A Trigger and DAQ system for Test Beams

The EUDET-type Beam Telescopes

Jan Dreyling-Eschweiler
jan.dreyling-eschweiler@desy.de
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Prelude

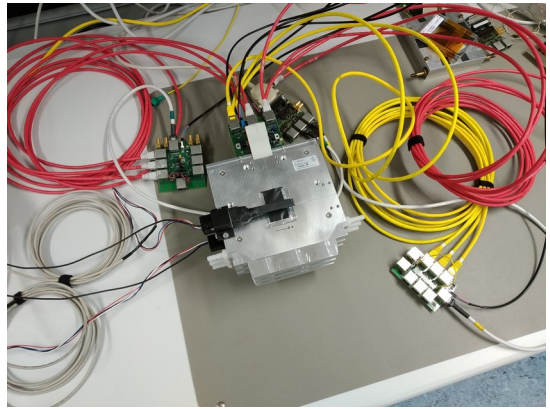
- Thanks: Simon Spannagel for some slides of his talk at ISOTDAQ2018
- Disclaimer: I am working since 2015 in this area, the development started 2006 on this common tool and infrastructure!
- Reminder: Where/What is DESY?

Deutsches Elektron-Synchrotron, Hamburg, Germany

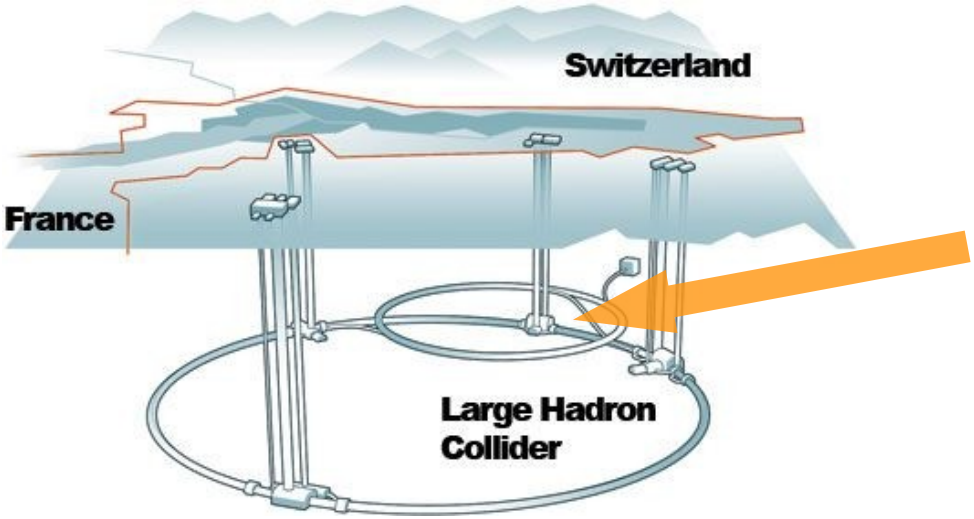
Note: HERA (6.3km) was shutdown in 2007 (Gluons in Proton)

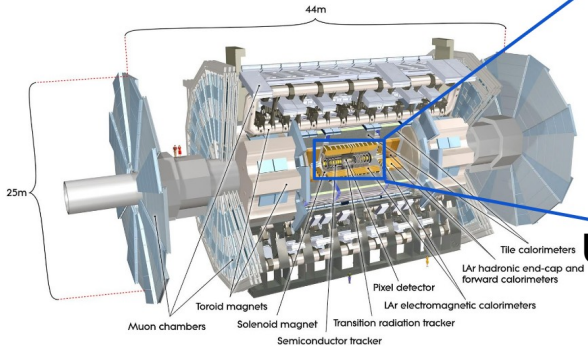
Outline

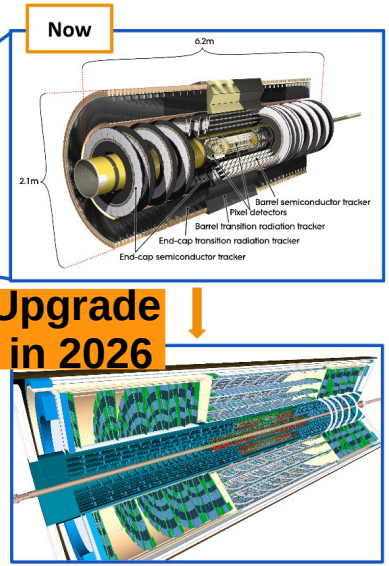
- What is a Test Beam and a Beam Telescope?
- TDAQ system of the EUDET-type Beam Telescopes
  - Sensors and Trigger Logic
  - Software framework
  - Operating the system
- Improving the TDAQ system



R&D of detectors in particle physics







E.g. ATLAS Inner Tracker (ITk) upgrade for the high-luminosity LHC

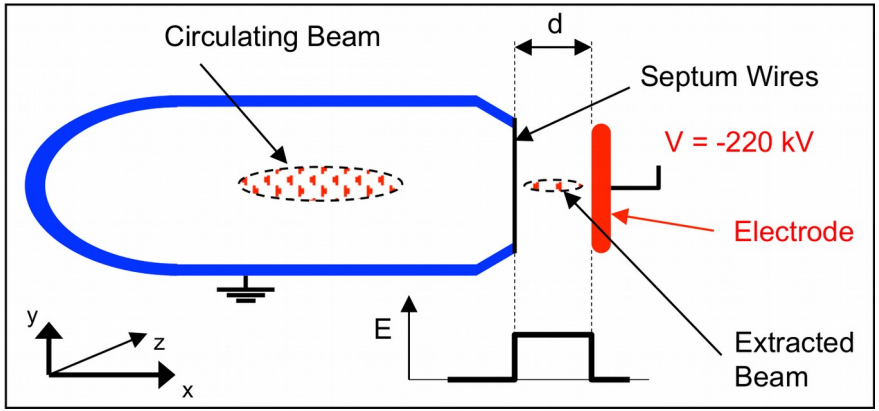
- Challenge for tracking detectors: higher **particle flux** (rate per area)
- In total ~12 years of R&D in laboratories and at **test beams**

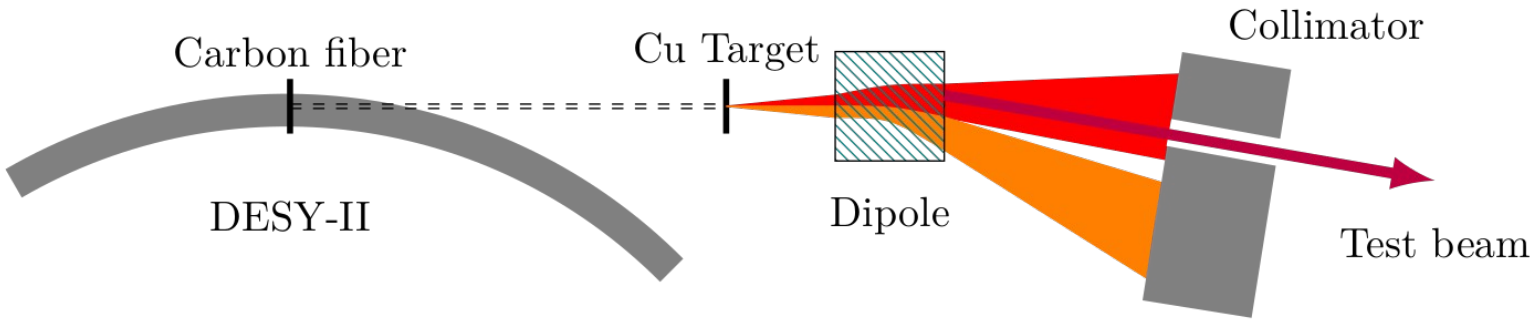
What is a Test Beam?

*Well-known charged **particle** source extracted from accelerators for **measuring** sensor response.*

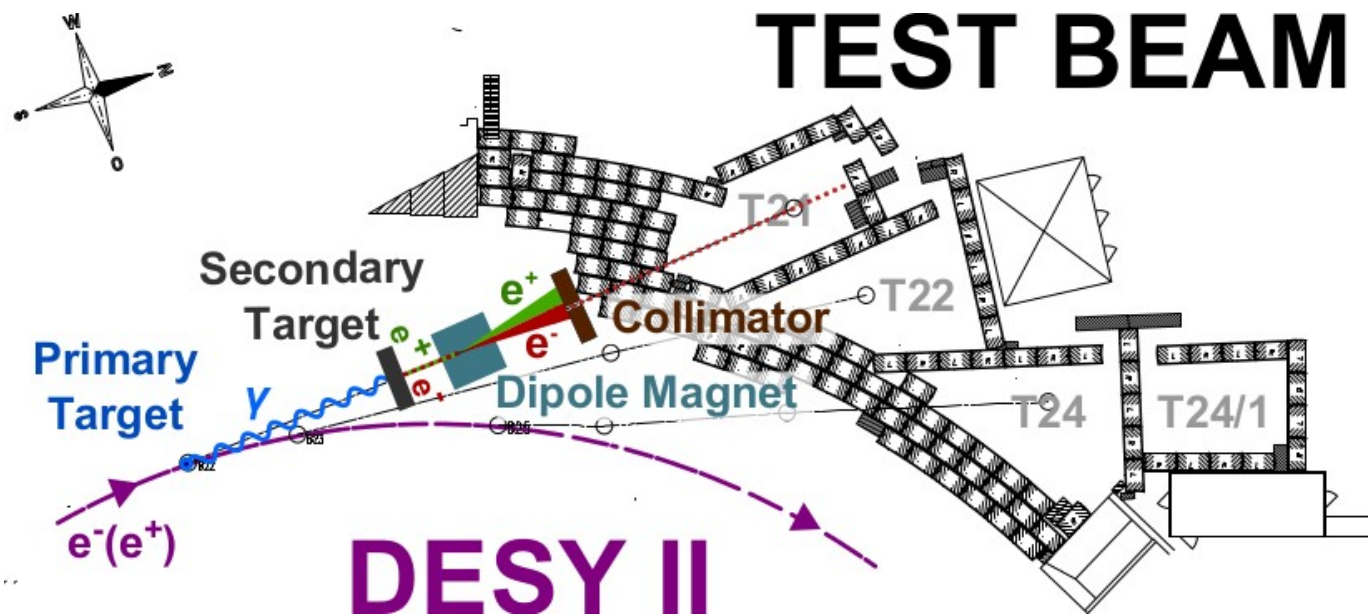
Beam Generation

- “Extraction” of charged particles from accelerators
- Dedicated source for detector & electronics testing (in HEP)
- @CERN, SPS: Slow extraction
- @DESY, DESYII: Conversion





DESY II Test Beam Facility



- 3 beam lines
- Continuous-like **electron** (positron) source
- Selectable momenta between **1-6 GeV/c**
- Average particle flux (@ 2 GeV/c): **1-10 kHz/cm²** electrons

SLAC NATIONAL ACCELERATOR LABORATORY

PAUL SCHERRER INSTITUT PSI

MAMI MAINZER MIKROTRON

CERN

Budker Institute of Nuclear Physics

ELSA

Fermilab

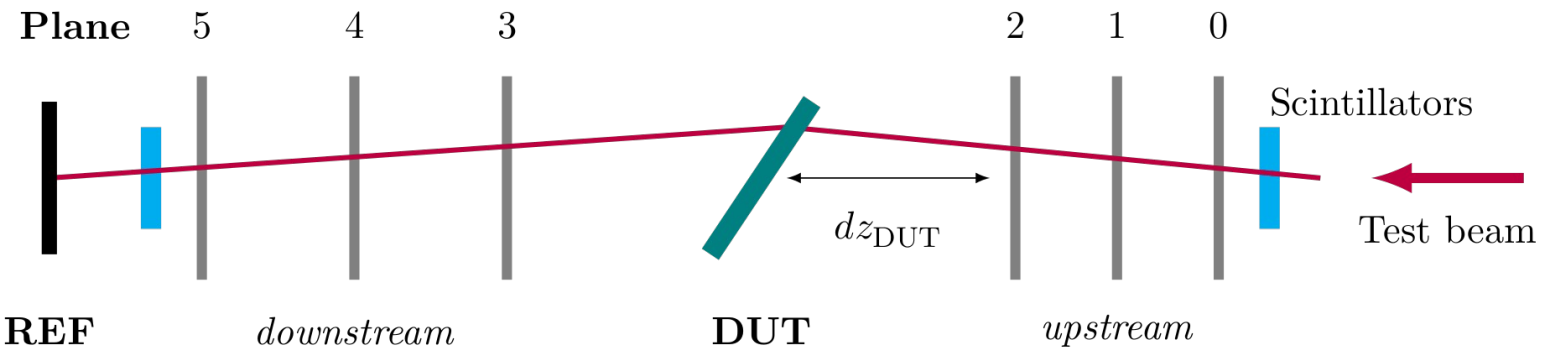
DESY.

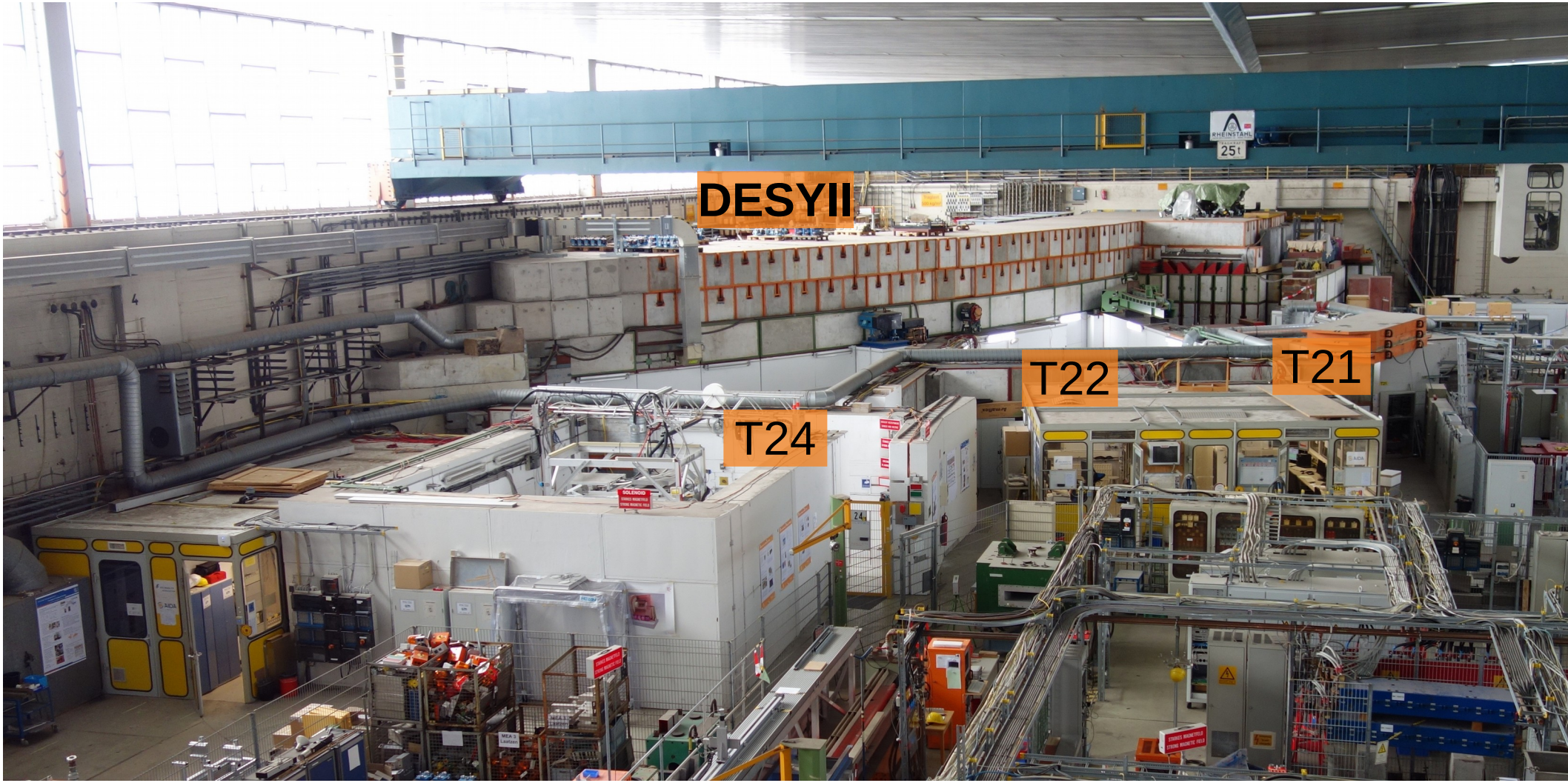
INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

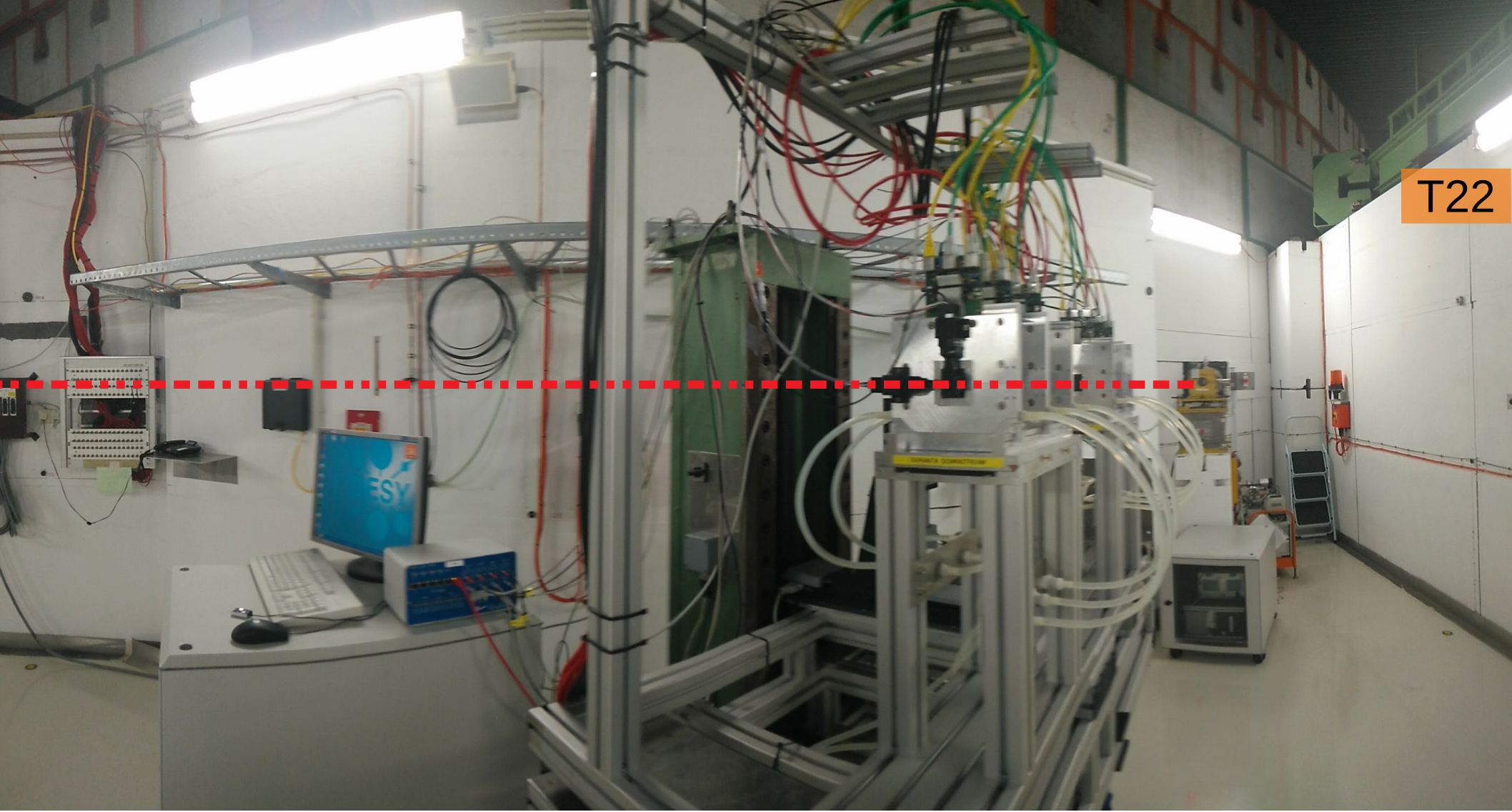
Many accelerators – many beams – many different parameters

Typical Test Beam Setup

- New sensor/detector prototypes require testing
  - Operated as “device under test” (**DUT**)
  - Quantify properties/response with respect to well-known reference
- Reference particle tracks provided by a **beam telescopes / tracker**
  - Two arms, place DUT in the center (best spatial resolution)




