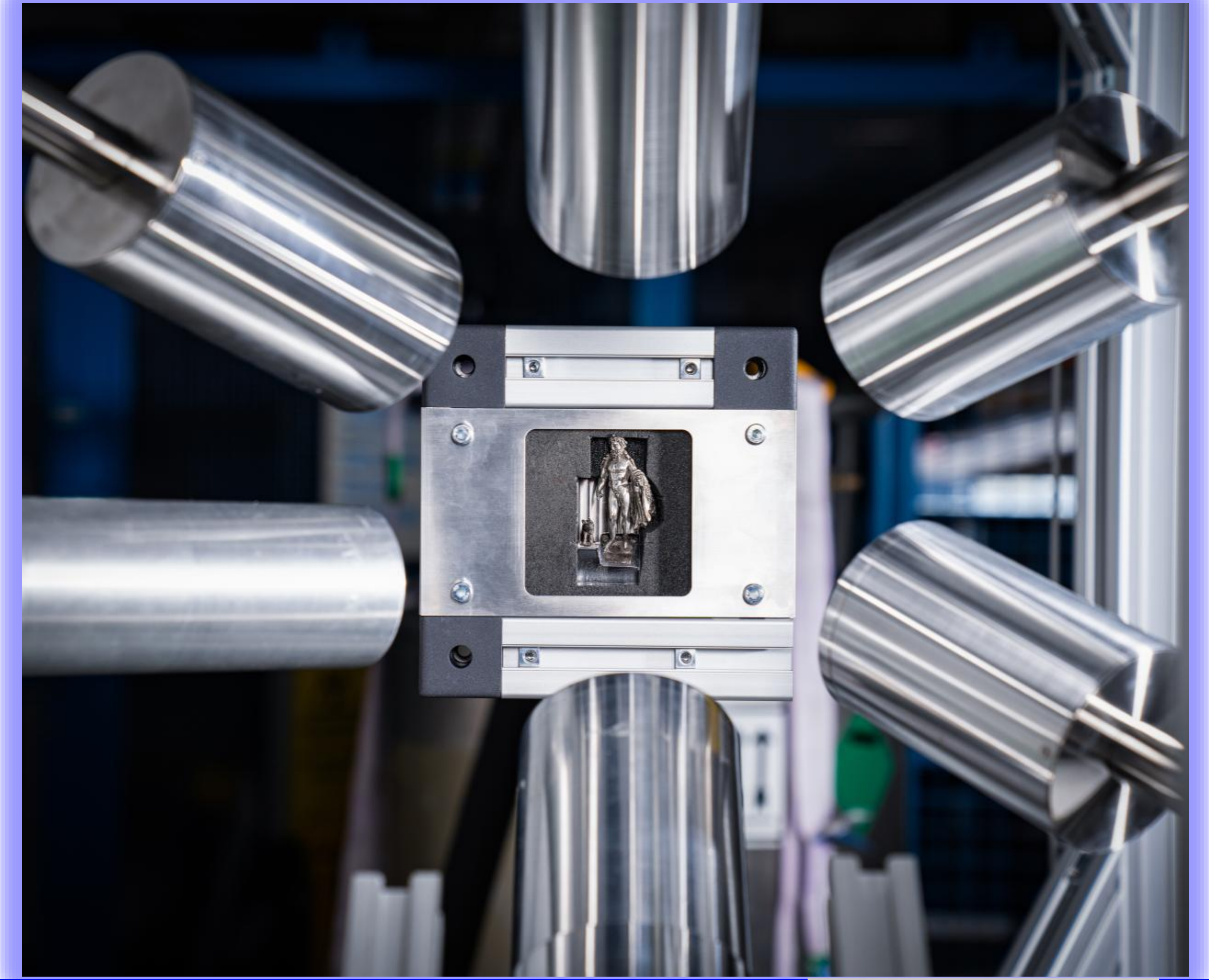
PSI Center for Neutron and Muon Sciences

Muon-Induced X-ray Emission (MIXE) at PSI: Technique and Applications



Maxime Lamotte, on behalf of Michael W. Heiss, Xiao Zhao, and Issa Briki

Laboratory for Muon Spin Spectroscopy (LMU)

International Workshop on Muon Physics at the Intensity and Precision Frontiers (MIP) 2026, 24-28 of April 2026

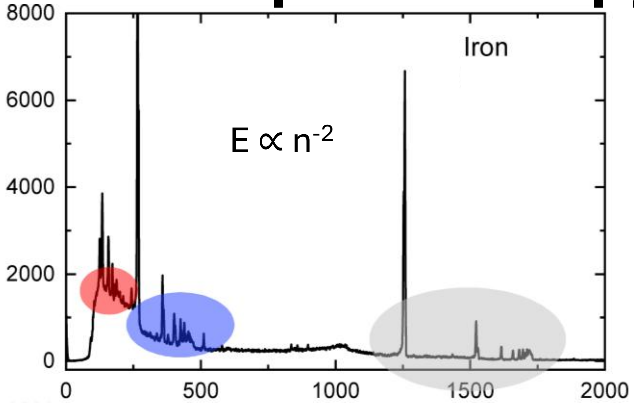
Content

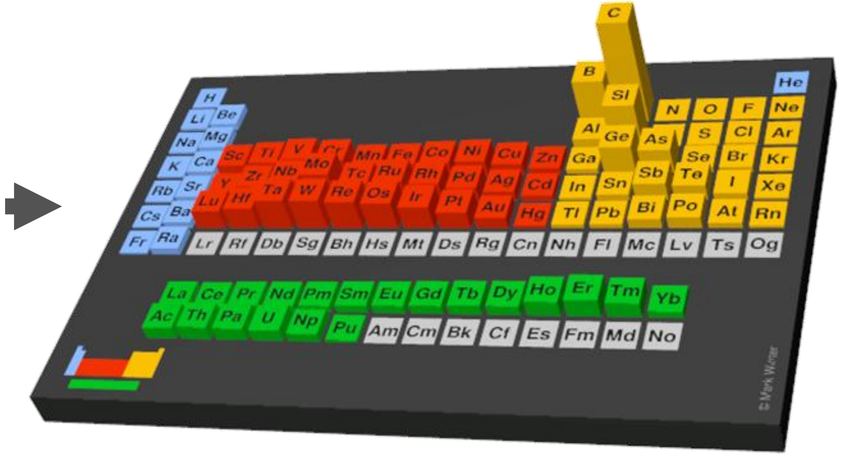
I. Quick introduction
II. Facility & GIANT instrument
III. Cultural heritage examples
IV. Energy storage examples
V. Outlook and updates

Part I

Muon Induced X-ray Emission

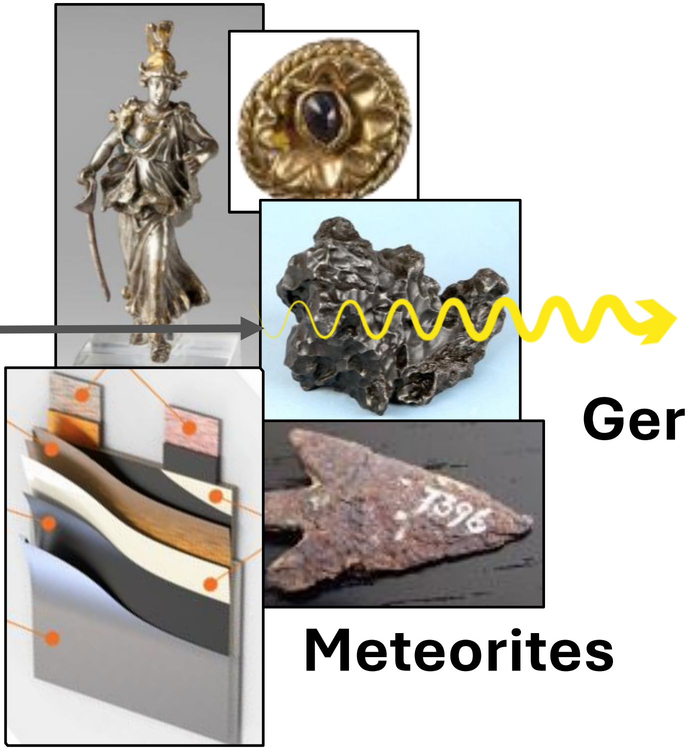
MAXS: Muonic Atom X-ray Spectroscopy
MIXE: Muon Induced X-ray Emission
µXES: µ(muonic) X-ray Emission Spectroscopy





Archeological artifacts

μ^-



Meteorites

Batteries

and more!

High-Purity Germanium Detectors (HPGe)

Highlights:

Sensitive to **all elements** (Z≥2)

Isotopic composition (high Z)

Indications of **chemical states**

Depth-resolved (~*µm* to ~*cm*)

Non-destructive

Tomography capable

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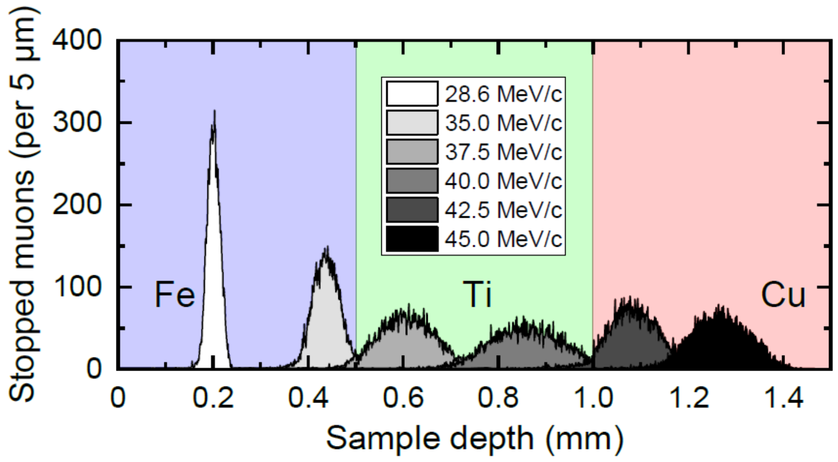
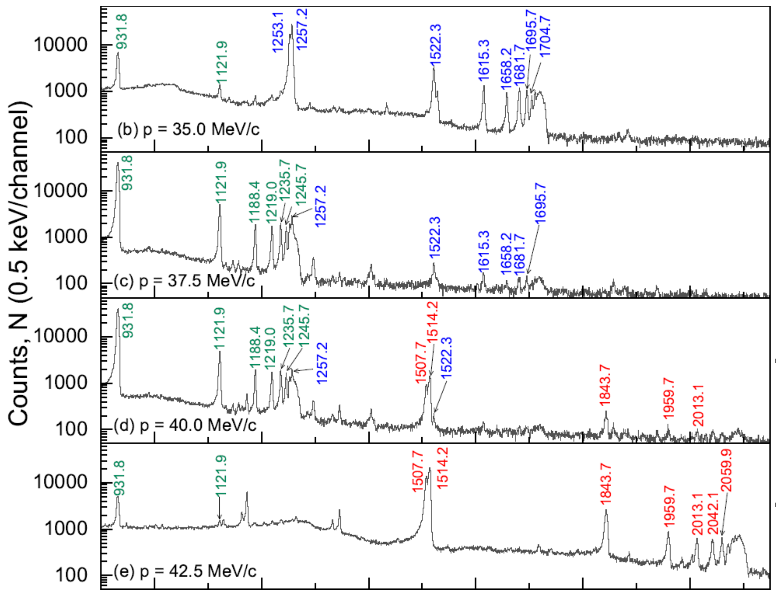
MIXE: Muon Induced X-ray Emission – Physics

- Muon is implanted (Bragg peak; depth given by momentum and density of material)
- M … gher excited states around:



- C … e … th …
- M …



35 MeV/c

37.5 MeV/c

40 MeV/c

42.5 MeV/c

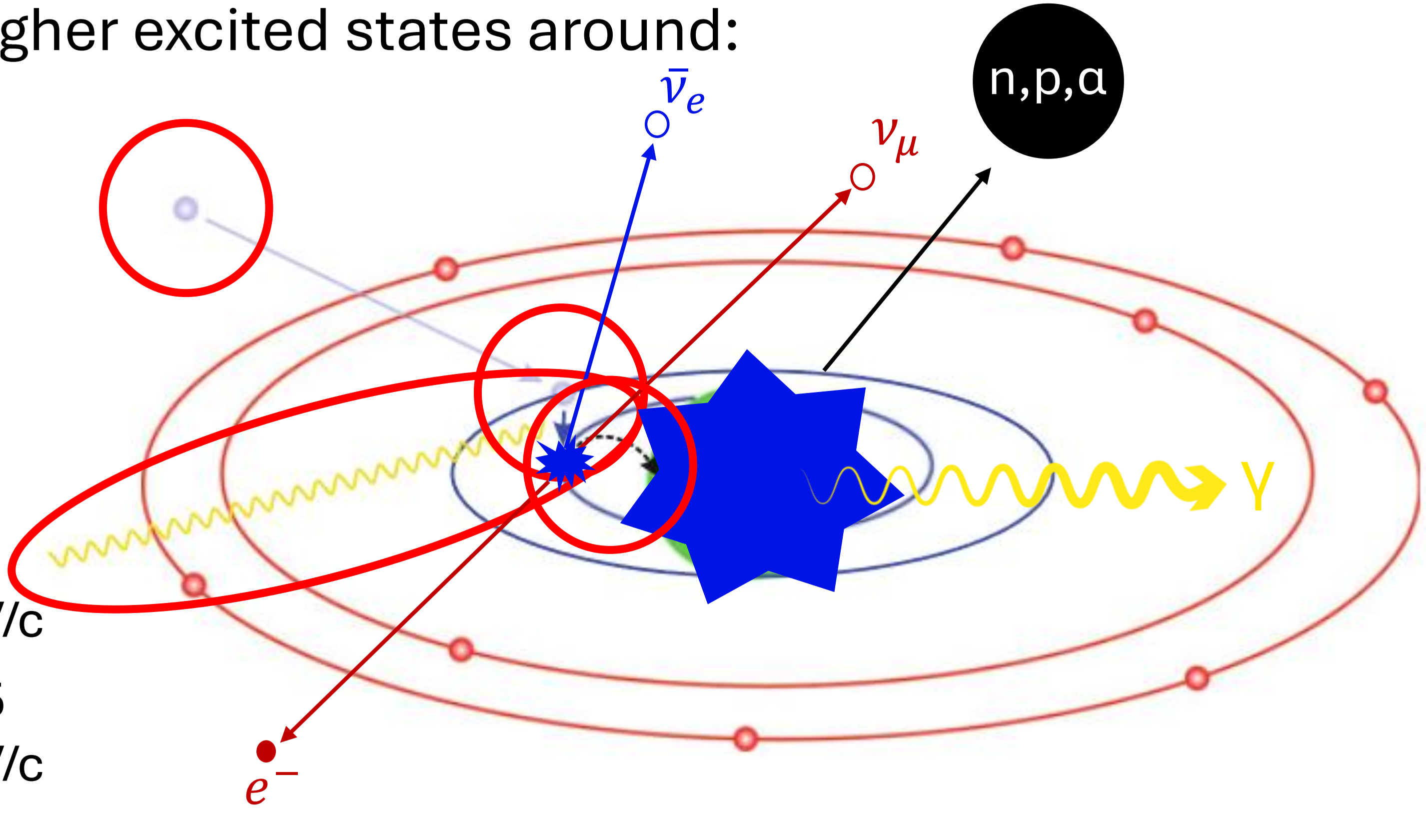
Fe

- M …

Ti

Cu

effe…



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

See Elemental Analysis I (A. Hillier) Lecture!

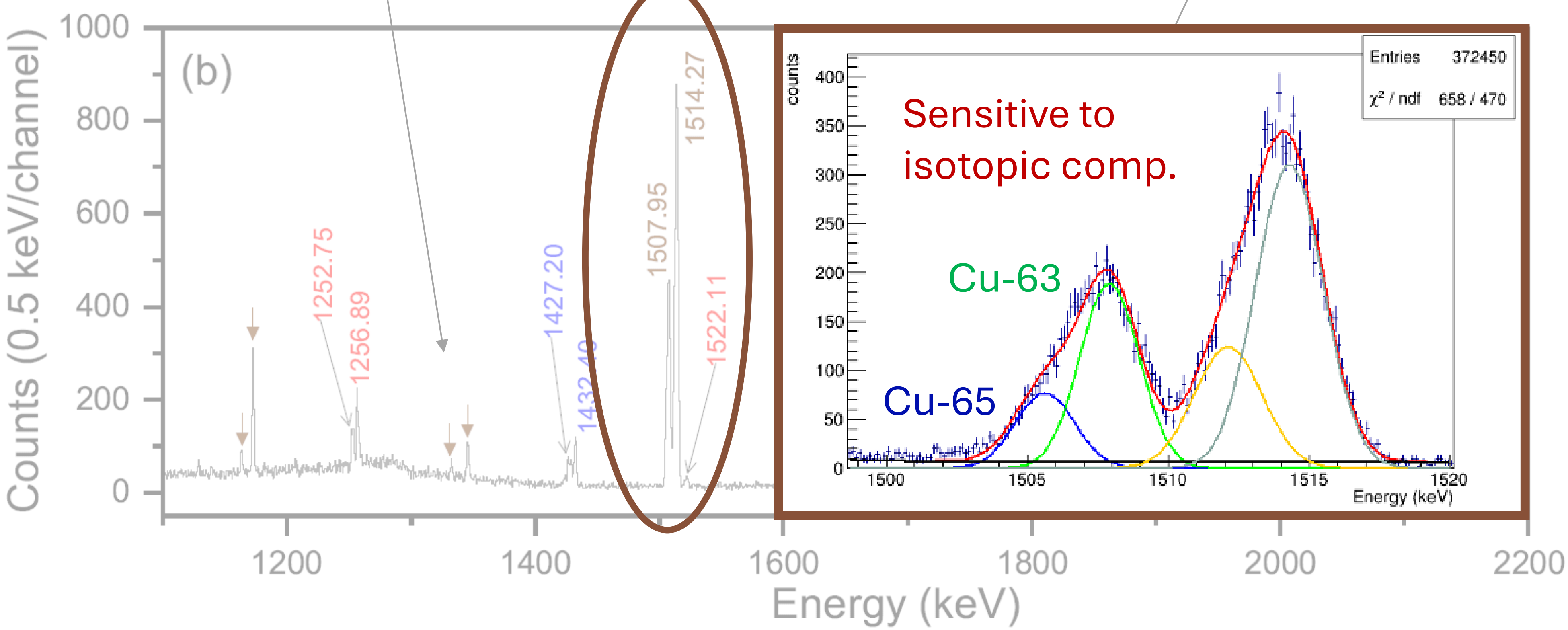
MIXE: Muon Induced X-ray Emission – Example: Copper

X-ray cascade:
prompt, ROI: <100ns

compare:
e-K_α = 8.04 keV

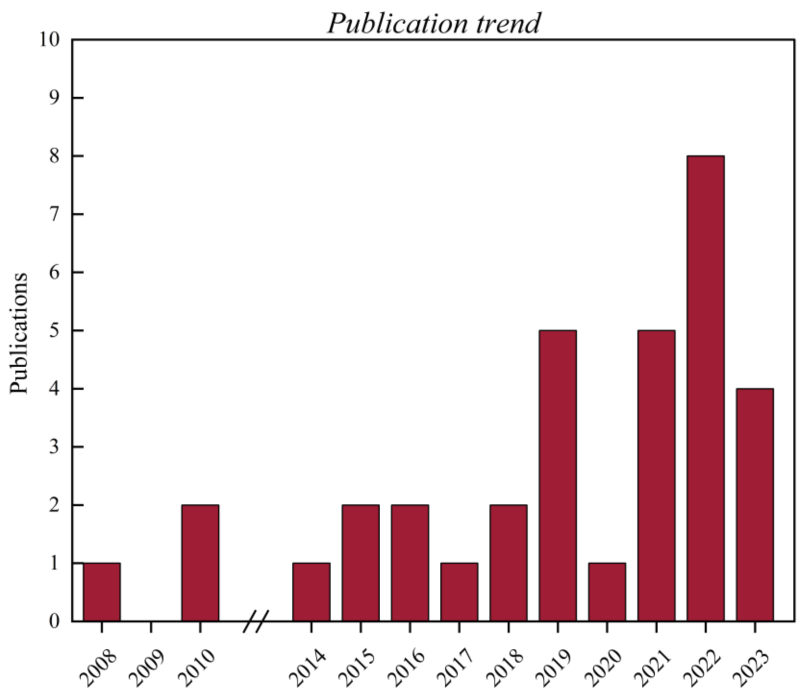
μ-K_α (2p-1s)

Nuclear Capture and
subsequent decay:
delayed, ROI: >100ns



See Elemental Analysis I (A. Hillier) Lecture!

MIXE: Muon Induced X-ray Emission – A quick history



MIXE publications in cultural heritage

Source: M. Cataldo, PhD thesis, 2024

Part II

Muon Induced X-ray Emission

Facility & GIANT instrument

High Intensity Proton Accelerator Facility (HIPA)

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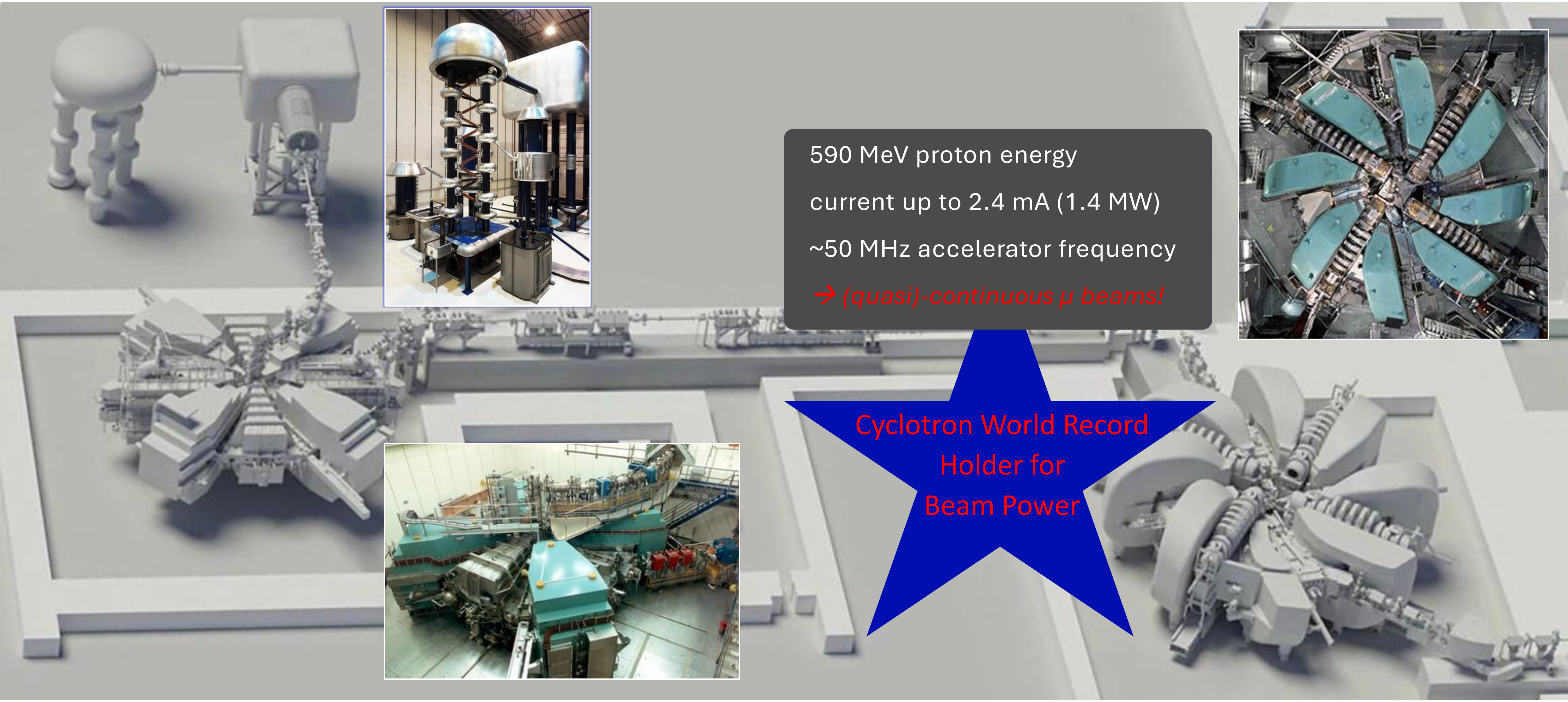

590 MeV proton energy

current up to 2.4 mA (1.4 MW)

~50 MHz accelerator frequency

→ *(quasi)-continuous μ beams!*

Cyclotron World Record Holder for Beam Power

See Muon Production (A. Amato) and Facilities Lectures!

