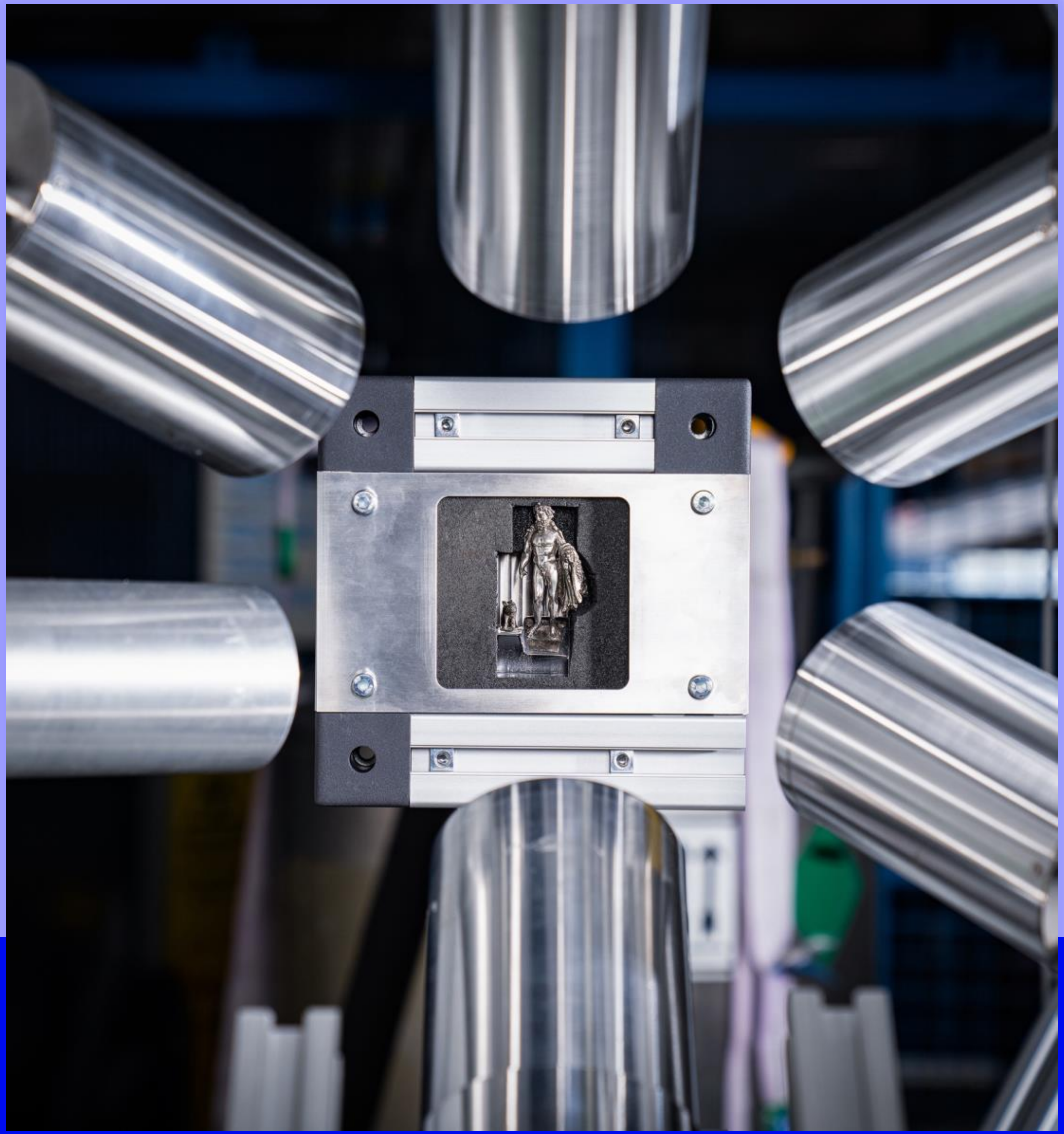
PSI Center for Neutron and Muon Sciences

HELSINKI INSTITUTE OF PHYSICS

A novel technology for element-sensitive 3D tomography using MIXE

An effort to MIXE-T(omography)



Xiao Zhao on behalf of the MIXE team
Hefei, 16 October 2024

Outline

- Introduction to Muon Induced X-ray Emission (MIXE)
- MIXE Experimental Setup
  - Location
  - GIANT
  - Efforts toward MIXE-T(omography)
- MIXE-T(omography): First Result
- Outlook

Introduction to MIXE

Muon Induced X-ray Emission

- Muon is implanted (depth given mainly by momentum and density of the material)
- Low energy muon is captured by the atom in higher excited states:

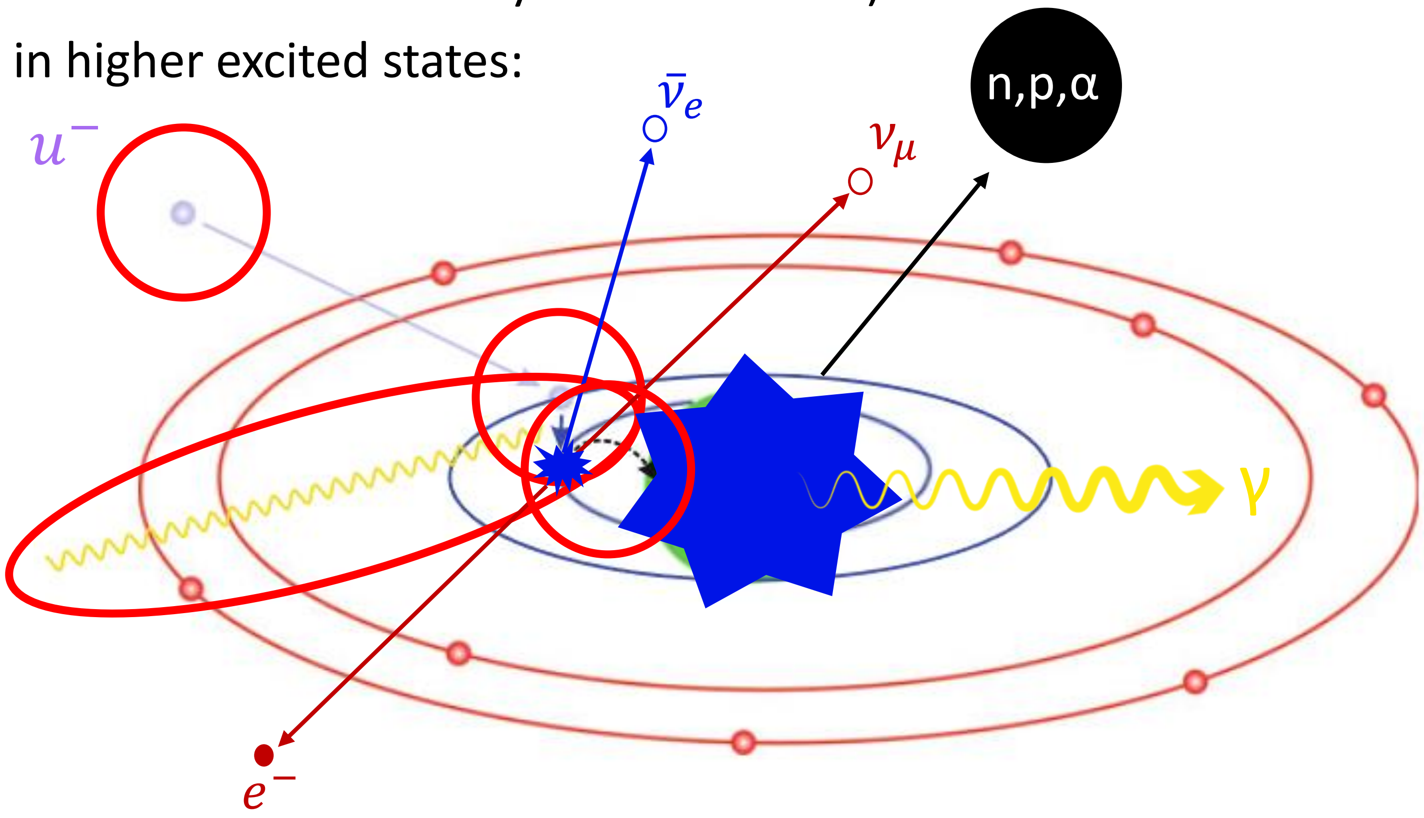
$$n_\mu \approx \sqrt{\frac{m_\mu}{m_e}} \approx 14$$

- Cascades down to $n_\mu = 1$ while emitting X-rays characteristic to the element / isotope
- Muon is unstable and decays

or

- Muon is captured by nucleus

$$\mu^- + p \rightarrow \nu_\mu + n \quad (+ \text{~10-20 MeV})$$



- Nucleus loses excess energy by emitting (some combination of) n, p, α, γ

Amato, A., & Morenzoni, E. (2023). *Introduction to Muon Spin Spectroscopy*. Springer.

