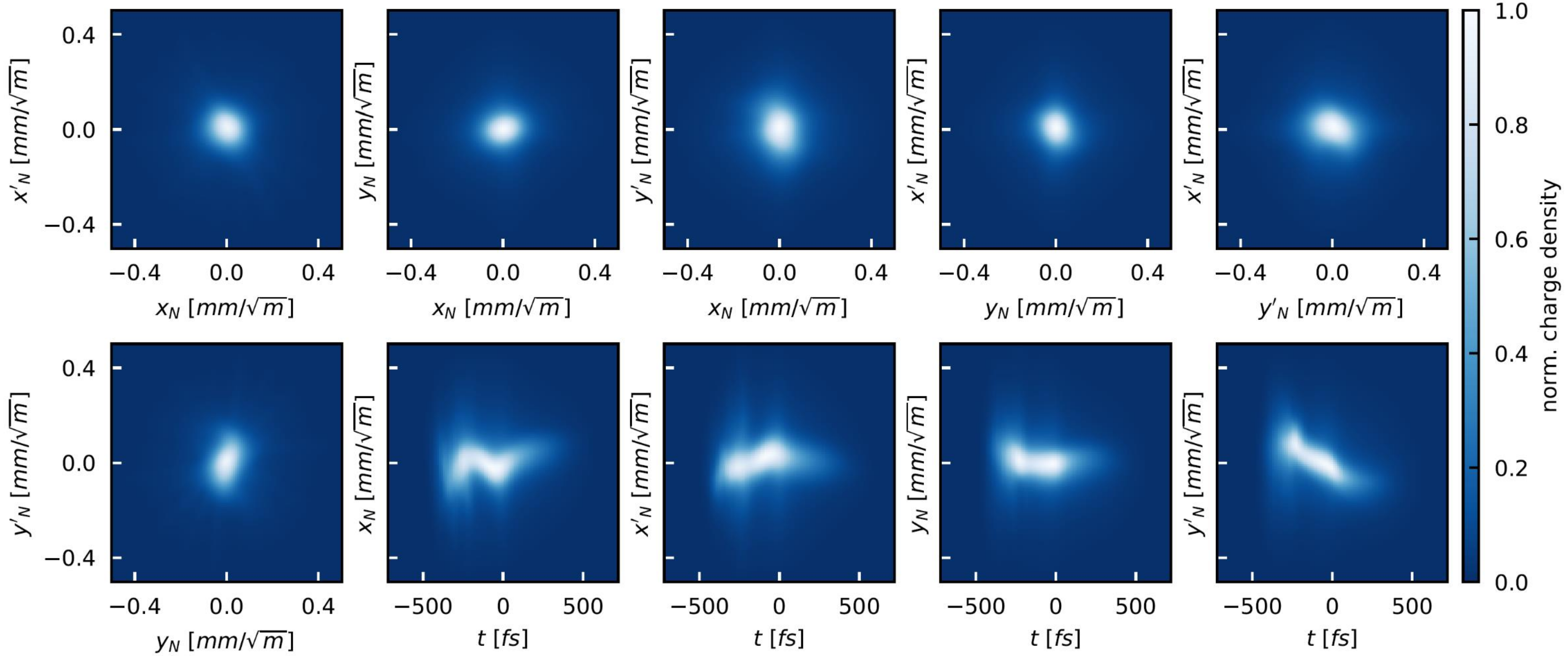
Average longitudinal resolution of **20 fs**.

Reconstruction of **72 bins** in the **longitudinal** plane and **301 bins** (3.3 µm/√m) per **transverse** plane.

