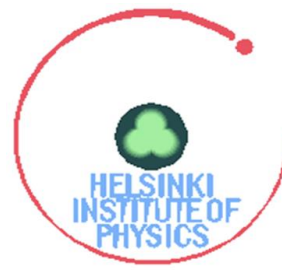
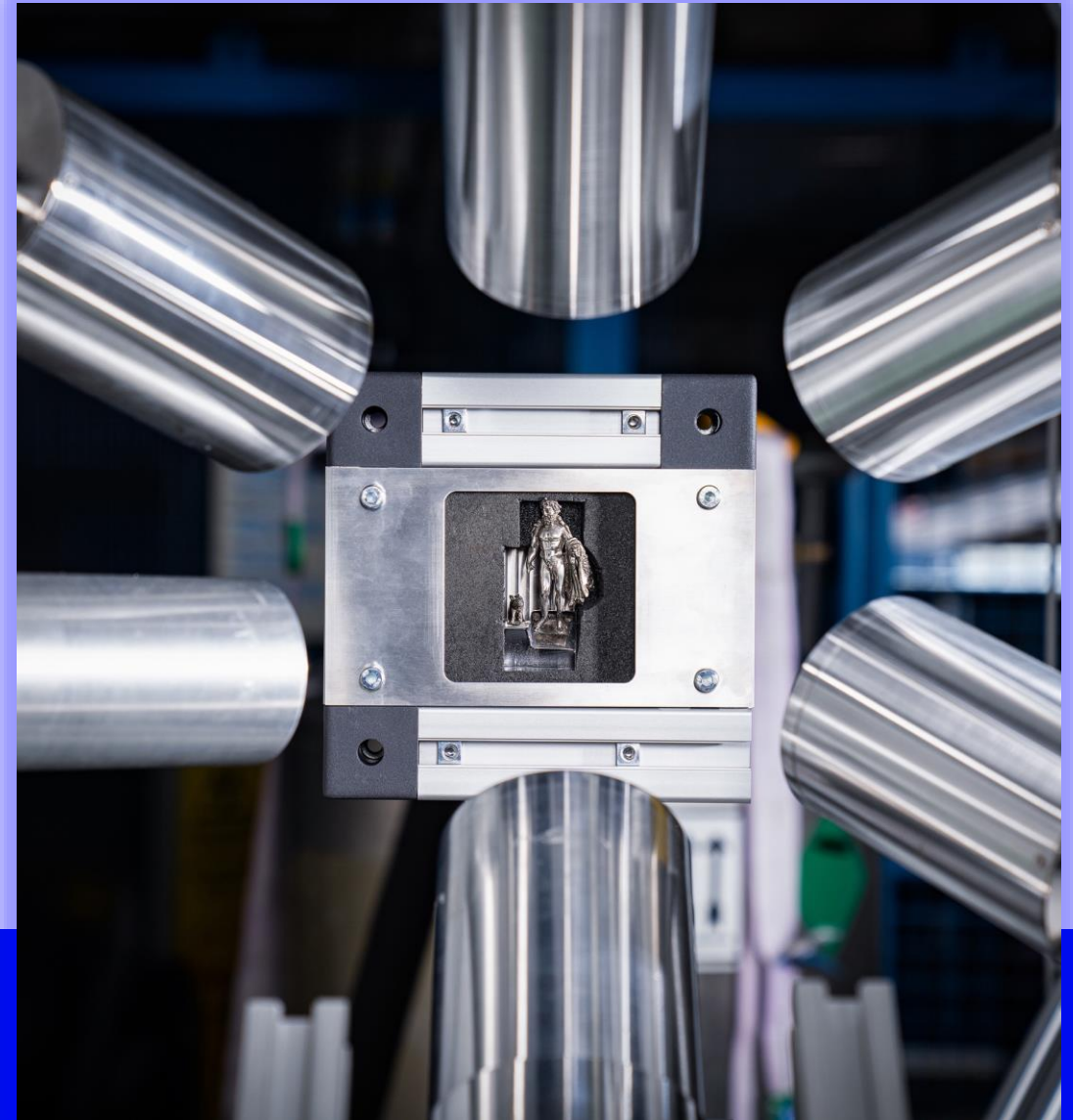


PSI Center for Neutron and
Muon Sciences



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

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

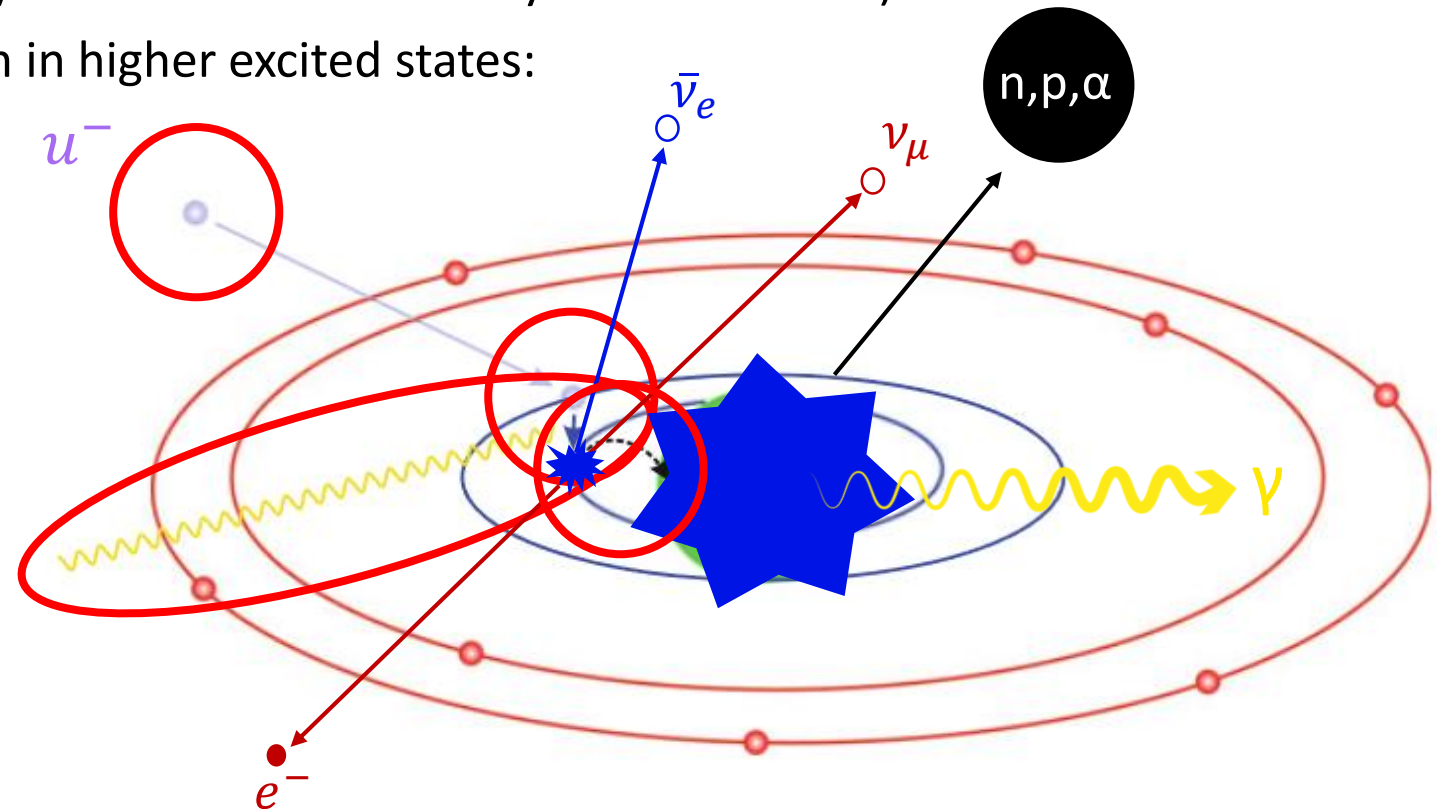
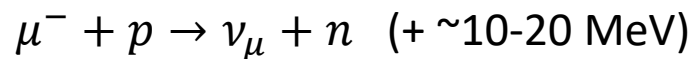
Introduction to MIXE

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



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

- 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 ($\sim \mu\text{m}$ to $\sim \text{cm}$)
 - 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

