Mu2e crystal calorimeter front-end electronics: design and characterisation

Calor 2022

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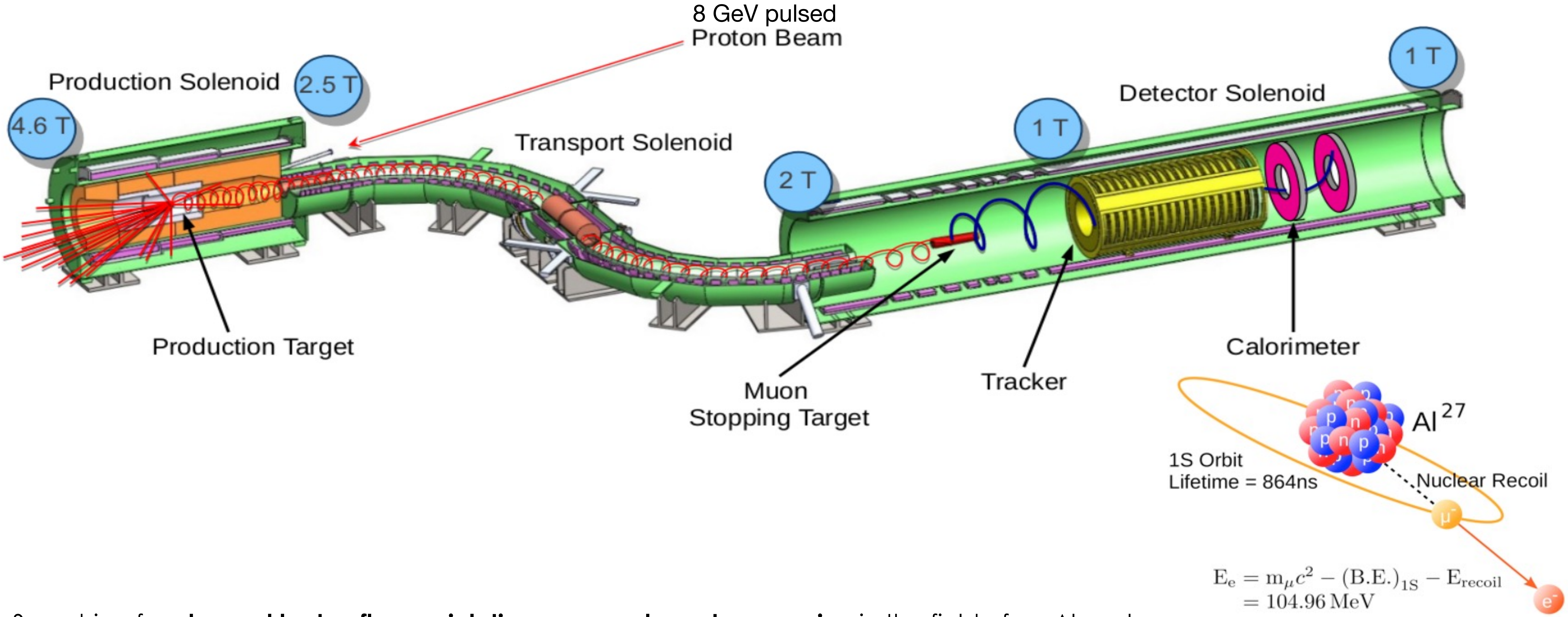
Fermilab

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

Mu2e

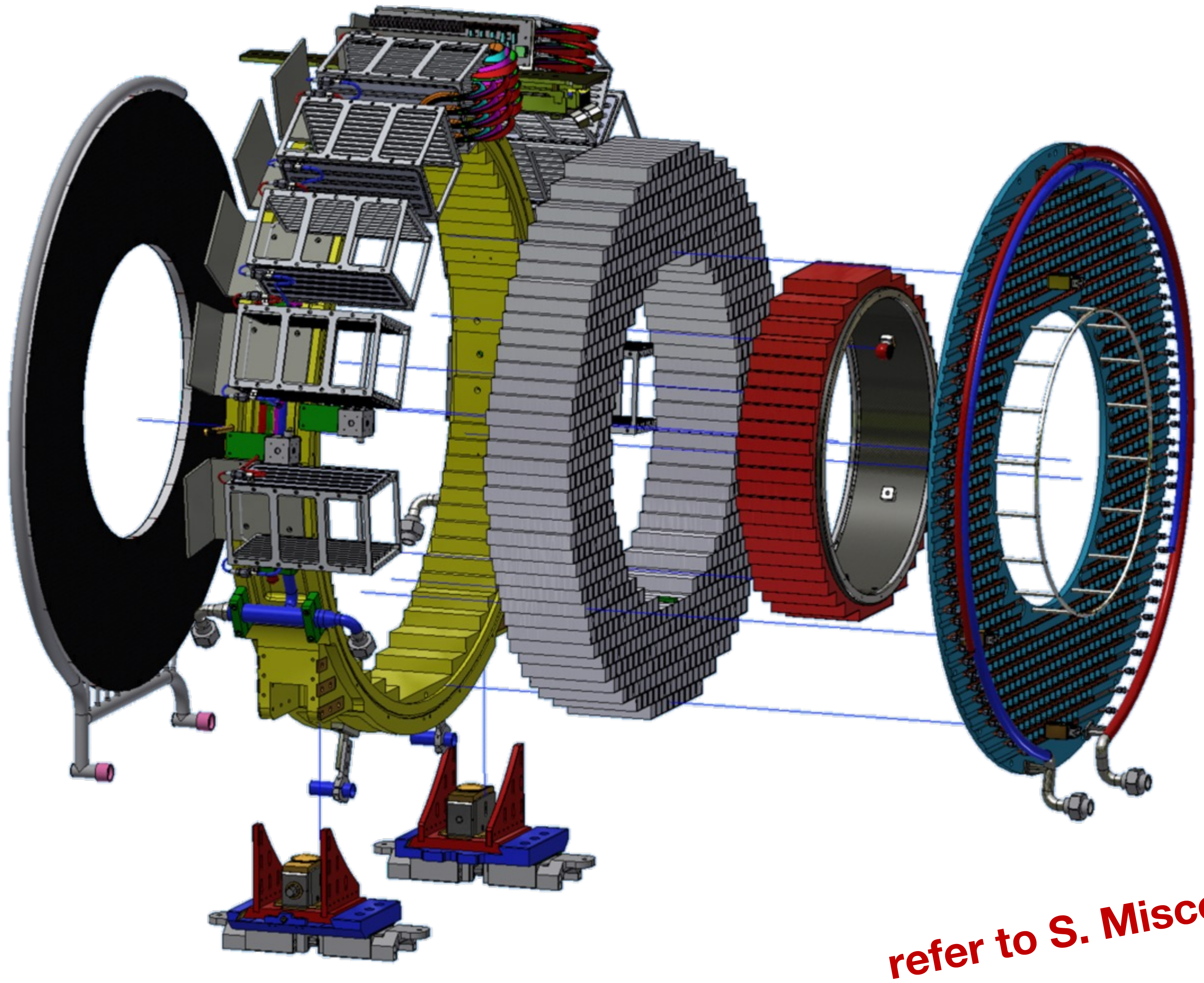
A glimpse of Mu2e



- Searching for **charged lepton flavor-violating $\mu \rightarrow e$ coherent conversion** in the field of an Al nucleus
- Intensity frontier experiment: CLFV process strongly suppressed in SM (BR ≤10^{-54}) → its observation implies BSM physics
- Probing a conversion/capture rate $R_{\mu e} < 3 \cdot 10^{-17}$ (@ 90% C.L.), representing a 10^4 improvement on the current experimental limit
- **10^{10} μ/s selected and transported** via superconducting magnet system to the Al stopping target where they undergo nuclear capture
- The **104.96 MeV conversion e^-** signature is identified via a complementary measurement carried out by **the straw-tube tracker** ($\sigma_p < 200\ keV/c$) and the **EM calorimeter**

Calorimeter at a glance

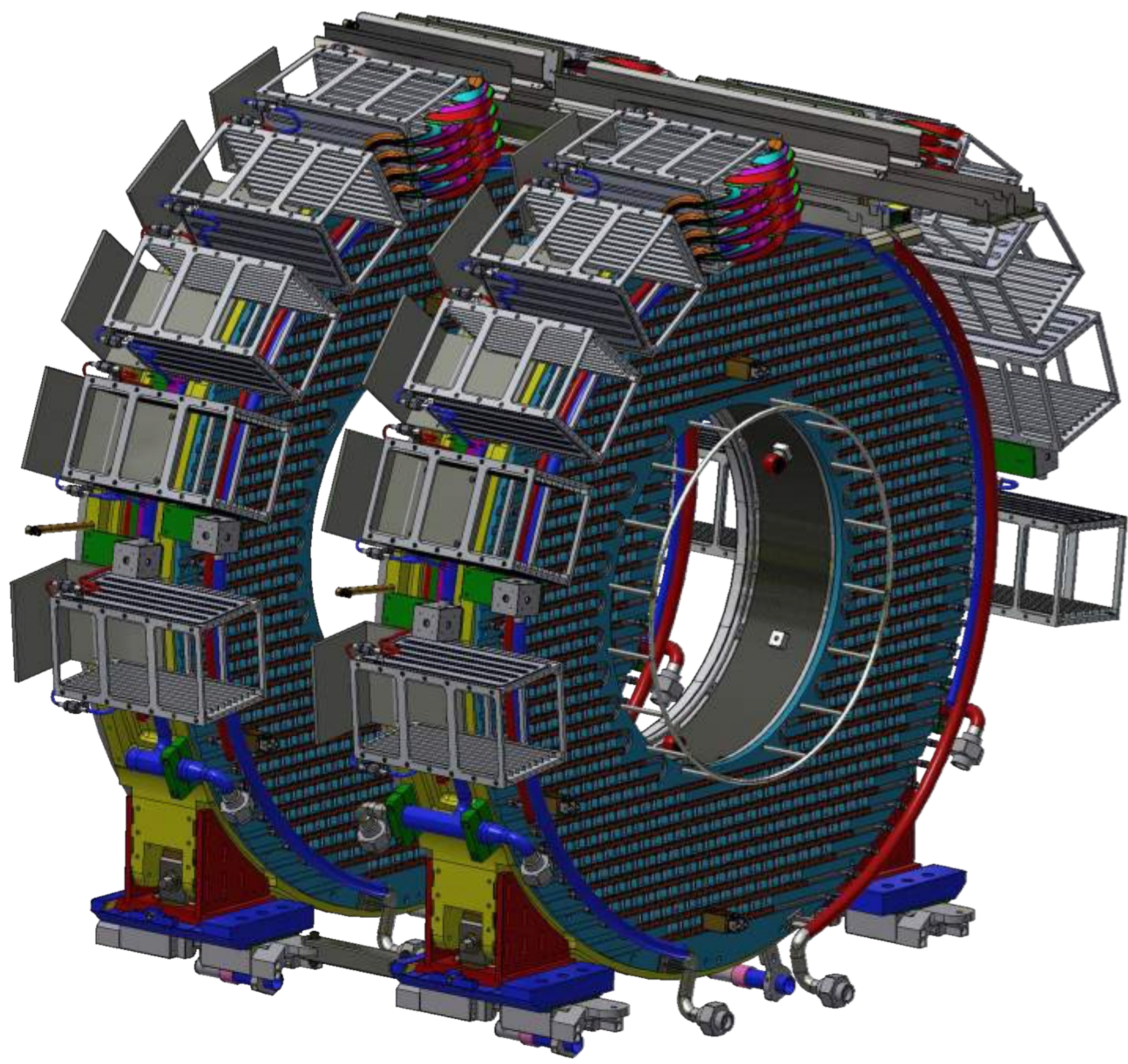
D. Paesani



refer to S. Miscetti's talk

Tasks

- PID capabilities w/ e^-/μ rejection factor > 200
- Stand alone online trigger capability (HLT)
- Cluster-based seeding for track finding
- Large acceptance for conversion electrons



Requirements

- energy resolution $\sigma_E/E = O(10\ \%)$ @ 100 MeV
- timing resolution $\sigma(t) < 500$ ps @ 100 MeV
- Fast signal for Pileup and Timing
- $\sigma_{xy} < 1$ cm

Operating environment

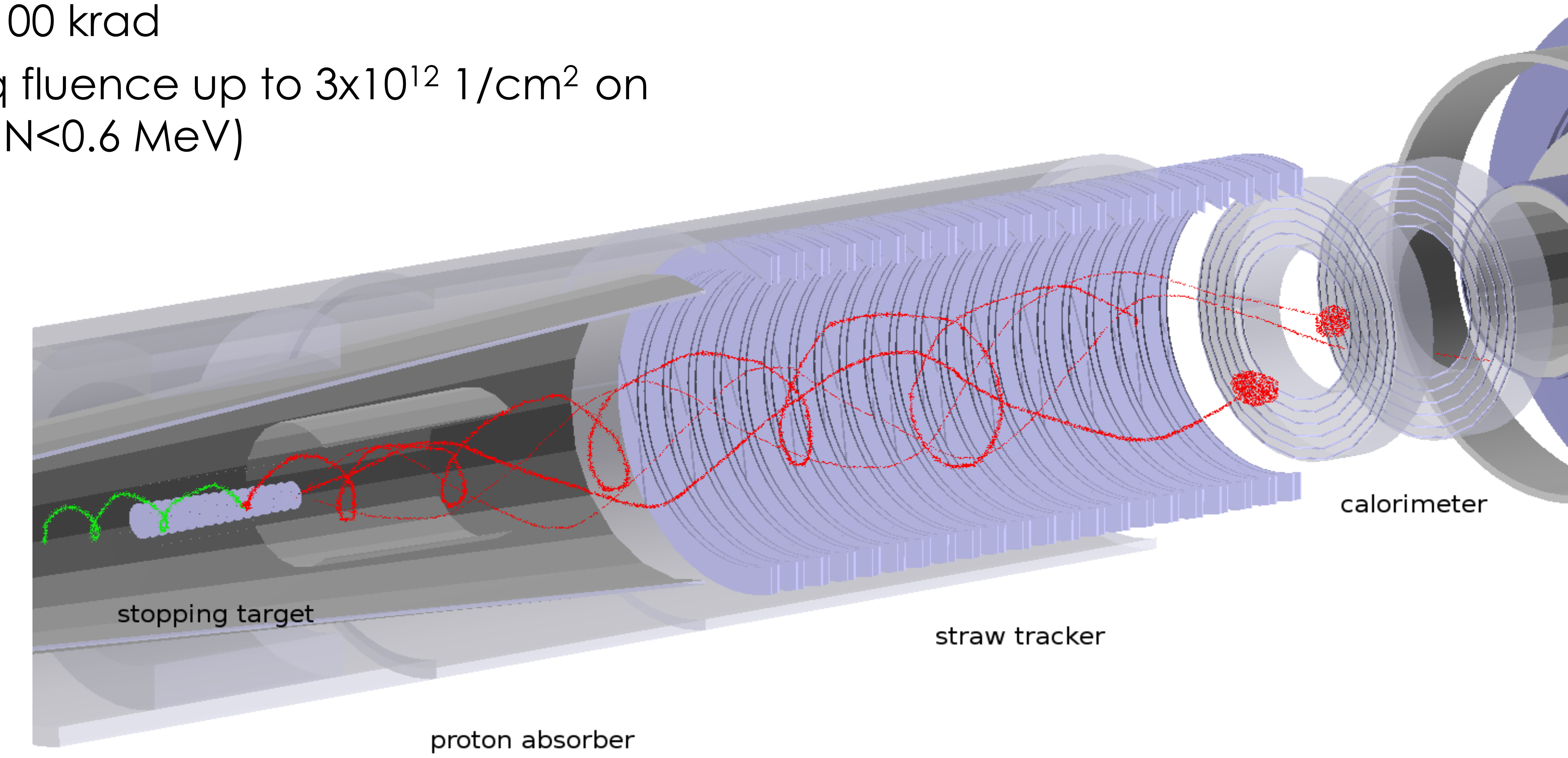
- 1 T B-field
- 10^{-4} mbar vacuum
- TID up to 100 krad
- 1MeV-neq fluence up to $3\text{x}10^{12}$ 1/cm^2 on crystals (RIN<0.6 MeV)

Calorimeter architecture

- Two annular disks w/ 674 undoped CsI 34 x 34 x 200 mm^3 crystals each
- 10 X_0 (200 mm) crystal depth and 70 disk cm spacing
- 30 cm inner disk bore, 66 cm outer bore
- Readout via 2 large area UV-extended SiPMs per crystal
- SiPM + FEE fluid cooling down to –10° C

Calibration methods

- 530 nm laser for SiPM gain monitoring and timing alignment
- Liquid radio source for crystal equalisation w/ 6 MeV photon
- In-situ calibration with crossing MIPs, DIO's and other physics processes



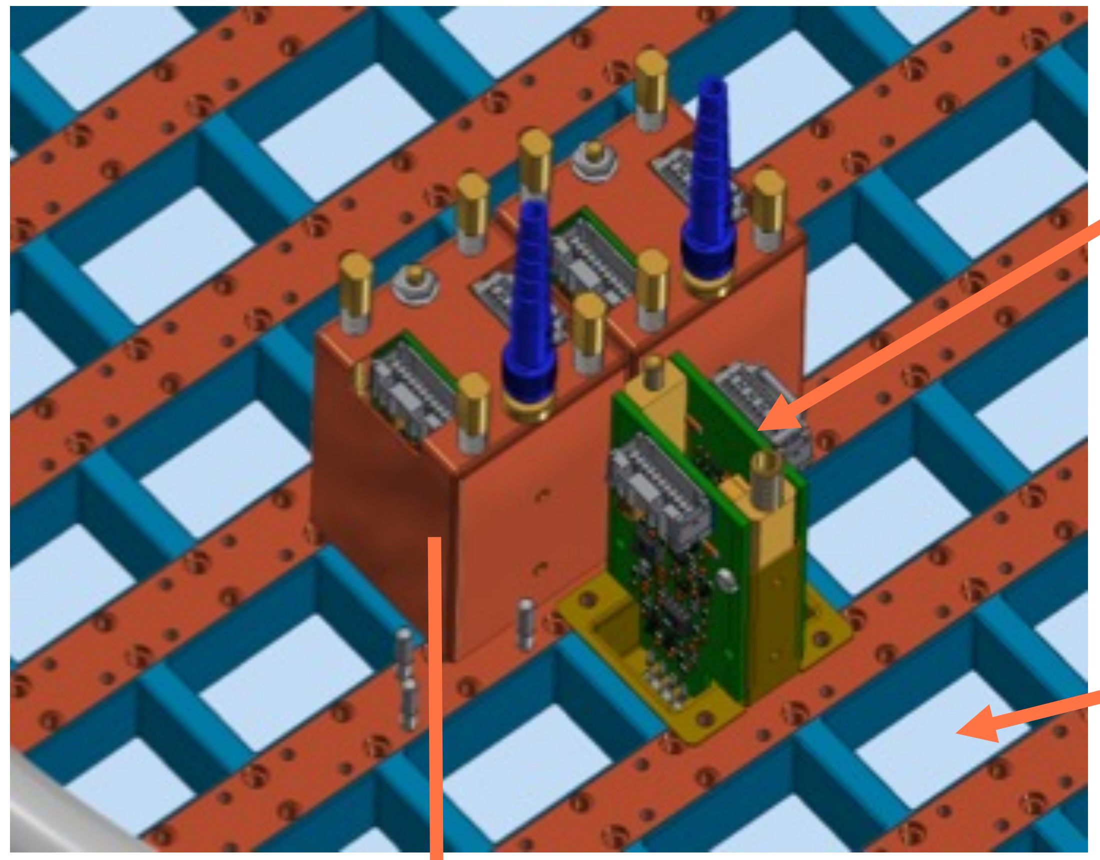
Signal chain overview

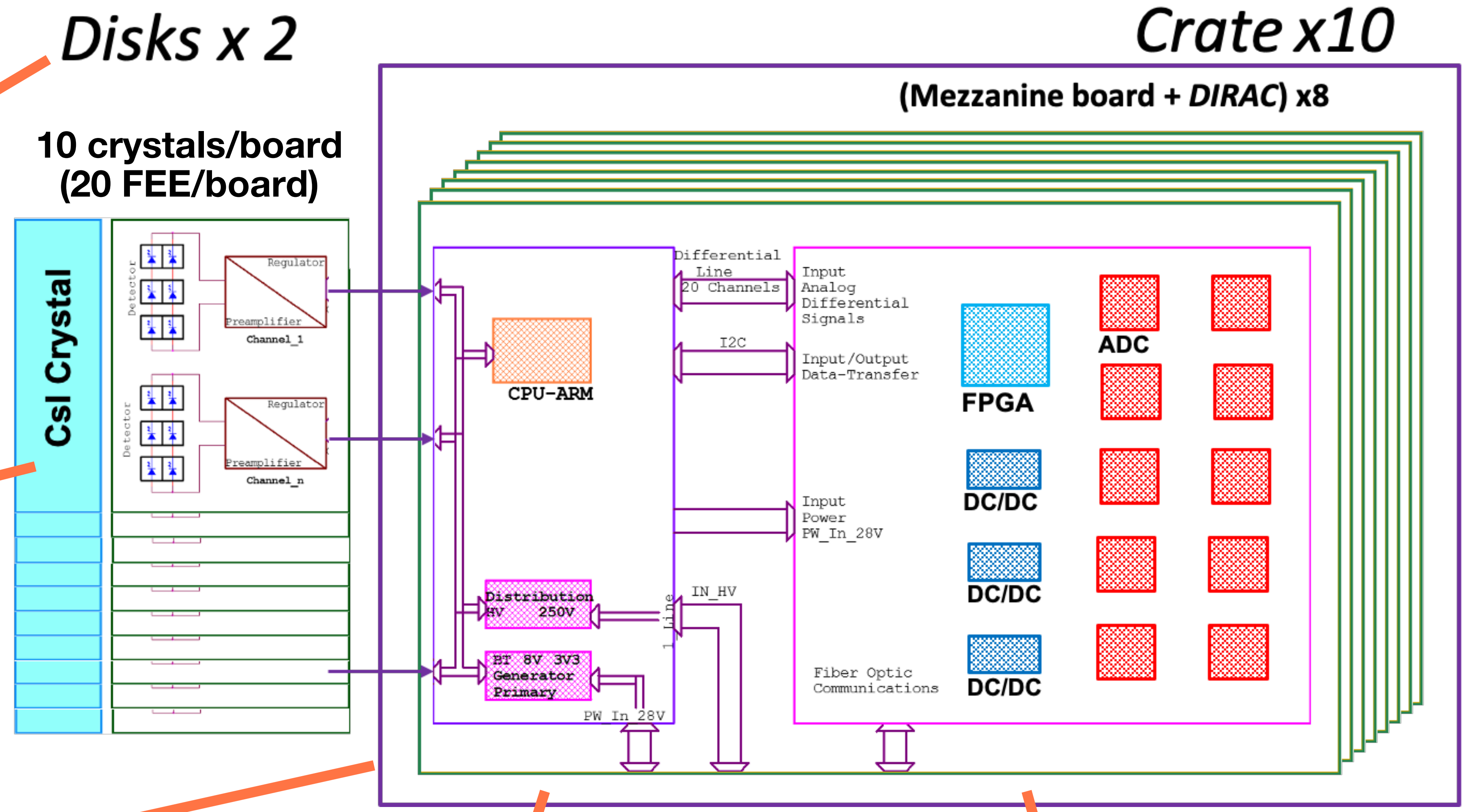
- 2700 readout channels w/ fully custom readout chain (from SiPM to DAQ)
- 10 electronics crates/disk (280 boards total)
- SiPM cooling to -10 °C

