Simulation and Design of the Diagnostics Stations for Eupraxia@Sparc_Lab

Francesco Demurtas – PhD Seminar 2° year – 24/10/2024

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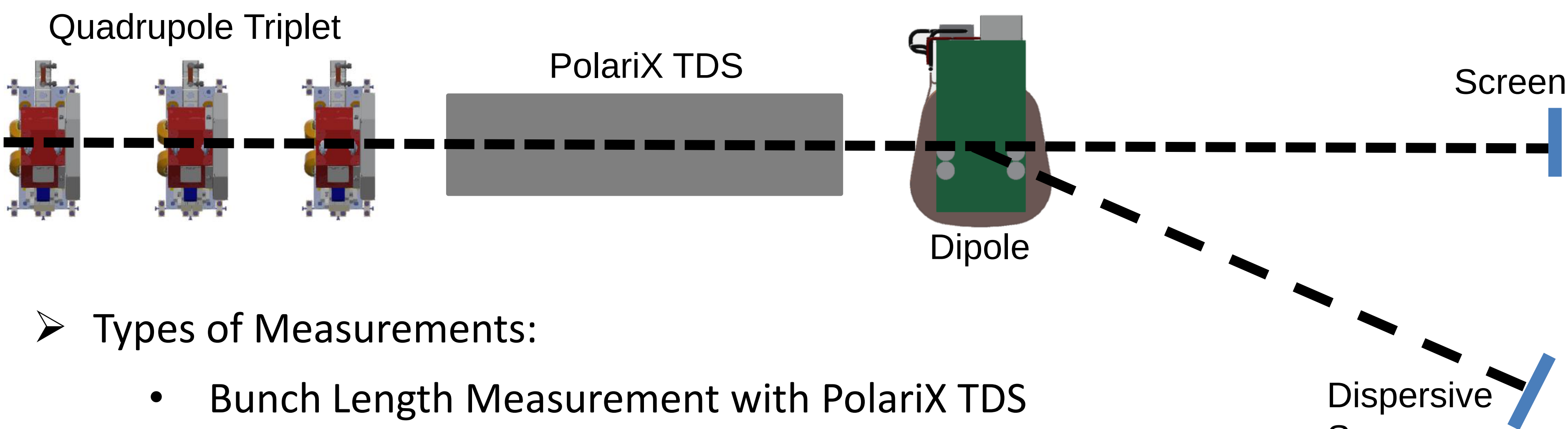
Outline

- Diagnostics Stations in Eupraxia: High-Energy diagnostics
- Polarizable X Band Transverse Deflecting Structure (PolariX), working principle and design
- Measurement Simulation at High-Energy:
  - Length Measurement with the PolariX TDS
  - Emittance Measurement in Both Planes
- Jitter Measurement at SPARC: Electro-Optical Sampling
- Collaboration with PSI: Activities on PolariX TDS

Diagnostics Station and Measurements

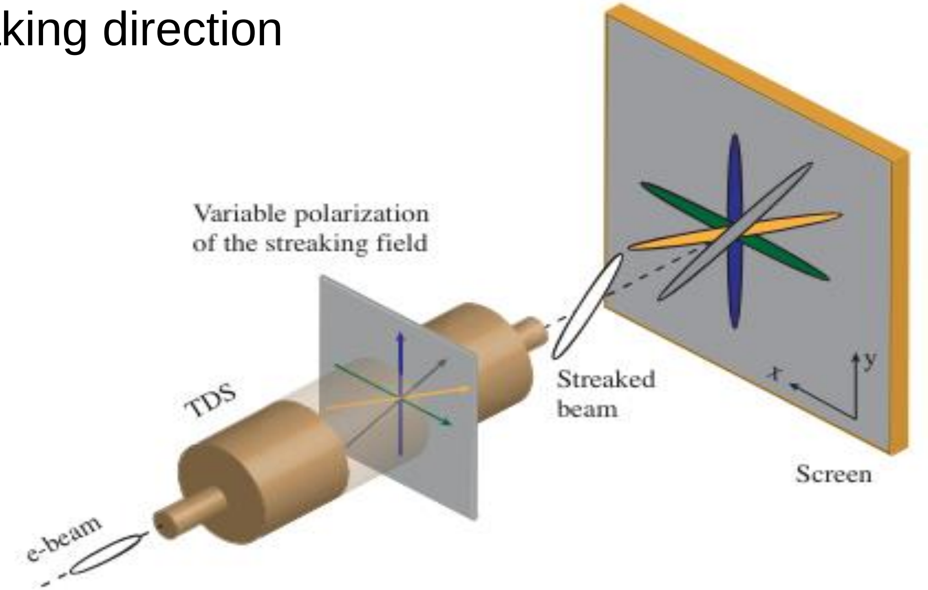
- Eupraxia Electron Diagnostic Station Positions:
  - After the Photoinjector at $E \sim 80 - 250$ MeV → 60 cm TDS
  - Before the Plasma at $E \sim 750$ MeV
  - After the Plasma and Before the Undulator at $E \sim 1$ GeV → 96 cm TDS



- Types of Measurements:
  - Bunch Length Measurement with PolariX TDS
  - Beam Emittance in both Transverse Planes
  - Energy Measurement
  - Slice Emittance in both Transverse Planes with the same PolariX TDS
  - Energy Jitter Measurement to the spectrometer with the Electro Optical Sampling

PolariX Transverse Deflecting Structure

- The **PolariX** is a Transverse Deflecting Structure with the feature of changing the beam streaking direction



➢ Allows to perform tomography of the beam to retrieve the 3D beam distribution

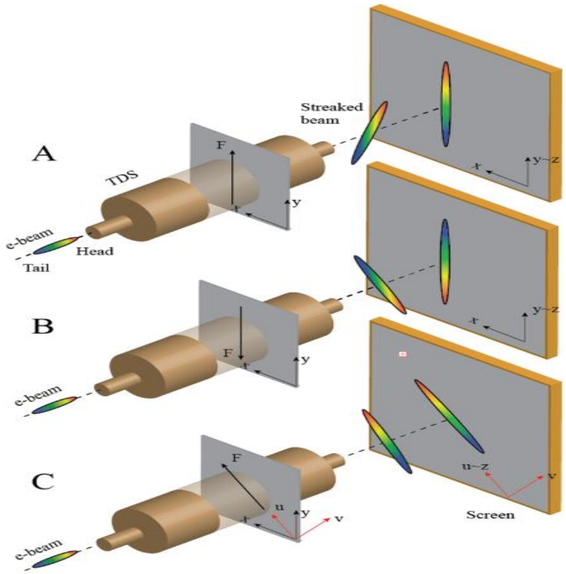
➢ Allows to measure the slice emittance on different transverse planes by using the same TDS device

