PSI Center for Neutron and Muon Sciences

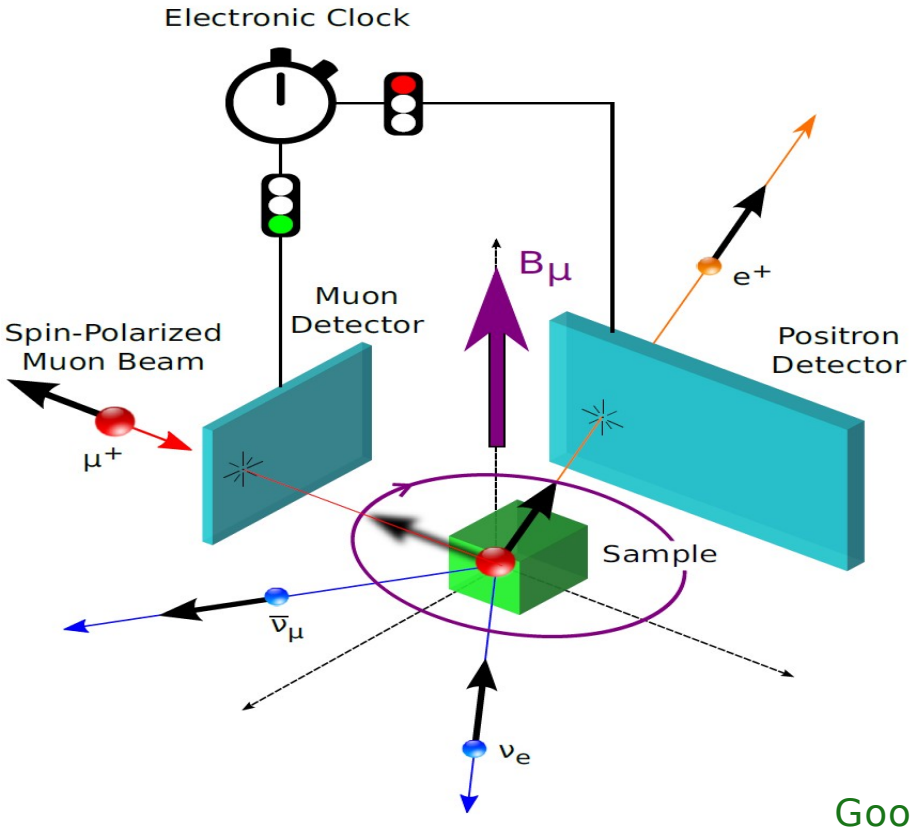
Advanced Muon-Spin Spectroscopy Using Si-Pixel Detectors - A New Dawn for µSR

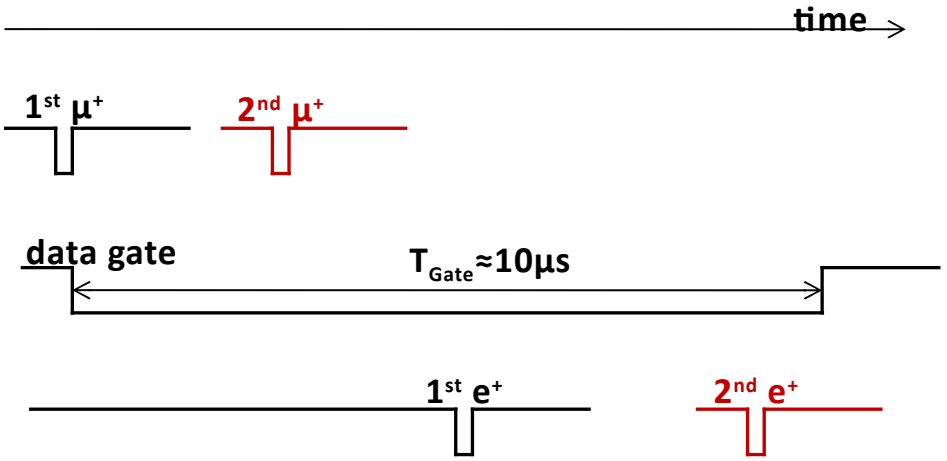
Pascal Isenring
µSR2025, St. John‘s, 22 July 2025

Outline

- μSR at PSI and its limitations
- What to overcome?
- Vertex Reconstructed μSR (vx-μSR)
- Detector technology
- First Si-Pixel μSR spectrometer
- Measurements and examples

μSR at PSI and its limitations

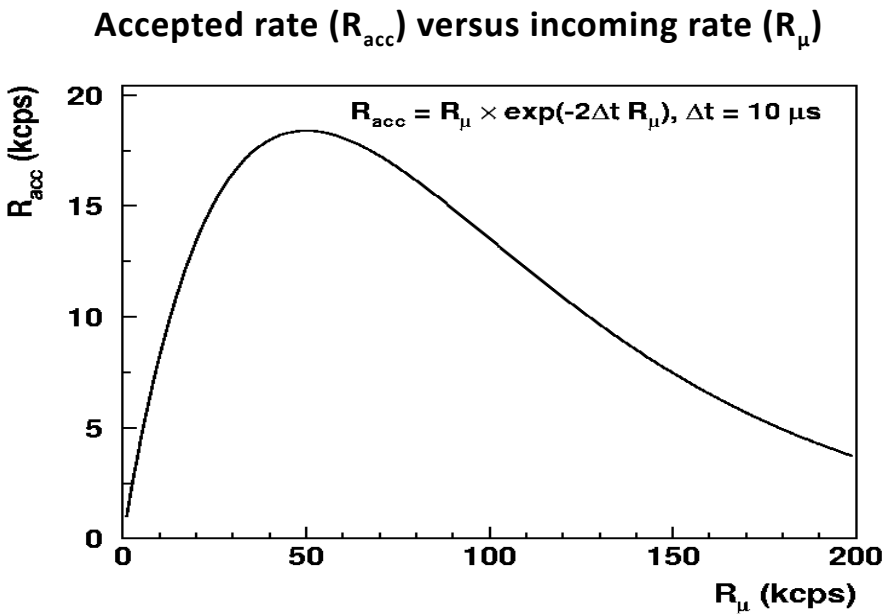




- 1st μ^+: there was **no** other μ^+ for at least T_{Gate} in the past
- Single muon detection: only **one** μ^+ and **one** e^+ in observation window ($T_{Gate}\approx10\mu s$)
- Second μ^+ / e^+ rejection electronically and by rate limitation

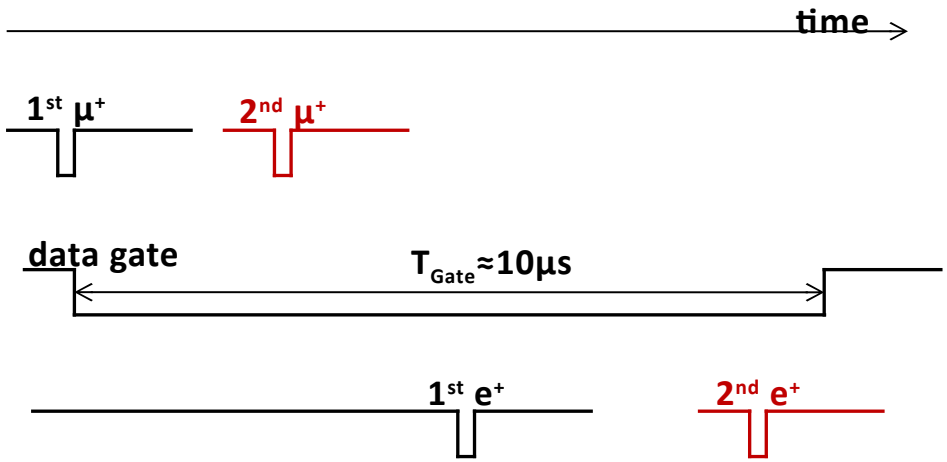
Good Event = (data gate) ^ (1st e^+) ^ (**no** 2nd μ^+) ^ (**no** 2nd e^+)

