A Silicon Pixel Tracker for future µSR experiments

Results from an HV-MAPS-based Detector Prototype for Position-Resolved µSR Measurements

BTTB 13 - Valencia

Lukas Mandok

Physikalisches Institut Heidelberg

22.05.2025

µSR Principle

Muon Spin **R**otation/**R**elaxation/**R**esonance

µSR Principle

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Material science technique

Measure local magnetic fields

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Implant spin polarized muons in sample material

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Implant spin polarized muons in sample material

Muon spin evolves in internal and external magnetic field

µSR Principle

Muon Spin Rotation/Relaxation/Resonance

Material science technique

Measure local magnetic fields

Battery materials

Superconducting materials

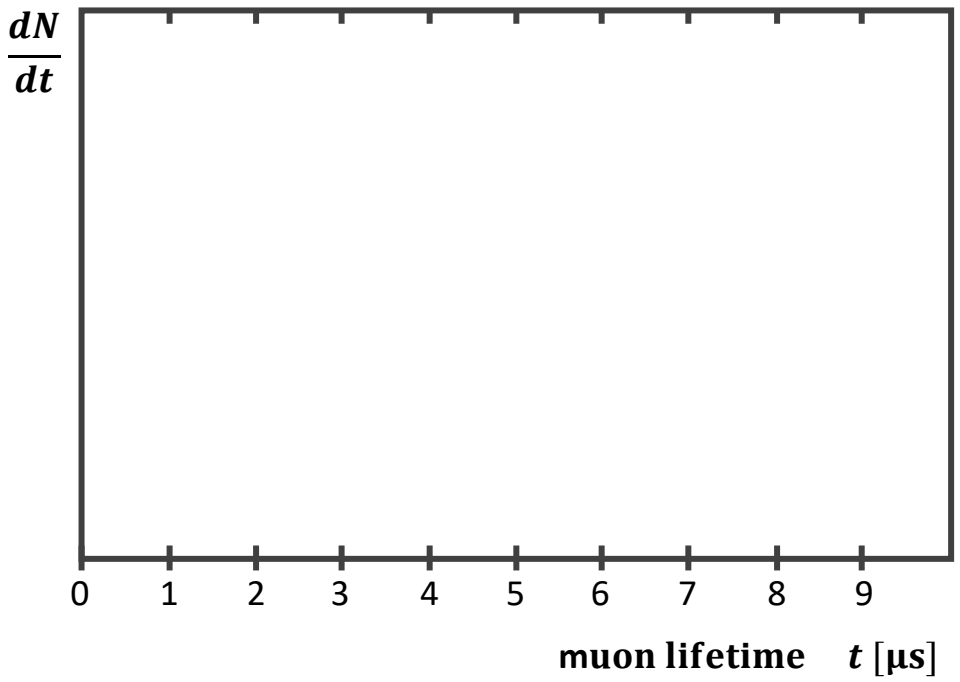
Implant spin polarized muons in sample material

Muon spin evolves in internal and external magnetic field

Measure anisotropic decay to positrons

µSR Signal

Positron rate: $$dN(t)/dt = B_0 + N_0 \cdot \exp\left(-t/\tau_\mu\right) \cdot \left[1 + A_0 G_\perp(t)\, cos\left(\bar{\omega}_\mu t + \phi\right)\right]$$

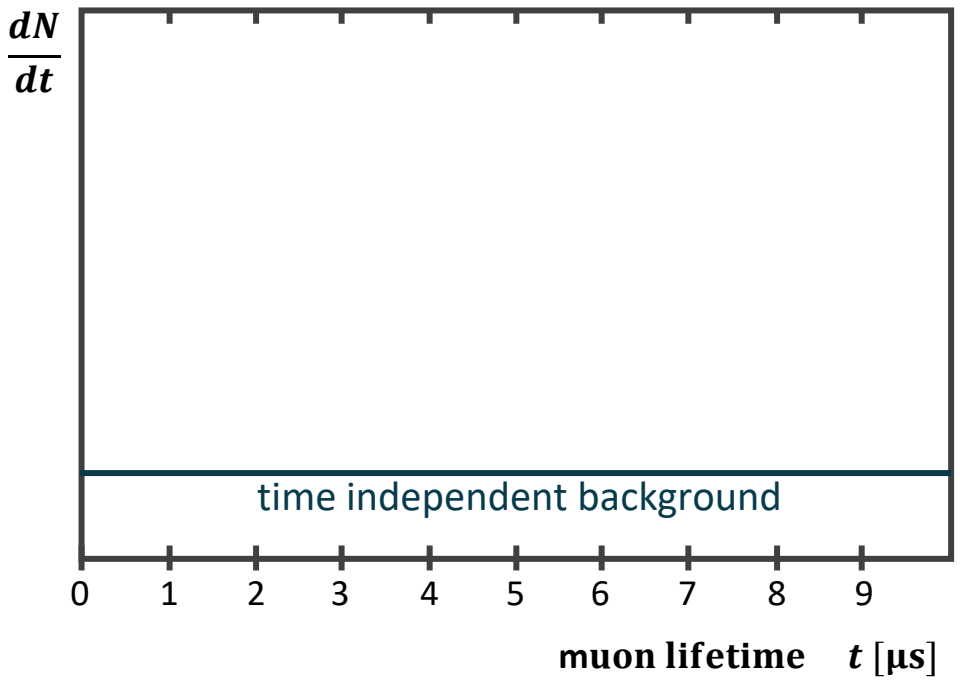


Positron detector $\frac{dN(t)}{dt}$

µSR Signal

Background

Positron rate: $$dN(t)/dt = \boldsymbol{B_0} + N_0 \cdot \exp\left(-t/\tau_\mu\right) \cdot \left[1 + A_0 G_\perp(t)\, cos\left(\bar{\omega}_\mu t + \phi\right)\right]$$



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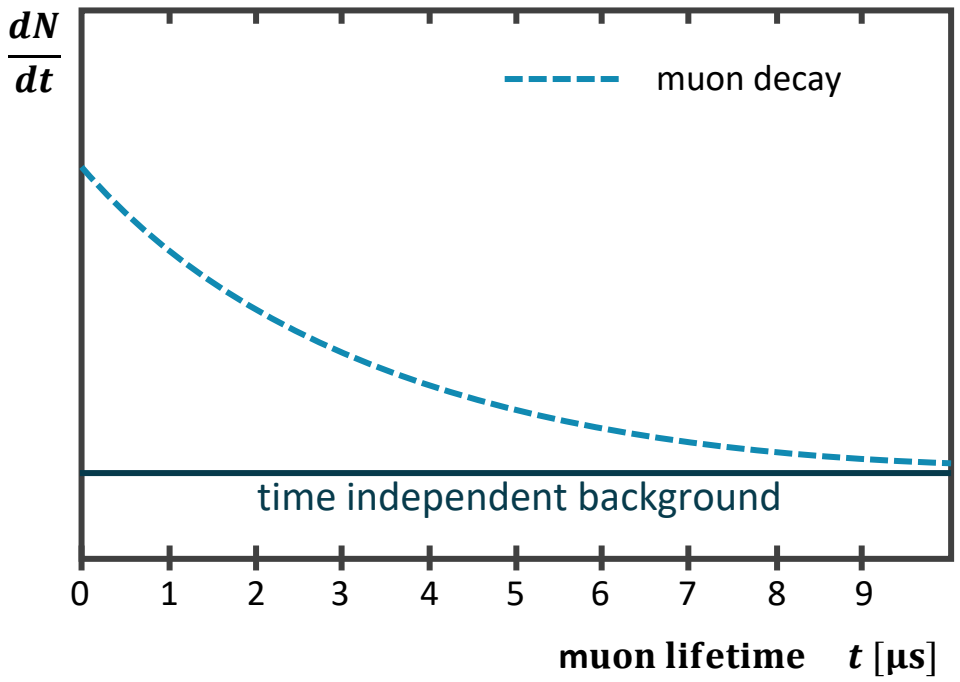
µSR Signal

Positron rate:

$$dN(t)/dt = \underbrace{B_0}_{\text{Background}} + \underbrace{N_0 \cdot \exp\left(-t/\tau_\mu\right)}_{\text{Exponential muon decay}} \cdot \left[1 + A_0 G_\perp(t)\, cos\left(\bar{\omega}_\mu t + \phi\right)\right]$$



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µSR Signal

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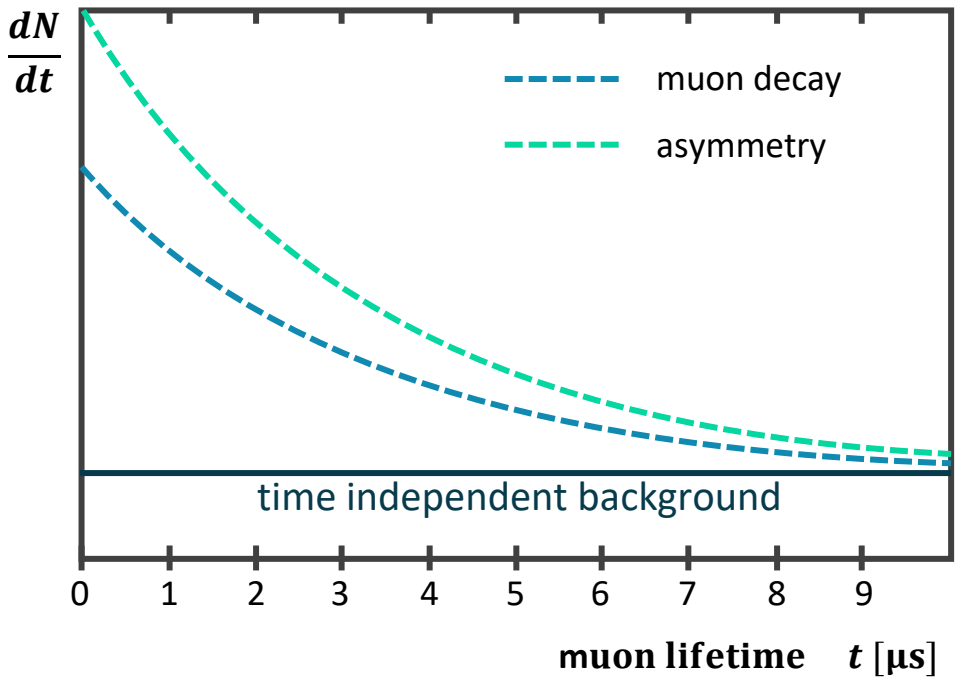
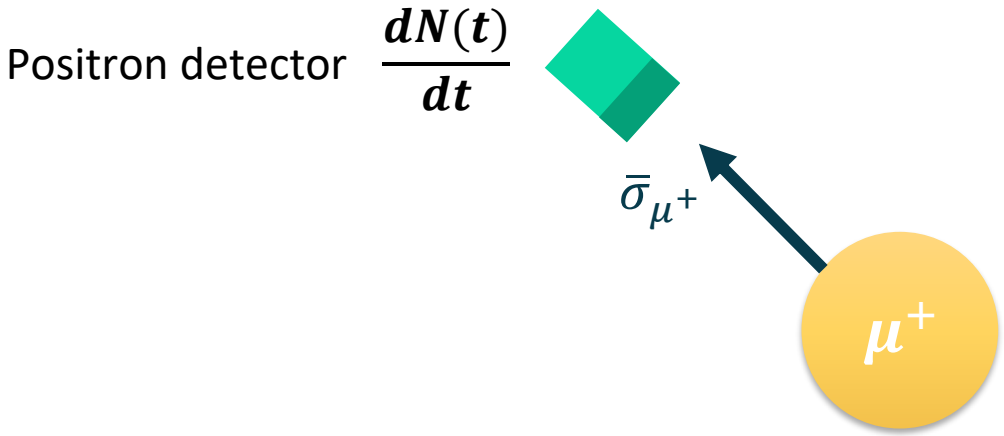
$$dN(t)/dt = \underbrace{B_0}_{\text{Background}} + \underbrace{N_0 \cdot \exp(-t/\tau_\mu)}_{\text{Exponential muon decay}} \cdot \left[1 + \underbrace{A_0}_{\text{Intrinsic asymmetry parameter of weak decay}} G_\perp(t)\, cos(\bar{\omega}_\mu t + \phi)\right]$$





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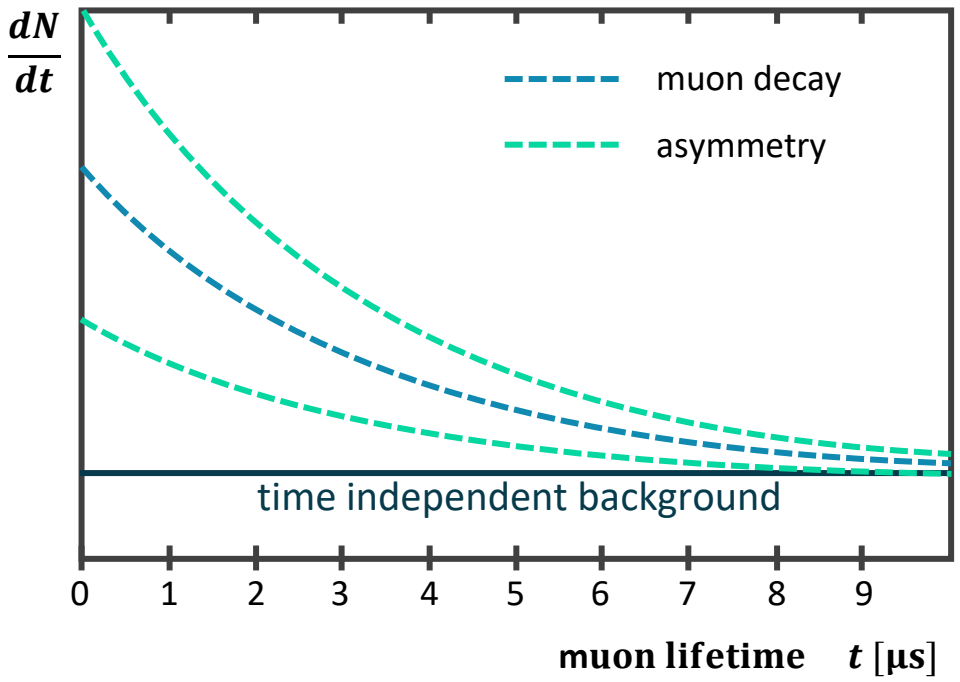

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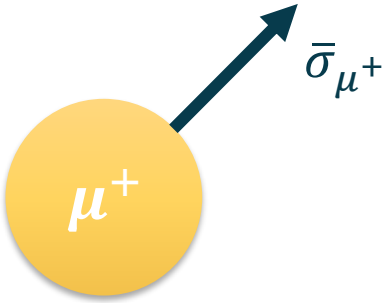
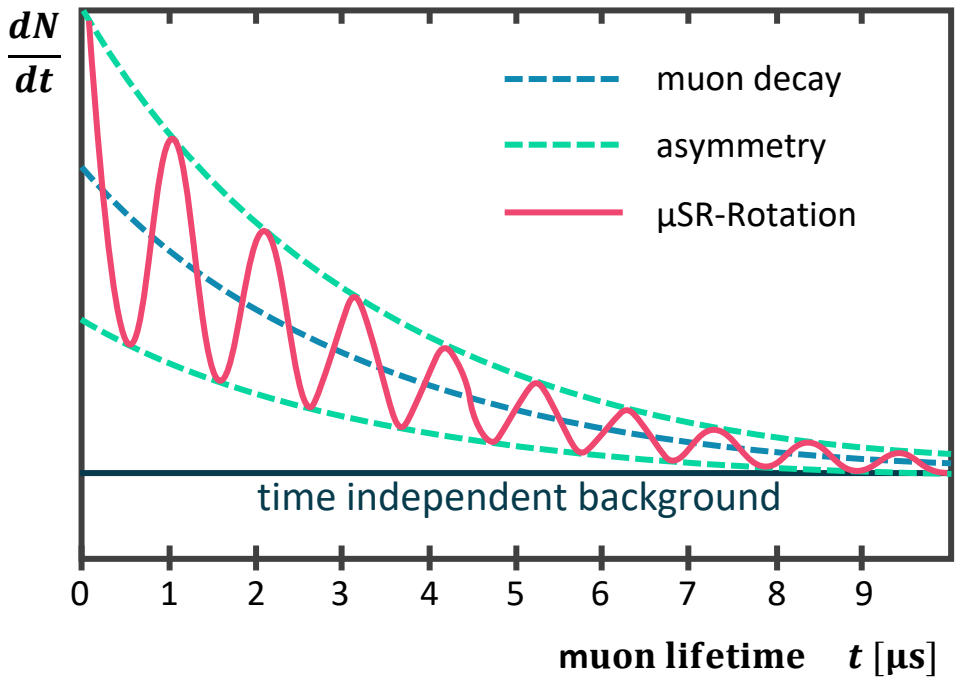


µSR Signal

Positron rate:

$$dN(t)/dt = B_0 + N_0 \cdot \exp(-t/\tau_\mu) \cdot [1 + A_0 G_\perp(t)\, cos(\bar{\omega}_\mu t + \phi)]$$

- B_0: **Background**
- A_0: **Intrinsic asymmetry** parameter of weak decay
- ϕ: Angle between positron and muon spin direction
- $N_0 \cdot \exp(-t/\tau_\mu)$: Exponential muon **decay**
- $\bar{\omega}_\mu$: Larmor frequency of muon **spin precession**: $\bar{\omega}_\mu = \gamma_\mu \cdot (\boldsymbol{B}_{\mathbf{ext}} + \langle \boldsymbol{B}_{\mathbf{int}} \rangle)$



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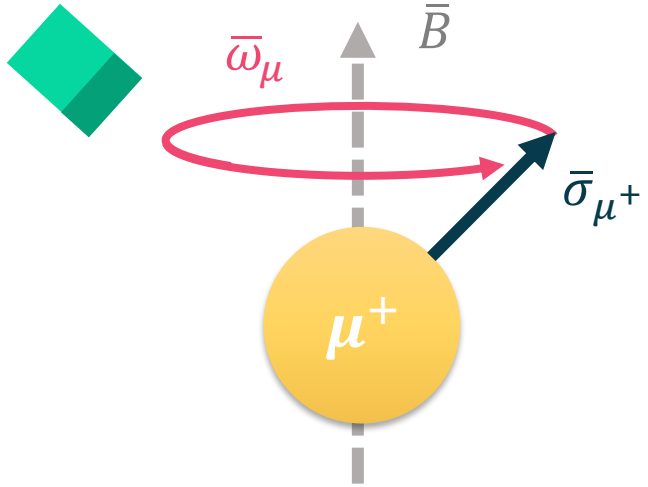
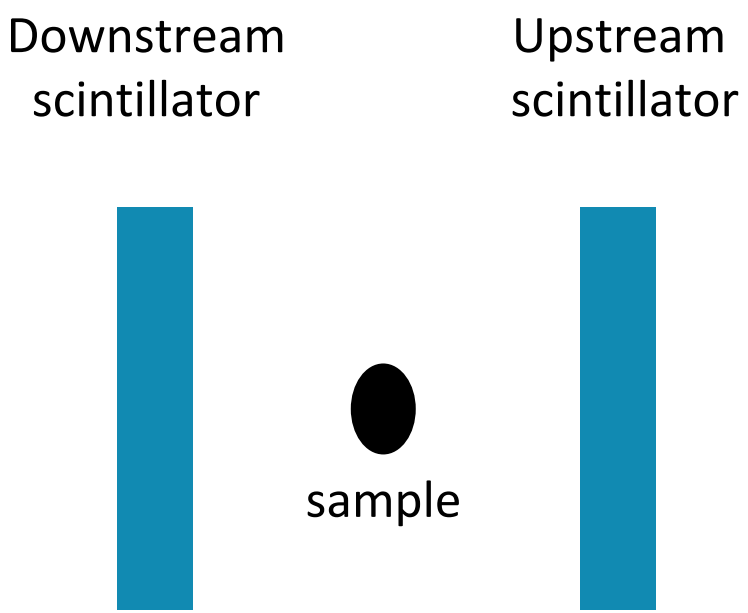


Current Generation

Scintillator-based Detector



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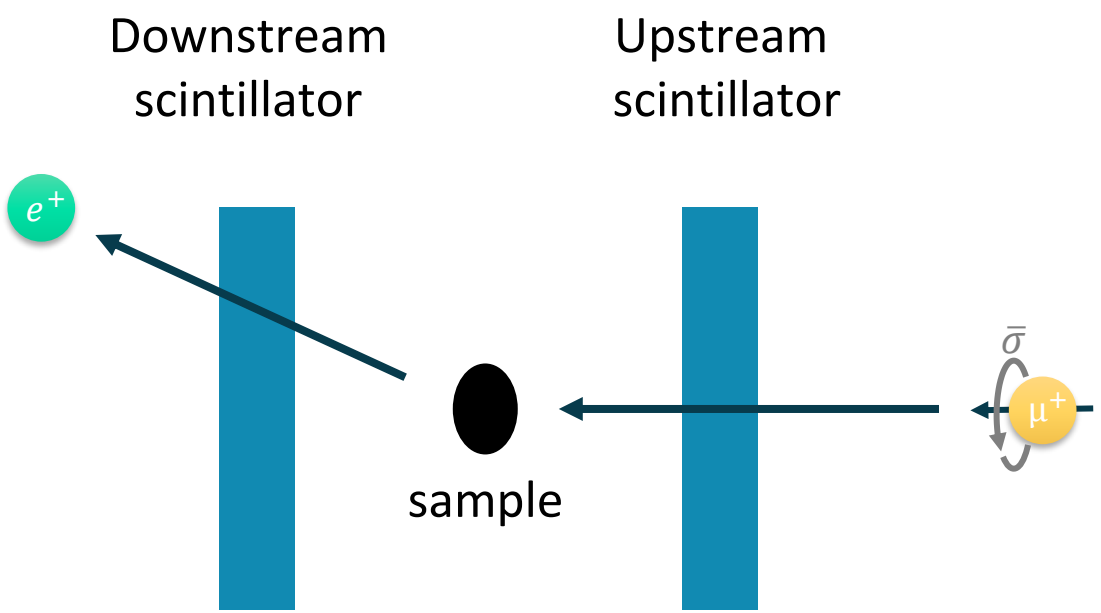
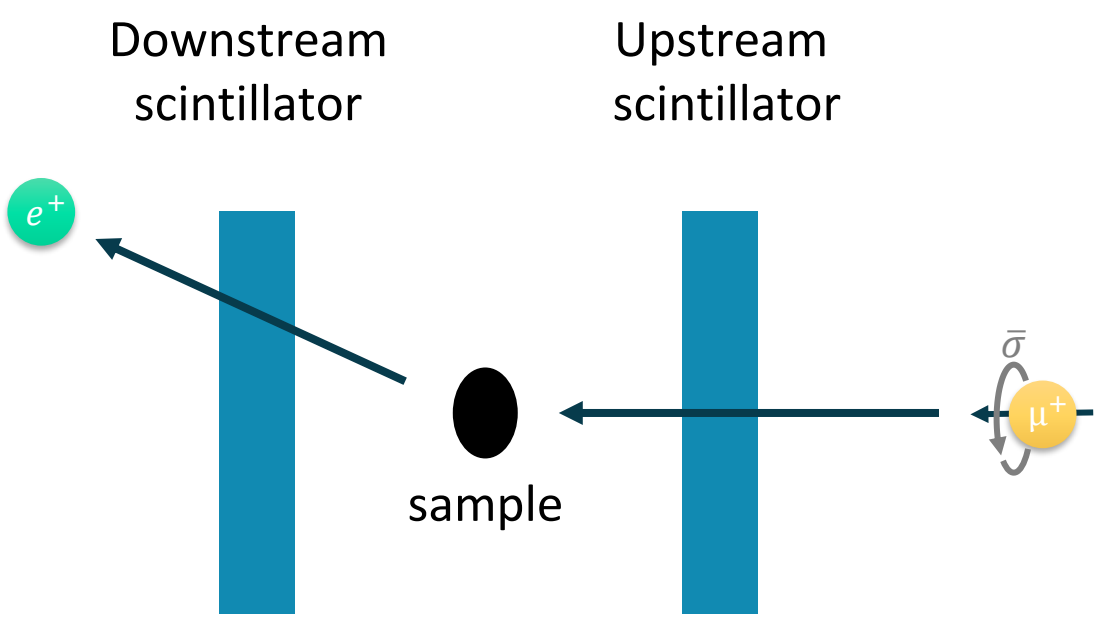


Current Generation

Scintillator-based Detector

- Time differential measurement
  - Forward-backward arrangement



Current Generation

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- Time differential measurement
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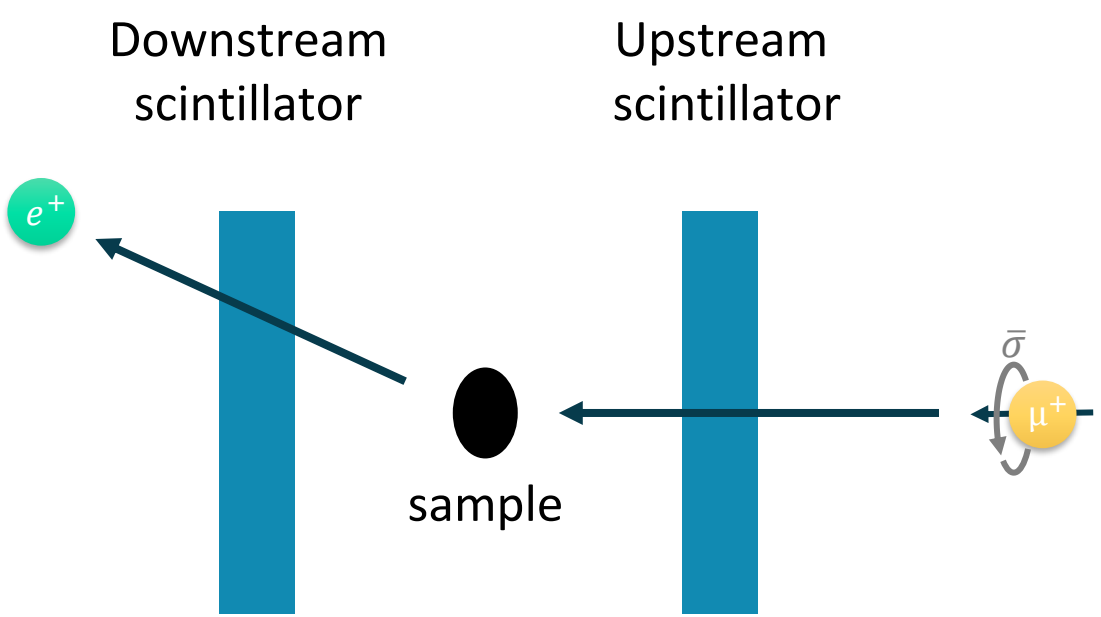
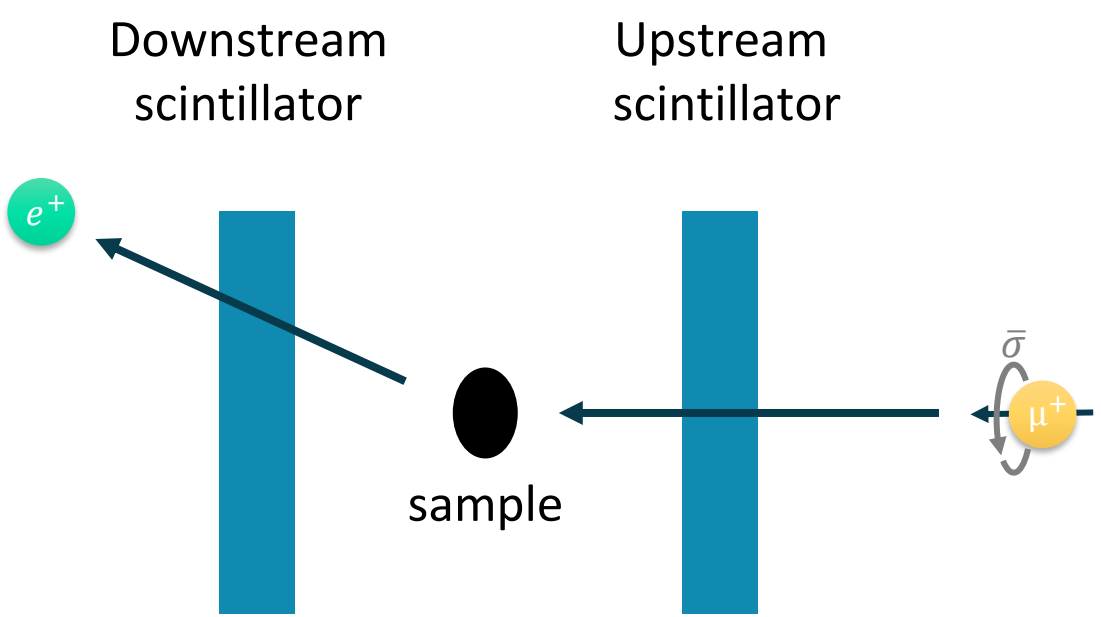
- Limitations:
  - No spatial information within sample



