MuPix (Quad) Beam Telescope

PSI General Beam Profile Monitor Kick-off

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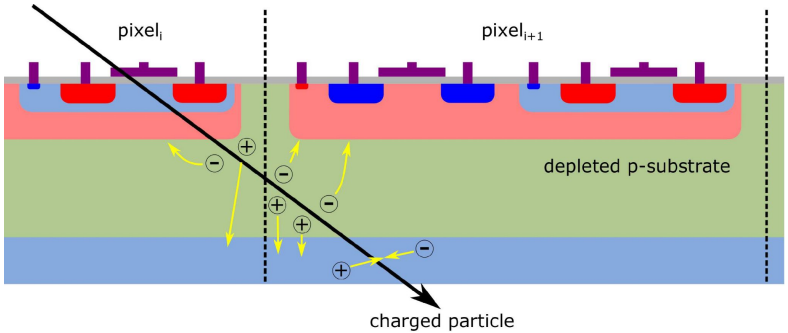
MuPix chips

High-Voltage Monolithic Active Pixel Sensor (HV-MAPS)

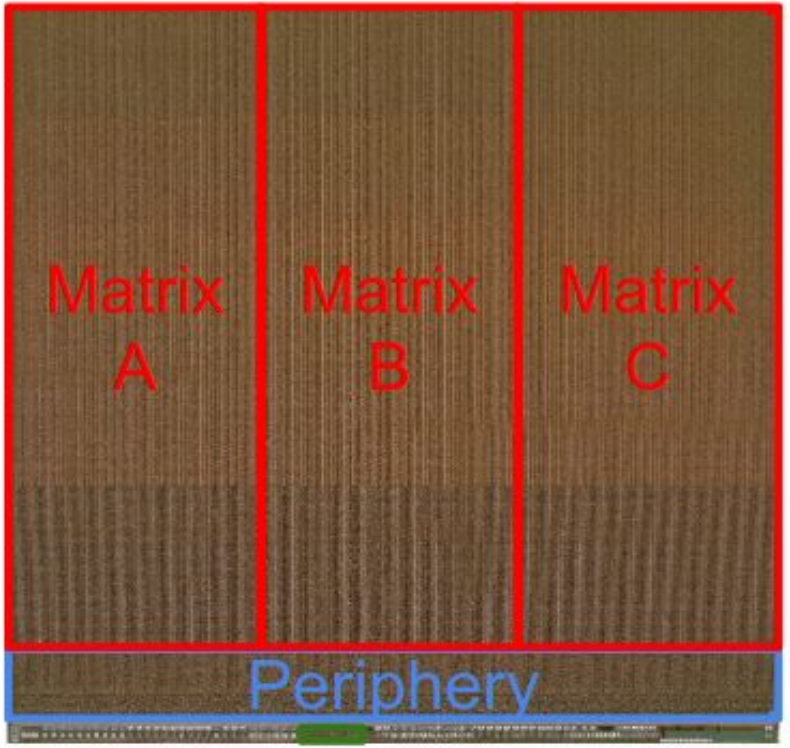
- Combine particle detection & readout in one entity
- Digitalization & zero suppression on chip
- Thin (≥ 50 µm)
- Fast charge collection via drift
  - Deep n-well as diode
  - Substrate biased by HV
- Particle identification via Time-over-Threshold (ToT)



MuPix11

Chip characteristics

Sensor size	[mm²]	20.66 x 23.18
Pixel size	[µm²]	80 x 80
Pixel matrix		256 x 250
Thickness	[µm]	50 & 70
Substrate	[Ωcm]	80 & 370
Data link		3 + 1 (MUX)
Data speed	[Gbit/s]	1.25
Time resolution		< 20 ns
Hit detection efficiency		> 99 %