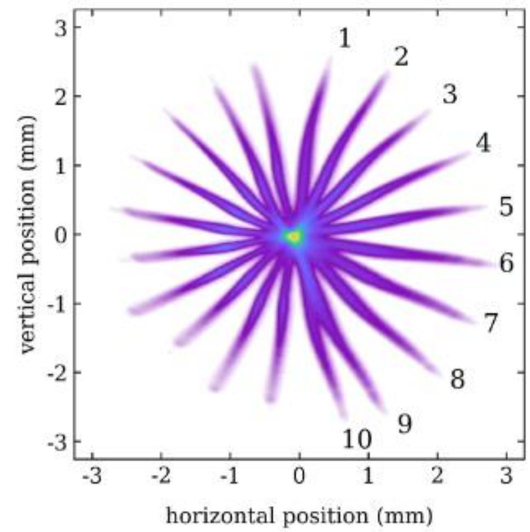
➢ Combined with a quadrupole scan and a magnetic spectrometer allows to measure the full 6D beam distribution

Marx, Daniel. Characterization of ultrashort electron bunches at the SINBAD-ARES Linac. No. DESY-THESIS--2019-026. Hamburg, Germany: Deutsches Elektronen-Synchrotron, 2019.

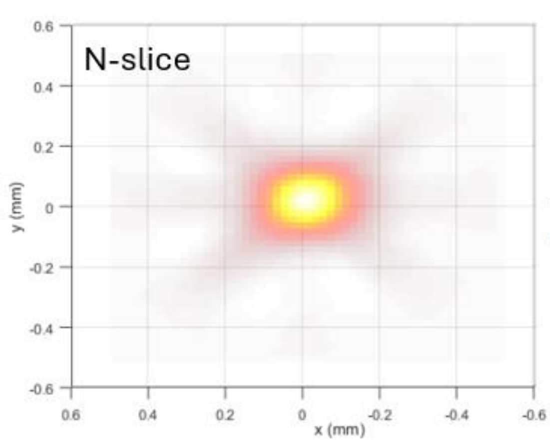
3D Charge Distribution Reconstruction

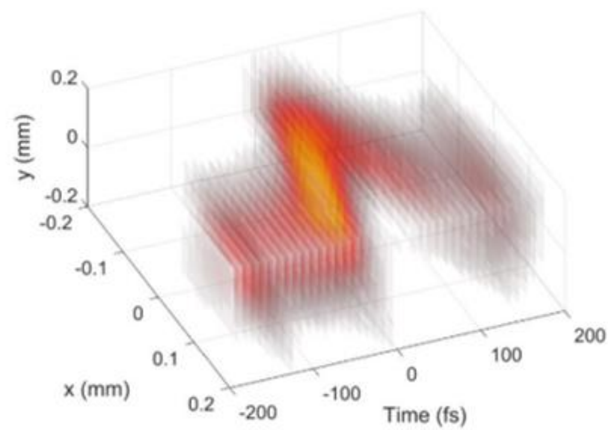
- The reconstruction requires to take one streaked image for each angle of streaking



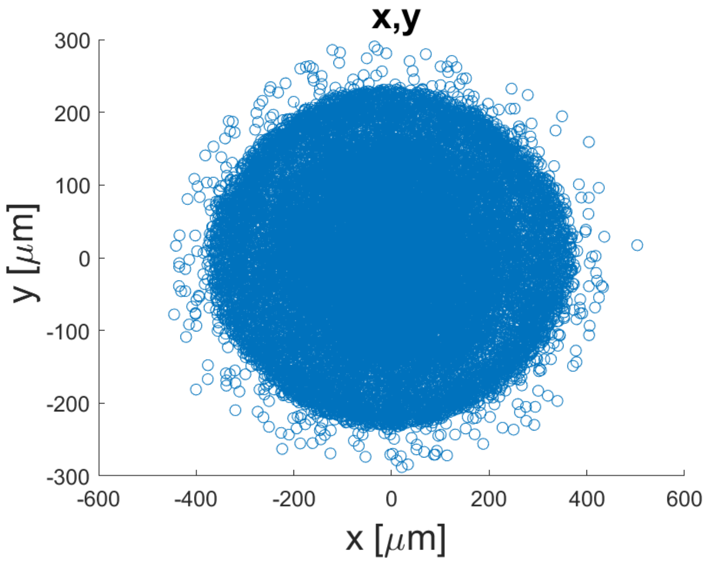


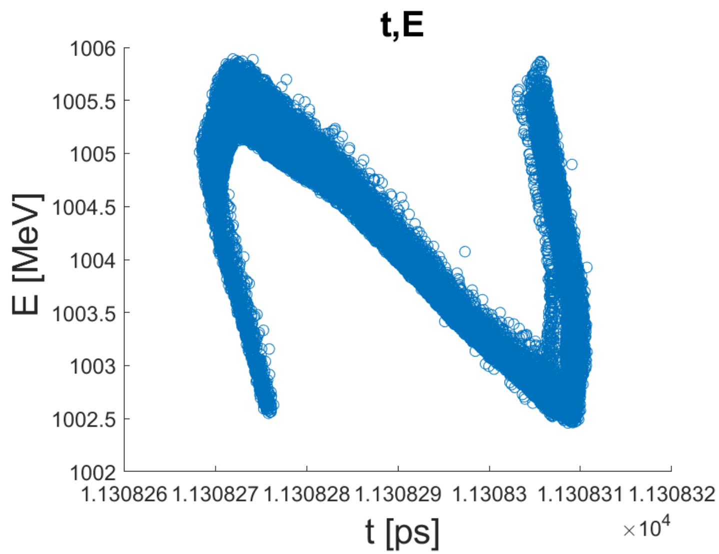
- 2D Distribution is Obtained from tomographic algorithm





Input Beam (After Separation Chicane)



