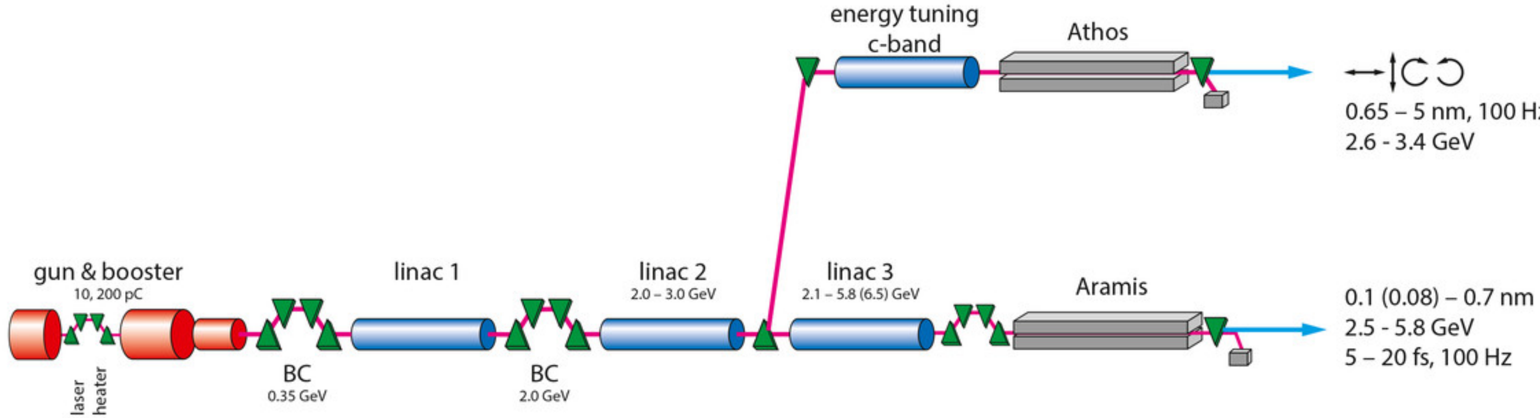
Antoine Sarracini :: Postdoc | Maloja | SwissFEL :: Paul Scherrer Institute

Using Cold Target Recoil Ion Momentum Spectroscopy for Polarization Characterization of SASE Pulses

EuPRAXIA Electron & Photon Diagnostics
June 13 2023

The ATHOS Beamline at SwissFEL

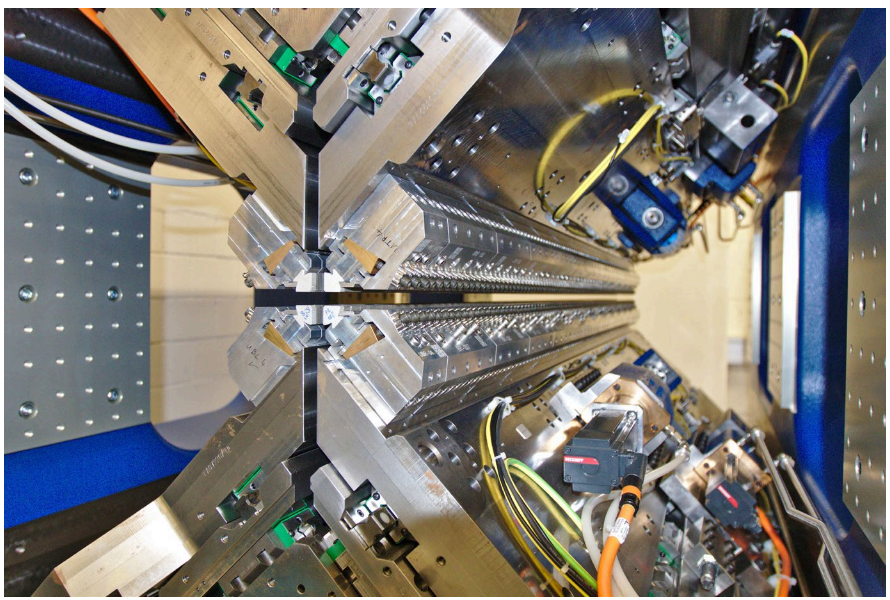


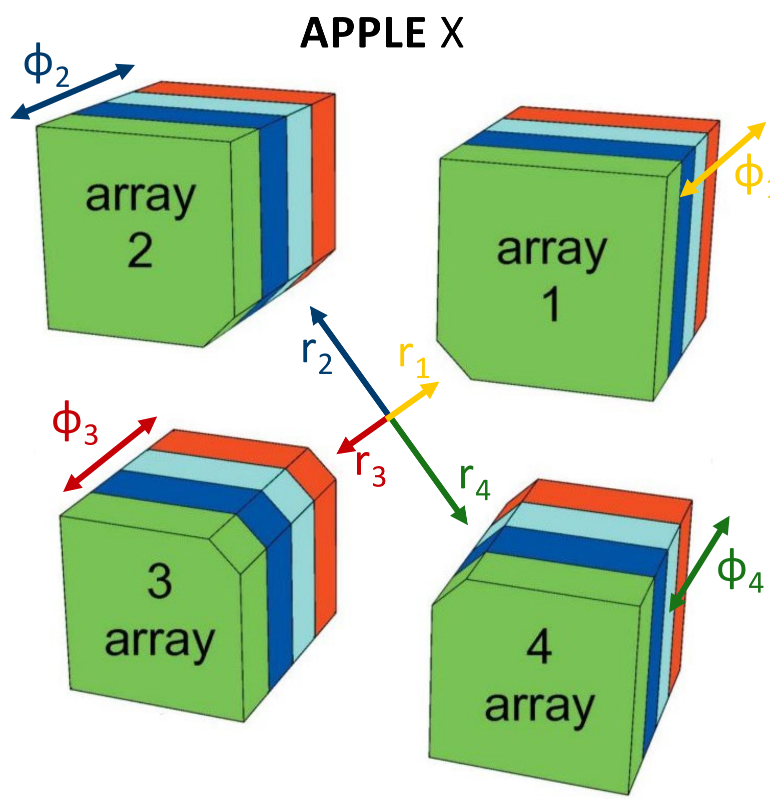
- Up to 3.4 GeV linac, 16 APPLE X undulators
- 250 – 1800 eV soft X-ray beamline
- 80 fs pulse duration @ 100 Hz with special modes (short pulse 20 fs, two color X-ray pump-probe up to 500 fs delay)
- Maloja: modular atomic, molecular and nonlinear X-ray physics

APPLE X Soft X-Ray Undulators

- Symmetric and compact 2m long design
- Can arbitrarily tune sinusoidal electron trajectory by independent adjustment of phase and gap of magnet arrays
  - – 4x translation degrees of freedom
  - – 4x radial degrees of freedom

