High-dimensional beam tomography with PolariX: Experimental results from DESY and PSI

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With special thanks for slide input to: J. Wood, L. Boulton, M. Hohmann, D. Samoilenko (FLASHForward), L. Schaper, J. Rönsch-Schulenburg, M. Vogt, P. Amstutz (FLASH)

HELMHOLTZ

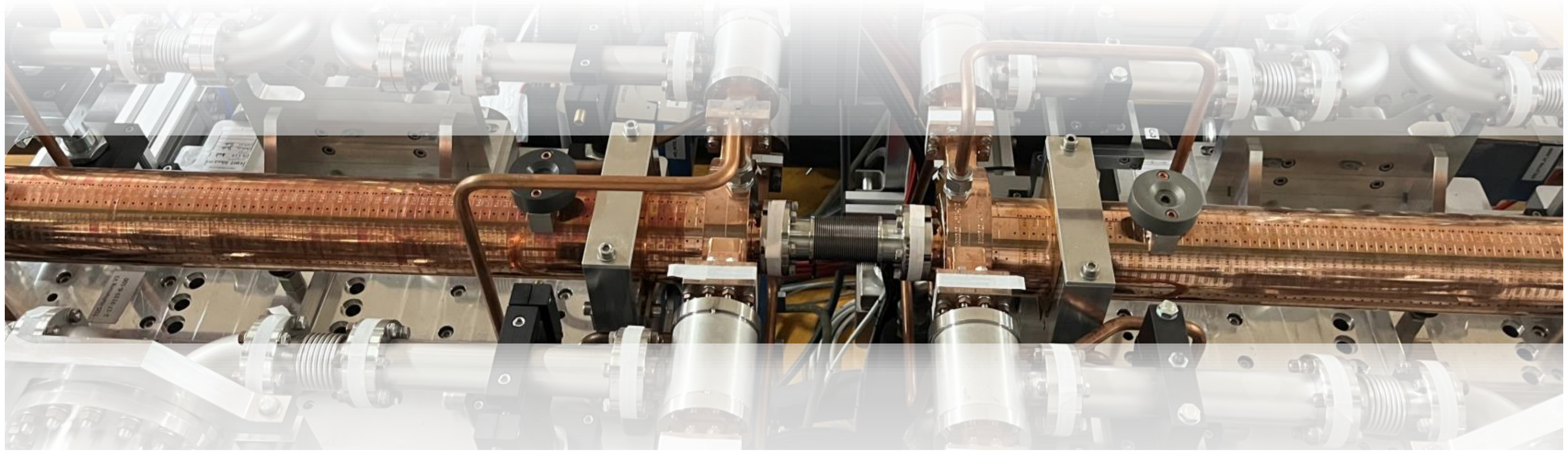
DAEJEON LINAC 2026

PSI

DESY.

The PolariX TDS: a versatile tool for beam diagnostics

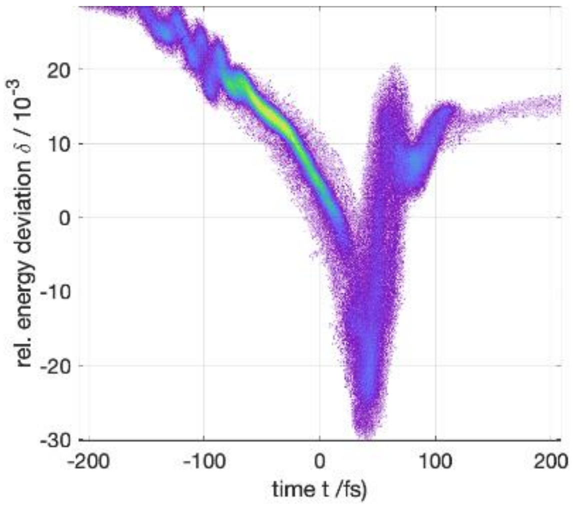
- Developed in **collaboration** between CERN, PSI and DESY [1-5].
- Operated at **X-band** frequency enabling **sub-fs** resolution.
- Unique feature: **Variable** streaking angle.
- Installed: FLASH 2, FLASHForward, ARES, SwissFEL.



Picture of the PolariX TDSs at ARES. Courtesy: M. Maxton

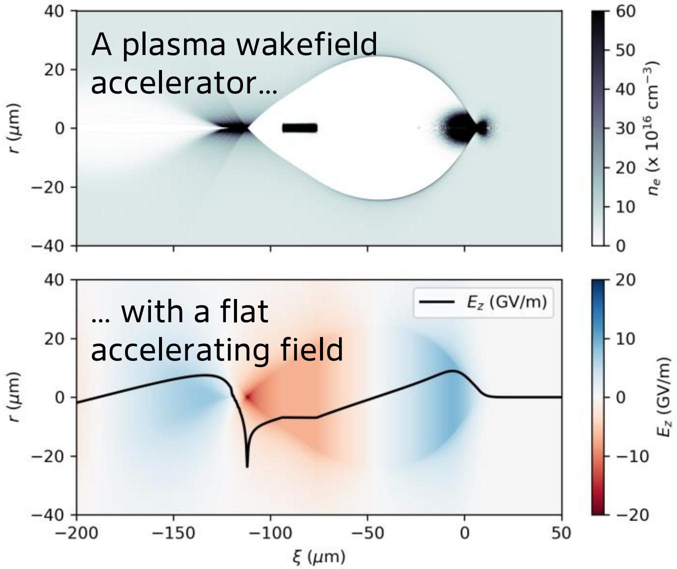
One device, various applications

Free-electron lasers:
FLASH 2, DESY + Athos, PSI



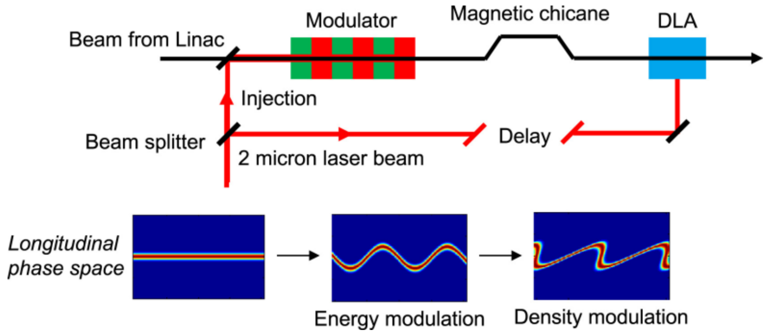
Courtesy: L. Schaper, J. Rönsch-Schulenburg

Plasma Wakefield Acceleration:
FLASHForward, DESY

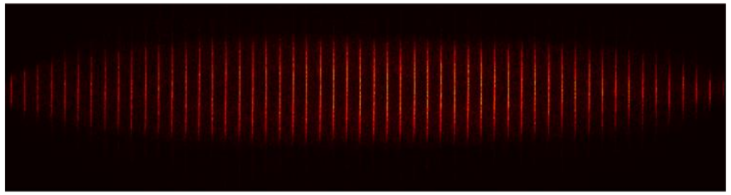


Courtesy: J. Wood, L. Boulton, M. Hohmann, D. Samoilenko

Short pulses, accelerator R&D:
ARES, DESY



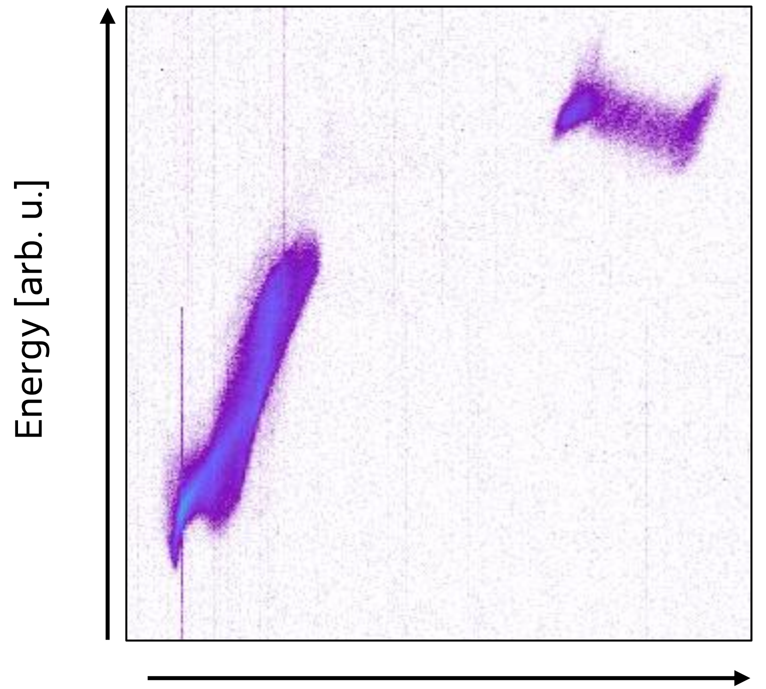
F. Mayet, et al., NIMA 909 (2018): 213-216.



