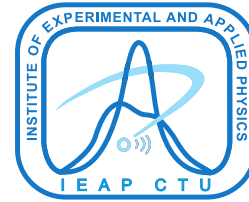


# High-performance software package for Timepix3 data acquisition, online analysis and automation

Petr Mánek<sup>1,2</sup>, petr.manek@utef.cvut.cz

<sup>1</sup>Institute of Experimental and Applied Physics, Czech Technical University, Prague

<sup>2</sup>Department of Physics and Astronomy, University College London



# On the menu today...

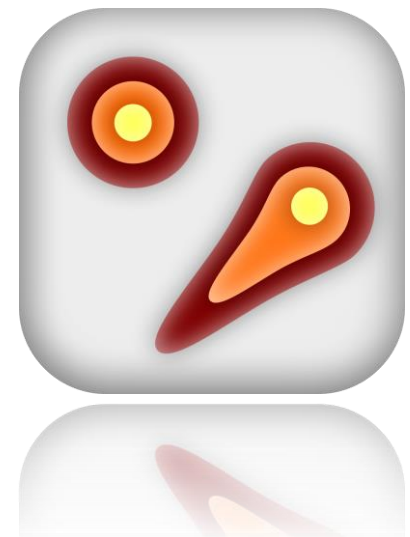
Background: Timepix3

About the software:

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

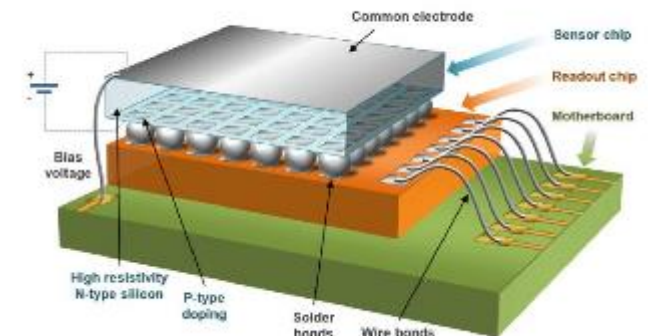
Example applications of Track Lab

Future development



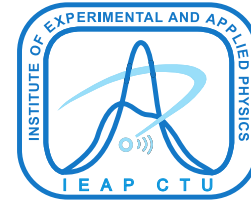
# Background: Timepix3

- 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)

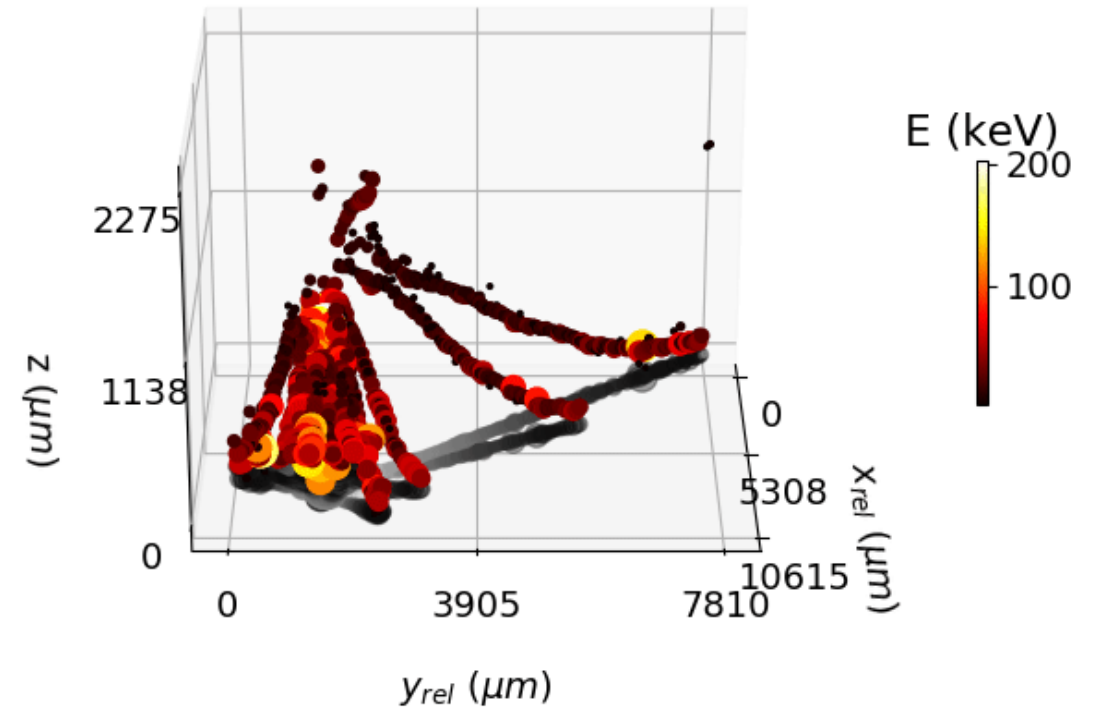
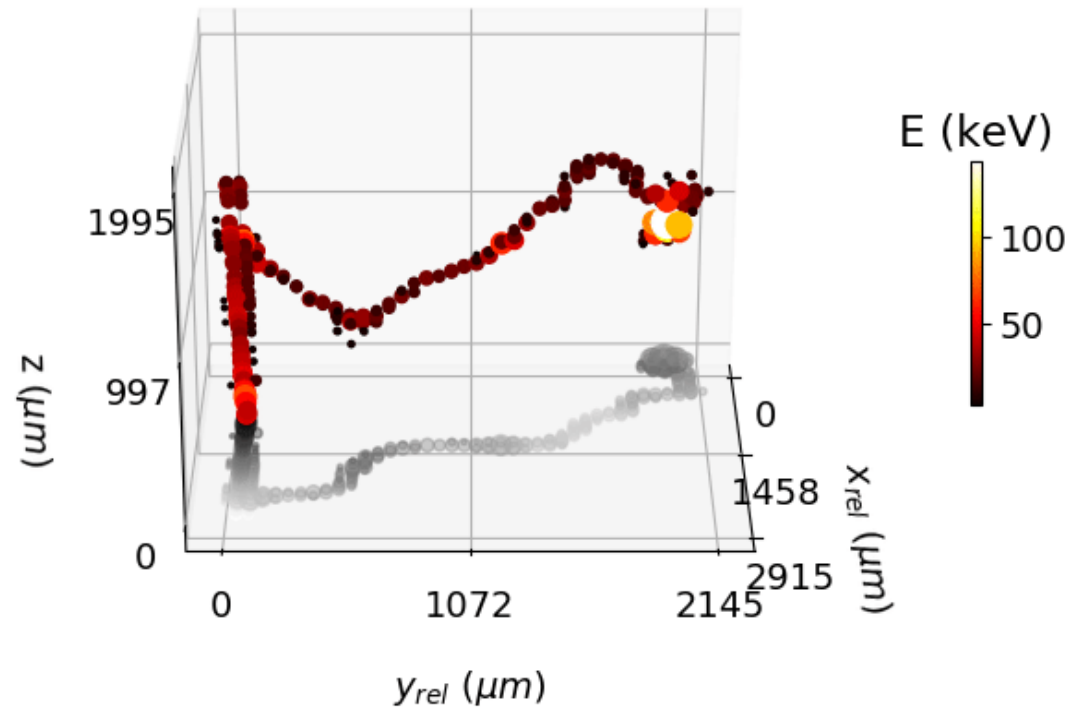


**More information:** Poikela, Timepix, et al. "Timepix3: a 65K channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout." *Journal of instrumentation* 9.05 (2014): C05013.




# Background: Timepix3

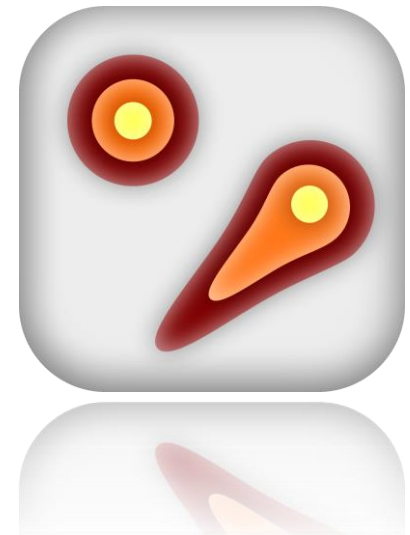


- Z-coordinate reconstruction examples:



# 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






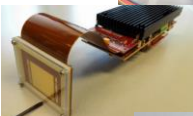


# What can Track Lab do?

**Take data from detectors**

**Run analysis in real-time**

**Automate repetitive tasks**

# Data taking: device support

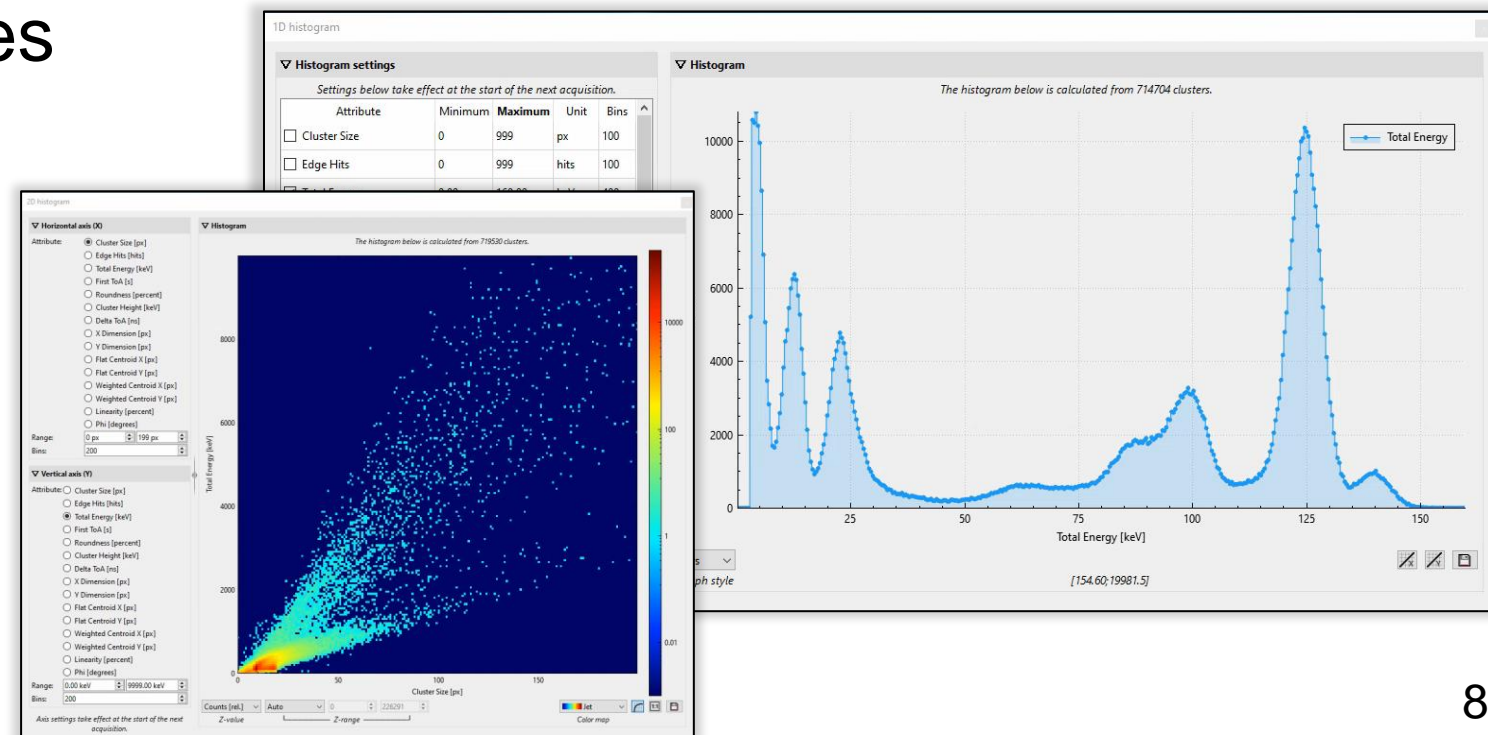
Readout	Sensor(s)	Connection	Readout	Sensor(s)	Conn.
 Katherine Gen1	1x Timepix3	1 Gbit Ethernet	Timepix2 Mini	1x Timepix2	USB 2
	1x Timepix2	1 Gbit Ethernet	MiniPIX EDU	1x Timepix	USB 2
 Katherine Gen2	8x Timepix3	1 Gbit Ethernet	MiniPIX*	1x Timepix	USB 2
		USB 3		1x Timepix2	USB 2
		PCIe 3 x4		1x Timepix3	USB 2
 HardPix	1x Timepix3	USB 3	AdvaPIX*	1x Timepix	USB 3
 SPIDR4*	1x Timepix4	10 Gbit Ethernet		1x Timepix3	USB 3
 COMBO+Spectrig*	1x SiPM	USB 2	WidePIX L*	10x Medipix3	1 Gb. E.
 MicroDAQ	28x PMT	1 Gbit Ethernet			