μ^- →



Archeological artifacts



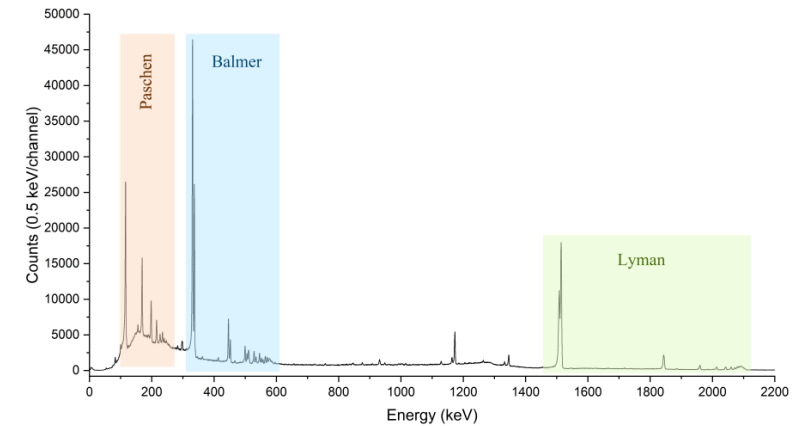
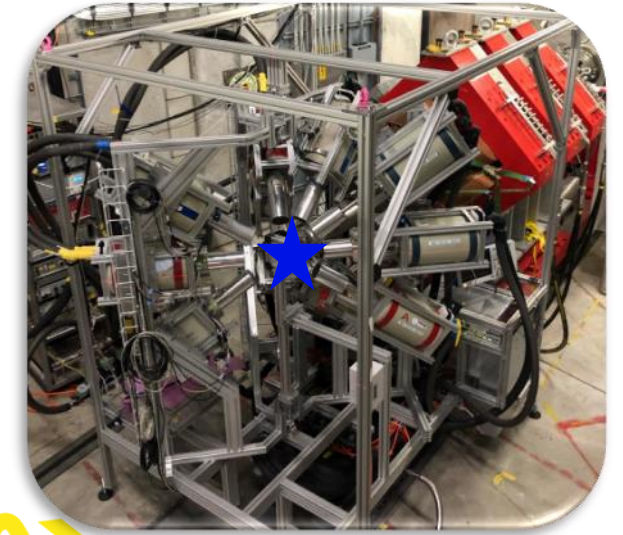
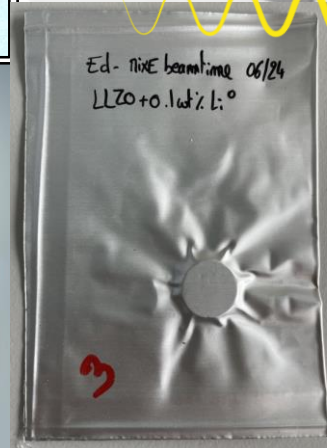
Meteorites



1 cm



Batteries



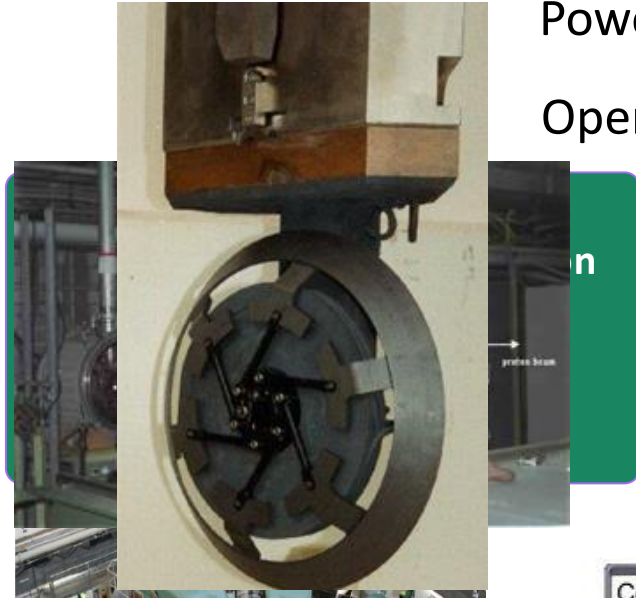
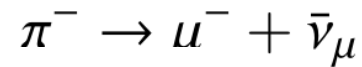
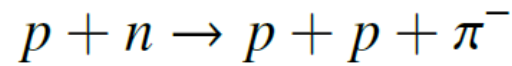
MIXE spectrum of Cu

MIXE Experimental Setup

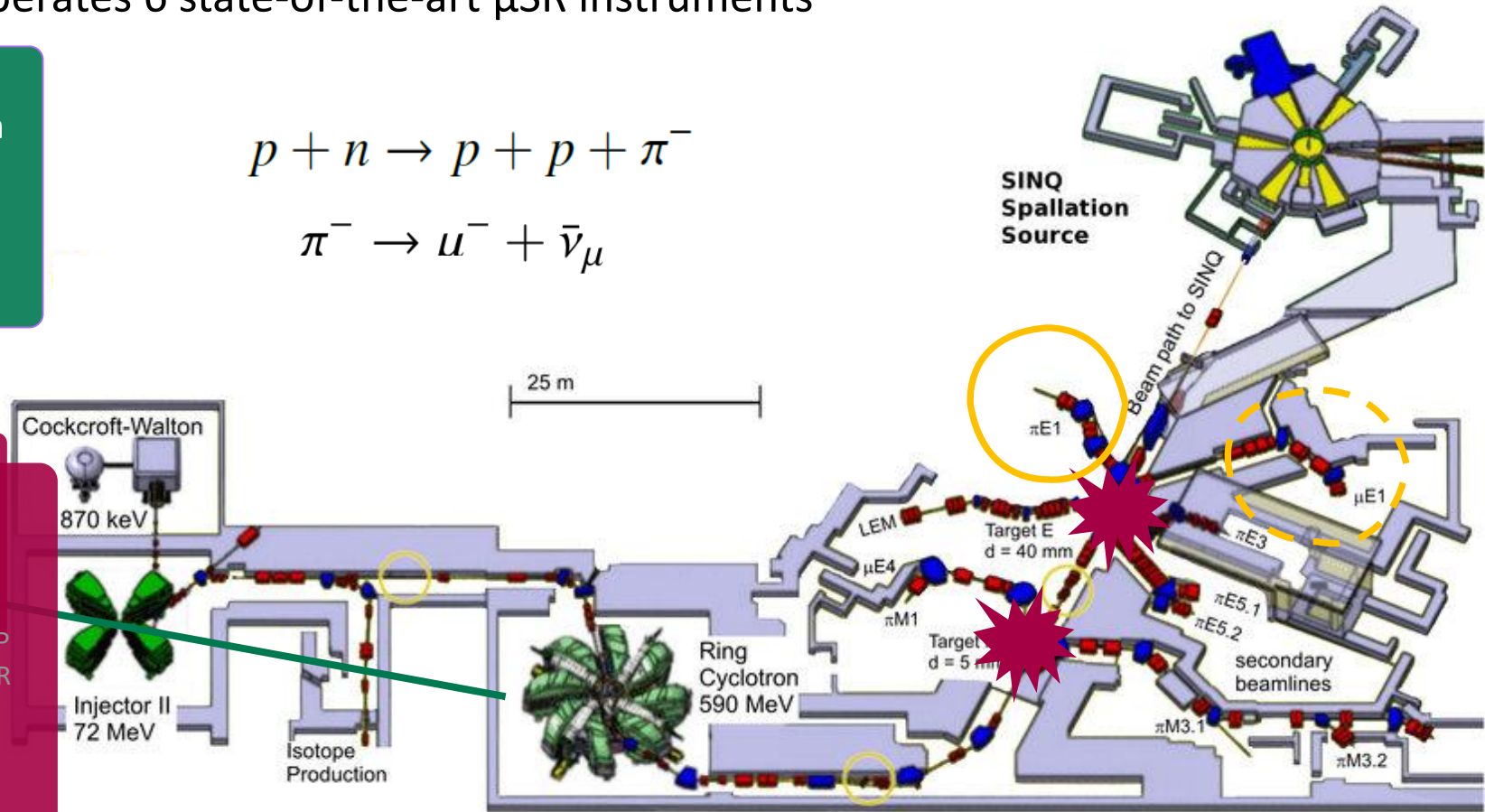
Swiss Muon Source (SμS)