Current Generation

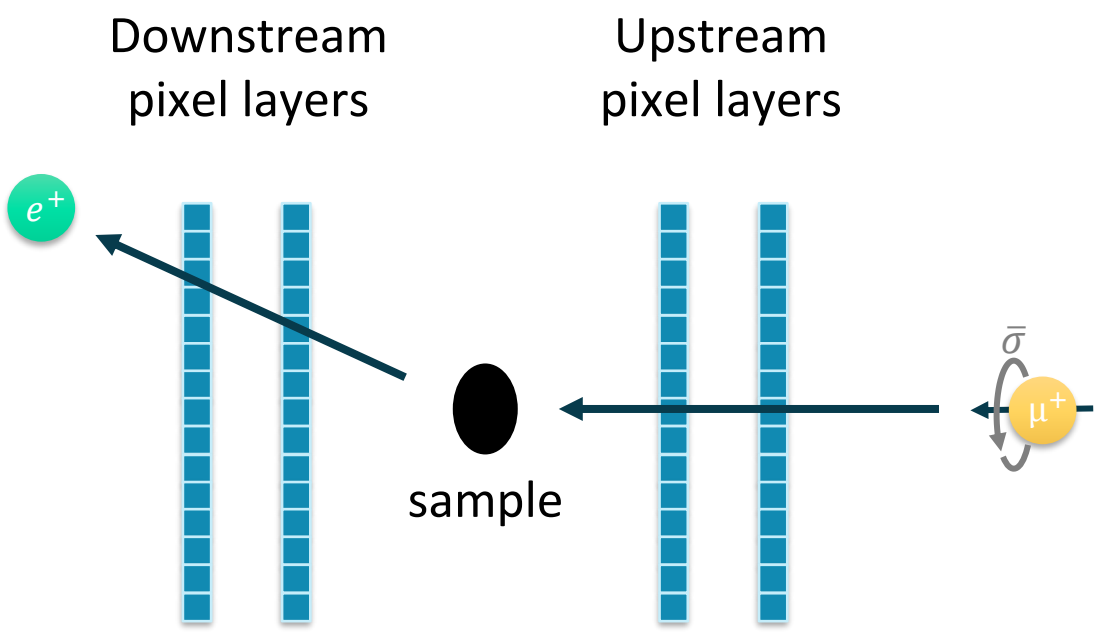
Scintillator-based Detector

- Time differential measurement
  - Forward-backward arrangement
- Limitations:
  - No spatial information within sample
  - Maximal 1 muon at a time
    - ⇨ Rate limitation: $18\ \mathrm{kHz}$



Next Generation

Pixel-based Detector



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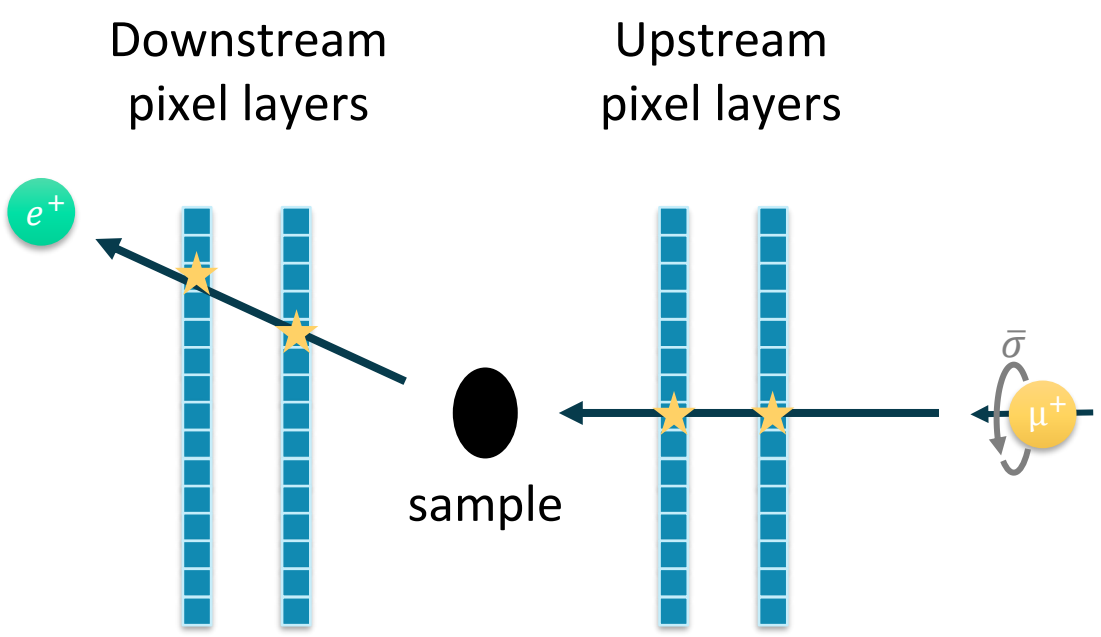
Pixel-based Detector

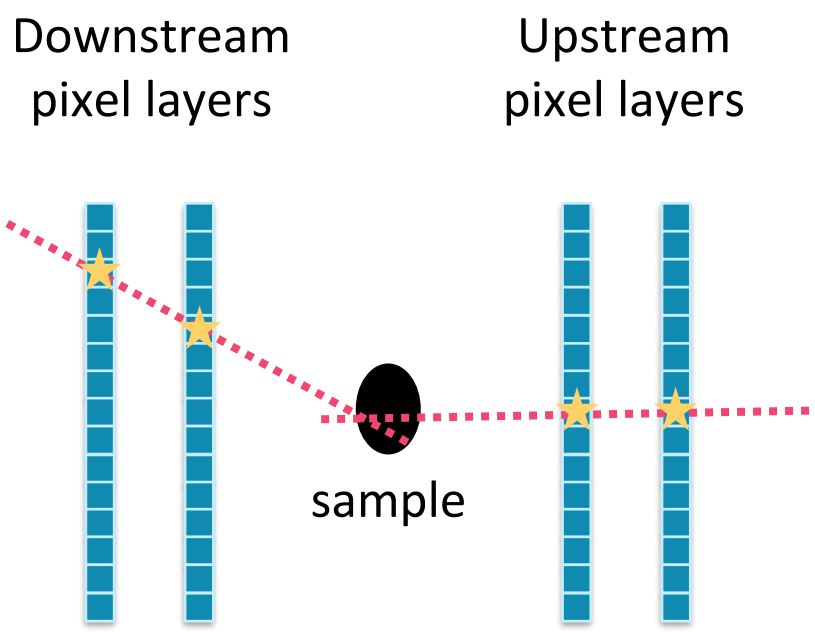
- 2-layer tracking using pixel sensors



Next Generation

Pixel-based Detector

- 2-layer tracking using pixel sensors
  - ⇨ Tracklet matching in **Corryvreckan**



Next Generation

Pixel-based Detector

- 2-layer tracking using pixel sensors
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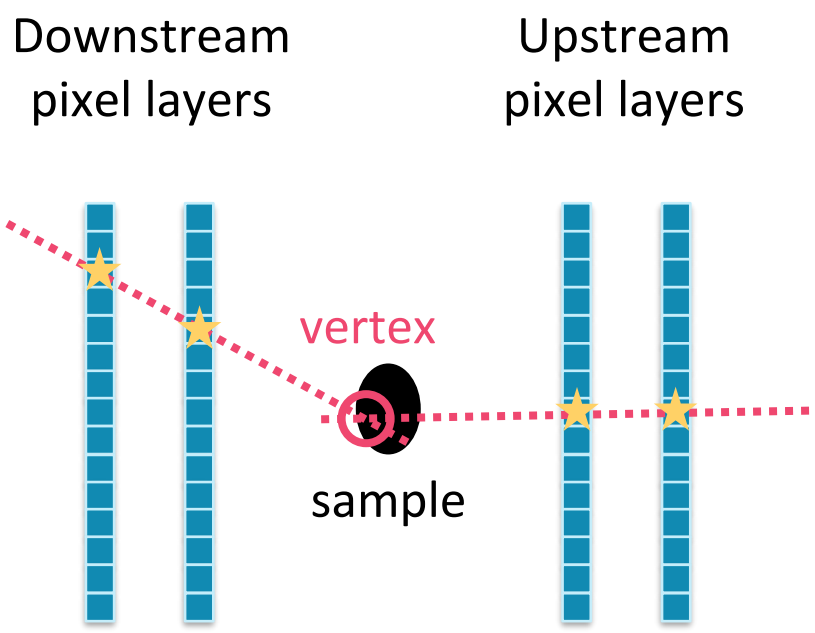
- Vertex reconstruction



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- 2-layer tracking using pixel sensors
  - ⇨ Tracklet matching in **Corryvreckan**
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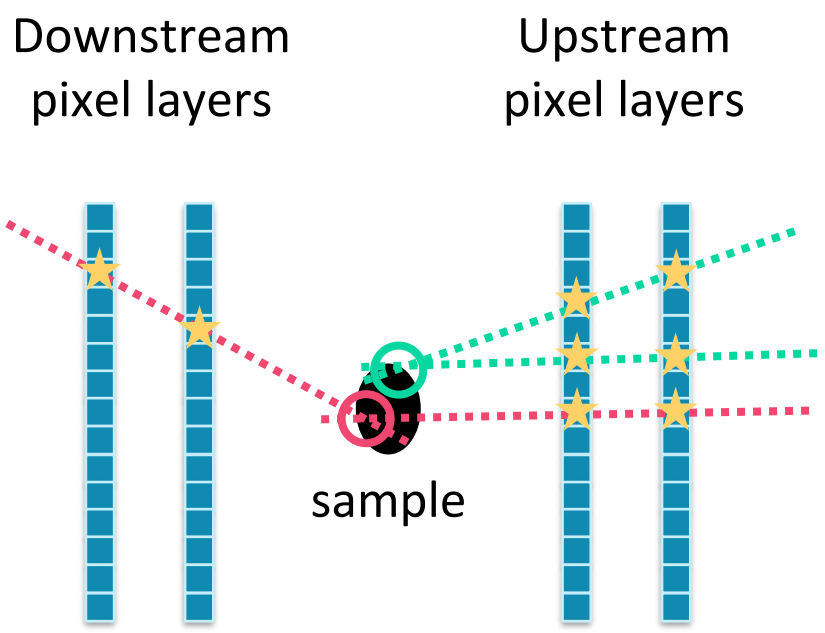
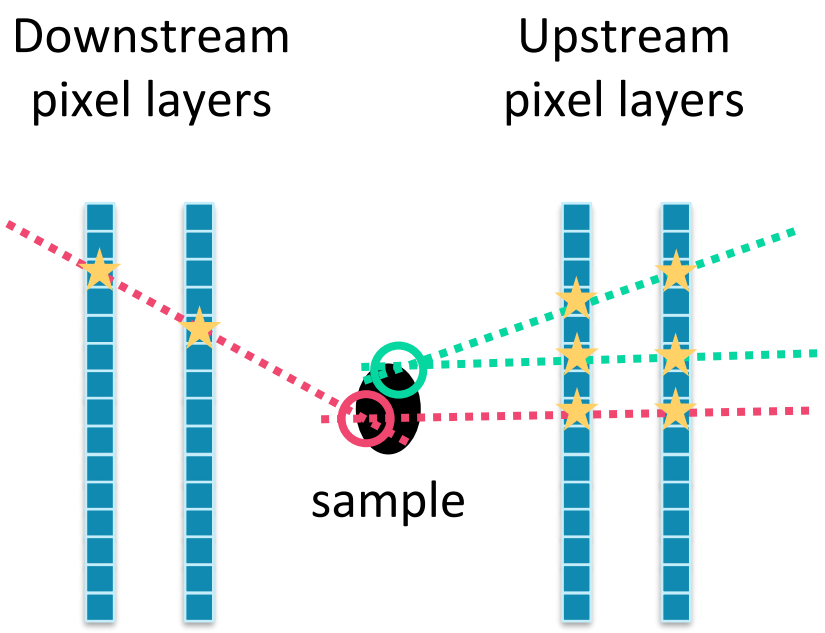
  - ⇨ Differentiate between simultaneous events



Next Generation

Pixel-based Detector

- 2-layer tracking using pixel sensors
  - ⇨ Tracklet matching in **Corryvreckan**
- Vertex reconstruction
  - ⇨ Differentiate between simultaneous events
- Improvements:
  - ⇨ Increased muon rate by $10 - 100$ times
  - ⇨ Several smaller samples at once
  - ⇨ Probe local domains within sample



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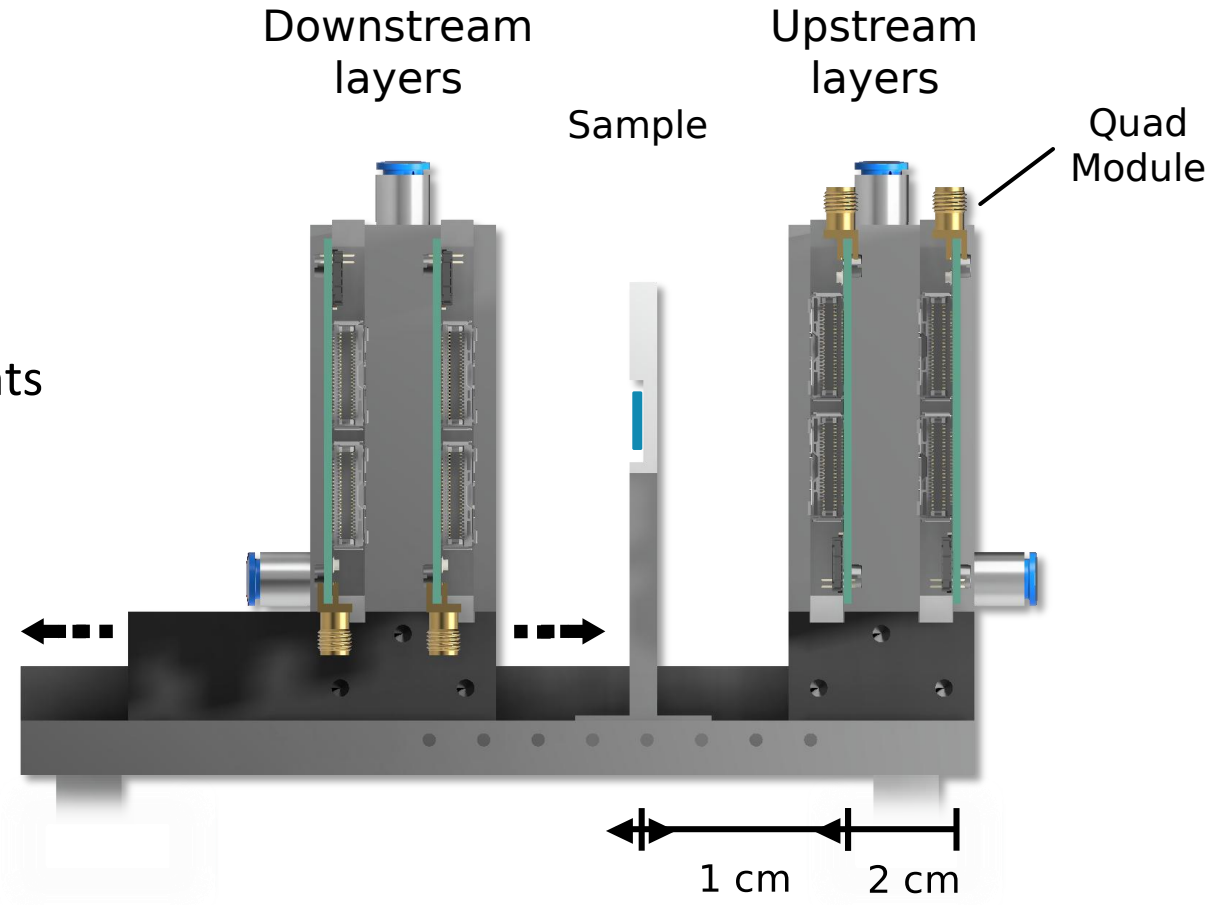


Next Generation

Quad Module

First 2×2 **MuPix11** Module

- $(4 \times 4)\ \mathrm{cm}^2$ active area
- $50 - 100\ \mu\mathrm{m}$ sensor thickness

High-**V**oltage **M**onolithic **A**ctive **P**ixel **S**ensor

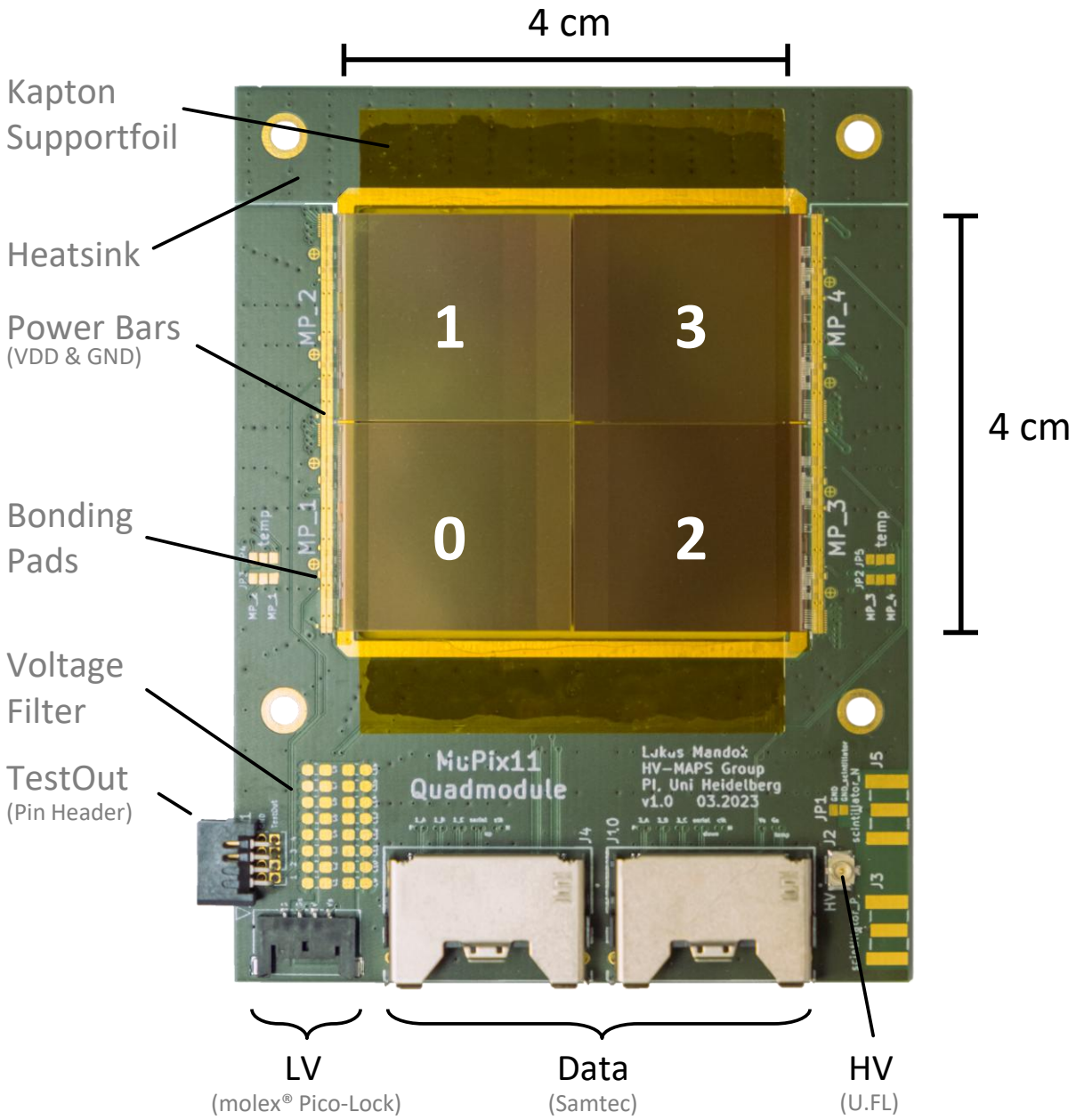
- 180 nm HV-CMOS technology

MuPix11:

Pixel Matrix:	256×250
Pixel Size:	$(80 \times 80)\ \mu\mathrm{m}^2$
Time Binning:	8 ns
Datalink Speed:	3×1.25 Gbps

More Information:
Heiko Augustin
Thomas Rudzki

⇨ Ruben Kolb Lucas Dittmann (Friday)



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⇨ reduce multiple Coulomb scattering

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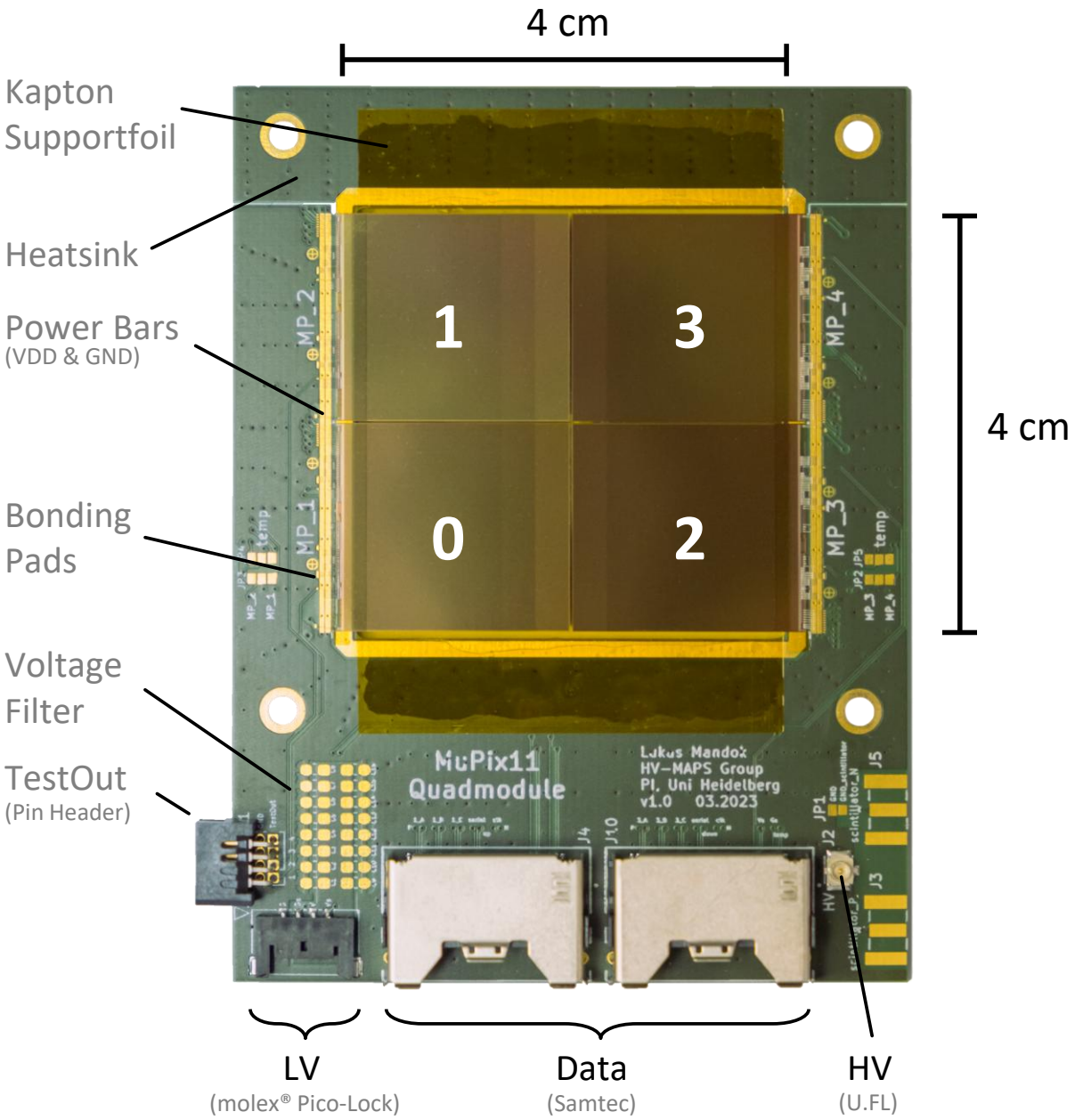

μSR Setup

Testbeams

- Transversal polarized surface μ^+ beam $(40\ kHz)$ @ PSI – PiE3 beamline (HAL 9500)
- Dates:
  - 09.2023 Initial Testbeam
  - 09.2024 / 12.2024 Refined Measurements

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- Dates:
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- Results
  - Spin rotation measurement
  - Sample reconstruction & sample resolution
  - Magnetic field reconstruction

Analysis

Corry

Corryvreckan

Analysis

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Metronom

MidasEventLoader

⇩

Clustering

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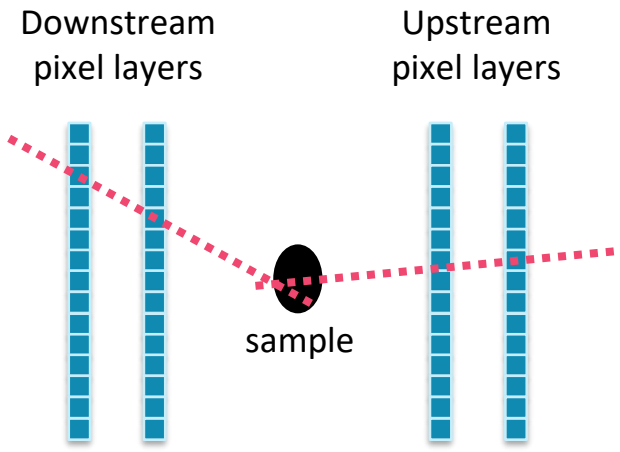
TrackingMusr



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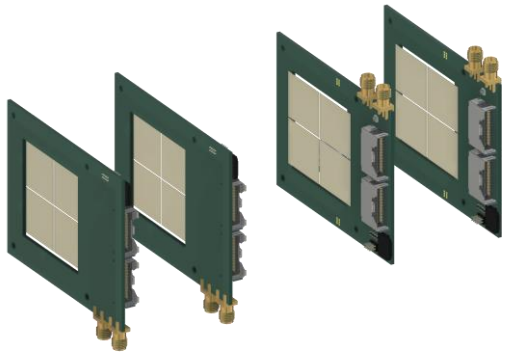
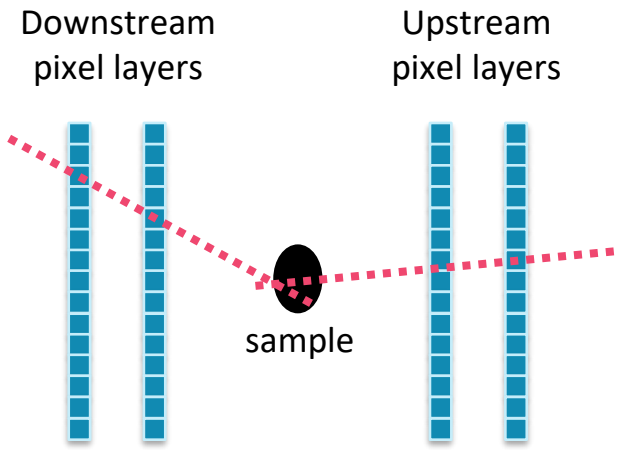


- Sensor Modules



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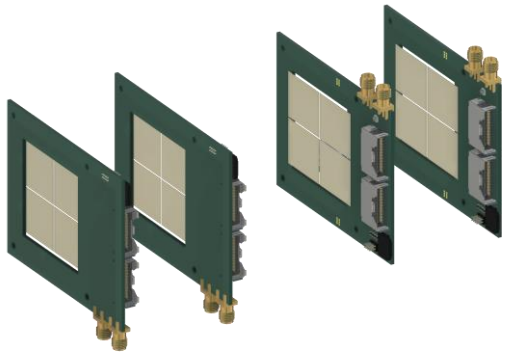
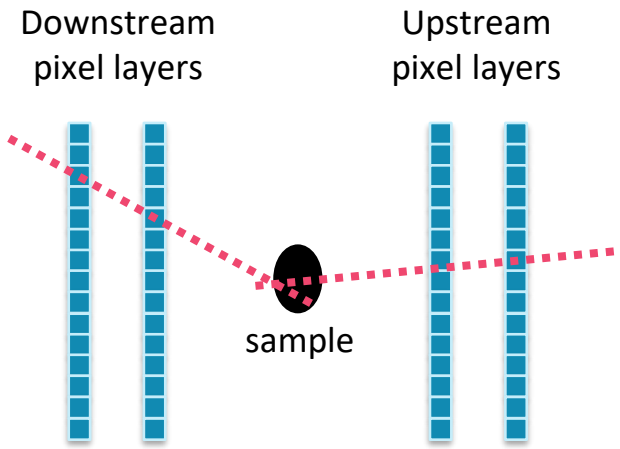
- Sensor Modules
- Tracklet Finding
- Tracklet Matching





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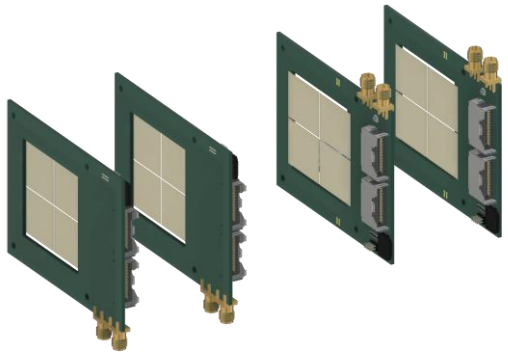

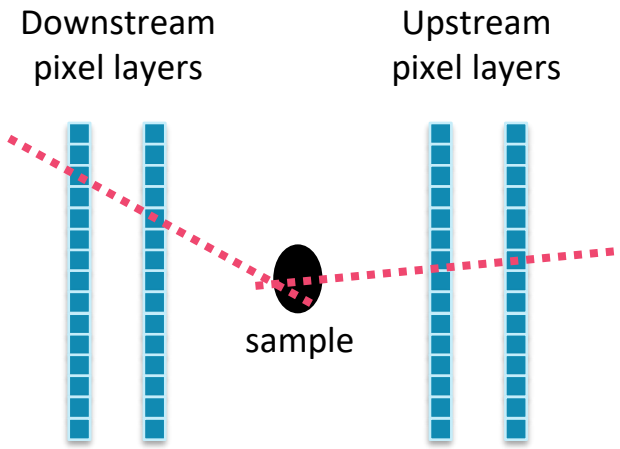

- Sensor Modules
- Tracklet Finding
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Particle Selection