\* experimental support / work in progress

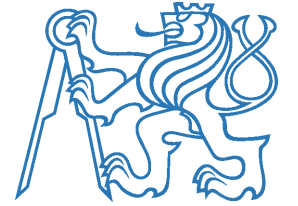
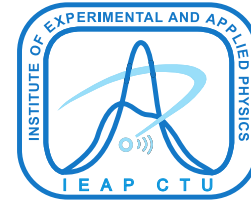
# Real-time analysis

- 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:

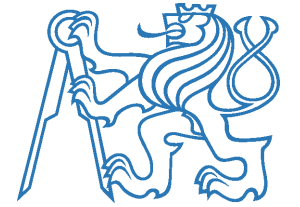
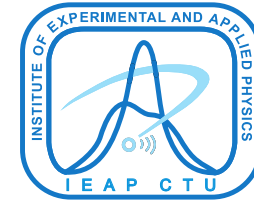
- Motorized stages (rotation, linear)
- 3D positioning arms
- X-ray tubes



In software:

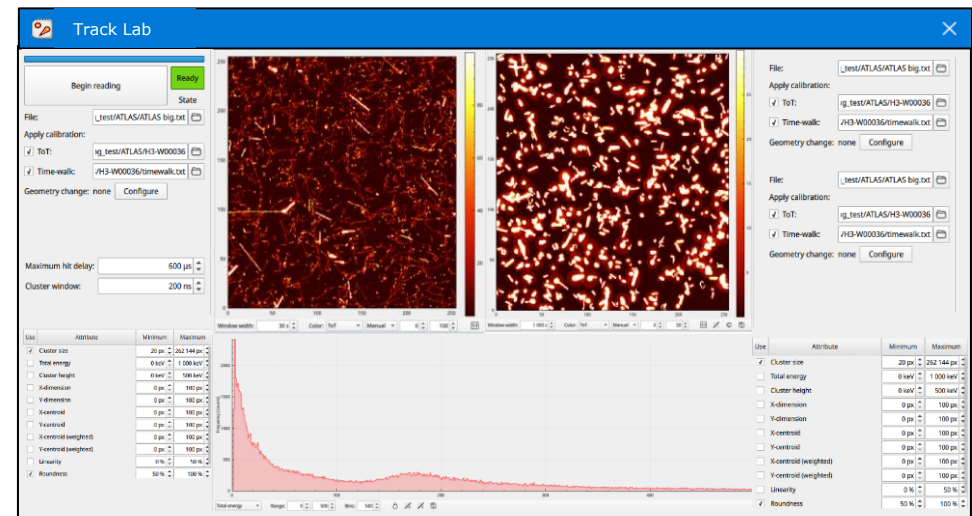
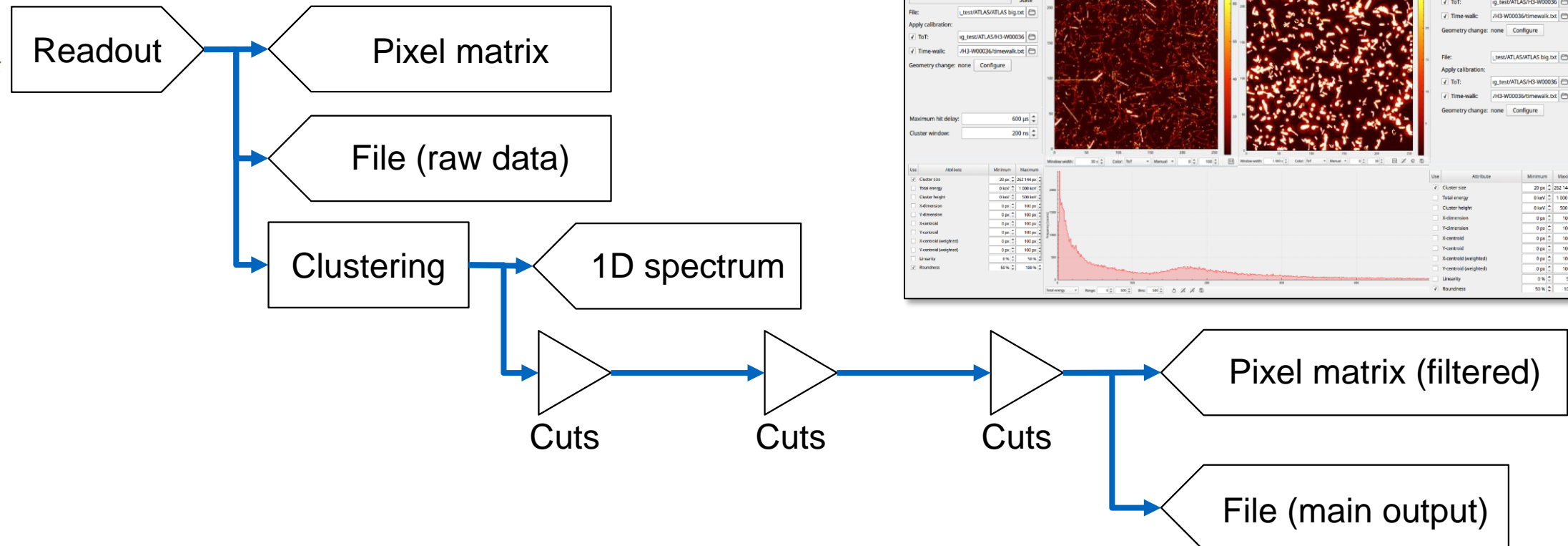
- Acquisition repetition
- Direct control from plug-ins (orchestration of multiple instruments)
- Scripting (experimental)

# How does Track Lab work?



# How does Track Lab work?

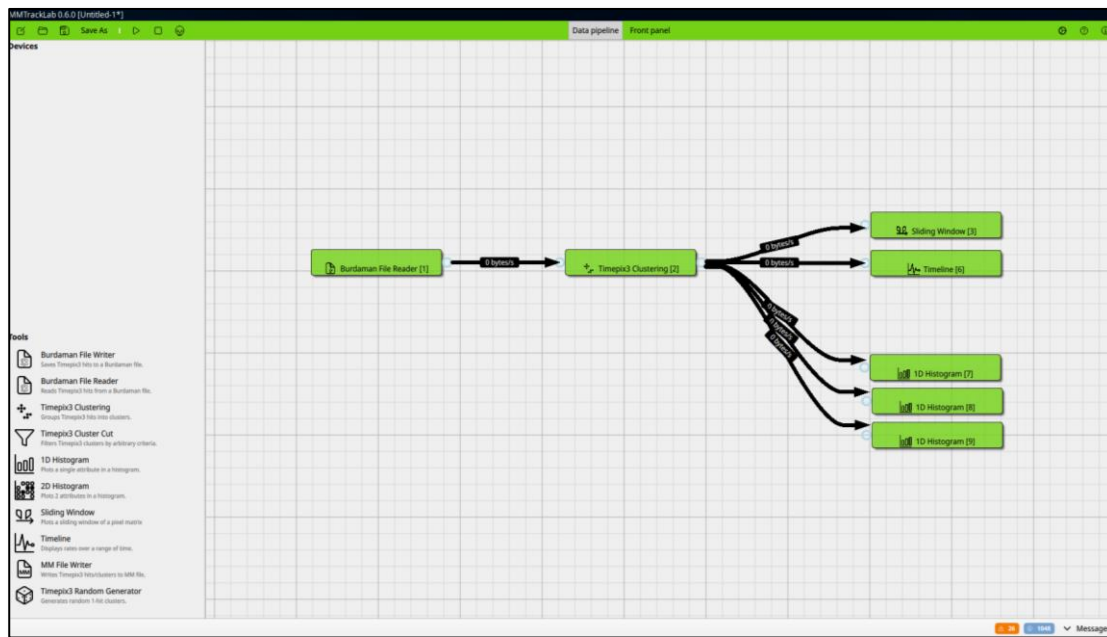
User builds data pipeline from many single-purpose elements.



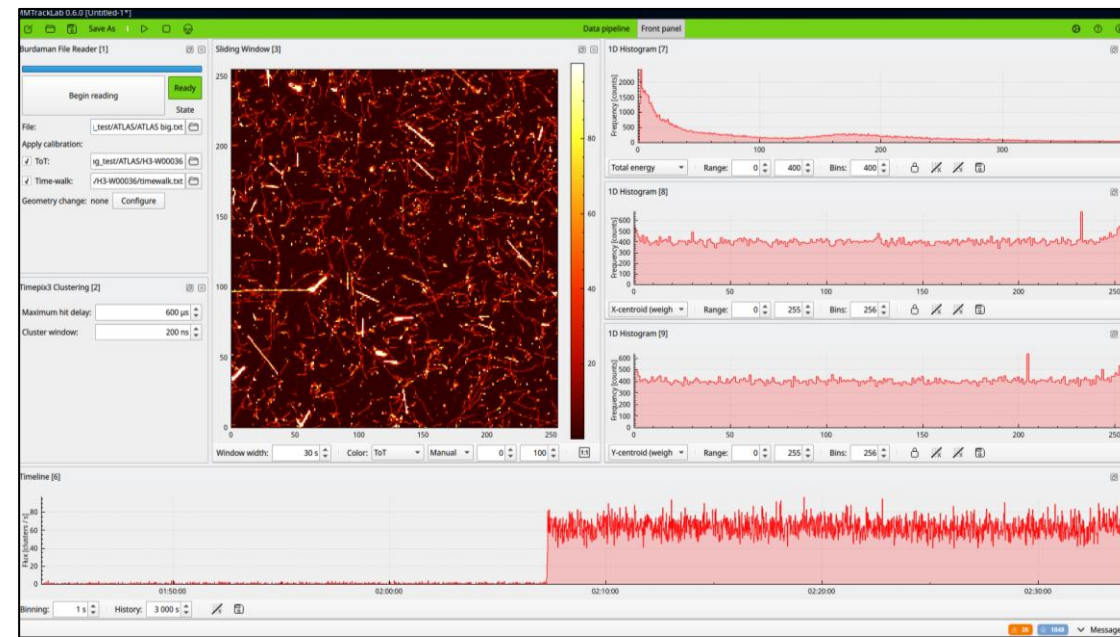
# User interface

User builds data pipeline from many single-purpose elements.