DESYII
T24
T22
T21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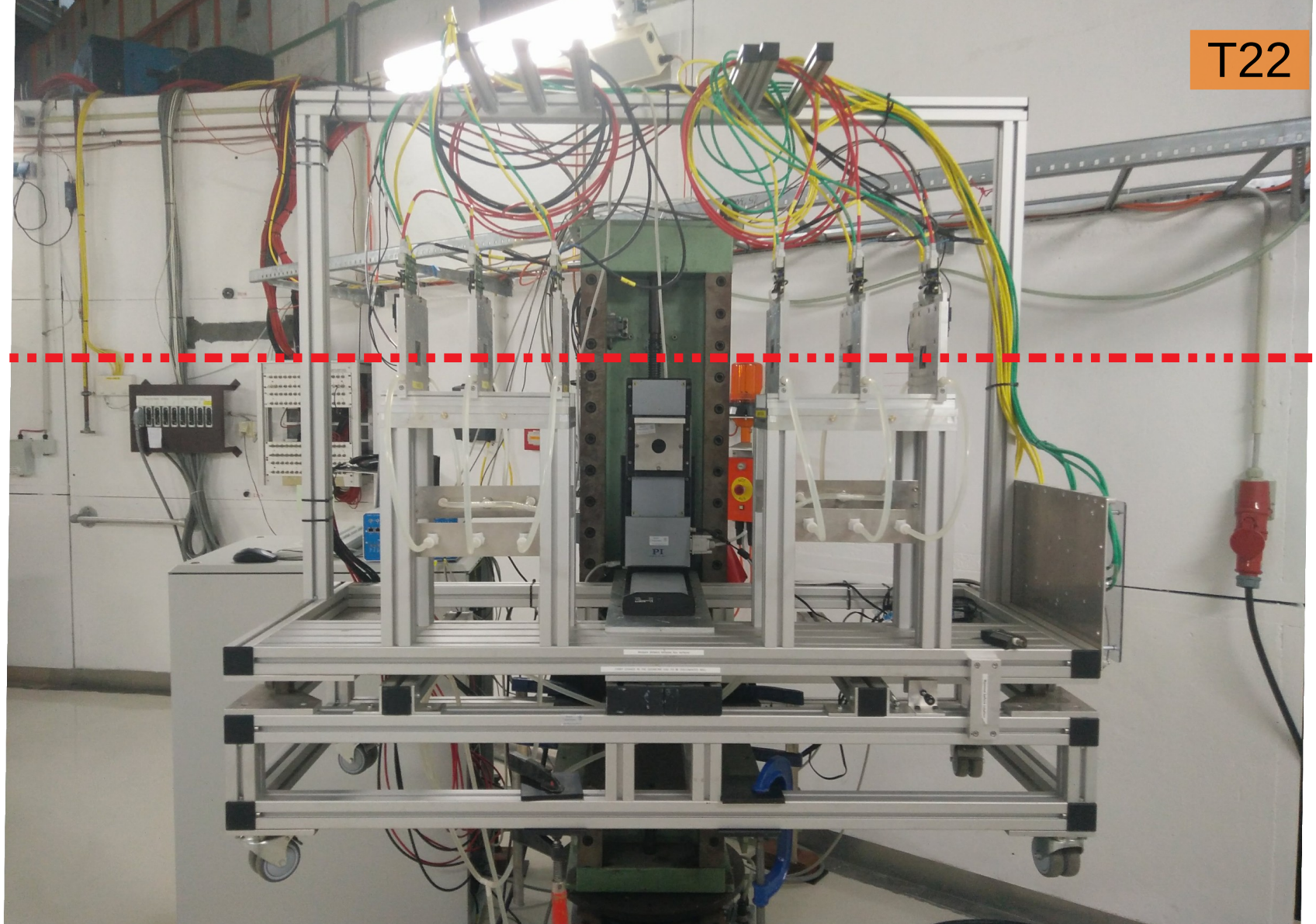
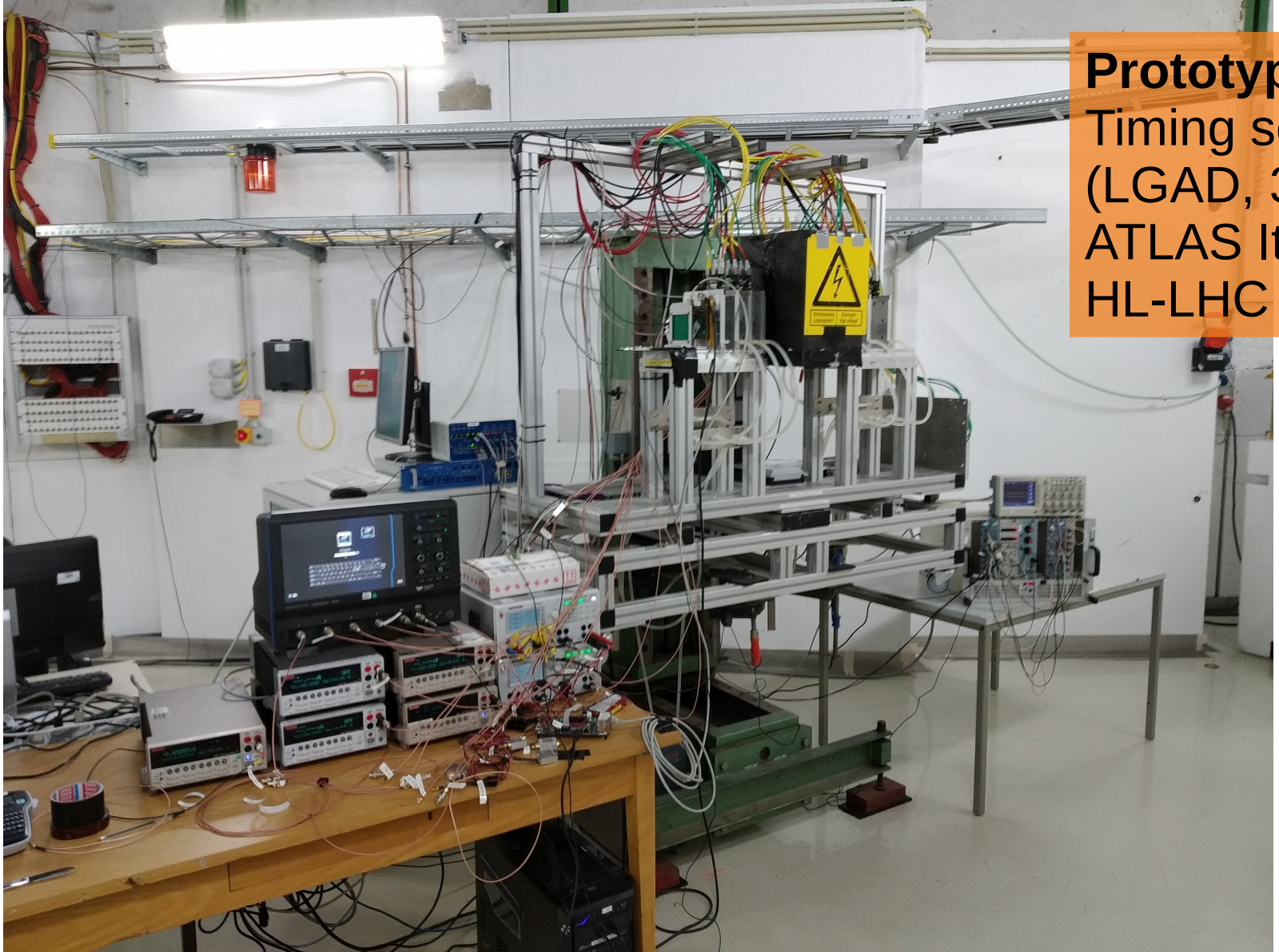

T22

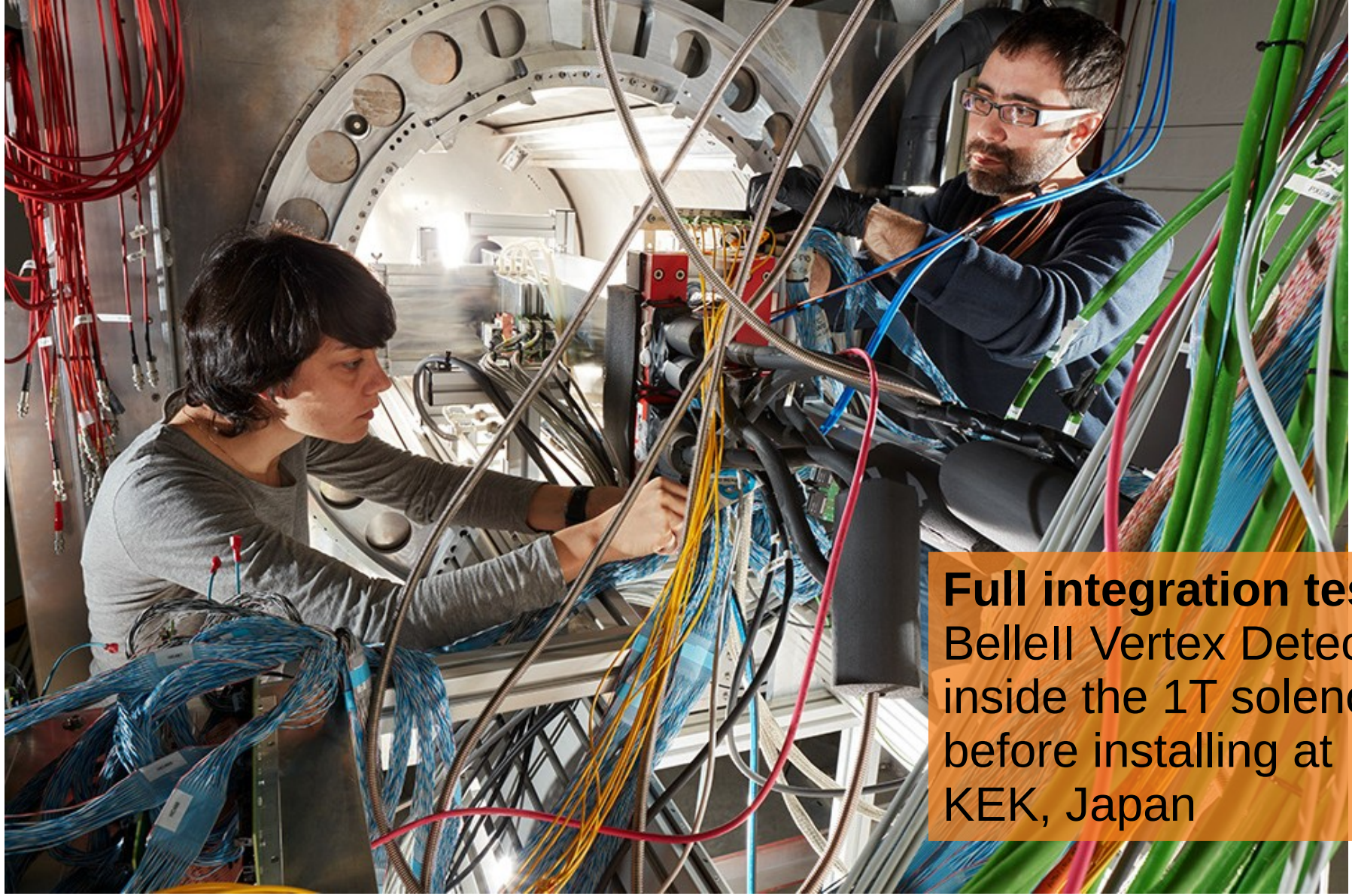
Why test beams?

- Laboratory setups are limited
  - Particles only from radioactive sources (< MeV)
  - Usually no reference measurement → no efficiency measurements
- Test beam measurements allow full testing
  - Operate close to final deployment situation
  - Externally triggered
  - Spatial & temporal correlation with other devices
- Run device as in **final experiment**: multiple layers, tracking, alignment…

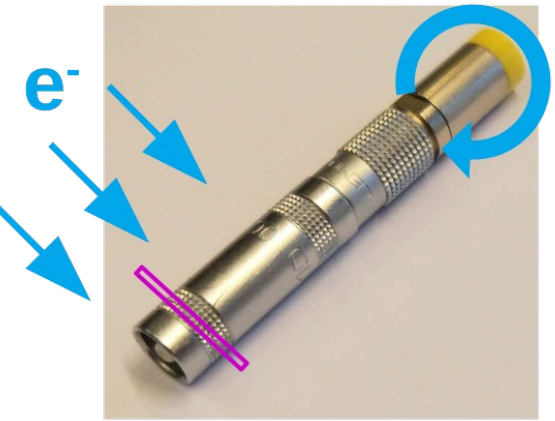


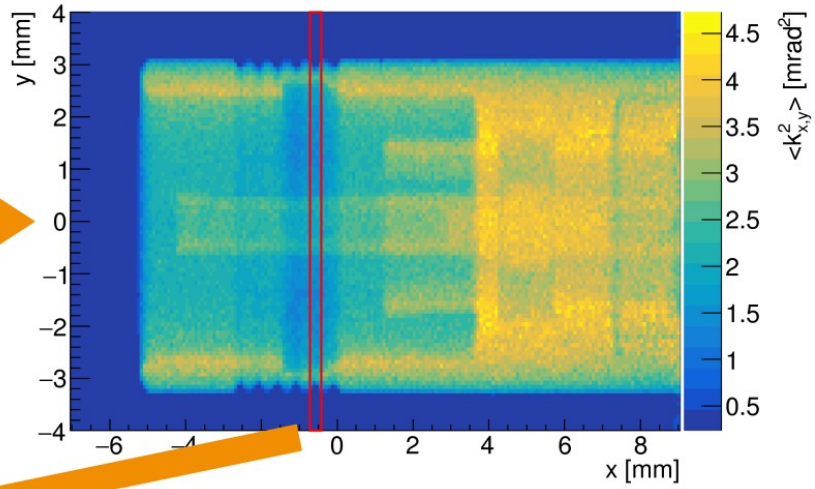
Prototyping:
Timing sensors (LGAD, 3D)
ATLAS Itk for the HL-LHC upgrade

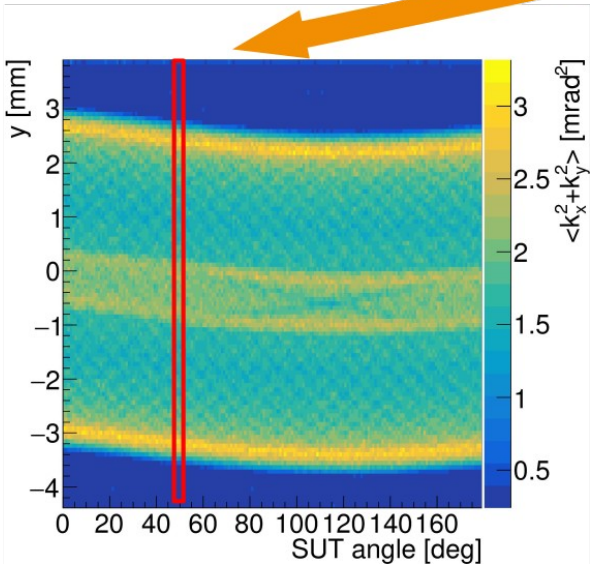
Property studies: Tracker module (Strips) ATLAS ITk for the HL-LHC upgrade 2025

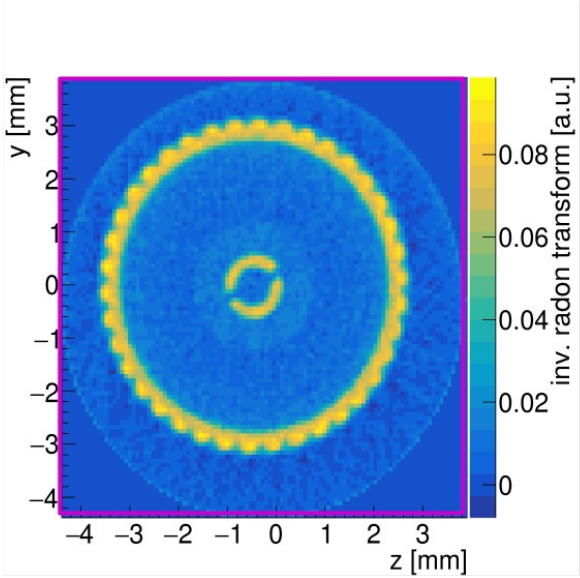


Full integration tests:
BelleII Vertex Detector inside the 1T solenoid before installing at KEK, Japan





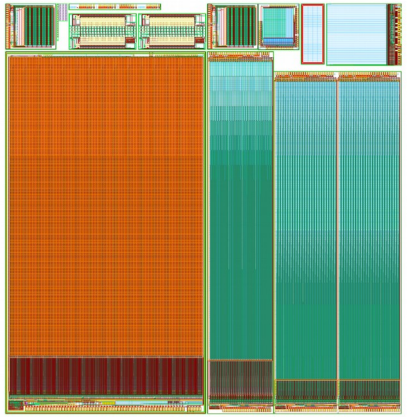


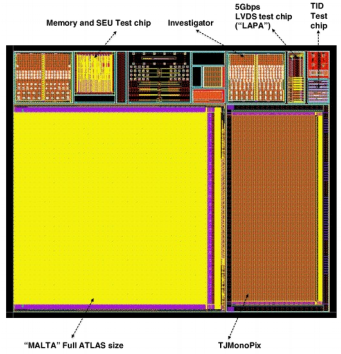


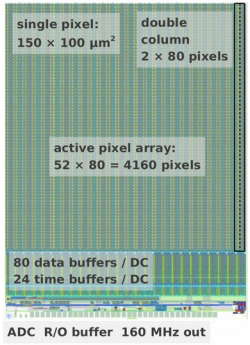
Material Budget Imaging (X0) and Tomography:
Using the scattering angle. For thick scatterer.

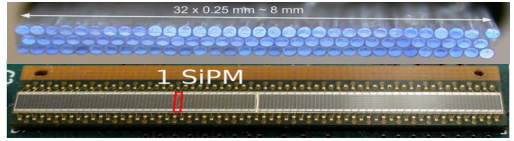
Why special TDAQ needs?

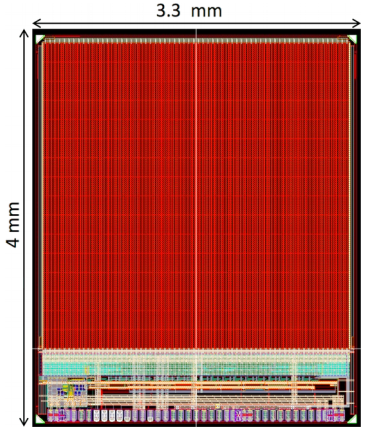
- Rapid turnaround in prototyping detectors / front-ends
- Many different groups – with similar needs
  - Vertex, tracking detectors, calorimeters, timing...

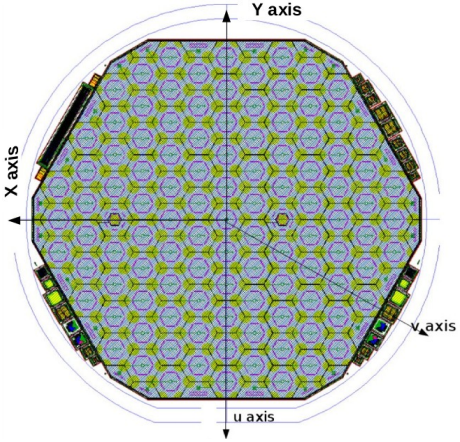


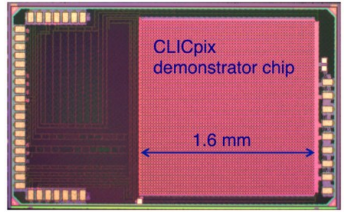


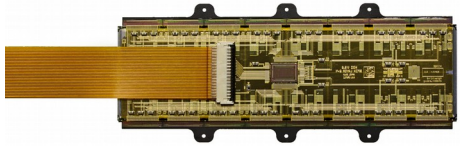




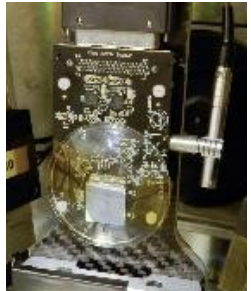








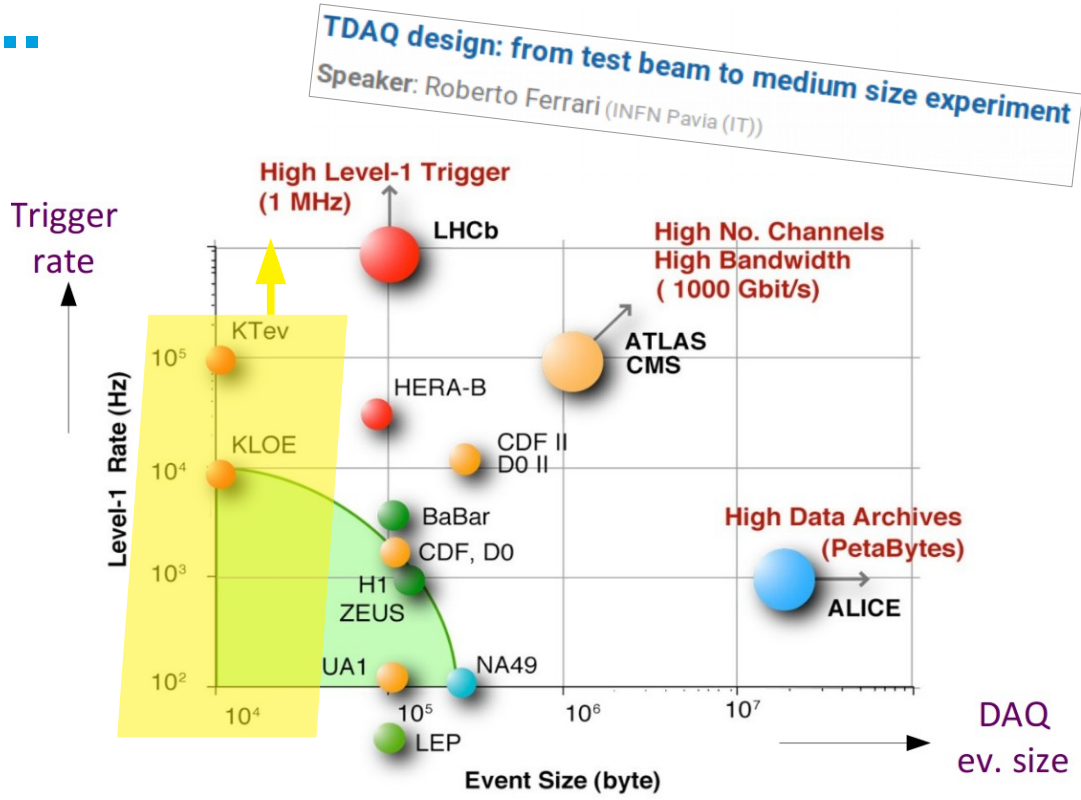
(not to scale)



Task: combine detectors...