S. Jaster-Merz et al., https://doi.org/10.48550/arXiv.2505.13724

Reconstructed 5D phase space enables new insights

Previously hidden transverse-longitudinal correlations are retrieved



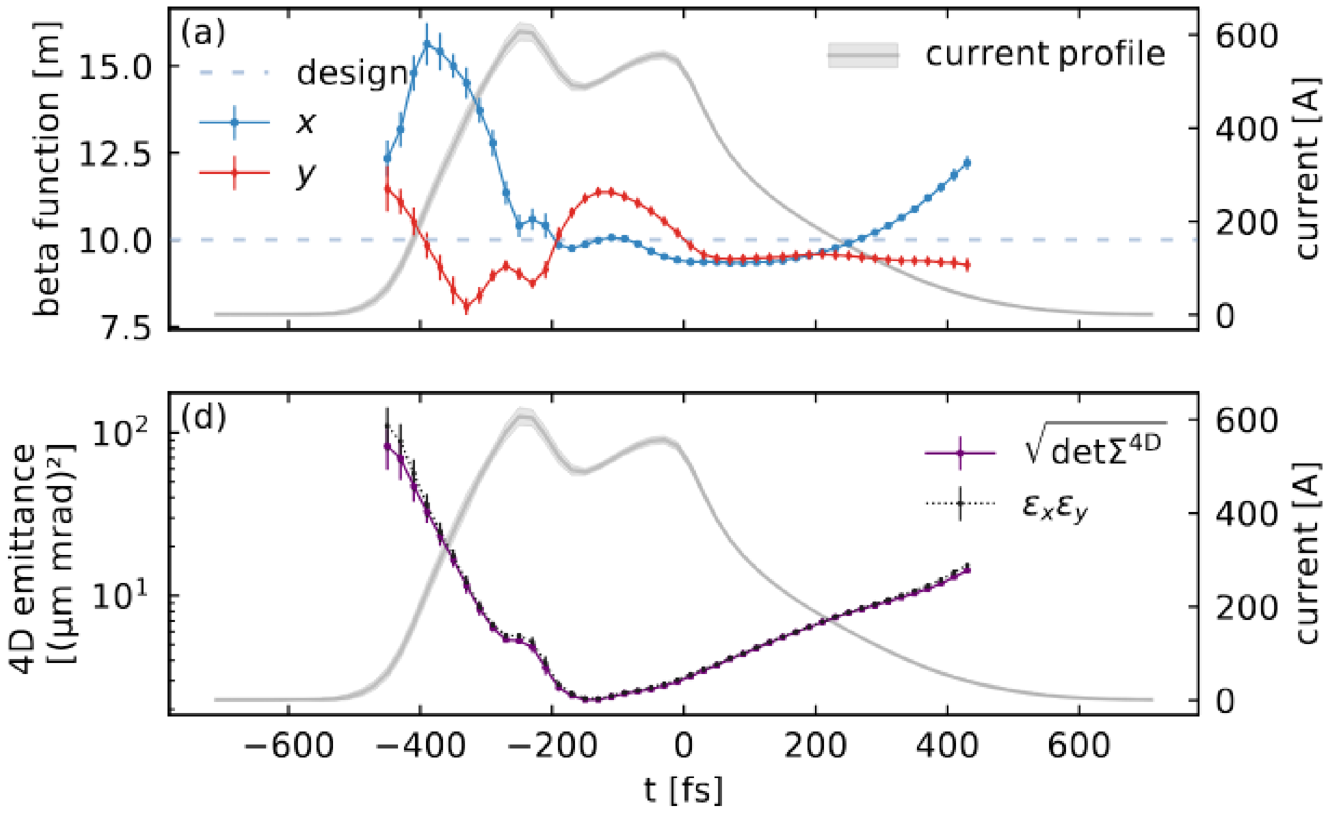
S. Jaster-Merz et al., https://doi.org/10.48550/arXiv.2505.13724

All 2D projections of the 5D phase space obtained from the reconstruction.

Transverse phase space reconstruction **validated** against dedicated **4D tomography** measurement.

Extraction of sliced beam parameters from reconstruction

Information about both transverse planes can be obtained simultaneously



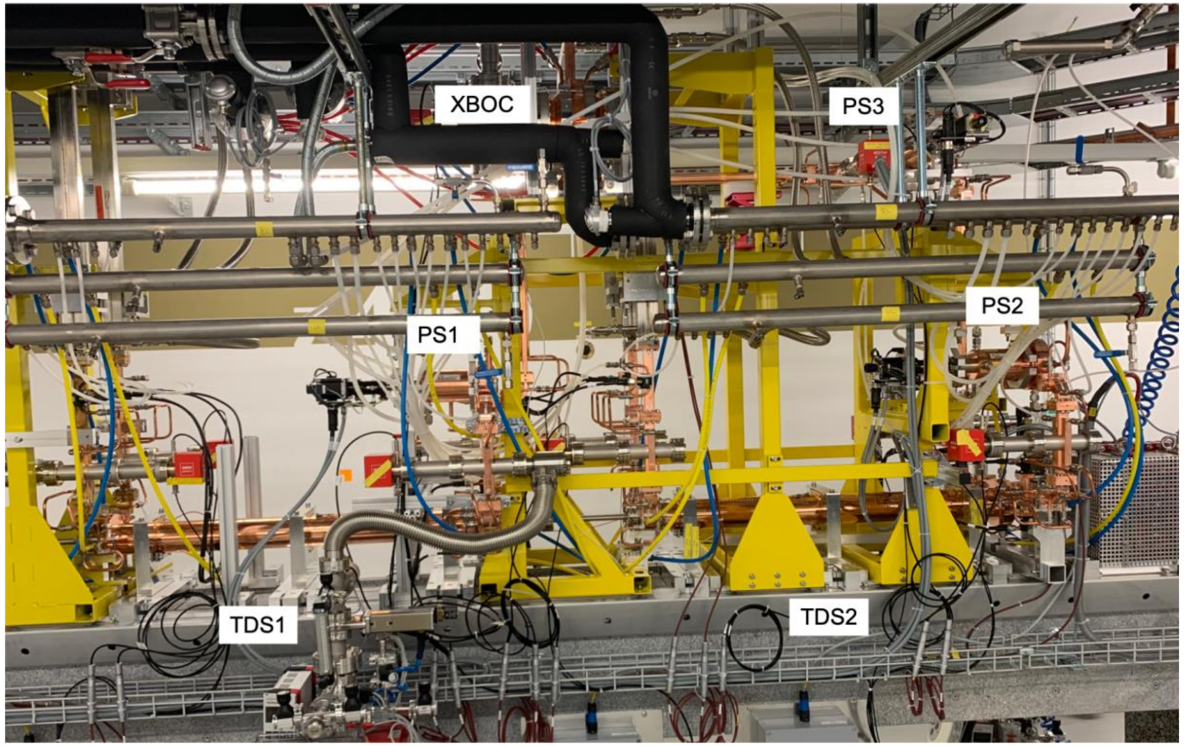
S. Jaster-Merz et al., https://doi.org/10.48550/arXiv.2505.13724