Arbitrary polarization control





M. Calvi et al. J. Synchrotron. Rad. 2017

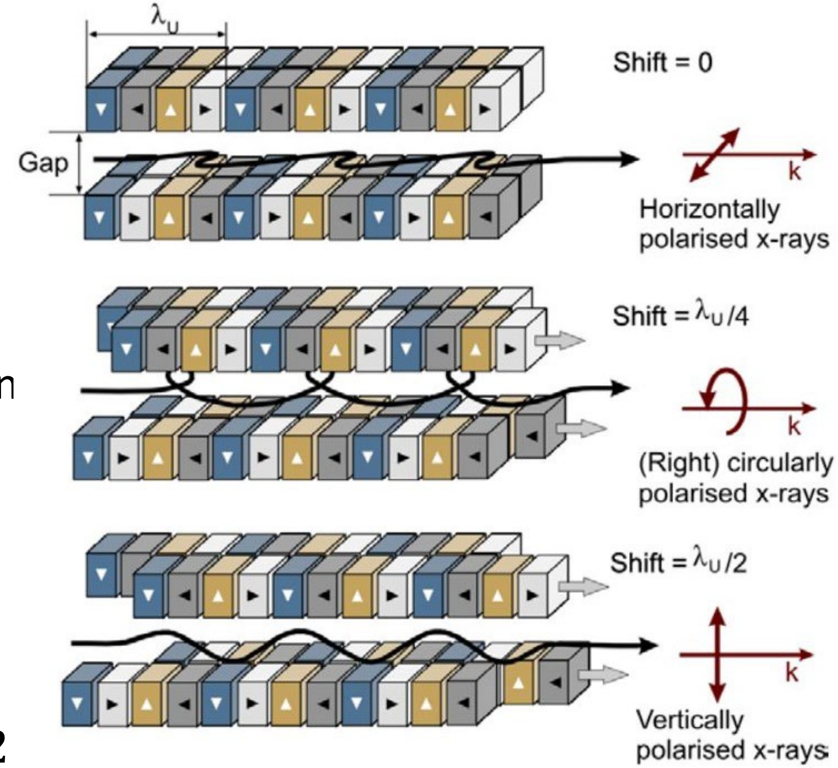
Polarization Control with APPLE X

- Diagonal magnet arrays shifted to produce different polarizations

- Linear Polarizations:
  – Horizontal $\alpha = 0°$: $\phi_U = 0$
  – Vertical $\alpha = 90°$: $\phi_U = \lambda_U/2$
  – Other α : Shift arrays in opposite direction

$$\alpha = \tan^{-1}\left(\cot^2\left(\frac{1}{2}\phi_U\right)\right)$$

- Circular Polarizations:
  – Fully circular: $\phi_U = \lambda_U/4$
  – Elliptical: $\phi_U = 0 - \lambda_U/4 \ || \ \lambda/4_U - \pi/2$



C. Schmitz-Antoniak. Rep. Prog. Phys. 2015

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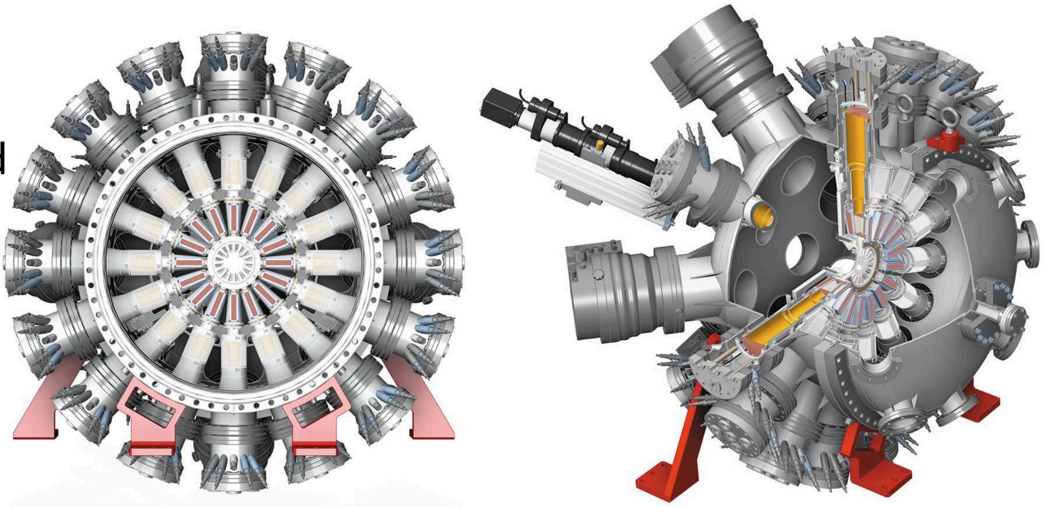
Polarization Control with APPLE X

M. Calvi. 2021

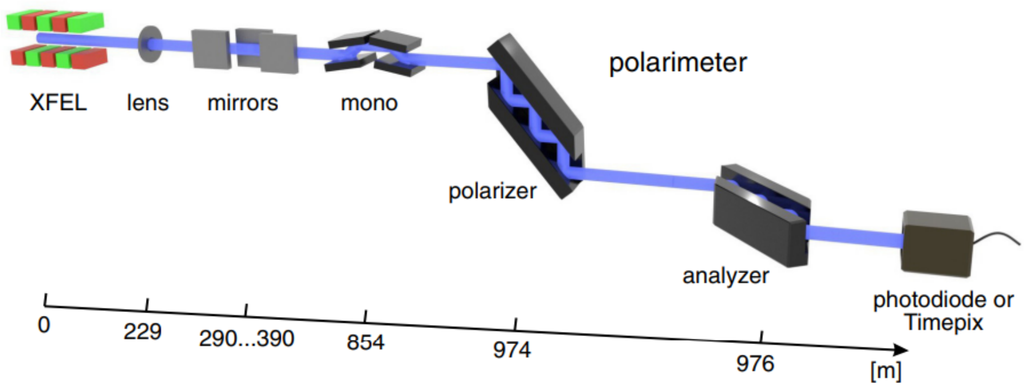
Measuring Polarization at XFEL Facilities

P. Walter et al. J. Synchrotron. Rad. 2021

- “Cookiebox” e$^-$-TOF
  - 16 TOF spectrometers arranged radially
  - Developed at Petra III - P04 beamline
  - In use at Eu-XFEL, LCLS, FLASH, FERMI

