12th edition of the Beam Telescopes and Test Beams Workshop

April 15-19 2024, Edinburgh, UK

On-beam test for the LHC Phase-II CMS Electromagnetic PbWO4 calorimeter

Giulia Lavizzari

on behalf of the CMS Collaboration

Istituto Nazionale di Fisica Nucleare
Sezione di Milano-Bicocca

Università degli Studi di Milano Bicocca

LHC Phase II

The High Luminosity upgrade of the LHC (HL-LHC) at CERN will provide **unprecedented instantaneous and integrated luminosities**

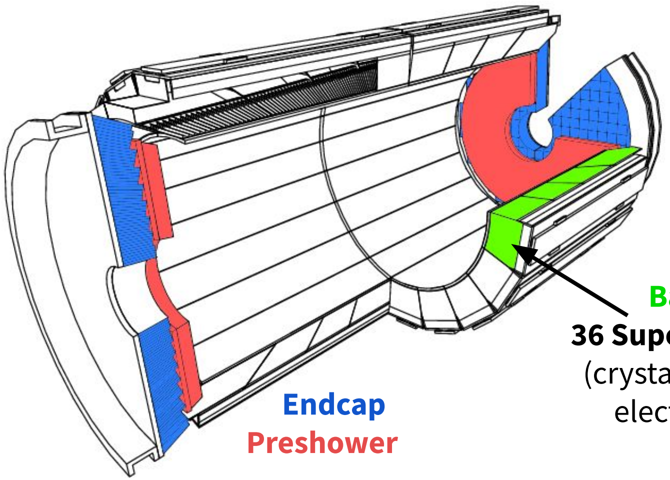
New challenges:

- **Higher number of collisions** per bunch crossing (40 to 200)
  - requires better discrimination of spurious events
- **Higher radiation levels**
  - detectors need to be more radiation tolerant
- More stringent requirements: **longer latency** (from 3.5 μs to 12 μs) **and higher trigger rates** (from 100 kHz to 750 kHz)
  - detectors need to have longer pipelines and faster readout

The CMS electromagnetic calorimeter (ECAL)

key role in the **detection of electrons and photons** for the CMS experiment at LHC

- homogeneous, fine grained, high-resolution calorimeter
- $PbWO_4$ scintillating crystals
  - avalanche photodiodes (APD) in barrel
  - vacuum phototriodes in endcaps



Upgrade for Phase II:

- endcaps and forward calorimeters will be replaced by HGCAL
- **barrel:**
  - **full refurbishment of electronics**
  - **crystals + APDs will not change**, but will be **operated at lower temperature**
- further goal: time resolution
  - 30 ps for electromagnetic showers above 50 GeV

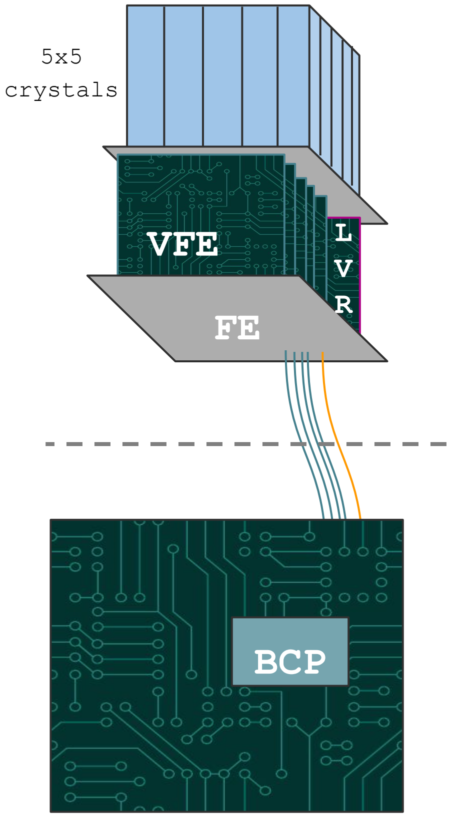
ECAL barrel upgrade: new electronics

On-detector

- **Very Front End cards**
  - CATIA (analog ASIC)
    - 2x transimpedance amplifier
  - LiTE-DTU (digital ASIC)
    - 2x 12-bit ADCs sampling at 160 MHz
    - gain selection and data transmission unit
- **Front End cards**
  - LpGBT optical transmission system
- **Low Voltage Regulator cards**

Off-detector

- **Barrel Calorimeter Processor (BCP)**
  - high-end FPGAs
  - from VME to ATCA protocols



ECAL barrel upgrade: new electronics

On-detector

- **Very Front End cards**
  - CATIA (analog ASIC)
    - 2x transimpedance amplifier
  - LiTE-DTU (digital ASIC)
    - 2x 12-bit ADCs sampling at 160 MHz
    - gain selection and data transmission unit
- **Front End cards**
  - LpGBT optical transmission system
- **Low Voltage Regulator cards**

faster analog electronics

- larger analog bandwidth
- sampling rate from 40 to 160 MHz, with 12-bit resolution
- loss-less data compression mechanism

→ better time resolution
→ better noise discrimination

fast optical links

Off-detector

- **Barrel Calorimeter Processor (BCP)**
  - high-end FPGAs
  - from VME to ATCA protocols

powerful off-detector processor

- trigger objects reconstructed off-detector

→ 25x more granular trigger primitives

ECAL recent Test Beams

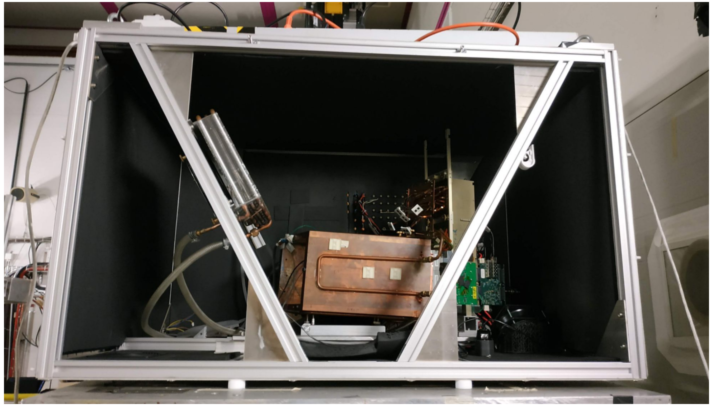
H4 test beam line at the North Area of the **CERN SPS: e^+/e^- (20 - 300 GeV**, $\Delta p/p < 0.5\%$)