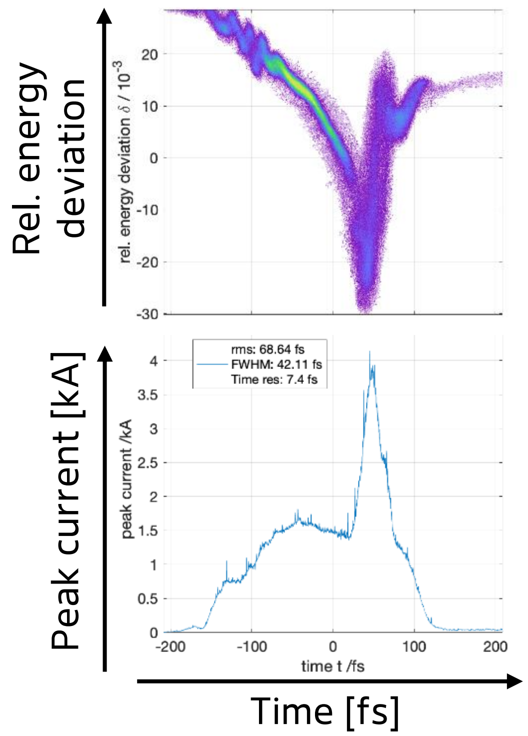
Courtesy: F. Mayet

Characterization of bunches at FLASH

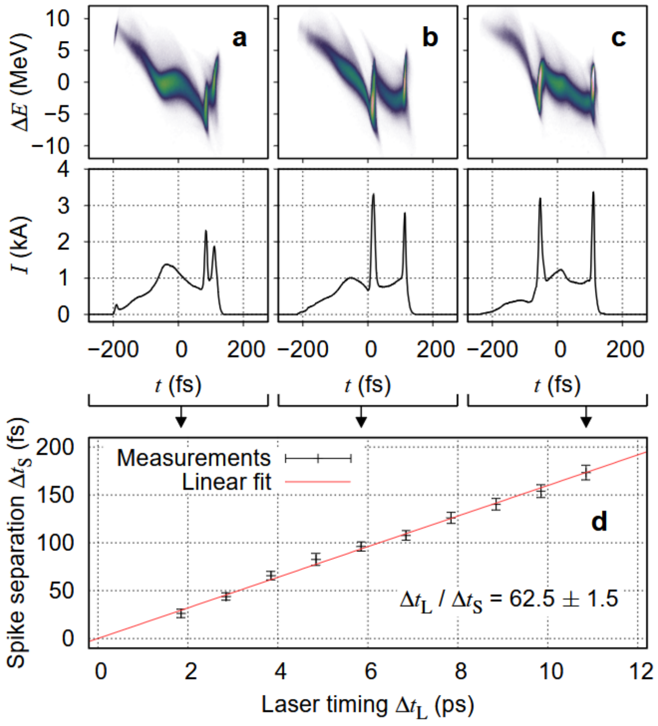
Twin electron bunches from photocathode



Single spike characterization



Generation of ultrashort double bunches via FLARE



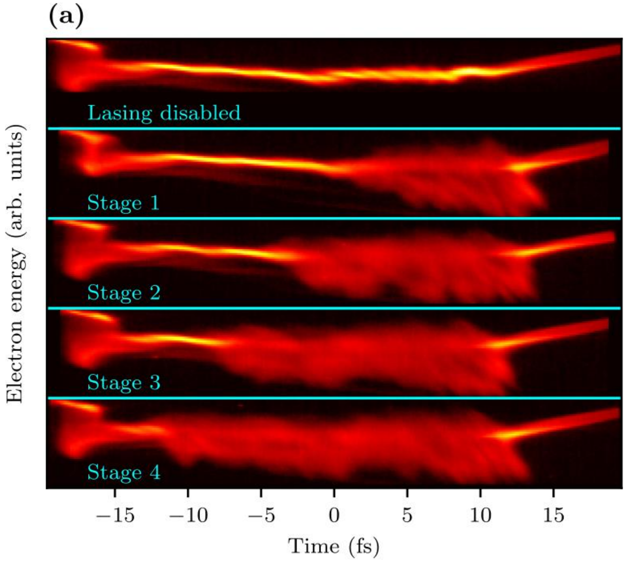
Ph. Amstutz, et al., arXiv:2508.14592

FLASH
Free-Electron Laser in Hamburg

Courtesy: L. Schaper, J. Rönsch-Schulenburg, M. Vogt, P. Amstutz

LPS measurements for development of special FEL operation modes at SwissFEL Athos

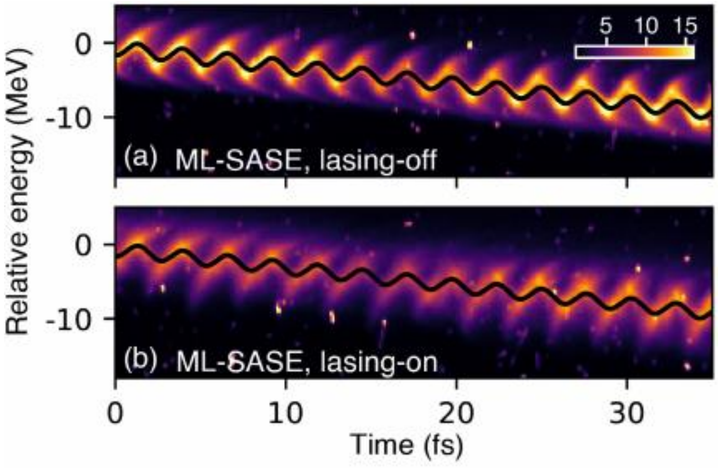
Multistage amplification



Generating a few-fs high-power FEL pulse by aligning fresh slices in different parts of the undulator.

Wang et al., PRL **132**, 035002 (2024)

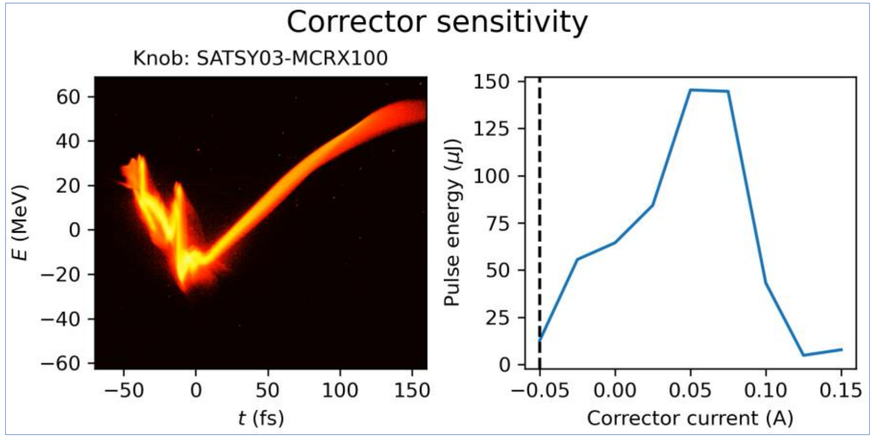
Mode-locked SASE



Energy modulation by an optical laser, then generating a periodic pulse train. LPS measurement with sub-fs resolution.

Hu et al., PRL **135**, 265001 (2025)

Attosecond-scale FEL pulse generation



Photocathode laser temporal shaping generates a current spike at the center of a long beam. Rapid pulse duration switching from sub-fs to few fs by adjusting a single corrector magnet.

Guo et al., arXiv:2606.31335 (2026)

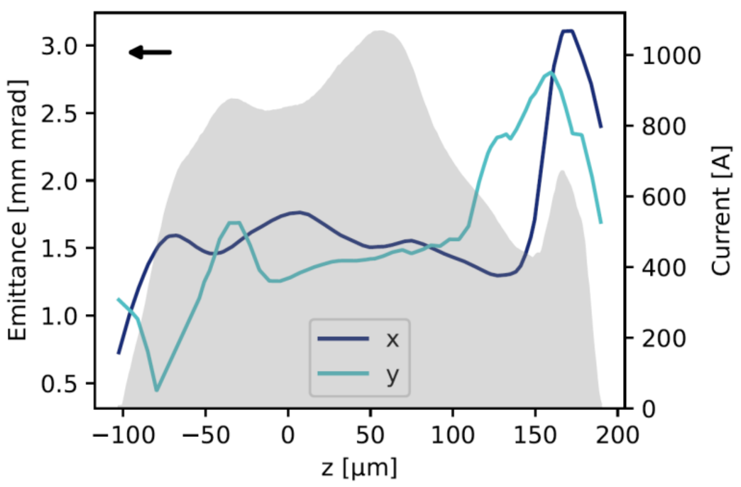
The Polarix structure is essential for these and other special FEL mode developments at the soft X-ray beamline Athos at SwissFEL!

Courtesy: P. Dijkstal, P. Craievich

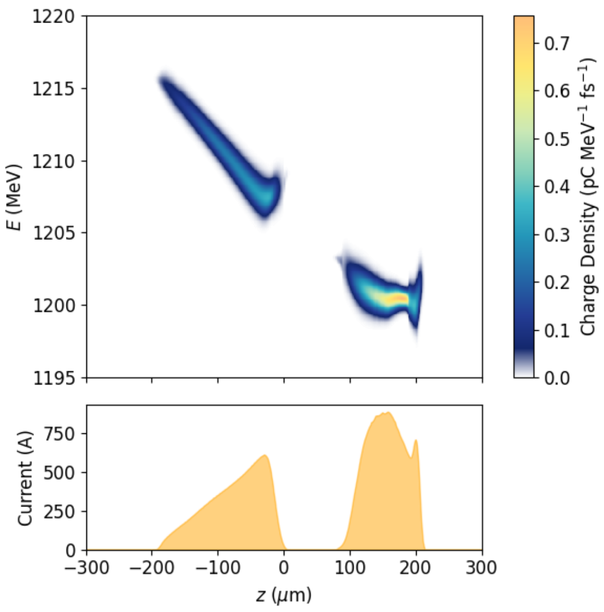
FLASHForward - Plasma Wakefield Acceleration

PolariX use in set-up and to study PWFA beam loading

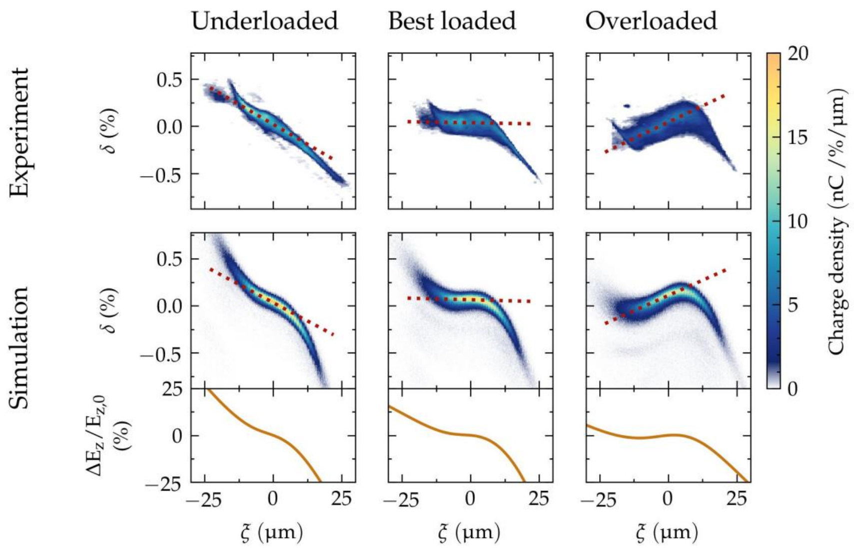
Slice emittance characterization in both transverse planes



LPS characterization to optimize a bunch pair for PWFA



Study beam loading



P. González Caminal, PhD Thesis, University of Hamburg (2022).

FLASHForward

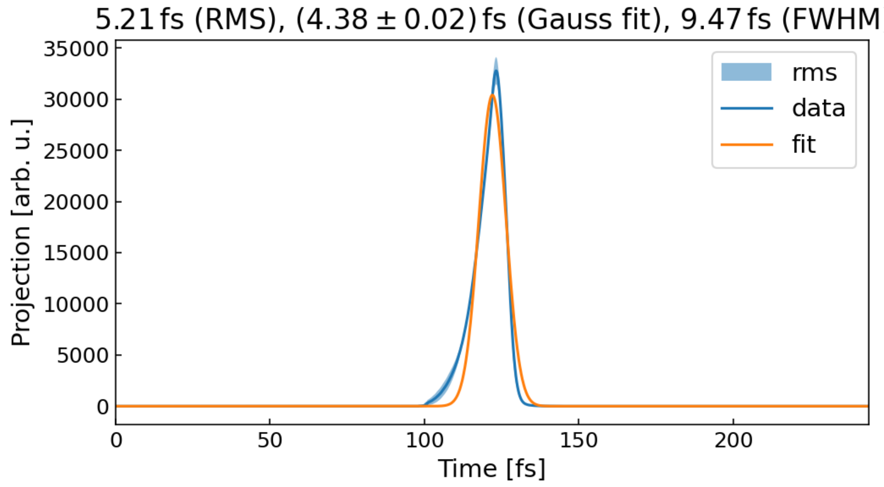
Courtesy: J. Wood, L. Boulton, M. Hohmann, Dmitrii Samoilenko