- with different DAQ systems
  - … with and without clocks
  - … triggered, untriggered
  - … different read-out schemes
- at various beam lines
  - … with different rates
  - … beam energies
  - … availability of infrastructure

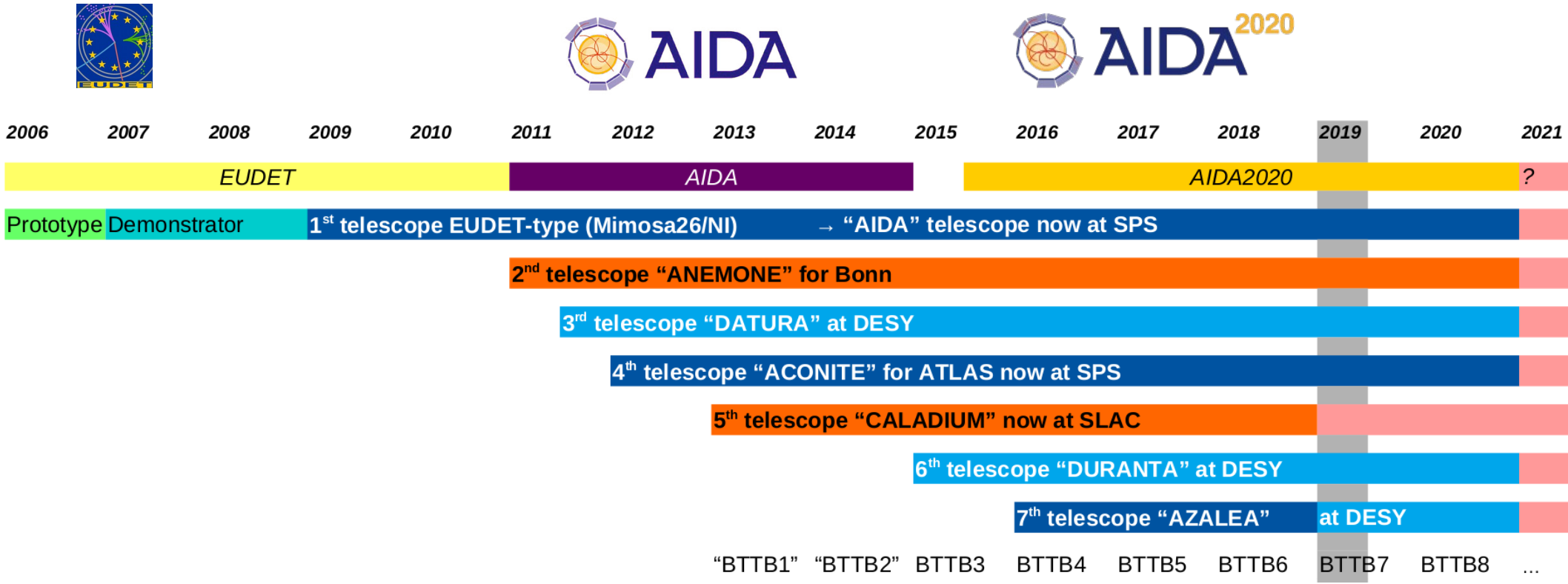
… on a very **short time scale & limited manpower**



How to cope with this?

- Common infrastructure! Since 2006.
  - reduces resource needs per development cycle
  - Developed within EU framework programs (EUDET → AIDA → AIDA2020 → ???)
- “EUDET-type beam telescopes”
  - 7 copies produced
  - Located at DESY, CERN, Bonn, SLAC
- Trigger Logic, DAQ & reconstruction software
- Support for whole system offered by DESY

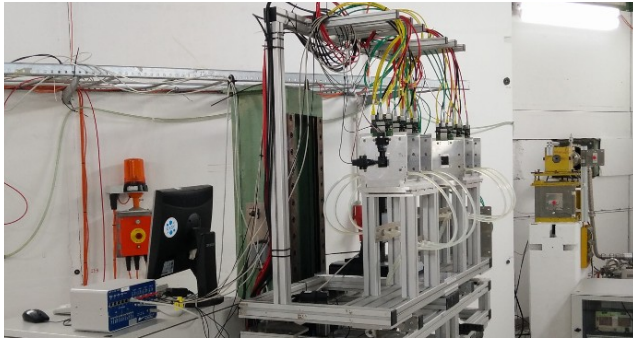
Infrastructure: 7 copies around the world



The EUDET-type telescope infrastructure

Hardware

- **6x Mimosa sensors & DAQ**
- Mechanics
- **Trigger System**

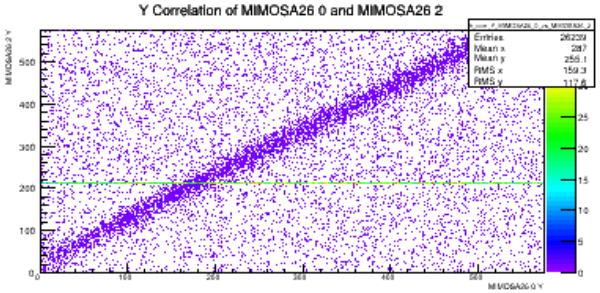


telescopes.desy.de

EUDAQ

Top-Level DAQ software

- **Central run control & monitoring**
- **Synchronisation & acquisition**

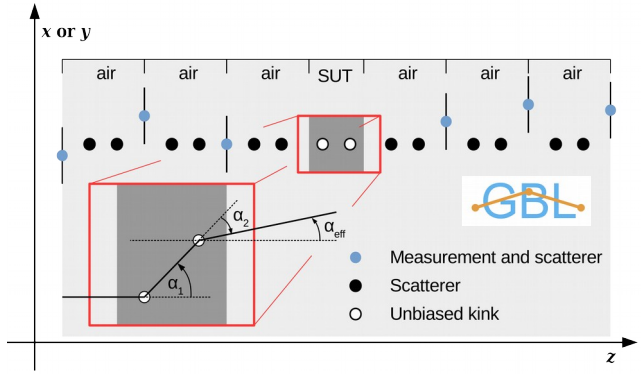


eudaq.github.io

EUTelescope

Track reconstruction framework

- Masking, Clustering, Alignment, ...
- Track finding & results



eutelescope.github.io

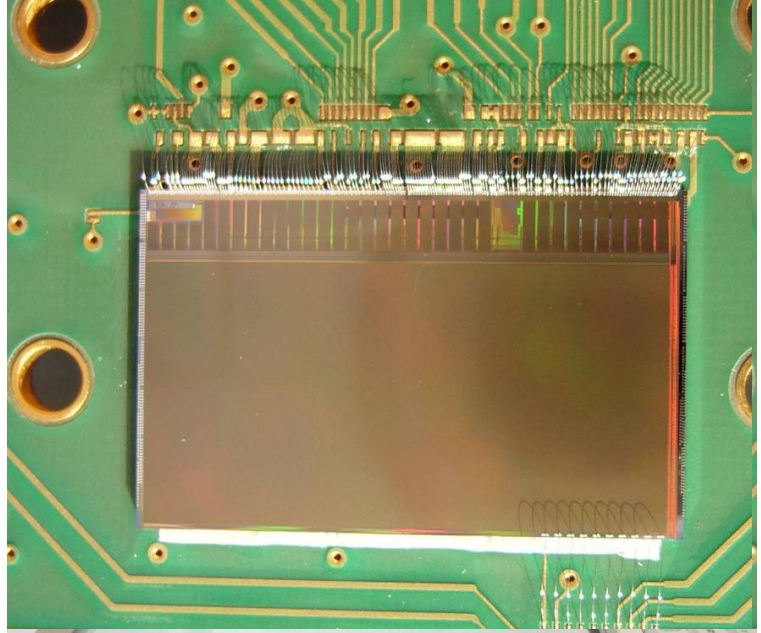
TDAQ of the EUDET-type Beam Telescopes

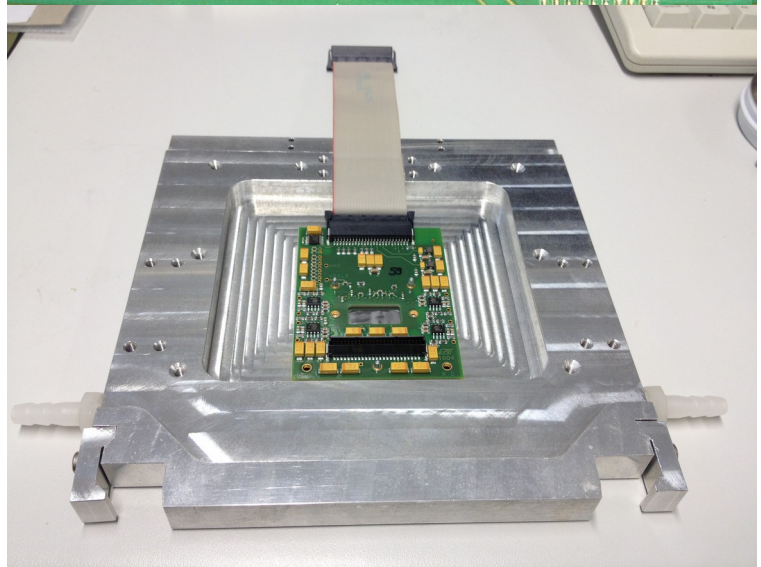
The Telescope System

- Tracking sensors & DAQ
- Trigger Logic Unit (& DAQ)
- DAQ software
- Others
  - um-precision xy-stage
  - Local network
  - Raid disk
  - Slow control options
  - ...

MIMOSA26 Sensor

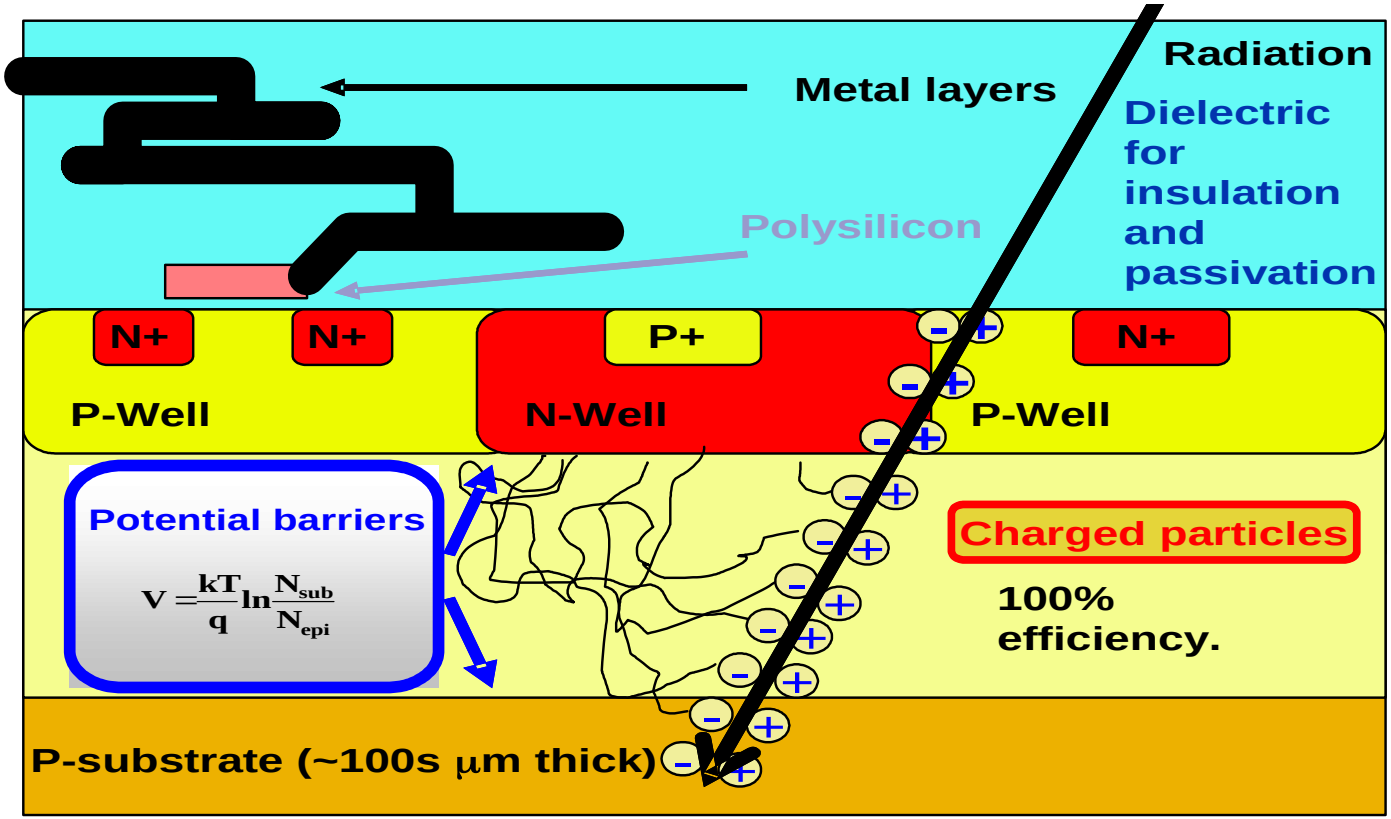
- MAPS ”Monolithic Active Pixel Sensor”
  - 50um silicon (of which ~15um depleted)
  - Pitch 18.4x18.4um, res. ~3um
  - 2x1cm active area
- All FE electronics implemented
  - Integration time ~115.2us
  - Rolling shutter readout
  - Correlated double sampling
  - → 10^6 particles/cm^2/s





For more details see the Manual:
https://twiki.cern.ch/twiki/pub/MimosaTelescope/MIMOSA26/M26_UserManual_LQ.pdf

Silicon CMOS pixel for particle detection



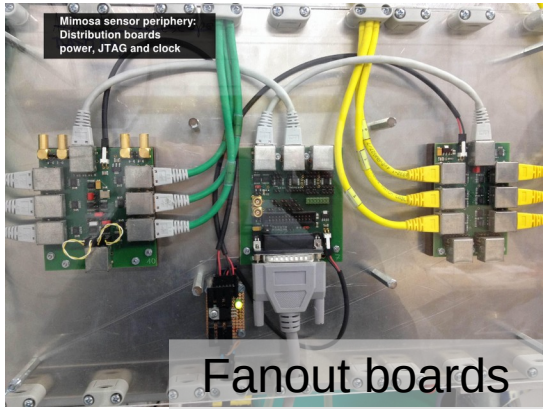
Doped Silicon → Depletion zone → built-in bias voltage → Drift field

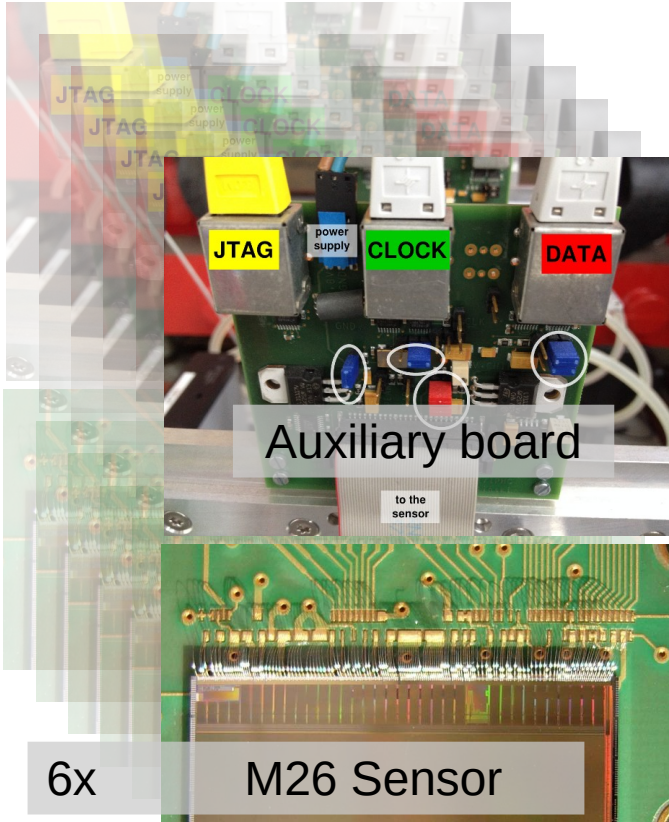
Commercial off-the-shelf hardware for DAQ

- National Instruments system: NI PXIe crate (CPU system)
  - FlexRIO FPGA card (Xilinx Virtex5) + front-end for data input
  - Parallel port for slow control (JTAG)
  - + No custom DAQ to be developed
    - Relatively high cost per system

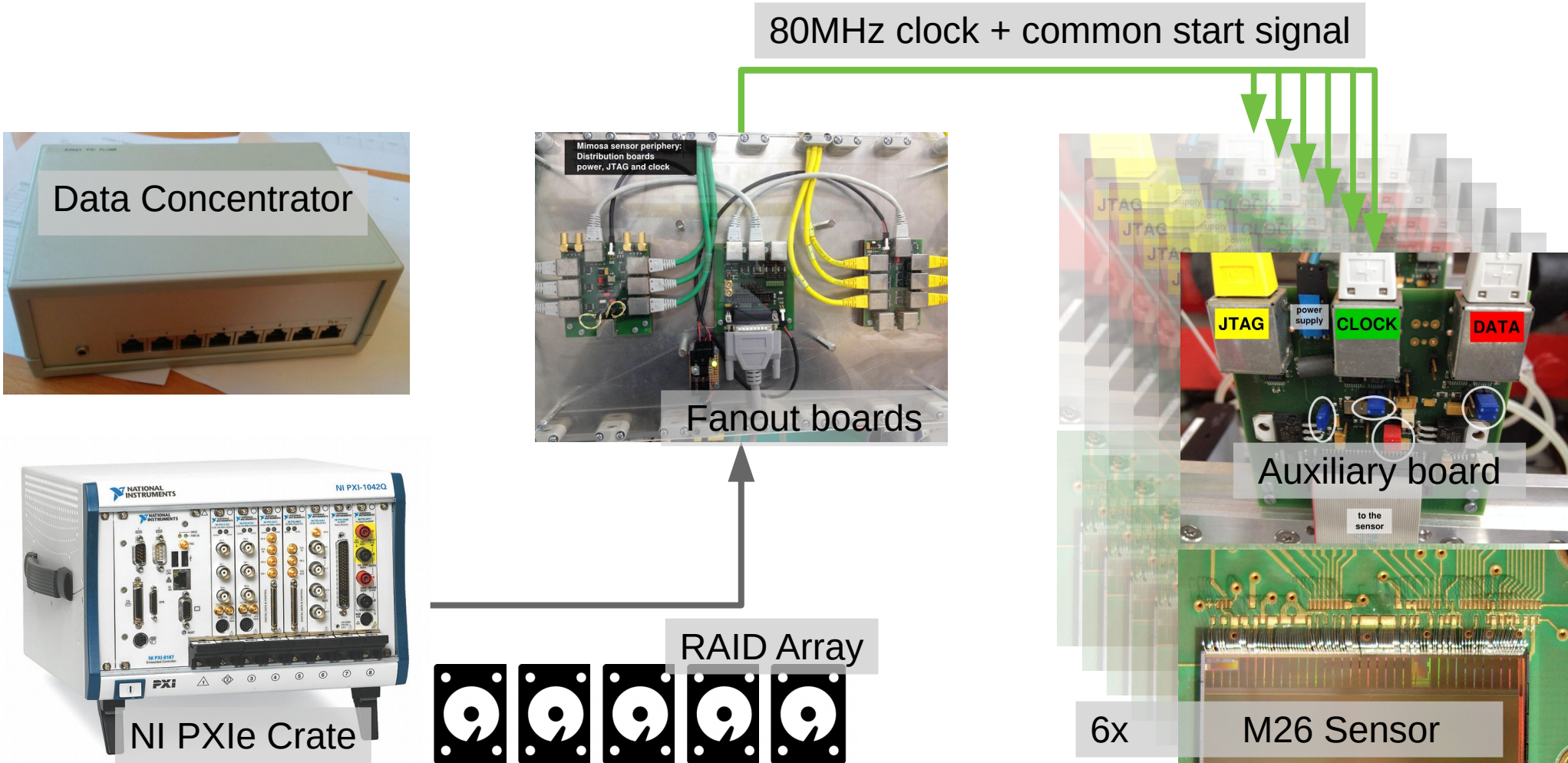
LVDS front-end + FlexRIO Virtex-5 + PXIe crate