Main goals:

- timing and energy resolution
- test system stability

2021:

- **5 VFE cards tested**
  - only 25 crystals, with custom electronic chain for the test
  - data for physics performance evaluation



2022:

- **Commissioning of the full readout chain** (similar setup to 2023)
  - few data taken for physics → mainly system commissioning and stability tests

ECAL 2023 Test Beam

H4 test beam line at the North Area of the **CERN SPS: e^+/e^- (20 - 300 GeV**, $\Delta p/p < 0.5\%$)

Main goals:

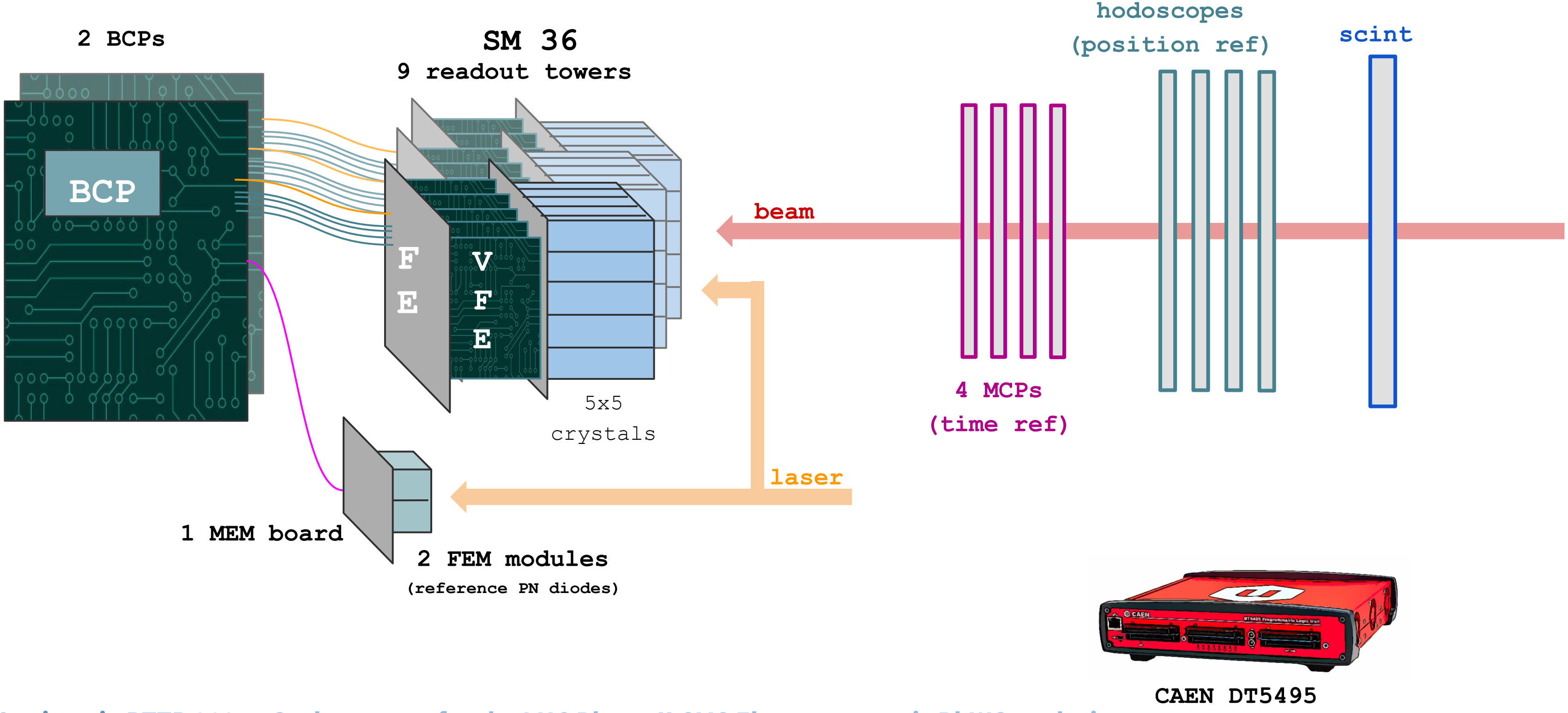
- timing and energy resolution
- test system stability

2023:

- **The whole electronic chain** is mounted on a **spare SuperModule** (SM36)**, identical to the ones in ECAL**
  - 25 crystals x 9 readout units
  - full-setup test, very close to real detector conditions!
  - first time taking physics data with BCPs
- **Upgrade laser monitoring**, between e^+/e^- fills
  - laser is used in ECAL to monitor crystal transparency