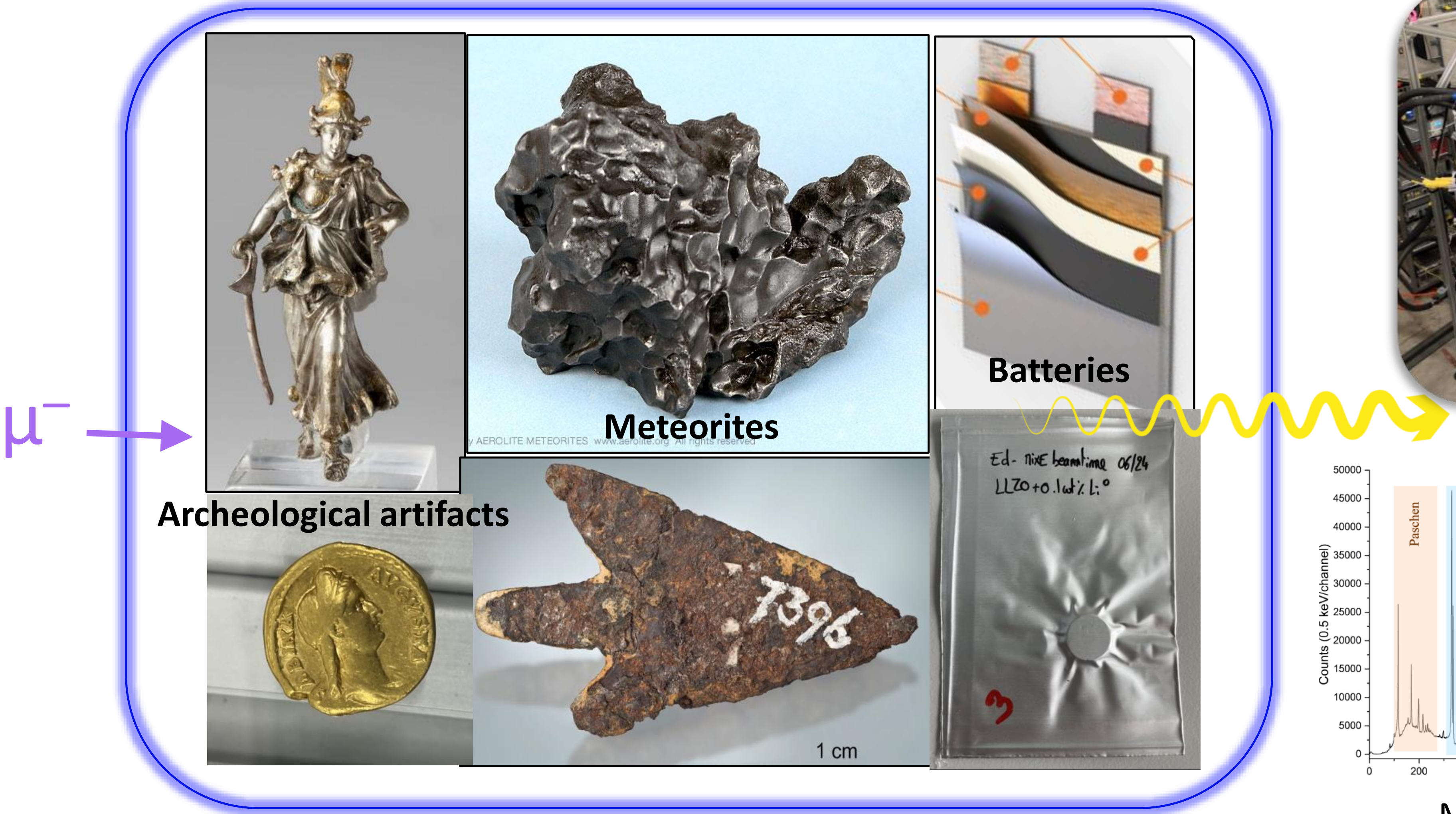
Muon Induced X-ray Emission

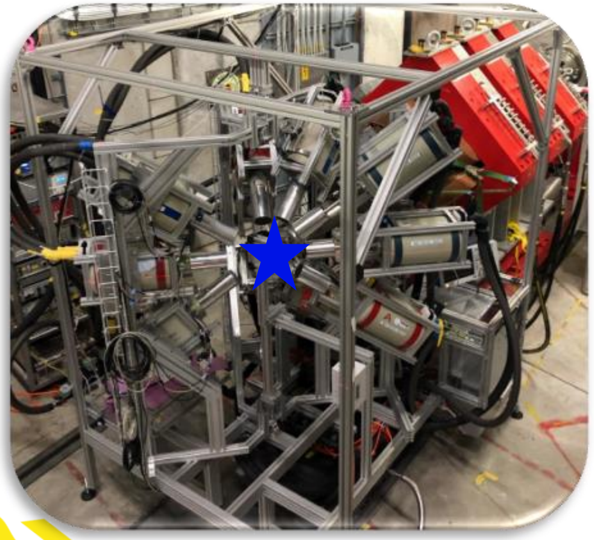
- MIXE is the only elemental analysis method that combines:
  - Sensitivity to basically **all elements** (often even isotopes, indication of chemical states)
  - **Depth-resolved** from surface to bulk (~ µm to ~ cm)
  - Completely **non-destructive**

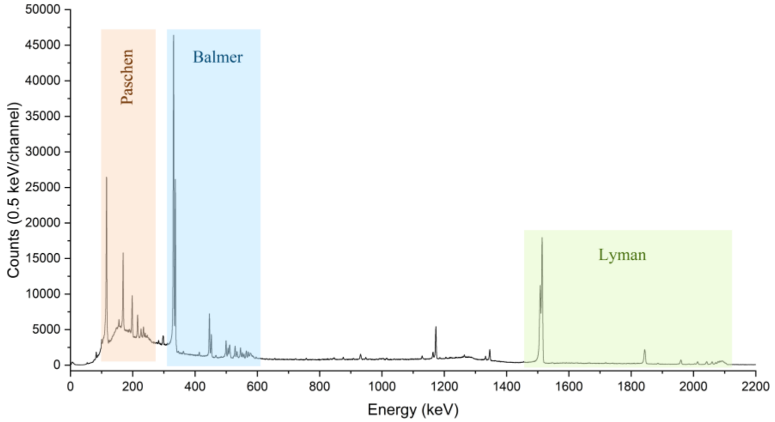
- This makes it an especially unique tool for depth-dependent studies
  - **Precious samples** that cannot be altered (Cultural heritage artifacts, etc.)
  - Samples that need to be measured **in-situ** or **in-operando** (e.g. Li batteries)
  - Other applications

Muon Induced X-ray Emission

Targets: almost all element







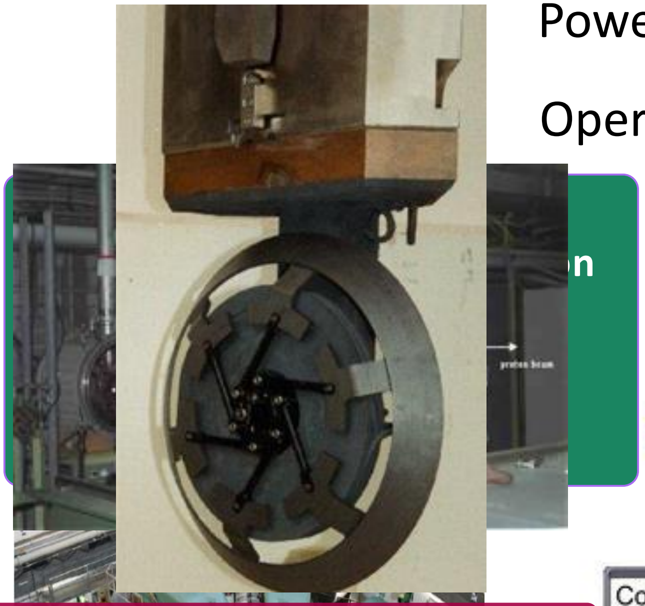
MIXE spectrum of Cu

MIXE Experimental Setup

Swiss Muon Source (SμS)

Powered by: **High Intensity Proton Accelerator**

Operates 6 state-of-the-art μSR instruments



$$p + n \rightarrow p + p + \pi^-$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Target E (epaisse) – 40mm graphite designed for π/μ production (high rate)