Data diagram

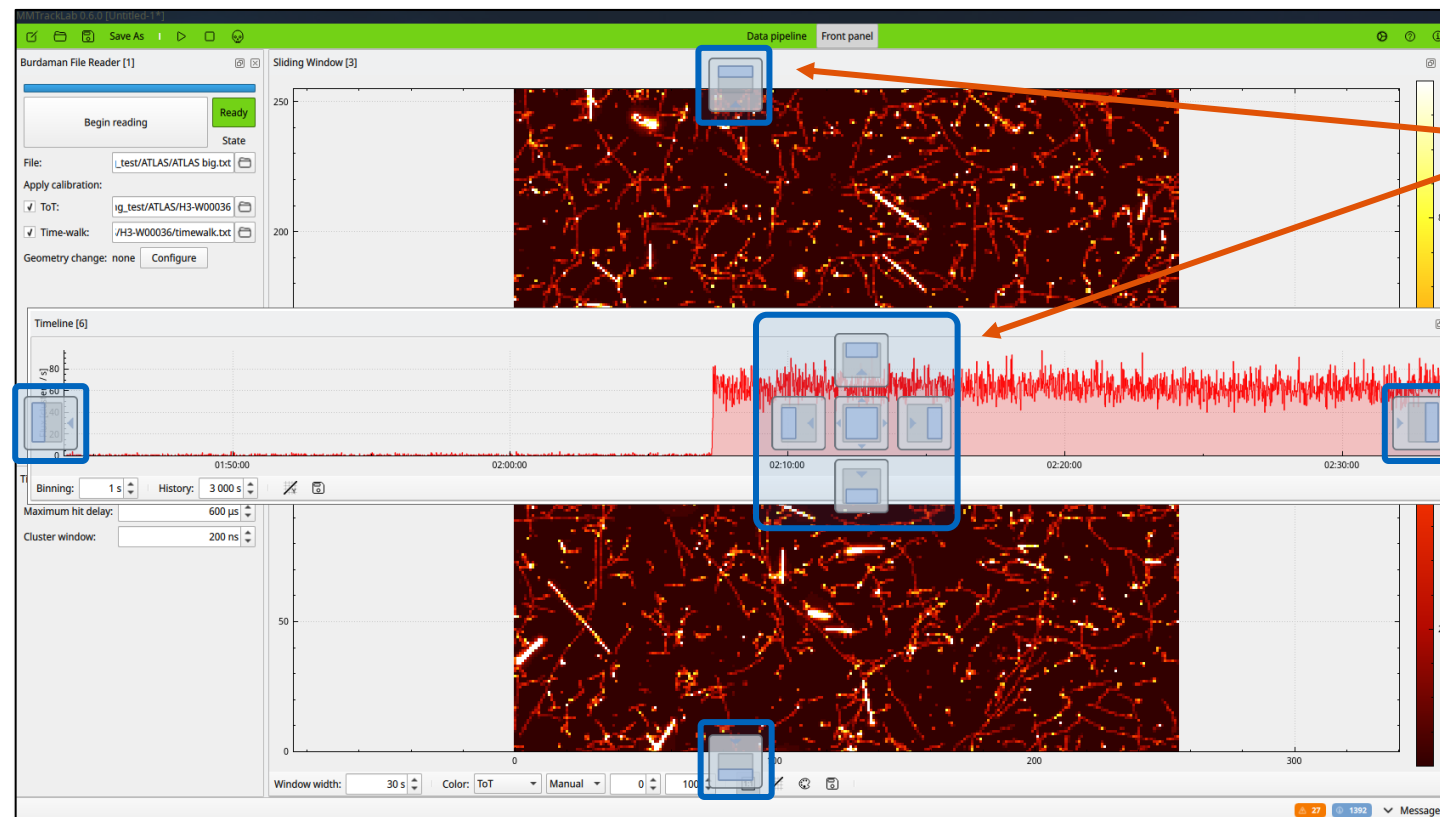


Front panel



# User interface: extensibility

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



**Docking anchors appear when a panel is dragged**

# User interface: examples

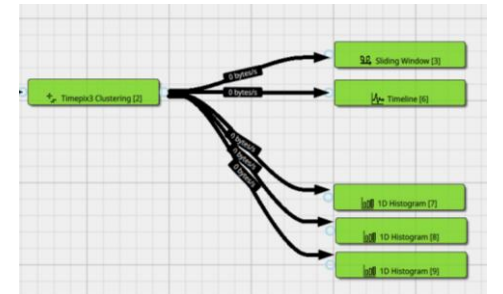


Can be saved to & loaded from file

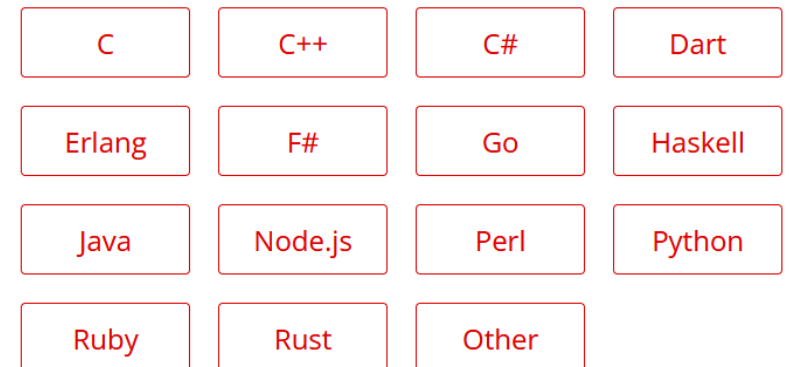
*I made all these layouts by dragging panels around in less than 5 min...*

# 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.
  - Future: real sockets, distribute over network
- File I/O facilitated by memory mapping.

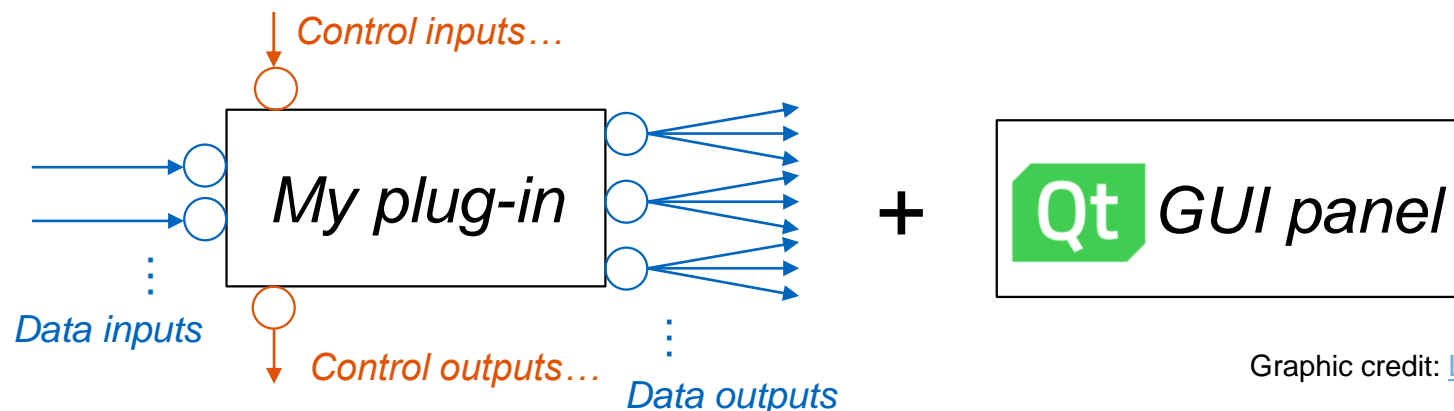


Pick your language

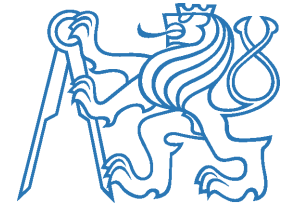
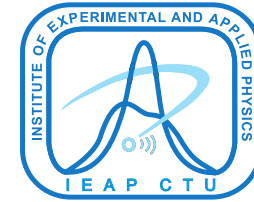


# Extendibility

- Anyone can make their own  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







# Example applications

# Example: PAN beam tests

(carried out in 2021-2022)

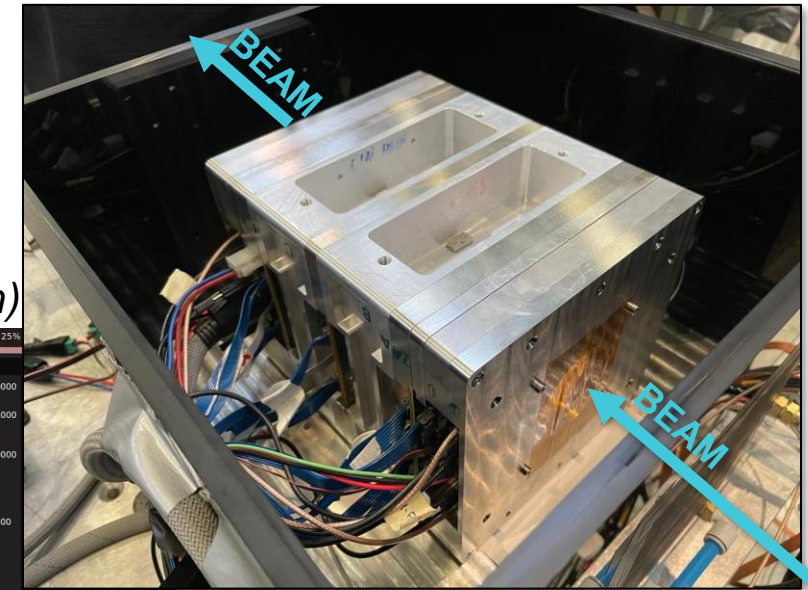
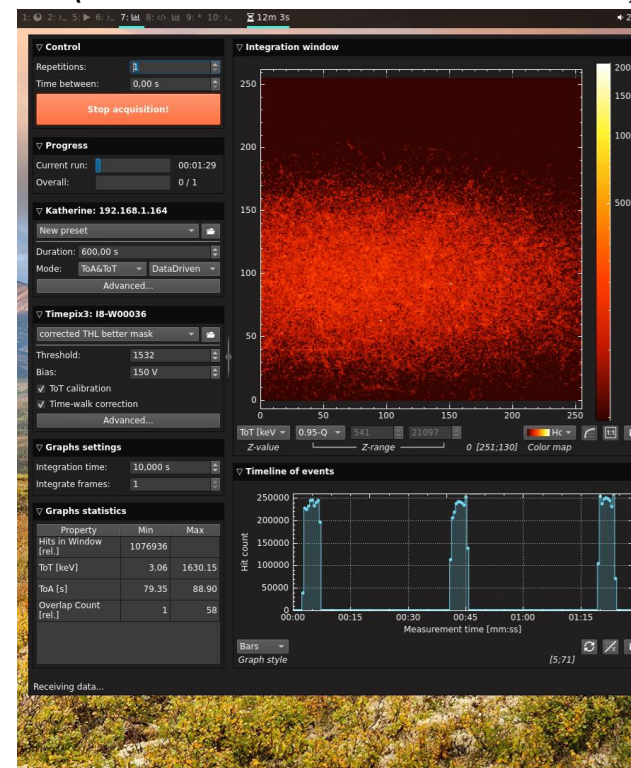
120 GeV/c hadron beam (90% pions) + setup:

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

## Software challenges:

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

(video shows older UI version)

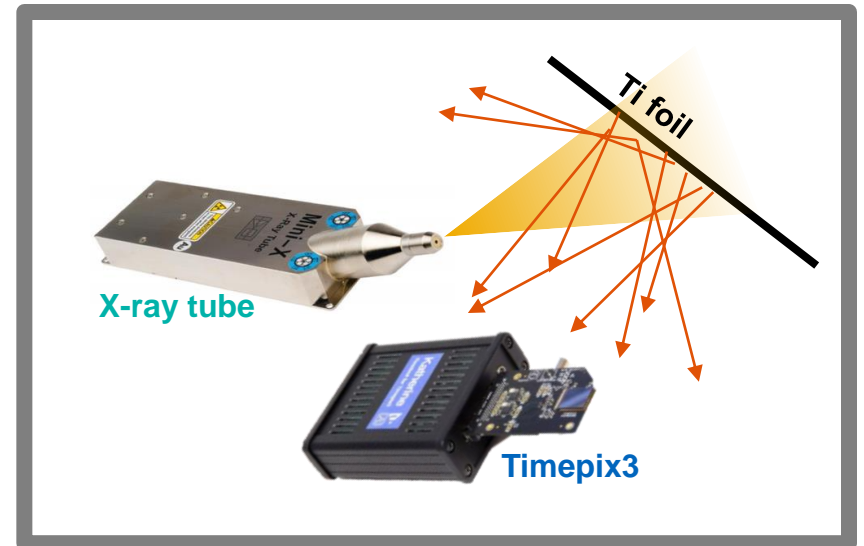


# Example: calibration with XRF

Our in-house method for calibrating ToT.

