High-dimensional and ultra-sensitive diagnostics for electron beams

THBI1

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Sonja Jaster-Merz* for the

5D tomography team: R. W. Assmann, J. Beinortaitė, J. Björklund Svensson, R. Brinkmann, F. Burkart, P. Craievich, R. D’Arcy, H. Dinter, P. Gonzalez Caminal, W. Hillert, A. L. Kanekar, M. Kellermeier, W. Kuropka, F. Mayet, J. Osterhoff, B. Stacey, M. Stanitzki, T. Vinatier, S. Wesch

STRIDENAS team: R. W. Assmann, F. Burkart, H. Dinter, W. Hillert, M. Kellermeier, U. Krämer, W. Kuropka, F. Mayet, B. Stacey, M. Stanitzki, T. Vinatier

*sonja.jaster-merz@desy.de

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG

SINBAD

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DESY.

Accelerators enable new scientific discoveries

Essential for fundamental research, the production of photon pulses, medical applications …

“An accelerator is just as good as its diagnostics”

Picture may not be published

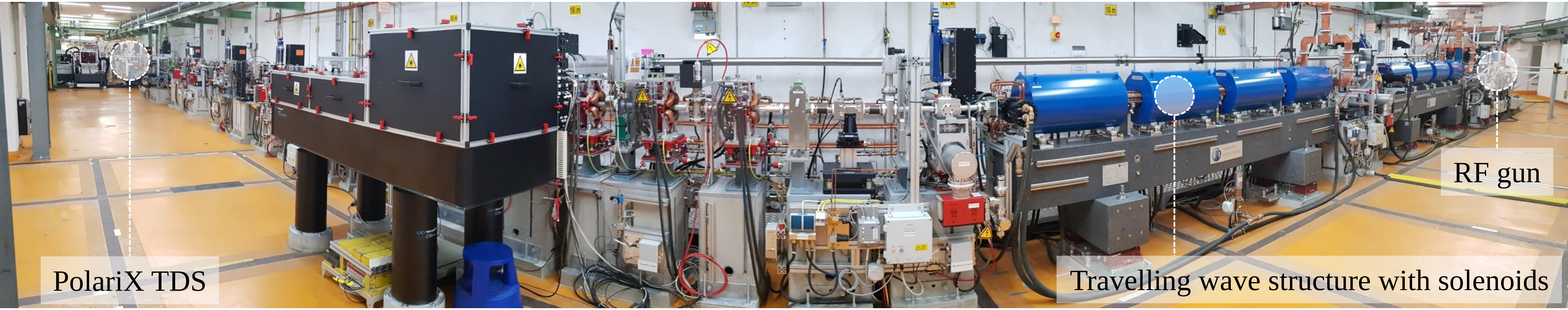
High-energy physics experiment:
Example event at the ATLAS detector [1].

The free-electron laser FLASH produces **electron bunches** of **high brightness** for the production of photon pulses.

Novel diagnostics are key to advance accelerator technology.

The ARES linac is designed for accelerator R&D [2-5]

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



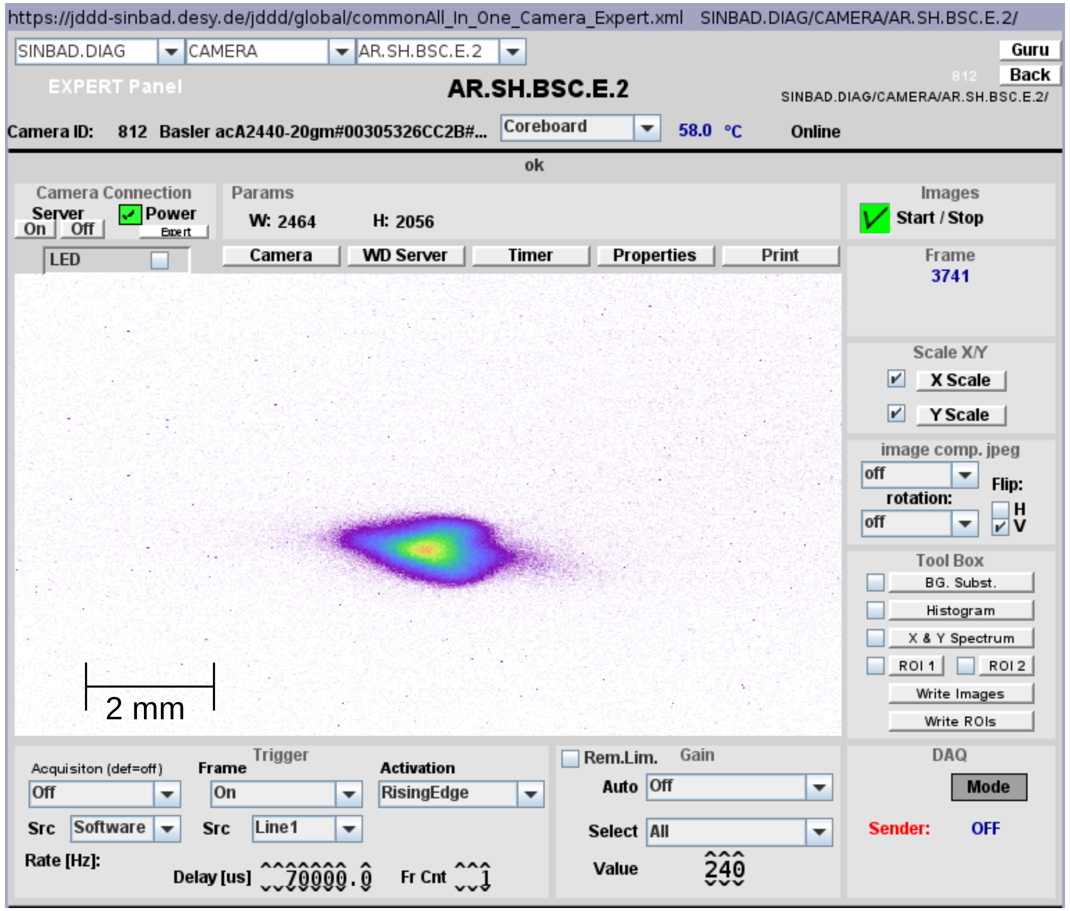
- Designed to produce and characterize bunches of **high quality** with **sub-fs** duration.
- Applications using **sub-pC** charge beams.
- Drive towards high-precision **longitudinal** diagnostics, detailed **phase-space characterization**, and **highly sensitive** diagnostic tools.
- **Advanced diagnostics** also useful for free-electron lasers or beam-driven plasma acceleration facilities.

