High-performance software package for Timepix3 data acquisition, online analysis and automation

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On the menu today…

Background: Timepix3

About the software:

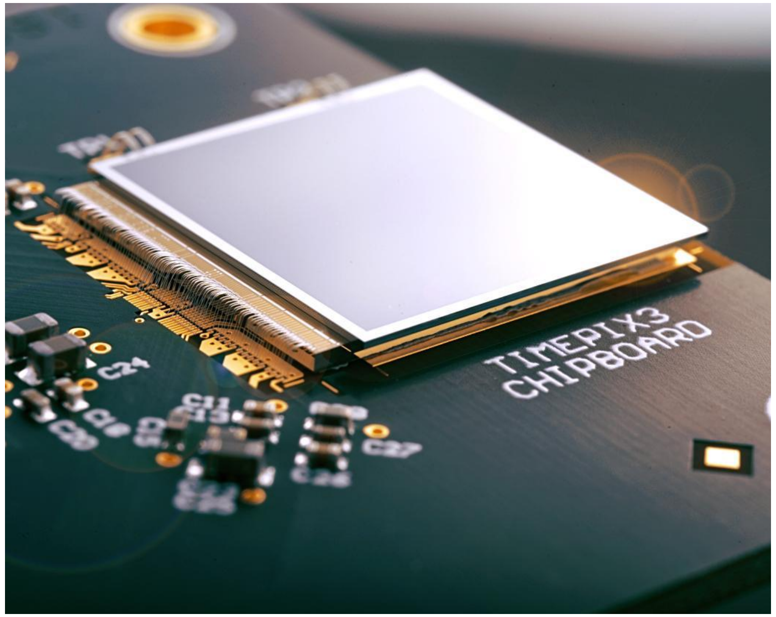
- What is it?
- What can it do? (…for you?)
- How does it work?
- How is it better than competition?

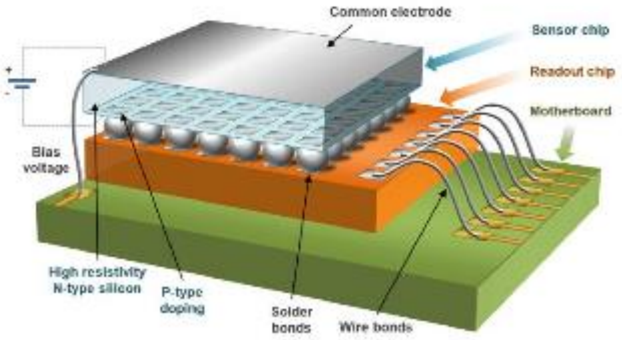
Example applications of Track Lab

Future development

Background: Timepix3

- Solid-state hybrid pixel detectors
  - 256 × 256 pixels, 55 µm pitch
  - Sensor materials: Si, GaAs, CdTe, …
  - Typical sensor thickness: 100 µm – 5 mm
- Can measure simultaneously:
  - Time over Threshold: calibrate to keV using XRF
  - Time of Arrival: 1.56 ns resolution
  - In data-driven mode: ‘zero’ dead time
  - In Z-axis: using charge carrier drift model (ToA)

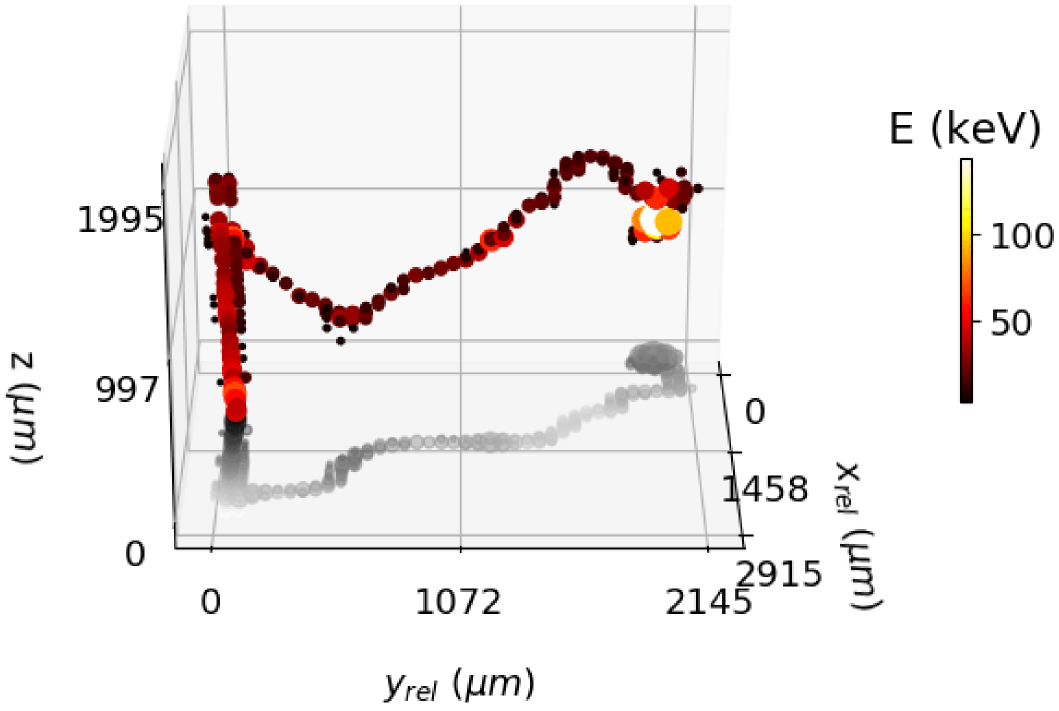


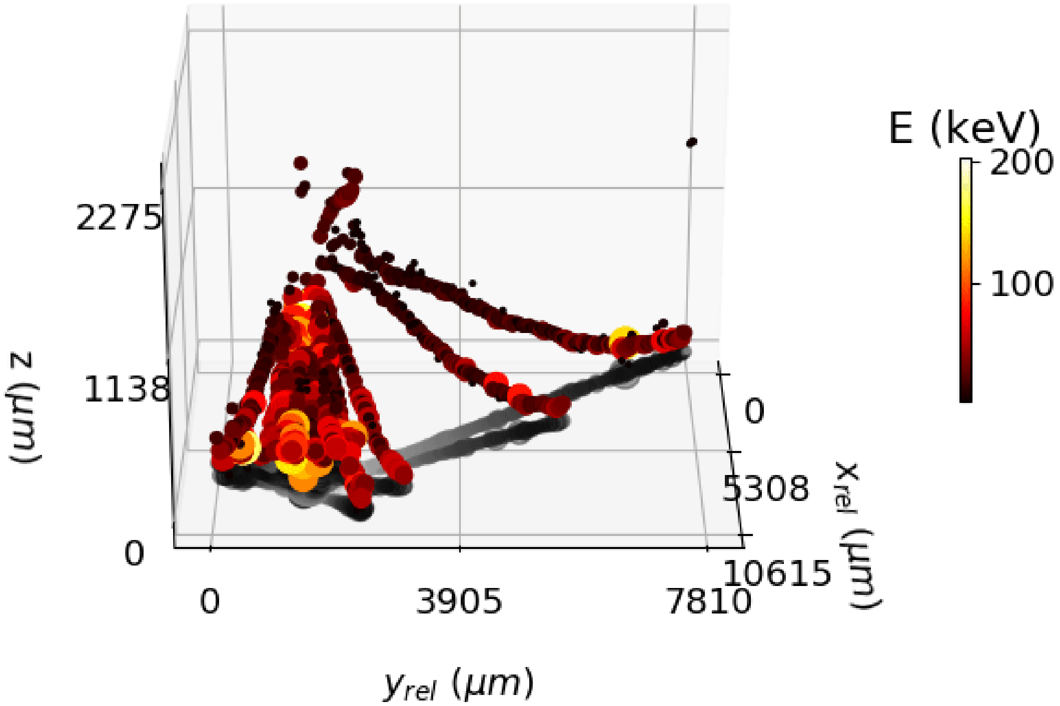


More information: Poikela, Timepix, et al. "Timepix3: a 65K channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout." *Journal of instrumentation* 9.05 (2014): C05013.

Background: Timepix3

- Z-coordinate reconstruction examples:

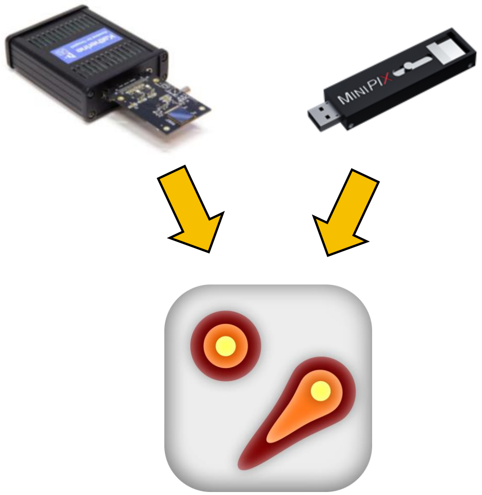




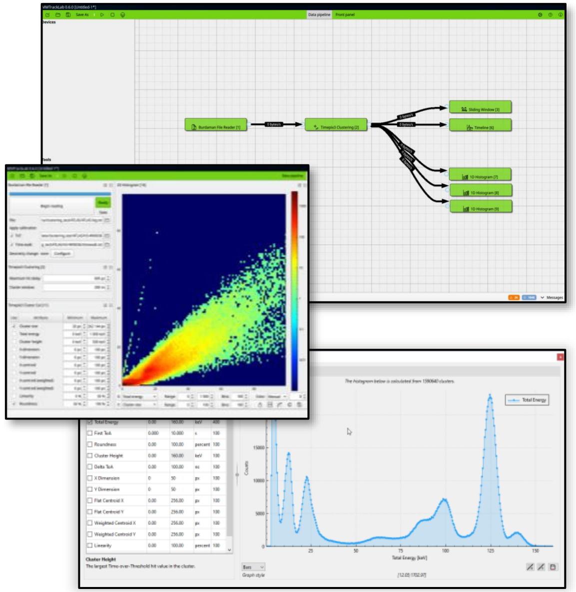
What is Track Lab?

- Data acquisition (DAQ) and analysis software
- Runs on all major platforms:
- Originally aimed at pixel detectors, now can do much more…
- Focus on:
  - High performance
  - Versatility and extendibility
  - Live feedback

What can Track Lab do?



Take data from detectors



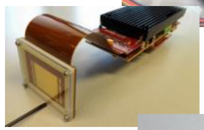
Run analysis in real-time

Automate repetitive tasks

Photo credit: University of West Bohemia, Advacam, Standa LTD, Amptek Inc., Universal Robots A/S

Data taking: device support





Readout	Sensor(s)	Connection
Katherine Gen1	1x Timepix3	1 Gbit Ethernet
	1x Timepix2	1 Gbit Ethernet
Katherine Gen2	8x Timepix3	1 Gbit Ethernet
		USB 3
		PCIe 3 x4
HardPix	1x Timepix3	USB 3
SPIDR4*	1x Timepix4	10 Gbit Ethernet
COMBO+Spectrig*	1x SiPM	USB 2
MicroDAQ	28x PMT	1 Gbit Ethernet

