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

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Talk outline

1. **Motivations and goals** of the presented experimental activities

2. Description of the **Polarizable X-Band Transverse Deflection Structure system**

3. Description of the **3D and 5D tomographic techniques**

4. Preparations of the **experimental setup:**
   - Athos SwissFEL diagnostics beamline
   - Beam optics calculation
   - PolariX TDS multiple streaking
   - Deflector calibration

5. **Experimental results of the 3D and 5D reconstruction**

6. **Summary and conclusions**

Motivations and goals

➢ The presented experimental activity is a result from a collaboration between PSI center, DESY and INFN-LNF

PSI ➢ Development of the PolariX TDS

DESY. ➢ Development and first demonstration of the tomographic reconstruction method

SPARC LAB EuPRAXIA ➢ PolariX TDS implementation into the diagnostic system

➢ **Necessity:**

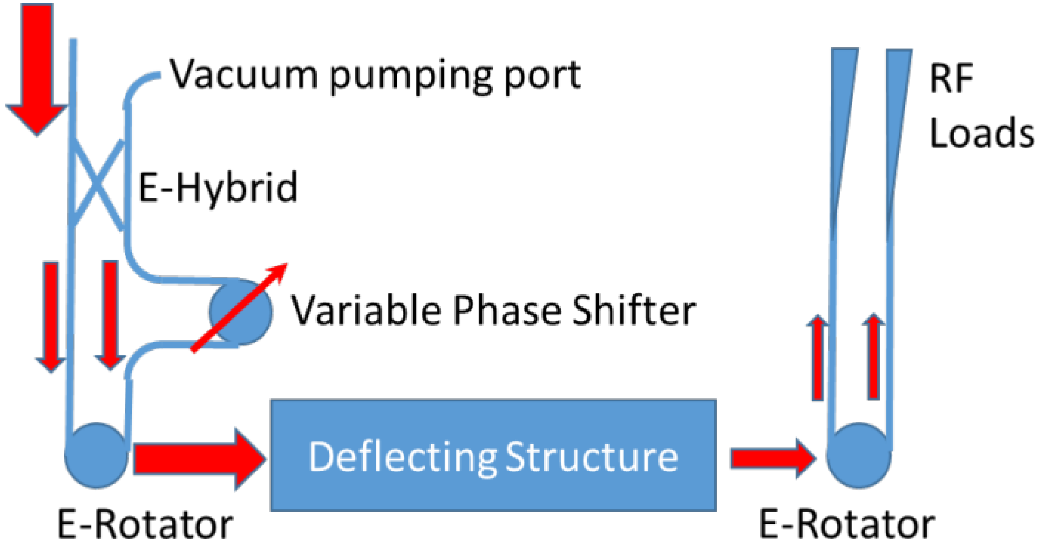
- **High longitudinal resolution** $\sim fs \Rightarrow$ **PolariX TDS**
- **Full phase-space reconstruction** $\Rightarrow$ **Tomographic techniques** (3D/5D reconstruction)

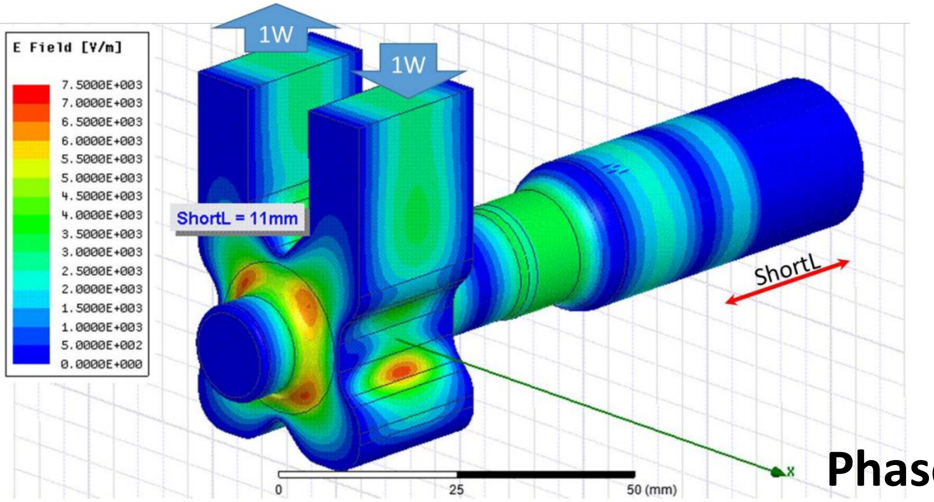
➢ **Goal:**

- **Demonstrate feasibility of 3D/5D reconstructions**

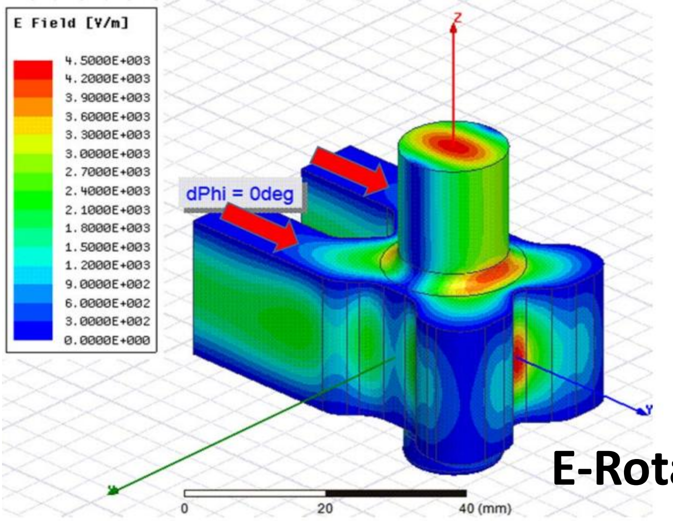
PolariX TDS: RF system

- The **PolariX** is an X-band Transverse Deflection Structure with the feature of changing the beam streaking direction
  - The power is split into two branches
  - The **phase shifter** introduces a phase difference between ports 1 and 2:
    - 0 deg -> vertical polarization
    - 180 deg -> horizontal polarization
  - The two branches are then recombined into the **E-rotator**





