Advanced Beam Diagnostics with PolariX TDS: Experimental 5D Reconstruction at SwissFEL

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Francesco Demurtas[1], E. Chiadroni[1,4], P. Craievich[2], P. Dijkstal[2], E. Ericson[2], A. Giribono[4], R. Ischebeck[2], S. Jaster-Merz[3], F.Marcellini[2], E. Prat[2], S. Reiche[2]

[1] Sapienza University of Rome, Roma, Italy
[2] Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland
[3] Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[4] Frascati National Laboratories INFN-LNF, 00044 Frascati (RM), Italy

1. PolariX transverse deflection structure

- A transverse deflecting structure is an RF cavity where the Lorentz force is directed in the transverse plane, particles in different points along the beam will feel a different field so that a correlation is imprinted between the transverse coordinate at the screen and particle's longitudinal position
- The **PolariX** is an X-band Transverse Deflecting Structure with the feature of changing the beam streaking direction

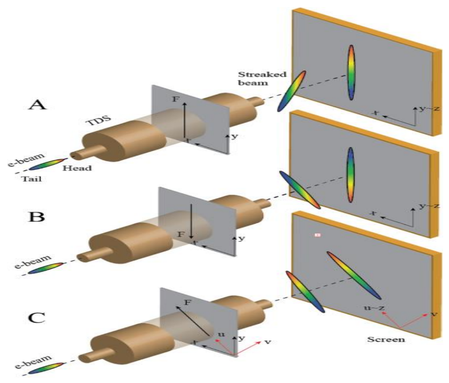


FIG 1: PolariX TDS working principle [1]

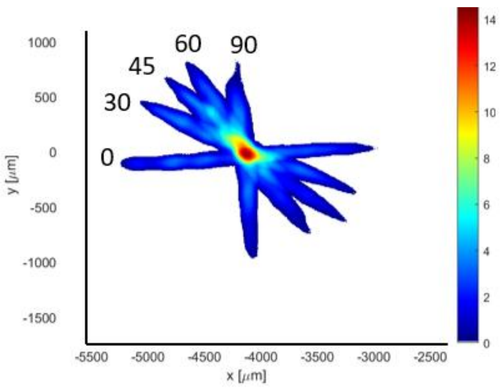


FIG 2: Multiple polarizations

2. 3D and 5D Reconstruction methodology

➢ Combination of **two scans**:
- **Quadrupole scan** → change optics, vary transverse phase advance
- **Polarix TDS scan** → streaking at 10 polarization angles (~180° coverage)

➢ For each **quadrupole settings**:
- **Acquire 10 streaked images**
- **Each image is divided into longitudinal slices**

➢ **3D Reconstruction**
- **Each slice (1D in time) + 10 projections → tomographic 2D reconstruction (x–y) with SART algorithm**
- **Stacking slices → 3D charge distribution (x, y, t)**

FIG 3: Streaked images [2]

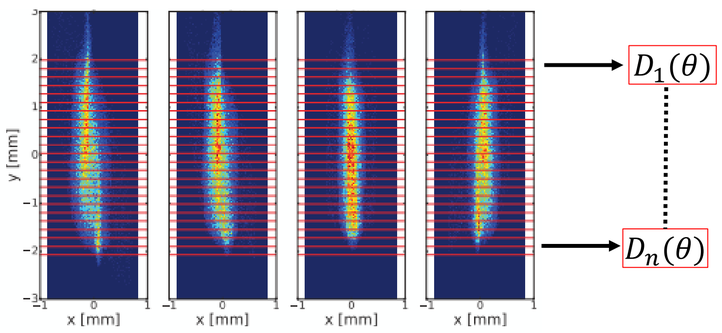
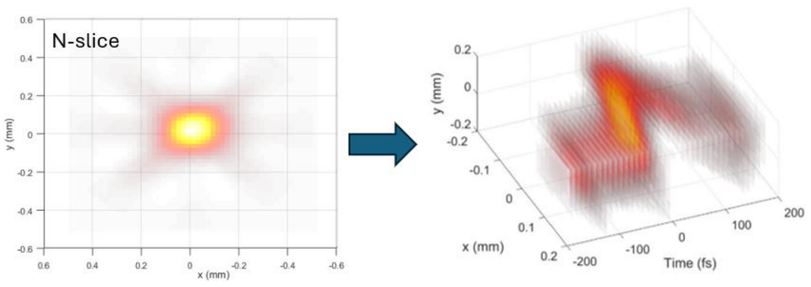