- Angle
- Beam Origin
- (ToT)
- Trigger

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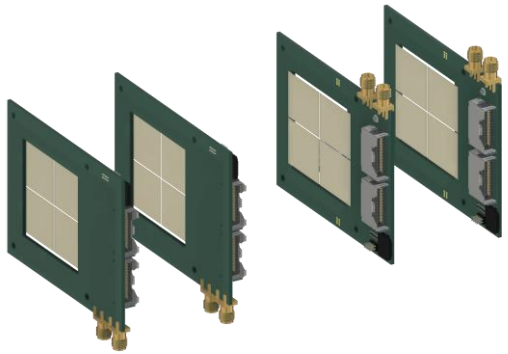

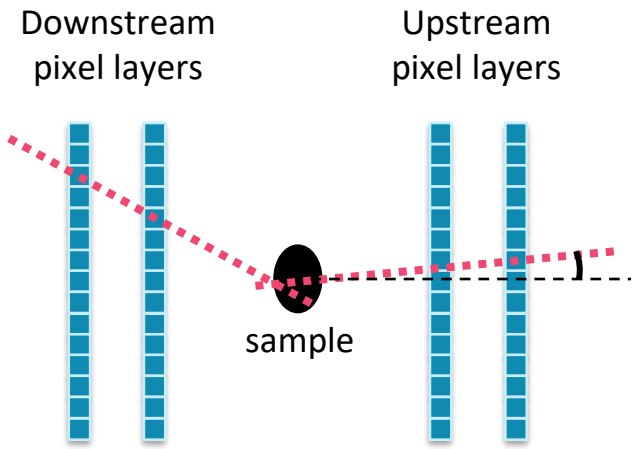

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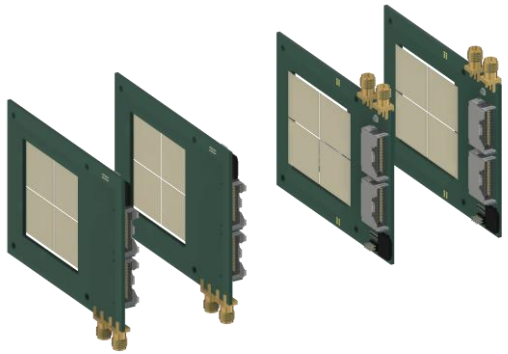

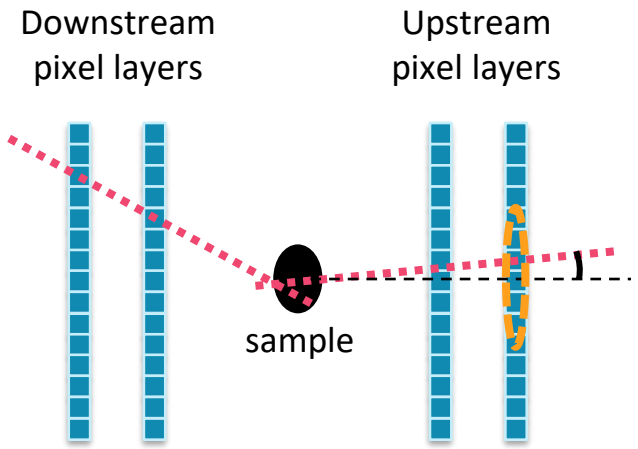

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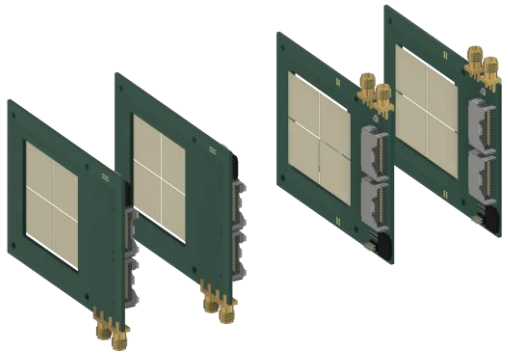

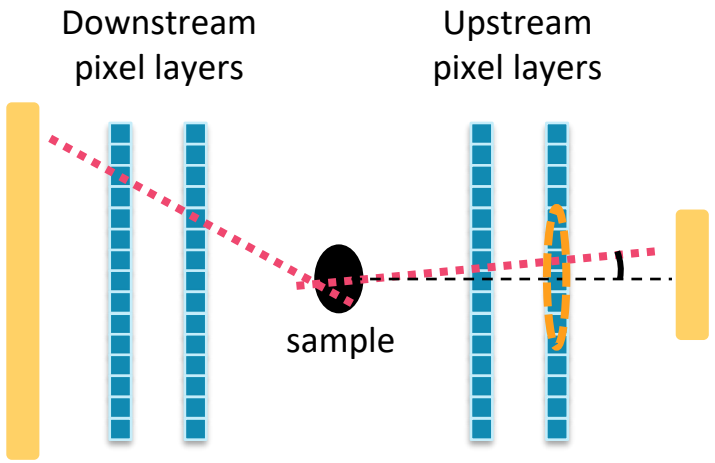

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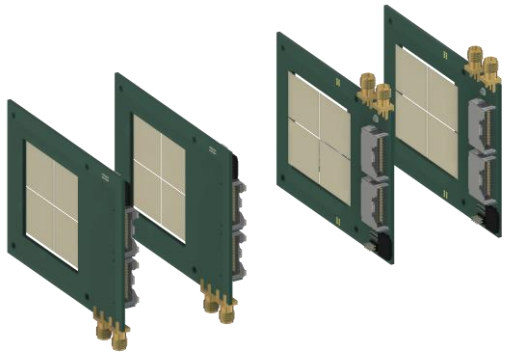
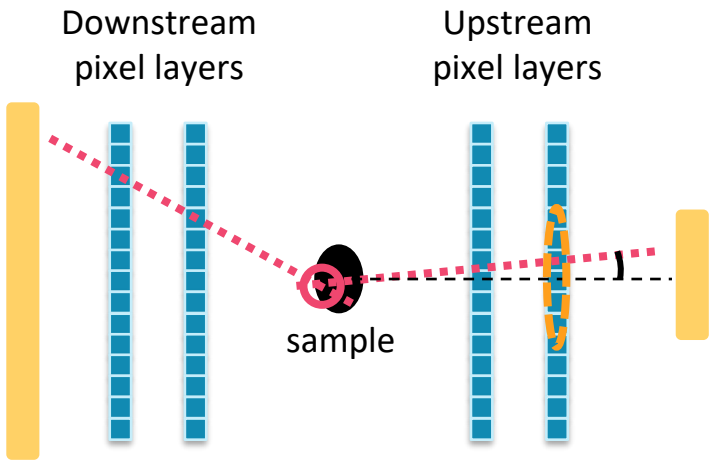




- Sensor Modules
- Tracklet Finding
- Tracklet Matching

Particle Selection

- Angle
- (ToT)
- Beam Origin
- Trigger

Decay Selection

- Distance Cuts (1 mm)
- Time Cuts (30 us)

Corryvreckan

Analysis
Corry

Metronom

MidasEventLoader

⇩

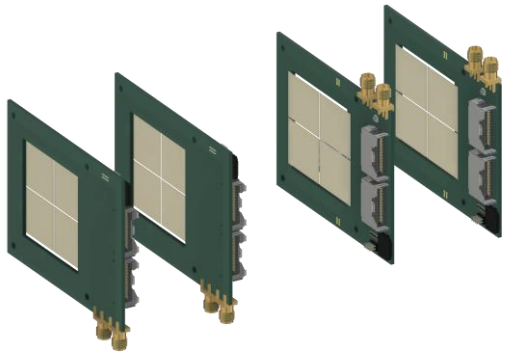
Clustering

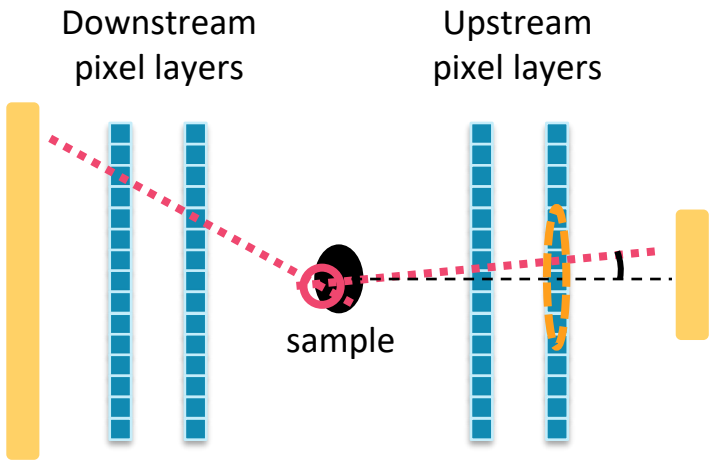
⇩

TrackingMusr

⇩

AnalysisMusr





- Sensor Modules
- Tracklet Finding
- Tracklet Matching

- Lifetime fitting
- Magnetic field reconstruction
- Sample Reconstruction

Particle Selection

- Angle
- (ToT)
- Beam Origin
- Trigger

Decay Selection

- Distance Cuts (1 mm)
- Time Cuts (30 us)

Corryvreckan

Analysis
Corry

Metronom

MidasEventLoader

Clustering

Tracking4D

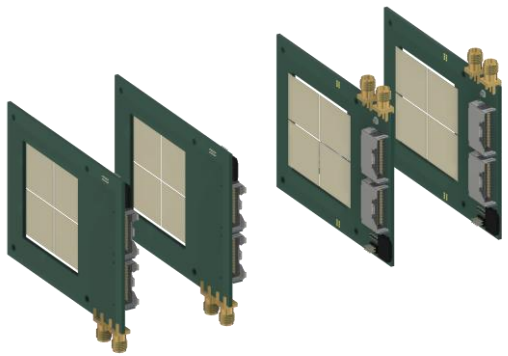
TrackingMusr

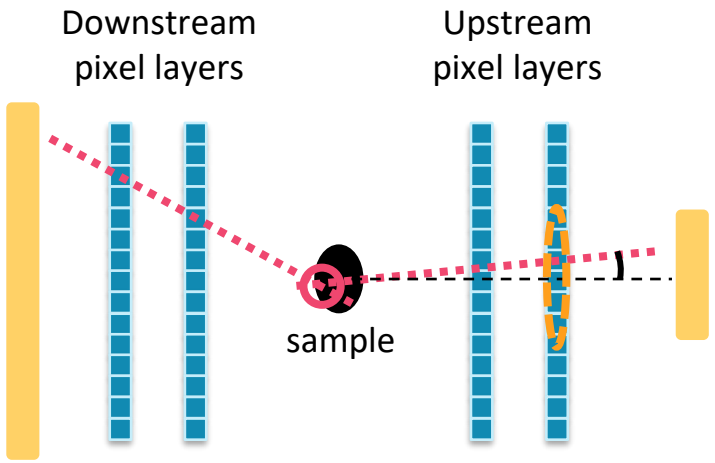
Alignment

AnalysisMusr

- Sensor Modules
- Tracklet Finding
- Tracklet Matching

- Lifetime fitting
- Magnetic field reconstruction
- Sample Reconstruction





Particle Selection

- Angle
- (ToT)
- Beam Origin
- Trigger

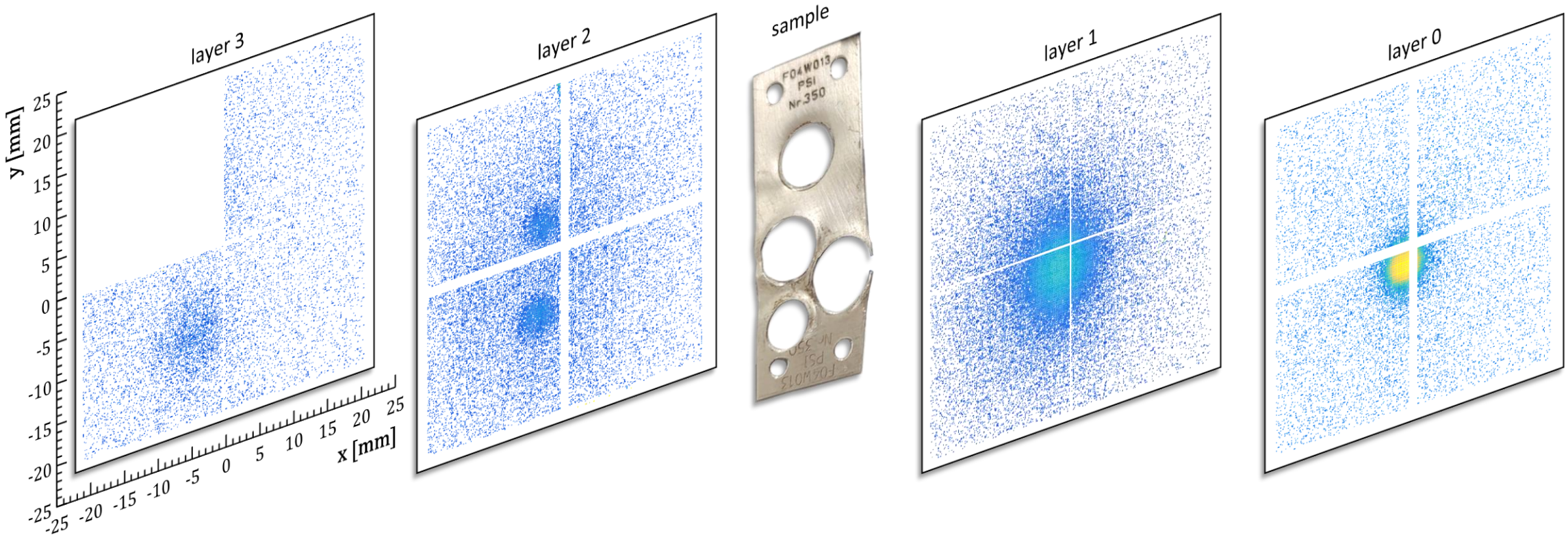
Decay Selection

- Distance Cuts (1 mm)
- Time Cuts (30 us)

Corryvreckan

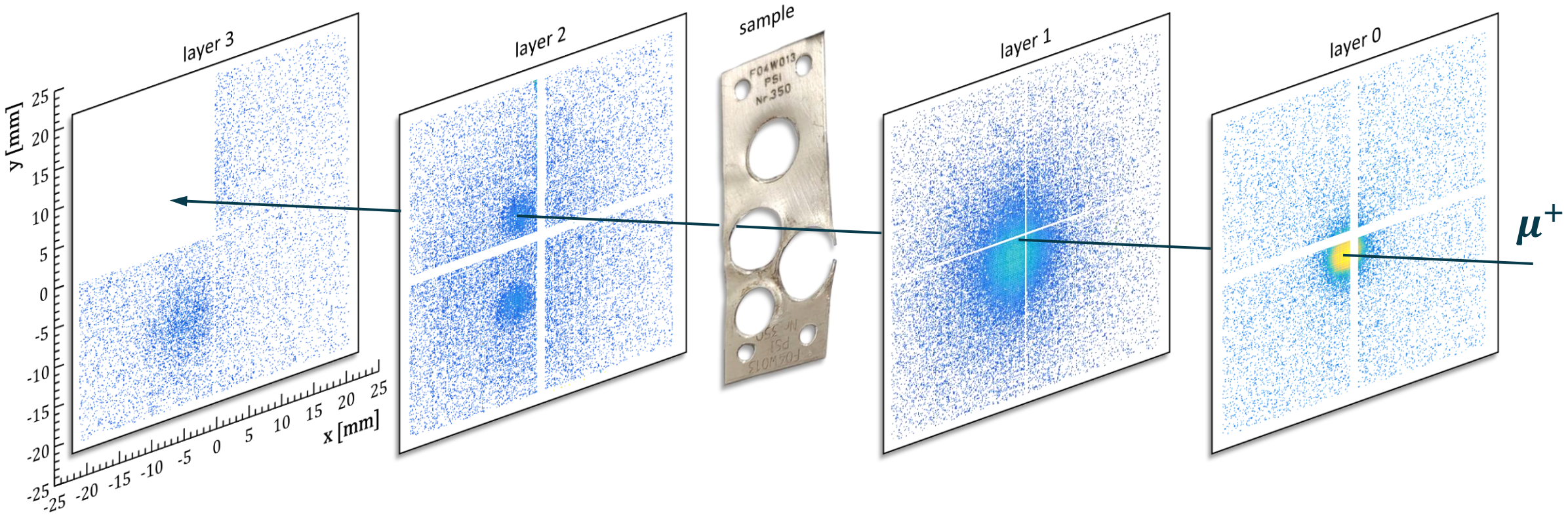
Analysis

Event Reconstruction



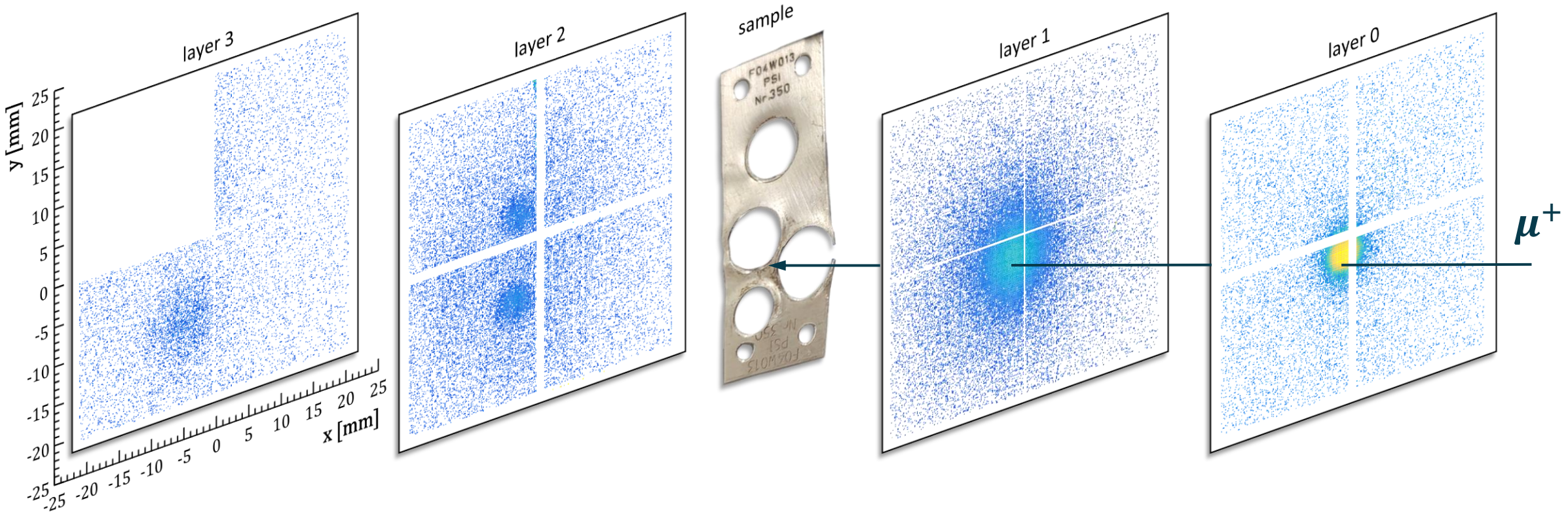
Analysis

Event Reconstruction



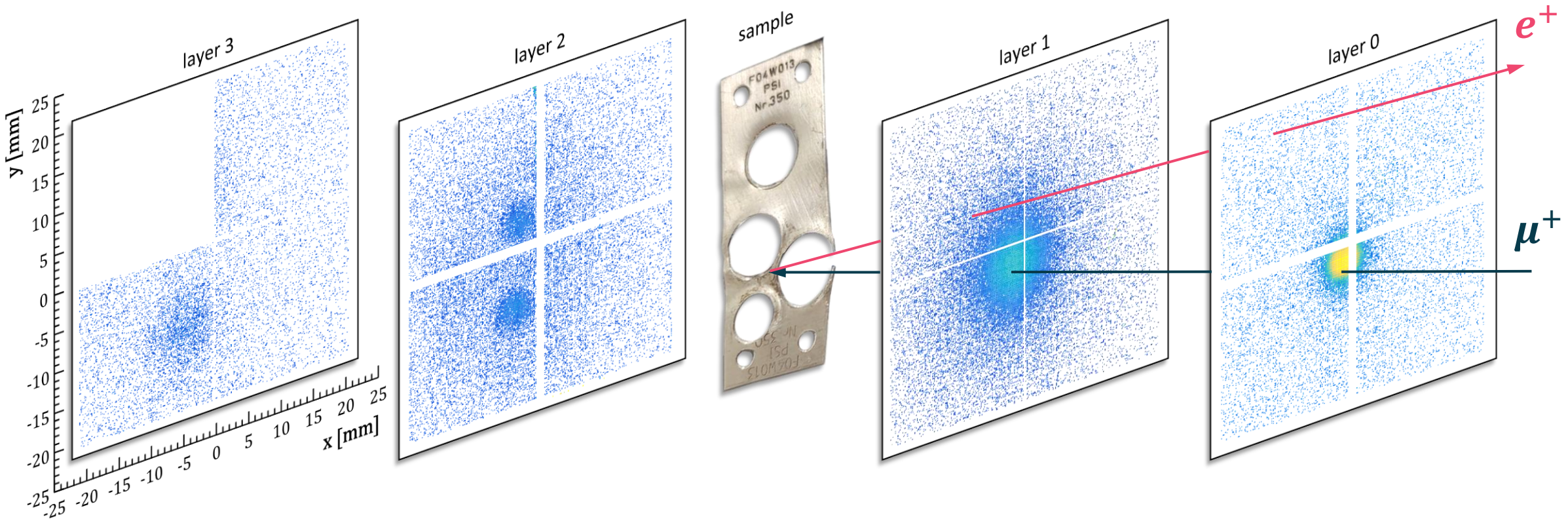
Analysis

Event Reconstruction



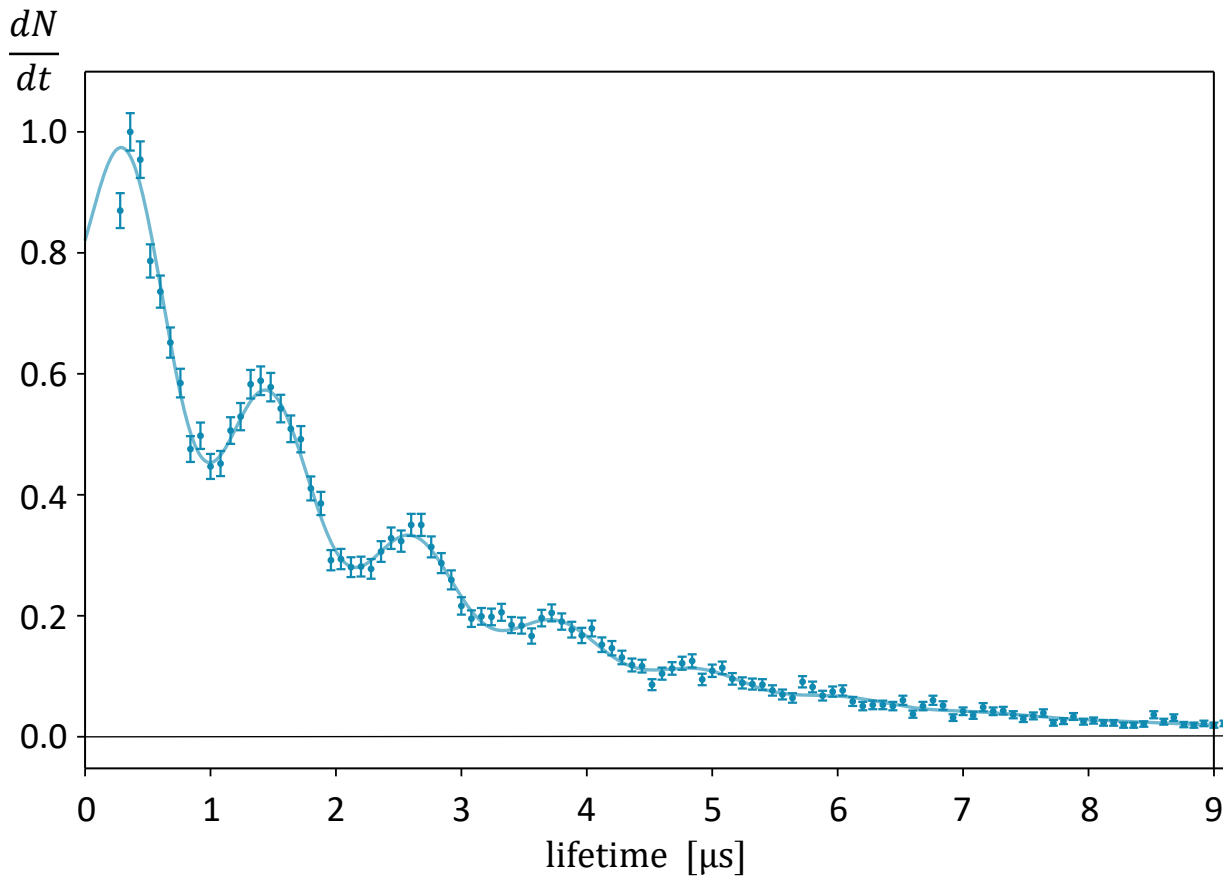
Analysis

Event Reconstruction

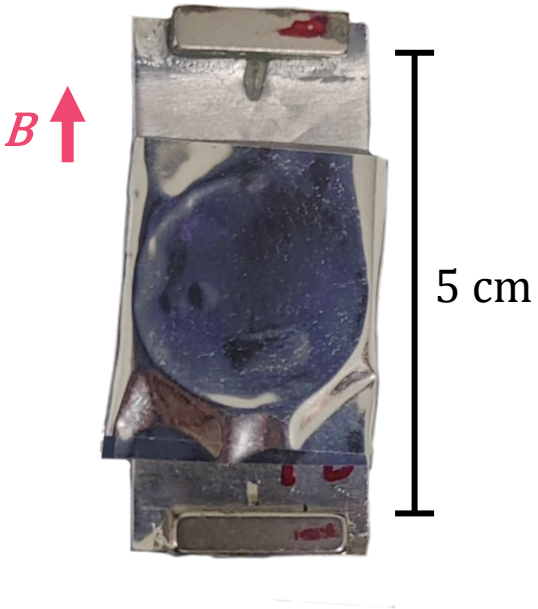


Results

Spin Rotation

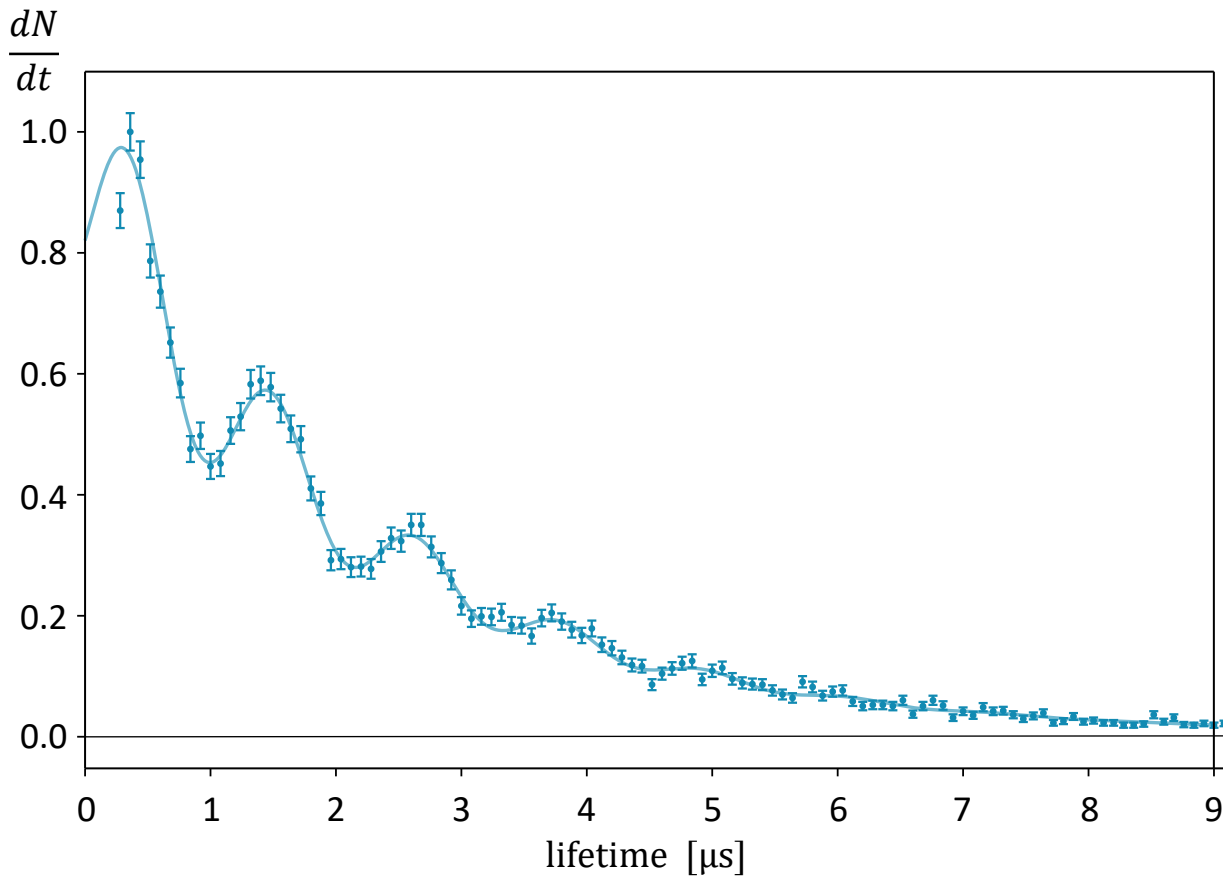


- Sample
  - Aluminum disk
  - $\emptyset = 6\ \mathrm{mm}$
  - $B_{\perp} = 6.3\ \mathrm{mT}$