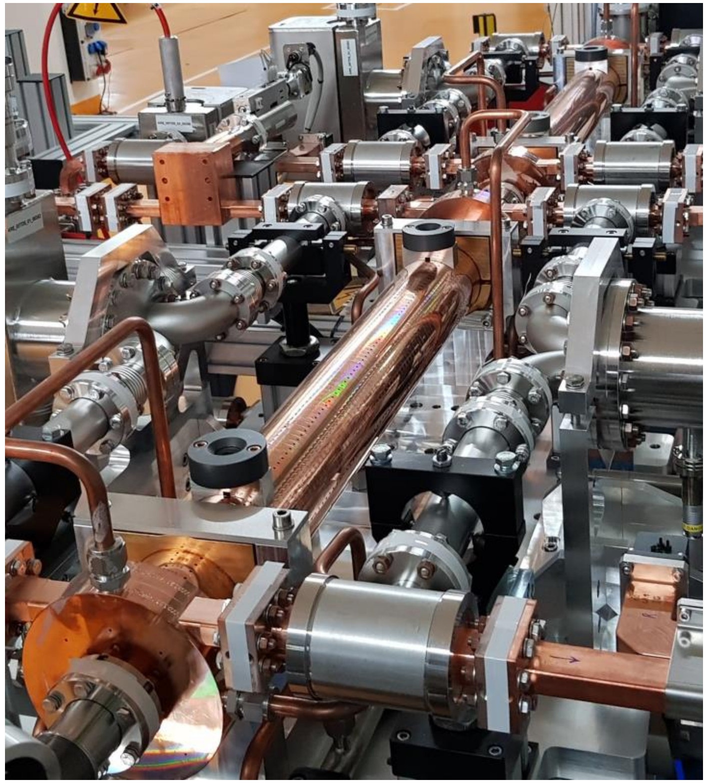
The ARES linac

PolariX is used to characterize fs to sub-fs bunches

Bunch duration measurements of single-digit fs bunches:

- Velocity bunching.
- Magnetic compression.



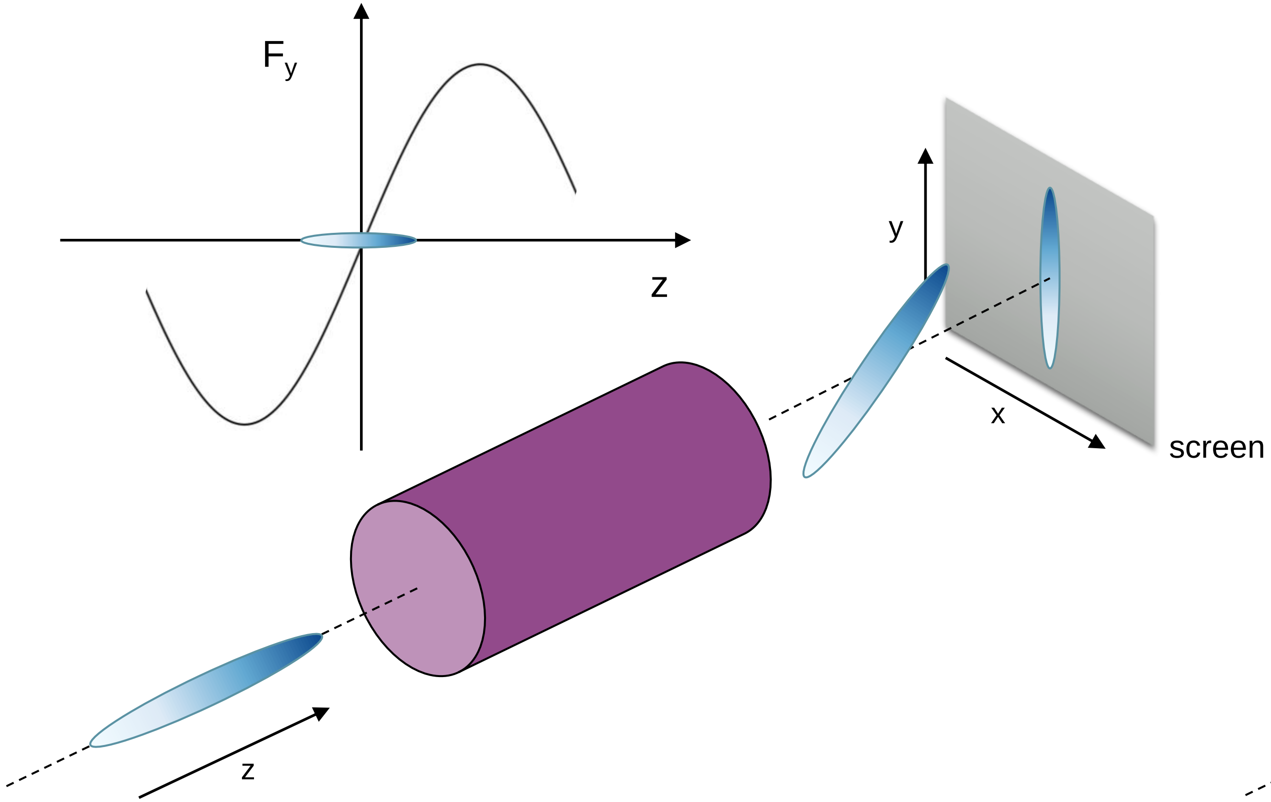


SINBAD

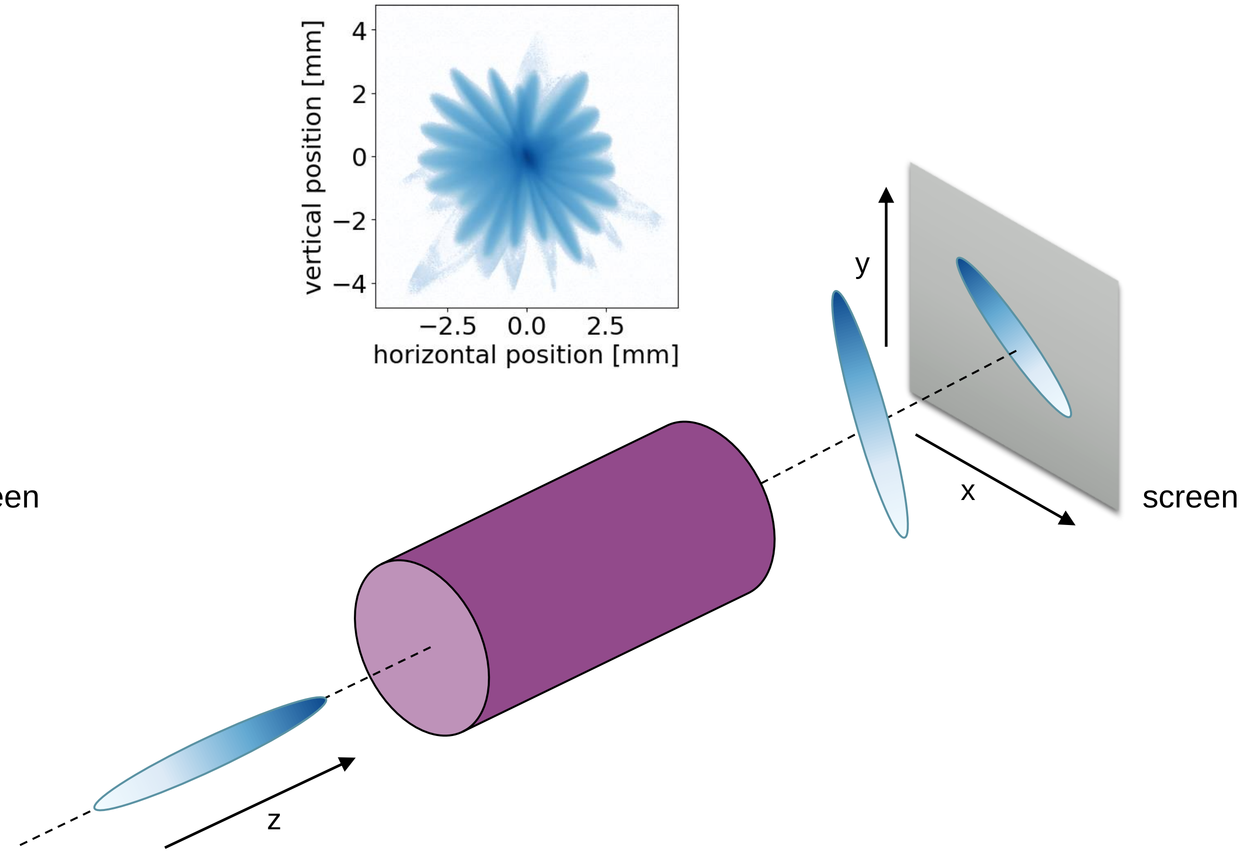
A variable streaking angle

The distinguishing feature of PolariX

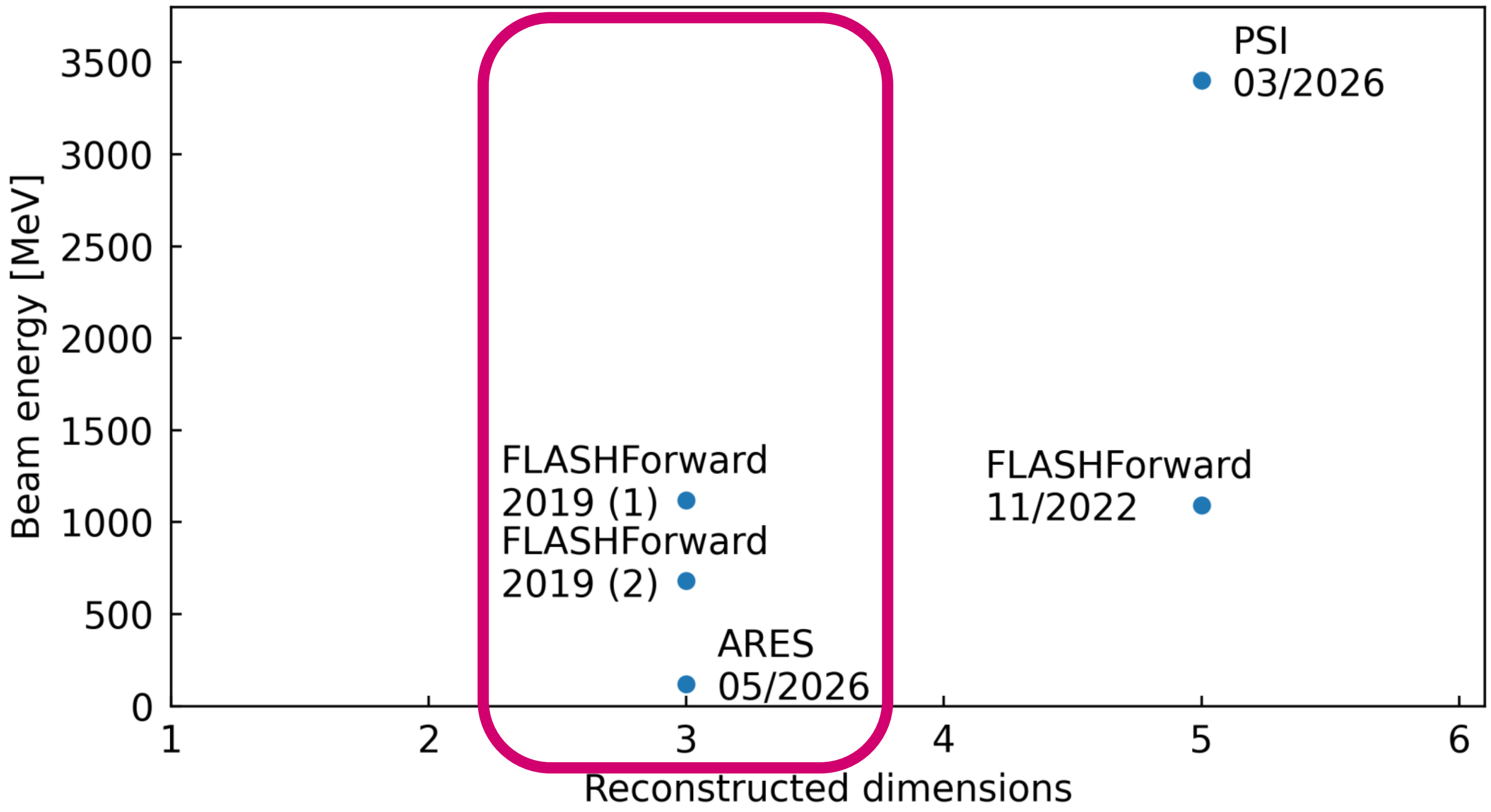
- Standard TDS: streaking in a **fixed** direction (e.g., vertical)