Characterizing particle beams

Beam diagnostics provide an insight into the phase-space distribution

- Particle beam is described by **6D phase space:**
  Spatial positions x, y, z;
  Transverse divergences x', y';
  Energy E.
- **Ideally:** As much information as possible about this distribution.
- Diagnostics are limited to **lower dimensions** and have a limited charge **sensitivity**.

Screen image example (~1pC / 10^7 e^-) : (x, y) projection



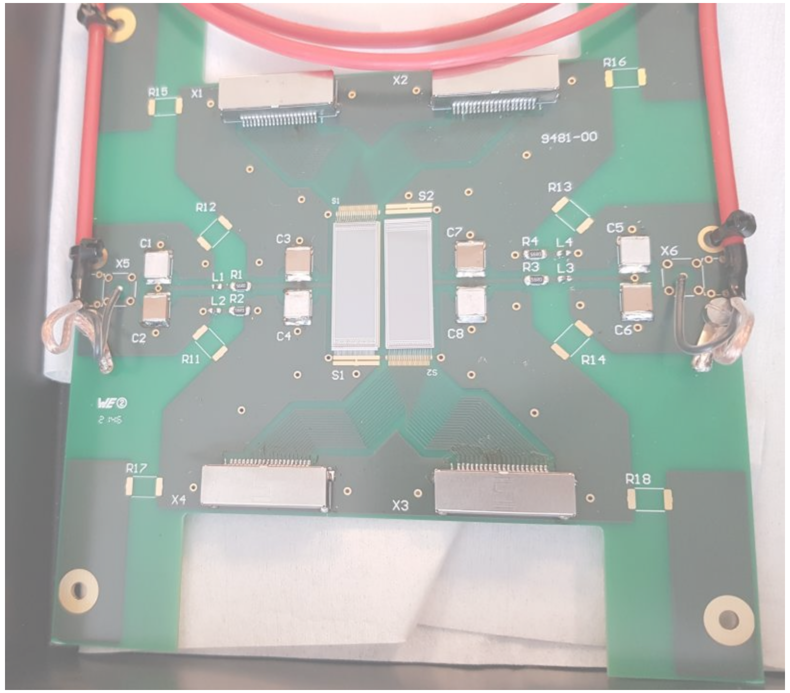
Scope of this talk

Development of novel beam diagnostics

Novel method for **5D phase space** reconstruction

Picture may not be published

Ultra-sensitive **silicon-based** profile monitor



State of the art

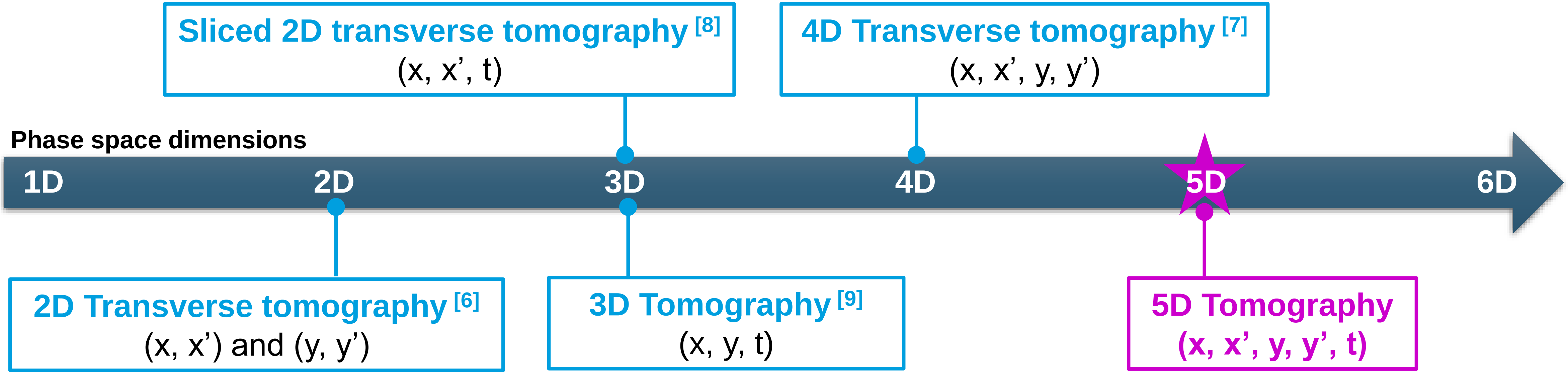
Various methods exist to obtain higher-dimensional information about particle beams

A variety of methods exist to obtain information about the phase space:

- Slit scans [10], machine learning approaches [11,12, 20].

Phase-space tomography:

- A phase-space tomography uses lower-dimensional **projections** to obtain higher dimensional information.



Polarizable X-band transverse deflection structure (TDS)

PolariX enables new diagnostic methods and allows for sub-fs longitudinal resolution

PolariX TDS installed at the ARES linac.

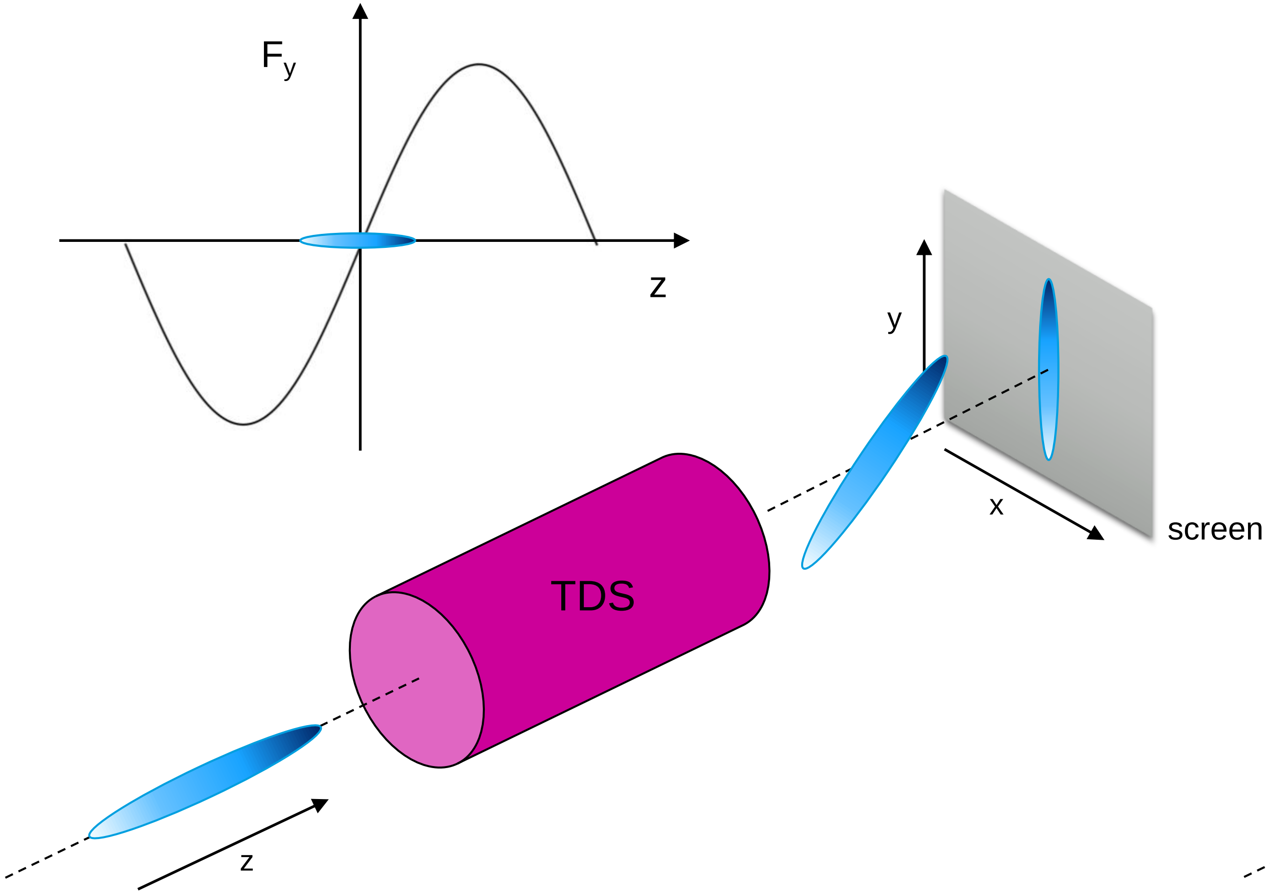
PAUL SCHERRER INSTITUT PSI CERN DESY.