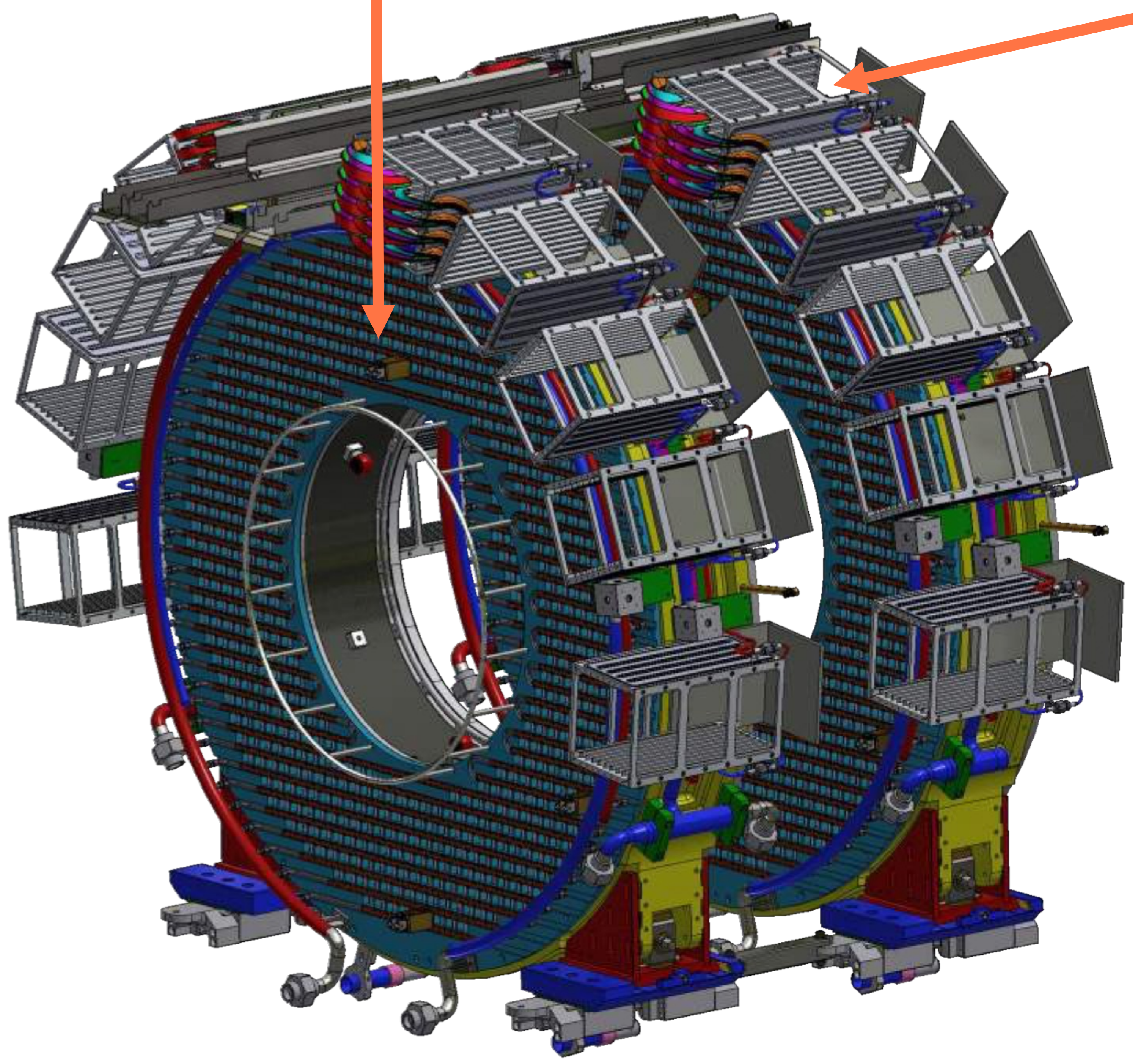
- **2700 Read-Out Units**
  - Two fully independent readout channels per cry
  - 2 large-area UV-extended SiPM
  - **2 Front-End Electronics (FEE) boards**
    - SiPM amplification and shaping
    - Digitally controlled SiPM monitoring and biasing

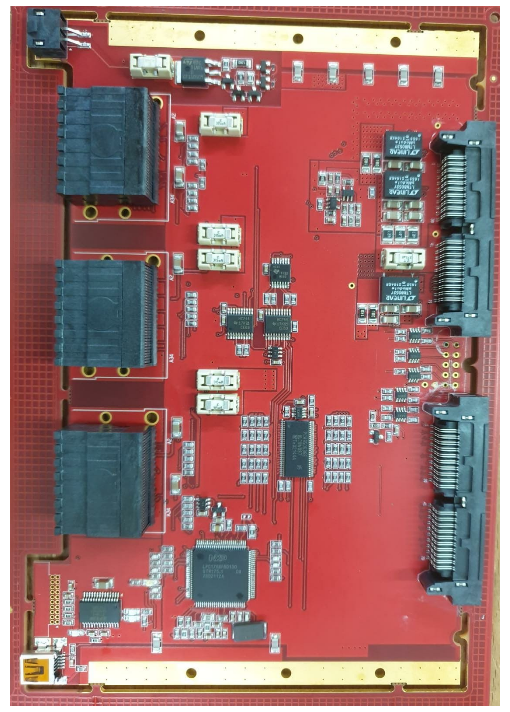
- **140 Mezzanine Boards (MB)**
  - Slow-control distribution
  - FEE power distribution
  - ARM-microprocessor based

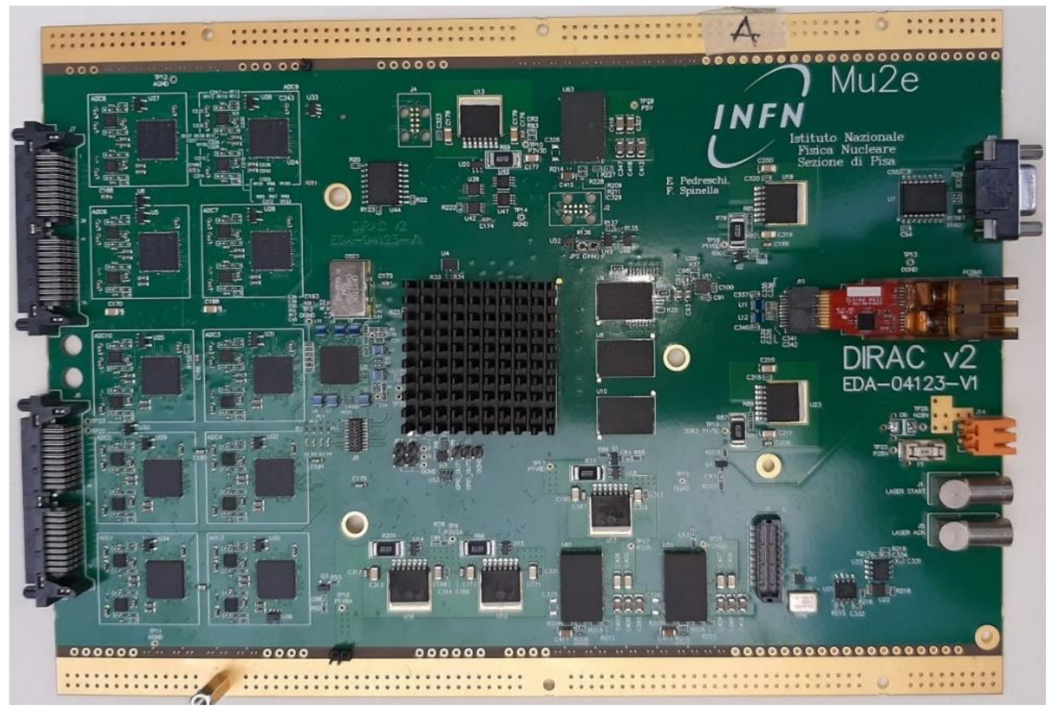
- **140 custom digitiser boards (DIRAC)**
  - Signal digitisation @ 200 Msps w/ 12-bit flash ADC
  - Digitisation to allow good signal reconstruction despite the high expected pileup
  - *PolarFire* rad-hard FPGA
  - VTRX 10 Gbps optical link to Detector Control System
  - DIRAC v3 prototype ready





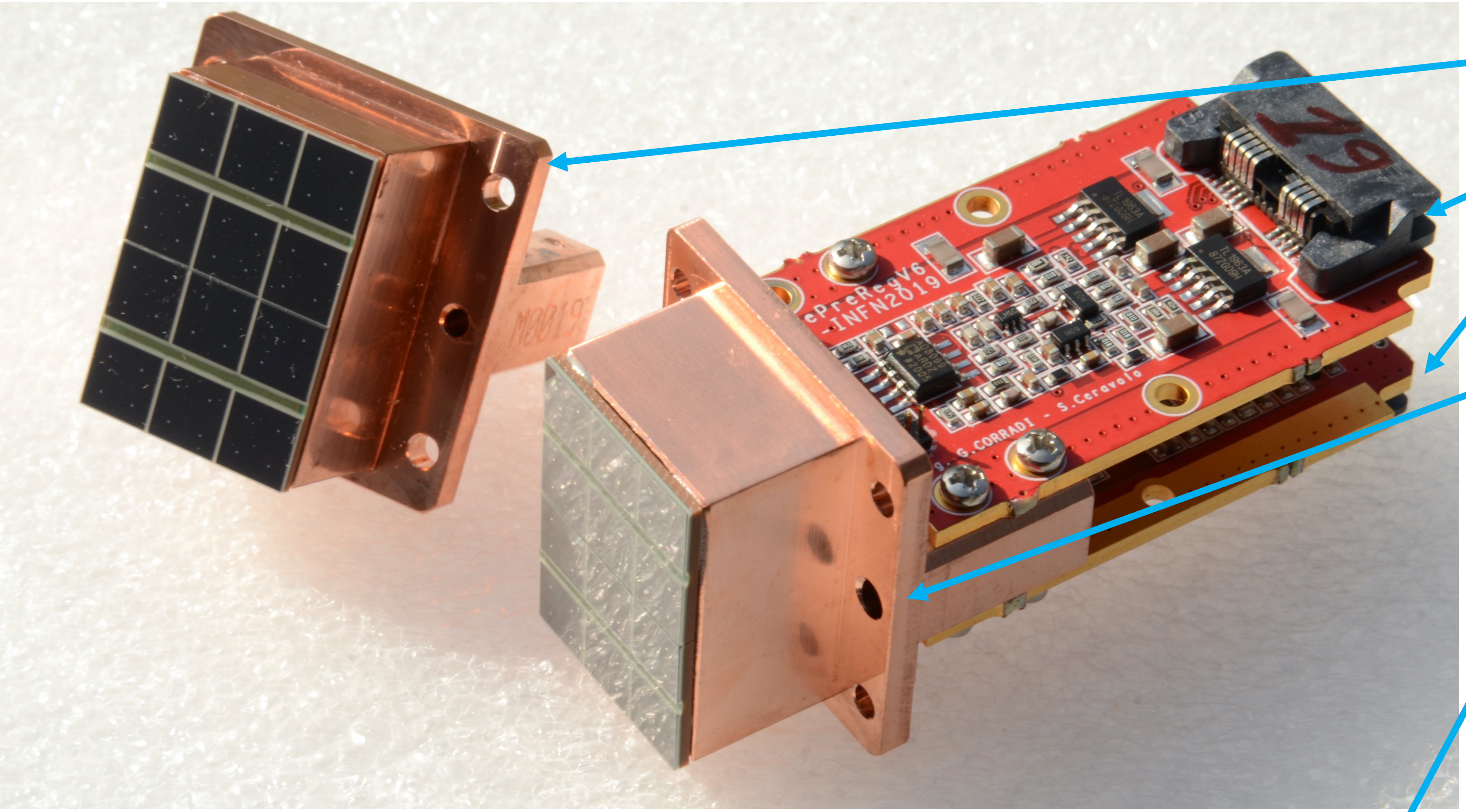






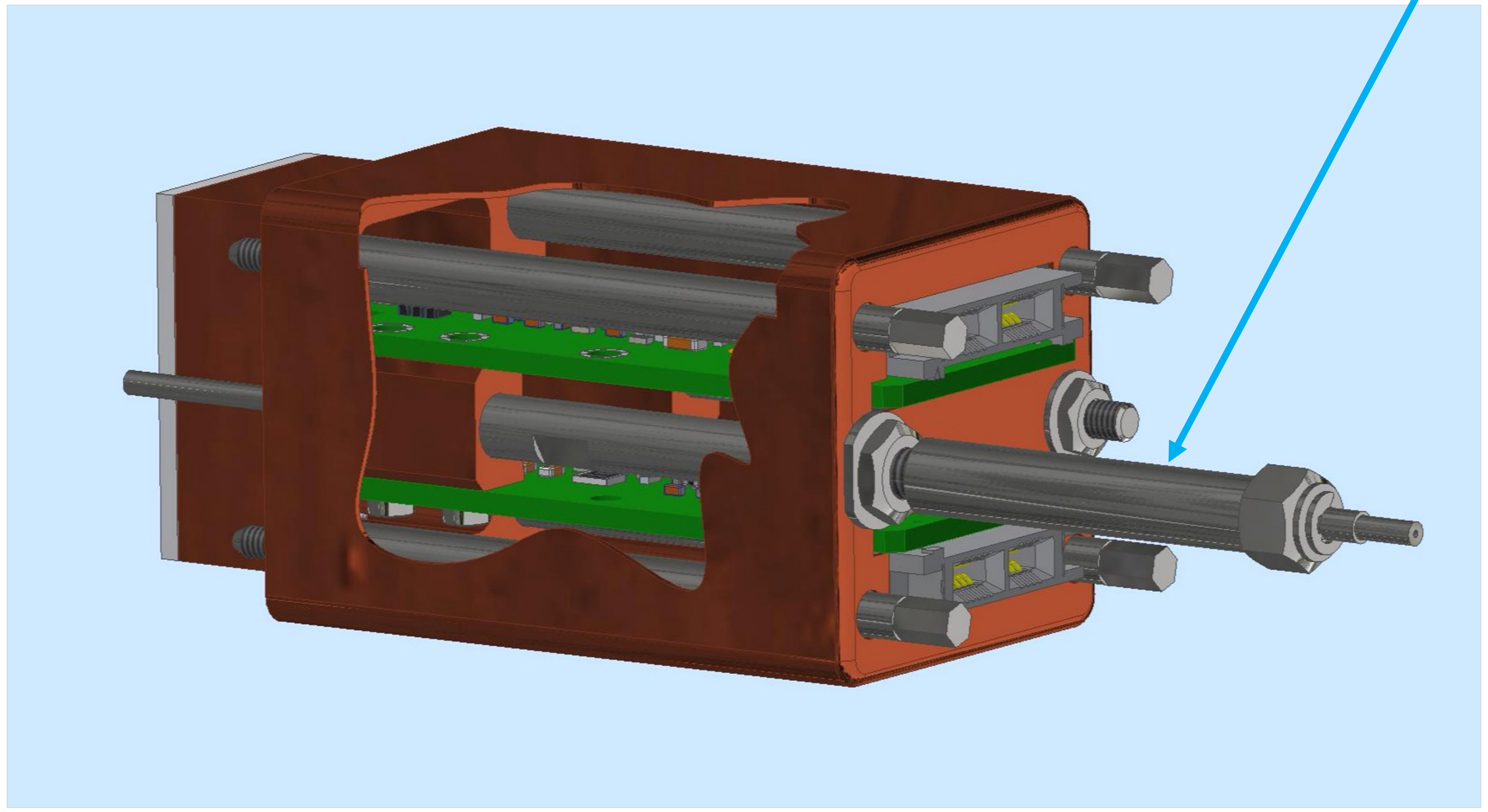
In this talk we will mainly focus on **FEE** and **MB** systems (currently in production)

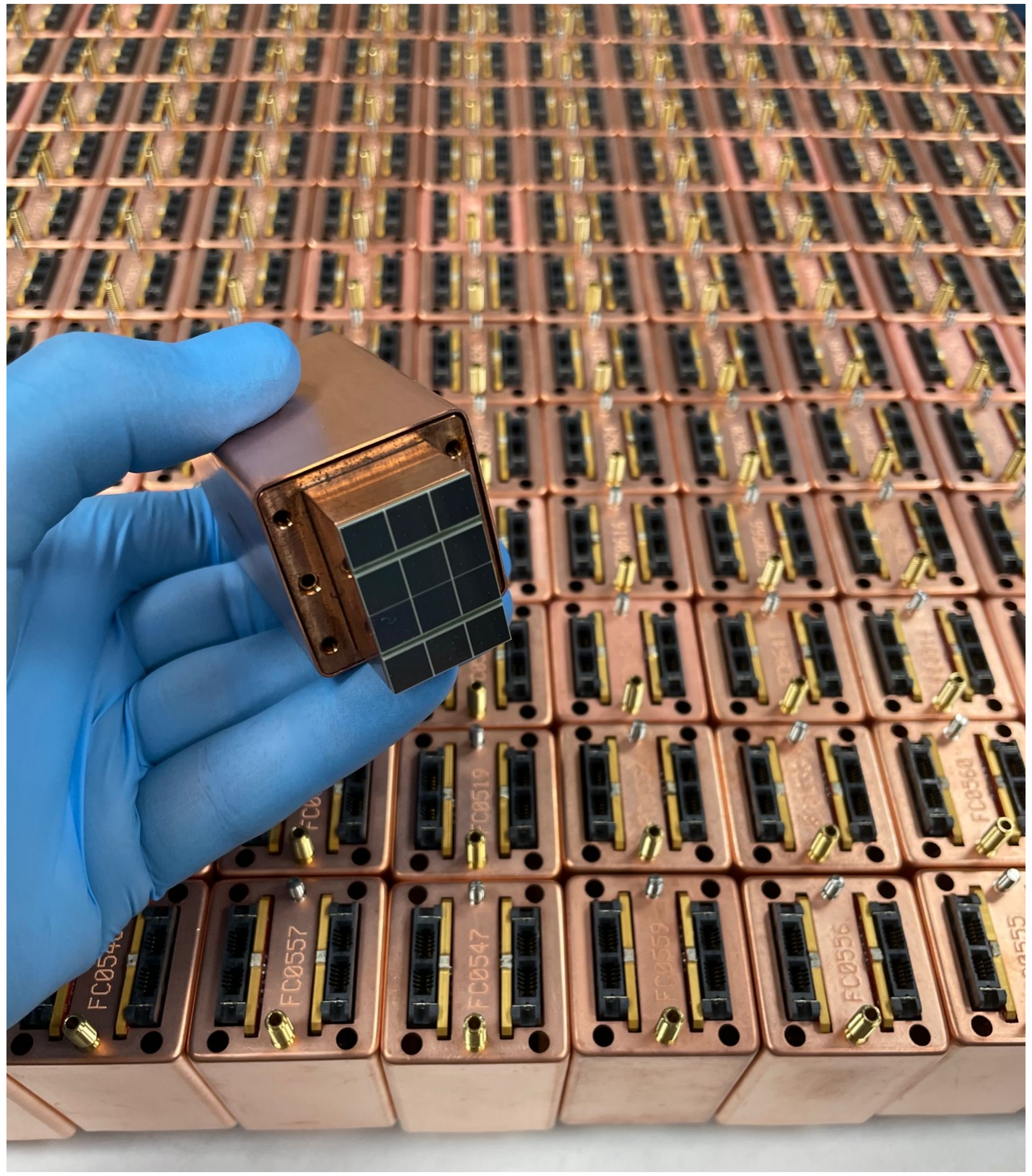
Read-out units



- Two custom large area SiPMs from Hamamatsu
- Two independent readout channels per crystal
- Integrated FEE + slow control board

- Thermal block for SiPM cooling
- Fibre optic coupler for laser system distribution





SiPM qualification and QC

Mu2e SIPM

- **6 individual 6x6 mm² 50 μm px MPPCs** (Hamamatsu)
- **UV-extended** design matches the CsI 315 nm emission peak (silicone protection layer)
- 30 % PDE @ 300 nm

TNID qualification

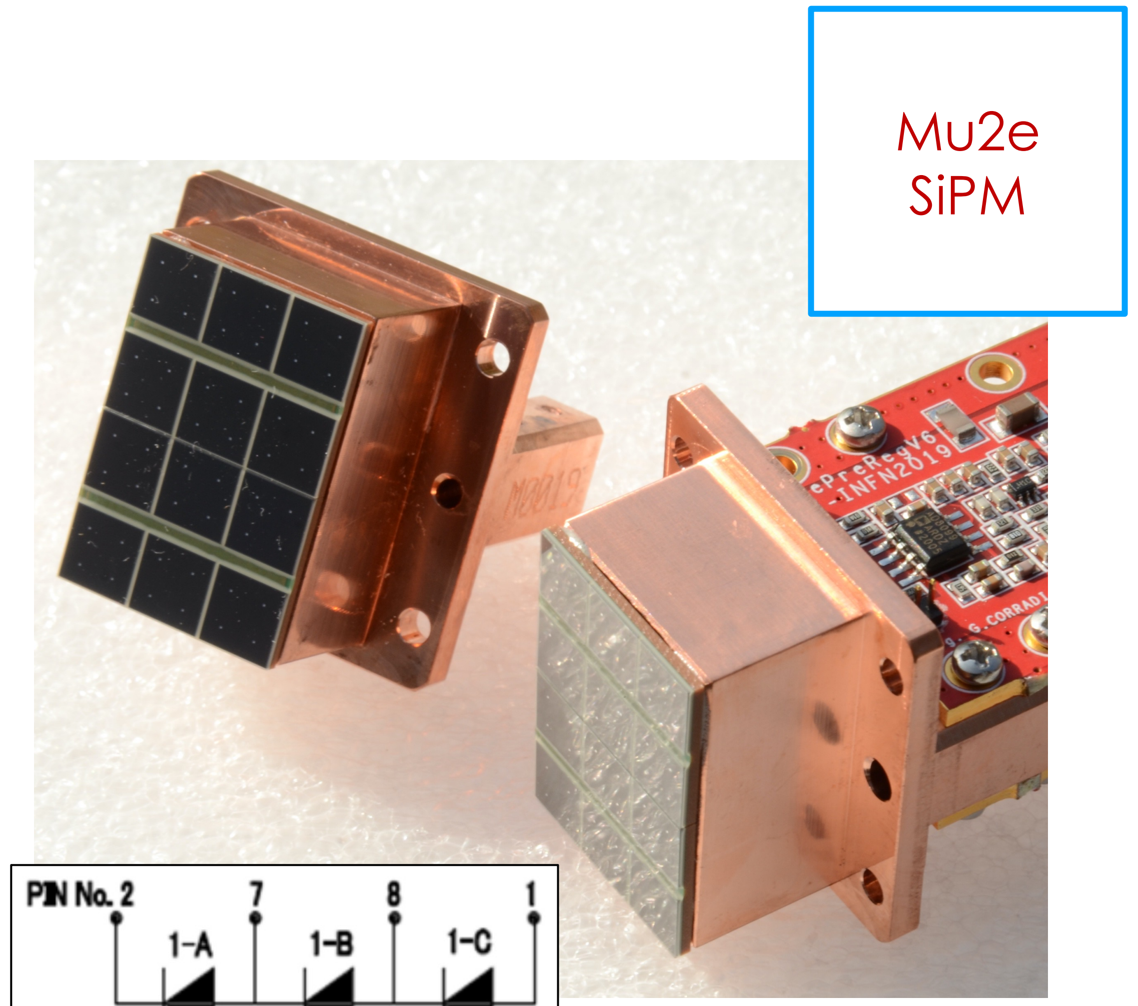
- Neutron irradiation tests @ ENEA-FNG and HZDR
- Required gain drop < 2 after irradiation
- Allowable I_{dark} increase → 2 mA/SiPM limit on FEE linear regulator
- ROU cooling from 0 to -10° C to extend SiPM operation (I_{dark} halves every 10 °C reduction)