Swiss Muon Source (SμS)

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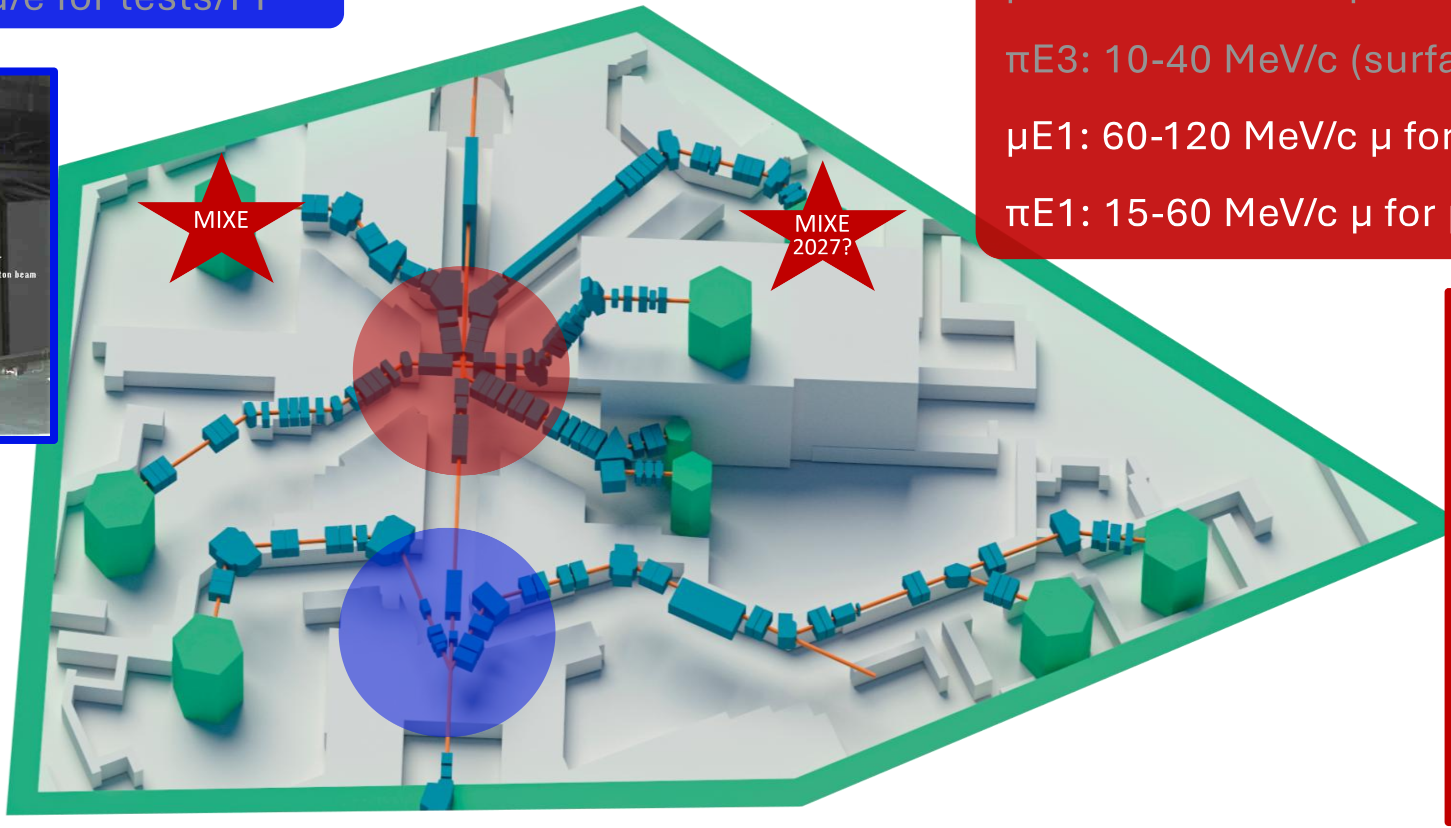
Target M (mince) – 5mm graphite

designed for π production (low rate)

πM3: 10-40 MeV/c (surface) μ^+ for μSR

πM1: 10-300 MeV/c π → μ/e for tests/PP

$$\mu^+ + \nu_\mu \leftarrow \pi^+$$
$$\mu^- + \overline{\nu}_\mu \leftarrow \pi^-$$



Target E (epaisse) – 40mm graphite

designed for π/μ production (high rate)

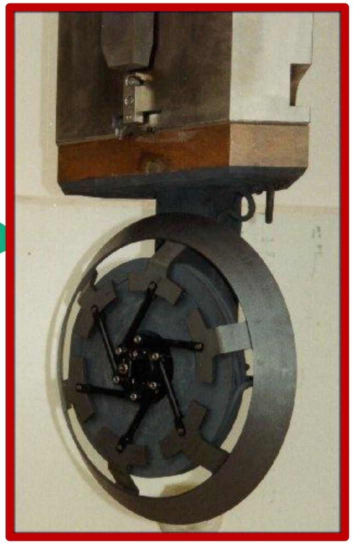
πE5: 20-120 MeV/c high rate μ for PP

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

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

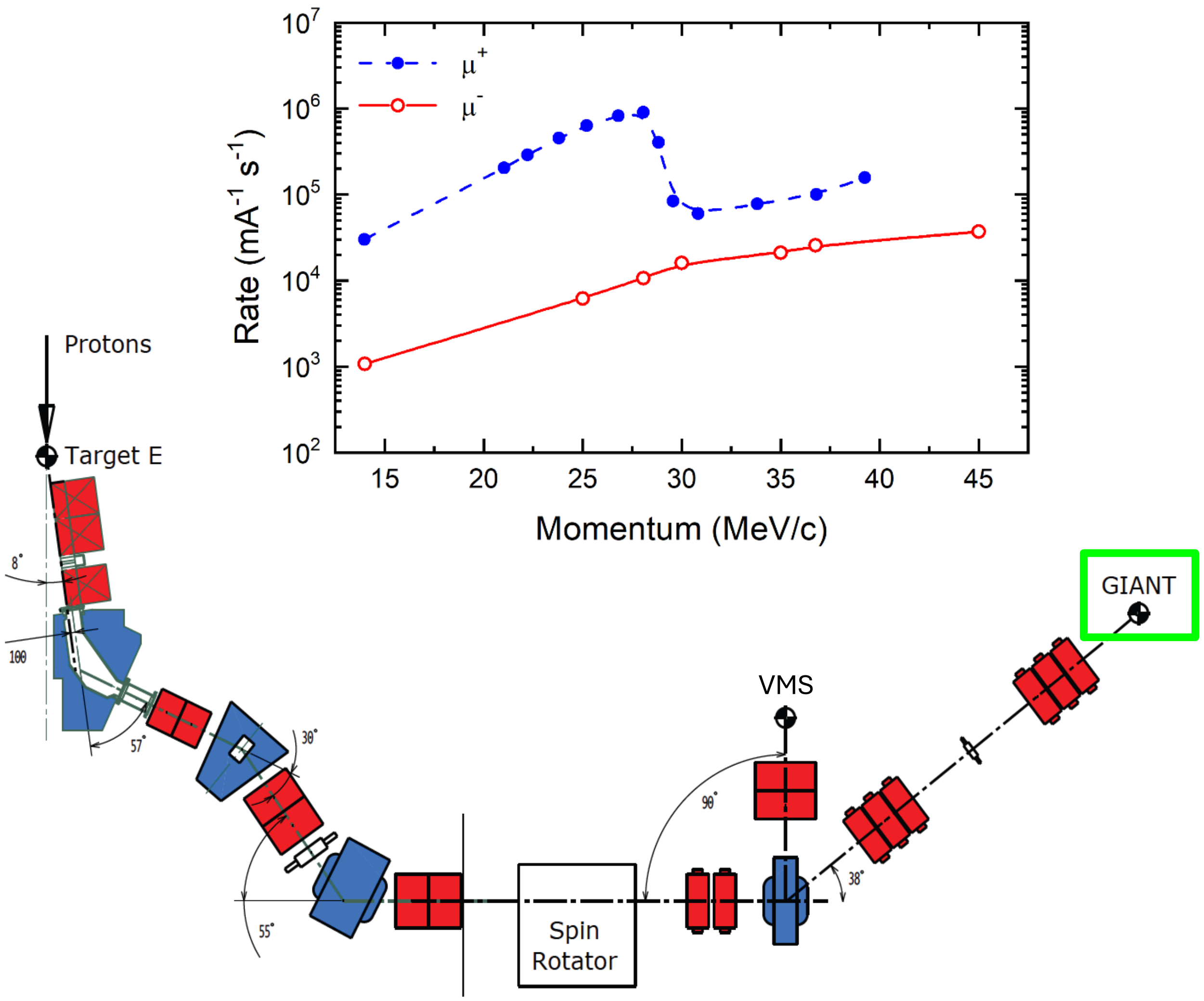
μE1: 60-120 MeV/c μ for μSR (and future **MIXE**)

πE1: 15-60 MeV/c μ for μSR, **MIXE**, PP



See Muon Production (A. Amato) and Facilities Lectures!

Muon Induced X-ray Emission – Beamlines: πE1



High intensity π beamline at target E

- production of "cloud" π^- and decay to μ^-
- typical μ^- momenta: **15-60 MeV/c**

  momentum bite: **~0.2% to 3% (FWHM)**

  implantation depths: **~10um to ~cm**

Rates from 10^3 up to 10^5 μ^-/s on target

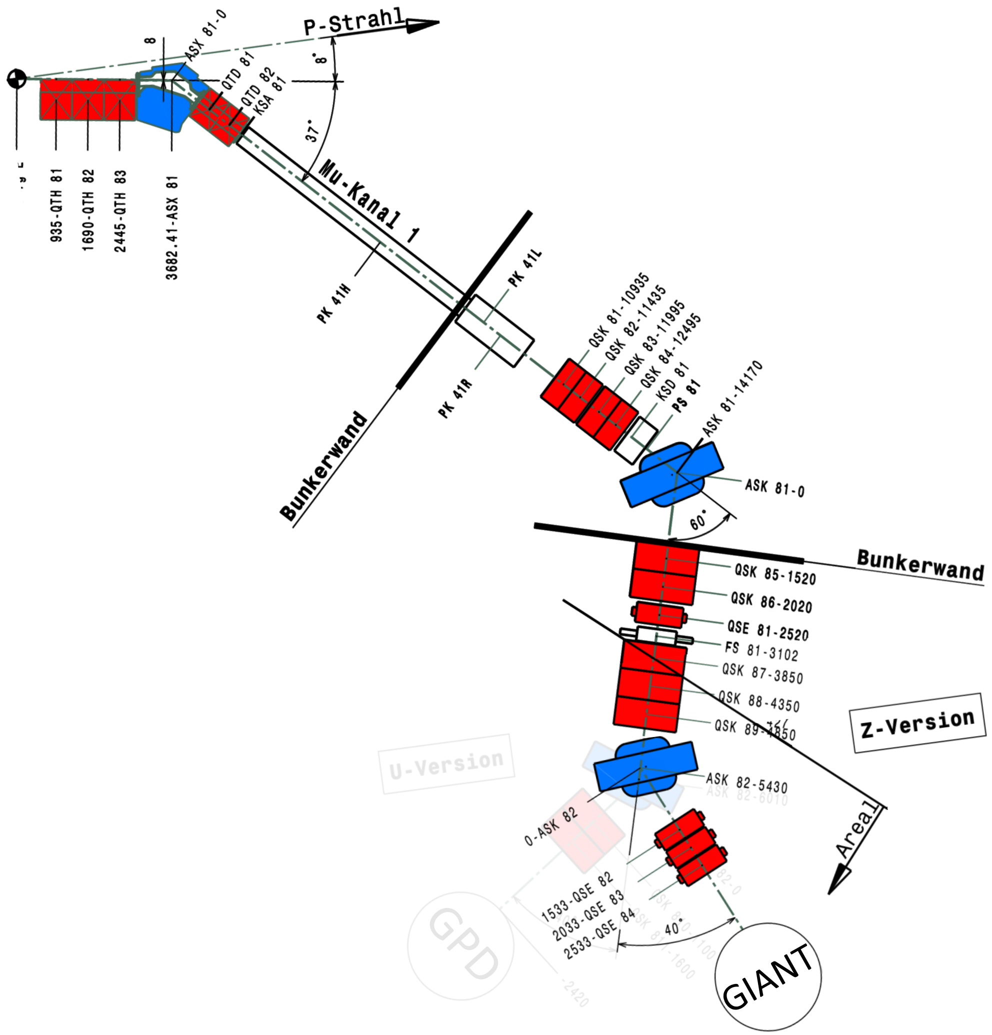
- *For the "average" sample, we collect enough statistics within ~1 hour*

All past MIXE campaigns hosted at πE1.2

- non-permanent installation

Biswas et al., Appl. Sci. 2022, 12(5), 2541

Muon Induced X-ray Emission – Beamlines: μE1



High intensity μ beamline at target E

- (cold-bore) superconducting decay solenoid
- typical μ^- momenta: **60-120 MeV/c**

  momentum bite: **1% to 3% (FWHM)**

  implantation depths: **~mm to ~10cm**

Rates from 10^7 up to 10^8 μ^-/s on target

Dual configuration: U (GPD) and Z (GIANT)

Future beam-line for MIXE

- high momentum / high-rate studies (degrader)
- shorter πE1 campaign for low mom. / high res.

See High Pressure (R. Khassanov) Lecture!