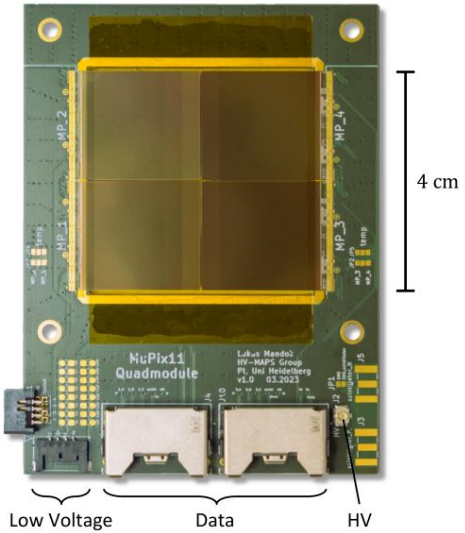
MuPix - Key characterisitics

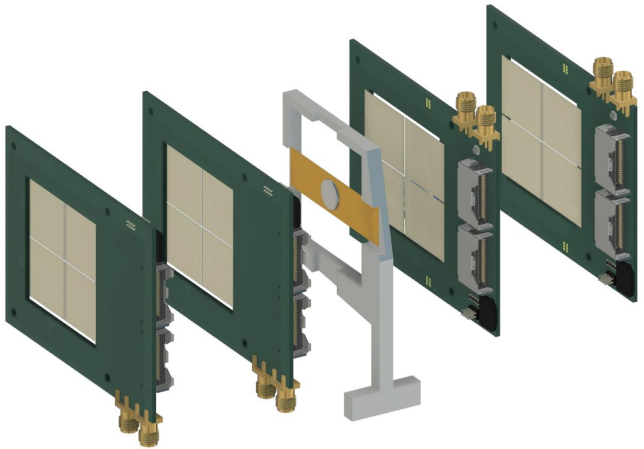
- Minimal material budget ✅
  - Low momentum particles → multiple scattering dominates
  - Requires ultra-thin sensors and support structures
- High particle rates ✅
  - Good time resolution (~ ns) ⏳ ← Even faster pixels would enhance performance
  - High granularity to resolve hit ambiguities
- Spatial precision ✅
  - 80 µm x 80 µm pixels
- Continuous, triggerless readout ✅
  - Handles continuous muon beams
  - No need for external triggers

Quad detector

Multi-purpose pixel telescope

- PCB carries 2x2 MuPix11 chips → “Quad module”
- Minimal integration
  - LV, HV, and data cables
- 2x upstream layers
  - Muon tracking + positron tracking
- 2x downstream layers
  - Muon veto (no track) + positron tracking
- Thermal coupling to cooling block
  - Operation in vacuum chamber

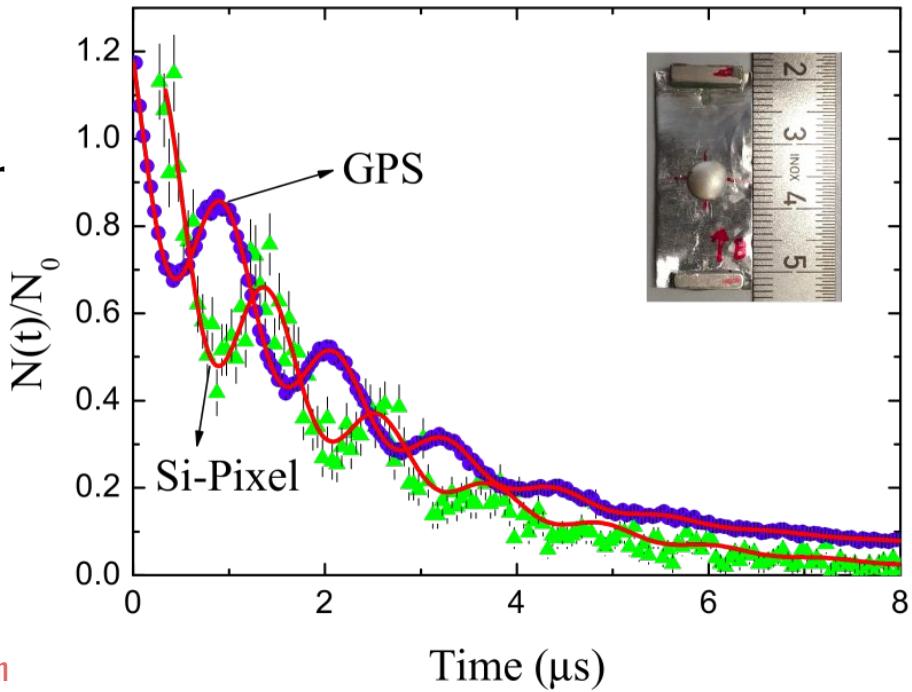




Quad detector - μSR results

Basic proof-of-concept

- Aluminium disk with permanent magnet
- Comparison measurement with GPS detector (standard μSR detector at PSI)
  - Compatible signal in seconds for vx-μSR vs minutes for GPS
  - Reduced background