µSR at PSI and its limitations



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

100x more rate with HIMB



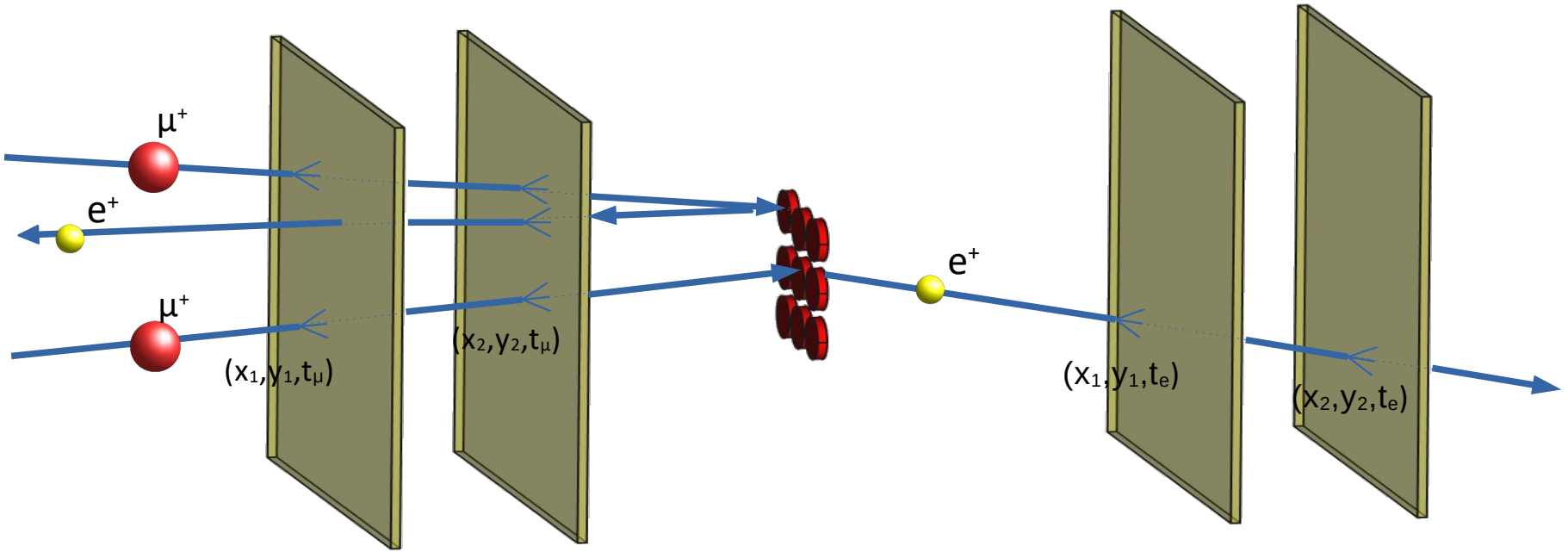
- 1st µ⁺: there was **no** other µ⁺ for at least T_{Gate} in the past
- Single muon detection: only **one** µ⁺ and **one** e⁺ in observation window (T_{Gate}≈10µs)
- Second µ⁺ / e⁺ rejection electronically and by rate limitation

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

What are the limitation we want to overcome?

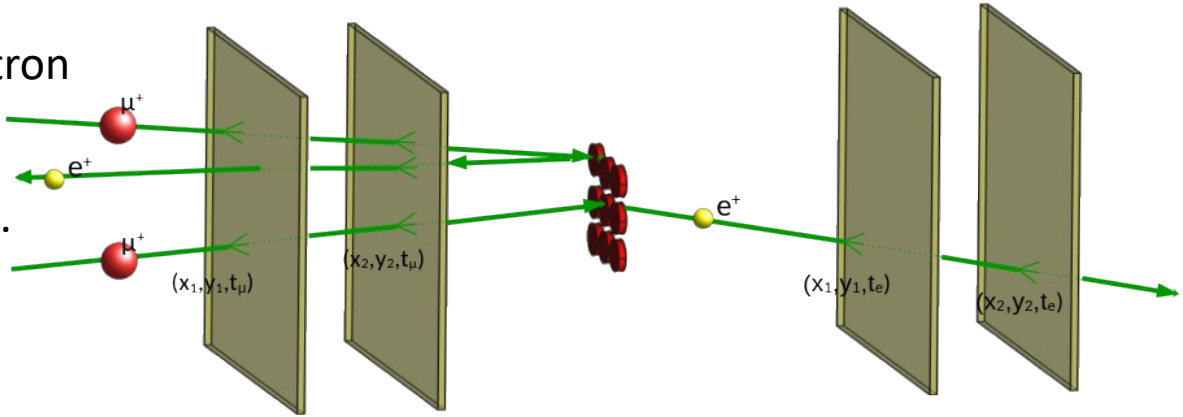
	Current limit	Aim
Incoming muon rate	< 40kHz @ 10µs	> 400 kHz @ 20µs
Sample size	> 4x4 mm^2	< 1x1 mm^2
Number of samples	One at a time	> 1
Veto detectors	necessary	obsolete
Data gate length	10µs or 20µs with MORE (muons on request)	20-30µs

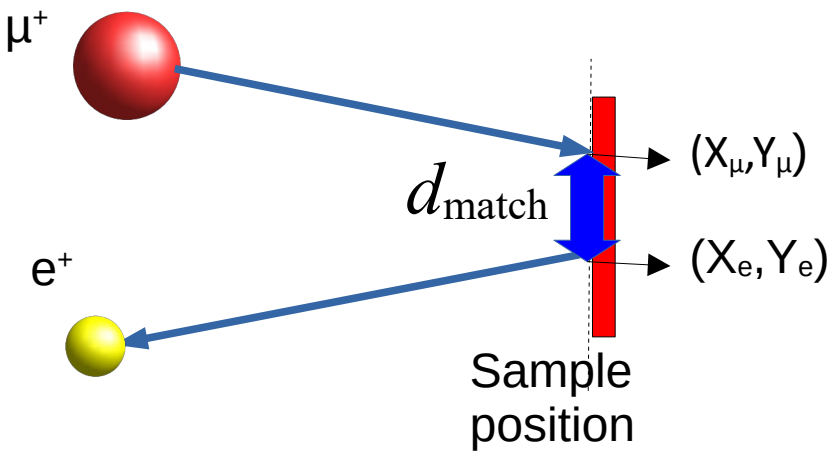
Vertex Reconstruction Scheme



How to Produce Vertex Reconstructed μSR (vx-μSR)

- 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.

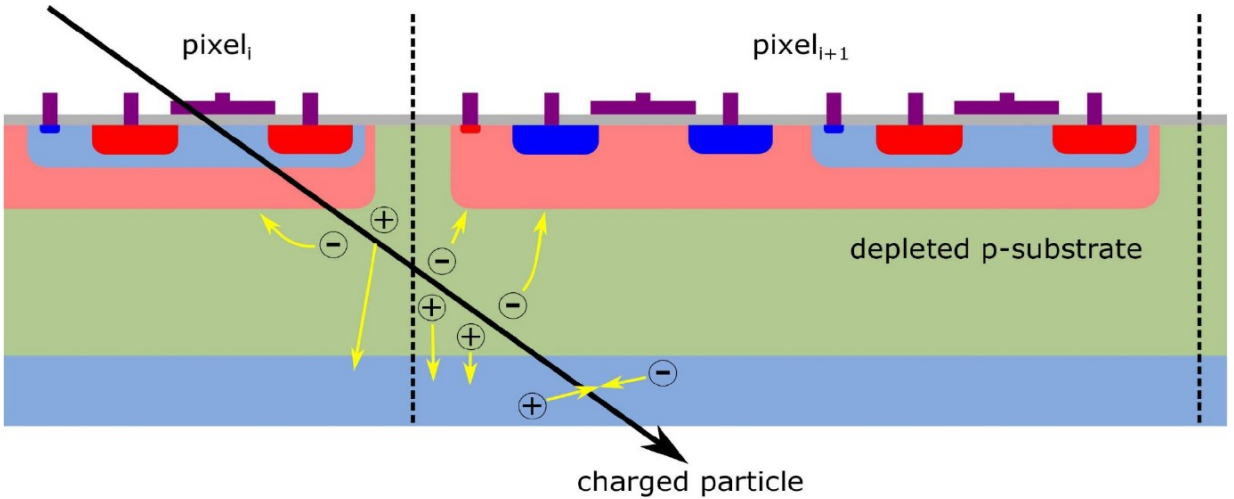


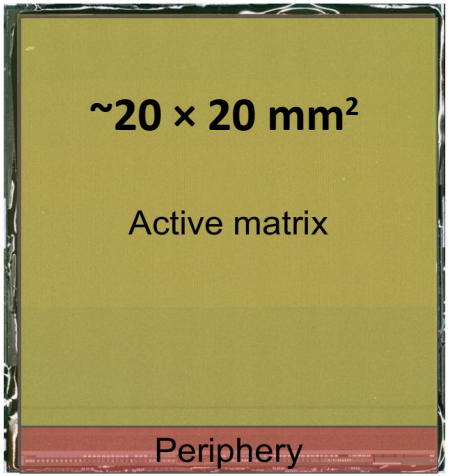


High-voltage monolithic active pixel sensor (HV-MAPS)