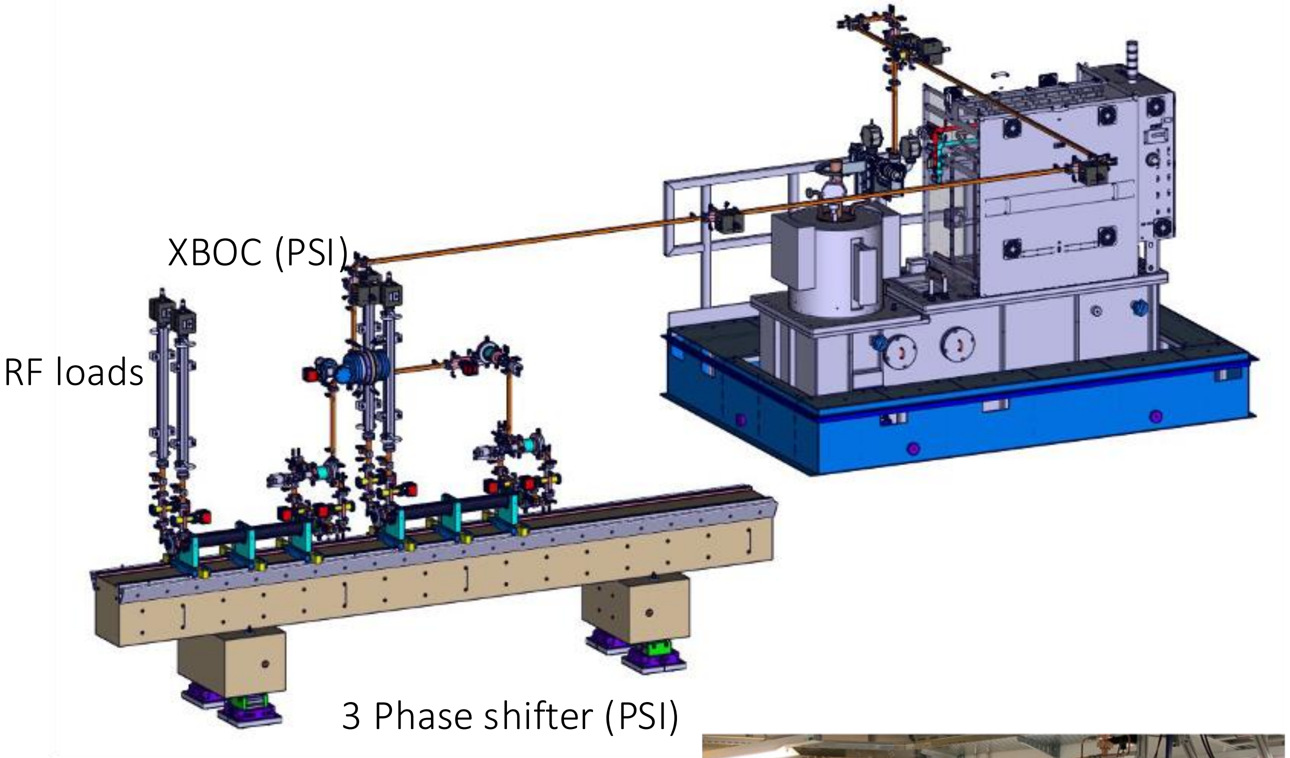
In addition to the full 5D phase space distribution the reconstruction allows to obtain:

- Sliced transverse beam parameters,
- Bunch duration and current profile,
- Sliced 4D emittance.
- Projected transverse beam parameters.

Projected quantities **validated** against multi-quadrupole scan and TDS bunch duration measurements.