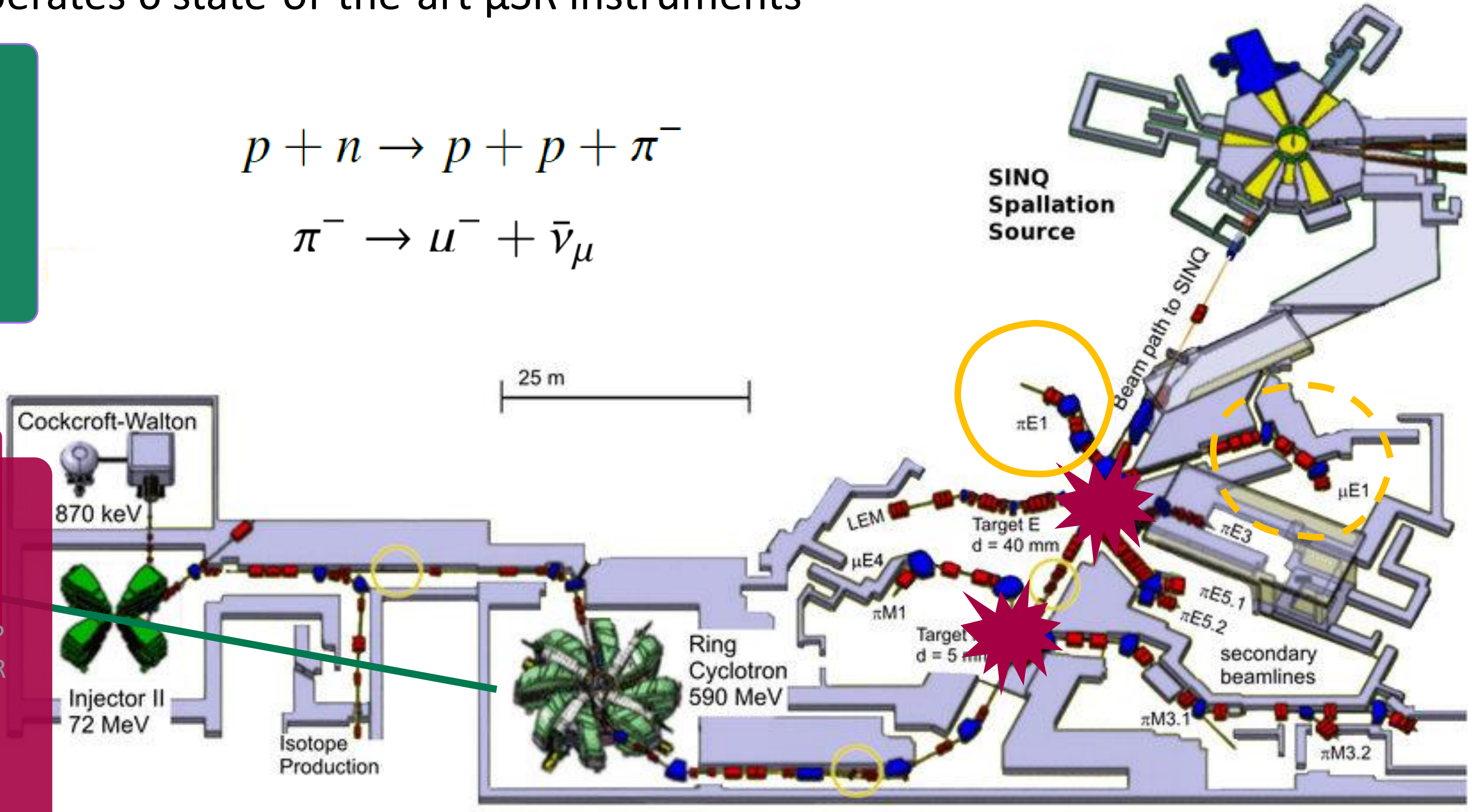
πE5: 20-120 MeV/c high rate μ for PP

μE4: 10-40 MeV/c μ^+ for LEM – μSR and PP

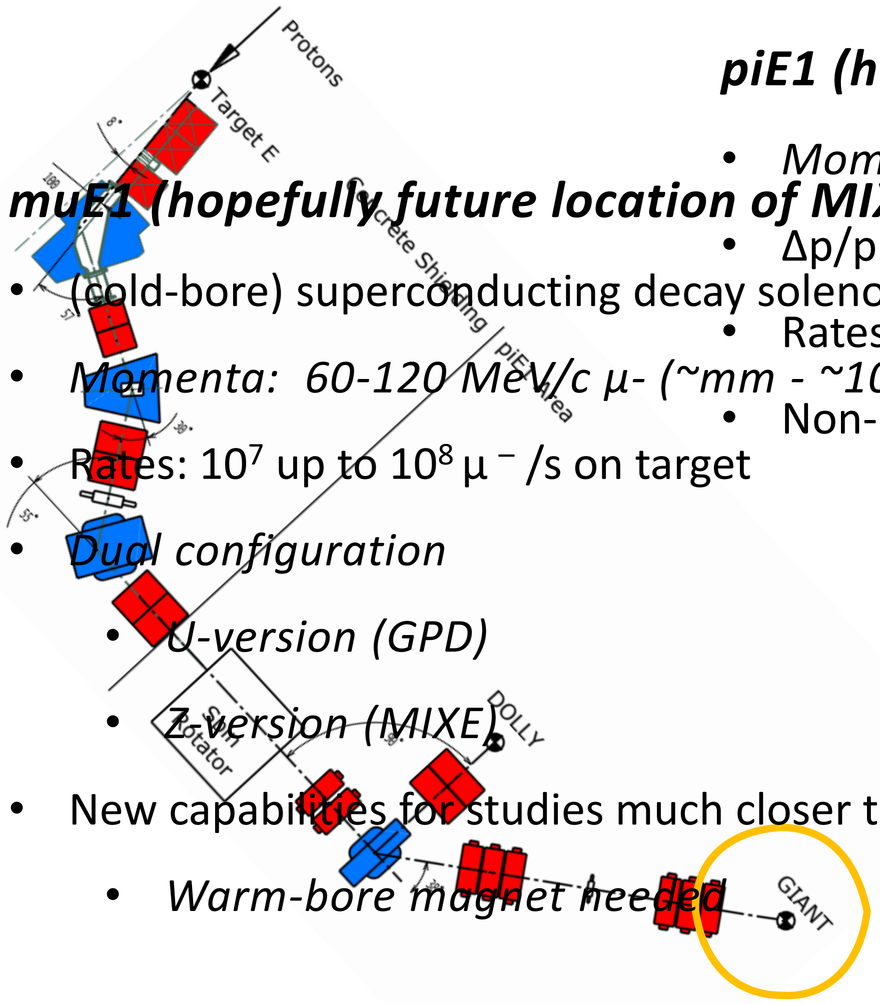
πE3: 10-40 MeV/c (surface) μ^+ for bulk μSR

μE1: 60-120 MeV/c μ for μSR *(and MIXE?)*

πE1: 10-120 MeV/c μ for μSR, MIXE, PP

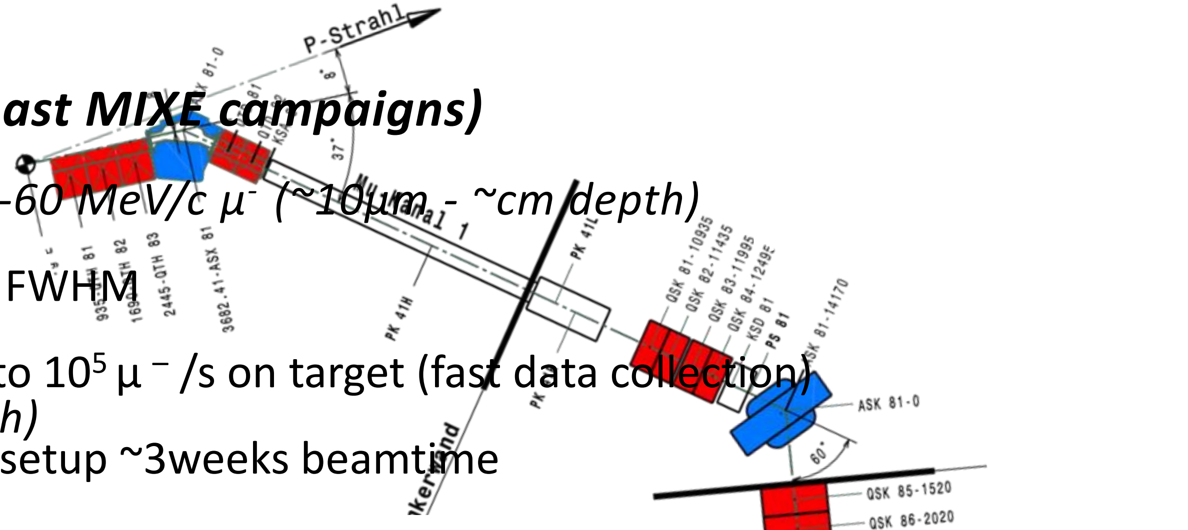


MIXE location



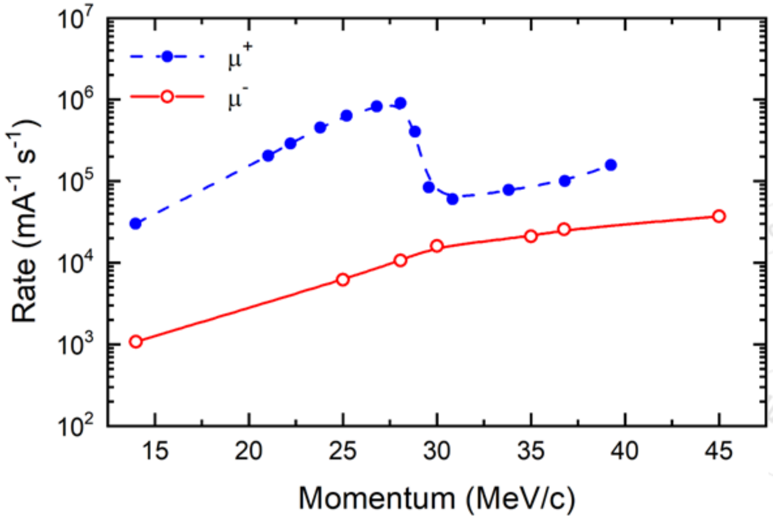
muE1 (hopefully future location of MIXE)

- (cold-bore) superconducting decay solenoid
- *Momenta: 60-120 MeV/c μ- (~mm - ~10cm depth)*
- Rates: 10^7 up to 10^8 μ^- /s on target
- *Dual configuration*
  - *U-version (GPD)*
  - *Z-version (MIXE)*
- New capabilities for studies much closer to s
  - *Warm-bore magnet needed*

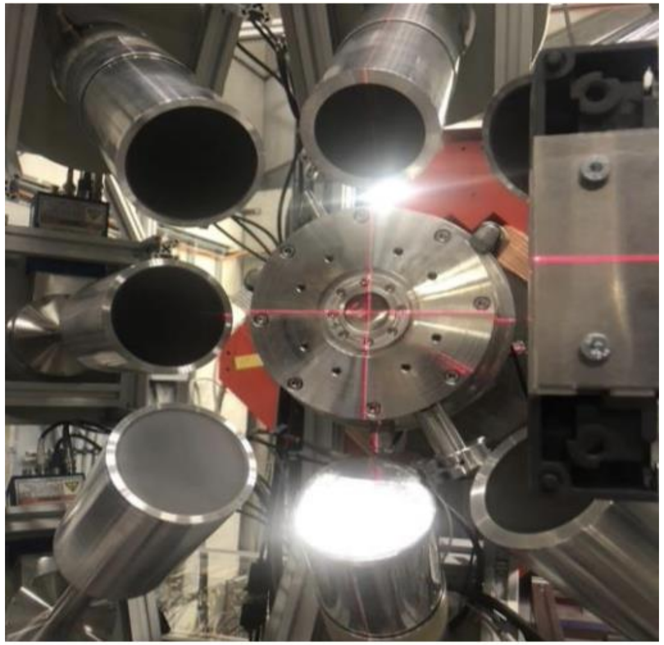


piE1 (host all past MIXE campaigns)

- *Momenta: 15-60 MeV/c μ^- (~10μm - ~cm depth)*
- Δp/p : 1 ~ 8 % FWHM
- Rates: 10^3 up to 10^5 μ^- /s on target (fast data collection)
- Non-perment setup ~3weeks beamtime