Data Acquisition System - Overview

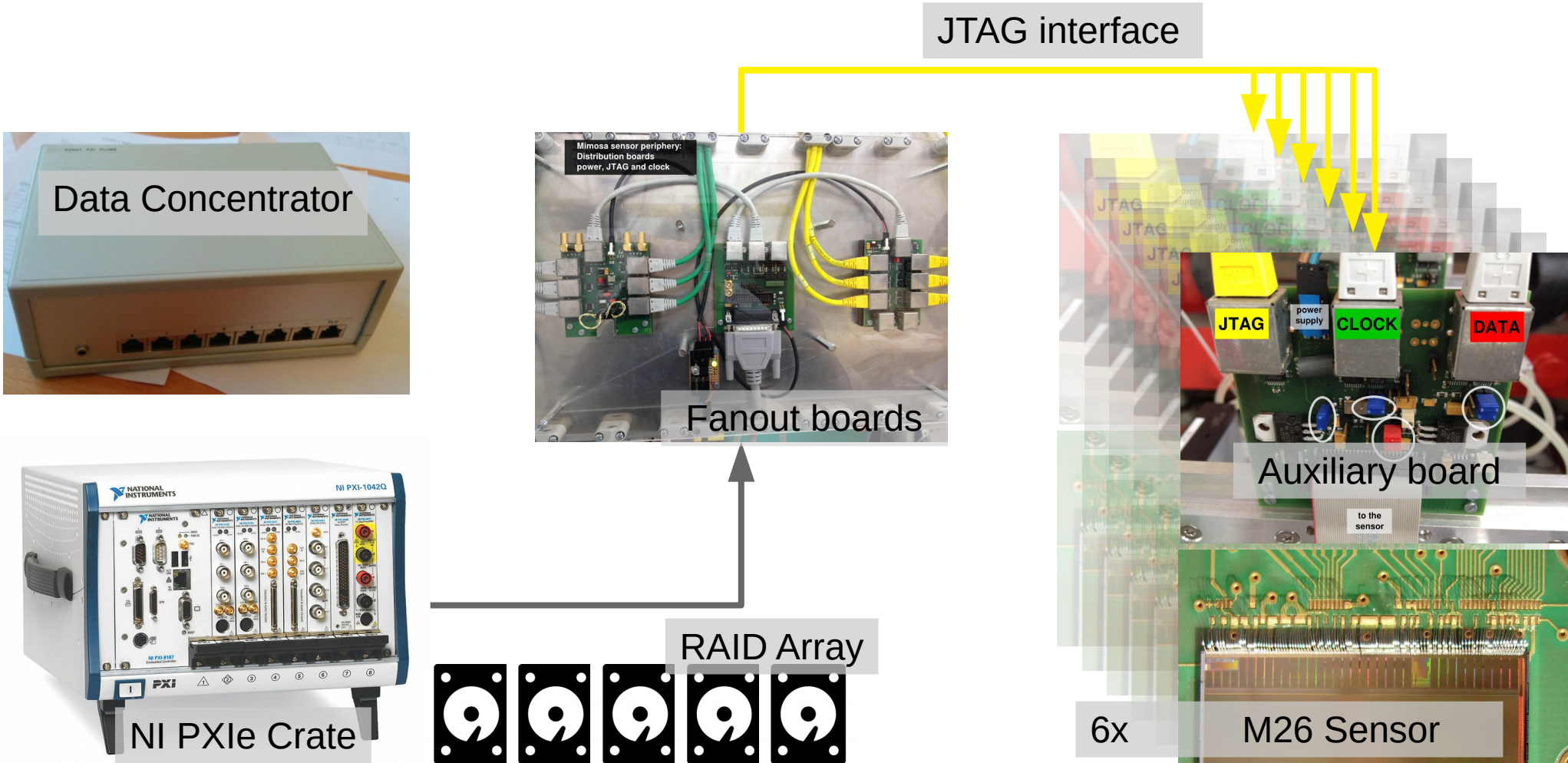




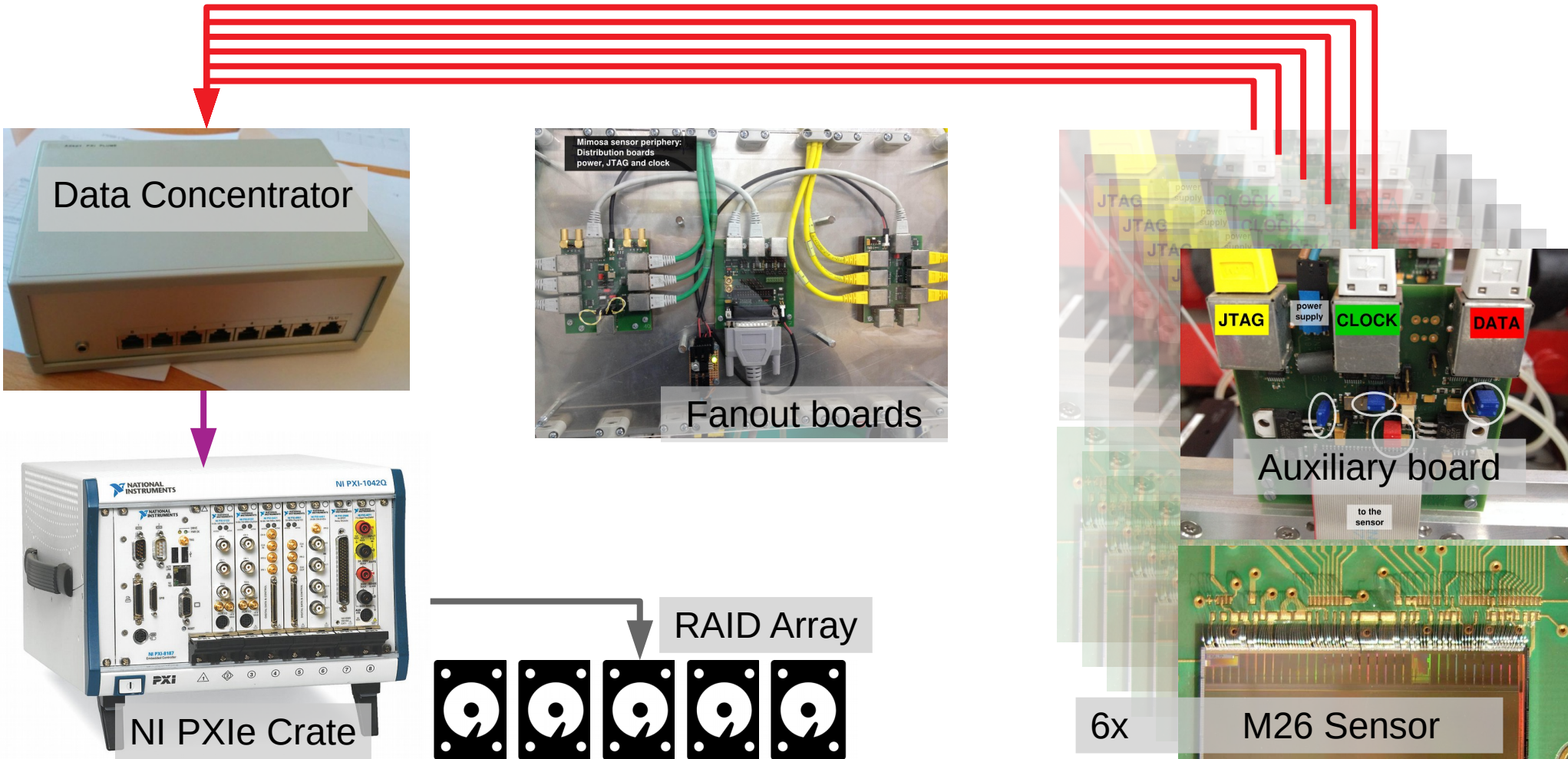
Common Clock Distribution



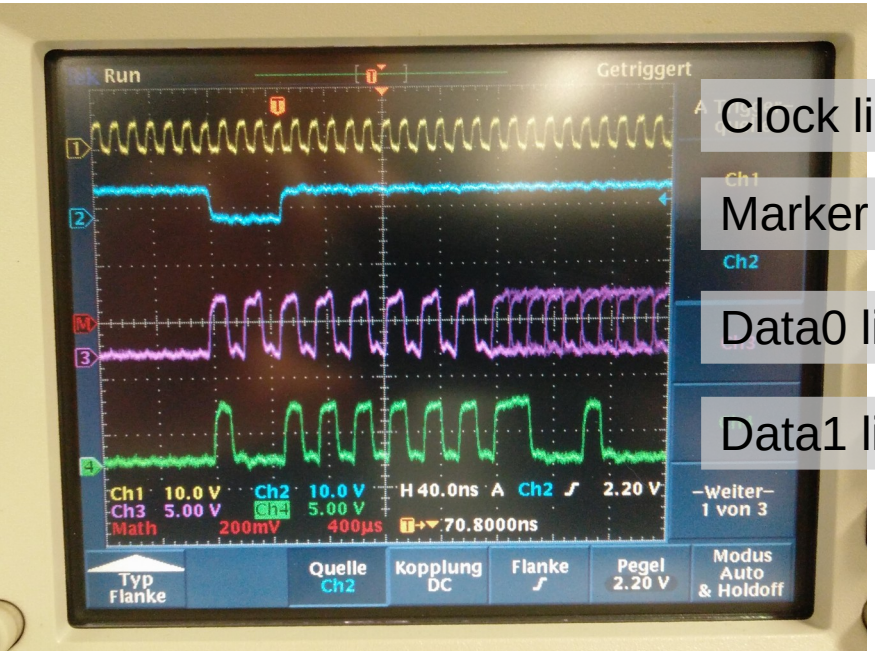
Device Configuration



Data Acquisition



Data lines and handling

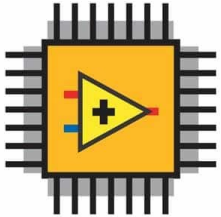


Clock line

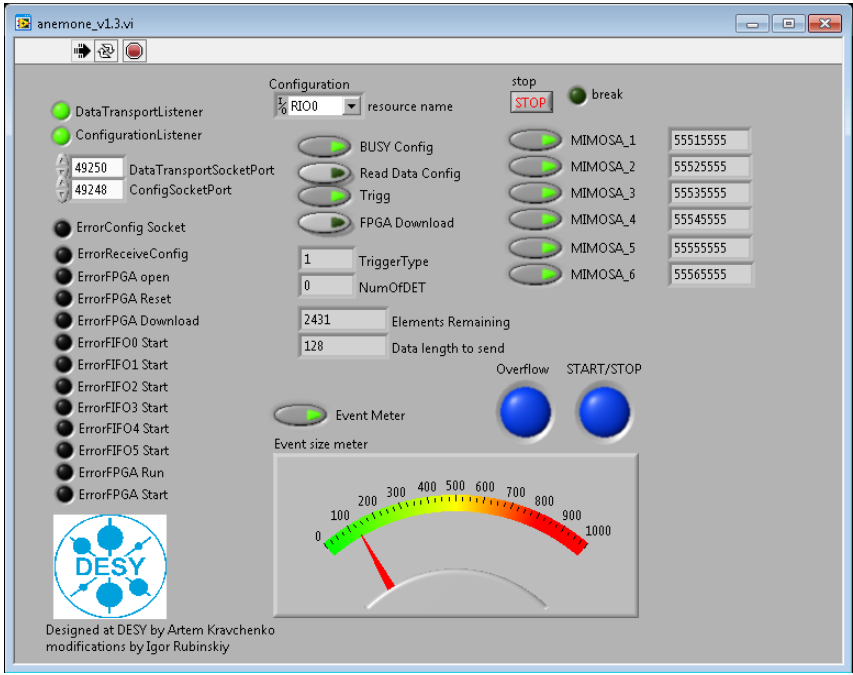
Marker line

Data0 line

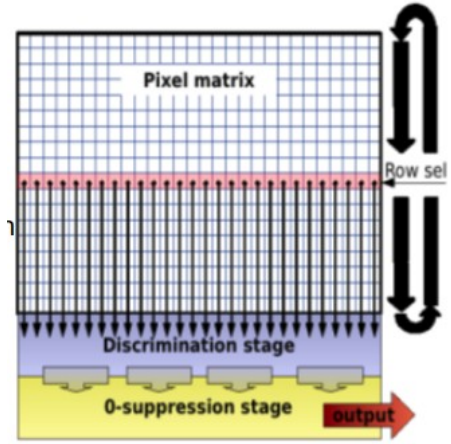
Data1 line



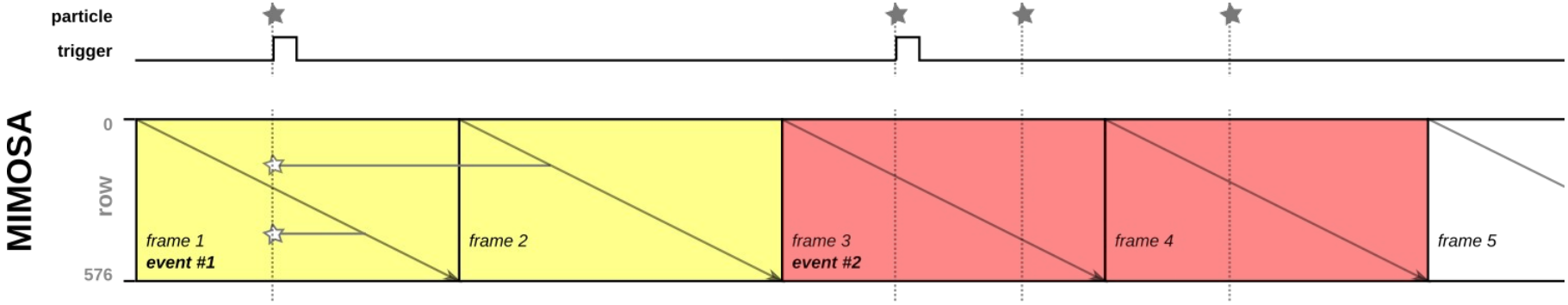
FPGA



Rolling Shutter Frames



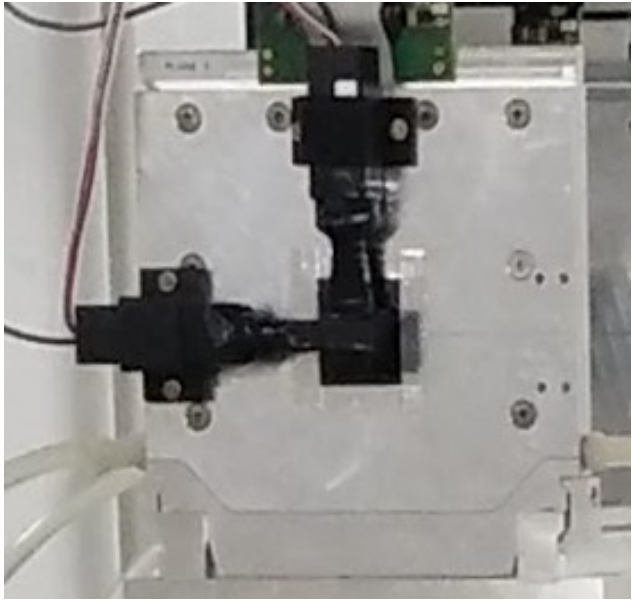
- No synchronization shutter ↔ beam
  - Particles arrive at any time in frame
  - Might only be read out in subsequent frame
- DAQ combines two consecutive frames per event when ***triggered***

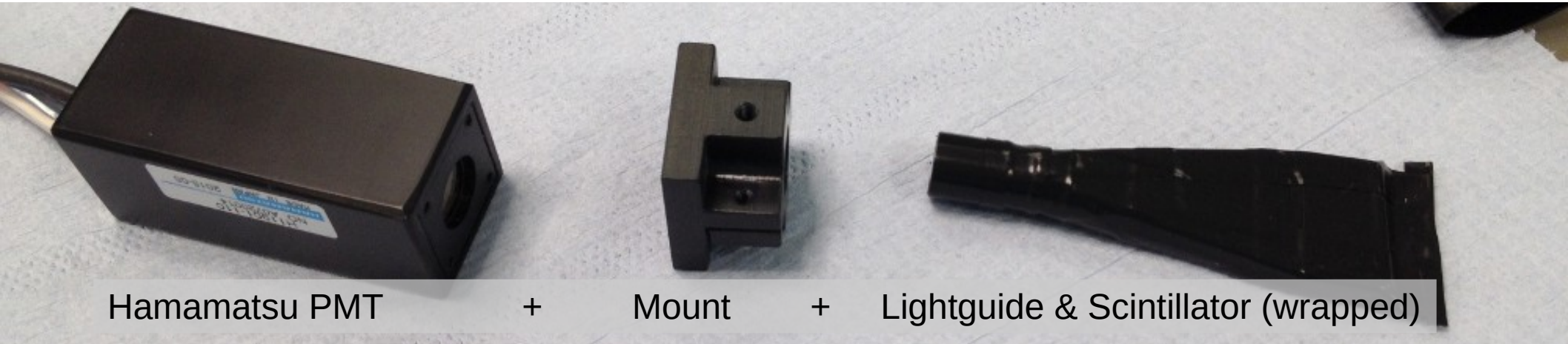


Trigger communication

Trigger Devices: PMT+Scintillators

- Limit acceptance to M26 sensor: 2x1cm
  - Two crossed scintillators
- Ensure particles go through telescope
  - Pairs before 1st and after last plane





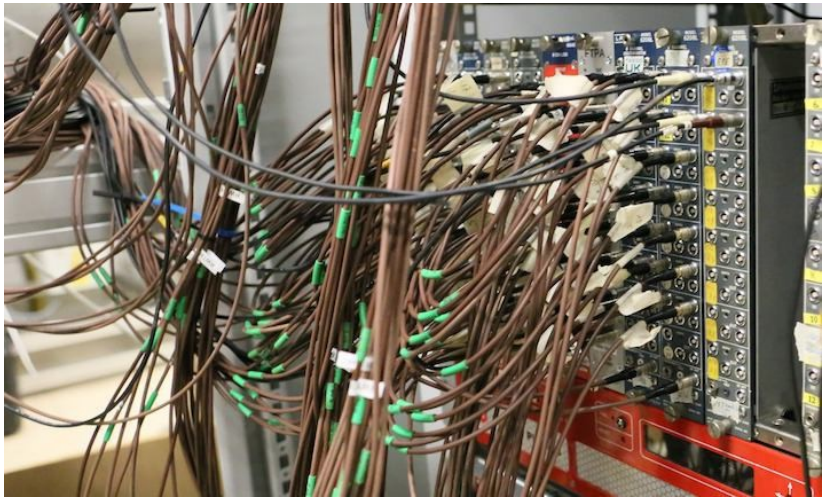
Triggering needs

- Generate coincidence of scintillator triggers
- Mark interesting frames of continuous telescope readout
- Distribute trigger information to DUTs for event synchronisation

→ requires a **central trigger logic**

NIM logic?
- + Usually available
- + Normally easy to set up, flexible
- - No remote configuration
- - No data acquisition capabilities

or...