- Designed in **collaboration** between CERN, PSI and DESY [13-15].
- Installed: FLASH 2, FLASHForward, ARES, SwissFEL.
- **Sub-fs** resolution.
- Unique feature: **Variable** streaking angle.

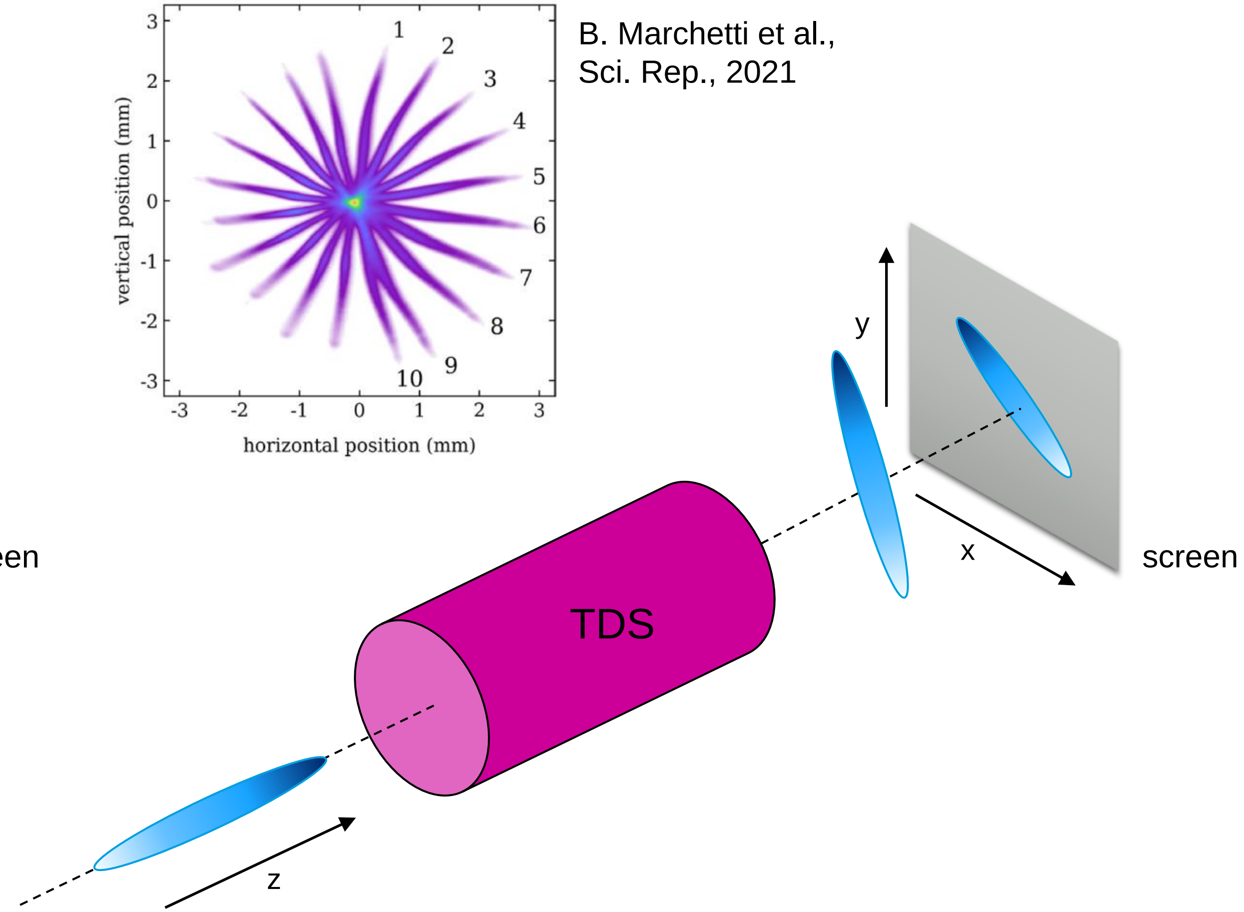
A TDS provides longitudinal information of the bunch

A time-dependent transverse kick is applied to map the longitudinal profile on a transverse plane

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



- PolariX TDS: streaking in **any** direction



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

The 5D phase-space tomography method

Reconstructing the full transverse phase-space of each longitudinal slice

4D transverse tomography [7]