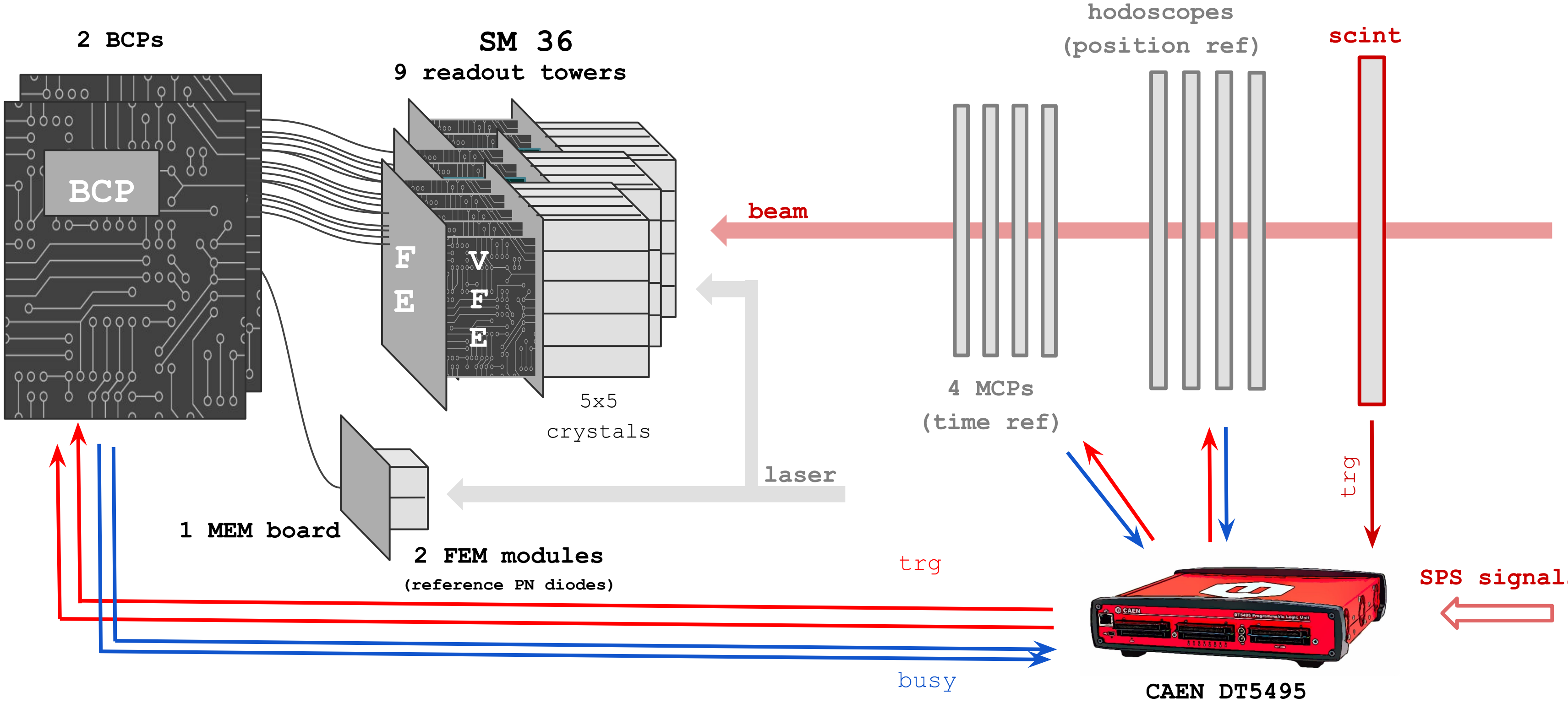
Hardware setup

- SM36 is equipped with **9 readout towers**, read by **2 BCPs**
- Scintillators and other detectors on the beamline to give triggers and time/position reference



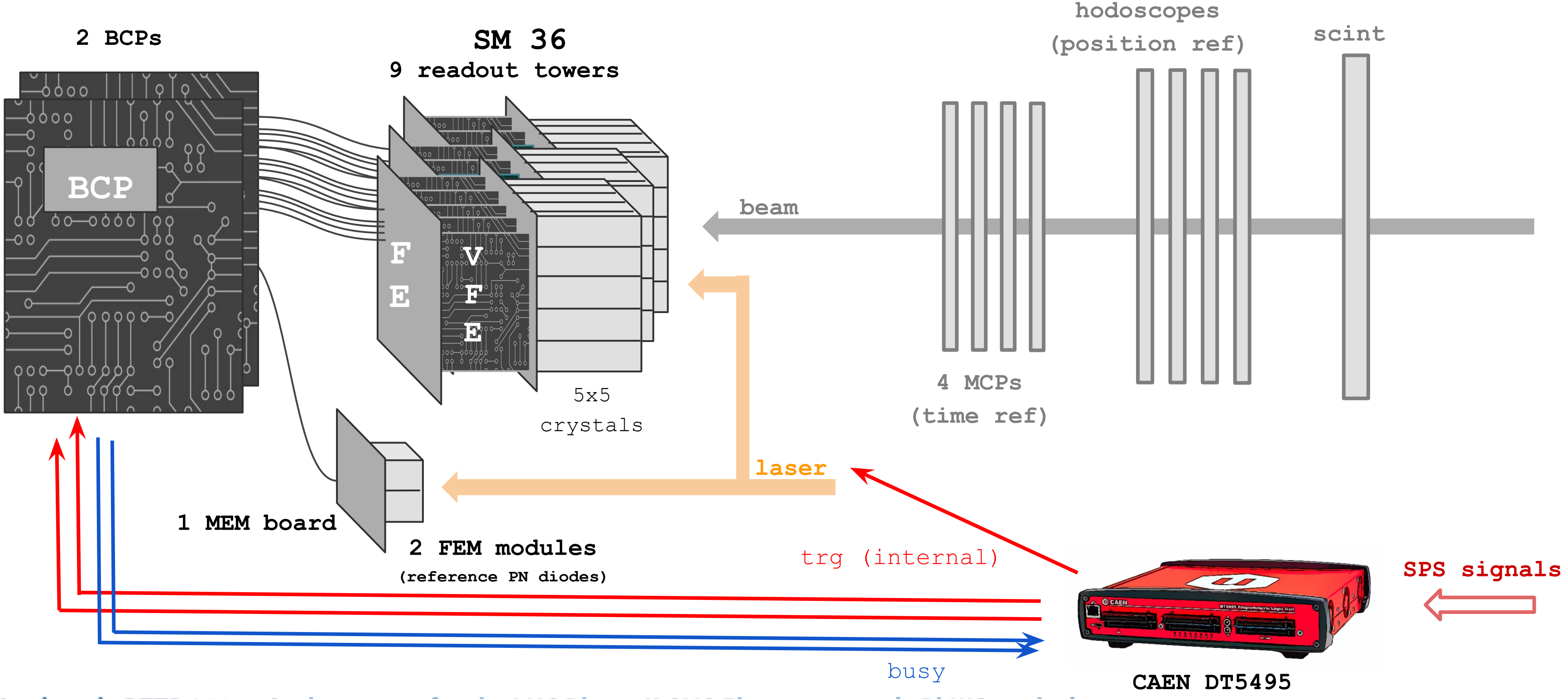
DAQ: physics events

- SPS signals warn the system of an **incoming beam spill**
- Trigger given by plastic scintillator
- Acquisition allowed if we have trigger & no BUSY flags