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





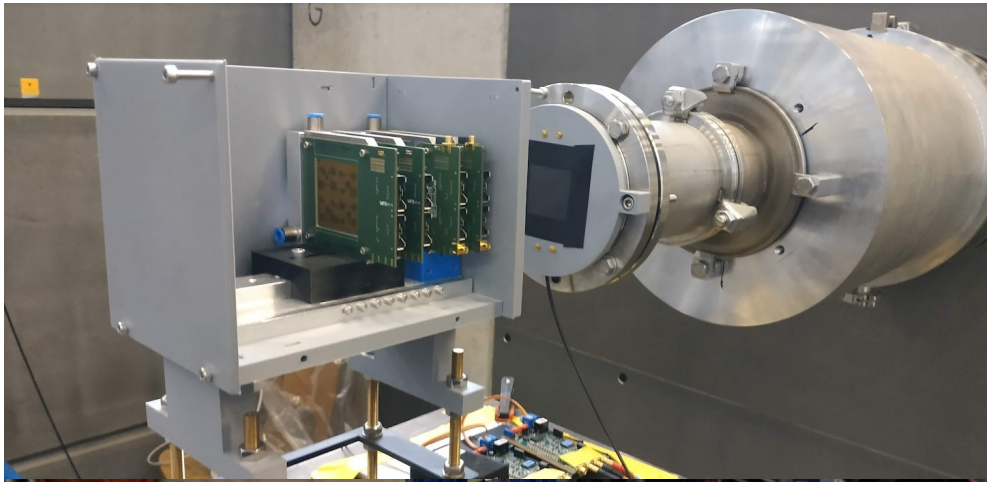
Figures and details from Thomas Rudzky

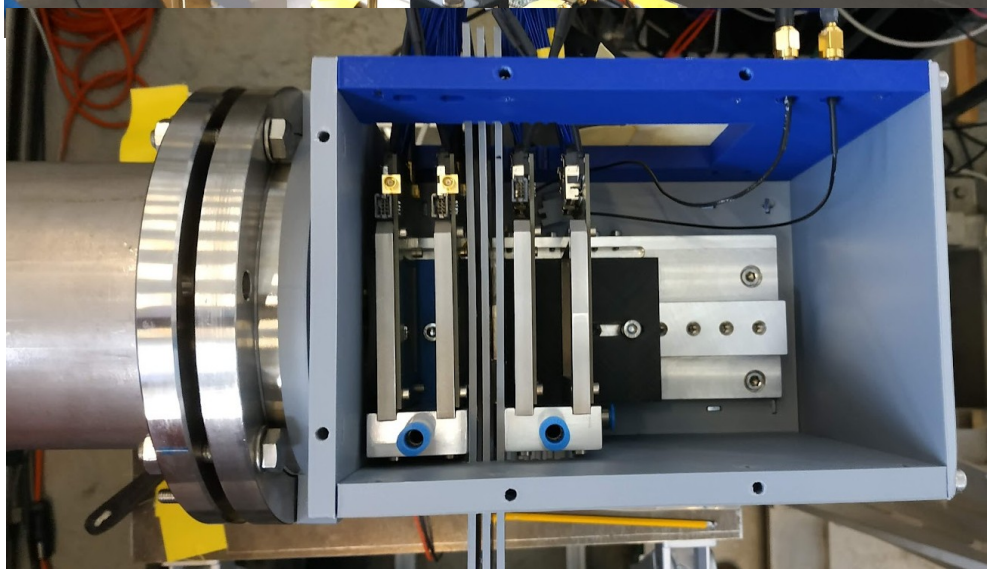
See: https://archiv.ub.uni-heidelberg.de/volltextserver/30885/

First Si-Pixel μSR Spectrometer

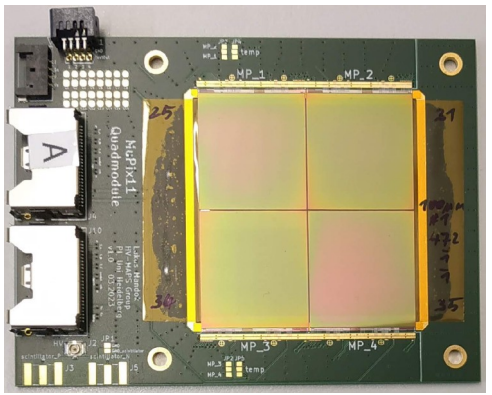
https://arxiv.org/abs/2503.08891

- Four layered spectrometer: upstream and downstream set
- MuPiX11 sensors: four chips per layer → active region of ~40 x 40 mm^2
- Variable distance between upstream and downstream set
- Per pixel hit rate of >> 40 kHz possible

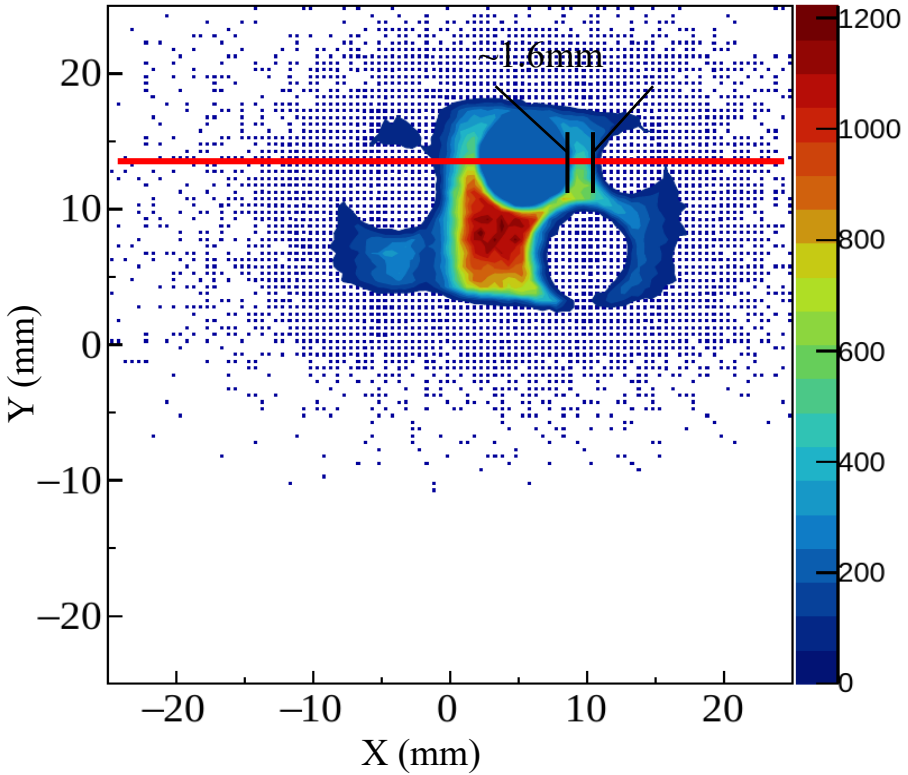




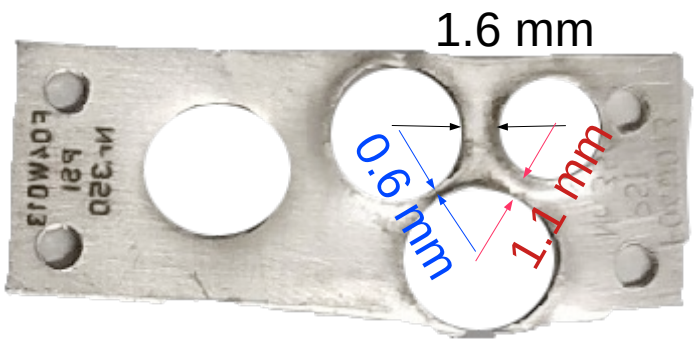
- In air
- No cryostat
- No magnet



Lateral Resolution of vx-μSR
Fine Details



- Choose a sample with clear features
- Map the sample
- Extract cuts to examine features



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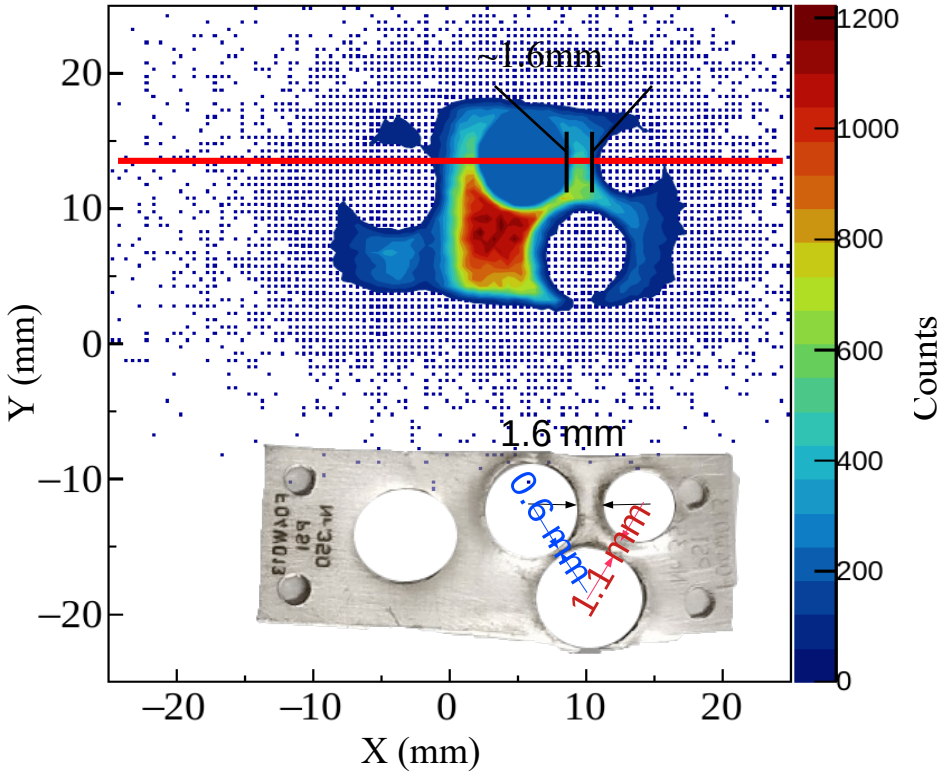