Many transverse phase-space rotations

+

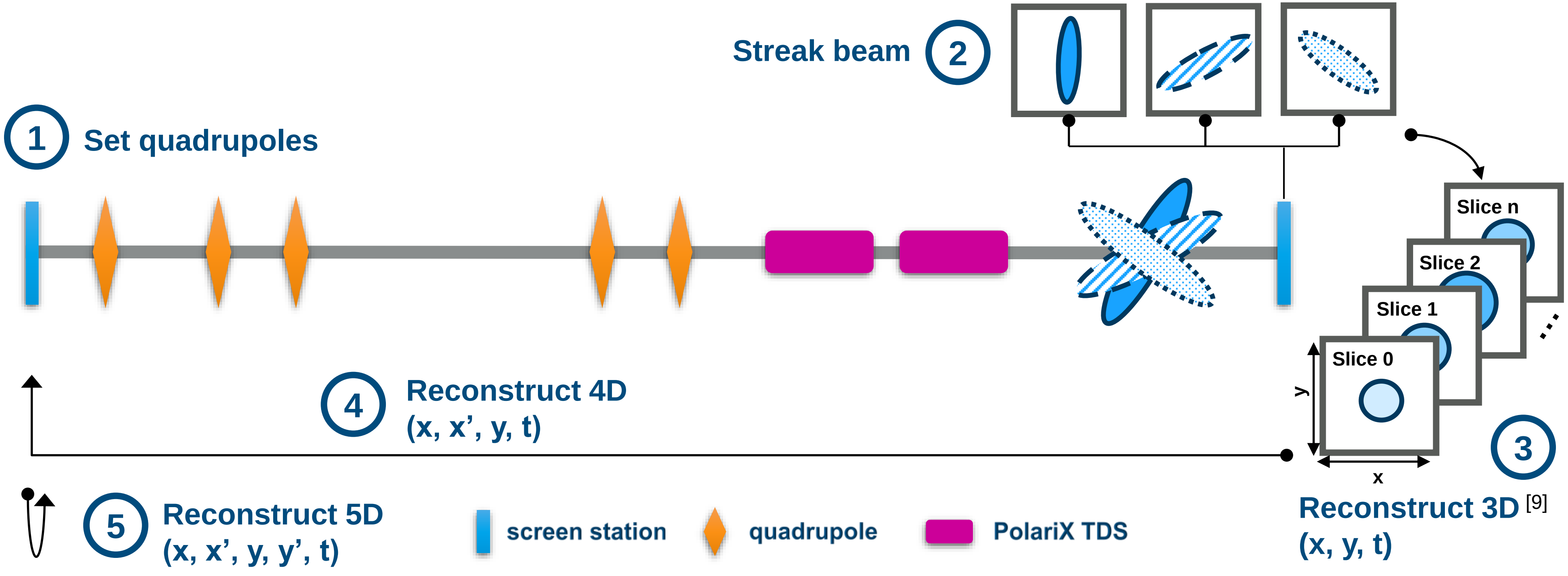
PolariX TDS [13]

Many streaking angles

→

Full 5D (x, x', y, y', t) reconstruction.

Longitudinally-sliced 4D transverse tomography

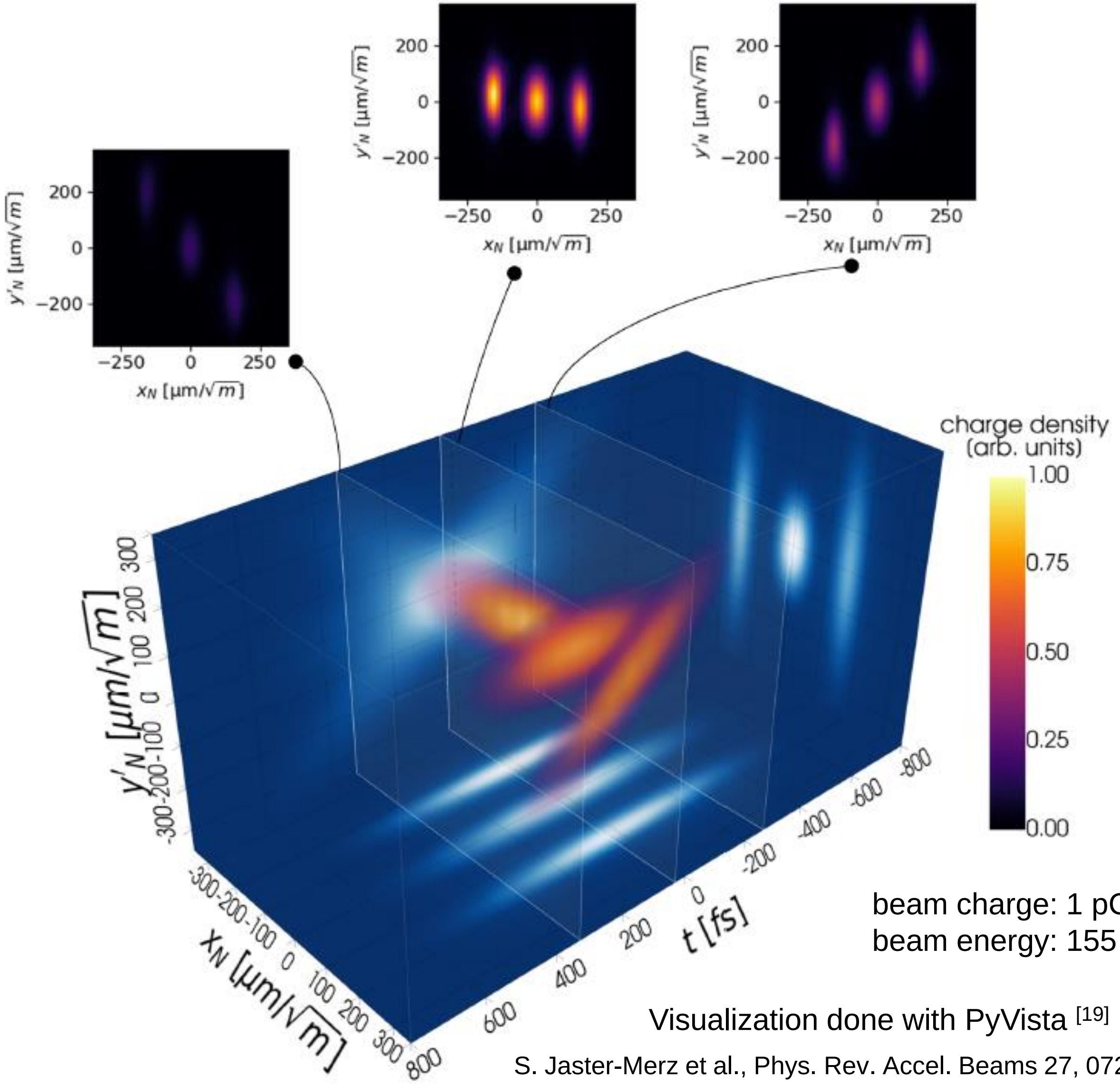


S. Jaster-Merz et al., Phys. Rev. Accel. Beams 27, 072801 (2024)

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 **≲ 5%** discrepancies.
- Extraction of **sliced** beam parameters and the **4D slice emittance** possible.