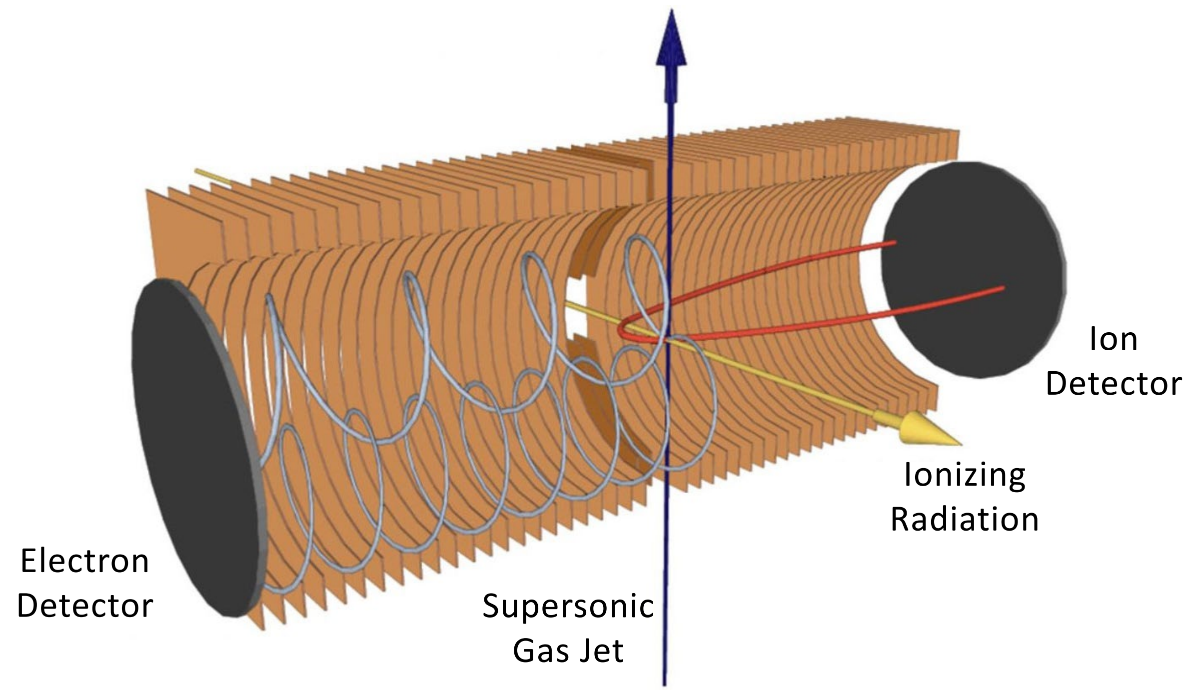


- Silicon channel-cut crystal
  - Bragg reflections from crystal select polarization
  - Rotatable analyzer
  - Photodiodes measures X-rays downstream of analyzer
  - Tested at Eu-XFEL



K. S. Schultze et al. Phys. Rev. Res. 2022

Measuring SASE Polarization: COLTRIMS



- Use XFEL beam of varying polarization to ionize He gas target
- Measure angular distribution of photoelectron momentum
  - Cold Target Recoil Ion Momentum Spectroscopy (COLTRIMS)
- Fit photoelectron momentum distribution to dipole & extract angle

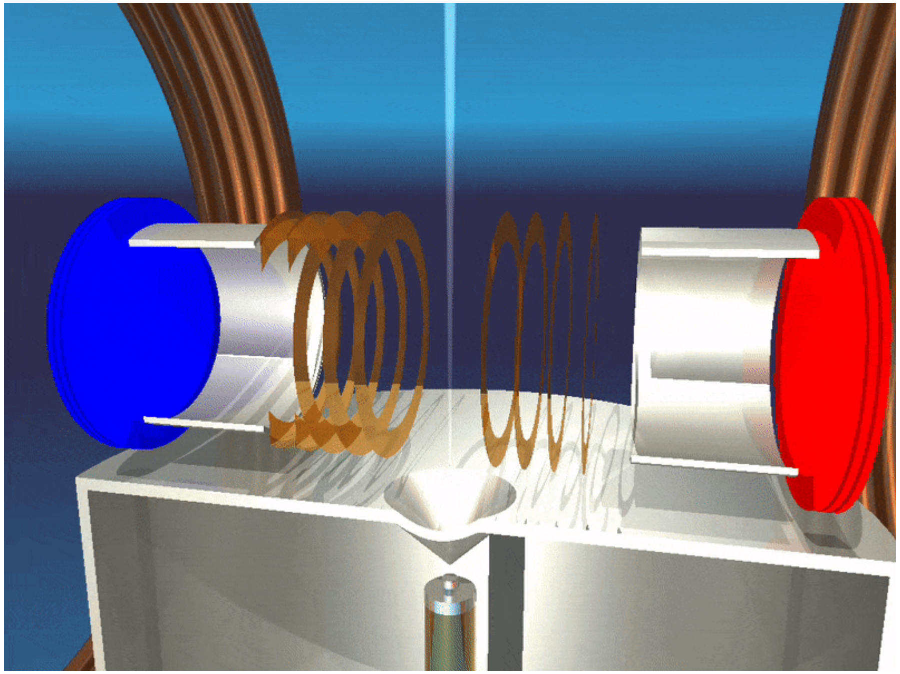
H. Schmidt-Böcking et al. Ann. Phys. 2021

Cold Target Recoil Ion Spectroscopy Basics

- Momentum imaging technique
  - $\Delta p < 0.1$ a.u. momentum resolution and 4π solid angle collection