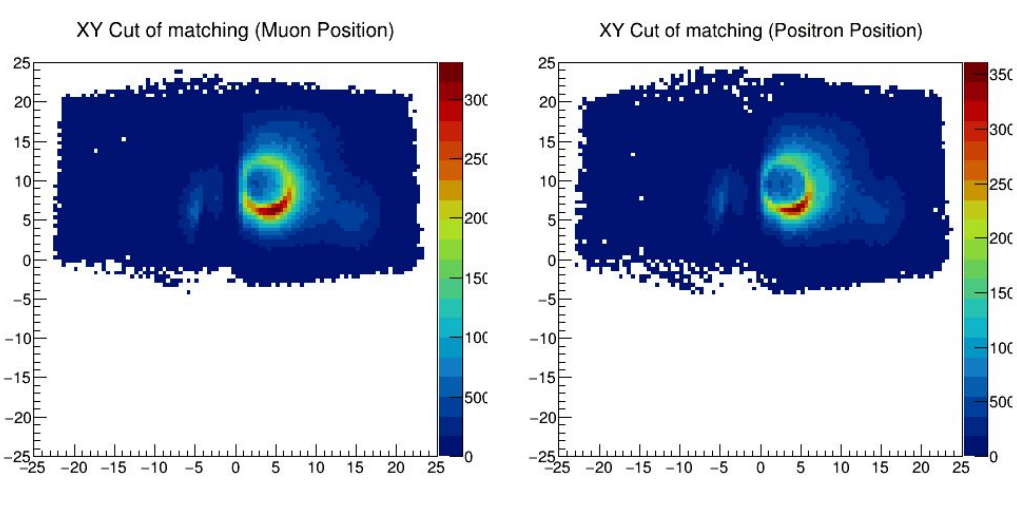
Signal (transfer Field):

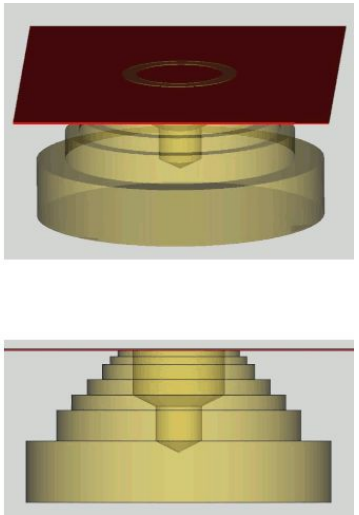
$$N(t) = B_0 + N_0 e^{-t/\tau}(1 + A_0 e^{-\lambda t}\cos(\omega t+\varphi))$$

Background Muon decay Time evolution of spin polarization

Quad detector - μSR results

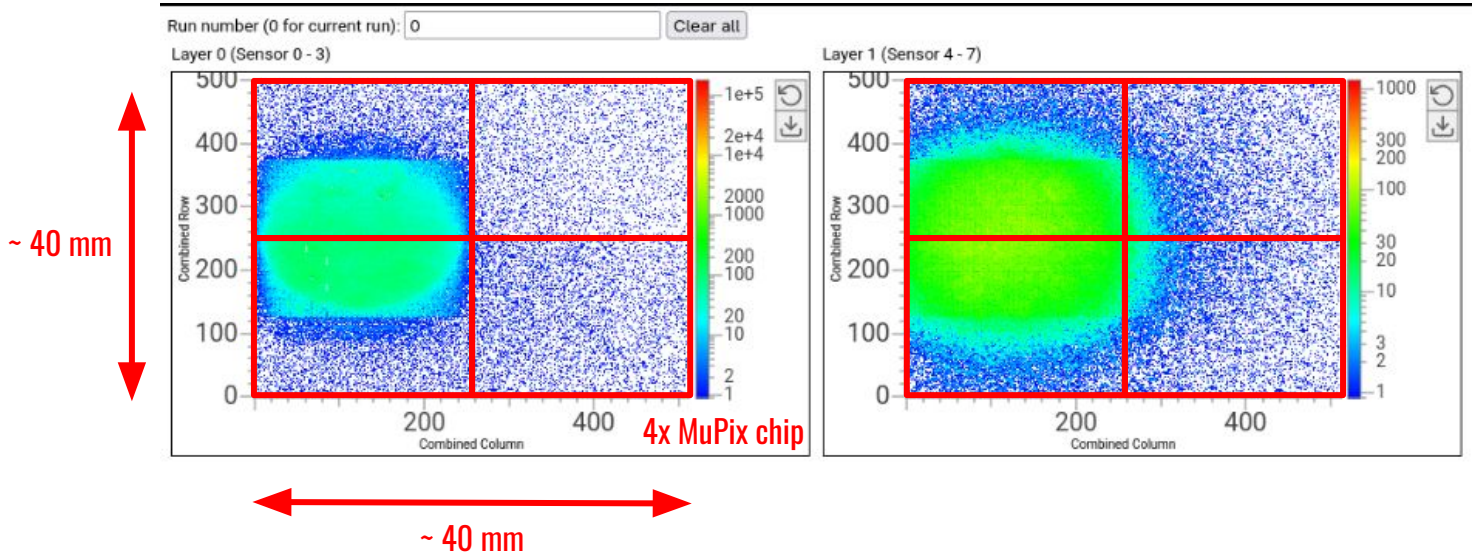
- 2-layer tracking of incoming muons/outgoing positrons
- “Tomography” of samples