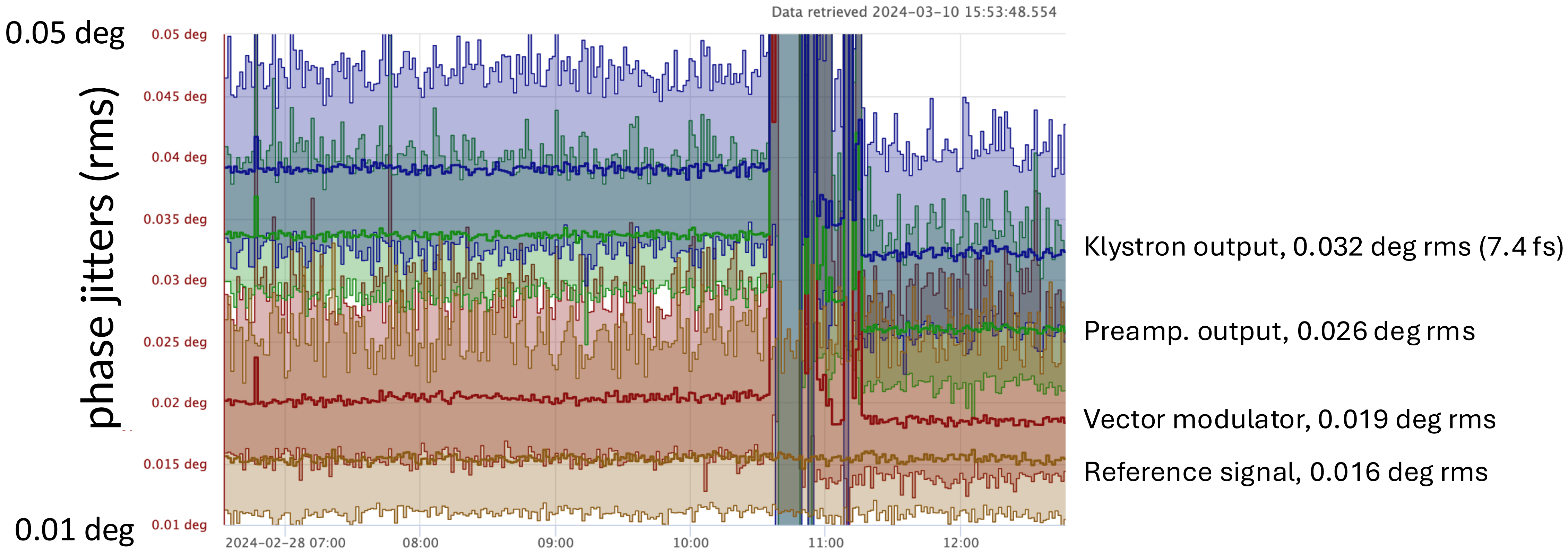
PolariX TDS and RF components at PSI



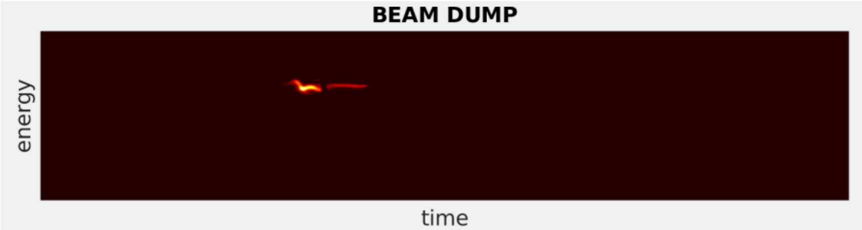


- All waveguide RF components including the XBOC, and phase shifters were designed and built at PSI, 50 MW X-Band Klystron **(max used rf power 35 MW).**
- PSI HV klystron modulator: **developed and built in-house (400 kV, 3 ms).**
- Deflecting voltage ~90 MV.

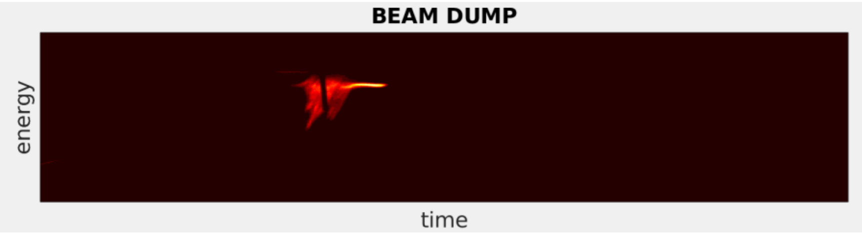
RF phase jitter and centroid jitter on the screen