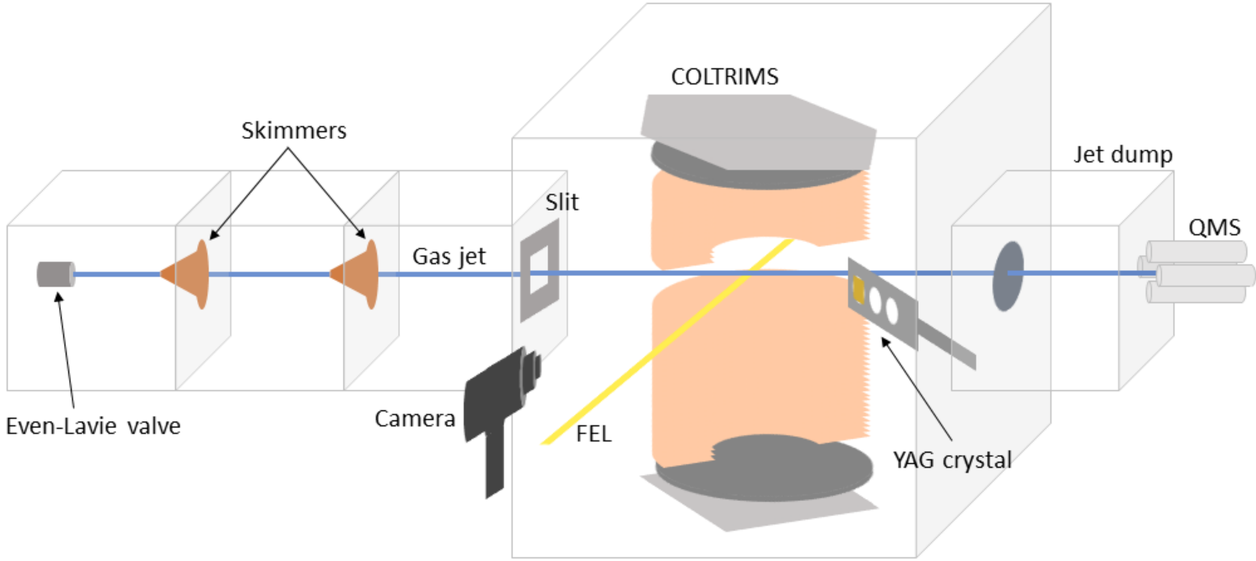
- Uses time-of-flight and ion / e^- position detection to reconstruct momenta in ionization / fragmentation processes
  - 4π solid angle collection by confining ions and electrons to detector areas
  - Ions accelerated to detector using E-field
  - Electrons confined to detector area using B-field

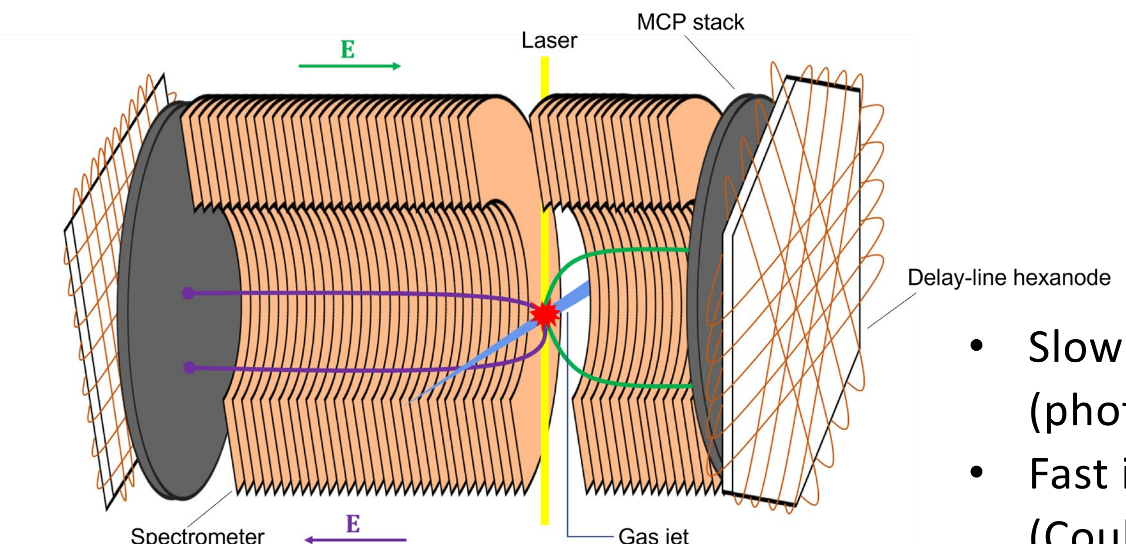
- Resolution limited by gas velocity spread (temperature)
  - Supersonic gas jet into vacuum cools target to < 1K



R. Doerner, Uni. Frankfurt.

The COLTRIMS Detector at Maloja



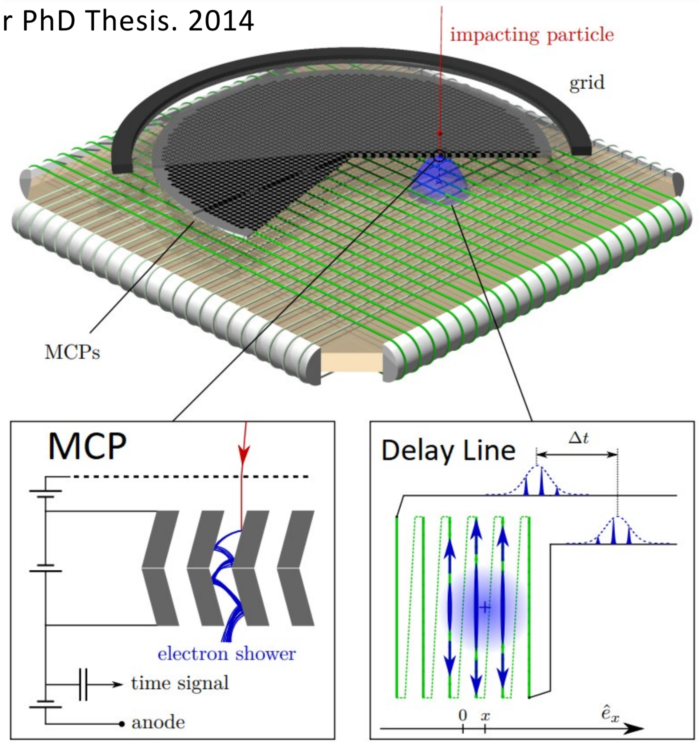


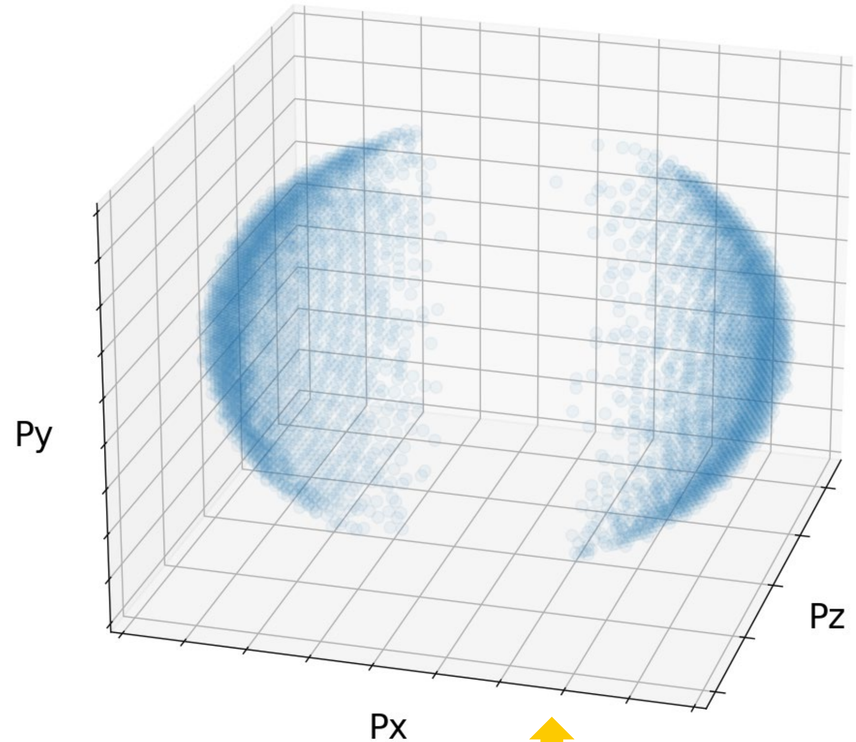
- Slow ion detection on long side (photoemission)
- Fast ion detection on short side (Coulomb explosion)
- No direct electron detection (yet)