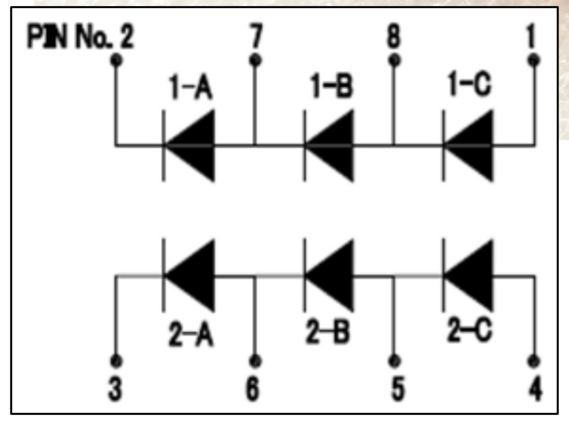
QC steps

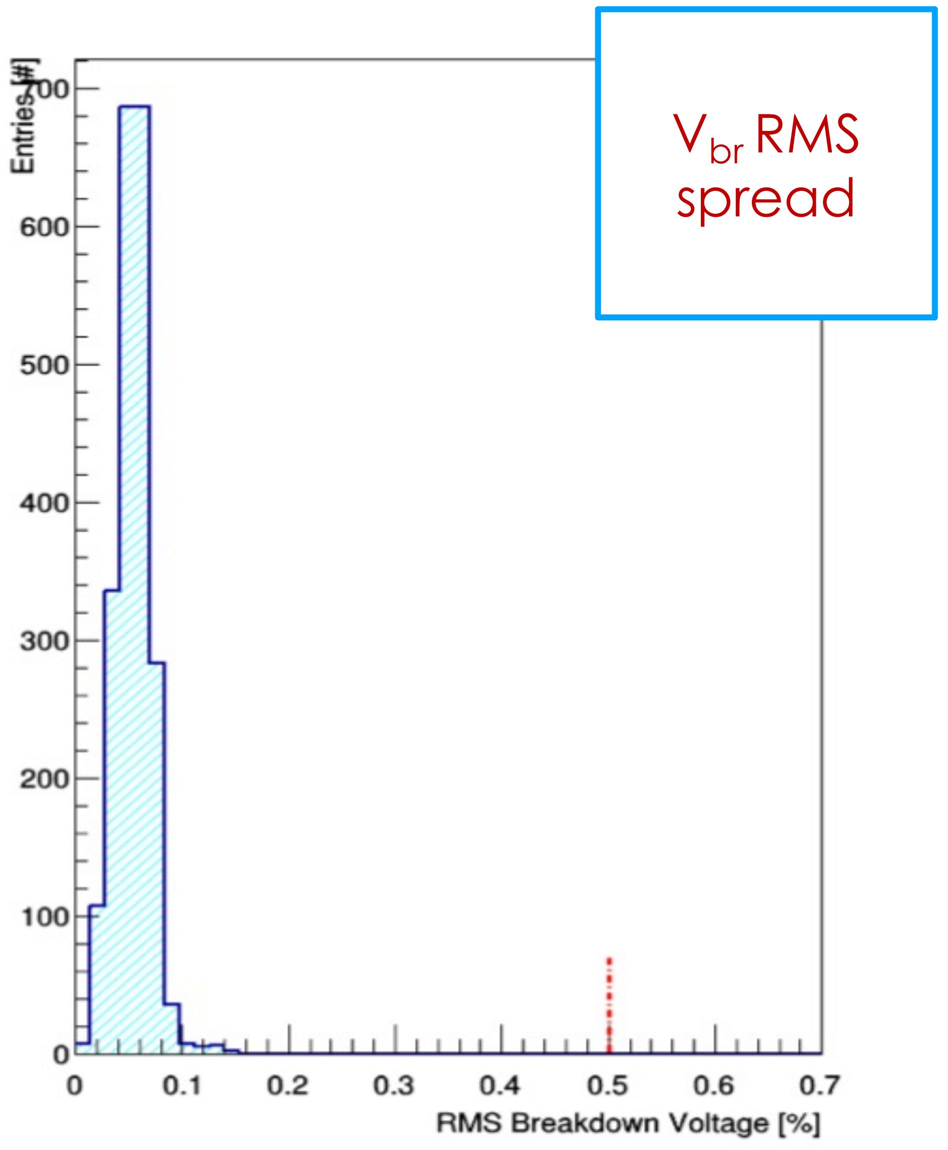
- V_{br}, I_{dark}, gain*PDE measured for each cell
- 5 SiPM/batch underwent 10^{12} n_{1MeV}/cm^2 irradiation test
- QC on all production SiPMs completed in late 2019
- 2 % of out-of-spec components

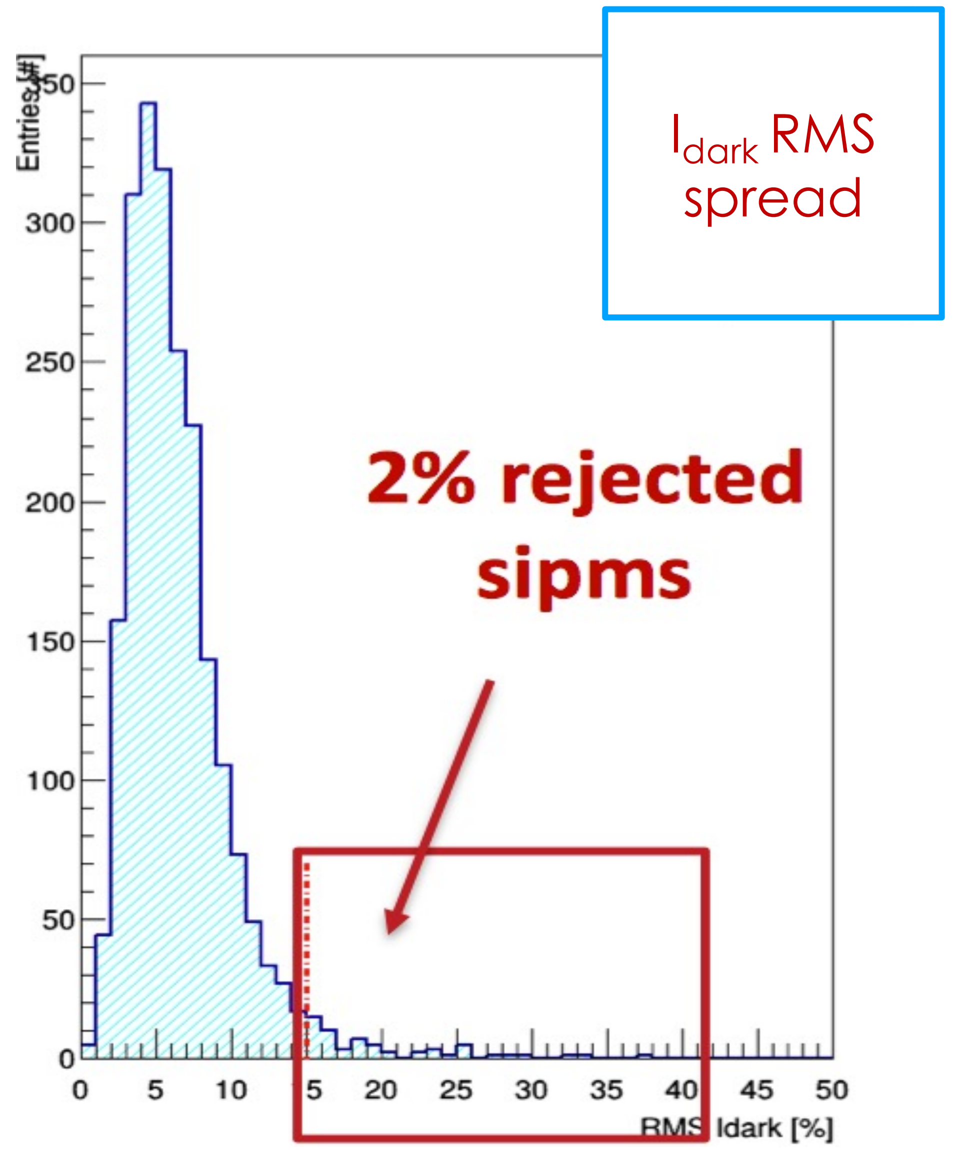
Other requirements

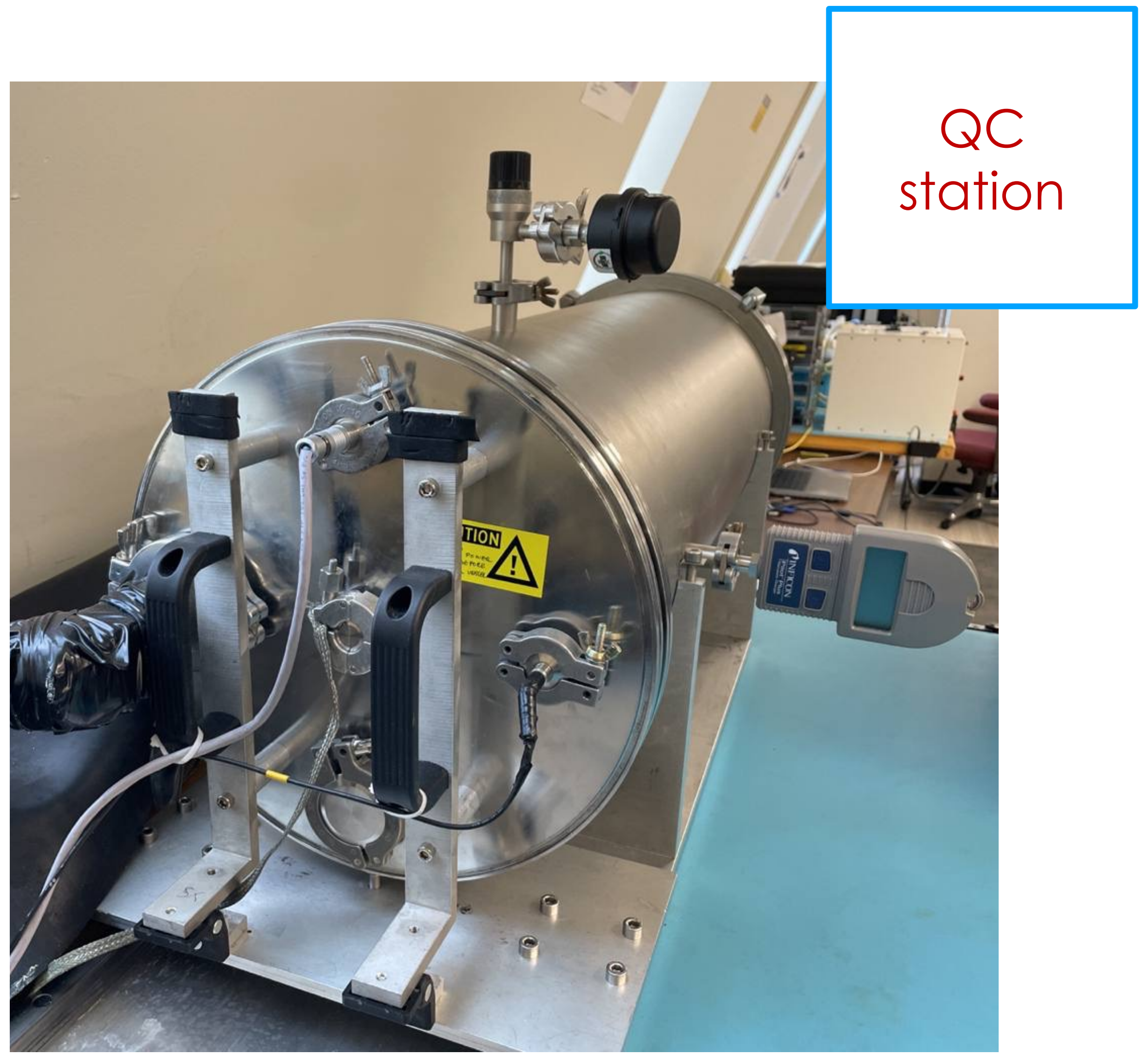
- gain > 10^6 @ V_{ov} = 3 V
- recovery time < 100 ns @ 15 ohm
- Good V_{bd} and I_{dark} matching over 6 cells
- MTTF > 10^6 h @ 20 °C
- Low thermal resistance

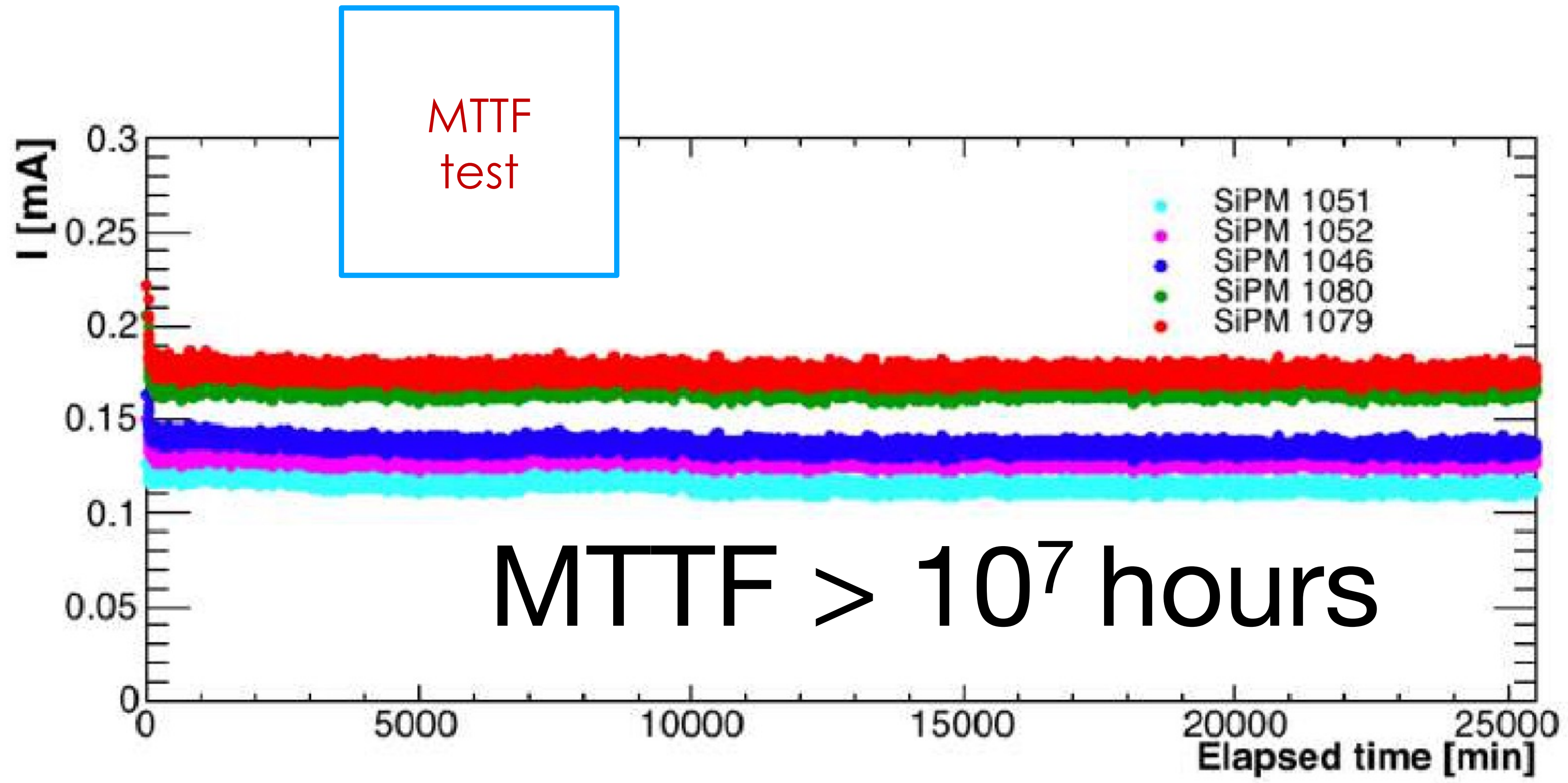








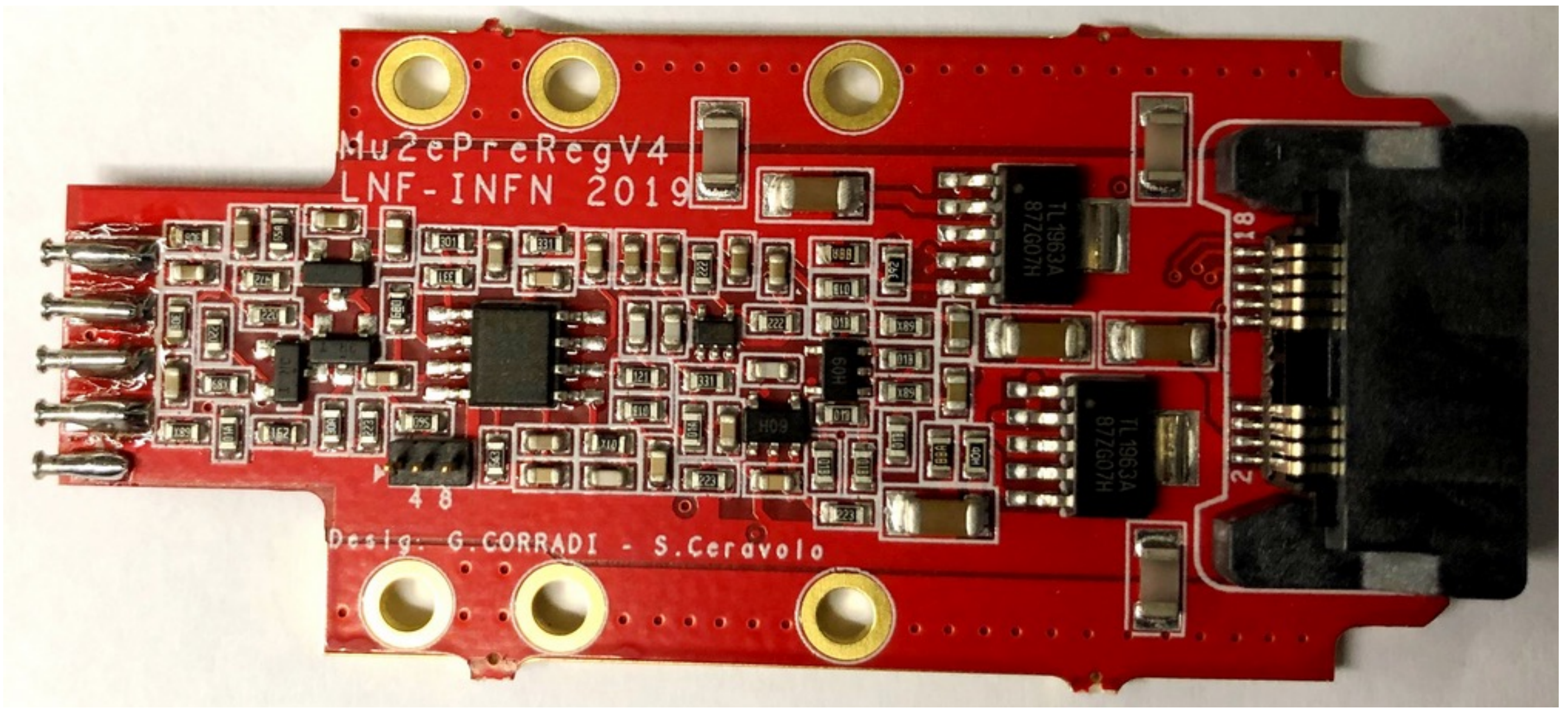


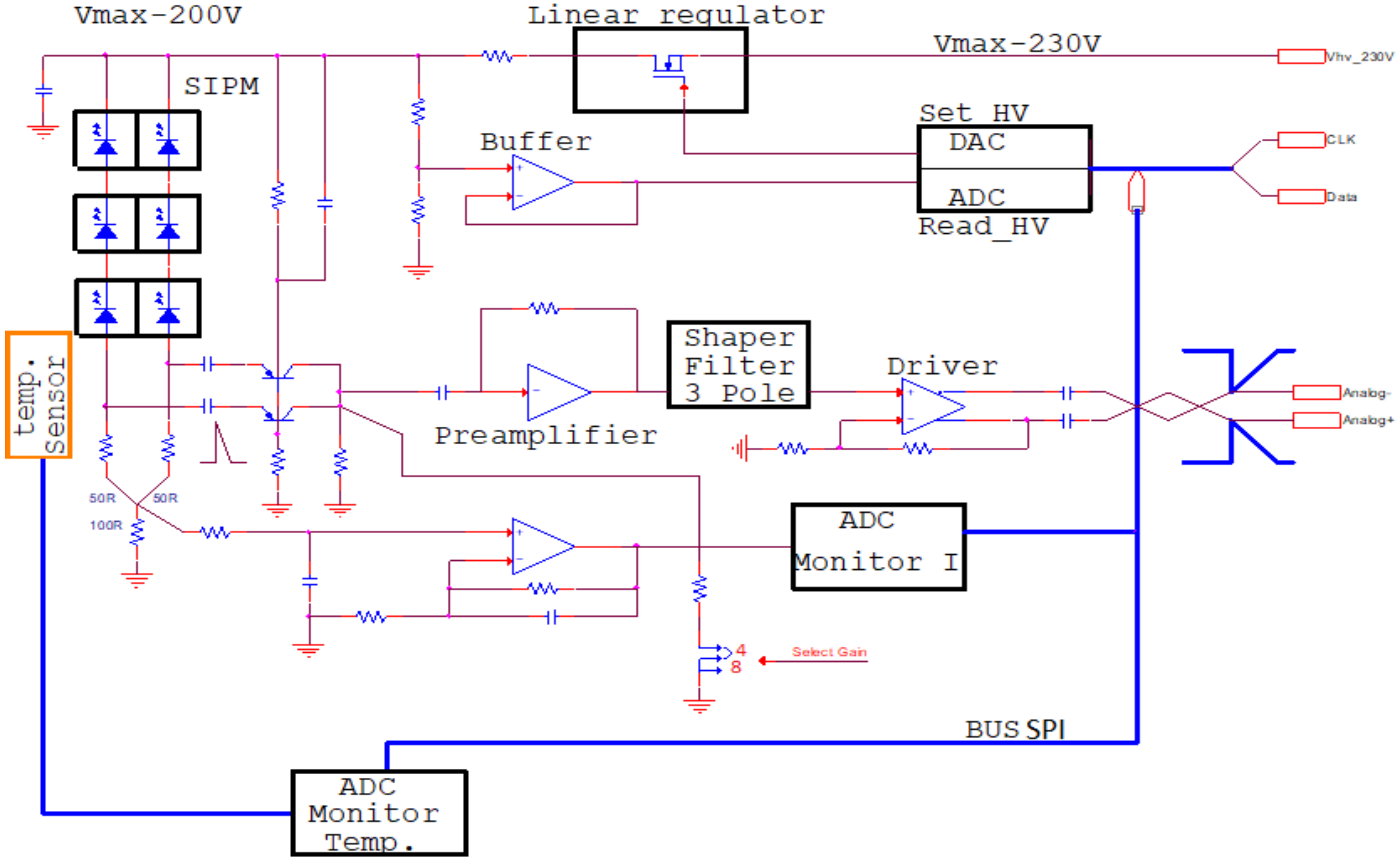


Front-end boards

Requirements

- Signal rise time > 25 ns for appropriate time reconstruction
- Rate capability up to 1 MHz, short fall time
- High stability SiPM management
- Rad-hardness (100 krad TID, 10^{12} 1MeV-neq/cm^2)





Signal chain

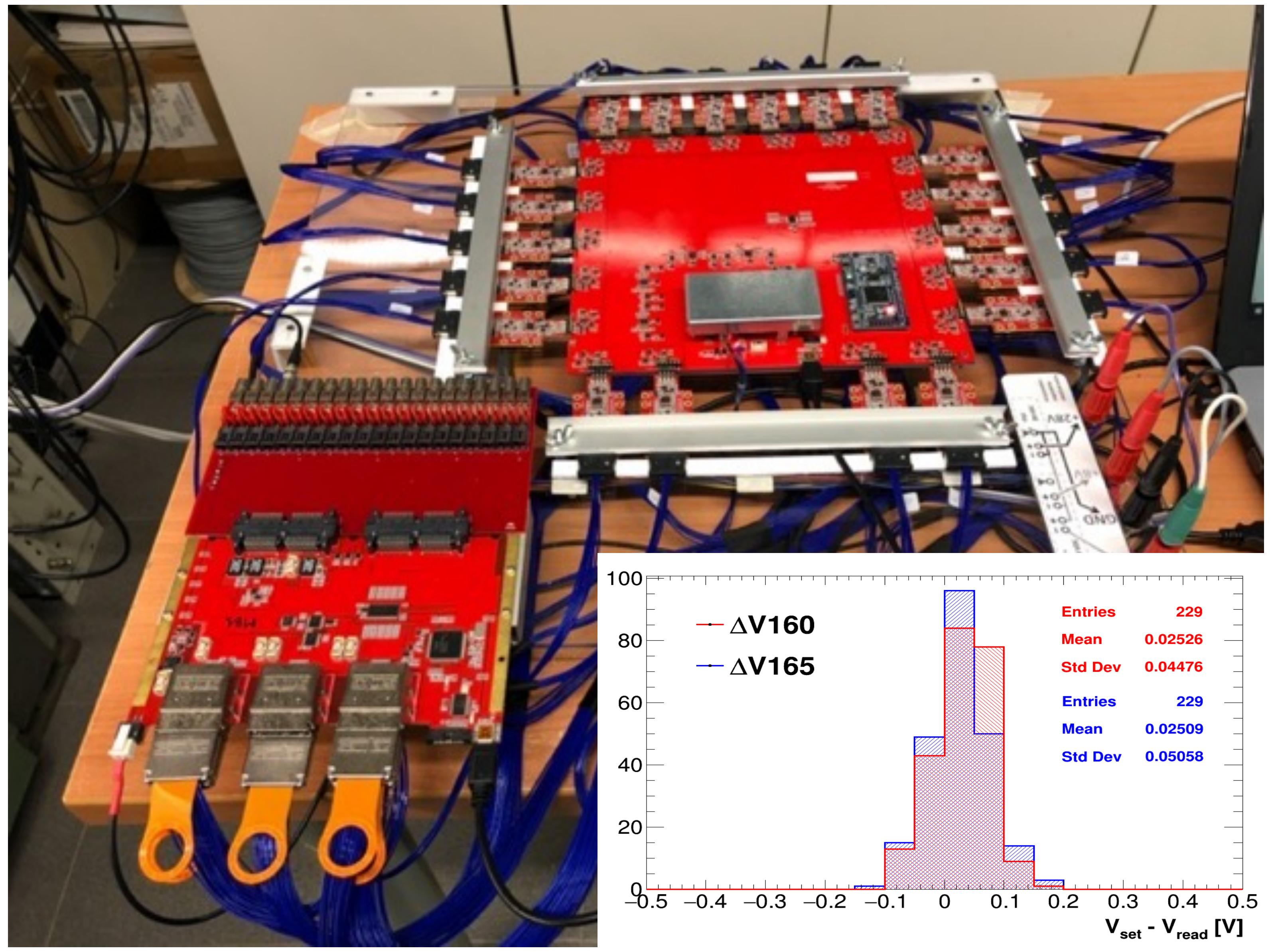
- 2 x 3-series SiPM connection to decrease MPPC capacitance
- Common-base BJT fast current adder with low input Z
- Selectable gain (1 or 2) w/ 2 V dynamic range
- Pole-zero cancellation
- 3-pole pulse stretcher
- Differential line driver