FIG 4: 3D Reconstruction [3]



➢ **4D Reconstruction**
- **2D slice images interpreted as projections of full 4D phase space (x, x', y, y') rotated by an angle depending on the phase advance**

$$I(x,y) = \int\int f_b(x,x',y,y')dx'dy'$$

$$\begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = \begin{pmatrix} \cos(\theta_x) & -\sin(\theta_x) \\ sin(\theta_x) & \cos(\theta_x) \end{pmatrix} = \begin{pmatrix} x \\ x' \end{pmatrix}$$

- $I_y(x_1, \theta_x)$ **is the projection along the θ_x direction in the horizontal phase space**
- **Back-projection algorithm recovers transverse momenta x',y'**

$I_{y,\theta_x}(x)$ —1° iteration→ $f_y(x,x')$ —2° iteration→ $f(x,x',y,y')$

➢ **5D Reconstruction**
- **Combine transverse phase space (4D) with longitudinal coordinate (t)**
- **Result: full 5D beam distribution**

3. ATHOS diagnostics beamline at SwissFEL

- ATHOS is the soft X-rays beamline at SwissFEL at 3 GeV , **two PolariX TDS** are installed to measure the longitudinal properties of the beam

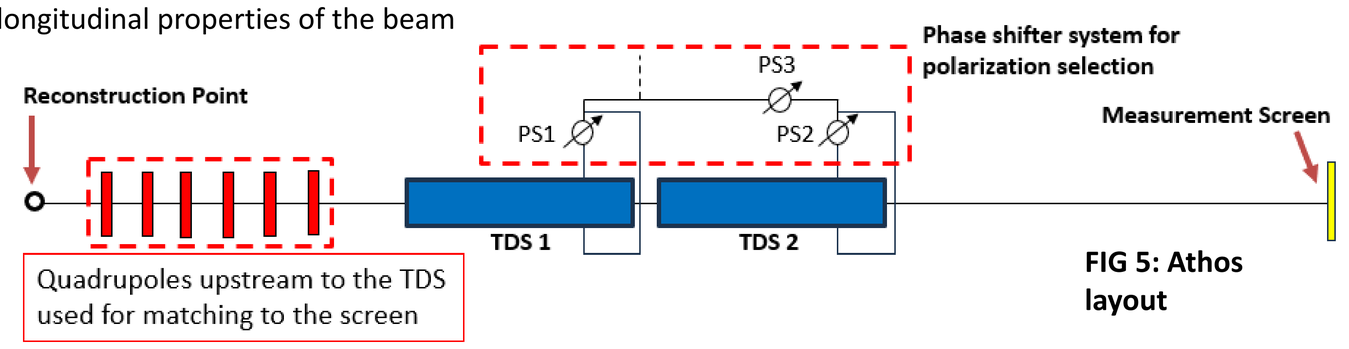


FIG 5: Athos layout

TDS Parameters	
TDS Length	1.2 m
TDS Voltage	70 MV
Klystron Power	28 MW

Measurement Parameters	
Charge	200 pC
Energy	3.4 GeV
TDS Calibration	16.5 $\mu m/fs$