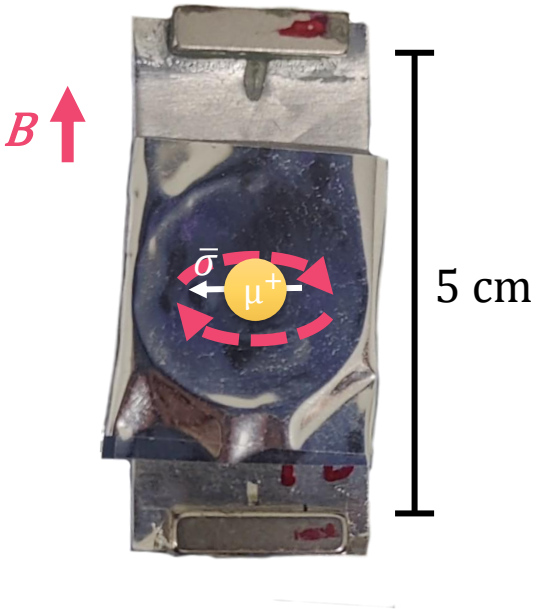


Results

Spin Rotation

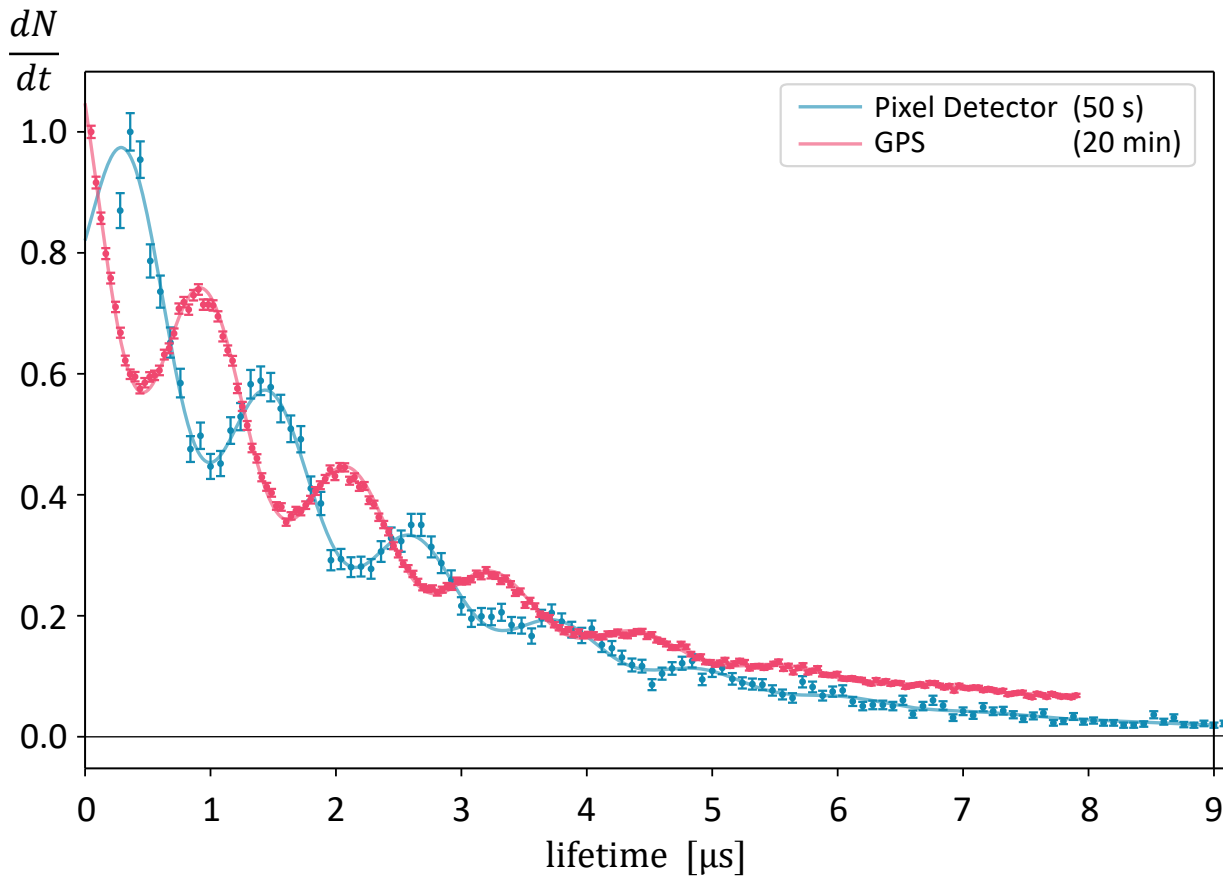


- Sample
  - Aluminum disk
  - $\emptyset = 6$ mm
  - $B_{\perp} = 6.3$ mT

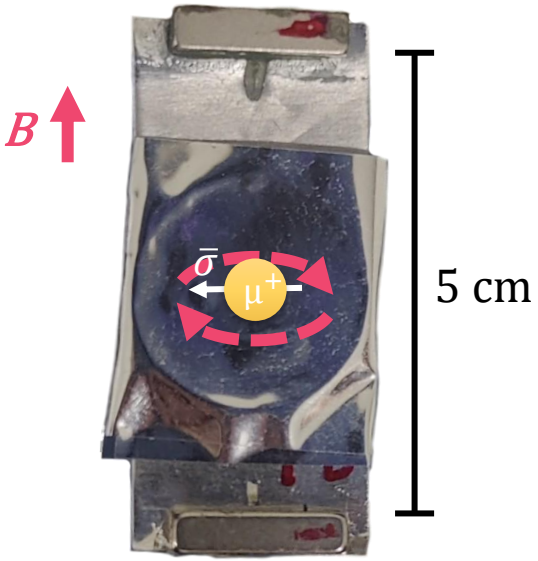


Results

Spin Rotation

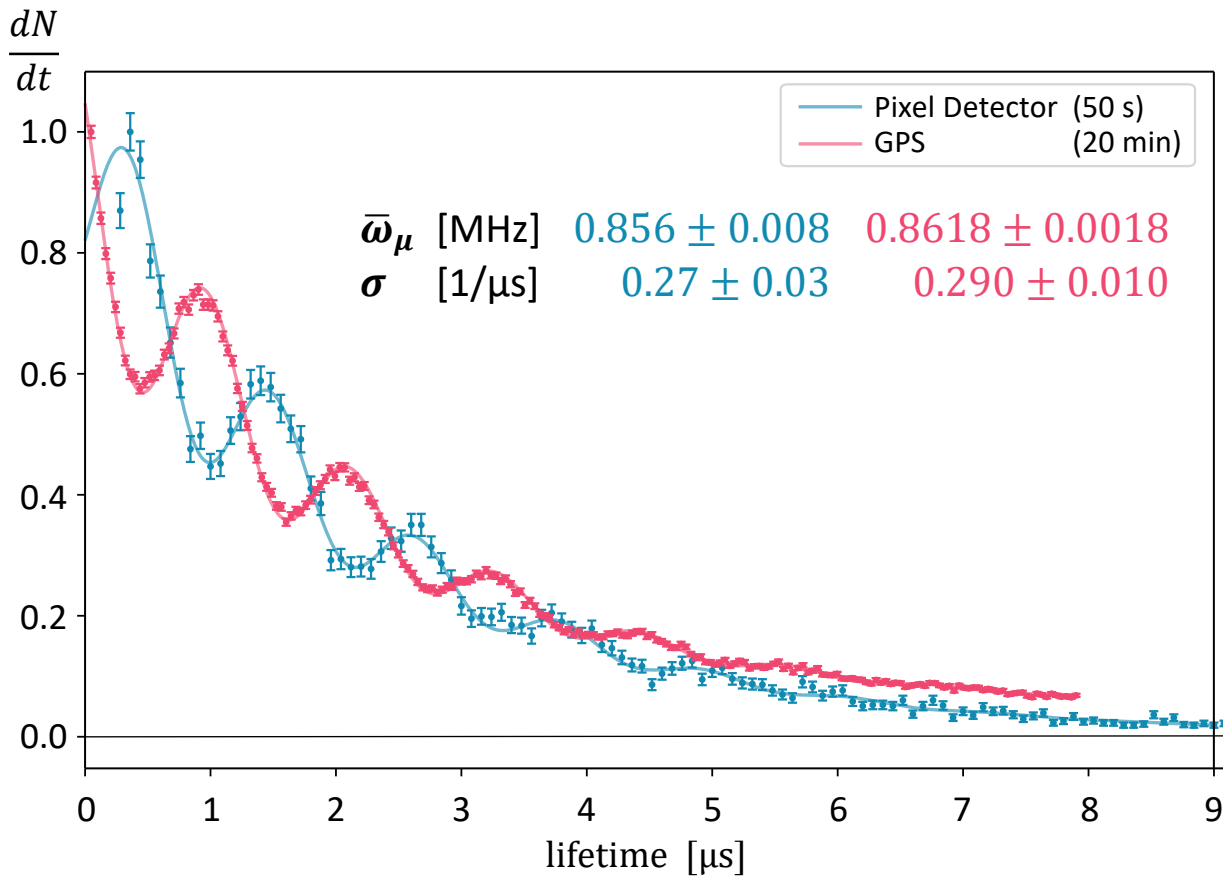


- Sample
  - Aluminum disk
  - $\emptyset = 6$ mm
  - $B_{\perp} = 6.3$ mT

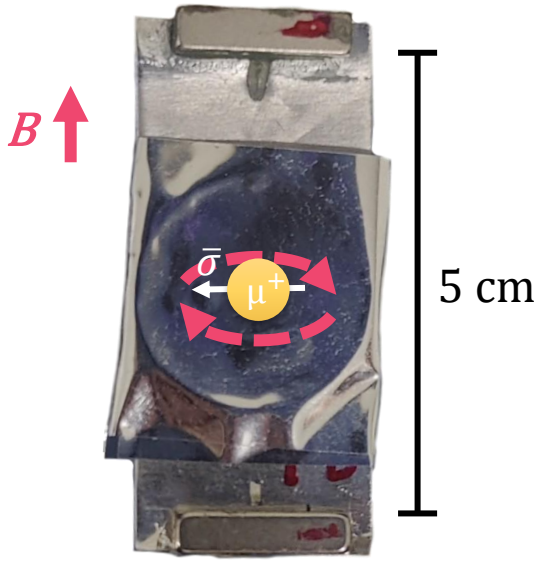


Results

Spin Rotation



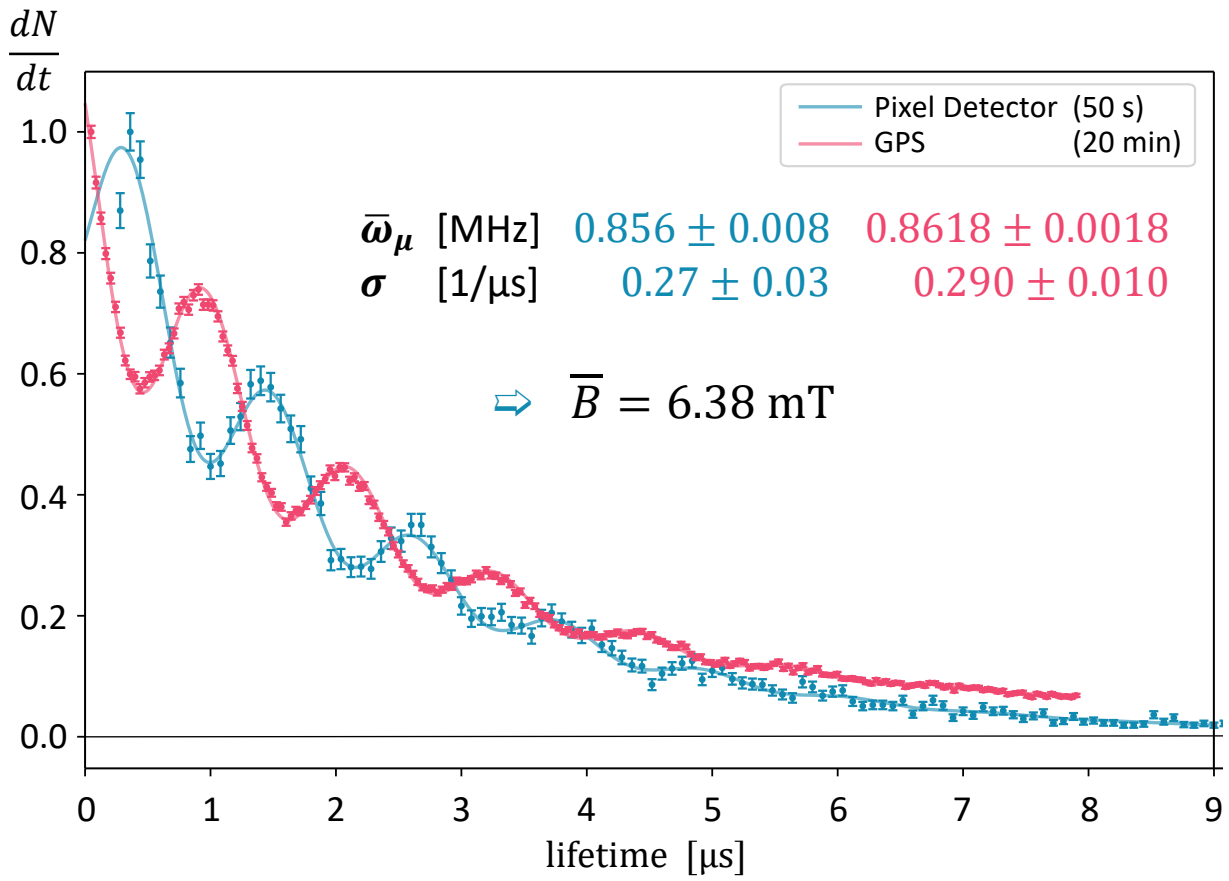
- Sample
  - Aluminum disk
  - $\emptyset = 6$ mm
  - $B_\perp = 6.3$ mT



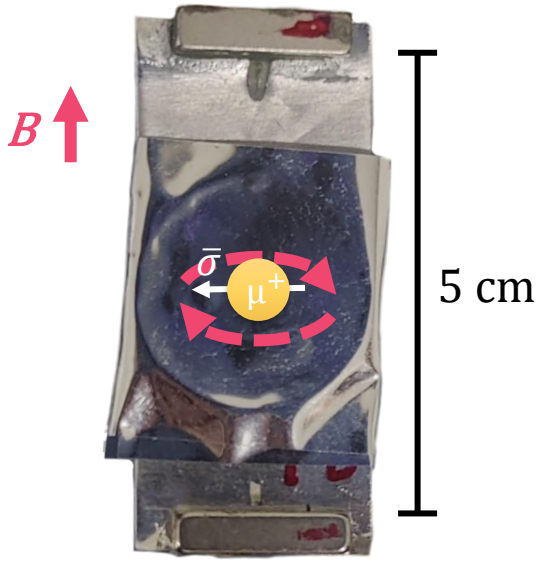
- Results
  - Identical Lamor frequency $\bar{\omega}_\mu$ and dampening rate σ

Results

Spin Rotation



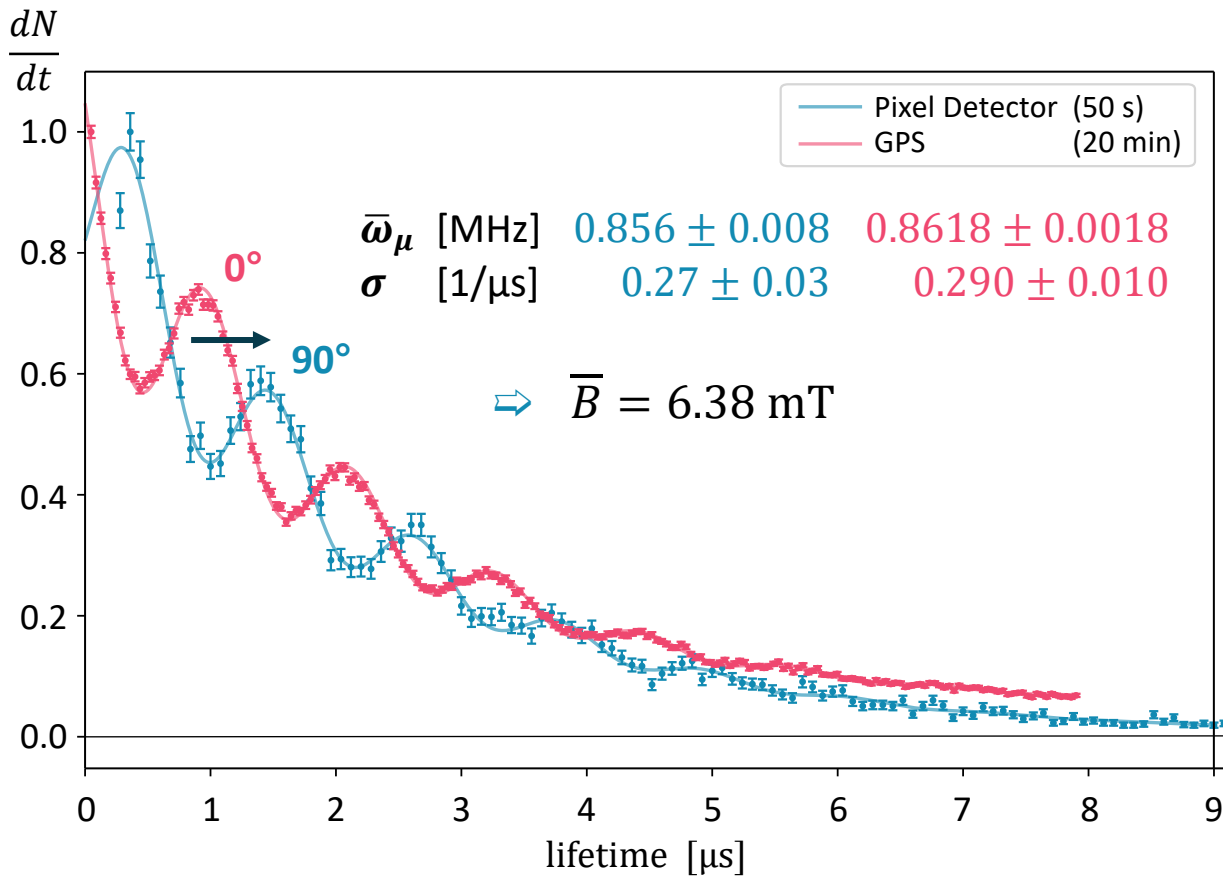
- Sample
  - Aluminum disk
  - $\emptyset = 6$ mm
  - $B_\perp = 6.3$ mT



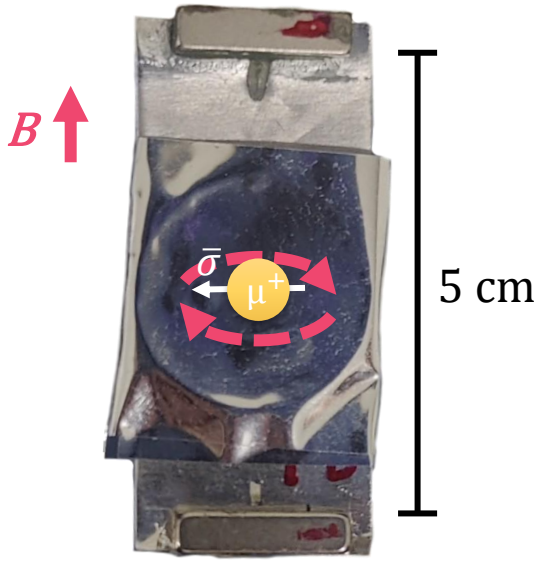
- Results
  - Identical Lamor frequency $\bar{\omega}_\mu$ and dampening rate σ

Results

Spin Rotation



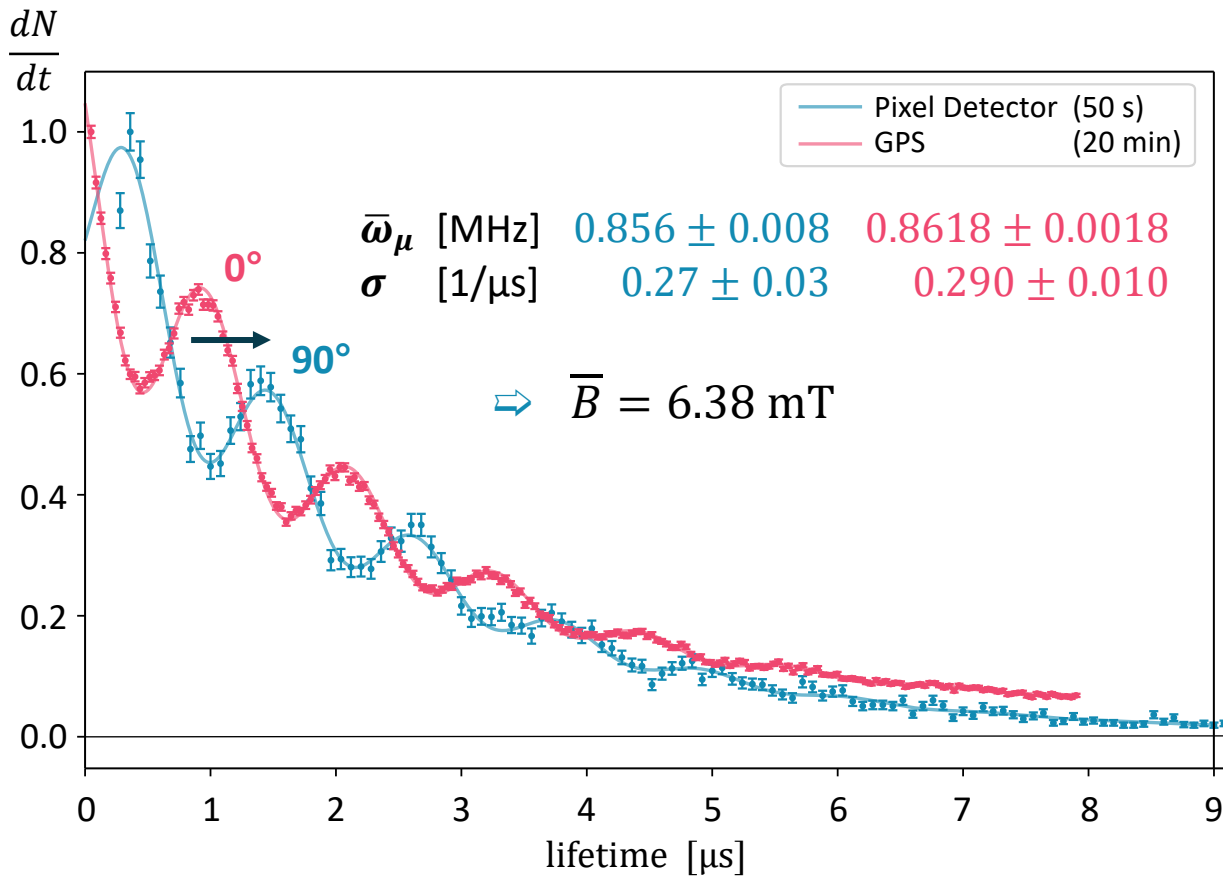
- Sample
  - Aluminum disk
  - $\emptyset = 6$ mm
  - $B_\perp = 6.3$ mT



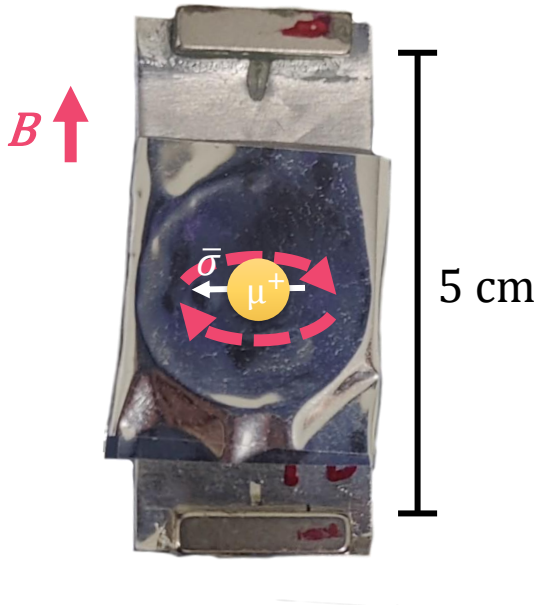
- Results
  - Identical Lamor frequency $\bar{\omega}_\mu$ and dampening rate σ
  - Phase shift due to initial polarization

Results

Spin Rotation



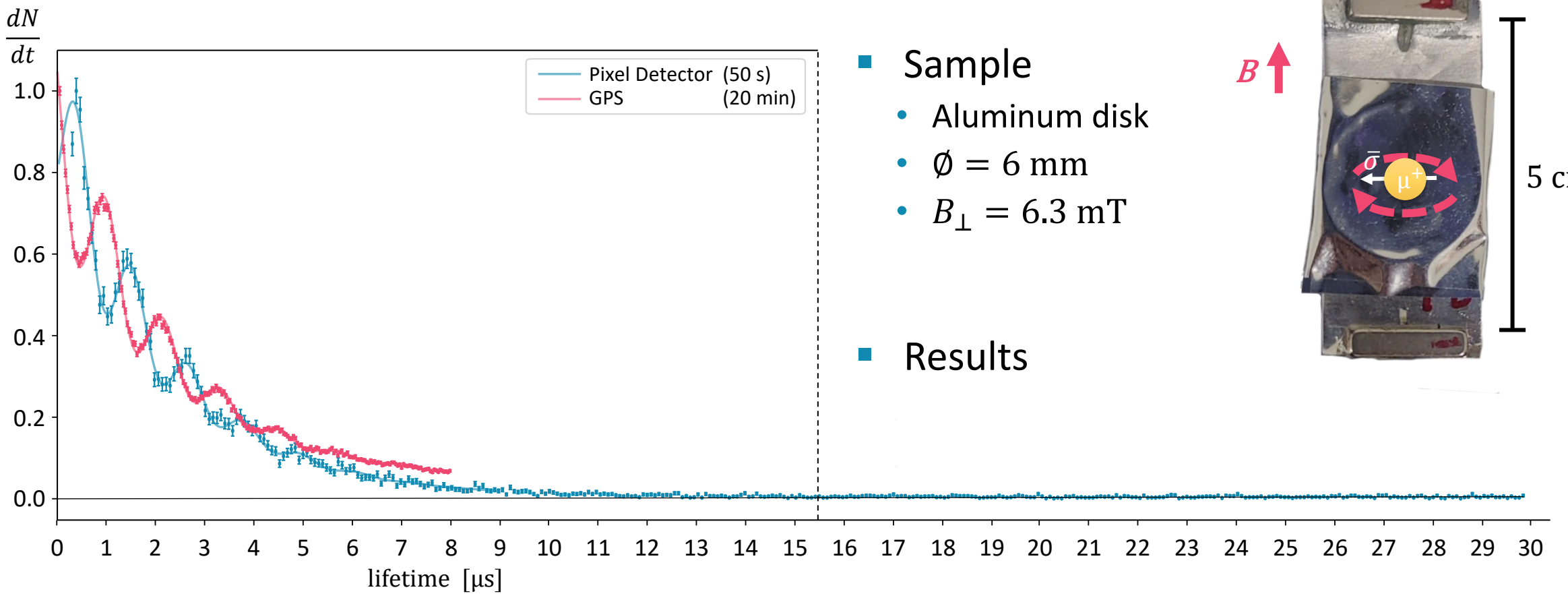
- Sample
  - Aluminum disk
  - $\emptyset = 6$ mm
  - $B_\perp = 6.3$ mT



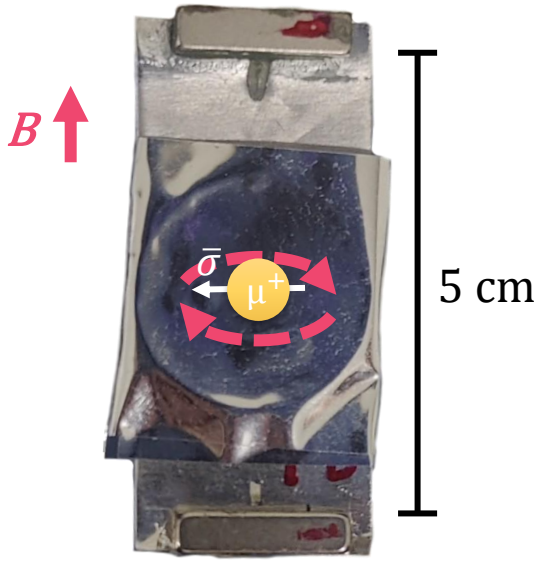
- Results
  - Identical Lamor frequency $\bar{\omega}_\mu$ and dampening rate σ
  - Phase shift due to initial polarization
  - Larger errors due to less statistics