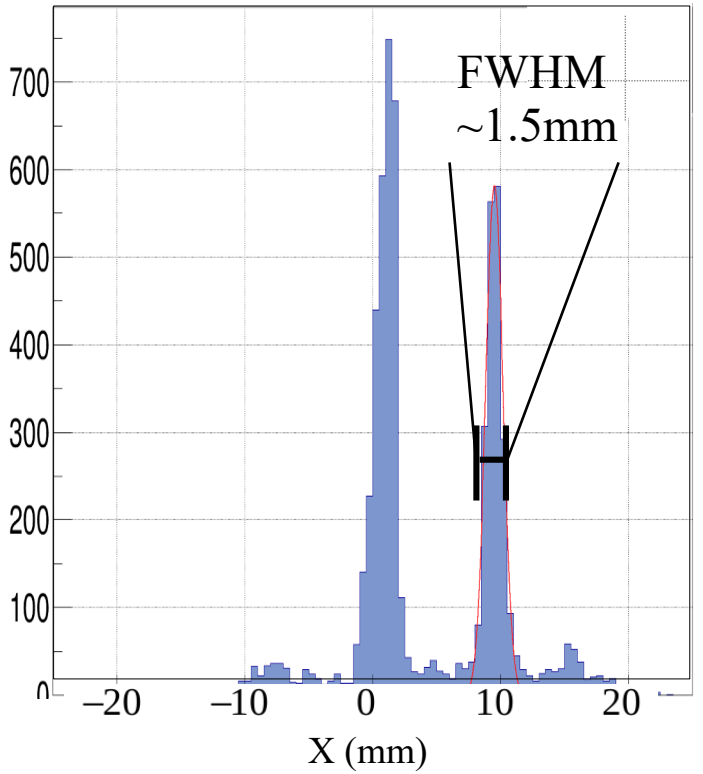

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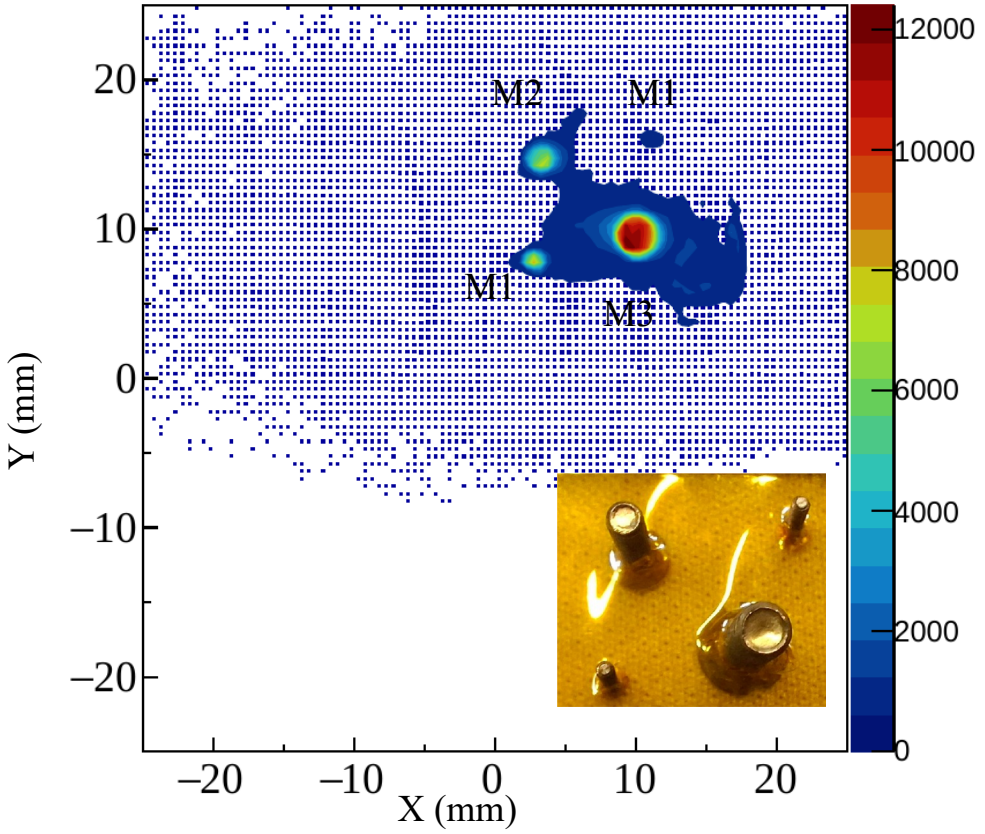
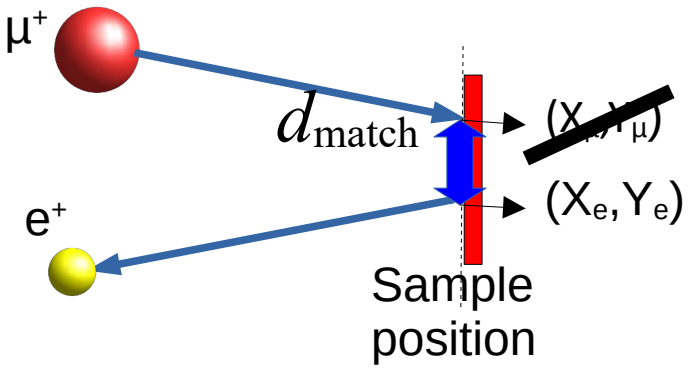
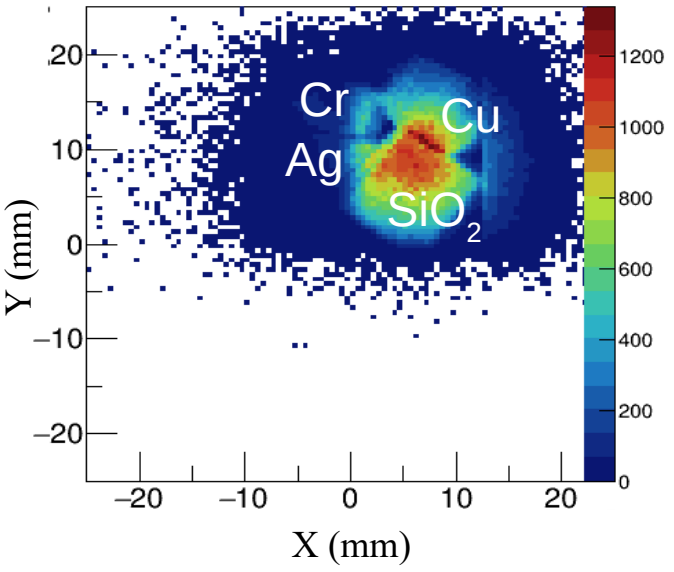
Fine Details



Lateral Resolution of vx-µSR
Multiple Samples Simultaneously





Lateral Resolution of vx-μSR
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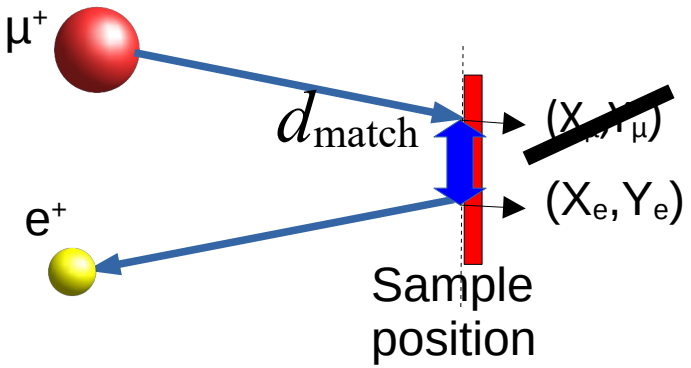
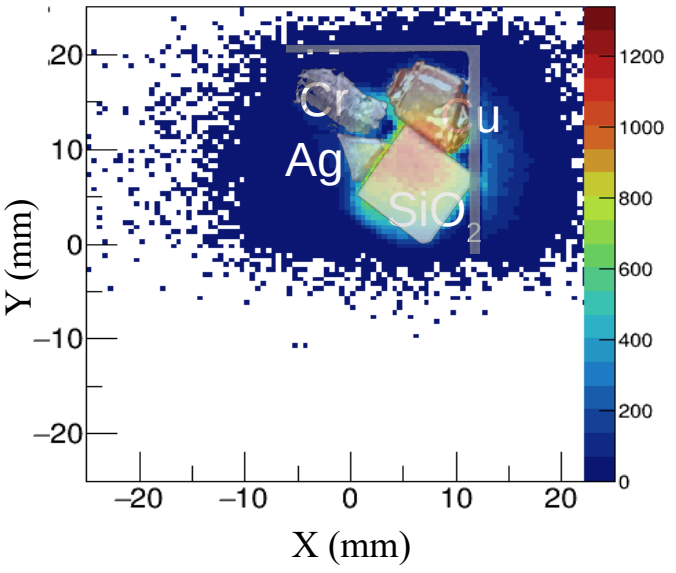
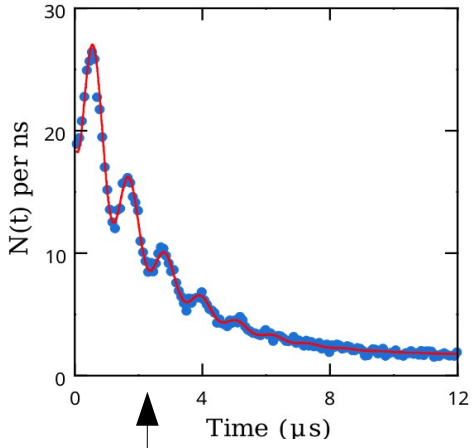
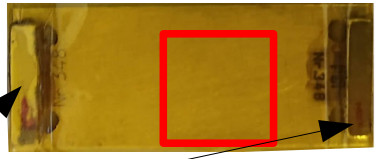




