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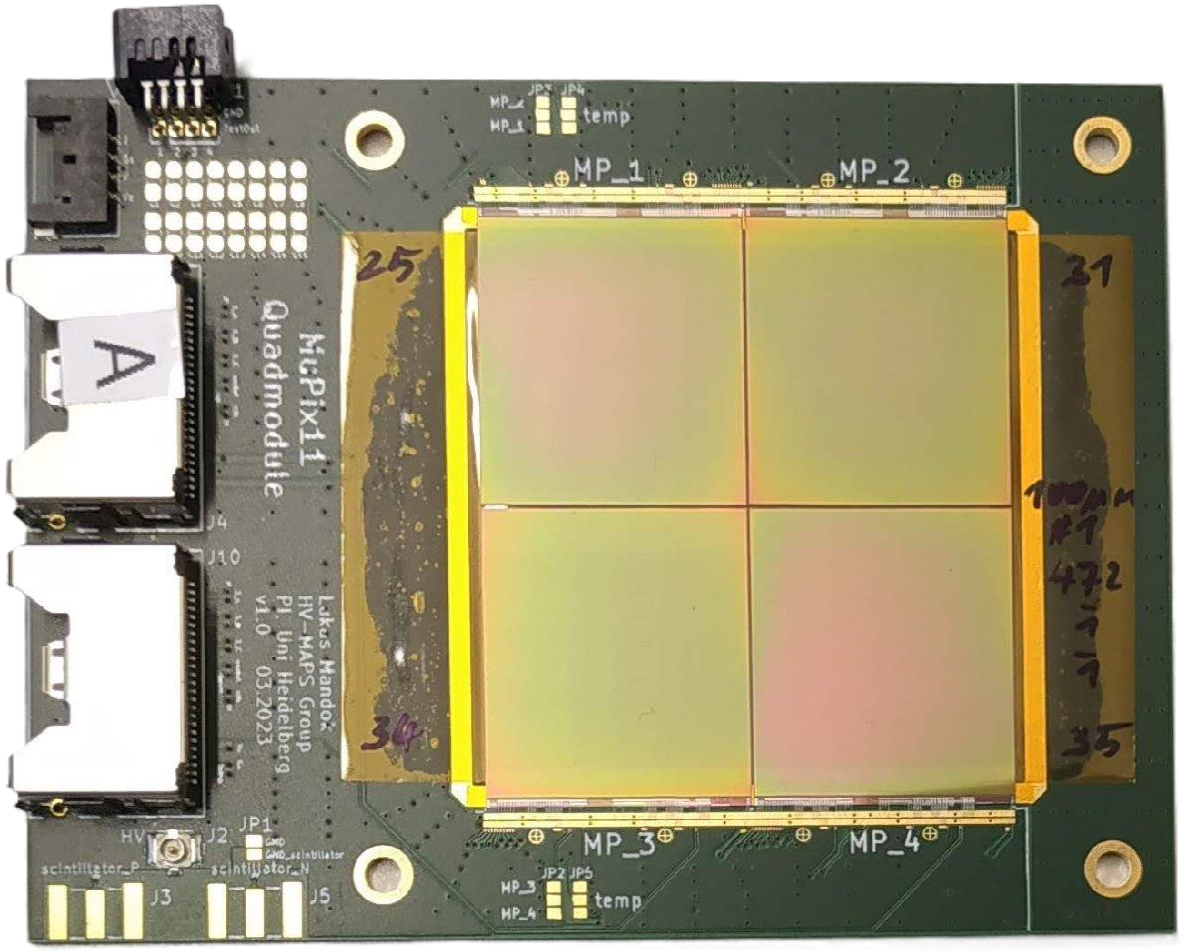
Si-pixel detectors for vertex reconstruction in µSR experiments



Maxime Lamotte,

on behalf of **Pascal Isenring**

PSI / CNM / LMU

BRIDGE conference, 22 October 2025 – Tokyo, Japan

Agenda

1 Legacy μSR method

2 Rationale for new detection method

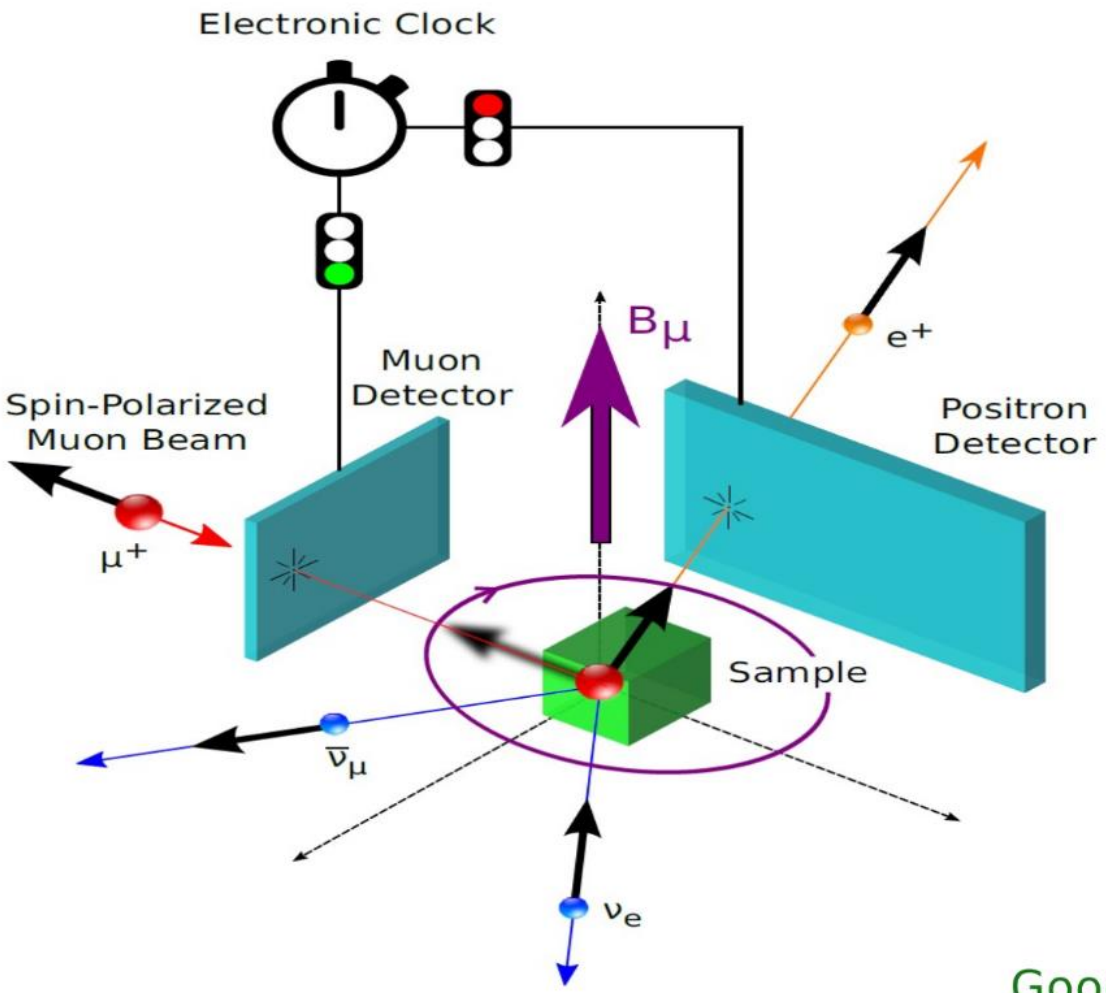
3 Concept of Vertex Reconstructed μSR (vx-μSR)

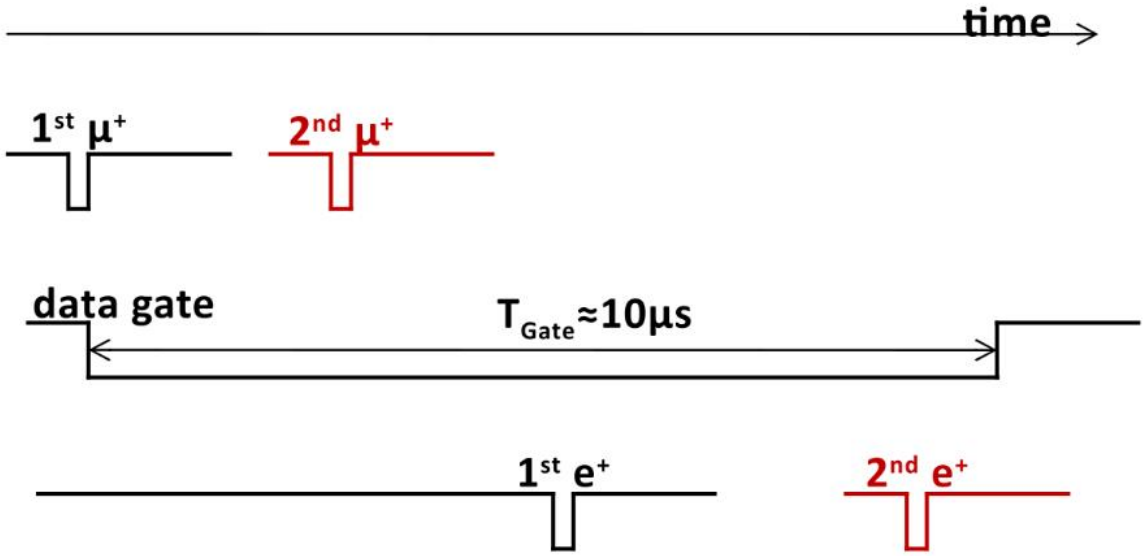
4 First of a kind vx-μSR

5 Latest results in real μSR conditions

6 Outlook and roadmap

Legacy μSR method – Detectors and Vetos





- 1st μ+: there was **no** other μ+ for at least T_{Gate} in the past
- Single muon detection: only **one** μ+ and **one** e+ in observation window (T_{Gate}≈10μs)
- Second μ+ / e+ rejection electronically and by rate limitation

Good Event = (data gate) ^ (1st e+) ^ (**no** 2nd μ+) ^ (**no** 2nd e+)