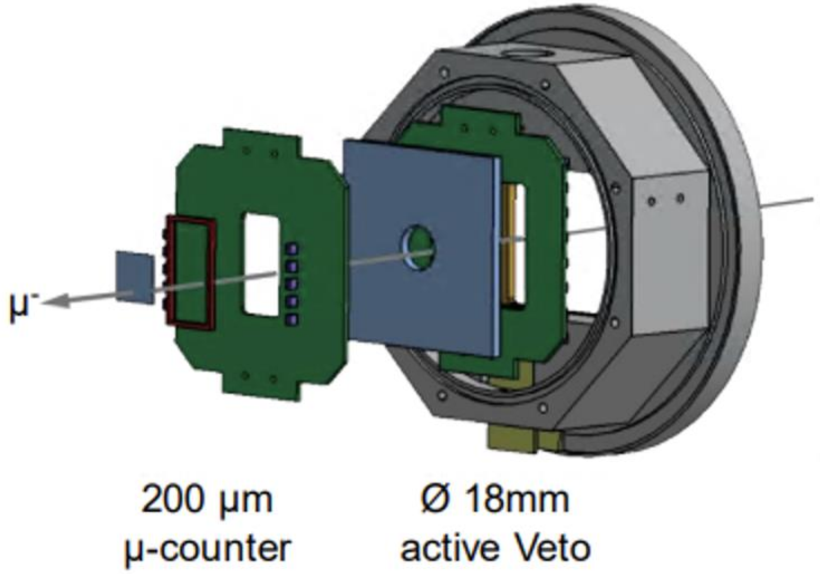


Tagging detector

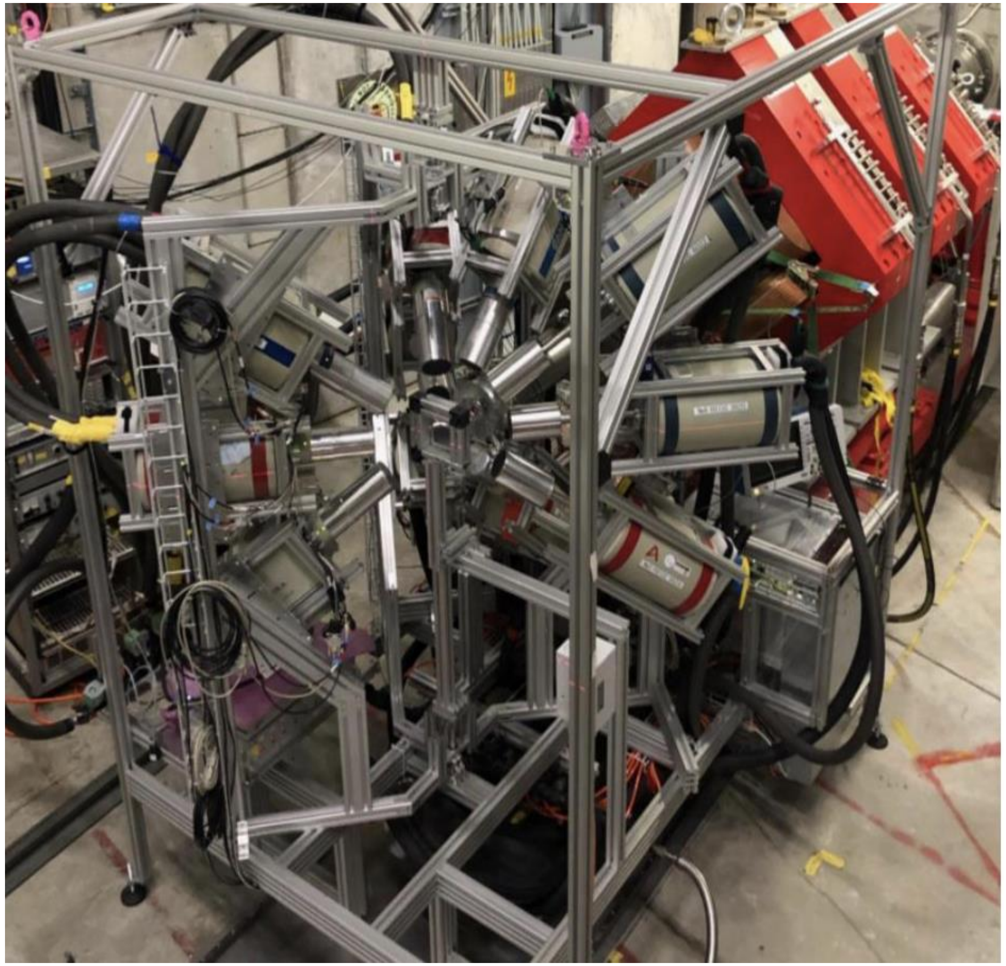


Beam Port
- 10µm titanium foil window
- Beam extraction to sample in air
    - approx. 10 cm distance
- System of collimators available for sample spot measurements

Tagging Detector (developed for muX experiment)
- Reduces uncorrelated BKG
- Allows for discrimination of nuclear capture events
- BC-400 plastic scintillators (Counter and Veto)
- SiPM readout using custom electronics



GIANT

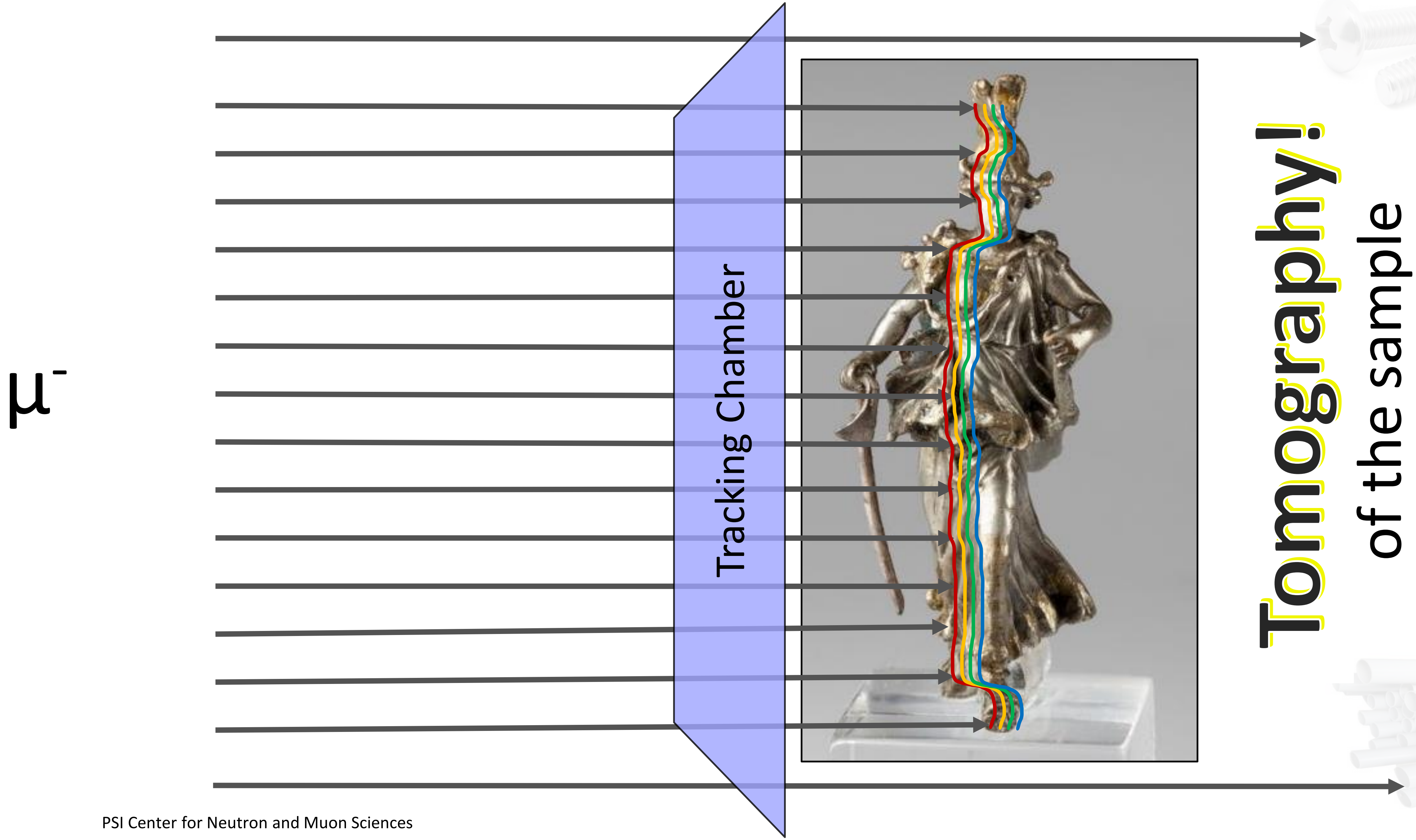


GIANT setup

- The module
  - Up to 8 freely rotating arms (curr. 5)
  - Up to 4 BigMac HPGe per arm
  - Up to 30 HPGe detectors (curr. ~12)
  - HPGes shared with multiple experiments
  - Reproducible positions and angles
- Fully movable as a unit
- Setup time ~6 hours
- Fully automatic LN2 refill
- Sample station twin in control room
  - Reduce time for sample change (~5min)

GermanIum Array for Non-destructive Testing

MIXE-T(omography) – Motivation



MIXE-T(omography)– Tracker

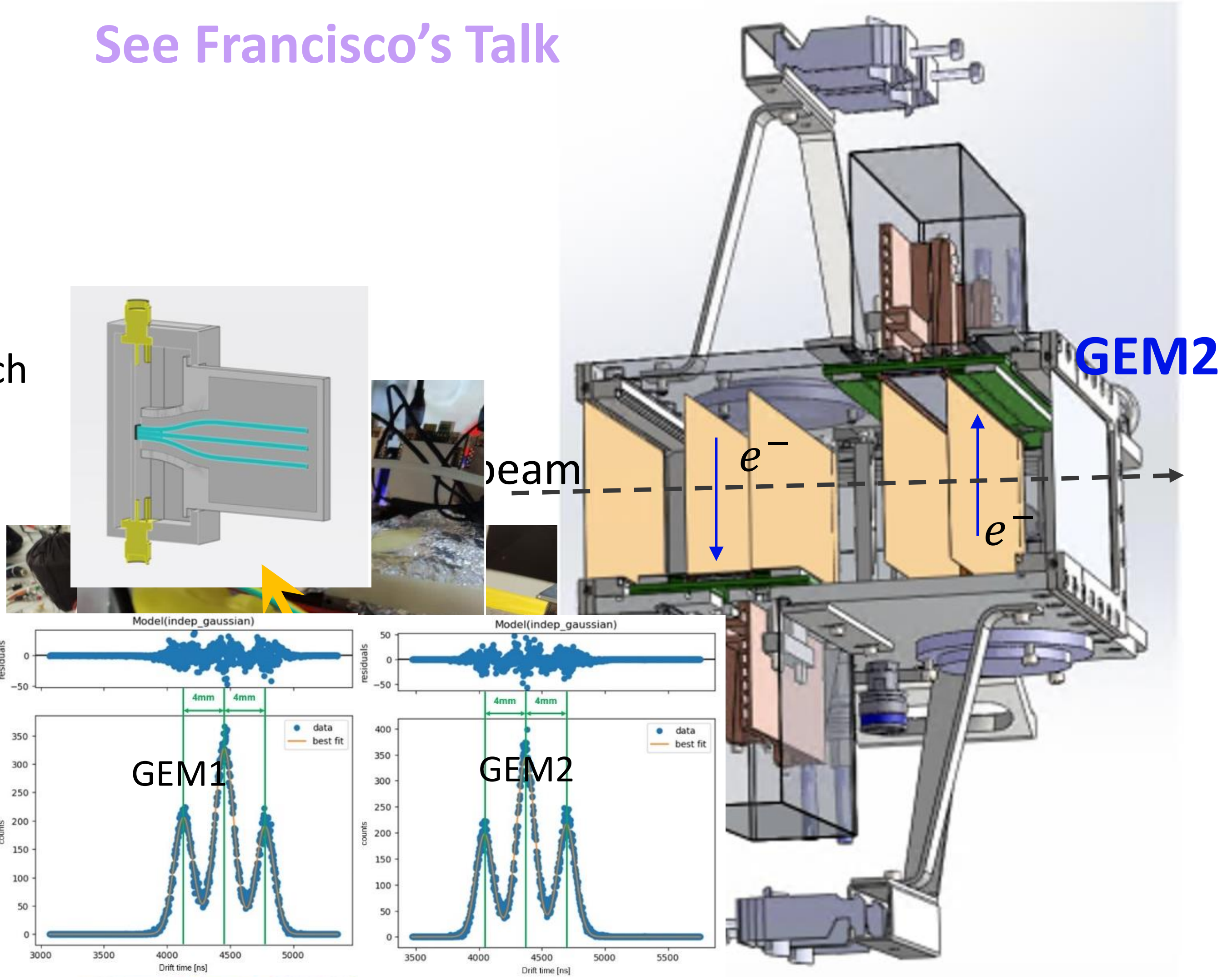
Twin GEM-TPC Tracking chamber HGB4

- Collaboration with F. Garcia (HIP)
- Collaboration with GDD lab and DRD1/CERN
- Active Area ~20x10 cm^2
- Triple GEM stack amplification stage
- 1D strip readout – 1024 ch in total – 0.4 mm pitch
- X position given by the projectiopn of cluster on strips
- Y position given by drift time(s)