GermanIum Array for Non-destructive Testing (GIANT)

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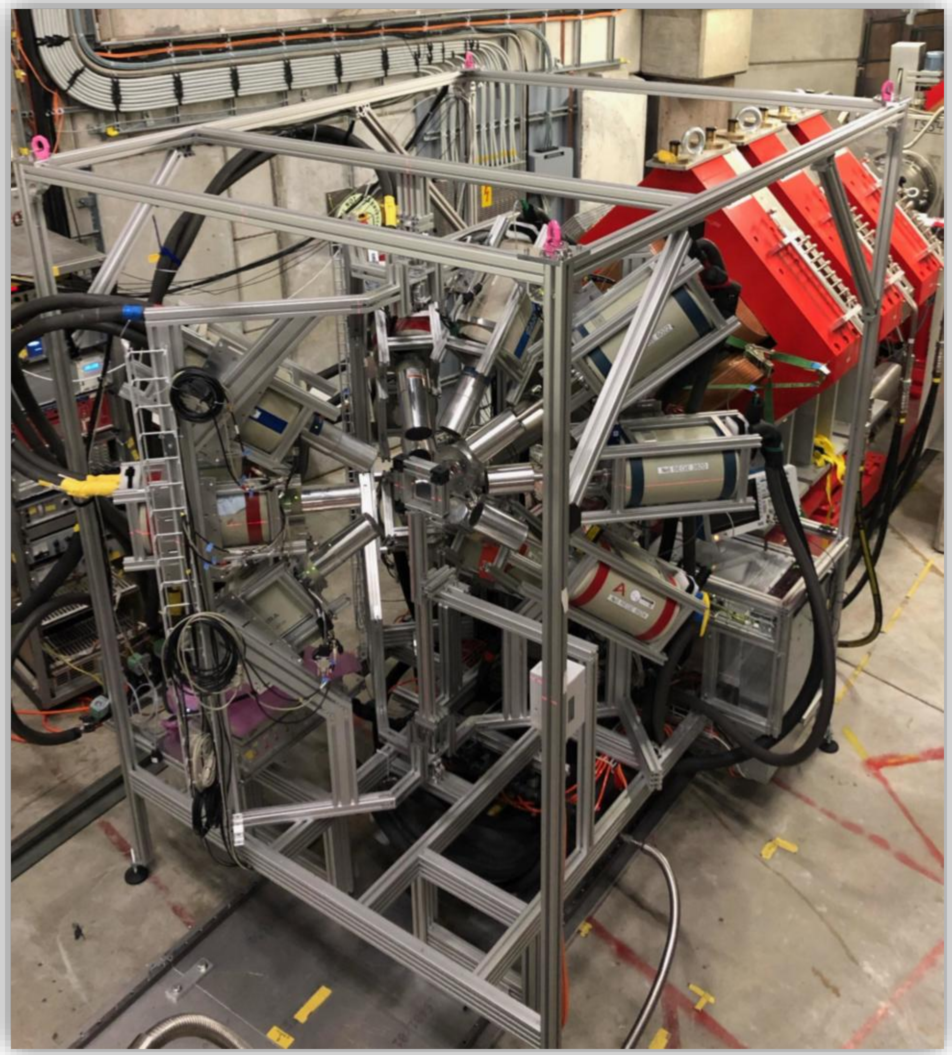


Large solid angle detector array

currently **~12 HPGe detectors** (up to 30) pooled with PP exp. (muX, Ref.Radii, MONUMENT, ...)

supports multiple **muon tracking** technologies

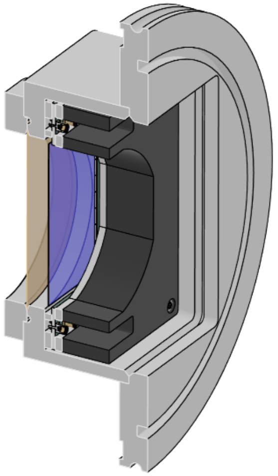
self-contained (rack+frame) and relocatable

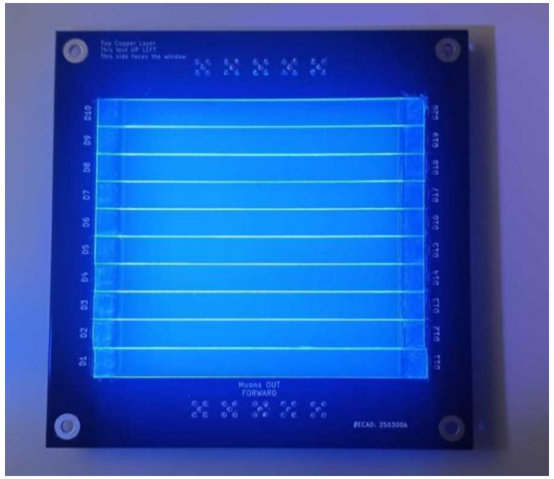
Accessible **sample** station **in air**

low material budget vacuum **window**

large area (7x7cm^2) **muon counter** (adaptable thickness)

segmented design to ease higher tracking rates





Gerchow et al., Rev. Sci. Instrum. 94, 045106 (2023)

Part III

Muon Induced X-ray Emission

Cultural Heritage Showcases

Arrowhead: Sample and Reception

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Bernisches Historisches Museum
Musée d'Histoire de Berne

UNI FREIBURG

NATUR HISTORI SCHES MUSEUM BERN

b UNIVERSITÄT BERN

Journal of Archaeological Science
Volume 157, September 2023, 105827

An arrowhead made of meteoritic iron from the late Bronze Age settlement of Mörigen, Switzerland and its possible source

Beda A. Hofmann [a b], Sabine Bolliger Schreyer [c], Sayani Biswas [d], Lars Gerchow [d], Daniel Wiebe [e], Marc Schumann [e], Sebastian Lindemann [e], Diego Ramírez García [e], Pierre Lanari [b], Frank Gfeller [a b], Carlos Vigo [d], Debarchan Das [d], Fabian Hotz [d], Katharina von Schoeler [f d], Kazuhiko Ninomiya [g], Megumi Niikura [h], Narongrit Ritjoho [i], Alex Amato [d]

Arrowhead: The search for "Heavenly Iron"

Bronze age

- **Metalworking** was known
- **Iron extraction** from ore *not yet discovered*

„Heavenly Iron"

- Iron from **meteorite** fragments
- **Production** of *jewelry, weapons, tools, …*
- Very *rare* and *valuable* **trade goods**

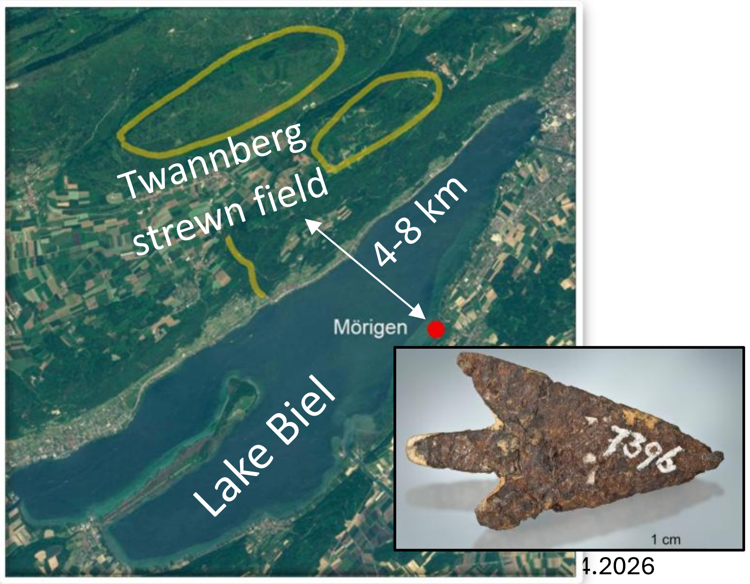
Search in **archaeological collections** (area of *Lake Biel*)

- *Twannberg*: largest **meteorite find** in Switzerland

Such an artifact identified: An **arrowhead**

- Find site: *Pile-dwelling settlement* in **Mörigen**
- Era: **Bronze Age** (900-800 BCE)

*XRF & gamma spectroscopy: Large **iron meteorite** (>2t)*



Arrowhead: The surprise!

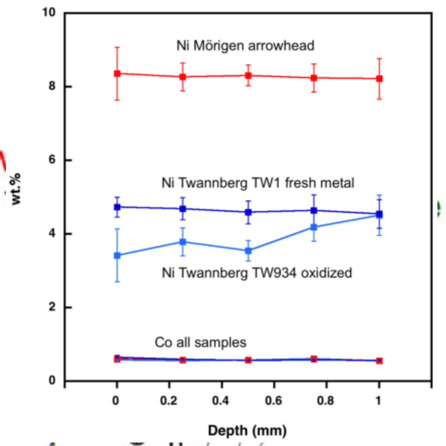
XRF is great but can't probe below thick corrosion layer and/or fusion crust!

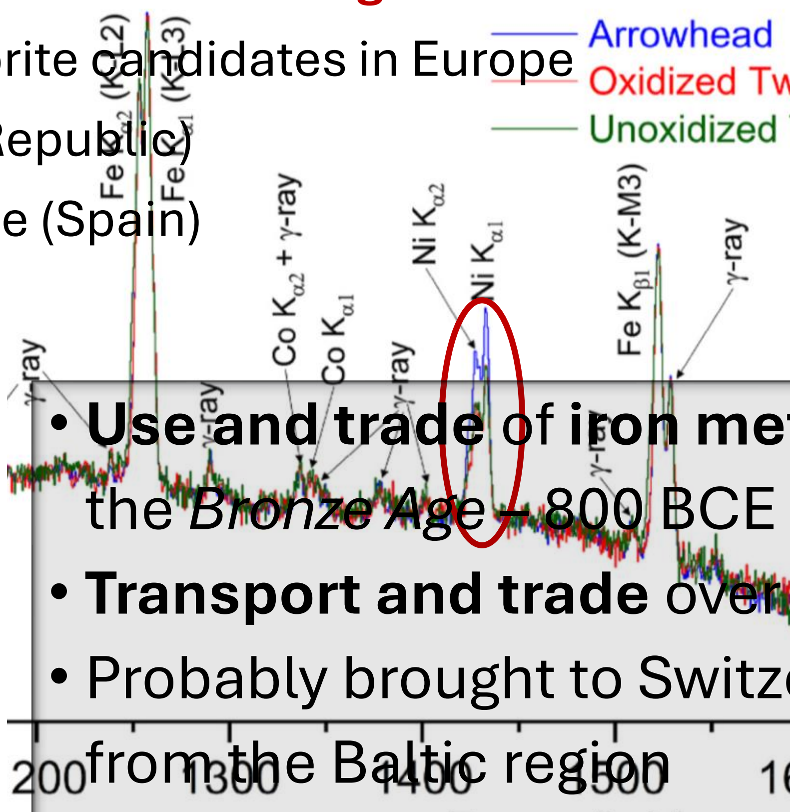
→ **MIXE** Study: Comparison to **Twannberg** reference metorite for *Iron*, *Nickel*, and *Cobalt*

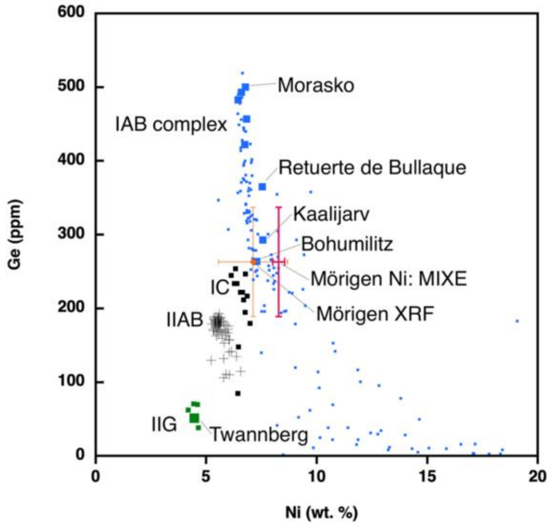
- **Arrowhead not made of Twannberg meteorite!**

Only 3 possible meteorite candidates in Europe

- Bohumilitz (Czech Republic)
- Retuerte de Bullaque (Spain)
- Kaalijarv (Estonia)







- **Use and trade** of **iron meteorites** in Europe as early as the *Bronze Age* – 800 BCE (or earlier).
- **Transport and trade** over **1.600 kilometers**
- Probably brought to Switzerland via **amber trade routes** from the Baltic region
- *High likelihood of additional similar discoveries!*

Fibula: Sample and Study

AUGUSTA RAURICA PSI

Biswas *et al. Heritage Science* (2023) 11:43
https://doi.org/10.1186/s40494-023-00880-0
Heritage Science

The non-destructive investigation of a late antique knob bow fibula (Bügelknopffibel) from Kaiseraugst/CH using Muon Induced X-ray Emission (MIXE)

Sayani Biswas[1*], Isabel Megatli-Niebel[2,3*], Lilian Raselli[3], Ronald Simke[3], Thomas Elias Cocolios[4], Nilesh Deokar[9], Matthias Elender[1], Lars Gerchow[1], Herbert Hess[5], Rustem Khasanov[1], Andreas Knecht[1], Hubertus Luetkens[1], Kazuhiko Ninomiya[6], Angela Papa[1,7], Thomas Prokscha[1], Peter Reiter[5], Akira Sato[6], Nathal Severijns[4], Toni Shiroka[1], Michael Seidlitz[5], Stergiani Marina Vogiatzi[1,8], Chennan Wang[1], Frederik Wauters[9], Nigel Warr[5] and Alex Amato[1]

Late-antique knob-bow fibula

- **excavated 2018** at Augusta Raurica (CH)
- **Leutkirch-type** fibula**, 400-500 CE**