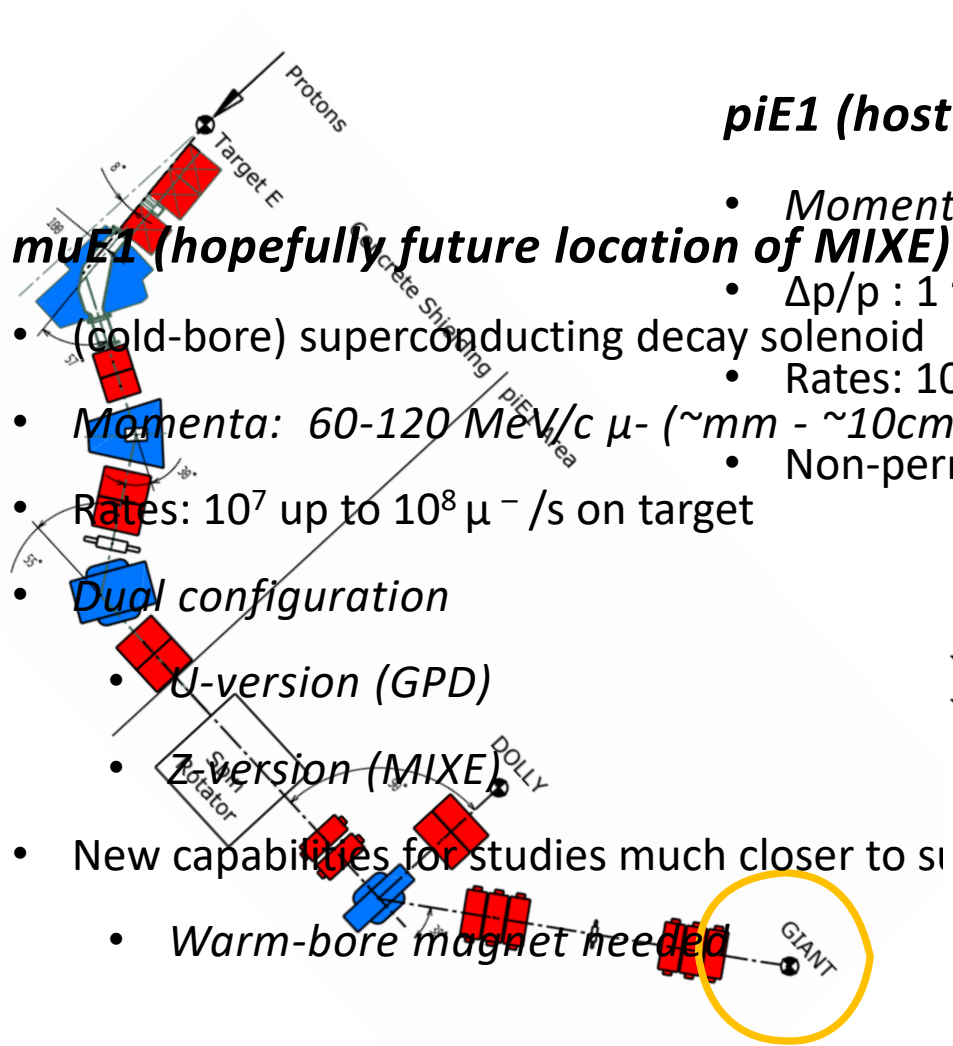
Powered by: **H**igh **I**ntensity **P**roton **A**ccelerator

Operates 6 state-of-the-art μSR instruments



Target M (mince) – 5mm graphite designed for π production (low rate)
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



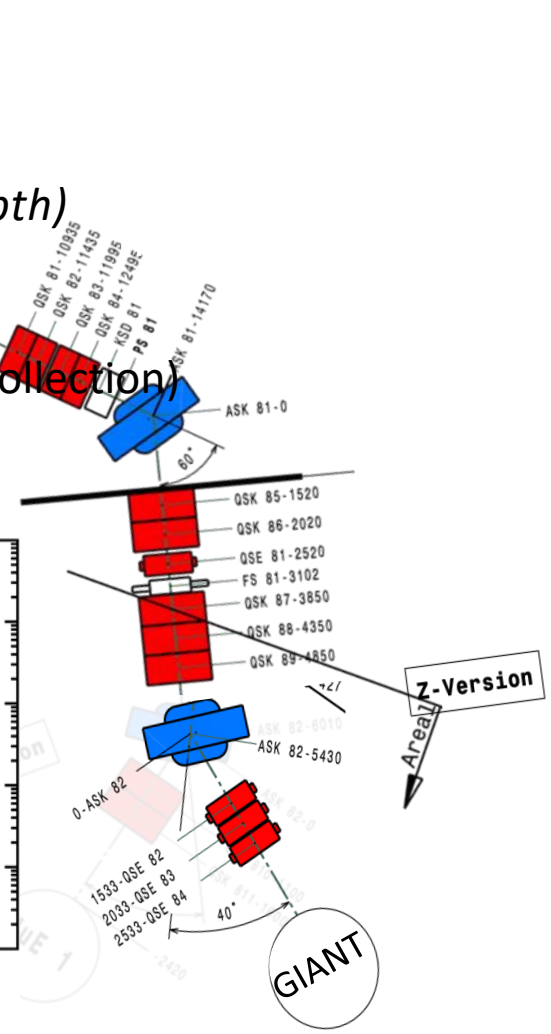
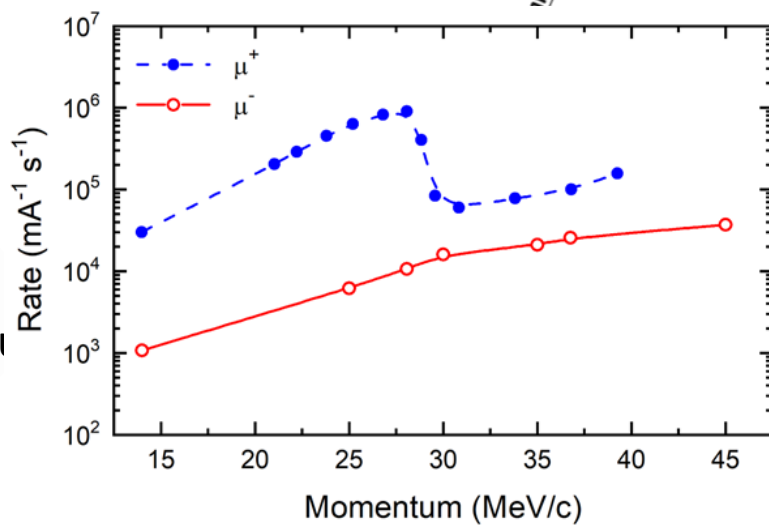


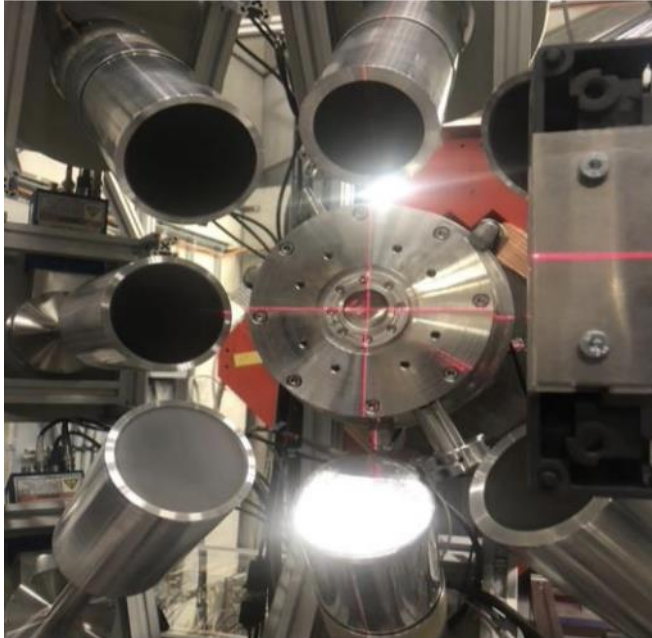
muE1 (hopefully future location of MIXE)

- (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 si
 - Warm-bore magnet needed

piE1 (host all past MIXE campaigns)