FEL OFF



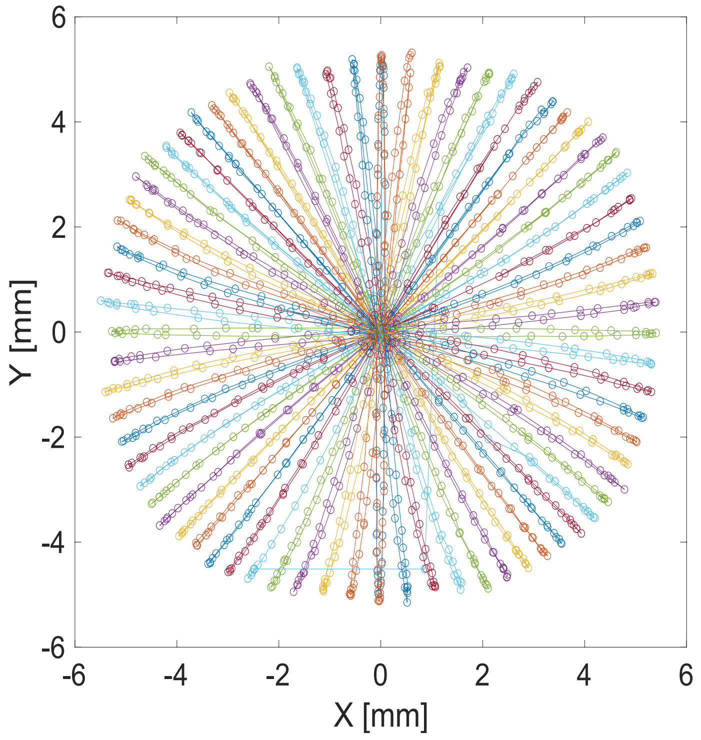
FEL ON

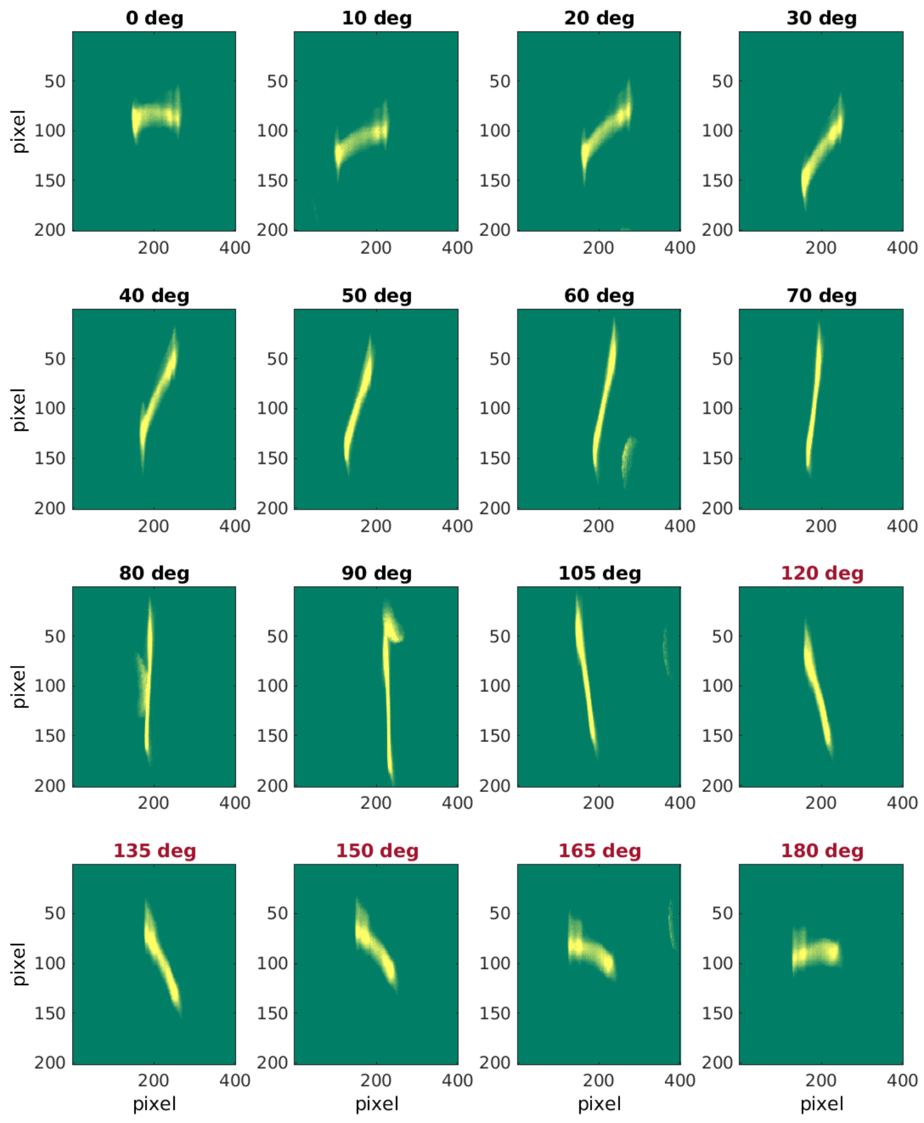


Example of centroid jitter and drift on the screen

Variable polarization – measurements at PSI at 3 GeV

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

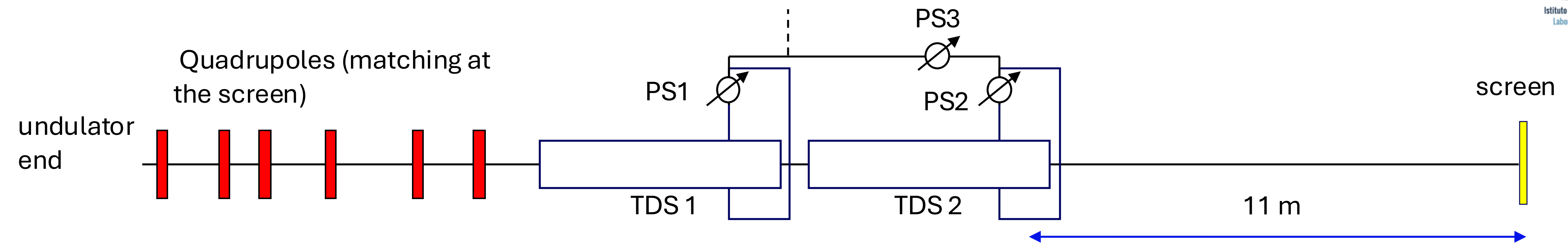




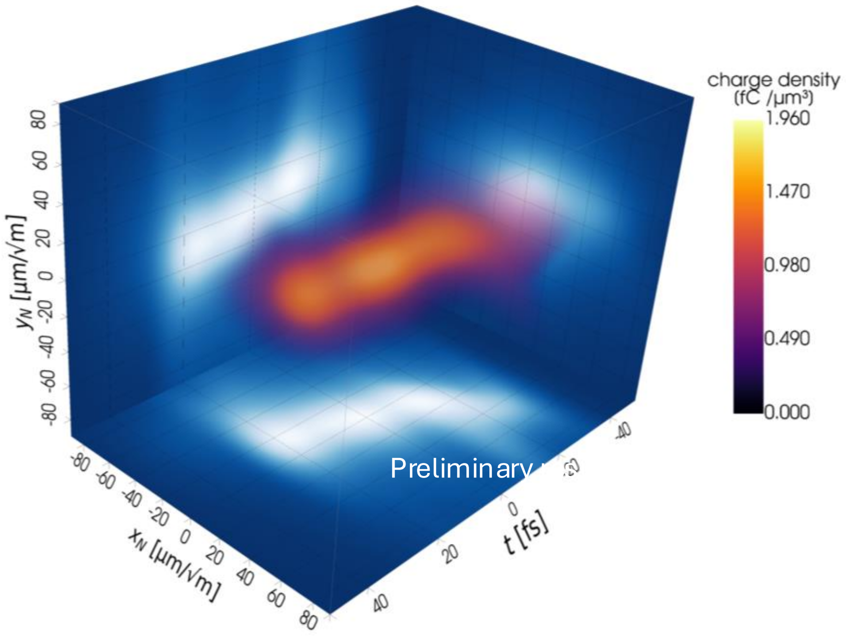
Right plots: Images on screen before dipole as a function of polarization angle. Dark polarization angles: 85 MW, red polarization angles: 72.8 MV.