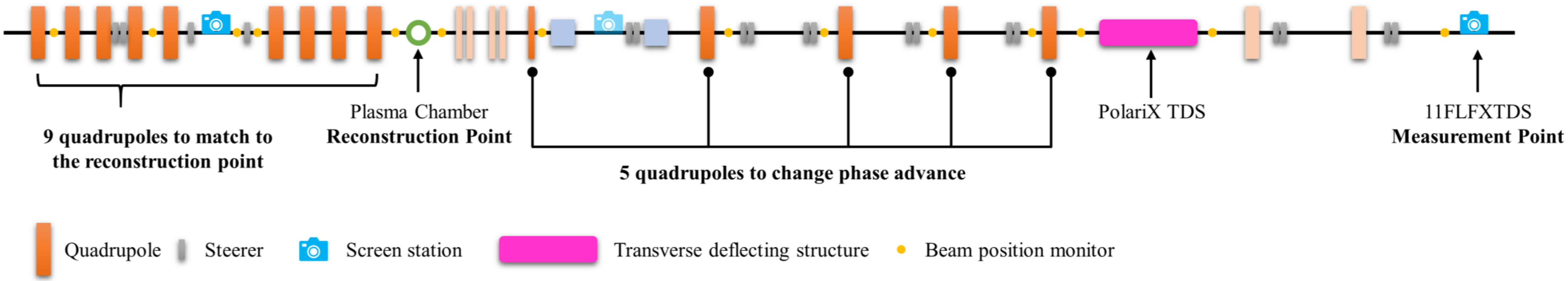
beam charge: 1 pC
beam energy: 155 MeV

Visualization done with PyVista [19]

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

Experimental demonstration at FLASHForward

Fully commissioned PolariX TDS and flexible diagnostic beamline available

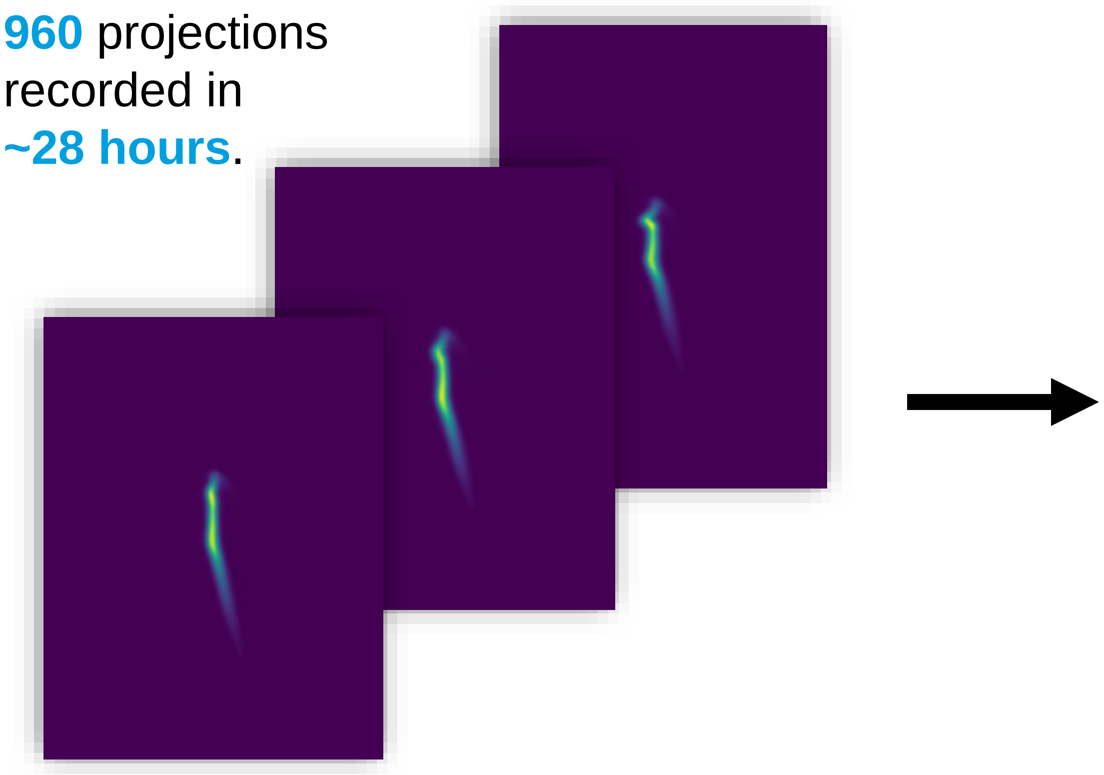


- Experimental facility dedicated to **beam driven plasma acceleration** experiments [16].
- Uses up to 1.3 GeV electron beams from the **FLASH linac** [17, 18].
- Measurement performed with 10 Hz **single bunch** operation, **~1.1 GeV** energy, **~0.3 nC** charge, and **~200 fs** RMS bunch duration.

First experimental 5D reconstruction

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

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



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

Reconstructed 5D phase space enables new insights

Previously hidden transverse-longitudinal correlations are retrieved

Picture may not be published

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

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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.

Scope of this talk

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Novel method for **5D phase space** reconstruction