Results

Spin Rotation

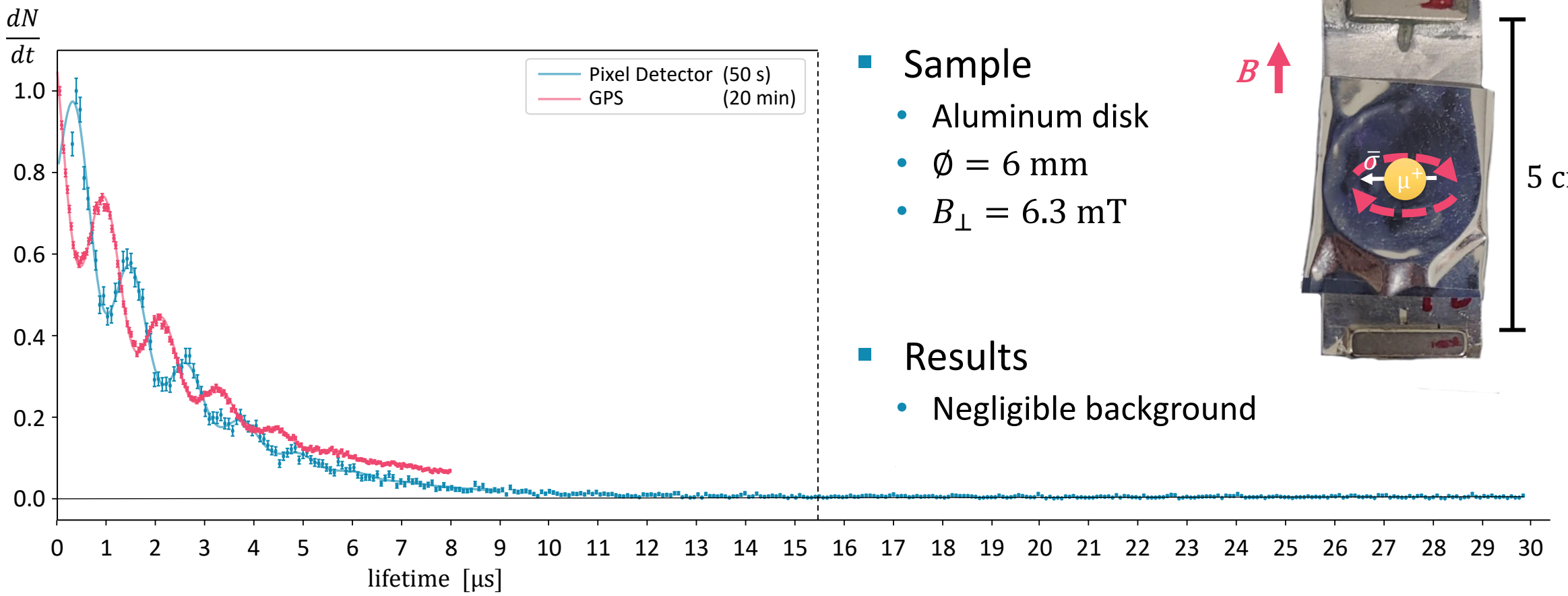


- Sample
  - Aluminum disk
  - $\emptyset = 6$ mm
  - $B_\perp = 6.3$ mT
- Results

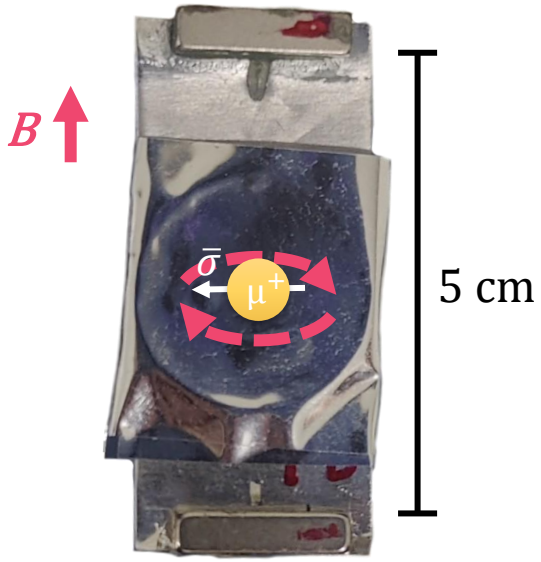


Results

Spin Rotation



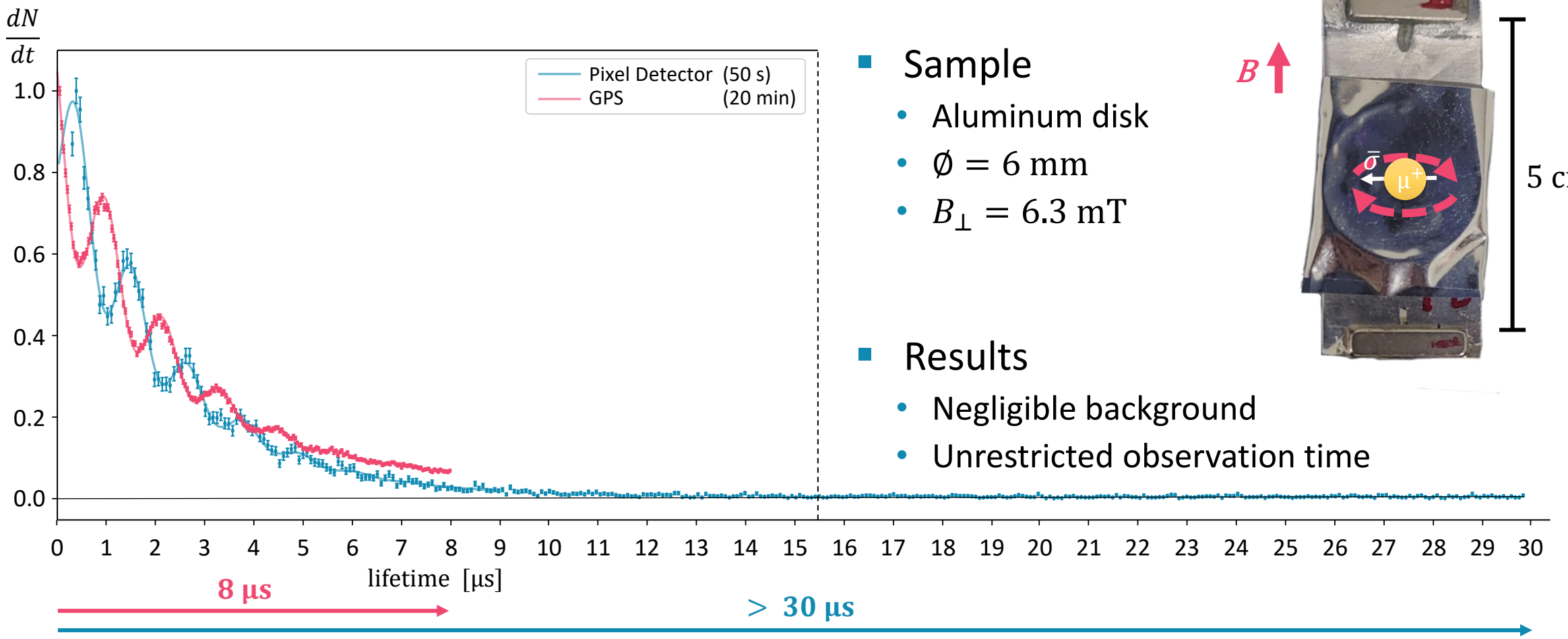
- Sample
  - Aluminum disk
  - $\emptyset = 6$ mm
  - $B_\perp = 6.3$ mT



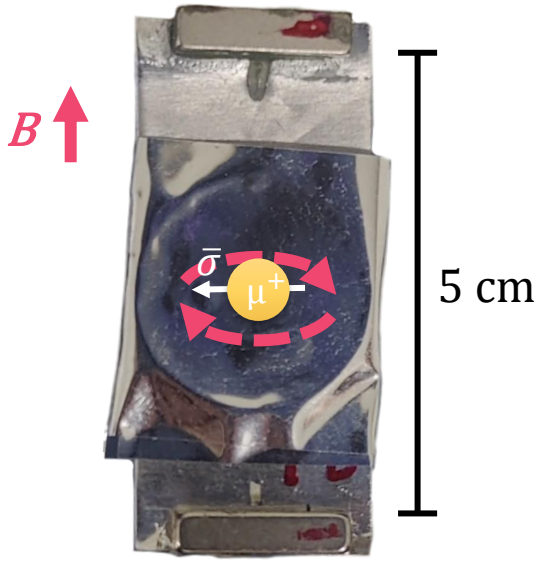
- Results
  - Negligible background

Results

Spin Rotation



- Sample
  - Aluminum disk
  - $\emptyset = 6$ mm
  - $B_\perp = 6.3$ mT



- Results
  - Negligible background
  - Unrestricted observation time

Results

Sample Resolution

- Sample
  - Silver plate with cutouts
  - Various feature sizes

Results

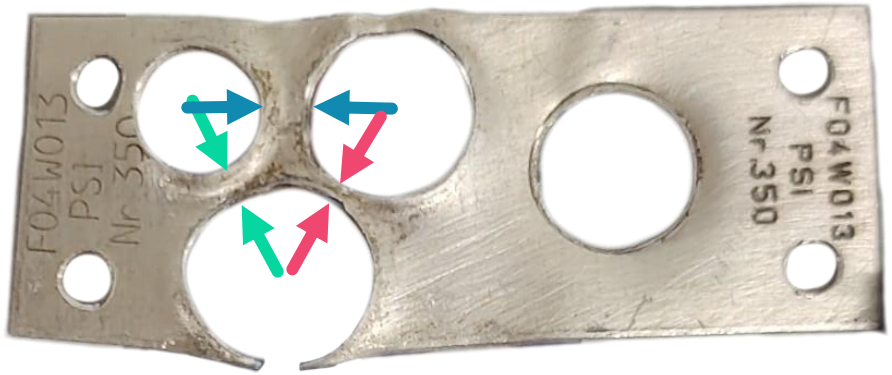
Sample Resolution

- Sample
  - Silver plate with cutouts
  - Various feature sizes

0.6 mm

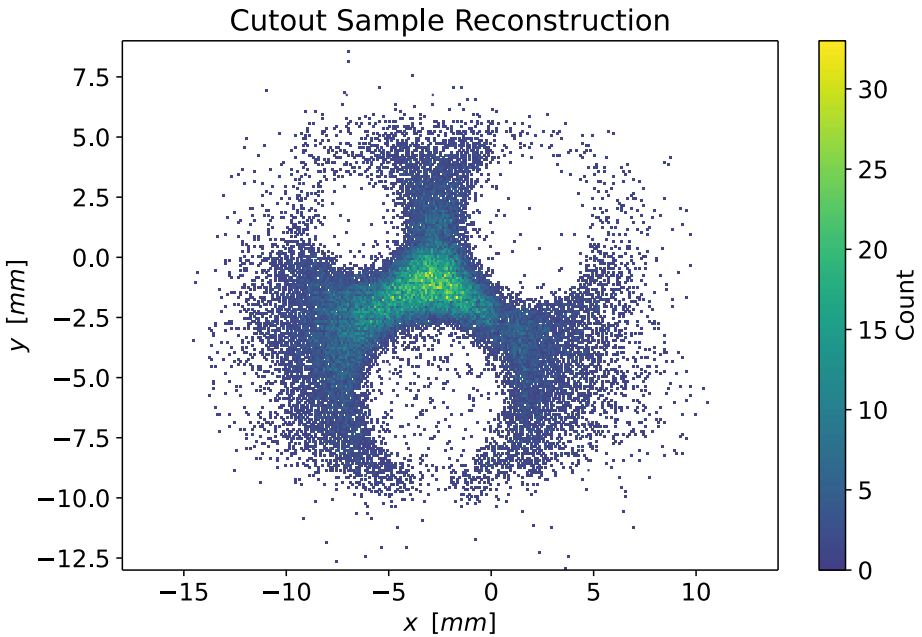
1.1 mm

1.6 mm



Results

Sample Resolution

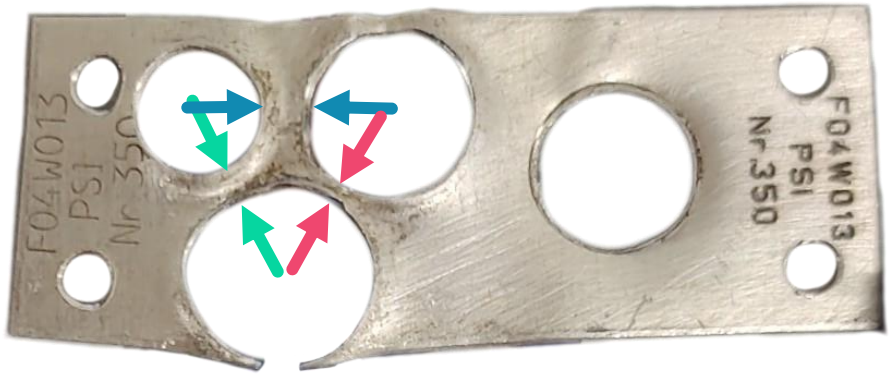


- Sample
  - Silver plate with cutouts
  - Various feature sizes

0.6 mm

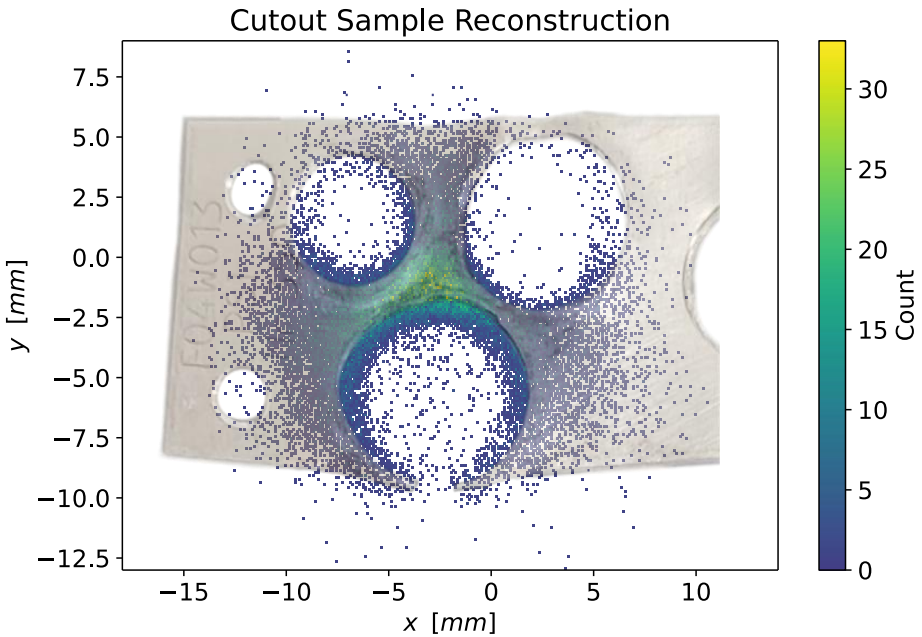
1.1 mm

1.6 mm



Results

Sample Resolution

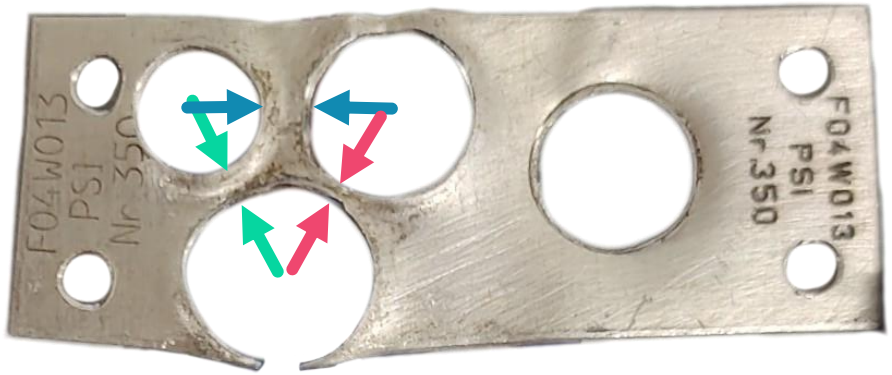


- Sample
  - Silver plate with cutouts
  - Various feature sizes

0.6 mm

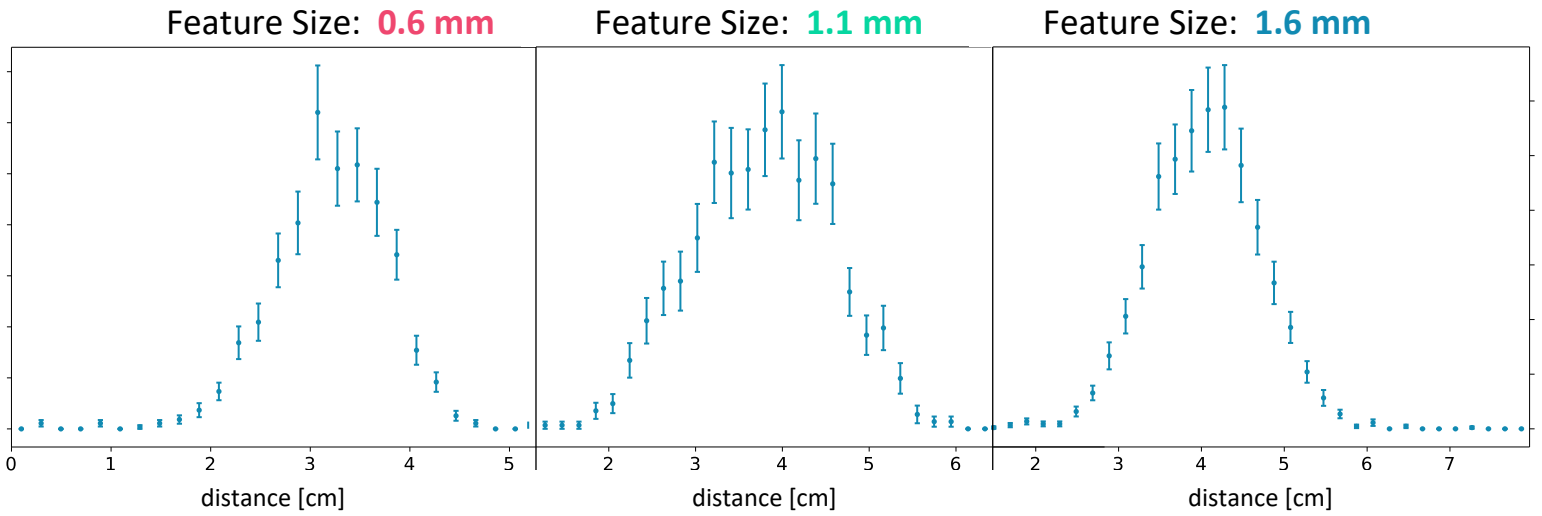
1.1 mm

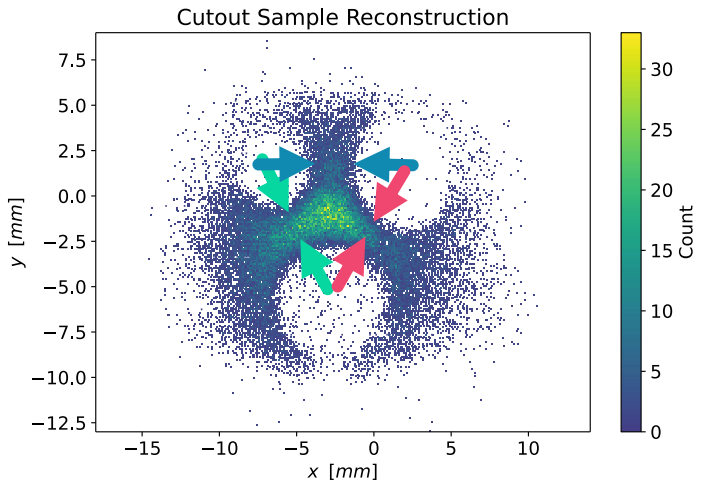
1.6 mm



Results

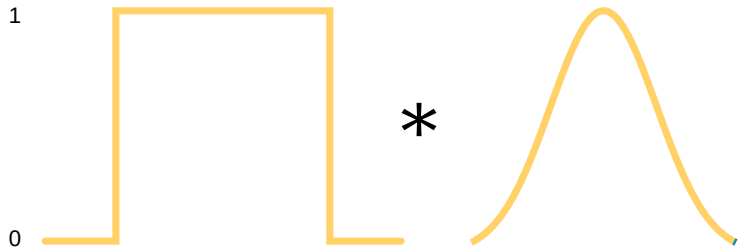
Sample Resolution



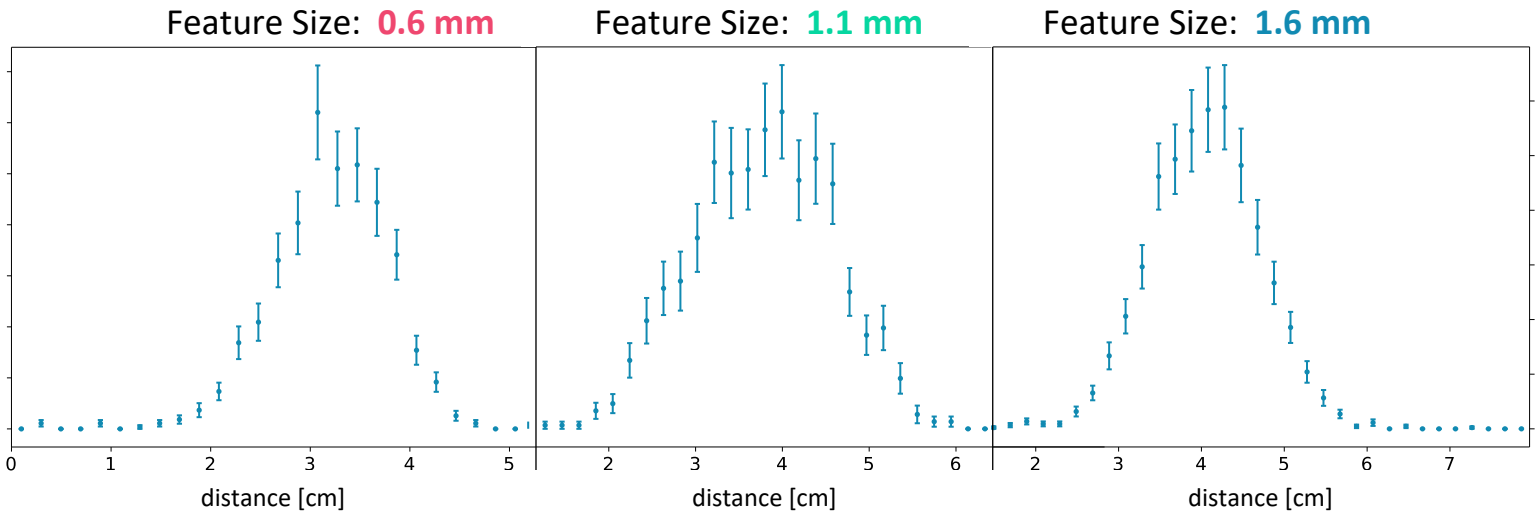


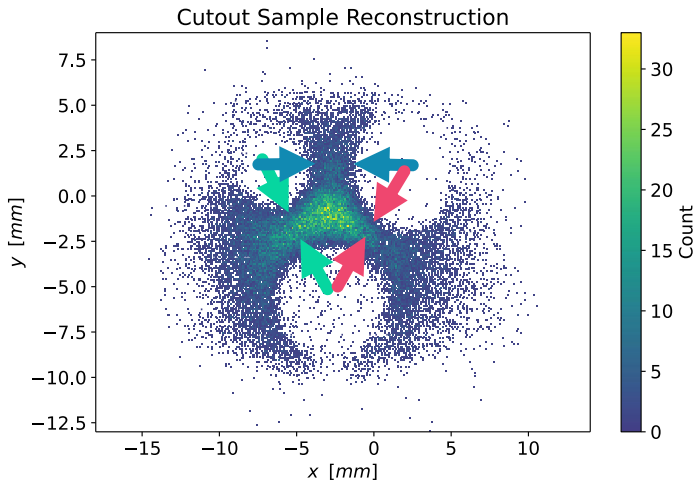
Results

Sample Resolution



$\mathrm{rect}(x, a)$ $\quad * \; g(x, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}}$

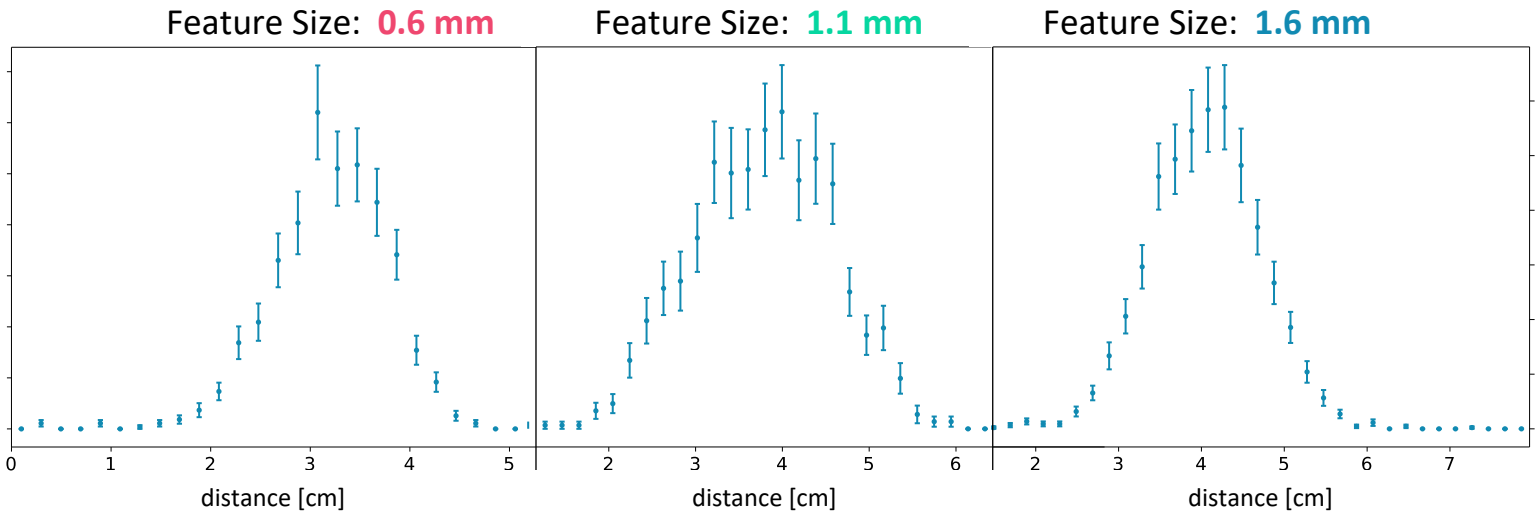


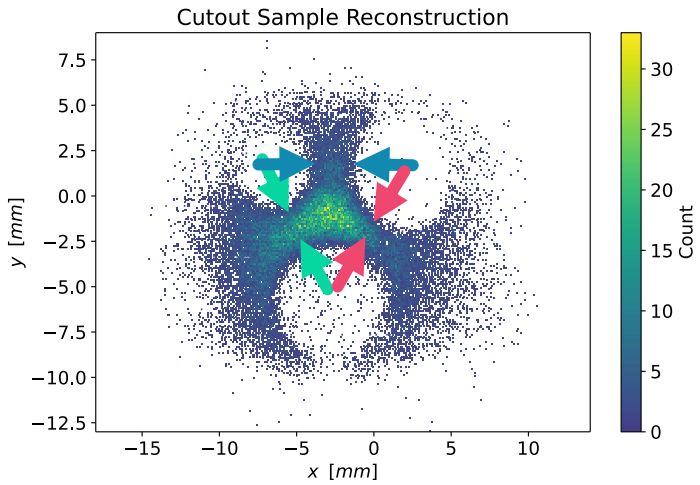


Results

Sample Resolution

$$\mathrm{rect}(x,a) \quad * \quad g(x,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}} \quad = \quad \frac{1}{2}\left(\mathrm{erf}\left(\frac{x+\frac{a}{2}}{\sigma\sqrt{2}}\right) - \mathrm{erf}\left(\frac{x-\frac{a}{2}}{\sigma\sqrt{2}}\right)\right) \quad = \quad (\mathrm{rect} * g)(x)$$