Rationale for new detection methods – Rate limitation

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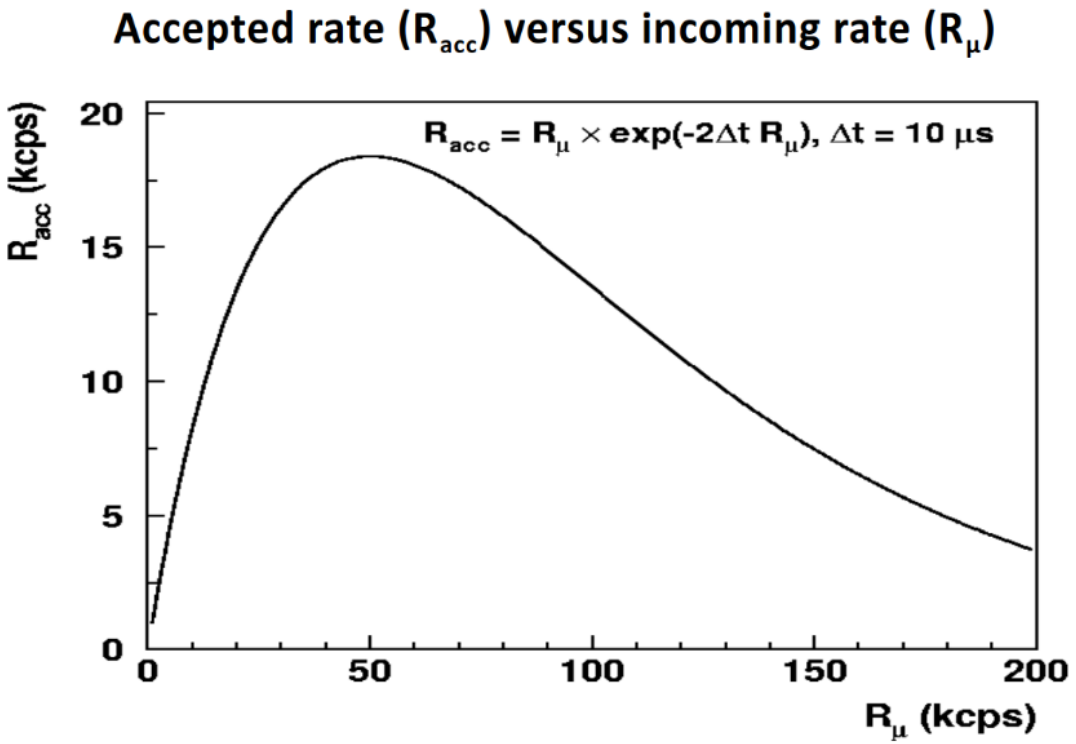
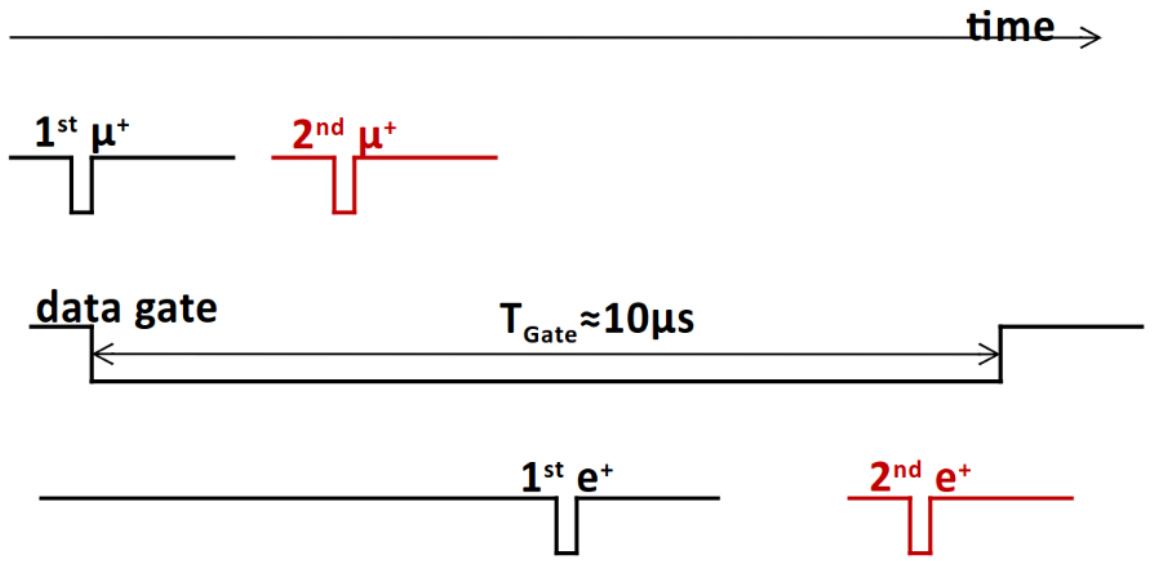


Current rate limit for T_{Gate}=10 µs is **~40k µ⁺/s**

100x more rate with HIMB



- 1st µ⁺: there was **no** other µ⁺ for at least T_{Gate} in the past
- Single muon detection: only **one** µ⁺ and **one** e⁺ in observation window (T_{Gate}≈10µs)
- Second µ⁺ / e⁺ rejection electronically and by rate limitation

Good Event = (data gate) ^ (1st e⁺) ^ (**no** 2nd µ⁺) ^ (**no** 2nd e⁺)

How to use each of these numerous HIMB muons for µSR?

One-by-one muon readout reached its limit: need for a **disruptive innovation**

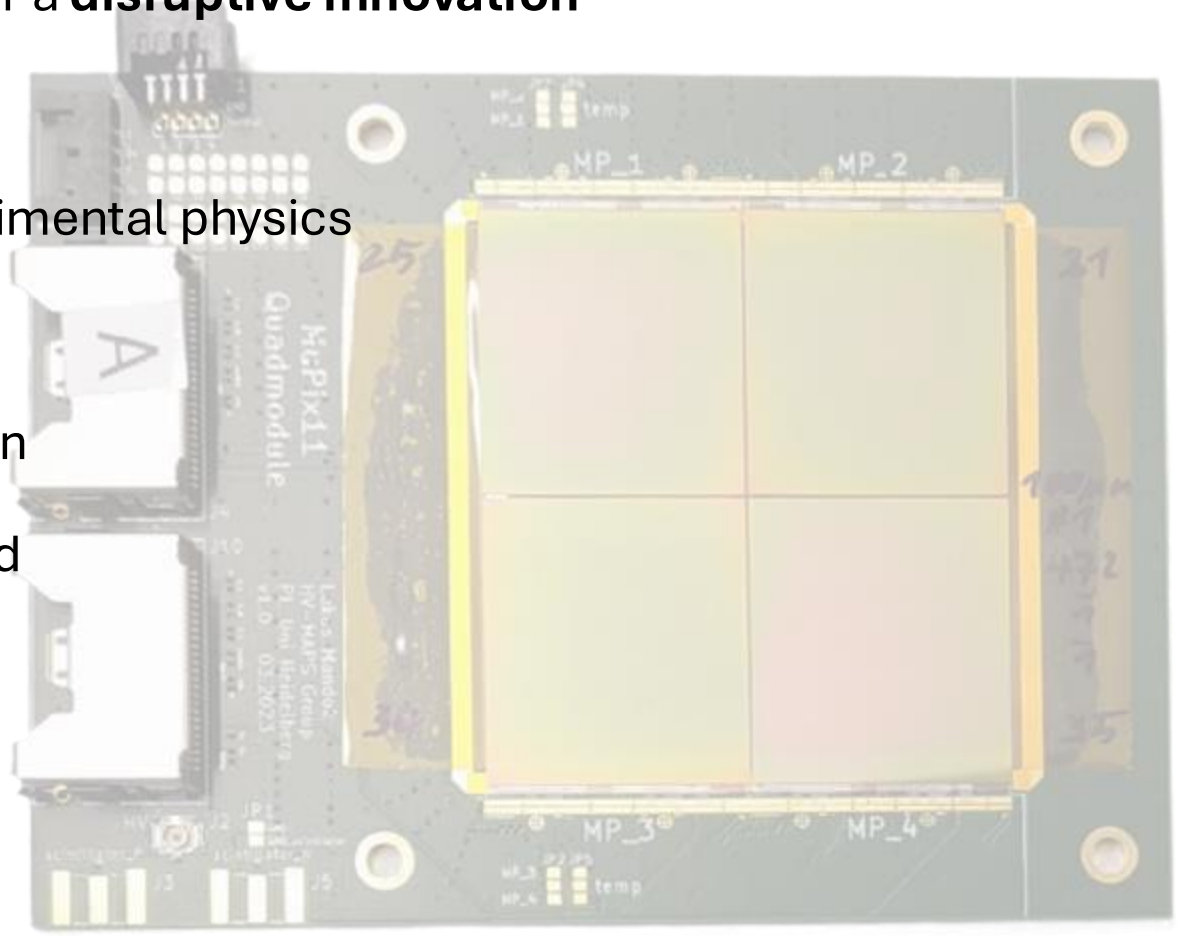
Silicon Pixel detectors have long been used in experimental physics

>> Parallel readout of thousands of small detectors

>> Energy deposition readout + Vertex reconstruction

>> The track of each muon / positron can be resolved

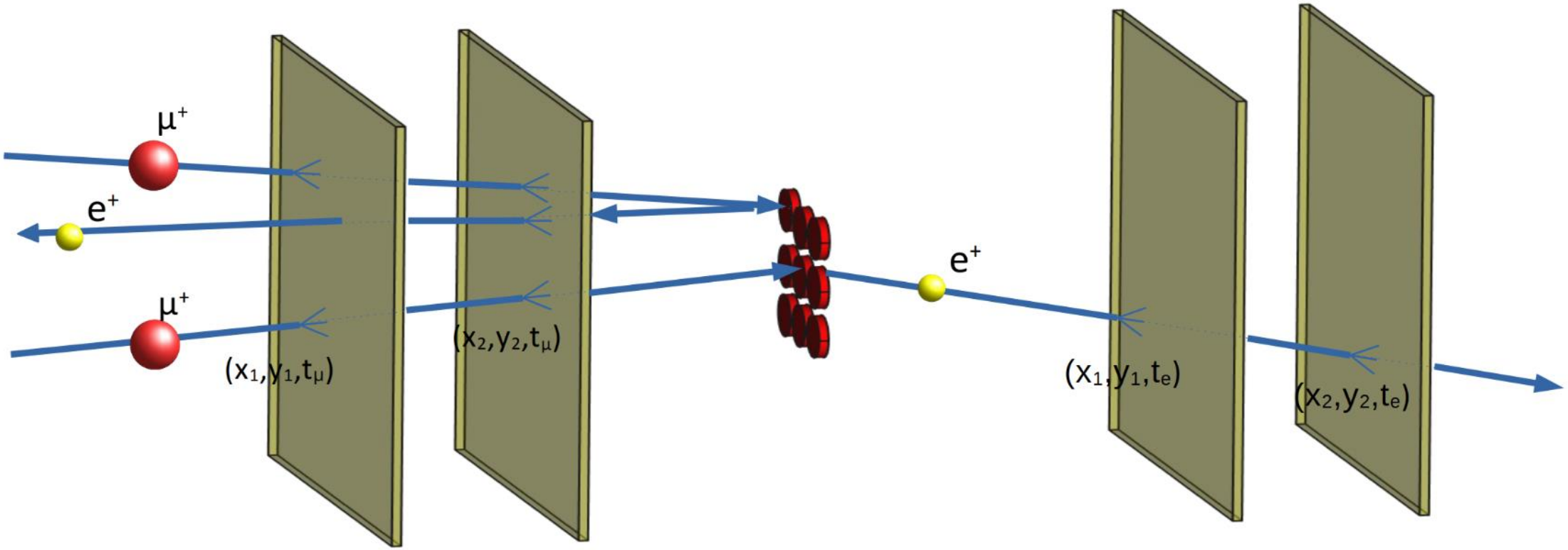
>> No more intrinsic rate limit



Objectives of a new readout method

	Current limit	Aim
Incoming muon rate	< 40kHz @ 10µs	> 400 kHz @ 20µs
Sample size	> 4x4 mm^2	< 1x1 mm^2
Number of samples	One at a time	> 1
Veto detectors	necessary	obsolete
Data gate length	10µs or 20µs with MORE (muons on request)	20-30µs