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



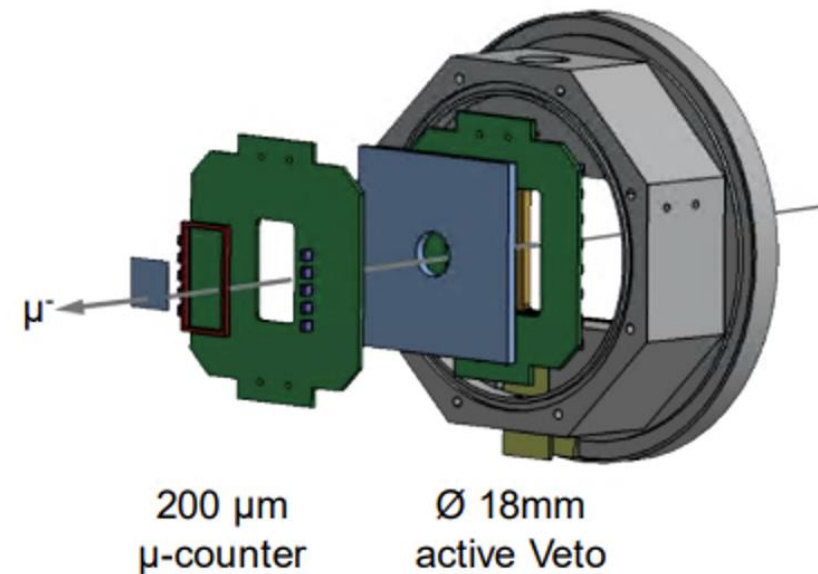


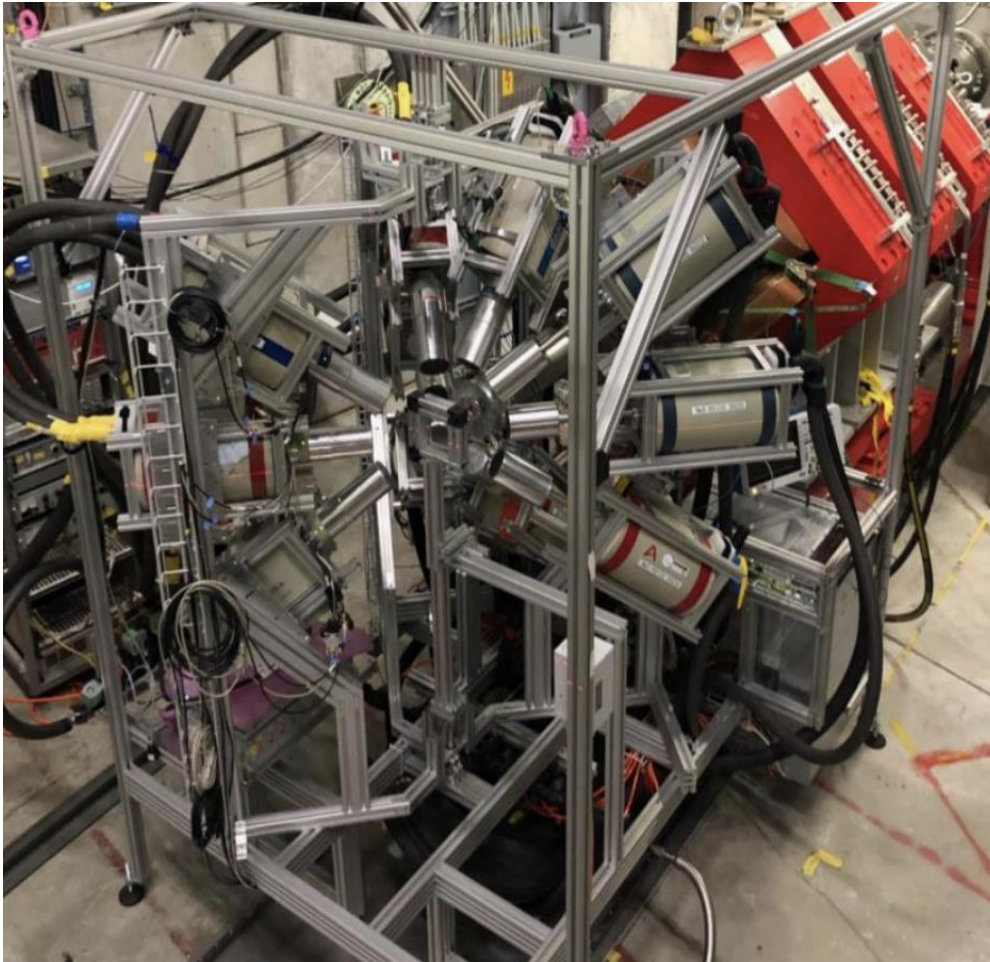
Beam Port

- 10 μ m 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





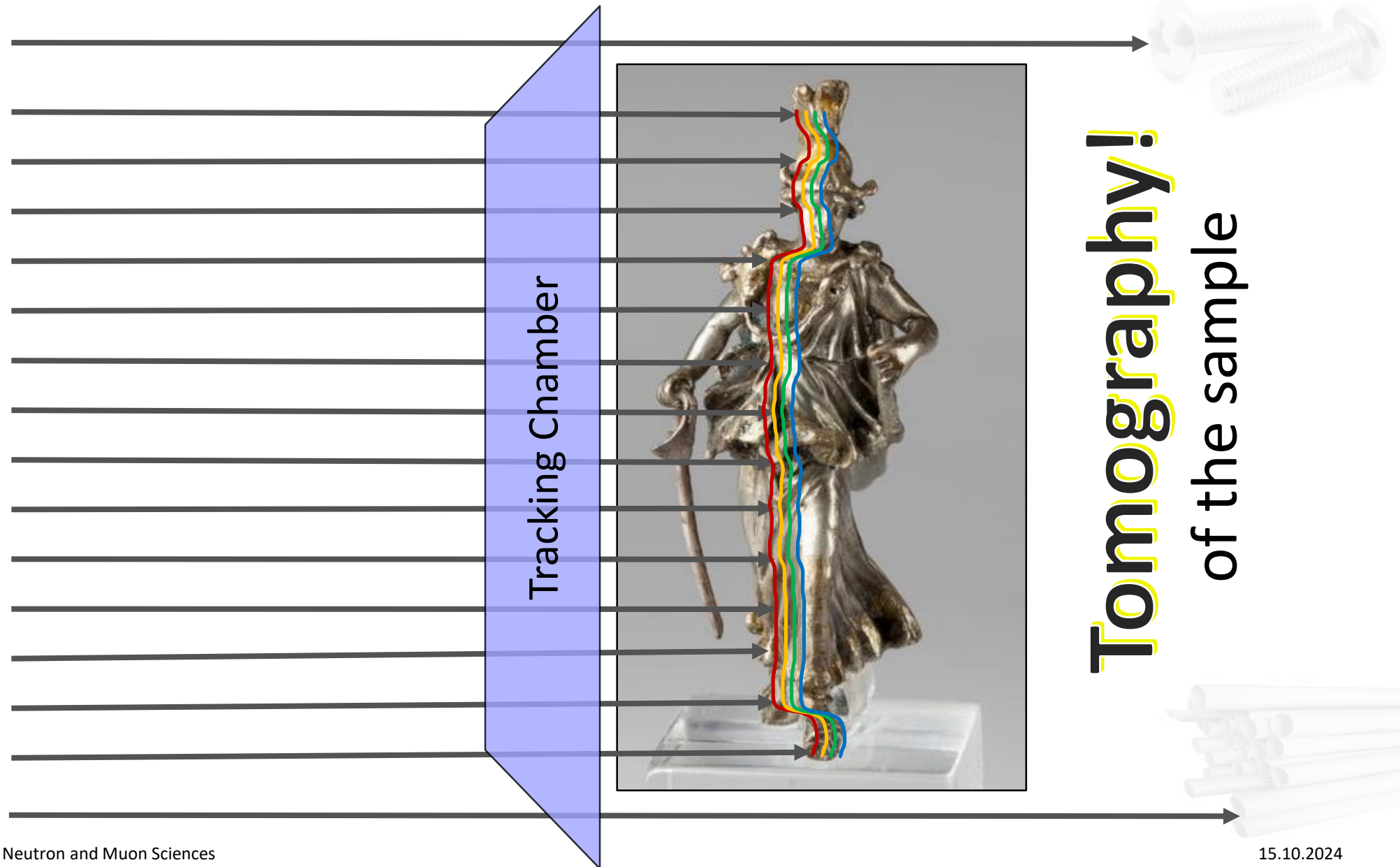
GIANT setup

- The module
 - Up to 8 freely rotating arms (curr. 5)
 - Up to 4 BigMac HPGe per arm
 - Up to 30 HPGe detectors (curr. ~12)
 - HPGe's 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