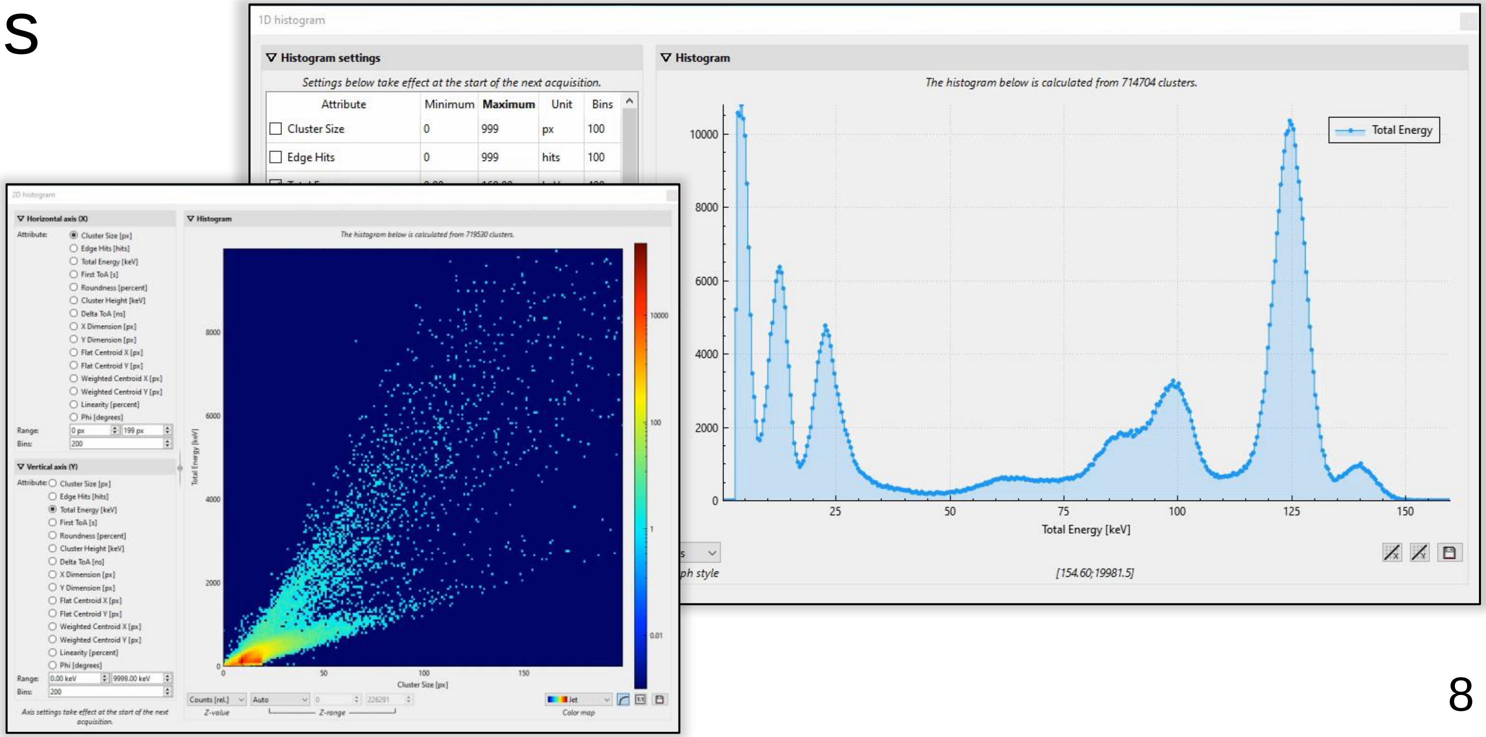
Readout	Sensor(s)	Conn.
Timepix2 Mini	1x Timepix2	USB 2
MiniPIX EDU	1x Timepix	USB 2
MiniPIX*	1x Timepix	USB 2
	1x Timepix2	USB 2
	1x Timepix3	USB 2
AdvaPIX*	1x Timepix	USB 3
	1x Timepix3	USB 3
WidePIX L*	10x Medipix3	1 Gb. E.



* experimental support / work in progress

Real-time analysis

- Application of geometry, ToT calibration, time-walk correction
- Clustering and coincidence analysis
- Cuts on cluster attributes
- Live 1D and 2D plots
- Possibility to combine above elements into arbitrary data pipeline



Automation options

In the physical world:

- Motorized stages (rotation, linear)
- 3D positioning arms
- X-ray tubes

UNIVERSAL ROBOTS

standa

AMPTEK

In software:

- Acquisition repetition
- Direct control from plug-ins (orchestration of multiple instruments)
- Scripting (experimental)

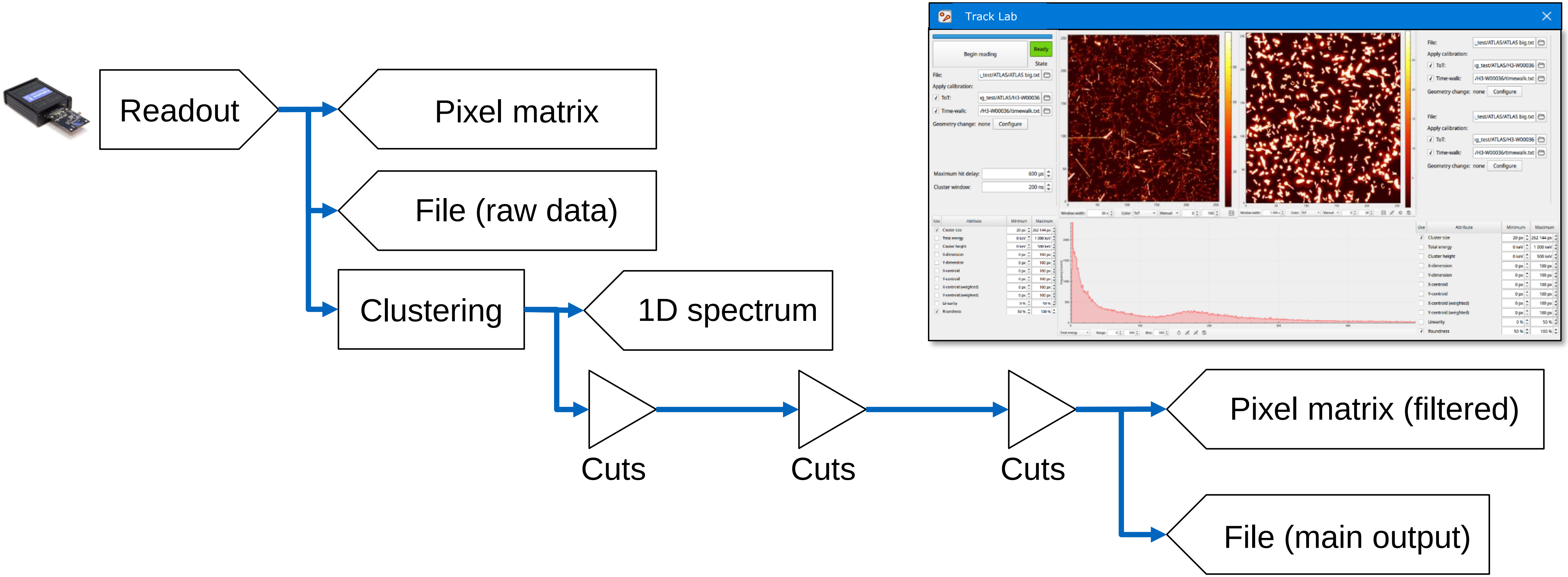
Photo and graphic credit: [Standa LTD](), [Amptek Inc.](), [Universal Robots A/S]()

How does Track Lab work?

Graphic credit: LEGO System A/S

How does Track Lab work?

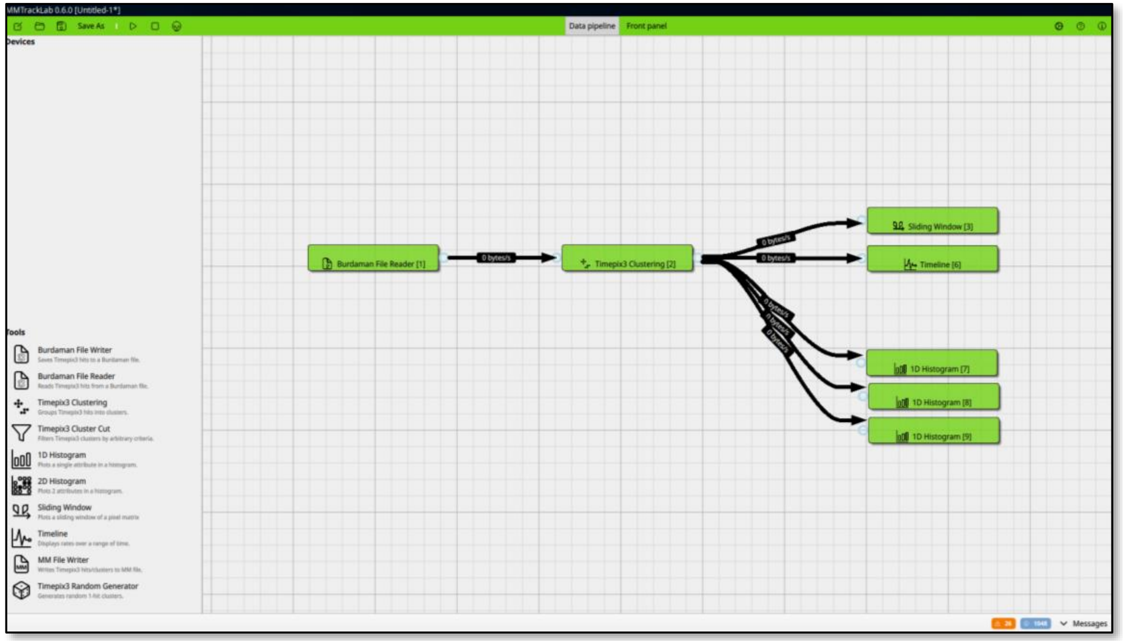
User builds data pipeline from many single-purpose elements.



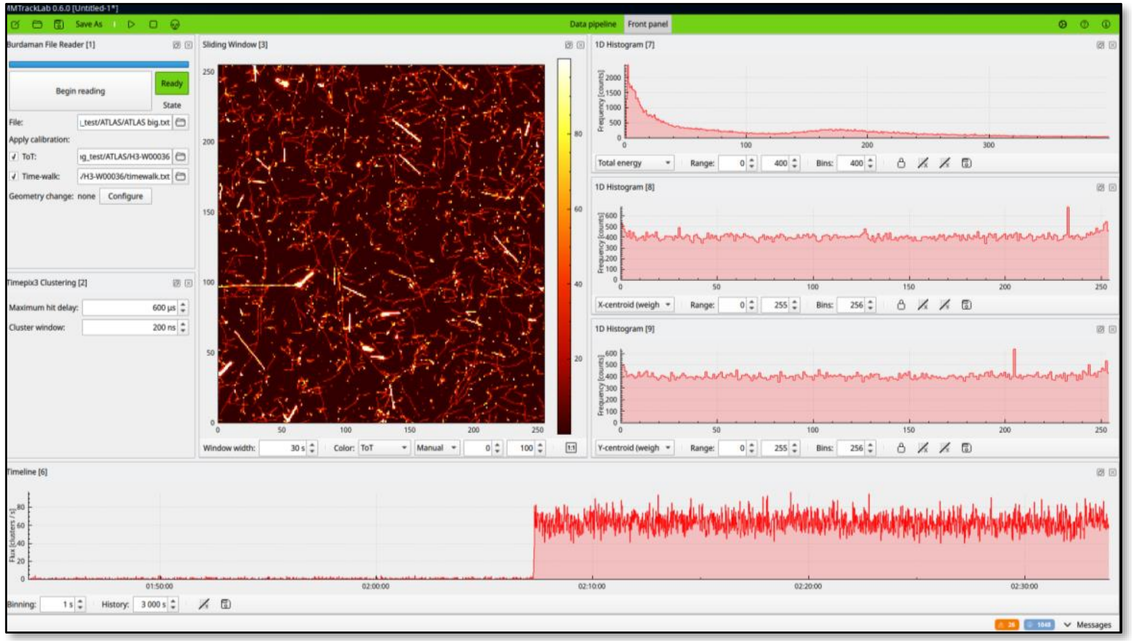
User interface

User builds data pipeline from many single-purpose elements.

Data diagram

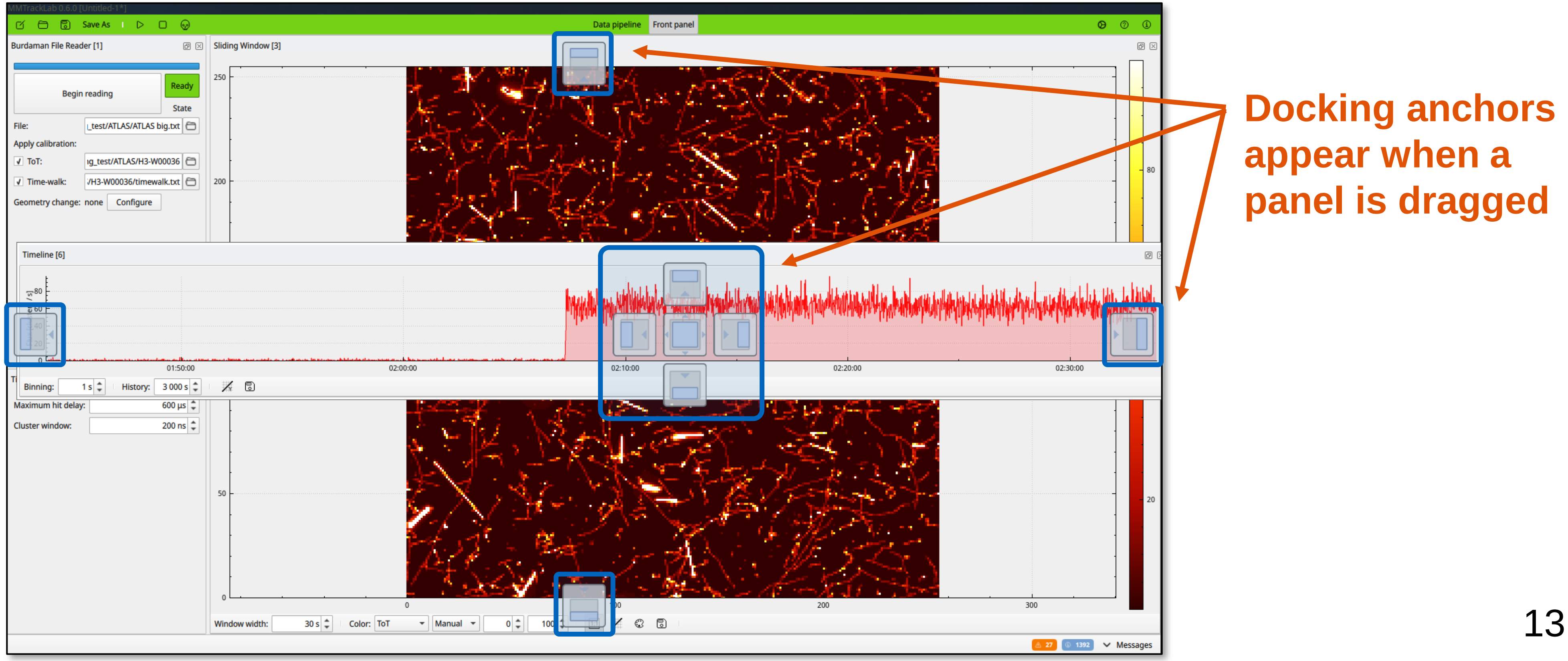


Front panel



User interface: extensibility

Panels can be detached, moved and docked into arbitrary grid layout by drag & dropping with mouse.