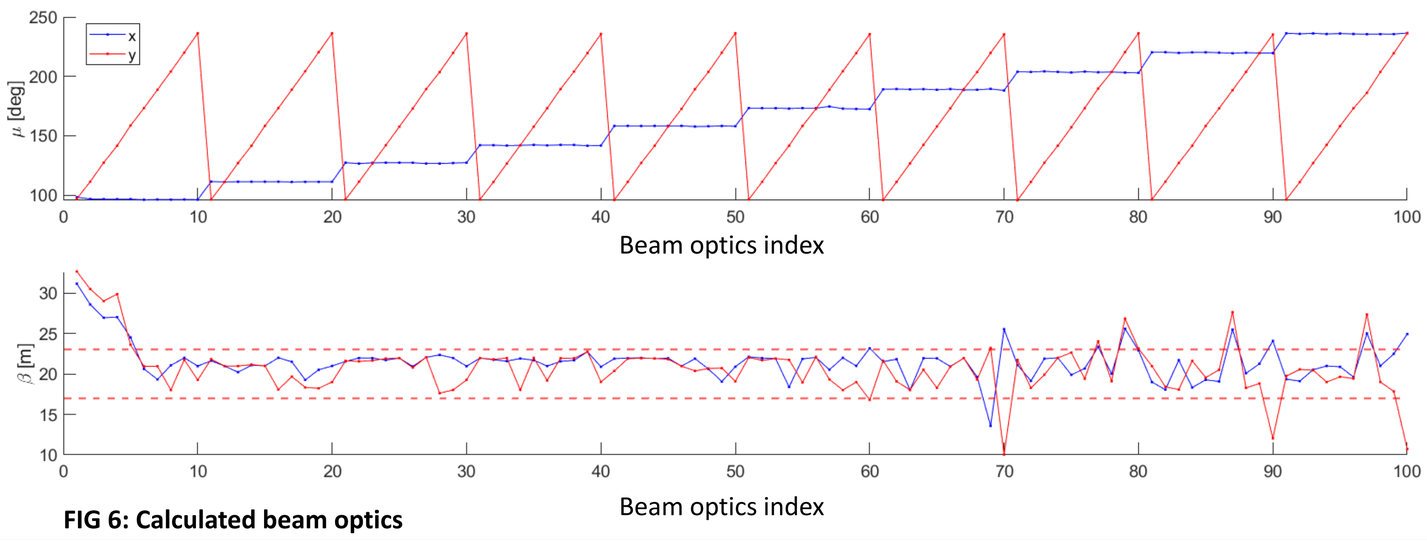


FIG 6: Calculated beam optics

4. Results

Courtesy: S. Jaster-Merz (DESY)

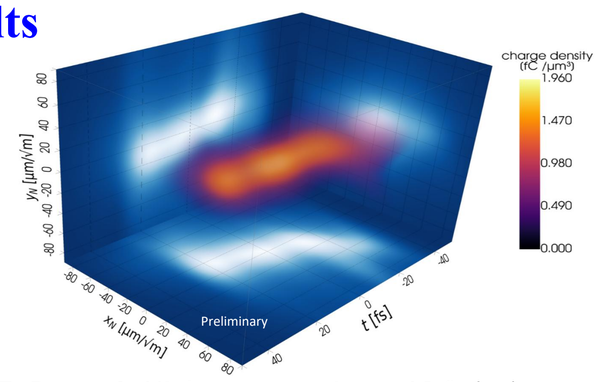


FIG 7: Beam 1: High compression ~19 fs (σ_t)

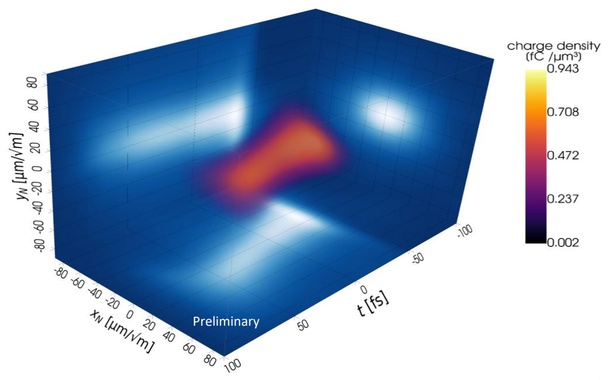


Fig 8: Beam 2: Moderate compression ~ 40 fs (σ_t)