Slow control

- on-board high-stability, low-ripple HV linear regulator
- Programmable bias up to 200V via 12-bit DAC (50 mV/lsb)
- 2 mA SiPM current capability w/ OCP
- Integrated SiPM bias, current and temperature monitor via 12-bit SPI ADC

General qualification steps

- **Radiation hardness** qualification (next slides)
  - TID: dose up to 100 krad (SF = 12)
  - TNID: fluence up to 3E+11 1-MeV-neq(Si)/cm^2 (SF = 6)
  - High-energy hadrons (> 20 MeV) fluence up to 1E+10 p/cm^2 (SF=6)
- **B-field** tests up to 1.5 T to check DC-DC efficiency and power dissipation (+ 20 % increase)
- Tests in **vacuum**

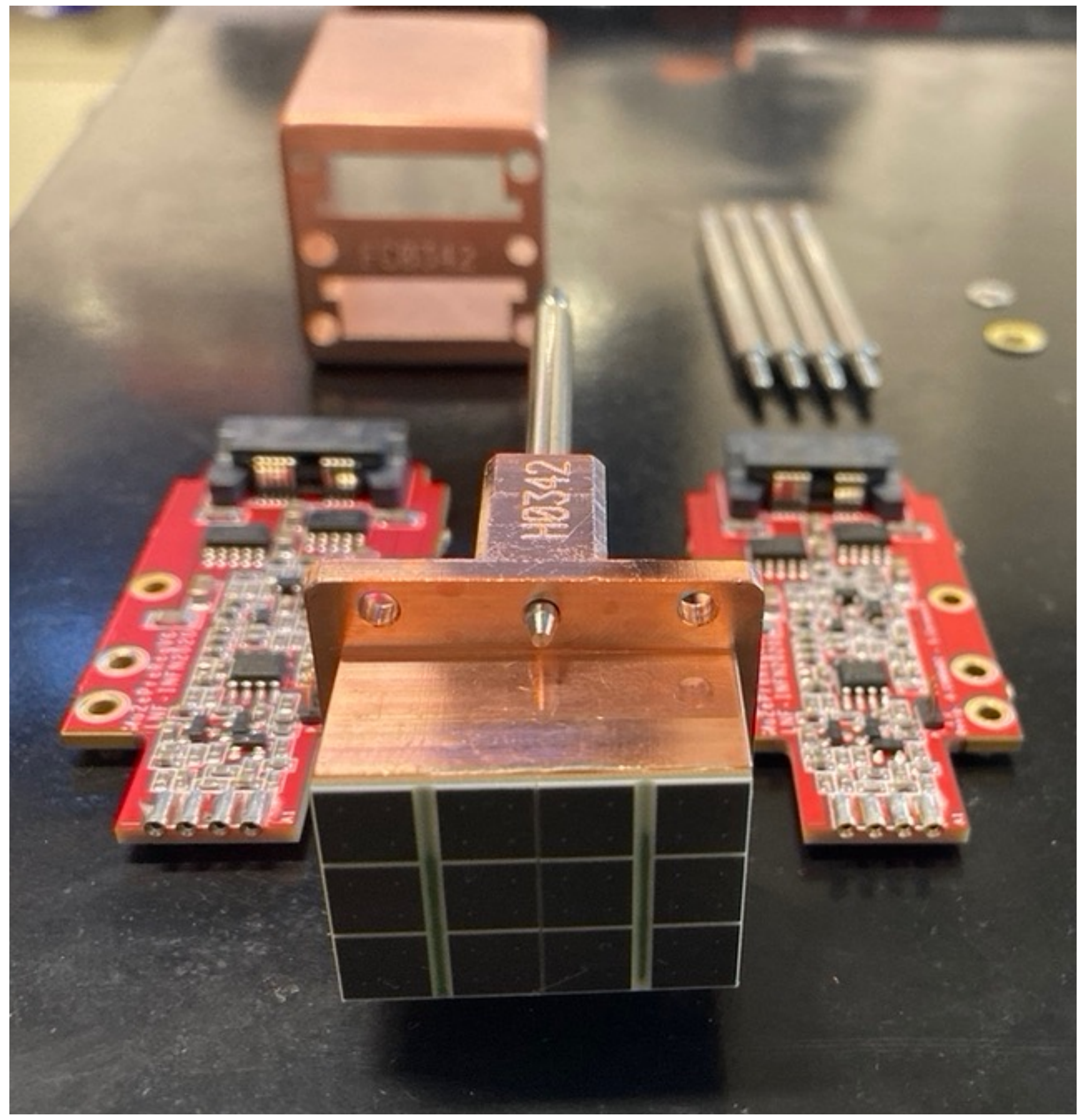


FEE calibration and QC

- 6 hours **burn-in** test @ 65 °C
- Calibration of **linear regulator** output
- Calibration of **temperature and current** monitors
- FEE pulsing to evaluate **signal shape and gain linearity**

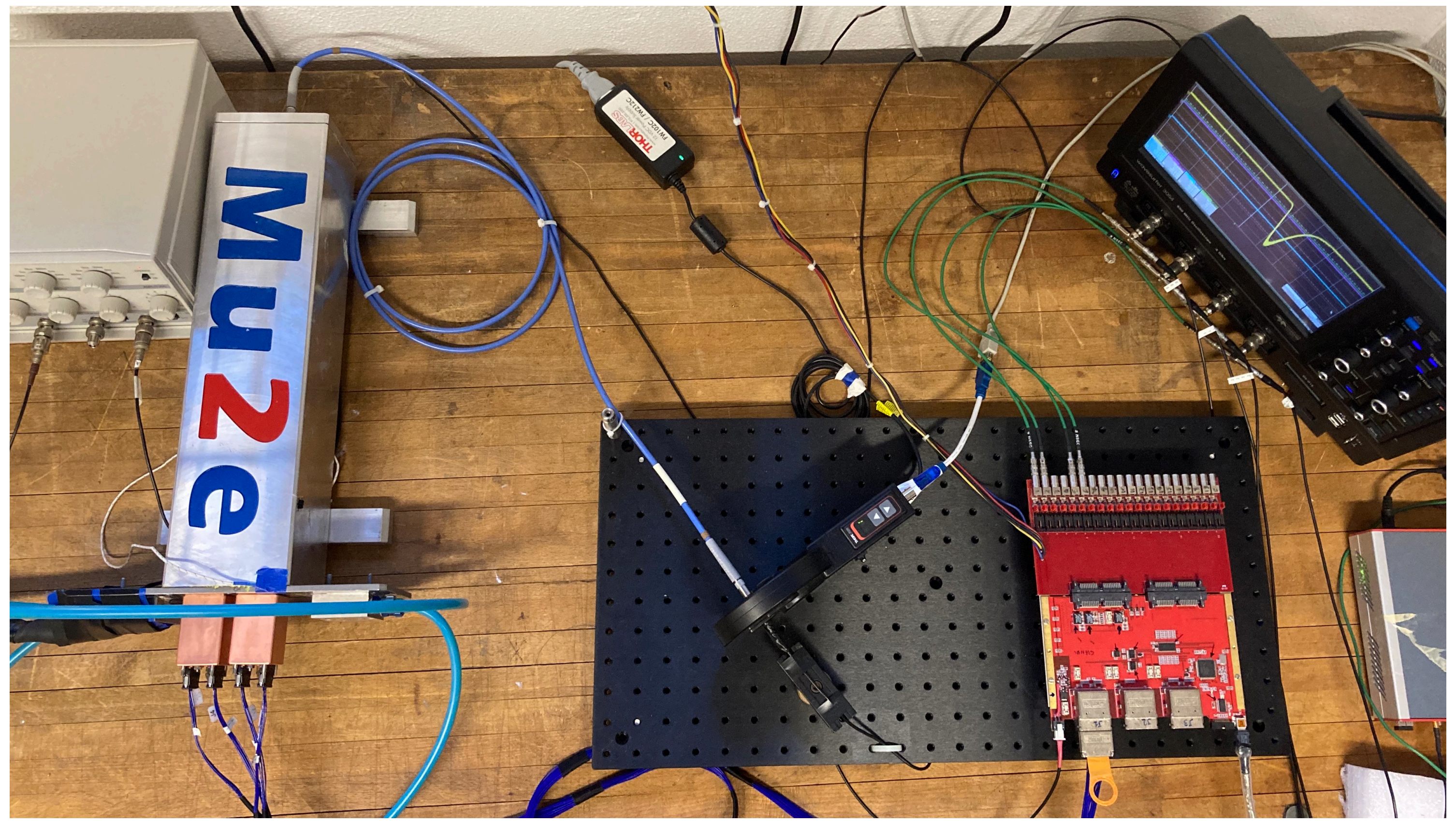
FEE status

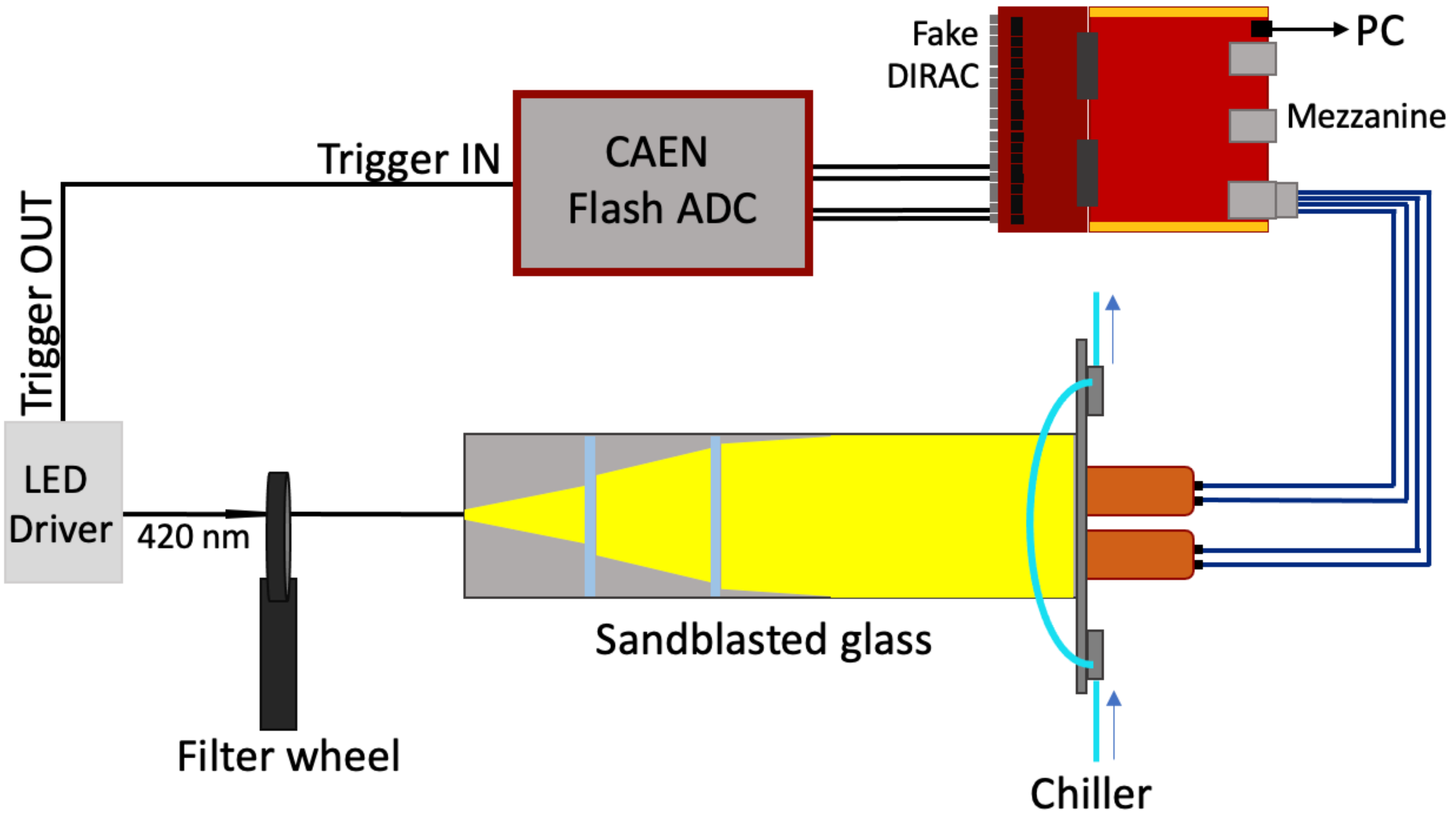
- **Production** completed in late 2021
- Read-out Units **assembly** in progress
- **QC** in progress (2250/2500 completed ROUs @ FNG)

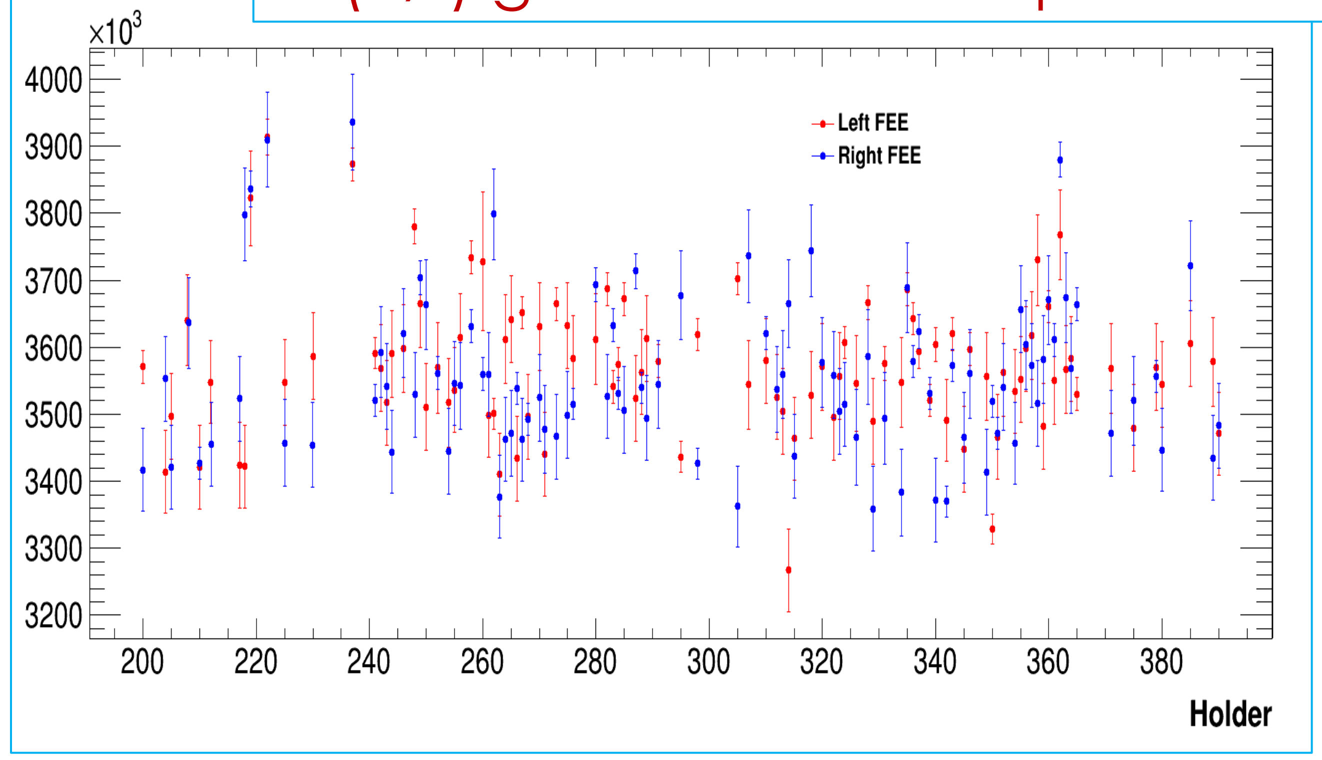


Read out units QC

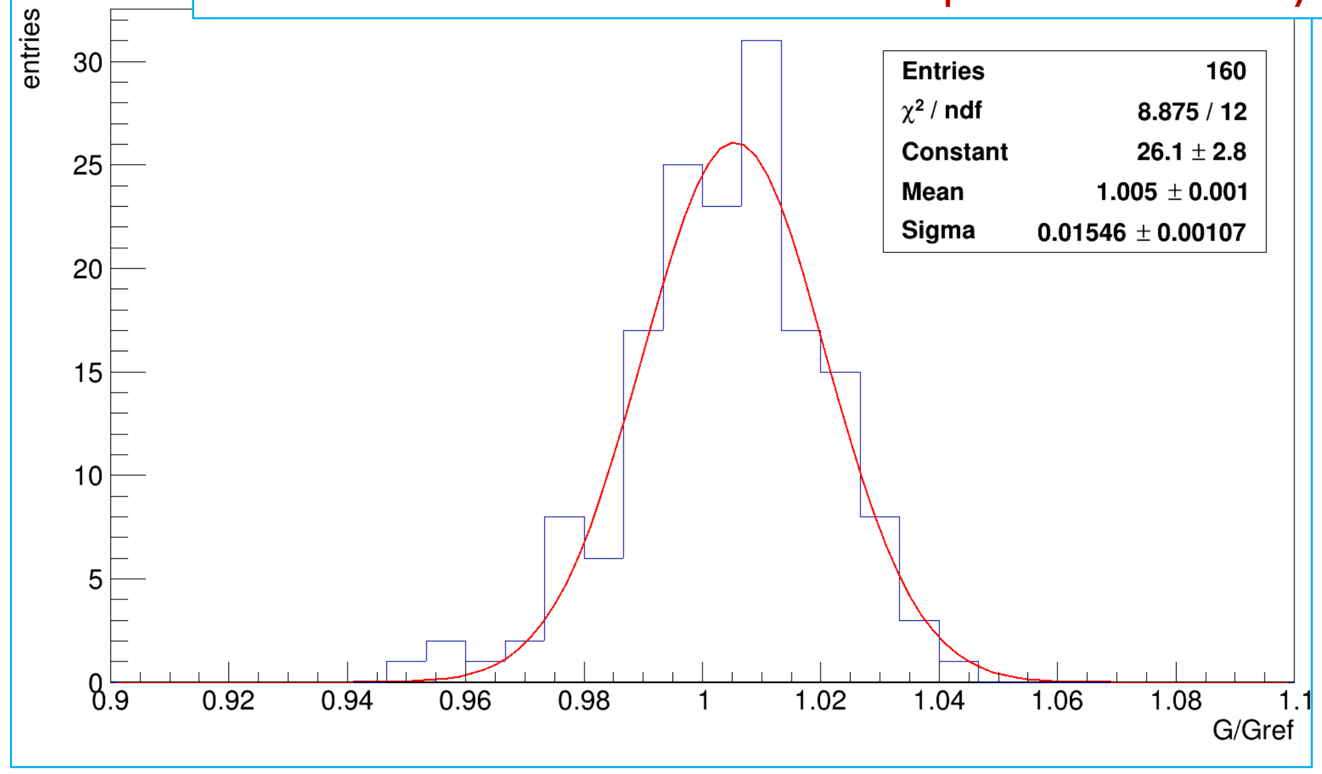
- **Automated station** to illuminate uniformly 2 ROU w/ **ns pulses @ 420 nm**
- SiPM temperature control
- Neutral density filter selector to attenuate source intensity
- **Gain*PDE** and **NPE check** at different V_{ov} and temperature
- **Gain matching** check (for dual readout)
- ROU gain **calibration** before installation
- Calibration of gain dependency on V_{ov}