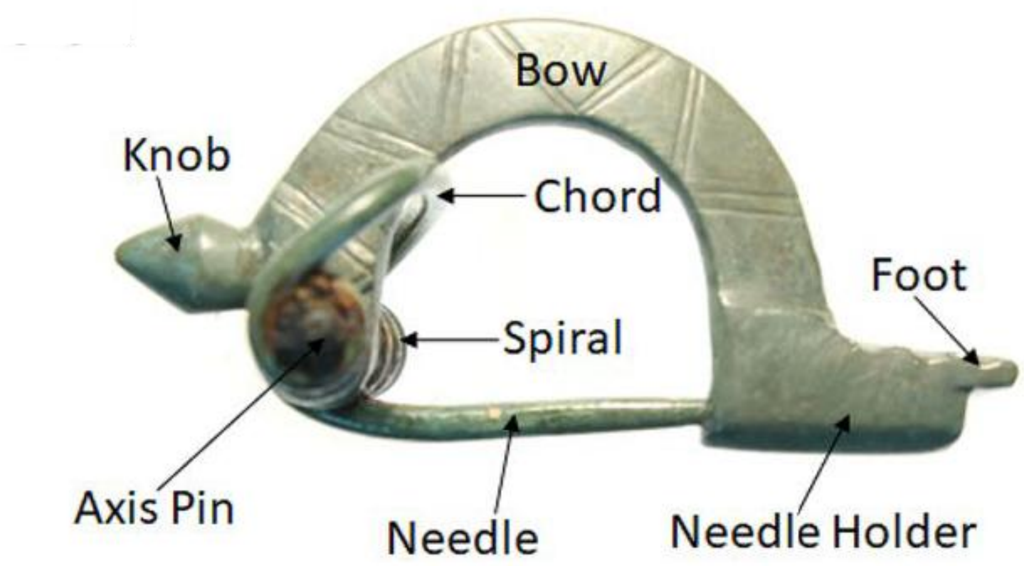
Sample **not suitable for XRF**

- surface completely **covered** with **patina**
- **corrosion layer** on parts of **spiral**
- **coated** in **acrylic resin** for conservation

Six measurements (**~1.5 hours** each):

- **positions:** bow (3x), knob, foot, and spiral
- 1 cm **PE collimator** with **3 mm aperture**
- momentum: **33 MeV/c** – depth: **~320 µm**

3 Brass and **2 Bronze CRMs** for calibration



Fibula: Results and Relevance

AUGUSTA RAURICA PSI

Elemental Composition

- Positions 1-5: **High ratio** of **alloyants** (esp. Pb)
- Position 6: **Low ratio** of **alloyants**

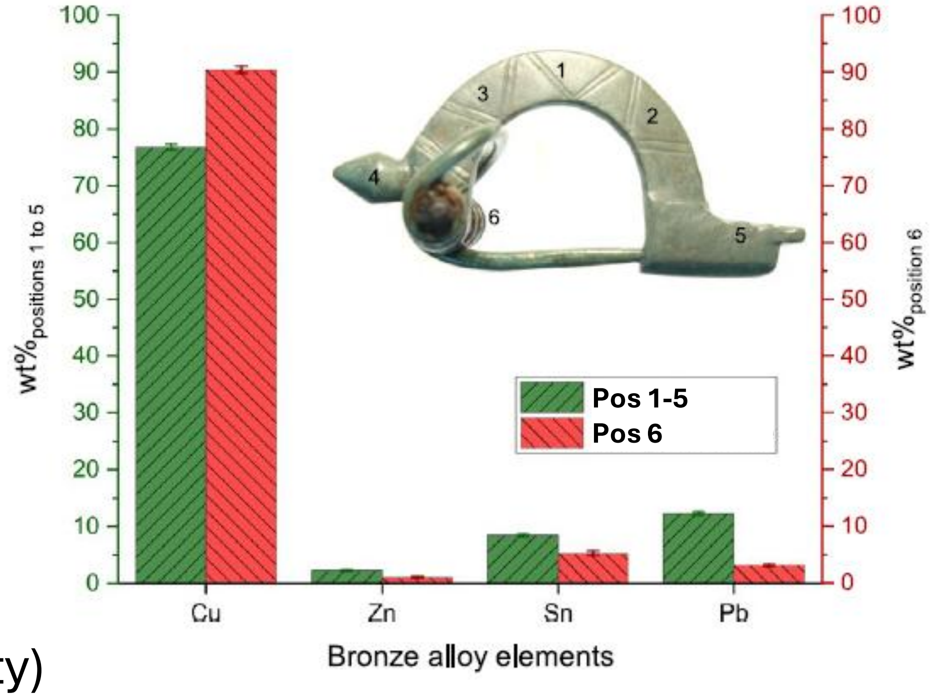
Detection limit: **0.4 wt%** in **~1.5h**

Manufacturing Insights

- **Main body** (knob, bow, foot) **alloy** indicative of **casting** (low-melting point and bubble-free flow)
- **Spiral alloy** indicative for **forging** (high strength and ductility)

Conclusions

- **two-workpiece construction** reflecting **conscious alloy selection**
- **decentralized workshop** practice with **recycling** and **local mixing** of source metals



Part IV

Muon Induced X-ray Emission

Energy Materials Showcases

MIXE 4 Batteries: Charge Carrier Ion Transport

Goals:

- Tracking **charge carrier** ion **distributions** (especially relevant for thick electrodes)
- Mapping **parasitic ion** depositions (e.g. dendrite formation – common failure mode)

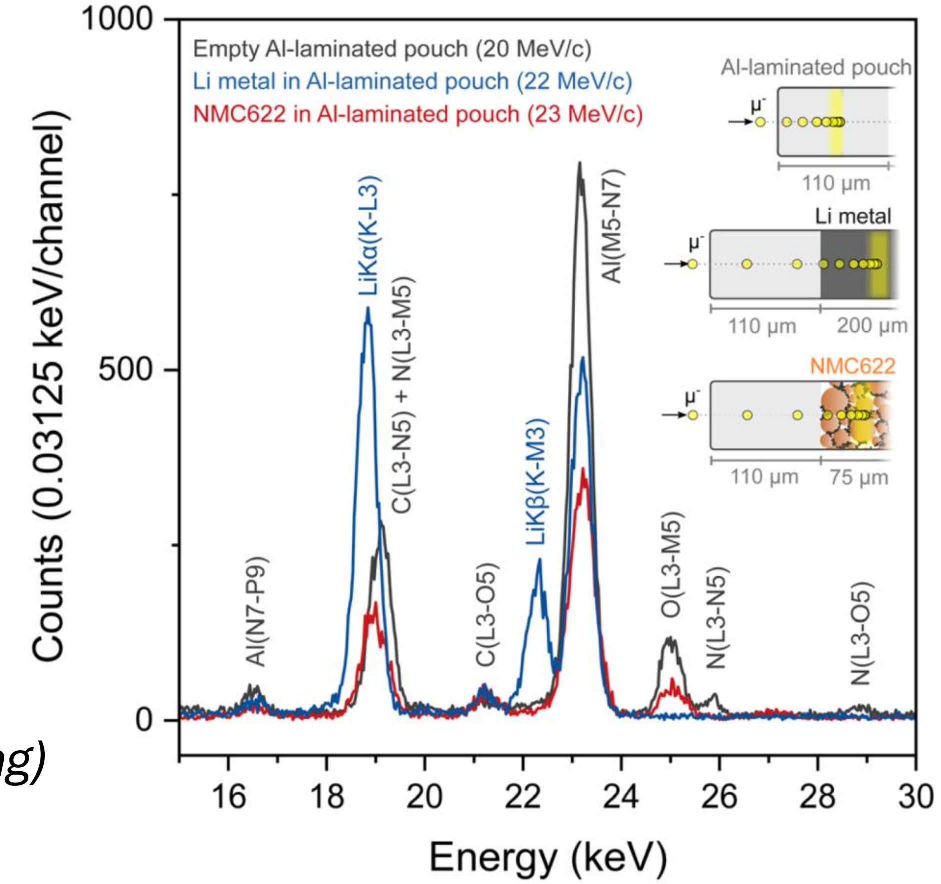
K_α X-ray energies and **attenuation lengths** (here in PP)

Li: 54 eV (electronic) ~100 nm Na: 1 keV (electronic) ~5 µm

18.8 keV (muonic) ~10 mm 250 keV (muonic) ~40 mm

Measurement: empty pouch, Li metal and NMC622 (in pouch)

- **Clear Li signal** observed in Li metal
- Li **tracking in electrode** material **very challenging**
  - **Low efficiency** for HPGes *(other tech.: thick SDD / CdTe)*
  - **Low muon capture probability** (e.g. ~16 in Ni vs. Li)
  - **Masked** by **C-L_β** and **N-L_α** *(He bag & beam dump)*
- *Very **promising** first results for **Na cells** (early analysis ongoing)*



Querel et al., J. Mater. Chem. A, 2025,13, 2275-2284

MIXE 4 Batteries: Stoichiometry of Electrodes

PSI

Goal:

- Accurate **in-situ elemental quantification** of **electrode layers**

Measurement:

- 3x **NMC** (1h each) with **different** Ni:Mn:Co **ratios**
- **Fitting** of Mn, Co, and Ni **K_α peaks**

  could even recover Ni isotopic abundance

*Result **reproduces** known elemental **composition** with **high accuracy**!*

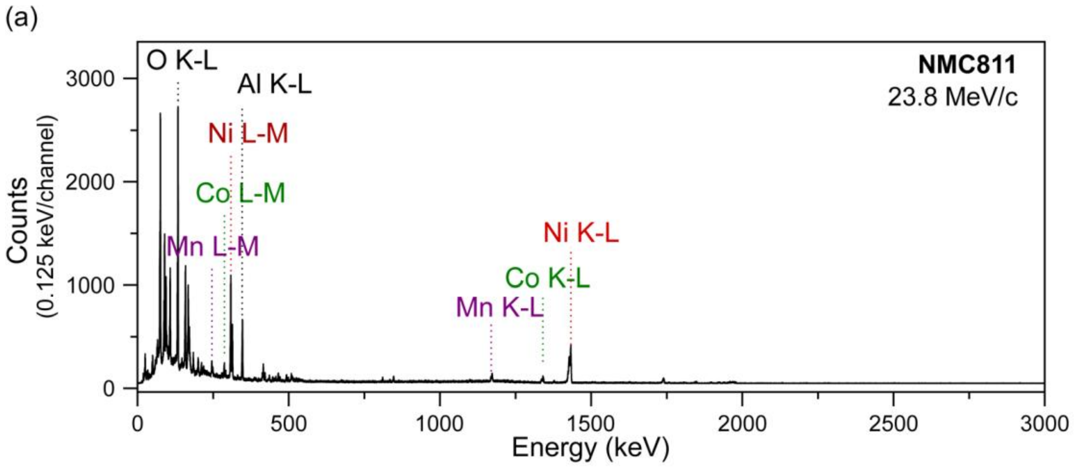
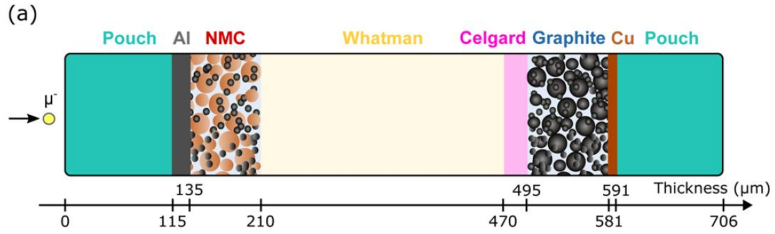


Table 1 Experimentally measured ratios for three different NMC electrodes

NMC type	Nominal composition	Ni/(Ni + Mn + Co)	Mn/(Ni + Mn + Co)	Co/(Ni + Mn + Co)
NMC111	$Li_{1-x}Ni_{0.33}Mn_{0.33}Co_{0.33}O_2$	0.32 ± 0.02	0.35 ± 0.02	0.32 ± 0.01
NMC622	$Li_{1-x}Ni_{0.6}Mn_{0.2}Co_{0.2}O_2$	0.58 ± 0.05	0.21 ± 0.02	0.21 ± 0.02
NMC811	$Li_{1-x}Ni_{0.8}Mn_{0.1}Co_{0.1}O_2$	0.80 ± 0.03	0.103 ± 0.005	0.10 ± 0.02

Querel et al., J. Mater. Chem. A, 2025,13, 2275-2284

MIXE 4 Batteries: Full depth profiling



Goal:

- **In-situ** elemental **depth-profiling** of functional cells

Measurement:

- Custom **NMC811 / graphite pouch cell**

  commercial materials – 0.7mm total thickness

- **Full** GEANT4 / PHITS **simulation** of **sample and instrument**

  accurate **modelling** of **energy loss** → **implantation profile**

- **Spectra** acquired for **eleven momenta** (30min each)
- **Fingerprint** signals for each layer (**Al, Ni/Mn/Co, Si, Cu**) & C