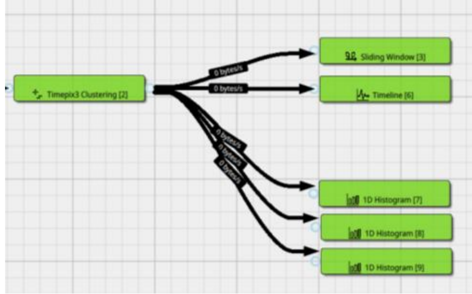
User interface: examples

Can be saved to & loaded from file

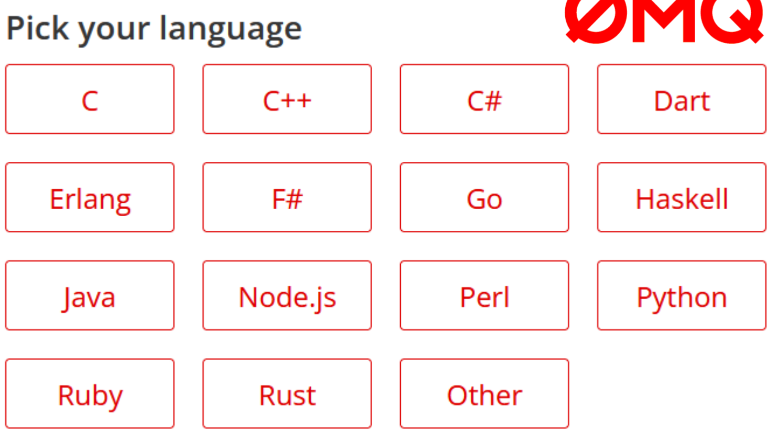
I made all these layouts by dragging panels around in less than 5 min…

High performance

- Entire software written in C++20
- Horizontal scalability: each node runs on a separate CPU thread, simultaneously with others.
- Data connections facilitated by ZeroMQ “sockets”.
  - Easy interoperability with other programs.
  - In-memory multiplexing at (nearly) no cost.
  - <u>Future:</u> real sockets, distribute over network
- File I/O facilitated by memory mapping.



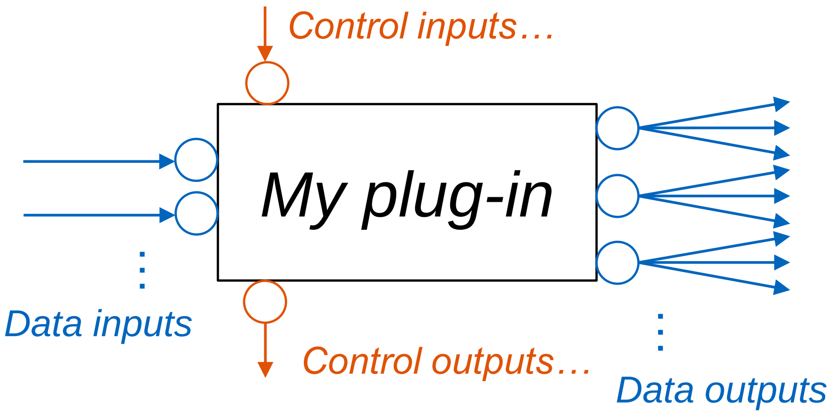
ØMQ



Graphic credit: [ZeroMQ]

Extendibility

- Anyone can make their own LEGO brick!
- We do this too: everything you saw implemented as plug-ins.
- API is well-defined, source code available to collaboration.
- More examples, consultations can be provided upon request.
- Requirements: C++20, Qt6 programming skills



+

Graphic credit: LEGO System A/S, The Qt Company

Example applications

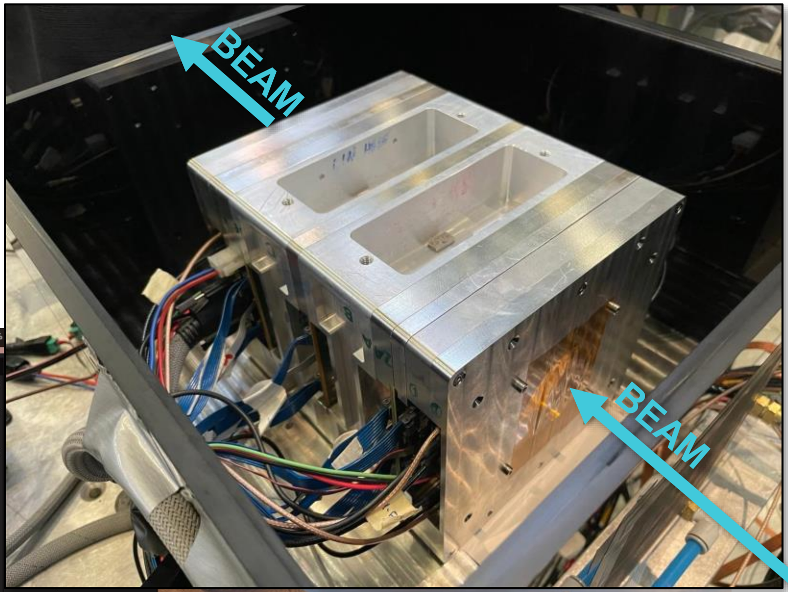
Example: PAN beam tests

(carried out in 2021-2022)

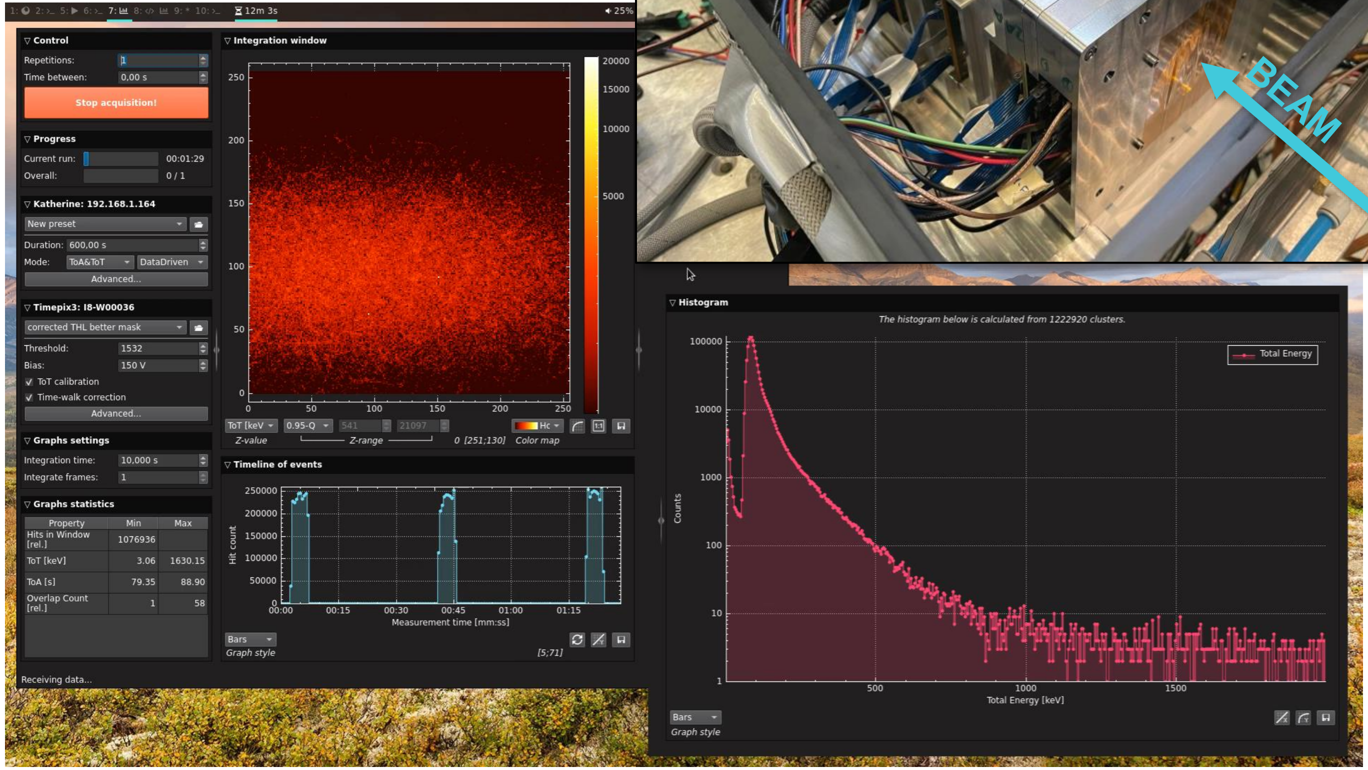
Penetrating Particle Analyzer

120 GeV/c hadron beam (90% pions) + setup:

- 2x Katherine Gen2 + 8x Timepix3 (2x Quad)
- 1x Standa rotation stage
- Trigger input (scintillator)
- Trigger out to other detectors



(video shows older UI version)



Software challenges:

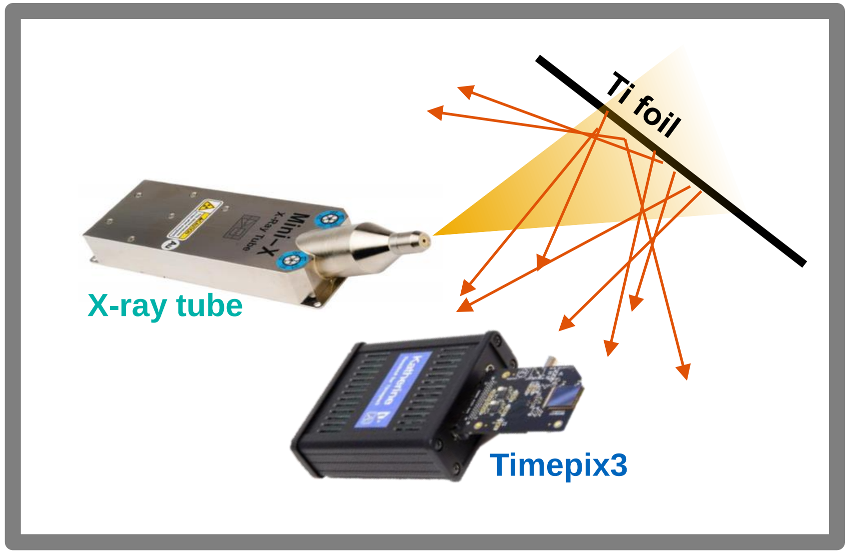
- Pulsed large data rates
- Live analysis (e.g. cluster centroids to align in beam)
- GPIO time signals (input timestamping, out pulse gen.)

Example: calibration with XRF

Our in-house method for calibrating ToT.

Setup:

- 1x Katherine Gen1 + 1x Timepix3 (varies)
- 1x Amptek Mini-X2 X-ray tube
- Set of foils (Ti, Cu, Zr,Cd)



Shielded enclosure with interlocks

Software challenges:

- Sustained large (but controllable) data rate → performance tuning
- Feedback: pulse X-ray & measure until enough clusters are collected
- Foil rotation using motorized carousel (WIP)

Photo credit: University of West Bohemia, Amptek Inc.