Setup:

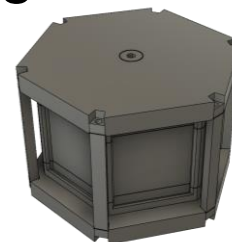
- 1x Katherine Gen1 + 1x Timepix3 (varies)
- 1x Amptek Mini-X2 X-ray tube
- Set of foils (Ti, Cu, Zr, Cd)



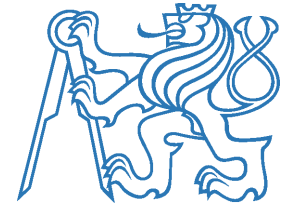
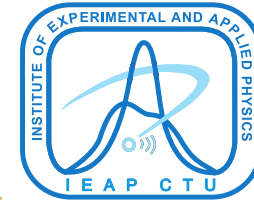
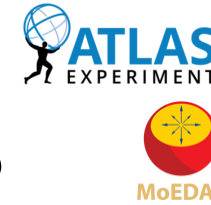
Shielded enclosure with interlocks

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)



# 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)

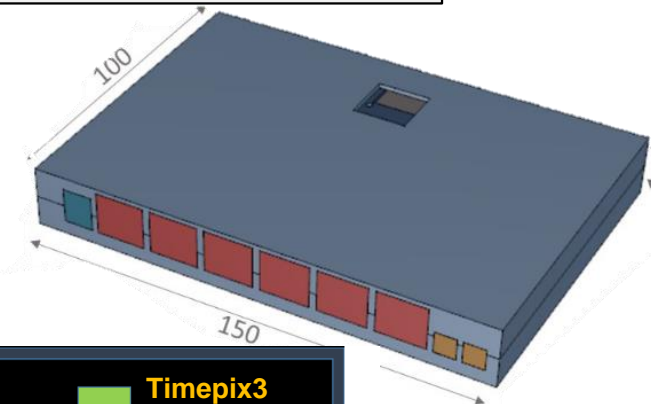
- 6x Timepix3 (sandwiched in pairs)
- 1x Katherine Gen2 (PCIe)

## Software challenges:

- ML-powered anomaly detection



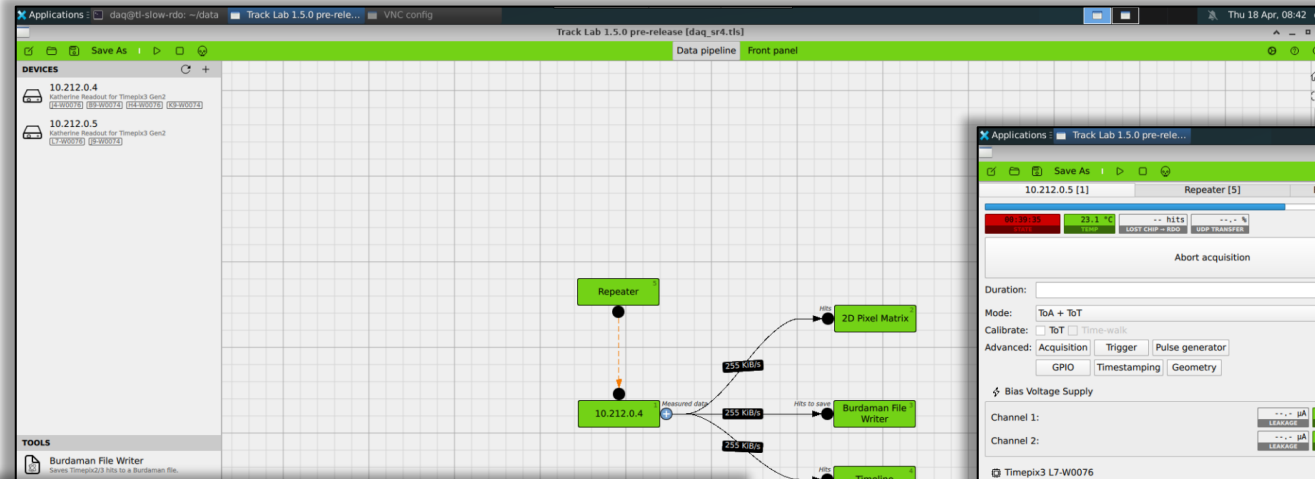
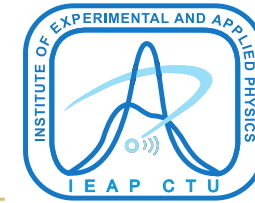
Single unit:



Profile:



# Examples: detector networks



Track Lab 1.5.0 pre-release [test\_sr5.ts]

10.212.0.5 [1] Repeater [5] Burdaman File Writer [4] 2D Pixel Matrix [2]

Duration: 3,600 s

Mode: ToA + ToT

Channel 1: 200 V

Channel 2: 50 V

Timepix3 L7-W0076

Timepix3 J9-W0074

Timeline [3]

LHC Page1 Fill: 9537 E: 6799 GeV t(SB): 05:32:32 18-04-24 10:51:39

## PROTON PHYSICS: STABLE BEAMS

Energy: 6799 GeV | B1: 2.02e+14 | B2: 2.03e+14

Beta\* IP1: 0.30 m | Beta\* IP2: 10.00 m | Beta\* IP5: 0.30 m | Beta\* IP8: 2.00 m

Inst. Lumi [(ub.s)^-1] IP1: 13772.22 IP2: 8.93 IP5: 14150.49 IP8: 673.09

FBCT Intensity and Beam Energy

Instantaneous Luminosity

BIS status and SMP flags		B1	B2
Link Status of Beam Permits		true	true
Global Beam Permit		true	true
Setup Beam		false	false
Beam Presence		true	true
Moveable Devices Allowed In		true	true
Stable Beams		true	true

Comments (18-Apr-2024 08:18:33)

\*\*\* STABLE BEAMS \*\*\*

all IPs on target

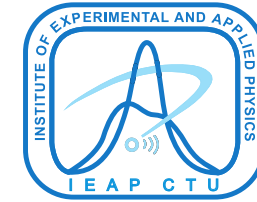
IP1/5 sep levelling

IP2/8 Sep. Levelling

XRP's IN

AFS: 25ns\_1791b\_1772\_1191\_1260\_144bpi\_18inj\_3INDIV:PM Status B1 **ENABLED** PM Status B2 **ENABLED**

# Example: tissue scanning

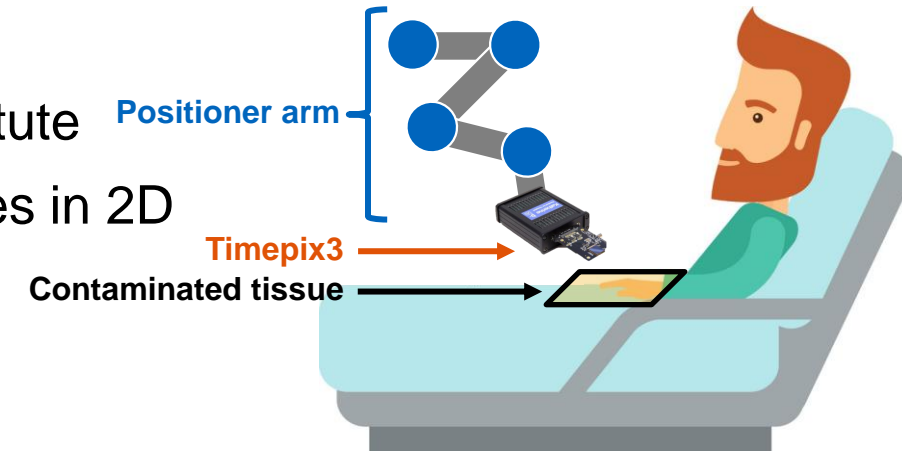


Collaboration with Czech National Radiation Protection Institute

Objective: map radioactive contamination of biological tissues in 2D

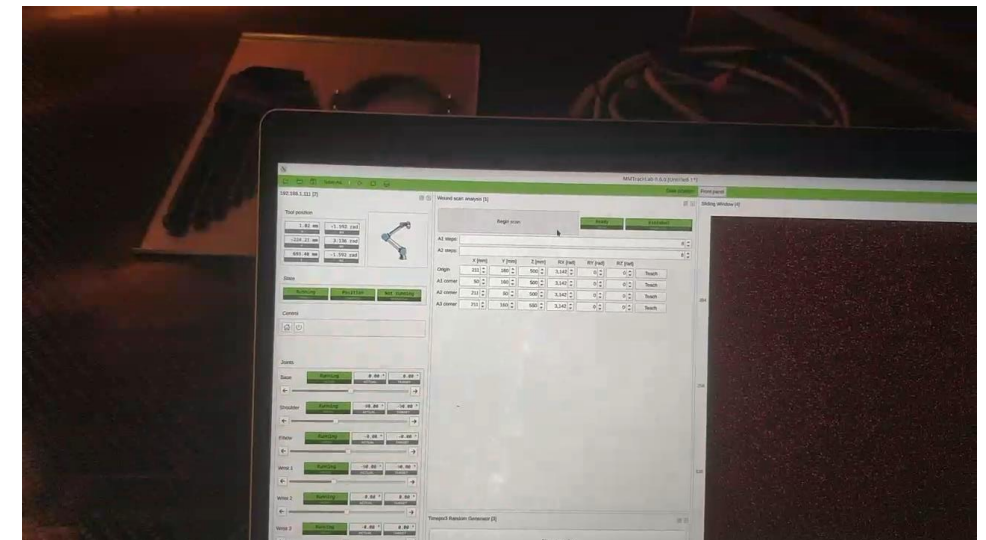
Setup:

- Katherine Gen1 + 1x Timepix3 (Si, 300 $\mu$ m thick)
- COMBO + SiPM for  $\gamma$ -spectroscopy
- UR3 positioner arm (5 joints)

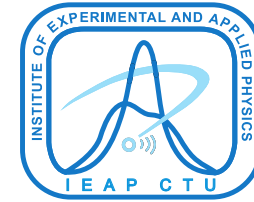


## Software challenges:

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



...still a work in progress



# 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](https://software.utef.cvut.cz) 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]