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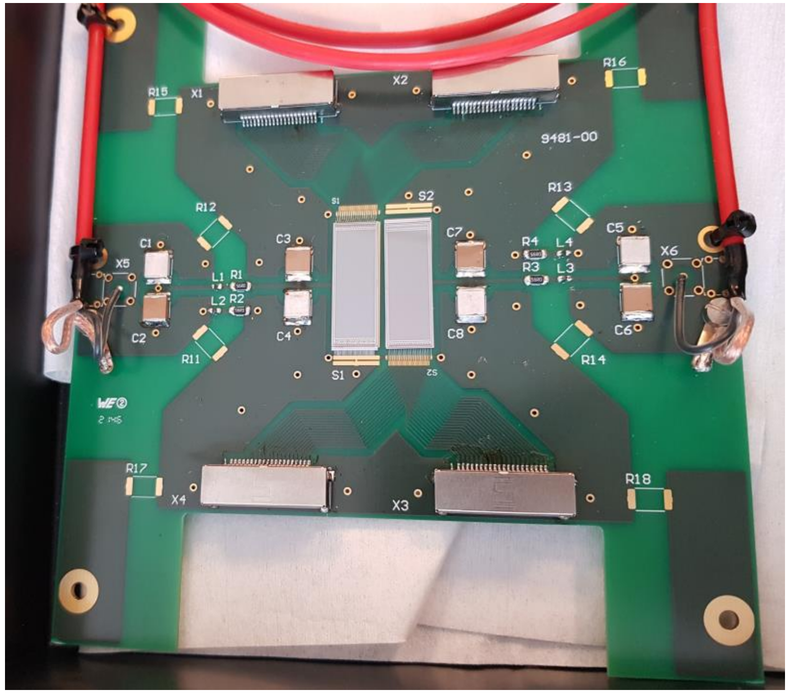
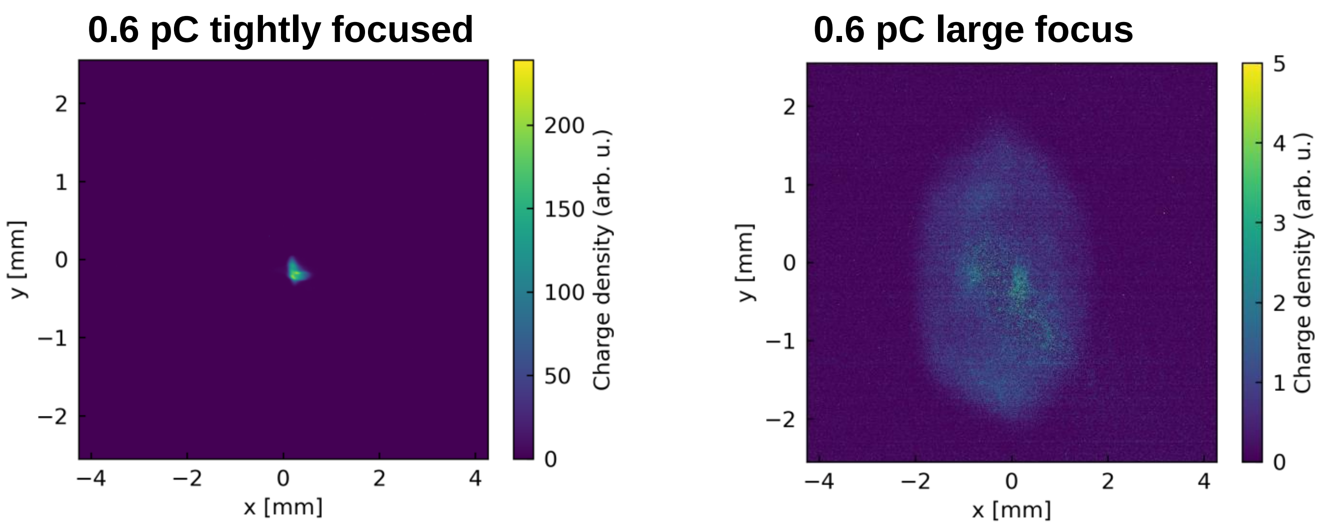
Ultra-sensitive **silicon-based** profile monitor



Measuring fC charge beams

Conventional beam diagnostic tools are limited in charge sensitivity

- Beams with **fC charge** required, e.g., for dielectric laser acceleration and medical applications.
- Conventional beam diagnostics are not sensitive in the fC-range ($10^4 – 10^6$ e^-).
- ARES **scintillating screens** specified for > 0.5 pC:



How can the charge sensitivity be increased further?

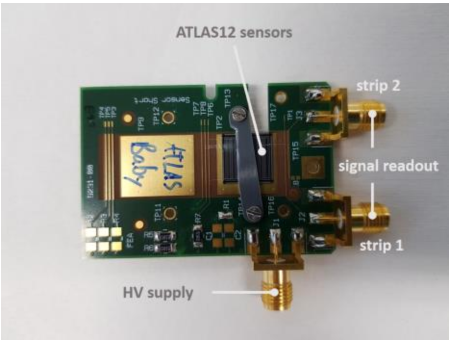
STRIDENAS – Strip Detector for Novel Accelerators at Sinbad

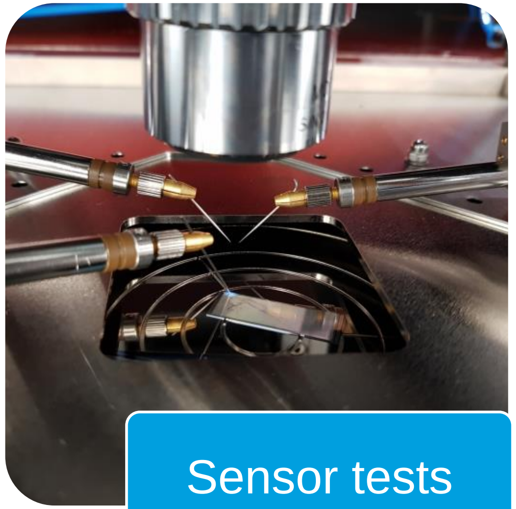
A device to detect fC beams

Using **silicon sensors** to characterize fC-beams in accelerators:

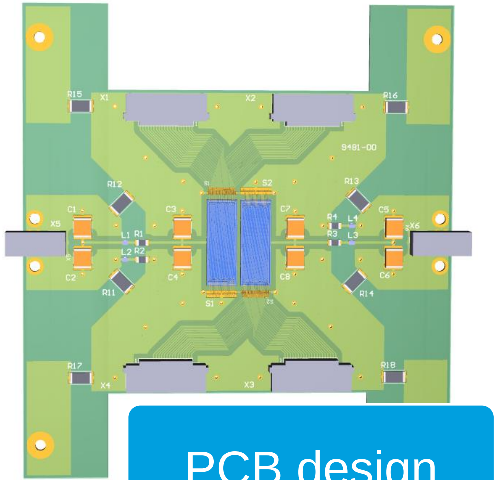
- Two silicon strip sensors from ATLAS (LHC).
- Sensor size: 0.88 cm x 2.53 cm.
- 104 strips per sensor, 75.5 µm pitch.
- Every 3rd strip bonded for readout.

In addition: Early prototype using a smaller sensor.