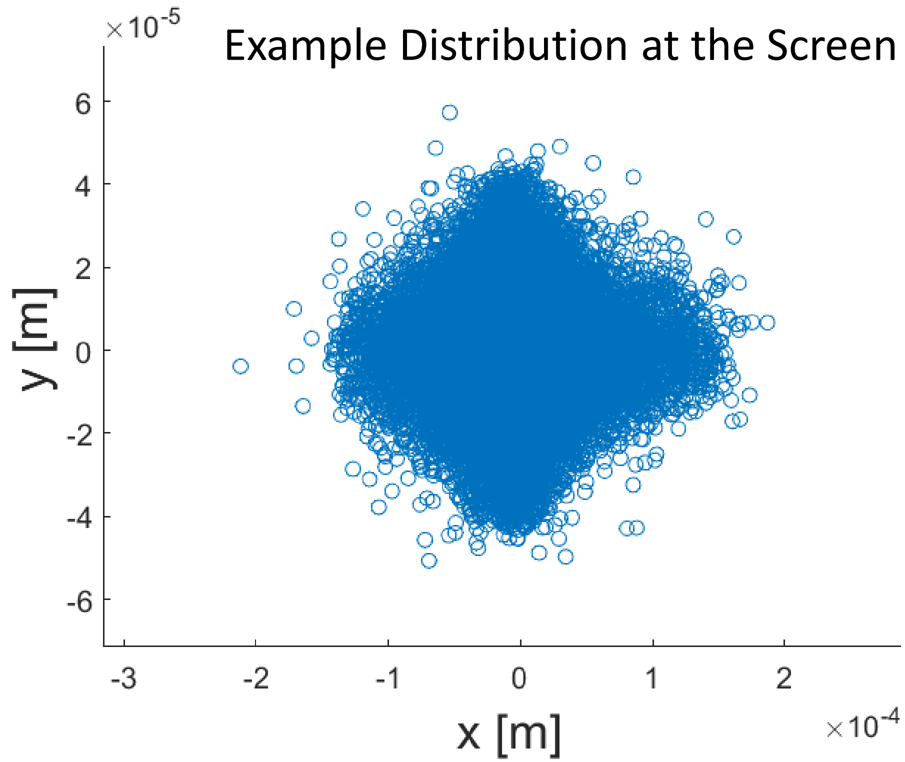


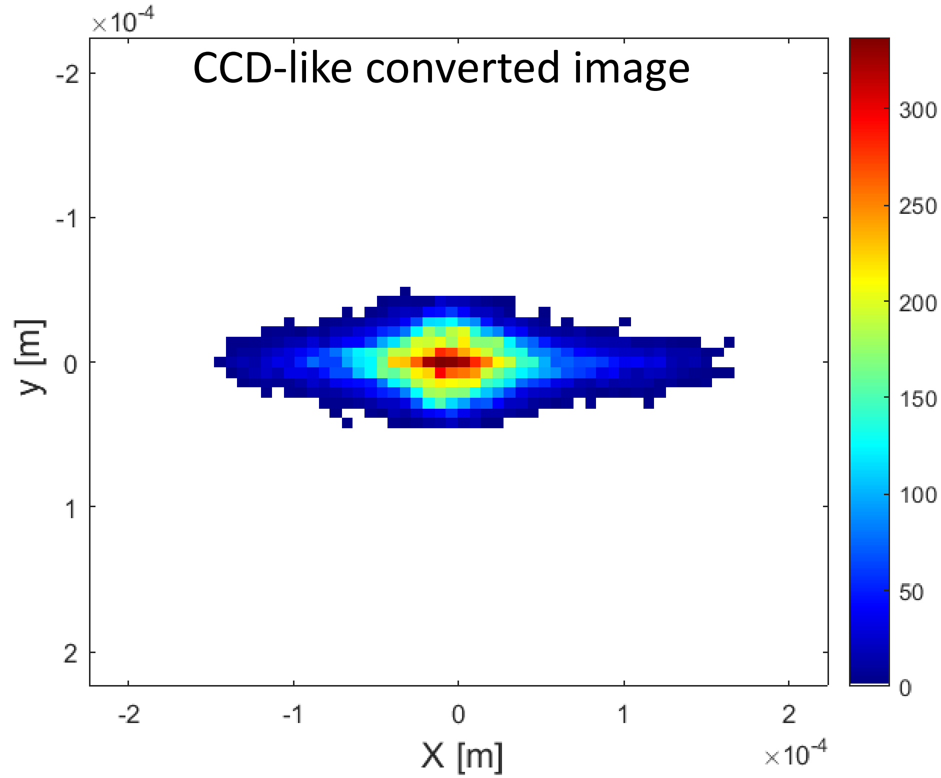
Beam Parameters		
$Q\ [pC]$	23.86	
$E\ [GeV]$	1	
$E_{spread}\ [\%]$	0.09	
$RMS\ Beam\ Duration\ [fs]$	14.7	
$RMS\ Beam\ Size\ x, y\ [\mu m]$	157	105
$RMS\ Beam\ Emittance\ x, y\ [mm\ mrad]$	1.43	1.17

Distribution – CCD Conversion

- Conversion of the distribution obtained from the simulation into a CCD-like image to compute the beam size and centroids

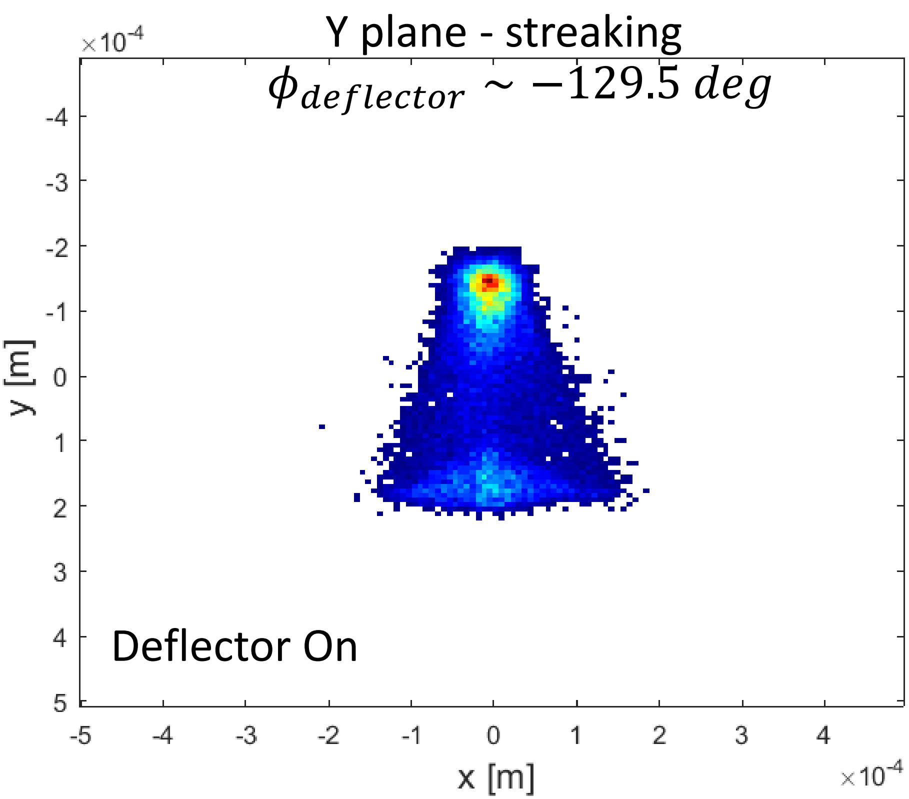
Size Camera : 1200 x 1920 Pixel
Calibration : 3.5 μm/Pixel