- PolariX TDS: streaking in **any** direction [3]

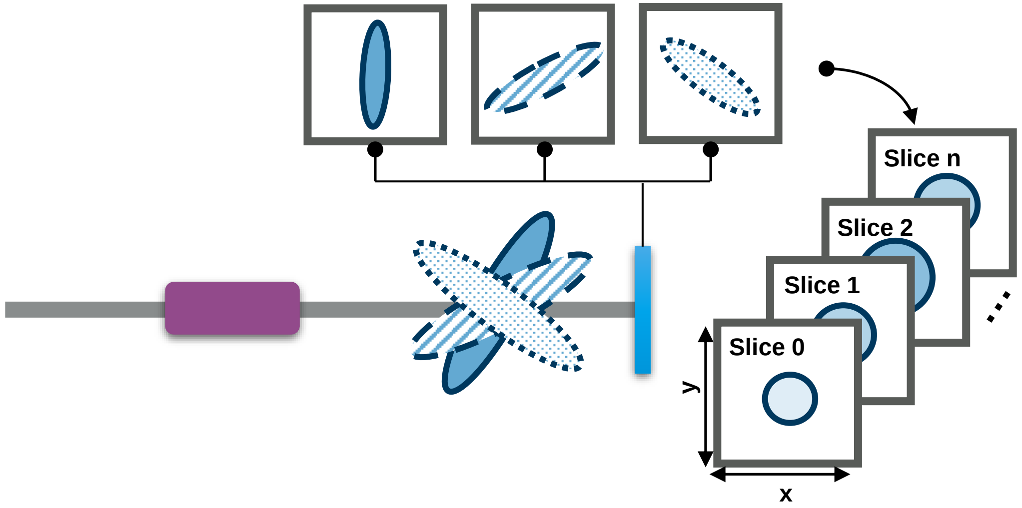


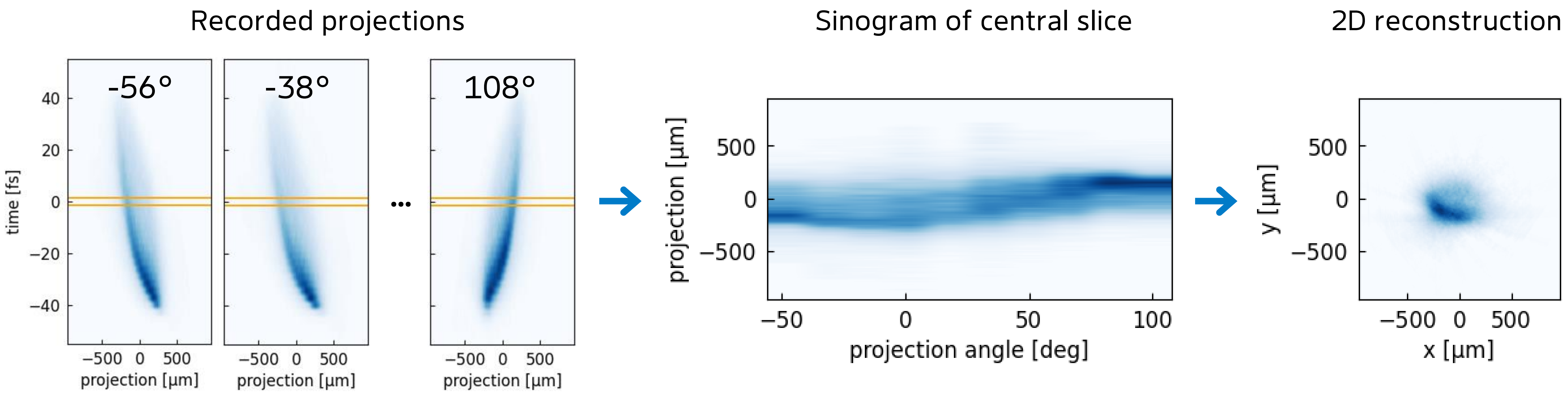
The PolariX TDS enables multi-dimensional beam tomography



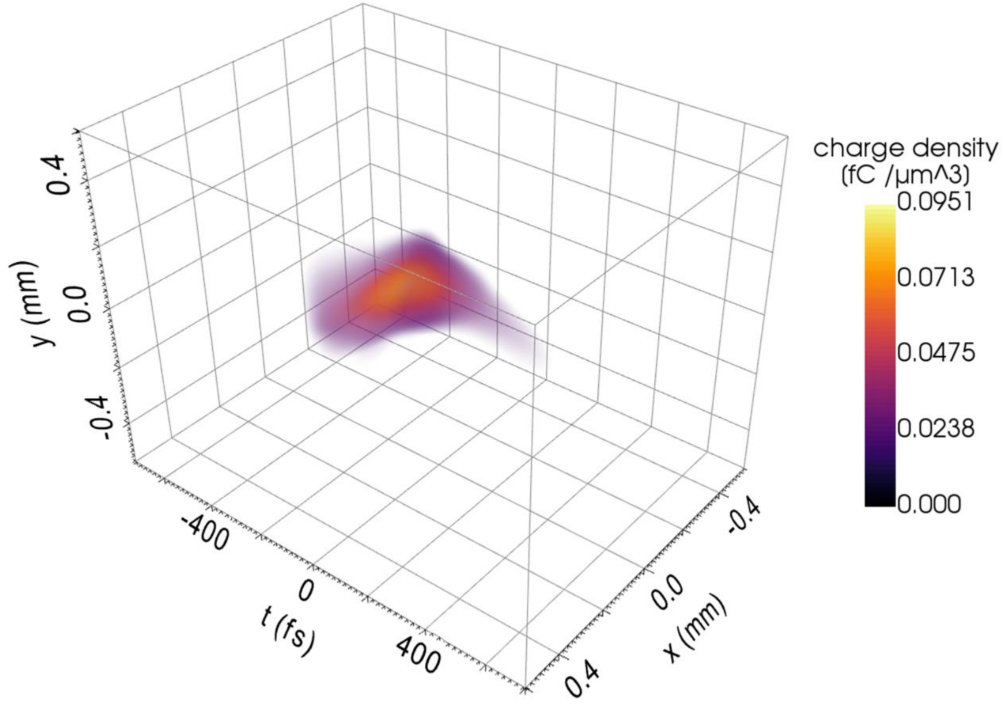
3D tomography [6]

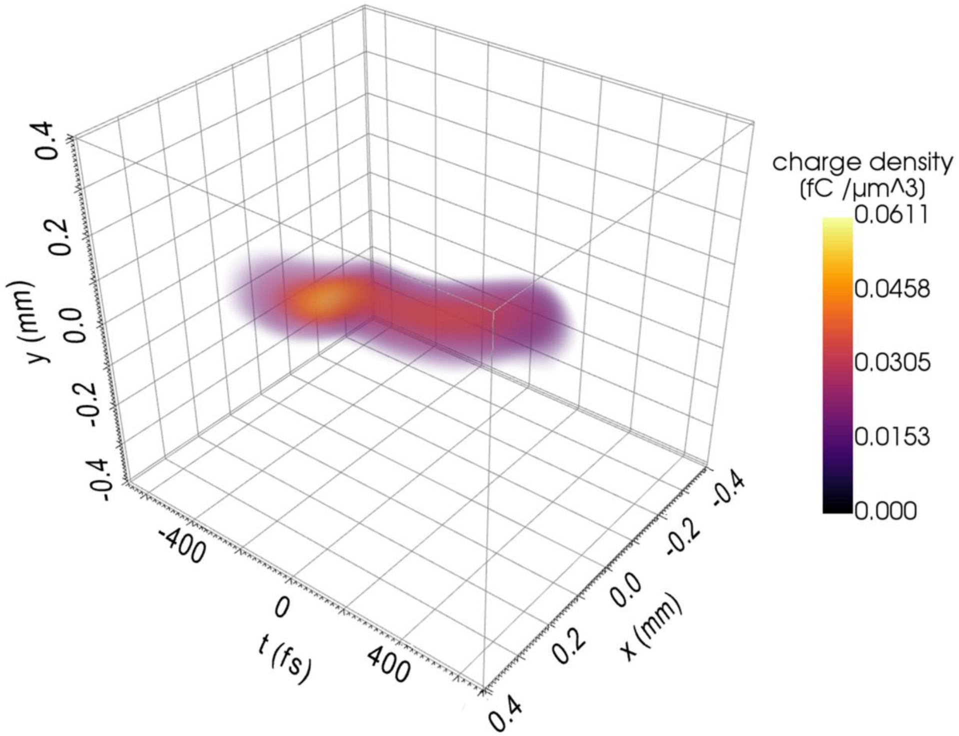
Example of the reconstruction of the central slice