The Trigger Logic Unit (TLU)

University of BRISTOL

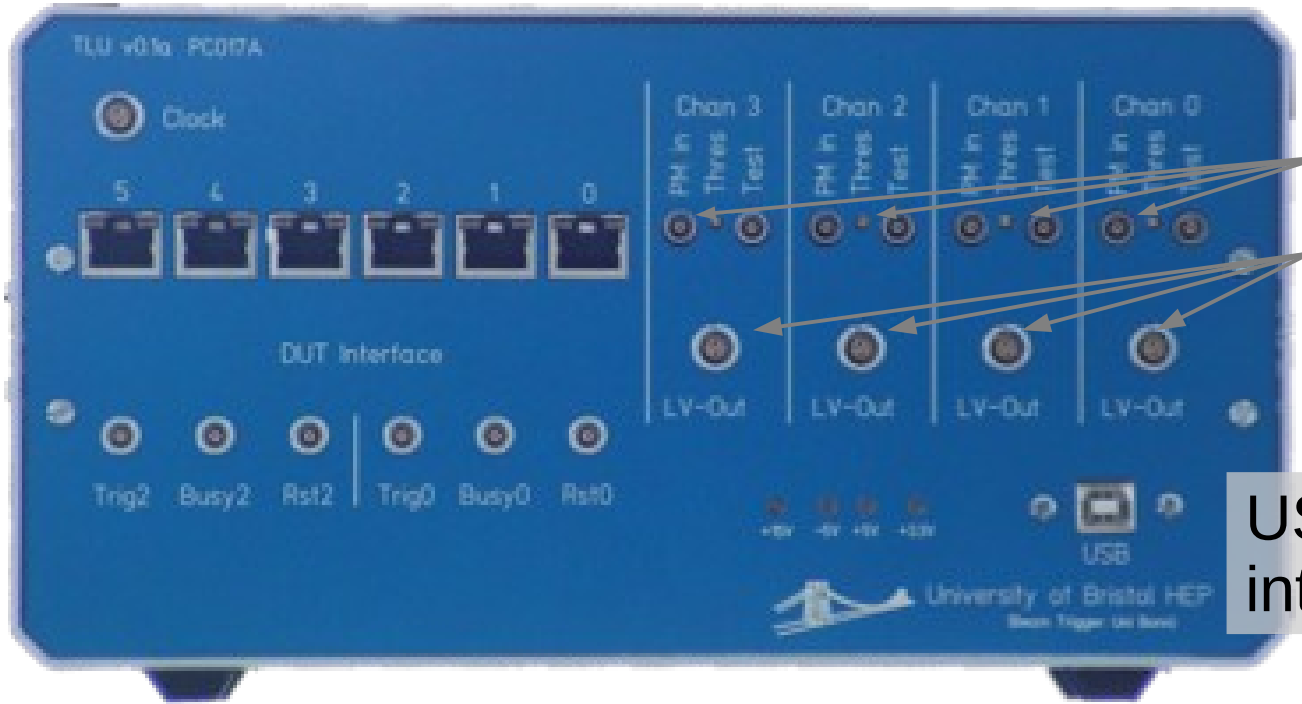
- Control of trigger devices
  - Power for PMTs (15V and contral voltage)
  - Discriminators (+-1.0V) for input signals (max. +-5.0V)
- Configurable FPGA via USB
  - Configure inputs and coincidence logic (AND/OR)
  - Configuring DUT connections and trigger mode
- Records arrival time (timestamps) read-out via USB
  - Timestamps stored as 64bit with 1/8 clock precision (e.g. 40 MHz clock provides 3.125ns resolution)

Hardware Interfaces of the TLU

Outputs of DUT communication ← Inputs of trigger devices

LVDS signals via RJ45

NIM or TTL signals via LEMO



Trigger signals

PMT power

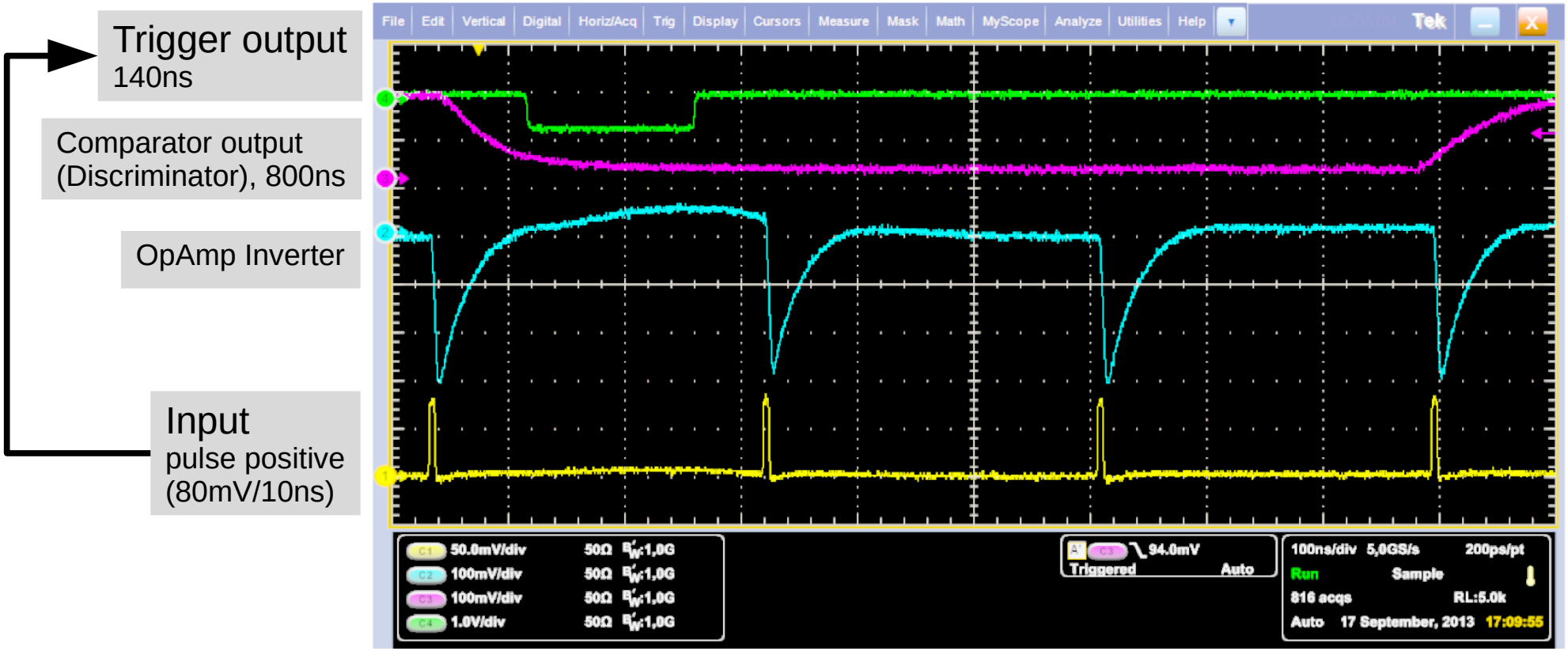
USB Host interface

Input signals

raw signals of the PMTs

- PMT/scintillator signals
  → negative
- Maybe other signals
  → mostly positive
  - Kicker signal from beam line
  - HitOr output from sensor
  - Pulse Generator
  - ...

Example: Input + Inverter + Output



Latency (diff input output): ~80 ns → important for DUT-DAQ buffer architecture!!

Trigger modes in handshake

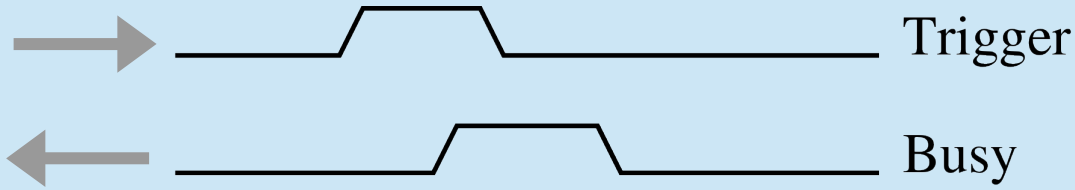
TLU ⟷ DUT

No handshake

fixed-width trigger pulse

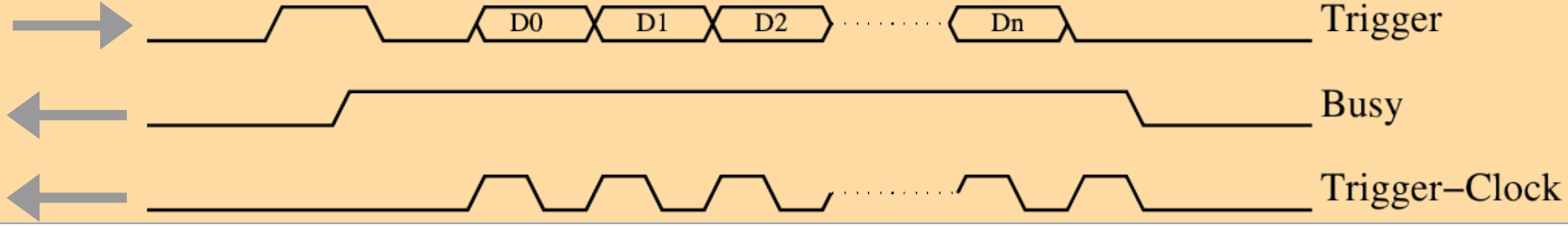
Simple handshake

wait for busy, de-assert trigger, block while busy

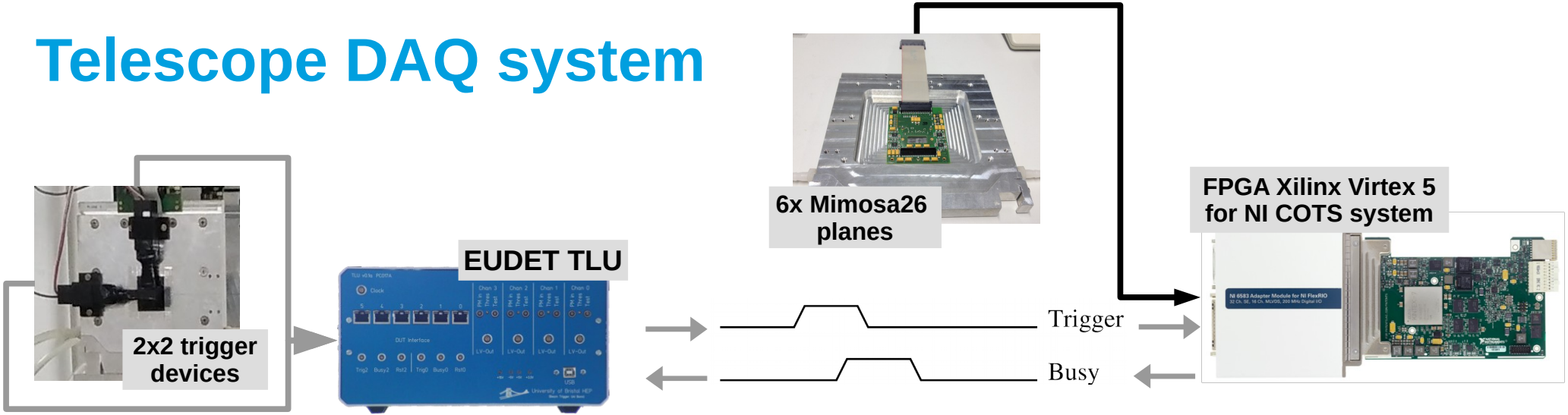


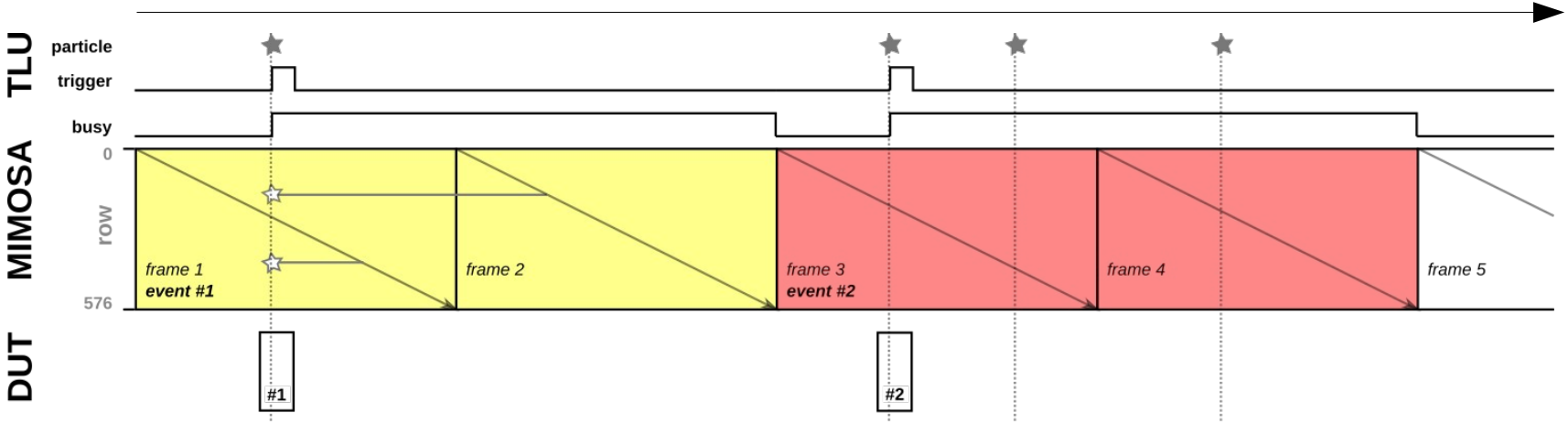
Trigger data handshake

clock out 15bit trigger ID on trigger line, block while busy



Telescope DAQ system

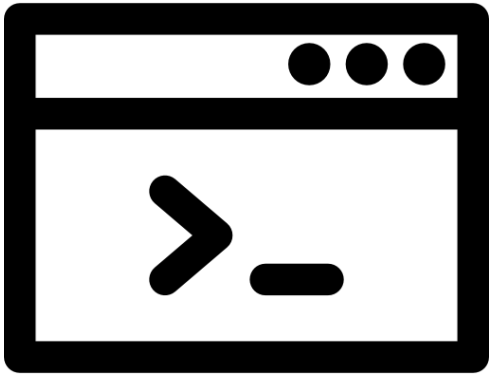




DAQ software

Common DAQ Software

- Common data taking for different independent devices
- Purpose
  - Top level DAQ
  - Start/stop run signal distribution
  - Data management
- Demands
  - Be lightweight → no huge dependencies
  - Flexible → different operating systems
  - Provide defined user interface



A scalable, portable DAQ system design

Speaker: Martin Lothar Purschke (Brookhaven National Laboratory (US))

or compare with design buzzwords

EUDAQ

- **Modular:** Distributed DAQ software framework (C++11 standard)
  - TCP/IP communication between components (via sockets)
- **Simplicity:** Interface for device controllers (“producer”)
  - C++ interface & Python bindings
- **Maintenance:** Stable system, maintained & extended since 2007

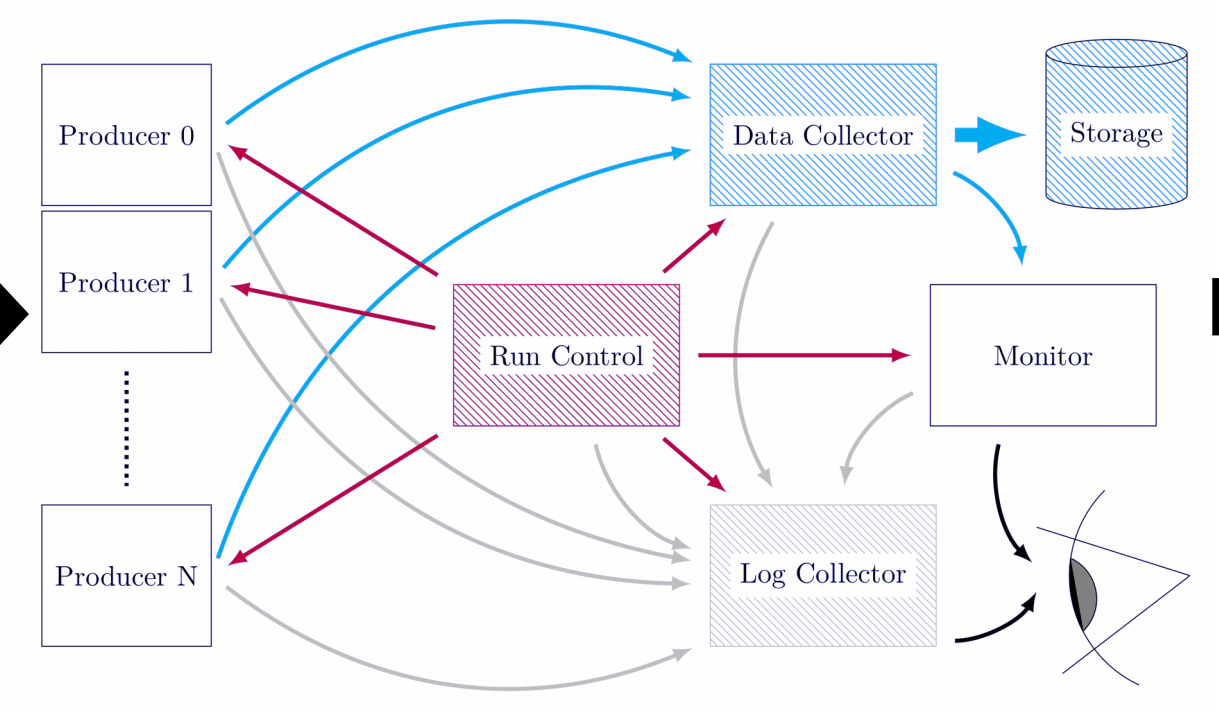
Unix

MacOS

Windows

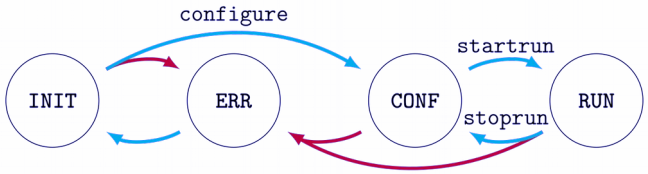
EUDAQ architecture

Data input from DAQs: Mimosa, TLU, DUTs, ...



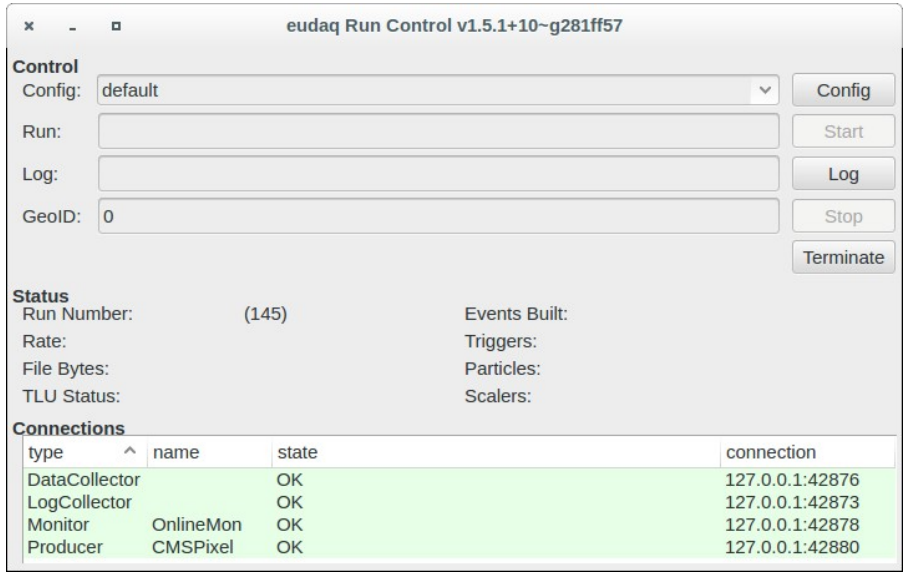
Data out for monitoring and offline analysis

Including a Finite state machine (FSM):



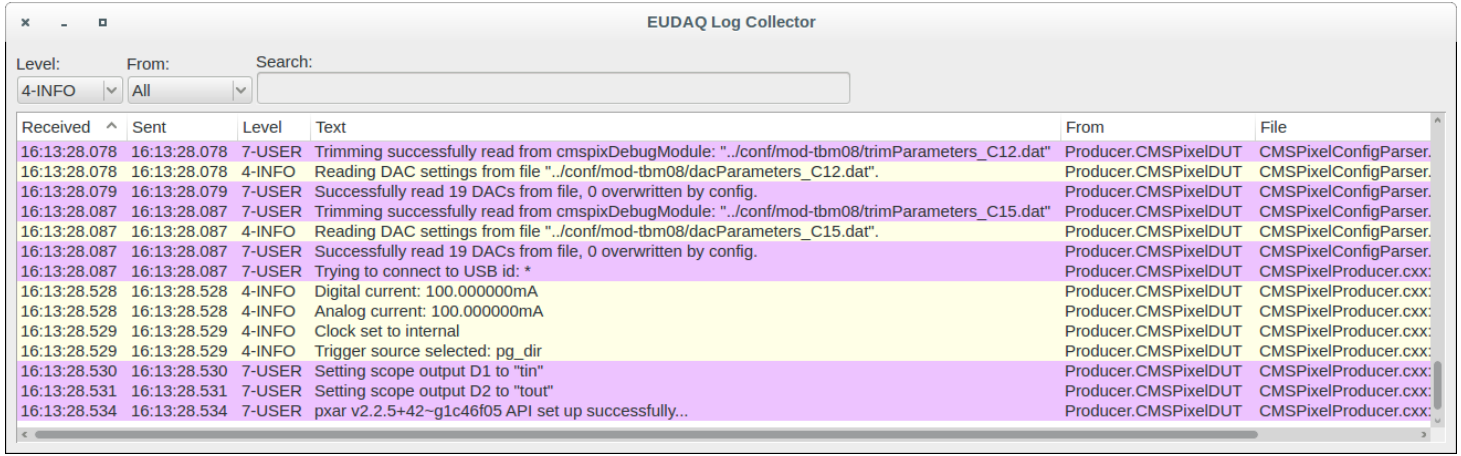
The Run Control

- Central GUI interface for shifters
  - Control of FSM
  - Configure/start/stop runs
- System information overview
  - Connected producers
  - Run parameters
- Run Control acts as “server”
  - Individual producers as “client” connect to RC
  - List of connected producers with their FSM state



The Log Collector

- Monitoring of DAQ system status
  - Collecting log messages from all network nodes
  - Storing to log file, displayed in GUI or console
- Log slow data as voltages, DAC settings...