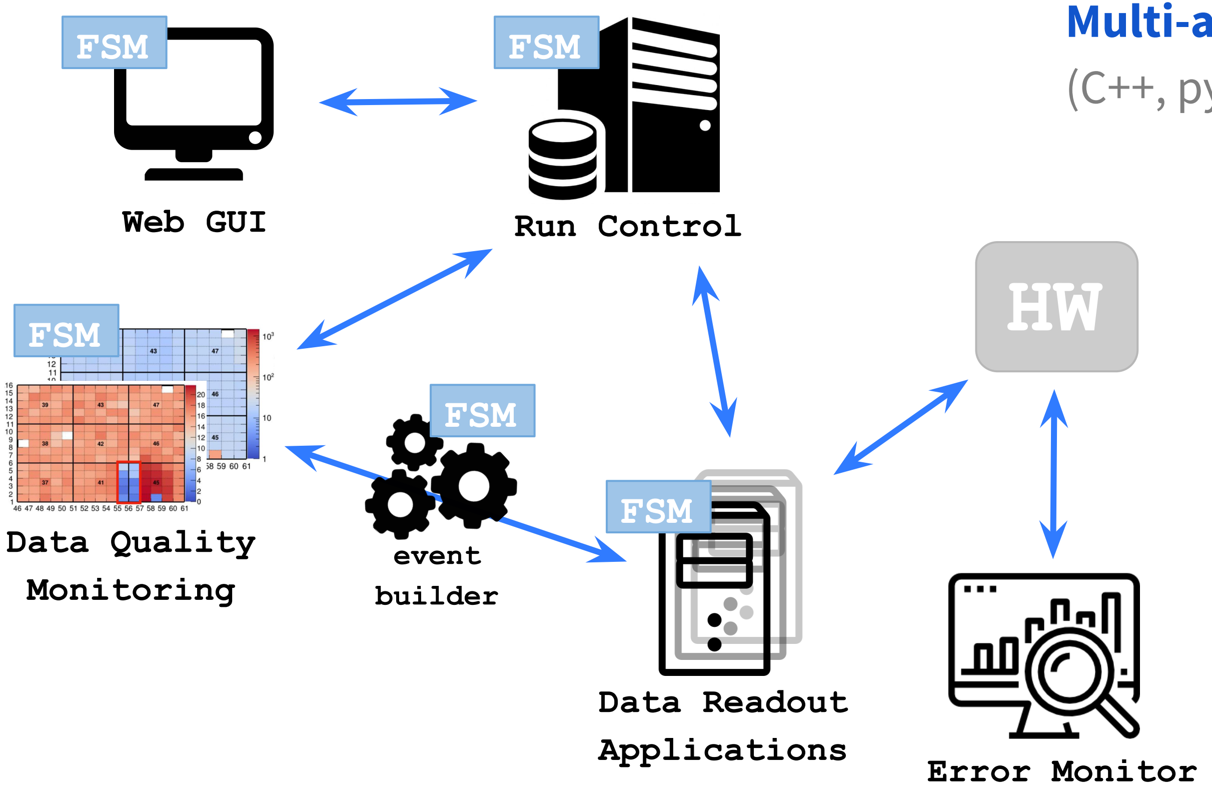


DAQ: laser

- Laser runs happen during **interspill**, i.e. when SPS is not sending e^+/e^-
- Trigger generated internally, allows for laser to fire and for BCPs to acquire data



Software structure

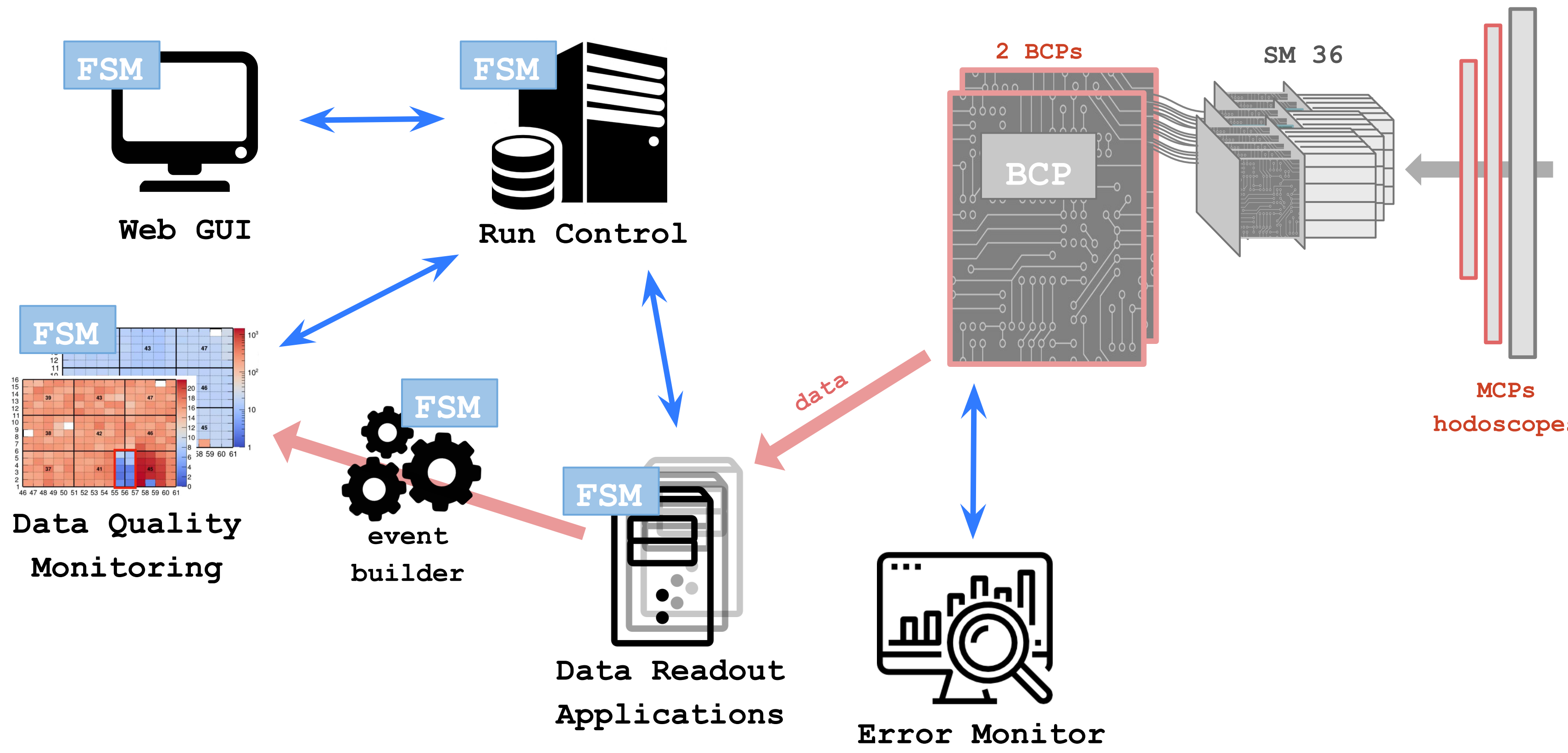


Multi-application distributed system

(C++, python, javascript)