5D tomography method successfully applied at PSI

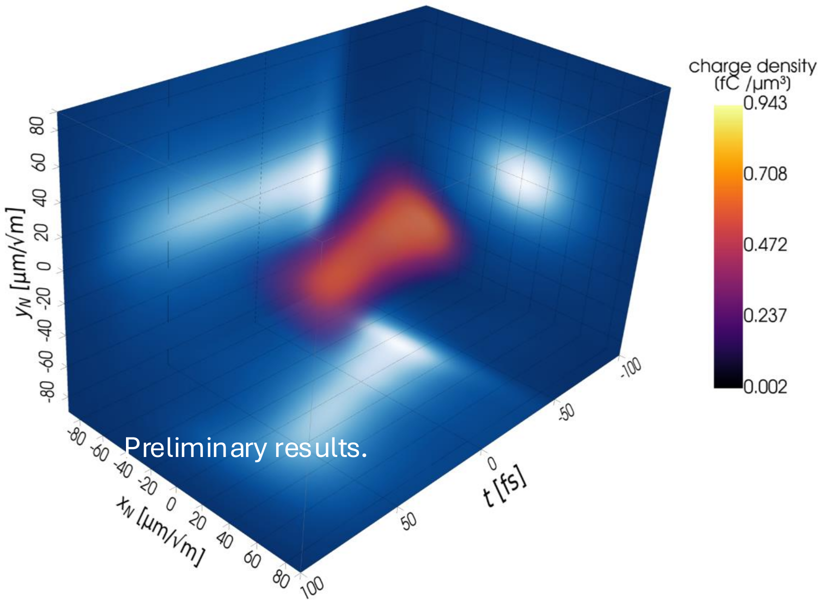
Two 5D datasets for different beam settings were recorded, energy 3.4 GeV, charge 200 pC



Beam 1: Compressed ~56 fs short (FWHM)



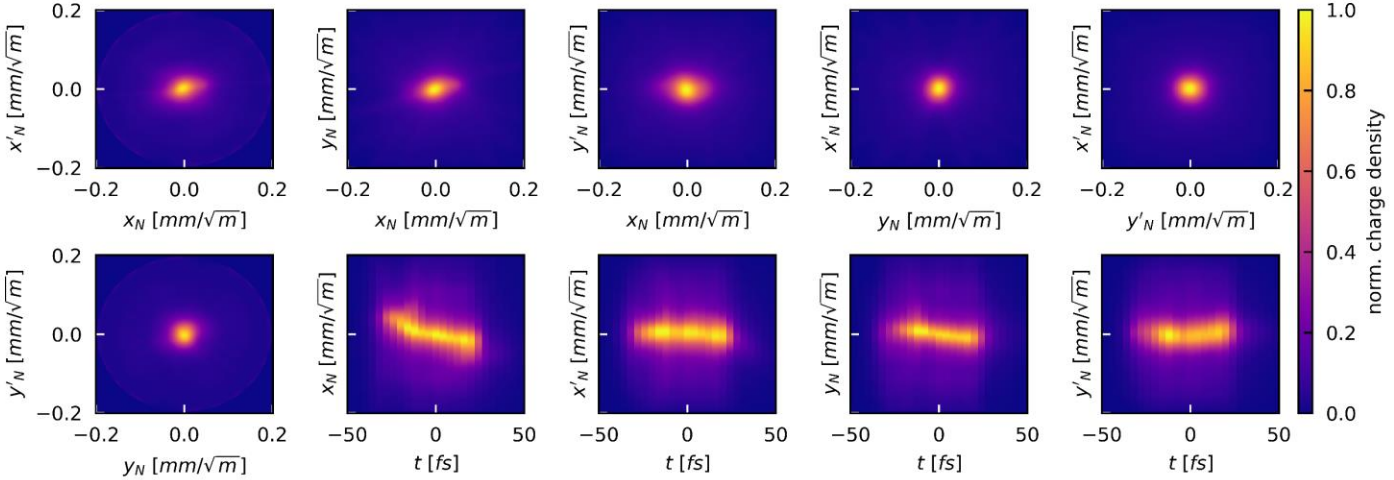
Beam 2: Reduced beam tilts, ~103 fs (FWHM)



For each dataset, we acquired 5 images for each combination of 100 quadrupole settings and 10 polarizations (+unstreaked case) in about 7 hours.
Beam repetition rate: 1 Hz.

