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
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)
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: Belle-II 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?

  - 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

Prototype Demonstrator
- 1st telescope EUDET-type (Mimosa26/NI)
- 2nd telescope “ANEMONE” for Bonn
- 3rd telescope “DATURA” at DESY
- 4th telescope “ACONITE” for ATLAS now at SPS
- 5th telescope “CALADIUM” now at SLAC
- 6th telescope “DURANTA” at DESY
- 7th telescope “AZALEA” at DESY

“BTTB1” “BTTB2” BTTB3 BTTB4 BTTB5 BTTB6 BTTB7 BTTB8 ...

EUDET
AIDA
AIDA 2020
The EUDET-type telescope infrastructure

Hardware

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

EUDAQ

Top-Level DAQ software

- Central run control & monitoring
- Synchronisation & acquisition

EUTelescope

Track reconstruction framework

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

telescopes.desy.de
eudaq.github.io
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
  - \( \rightarrow 10^6 \text{ particles/cm}^2/\text{s} \)

For more details see the Manual:
Silicon CMOS pixel for particle detection

Doped Silicon $\rightarrow$ Depletion zone $\rightarrow$ built-in bias voltage $\rightarrow$ Drift field

Potential barriers

$$V = \frac{kT}{q} \ln \frac{N_{sub}}{N_{epi}}$$

Metal layers

Polysilicon

Radiation

Dielectric for insulation and passivation

P-Well

N-Well

P-Well

Charged particles

100% efficiency.
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
Data Acquisition System - Overview

- Data Concentrator
- NI PXIe Crate
- Fanout boards
- RAID Array
- 6x M26 Sensor
- Auxiliary board
Common Clock Distribution

80MHz clock + common start signal

Data Concentrator

NI PXIe Crate

Fanout boards

Auxiliary board

RAID Array

6x M26 Sensor
Device Configuration

- Data Concentrator
- NI PXIe Crate
- RAID Array
- Fanout boards
- Auxiliary board
- JTAG interface
- 6x M26 Sensor
Data Acquisition

- 6 x 2 data links @ 80MHz

- Data Concentrator

- Fanout boards

- RAID Array

- Auxiliary board

- 6x M26 Sensor

- NI PXIe Crate
Data lines and handling

Clock line
Marker line
Data0 line
Data1 line

FPGA

DESY. Jan Dreyling-Eschweiler | TDAQ of EUDET-type Telescopes | 10th April 2019
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
Triggereing 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)

- Control of trigger devices
  - Power for PMTs (15V and control 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

PMT power via LEMO

LVDS signals via RJ45

NIM or TTL signals via LEMO

Inputs of trigger devices

Trigger signals

USB Host interface

PMT power
Input signals

- PMT/scintillator signals → negative
- Maybe other signals → mostly positive
  - Kicker signal from beam line
  - HitOr output from sensor
  - Pulse Generator
  - ...
Example: Input + Inverter + Output

- **Trigger output**: 140 ns
- **Comparator output (Discriminator)**: 800 ns
- **OpAmp Inverter**
- **Input pulse positive**: (80 mV/10 ns)

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

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

- **6x Mimosa26 planes**
- **FPGA Xilinx Virtex 5 for NI COTS system**
- **2x2 trigger devices**
- **EUDET TLU**
- **Trigger**
- **Busy**

Diagram showing the DAQ system flow with labeled components and connections. The diagram includes a timeline with trigger events and corresponding busy signals for MIMOSA and DUT. The timeline illustrates the sequence of events and the status of the 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
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
EUDAQ architecture

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

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...

![EUDAQ Log Collector Screenshot](image)
Producer interface in 26 lines C++

```cpp
#include <eudaq::Producer.h>

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(), rc ctrl.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

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### 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
- DUT1 Producer
- DUT2 Producer
- Telescope Prod.
- Run Control
Start up connections

Hardware
- TLU Control
- DUT1 DAQ
- DUT2 DAQ
- Telescope DAQ

Software
- TLU Producer
- Data Collector
- Online Monitor
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- DUT1 Producer
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- Run Control
Configuration

Hardware
- TLU Control
- DUT1 DAQ
- DUT2 DAQ
- Telescope DAQ

Software
- TLU Producer
- Data Collector
- Online Monitor
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- Run Control
- DUT1 Producer
- DUT2 Producer
- Telescope Prod.
Trigger!

Hardware

- Trigger
- 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
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 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, ...
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**

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[Diagram showing the timeline and synchronization process.]

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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

- 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

EUDET-type hardware \(\rightarrow\) EUDAQ v1

- **"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!

Reminder how it was before

<table>
<thead>
<tr>
<th>Evt. ID</th>
<th>TLU</th>
<th>DUT</th>
<th>Mimosa</th>
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<tbody>
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</tbody>
</table>
“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

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
    - 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

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

EUDAQ 2 – more flexible

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

### Data-taking modes of EUDAQ and EUDET TLU

<table>
<thead>
<tr>
<th>Modes</th>
<th>Trigger comm.</th>
<th>Sync. by</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUDET</td>
<td>Global</td>
<td>Event ID</td>
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<td></td>
<td>Trigger-Busy</td>
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</tr>
</tbody>
</table>

### Available data-taking modes of EUDAQ2 and AIDA TLU

<table>
<thead>
<tr>
<th>Modes</th>
<th>Trigger comm.</th>
<th>Sync. by</th>
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<tbody>
<tr>
<td>Standard/ EUDET</td>
<td>Global Trigger-Busy</td>
<td>Event ID/ Trigger ID</td>
</tr>
<tr>
<td>mixed</td>
<td>Individual Trigger-Busy</td>
<td>Trigger ID</td>
</tr>
<tr>
<td>Timestamp/ AIDA</td>
<td>Common Clock</td>
<td>Timestamps</td>
</tr>
</tbody>
</table>
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!?!

• 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 and 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