Received	Sent	Level	Text	From	File
16:13:28.078	16:13:28.078	7-USER	Trimming successfully read from cmspixDebugModule: "../conf/mod-tbm08/trimParameters_C12.dat"	Producer.CMSPixelDUT	CMSPixelConfigParser.
16:13:28.078	16:13:28.078	4-INFO	Reading DAC settings from file "../conf/mod-tbm08/dacParameters_C12.dat".	Producer.CMSPixelDUT	CMSPixelConfigParser.
16:13:28.079	16:13:28.079	7-USER	Successfully read 19 DACs from file, 0 overwritten by config.	Producer.CMSPixelDUT	CMSPixelConfigParser.
16:13:28.087	16:13:28.087	7-USER	Trimming successfully read from cmspixDebugModule: "../conf/mod-tbm08/trimParameters_C15.dat"	Producer.CMSPixelDUT	CMSPixelConfigParser.
16:13:28.087	16:13:28.087	4-INFO	Reading DAC settings from file "../conf/mod-tbm08/dacParameters_C15.dat".	Producer.CMSPixelDUT	CMSPixelConfigParser.
16:13:28.087	16:13:28.087	7-USER	Successfully read 19 DACs from file, 0 overwritten by config.	Producer.CMSPixelDUT	CMSPixelConfigParser.
16:13:28.087	16:13:28.087	7-USER	Trying to connect to USB id: *	Producer.CMSPixelDUT	CMSPixelProducer.cxx:
16:13:28.528	16:13:28.528	4-INFO	Digital current: 100.000000mA	Producer.CMSPixelDUT	CMSPixelProducer.cxx:
16:13:28.528	16:13:28.528	4-INFO	Analog current: 100.000000mA	Producer.CMSPixelDUT	CMSPixelProducer.cxx:
16:13:28.529	16:13:28.529	4-INFO	Clock set to internal	Producer.CMSPixelDUT	CMSPixelProducer.cxx:
16:13:28.529	16:13:28.529	4-INFO	Trigger source selected: pg_dir	Producer.CMSPixelDUT	CMSPixelProducer.cxx:
16:13:28.530	16:13:28.530	7-USER	Setting scope output D1 to "tin"	Producer.CMSPixelDUT	CMSPixelProducer.cxx:
16:13:28.531	16:13:28.531	7-USER	Setting scope output D2 to "tout"	Producer.CMSPixelDUT	CMSPixelProducer.cxx:
16:13:28.534	16:13:28.534	7-USER	pxar v2.2.5+42~g1c46f05 API set up successfully...	Producer.CMSPixelDUT	CMSPixelProducer.cxx:

Producer interface in 26 lines C++

```
class ExampleProducer : public eudaq::Producer {
public:
    ExampleProducer(const std::string & name, const std::string & rc) : eudaq::Producer(name, rc) {}
    virtual void OnConfigure(const eudaq::Configuration & config) {
        // Configure your device...
    }
    virtual void OnStartRun(unsigned param) {
        // Prepare device and start run...
    }
    virtual void OnStopRun() {
        // Stop the data acquisition...
    }
    virtual void OnTerminate() {
        // Shut down all devices, exit program
    }
    void ReadoutLoop() {
        while (!terminate) { // Loop until Run Control tells us to terminate
            // Read data from device
        }
    }
};
int main(int /*argc*/, const char ** argv) {
    ExampleProducer producer(name.Value(), rctrl.Value()); // Create producer
    producer.ReadoutLoop();                                // Run readout thread
    return 0;
}
```

- DUT Interface
- Interaction to sub-DAQs
  - TLU
  - MimosaDAQ
  - DUT x
  - DUT y
  - DUT z
  - ...

The Data Collector

- Central data collection synchronizes by event number
- Stores internal event format
  - Global run header with run information
  - Events with all detectors data
  - Detector data stored as raw binary format
- Decoding ("bit-shifting") when used for monitoring or offline analysis
  - Minimizes risks from flawed decoding
  - Raw data retains all information

Run Header
Run Number, timestamp
Full Configuration

Event #1
Event ID, timestamp, detectors

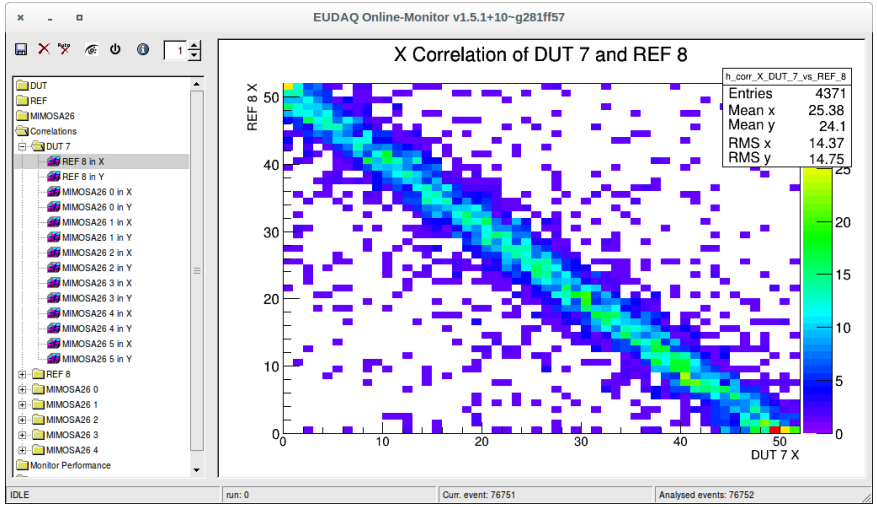
Detector #0
0xF3 0x1E 0xBE 0xA5 0xD2 0x31

Detector #1
0xC001 0xCAFE 0x5FD2 0x31BA 0x5FD2 0x31BA
0x54F3 0xD1D1 0x54F3 0xDEAD 0xBEEF 0x8B44

⋮

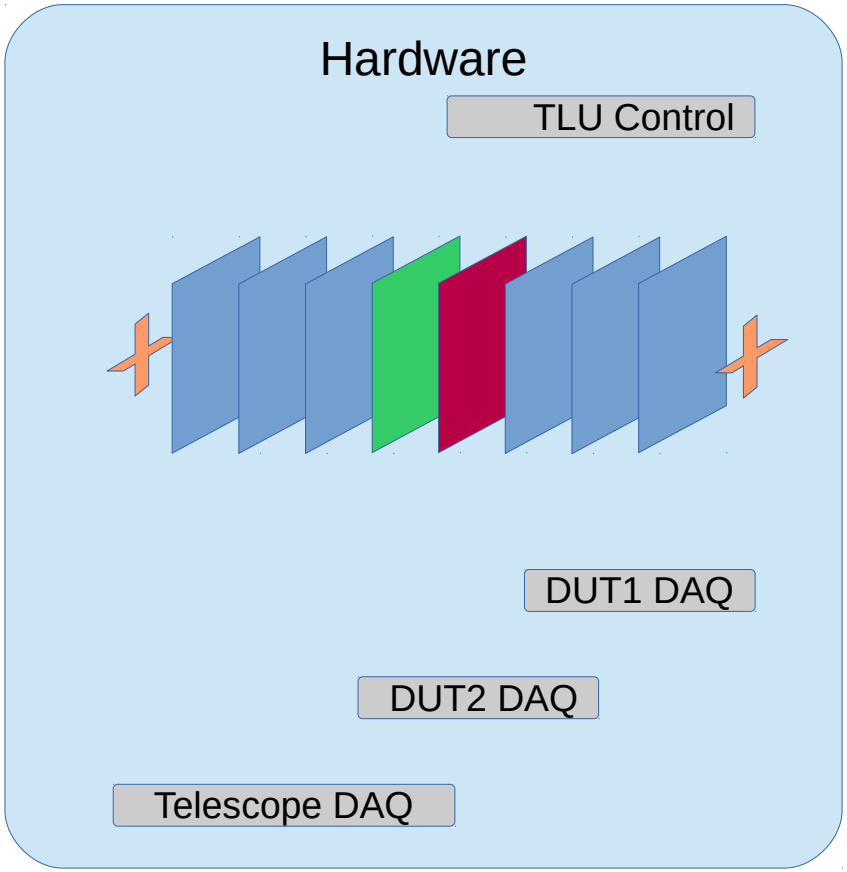
The Online Monitor

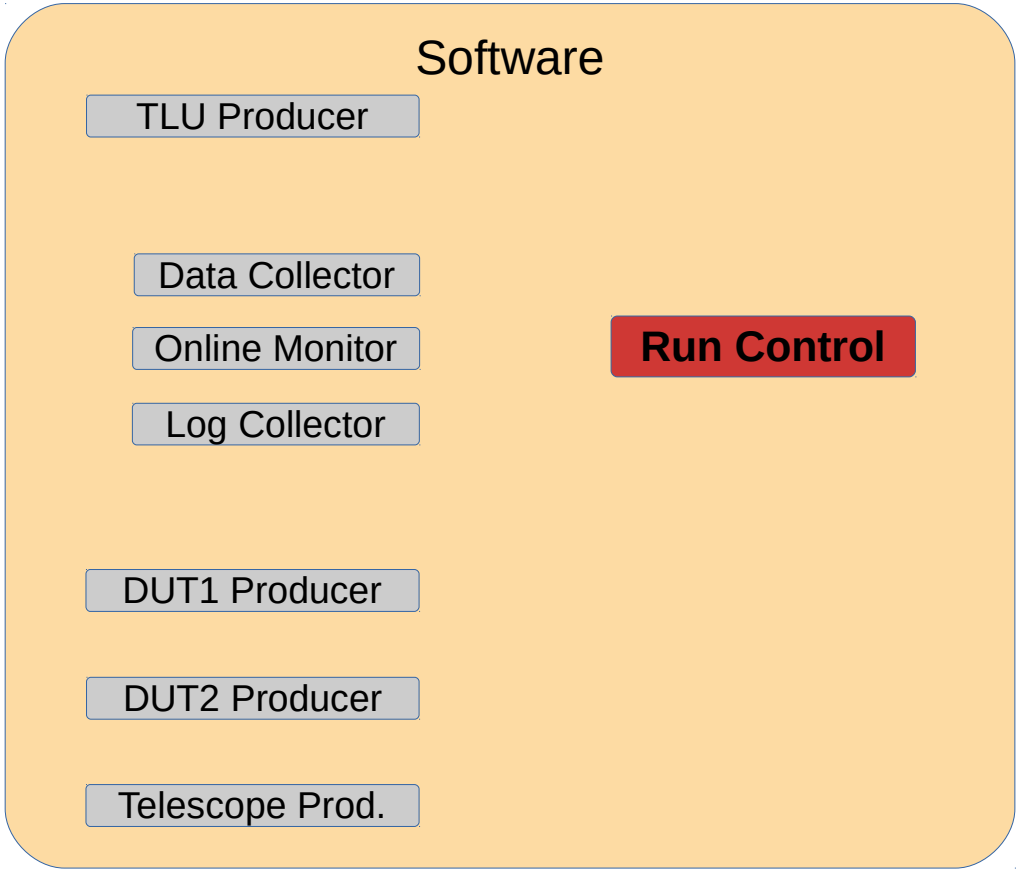
- Data Quality Monitoring
  - Time/trigger correlation
  - Spatial correlation
  - Performance plots
    - noise/signal/cluster size/...
- Requests every (x%n == 0) events from storage (PULL)
- Decodes detector raw data on-the-fly with decoding modules



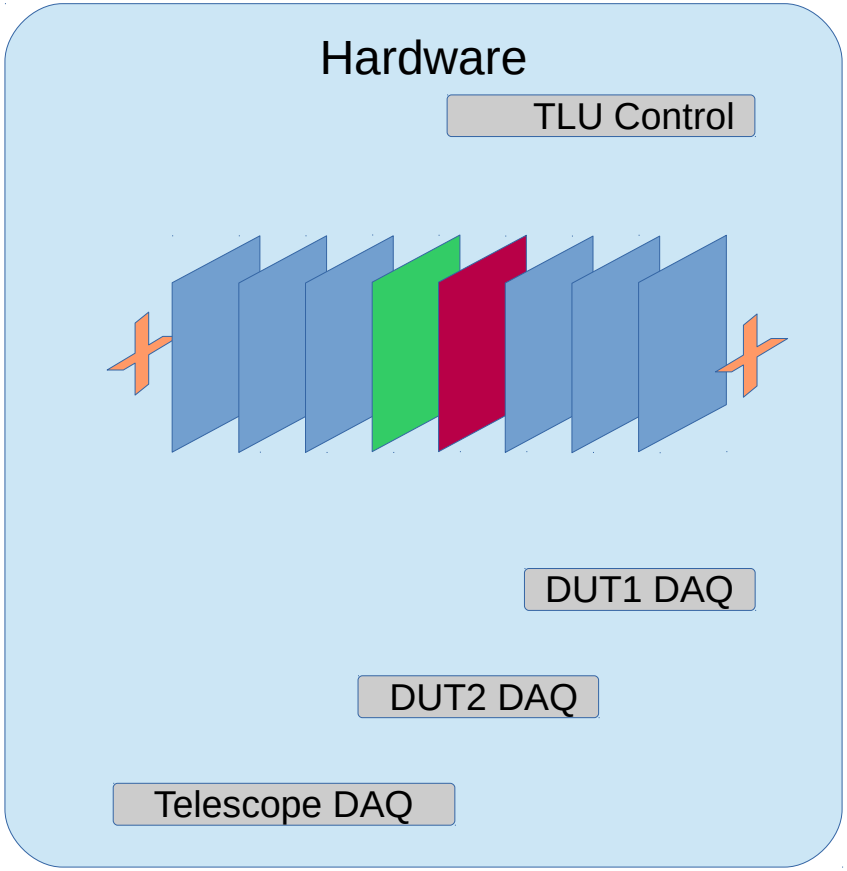
Operating the system

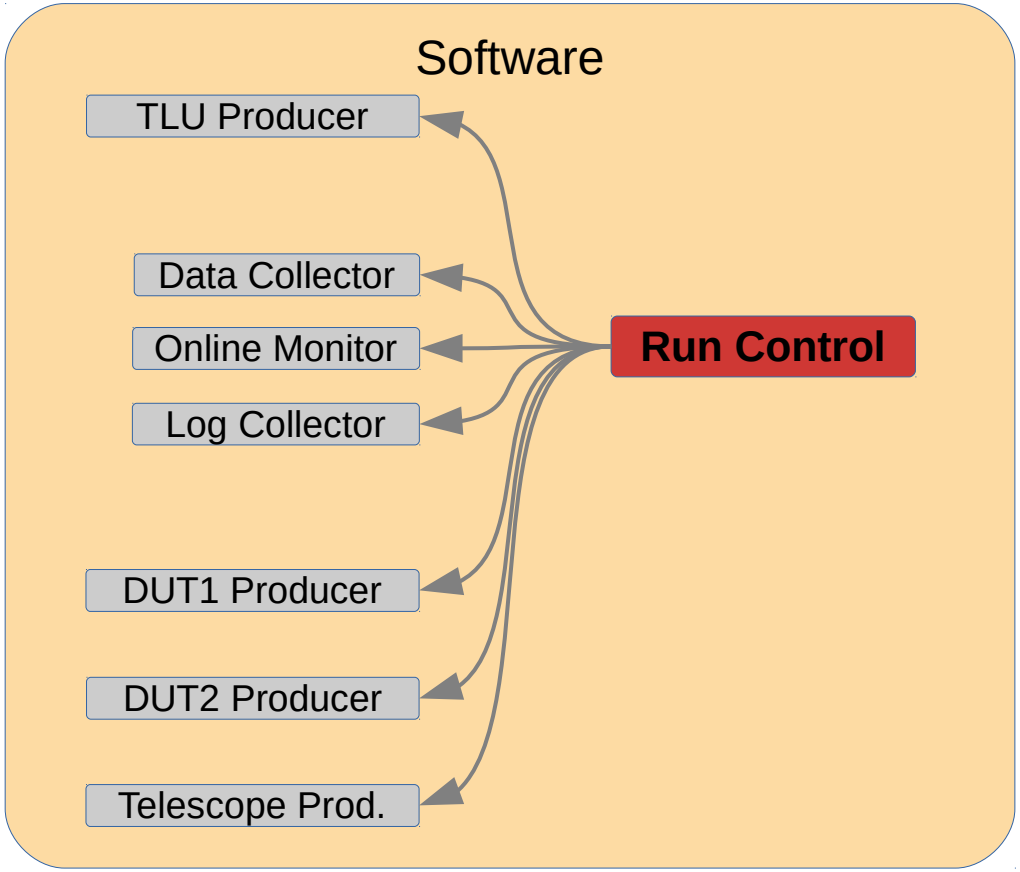
Components


Hardware
TLU Control
DUT1 DAQ
DUT2 DAQ
Telescope DAQ

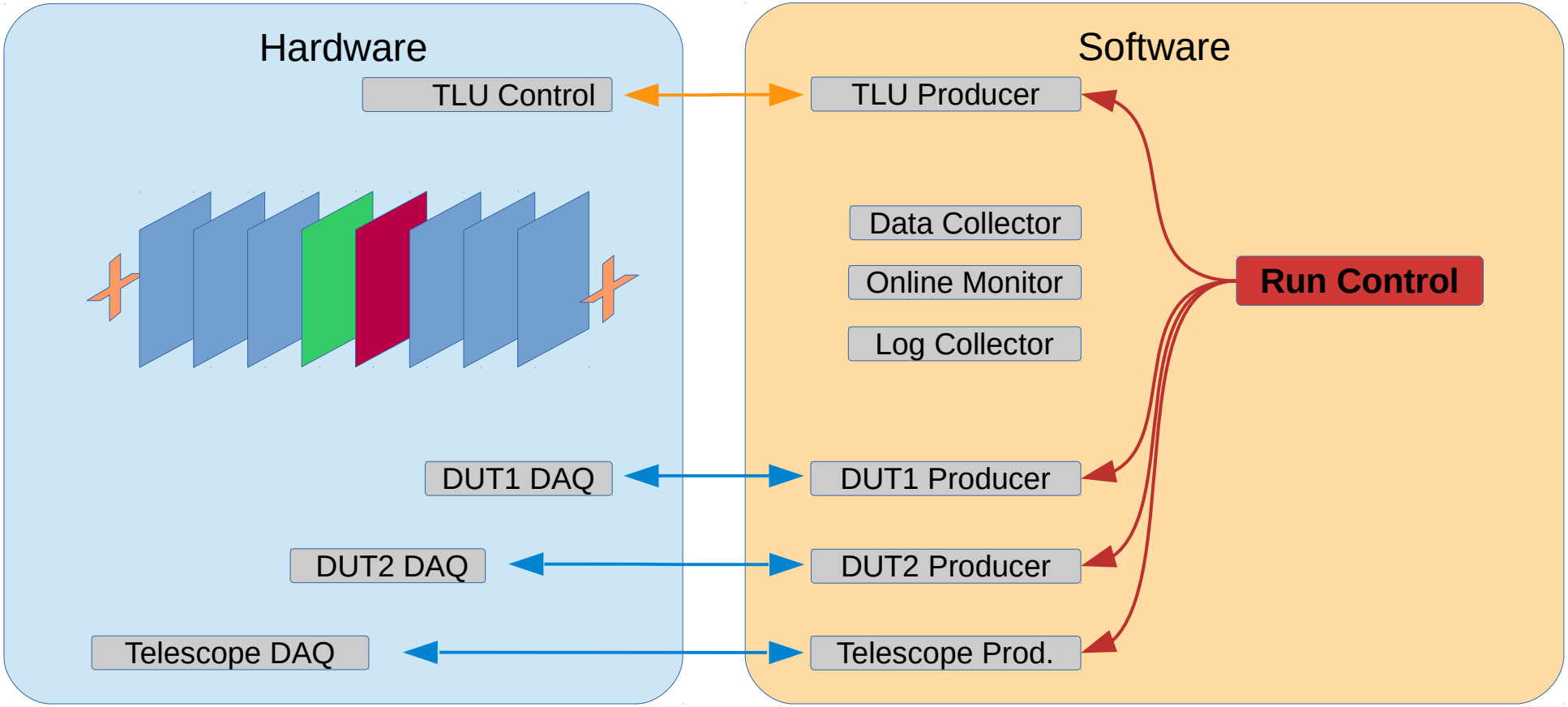

Software
TLU Producer
Data Collector
Online Monitor
Log Collector
Run Control
DUT1 Producer
DUT2 Producer
Telescope Prod.