μ^-



MIXE-T(omography)– Tracker

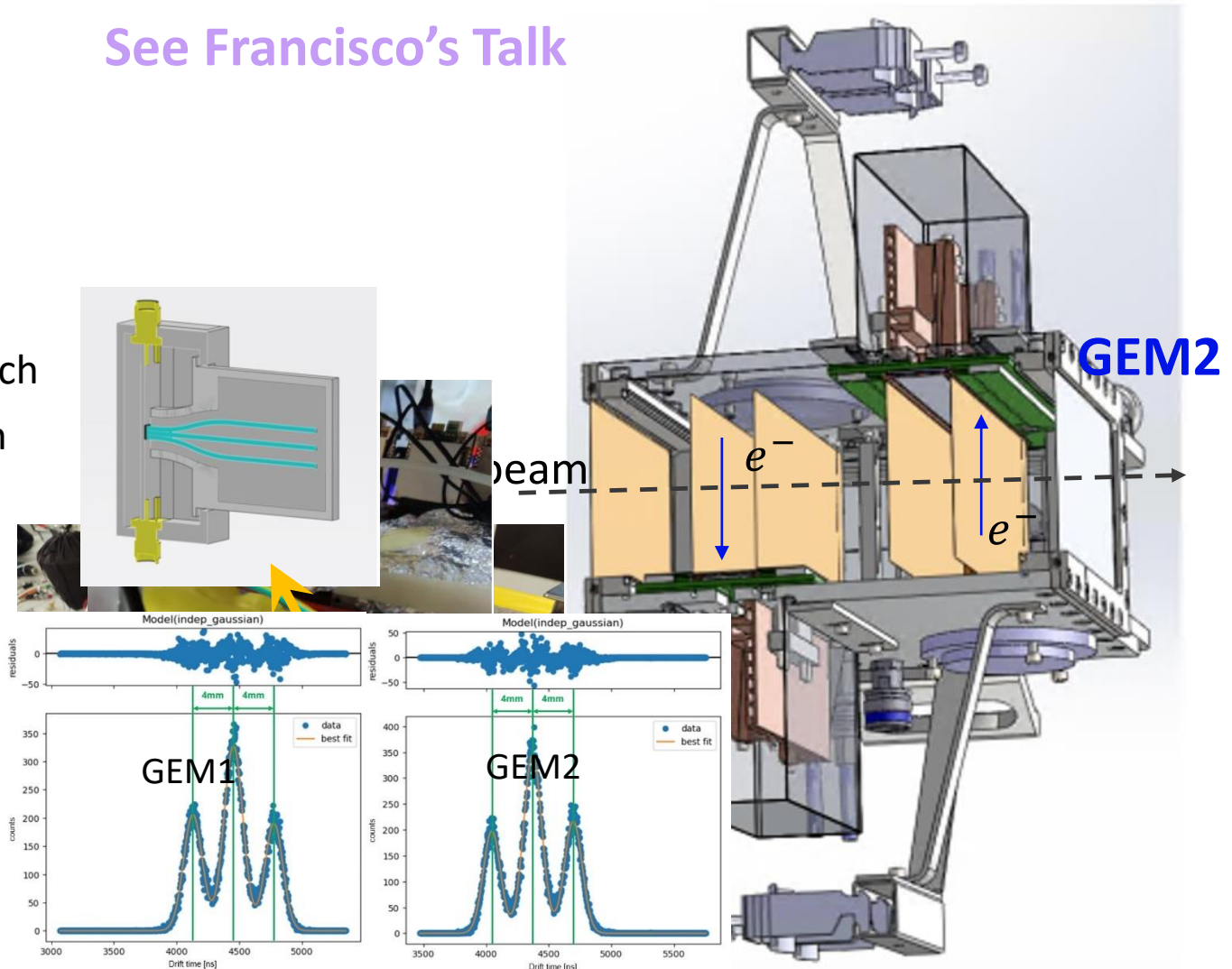
Twin GEM-TPC Tracking chamber HGB4

- Collaboration with F. Garcia (HIP)
- Collaboration with GDD lab and DRD1/CERN
- Active Area $\sim 20 \times 10 \text{ cm}^2$
- Triple GEM stack amplification stage
- 1D strip readout – 1024 ch in total – 0.4 mm pitch
- X position given by the projection 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

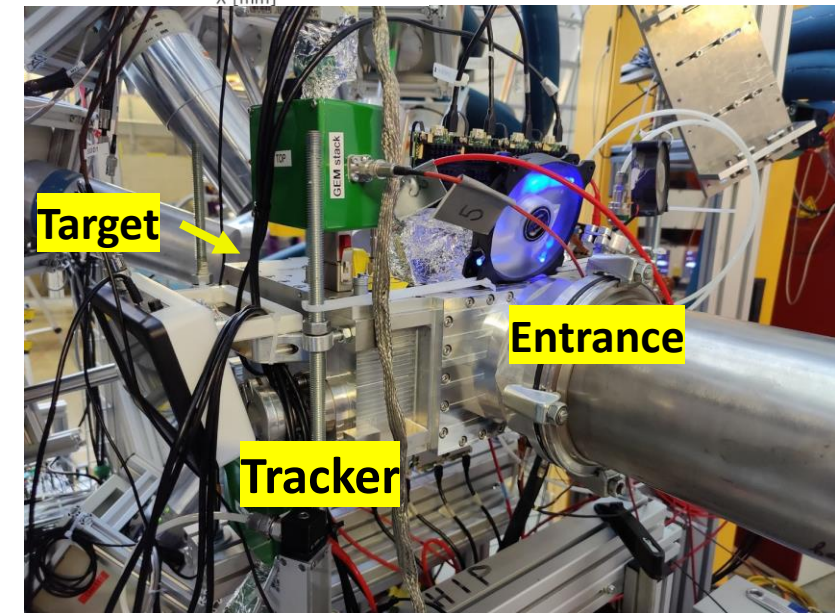
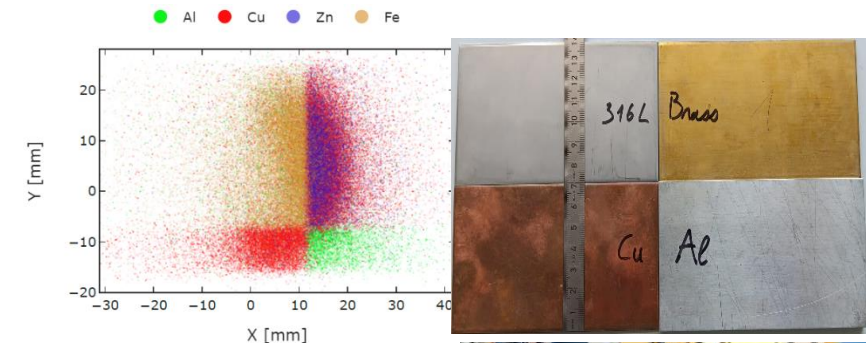
See Francisco's Talk



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 π E1 in Jun 2023
- First universal elemental imaging/tomography using 50-65 MeV/c muons at π E1 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 used during full Jun 2024 MIXE campaign – **analysis ongoing**



MIXE-T(omography): First Result

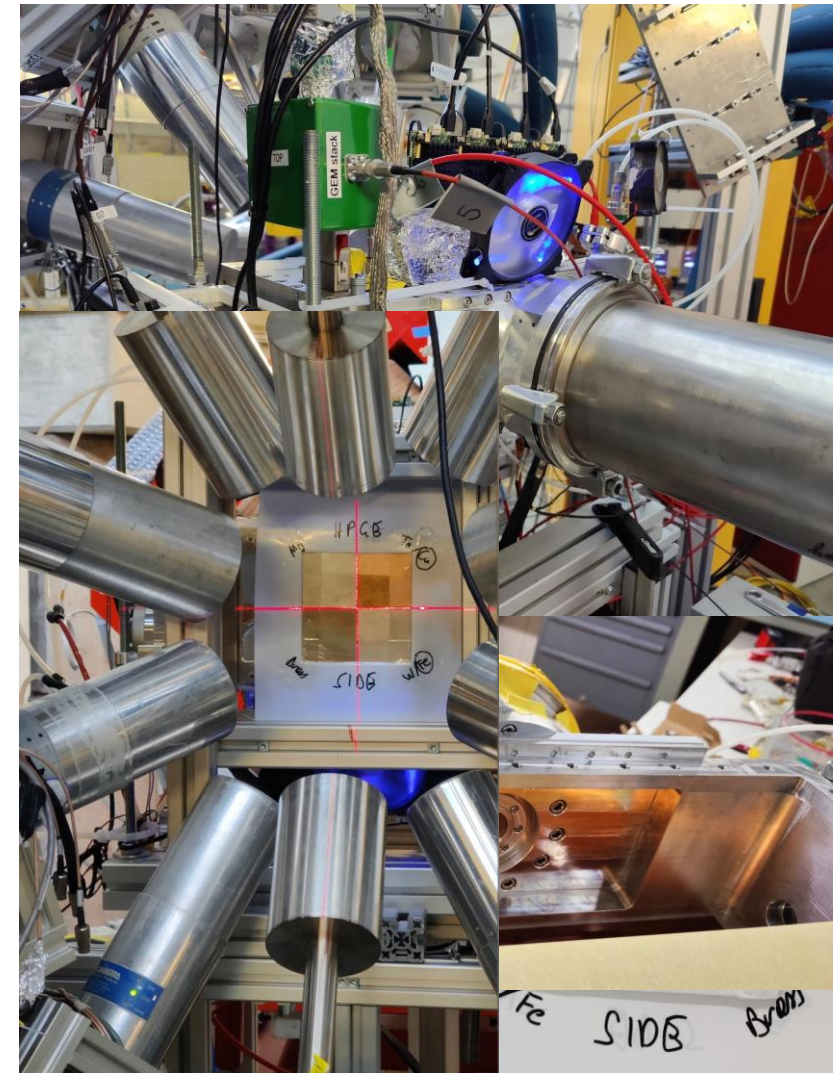
Elemental (isotopic) Imaging: First Result