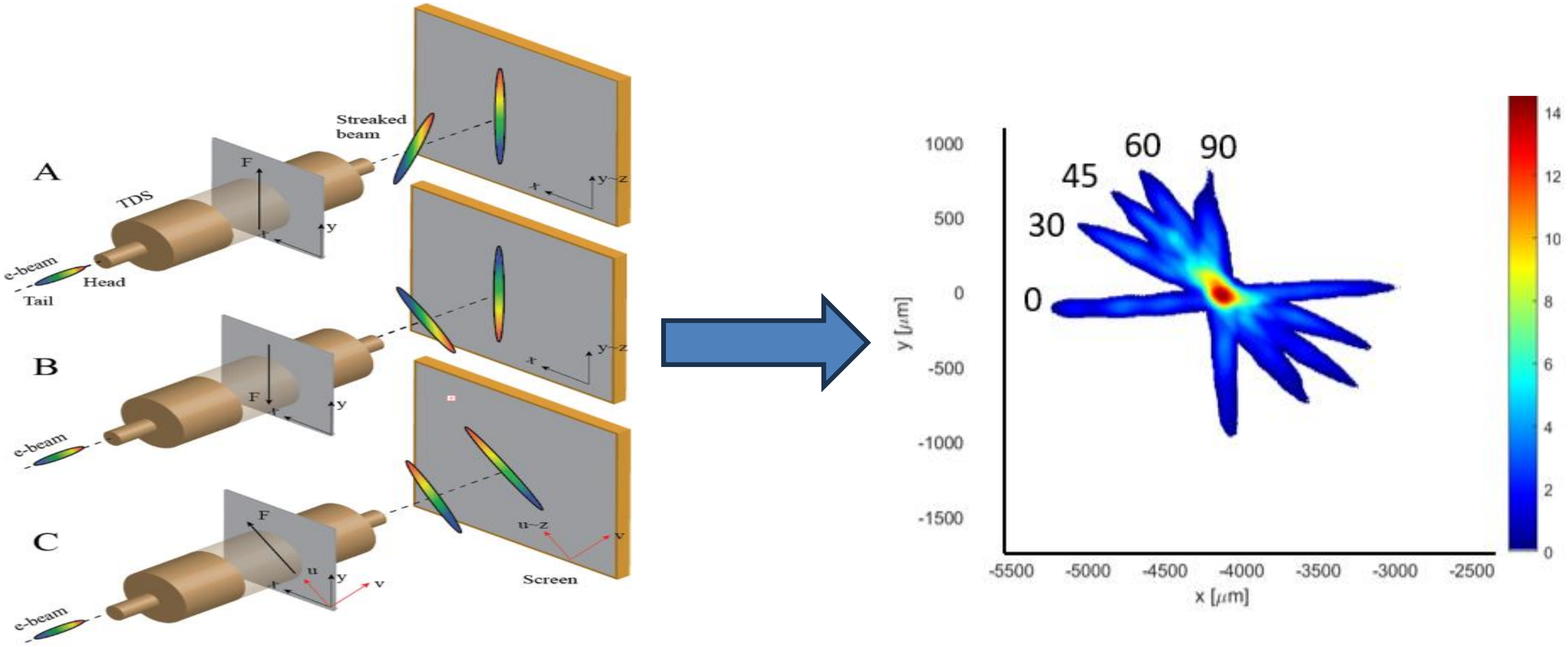
Phase Shifter



E-Rotator

Ref. : Grudiev, Alexej. Design of compact high power RF components at X-band. No. CERN-ACC-NOTE-2016-0044. 2016.

PolariX TDS: Working principle



- It is capable of measuring the longitudinal properties of the beam in both transverse planes with **fs-resolution**
- Allows for a **tomography** of the beam to reconstruct the **3D (x,y,t) and 5D (x,x',y,y',t) beam distribution**, by streaking the beam for different field polarizations

Ref.: Marchetti, Barbara, et al. "Experimental demonstration of novel beam characterization using a polarizable X-band transverse deflection structure." Scientific reports 11.1 (2021): 3560.

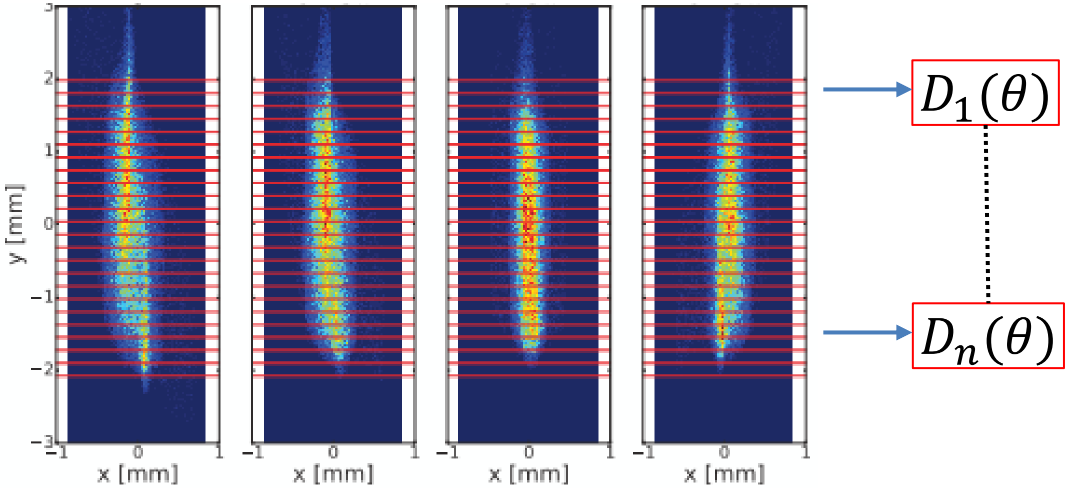
Ref.: Jaster-Merz, S., et al. "5D tomographic phase-space reconstruction of particle bunches." Physical Review Accelerators and Beams 27.7 (2024): 072801.

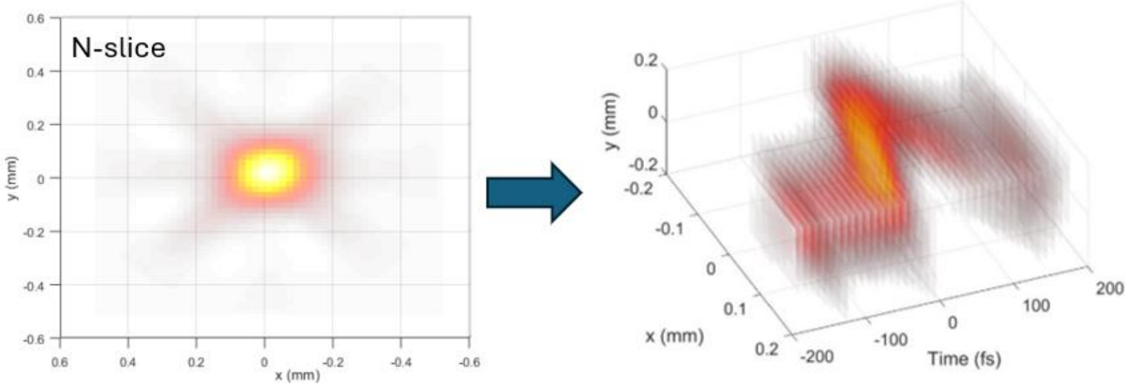
PolariX TDS: Tomographic reconstruction

- Combination of **two scans:**
  - **Quadrupole scan** → change optics, vary transverse phase advance
  - **PolariX TDS scan** → streaking at 10 polarization angles ($\sim 180\ deg$ coverage)

- For each **quadrupole setting:**
  - **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)**
  - **Stacking slices → 3D charge distribution (x, y, t)**





Ref.: Marx, Daniel, et al. "Reconstruction of the 3D charge distribution of an electron bunch using a novel variable-polarization transverse deflecting structure (TDS)." Journal of Physics: Conference Series. Vol. 874. No. 1. IOP Publishing, 2017.
Ref.: Marx, Daniel, et al. "Simulations of 3D charge density measurements for commissioning of the PolariX-TDS." Journal of Physics: Conference Series. Vol. 1067. IOP Publishing, 2018.