Fiber Detector for calibration

- Placed in front of tracker
- 3 scintillating fibers in exactly 4mm distance
- SiPM as fast readout
- Only use parallel tracks

See Francisco's Talk

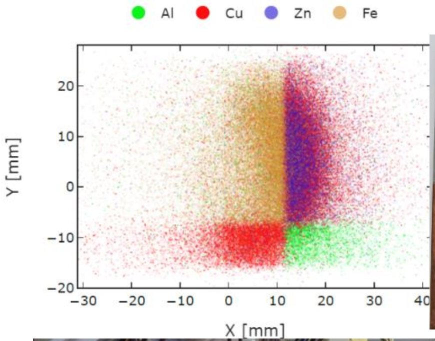


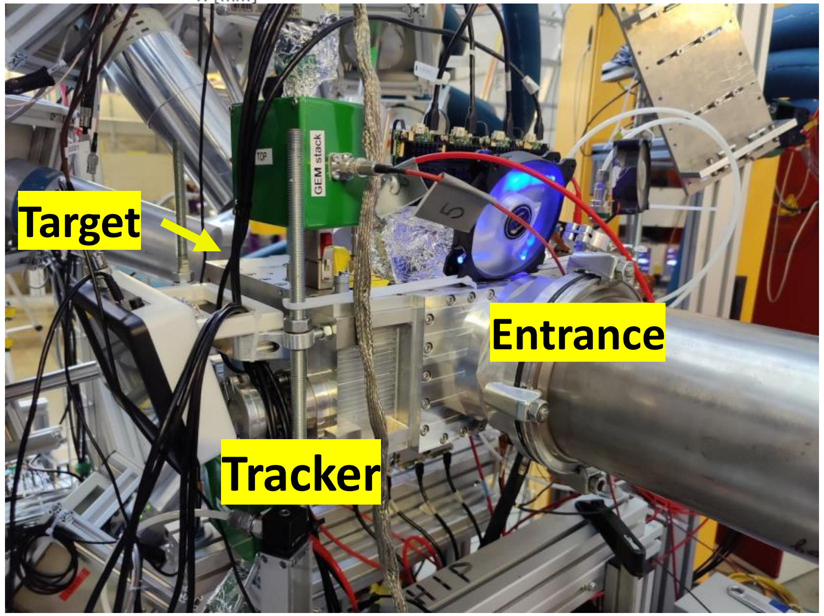
Garcia, F., et al. "The Super-FRS GEM-TPC prototype development-TDR." *arXiv preprint arXiv:1612.05045* (2016).

MIXE-T(omography)– Tracker

See Francisco's Talk

- Successful beam tests of adapted detector using GeV muons at CERN/SPS-H4 in May 2023
- Successful proof-of-concept elemental imaging using 60 MeV/c muons at πE1 in Jun 2023
- First universal elemental imaging/tomography using 50-60 MeV/c muons at πE1 in Sep 2023 (results shown in next section)
- Resolution/momenta limited due to **multiple scattering** in high-density gas (Ar/CO2 75:25)
- First operation of a GEM-TPC detector using low density gas mixture (He/CO2 90:10) at CERN/SPS-H4 in Apr 2024 – **found performance to be excellent**
- Tracker with He/CO2 during full Jun 2024 MIXE campaign – **analysis ongoing**





MIXE-T(omography): First Result

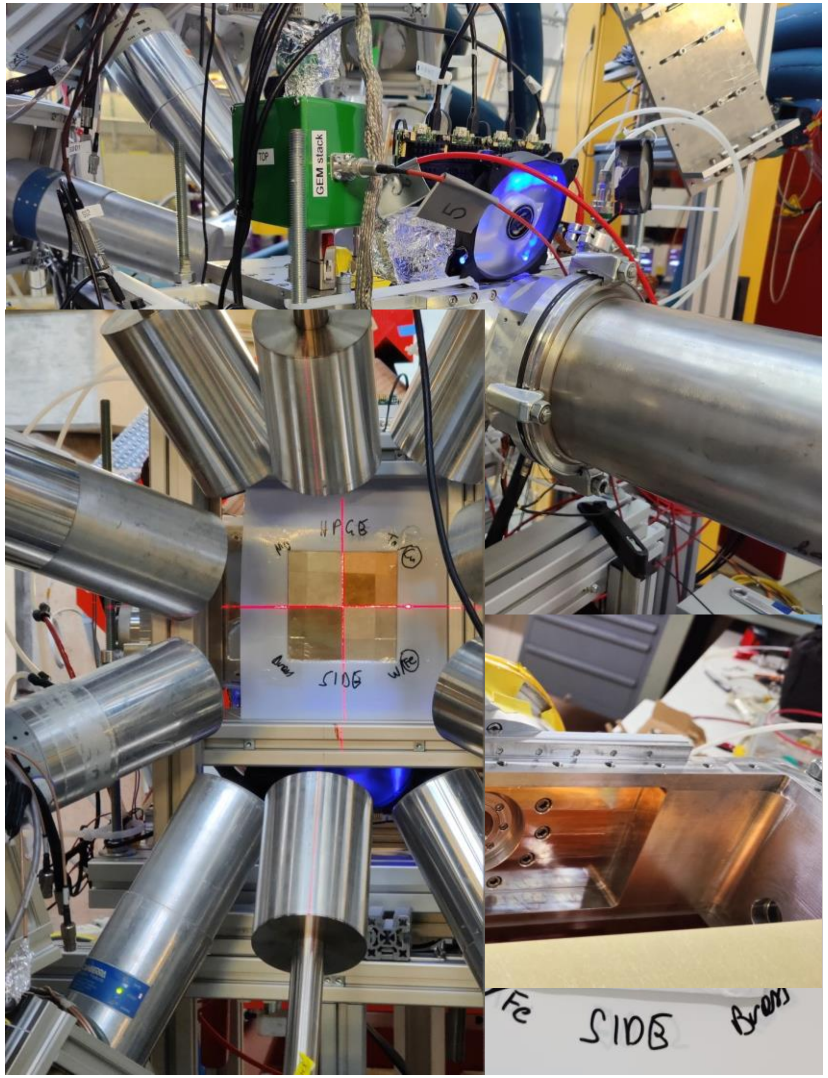
Elemental (isotopic) Imaging: First Result

Reference targets

- Pure metals (except brass: Cu 63% & Zn 37%)
- Layered to check depth resolution (Ta/Cu & W/Fe)
- Optimized thicknesses by muon momentum
- Aligned to beam center
- Scan from 50 MeV/c to 60MeV/c