I. Swiderska MSc Thesis. 2022

Momentum Reconstruction Process

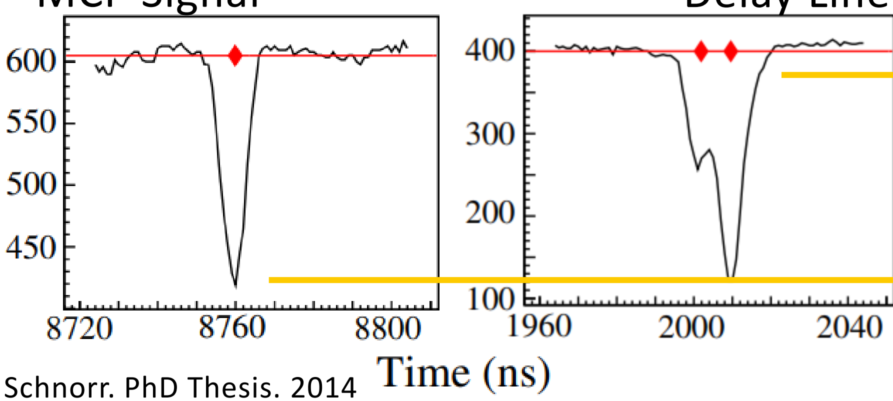
L. Fechner PhD Thesis. 2014





MCP Signal

Delay Line Signal



x_{DL}

z_{DL}

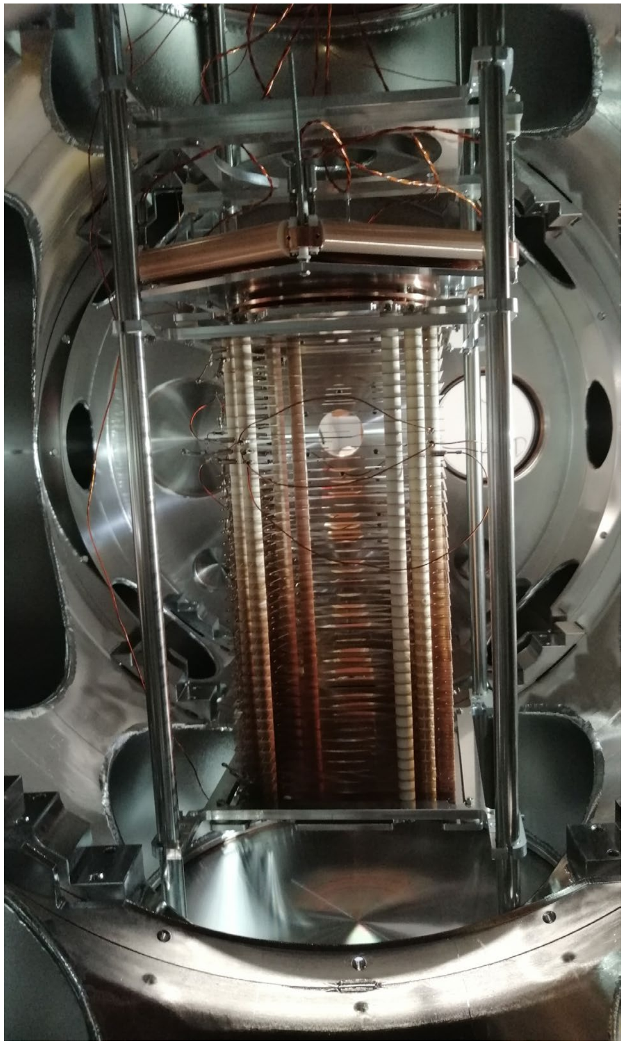
$$p_x = m\left(\frac{x_{DL}}{t} - v_{jet}\right)$$