3D tomography was experimentally demonstrated at FLASHForward



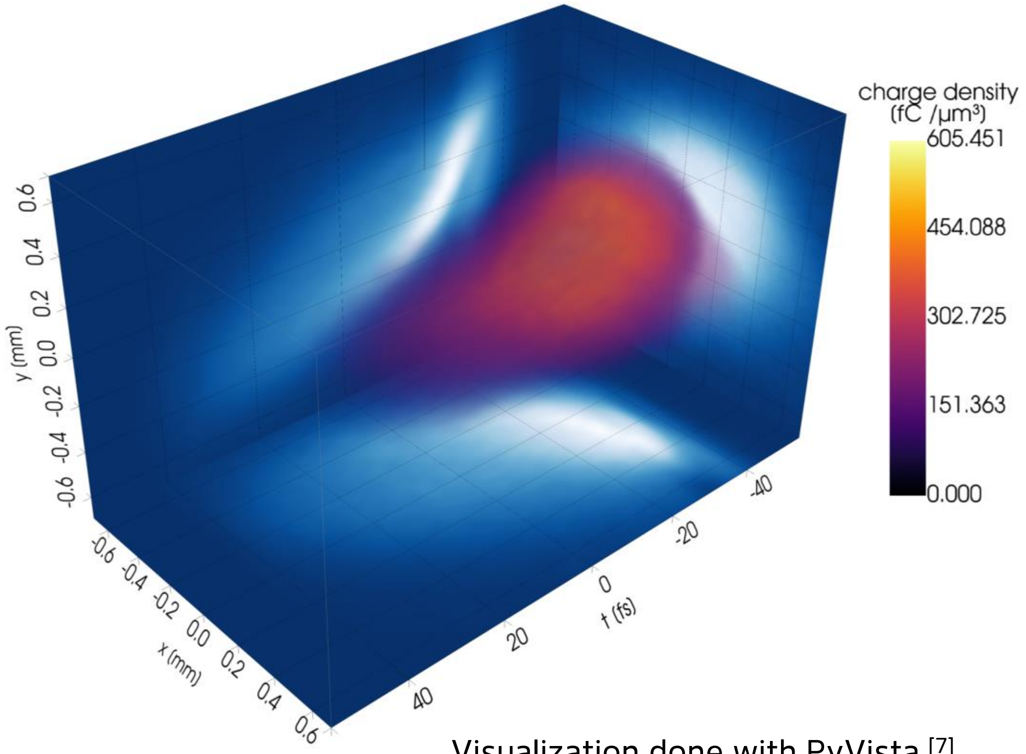


Beam energy: 1120 MeV
Beam charge: ~0.6 nC
RMS bunch length: 230fs

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

Beam energy: 680 MeV
Beam charge: ~0.3 nC
RMS bunch length: 270fs

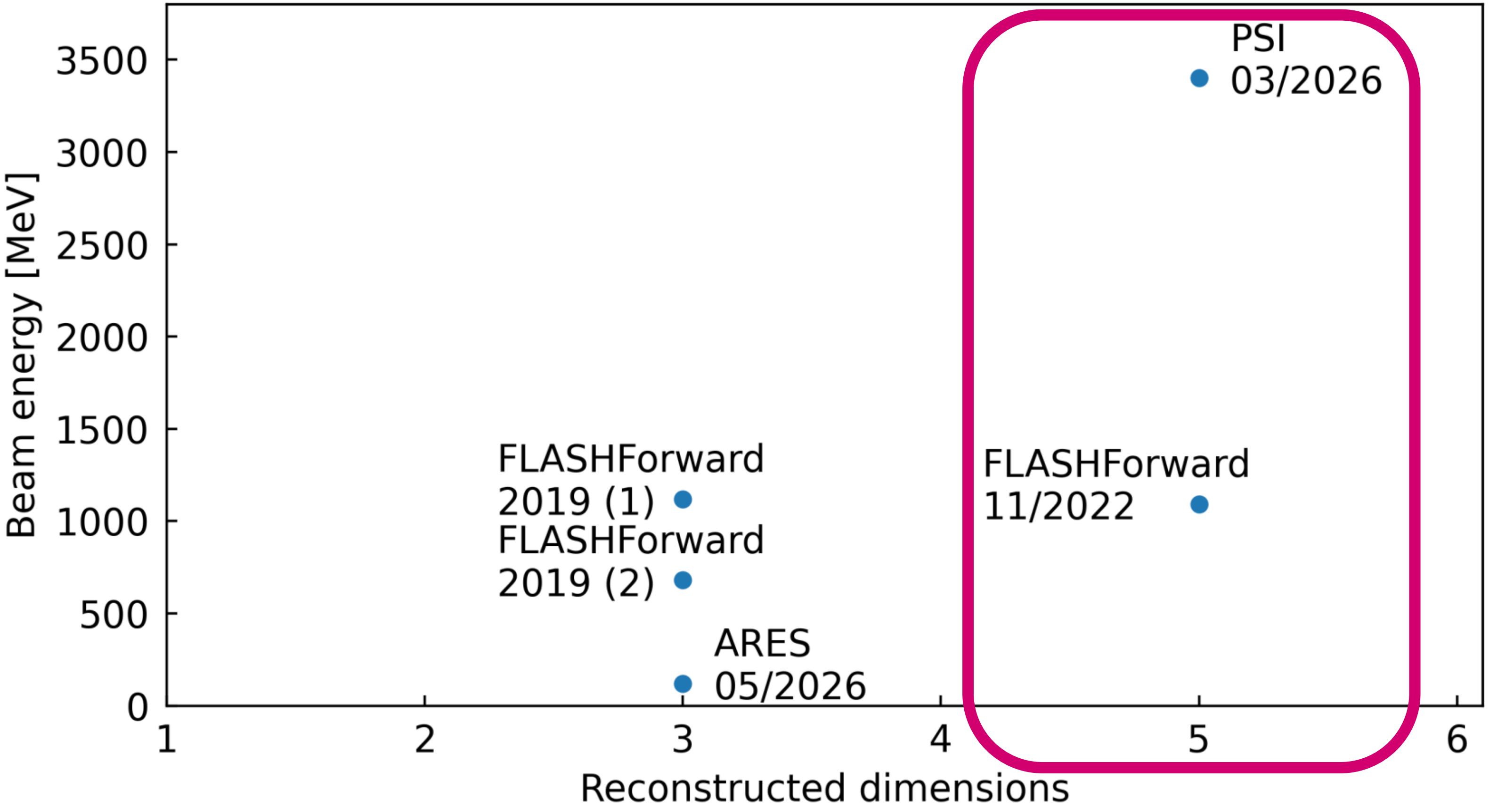
3D charge-density at ARES provides insights into magnetically compressed bunches



Visualization done with PyVista [7]

- **Parameters** of reconstructed bunch:
  - Beam energy: ~120 MeV.
  - RMS bunch duration: ~40 fs.
  - Longitudinal resolution: ~7fs.
- Used to characterize bunch features such as tilts.
- Important for example for the development of radiation-based longitudinal beam diagnostics [8,9].

The PolariX TDS enables multi-dimensional beam tomography



The 5D phase-space tomography method

Reconstructing the full transverse phase-space of each longitudinal slice

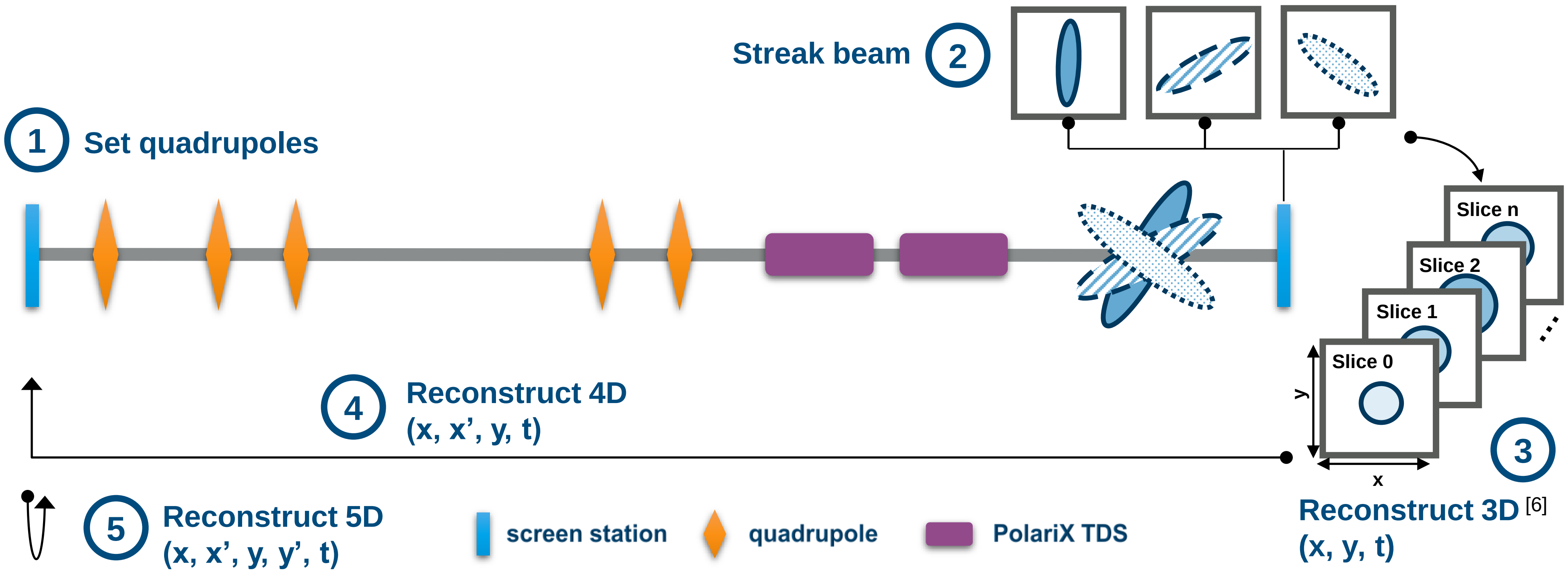
4D transverse tomography [10]
Many transverse phase-space rotations