  ***Good agreement** of simulation and data*

- **Cross-check** of quantitative results: **NMC Stoichiometry**

  Reproduces 8:1:1 ratio very well **over full thickness**

Querel et al., J. Mater. Chem. A, 2025,13, 2275-2284

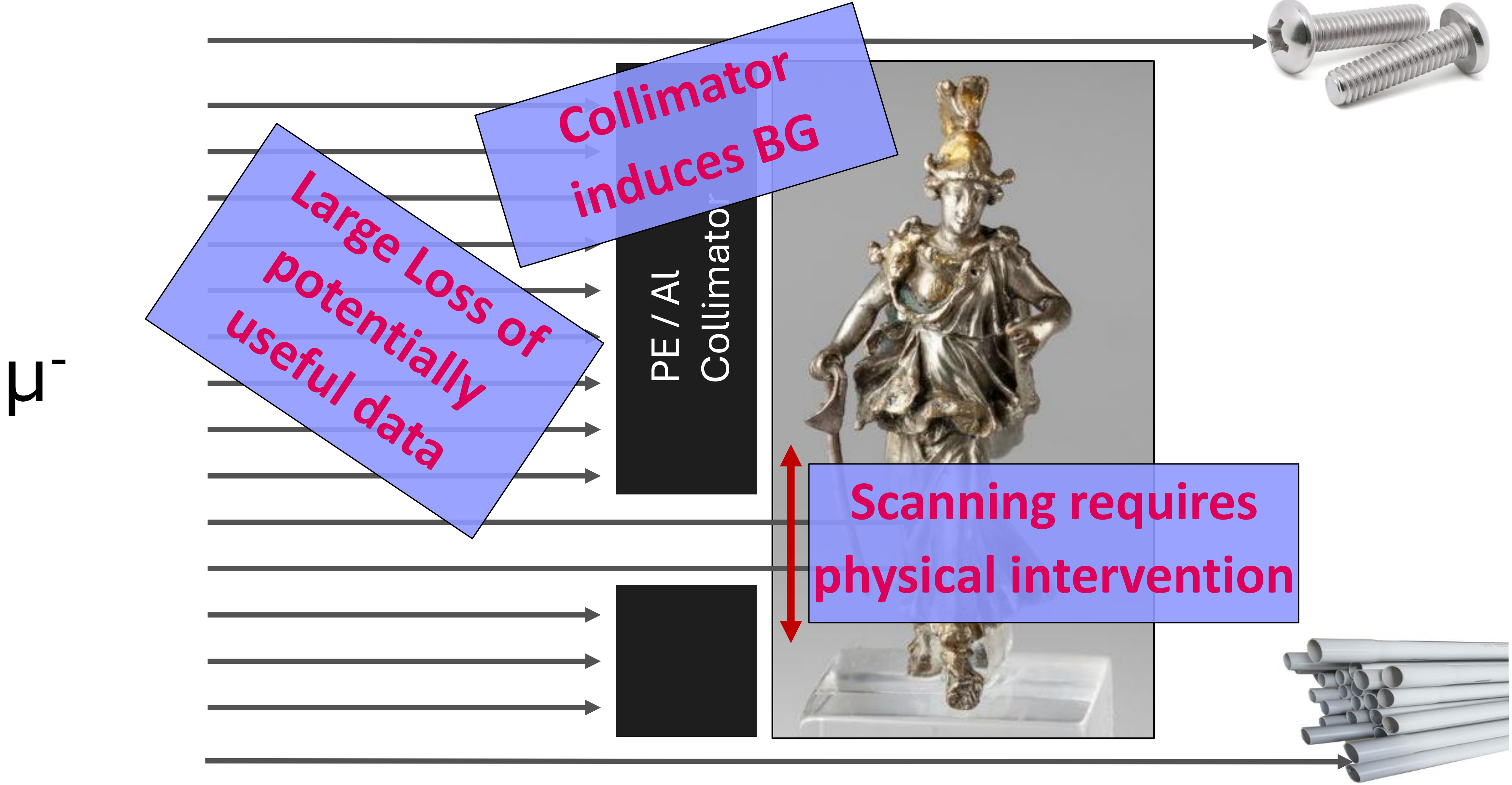
Part V

Muon Induced X-ray Emission

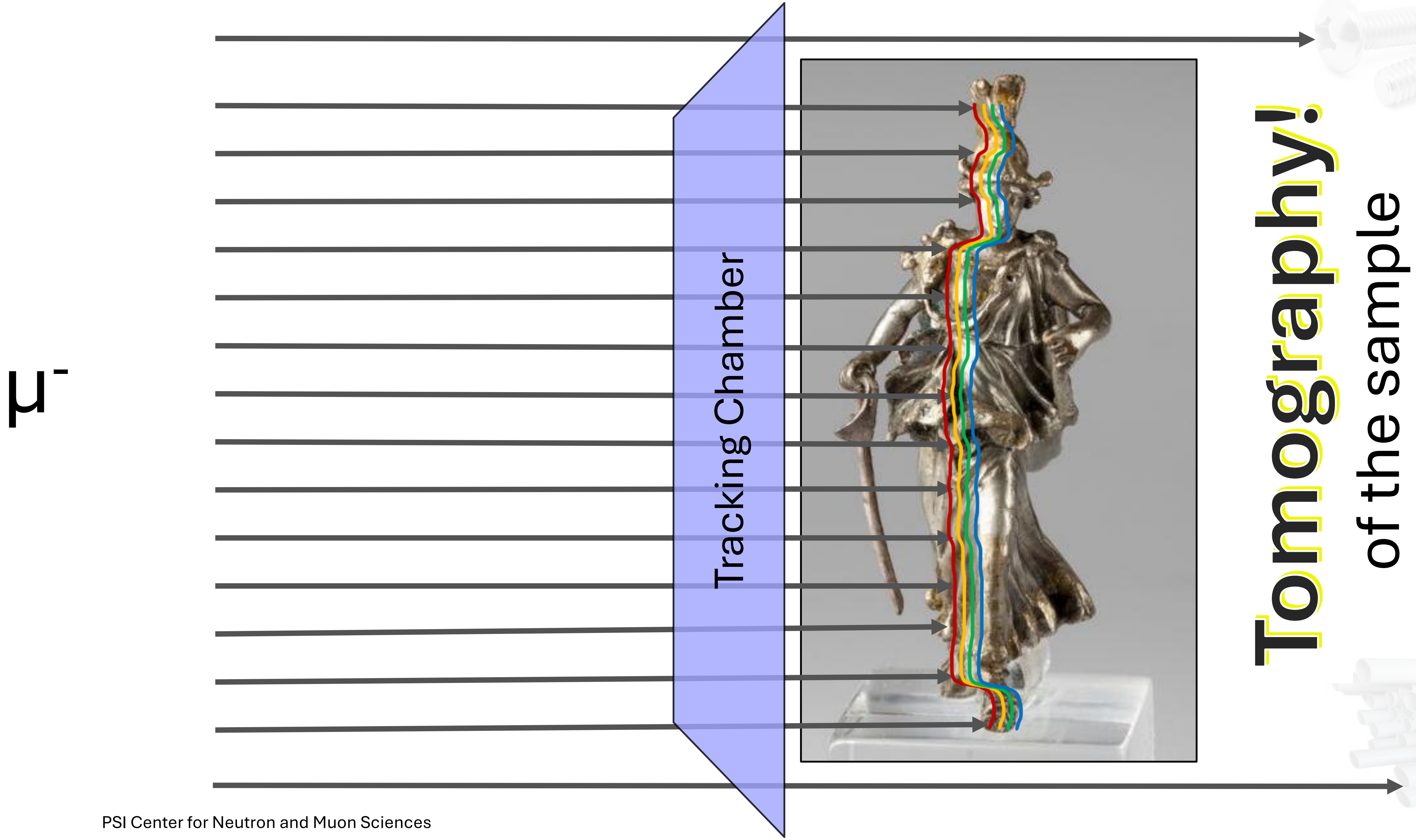
Outlook and updates

MIXE-T(omography): Introduction

MIXE-T(omography): Introduction

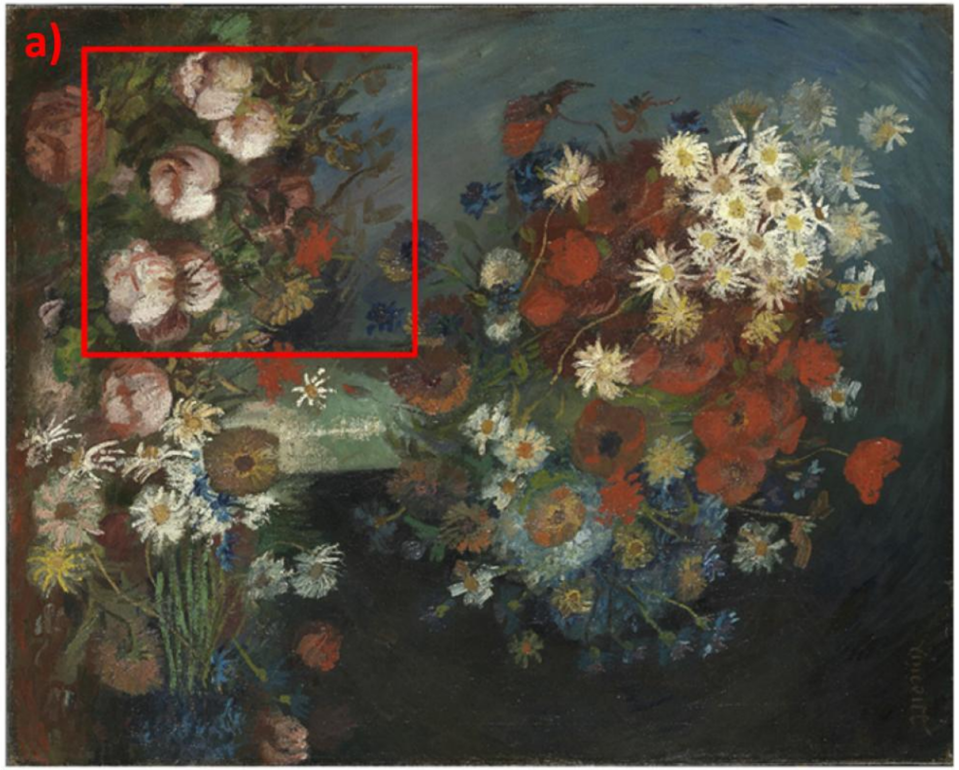


MIXE-T(omography): Introduction



MIXE-T(omography): Completely New Possibilities!

Study using **XRF**



a) Vincent van Gogh's Flower Still Life with Meadow Flowers and Roses, summer 1886 (Kröller–Müller Museum, Otterlo, the Netherlands), rotated for illustration purposes.

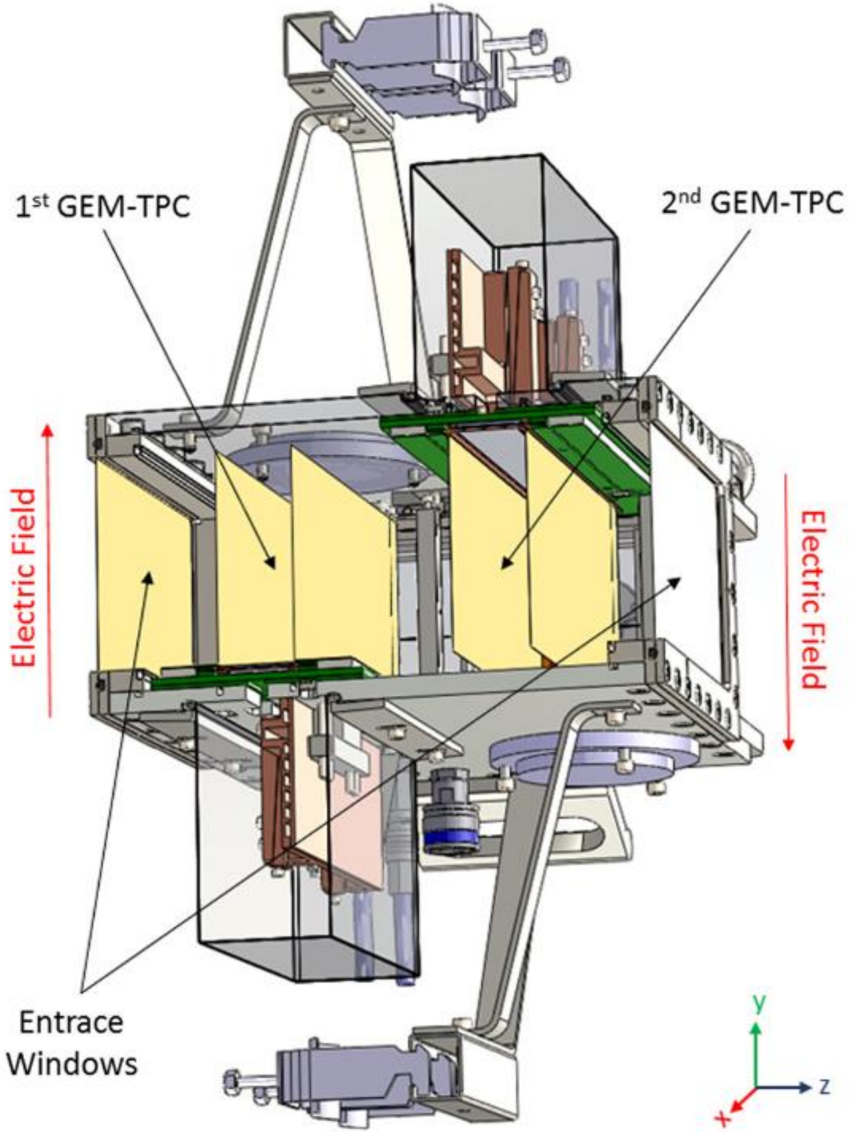
MIXE-T could image all elements over full canvas with much higher depth-resolution!