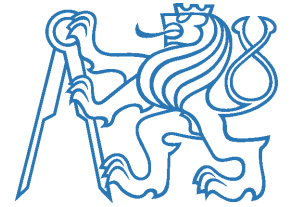
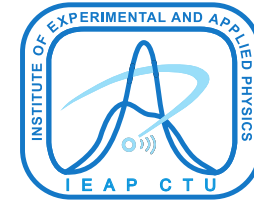


Windows 10 [x86\_64, arm64]



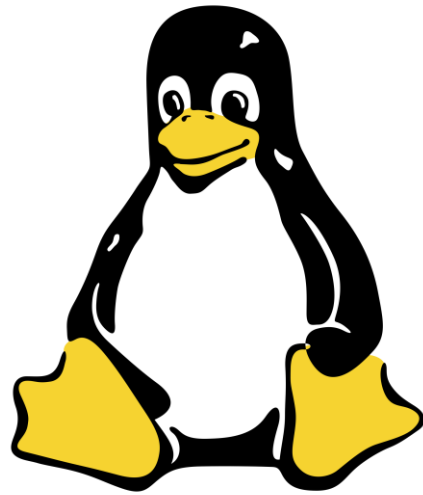
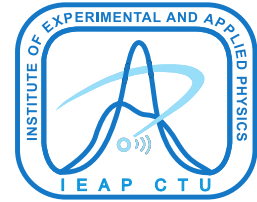
macOS Monterey [x86\_64, M1]



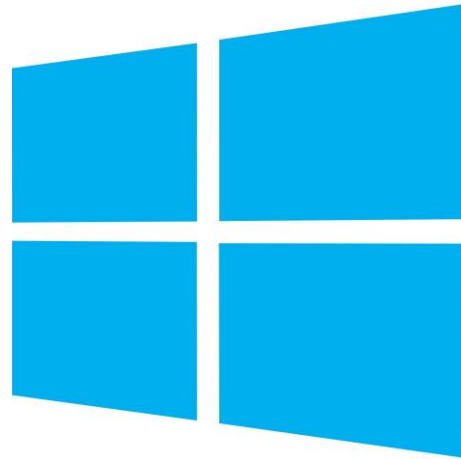


# Backup slides

# Supported operating systems



**GNU/Linux**  
64-bit, glibc 2.35

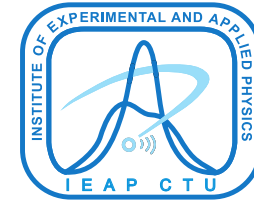


**Windows 10**  
64-bit (X64 or ARM)



**macOS 14 Monterey**  
Intel & M1 compatible

# Version history

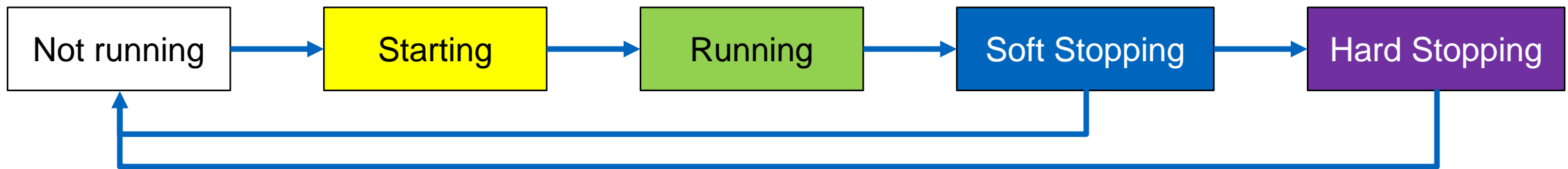


Date	Release
2020-11-04	v0.1 – initial release, very rudimentary DAQ for single readout
2021-03-10	v0.2 – multiple readouts, full configuration GUI, settings import
2021-05-05	v0.3 – pixel masking, beta threshold equalization, data flow monitor
2021-05-06	<i>v0.3.1 – quick bug fix</i>
2021-07-02	v0.4 – 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
...	
<b>2023-03-01*</b>	<b>v1.0 – new data core, completely new GUI, Gen2 and Quad support</b>

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

# Data element lifecycle

Color-coded states:

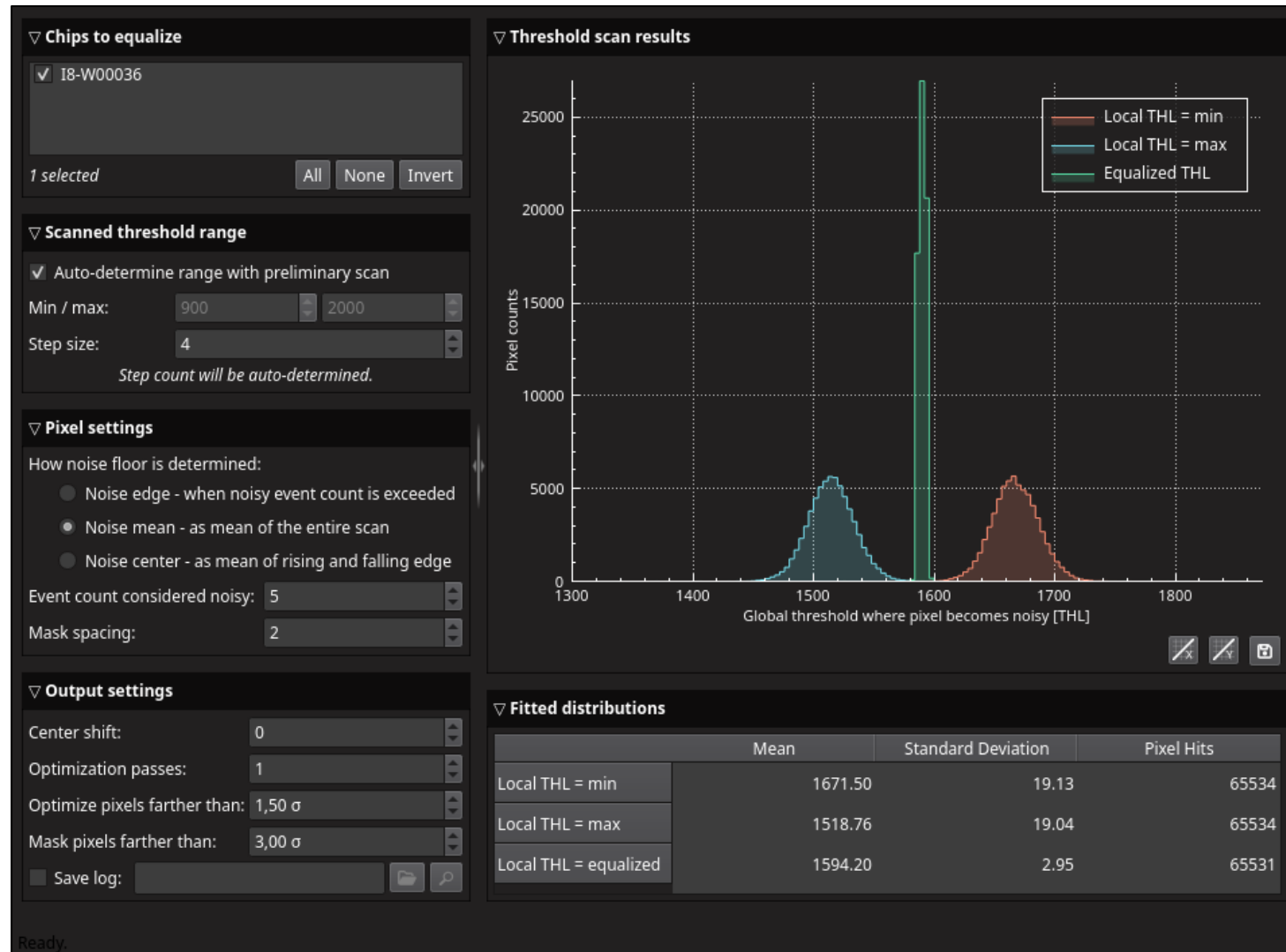


*...formulated as a state machine: state of the system is aggregation of the states of its elements.*

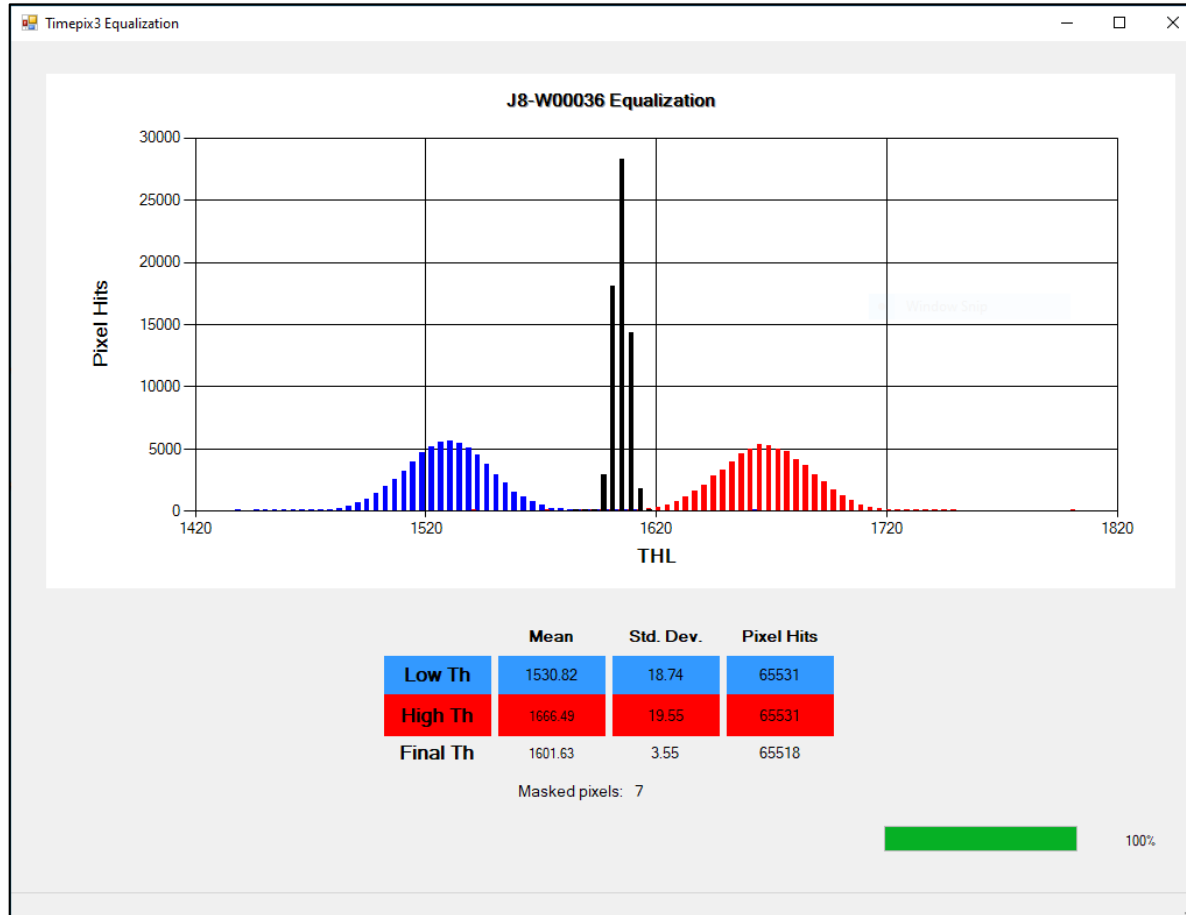
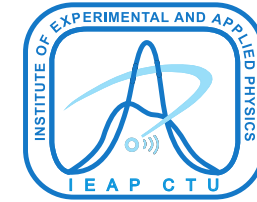
Added deterministic shutdown logic that was not previously present:

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

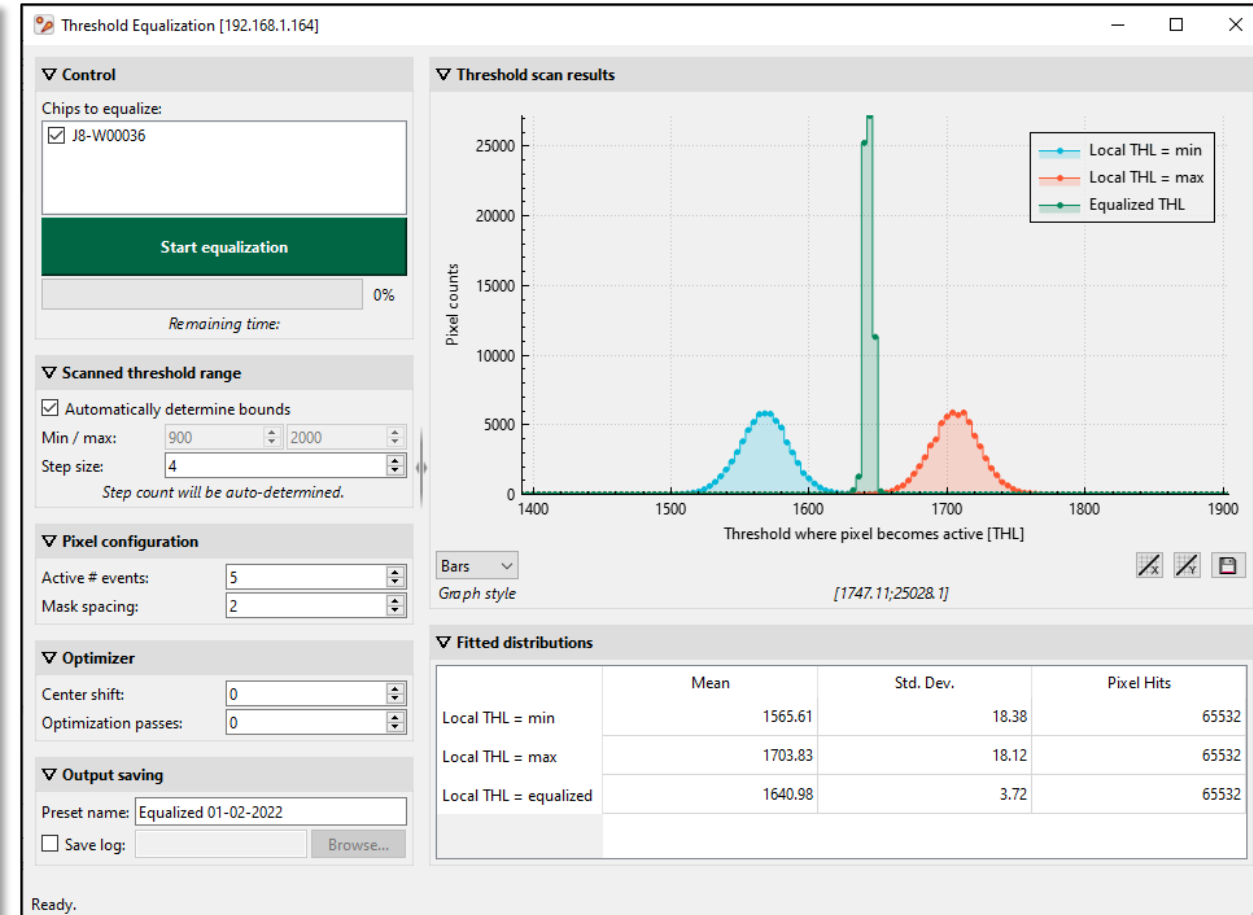
# Example of THL equalization



# Example of THL equalization

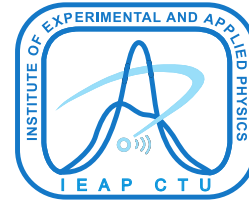


Reference software (UWB)



Track Lab

# More screenshots



Readout settings: 192.168.1.37 [1]

Acquisition Timing Trigger **Chip geometry**

C4 W00053	G6 W00053
C8 W00054	K10 W00053

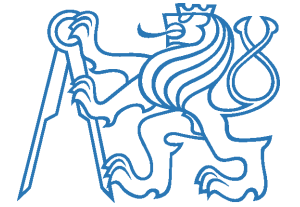
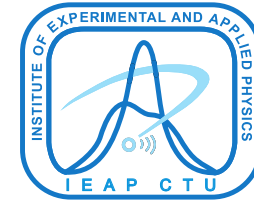
Flip:  X-axis  Y-axis  
Rotate:  0°  90°  180°  270°  
*(all rotations counterclockwise)*  
Offset X: 256 px Y: 256 px  
Divide X: 1 Y: 1

*Device will be automatically reconfigured before acquisition.*

Close



# More screenshots



Timepix3 settings: K10-W00053

Threshold Mask Calibration All DACs

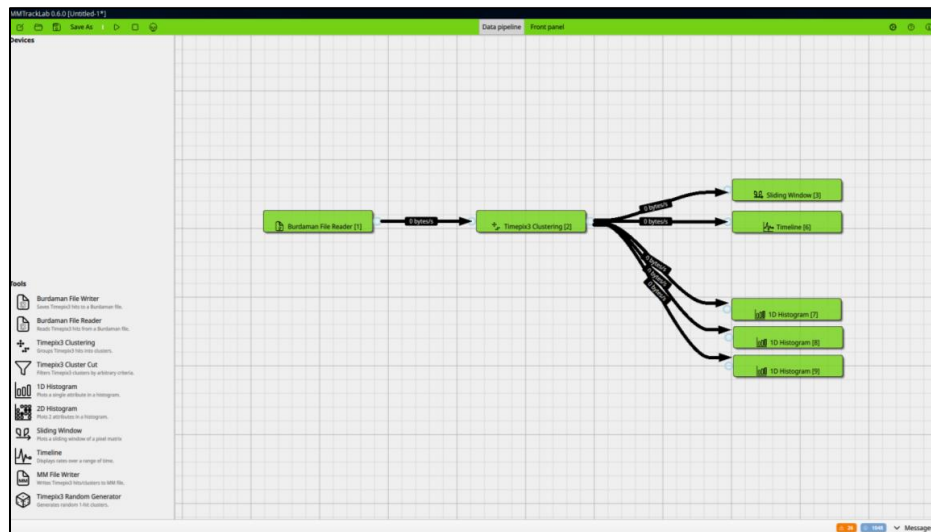
DAC:	Configured value:	Monitor:	DAC:	Configured value:	Monitor:
Ibias_Preamp_ON:	128	1.13 V	Ibias_DiscS2_ON:	128	0.33 V
Ibias_Preamp_OFF:	8	1.29 V	Ibias_DiscS2_OFF:	8	0.16 V
VPreamp_NCAS:	128	0.60 V	Ibias_PixelDAC:	140	0.91 V
Ibias_Ikrum:	15	0.89 V	Ibias_TPbufferIn:	128	1.09 V
Vfbk:	164	0.60 V	Ibias_TPbufferOut:	128	1.00 V
Vthreshold_fine:	470	0.73 V	VTP_coarse:	128	0.61 V
Vthreshold_coarse:	8	0.73 V	VTP_fine:	256	0.60 V
Ibias_DiscS1_ON:	100	0.98 V	Ibias_CP_PLL:	128	0.50 V
Ibias_DiscS1_OFF:	8	1.25 V	PLL_Vcntrl:	128	0.63 V
BandGap_output:	0	0.61 V	BandGap_temp:	0	0.64 V
Ibias_dac:	0	1.16 V	Ibias_dac_cas:	0	0.94 V

Apply DAC settings now Refresh monitors Reset to defaults

*Device will be automatically reconfigured before acquisition.*

Close

# Even more screenshots



192.168.1.168 [1]

Begin acquisition Ready 35.8 °C

Duration: 10 s

Mode: ToA + ToT  Data-driven

Calibrate:  ToT  Time-walk

Advanced: Acquisition Trigger Pulse generator  
GPIO Timestamping Geometry

Bias Voltage Supply

Channel 1:  μA 180.8 V 100 V

Timepix3 I8-W00036

I8-W00036 67.4 °C HoLes 0 px

Threshold: 1510 keV

Advanced: Threshold Adjustment Mask  
Calibration DACs Miscellaneous

Katherine settings: 192.168.1.168 [1]

Acquisition Trigger Pulse generator GPIO Timestamping Geometry

Acquisition start trigger

Input signal: Software start

Trigger event:  Rising edge  Falling edge

Delay: 0 μs

Acquisition stop trigger

Input signal: Timer (counts to frame duration)

Trigger event:  Rising edge  Falling edge

Delay: 0 μs

Ready signal composition

Composed ready = Local ready  GPIO1  GPIO2  GPIO3  GPIO4  
 ~GPIO1  ~GPIO2  ~GPIO3  ~GPIO4

Device will be automatically reconfigured before acquisition. Close

Katherine settings: 192.168.1.168 [1]

Acquisition Trigger Pulse generator GPIO Timestamping Geometry

Input trigger

Oscillator Frequency: 10 000 Hz

Signal Source: Local ready signal Event:  Rising edge  Falling edge

Generated outputs

Only enable output when acquisition is running (or ready to be started)

	Pulse delay	Pulse duration	Modifiers
<input type="checkbox"/> Internal channel	0 μs	0 μs	<input type="checkbox"/> Bypass <input type="checkbox"/> Invert
<input checked="" type="checkbox"/> Channel 1	0 μs	10 μs	<input type="checkbox"/> Bypass <input type="checkbox"/> Invert
<input checked="" type="checkbox"/> Channel 2	2 μs	10 μs	<input type="checkbox"/> Bypass <input type="checkbox"/> Invert
<input type="checkbox"/> Channel 3	0 μs	0 μs	<input type="checkbox"/> Bypass <input type="checkbox"/> Invert

Apply pulse generator settings now Reset to defaults

Device will be automatically reconfigured before acquisition. Close

Katherine settings: 192.168.1.168 [1]

Acquisition Trigger Pulse generator GPIO Timestamping Geometry

Time-of-Arrival clock settings

Frequency:  40 MHz  80 MHz  160 MHz

Phase distribution:  1  2  4  8  16

Enable fast voltage-controlled oscillator (640 MHz)

Assign Time-of-Arrival timestamps to signals

Label	Source signal	Trigger event
<input checked="" type="checkbox"/> Event 1 scint	GPIO 1	<input checked="" type="radio"/> Rising edge <input type="radio"/> Falling edge
<input checked="" type="checkbox"/> Event 2 feedback	GPIO 2	<input checked="" type="radio"/> Rising edge <input type="radio"/> Falling edge
<input type="checkbox"/> Event 3 Name this event...	GPIO 1	<input checked="" type="radio"/> Rising edge <input type="radio"/> Falling edge
<input type="checkbox"/> Event 4 Name this event...	GPIO 1	<input checked="" type="radio"/> Rising edge <input type="radio"/> Falling edge
<input type="checkbox"/> Event 5 Name this event...	GPIO 1	<input checked="" type="radio"/> Rising edge <input type="radio"/> Falling edge

Device will be automatically reconfigured before acquisition. Close

Katherine settings: 192.168.1.168 [1]