PolariX TDS: 5D tomography

➢ 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**

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

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

- $I_y\,(x_1, \theta_x\,)$ **is the projection along the $\boldsymbol{\theta_x}$ direction in the horizontal phase space**
- **Filtered back-projection algorithm recovers transverse momenta $\boldsymbol{x'}, \boldsymbol{y'}$**

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

➢ 5D Reconstruction

- **Combine transverse phase space slices (4D) with longitudinal coordinate (t)**
- **Result: full 5D beam distribution**
- **Developed and demonstrated for the first time at DESY.**

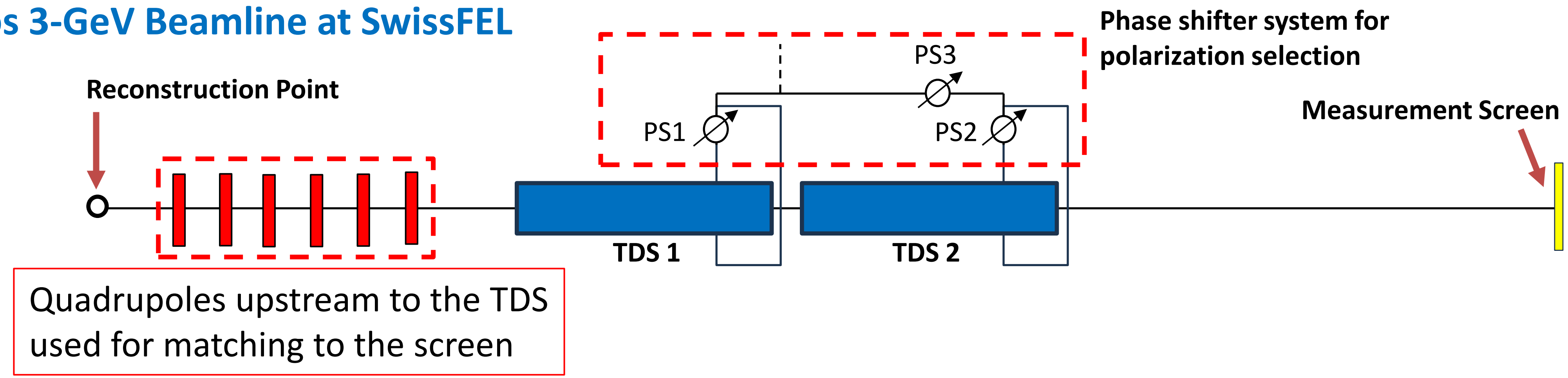
Ref.: Hock, K. M., and A. Wolski. "Tomographic reconstruction of the full 4D transverse phase space." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 726 (2013): 8-16.

Ref.: Jaster-Merz, S., et al. "5D tomographic phase-space reconstruction of particle bunches." Physical Review Accelerators and Beams 27.7 (2024): 072801

Ref.: Jaster-Merz, S., et al. "Experimental demonstration of a tomographic 5D phase-space reconstruction." arXiv preprint arXiv:2505.13724 (2025).

5D Reconstruction: Beamline layout

➤ **Athos 3-GeV Beamline at SwissFEL**



- Quadrupoles off after the TDS ⇒ Resolution depending on the **TDS-screen distance**, **TDS parameters**, and **unstreaked beam transverse size** at the screen

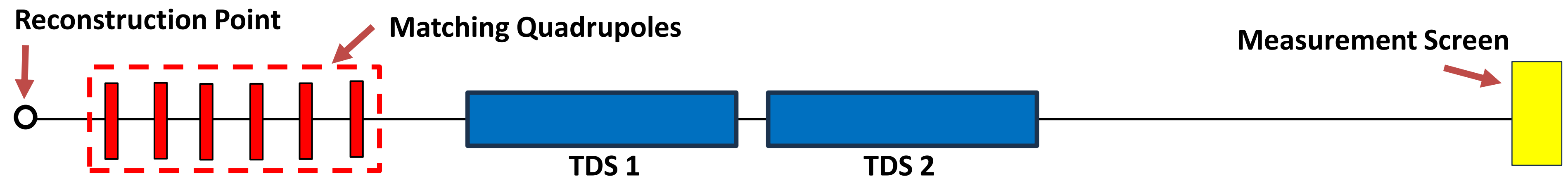
- System of 3 Phase Shifters needed for polarization selection and opposite kick compensation

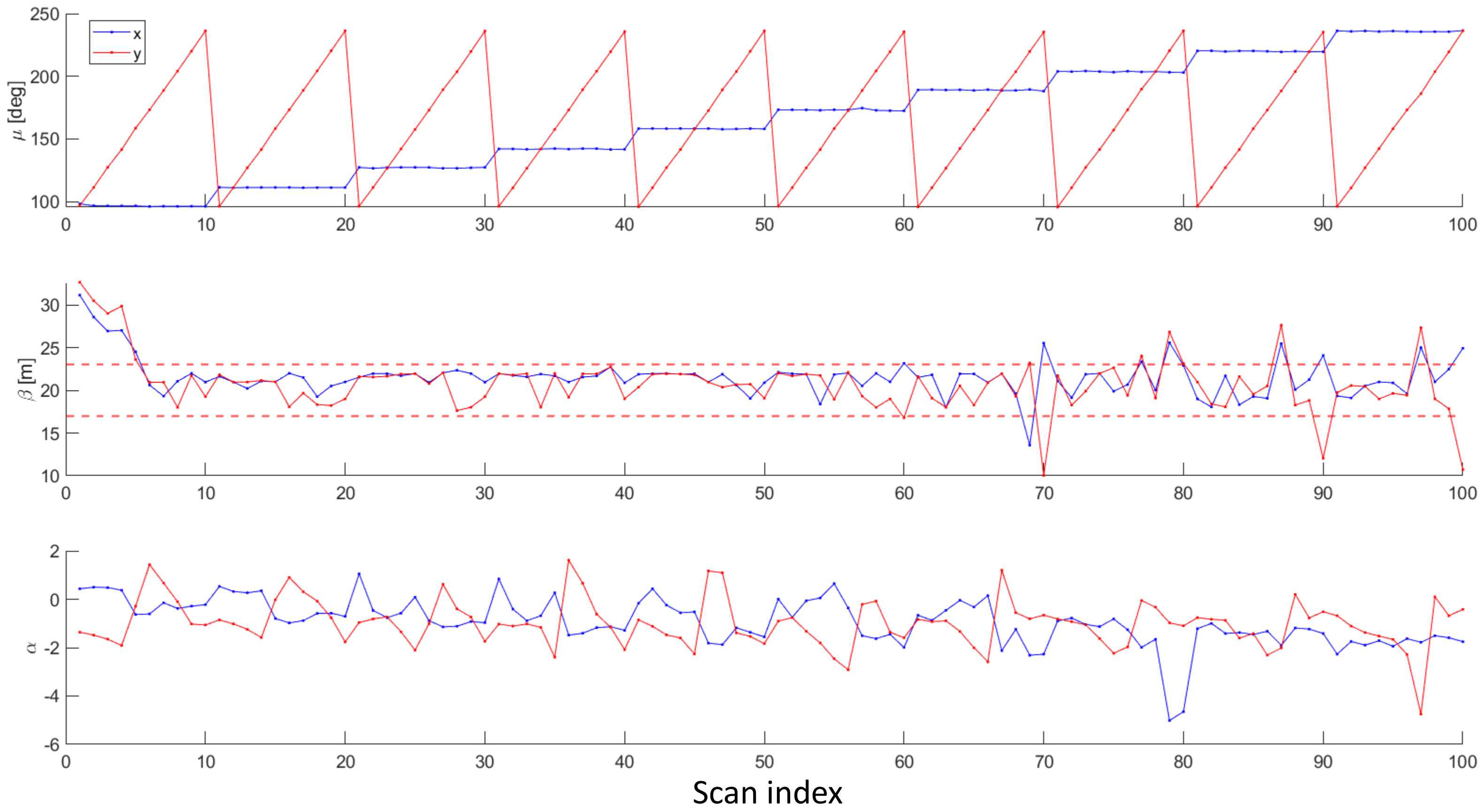
- **Two different beam configurations** with different bunch length