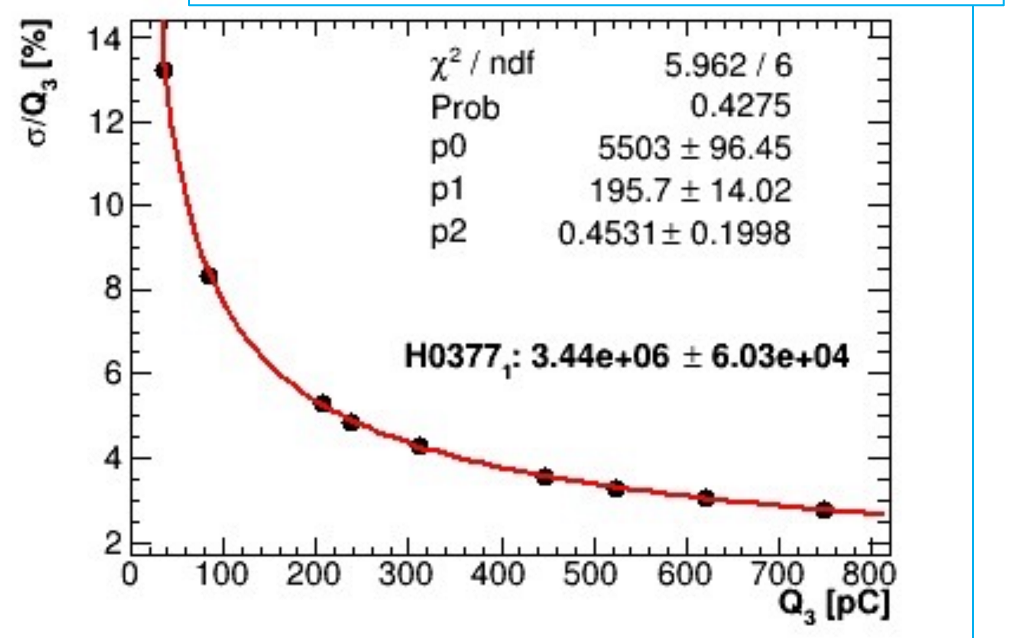


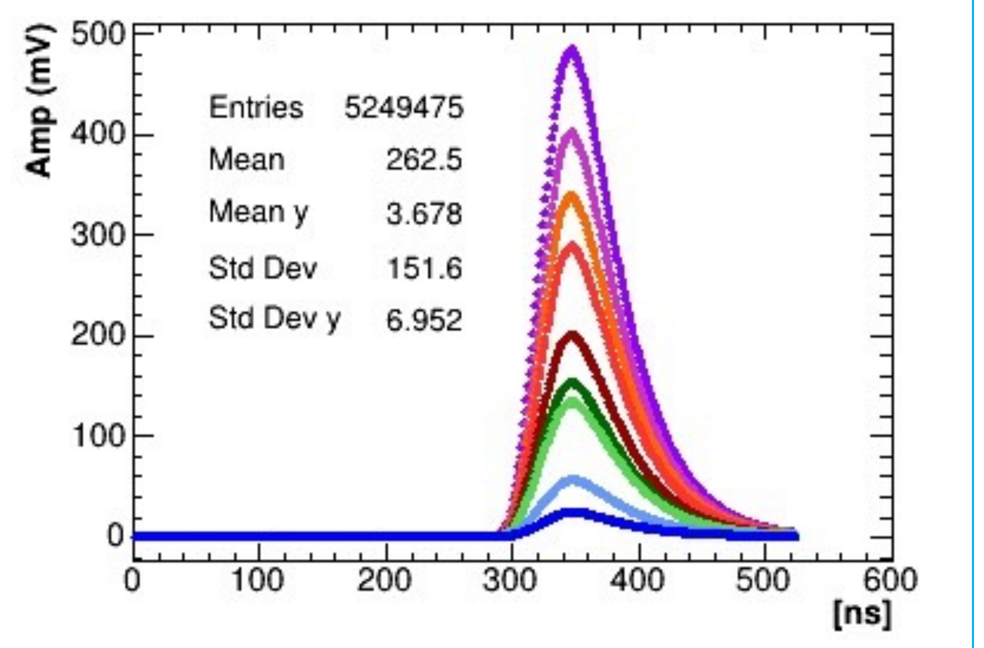
O(3%) gain variation for production

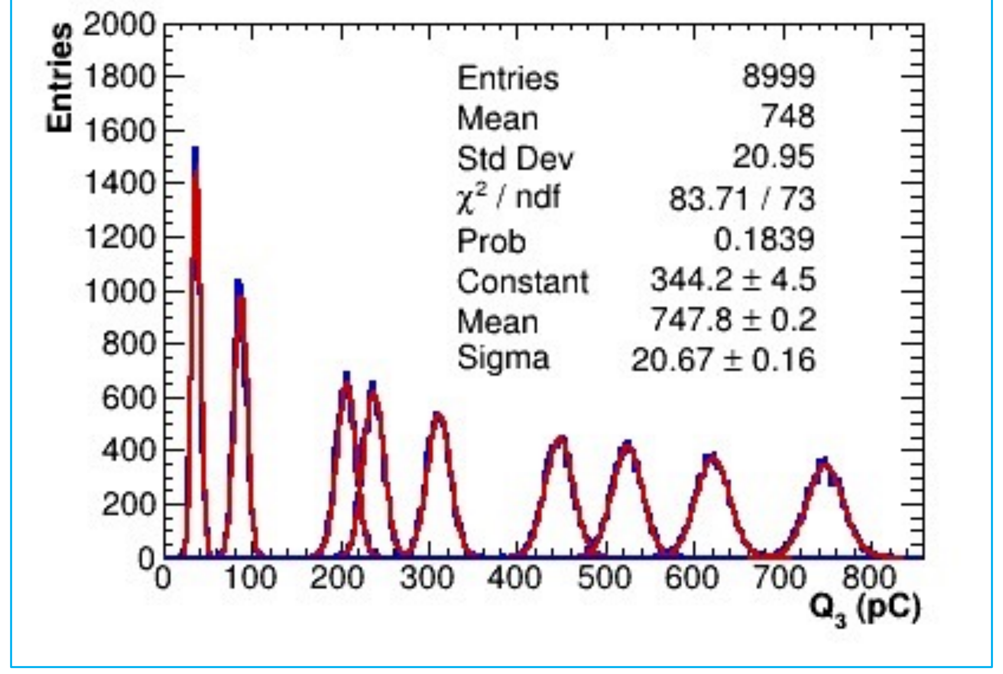


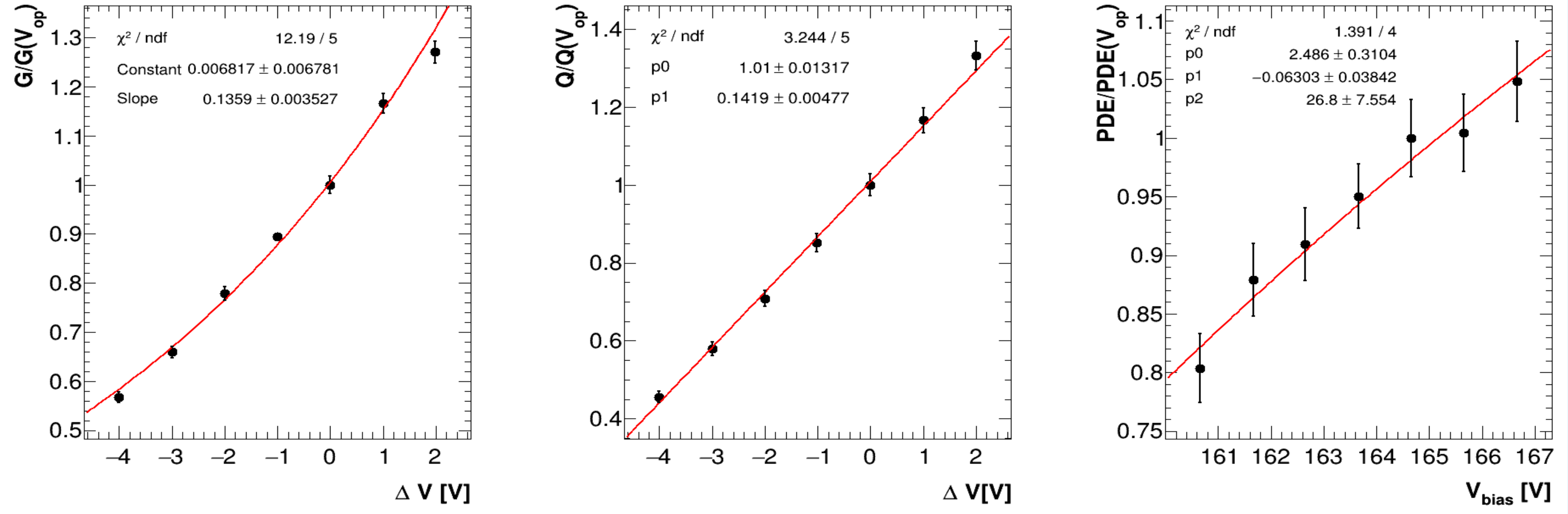
1.5 % measurement reproducibility

waveforms and charges









V_{ov} scans for gain, Q and PDE

FEE total ionising dose tests

TID campaign

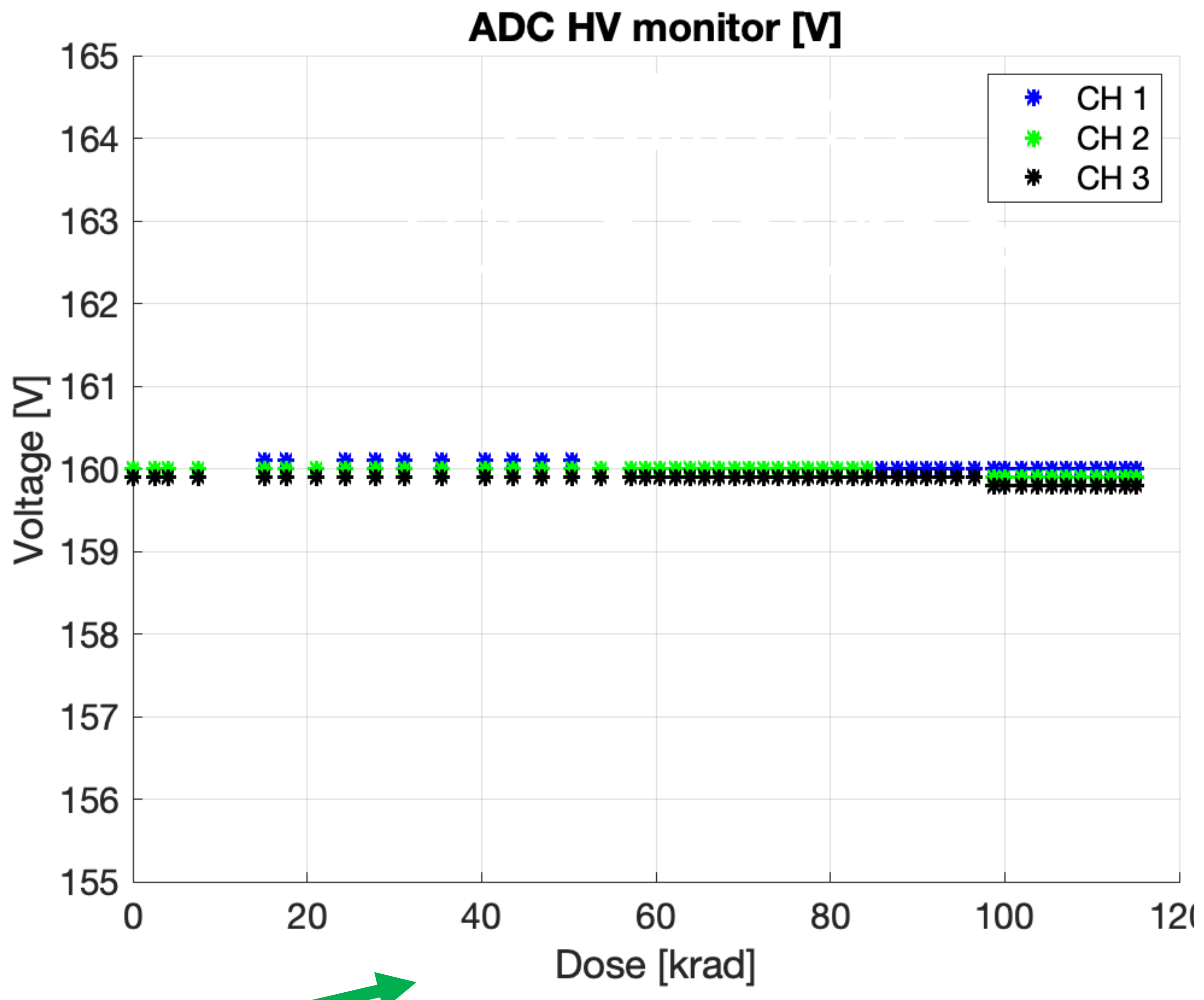
- Qualification @ ENEA-Calliope w/ ^{60}Co photons

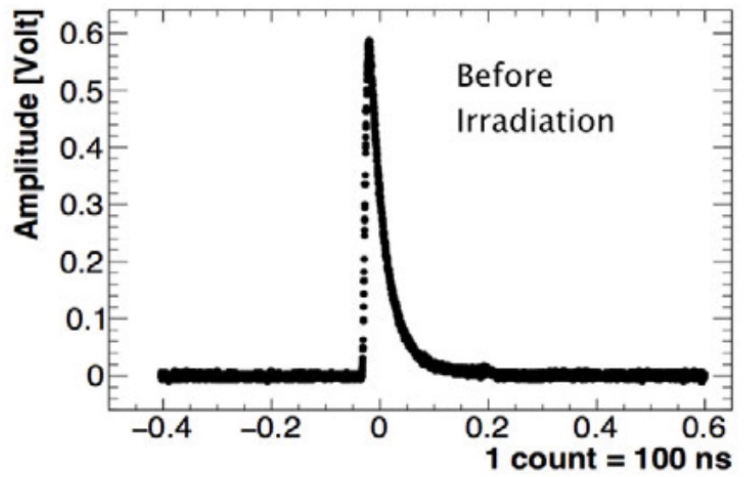
- TIDs for FEE up to **120 krad** @ 500 rad/h rate
- Different test configurations

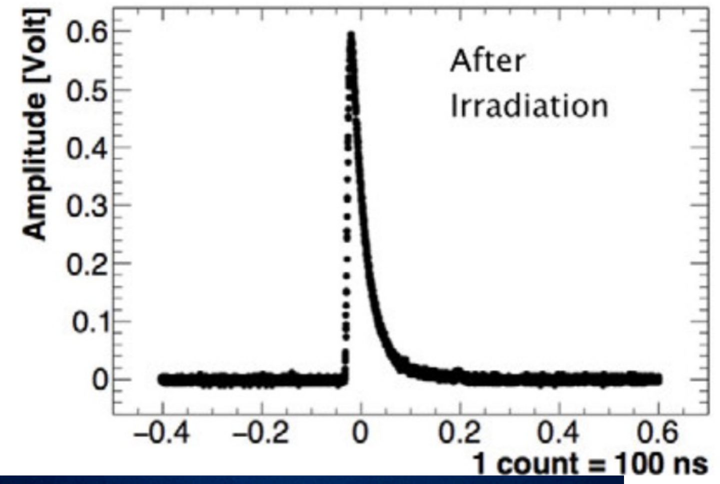
- Final **rad-hard components** choice after 2-y qualification (first ADC choice died after 100 krad):
  - SPI ADC1280S022CIMT (TI)
  - SPI 121S101CIMKX DAC (TI)
  - Rad-hard linear regulators
  - Design successfully validated

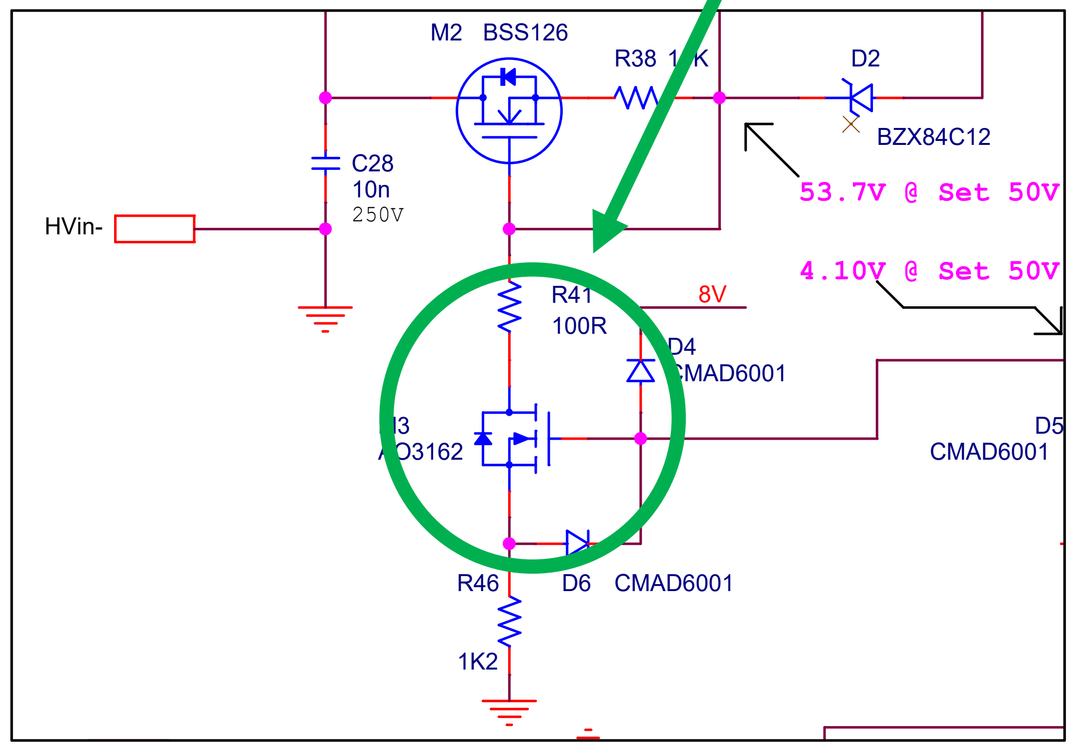
- Regulator and monitor **stability < 0.1 % up to 120 krad**
- Unaltered **WF shape** and FE **gain** after irradiation

- Failure of linear regulator drive MOSFET due to charge trapping observed for extreme operating conditions (never met during experimental runs)









CH1; HV Set: 160V; Load current: 2mA; ADC lot: “A”; DAC lot: “2”

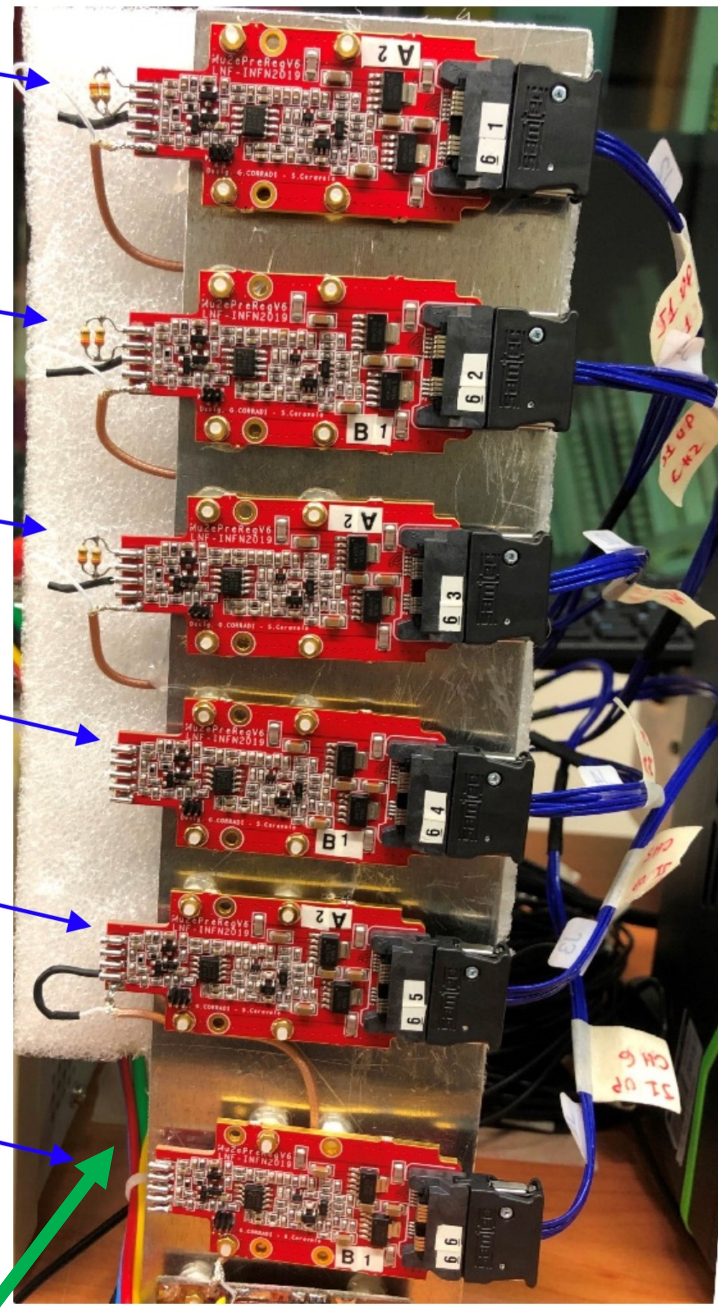
CH2; HV Set: 160V; Load current: 1mA; ADC lot: “B”; DAC lot: “1”

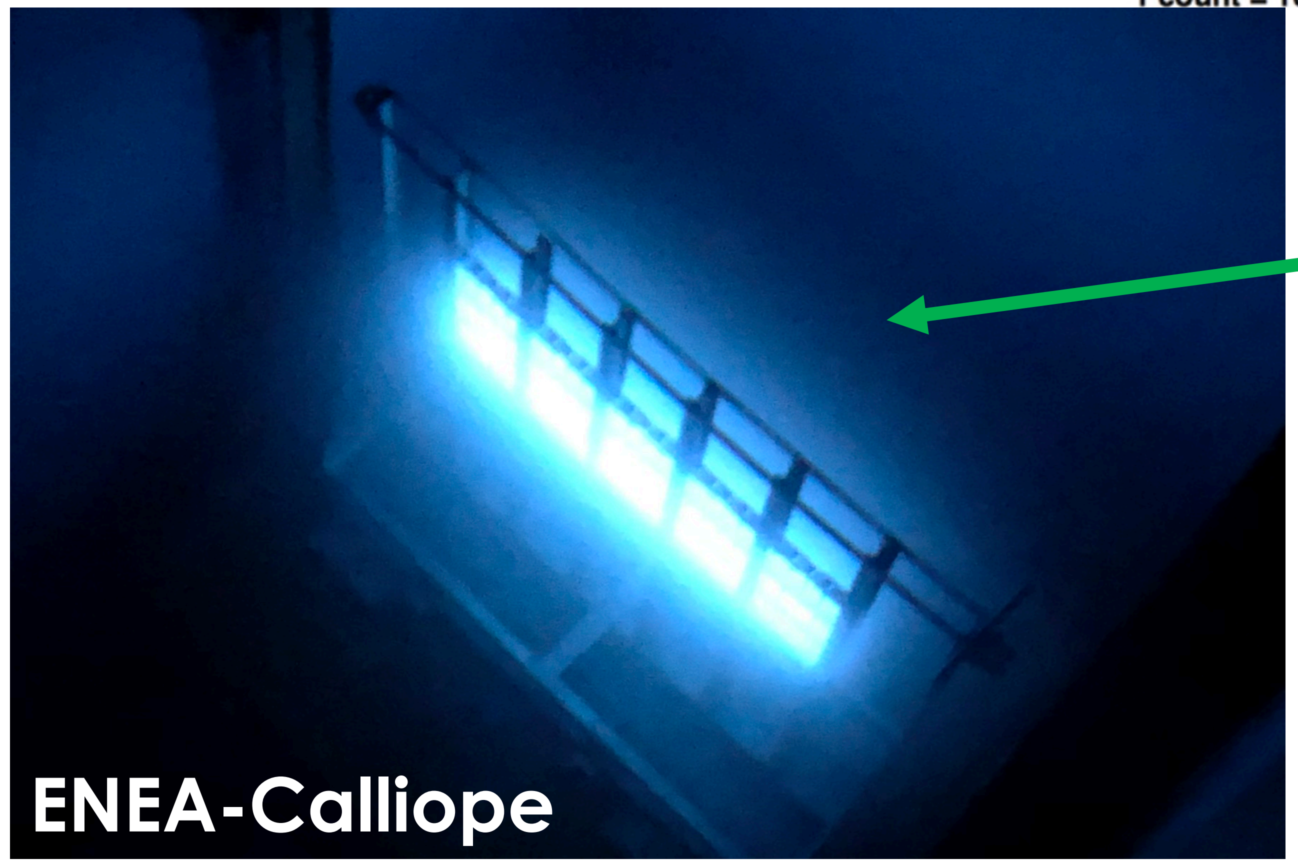
CH3; HV Set: 160V; Load current: 1mA; ADC lot: “A”; DAC lot: “2”

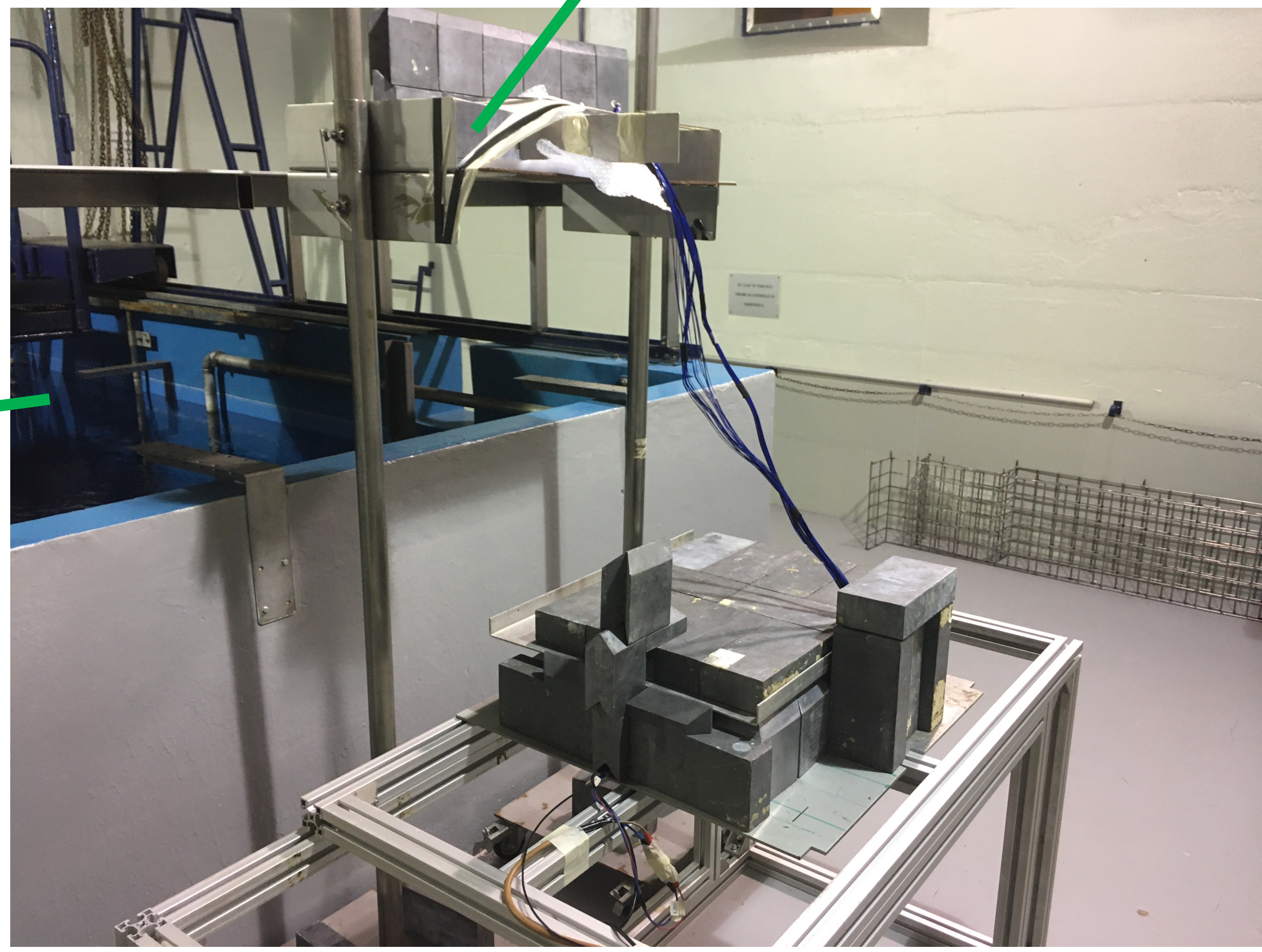
CH4; HV Set: 20V; ADC lot: “B”; DAC lot: “1”