Acquisition Trigger Pulse generator GPIO Timestamping Geometry

Signal mapping

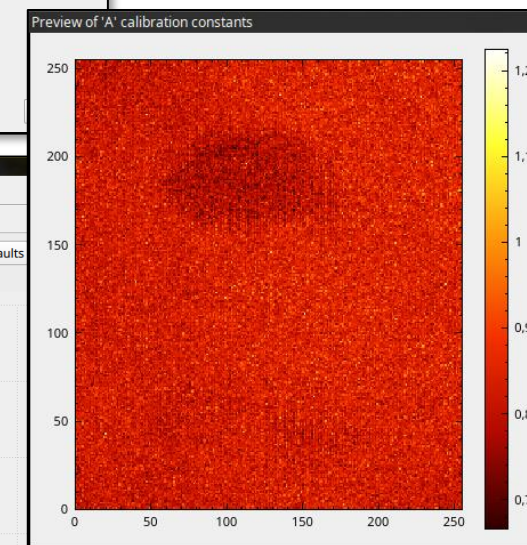
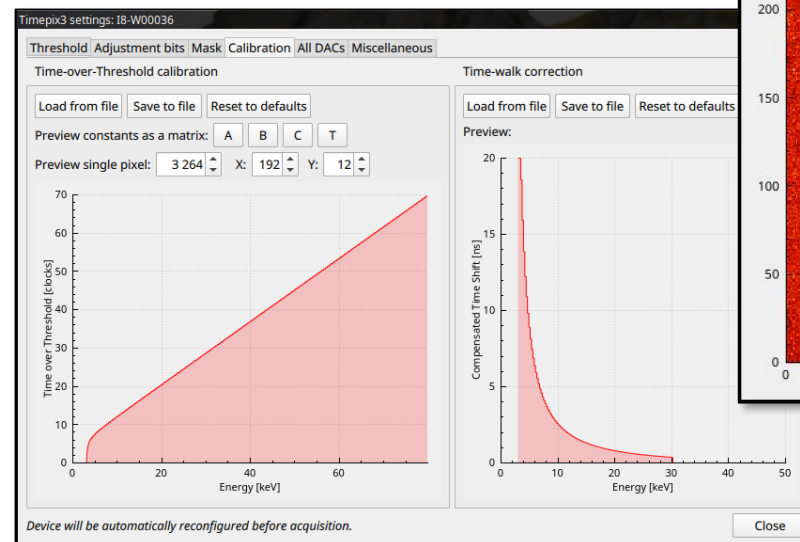
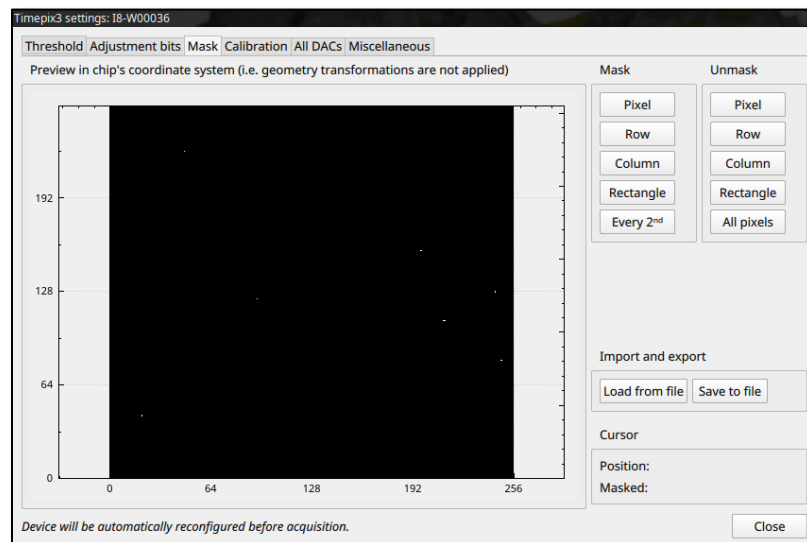
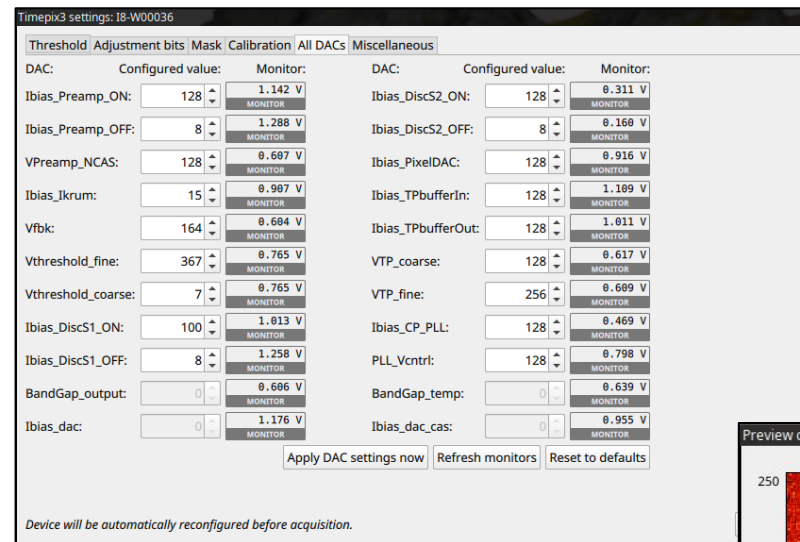
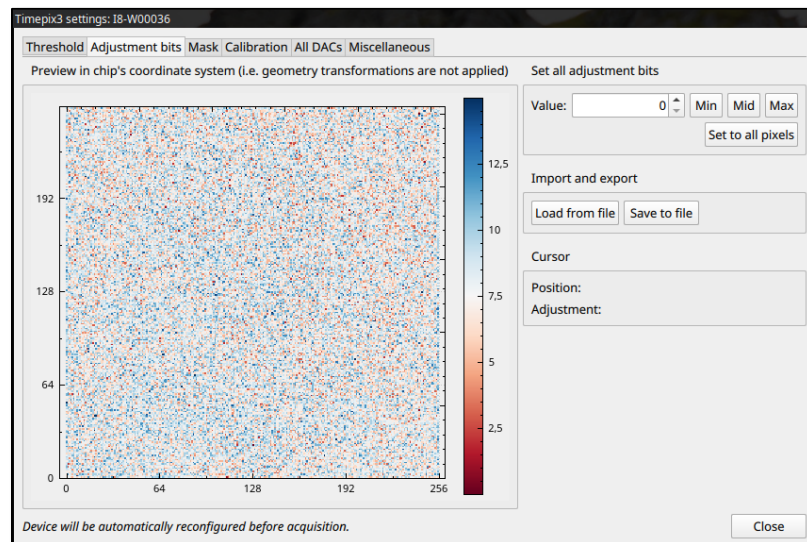
Port	Map to signal	Termination	Monitor
GPIO 1:	Input	<input type="checkbox"/> 100 Ω	<input checked="" type="checkbox"/> Constant low MONITOR
GPIO 2:	Input	<input type="checkbox"/> 100 Ω	<input checked="" type="checkbox"/> Constant low MONITOR
GPIO 3:	Input	<input type="checkbox"/> 100 Ω	<input checked="" type="checkbox"/> Constant low MONITOR
GPIO 4:	Input	<input type="checkbox"/> 100 Ω	<input checked="" type="checkbox"/> Constant low MONITOR
GPIO 5*:	Input	<input type="checkbox"/> 100 Ω	---
GPIO 6*:	Input	<input type="checkbox"/> 100 Ω	---
GPIO 7*:	Input	<input type="checkbox"/> 100 Ω	---
GPIO 8*:	Input	<input type="checkbox"/> 100 Ω	---

\*Some ports may not be accessible from outside of the enclosure.

Apply GPIO settings now Refresh monitors Reset to defaults

Device will be automatically reconfigured before acquisition. Close

# Even more screenshots



# Multi-chip configurations

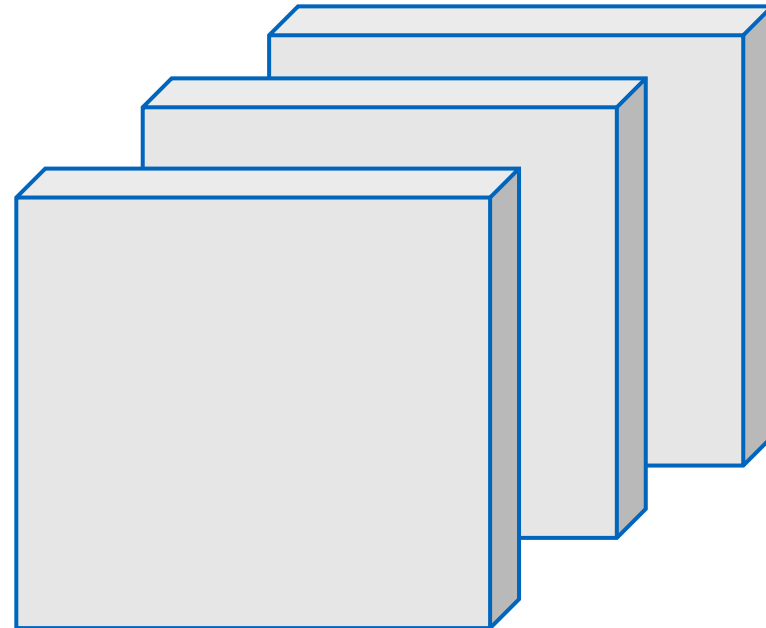
## Description (agreed with LM & PB):

- 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

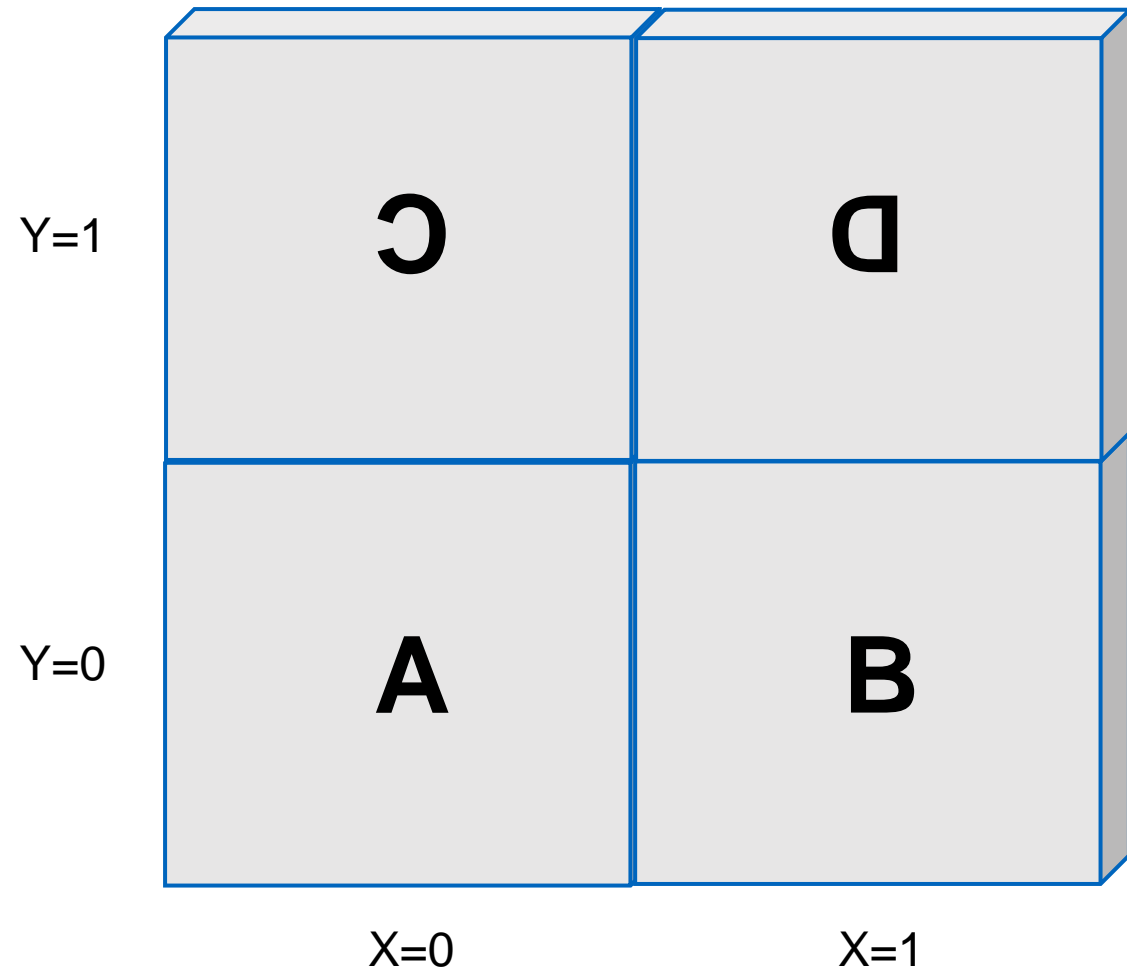
- Layer #1:  $[X;Y;Z]$ 
  - Chip,  $[0;0]$ ,  $0^\circ$  rotation
- Layer #2:  $[X;Y;Z+dz]$ 
  - Chip,  $[0;0]$ ,  $0^\circ$  rotation
- Layer #3:  $[X;Y;Z+2dz]$ 
  - Chip,  $[0;0]$ ,  $0^\circ$  rotation