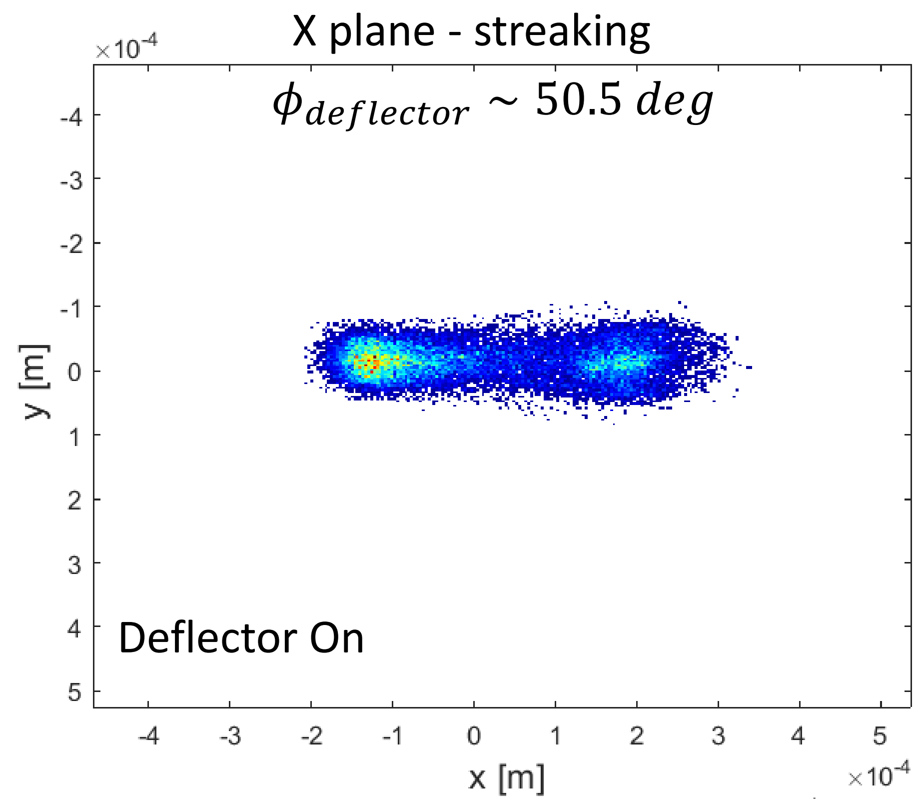




Beam Distribution at the Zero Crossing

- Implemented the PolariX 3D maps provided by PSI in Astra to simulate the length measurement
- Beam Streaked at Zero Crossing with 96 cm Transverse Deflecting Structure after a 3.07 m drift to the screen in two streaking direction





Resolution (Streaking in y-plane)

- General equation for RF deflector Resolution

$$R_y = \sqrt{\frac{\epsilon_y}{\beta_y^{PX\ center}}}\frac{1}{|sin\Delta\mu|}\frac{E}{eV_0 k_{rf}}$$

$$k_{rf} = \frac{\omega_{rf}}{c}$$

- Phase advance from the TDS center to the screen: $|sin\Delta\mu| \approx 1$
- $\beta_y^{PX\ center}$ as large as possible
- $\alpha_y = 0$ at the TDS entrance and screen

- In case of just a drift between the TDS and screen:

$$R_{34} = \sqrt{\beta_y^{PX\ center}\beta_{y_{screen}}}|sin\Delta\mu| = L_{drift}$$

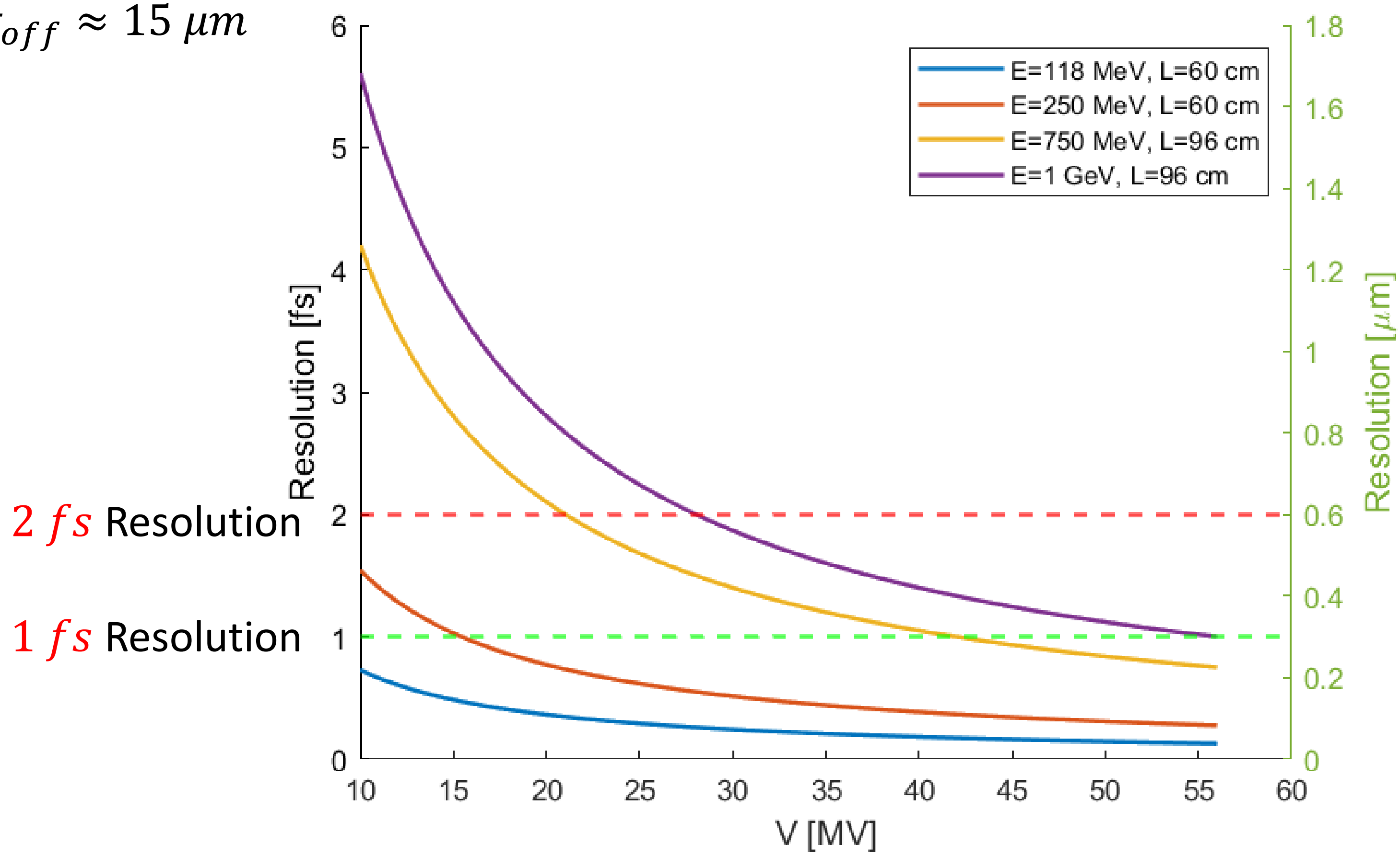
Calibration Factor: $$R_y = \frac{\sqrt{\epsilon_y \beta_{y_{screen}}}}{L_{drift}}\frac{E}{eV_0 k_{rf}}$$