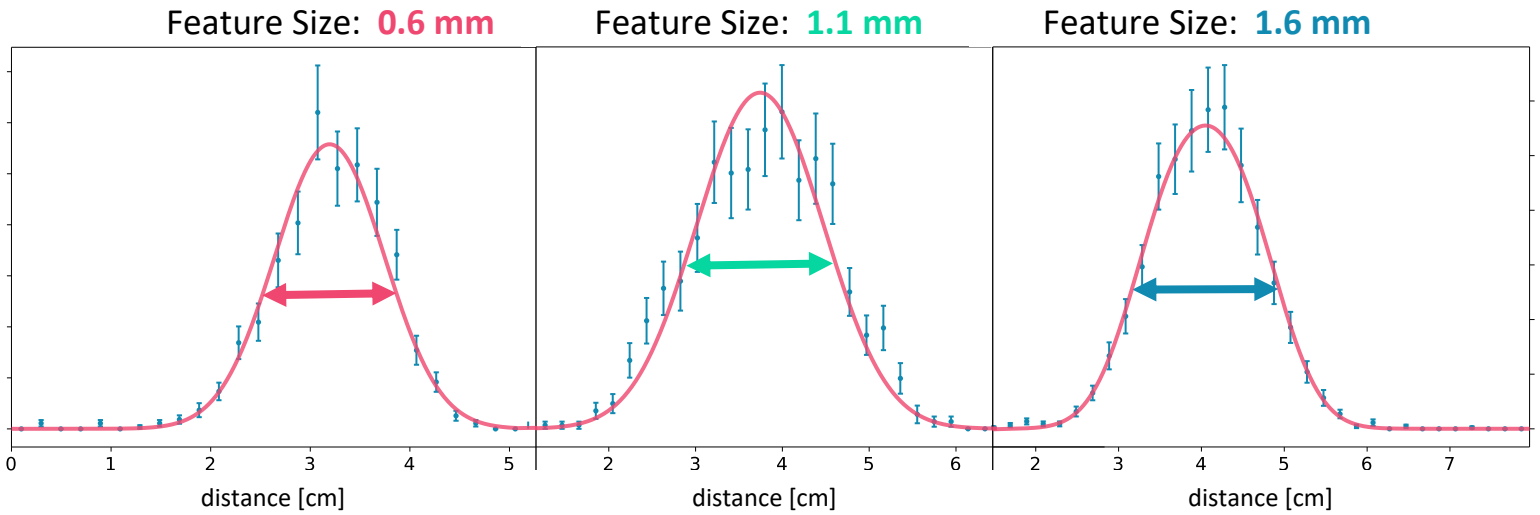


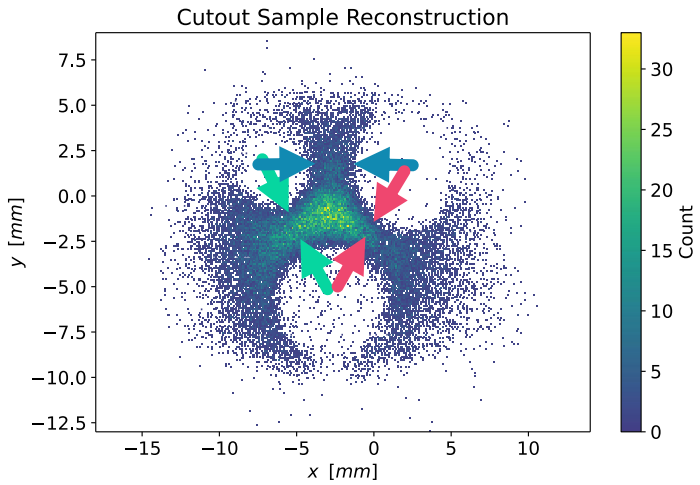


Results

Sample Resolution

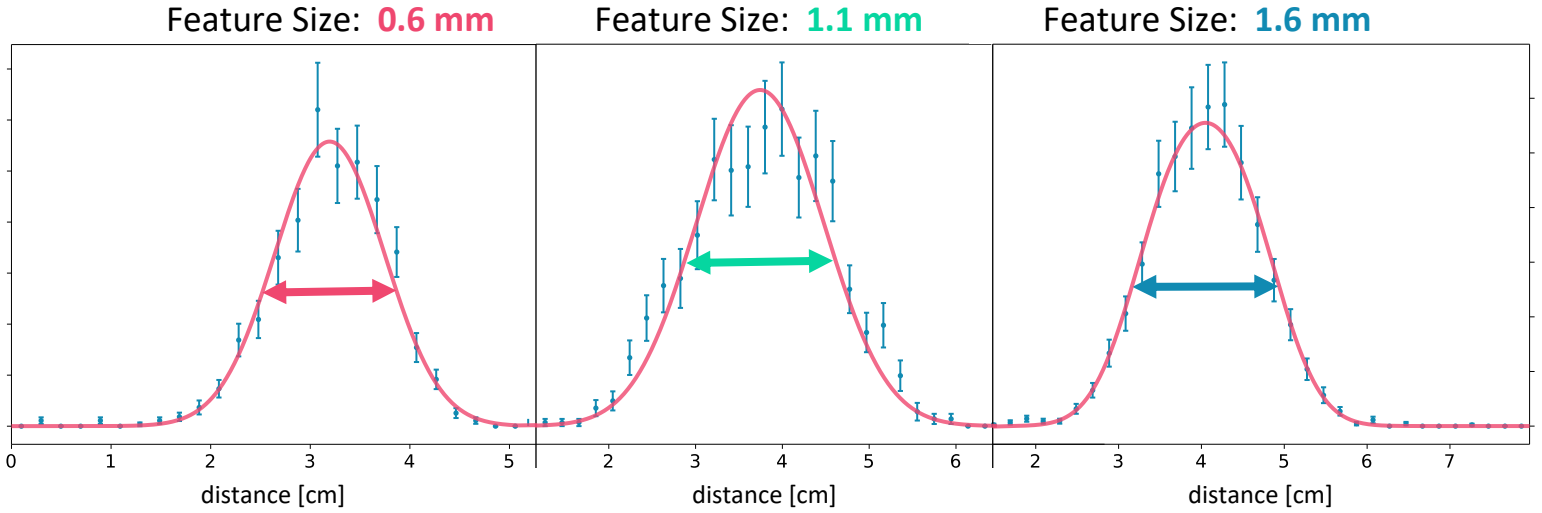
$$\mathrm{rect}(x,a) \quad * \quad g(x,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{x^2}{2\sigma^2}} \quad = \quad \frac{1}{2}\left(\mathrm{erf}\left(\frac{x+\frac{a}{2}}{\sigma\sqrt{2}}\right) - \mathrm{erf}\left(\frac{x-\frac{a}{2}}{\sigma\sqrt{2}}\right)\right) \quad = \quad (\mathrm{rect} * g)(x)$$

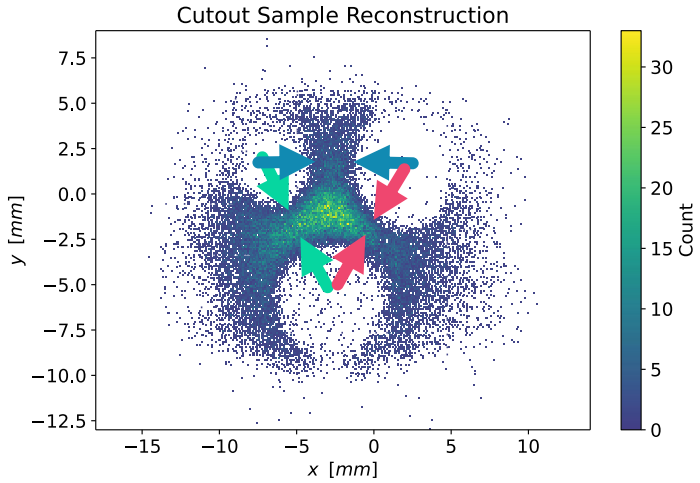




Results

Sample Resolution



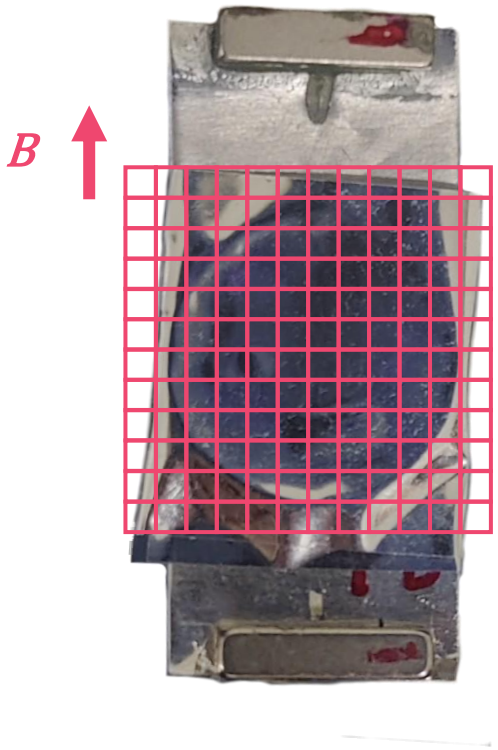


- Resolution:

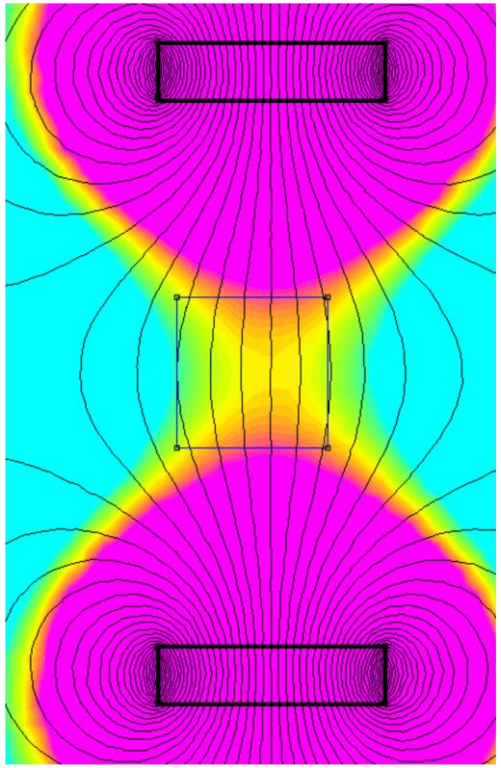
$\sigma = 0.52$ mm $\quad \sigma = 0.65$ mm $\quad \sigma = 0.46$ mm $\quad \Rightarrow \quad \bar{\sigma} = 0.53 \pm 0.16$ mm

Results

Magnetic Field Reconstruction



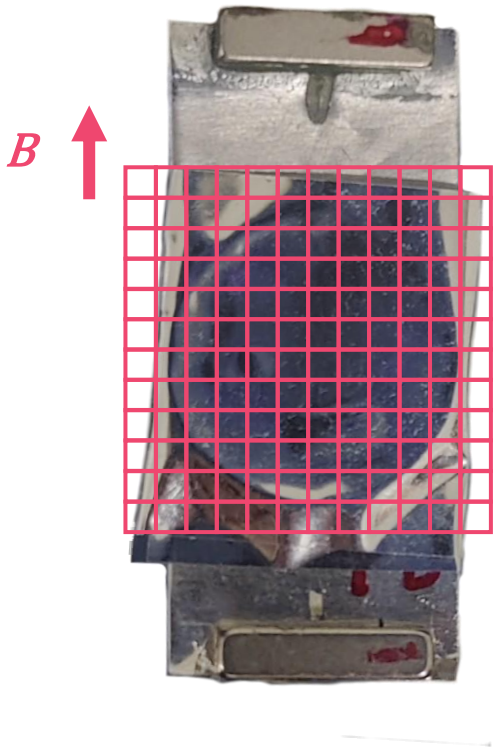
by Zaher Salman

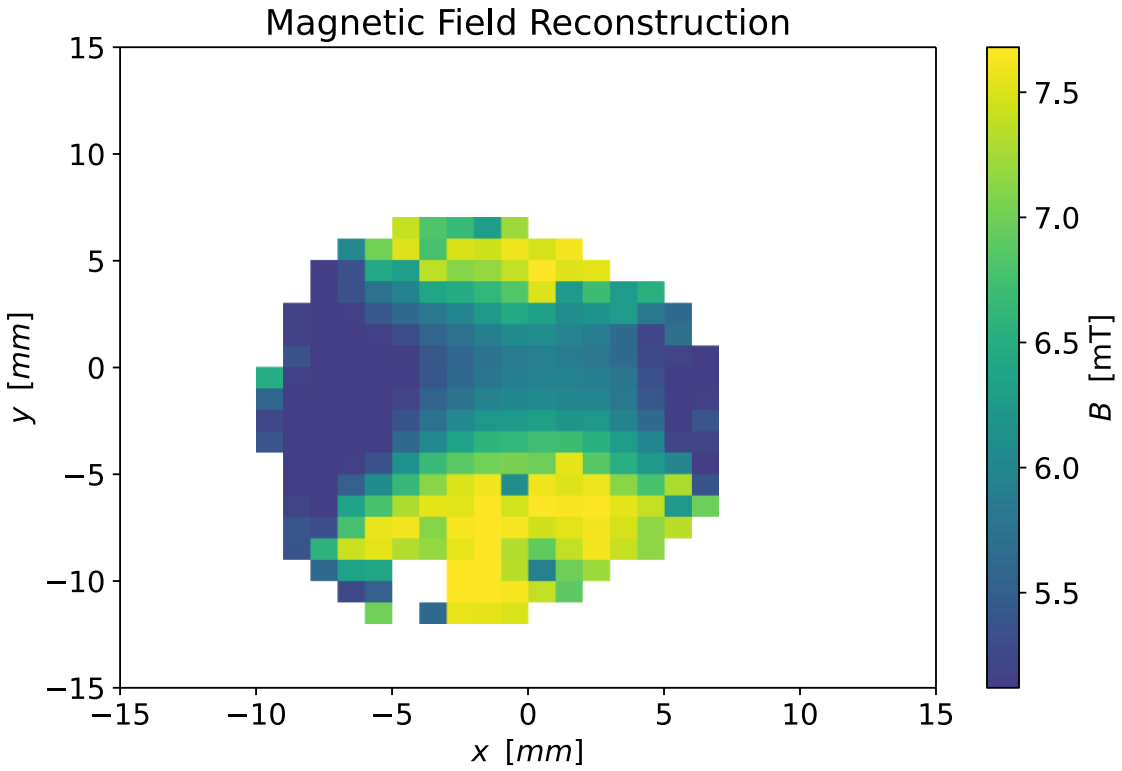


Simulation

Results

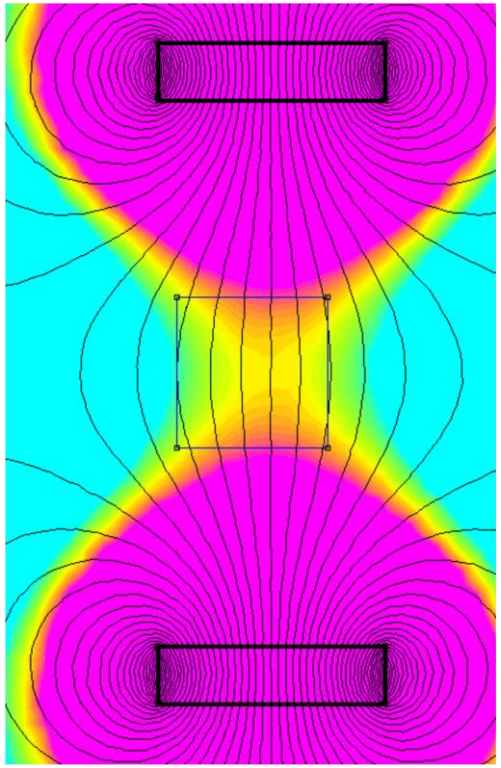
Magnetic Field Reconstruction





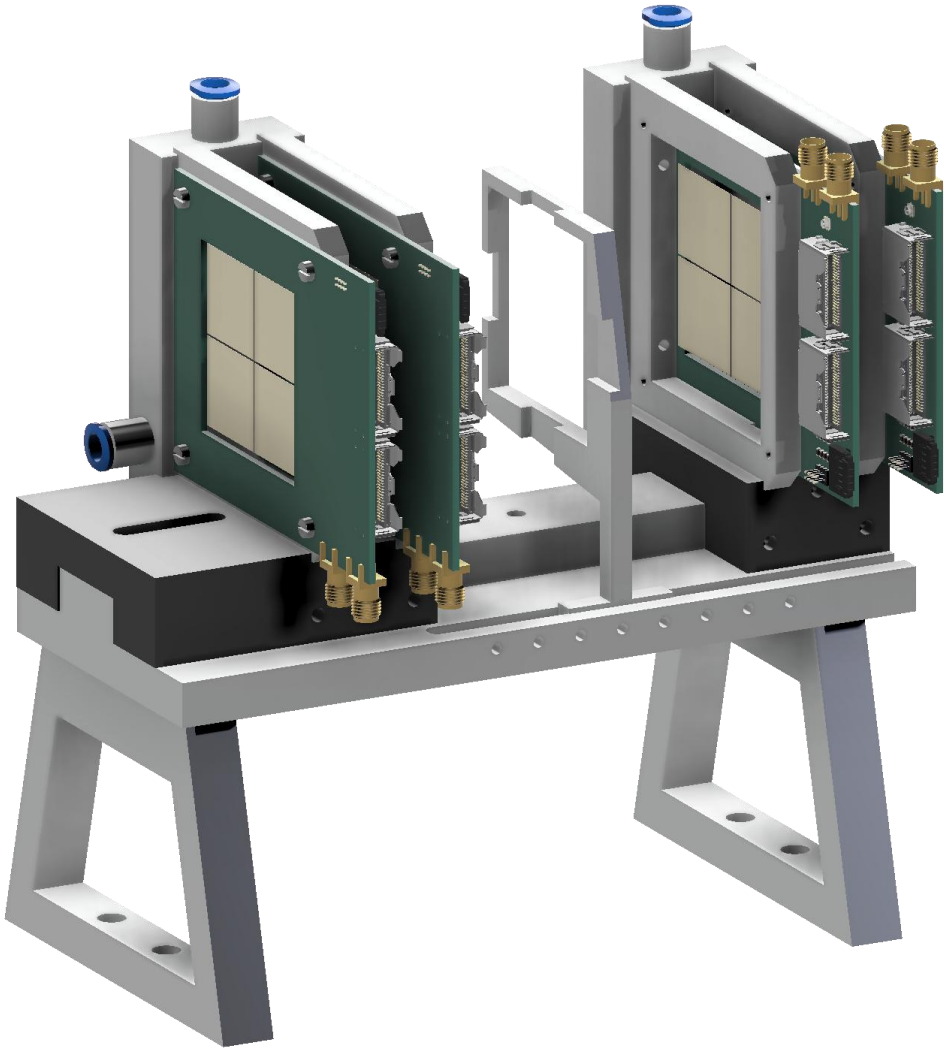
Data

by Zaher Salman



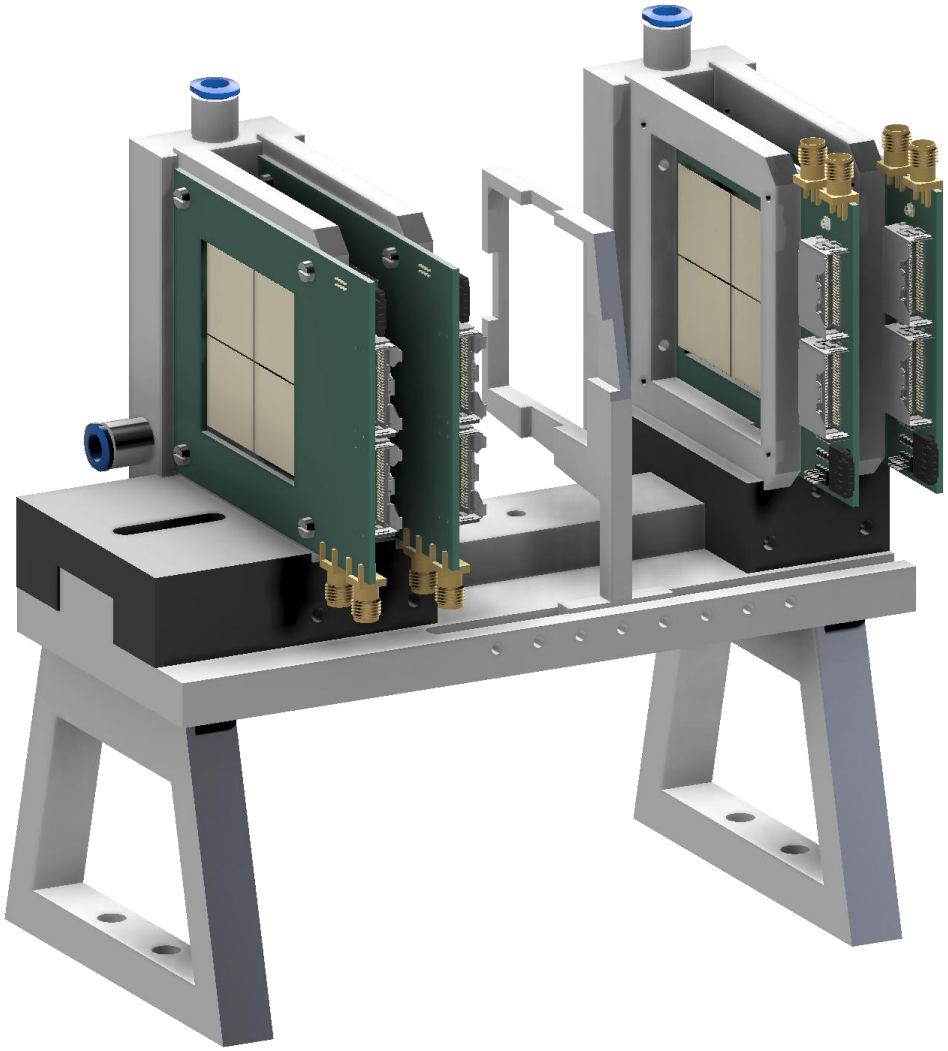
Simulation

Conclusion



Conclusion

- ☑ Successful proof-of-concept
- ☑ Comparable results to scintillators



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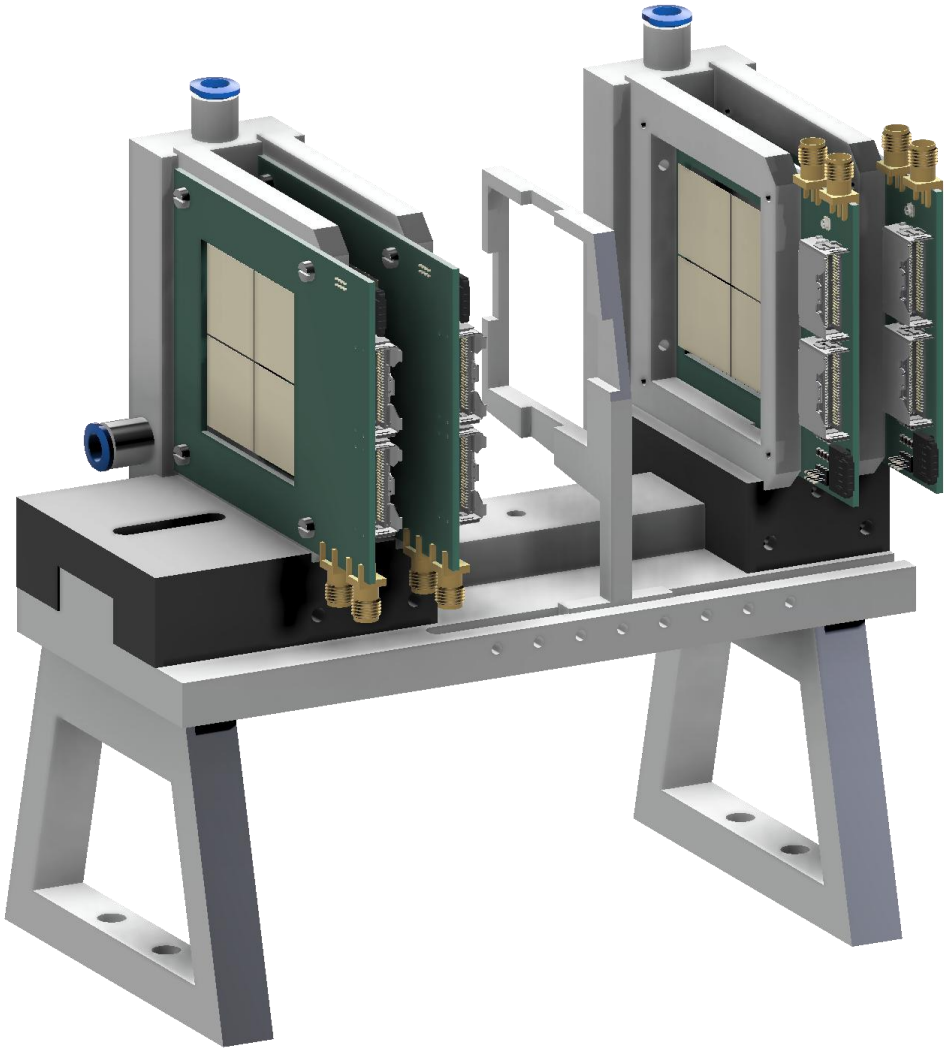

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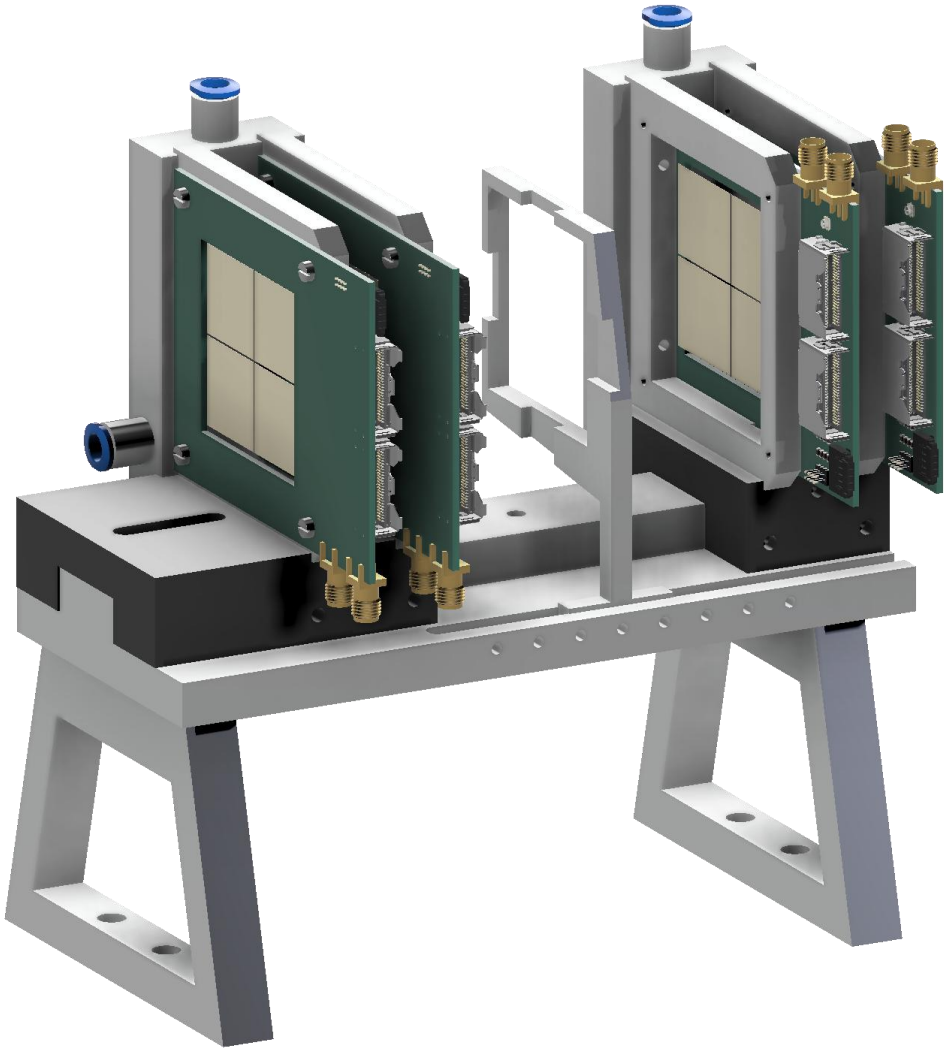

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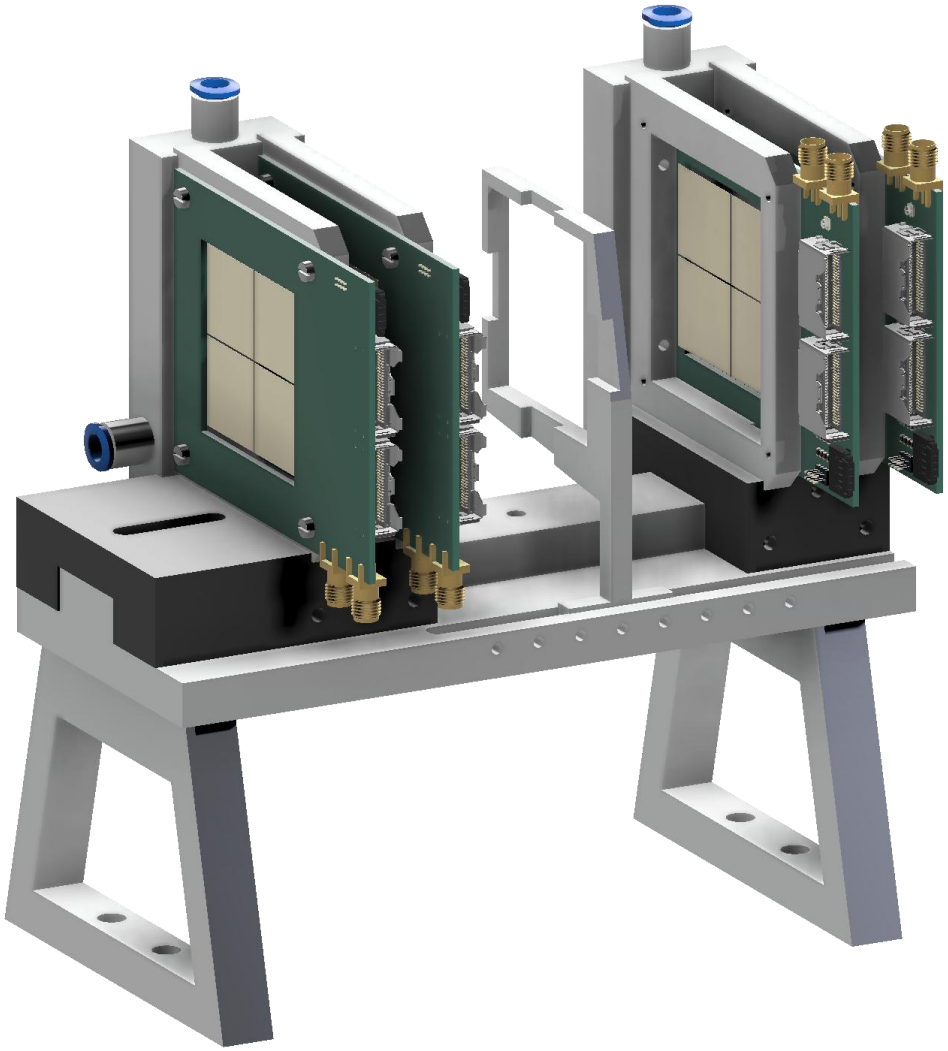