MIXE-T(omography): Muon Tracking

- Adaptation of existing tracking detector prototype
  - Collaboration with HIP & DRD1, CERN
  - Designed for heavy ion tracking @ GSI/FAIR

- Twin Time-Projection-Chamber (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 cluster on strips
  - Y position by drift time(s) – *requires calibration*

- Home-made, 3D-printed drift time calibration detector



Garcia et al., 2025 JINST 20 C04004; Zhao et al., 2025 JINST 20 C06067

MIXE-T(omography): First Elemental Imaging (Jun 23)

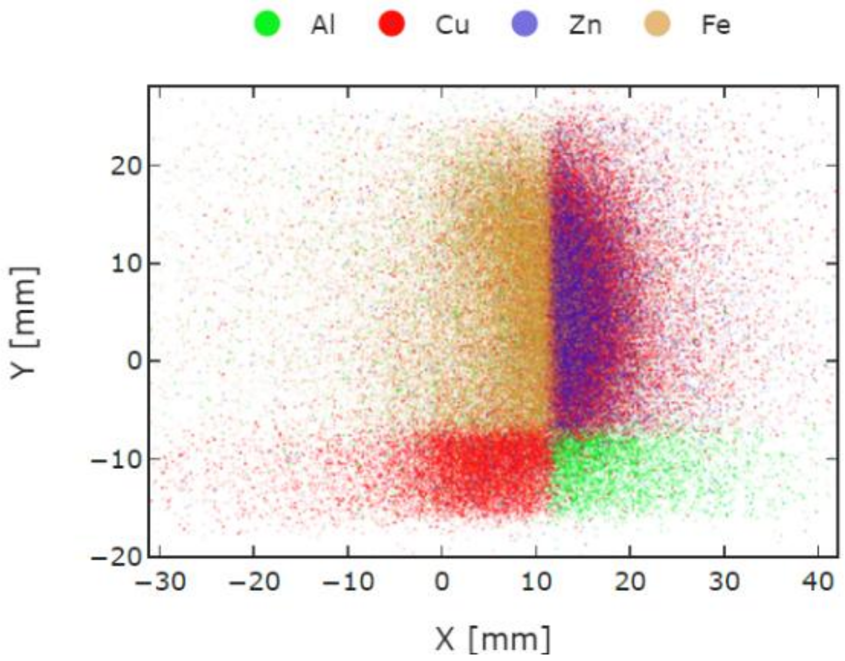
PRELIMINARY

Experimental setup

- Tracker mounted after beam port (roughly aligned)
- Standard Ar/CO2 (75:25) gas mixture
- Single HPGe detector
- 60 MeV/c muon beam

Reference targets

- Four metals:
  - Brass (37% Zn)
  - Aluminium
  - Copper
  - Stainless Steel: Fe, Cr, Ni, Mo, Mn, Si + traces
- Thicknesses optimized to stop downstream

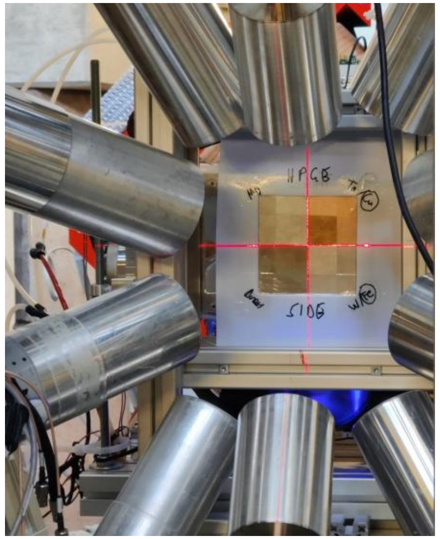


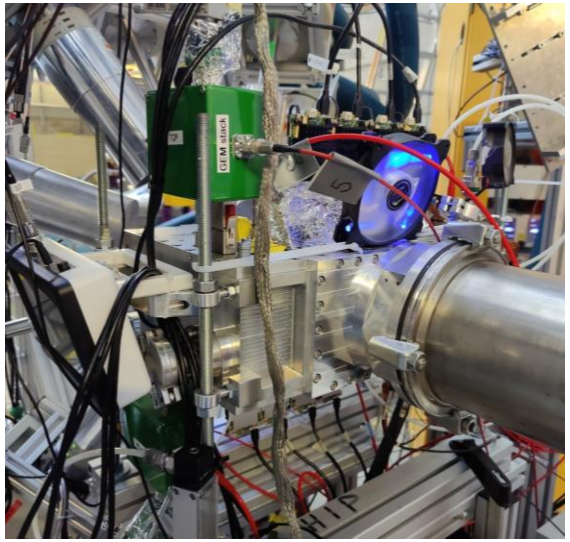
MIXE-T(omography): Spatial Resolution for Tomography

PRELIMINARY

Upgrades

- Layered targets & Momentum Scans
- Detector flanged directly to beamport
- Low density gas mixtures to reduce scattering
  - He/CO2 (90:10) in 2024
  - He/CO2 (97:3) in 2025



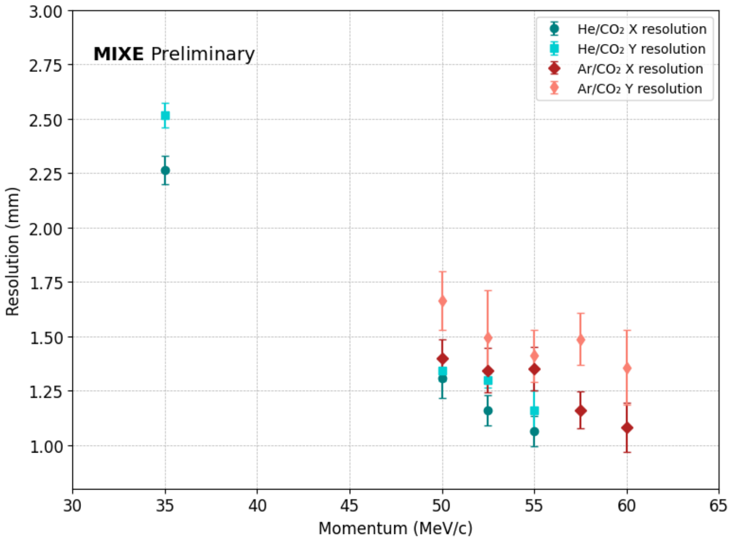


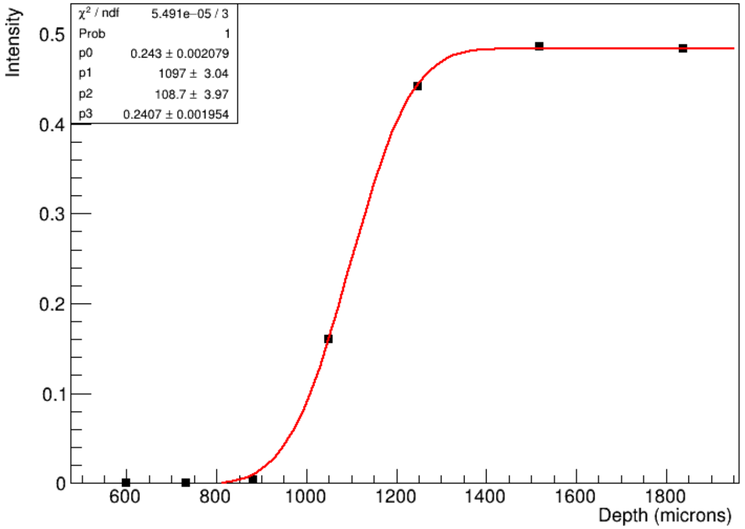
Results

- Spatial Resolution >50MeV/c:
  - X/Y: ~1 mm
  - Z: ~0.1 mm

Limited by large gas volume

Specialized prototype detector in development!

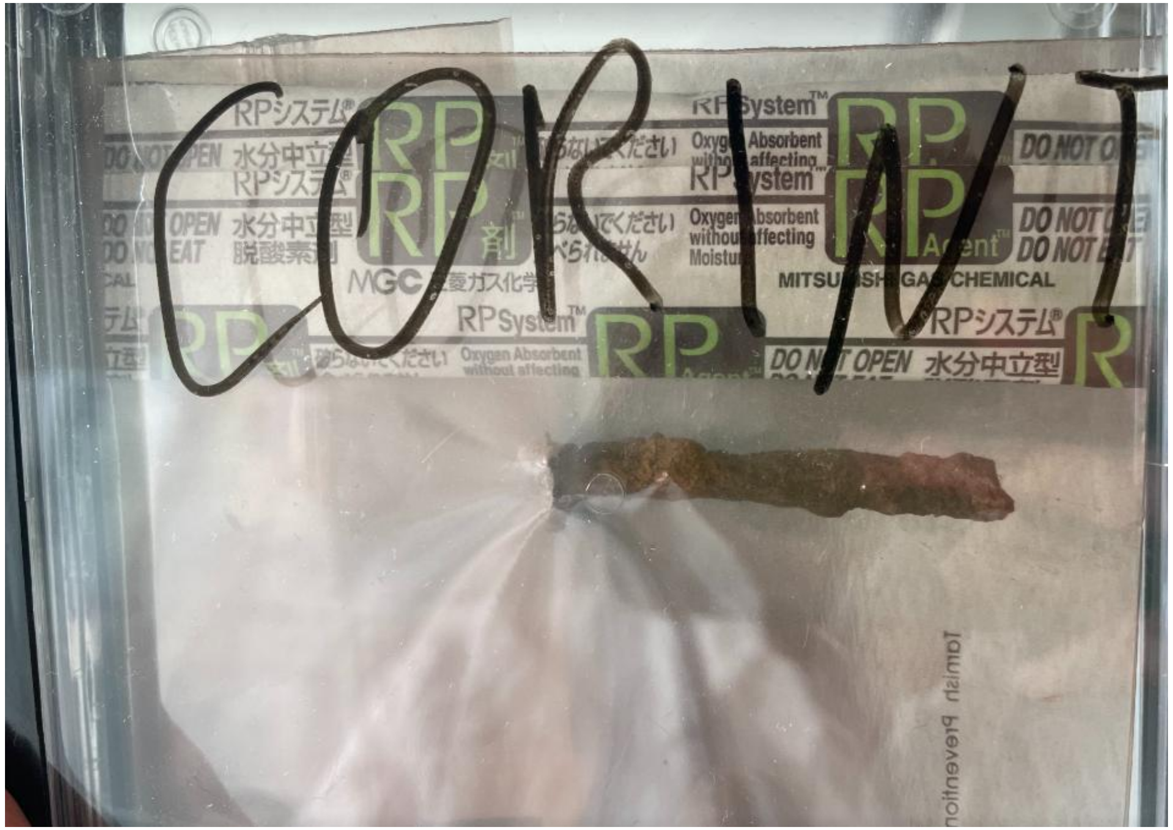




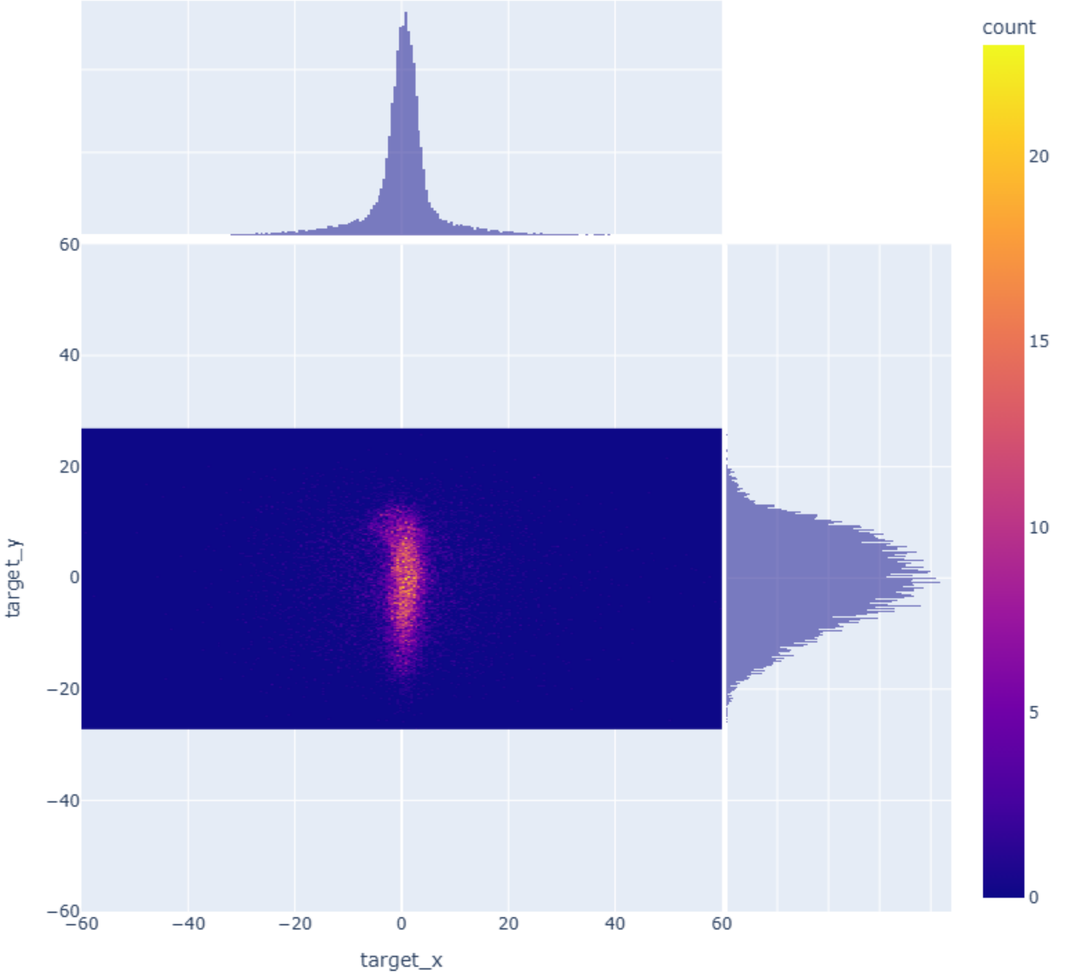
MIXE Imaging: “Real” Sample

PRELIMINARY

- Roman iron nail (fresh find – conservation study)
- ~1.5 hours data collection with 46 MeV/c muons
- Spot size covering only ~50% of the nail