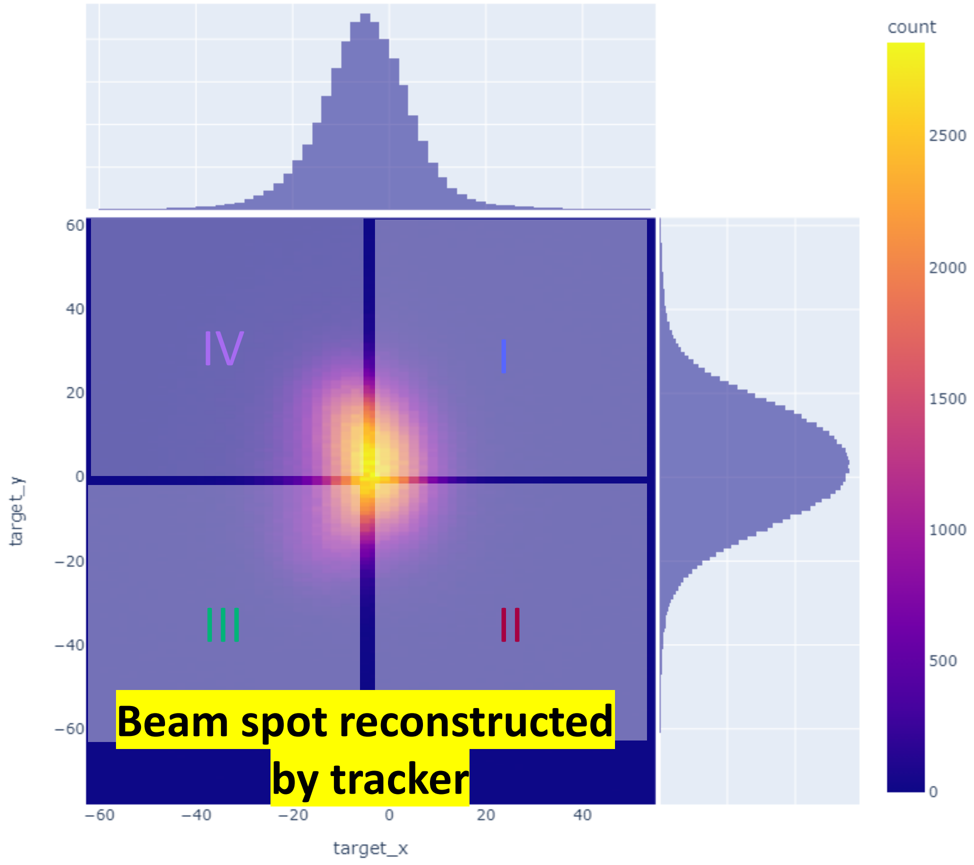
Experimental setup

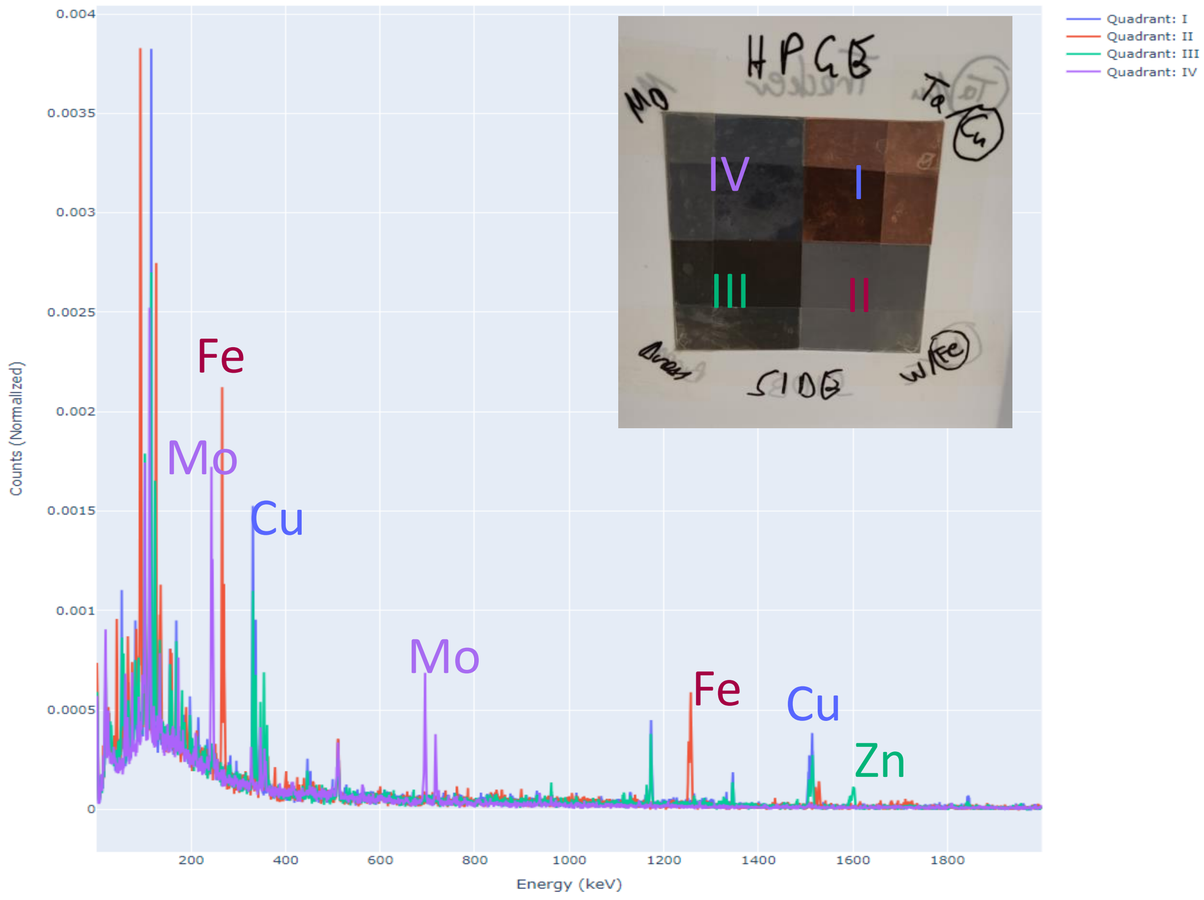
- Tracker flanged directly to beampipe
- Ar/CO2 75:25
- Full array of HPGe detectors (10)



Elemental (isotopic) Imaging: First Result

Result @60MeV/c

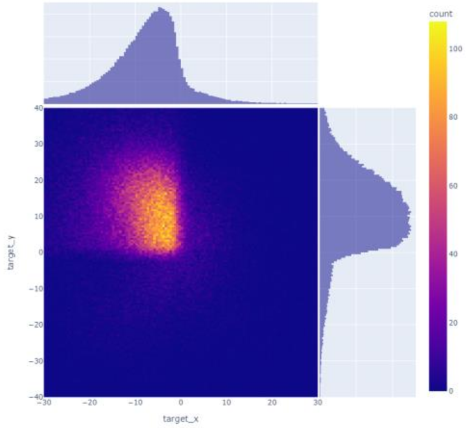




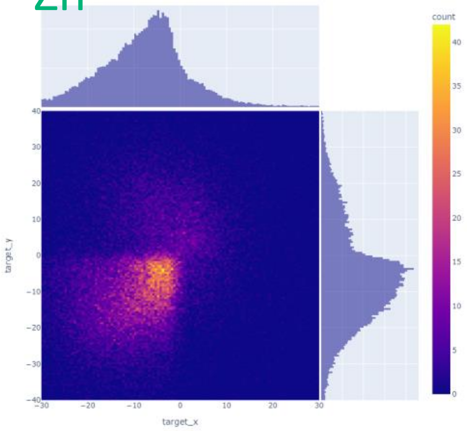
Elemental (isotopic) Imaging: First Result