Examples: detector networks

ATLAS-Timepix3

- 28x Timepix3 (sandwiched in pairs)
- 4x Katherine Gen2 (2 PCIe, 2 Eth)
- 4x Katherine Gen1

Software challenges:

- Demand on fast I/O (SSD RAID)
- Directional event reconstruction
- Timestamping LHC orbit clock

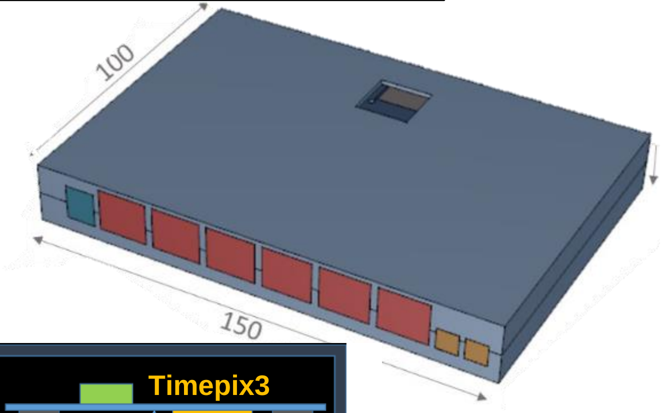
MoEDAL-Timepix3 (LHCb)

- 6x Timepix3 (sandwiched in pairs)
- 1x Katherine Gen2 (PCIe)

Software challenges:

- ML-powered anomaly detection

Single unit:



Profile:

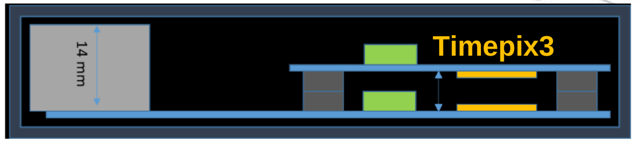
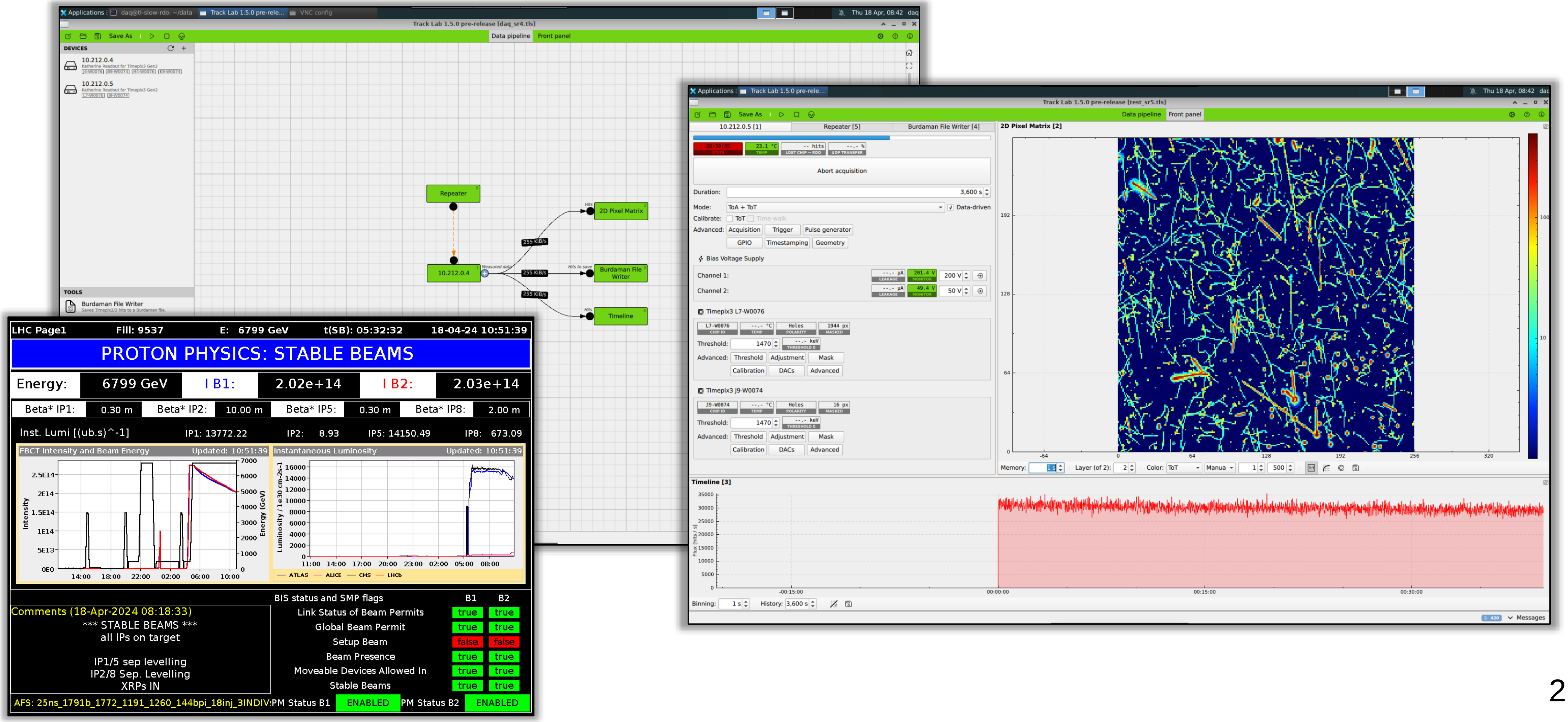


Photo credit: University of West Bohemia

Examples: detector networks



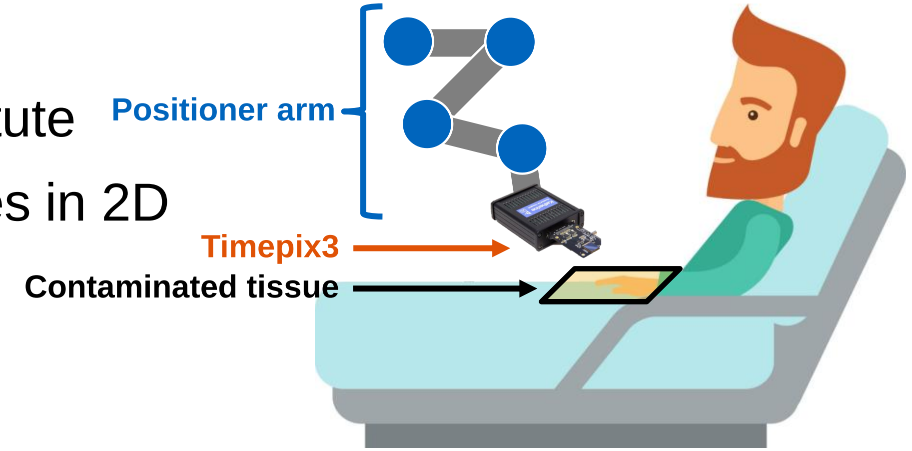
Example: tissue scanning

Collaboration with Czech National Radiation Protection Institute

Objective: map radioactive contamination of biological tissues in 2D

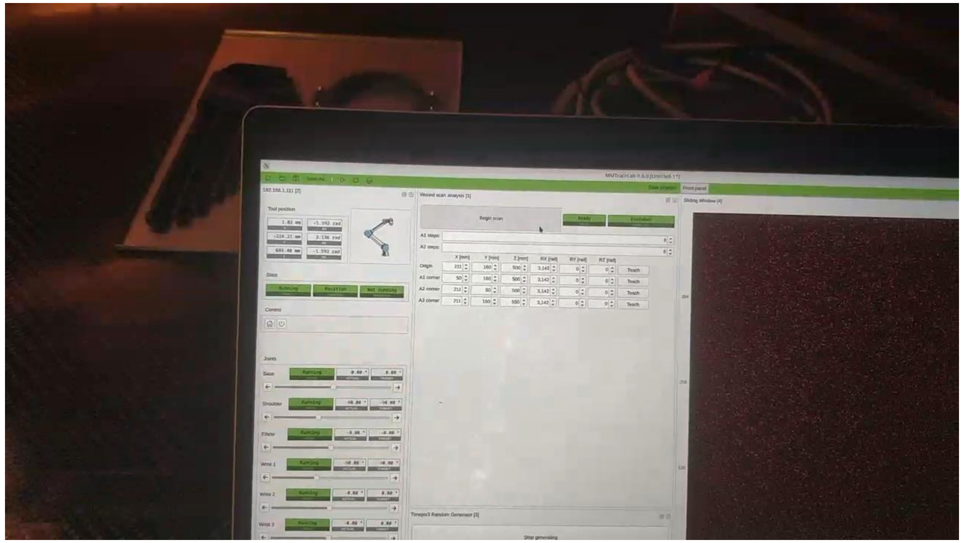
Setup:

- Katherine Gen1 + 1x Timepix3 (Si, 300μm thick)
- COMBO + SiPM for γ-spectroscopy
- UR3 positioner arm (5 joints)



Software challenges:

- Orchestrating large number of instruments
- Integrating multiple types of data
- Aggregation over multiple sampling points



…still a work in progress

Graphic credit: VectorStock, video credit: Milan Beneš

Conclusion

Summary

- Track Lab = versatile software for data acquisition and analysis
- Maturing over 3 years and 12 versions: moved from 1 to 20 devices.
- We would like to share it with the collaboration, and invite feedback.
  - Latest binaries available publicly at: https://software.utef.cvut.cz
  - Source code available at CERN GitLab to collaboration members upon request.
  - Happy to answer questions, organize workshops / demonstrations.

Why 2024 is not over yet:

- More hardware: Timepix4 is a priority, PCIe → larger bandwidth
- More analysis: machine learning, imaging, calibration, scans

Thank you for listening!

Petr Mánek, petr.manek@utef.cvut.cz

Try out Track Lab now:

Download v1.4 from
https://software.utef.cvut.cz

See article for details:

Available in J. Inst.
or arXiv:2310.08974

Minimum requirements:

- glibc 2.35 [x86_64, aarch64]
- Windows 10 [x86_64, arm64]
- macOS Monterey [x86_64, M1]

Backup slides

Supported operating systems

GNU/Linux
64-bit, glibc 2.35

Windows 10
64-bit (X64 or ARM)

macOS 14 Monterey
Intel & M1 compatible

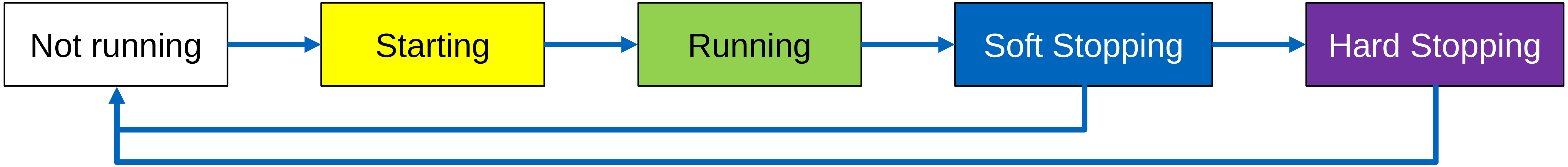
Version history

Date	Release
2020-11-04	v0.1 – initial release, very rudimentary DAQ for single readout
2021-03-10	v0.2 – multiple readouts, full configuration GUI, settings import
2021-05-05	v0.3 – pixel masking, beta threshold equalization, data flow monitor
2021-05-06	*v0.3.1 – quick bug fix*
2021-07-02	v0.4 – X-ray tubes, performance increase, temperature monitoring
2021-11-18	v0.5 – motor stages, real-time analysis, more file formats
2022-03-08	v0.6 – noise mean equalization, threshold scan, DAC scan, GaAs sensors
2022-07-31	v0.7 – mask patterns, file name wildcards, import/export of thresholds
…	
2023-03-01*	**v1.0 – new data core, completely new GUI, Gen2 and Quad support**

** planned release date, subject to last-minute changes*

Data element lifecycle

Color-coded states:

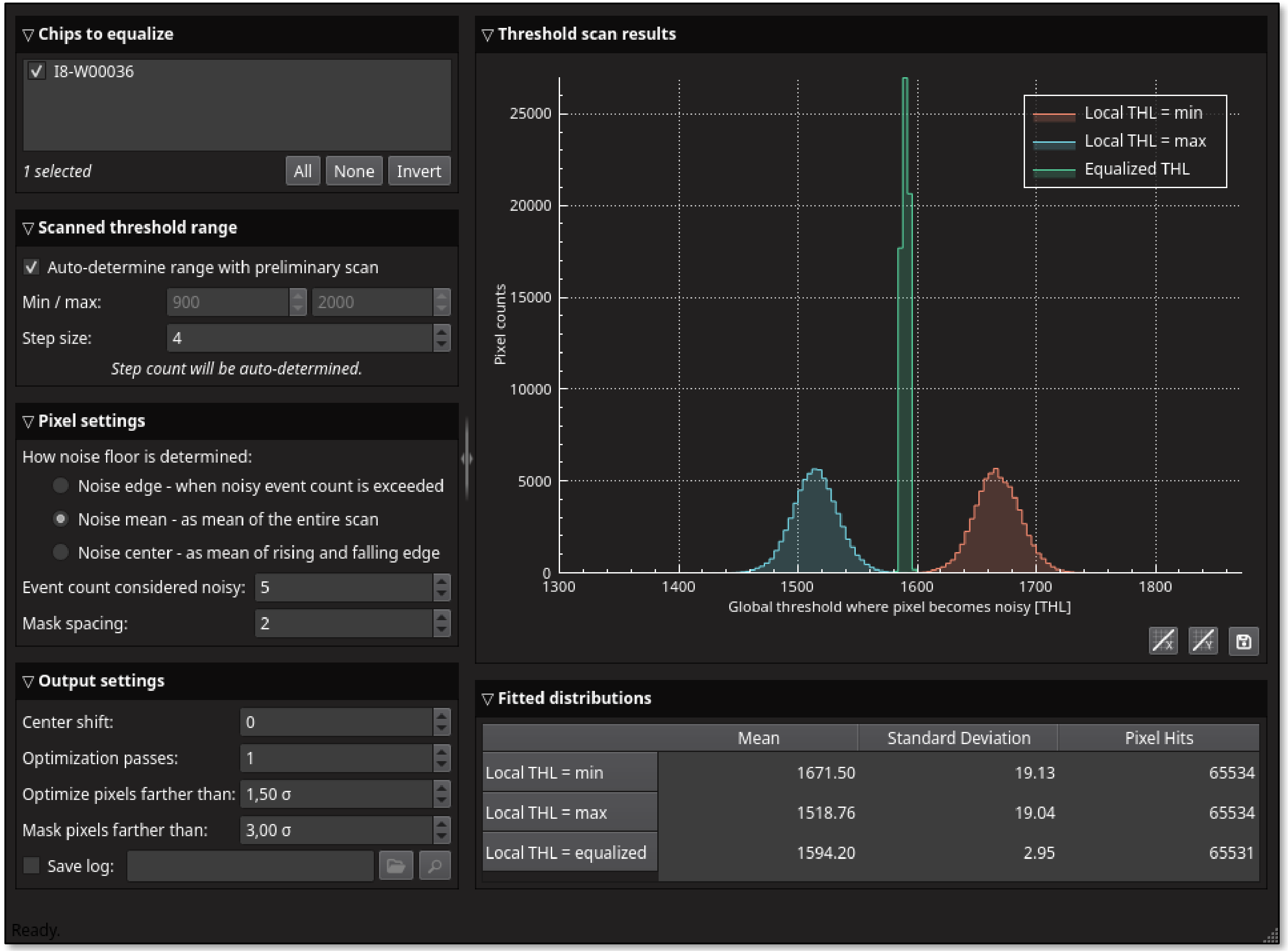


…formulated as a state machine: state of the system is aggregation of the states of its elements.

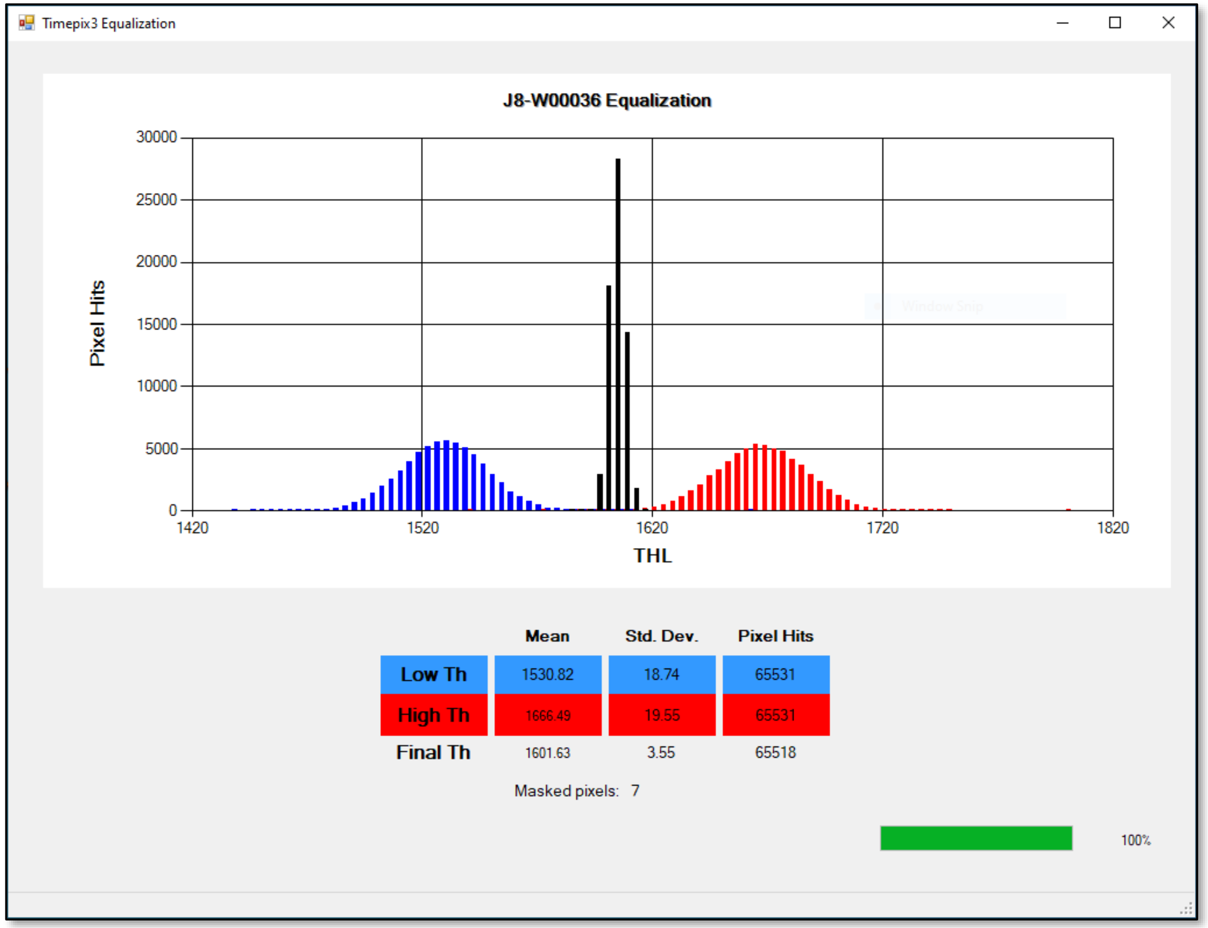
Added deterministic shutdown logic that was not previously present:

- Soft stop will finish processing data and terminate.
- Hard stop will terminate immediately – useful in emergencies!

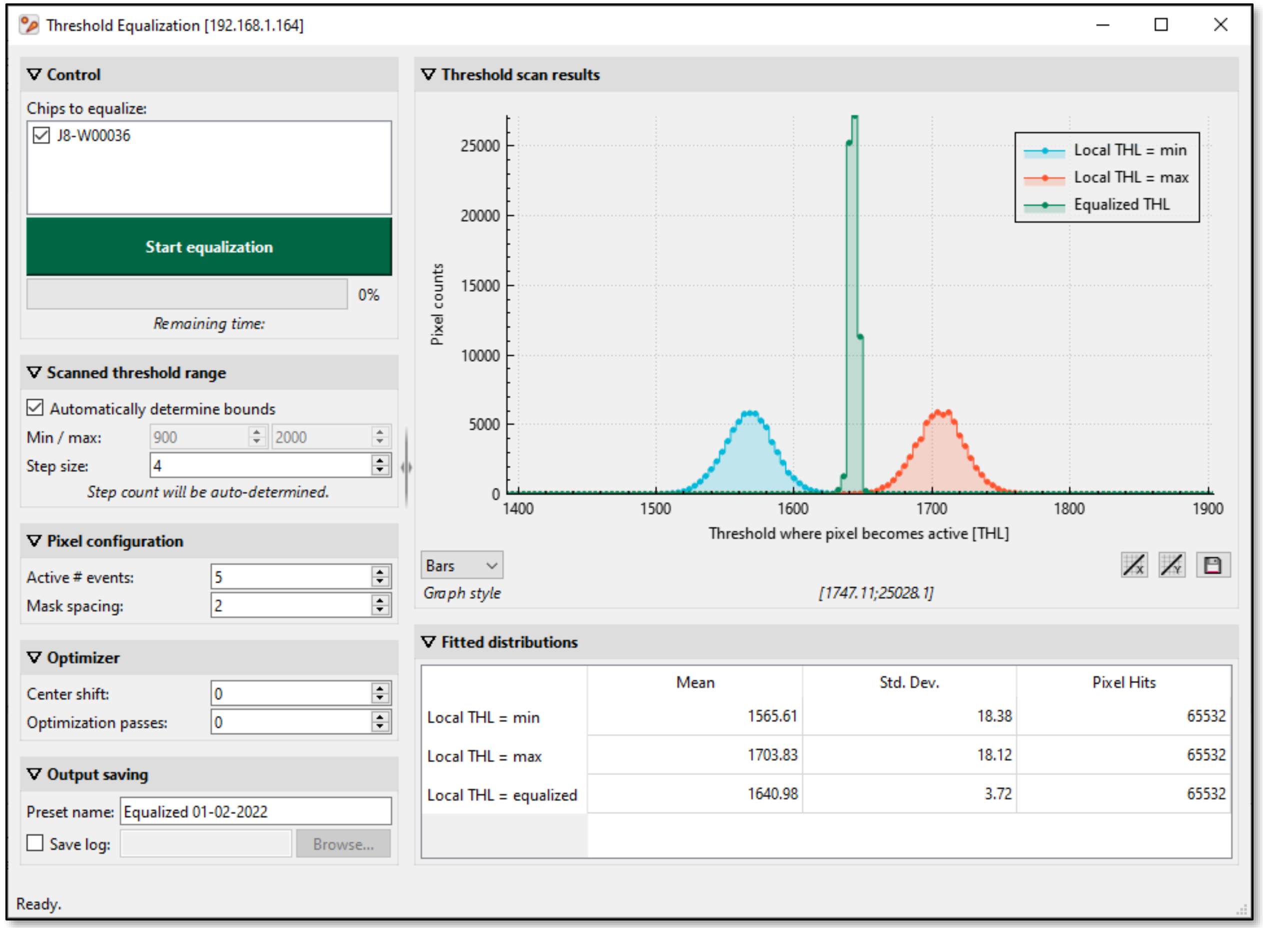
Example of THL equalization



Example of THL equalization

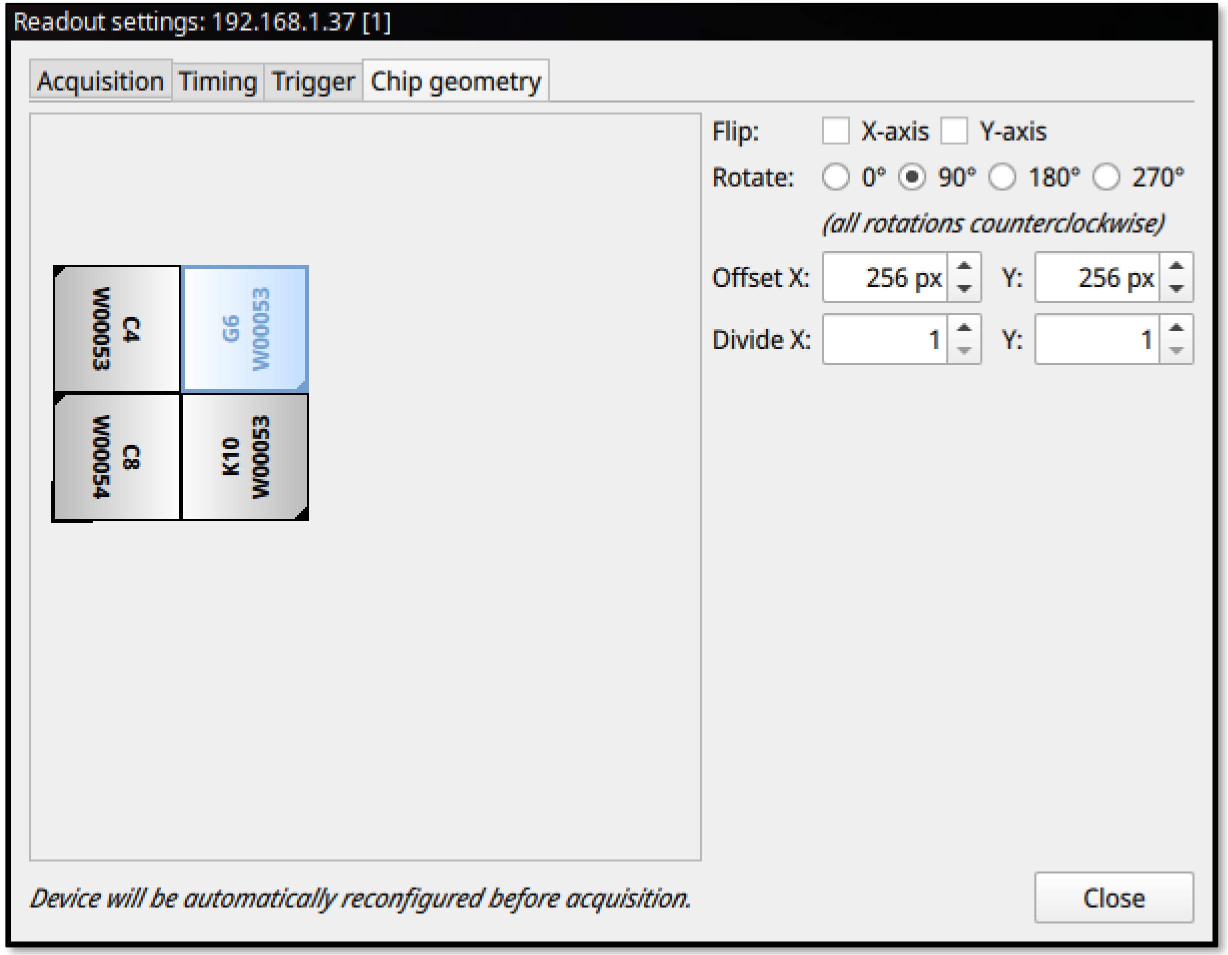


Reference software (UWB)