CH5; No HV; Current Pulsed (Amplitude: 1.5mA; Period: 200 ns, Card Gain: 4); ADC lot: “A”; DAC lot: “2”

CH6; HV Set: 10V; ADC lot: “B”; DAC lot: “1”







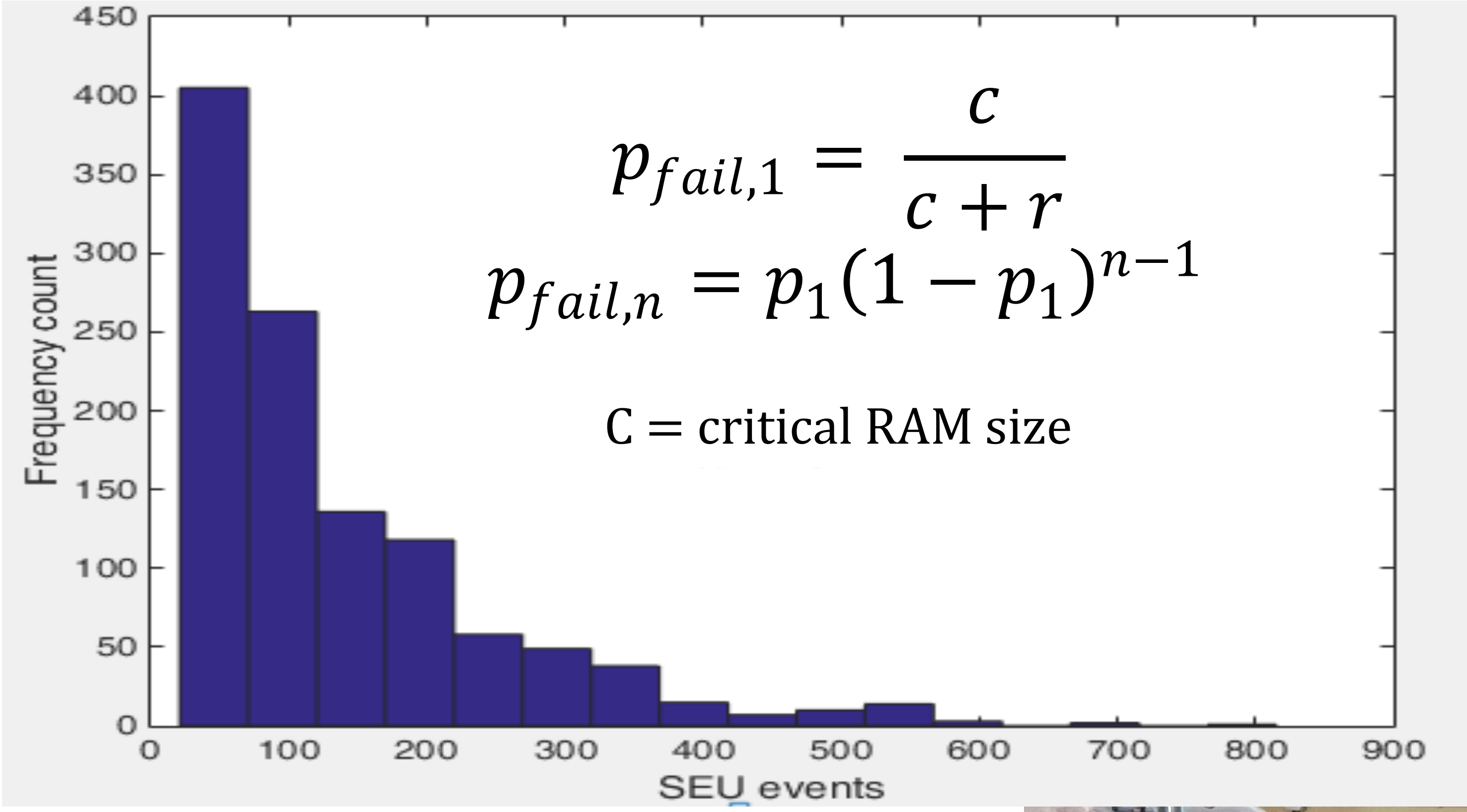
Neutrons and SEU vertical slice test

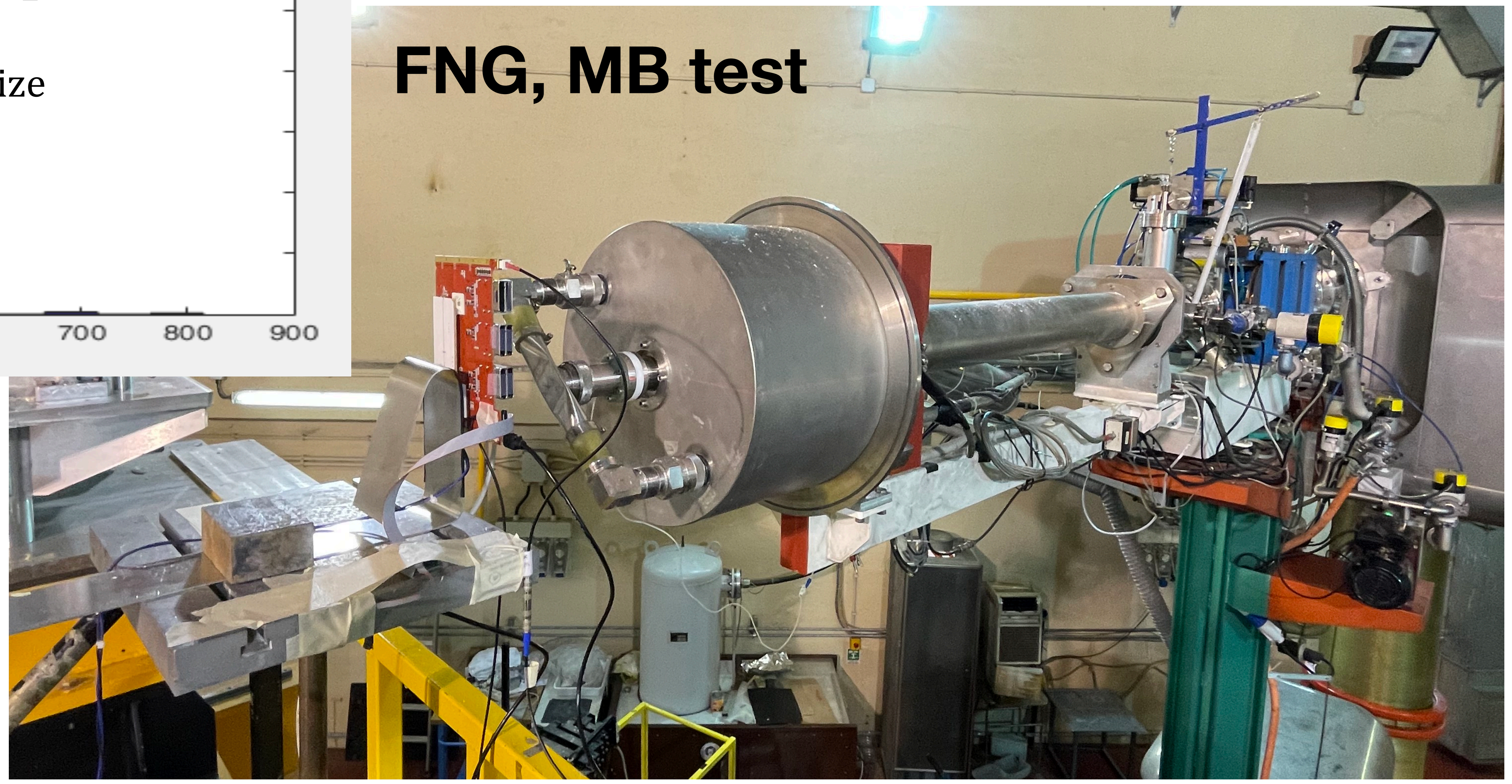
Neutron campaign

- Qualification @ ENEA Frascati Neutron Generator
- DT fusion 14 MeV neutron source
- TNID requirements up to **10^{12} 1-MeV-neq(Si)/cm^2**
- Exposure of both **FEE, MB and DIRAC** boards
- Cumulative TNID damage and SEU campaign

TNID cumulative damage

- No TNID effect on FE amplifier
- No TNID effect on slow control and signal chain stability





Neutron induced SEU on MB

- Neutron irradiation to check SEU occurrence and recovery on MB+FEE during 10^{12} n/cm^2 exposure
- Critical RAM size (≈ 327 bytes) determined via simulation on MB processor → 200 SEU on average cause functional interrupt

Test purpose

- Check corruption of
  - Microprocessor RAM and flash ROM
  - Communication (I2C, SPI) with FEE boards
- Validate SEU detection:
  - Communication checksums
  - Memory integrity check
- Validate SEU correction:
  - MB configuration memory scrubbing
  - Watch dog timer
  - Reset or power cycling

Results

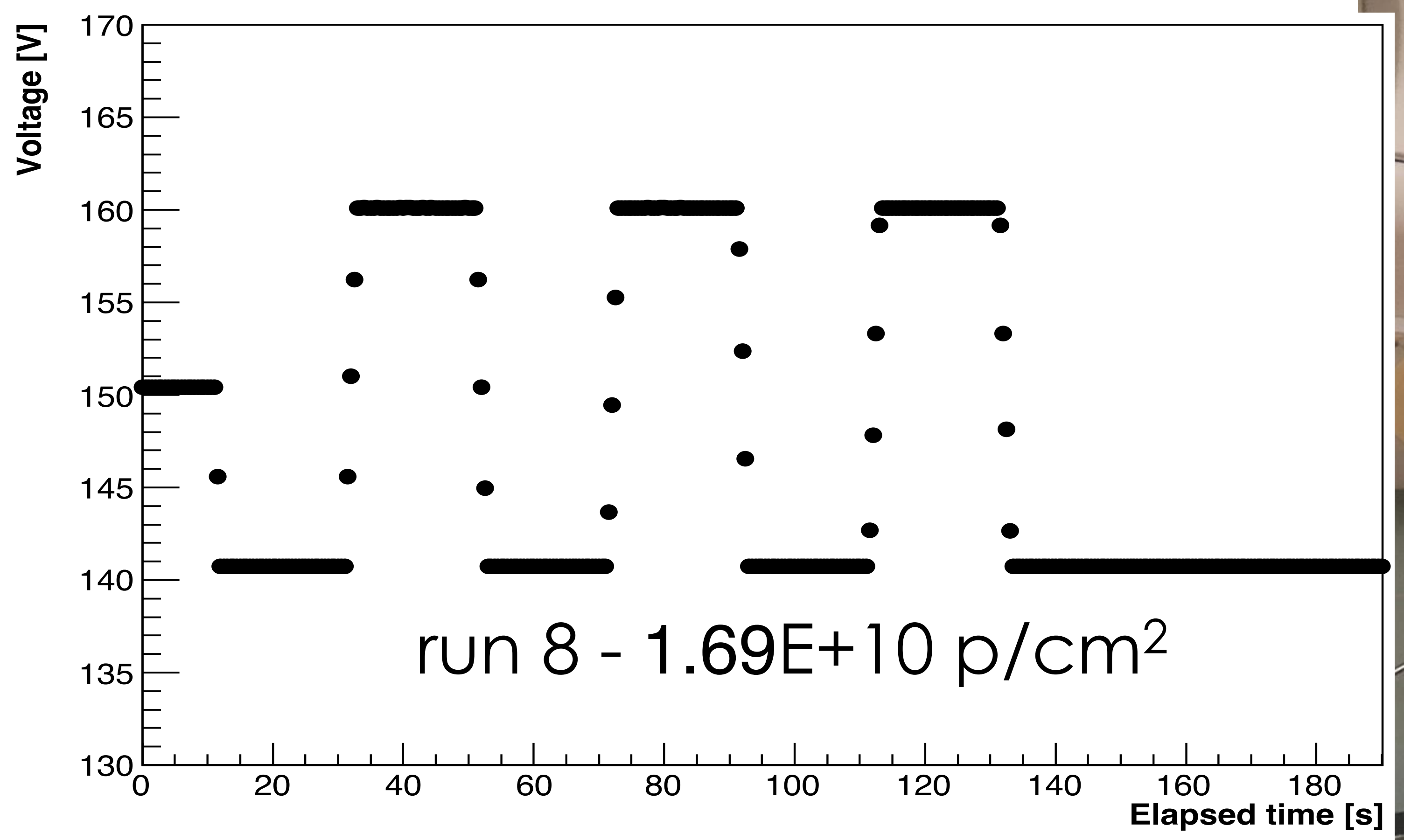
- 96 minutes test up to 10^{11} n/cm^2
- No single-event-latchup observed
- Functional interrupts due to SEU detected every 2*10 n/cm^2 → O(10 months) during data taking
- WDT triggered board reset correctly recovered operations of MB + FEE

Single event effects test with protons

- **10^{10} p/cm² high-energy (> 20 MeV) hadrons** fluence requirement for MB+DIRAC validation
- Tests at Warrenville Proton Centre w/ **200 MeV protons**
- Campaign started in 2019 with FEE+MB test

Warrenville Medical proton irradiation

- MB + FEE irradiation
- Slow control operated by ramping HV bias every 20s
- External monitoring of the setup and readout via DCS
- Fixed beam energy at 200 MeV, 10 cm beam spot

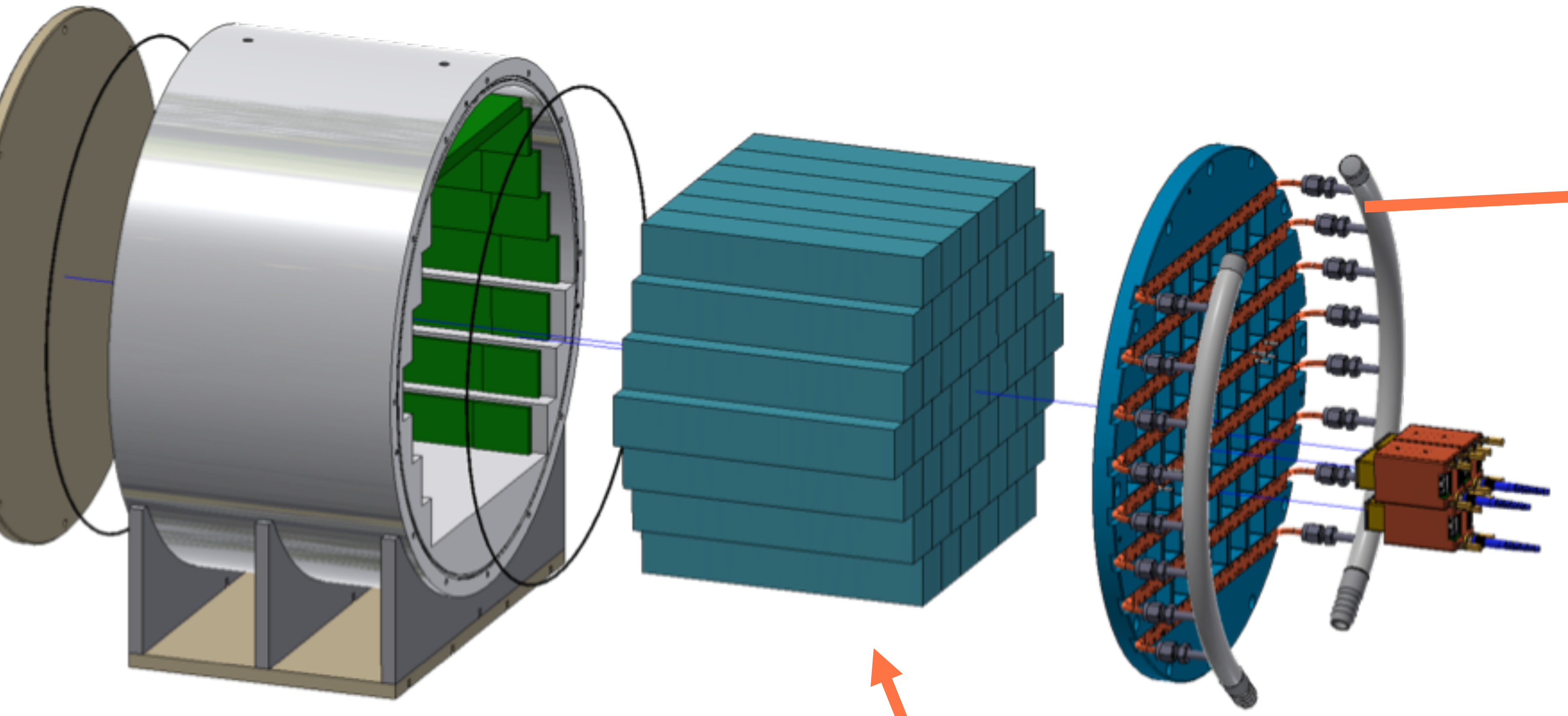


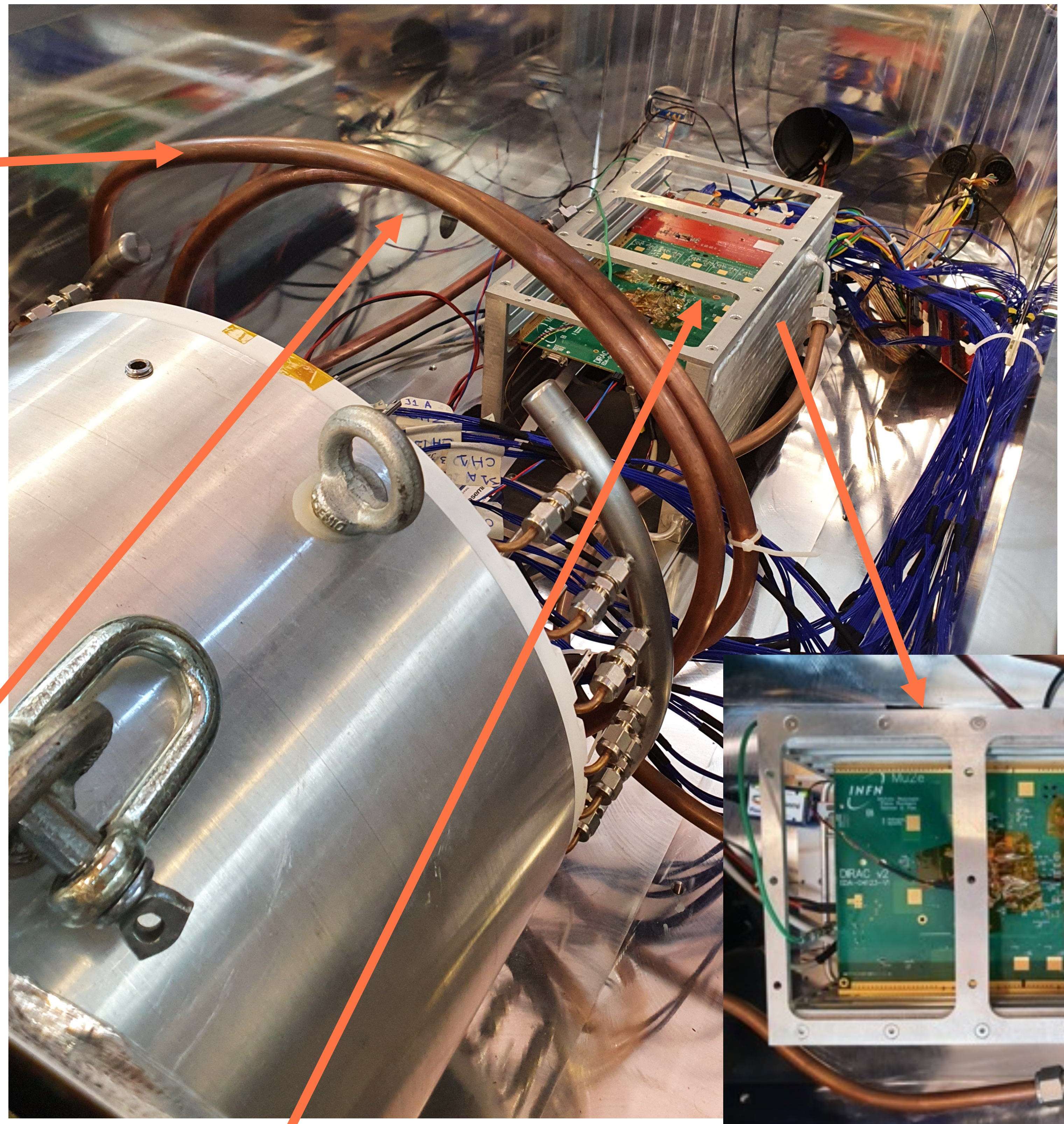
- Proton flux ramped up to 6E7 p/cm²/s
- **No SEL** detected
- **No erratic behaviour** was observed
- Slow control functionality was not impaired
- Occasional communication loss not due to MB, but to Ethernet controller