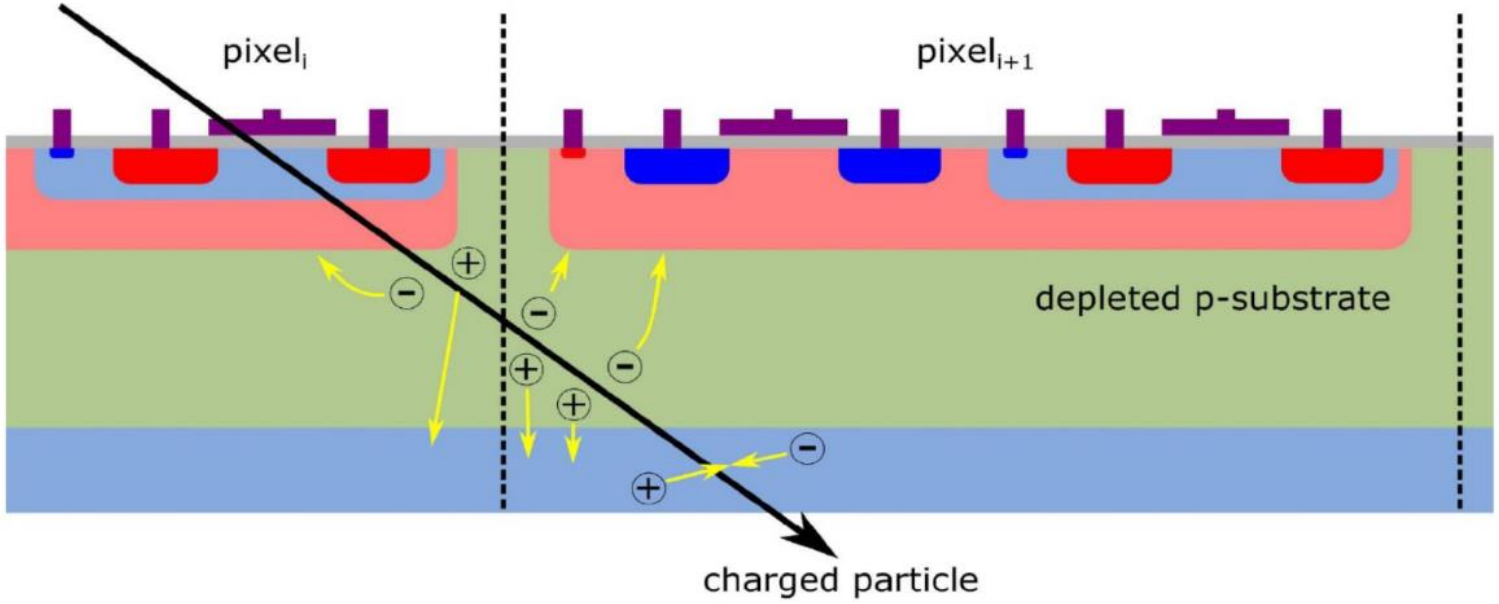
Vertex Reconstruction scheme



High-Voltage Monolithic Active Pixels sensor

Si-Pixel detectors – MuPix11

- Developed by the Mu3e collaboration.
- 180 nm HV-CMOS process
- Fully integrated digital readout
- Can be as thin as 50 micrometers with 80×80 μm^2 pixel size
- Continuous readout without trigger
- Less than 20ns time resolution

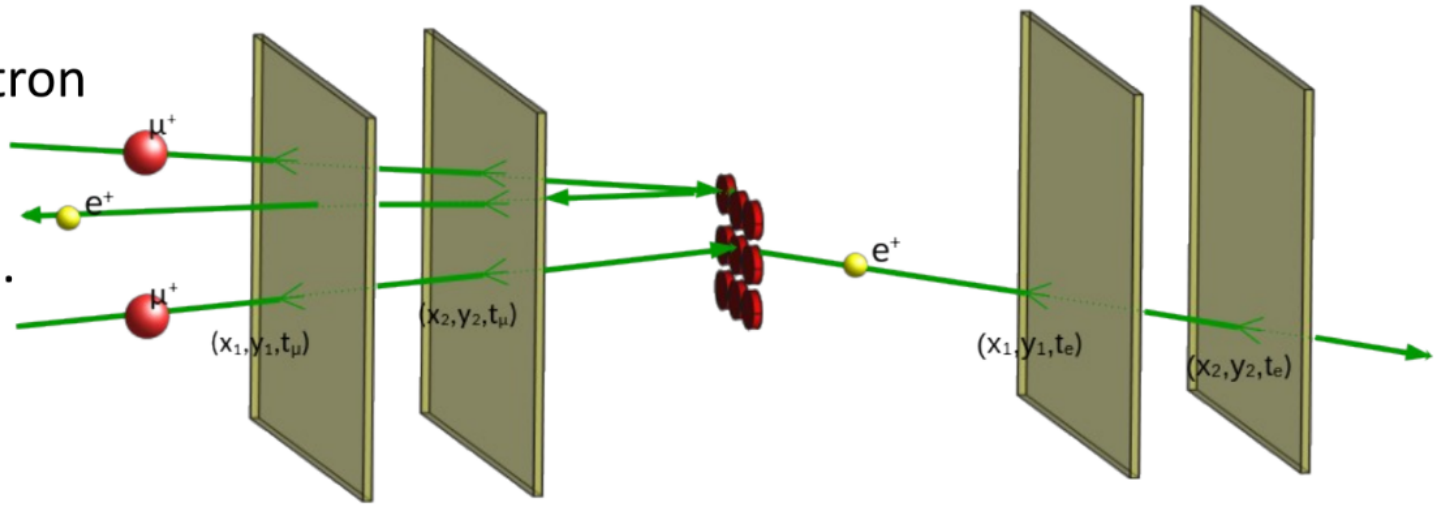


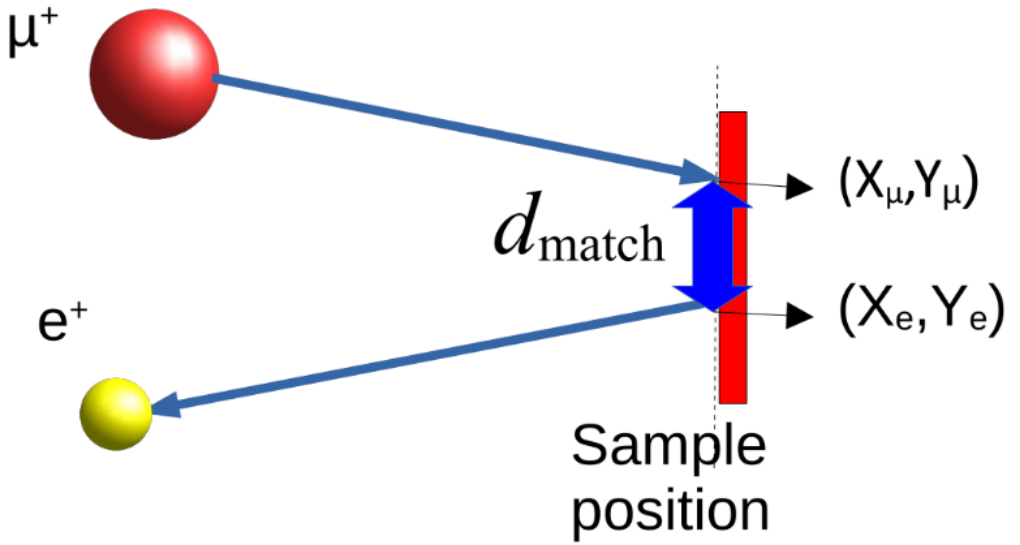
Figures and details from Thomas Rudzky

See: https://archiv.ub.uni-heidelberg.de/volltextserver/30885/

Vertex Reconstruction scheme with Quad Modules

- For each muon, look for a matching positron within a t_{gate} time (~12µs).
- Matching within d_{match} (~1mm) is allowed.
- If found, record:
  (X_μ,Y_μ), (X_e,Y_e) and $(t_e\text{-}t_\mu)$
- Construct time histograms:
  upstream/downstream depending on the positron trajectory.
- The time histograms can be added for specific regions in the sample.





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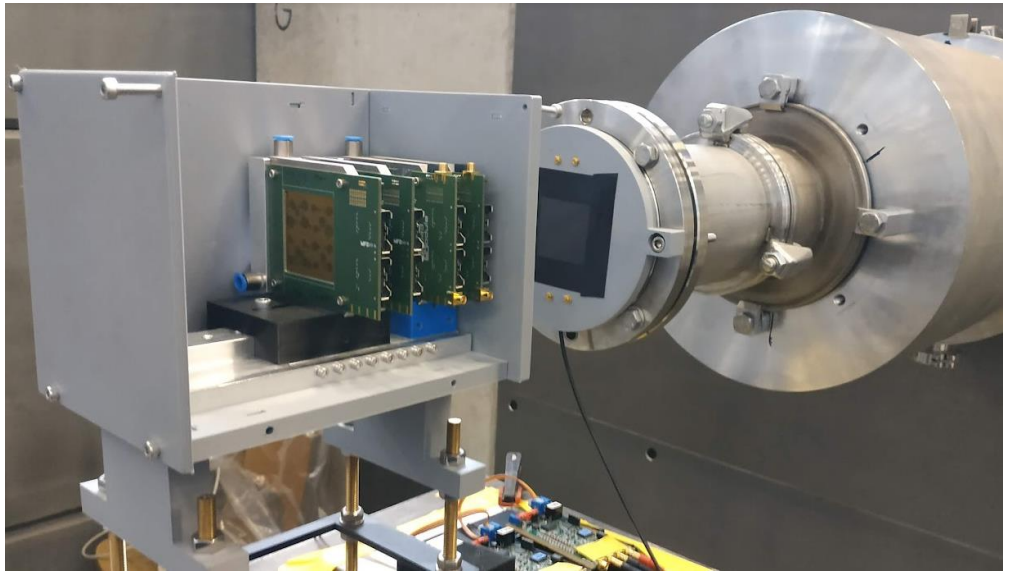
June 2024 beamtime