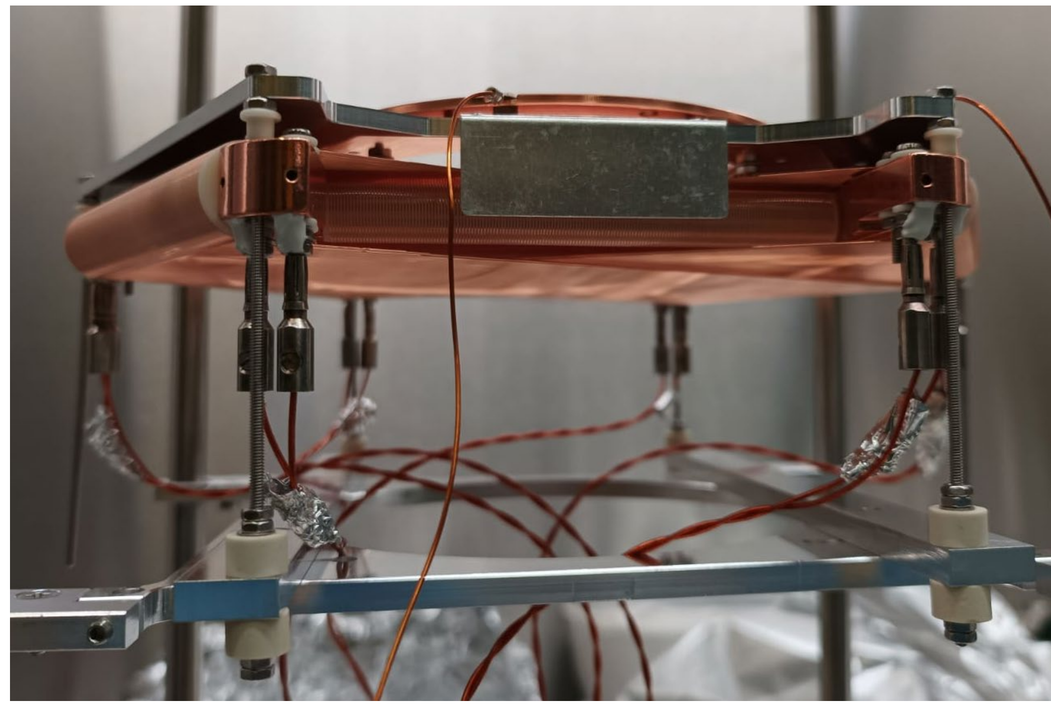
$$p_z = \frac{m y_{DL}}{t}$$

$$p_y = \frac{2md^2 - UQt_{MCP}^2}{2t_{MCP}d}$$

K. Schnorr. PhD Thesis. 2014

The COLTRIMS Detector at Maloja





I. Swiderska MSc Thesis. 2022

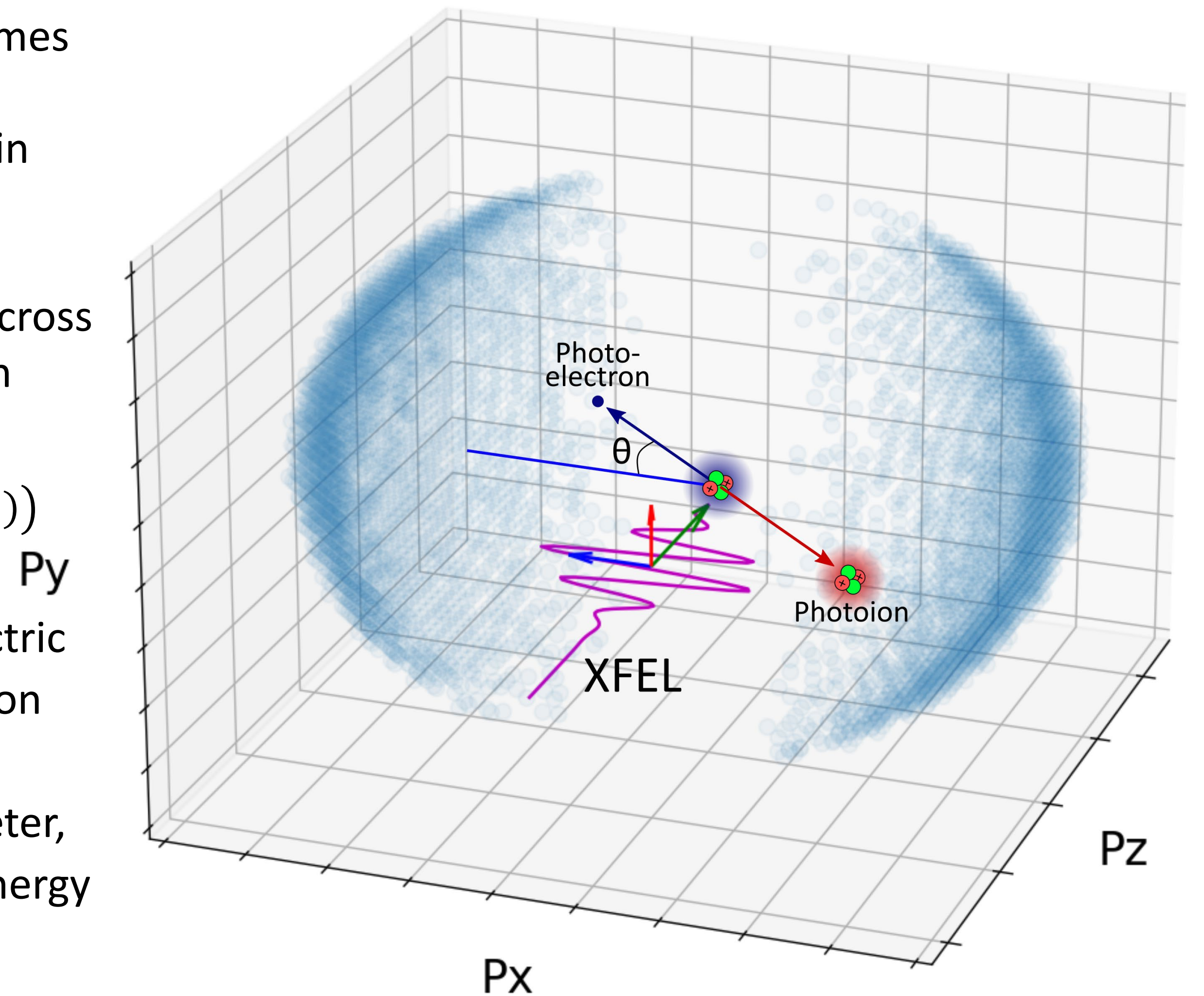
Angular Dependence of Photoelectron Momenta

- Angular dependence comes from initial angular momentum of electron in atom

- Angular dependence of cross section for single photon ionization:

$$\frac{d\sigma}{d\Omega} = \frac{\sigma}{4\pi}\left(1 + \beta\ P_2(cos\theta)\right)$$

  - θ: Angle between electric field vector and electron momentum
  - β: Asymmetry parameter, depends on photon energy



Angular Dependence of Photoelectron Momenta

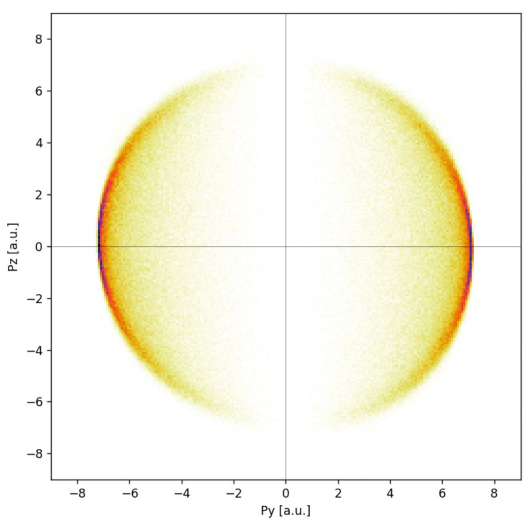
- Angular distribution of emitted photoelectrons described by:

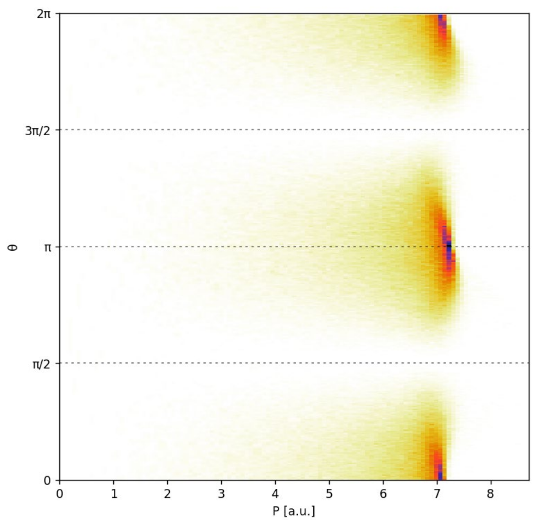
$$\frac{d\sigma}{d\Omega} = \frac{\sigma}{4\pi}\left(1 + \beta\ P_2(cos\theta)\right)$$