Start up connections

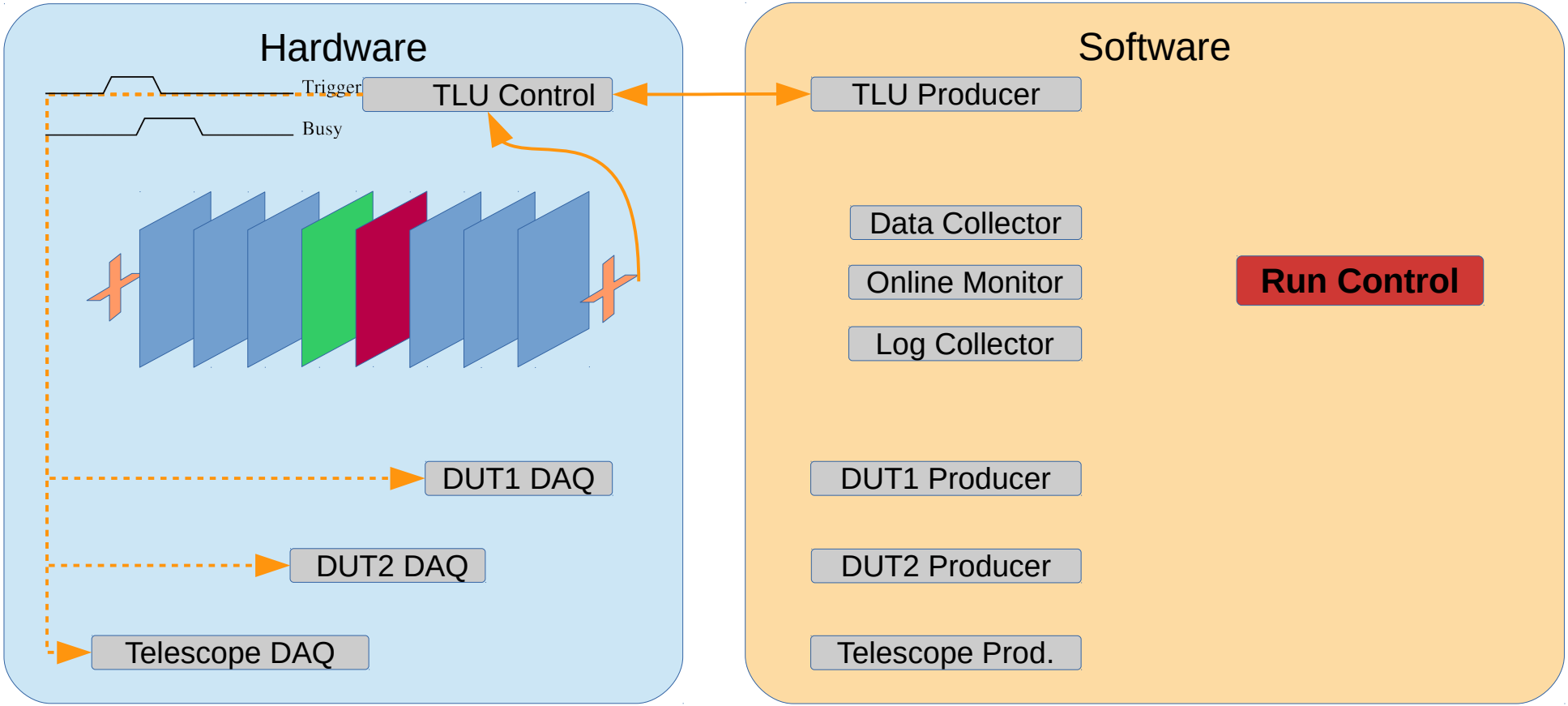




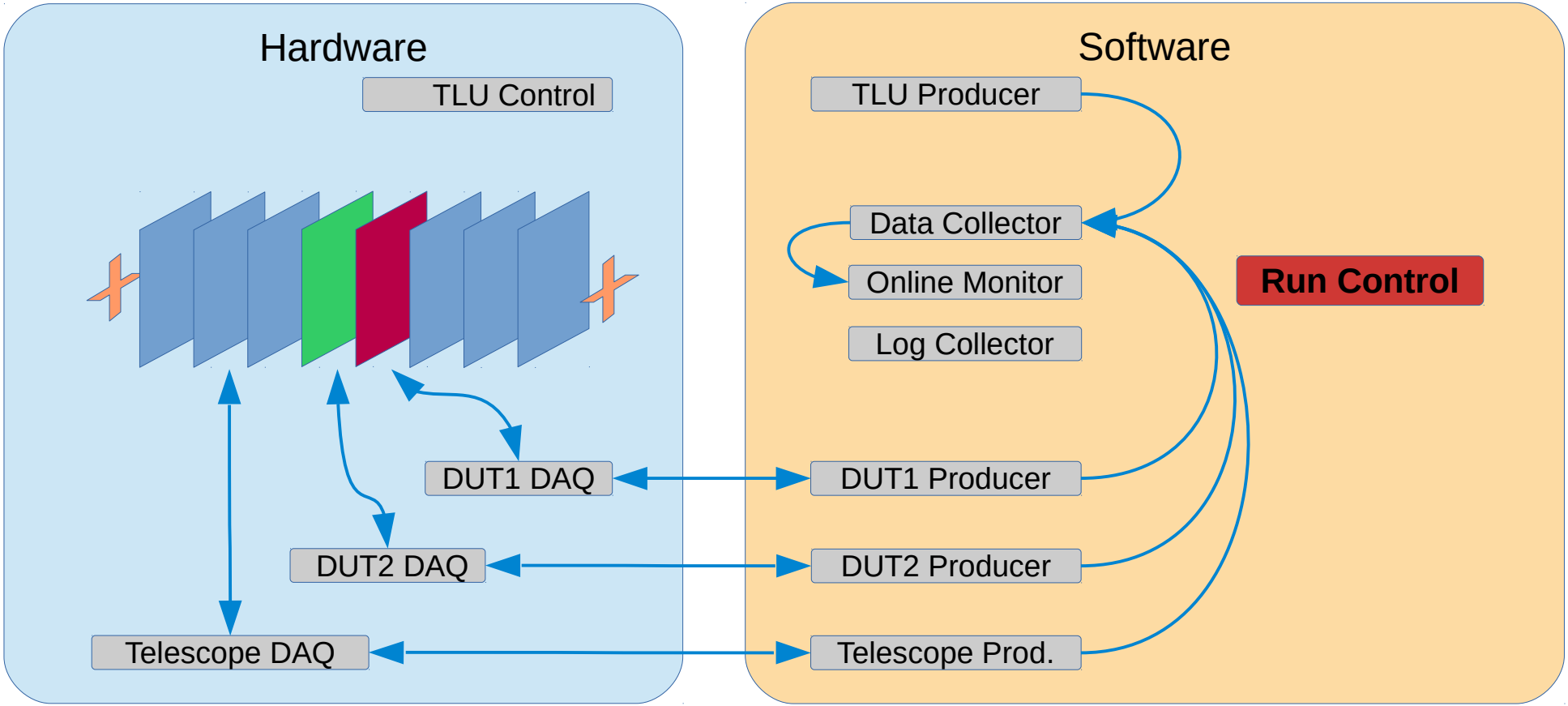
Configuration



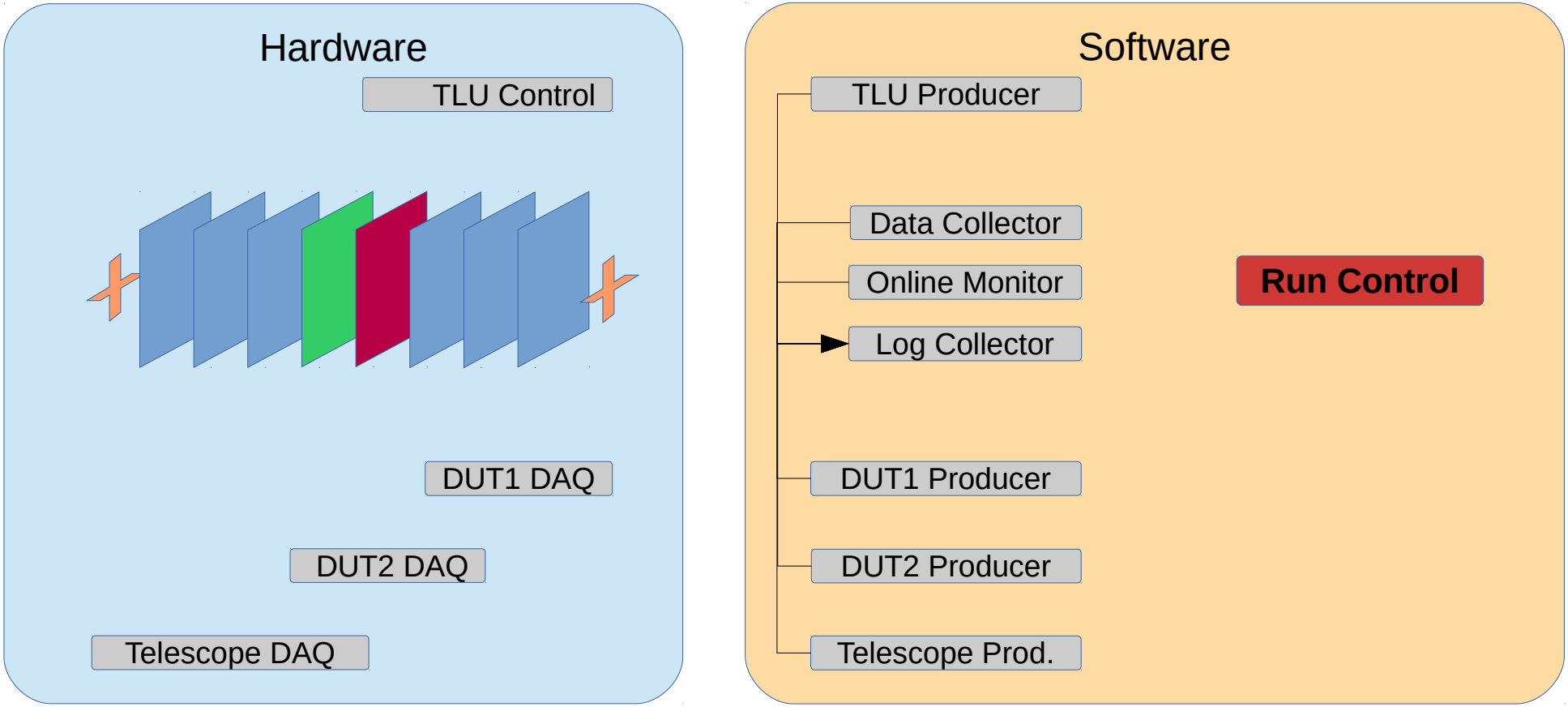
Trigger!


Hardware
Trigger
Busy
TLU Control
DUT1 DAQ
DUT2 DAQ
Telescope DAQ
Software
TLU Producer
Data Collector
Online Monitor
Log Collector
Run Control
DUT1 Producer
DUT2 Producer
Telescope Prod.

Data flow

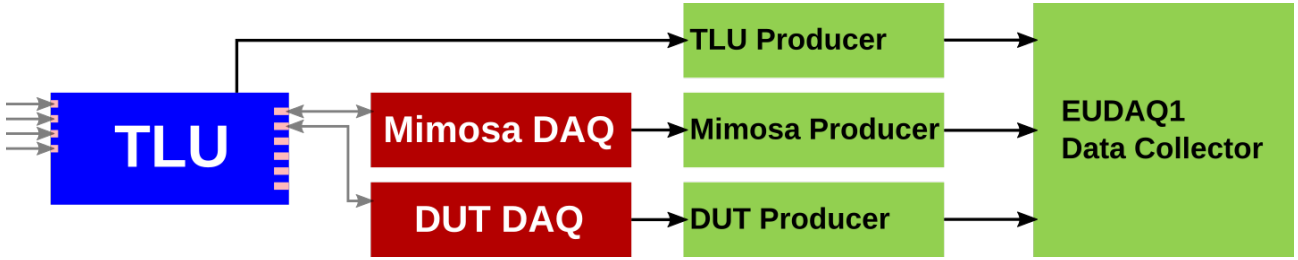

Hardware
TLU Control
DUT1 DAQ
DUT2 DAQ
Telescope DAQ
Software
TLU Producer
Data Collector
Online Monitor
Log Collector
Run Control
DUT1 Producer
DUT2 Producer
Telescope Prod.

Log flow


Hardware
TLU Control
DUT1 DAQ
DUT2 DAQ
Telescope DAQ
Software
TLU Producer
Data Collector
Online Monitor
Log Collector
DUT1 Producer
DUT2 Producer
Telescope Prod.
Run Control

Data flow and event building

EUDET-type hardware ⟷ **EUDAQ v1**



EUDAQ Data Collector

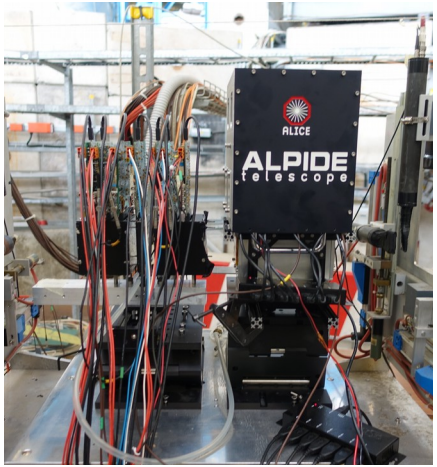
Evt. ID	TLU	DUT	Mimosa
1	1	1	1
2	2	2	2
3	3	3	3
4	4	4	4
5	5	5	5
6	6	6	6
7	7	7	7
8	8	8	8
9	9	9	9
10	10	10	10
11	11	11	11
12	12	12	12
..	..	..	..

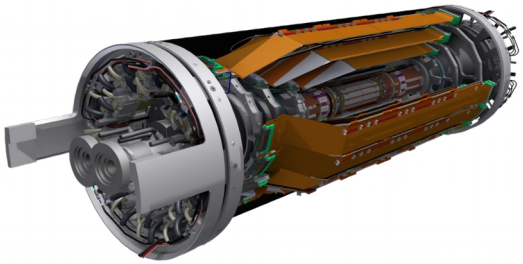
"EUDET mode": One trigger = one read-out from all devices

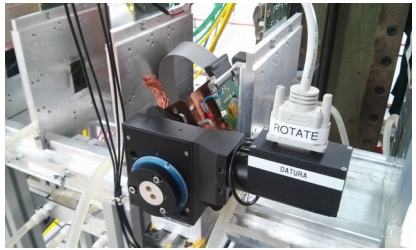
- Event-based synchronisation for robust data-taking
- Unique event definition: **EUDAQ1 event**
- **But trigger rate is limited by the slowest device!**

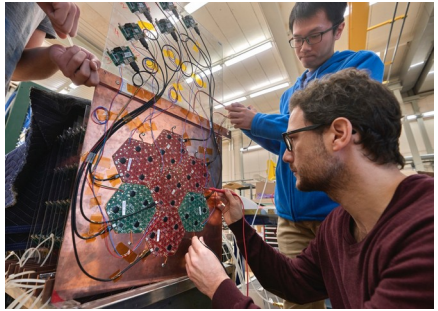
User examples

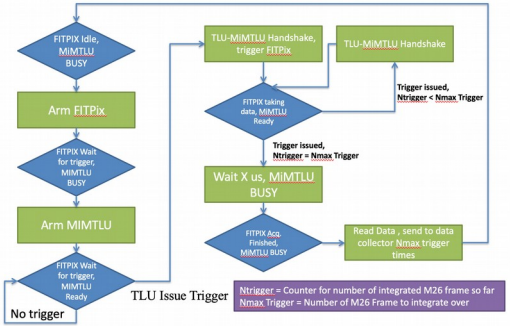
Many various and different applications

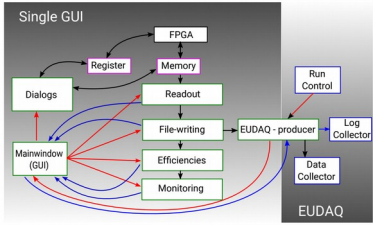


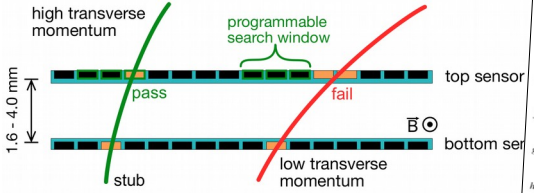






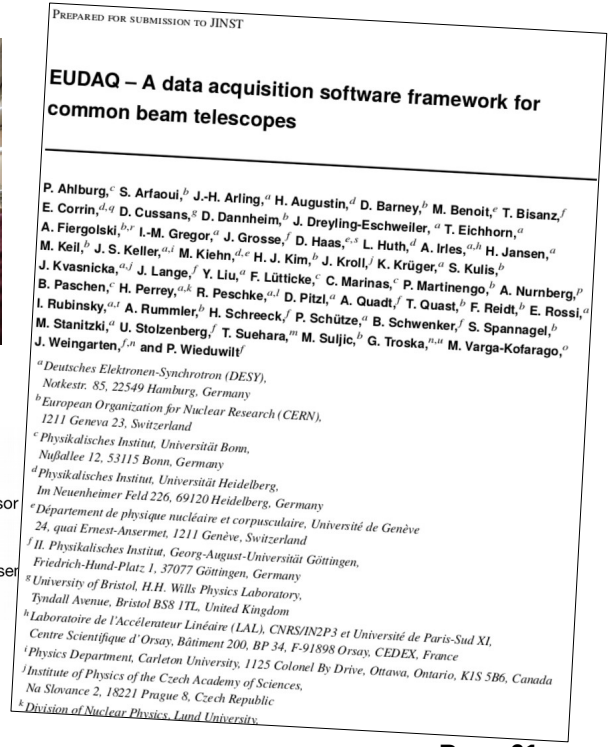






EUDAQ paper in editing phase:

Architecture and applications: ALICE ITS, ATLAS Itk, Belle II Vertex, CALICE, CLIC devel., CMS IT-PH1, CMS OT-PH2, CMS HGCAL, MIB, Mu3e devel., SiLab devel, outreach, ...