TDS Resolution

- After the Laser Heater: $L = 60\ cm$
- Before the Undulator: $L = 96\ cm$

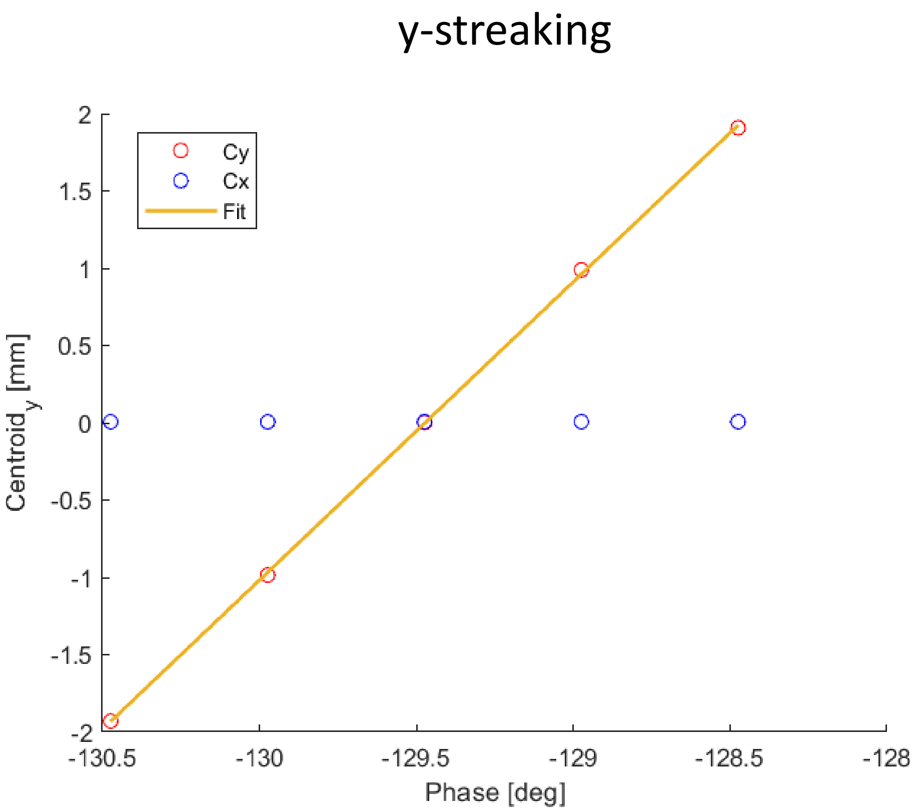
$$R_t = \frac{\sigma_{off}}{L_{drift}} \frac{E}{eV_0 k_{rf} c}$$

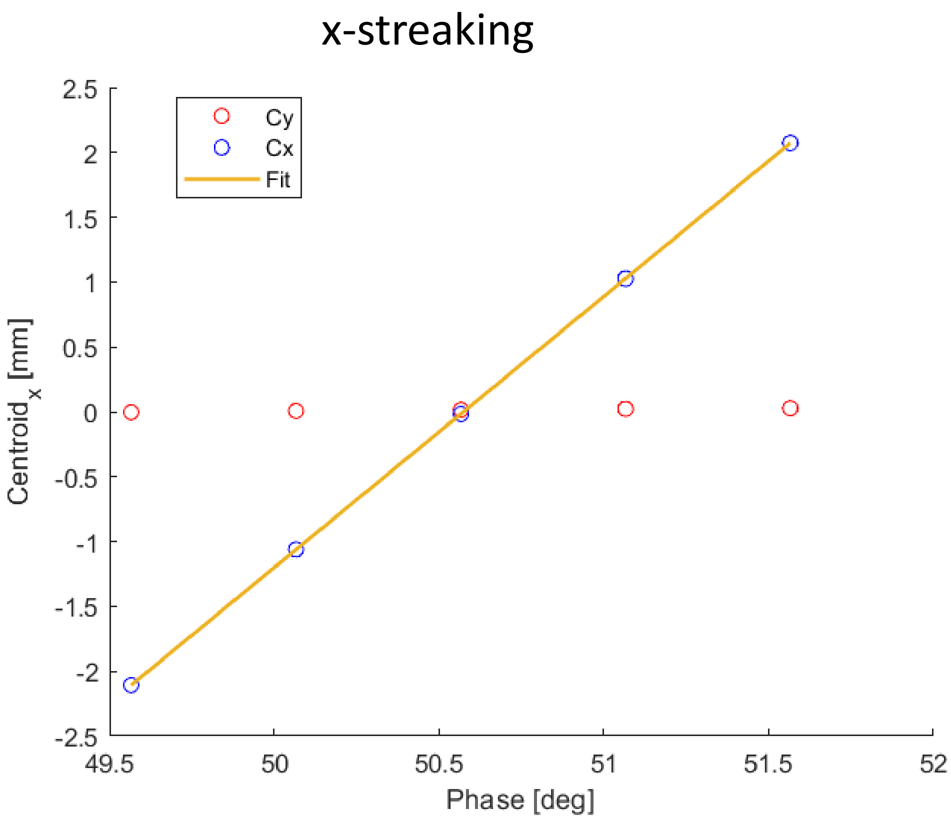
$\sigma_{off} \approx 15\ \mu m$



TDS Calibration in x-y planes

➢ PolariX Calibration: Integrated V~ 31 MV at a beam Energy of 1 GeV





- x-streaking Calibration : ~ 110.88 fs/mm
- y-streaking Calibration : ~ 117.53 fs/mm

Length Measurement in x-y planes

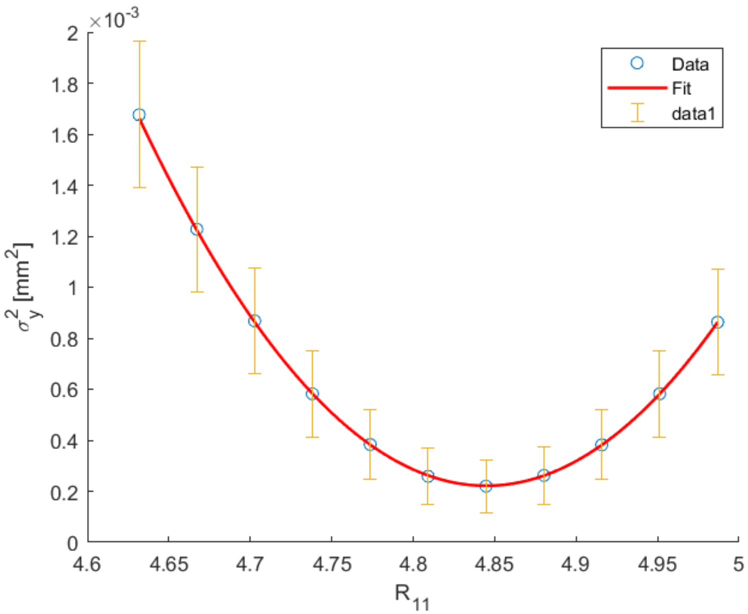
- Different sets of quadrupole strength for the two measurements, optimised to minimize the beam vertical and horizontal size to maximise the resolution