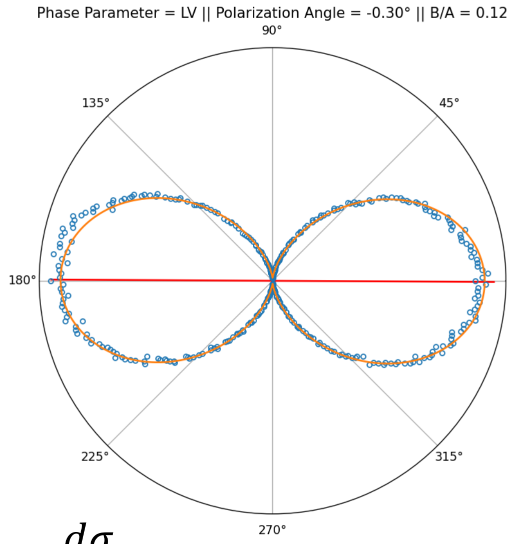
σ – Partial cross-section
$\beta = 2$ – Asymmetry parameter
$P_2(cos\theta) = \frac{1}{2}(3\cos^2\theta - 1)$ – 2nd Order Legendre Polynomial

Convert to Polar Coordinates

Integrate & Fit to Dipole





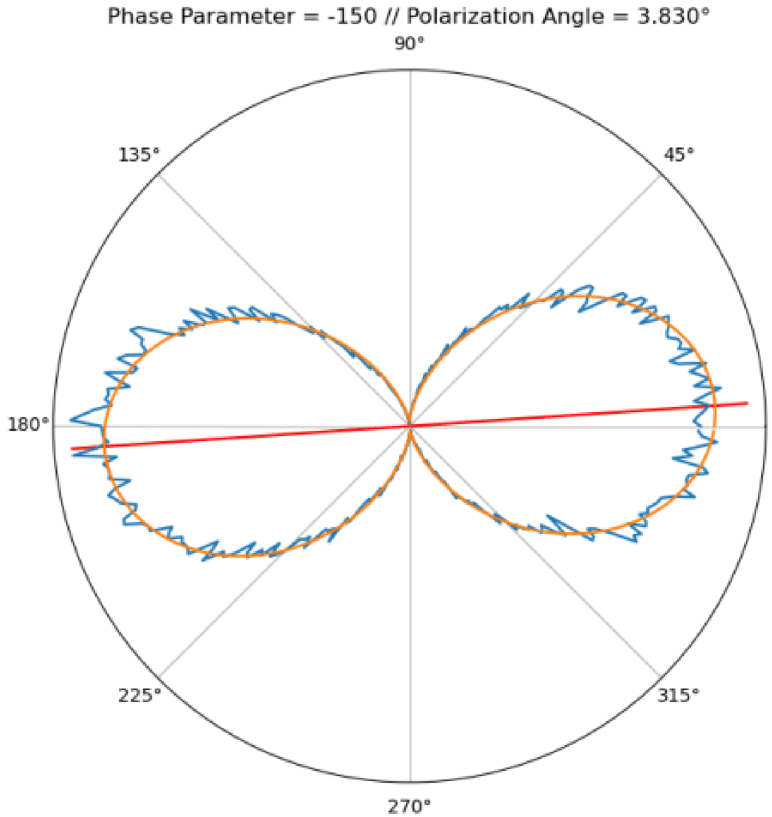


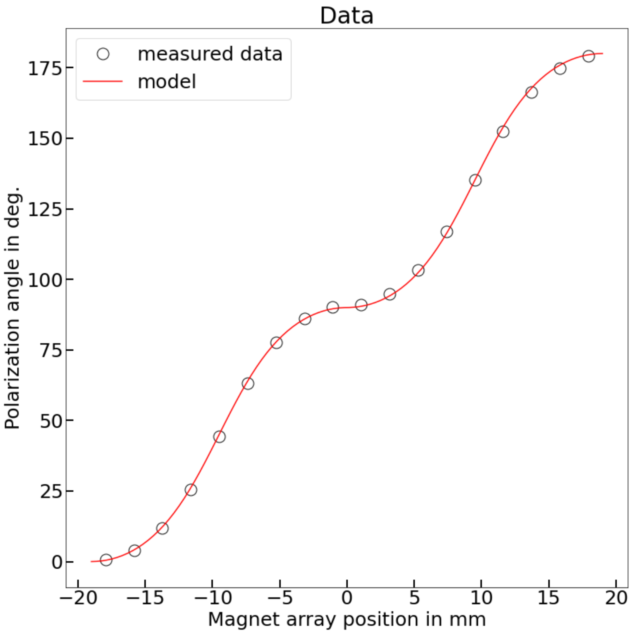
$$\frac{d\sigma}{d\Omega}(\alpha) \propto \cos^2(\theta - \alpha)$$

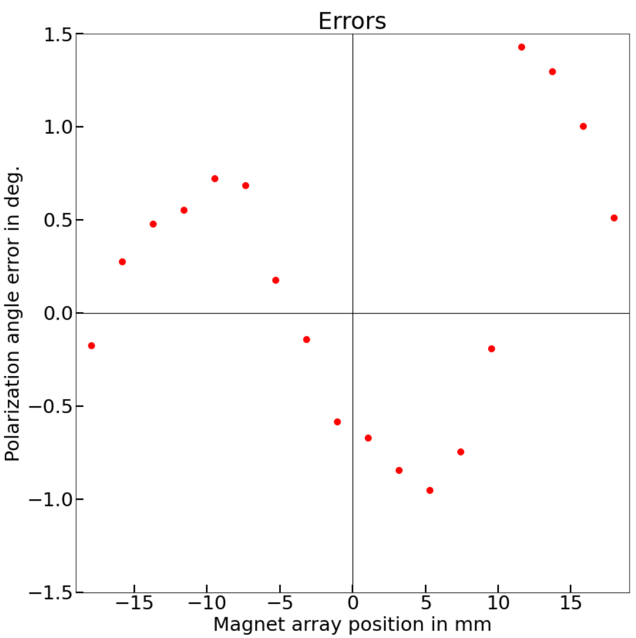
Undulator Scan

Model for polarization of beam (α) vs undulator phase parameter (ϕ):