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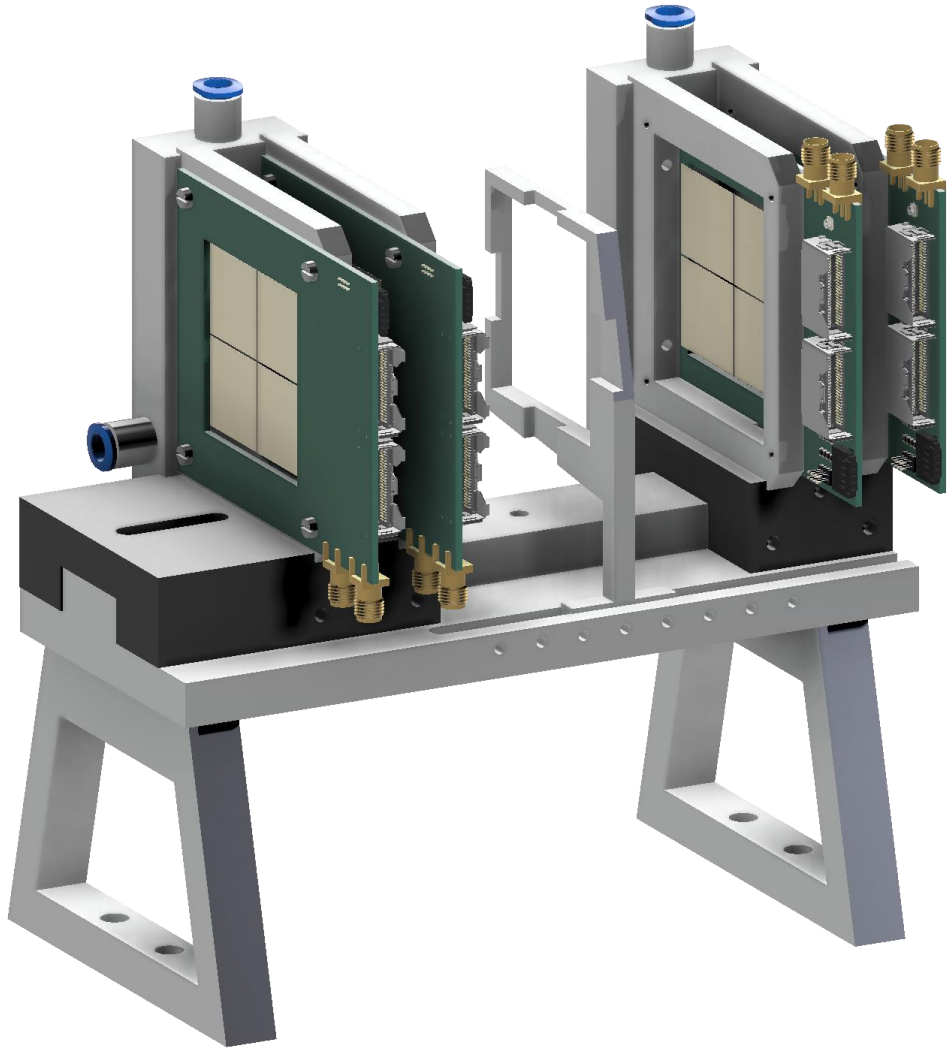
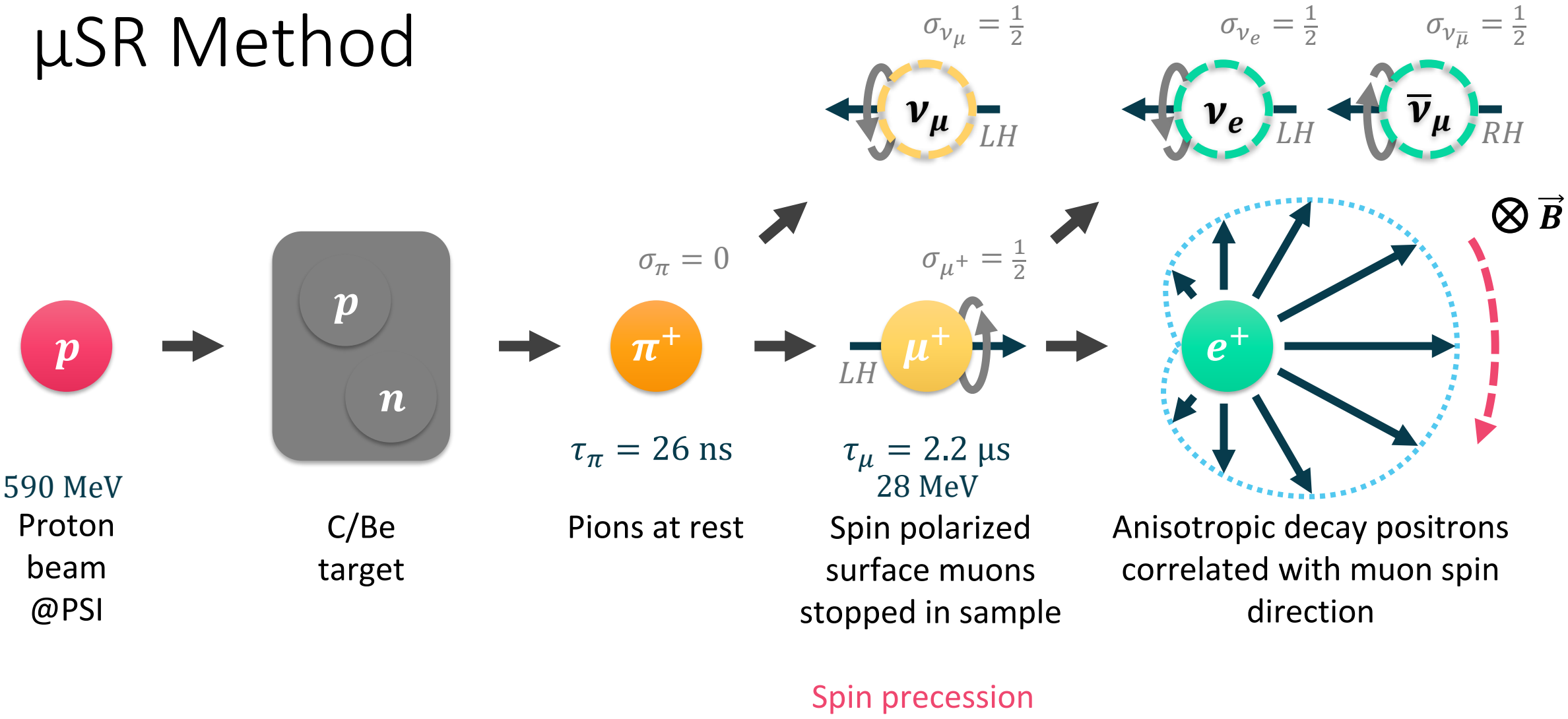
- ☐ Operation in Vacuum with Cryostat



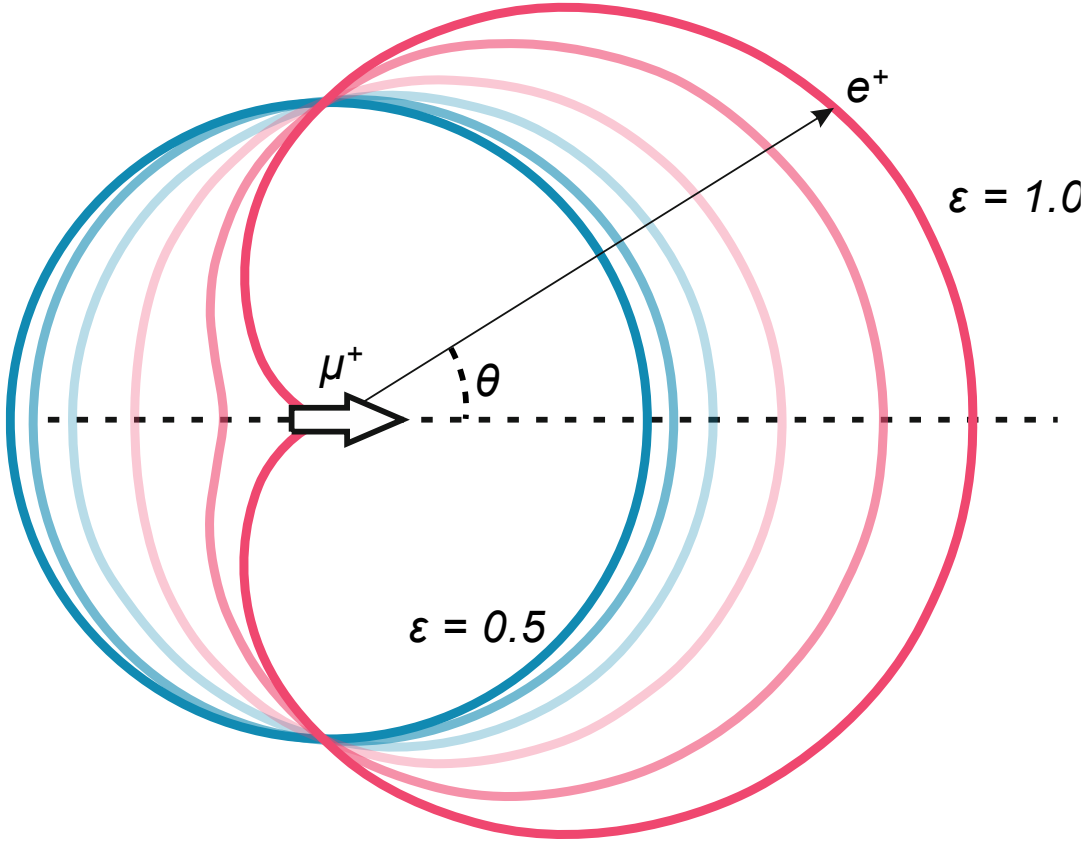
Thanks!

Backup

μSR Method


$\sigma_{\nu_\mu} = \frac{1}{2}$
ν_μ
LH
$\sigma_{\nu_e} = \frac{1}{2}$
ν_e
LH
$\sigma_{\nu_{\bar{\mu}}} = \frac{1}{2}$
$\bar{\nu}_\mu$
RH
p
p
n
$\sigma_\pi = 0$
π^+
$\tau_\pi = 26$ ns
$\sigma_{\mu^+} = \frac{1}{2}$
LH
μ^+
$\tau_\mu = 2.2$ μs
28 MeV
e^+
$\otimes \vec{B}$
590 MeV
Proton beam @PSI
C/Be target
Pions at rest
Spin polarized surface muons stopped in sample
Anisotropic decay positrons correlated with muon spin direction
Spin precession

Asymmetry



Current Generation

Scintillator-based Detector

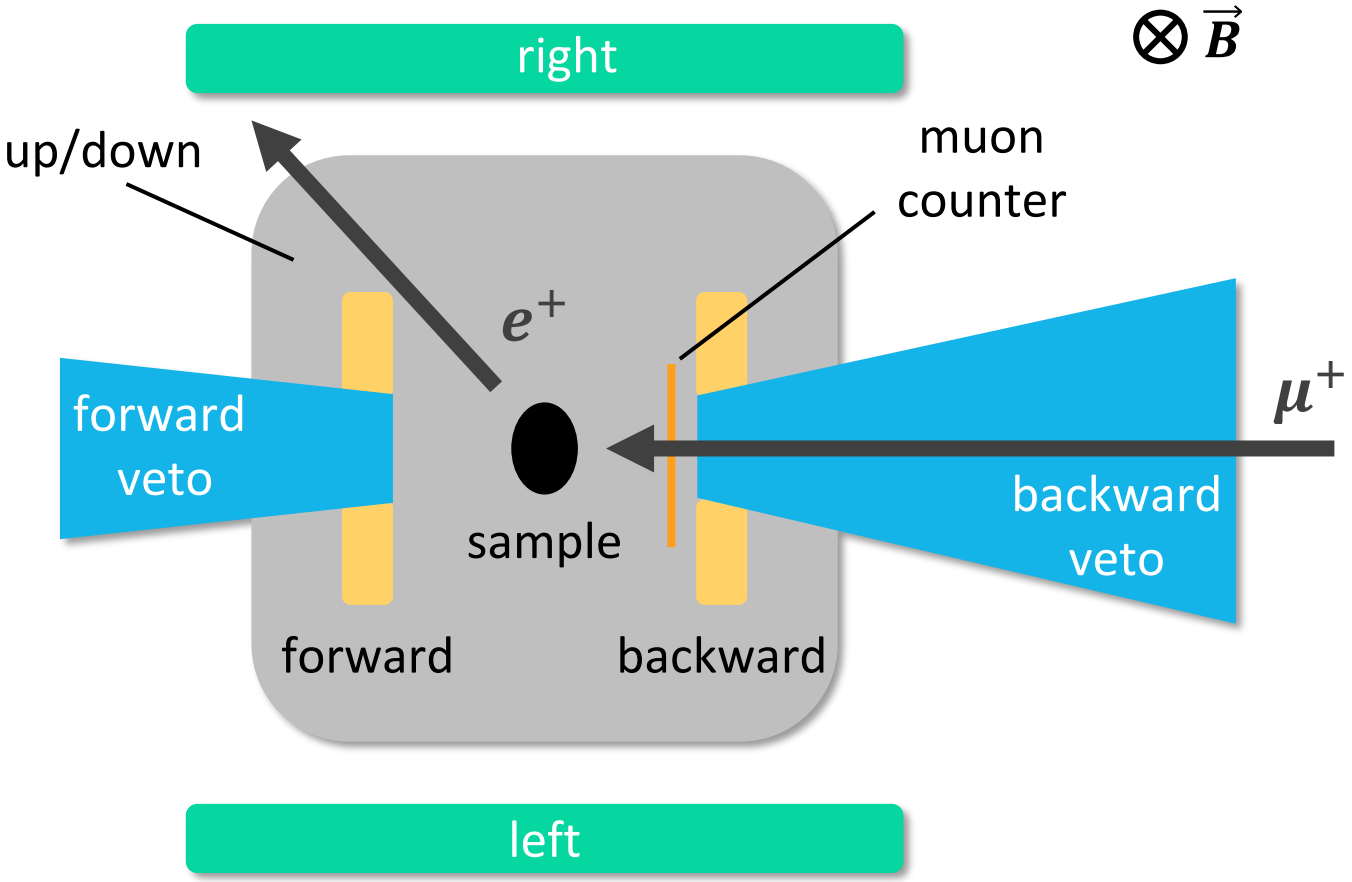
top view

Measure:

- Time of Arrival of μ^+ and e^+
- Temporal asymmetry between forward and backward signals

Limitations:

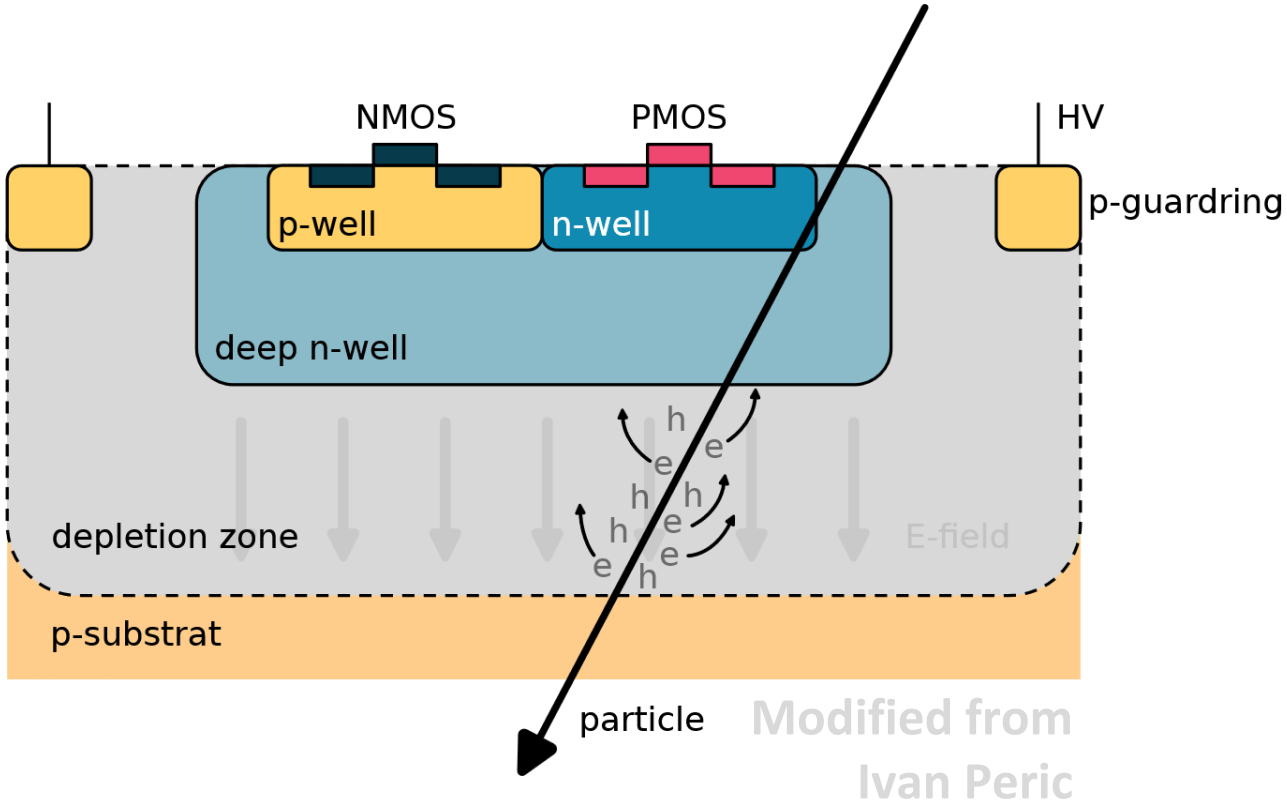
- No positional information of muon
- Rate limitation
  - Maximal 1 muon at a time
  - Limited observation time
    ⇨ 40 kHz (18 kHz acceptance)



Adapted from: General Purpose Surface-Muon Instrument (GPS). User Guide.

HV-MAPS

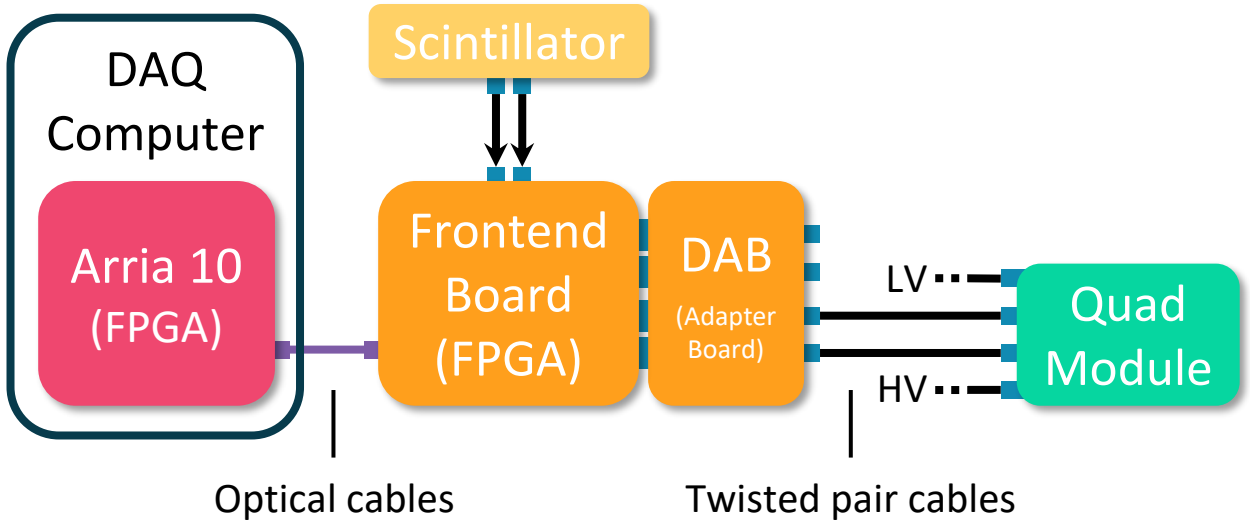
- High-Voltage Monolithic Active Pixel Sensor

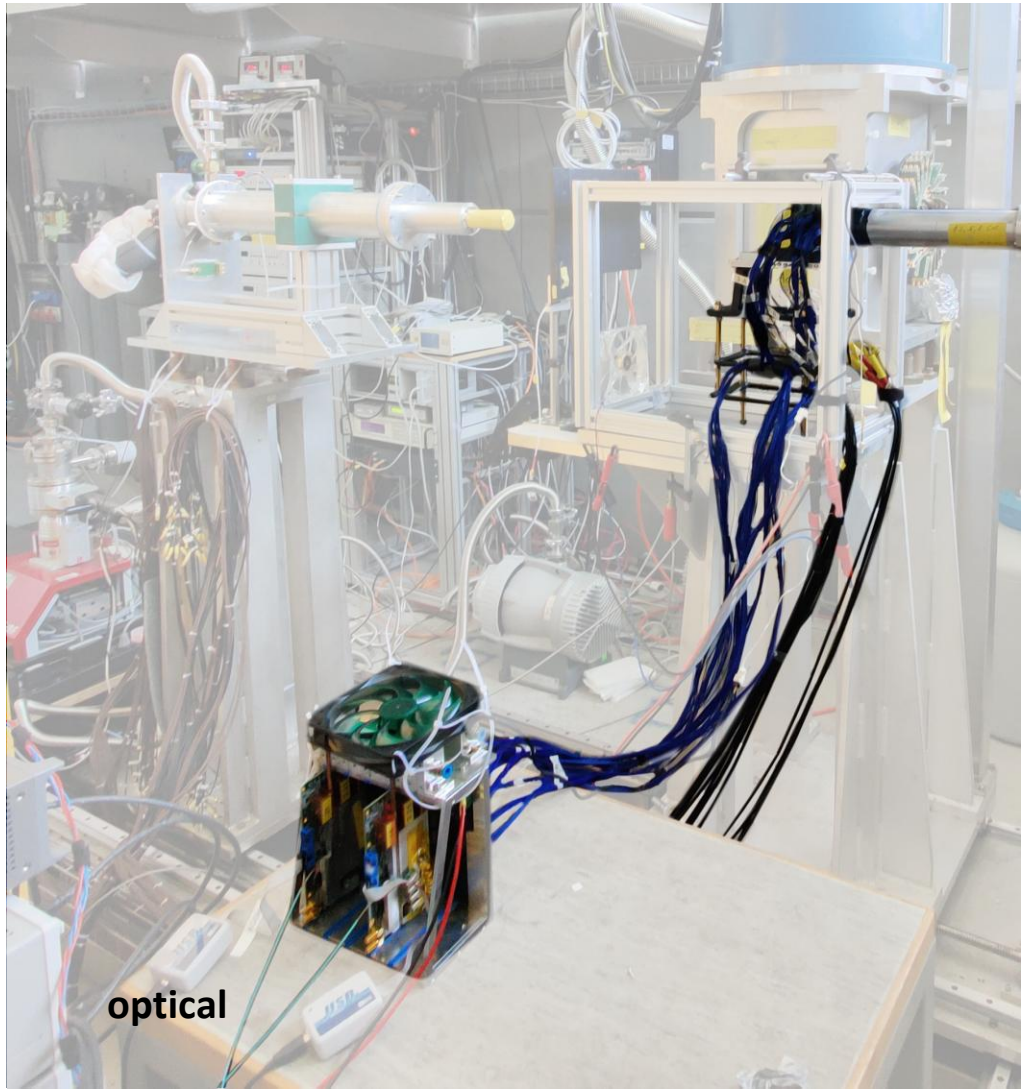


μSR Setup

DAQ

- 3 data-links per sensor $\times$ 1.25 Gbps
- Mu3e soft- and hardware
- Light sensitive sensors





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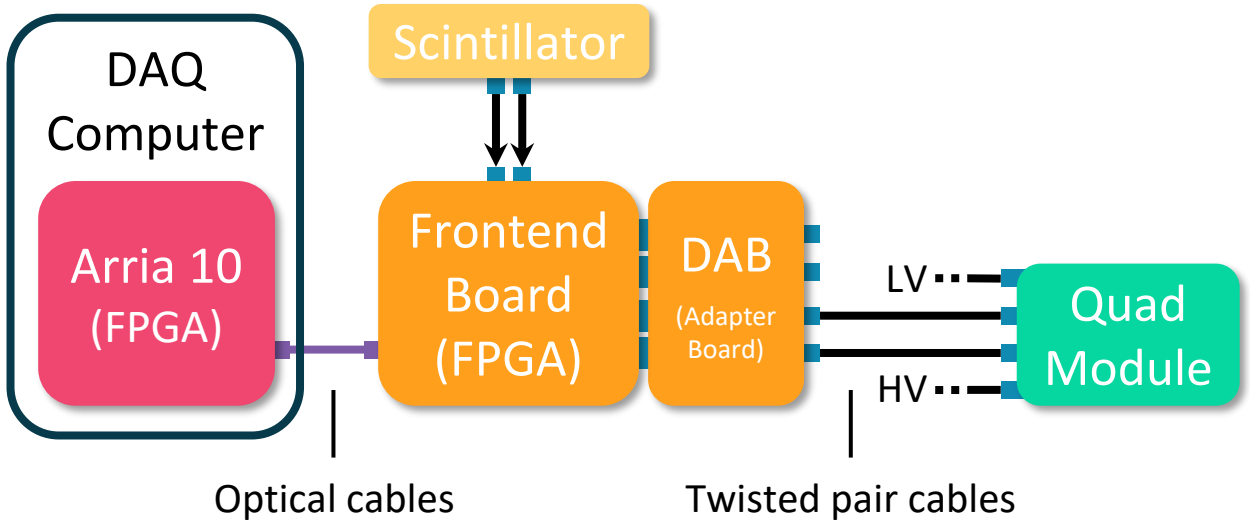