Quad detector - µSR results

Hit maps - beam profile



Readout

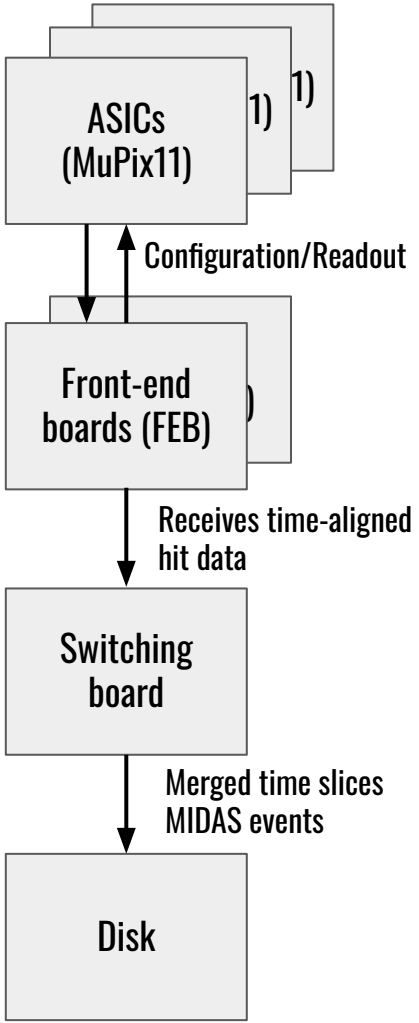
- FEBs aggregate data from multiple MuPix (MuTrigs for Scintillators)
- No trigger, time-stamped hits in streaming DAQ
- Hits are zero-suppressed
- Merging data based on time slices from multiple FEBs

MIDAS Event structure

- Event Header
- MIDAS banks (detector-specific)

Data Offline Analysis

- Event Loader in Corryvreckan (test beam data reconstruction framework)



Readout

MIDAS event structure

- Multiple banks from detectors in 1 event
  - Needed for logger efficiency
  - DS00, PH00, TH00
  - DS01, PH01, TH01
  - …
  - Debugging banks, Pixel hit banks, scintillator hit banks
- Pixel hit:
  - Sensor ID, column x row address of hit
  - Hit time (8ns base)
  - Time over Threshold (ToT) → Limited particle ID possible

PHIT	Pixel hit		
	Variable size, 64 bit per hit		
0	Hit	UINT64	Bits 63-62: are always 0 Bits 61-48: are 14 bits global sensor ID Bits 47-40: are 8 bit column Bits 39-32: are 8 bit row Bits 31-27: ToT Bits 26-0: Hit time

THIT	Scintillating tile hits		
	Variable size, 64 bit per hit		
0	Hit	UINT64	Bits 63-61: are always 0 Bits 60-53: are global ASIC ID Bits 52-48: are global Channel ID Bits 47-41: Reserved Bits 40-32: E-T (Short hit: 0x0 and 0x1ff for the energy flag) Bits 31-8: Time in 8ns bins Bits 7-5: Time in 1.6 ns bins (remain from devision) Bits 4-0: Time in 50 ps bins