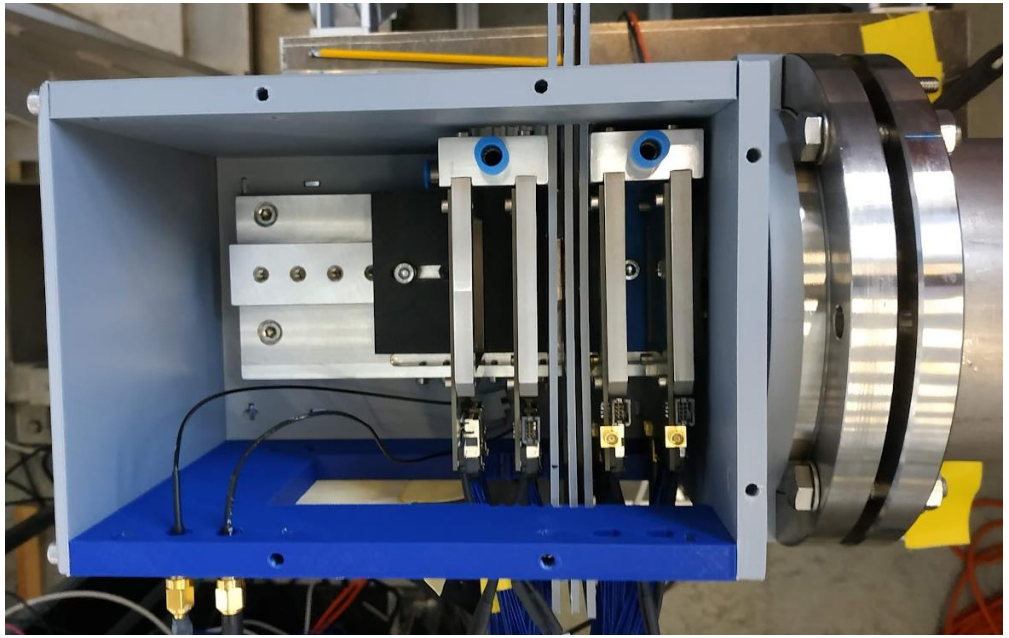
First experiment with muons

June 2024 – A first vx-μSR experiment with Silicon detectors

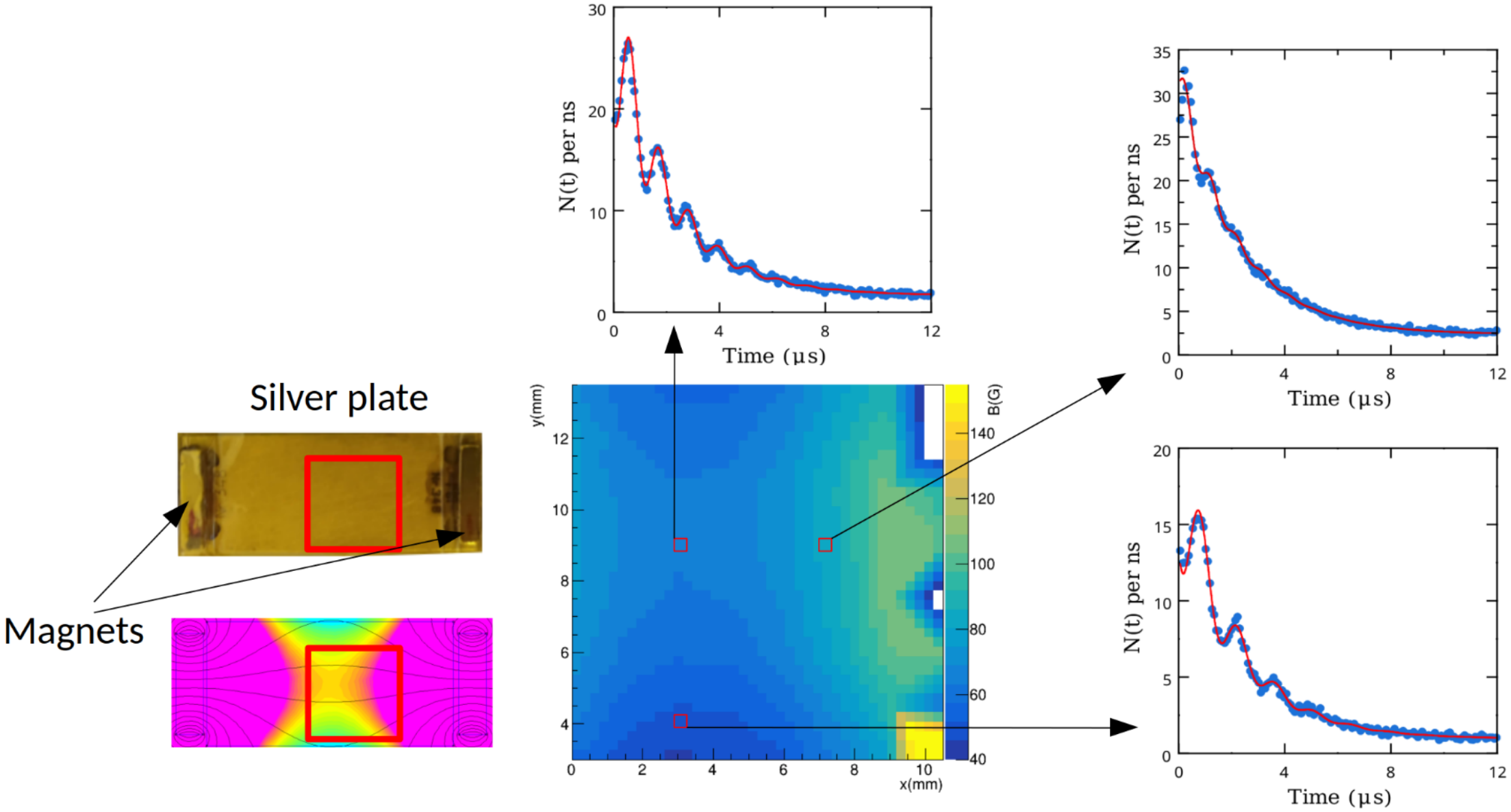
A complete and independent PSI setup

- Reliable operation over a week
- Measures multiple samples in parallel
- Identification of muon/positron from time over threshold (ToT)
- Can be water cooled for future vacuum operation

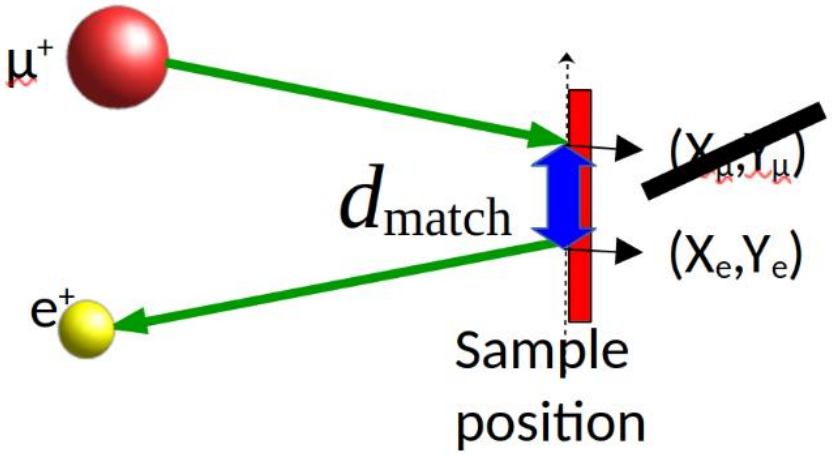


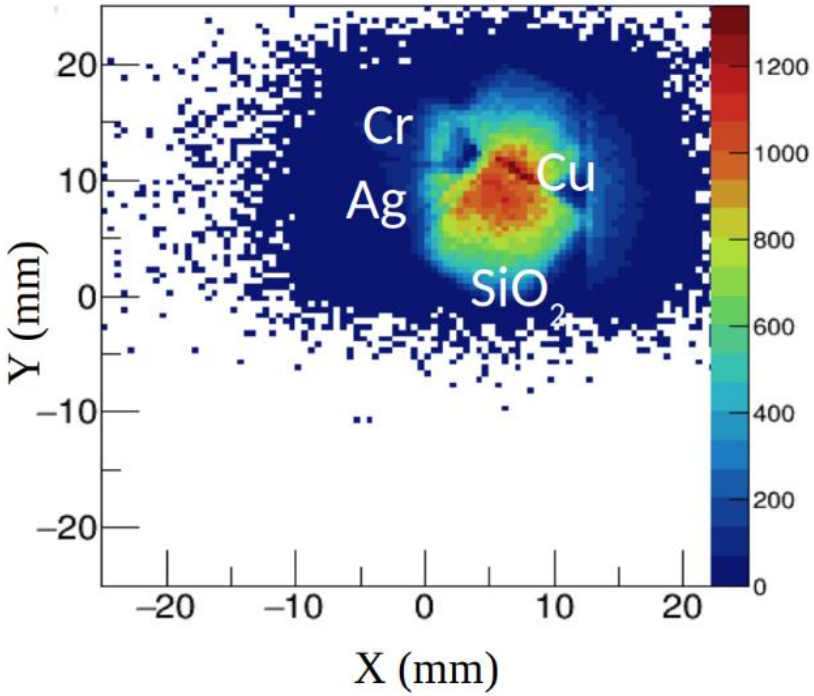


2D vx-μSR "Tomography"

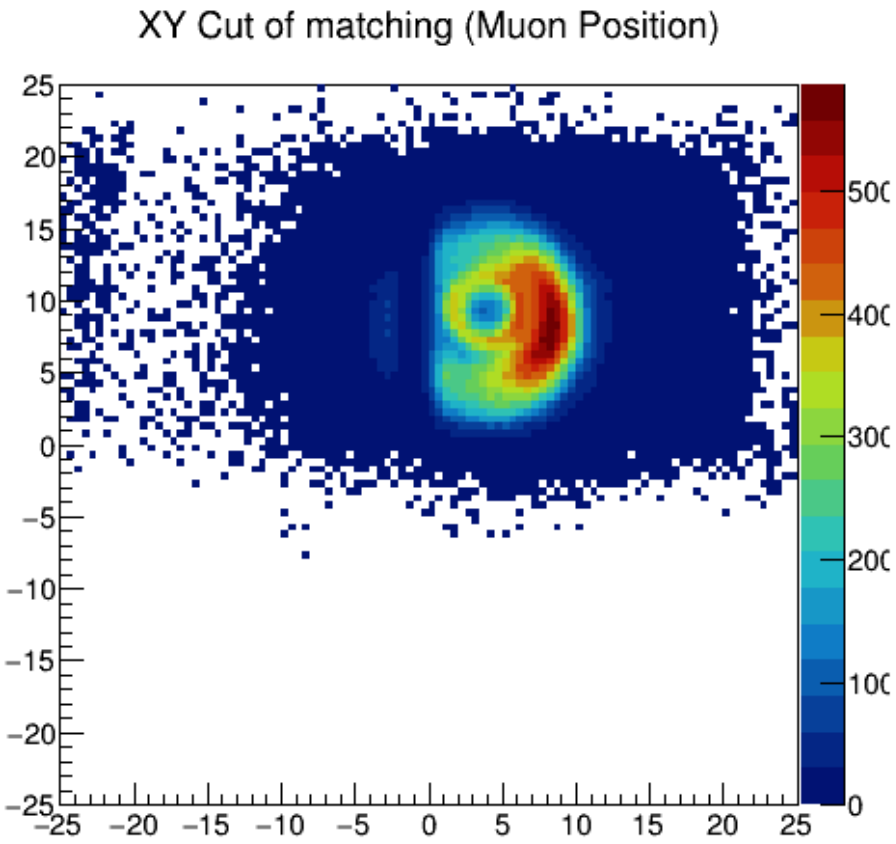


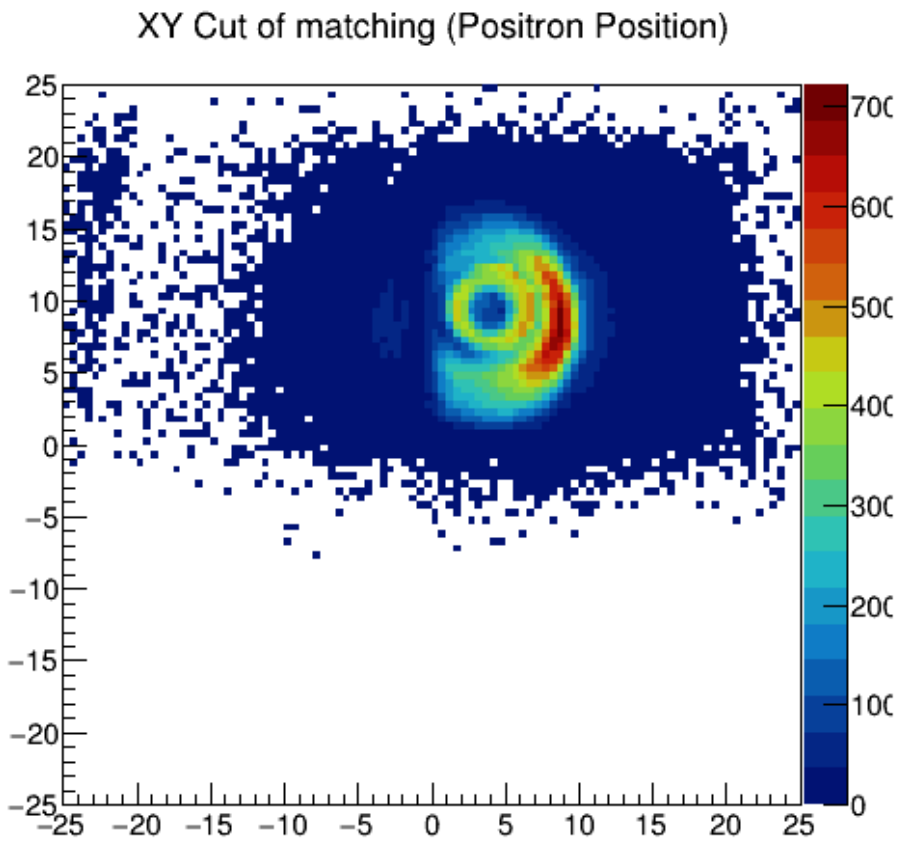
Lateral Resolution of vx-μSR
Multiple Samples Simultaneously