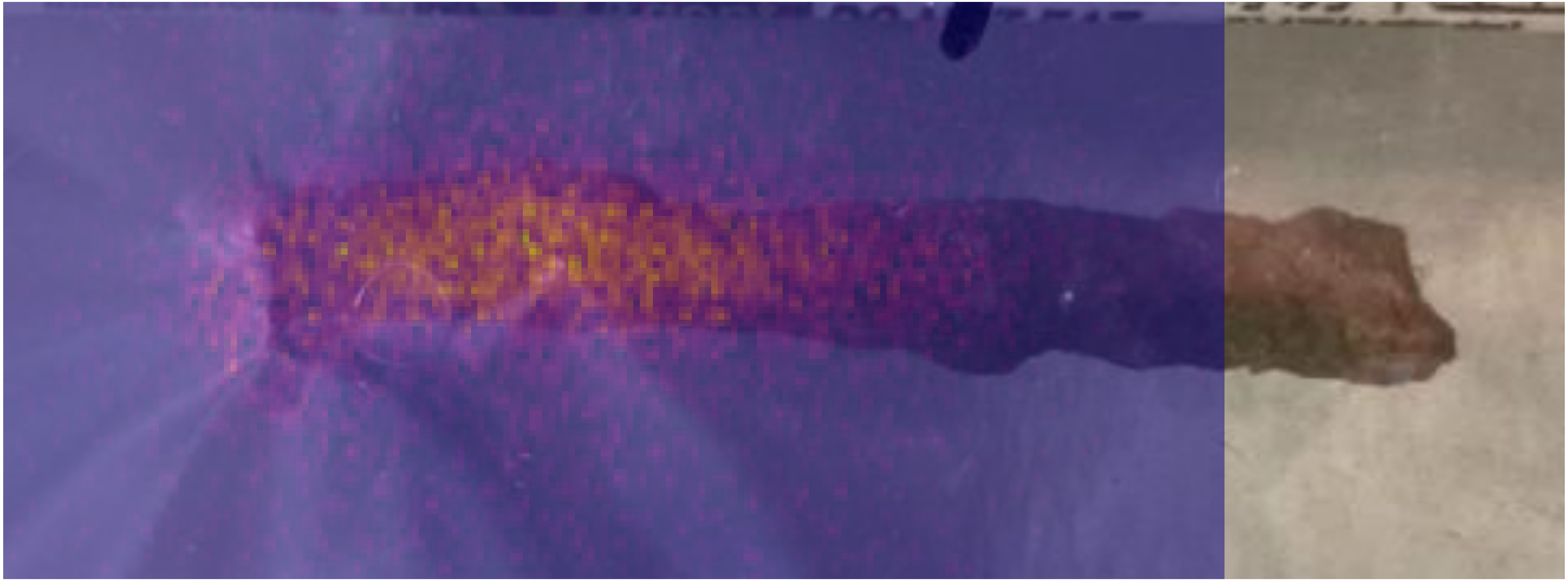


- Tracks filtered for Fe K_α and K_β peaks



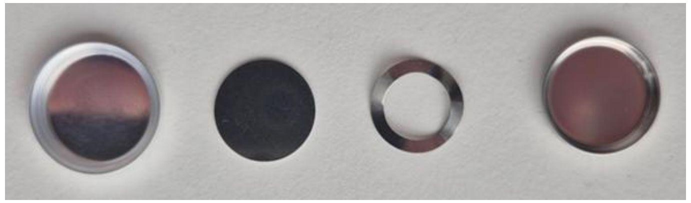
MIXE Imaging: “Real” Sample

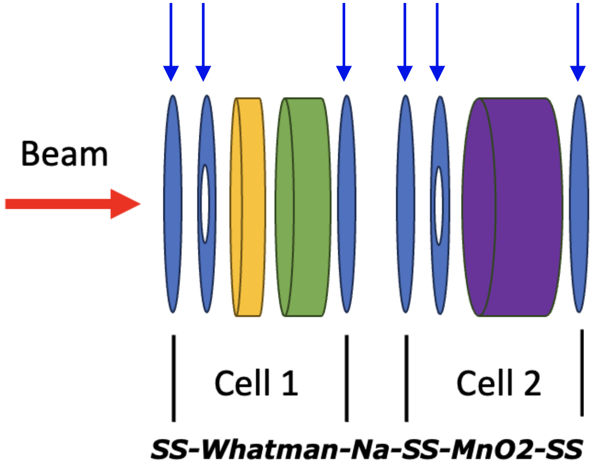
PRELIMINARY



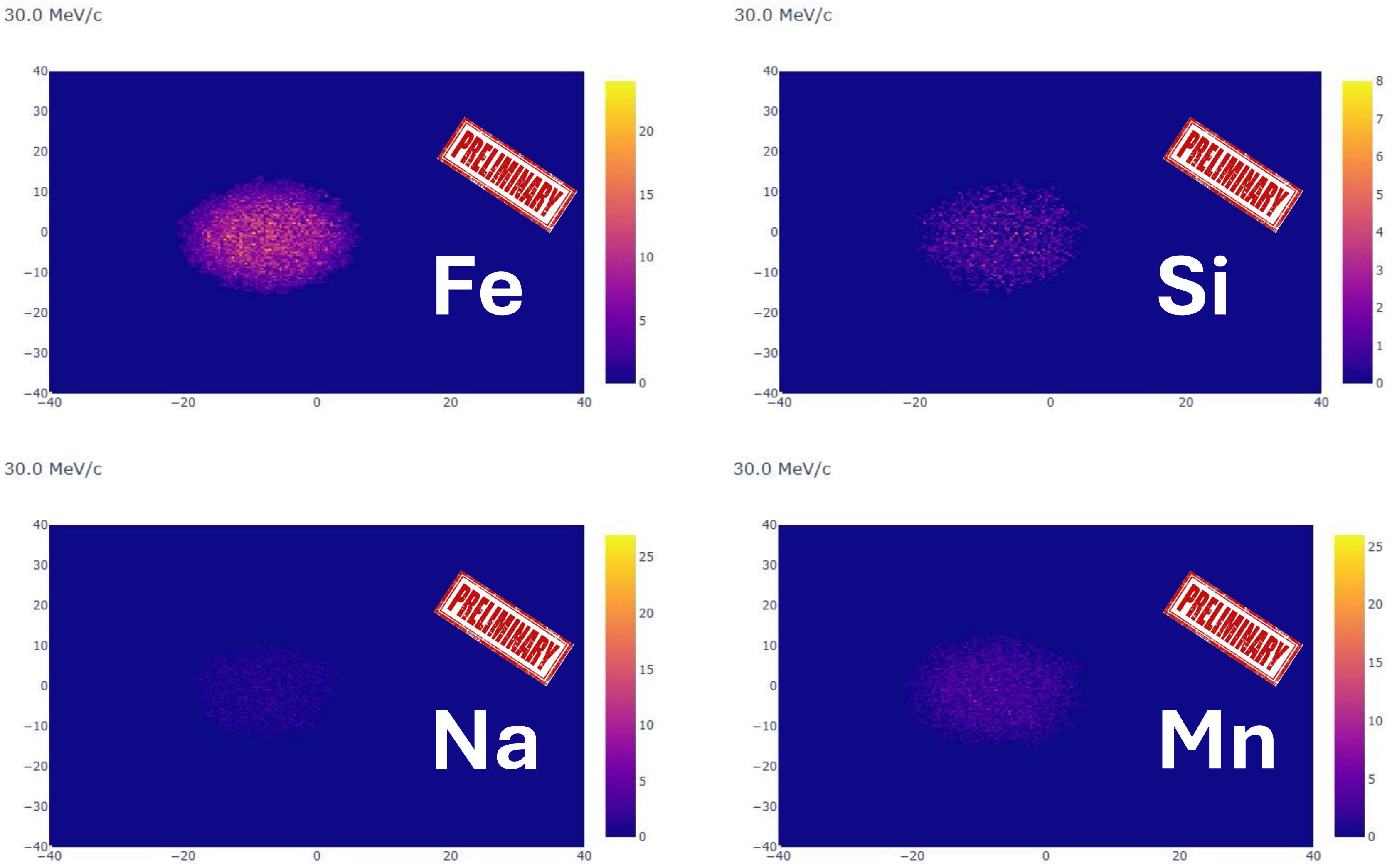
MIXE-T(omography): Battery tomography PoC

coin cell battery analogue





30/32/34/39/46/49/51
MeV/c
+interpolation



Towards the future: Truly universal elemental MIXE-T

PSI

Current **MIXE-T** setup is limited by several factors

- Large detector volume implies significant scattering
- Achievable resolution significantly worse than intrinsic detector resolution (~150 μm)
  - Imaging close to the surface (low momentum) not feasible
- Pileup at high rates complicates the analysis
- Depth-resolution depends on knowledge of shape and density of sample

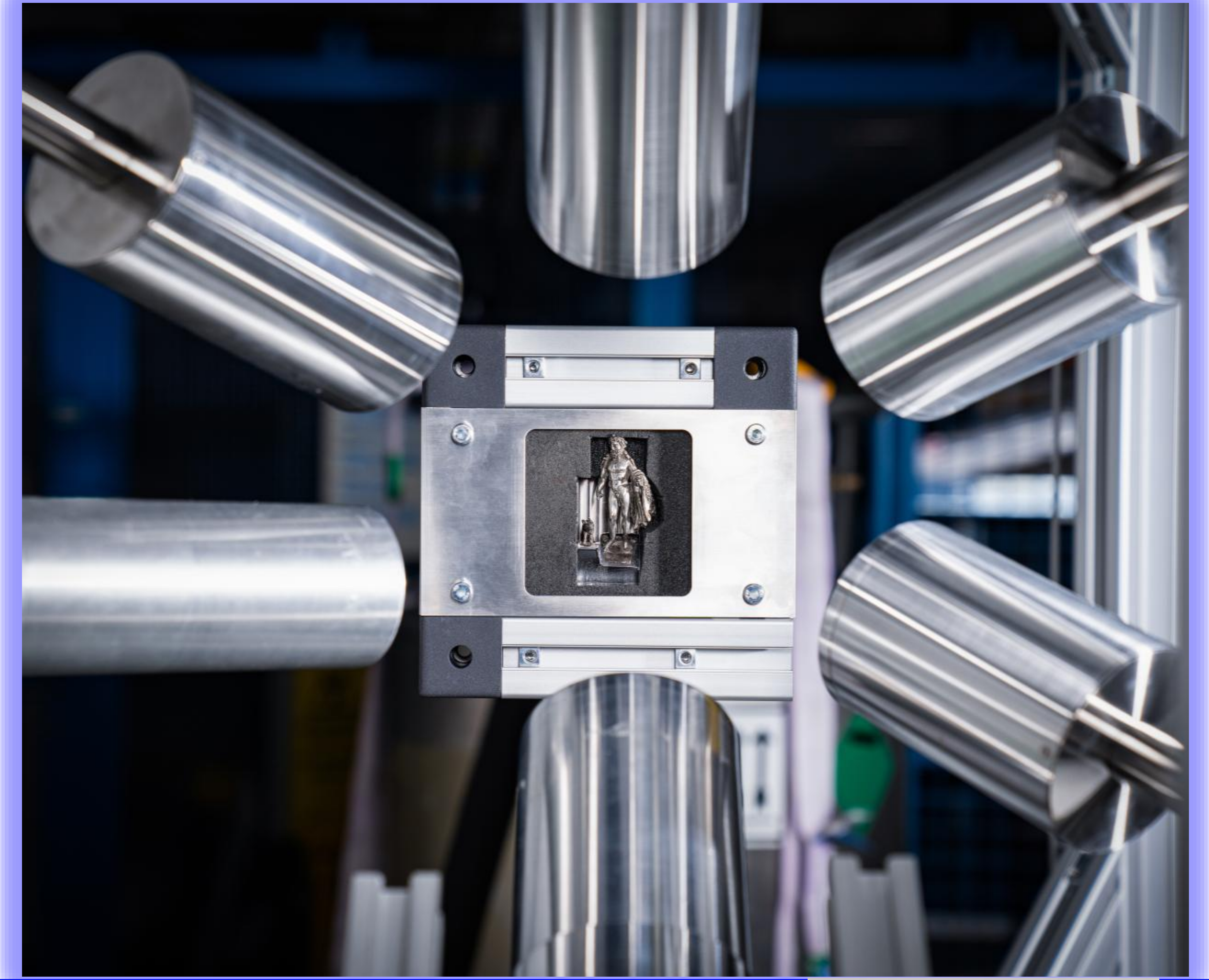
The solution: *A custom TPC detector for* ***MIXE-T****!*

Design in progress!

PSI Center for Neutron and Muon Sciences

Questions, comments and feedback are welcome!

Thank you for your attention



Maxime Lamotte, on behalf of Michael W. Heiss, Xiao Zhao, and Issa Briki

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