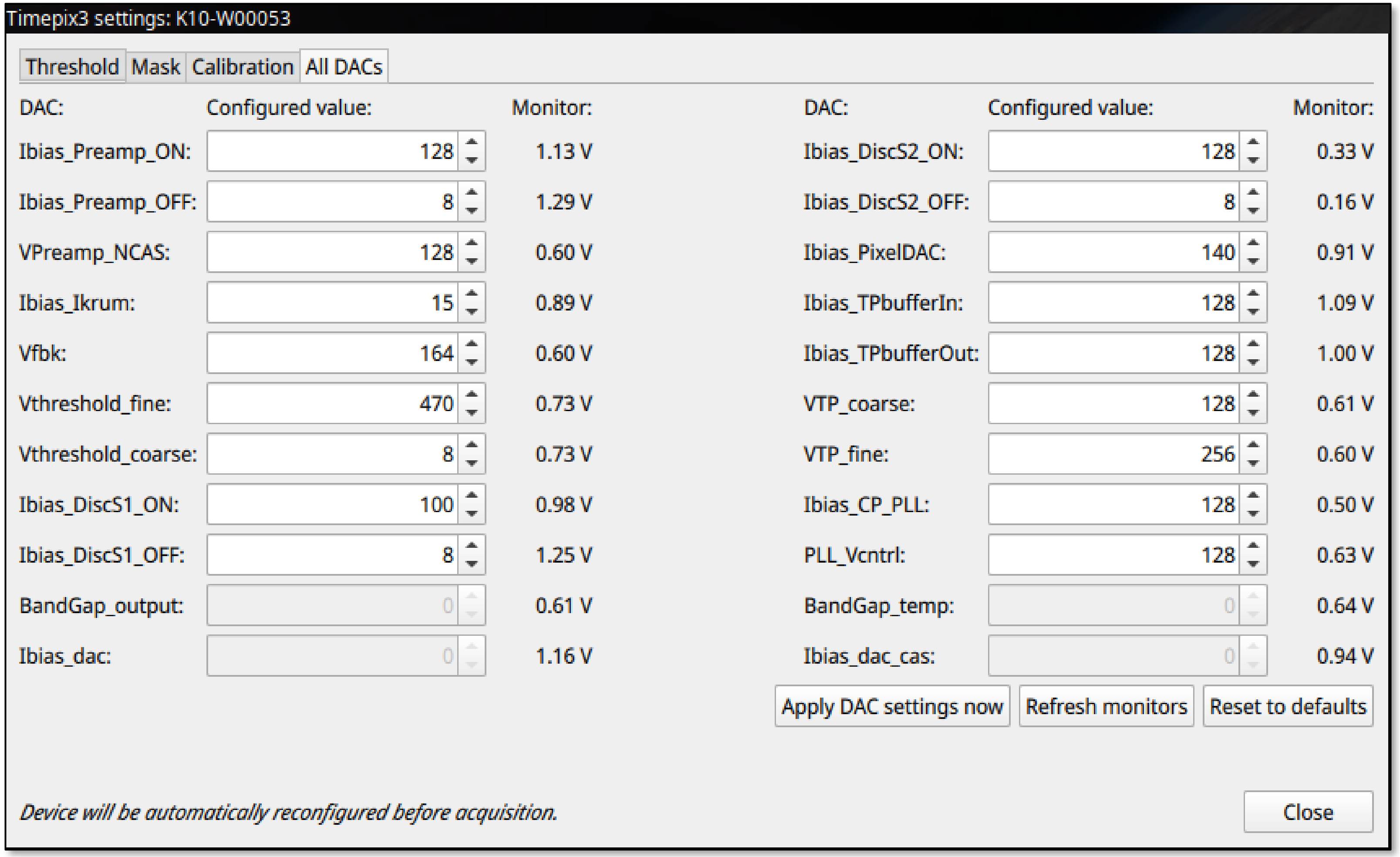


Track Lab

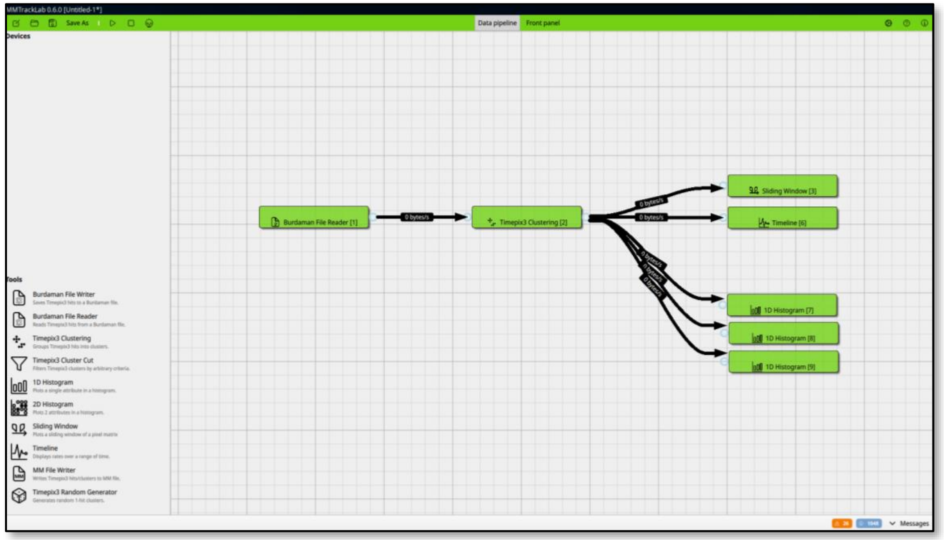
More screenshots

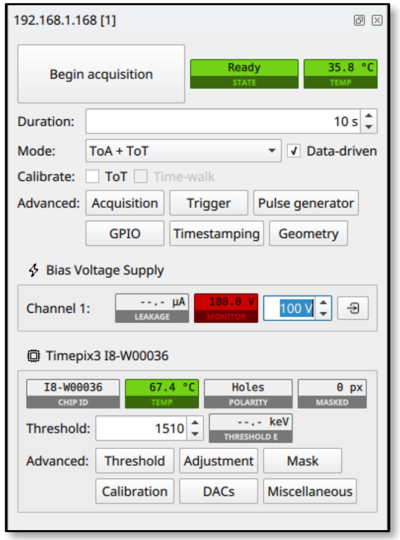


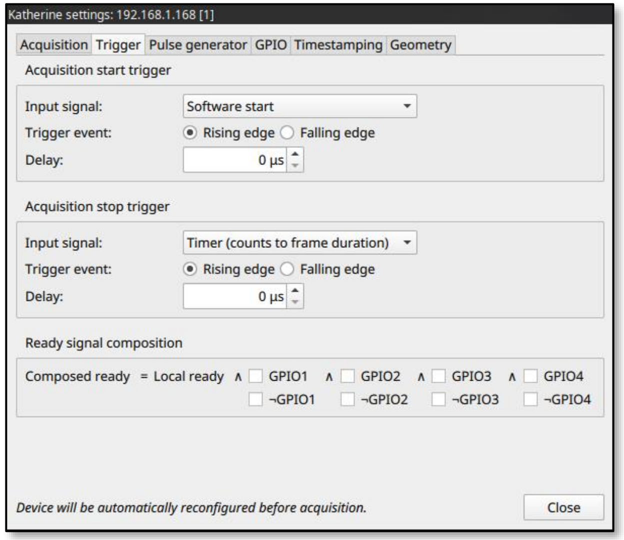
More screenshots

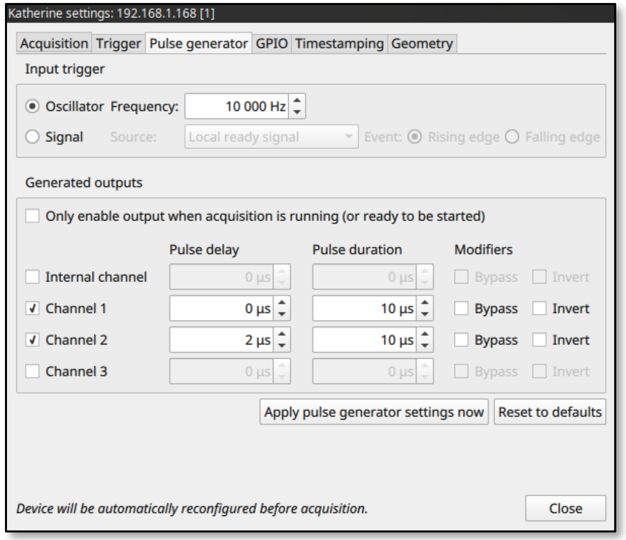


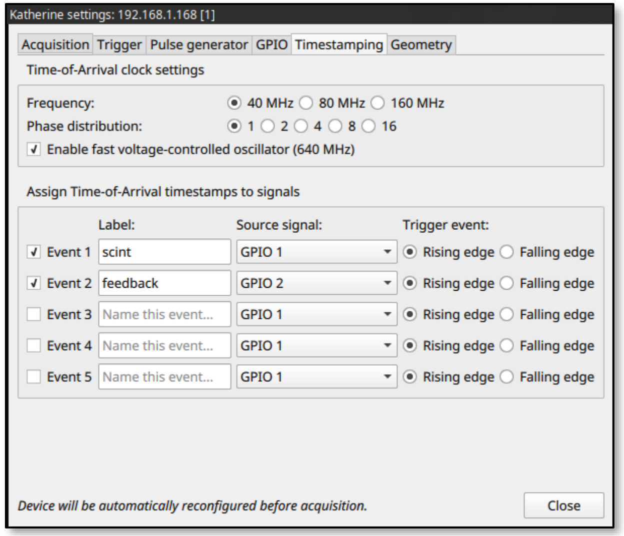
Even more screenshots

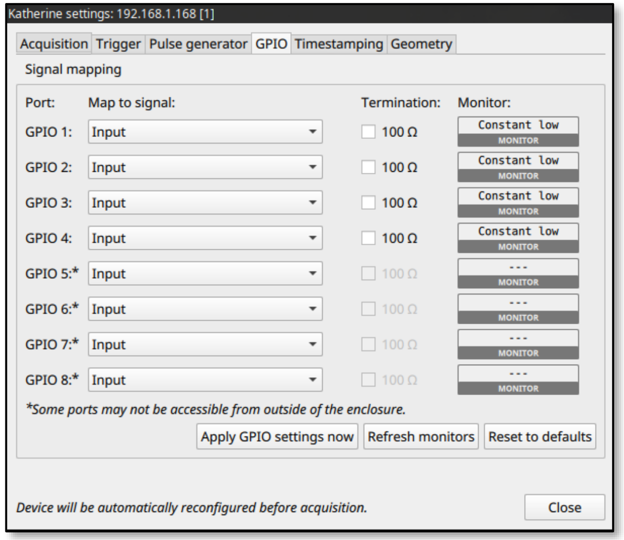




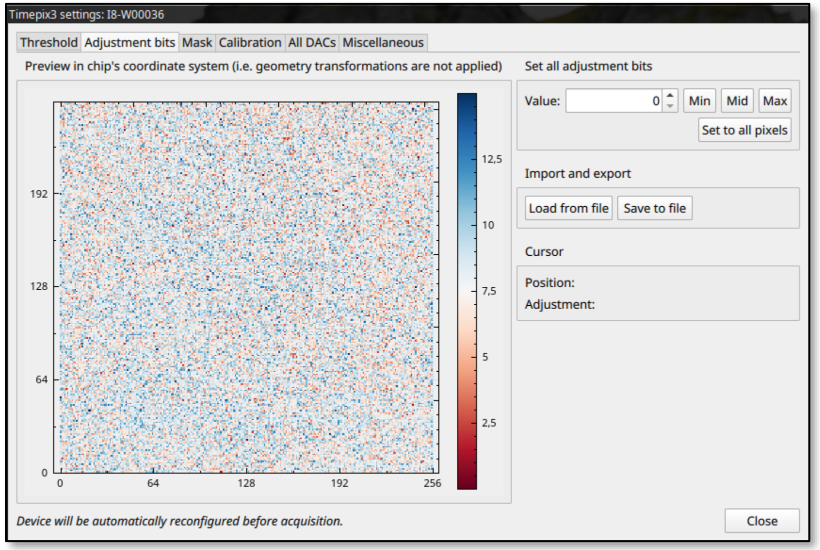


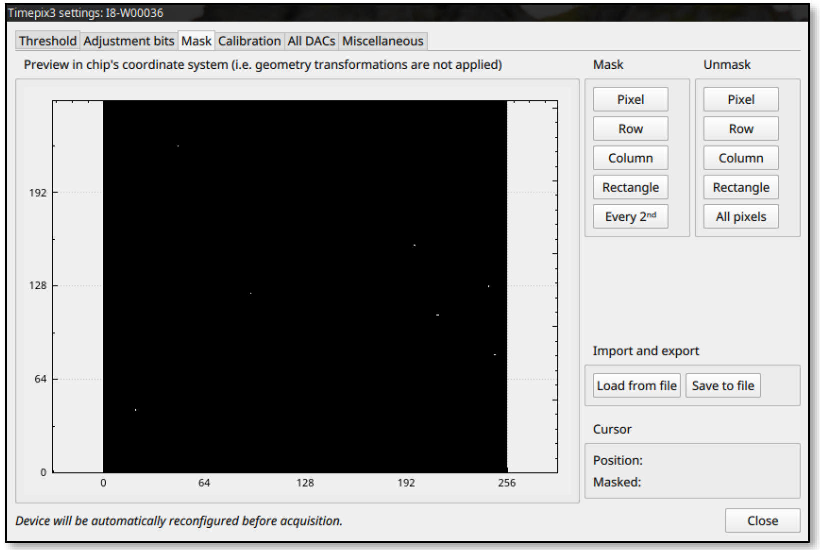


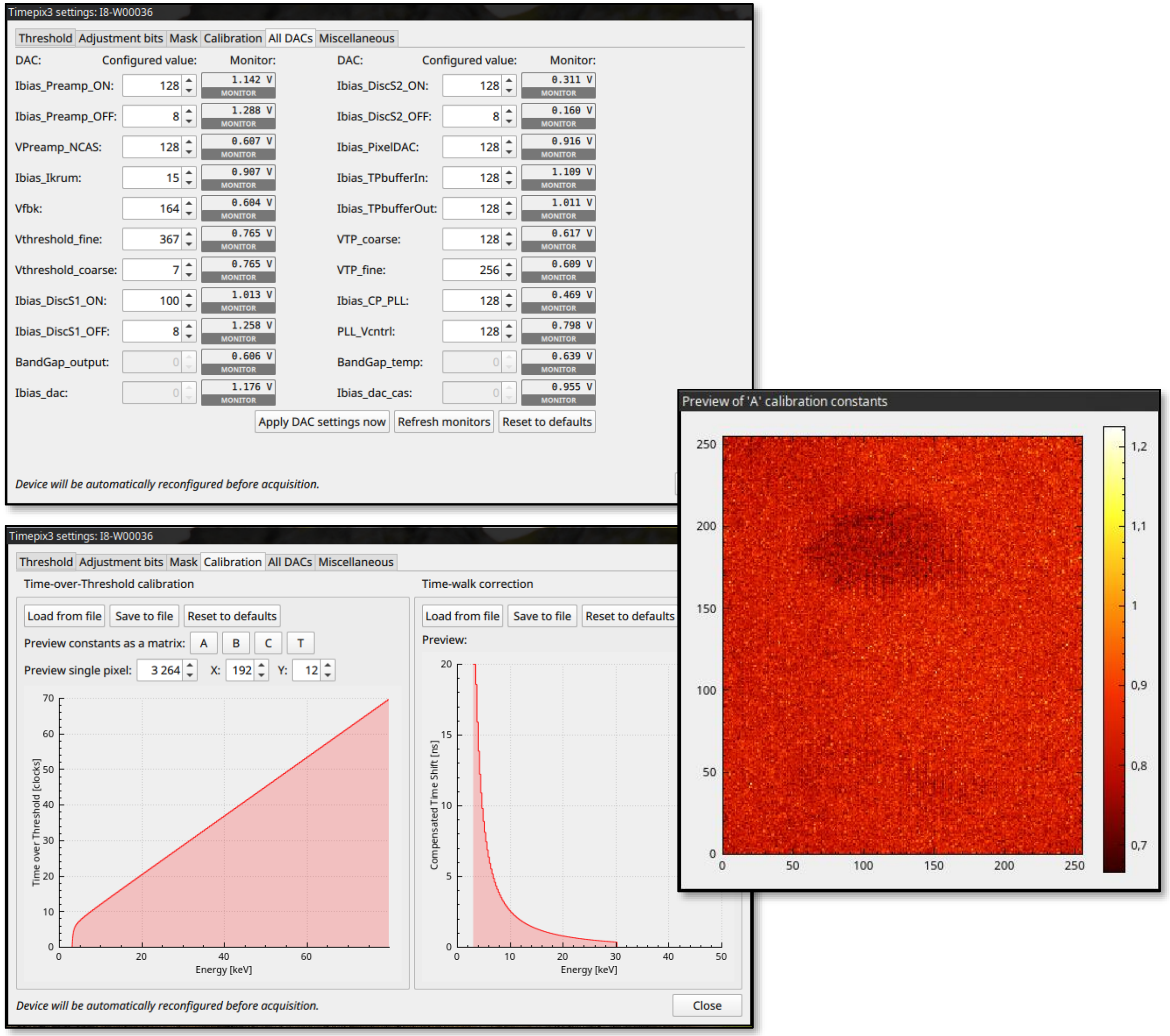




Even more screenshots







Multi-chip configurations

<u>Description (agreed with LM & PB):</u>