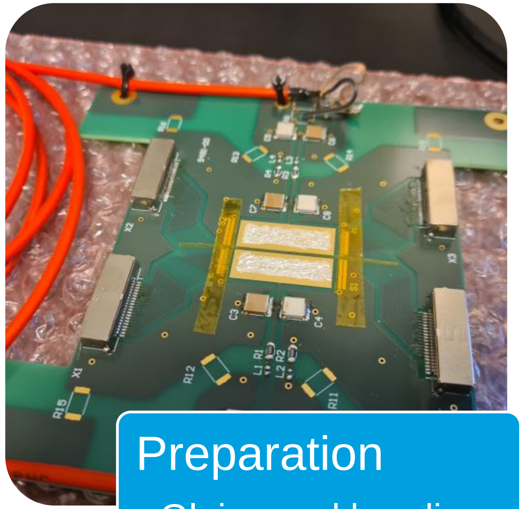




Sensor tests

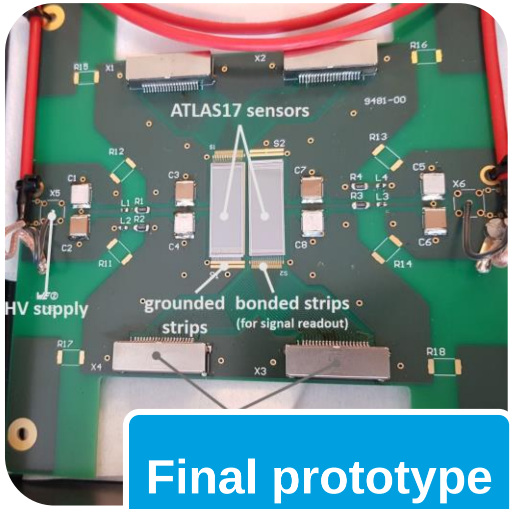


PCB design



Preparation

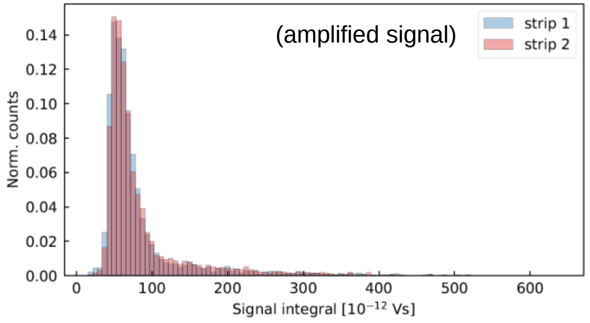
- Gluing and bonding

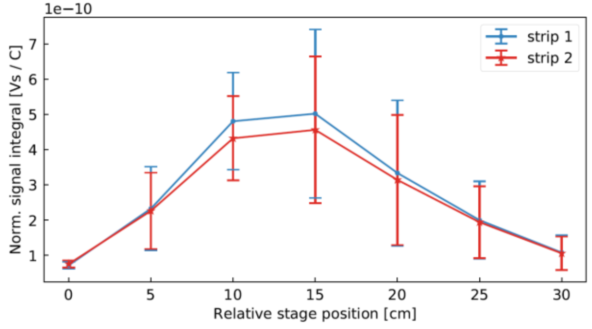


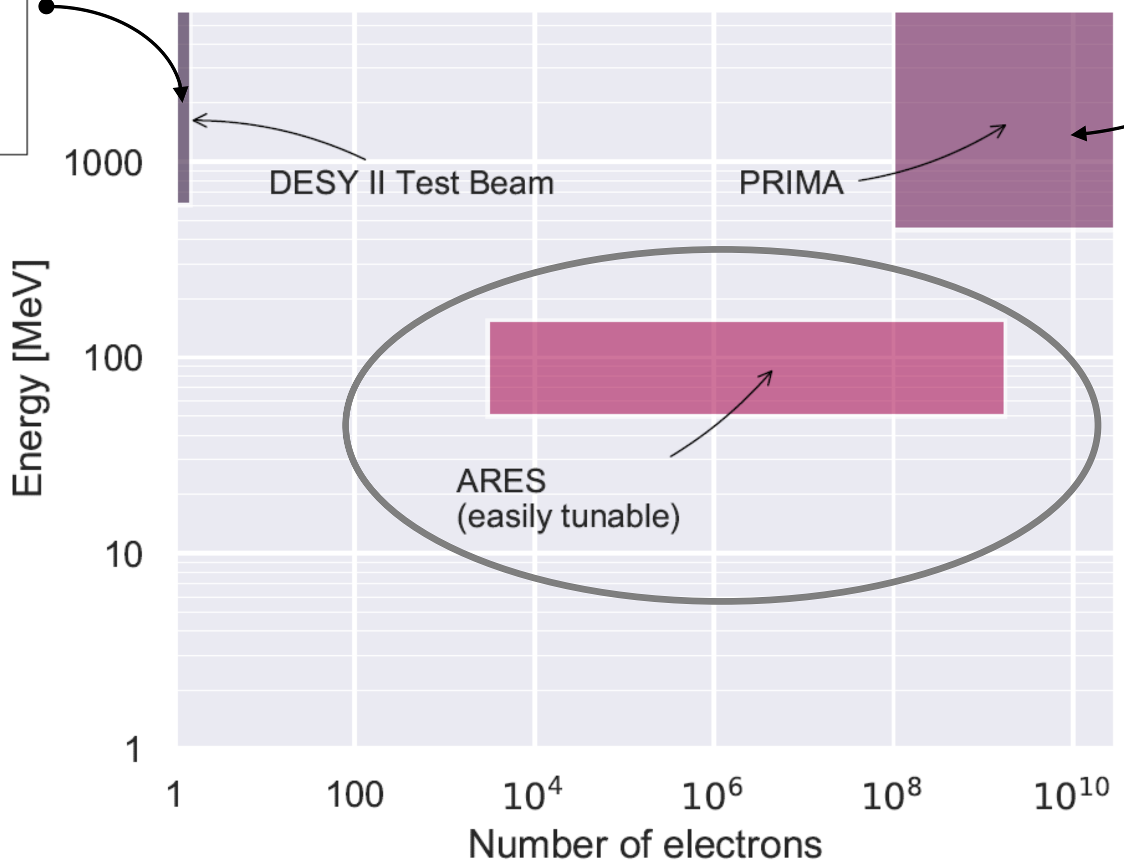
Final prototype

STRIDENAS tests were performed for various beam intensities

DESY provides test sites ranging from single electrons to high-intensity beams



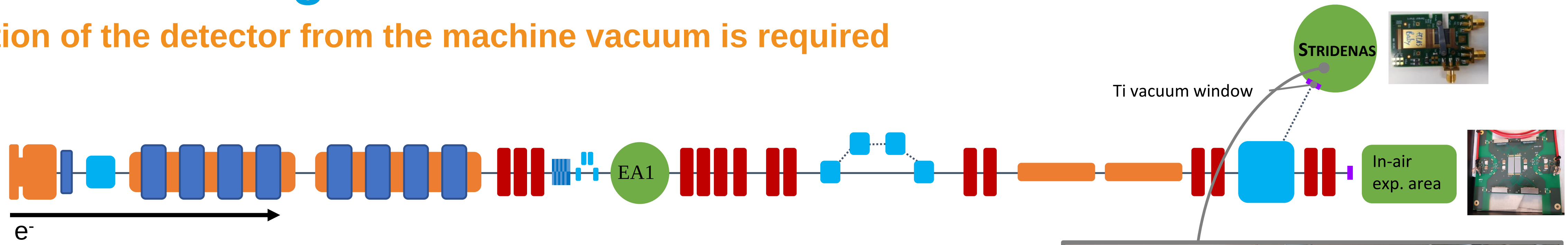




- **Single electron** detection tests (DESY II).
- **High-intensity** proof-of-concept tests (PRIMA beam halo).
- Detailed studies for **various** intensities at ARES.