- **ZeroMQ** library for communication
- **Rogue** library for hw interface
- **Vue.js** library for web pages (web gui and error monitor)
- **MongoDB** as database to store configuration settings

System control and data flow

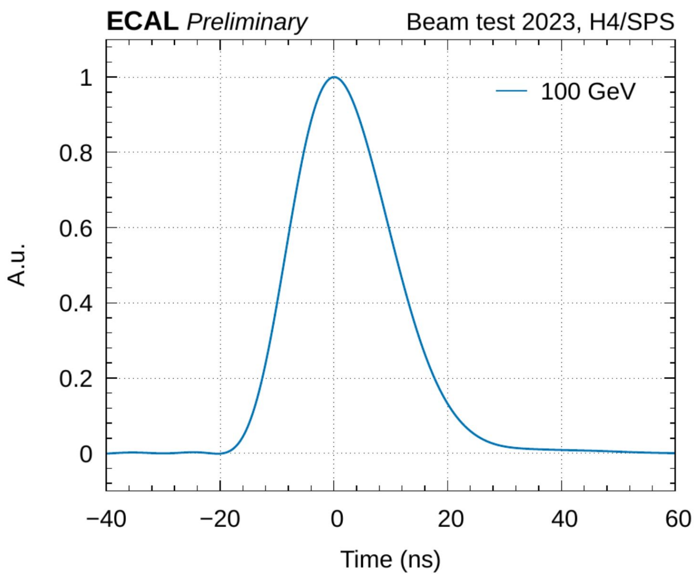


TB results: general considerations

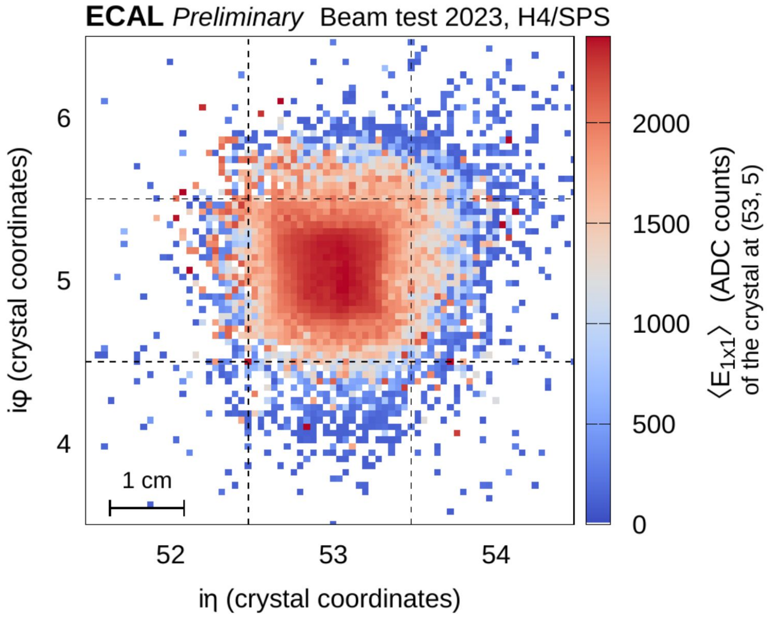
Electron signal amplitude A **and time** t_0 are reconstructed with a **template fit**:

$$f(x) = A \cdot template(t - t_0)$$

templates via sw oversampling in frequency domain



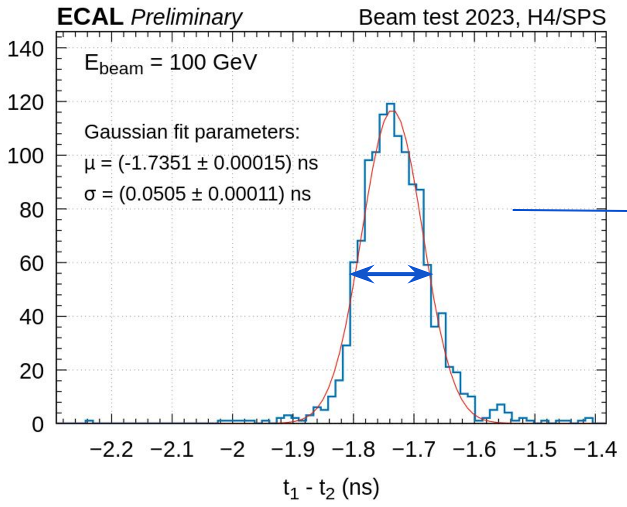
Electron impact position in a matrix of n crystals is reconstructed based on the energy deposits in each crystals:

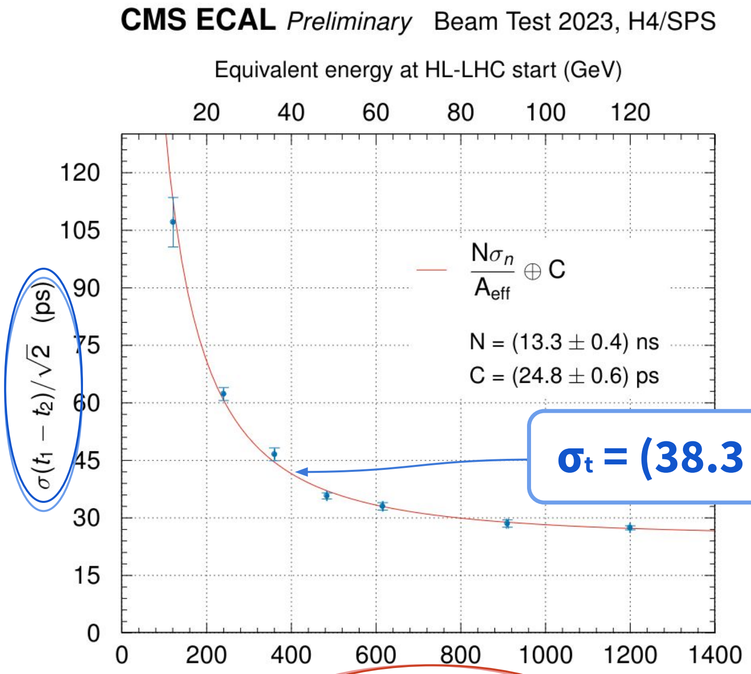


Timing resolution

Obtained using data collected with **beam firing between two crystals**

timing resolution → **width of the distribution of** the difference **Δt** of the signal arrival times