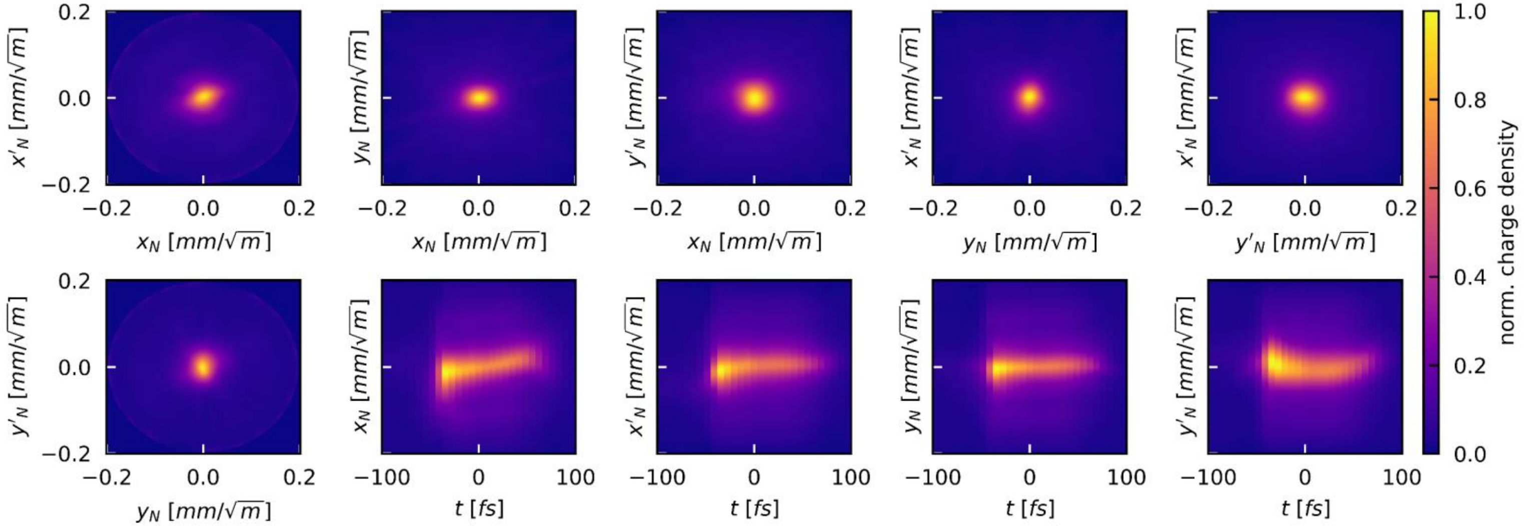
F. Demurtas (INFN-LNF), S. Jaster-Merz (DESY), P. Dijkstal (PSI) et al.

2D projections of the reconstructed phase space



Beam 1
Reconstructed 5D distribution reveals beam tilts

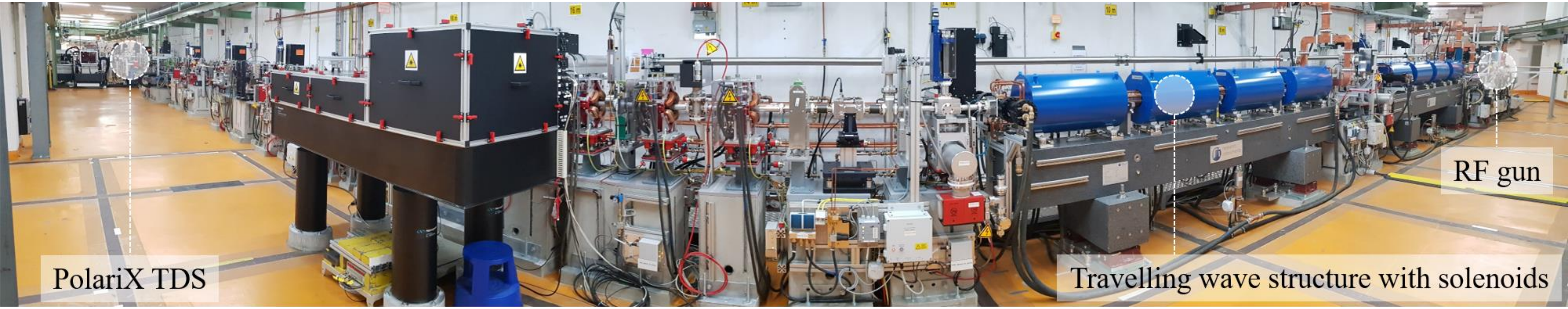
Beam 2
Relaxing the compression reduced tilts



Preliminary results.

Outlook: PolariX at ARES

Accelerator test facility for novel diagnostics, advanced acceleration schemes, medical applications, ...



- Designed to produce and characterize bunches of **high quality** with **sub-fs duration**, https://ares.desy.de/
- Applications using **sub-pC charge** beams: Drive towards high-precision longitudinal diagnostics, detailed phase-space characterization, and highly sensitive diagnostic tools.

→ **Two PolariX TDSs** with independent RF sources: 2 x 6 MW CPI klystrons + 2 BOCs.

  - Located downstream of first experimental chamber and bunch compressor.
  - Expected longitudinal resolution: ~0.2 fs assuming 20 MV peak voltage for each TDS.

- Commissioning is ongoing, and first 3D phase space reconstructions were performed.

Summary and outlook

PSI

– Temporal profile and longitudinal phase space measurements

- Time-resolved measurements of electron and photon beams are fundamental for FELs. Resolution at the fs level or below is desired.
- An RF deflector after the undulator allows parasitic measurements of both electron and photon beams with fs/sub-fs resolution
- We have shown at SwissFEL: Sub-fs resolution with C-band and X-band TDSs, electron bunch duration of ~1.5 fs rms (C-band), FEL pulse duration of hundreds of as (PolariX)
- Outlook: Attempt $R < 0.1$ fs with X-band by double streaking and extreme optic.