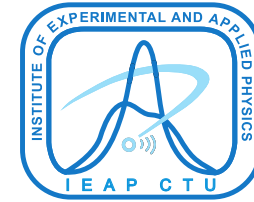
# Multi-chip configurations

## Example: 4-chip quad

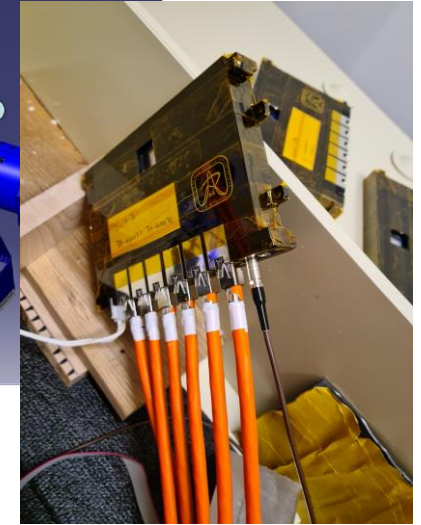
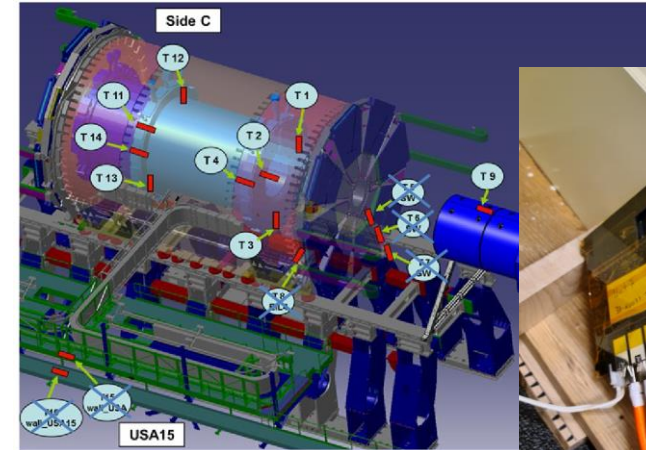
- Layer #1: [X;Y;Z]
  - Chip A, [0;0], 0° rotation
  - Chip B, [1;0], 0° rotation
  - Chip C, [1;0], 180° rotation
  - Chip D, [1;1], 180° rotation



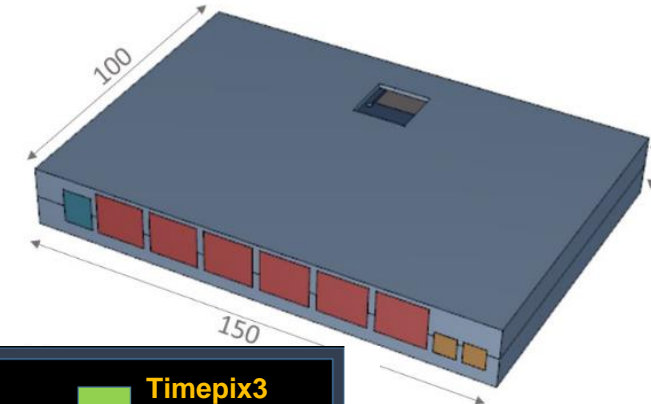
# ATLAS-TPX3 network



- 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:

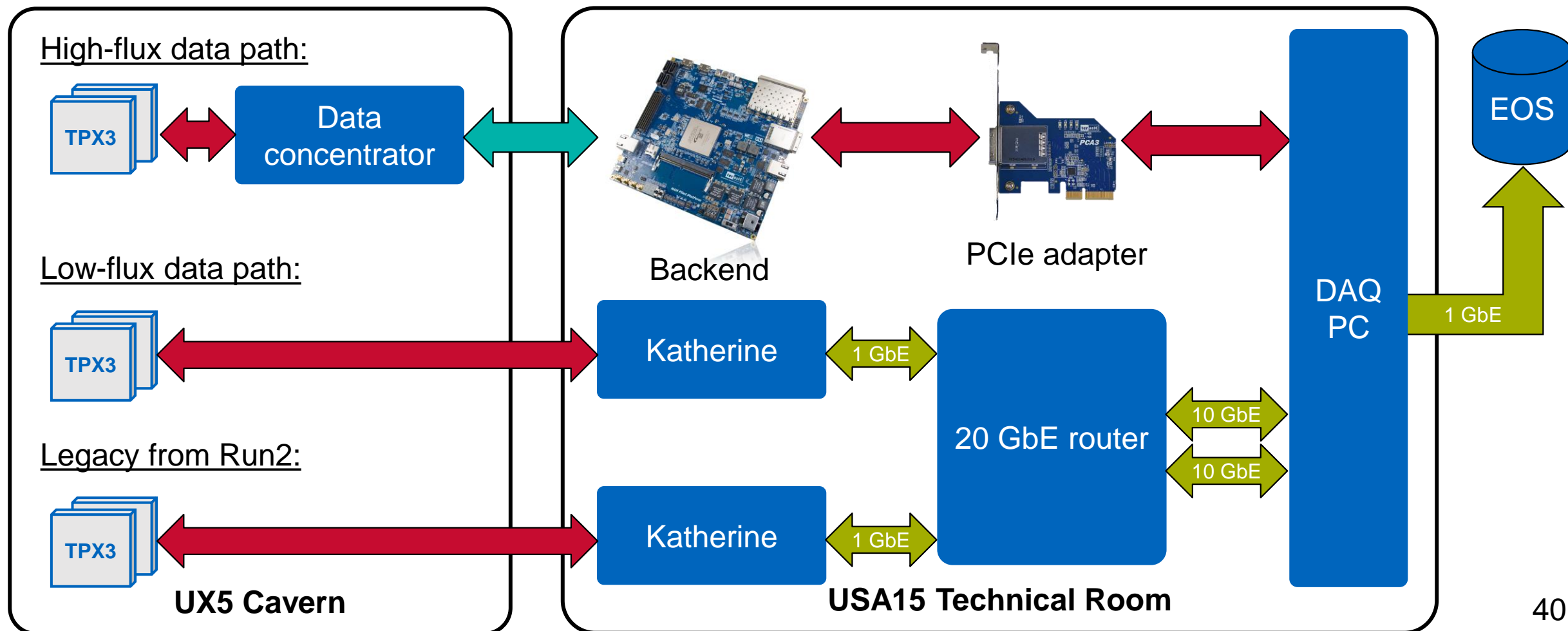
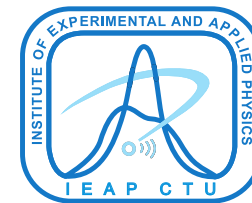


Profile:



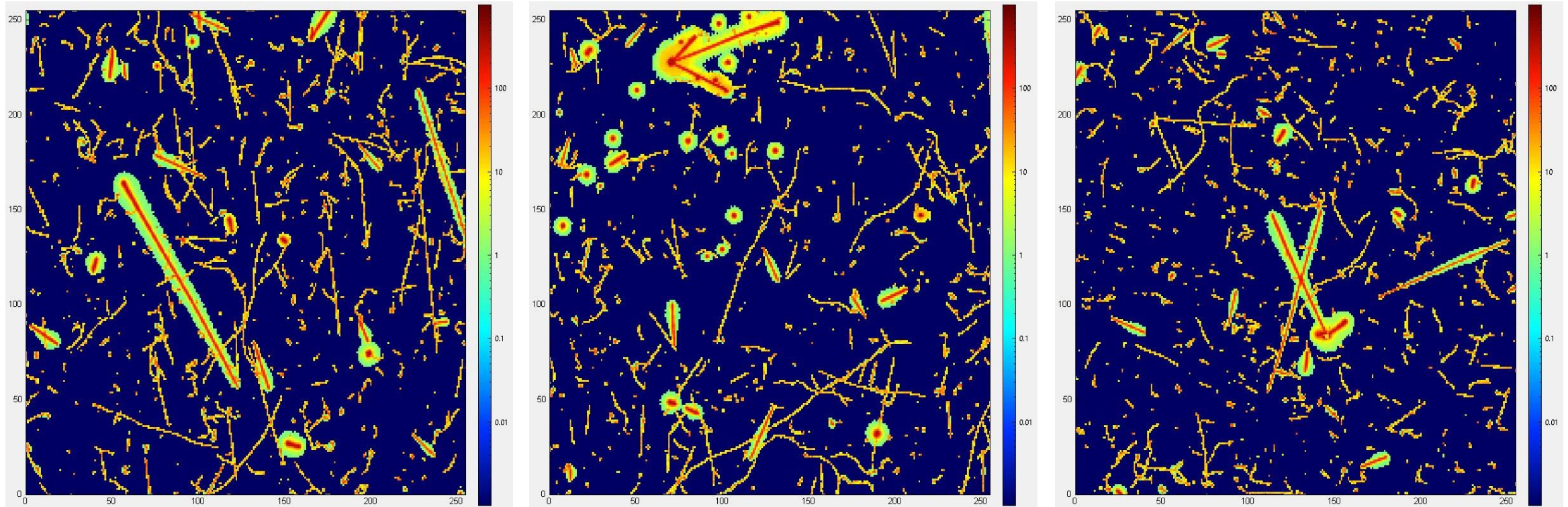
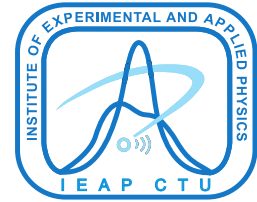
Proposal to measure the time dependence of the radiation field, induced radioactivity and luminosity with a network of Timepix3 detectors in ATLAS. (ATLAS Int. Note, 2021-03-16)

# Data acquisition diagram

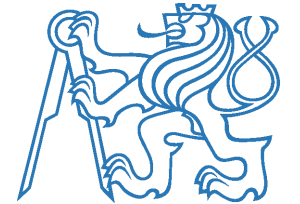
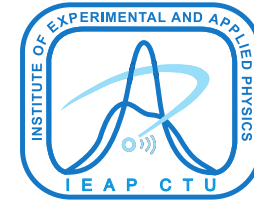




# First data! (autumn 2022)



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



Thank you for listening!

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<https://software.utef.cvut.cz>