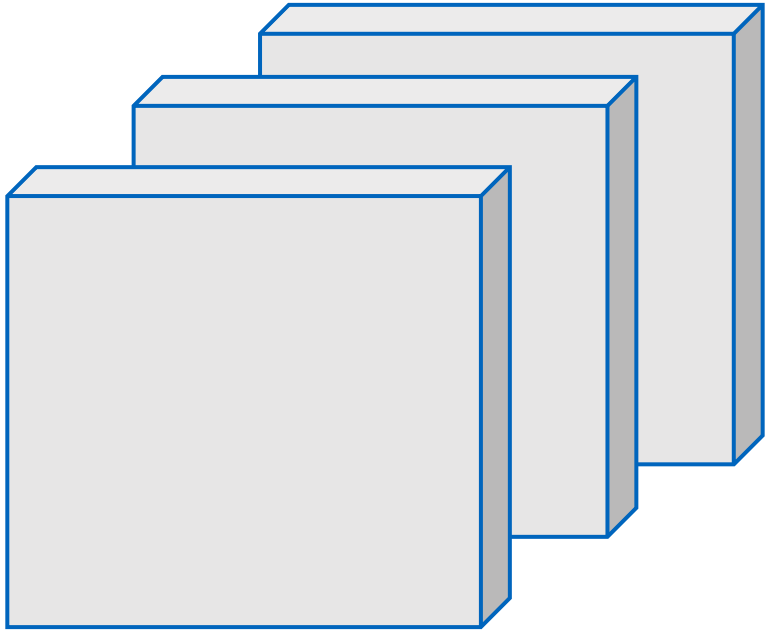
- Multiple layers:
  - [X;Y;Z] position in 3D space
  - Orientation in 3D space → not necessarily parallel to each other

- Each unit comprised of multiple chips:
  - All in the same plane
  - Position described in the unit of chip size
  - Orientation: increment of 90°

Multi-chip configurations

Example: telescope with 3 chips

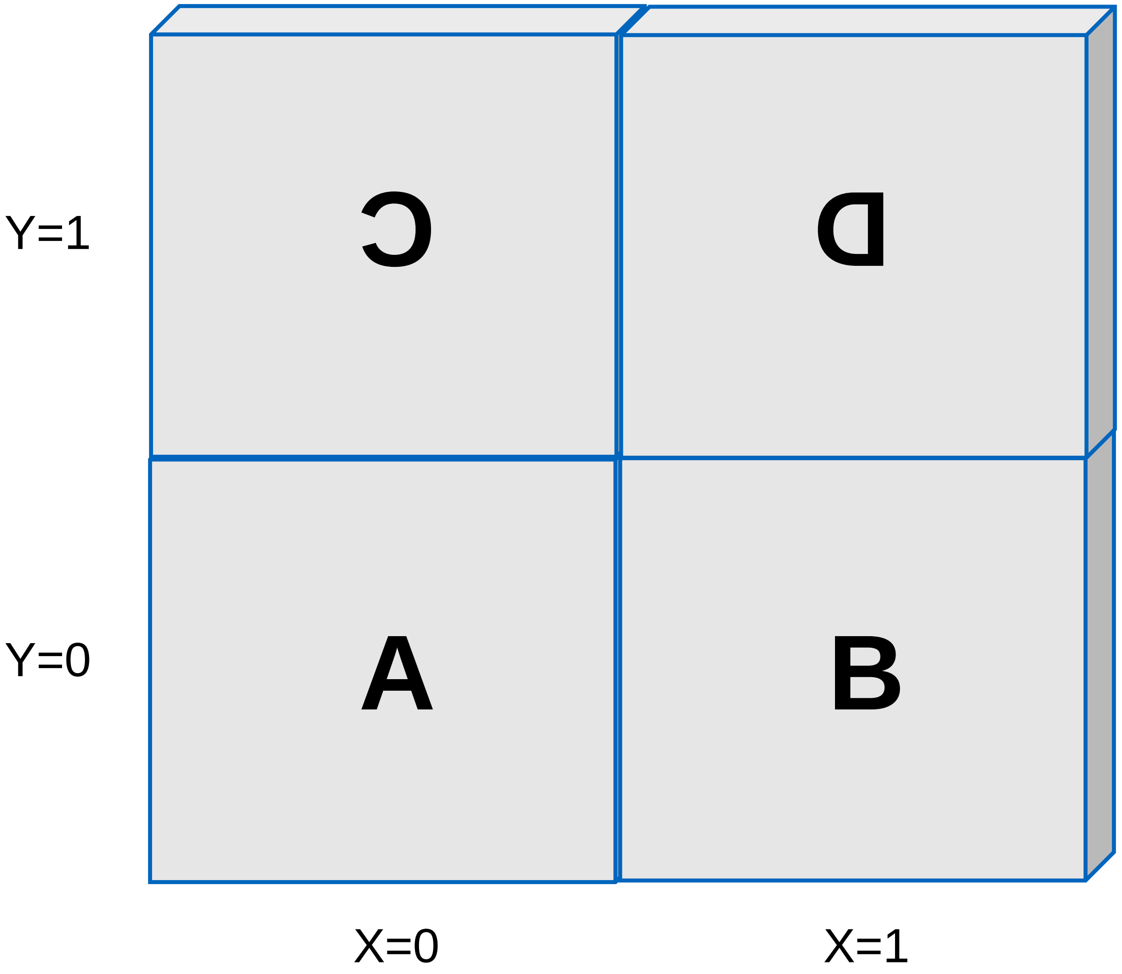
- Layer #1: [X;Y;Z]
  - Chip, [0;0], 0° rotation
- Layer #2: [X;Y;Z+dz]
  - Chip, [0;0], 0° rotation
- Layer #3: [X;Y;Z+2dz]
  - Chip, [0;0], 0° rotation