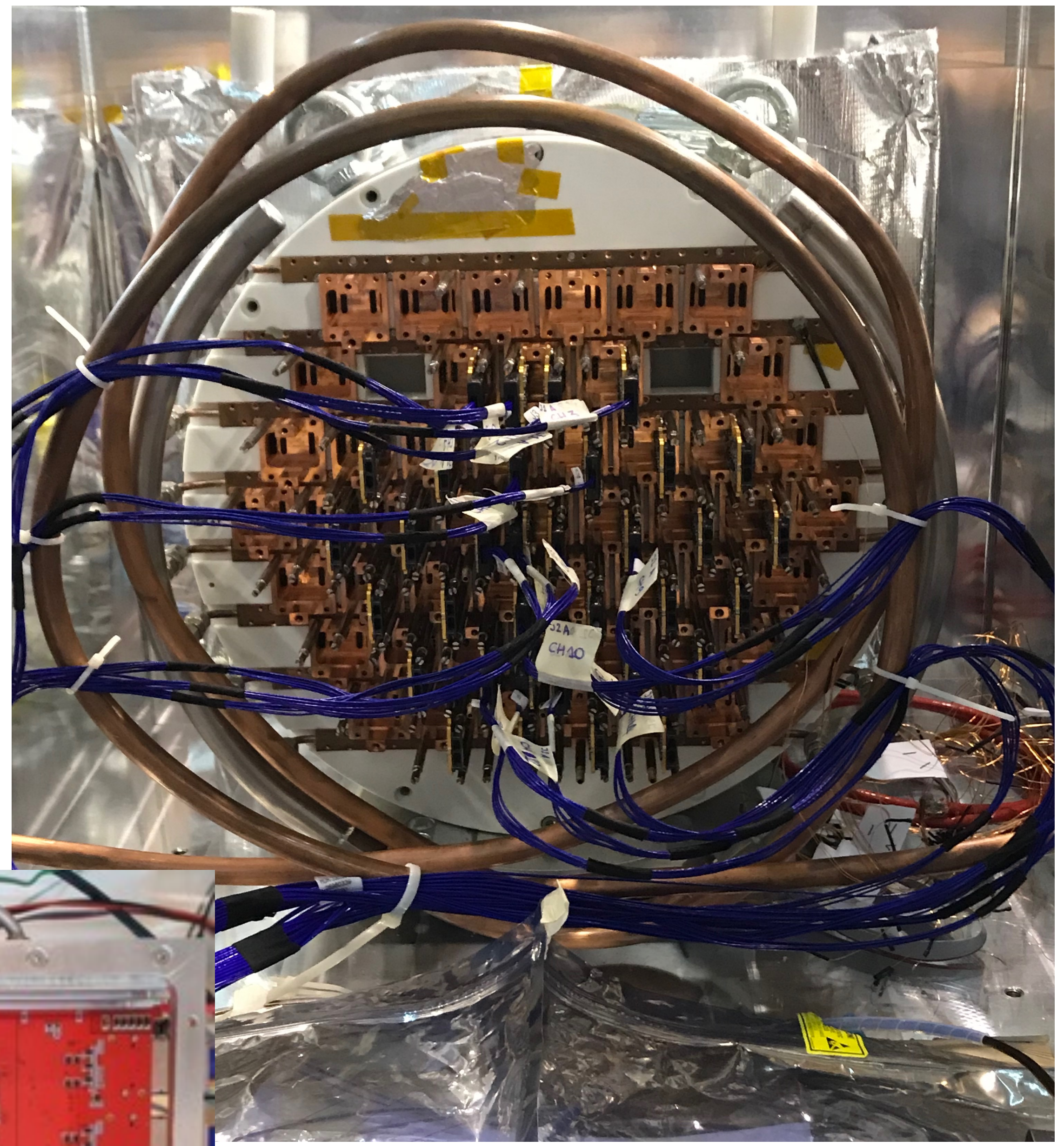
Next steps

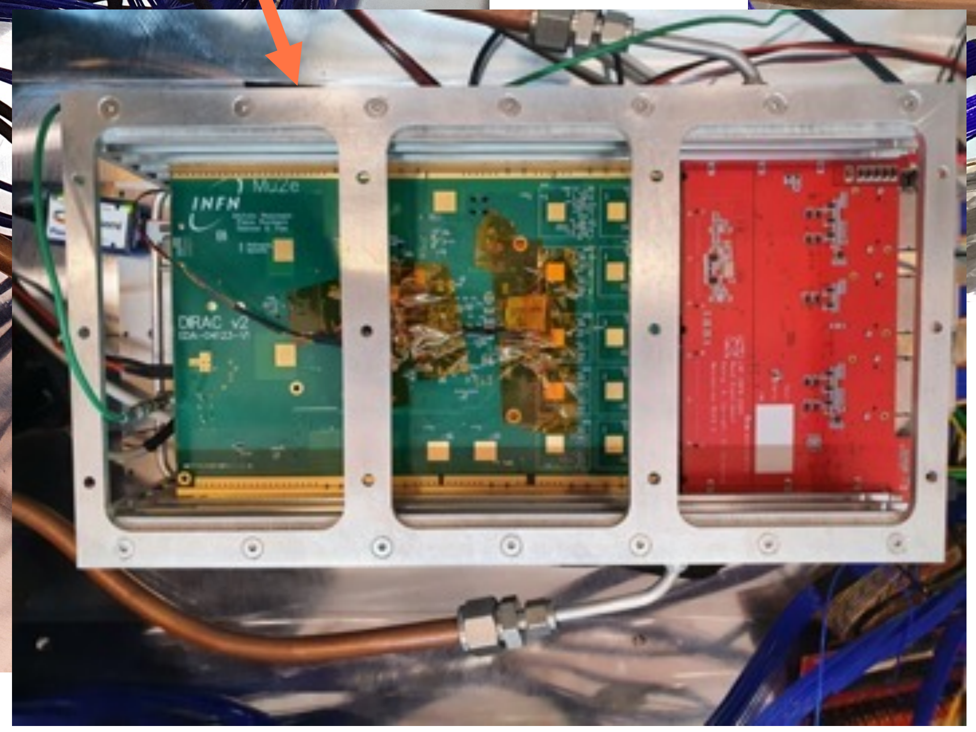
- **Final vertical slice test** of DIRAC, MB and FEE due in summer 2022
- Determining the necessary **scrubbing rate** for FPGAs, FEE and MB memory
- **Mean-time between functional interrupt** evaluation
- **SEU recovery** validation

VST with cosmics







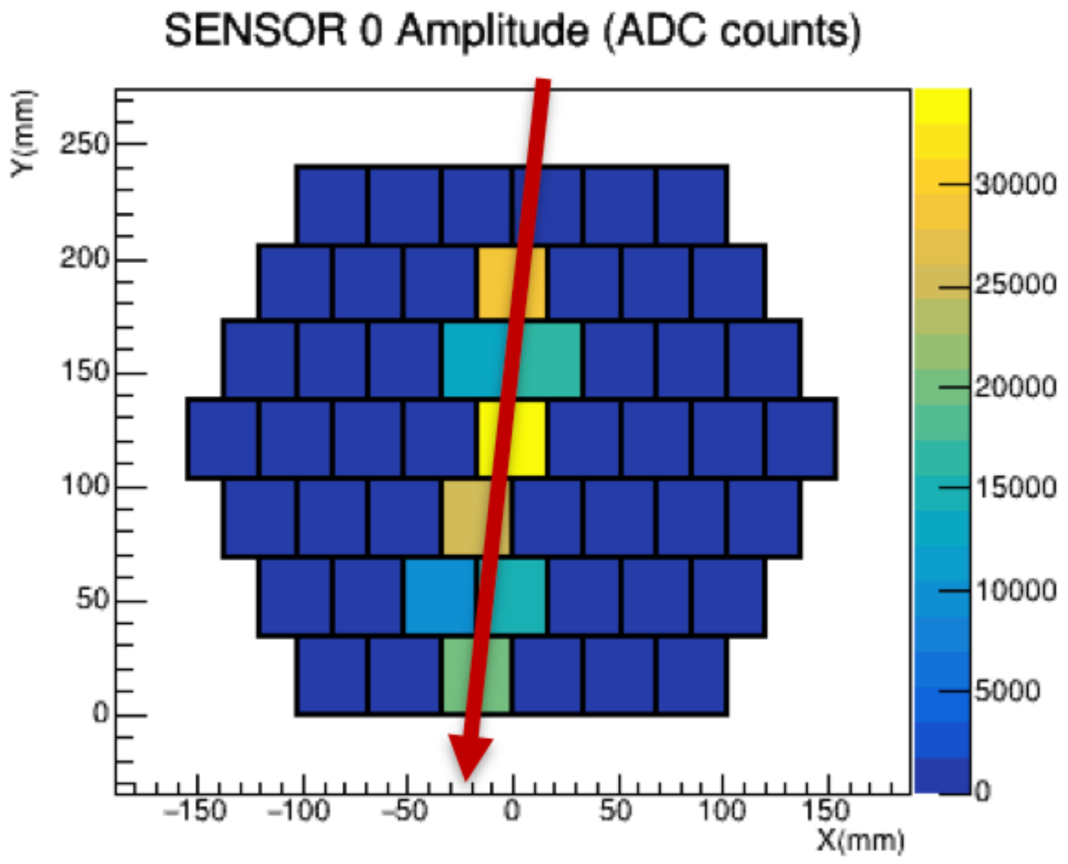


Module-0

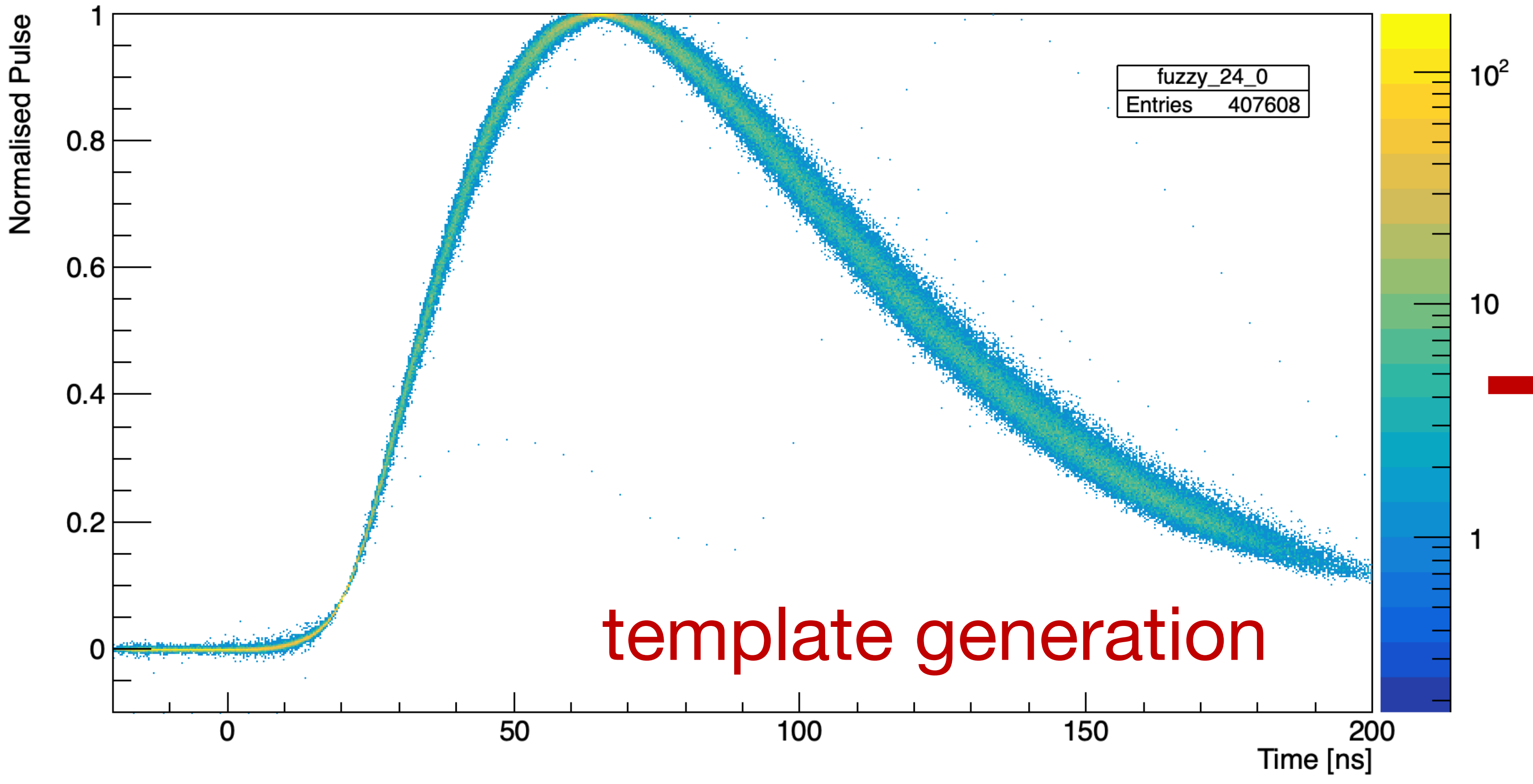
- **Large scale prototype** w/51 crystals matrix
- Same cooling system as final calorimeter
- Same fibre optic laser calibration system as final calorimeter

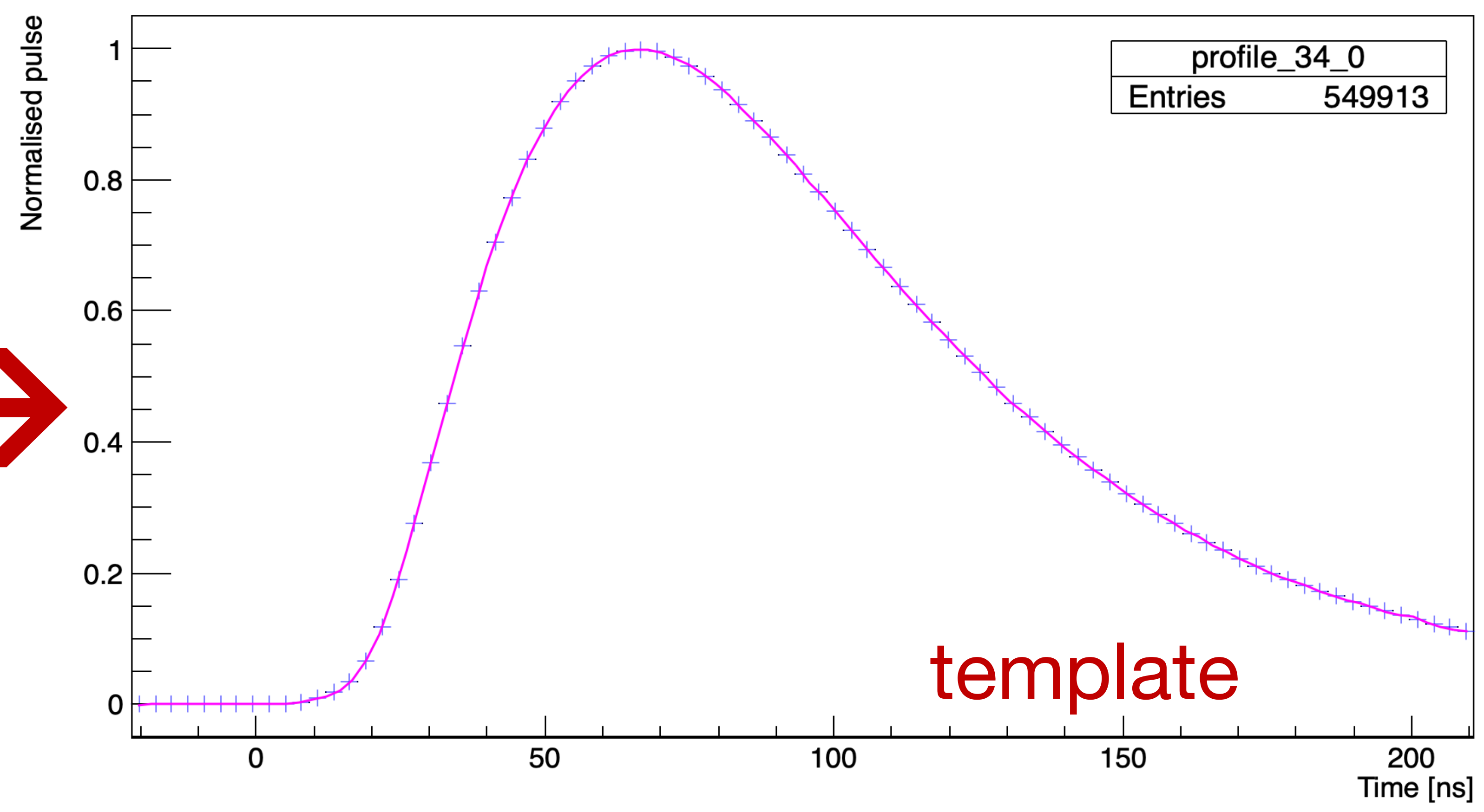
Vertical slice test

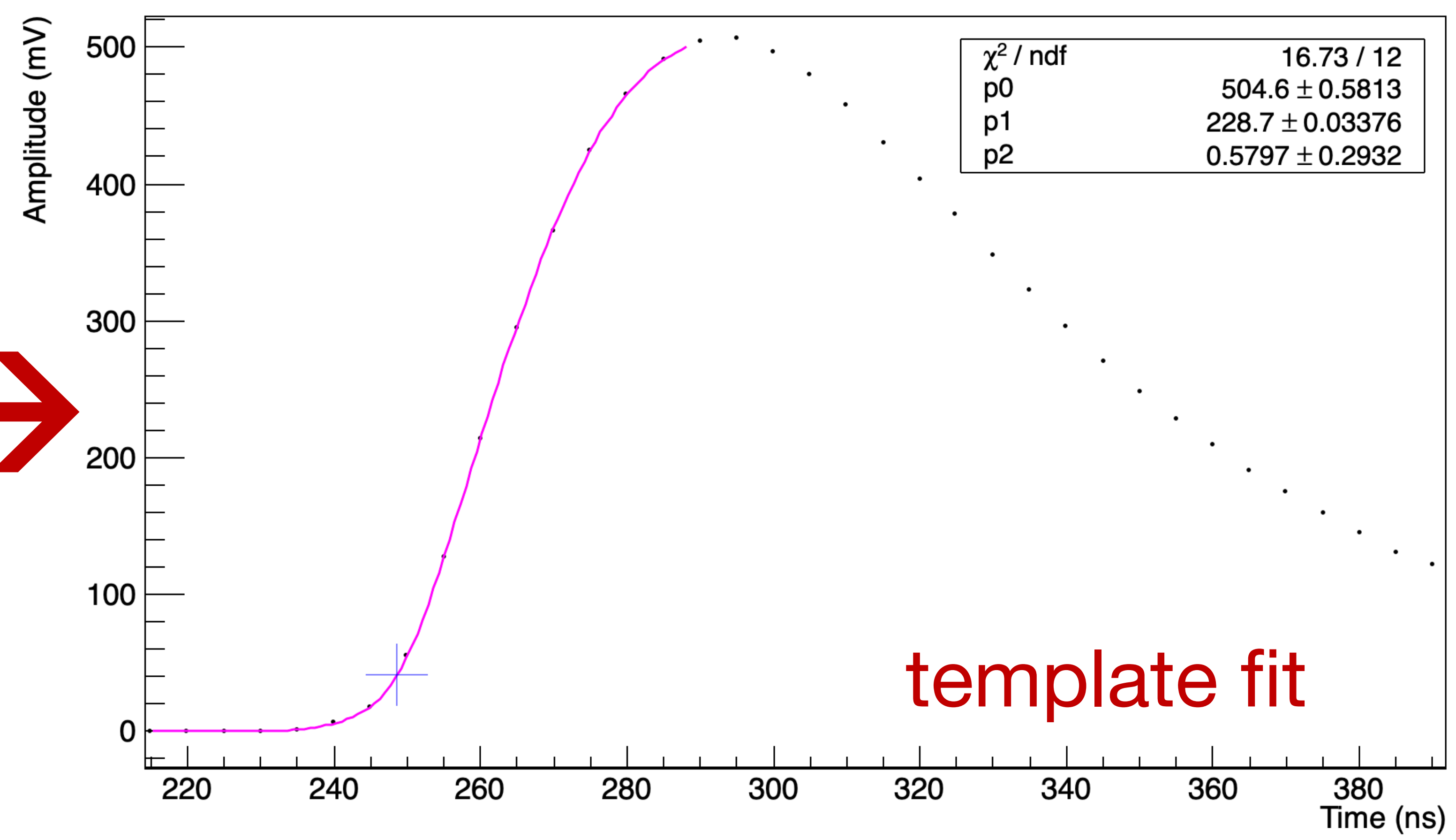
- Final MB and DIRAC versions installed on 1 electronics crate
- Final Mu2e readout chain implemented from FEE to DIRAC digitiser
- Cosmic selector to test whole signal chain with MIPs
- Validation of energy and timing calibration algorithms
- **Tests in vacuum and with cooling system**