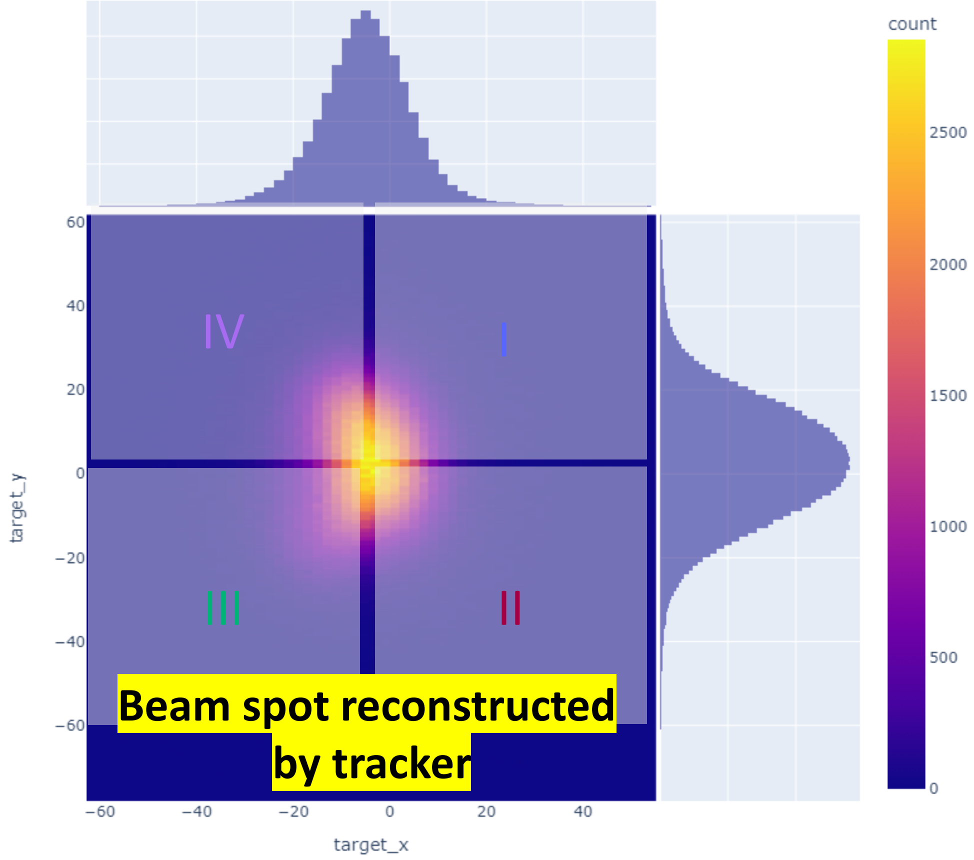
Result @60MeV/c

Mo

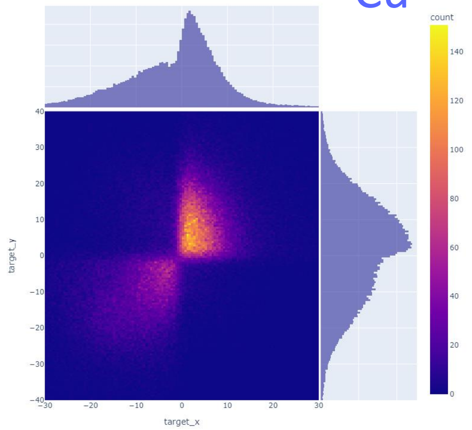


Zn

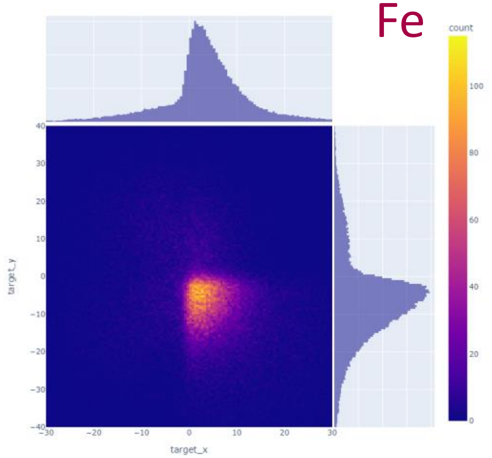




Cu

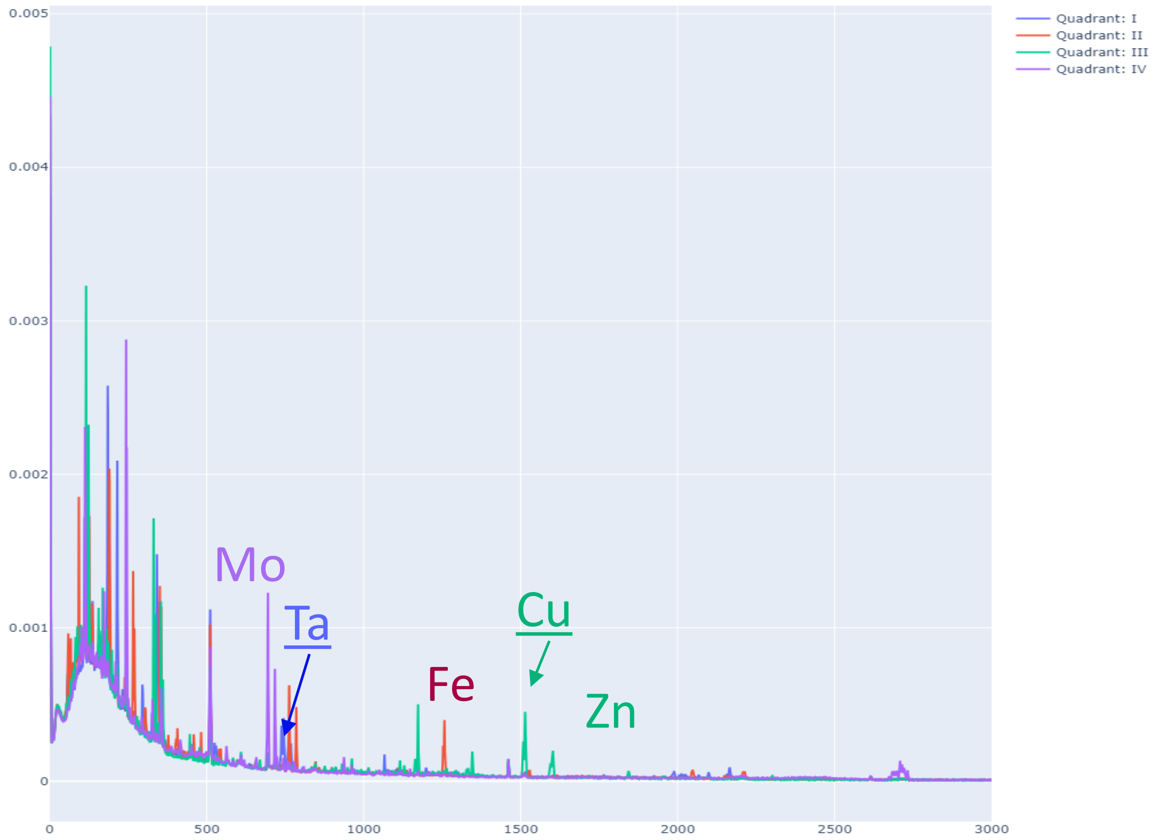


Fe

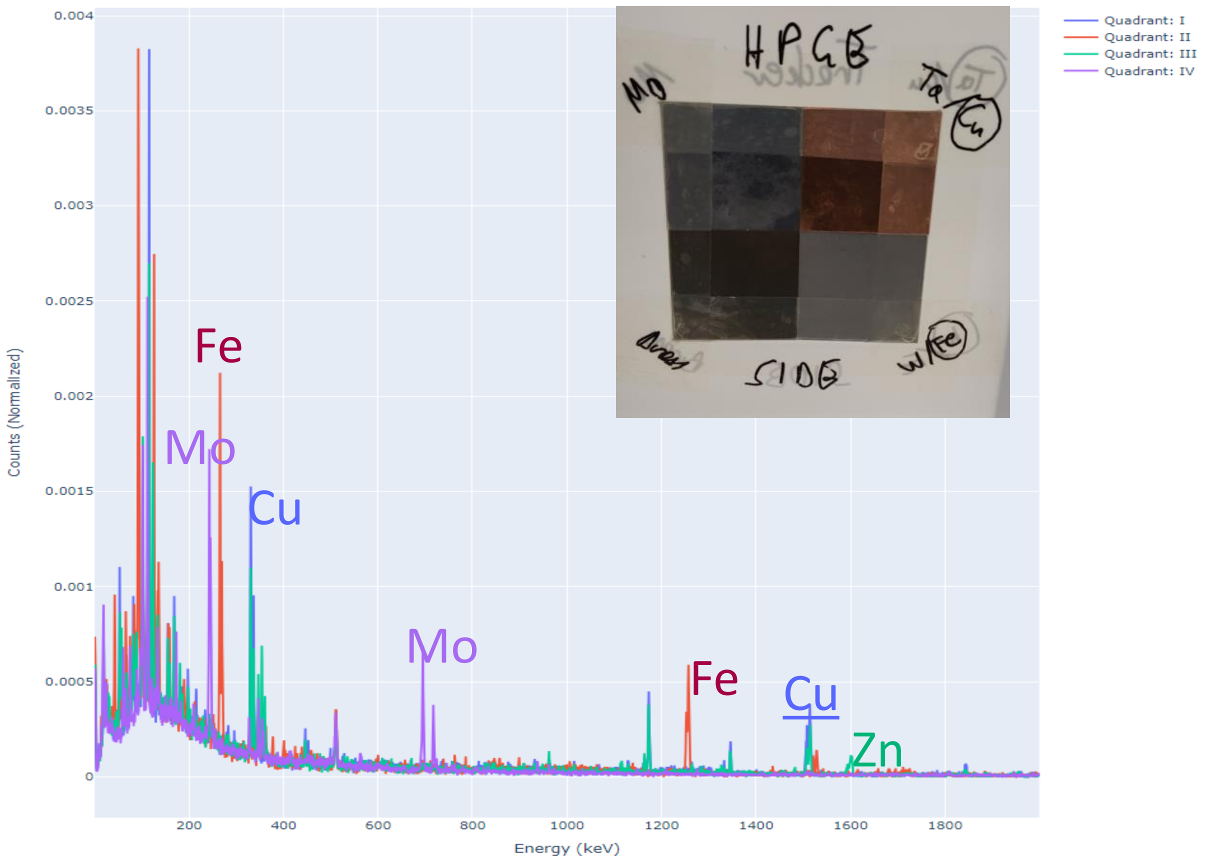


Elemental (isotopic) Imaging: First Result

As the energy increases, the Ta peak disappears, and the intensity of the Fe peak increases.