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 60 MeV/c

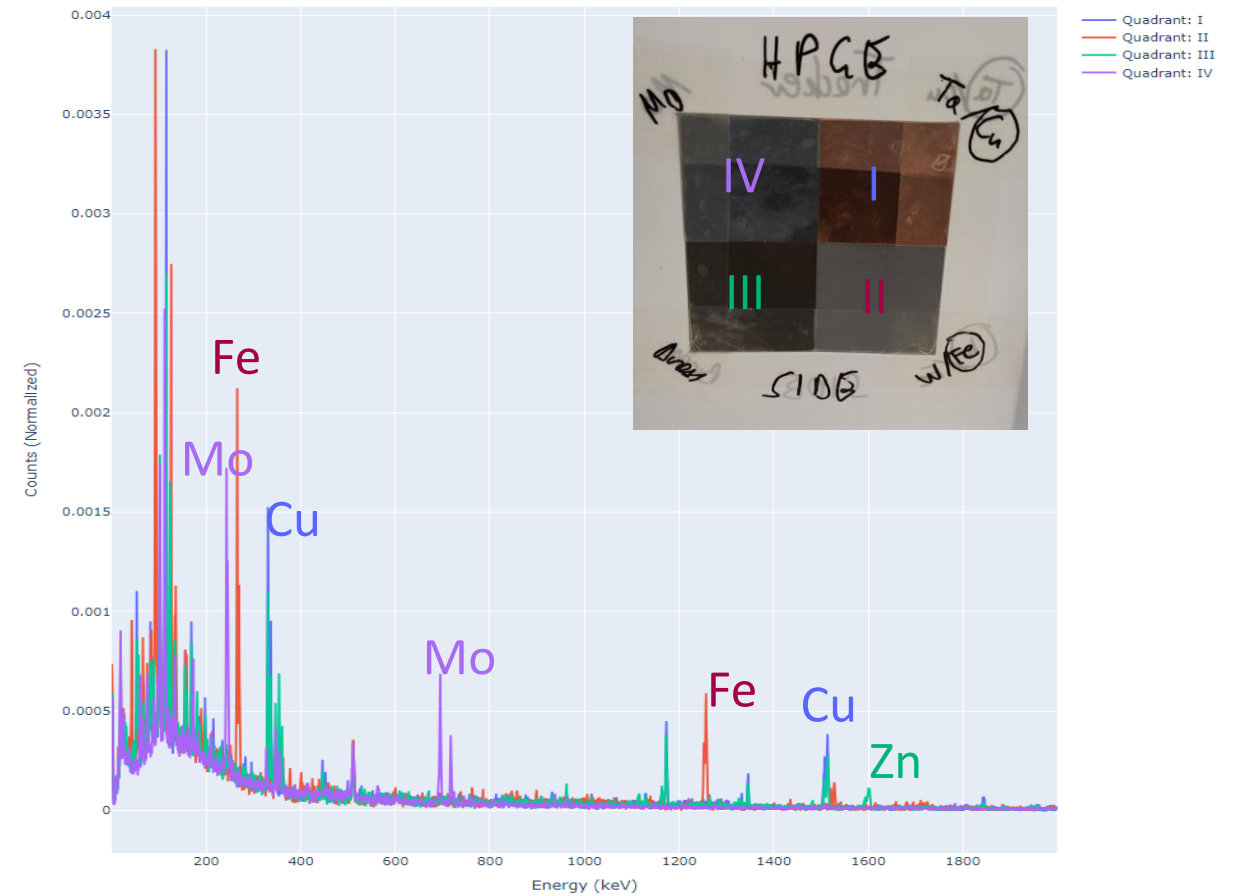
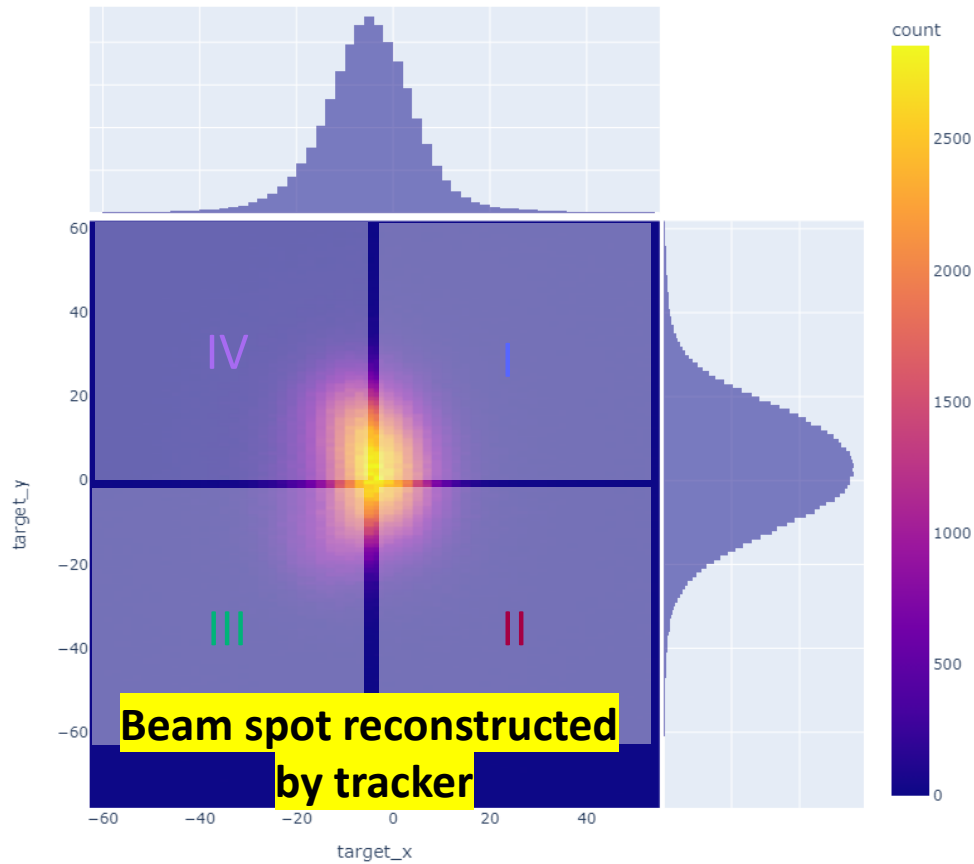
Experimental setup

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



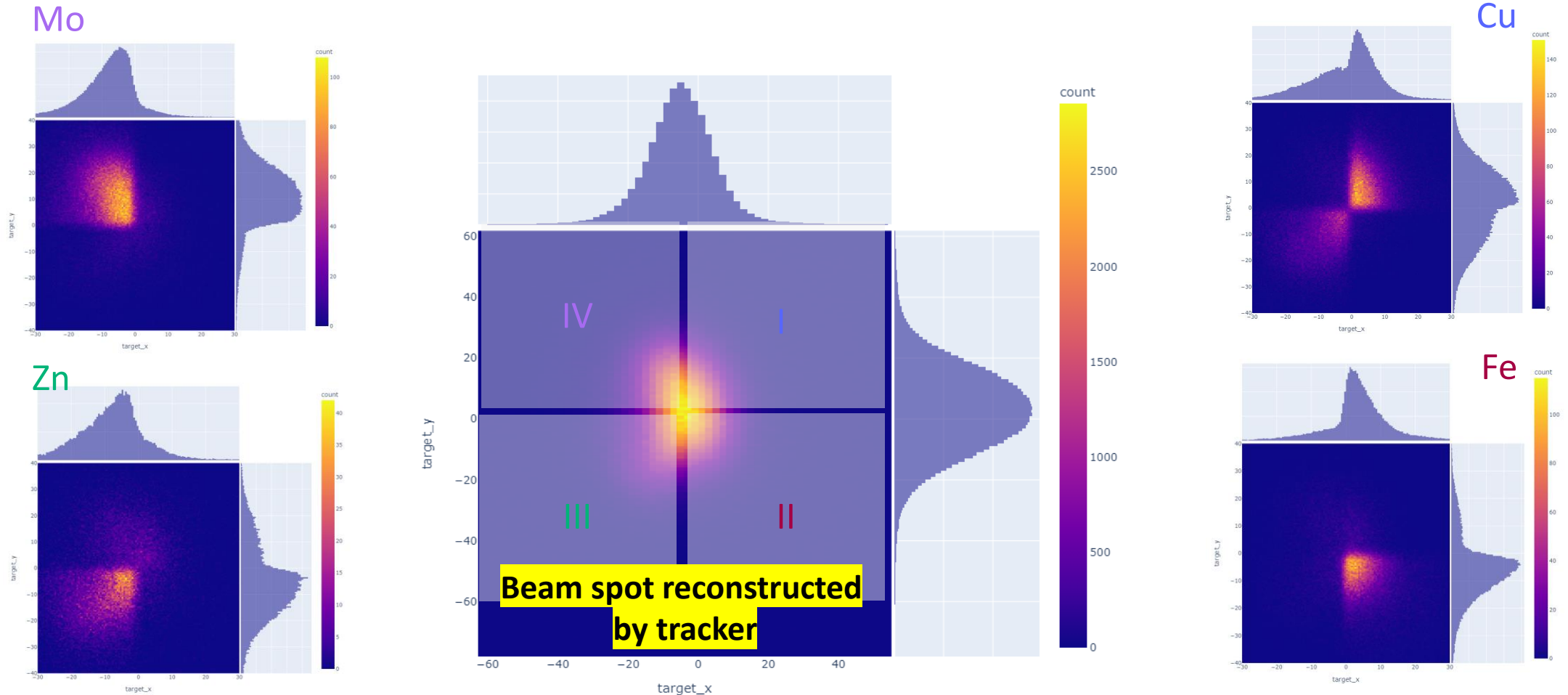
Elemental (isotopic) Imaging: First Result