Bank structure of Mu3e, from Mu3e spec book

Quad use cases

1. **Beam Monitor:** 1x Pixel layer
    a. Divergence/phase space: 2x Pixel layers
2. **Minimum tracker:** 2x Pixel layers
3. **Testing setup for other monitors:** DUT in-between 2/3x Pixel layers
4. **Scattering studies:** Material between 2x Pixel layers Upstream + 2x Pixel layers Downstream
5. **μSR detector:** 2x Pixel layers Upstream + 2x Pixel layers Downstream

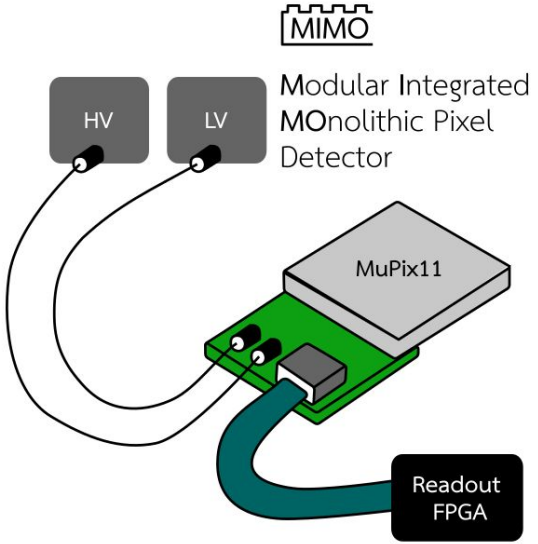
Current situation

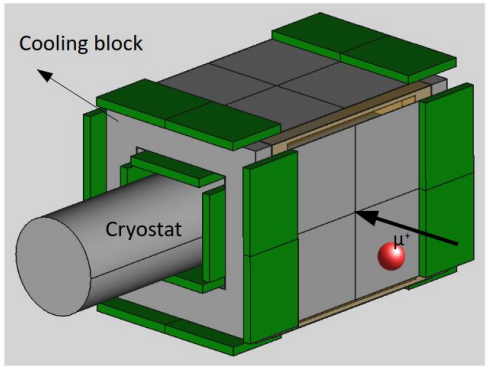
- µSR-Quad detector
  - 4 functional planes installed in vacuum chamber
  - Belongs to MuSiP group and is reserved for µSR beam times in 2026/27
- PIONEER quads
  - Optimized PCBs in production
    - Decoupling of HV domains between chips
    - Noise reduction
  - Min. 2 functional planes for the 2026 beam time (requested)

Future ideas

MIMO - Modular Integrated Monolithic (pixel) detector

- Standardized, modular platform fully integrated into MIDAS
- Basic building block for future PSI detectors
- Single monolithic chip on PCB
- Single, quad, (any) configurations possible
- Full (minimal) setup includes:
  - LV + HV supply
  - Generic (non-Mu3e) FPGA front-end board
  - Everything integrated into MIDAS
- Scintillator module as add-on





Challenges/Tasks

- Chip availability limited
  - Former MuPix vendor was bought by Bosch. They scrapped the 180 nm HV-CMOS process
  - Stock of MuPix11 chips fully reserved for Mu3e
  - Qualification of “new” vendor ongoing → AMS (used already for MuPix prototypes before 2019)
  - Adaptation not straightforward, e.g. different number of metal layer
  - Porting MuPix11 design → P2Pix → 1st submission in 2025 not successful ❌
- Mu3e FPGA board not commercially available
  - More simple & standard solution preferable
- Operation stability/user-friendliness
  - Operation routines still need some work
  - Simple interfaces for users to be developed

Synergies

- Compatible needs for Advanced Muon Spectroscopy Project (MuSiP) from Zaher Salman
  - Potential to share personpower on DAQ development
    - Front-end board firmware
    - MIDAS integration → user oriented
  - Potential common hardware development → PCBs
- Mu3e collaboration used the Quads for debugging
  - Simple system which helps to understand noise issue, readout limitation, etc.
  - Great interest in continuing the effort
- PIONEER beam monitor
  - Demand to understand the piE5 beam line
  - Using quads in 2026 for beam time (requested)
  - Long-term reliable beam monitor