+

PolariX TDS
Many streaking angles

→

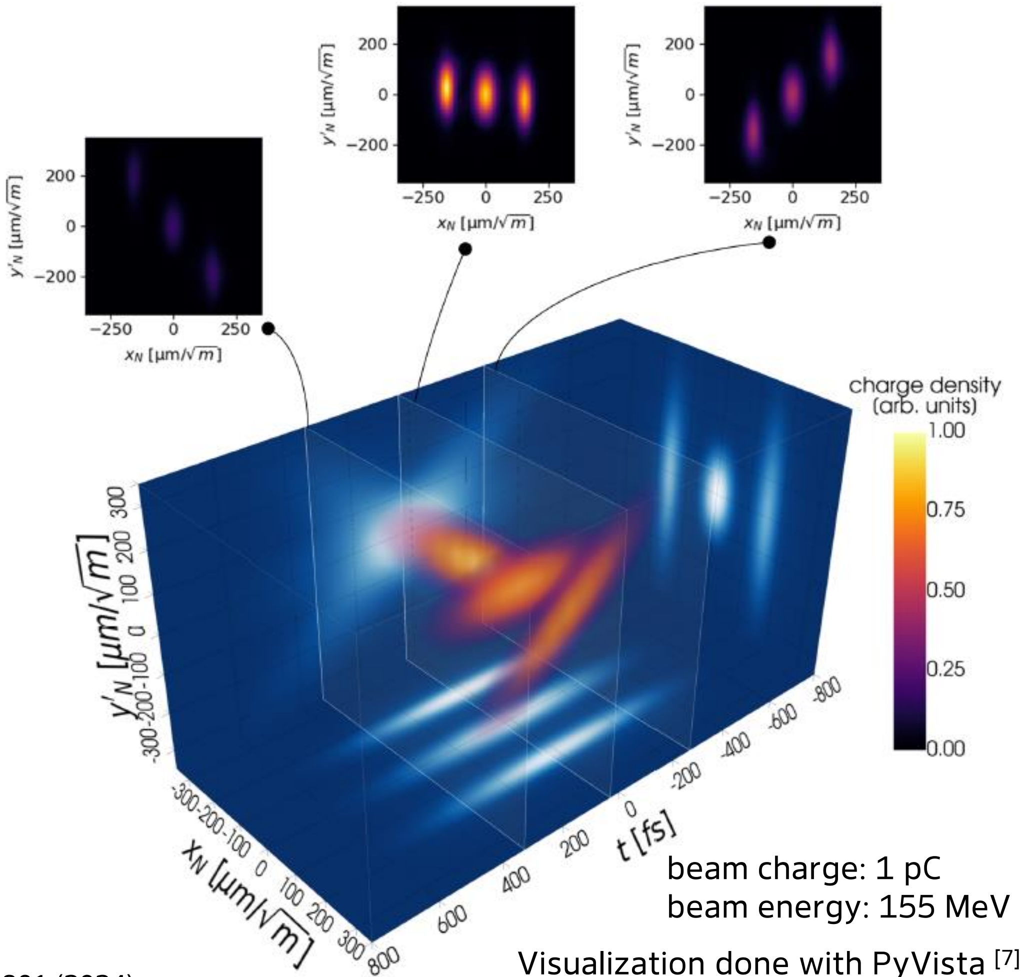
Full 5D (x, x′, y, y′, t) reconstruction.
Longitudinally-sliced 4D transverse tomography



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

Excellent performance demonstrated in simulations

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



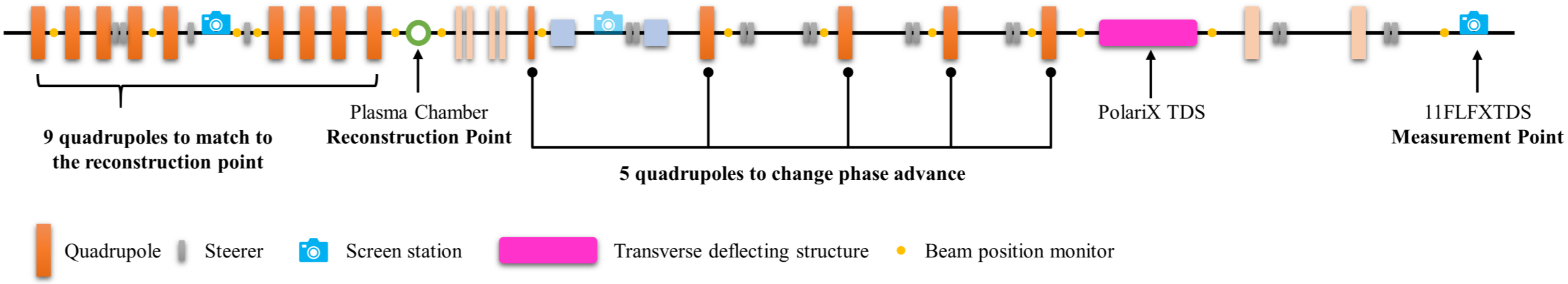
- **Full 5D** reconstruction of Gaussian and highly complex phase spaces.
- Beam parameters reconstructed with $\lesssim$ **5%** discrepancies.
- Extraction of **sliced** beam parameters and the **4D slice emittance** possible.

beam charge: 1 pC
beam energy: 155 MeV

Visualization done with PyVista [7]

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

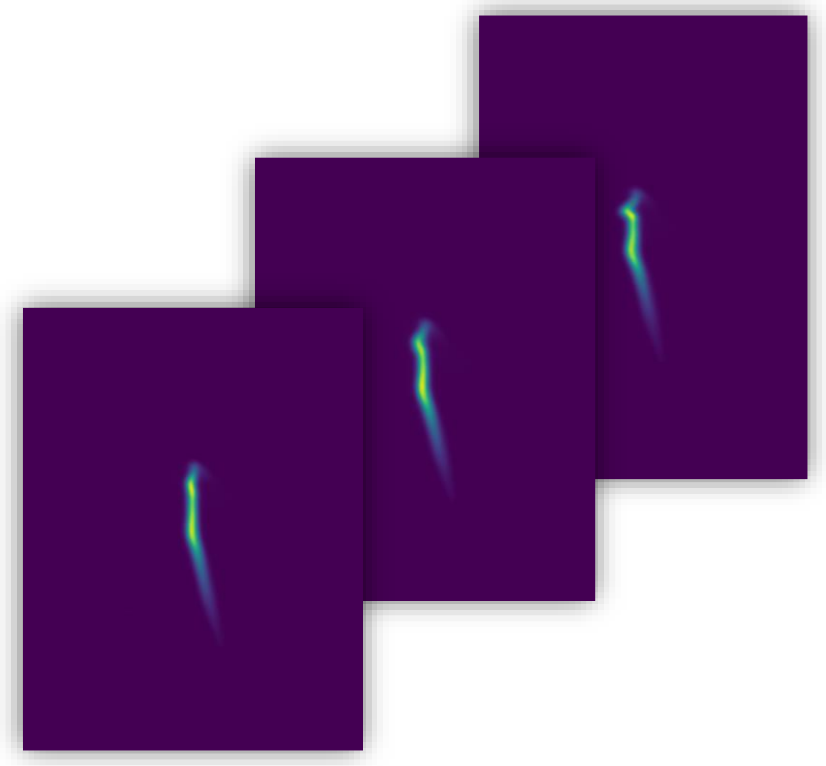
5D demonstrator experiment at FLASHForward [11]

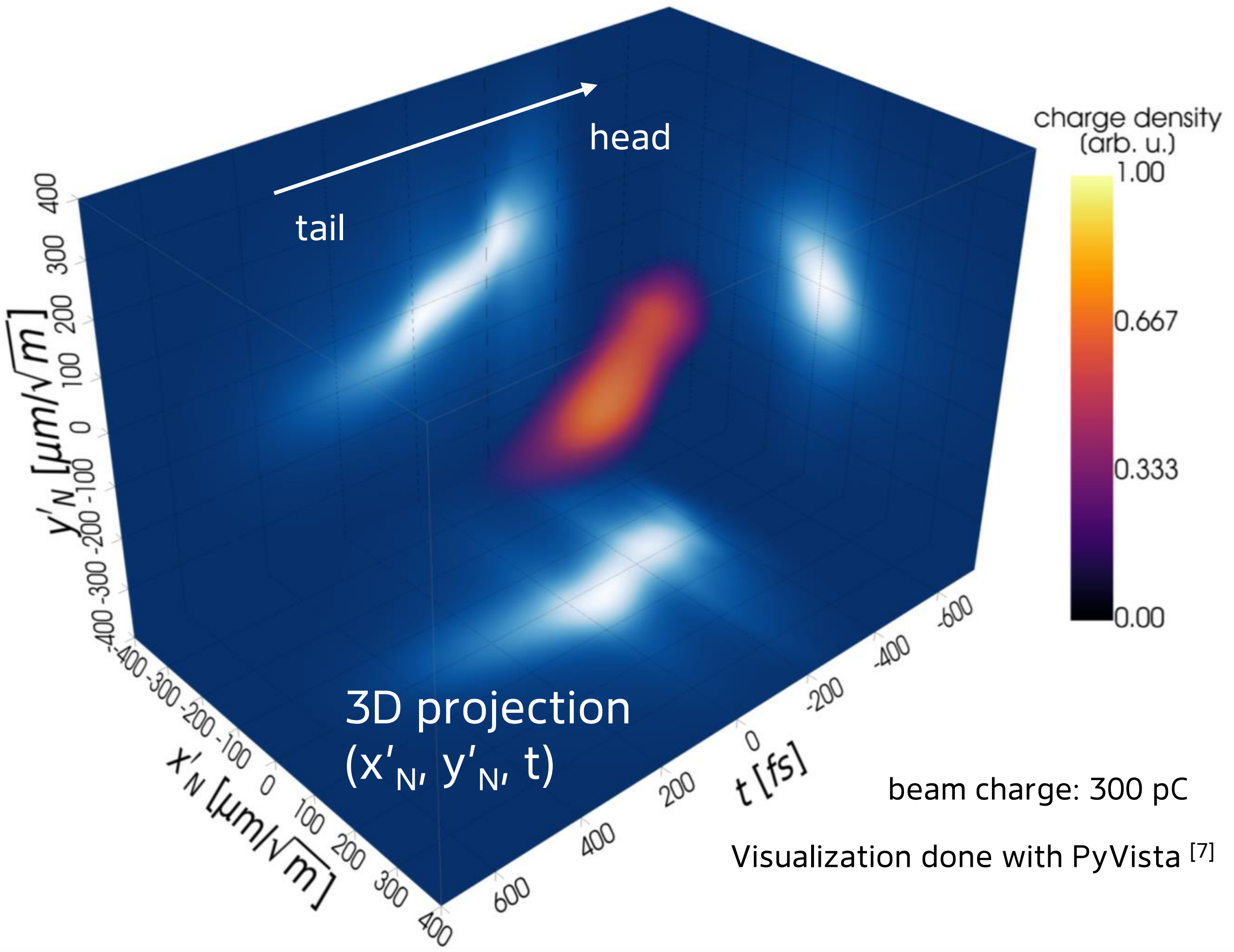


- Experimental facility dedicated to **beam driven plasma acceleration** experiments [12].
- Measurement designed with **100 phase advance combinations** and **10 streaking angles**.
- Measurement performed with 10 Hz **single bunch** operation, **~1.1 GeV** energy, **~0.3 nC** charge, and **~200 fs** RMS bunch duration.