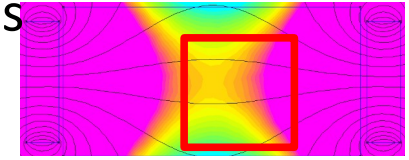
2D vx-μSR "Tomography"

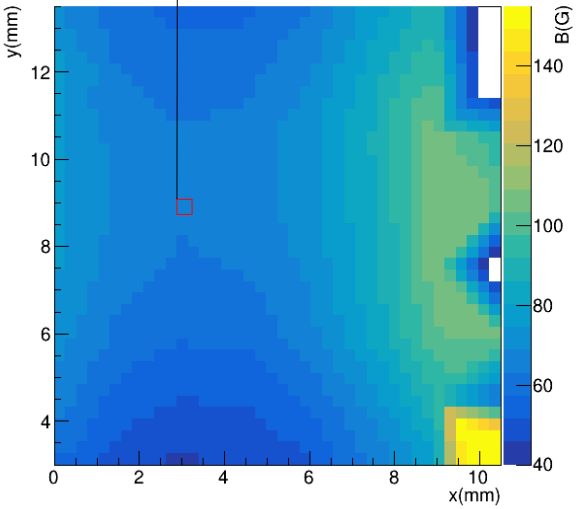


Silver plate



Magnets





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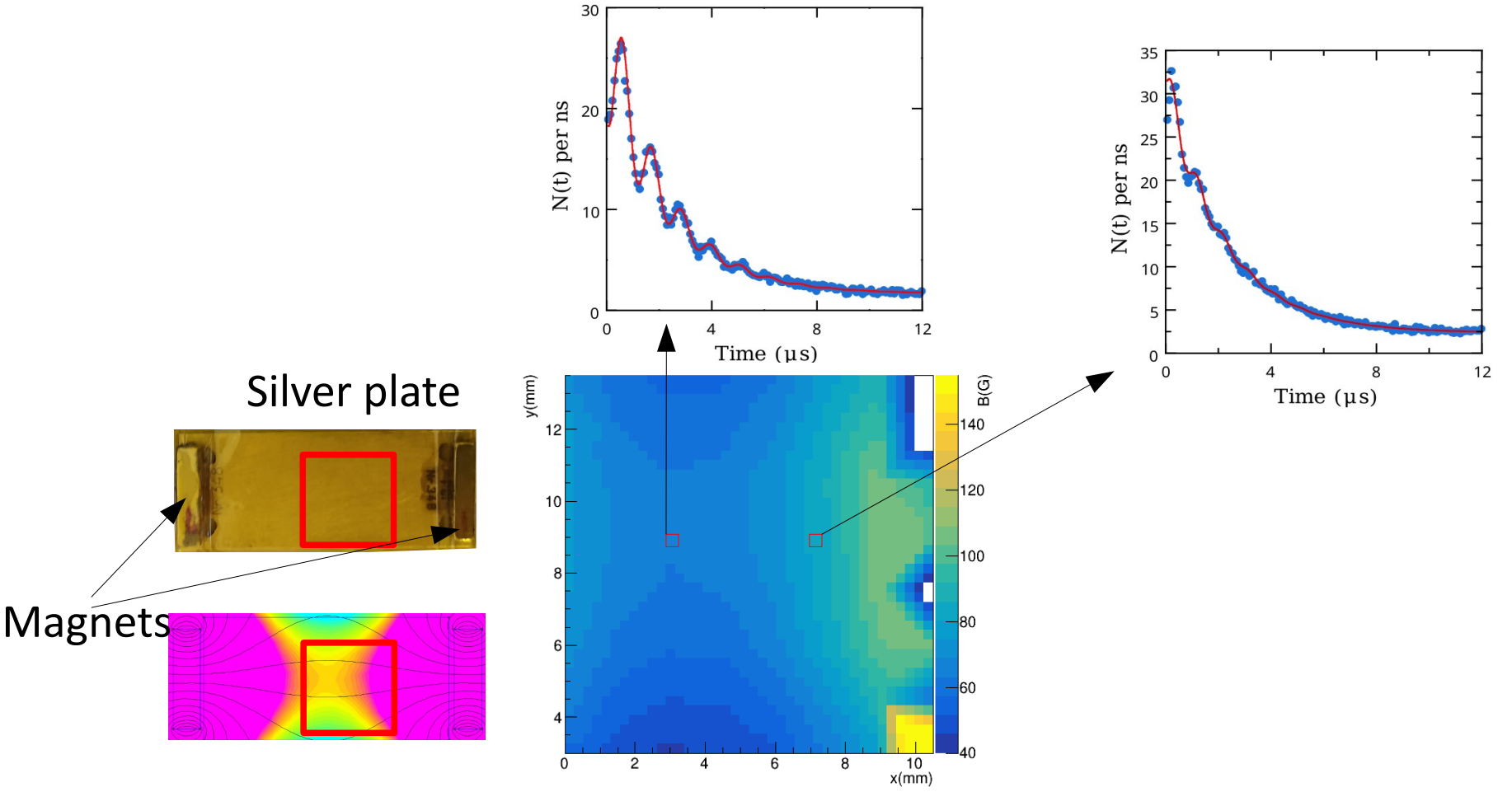

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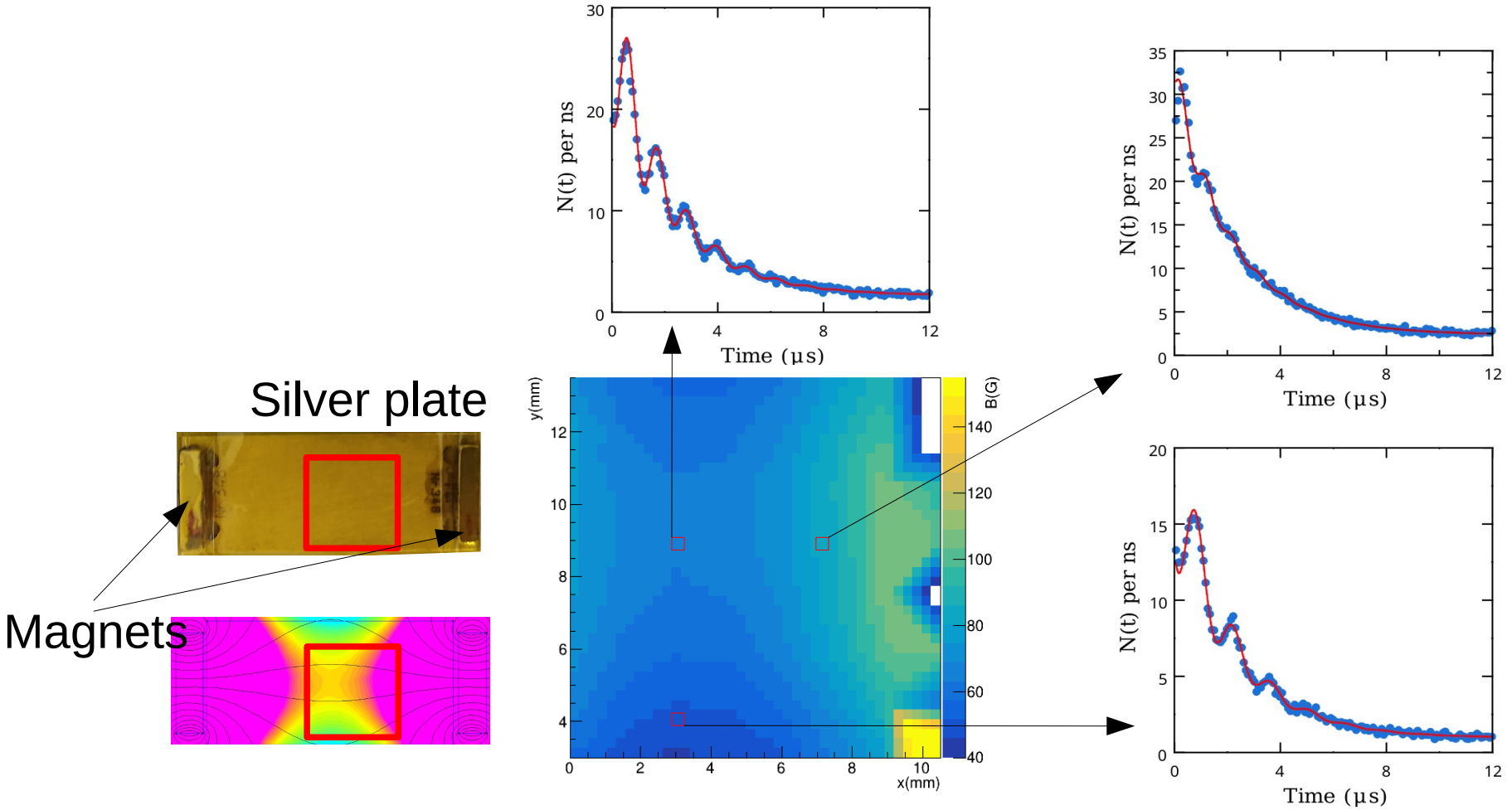