Beam and TDS parameters	
Charge	$200\ pC$
Energy	$3.4\ \ GeV$
TDS length	$1.2\ \ m$
Klystron power	$28\ MW$
TDS Voltage	$70\ \ MV$
TDS calibration	$16.5\ \mu m/fs$

5D Reconstruction: Optics simulations

➢ Single-particle simulations have been done to calculate the beam optics for the quadrupole scan





- **Phase advance scan: μ_x, μ_y from 96 to 236 deg**
- **Small β function (close to 20 m)**
- **Small α (close to 0)**

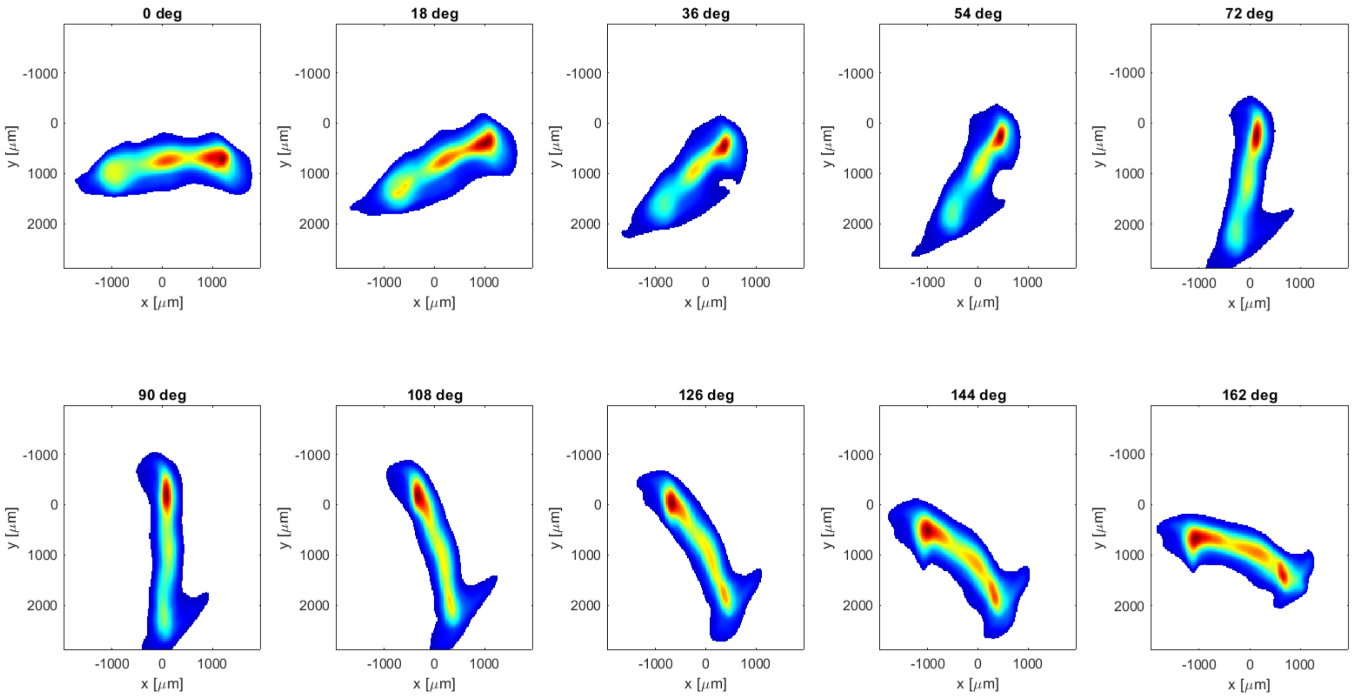
5D Reconstruction: TDS polarizations

- The beam is streaked, covering a polarization range of 180 degrees, and from the centroids, the streaking angle can be evaluated
- The polarization is set by **three phase shifters** that set the single cavity phase and the relative one

$$\theta = \tan^{-1}\left(\frac{C_y}{C_x}\right)$$

Polarization [deg]	Measured Angle [deg]
0	2.3 ± 0.3
18	19.6 ± 0.3
36	37.9 ± 0.2
54	56.6 ± 0.5
72	74.7 ± 0.5
90	92.9 ± 0.2
108	111.4 ± 0.4
126	130.1 ± 0.2
144	148.2 ± 0.3
162	165.2 ± 0.5