Result @60MeV/c



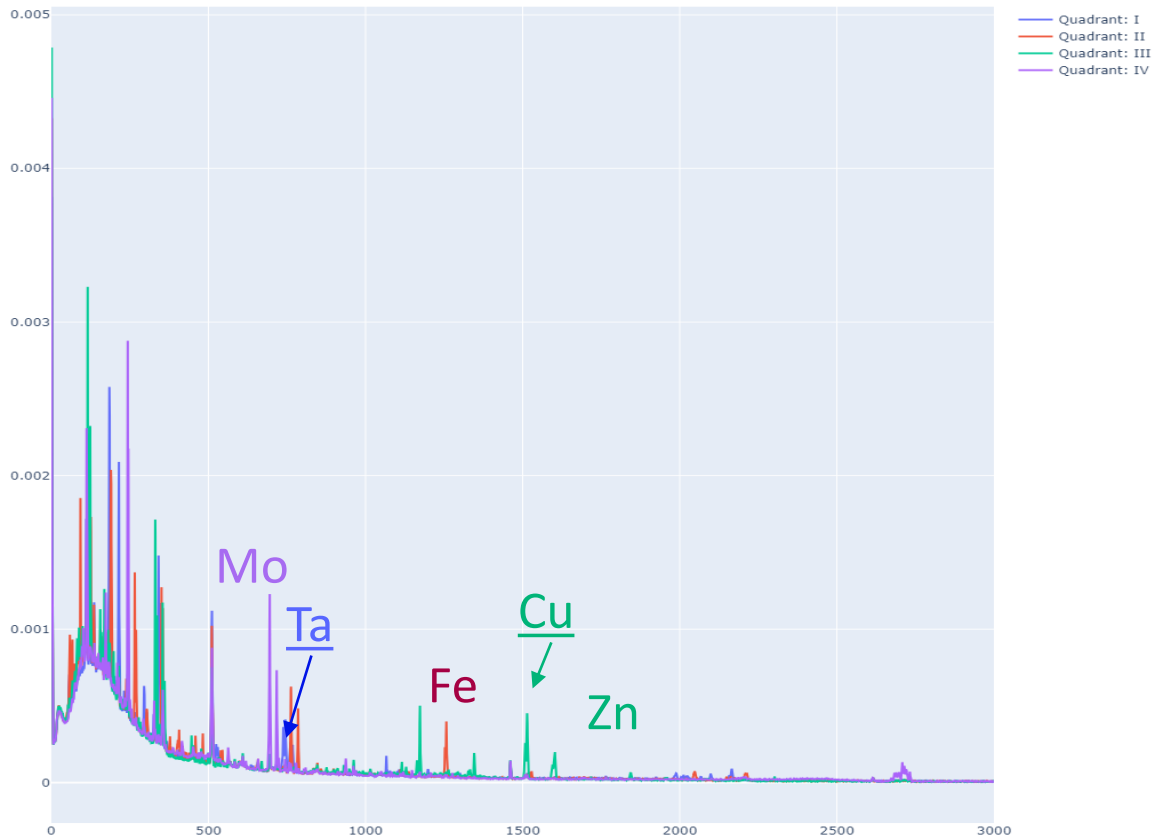
Elemental (isotopic) Imaging: First Result