– 5D phase space reconstruction

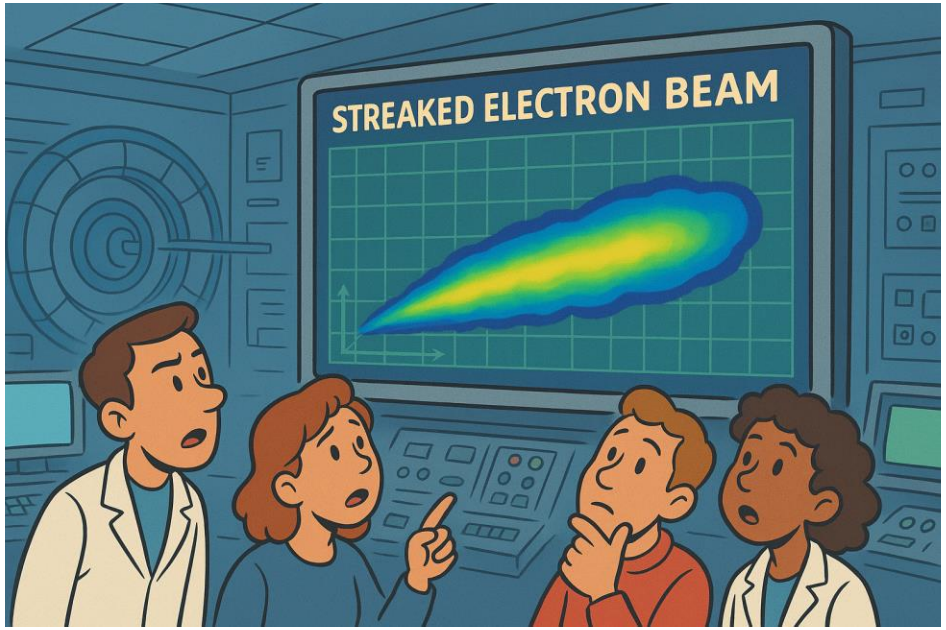
- The first X-band TDS with variable polarization was designed, built, and tested in a joint project between CERN, DESY and PSI.
- The 5D reconstruction method was successfully demonstrated at 2 facilities (SwissFEL and FLASH), with ARES results expected for 2026.
- Well established method but it takes a long measurement time to get the results (~ several hours)
- Outlook: Measurements with the PolariX TDS should be combined with generative machine learning techniques, as demonstrated for example by R. Roussel et al., Phys. Rev. Accel. Beams 27, 094601 (2024).

Aknowledgments

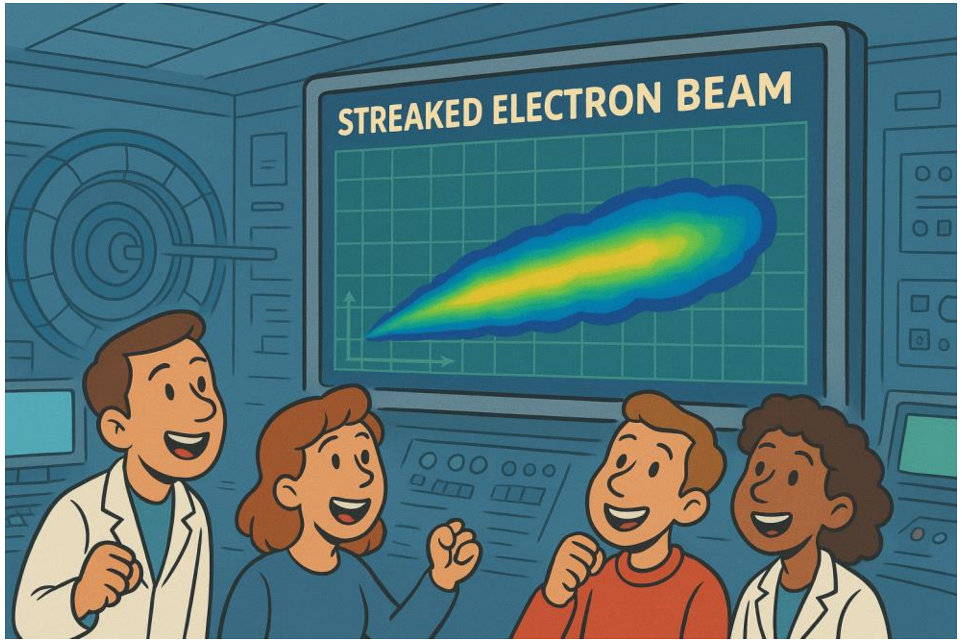
- E. Prat, P. Dijkstal, S. Reiche for providing me materials related to SwissFEL Aramis/Athos.
- F. Marcellini and Z. Geng for the optimization of the ‘complex’ RF system.
- Thanks to my colleagues in the RF section involved in the design, development and commissioning of the full TDS systems.
- DESY: S. Jaster-Merz, B. Beutner, R. W. Assmann, J. Beinortaitė, J. Björklund Svensson, R. Brinkmann, F. Burkart, H. Dinter, P. González Caminal, W. Hillert, A. L. Kanekar, M. Kellermeier, W. Kuropka, F. Mayet, J. Osterhoff, B. Stacey, M. Stanitzki, T. Vinatier, S. Wesch, R. D’Arcy
- Francesco Demurtas, Enrica Chiadroni, Anna Giribono (INFN LNF)
- Thanks also go to our colleagues at CERN involved in the collaboration for the useful discussions.

That's all!!

PSI



before..



(hopefully) after..