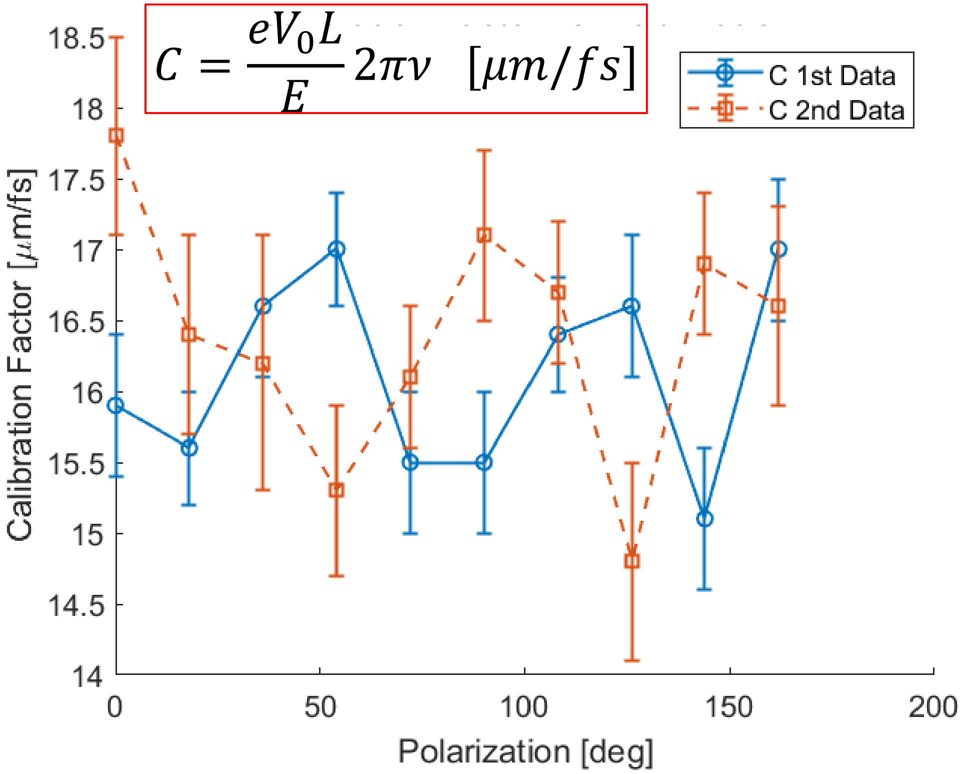
Angle from: Centroid Shift vs RF Phase

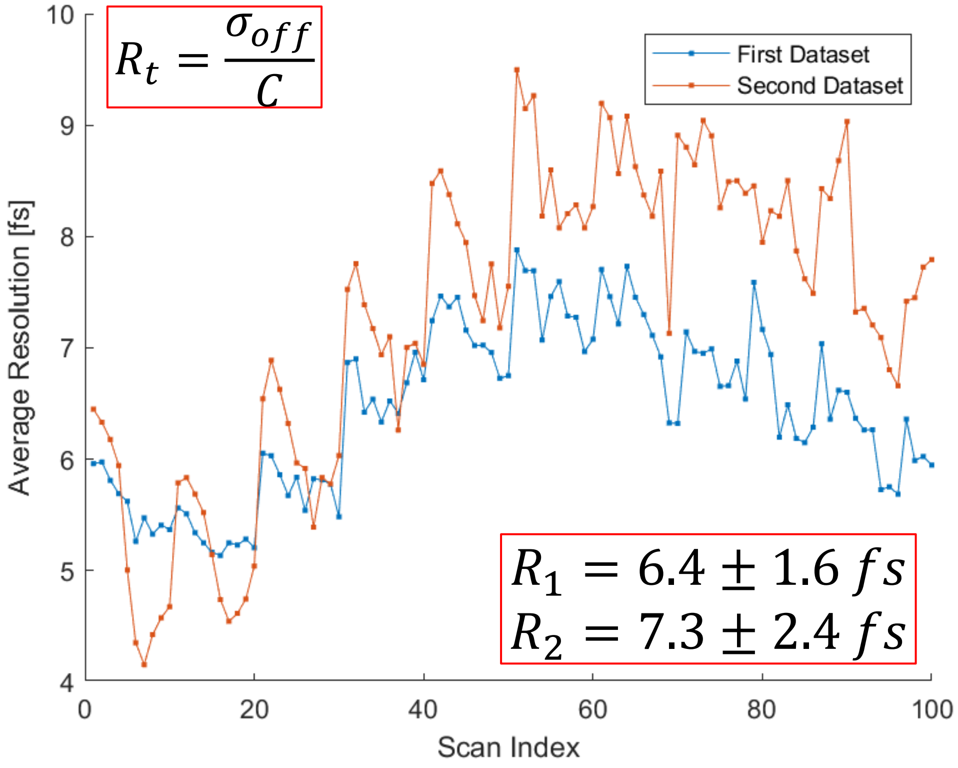


Beam Images at different polarizations

5D Reconstruction: Calibration results

- TDS calibration for different streaking angles → Measured the centroid shift when changing the cavity phase
- Expecting a low variation in the calibration factors depending on the streaking angle, due to not using quadrupoles after the TDS
- Average resolution rescaled to take into account shot-to-shot variations in the cavity voltage



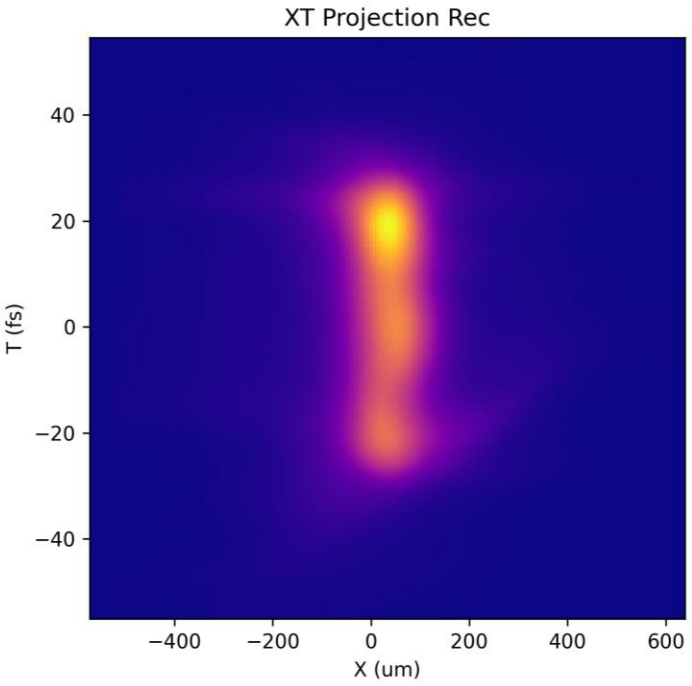


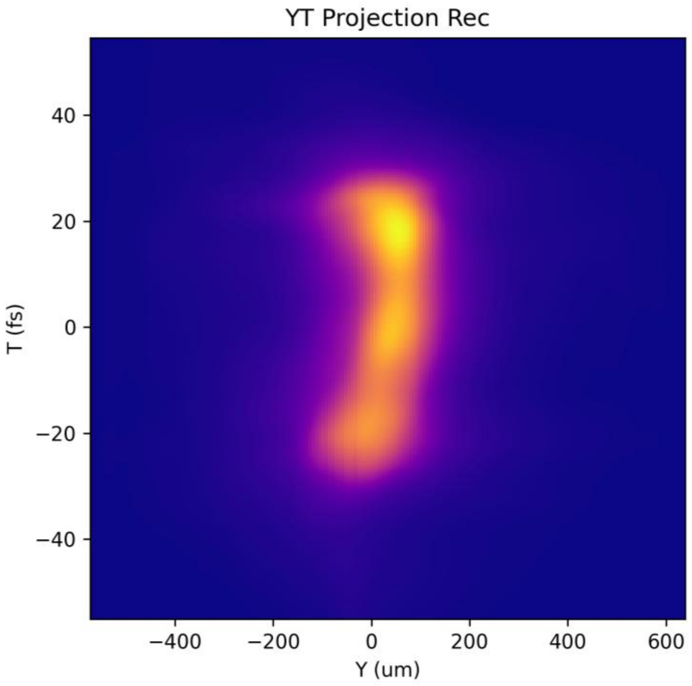
3D Reconstruction: 2D projections

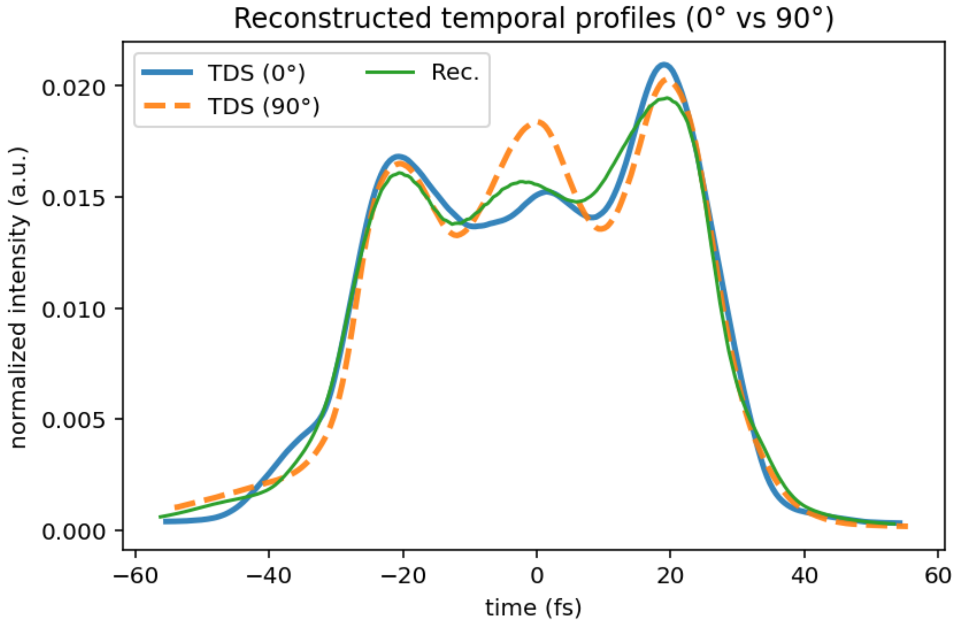
- For each dataset, we acquired 5 images for each combination of 100 quadrupole settings and 10 polarizations (Beam repetition rate: 1 Hz)

- For each beam optics the 3D reconstruction can be performed

2D projections from the reconstructed 3D distribution ($\mu_x = \mu_y = 96\ deg$):