$$\alpha = \arctan\left(\cot^2\left(\frac{1}{2}\phi\right)\right)$$





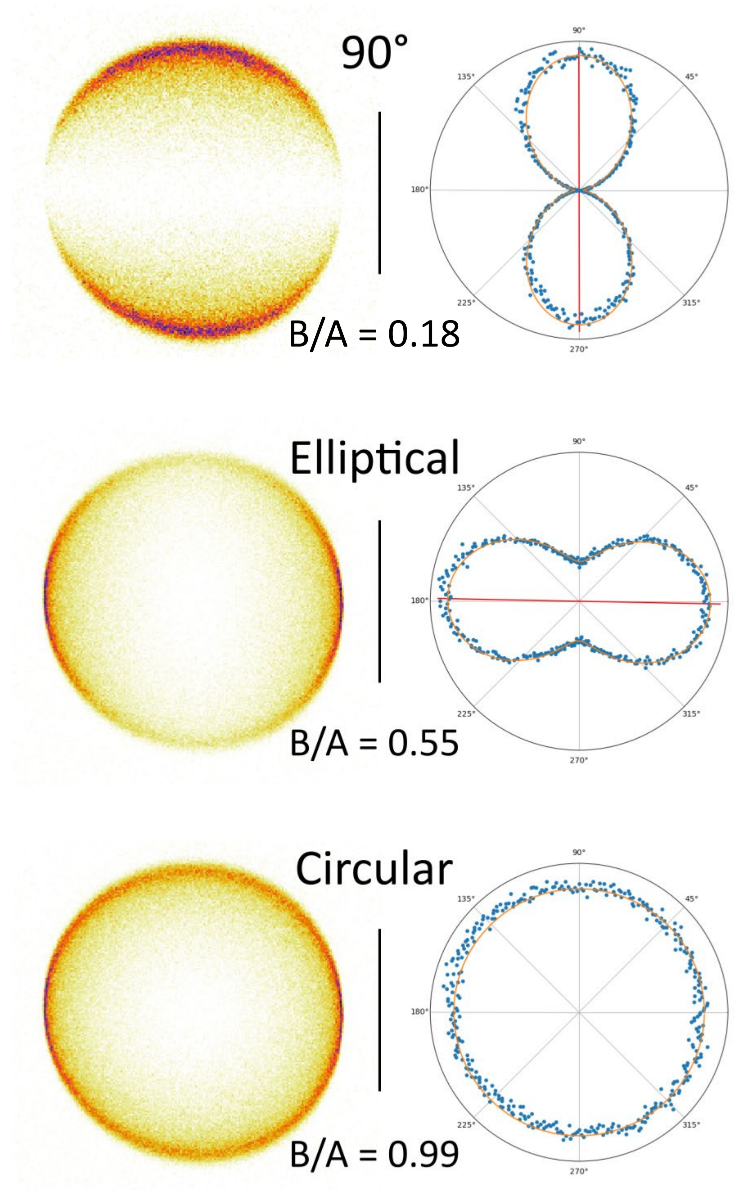


Circular and Elliptical Polarizations

Ellipticity were also characterized by fitting to perpendicular dipoles:

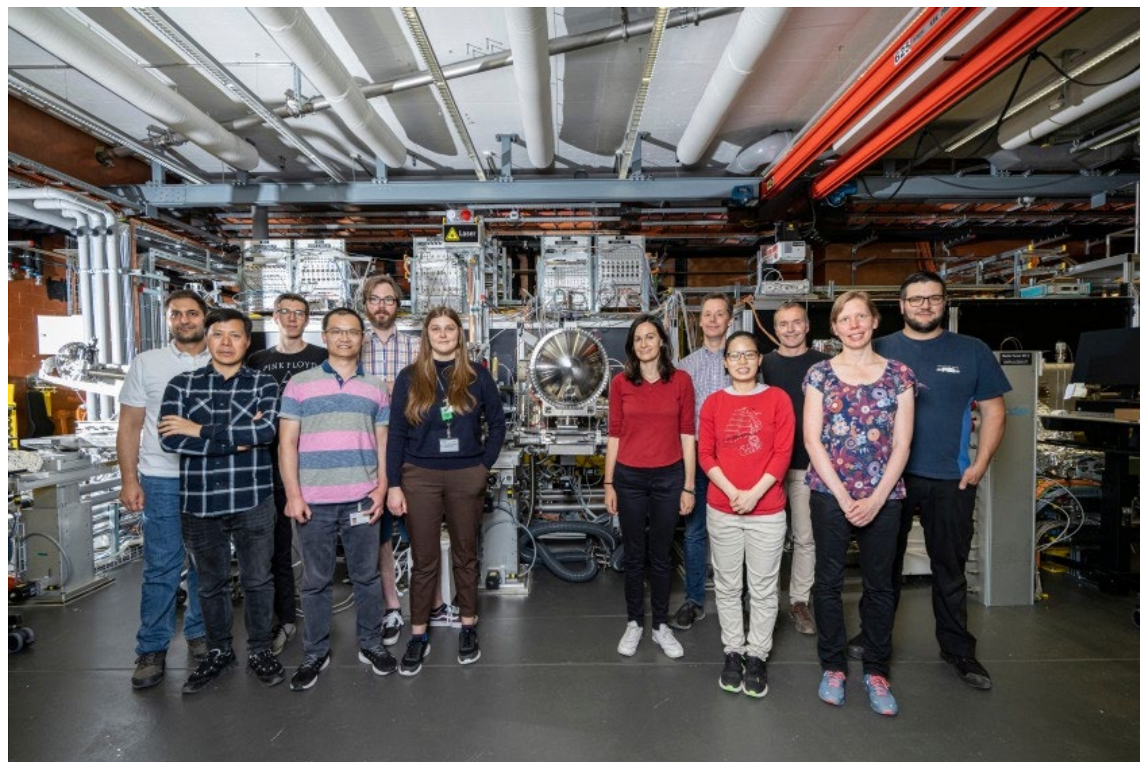
$$\frac{d\sigma}{d\Omega}(\alpha) = A^2 \cos^2(\theta - \alpha) + B^2 \sin^2(\theta - \alpha)$$

Ratio of B/A gives degree of ellipticity
- B/A = 0 is purely linear
- B/A = 1 is purely circular



Summary

- Arbitrary linear, elliptical and circular polarization of XFEL beam achieved in Athos by SwissFEL undulator / operations groups
- Polarizations characterized at Maloja endstation using COLTRIMS
- Excellent agreement with theoretical model
- Nice example of collaboration between machine development groups and experimental endstations (more in the future)



Wir schaffen Wissen – heute für morgen

Many thanks to:

- Maloja Group
- Undulator Group
- Operations Group
- Science IT Group
- Everyone who contributed!