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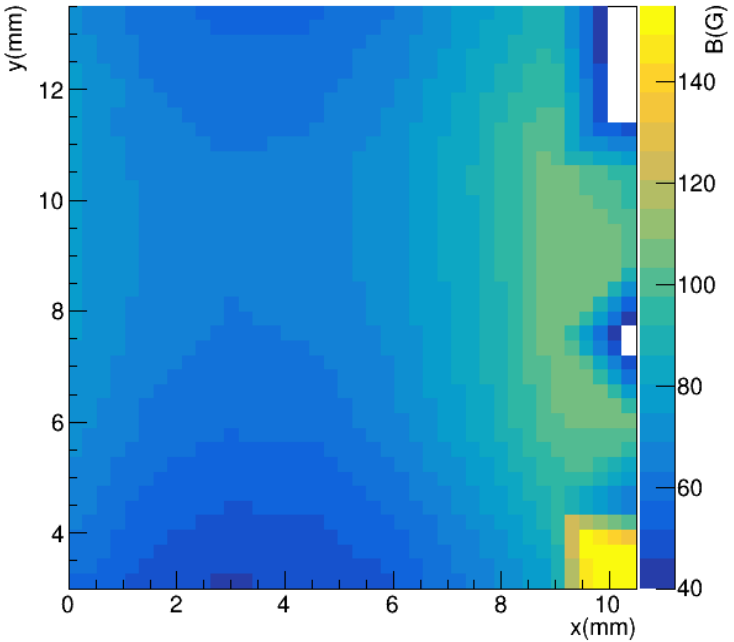

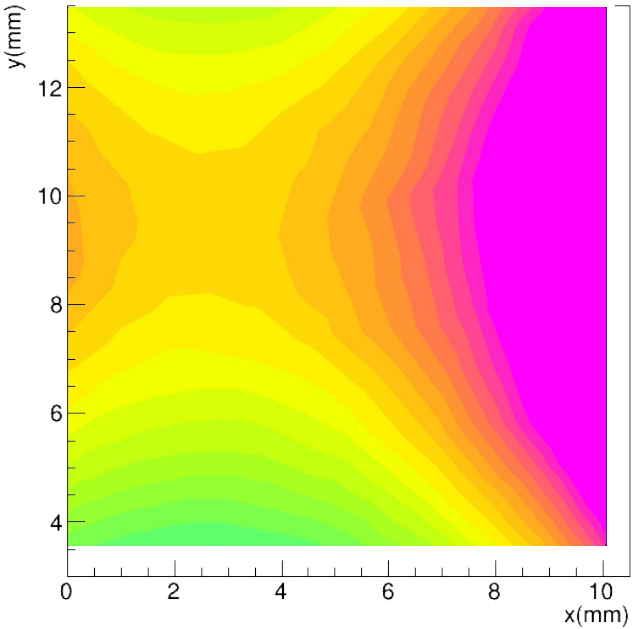

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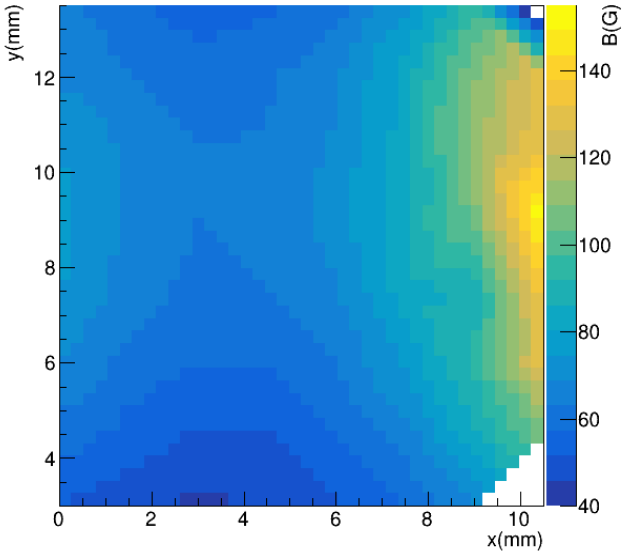
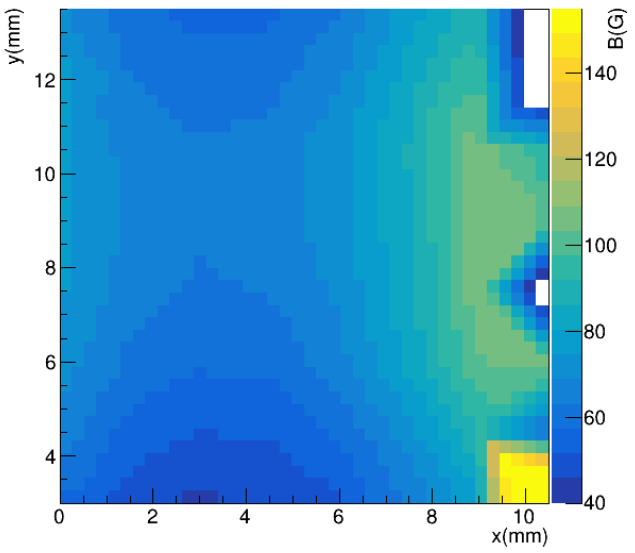
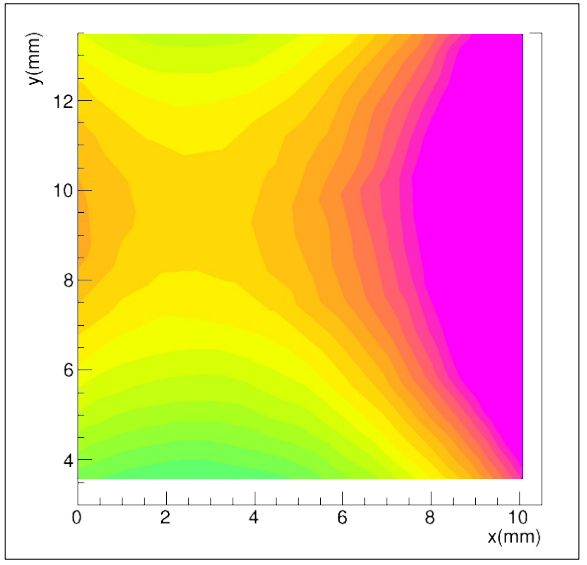