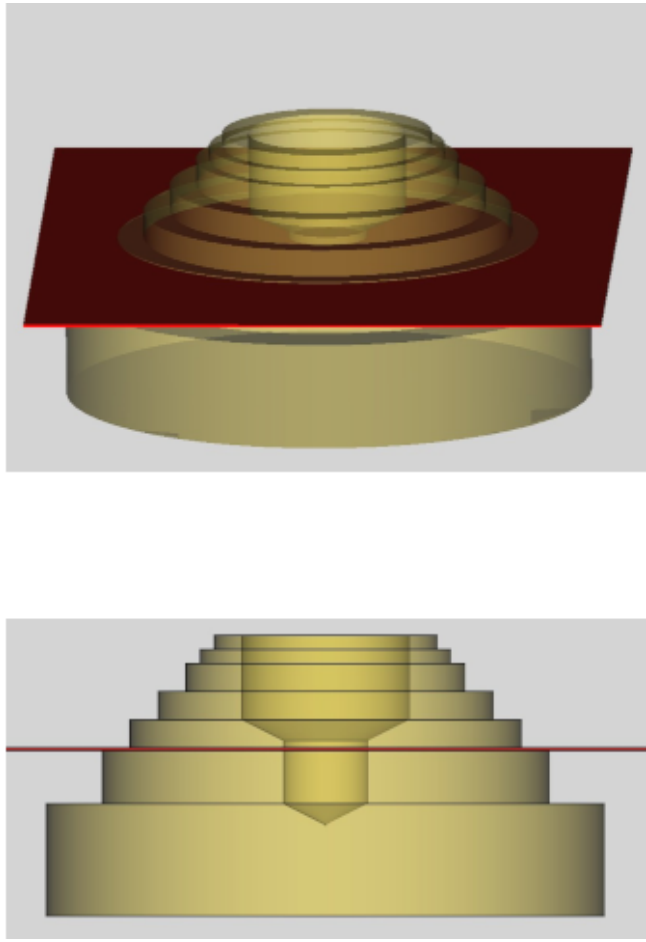




3D vx-μSR "Tomography"







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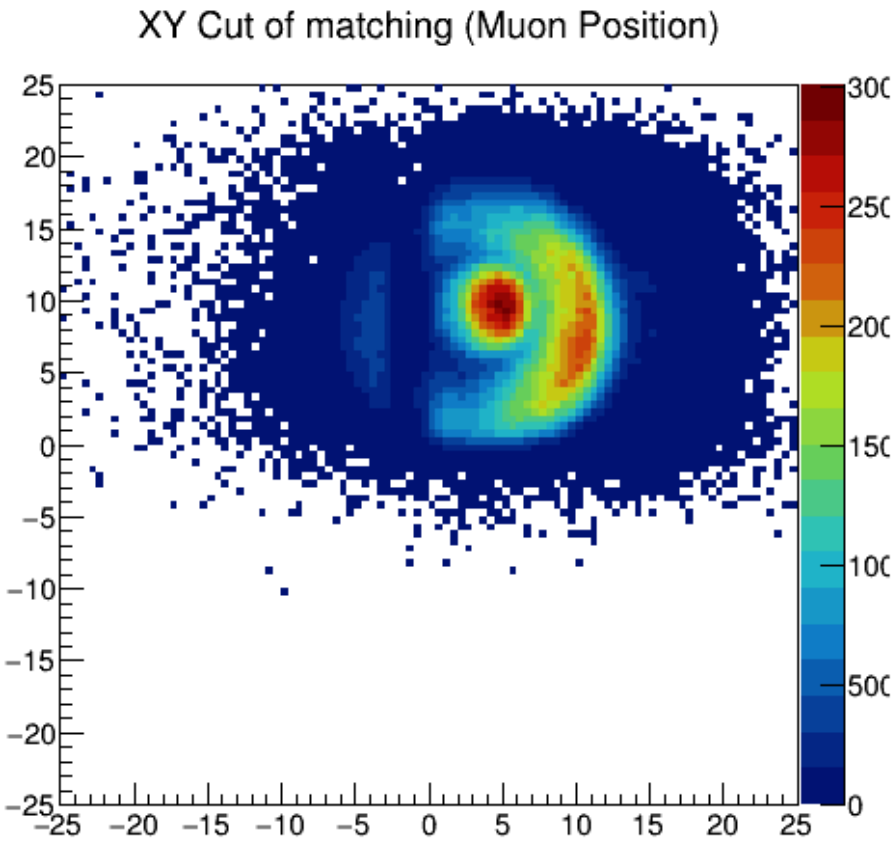

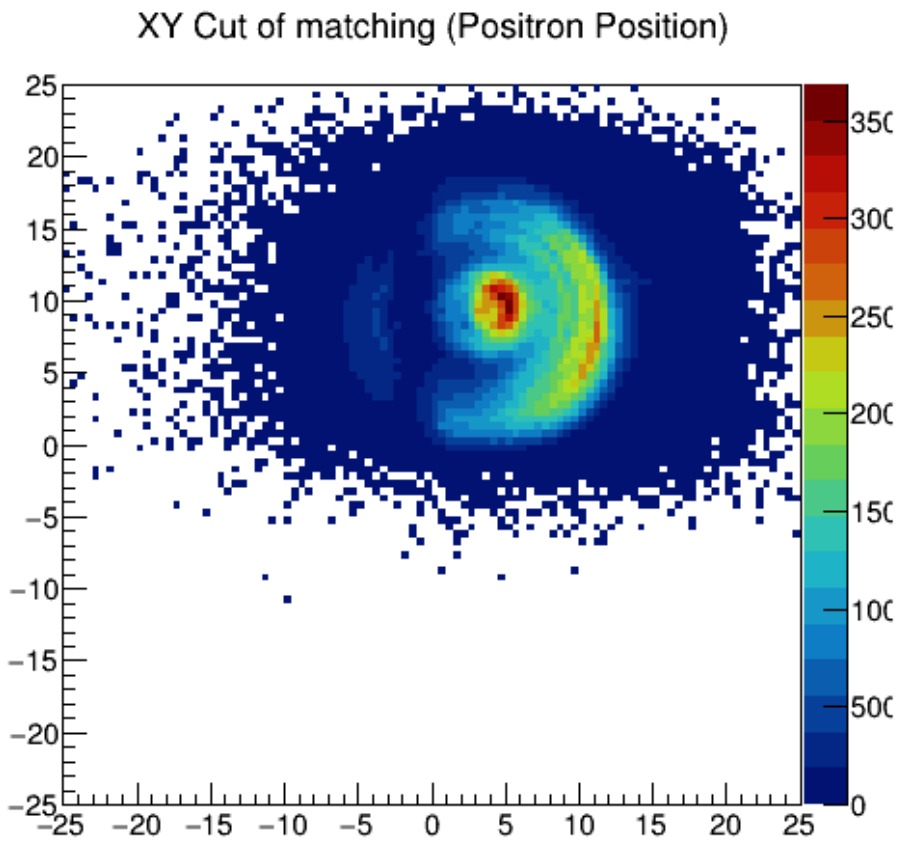

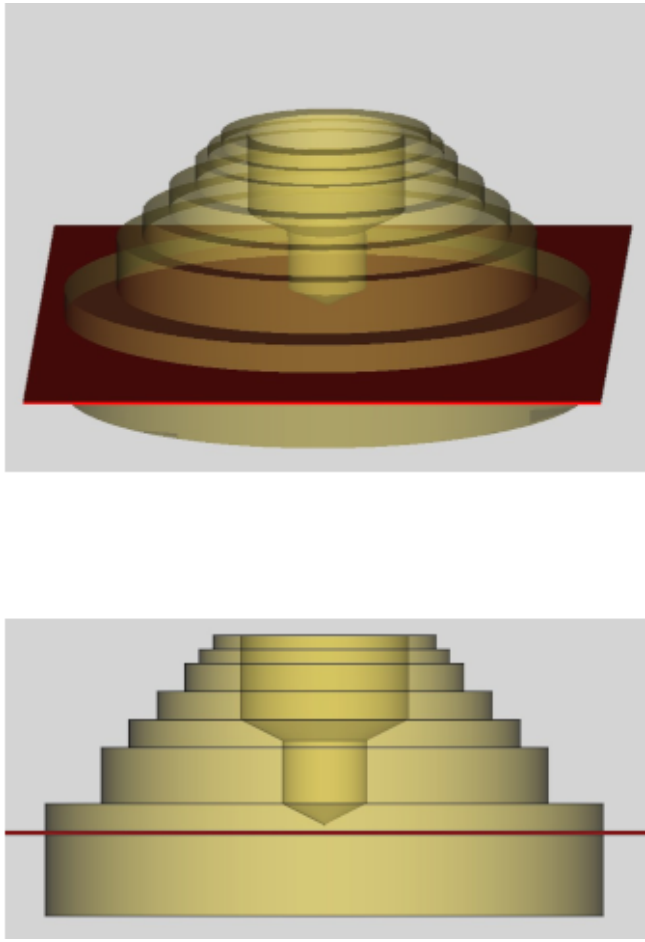

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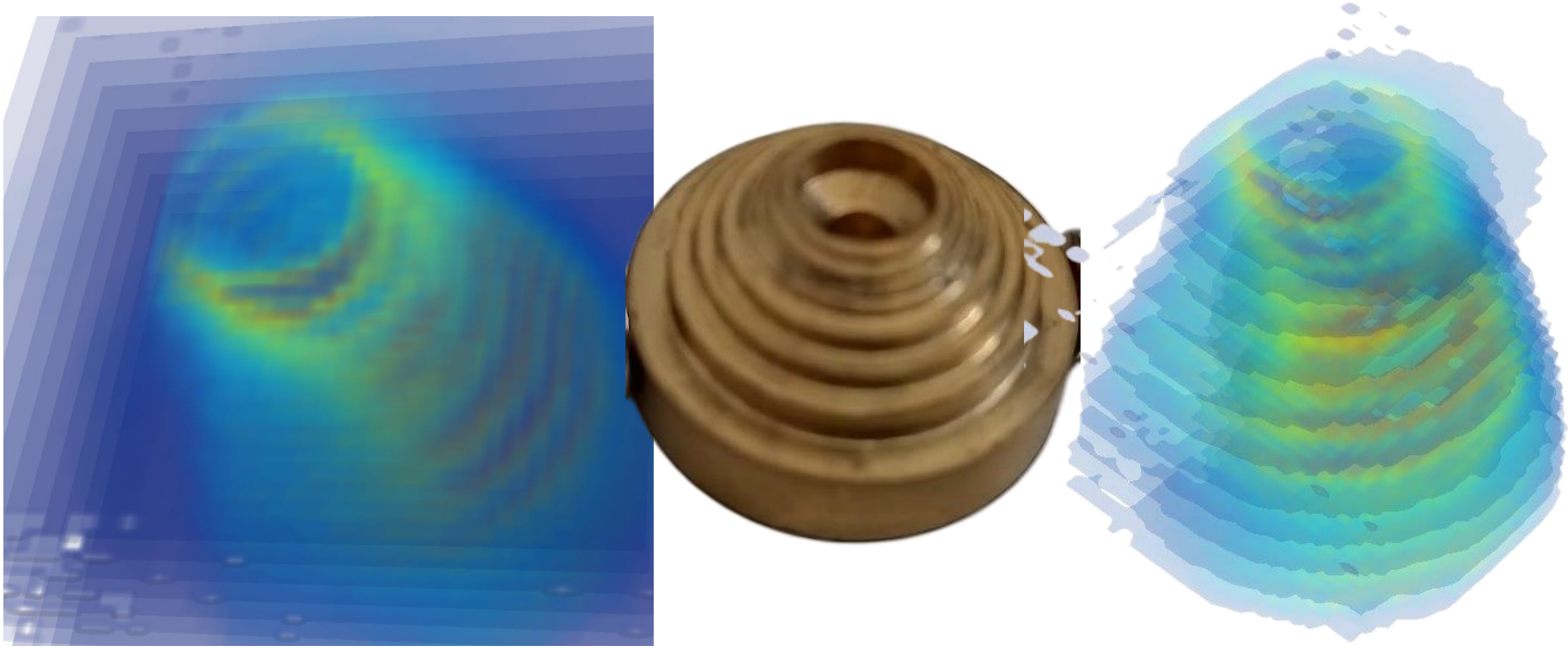
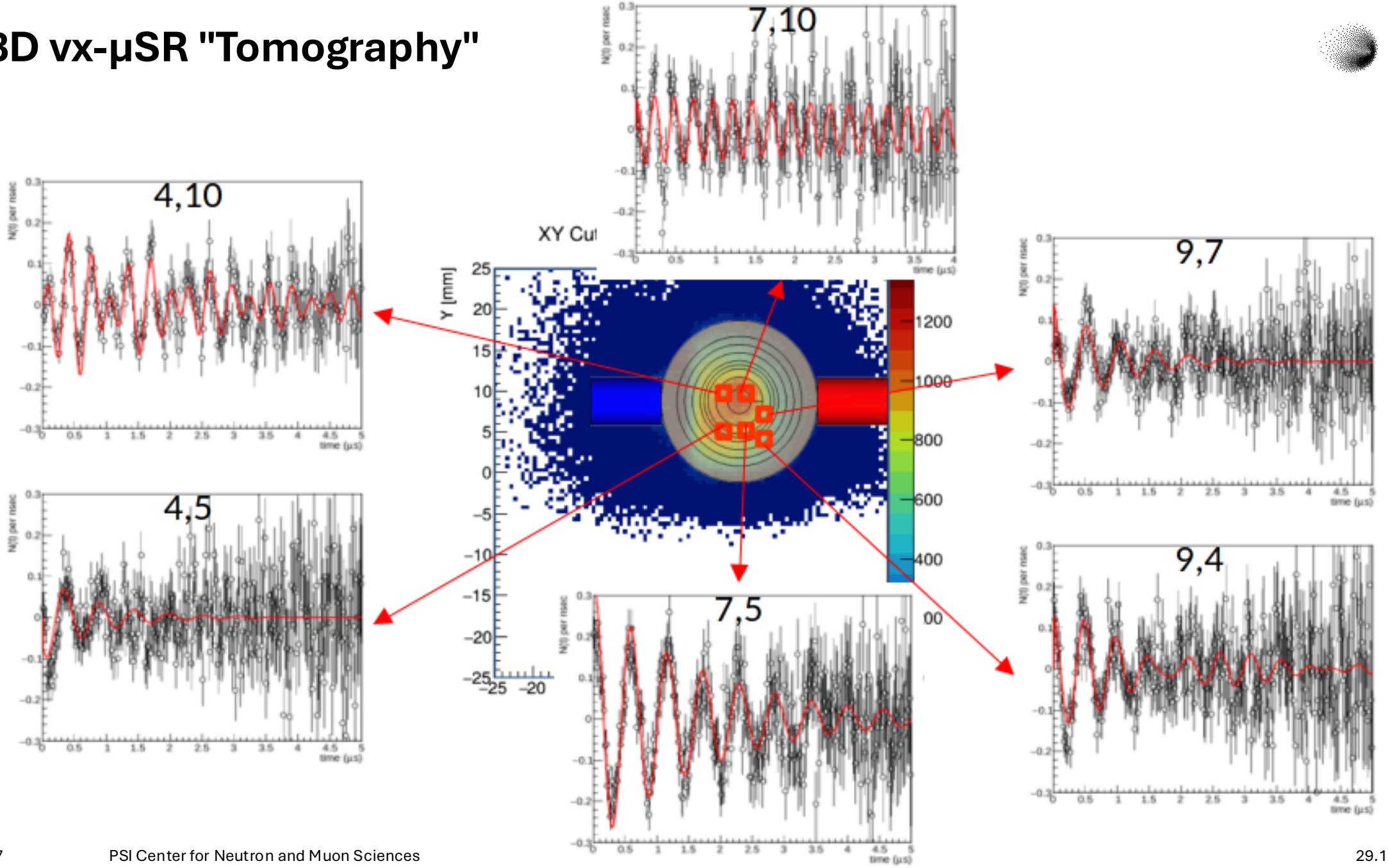