Parameters	Streaking y-plane	Streaking x-plane
σ_x Def. Off	$42.3\ \mu m$	$27.5\ \mu m$
σ_y Def. Off	$15.1\ \mu m$	$36.6\ \mu m$
$V_{deflector}$	$\sim 31\ MV$	$\sim 31\ MV$
Calibration	$\sim 117.53\ fs/mm$	$\sim 110.88\ fs/mm$
Resolution	$\sim 1.8\ fs$	$\sim 3.0\ fs$
σ_t	$(14.8 \pm 0.8)\ fs$	$(14.8 \pm 0.9)\ fs$

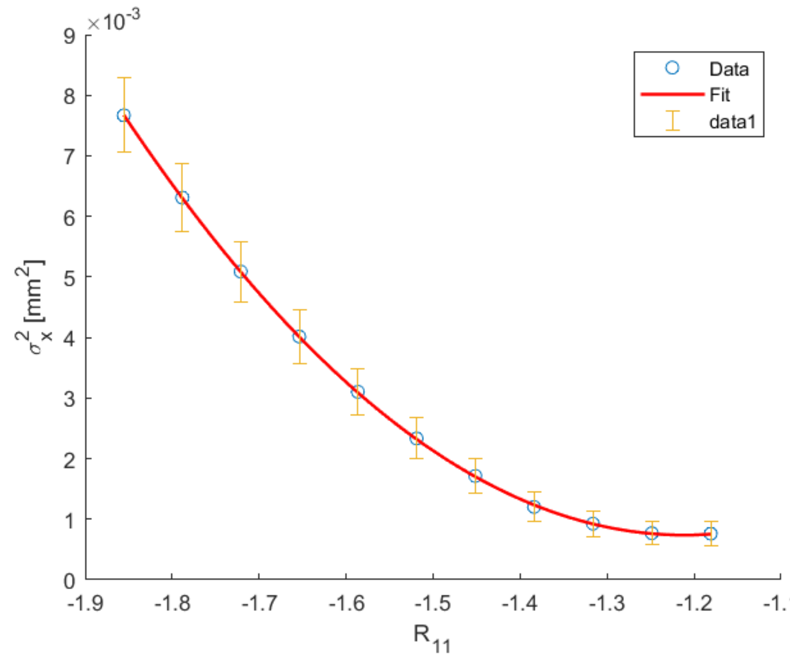
Emittance Measurement

- Last Quadrupole Strength Scan

$\alpha_y\ Range: [-2, 2]$
$k\ [m^{-2}]\ Range: [-3.93, -3.59]$



$\alpha_x\ Range: [-2, 1.5]$
$k\ [m^{-2}]\ Range: [2.24, 2.95]$



	$y\ Plane$	$x\ Plane$
$Expected\ \epsilon$	$\sim 1.17\ mm\ mrad$	$\sim 1.43\ mm\ mrad$
$Reconstructed\ \epsilon$	$(0.96 \pm 0.03)\ mm\ mrad$	$(1.44 \pm 0.05)\ mm\ mrad$

Emittance Resolution

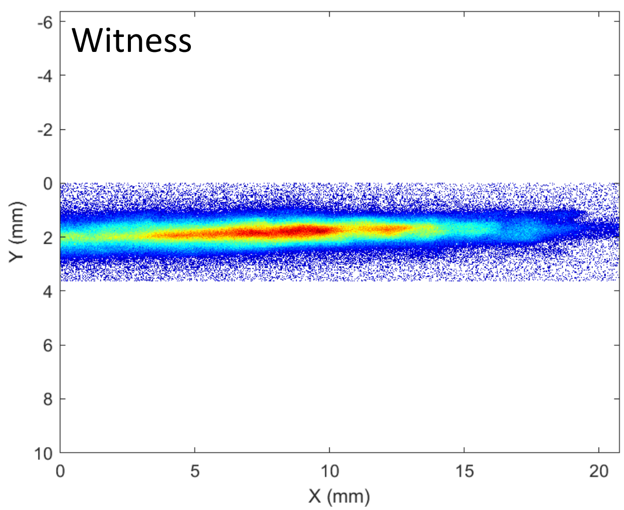
- Simulations to determine the resolution on the emittance measurement
- Repeated the simulations with beams with increasingly smaller emittance

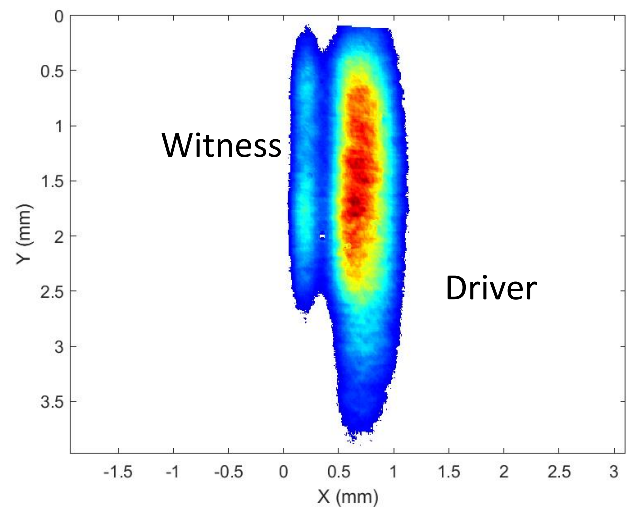
Beam	ϵ_x (Expected) [mm mrad]	ϵ_y (Expected) [mm mrad]	ϵ_x (Recon.) [mm mrad]	ϵ_y (Recon.) [mm mrad]	Rel. Error ϵ_x [%]	Rel. Error ϵ_y [%]
1	1.43	1.17	1.44	0.96	~ 3.5	~ 2.7
2	0.96	0.86	0.75	0.70	~3.9	~3
3	0.66	0.6	0.66	0.50	~4.5	~3.4
4	0.44	0.4	0.51	0.35	~5.1	~4.4

➢ Resolution in both planes at 1 GeV : $\sim 0.4\ mm\ mrad$

Energy Jitter Measurement at SPARC

- The witness energy measurement at the high-energy spectrometer will be combined with the measurement of the relative distance between the driver and witness beams
- This distance is affected by the jitter from the RF system, resulting in a jitter in the witness energy gain in the plasma
- The relative distance between the beams is measured with the Electro-Optical Sampling, a non-intercepting and single-shot device based on an external field, i.e. the beam coulomb field, which induces birefringence on an electro-optical crystal, ZnTe in this case.