σ_n = 100 MeV

A_{eff} = 50 GeV

σ_t = (38.3 ± 0.5) ps

studied as a function of the "effective amplitude"

$$\frac{A_{eff}}{\sigma_n} = \sqrt{\frac{2}{\left(\frac{\sigma_1}{A_1}\right)^2 + \left(\frac{\sigma_2}{A_2}\right)^2}}$$

Energy resolution

Computed using data obtained by firing the **beam at the center of a single crystal**

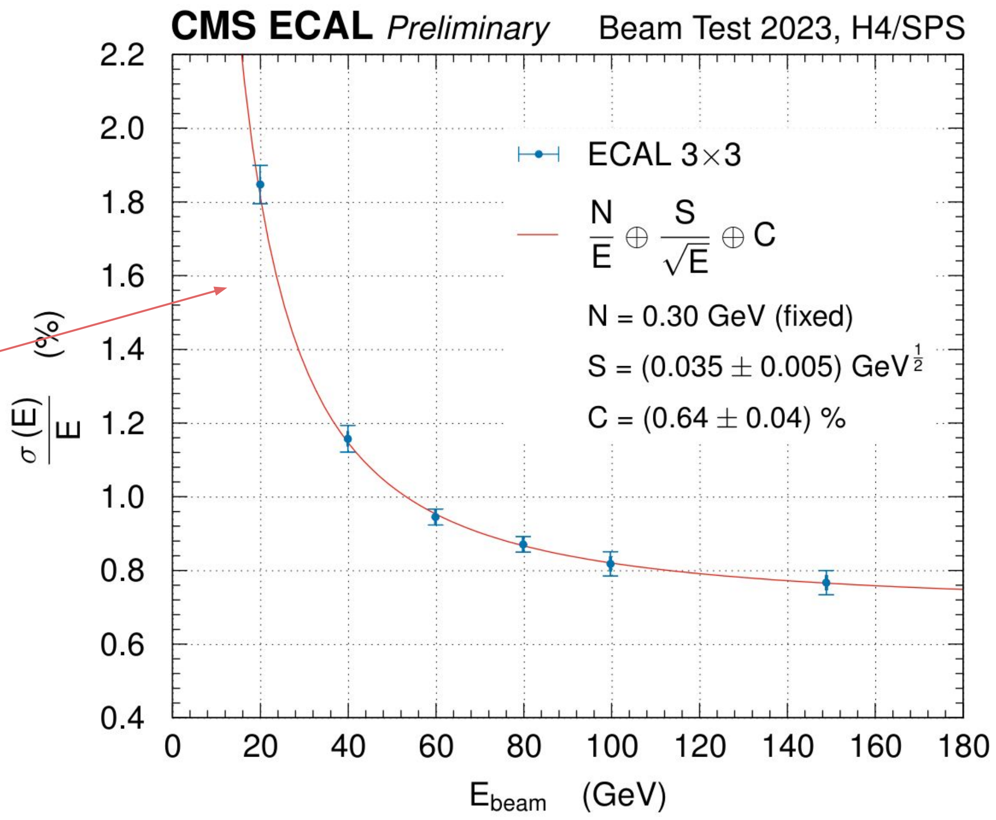
- Computed using a 3x3 crystal matrix

$$\frac{N}{E} \oplus \frac{S}{\sqrt{E}} \oplus C$$

noise term

stochastic term

constant term

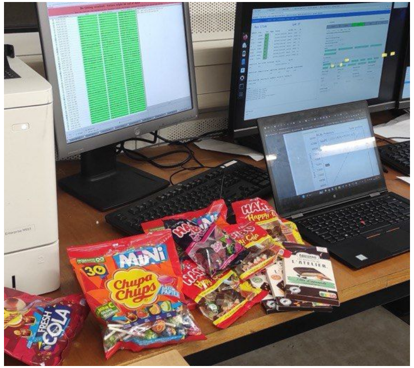


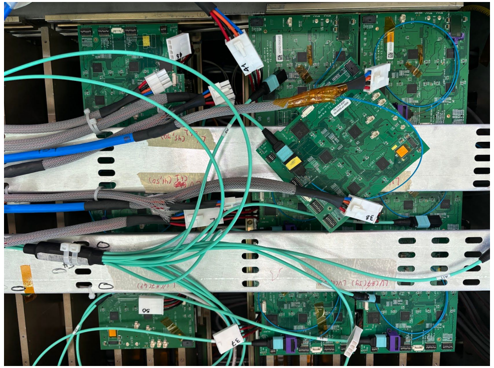
Conclusions

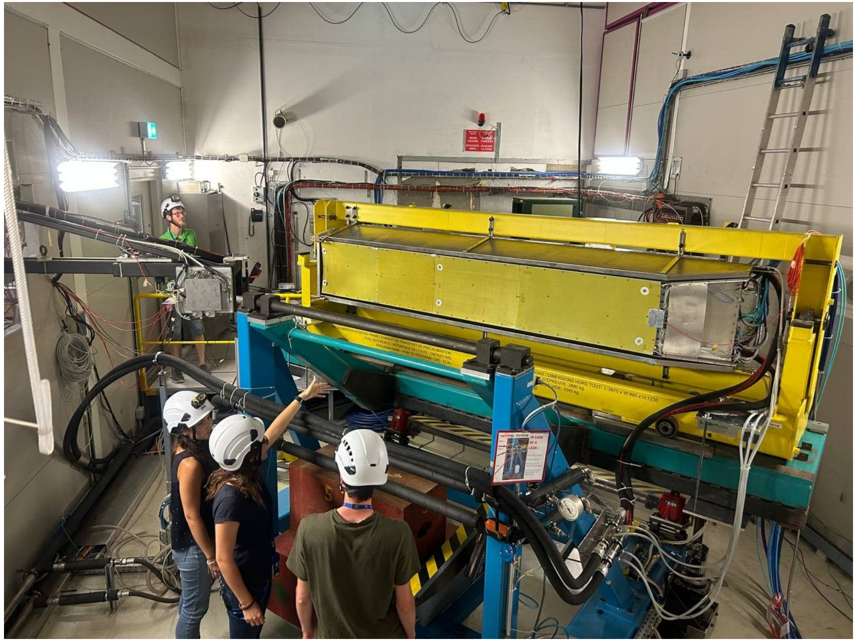
- **Test beam was successful**
  - Few stability issues (spotted promptly thanks to monitoring system → online/offline solutions)
  - Collected large dataset for physics performance evaluation