Upstream

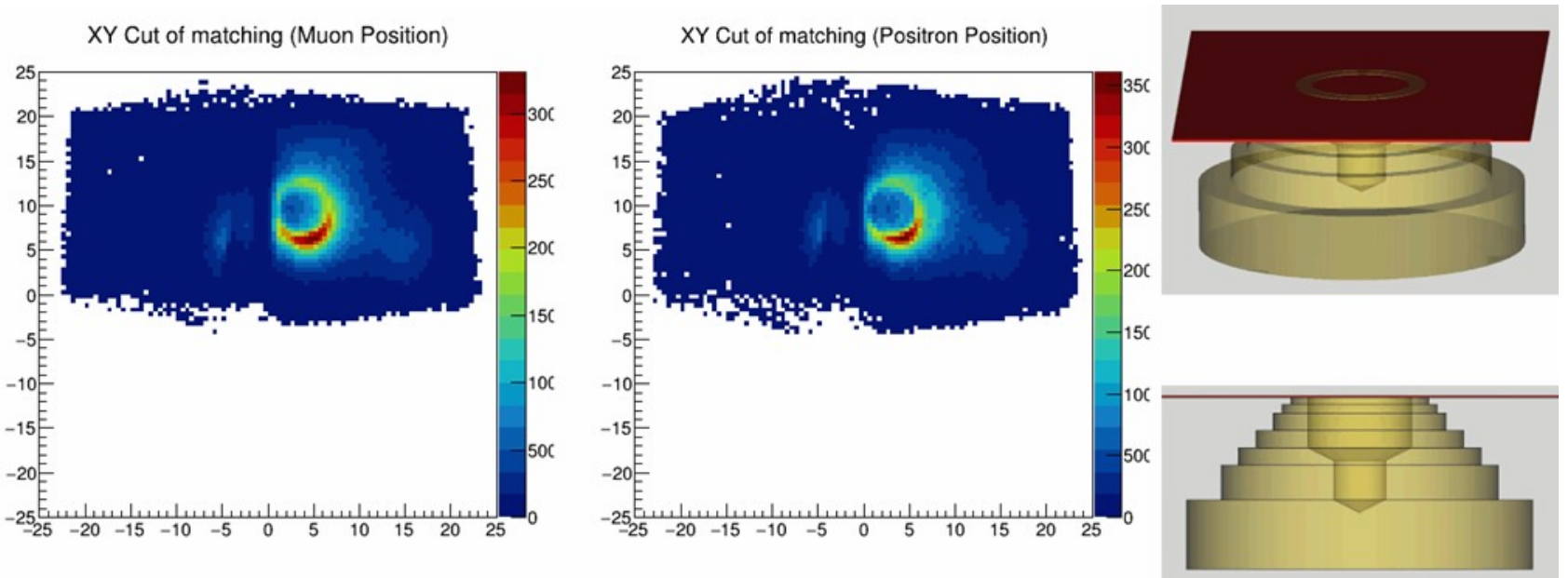


Downstream



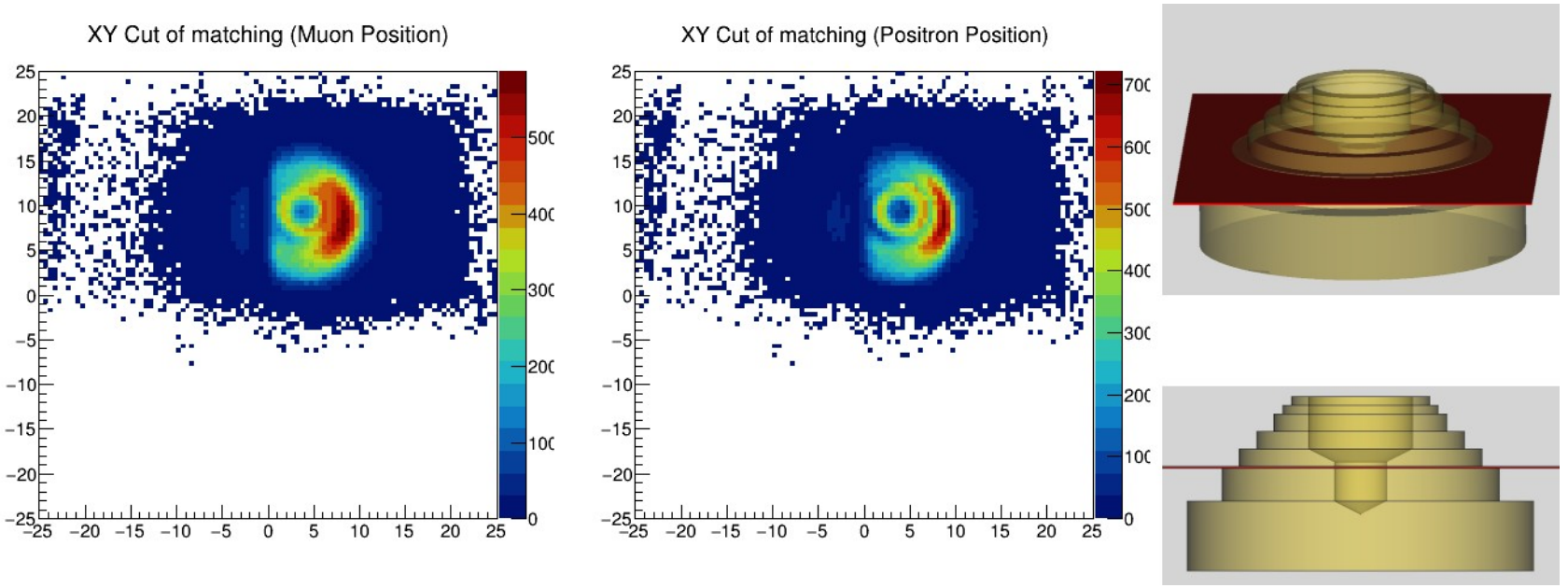
Simulation

3D vx-µSR "Tomography"



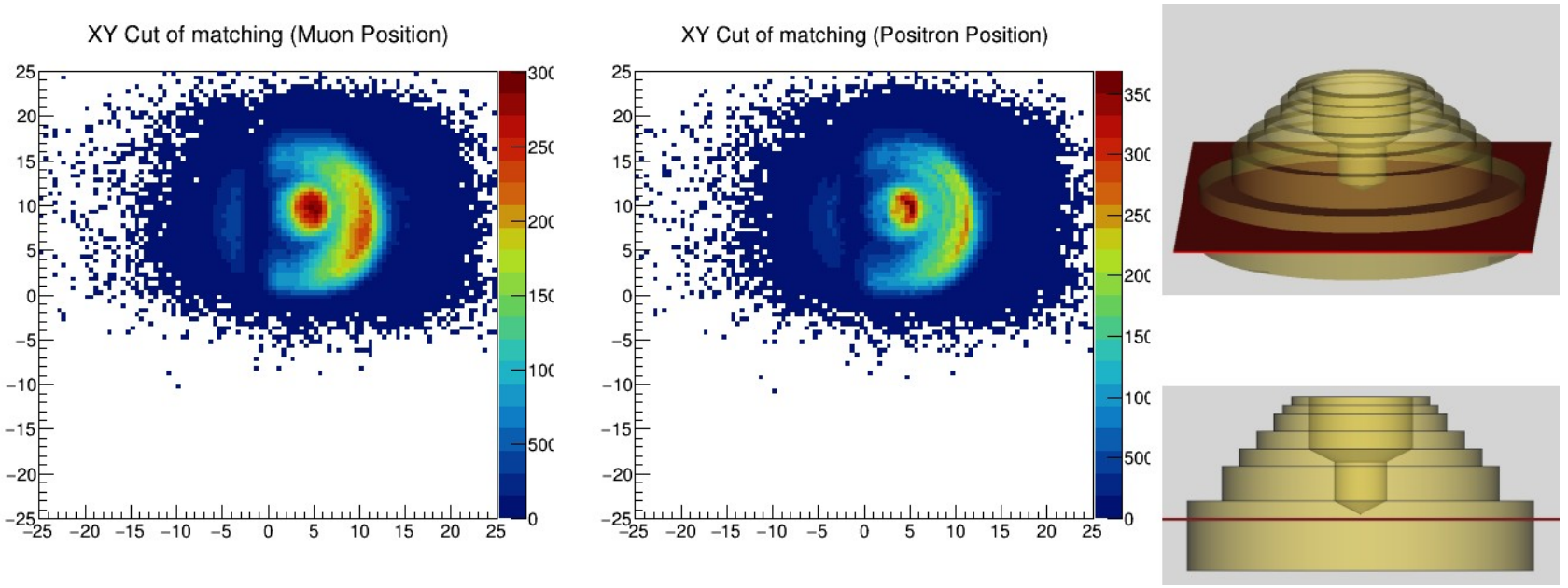
- Vertices from the (exposed) surface of the shape
- Steps of 1 mm
- Integrating layers of 1 mm thick in the beam direction

3D vx-μSR "Tomography"



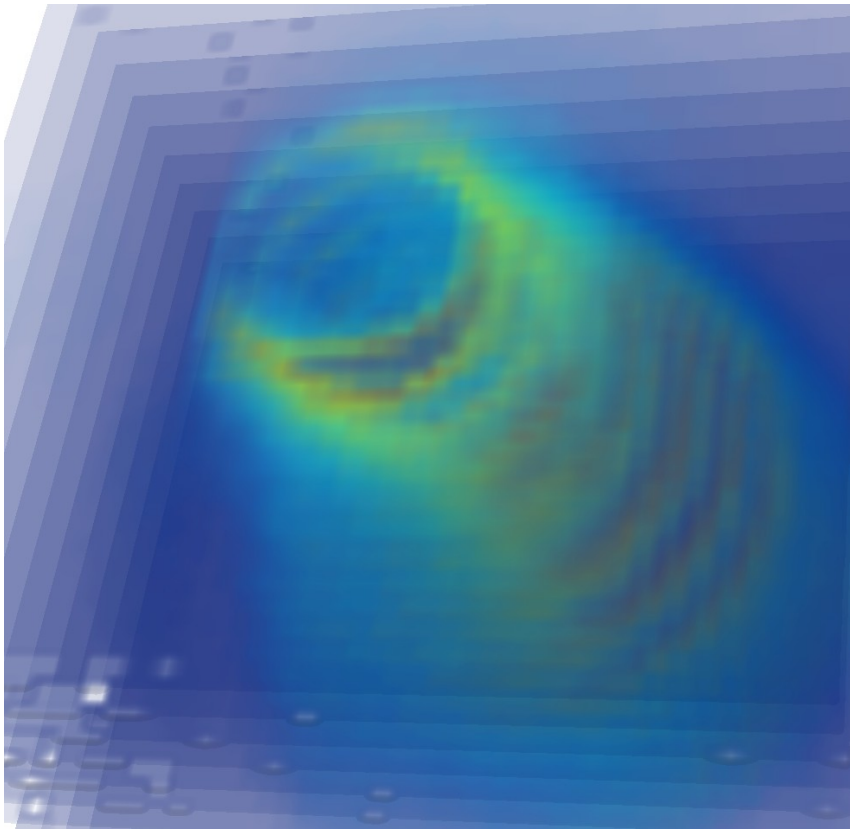
- Vertices from the (exposed) surface of the shape
- Steps of 1 mm
- Integrating layers of 1 mm thick in the beam direction