Prepared for submission to JINST

EUDAQ – A data acquisition software framework for common beam telescopes

P. Ahlburg,[c] S. Arfaoui,[b] J.-H. Arling,[a] H. Augustin,[d] D. Barney,[b] M. Benoit,[e] T. Bisanz,[f] E. Corrin,[d,g] D. Cussans,[g] D. Dannheim,[b] J. Dreyling-Eschweiler,[a] T. Eichhorn,[a] A. Fiergolski,[b,r] I.-M. Gregor,[a] J. Grosse,[f] D. Haas,[e,s] L. Huth,[d] A. Irles,[a,h] H. Jansen,[a] M. Keil,[b] J. S. Keller,[a,i] M. Kiehn,[d,e] H. J. Kim,[b] J. Kroll,[j] K. Krüger,[a] S. Kulis,[b] J. Kvasnicka,[a,j] J. Lange,[f] Y. Liu,[a] F. Lütticke,[c] C. Marinas,[c] P. Martinengo,[b] A. Nurnberg,[p] B. Paschen,[c] H. Perrey,[a,k] R. Peschke,[a,l] D. Pitzl,[a] A. Quadt,[f] T. Quast,[b] F. Reidt,[b] E. Rossi,[a] I. Rubinsky,[a,i] A. Rummler,[b] H. Schreeck,[f] P. Schütze,[a] B. Schwenker,[f] S. Spannagel,[b] M. Stanitzki,[a] U. Stolzenberg,[f] T. Suehara,[m] M. Suljic,[b] G. Troska,[n,u] M. Varga-Kofarago,[o] J. Weingarten,[f,n] and P. Wieduwilt[f]

[a] Deutsches Elektronen-Synchrotron (DESY), Notkestr. 85, 22549 Hamburg, Germany
[b] European Organization for Nuclear Research (CERN), 1211 Geneva 23, Switzerland
[c] Physikalisches Institut, Universität Bonn, Nußallee 12, 53115 Bonn, Germany
[d] Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany
[e] Département de physique nucléaire et corpusculaire, Université de Genève 24, quai Ernest-Ansermet, 1211 Genève, Switzerland
[f] II. Physikalisches Institut, Georg-August-Universität Göttingen, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany
[g] University of Bristol, H.H. Wills Physics Laboratory, Tyndall Avenue, Bristol BS8 1TL, United Kingdom
[h] Laboratoire de l'Accélerateur Linéaire (LAL), CNRS/IN2P3 et Université de Paris-Sud XI, Centre Scientifique d'Orsay, Bâtiment 200, BP 34, F-91898 Orsay, CEDEX, France
[i] Physics Department, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario, K1S 5B6, Canada
[j] Institute of Physics of the Czech Academy of Sciences, Na Slovance 2, 18221 Prague 8, Czech Republic
[k] Division of Nuclear Physics, Lund University,

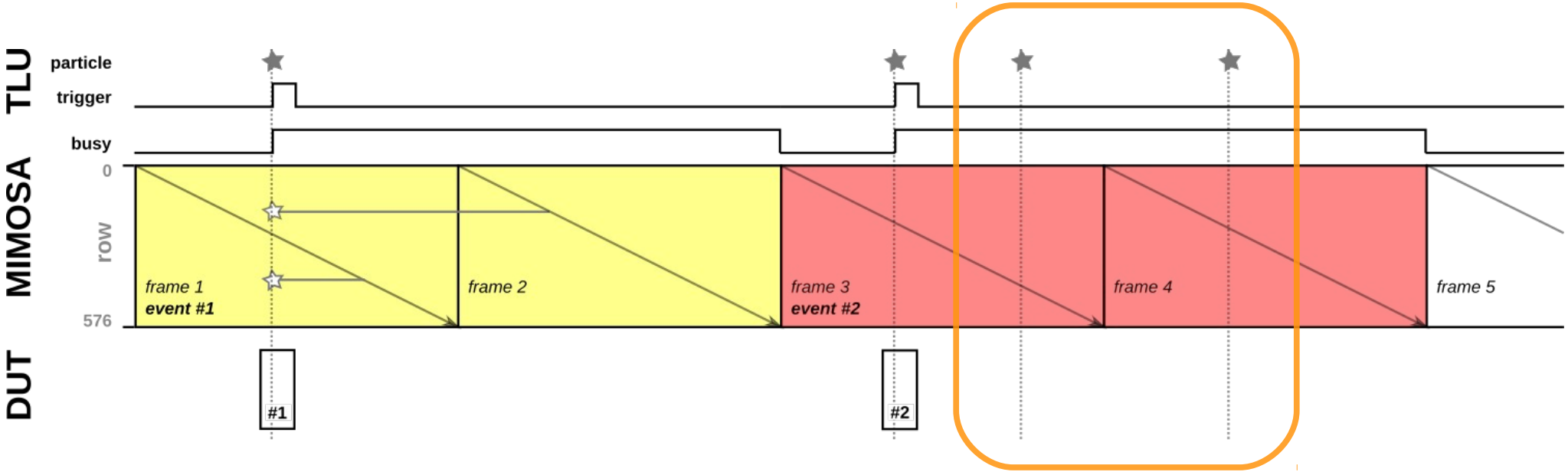
Improving the TDAQ

Why a second version?

1) Strategy for new mode

Allow **multiple** triggers within 1 telescope event

→ **ignore** busy from slow devices



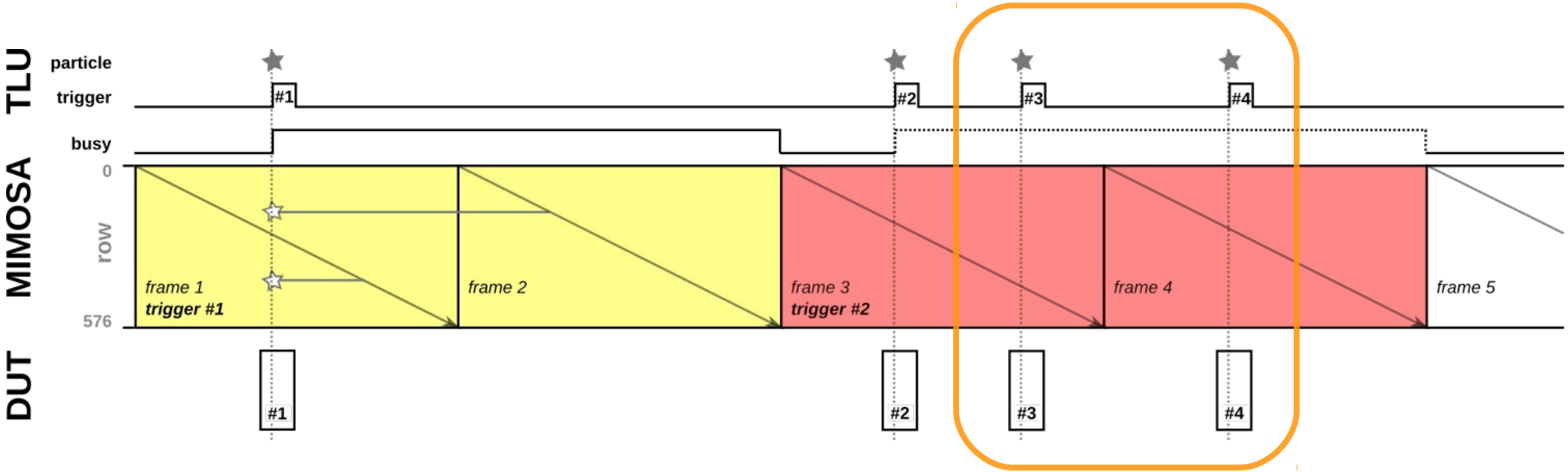
Why a second version?

1) Strategy for new mode

Allow **multiple** triggers within 1 telescope event

→ **ignore** busy from slow devices → no event-based sync.

→ synchronisation by **common clock or trigger ID**



Why a second version?

1) Strategy for new mode

Allow **multiple** triggers within 1 telescope event

→ **ignore** busy from slow devices → no event-based sync.

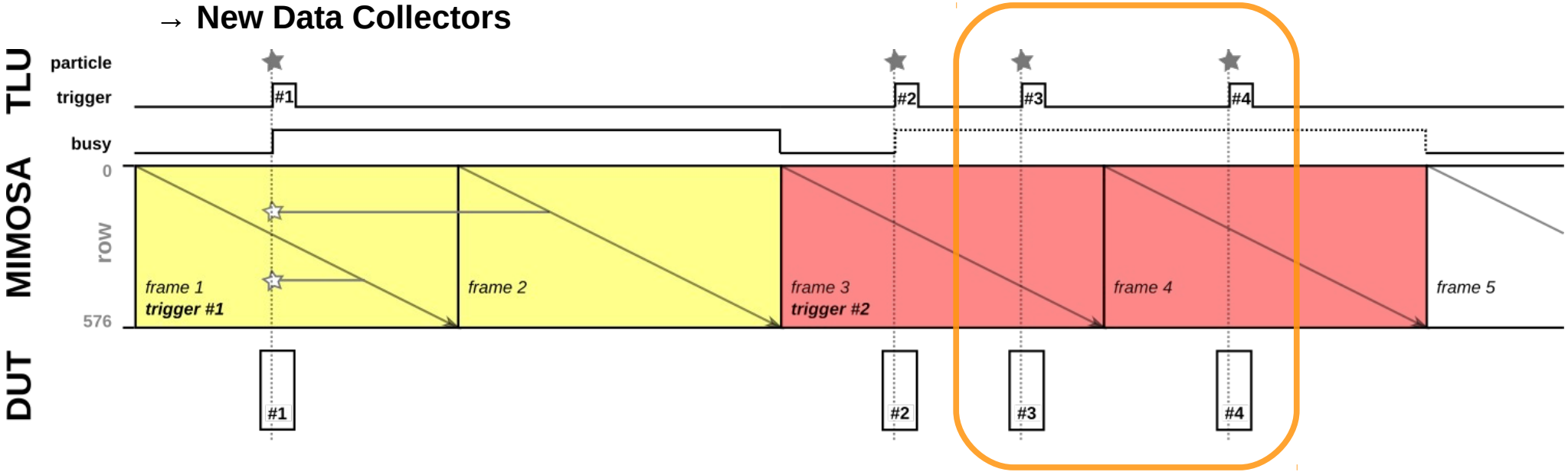
→ synchronisation by **common clock or trigger ID**

→ **New Data Collectors**

2) Motivation for WP5 AIDA2020

Common DAQ software framework – not only tracker devices, also for calorimeter...

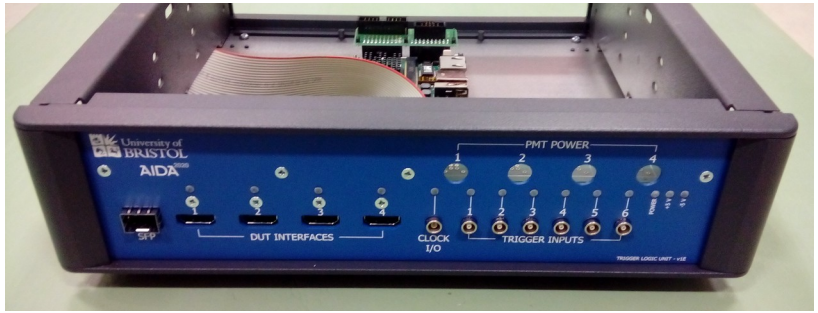
→ **EUDAQ1** suitable candidate



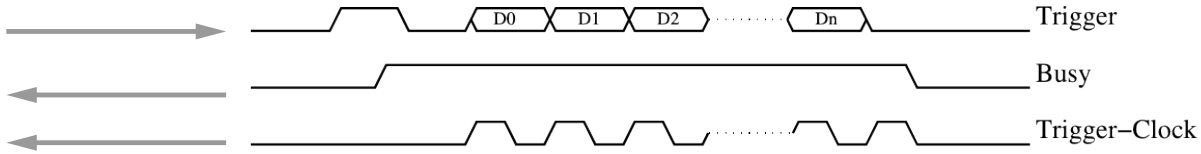
Telescope Upgrade: AIDA TLU ...

New options, faster and open

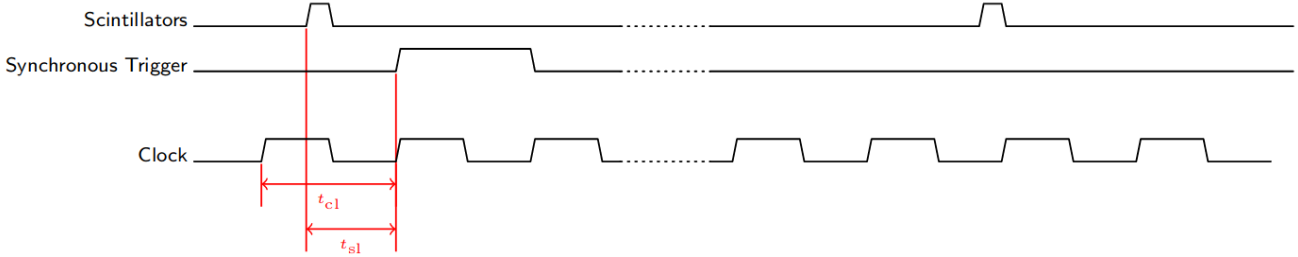
https://ohwr.org/project/fmc-mtlu



"Trigger-data-handshake"



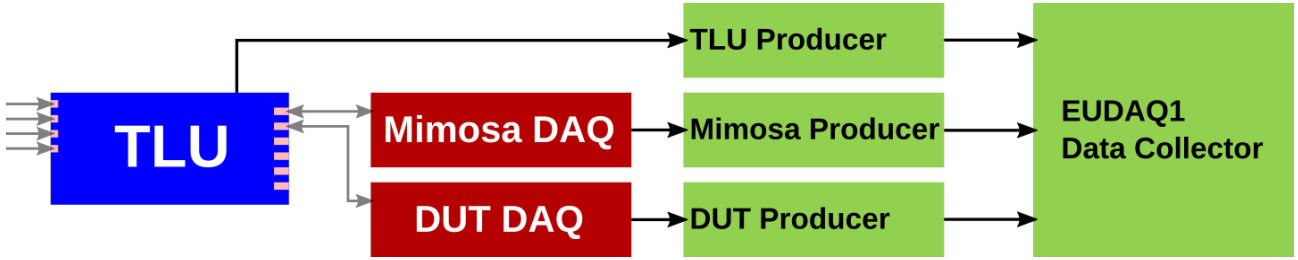
- New FPGA Xilinx Artix: 1 MHz maximum trigger rate
- 6x inputs for coincidence logic & 4x interfaces for DUT communication (HDMI)
- Individual busy & Backward-compatible (clock out Trigger ID)
- Common clock: Synchronous interface (clk, t0, trg, bsy, sync)



Data flow and event building

Reminder how it was before

EUDET-type hardware ⟷ **EUDAQ v1**



EUDAQ Data Collector

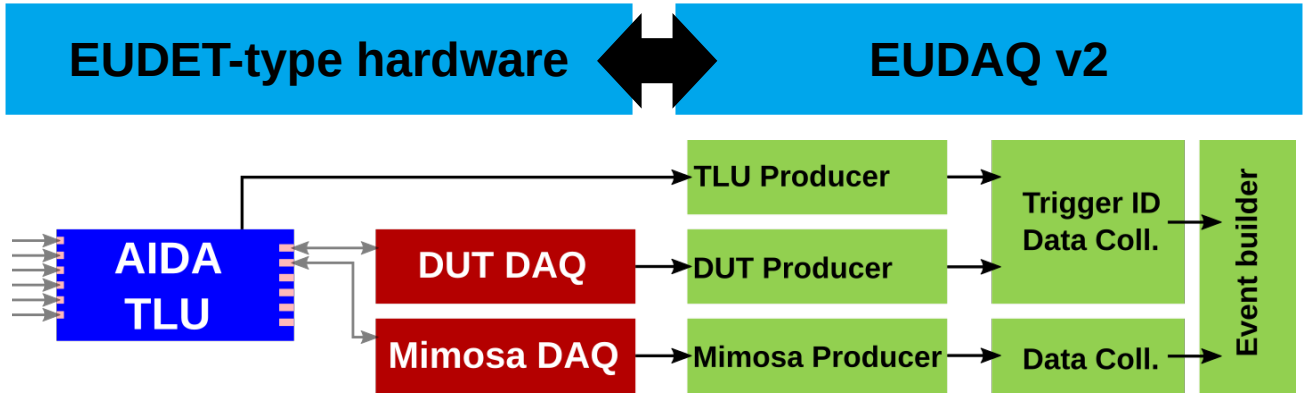
Evt. ID	TLU	DUT	Mimosa
1	1	1	1
2	2	2	2
3	3	3	3
4	4	4	4
5	5	5	5
6	6	6	6
7	7	7	7
8	8	8	8
9	9	9	9
10	10	10	10
11	11	11	11
12	12	12	12
..	..	..	..

"EUDET mode": One trigger = one read-out from all devices

- Event-based synchronisation for robust data-taking
- Unique event definition: **EUDAQ1 event**
- **But trigger rate is limited by the slowest device!**

Telescope Upgrade: … and EUDAQ2

Independent data flow and event building



EUDAQ 2 Sync. by Trigger ID

Trigg. ID	TLU	DUT	Mimosa
1	1	1	1
2	2	2	1
3	3	3	1
4	4	4	4
5	5	5	4
6	6	6	6
7	7	7	6
8	8	8	6
9	9	9	9
10	10	10	9
11	11	11	9
12	12	12	9
..	..	..	..

"Mixed mode": multiple trigger, not waiting for the slow devices

- Trigger ID-based synchronisation
  → New data collector options in EUDAQ version 2
- Event re-definition for analysis
  → e.g. EUDAQ1-like event by data duplication of Mimosa (duplicated track rejection after analysis)

Telescope Upgrade: Results for “Mixed mode”

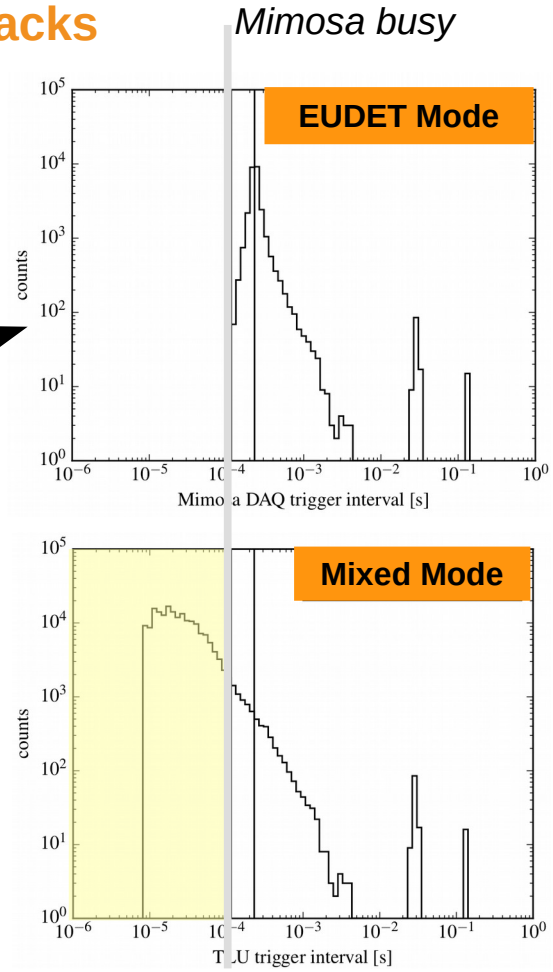
Getting more timestamped tracks

E.g. 2 GeV/c test run at DESY II TB using the telescope and a fast reference plane FEI4

Mixed mode — **EUDAQ 2 Sync. by Trigger ID**

Standard — **EUDAQ 1**

Trigg. ID	TLU	DUT	Mimosa	Evt. ID
1	1	1	1	1
2	2	2	1	x
3	3	3	1	x
4	4	4	4	2
5	5	5	4	x
6	6	6	6	3
7	7	7	6	x
8	8	8	6	x
9	9	9	9	4
10	10	10	9	x
11	11	11	9	x
12	12	12	9	x
..	..	..	..	..



Results & updated limits

- Trigger rate now limited by
  - busy time for clocking out trigger ID
    → here, 8.8 µs = **115 kHz** (**factor ~30**)
- Timestamped tracks (with FEI4)
  - **all** tracks with high time resolution
    → **factor 5.5** at 2 GeV/c @ DESY II
    → factor 2.6 at 3 GeV/c
    → factor 1.1 at 5 GeV/c
  - potential factor 6.9 at 2 GeV/c
    → losing tracks due to 2-frame read-out

EUDAQ version 1 and version 2

Data taking

EUDAQ 1 – robust

- ***Centralized*** data taking with EUDET TLU
  - One Data Collector
  - Online synchronisation by event number (unique event definition)

Data-taking modes of EUDAQ and EUDET TLU

Modes	Trigger comm.	Sync. by
EUDET	Global Trigger-Busy	Event ID

EUDAQ 2 – more flexible

- ***Decentralized*** data taking with AIDA TLU
  - Multiple Data Collector (and connections)
  - Online or **offline** synchronsiation by event number, **Trigger ID** or **timestamps**

Available data-taking modes of EUDAQ2 and AIDA TLU

Modes	Trigger comm.	Sync. by
Standard/ EUDET	Global Trigger-Busy	Event ID/ Trigger ID
mixed	Individual Trigger-Busy	Trigger ID
Timestamp/ AIDA	Common Clock	Timestamps

Test Beam and Telescope usage for you?

→ Come to the DESY Test Beam Facility

- BeamLine4Schools / Teacher education program
- Summerstudent program 2020: summerstudents.desy.de
- EDIT school at DESY in 2020, check www.desy.de/edit2020
- PhD/PostDoc in the DESY-ATLAS group
- Ongoing research with your group/collaboration!?!
  → schedule for 2019: https://bit.ly/2Vqxvx9
- Beam Telescopes and Test Beam (BTTB) Workshop
  →BTTB7: https://indico.cern.ch/event/731649/ → BTTB8: January 2020 in Georgia

In a nutshell…

Summary & Outlook

- Test beams are a challenge to TDAQ because

  …many different devices have to be integrated

  …on very short time scales an with limited manpower

- The EUDET-type beam telescope infrastructure help users

  …with a ready-to-run reference detector system

  …and a flexible and yet simple interface for integration

- Technology ages – new demands arise
  - Modular Infrastructure allows integration of new stuff
  - More focus on fast timing

Thank you!

Triggerless Readout for EUDET Telescope

- MMC3 board to replace NI FlexRIO system
  - Custom FPGA board with Ethernet connectors
  - TLU connection to store trigger time stamps
  - FPGA for data processing

- Continuous DAQ
  - Allows multiple triggers per frame
  - Disentangle via faster detector