- Results obtained so far are **compatible with the specifications**

- **More to come** in terms of analysis



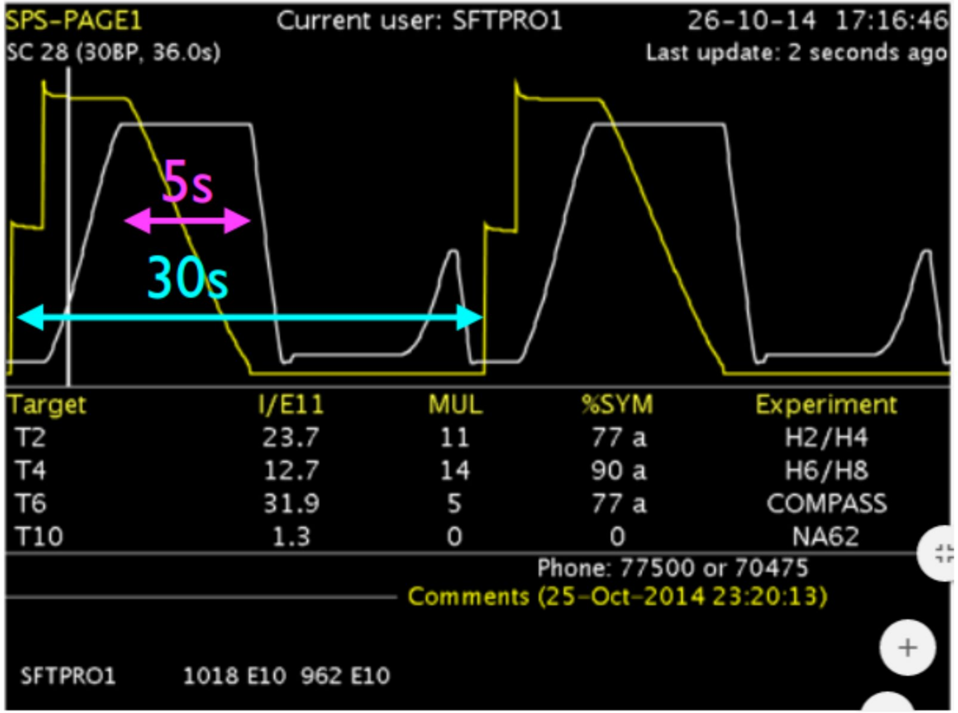




BACKUP slides

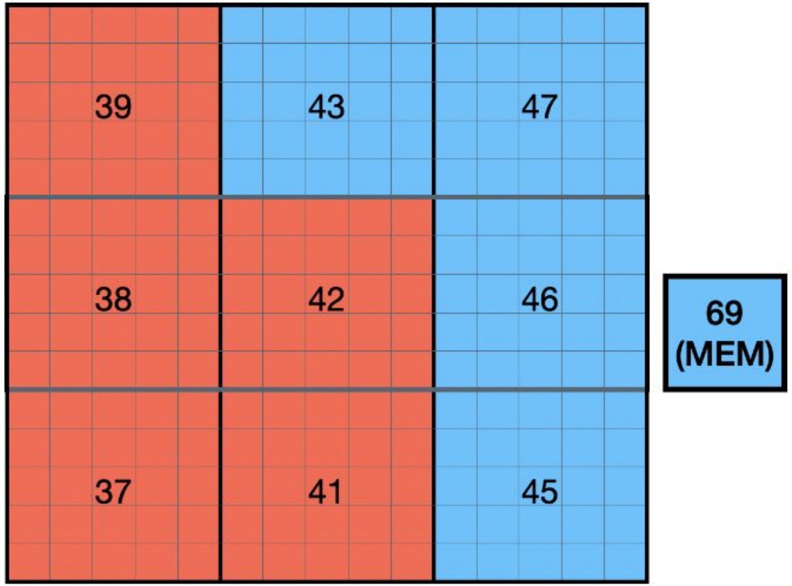
SPS injection scheme

Very pure e^+/e^- beam, $\Delta p/p < 0.5\%$ (20 - 300 GeV)