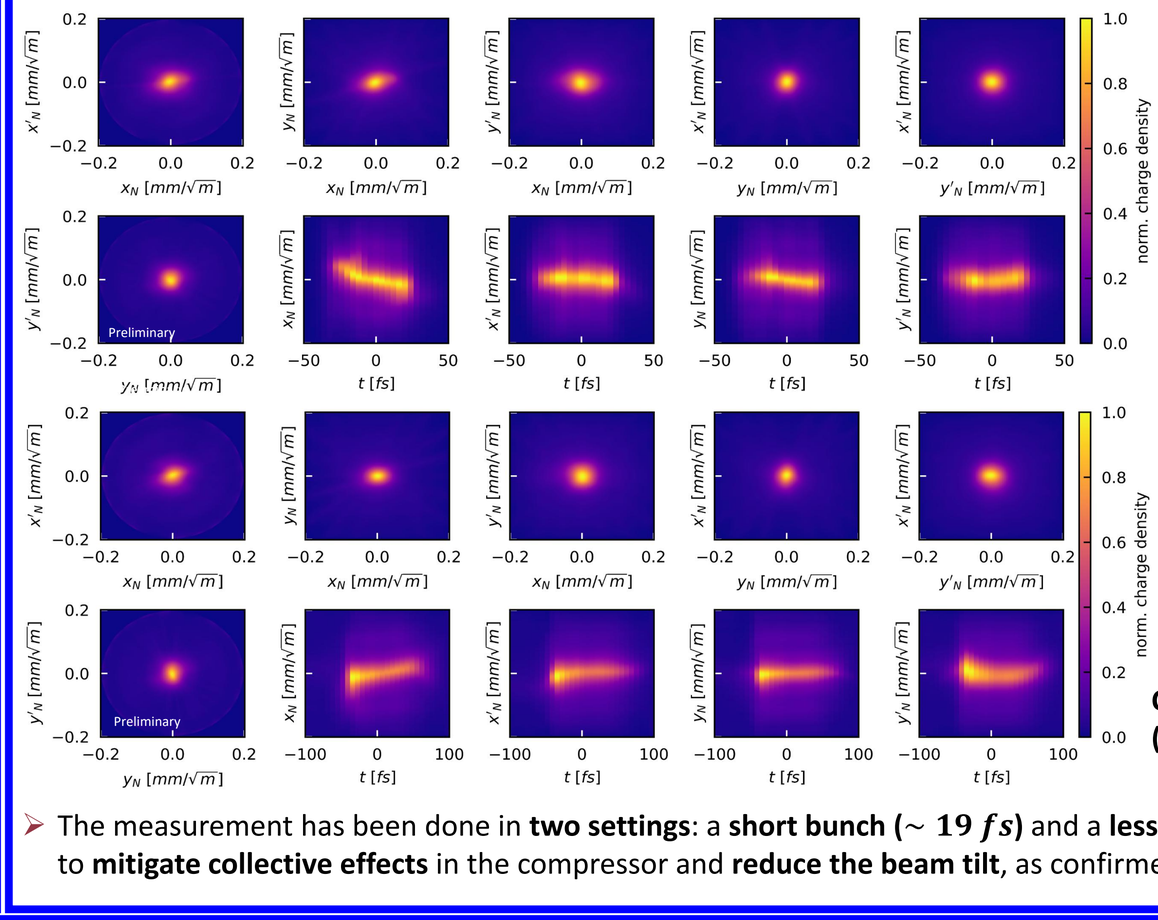


FIG 9: Beam 1: 5D Tomography

FIG 10: Beam 2: 5D Tomography

Courtesy: S. Jaster-Merz (DESY)

➢ The measurement has been done in **two settings**: a **short bunch ($\sim 19\ fs$)** and a **less compressed ($\sim 40\ fs$)** to **mitigate collective effects** in the compressor and **reduce the beam tilt**, as confirmed by the reconstruction.

References

[1] Craievich, Paolo, et al. "Novel X-band transverse deflection structure with variable polarization." *Physical review accelerators and beams* 23.11 (2020): 112001.
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[5] Jaster-Merz, S., et al. "5D tomographic phase-space reconstruction of particle bunches." *Physical Review Accelerators and Beams* 27.7 (2024): 072801.
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