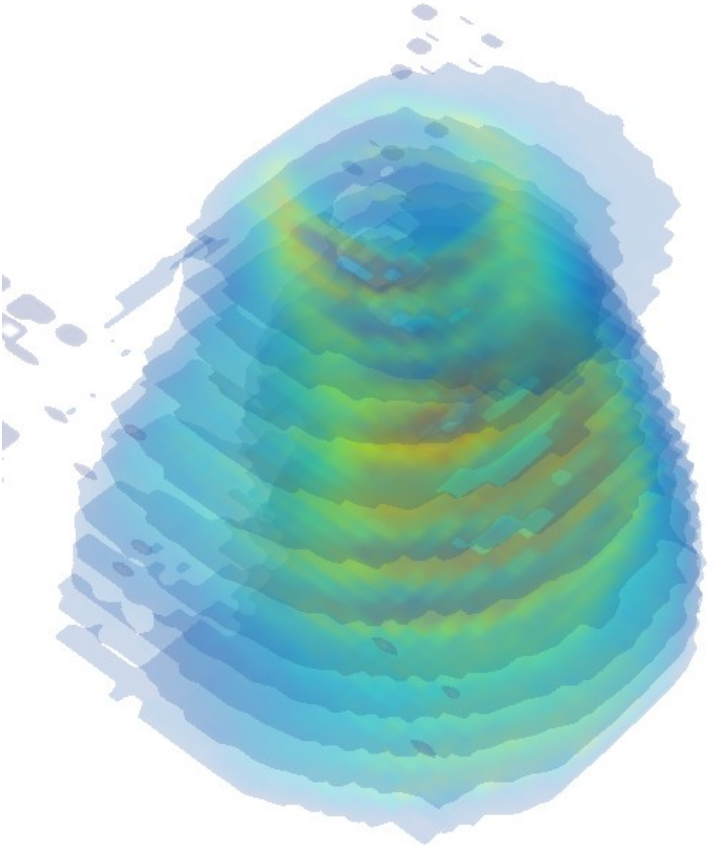
3D xv-μSR "Tomography"



- Vertices from the (exposed) surface of the shape
- Steps of 1 mm
- Integrating layers of 1 mm thick in the beam direction
- Note the circle in the middle from the hole in the center

3D vx-μSR "Tomography"





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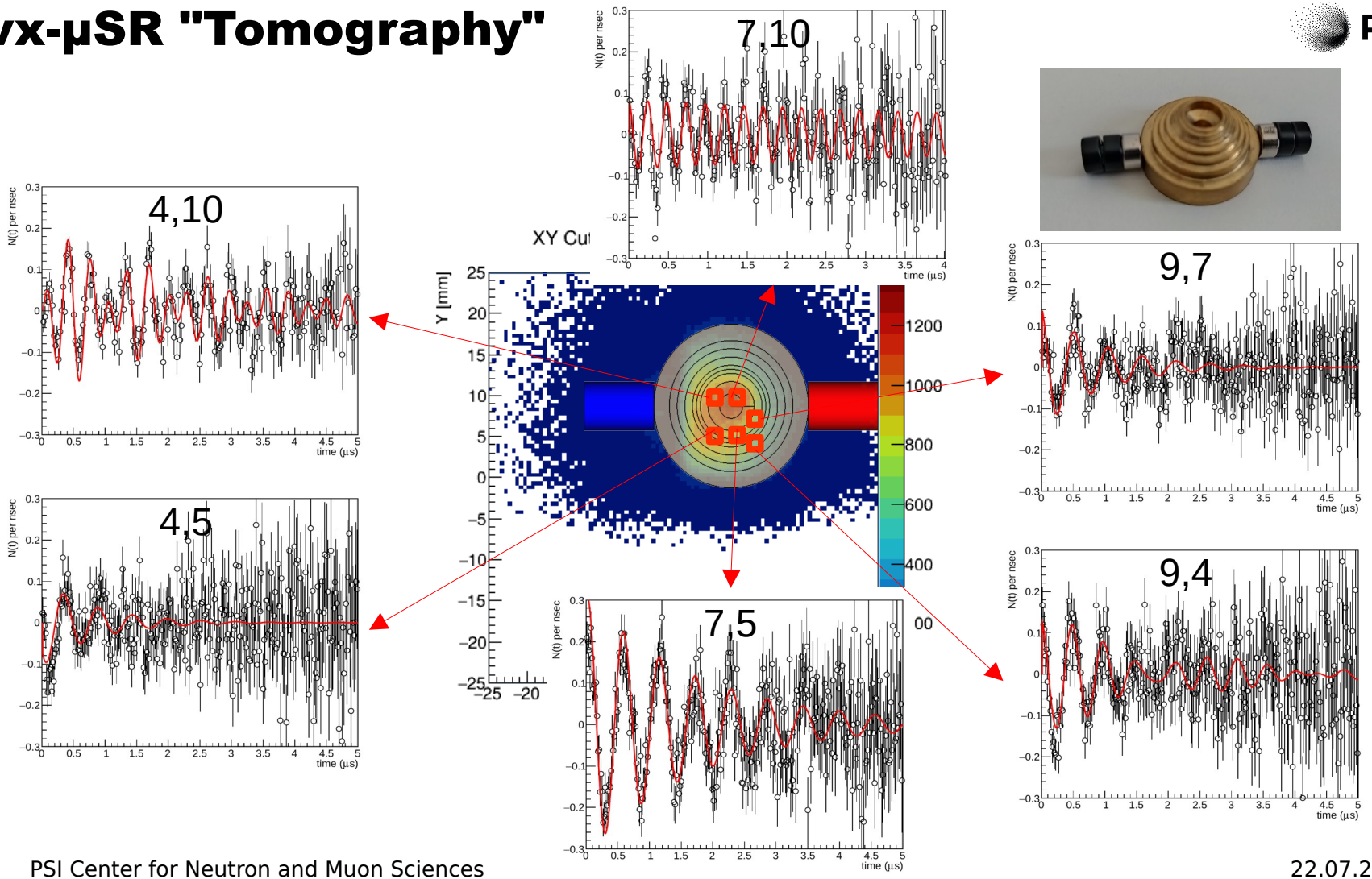


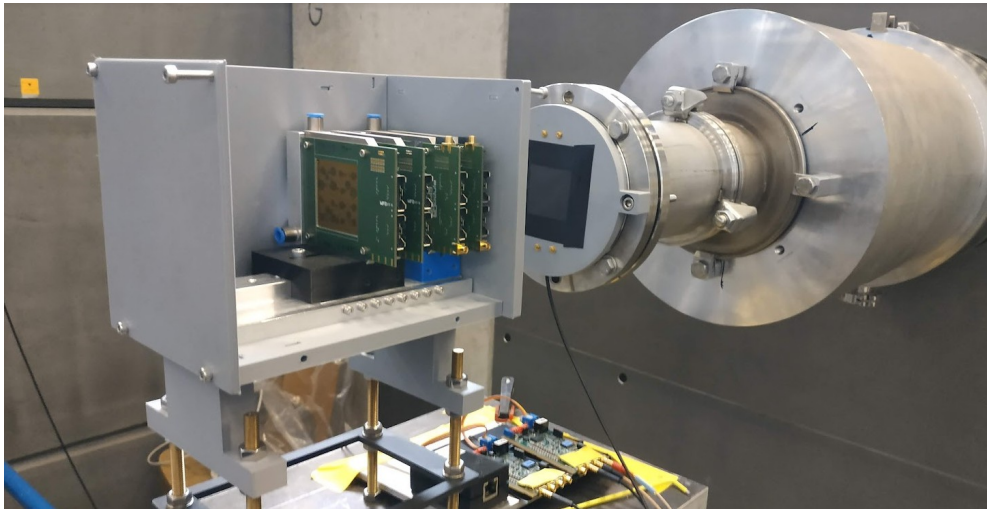
Conclusions

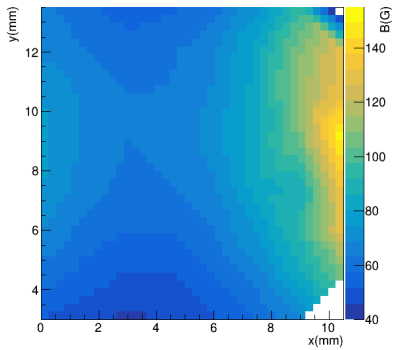
Operation at >200 kHz achieved

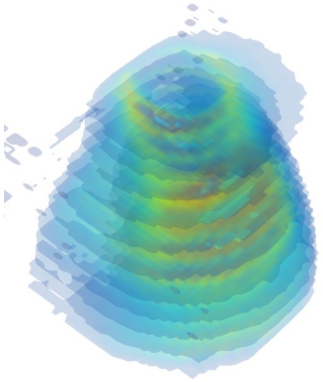
Sample sizes of ~1x1mm²

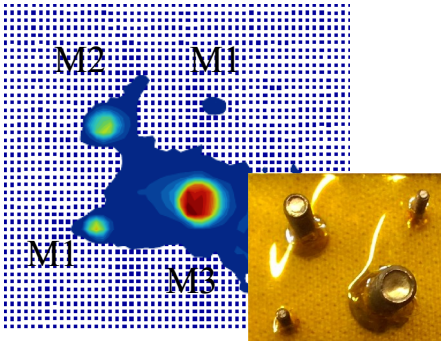
Multiple samples distinguishable

3D surface tomography









Thanks to …

PSI

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Maxime Lamotte
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Heidelberg

Thomas Rudzki (Postdoc)
Lukas Mandok (MSc)
Heiko Augustin (Postdoc)
Andre Schoening

Mainz

Nick Berger

PSI

Join as a

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Postdoc