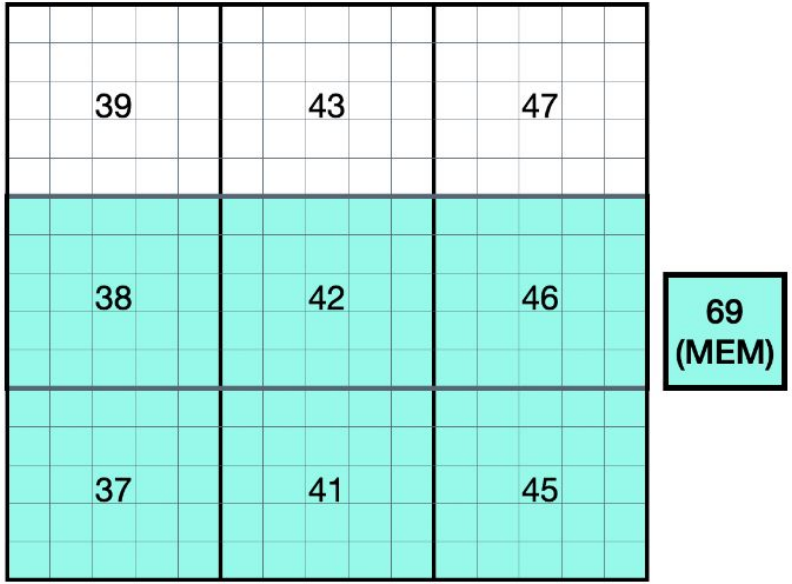
picture from Giacomo Cucciati

Readout units scheme



BCP0
5 RUs

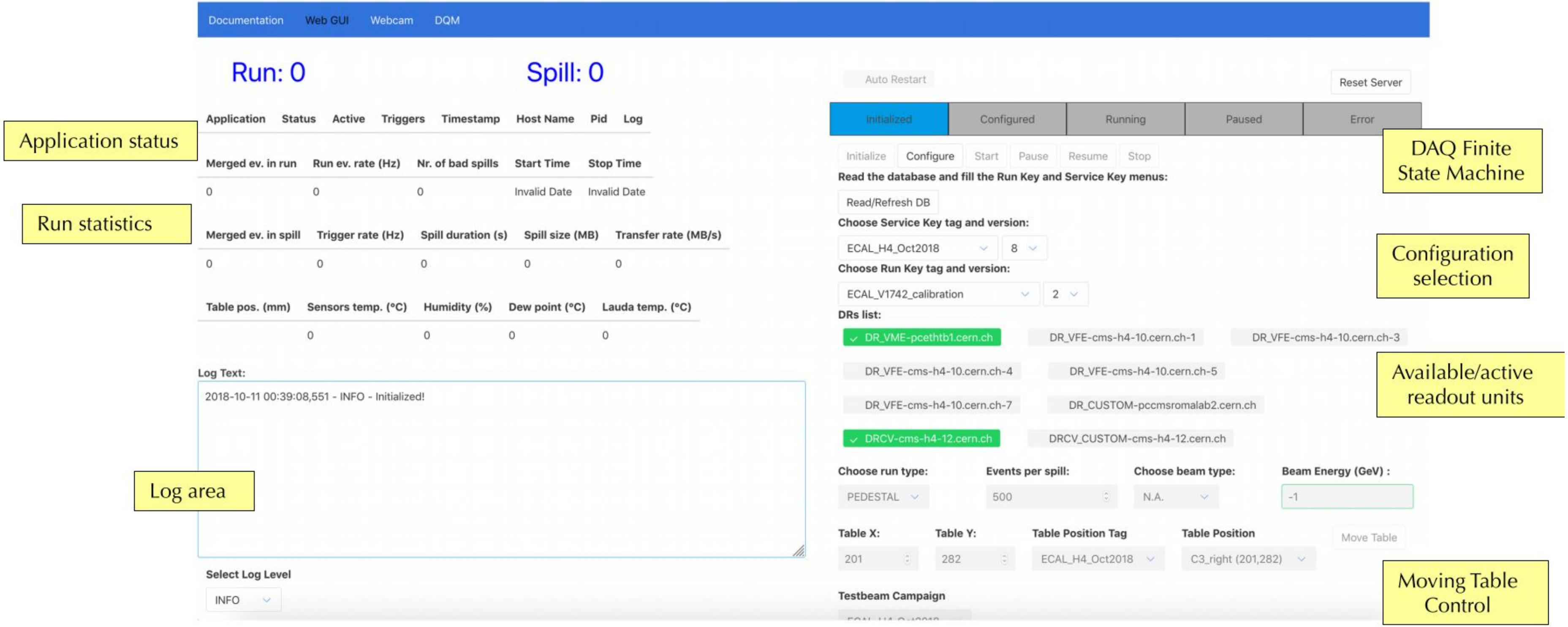
BCP1
4 RUs + MEM



Laser monitoring region
Laser runs taken inter-spill

picture from Chiara Amendola

WEB GUI

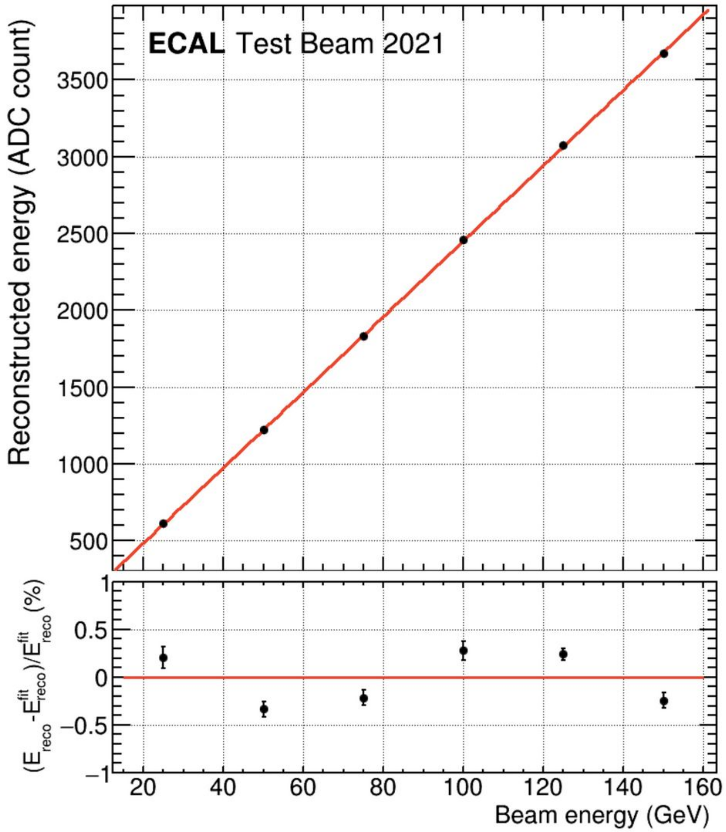


picture from Giacomo Cucciati

Error monitor

2021 TB data: linearity

Single crystal response in terms of average amplitude of the signal (in ADC counts) w.r.t. the energy of the incident electron-beam. In the lower panel we report the deviation of the reconstructed energy (in ADC count) with respect to the linear fit. Maximum deviation from linearity is < 0.3%.



2022 TB data: pulse shape vs APD spike

Comparison of the pulse shape from a scintillation event and a signal induced by a direct hit in the avalanche photodiode. The latter was identified using topological constraints. Pulses are re-aligned in time to the first sample of the rising edge. The solid line are the templates of the two signals.