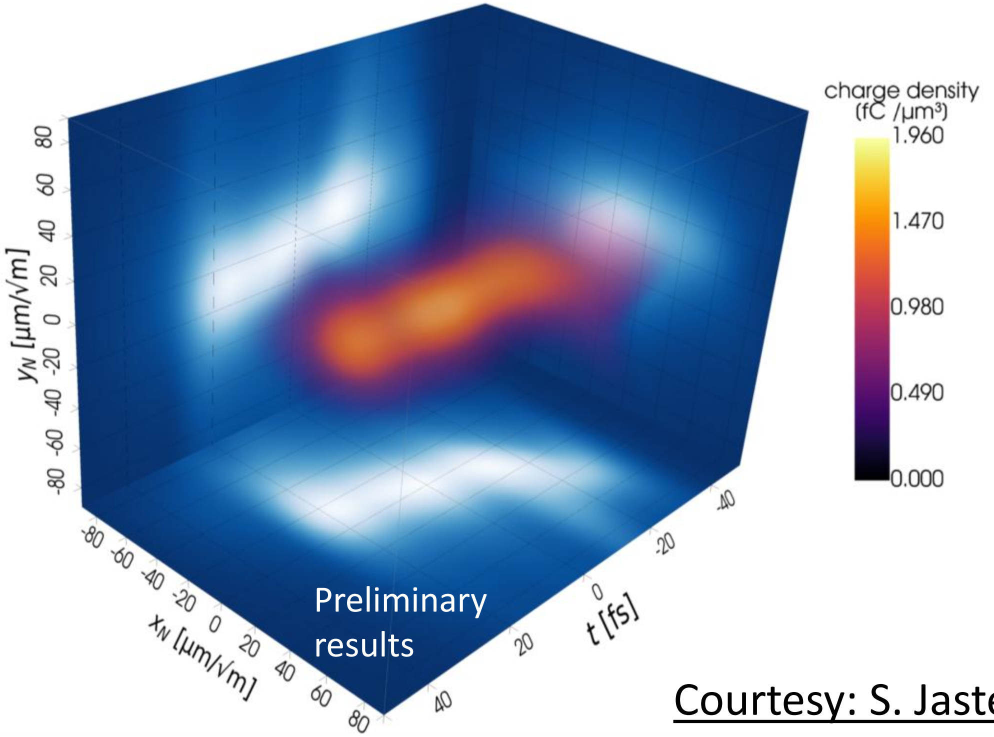


5D Reconstruction: Preliminary results

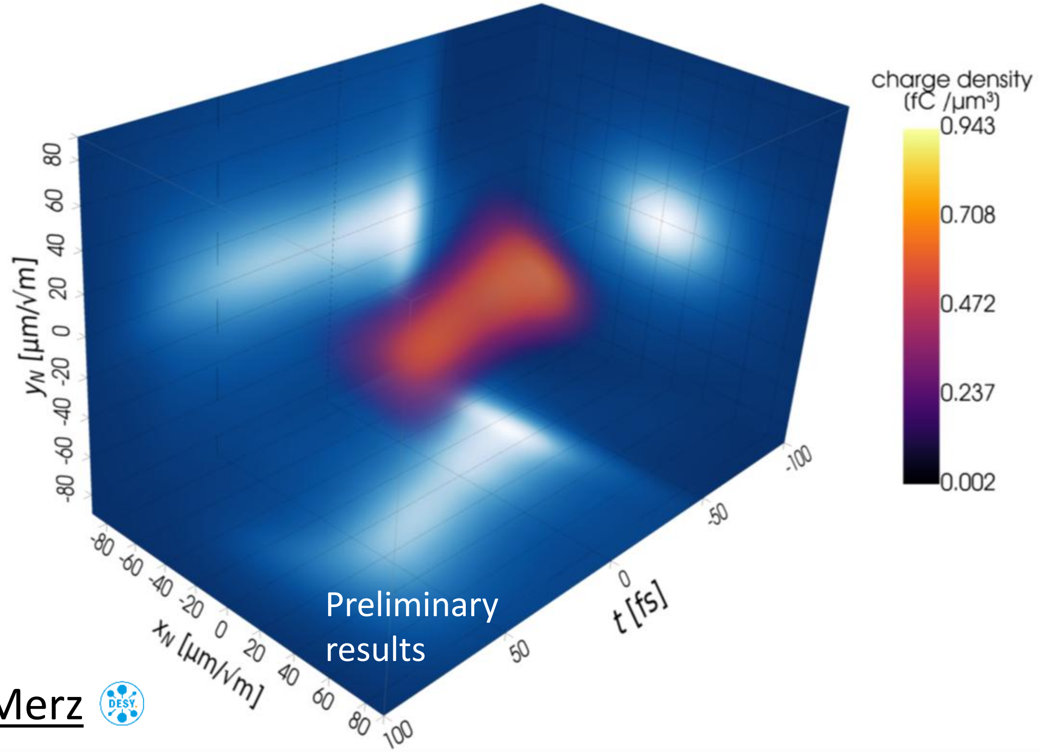
- The measurement has been done in **two settings**: a **short bunch ($\sigma_t \sim 19\ fs$)** and a **less compressed ($\sigma_t \sim 40\ fs$)** to **mitigate collective effects** in the compressor and **reduce the beam tilt**

3D beam charge density obtained as a projection of the reconstructed 5D distribution:

Beam 1: High compression $FWHM_t \sim 56\ fs$



Beam 2: Moderate compression $FWHM{\sim}103\ fs$

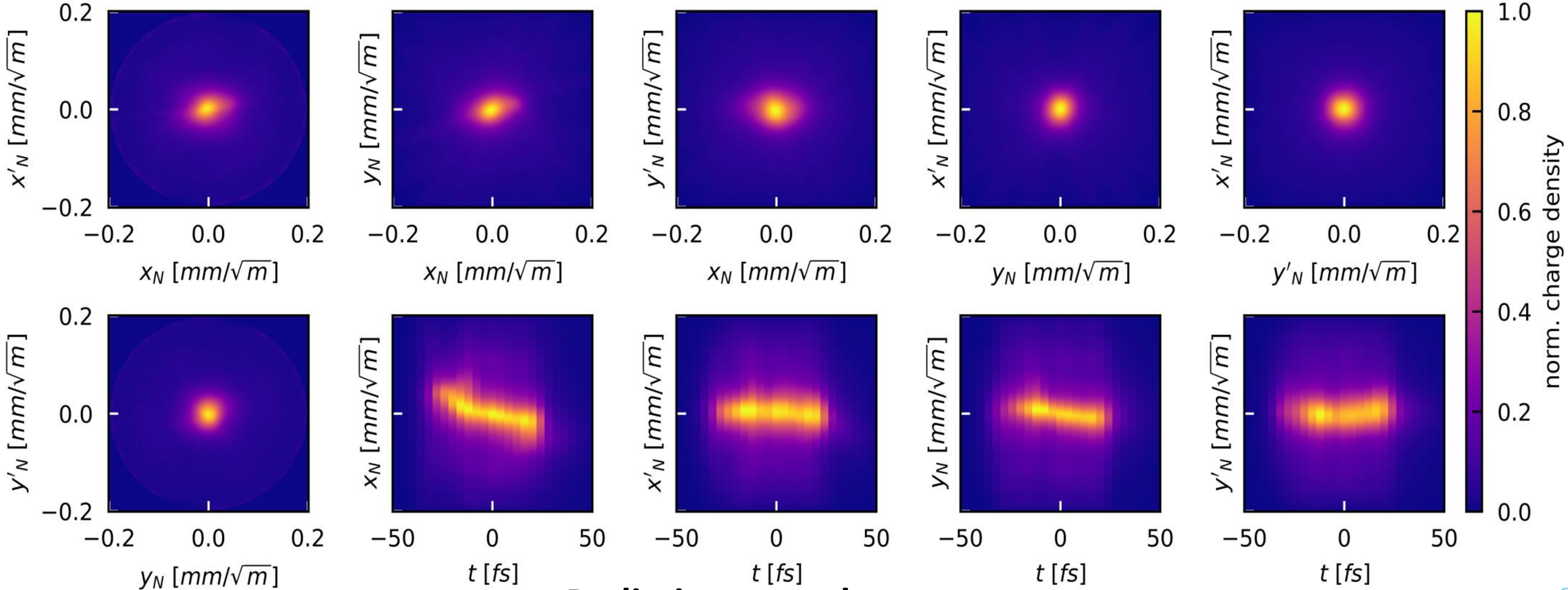


Courtesy: S. Jaster-Merz

5D Reconstruction: Bunch 1

- **Bunch 1, reconstructed 2D projections:**

$$x_N = \frac{x}{\sqrt{\beta_x}} \qquad y = \frac{y}{\sqrt{\beta_y}}$$



Preliminary results

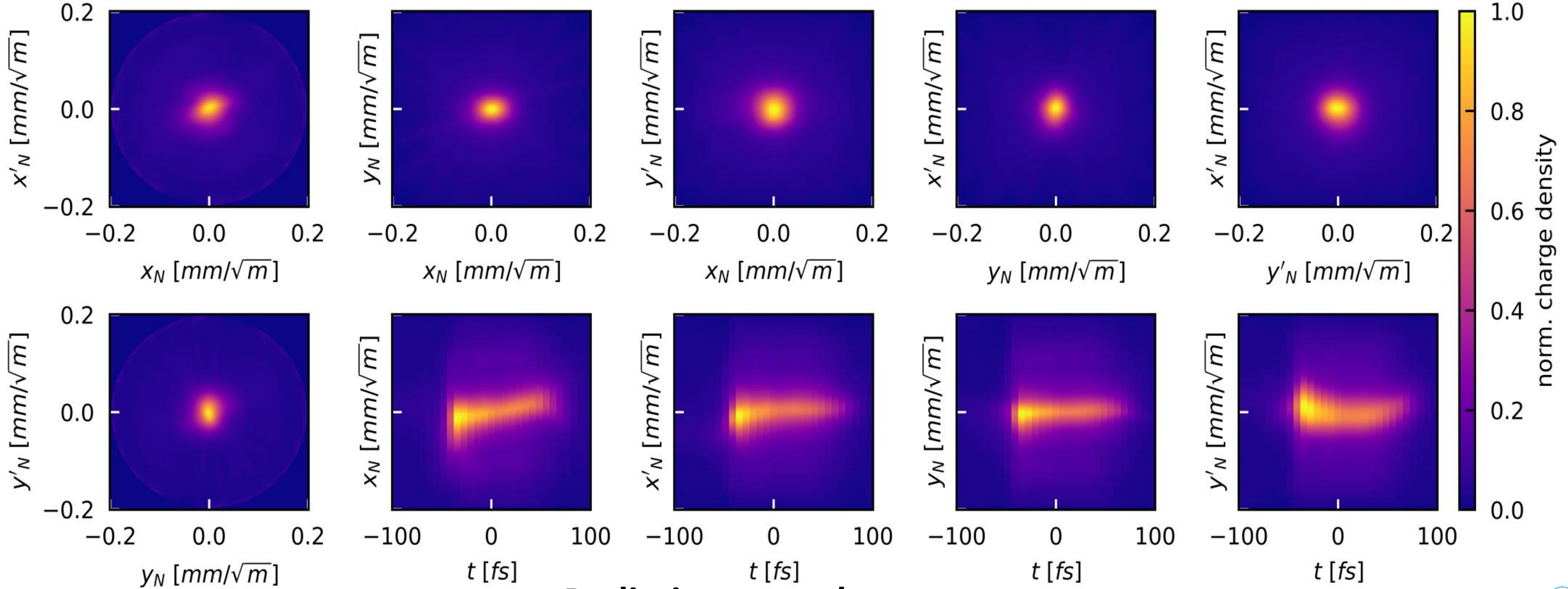
Courtesy: S. Jaster-Merz

- In the first beam configuration, the **high compression produces a very short bunch with an evident tilt in the (x,t) plane**

5D Reconstruction: Bunch 2

➢ **Bunch 2, reconstructed 2D projections:**

$$x_N = \frac{x}{\sqrt{\beta_x}} \qquad y = \frac{y}{\sqrt{\beta_y}}$$



Preliminary results

Courtesy: S. Jaster-Merz

➢ In the second beam configuration, the **relaxation of the bunch compression reduces the beam tilt**

Summary and conclusions

➢ Summary results

- Employed the 3D and 5D tomography at the 3 GeV Athos beamline at SwissFEL, to reconstruct beams for two different beam configurations

- Achieved the 5D tomography with $\sim fs\ Resolution$

➢ Next Studies:

- Employ this technique as diagnostics to characterize the nominal bunch at Athos SwissFEL

- Extend the 5D tomography method to perform the 6D Reconstruction, including the beam energy measurement at the spectrometer

Acknowledgements

- **INFN-LNF:** *E. Chiadroni, A. Giribono*
- **PSI center:** *P. Craievich, P. Dijkstal, F. Marcellini, E. Prat, S. Reiche, E. Ericson, R. Ischebeck*
- **DESY:** *S. Jaster-Merz, B. Beutner*

Thank you for your attention

BACKUP SLIDES

SART tomographic algorithm

➢ SART (Simultaneous algebraic reconstruction technique) TOMOGRAPHIC ALGORITHM

Working principle:

1. Sinogram: set of 1S projections D_j (called ray) in input to the algorithm
2. Initial guess $I_0(x, y)$ to calculate the projection $\mathrm{D}_{0_\mathrm{j}} = R_j I_0(x, y)$
3. Calculated the projection $\mathrm{D}_{0_\mathrm{j}}$ we define the difference between D_j and $D_{0\,j}$ and update the initial guess $I_0(x, y)$ to reduce the difference at each iteration

Advantages:

- It is simultaneous because it updates all pixels at the same time
- More accurate and robust than other similar algorithms
- Good reconstruction with few projection angles

Filtered Back Projection algorithm

➢ FILTERED BACK PROJECTION TOMOGRAPHIC ALGORITHM

Working principle:

1. 2D Projection of 4D distribution $I(x,y) = \int\int f_B(x,x',y,y')dx'dy'$
2. $(x,x') \Rightarrow (x_1,x_1')$ after a rotation $\theta_x \Rightarrow I(x_1,y) = P_{y,\theta_x}(x_1)$: Projection
3. Consider y as constant, and work only on the x,x' variables
4. Apply Fourier transform to P: $S_{y,\theta_x}(w) = \int_{-\infty}^{\infty} P_{y,\theta_x}(x_1)e^{-2\pi i w x_1}dx_1$
5. Apply high-pass filter and revert the transform: $Q_{y,\theta_x}(x_1) = \int_{-\infty}^{\infty} S_{y,\theta_x}(w)|w|\, e^{2\pi i w x_1}dw$
6. Compute the back-projection: $g_y(x,x') = \int_{-\pi}^{\pi} Q_{y,\theta_x}(x_1)d\theta_x$
7. Repeating the same process for y gives the 4D distribution