Result @60MeV/c

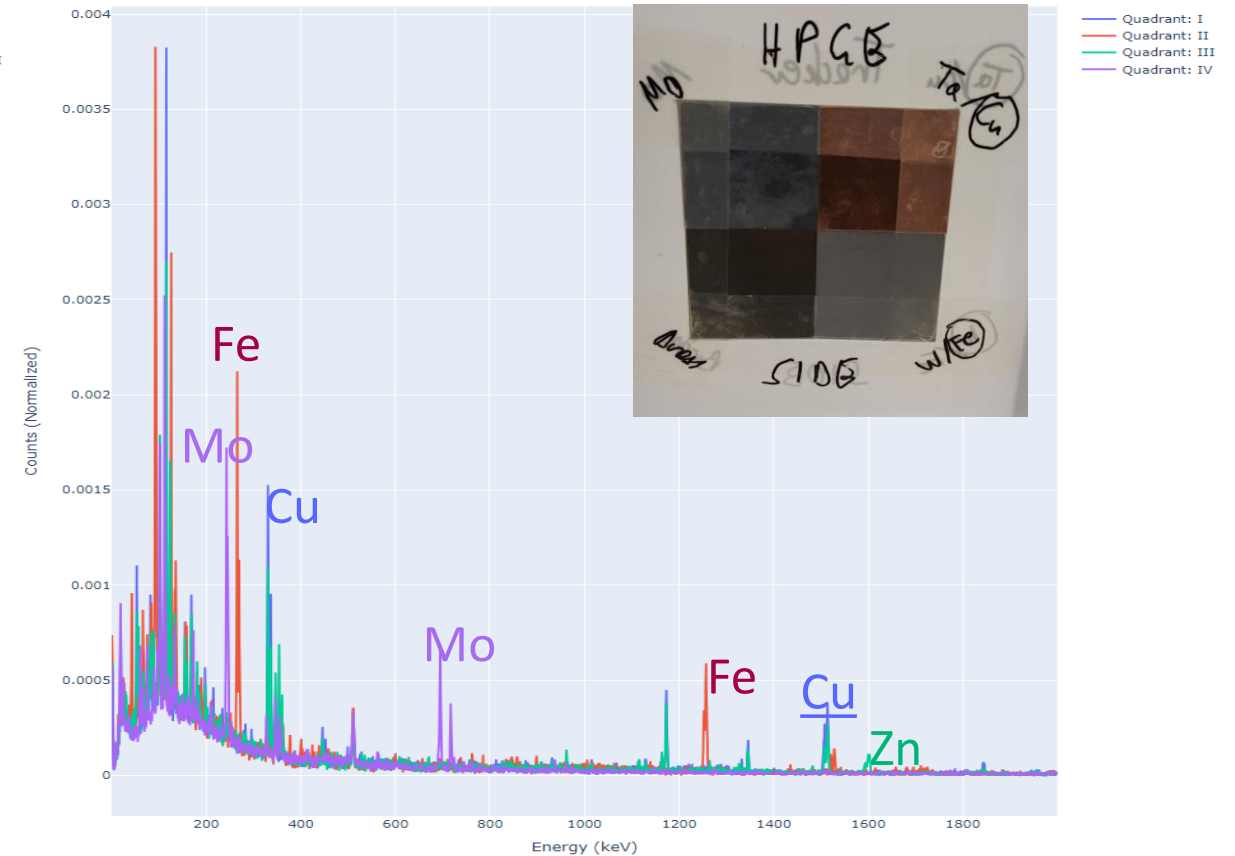


Elemental (isotopic) Imaging: First Result

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

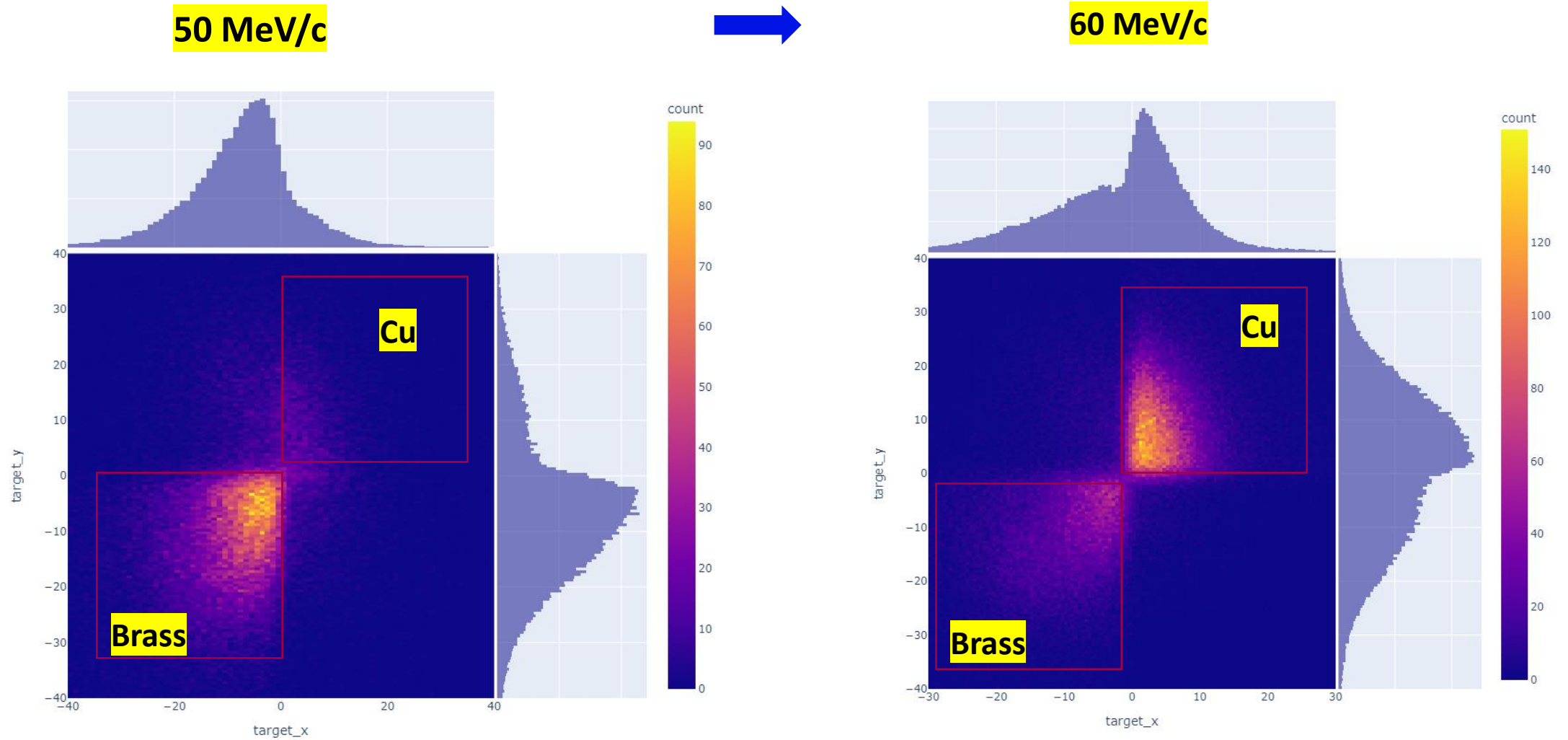


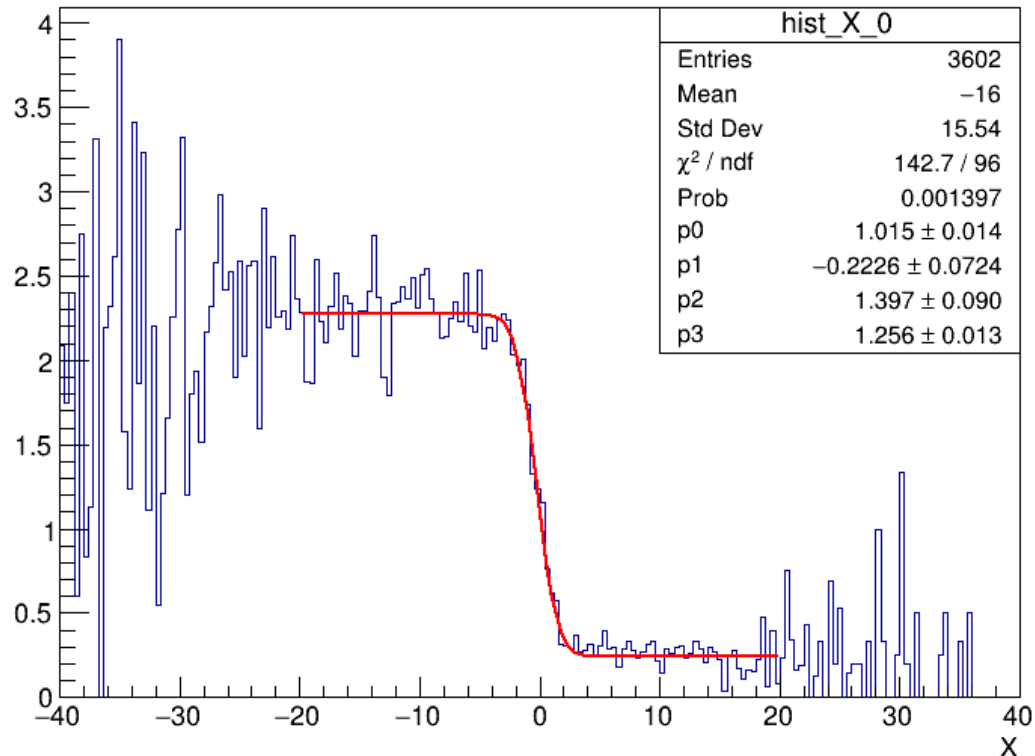
Result @50MeV/c



Result @60MeV/c

Elemental (isotopic) Imaging: First Result





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

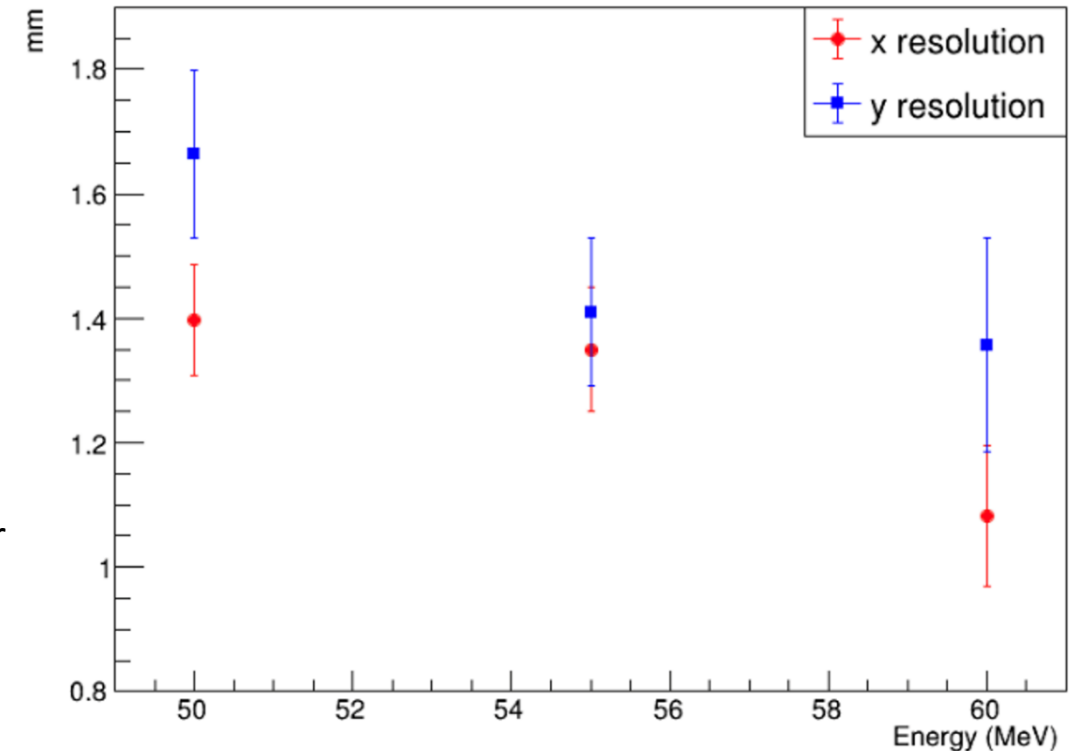
Step 5: Fit result using a Gauss error function

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

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

Elemental (isotopic) Imaging: First Result

- Spatial Resolution @ 60MeV/c with Ar/CO2 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/CO2 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!



First Robust Elemental Imaging/Tomography Demonstration!

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

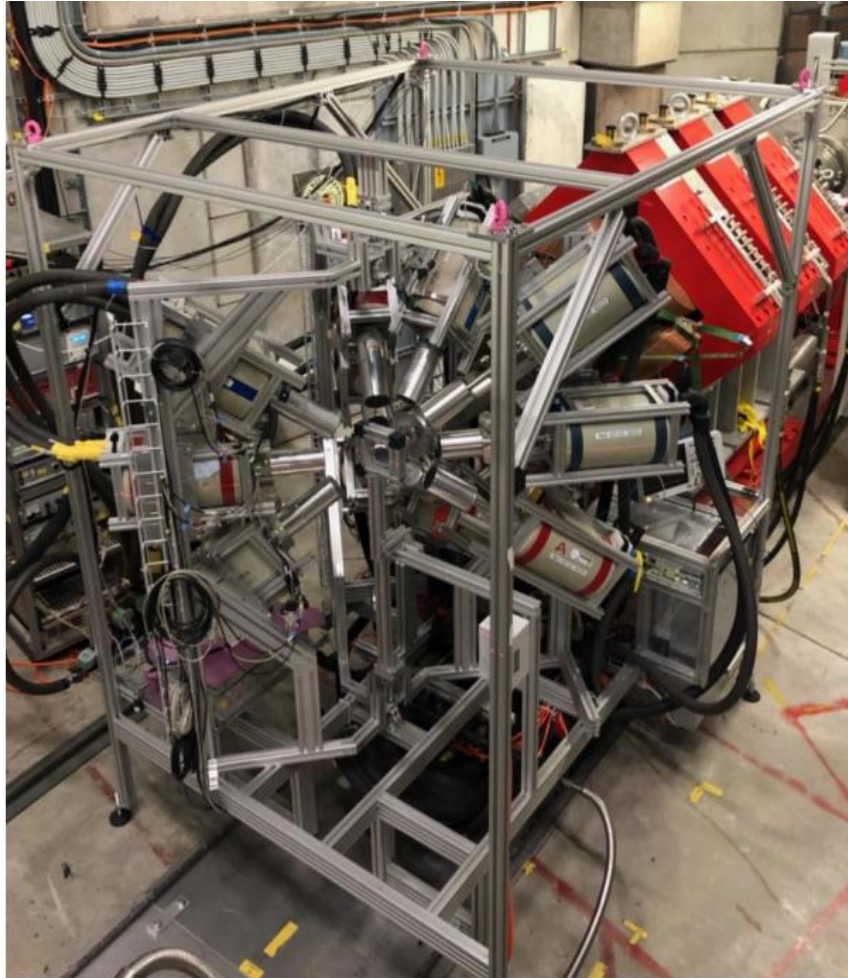
Ongoing Analysis:

- **He/CO₂ 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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muX and ReferenceRadii group

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