3D vx-µSR "Tomography"



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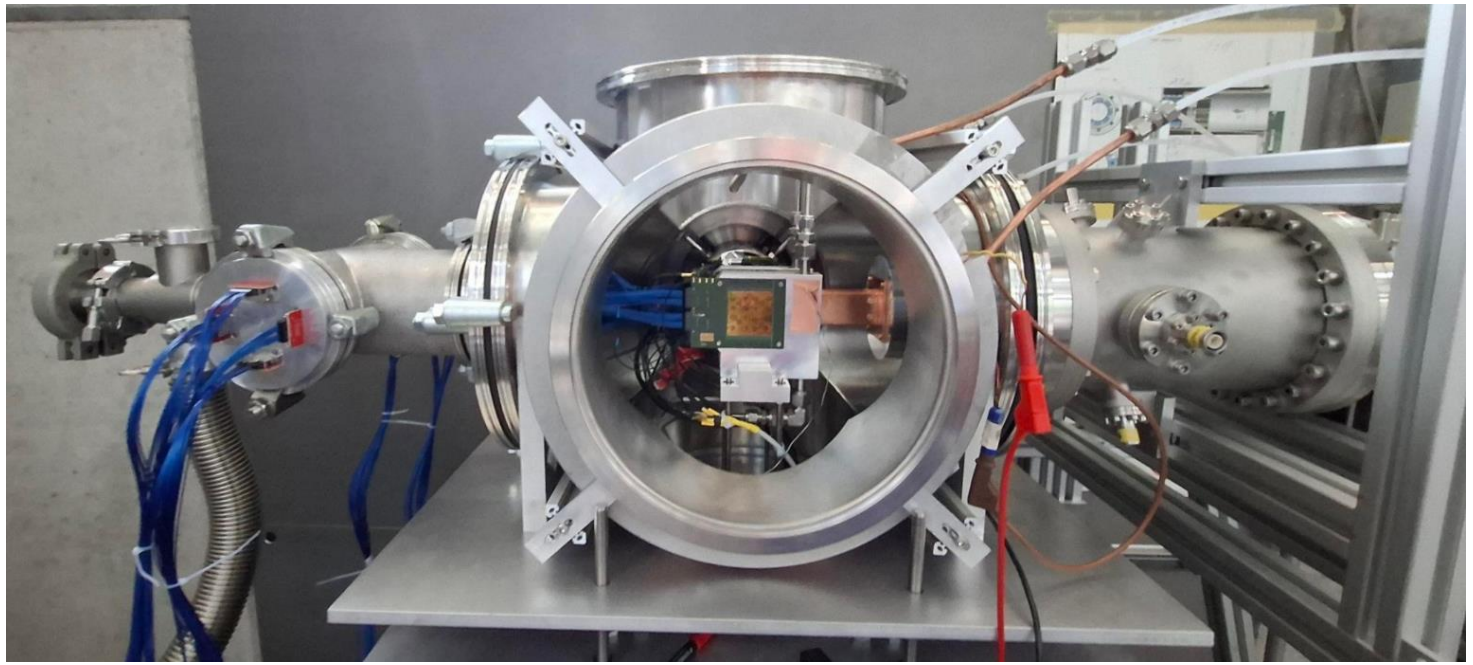
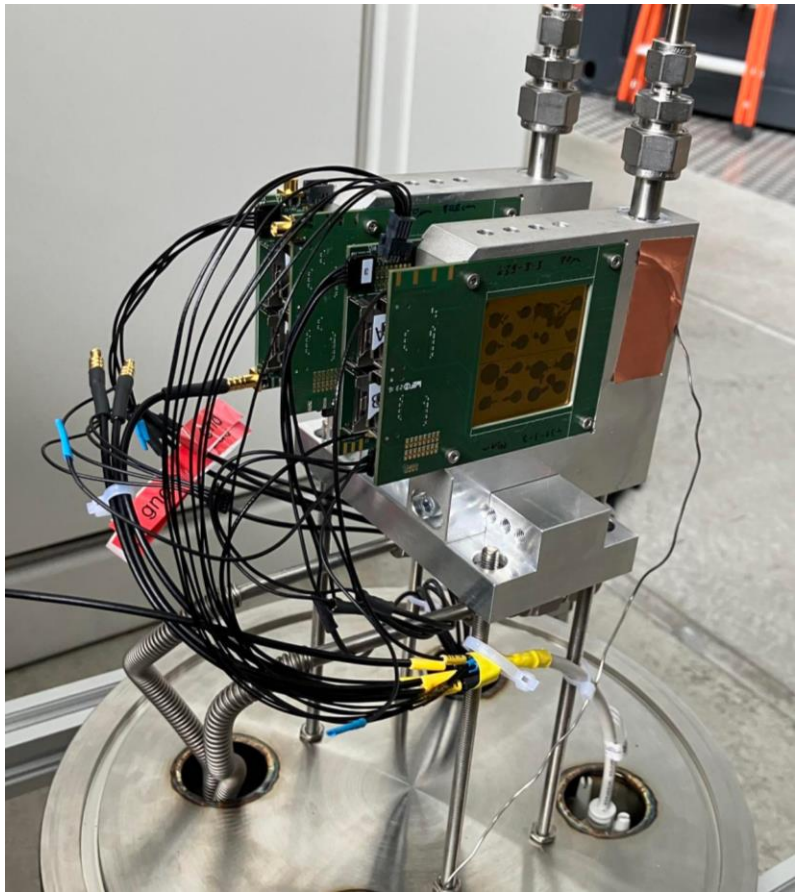
August 2025 beamtime

Real conditions run test

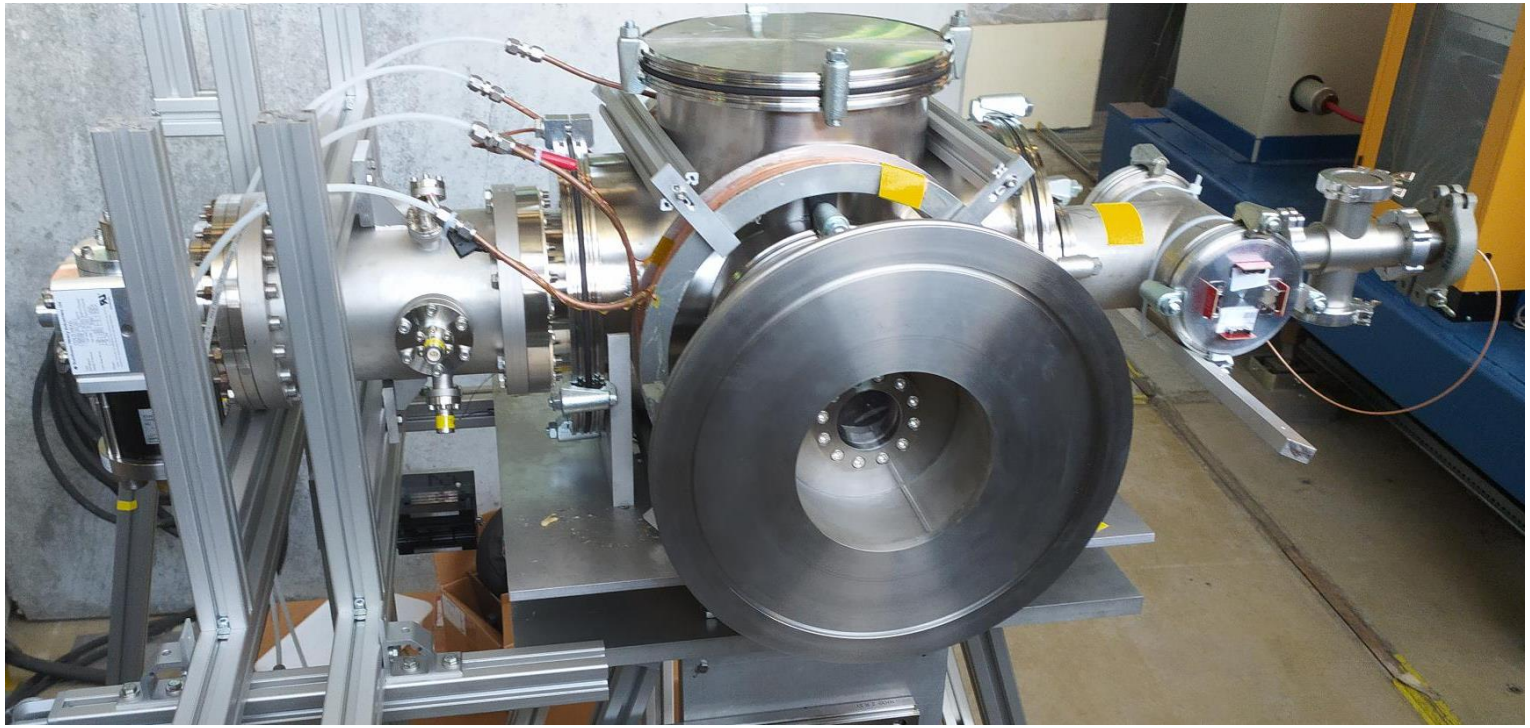
August 2025 beamtime, real conditions run test