First experimental 5D reconstruction

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



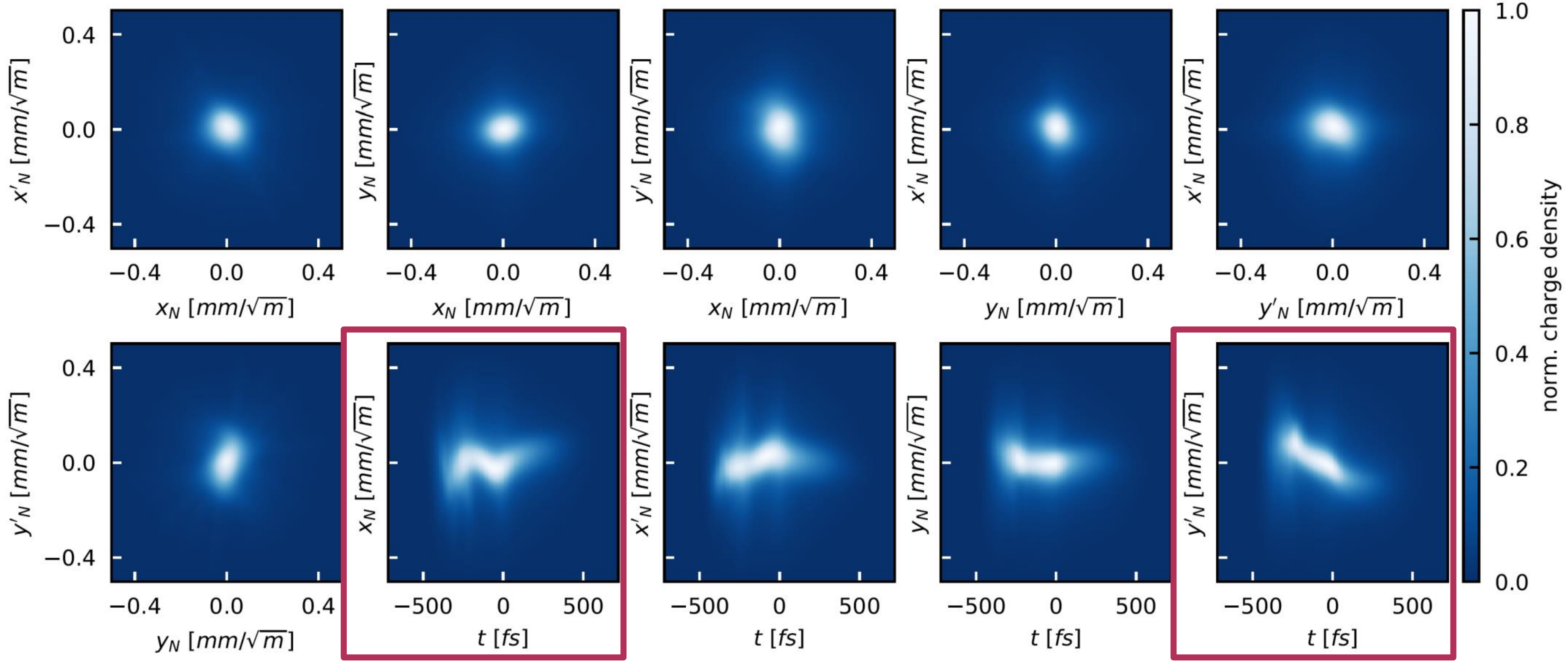


- Average longitudinal resolution of **20 fs**.
- Reconstruction of **72 bins** in the **longitudinal** plane and **301 bins** (3.3 µm/√m) per **transverse** plane.

S. Jaster-Merz et al., Physical Review Research, 2025

Reconstructed 5D phase space enables new insights

Previously hidden transverse-longitudinal correlations are retrieved



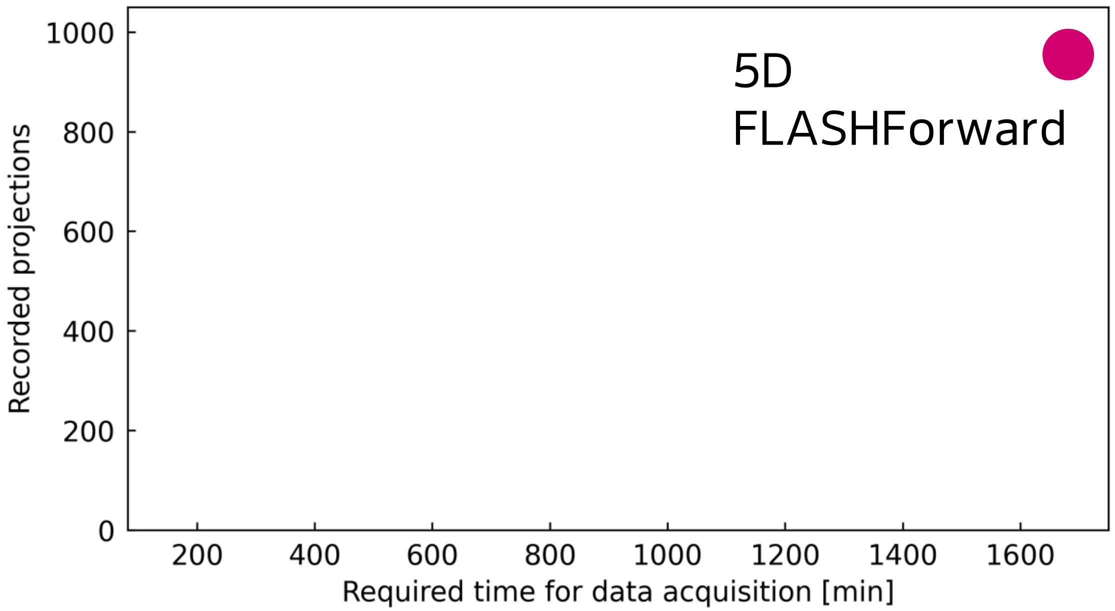
Full 5D phase-space distribution enables improved accelerator modelling, benchmarking of simulation codes.

S. Jaster-Merz et al., Physical Review Research, 2025

First 5D measurement was successful

… but it took a long time to record the data

- 960 projections (10 beam images + 10 background images) successfully recorded in ~28 hours.
- Long measurement time dominated by:
  - Cycling of the magnets.
  - Changing of the streaking angle.
  - Realigning the beam to the screen.



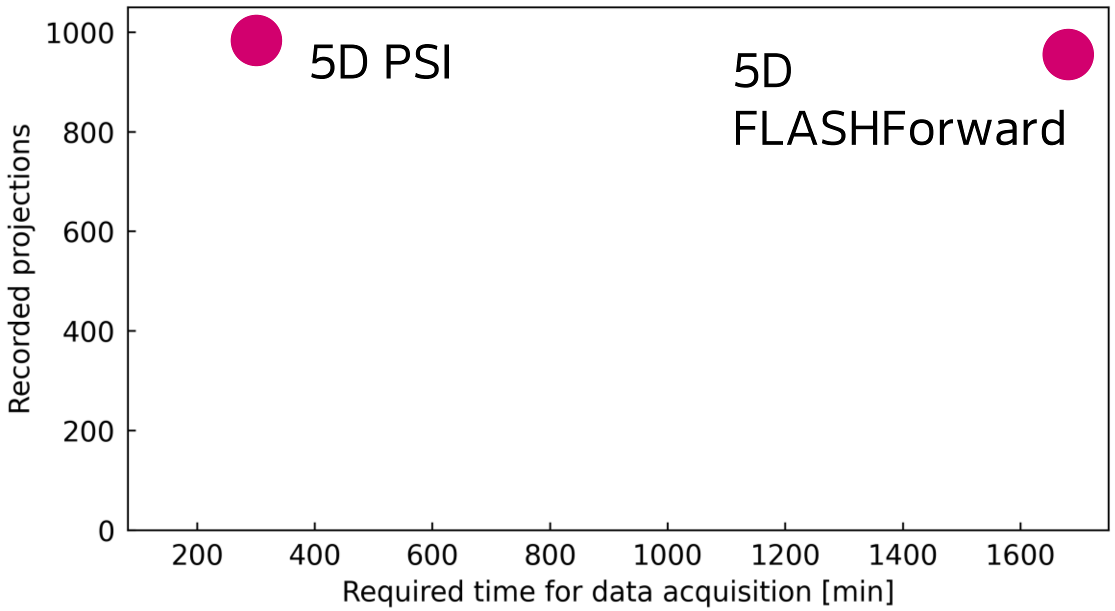
Towards a standard application

Measurements at SwissFEL (PSI) performed with a significant reduction in required measurement time

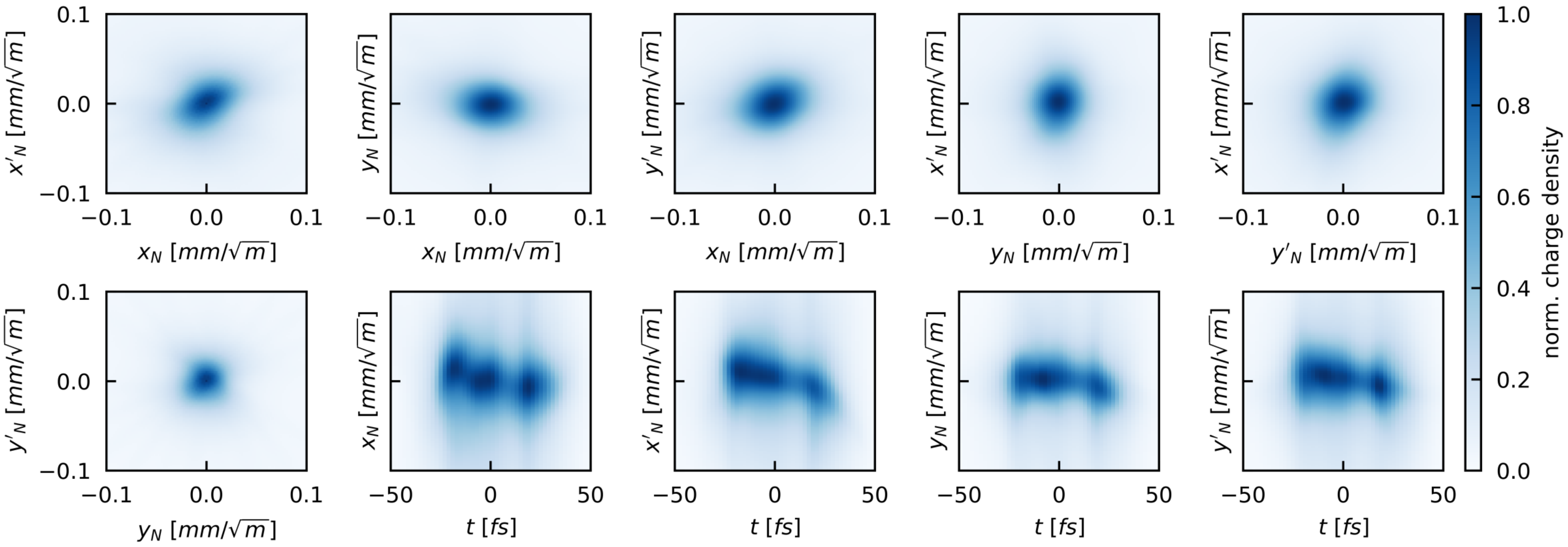
PSI

- Cycling of the magnets:
  → speed up by a factor of ~20.
- Changing the streaking angles:
  → speed up by a factor of ~8.
- Realignment to the screen:
  → no longer necessary.

- Total measurement time for 1000 projections with 5 beam images per projection at 1Hz: **5.3 hours.**



5D reconstruction of a standard SwissFEL SASE bunch



Preliminary 5D reconstruction of a ~20 fs RMS bunch with ~4fs resolution.