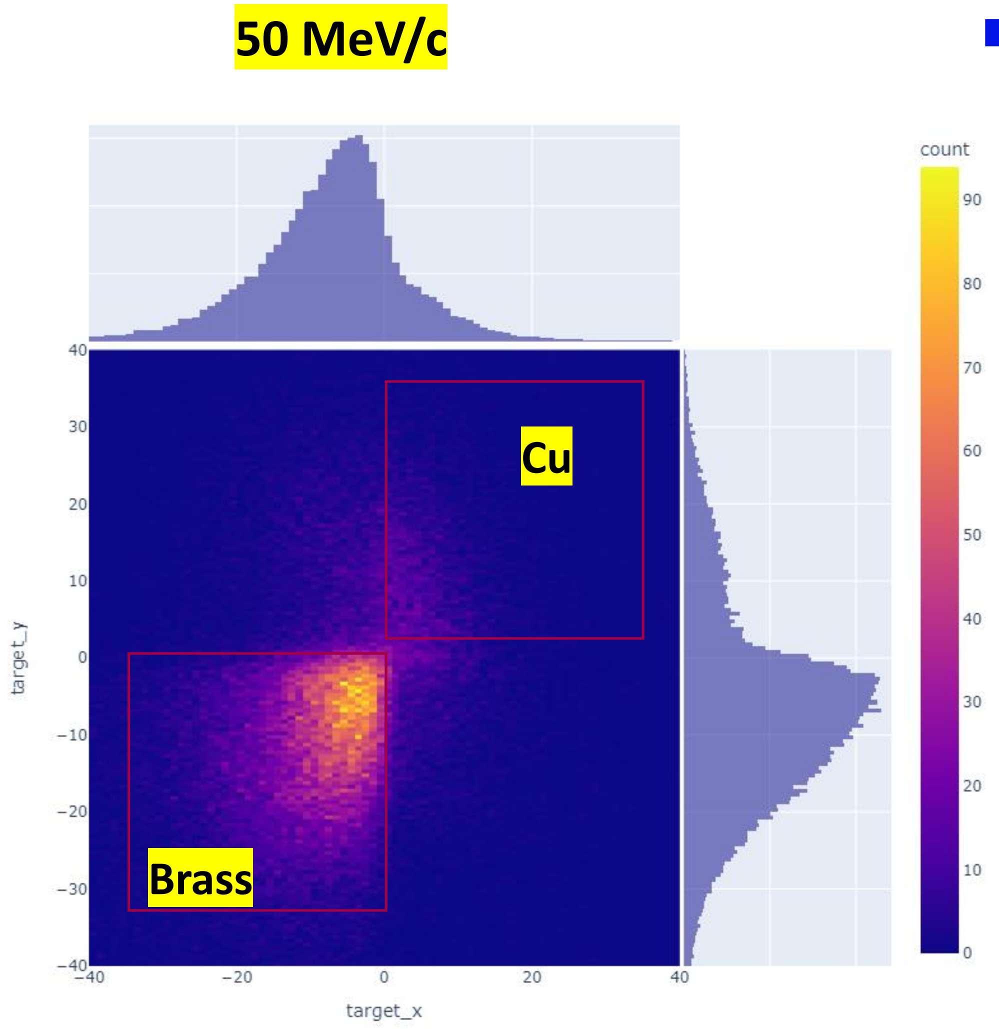


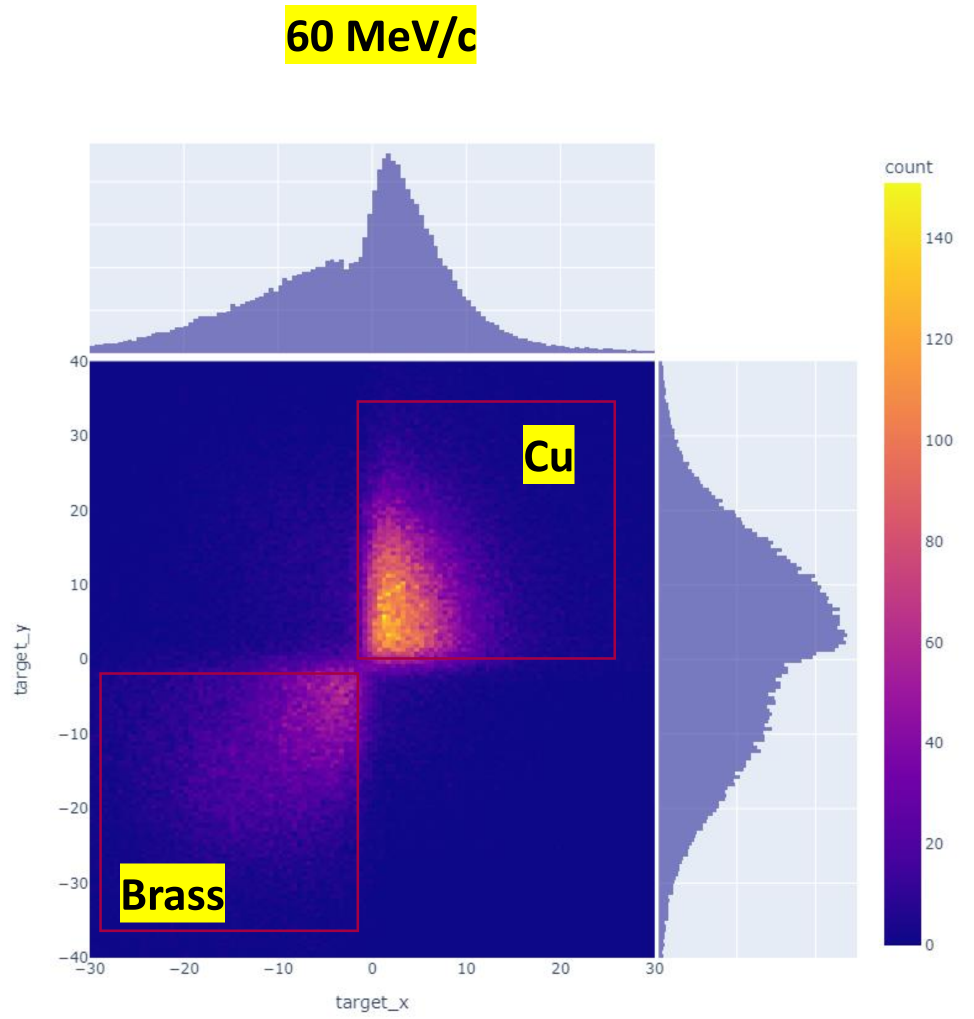
Result @50MeV/c



Result @60MeV/c

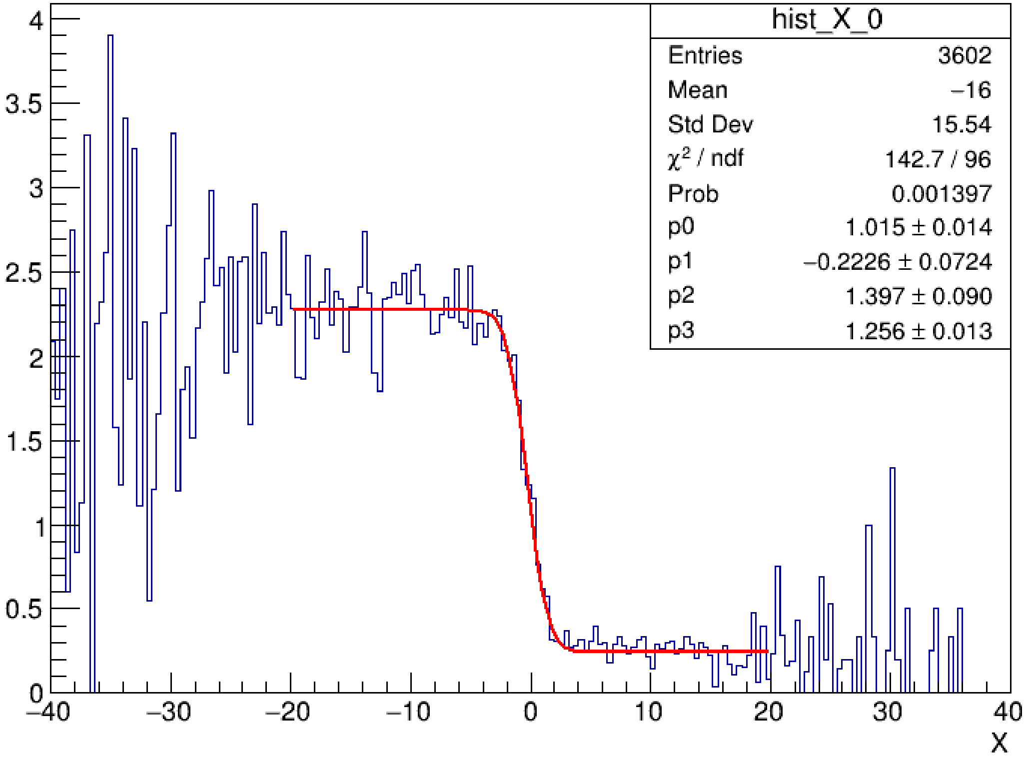
Elemental (isotopic) Imaging: First Result





Elemental (isotopic) Imaging: First Result

PSI



Step 1: Select the desired element (Mo)

Step 2: Normalize the data by the beamspot

Step 3: Select a X/Y range to remove background

Step 4: Sum the data along the X/Y axis

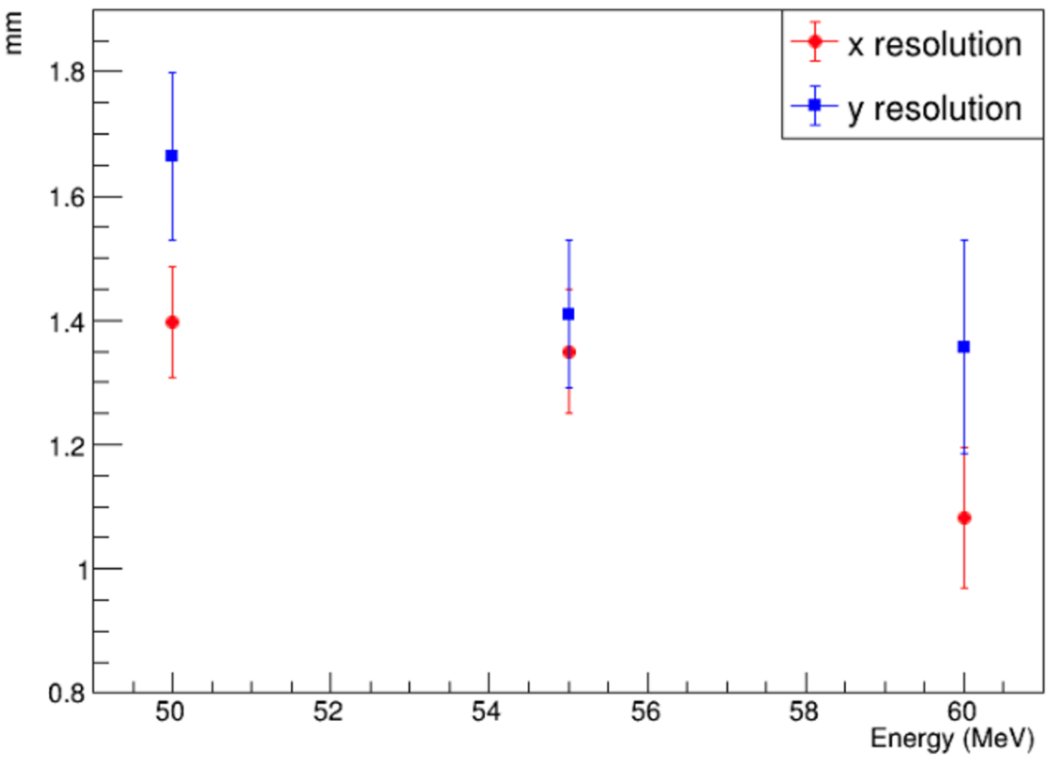
Step 5: Fit result using a Gauss error function

$$F(x) = \ P[3] + P[0]e^{\left(\frac{x-P[1]}{P[2]}\right)^2}$$

P[1]: mean P[2]: sigma

Elemental (isotopic) Imaging: First Result

- Spatial Resolution @ 60MeV/c with Ar/CO_2 75:25 HGB4
  - X Resolution: 1.083 ± 0.113 mm
  - Y Resolution: 1.357 ± 0.172 mm
- Mainly due to the multiple scattering effect in air and materials
- Resolutions should be improved by change to He/CO_2 gas
- Problems observed:
  - Y resolution is larger than X
  - May caused by pressure variations in the tracker chamber, or temperature fluctuations in the experimental hall, affecting drift velocity (Y-coordinate)
  - Any suggestions or insights on this issue are welcome. Thanks!



Outlook

PSI

First Robust Elemental Imaging/Tomography Demonstration!

- **Spatial Resolution**: Achieved mm-scale @60 MeV/c with basic analysis
- **Key Achievement:** Demonstrated depth sensitivity to materials

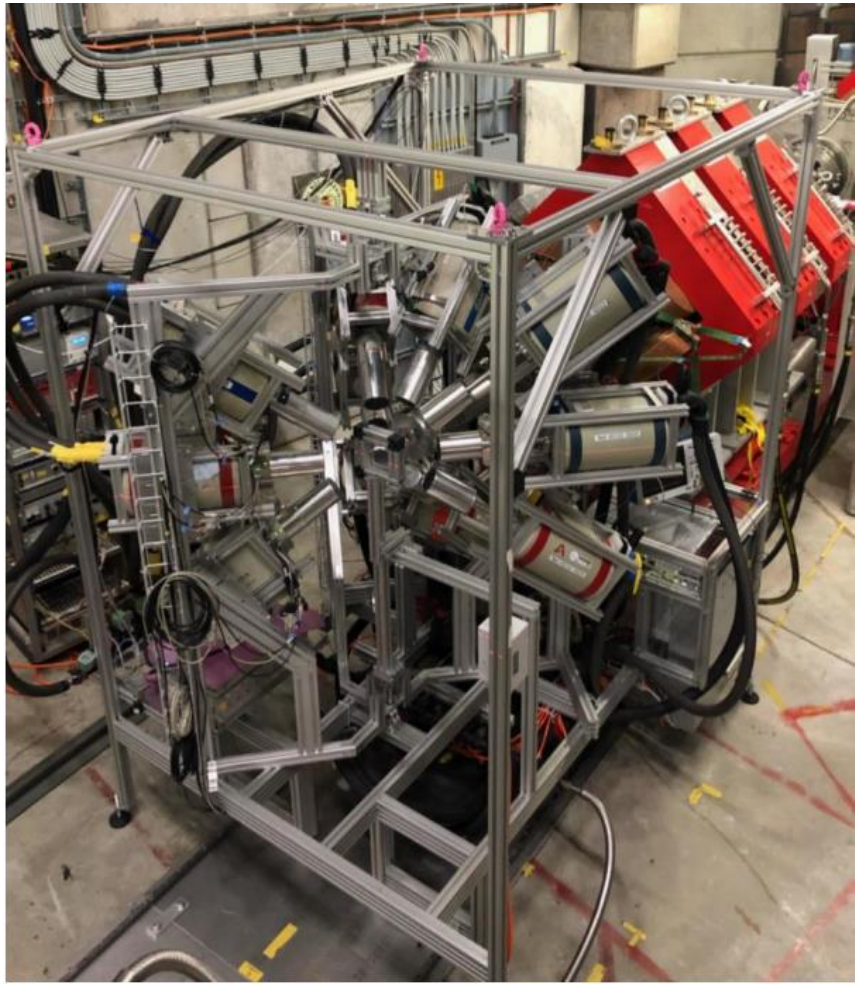
Ongoing Analysis:

- **He/CO_2 Data Analysis**: Aimed at reducing multiple scattering in gas
- **Lifetime Measurements**: Focus on low-Z elements (e.g., Li)

Future Developments:

- **Tracker enhancements:** Smaller size and pixel-based readout
- **muE1 as new site(?):** Exploring new capabilities for studies closer to the surface
- **Increased MIXE-T sensitivity:** Leveraging machine learning and algorithmic advancements

Acknowledgement



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