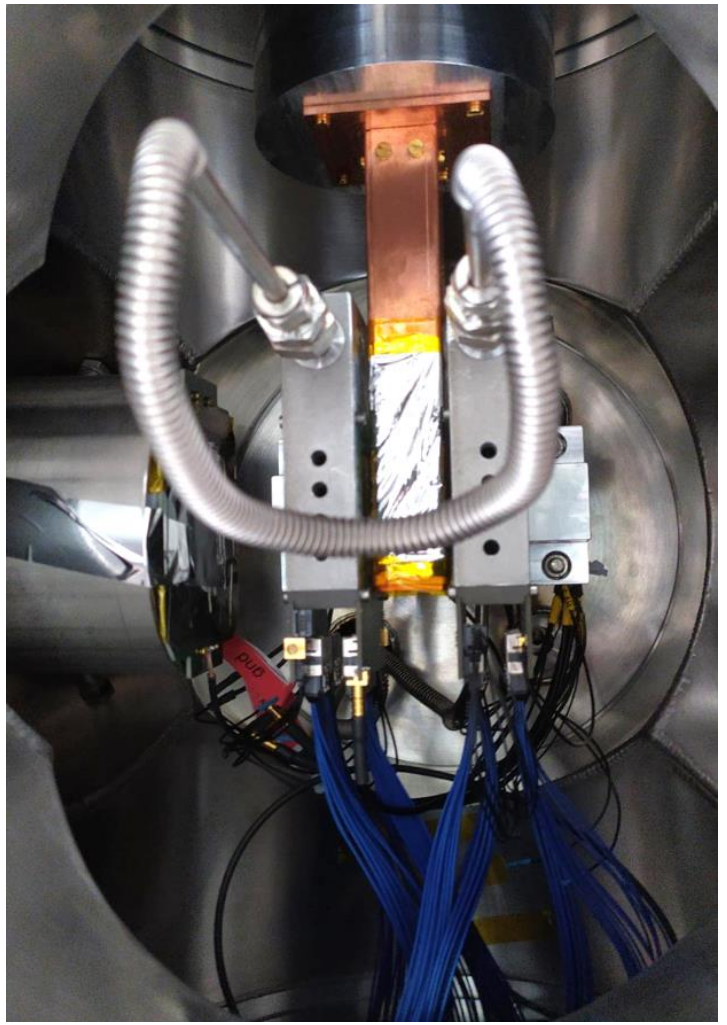
- Operation of Quad Modules under vacuum
- Cryostat + sample environment
- External magnetic field by electromagnets (LF)
- Assessment of Quad Modules cooling





August 2025 beamtime, real conditions run test





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Coming beamtimes

Hybrid setup for fast timing

November 2025 beamtime, hybrid detector concept

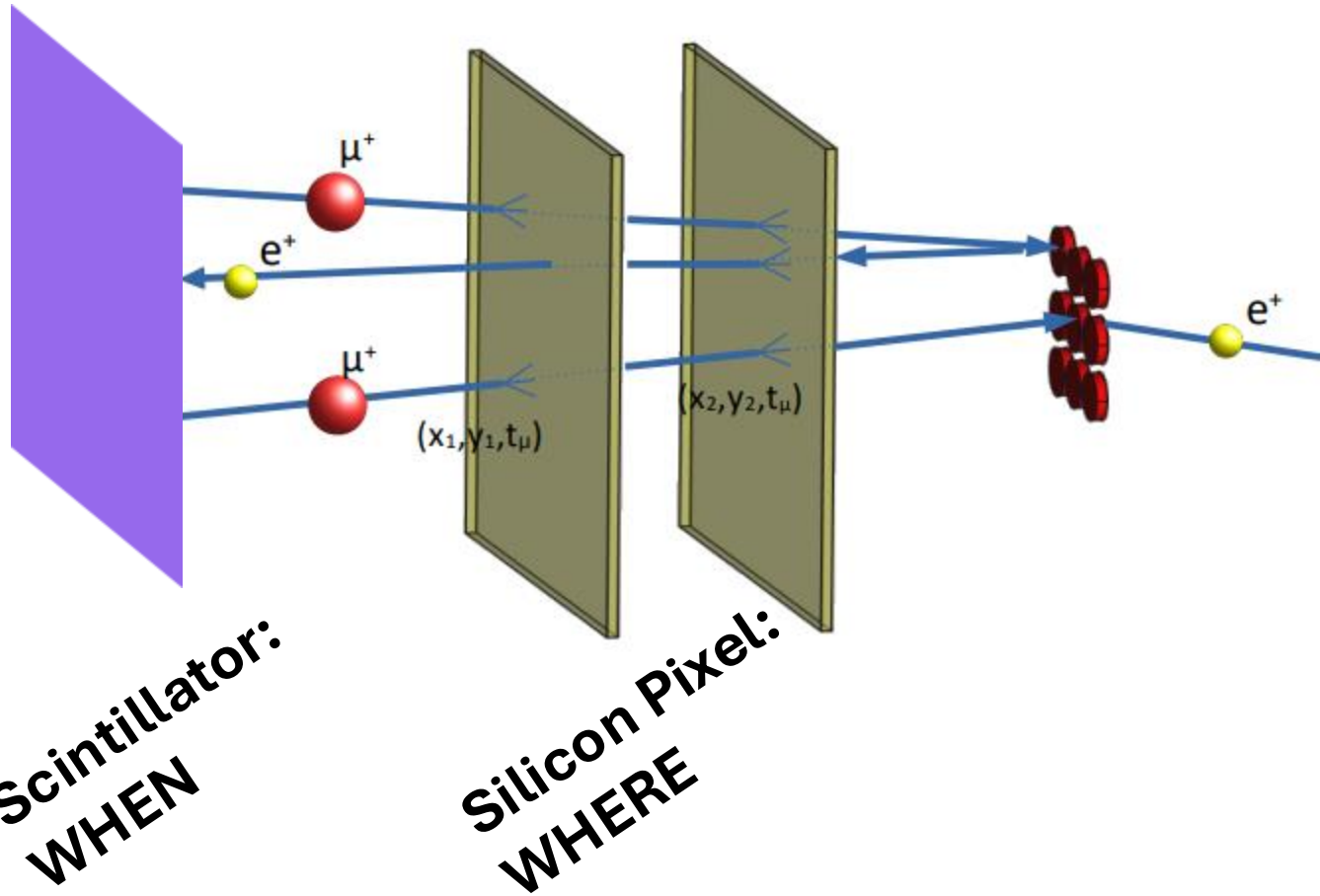
Let's combine:

> Spatial information from Quad modules
> Timing information from Positron scintillators

= Hybrid Detector

>> no need to develop faster Silicon Pixel Detectors

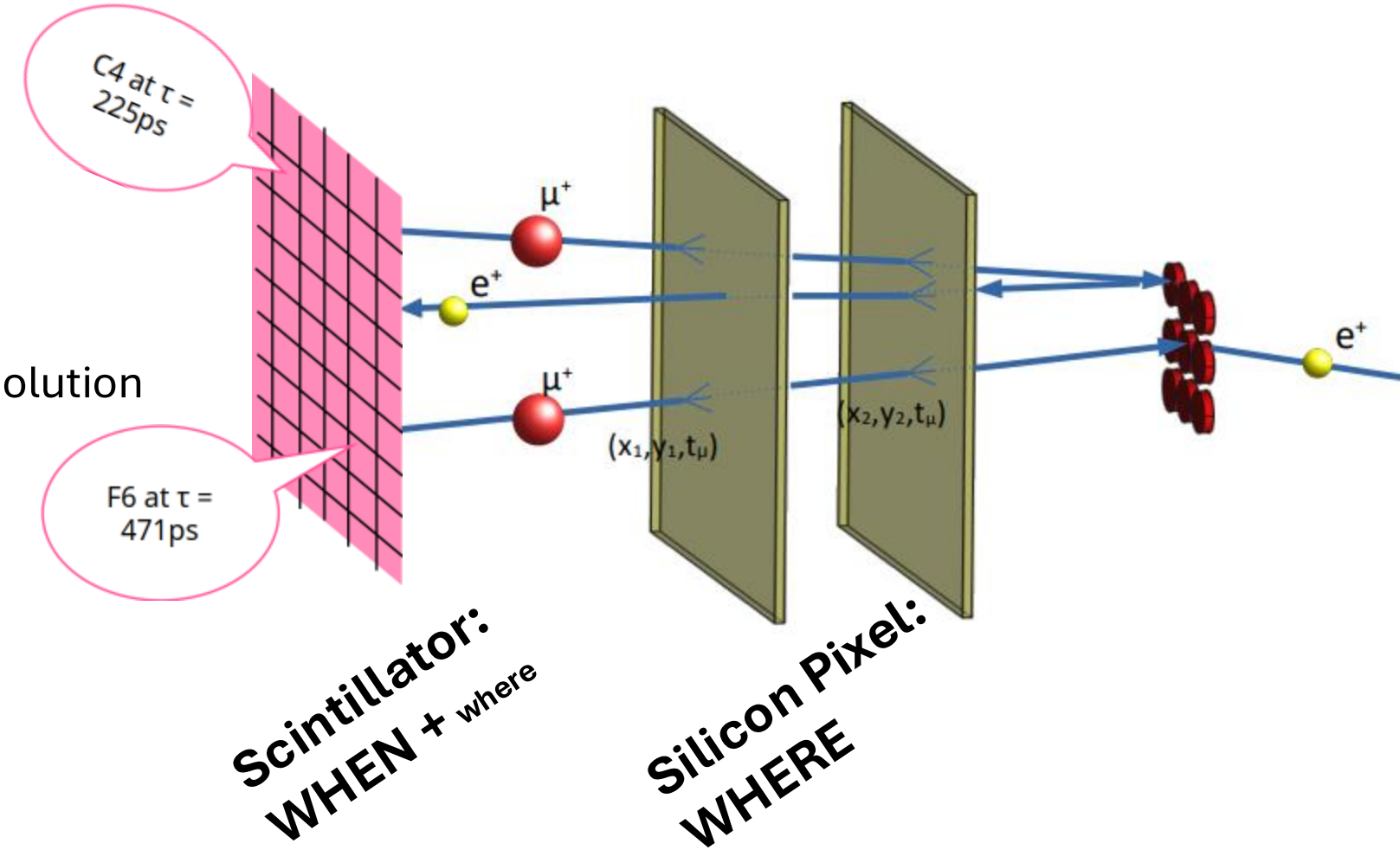
Reuse of Versatile Muon Spectrometer detectors
Interface with **muTRIG** v3 !