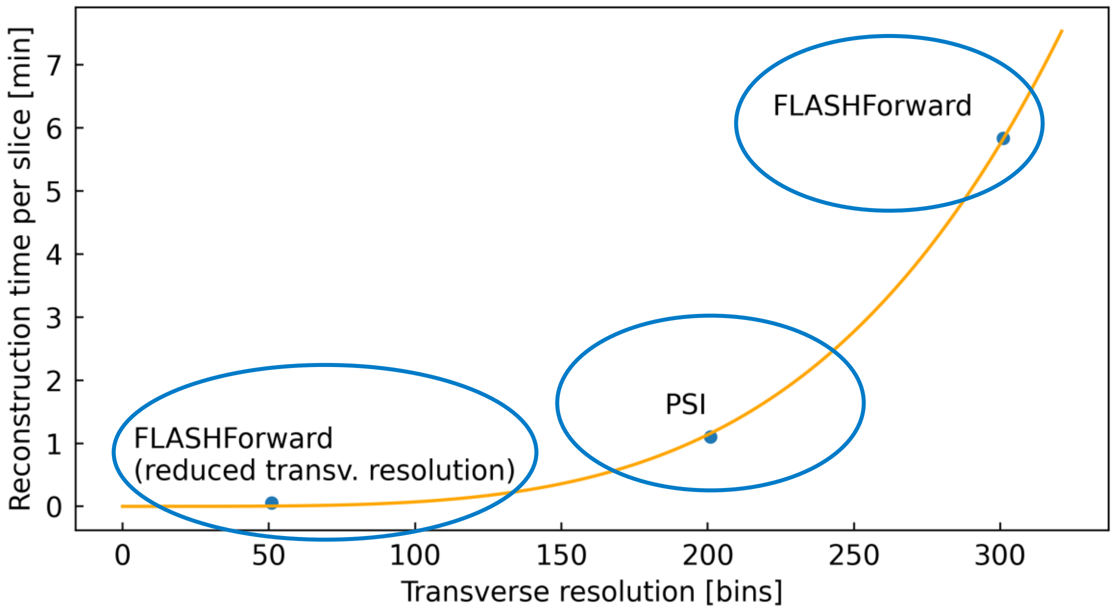
PSI

Computing the phase space tomography

Finding a balance between cost and resolution

- Reconstruction time depends on the resolution (i.e., number of bins) to the power of 5 (dimensions):
  - FLASHForward (72 slices + 301 transverse bins): 7 hours
  - PSI (50 slices + 201 transverse bins): 55 minutes
  - FLASHForward (72 slices + 51 transverse bins): **<4 minutes**

Performed using parallel computing on one AMD EPYC 75F3 node.



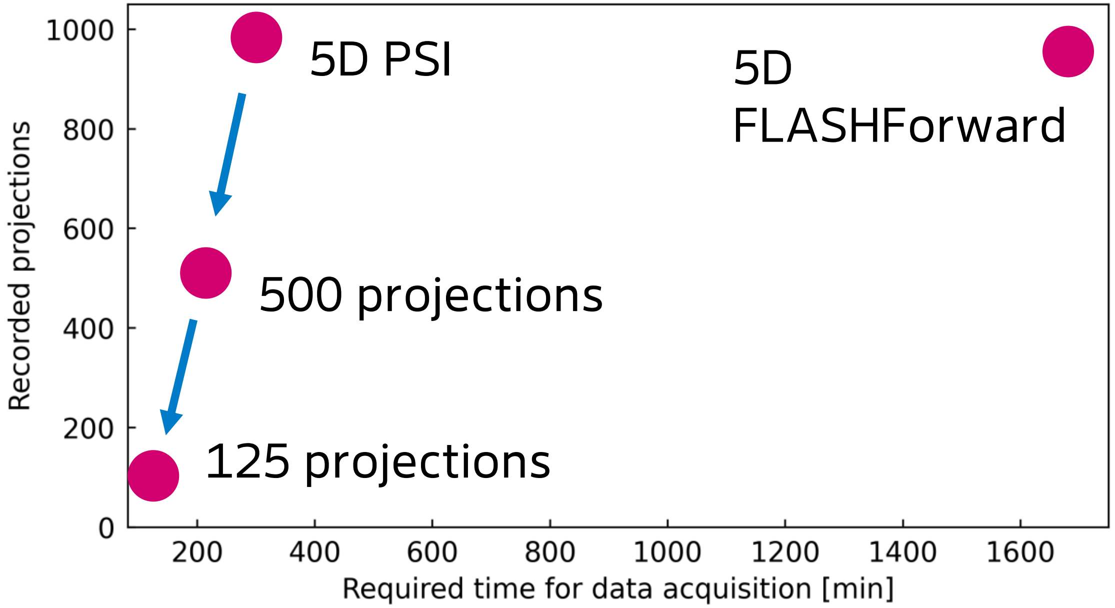
Further measurement time reduction

Possible with optimized data recording or new reconstruction approaches

- Approach 1: Increase **repetition rate**
- Approach 2: Reduce number of **required projections**
- Approach 3: Faster DAQ + no failures

Estimated measurement times

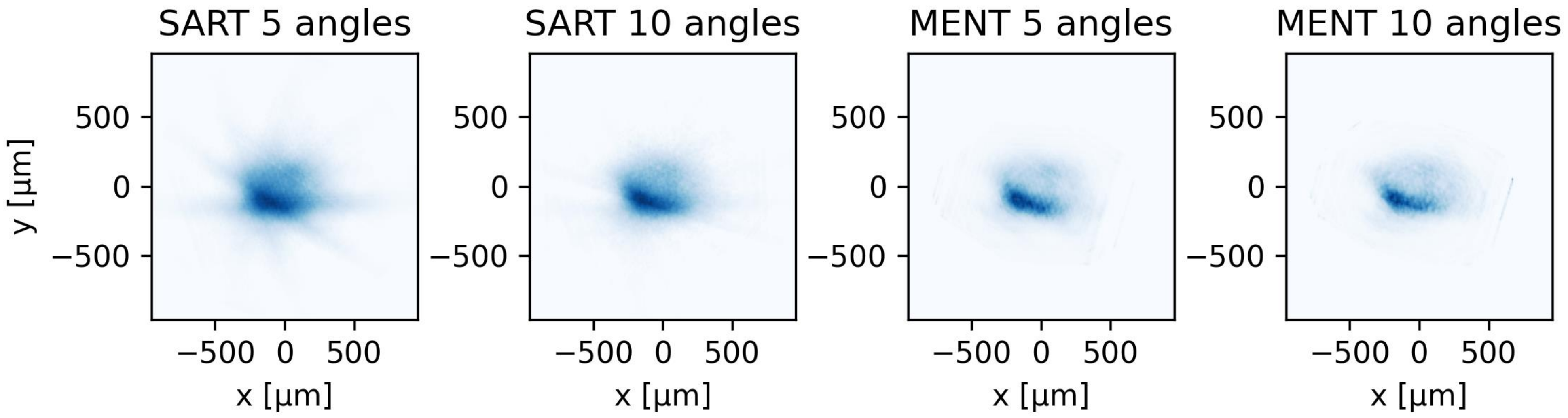
	1000 projections	500 projections	125 projections
1 Hz	5.27 h *	4.16 h	2.45 h
10 Hz	4.02 h	3.53 h	2.29 h



* Measured at PSI

MENT reconstruction – first results in 3D

First preliminary tests of the MENT algorithm show promising results



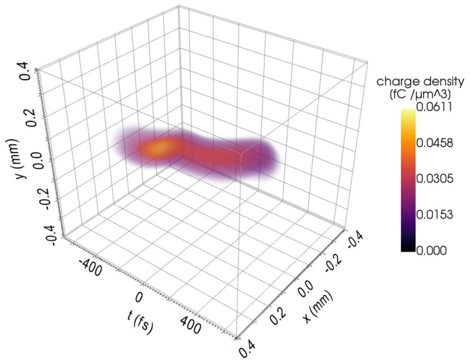
Experimental data from ARES.

MENT code from A. Hoover, https://github.com/austin-hoover/ment/tree/main, see also **talk MO1P001** today at 14:00!

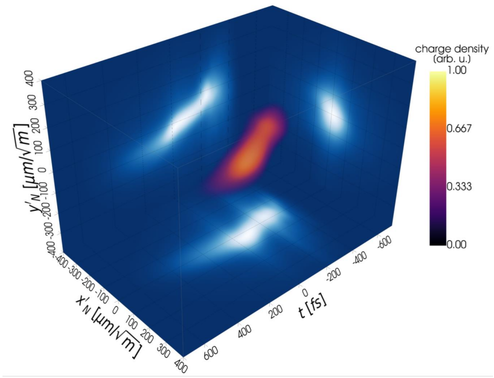
Summary

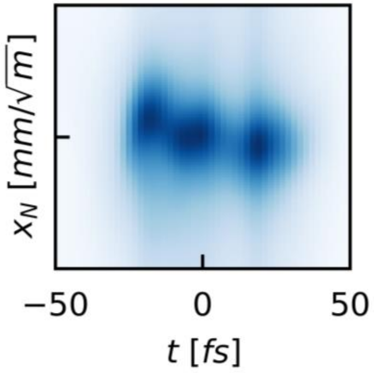
High-dimensional tomographic reconstructions were enabled for accelerators where PolariX TDSs are installed

Q3 2019
First **3D** demonstration



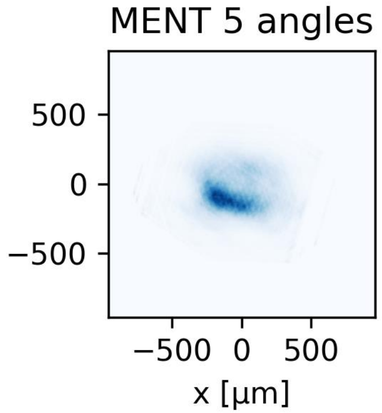
Q4 2022
First **5D** demonstration





Q1 2026
Fastest 5D data collection, best resolution

Q2 2026
3D tests with new method



Thank you

The PolariX collaboration:
R. W. Assmann, F. Burkart, F. Christie, B. Conrad, R. D'Arcy, H. Dinter, M. Foese, P. González Caminal, M. Hoffmann, M. Hüning, S. Jaster-Merz, R. Jonas, O. Krebs, S. Lederer, B. Marchetti, D. Marx, J. Osterhoff, M. Reukauff, H. Schlarb, S. Schreiber, G. Tews, T. Vinatier, M. Vogt, A. de Z. Wagner, S. Wesch
P. Craievich, M. Bopp, H.-H. Braun, A. Citterio, R. Fortunati, R. Ganter, T. Kleeb, F. Marcellini, M. Pedrozzi, E. Prat, S. Reiche, K. Rolli, R. Sieber, A. Grudiev, M. L. Millar, N. Catalan-Lasheras, G. McMonagle, S. Pitman, V. del Pozo Romano, K. T. Szypula, W. Wuensch
… and many others!

J. Wood, L. Boulton, M. Hohmann, D. Samoilenko, L. Schaper, J. Rönsch-Schulenburg, M. Vogt, P. Amstutz

All Technical Groups, the accelerator operators, and the Maxwell Cluster.

FLASH Free-Electron Laser in Hamburg   SINBAD   FLASHForward   DAEJEON LINAC 2026   PSI   DESY.

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