STRIDENAS integration into the ARES accelerator

Isolation of the detector from the machine vacuum is required



1. 50 µm titanium **vacuum window**.
2. UHV compatible and light-shielded **vacuum chamber**.

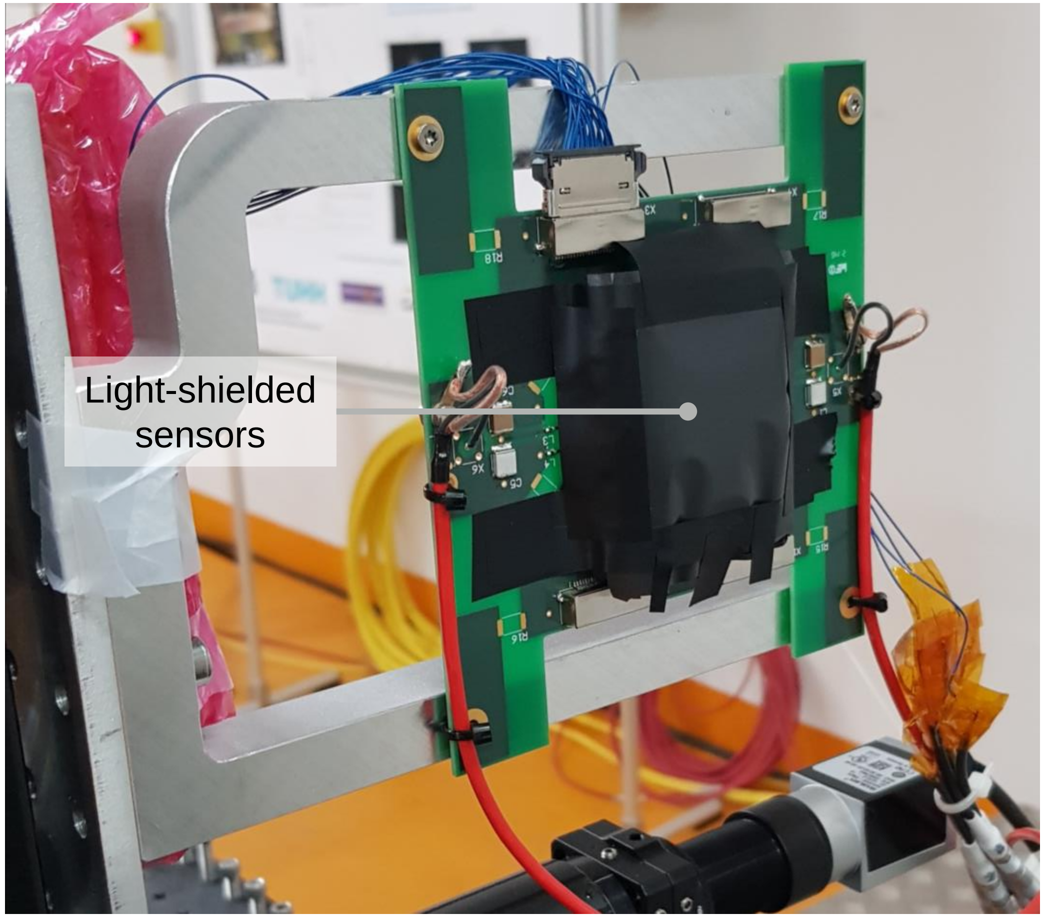
Energy **profiles** can be measured with STRIDENAS

Picture may not be published

- Electron beam with 85 fC charge and 150 MeV energy.
- Profile obtained by scanning the dipole strength.

STRIDENAS beam profile is in excellent agreement with camera

Beam profile recorded by sweeping the STRIDENAS board transversely through the electron beam



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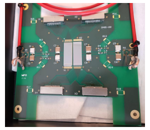
- Electron beam with **33 fC** charge (no signal amplification).

Successful single shot beam profile measurements



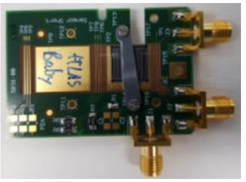
Profiles were recorded for a charge range from 30 fC to 700 fC

Picture may not be published

- **Four** sensor strips are connected for readout (limited by oscilloscope channels).
- Up to 104 channels per sensor will be possible with improved PCB and readout.
- ~330 fC beam compared with a camera image shows **excellent agreement**.

STRIDENAS enables time-resolved studies

Measurement of the time-resolved dark current and photo-pulse timing



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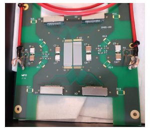
- Average over 500 shots.
- **Excellent agreement** with gun RF pulse duration (900 ns).
- Beam at ~680 ns after RF pulse start.

Silicon sensors for beam charge measurements



Demonstrated ability to measure beam charges from 14 fC to 2.5 pC

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- **Leakage current** of the sensor depends linearly on beam charge.
- By changing the bias voltage a wide range of beam charges can be covered.

Summary and outlook

The developed diagnostic methods and tools enable new insights into the properties of particle beams

5D phase space tomography

Picture may not be published

- First **experimental demonstration** of the 5D phase space tomography method.
  (**≤5%** discrepancies in the beam parameters in simulations).
- Reveals previously unavailable **information**.
- Future measurement with **high accuracy**.
- Enables highly realistic **simulations**.

Silicon-based beam profile monitor

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- STRIDENAS enables **ultra-sensitive** electron beam diagnostics from single electrons to pC beams.
- **Silicon strip sensors** are versatile beam diagnostics:
  - **Time-resolved** and **beam profile** measurements.
  - Leakage current based **beam charge** measurement.
- Future upgrades:
  - Readout of **every** strip with **direct digitization**.
  - Fully **vacuum compatible** design.

Thank you

The ARES Team

R. W. Assmann, J. Beinortaitė, J. Björklund Svensson, A. Boebel, R. Brinkmann, P. Craievich, R. D'Arcy, H. Dinter, A. Ferran Pousa, K. Flöttmann, F. Giesteira, P. Goettlicher, P. Gonzalez Caminal, L. Huth, A. L. Kanekar, M. Kellermeier, C. Kluth, U. Krämer, T. Külper, W. Kuropka, S. Lederer, B. Marchetti, D. Marx, M. Maxton, F. Mayet, C. Müller, E. Panofski, D. Pfannkuche, F. Reedwisch, B. Stacey, T. Schörner-Sadenius, L. van Tuyl, T. Vinatier, B. Wendland, S. Wesch, M. Weschke, A. Wolski, S. Yamin

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!

MVS and many more DESY Technical Groups, the FLASH operators, and the Maxwell Cluster

My PhD supervisors:

Florian Burkart

Wolfgang Hillert

Marcel Stanitzki

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