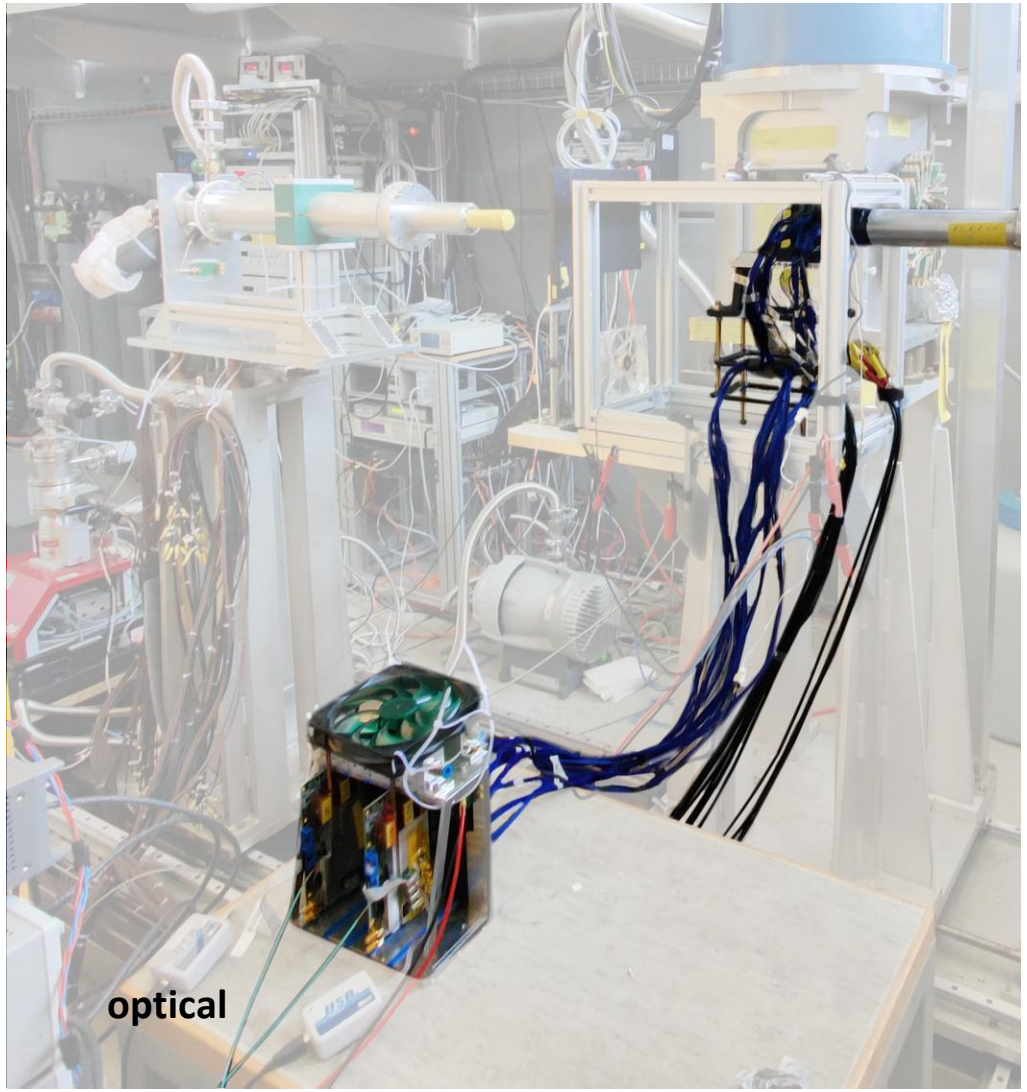

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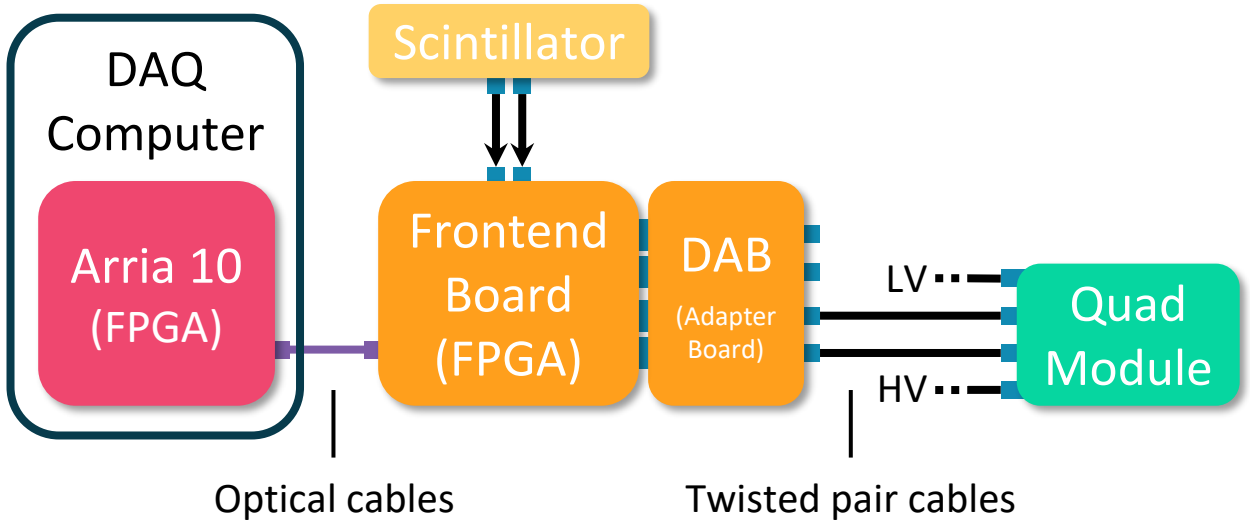
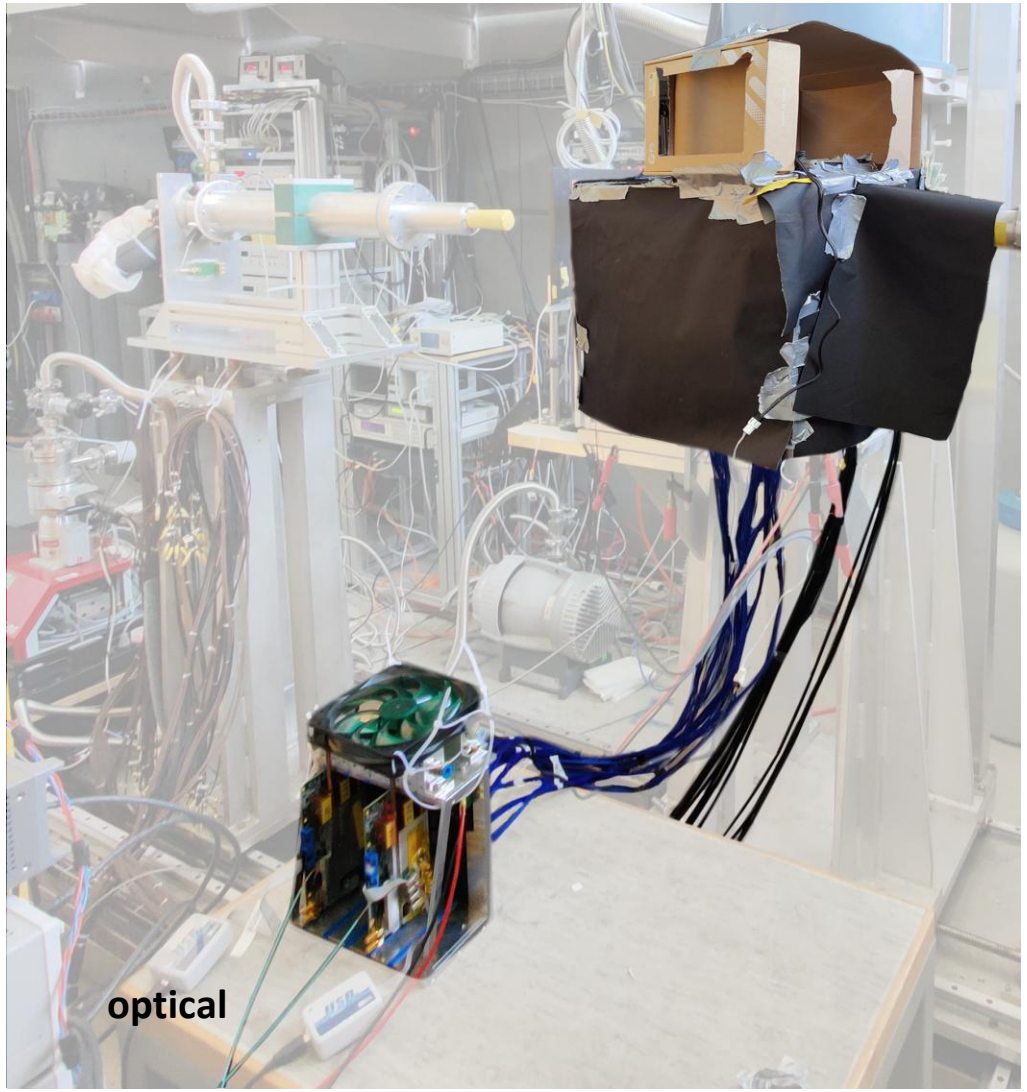
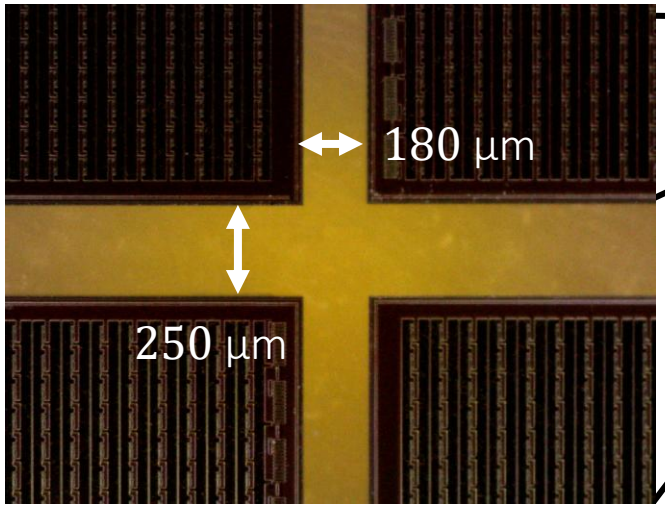


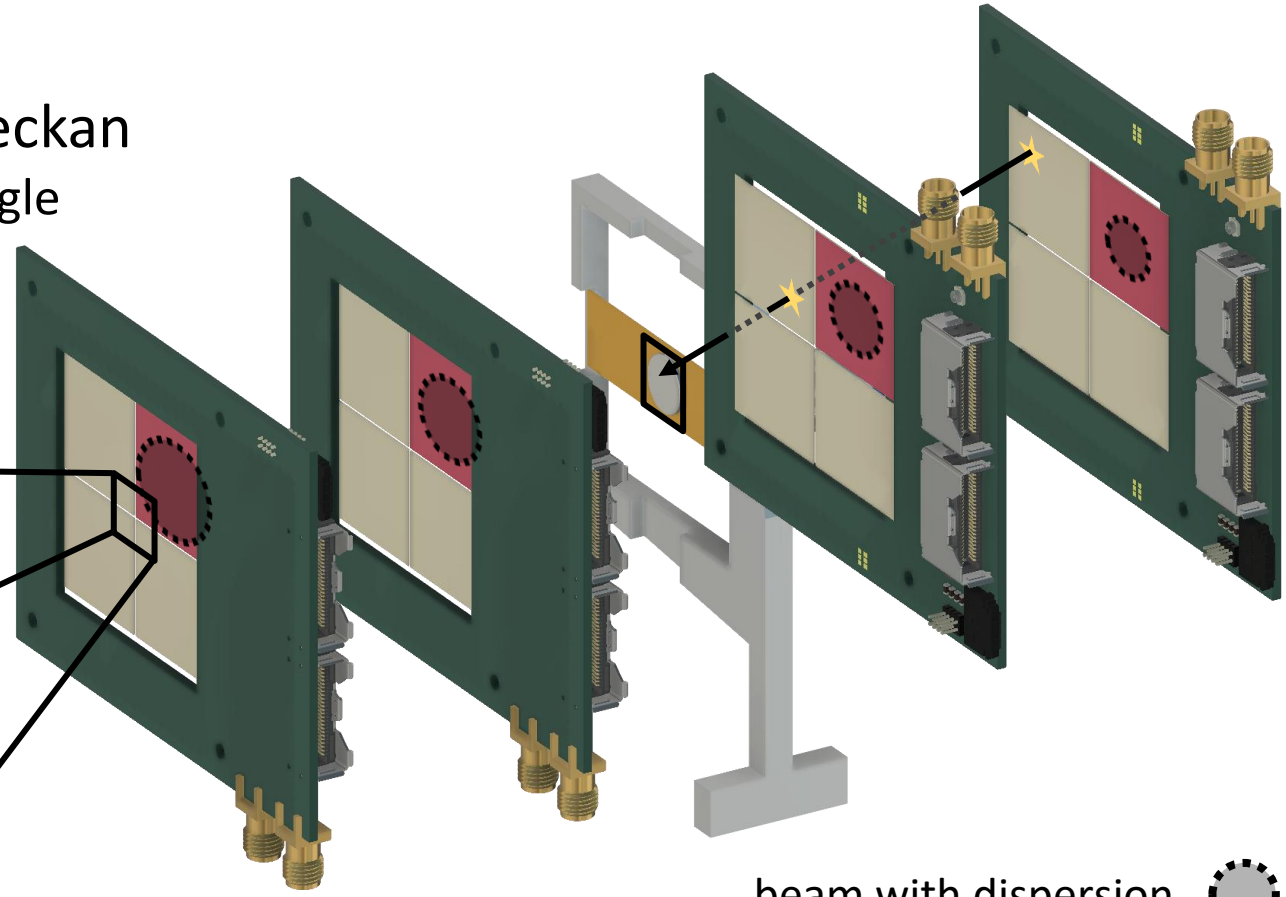


μSR Setup

Tracking

- Tracklet matching with Corryvreckan
  - ⇨ Cuts: spatial, temporal, charge, angle
- Manufacturing discrepancies
  - ⇨ Software alignment (difficult)





beam with dispersion

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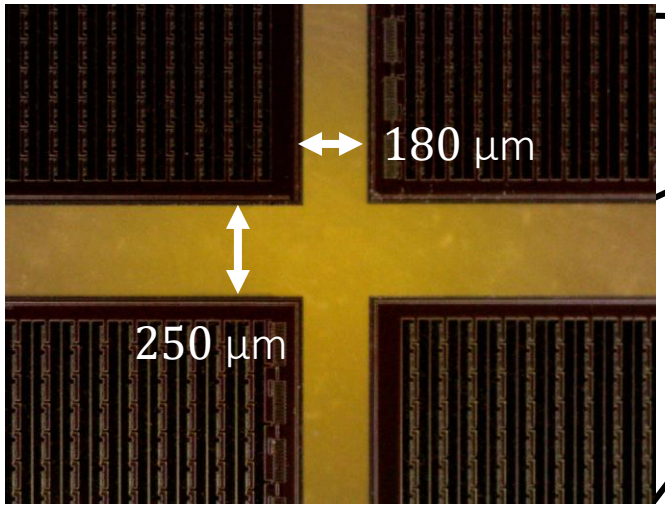

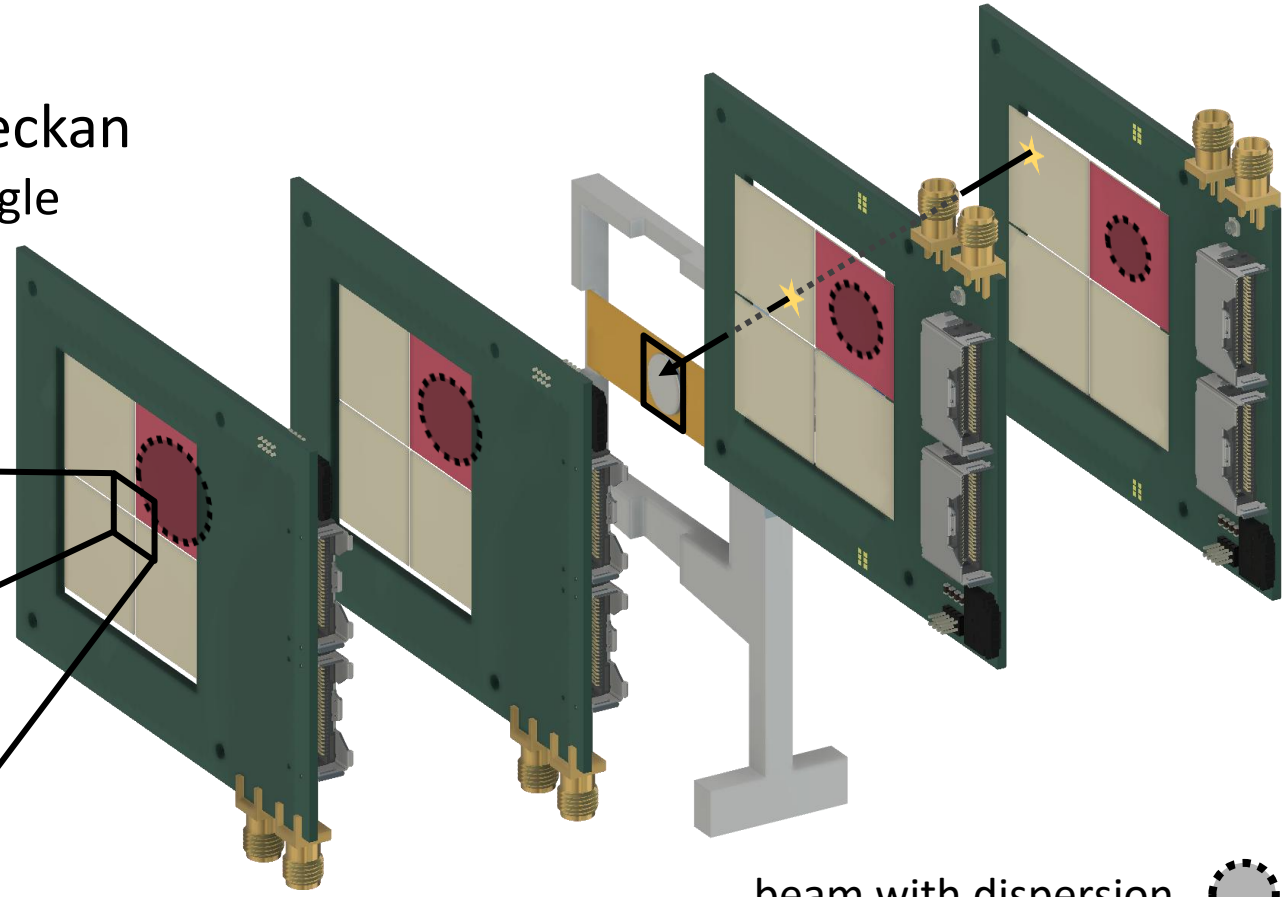

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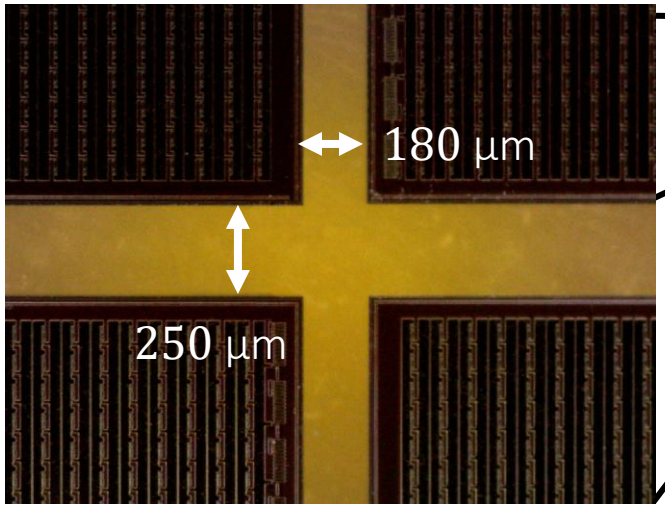

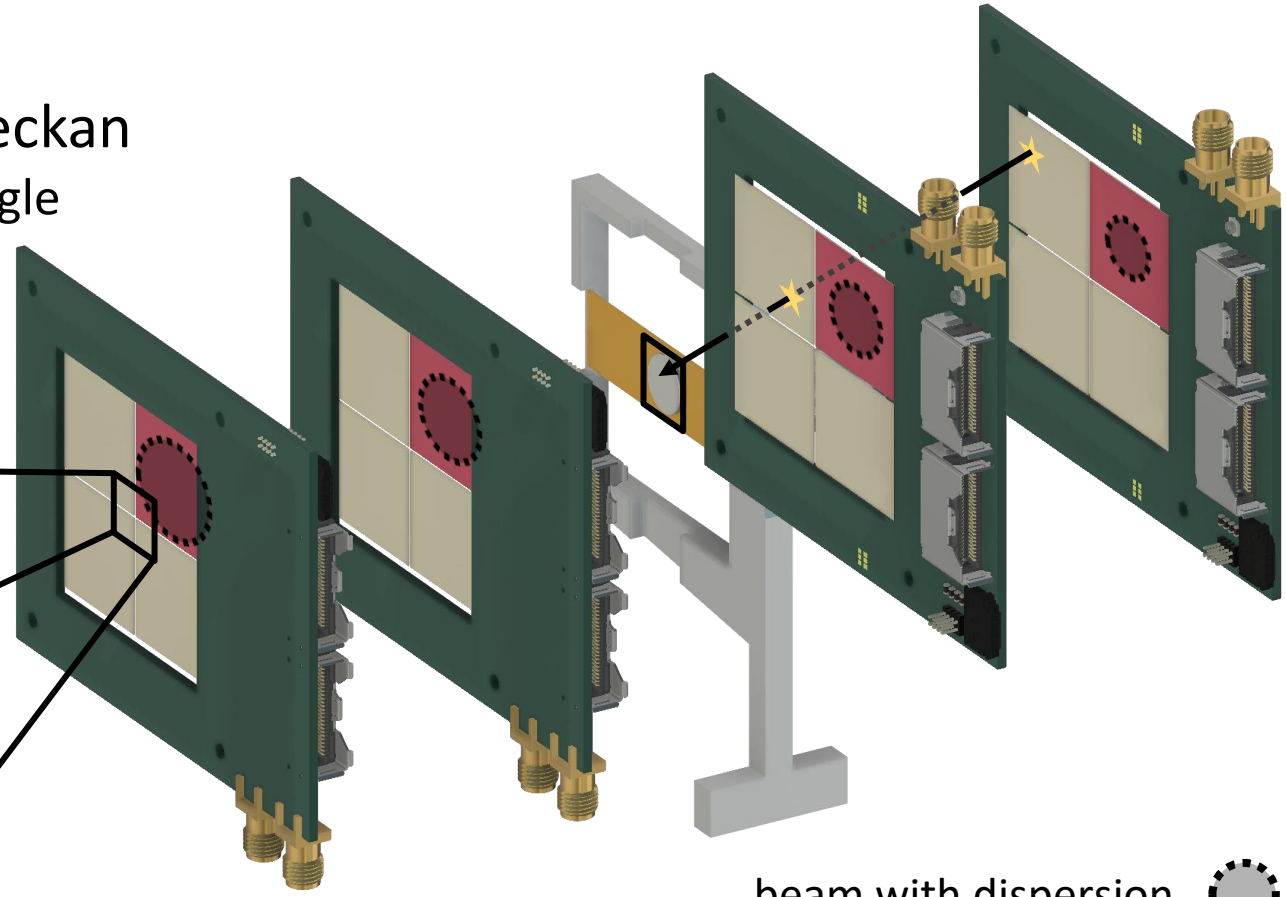

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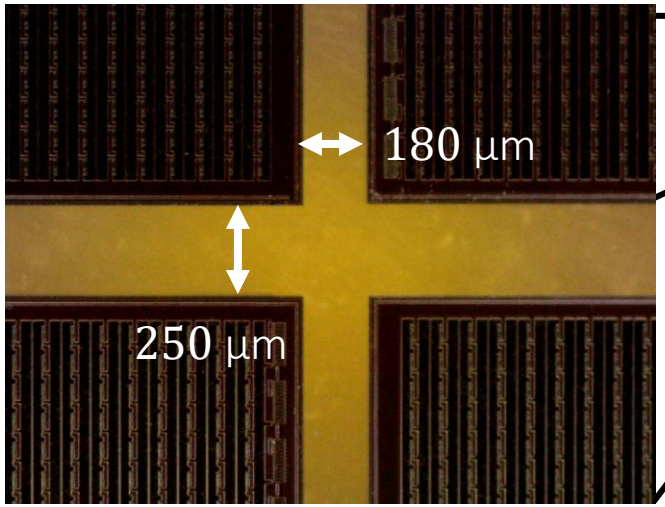
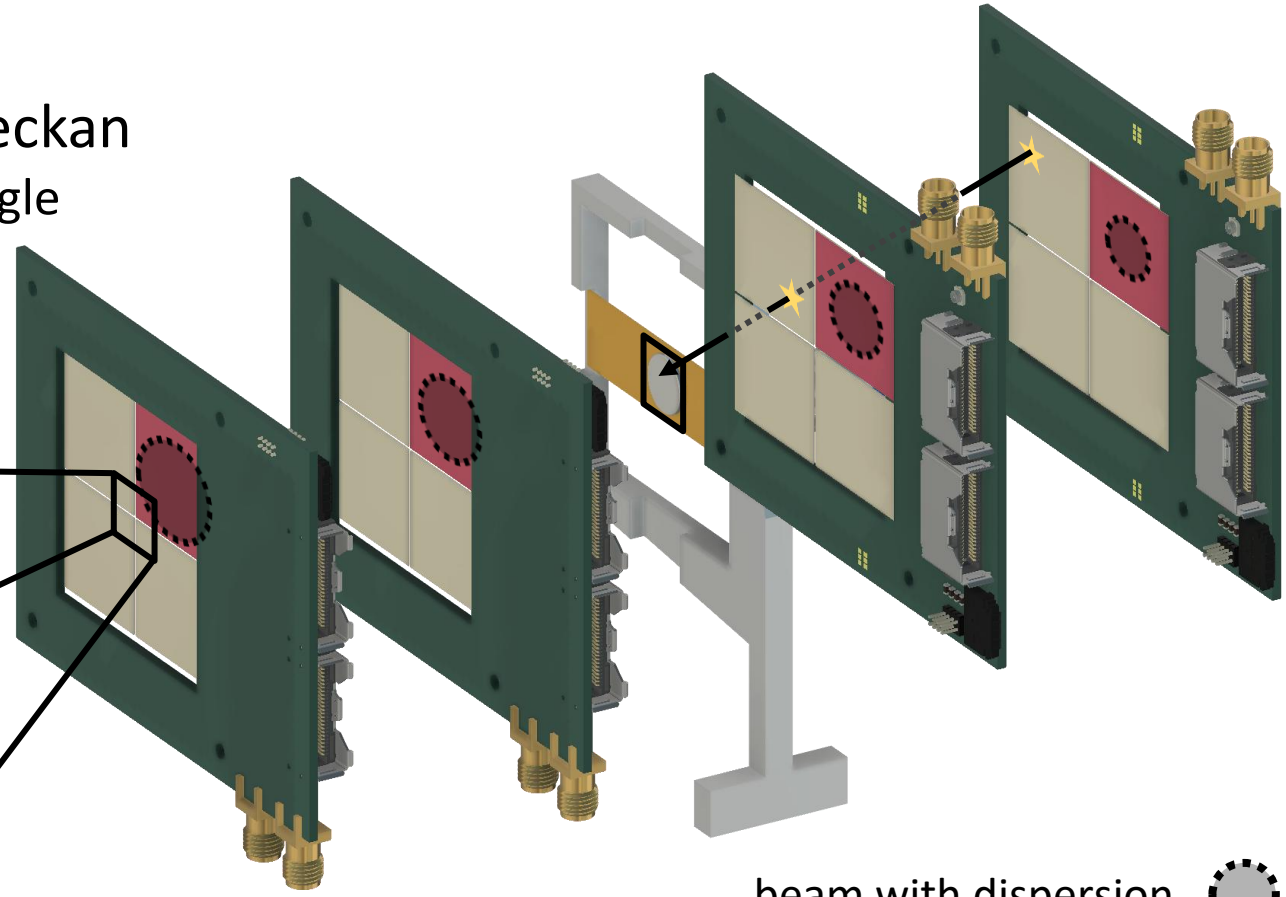
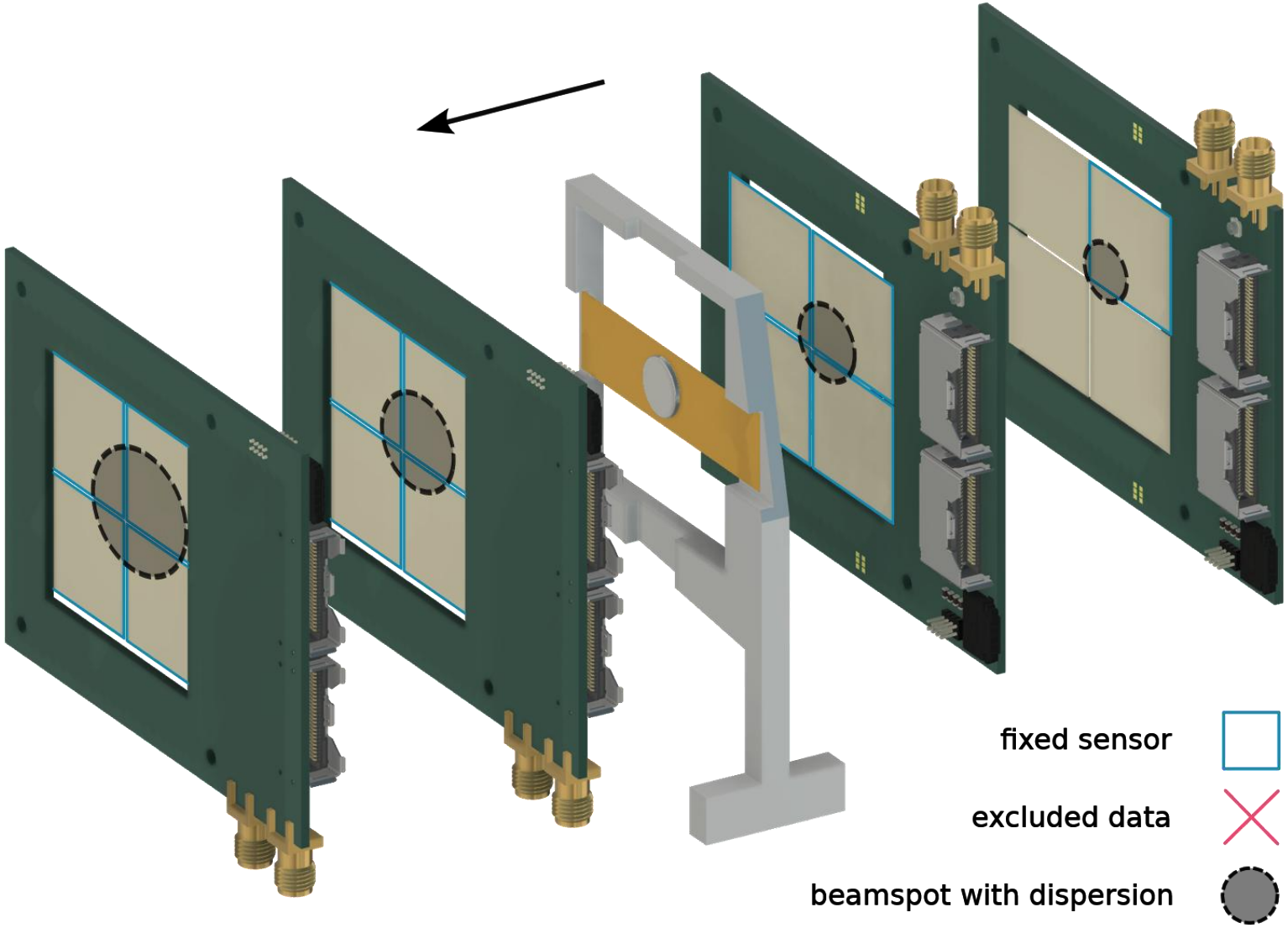




beam with dispersion

Analysis

Alignment