Multi-chip configurations

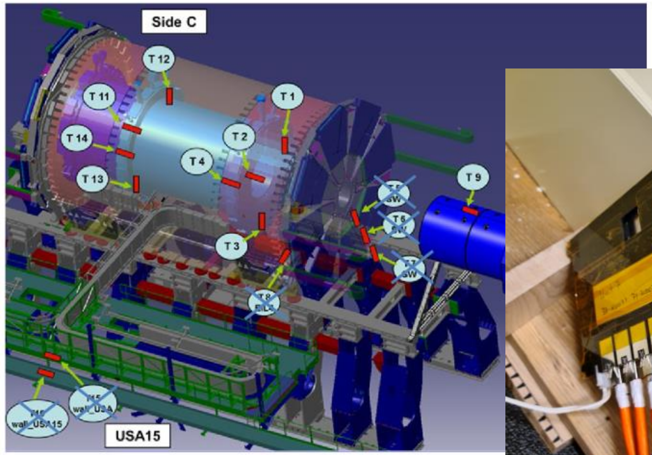
<u>Example:</u> 4-chip quad

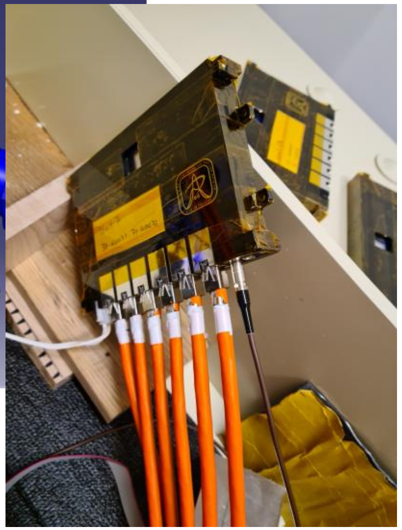
- Layer #1: [X;Y;Z]
  - Chip A, [0;0], 0° rotation
  - Chip B, [1;0], 0° rotation
  - Chip C, [1;0], 180° rotation
  - Chip D, [1;1], 180° rotation



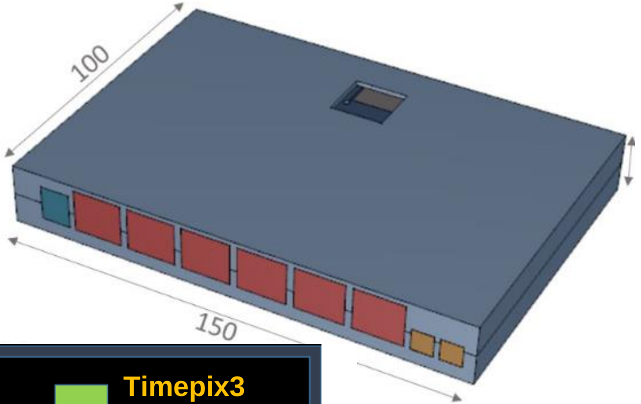
ATLAS-TPX3 network

- Run-3 continuation of the ATLAS-MPX and ATLAS-TPX projects.
- 14 detector units (each 2x Timepix3) installed in the ATLAS machine.
- Challenges:
  - Complex DAQ architecture, high data rates
  - Synchronization with LHC orbit clock
  - Real-time analysis (luminosity, radiation field characterization, neutron fluxes)

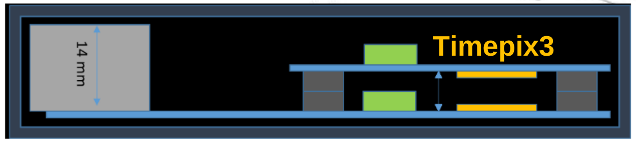




Single unit:

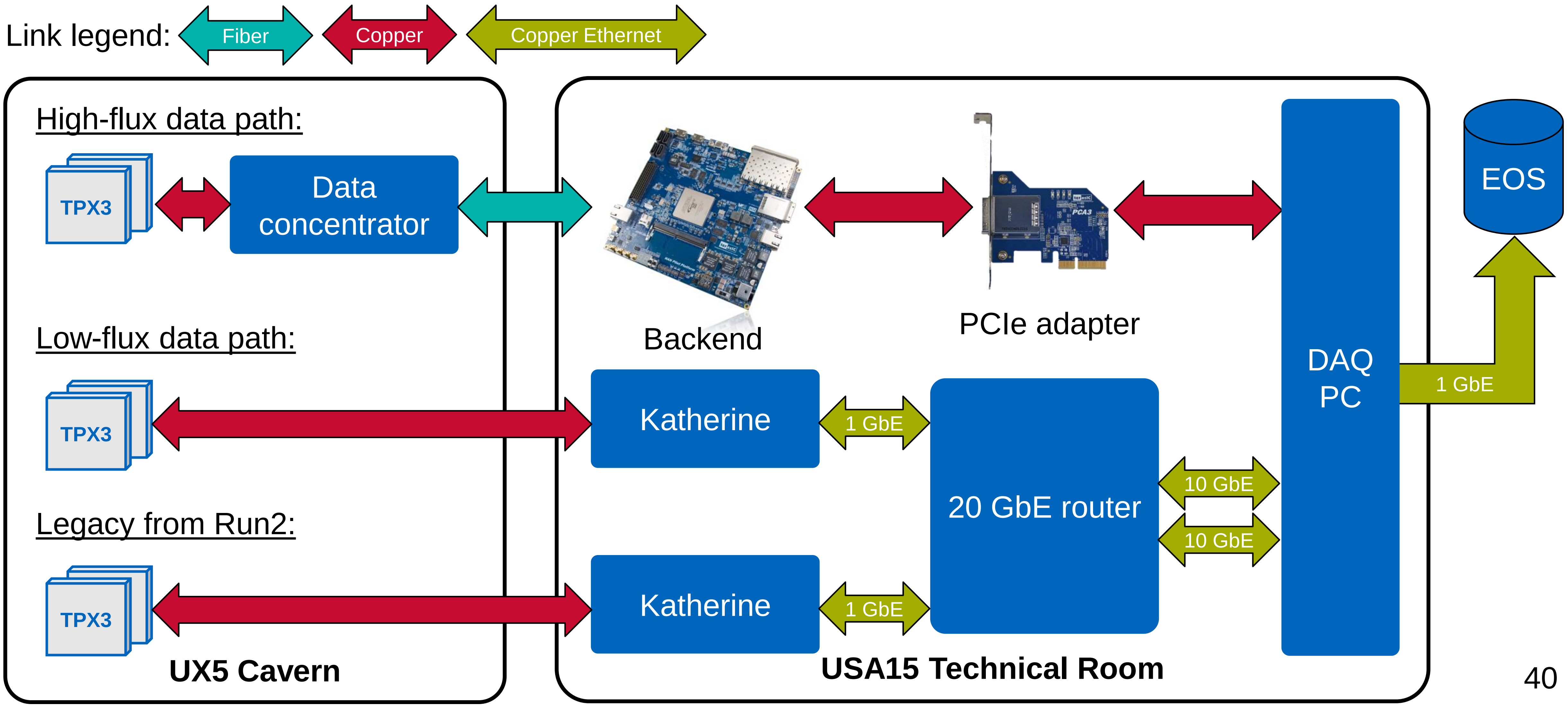


Profile:

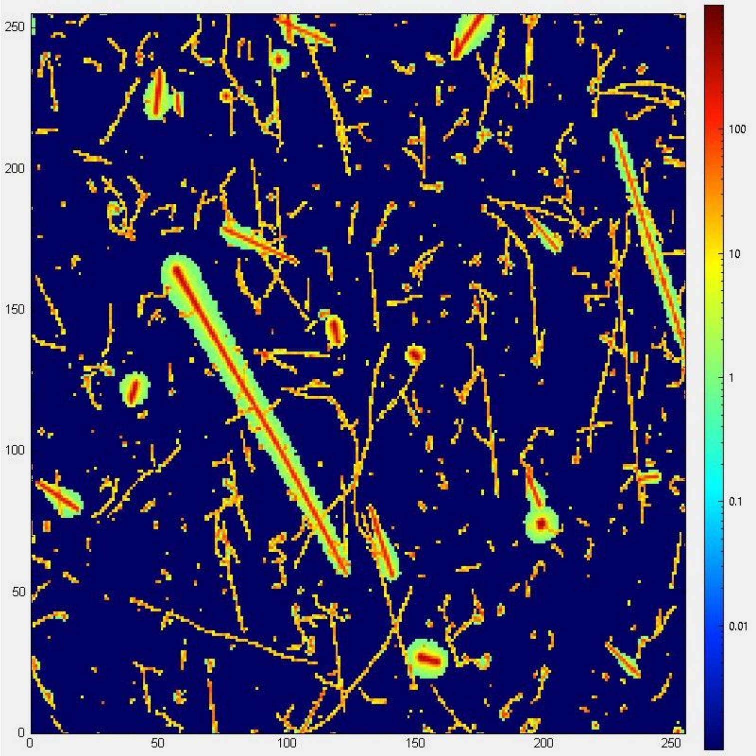


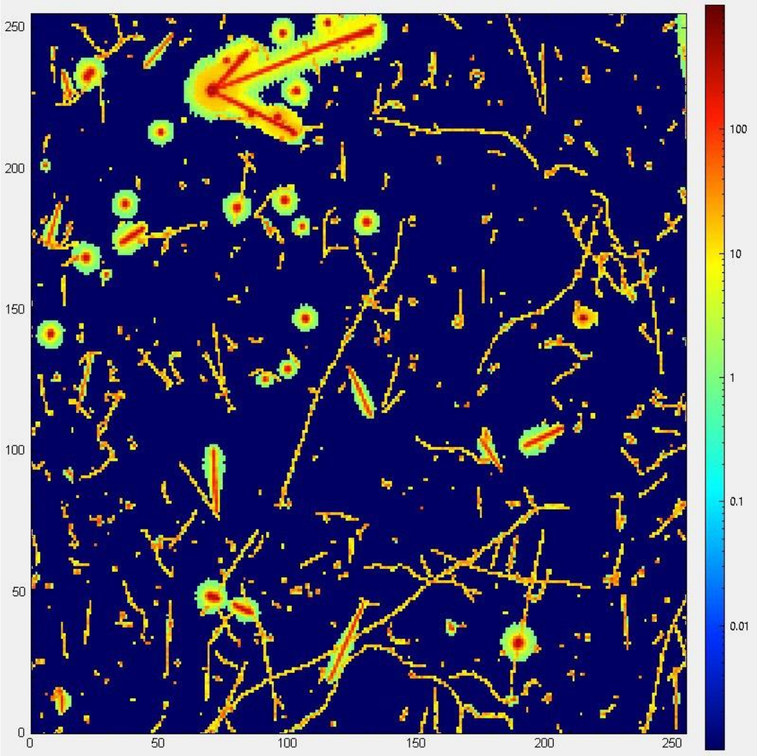
Proposal to measure the time dependence of the radiation field, induced radioactivity and luminosity with a network of Timepix3 detectors in ATLAS. (ATLAS Int. Note, 2021-03-16)

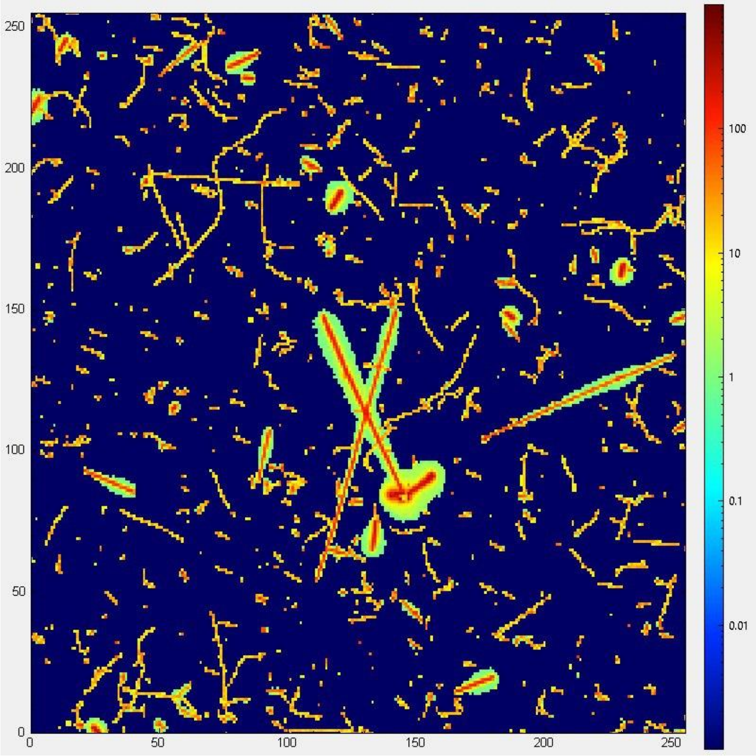
Data acquisition diagram



First data! (autumn 2022)







…this is just a very preliminary taste, more analysis is currently ongoing (help wanted!)

Thank you for listening!

Petr Mánek, petr.manek@utef.cvut.cz

https://software.utef.cvut.cz