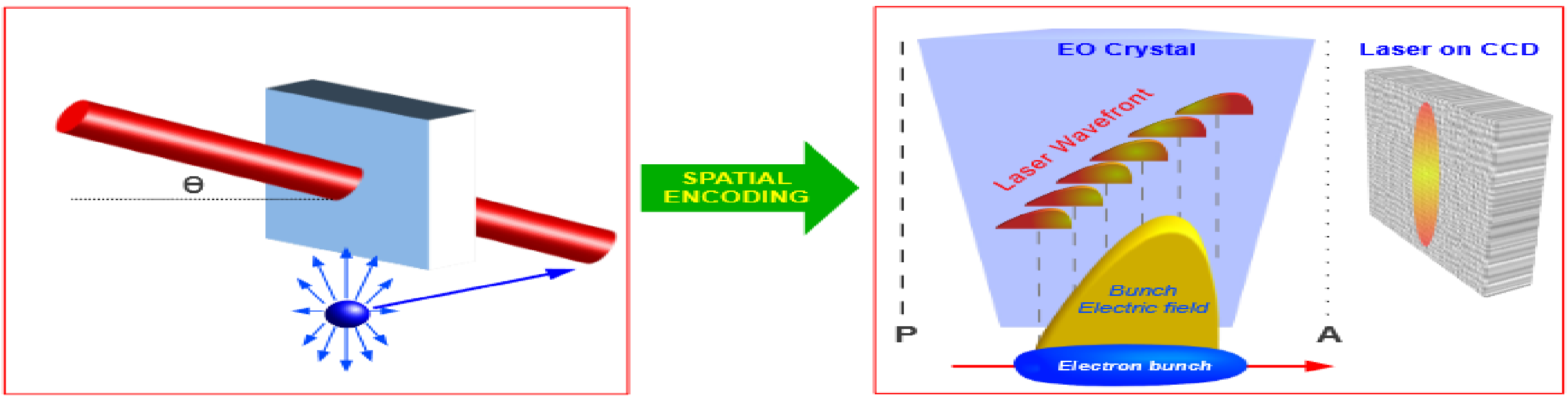




Electro-Optical Sampling

- This change in the refractive indexes, can be measured with an opportune polarized laser pulse that crosses the crystal.

- In the spatial decoding scheme the laser crosses the crystal with an angle $\theta = 30\ deg$, therefore different points across the transverse profile of the laser pass through the crystal at different times and acquire a different polarization



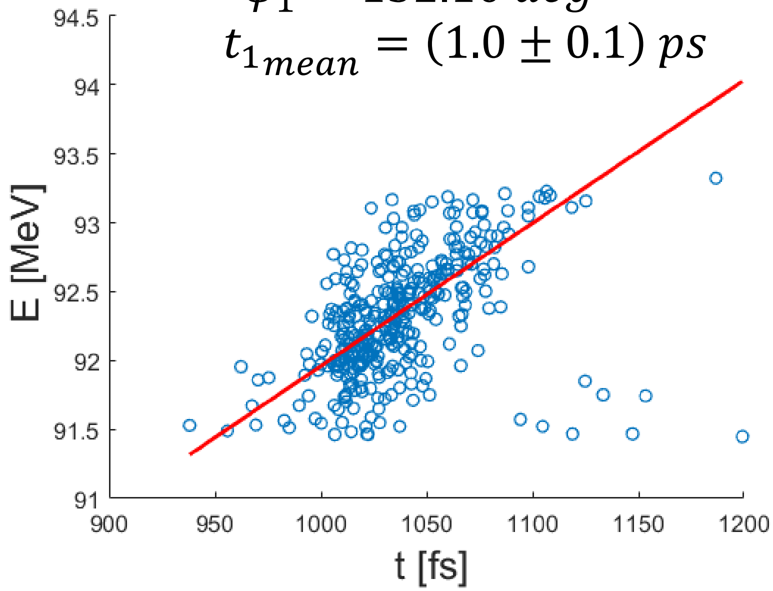
- The resolution in the measurement of the beam arrival time is of fs, so it is suitable for measuring the beam's arrival time and the driver-witness relative distance in each shot

Riccardo Pompili et al. "Femtosecond timing-jitter between photo-cathodelaser and ultra-short electron bunches by means of hybrid compression".In: New Journal of Physics 18.8 (2016), p. 083033.

Measurement Results

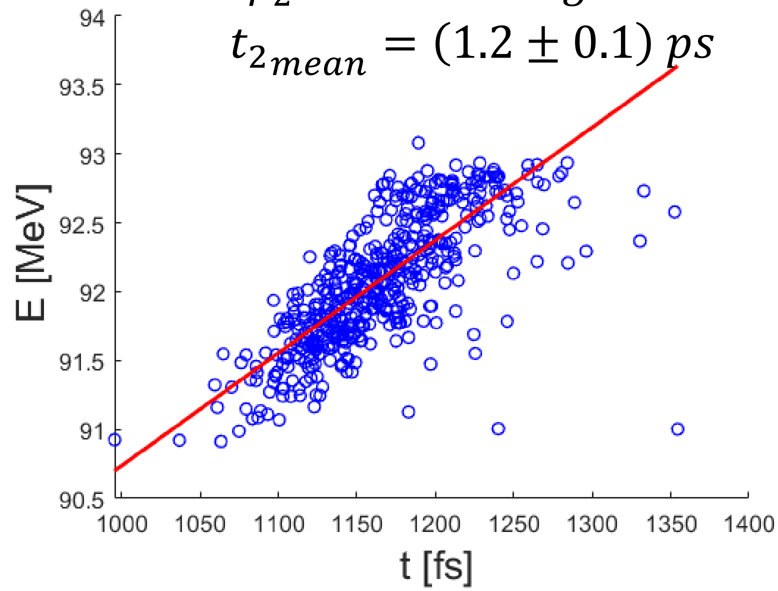
$\phi_1 = 132.10\ deg$

$t_{1mean} = (1.0 \pm 0.1)\ ps$



$\phi_2 = 131.30\ deg$

$t_{2mean} = (1.2 \pm 0.1)\ ps$



$$m_1 = (10 \pm 1)\frac{KeV}{fs}$$

$$m_2 = (8.2 \pm 0.6)\frac{KeV}{fs}$$

- The compression phase is slightly different: when the phase is smaller the compression is larger and therefore, the distance between the bunches increases.

- The different slope is dependent on the plasma density (the used density for the experiment is $\sim 10^{15}\ cm^{-3}$): the first measurement corresponds to a larger density and so it is higher the slope with respect to the second case.