May 2026 beamtime, hybrid detector v2

Coincidence readout of segments
1 horizontal and 1 vertical set
Ease track reconstruction
First position guess with scintillator
Must be fast and have some spatial resolution

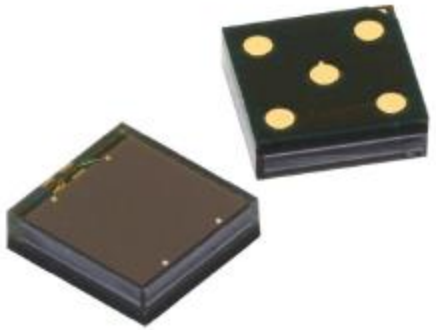
= Pixelized Tagging Scintillator (PTS)



May 2026 beamtime, PTS closeup

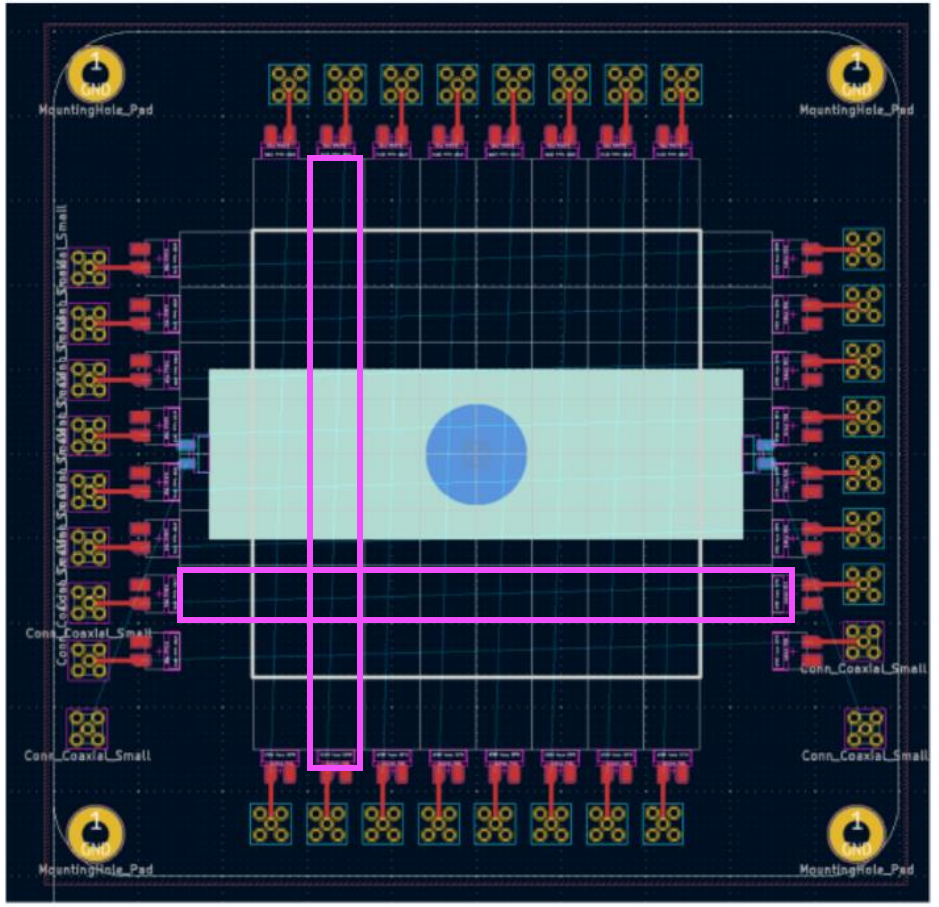
Detection layers

BC400/EJ-212 fast scintillator
6.6mm vertical / horizontal resolution
2mm thick for positron detection
200um thick for muon detection
Legacy GPS muon counter
Reflective Kapton for light insulation
Coincidence readout of each stripe
53mm opening -> 8x8 pixels
100x100mm overall size



Sensors

SiPM Broadcom AFBR-S4N44P014M
~ 3.8mm x 3.8mm detection window
32.5V breakdown voltage
Interface with TDC or MuTRIG v3

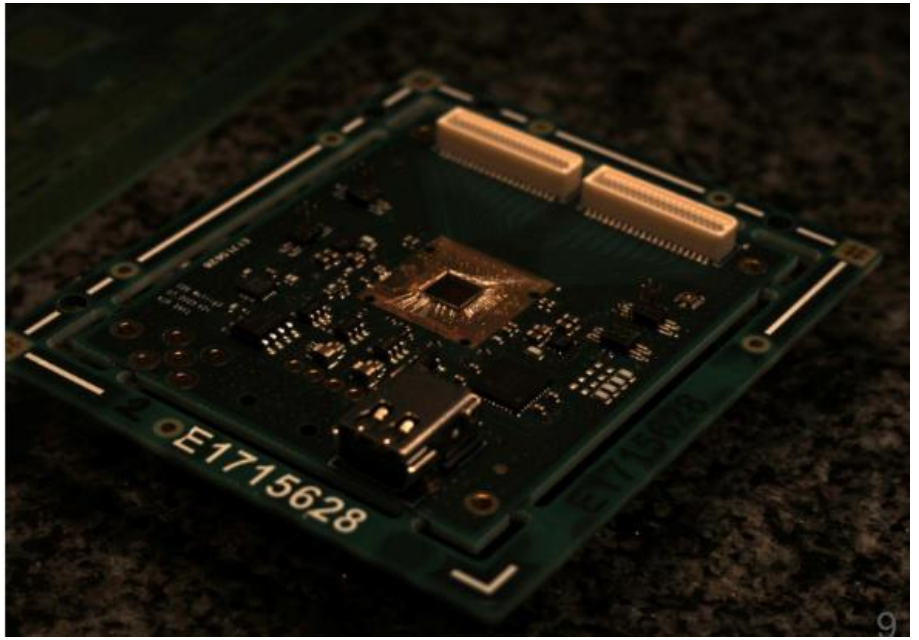


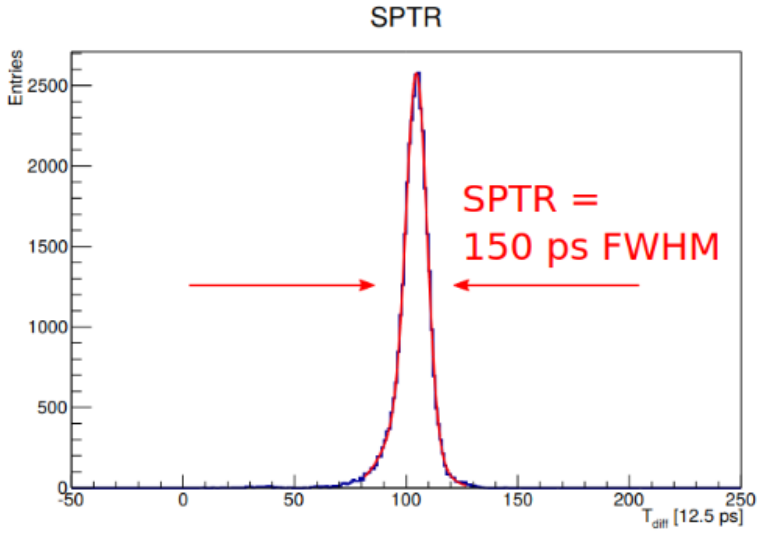
PTS, fail-safe version, for legacy TDC/Midas interface

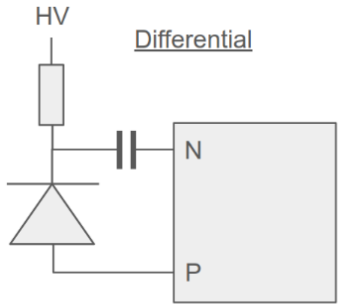
May 2026 beamtime, PTS interface with MuTrig

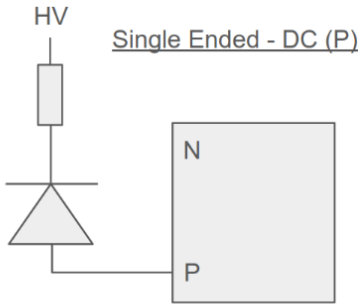
MuTRIG v3 board
Developed for Mu3e
32 input channels per board
New Wire Bounding technique
Limited footprint >> placed in vacuum

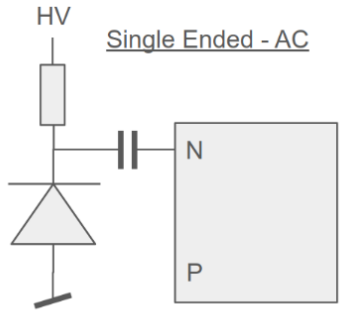
>> Easier synchronization scintillator – silicon pixels











vx-μSR – Roadmap

- June 2024 First setup in air, permanent magnets
- August 2025 First setup in vacuum, with cryostat and electromagnets
- **November 2025 First hybrid setup with fast timing capability**
- May 2026 First Highly Pixelized Fast Timing experiment
- Late 2026 Critical Design Review for a permanent instrument

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- June 2028 Commissioning of the new instrument (GPS beamline?)
- November 2028 User-ready vx-μSR instrument

vx-μSR – a team effort

PSI

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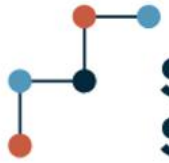

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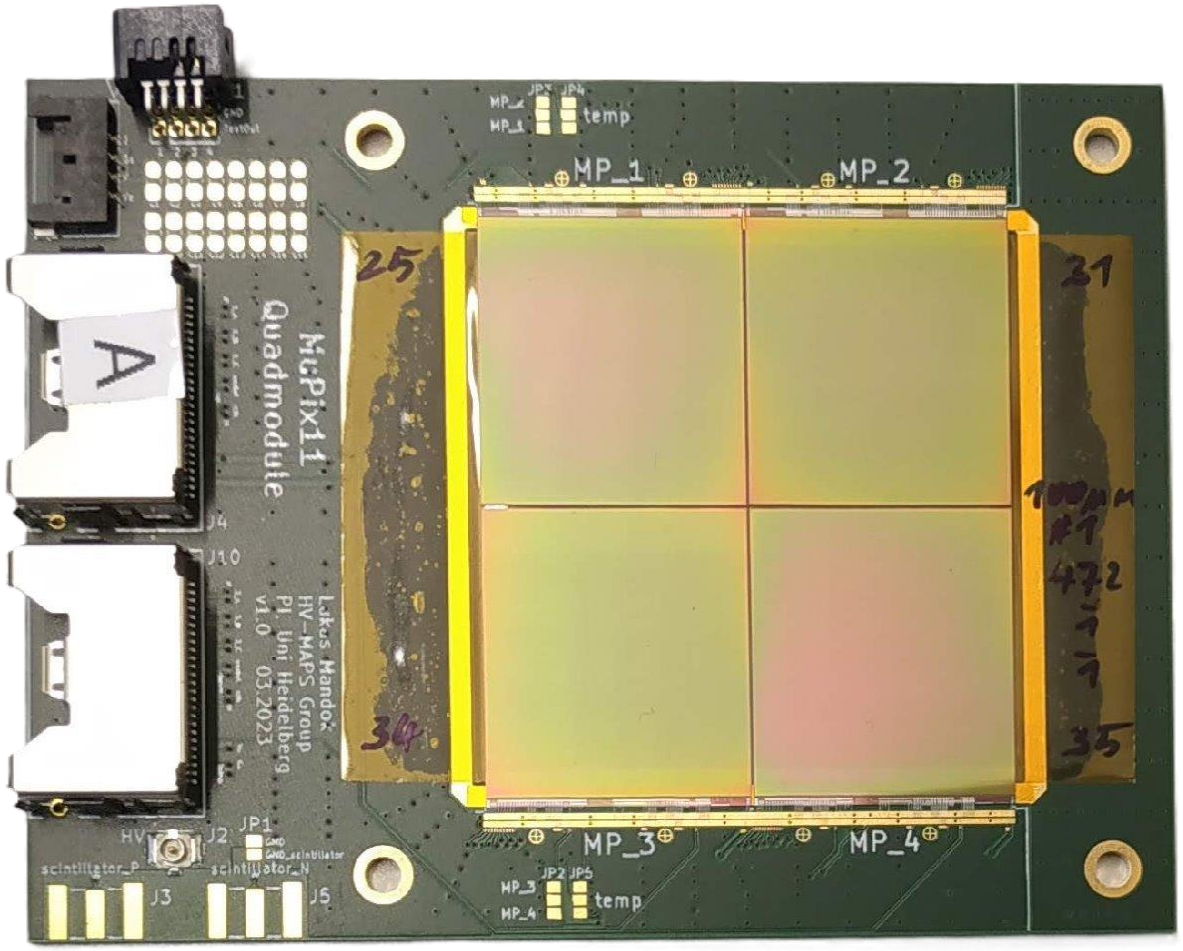

Maxime Lamotte,

on behalf of **Pascal Isenring**

PSI / CNM / LMU

BRIDGE conference, 22 October 2025 – Tokyo, Japan