Beamline optics

- The optics has been calculated to **match the Twiss parameters to screen**

- Since there are no quadrupoles active, but only a drift after the TDS, **the beta function at the TDS center and the beam size at the screen are dependent parameters**

$$\mu_x = \mu_y = 111\ deg$$

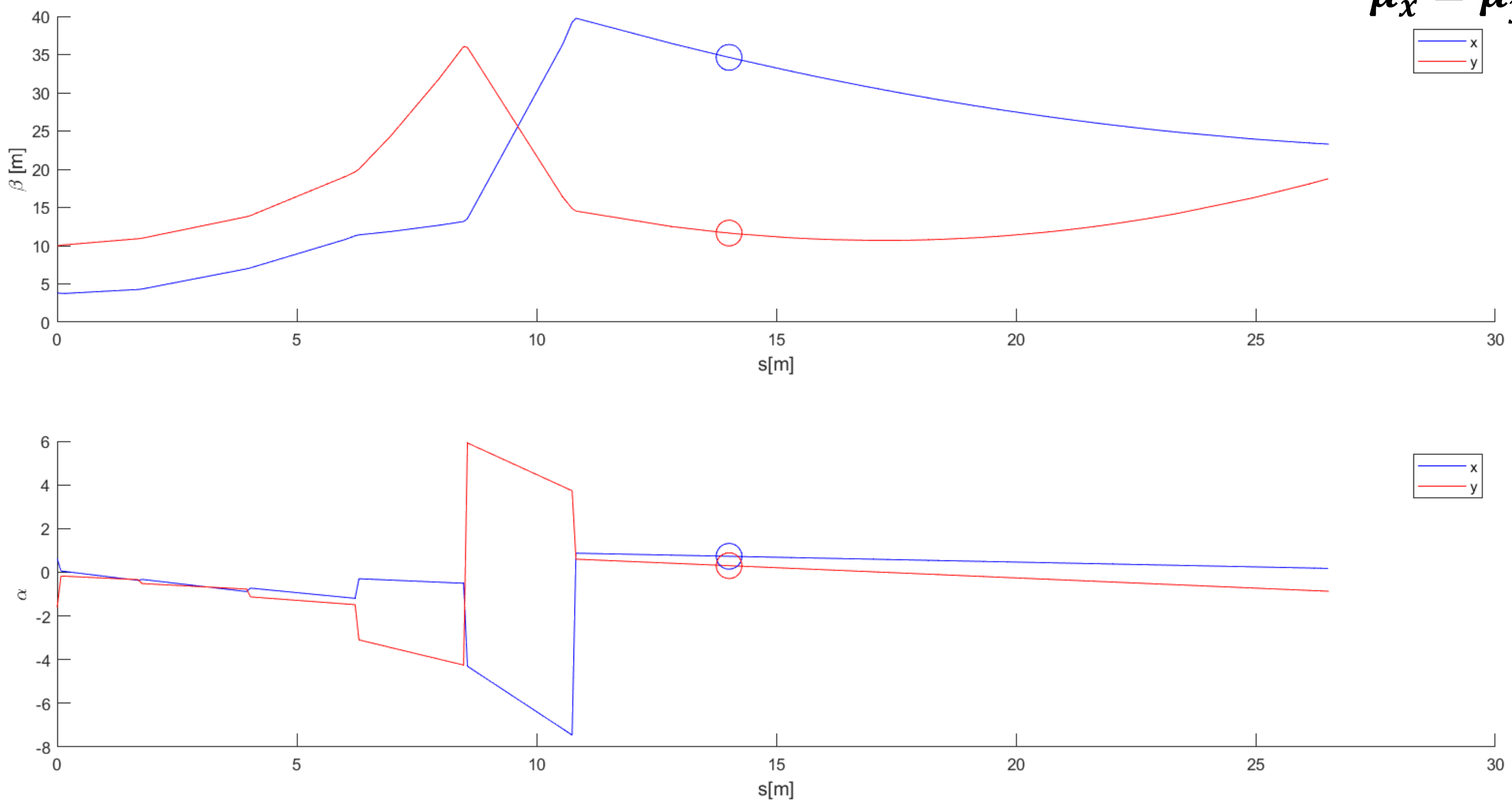


Image treating methodology

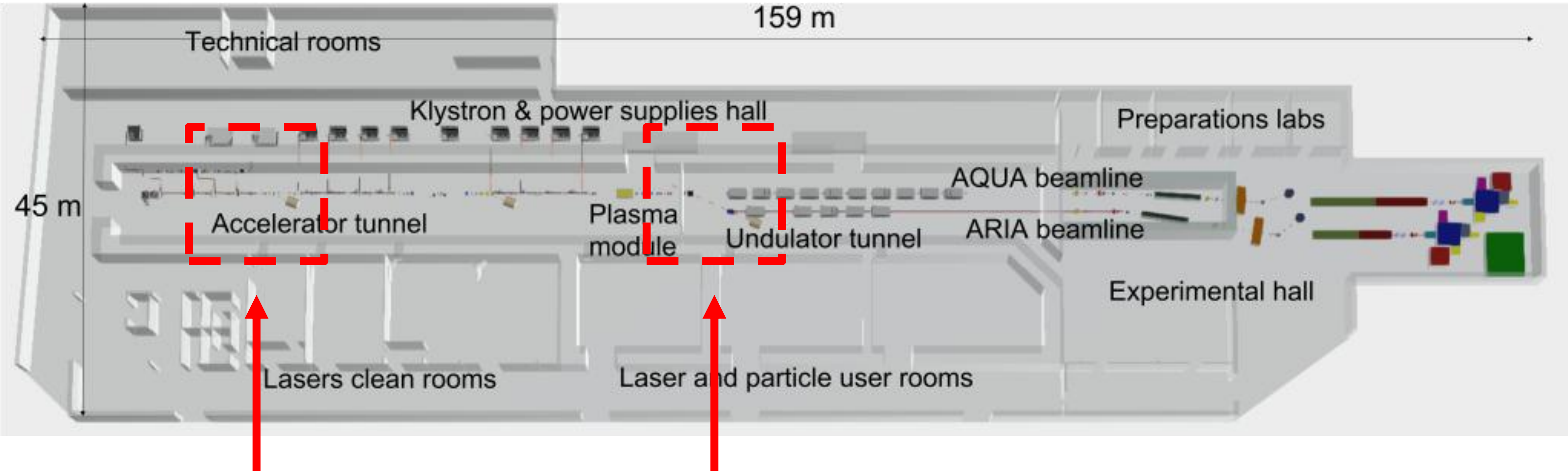
- **The images have to be prepared to perform the tomographic reconstruction**:

  1. Remove background and apply gaussian filters to the images
  2. Rescale images to have square pixels
  3. Rotate the images by the streaking angle
  4. Apply the calibration factor to the streaking axis and rescale the images to have the same temporal scale
  5. Center the images
  6. Set the ROI to select only the beam

- **This allows for the reconstruction, minimizing the artifacts that can arise from the disalignment in the images and from background contributions**

EuPRAXIA@SPARC_LAB

- **Two PolariX TDS will be implemented in the EuPRAXIA@SPARC_LAB diagnostics systems**



Photoinjector exit

$E \sim 118\ MeV$

- **60 cm TDS**

Plasma module exit

$E \sim 1\ GeV$

- **96 cm TDS**