Third Year Program

- Complete the Measurement Simulation at High-Energy:

  - Slice Emittance Virtual Measurement

  - Energy Measurement: Spectrometer Design

- Implementation of the simulated measurements in the other Diagnostics Stations in Eupraxia:

  - Low-Energy (120 MeV), including the 60 cm PolariX design

  - Mid-Energy diagnostics (750 MeV)

- PolariX activities in ATHOS at the PSI center

PolariX Activities Plan at PSI

- Slice Emittance Measurements
  - 1° step: Simulations to calculate the optics in the beamline for the measurement in both transverse planes
  - 2° step: Set up the Simulations of the measurement
  - 3° step: The Measurements will be done in November, and the Data Analysis will follow

- 5D Phase Space Measurement
  - The Experiment is planned for 2025, in collaboration with the DESY group working on the PolariX

- Specific Requests for Eupraxia Diagnostics
  - Study on the passive streaker in substitution of a PolariX TDS after the undulator
  - Design of the 60 cm deflector at 120 MeV

Thank you for your attention

BACKUP SLIDE

TDS parameters

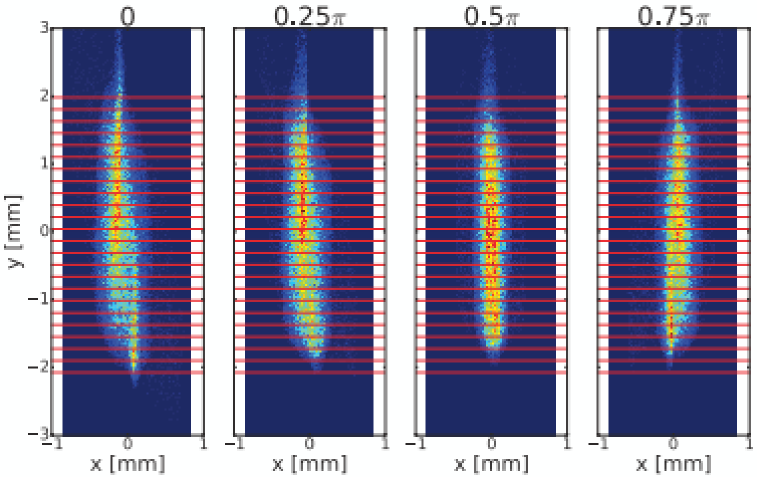
Cell parameter		**Unit**	
Frequency	11995.2	MHz	
Phase advance/cell	120	$^\circ$	
Iris radius	4	mm	
Iris thickness	2.6	mm	
Group velocity	-2.666	$\%c$	
Quality factor	6490		
Shunt impedance	50	$M\Omega/m$	
TDS parameter	**Short**	**Long**	**Unit**
n. cells	96	120	
Filling time	104.5	129.5	ns
Active length	800	1000	mm
Total length	960	1160	mm
Power-to-voltage	5.225	6.124	$MV/MW^{0.5}$
TDS + BOC	**Short**	**Long**	**Unit**
BOC Q_0	145000	145000	
BOC β@t_k=1.5μs	7	7	
Power-to-voltage	12.010	13.626	$MV/MW^{0.5}$

Craievich, Paolo, et al. "The Polarix-TDS Project: bead pull measurements and high power test on the prototype." *Proceedings of FEL*. 2019.

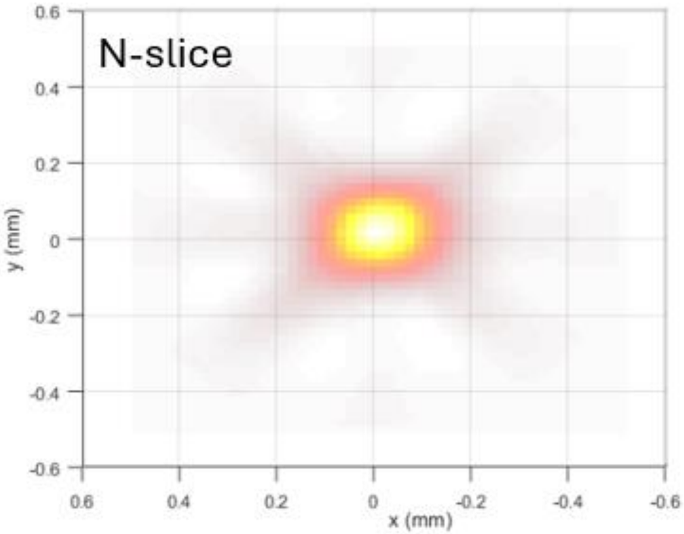
3D Charge Distribution Recontruction

- 1D distribution for each slice :

$$D_t(\theta)$$



- The SART reconstruction algorithm integrates the 1D distribution that is treated as a projection of the 2D distribution



5D Phase Space Recontruction

- The 5D reconstruction requires to streak the beam in different angles and also for different phase advance combinations in x and y, to also rotate the beam transverse phase space

Shear Parameter: $S = \frac{V_0 L k_{rf}}{E}$

- The Shear Parameter is determined for each streaking angle and phase advance combination, by measuring the beam centroid with respect to the changing of the deflector phase

- The 3D distribution is then reconstructed via tomography for each phase advance combination

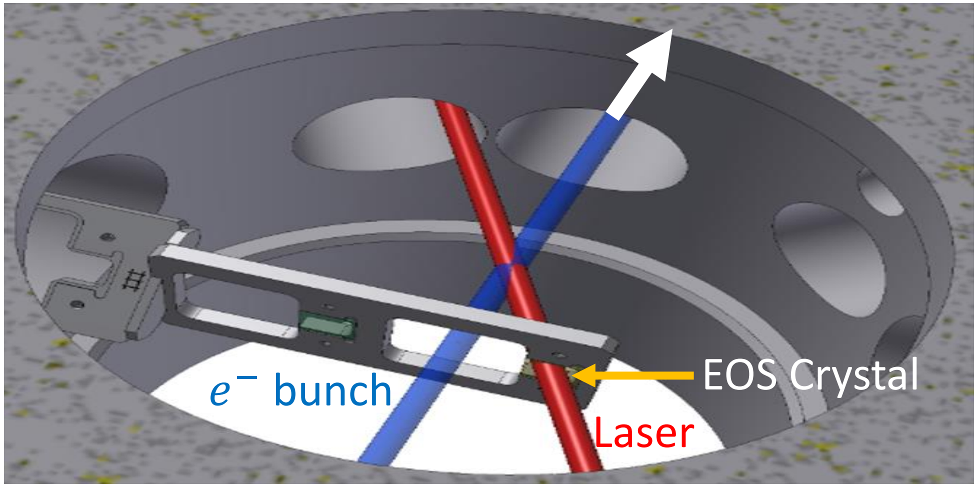
- Each 3D reconstruction can be seen as the projection of the (x, x', y, y', t) phase space on the (x, y, t) space, so for each slice they are combined with the filtered back projection technique, to obtain the full 5D distribution

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

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.

Electro-Optical Sampling

- EOS position: entrance of the experimental chamber



- Resolution of a few fs on the beam arrival time
- Resolution of tens of fs on the longitudinal beam distribution

➢ Complemented with the energy measurement of the witness allows for the measurement of the Beam Arrival Timing Jitter on the Plasma Acceleration