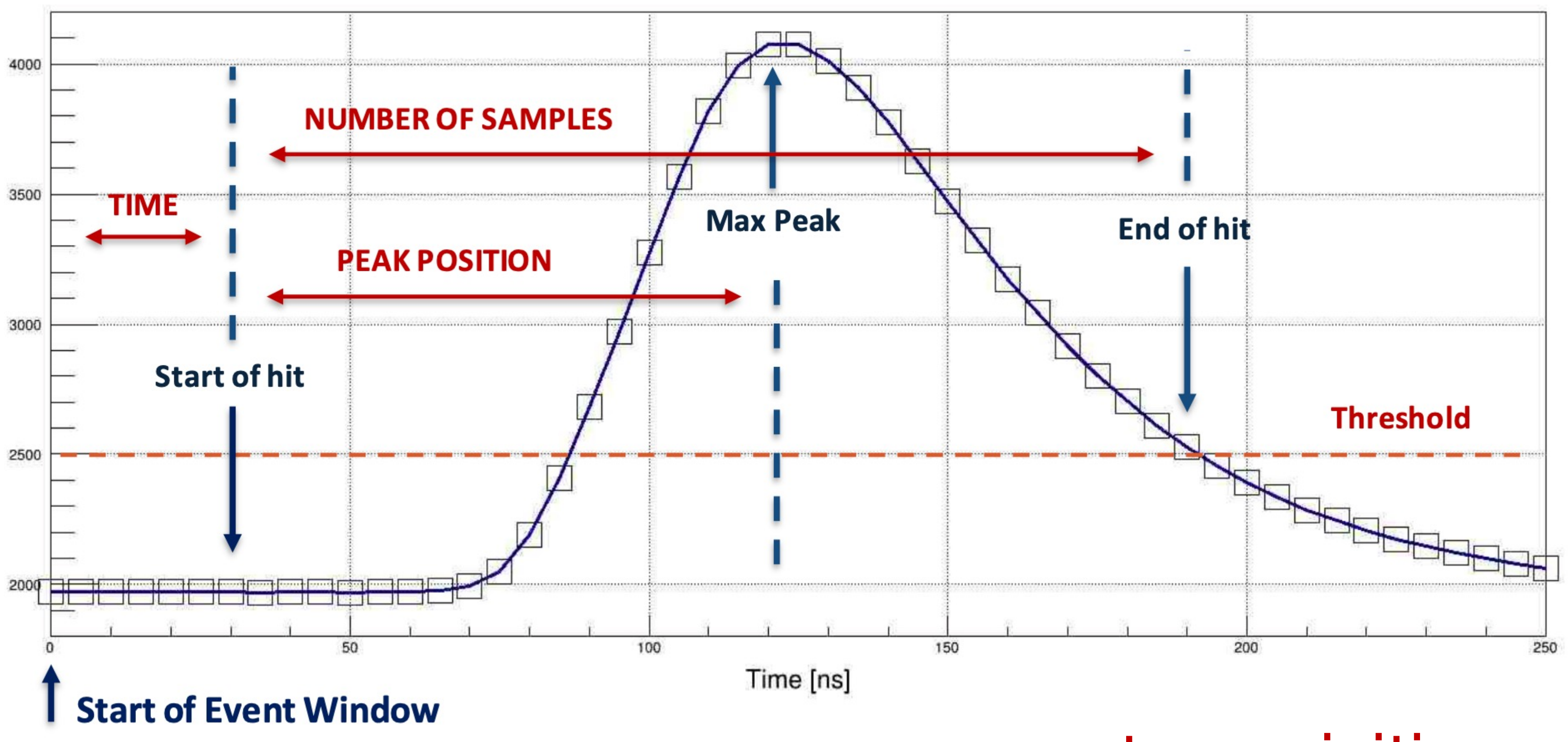
Pulse acquisition and processing

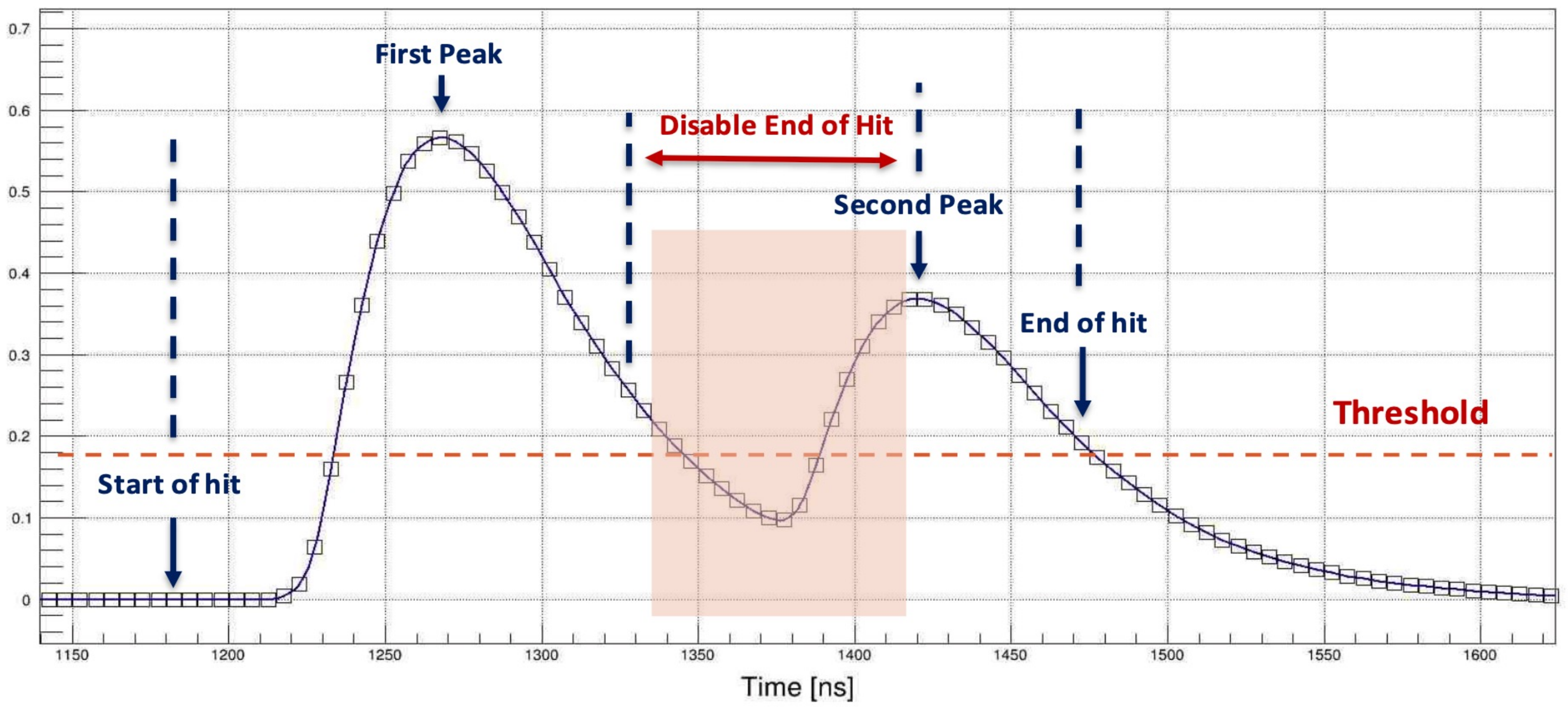






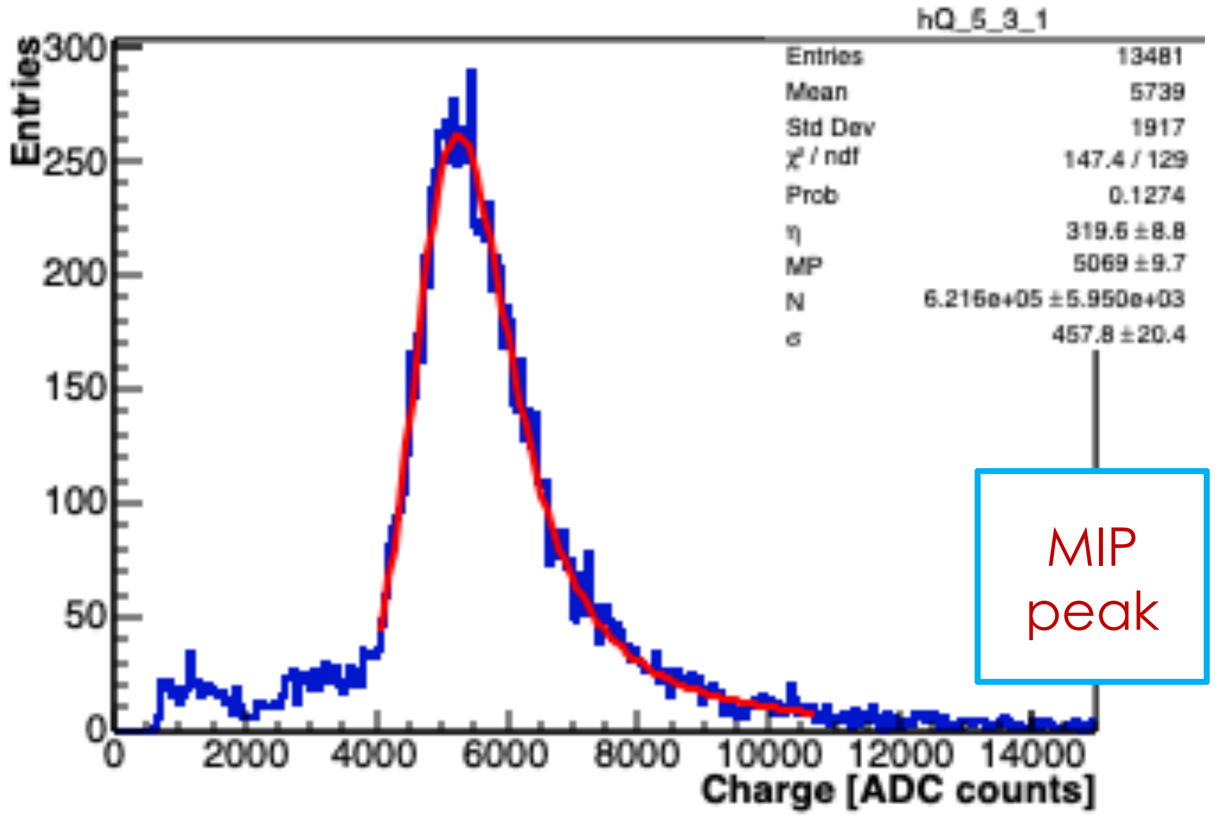
- Individual SiPM pulse templates are generated by aligning and averaging signals from a large dataset of hits
- Templates are **nodes with polynomial interpolation and fixed proportion**, fitted on each waveform using a **3 parameter optimization**
- Template fit is used for **timing and charge reconstruction**, along with **pile-up disentangling**
- Template fit performs well also in presence of **radiation-induced noise** on the WFs
- Individual templates for each channel (and particle)

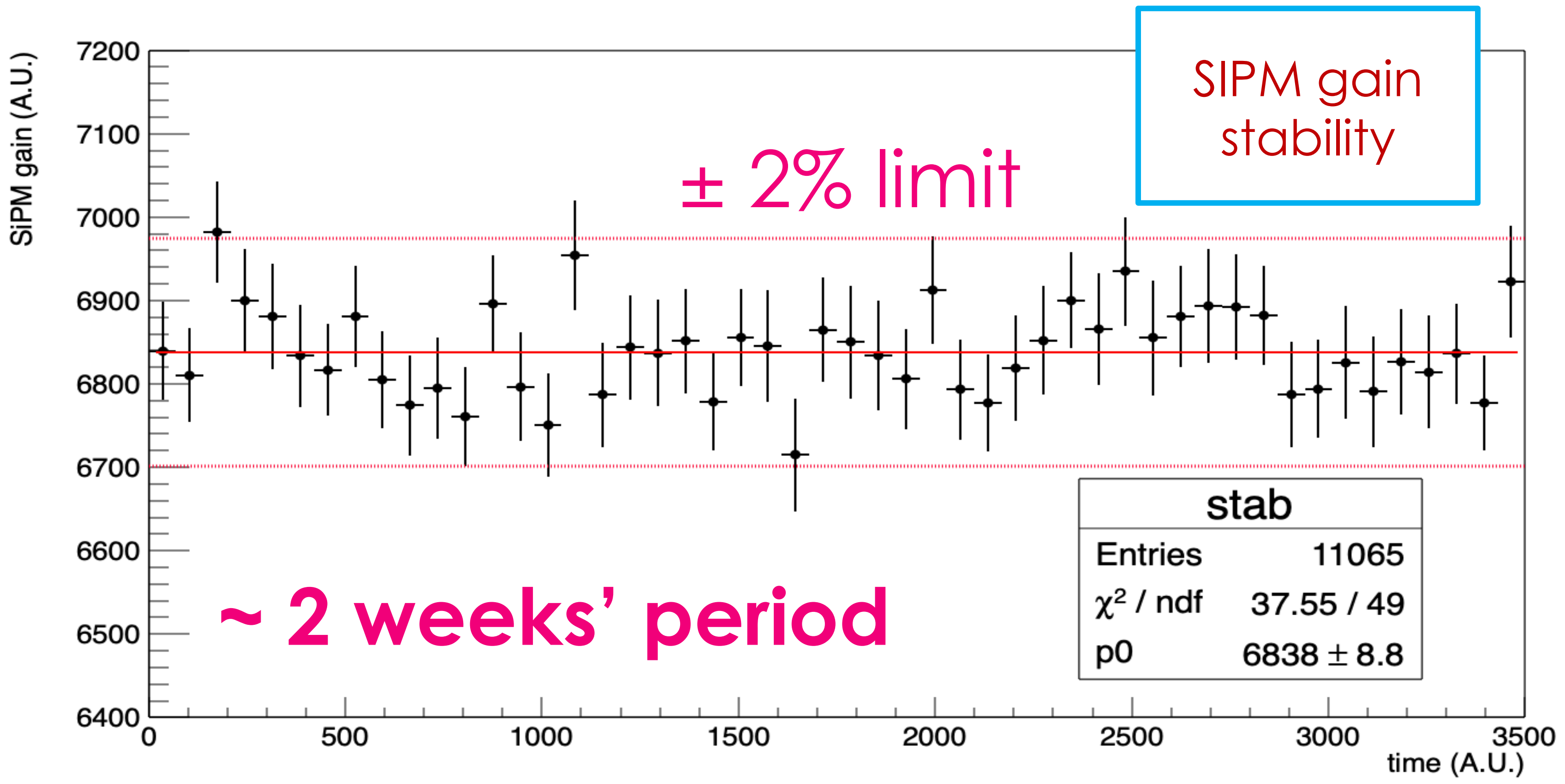


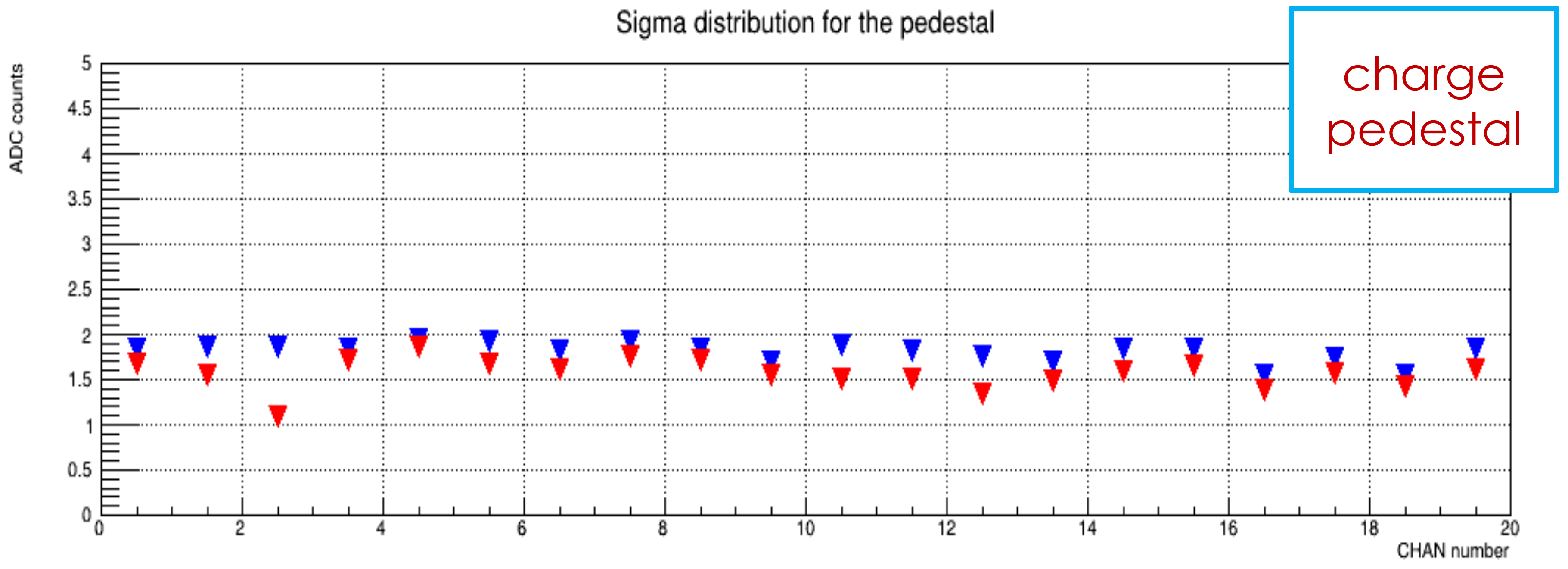


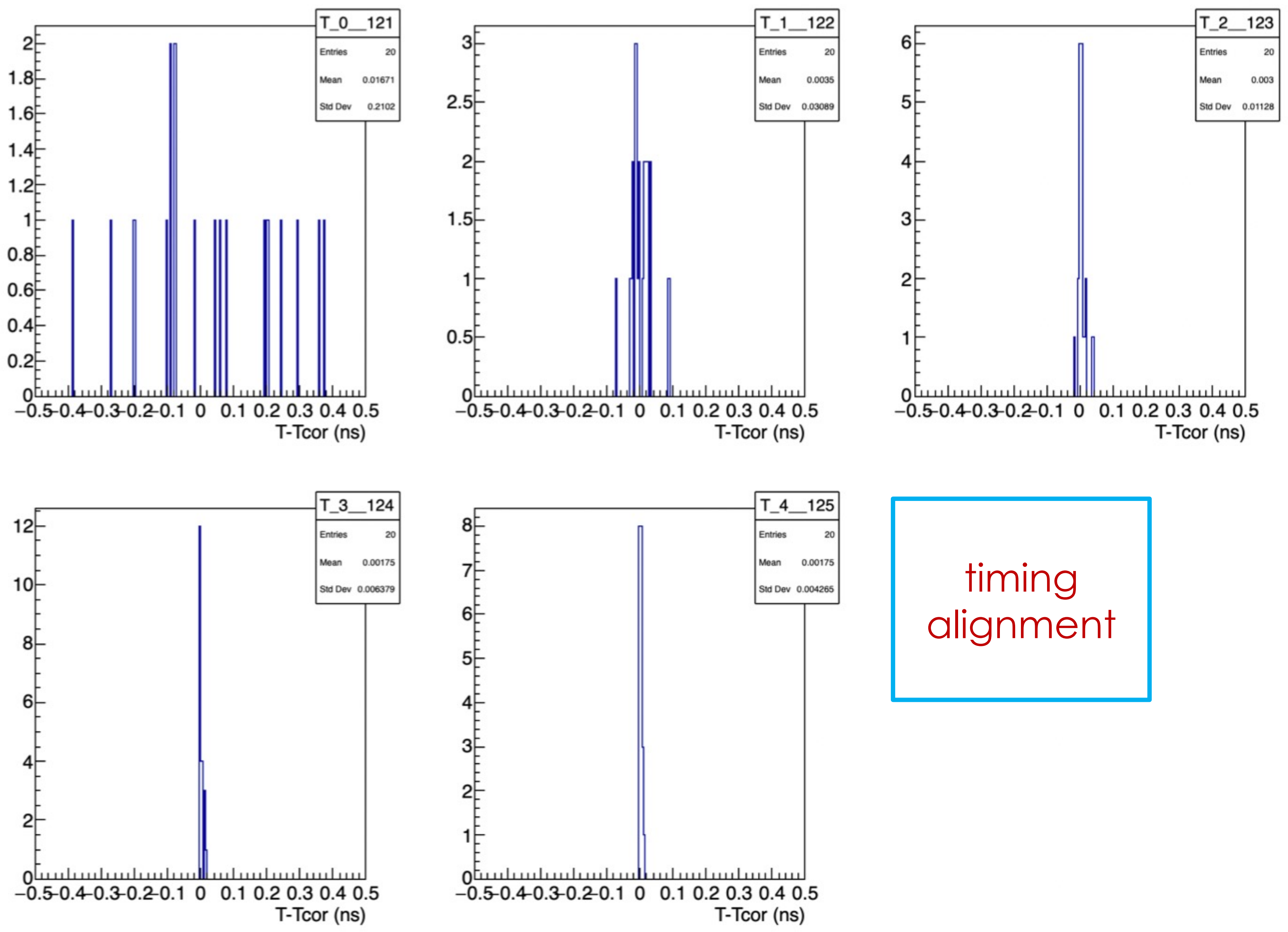
VST with cosmics results overview

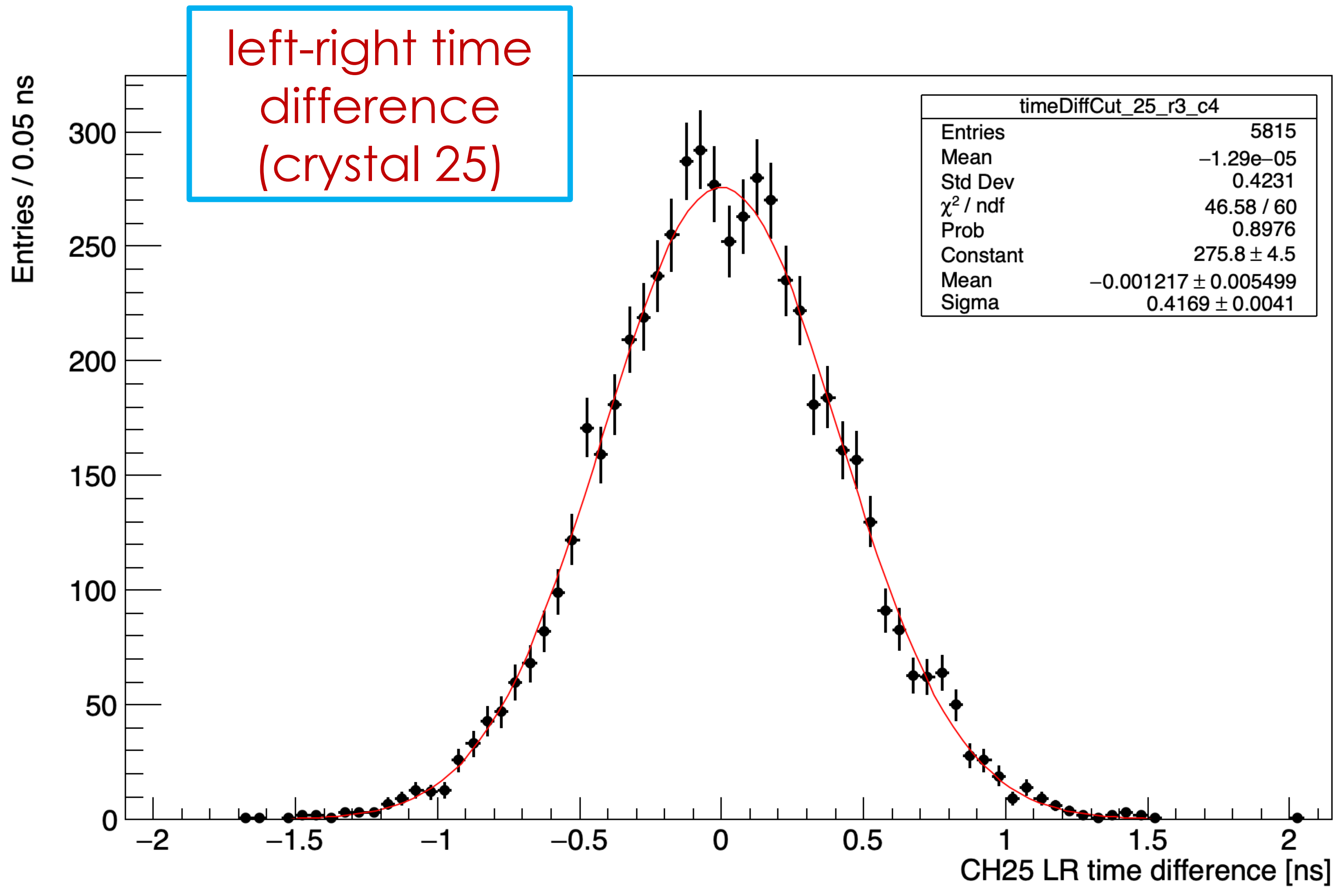
- Module-0 w/ final FEE and readout chain
- MIP selector with XY + YZ slope track reconstruction
- **Energy equalisation** on 21 MeV MIP peak
- NPE (from asymmetry) and **SiPM gain stability** check (+1.6 % /°C for SiPM gain)
- **Equivalent noise** ≈ 200 KeV
- Readout channels **timing offset** correction trough iterative algorithm to a level < 5 ps RMS
- Cell mean **time resolution** w/ MIPs ≈ 210 ps

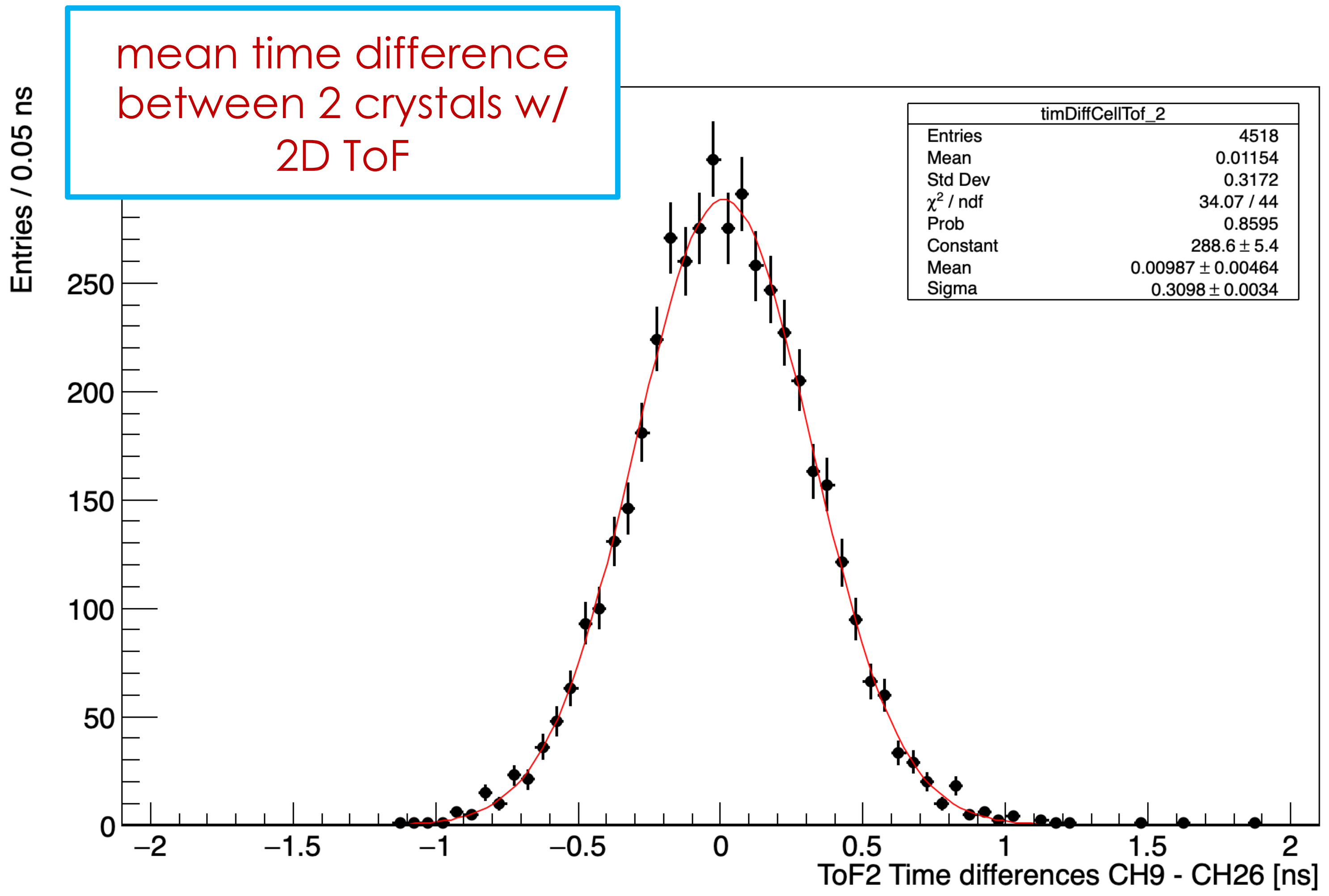












Conclusion

- ✓ The front-end and readout chain development for the Mu2e calorimeter had to face many challenges due to the harsh operating environment and the required high levels of precision and stability
- ✓ The readout chain design was qualified and validated trough long and extensive test campaigns
- ✓ The construction of the Mu2e experiment is under way and the calorimeter commissioning phase is approaching

Fermilab

Backup

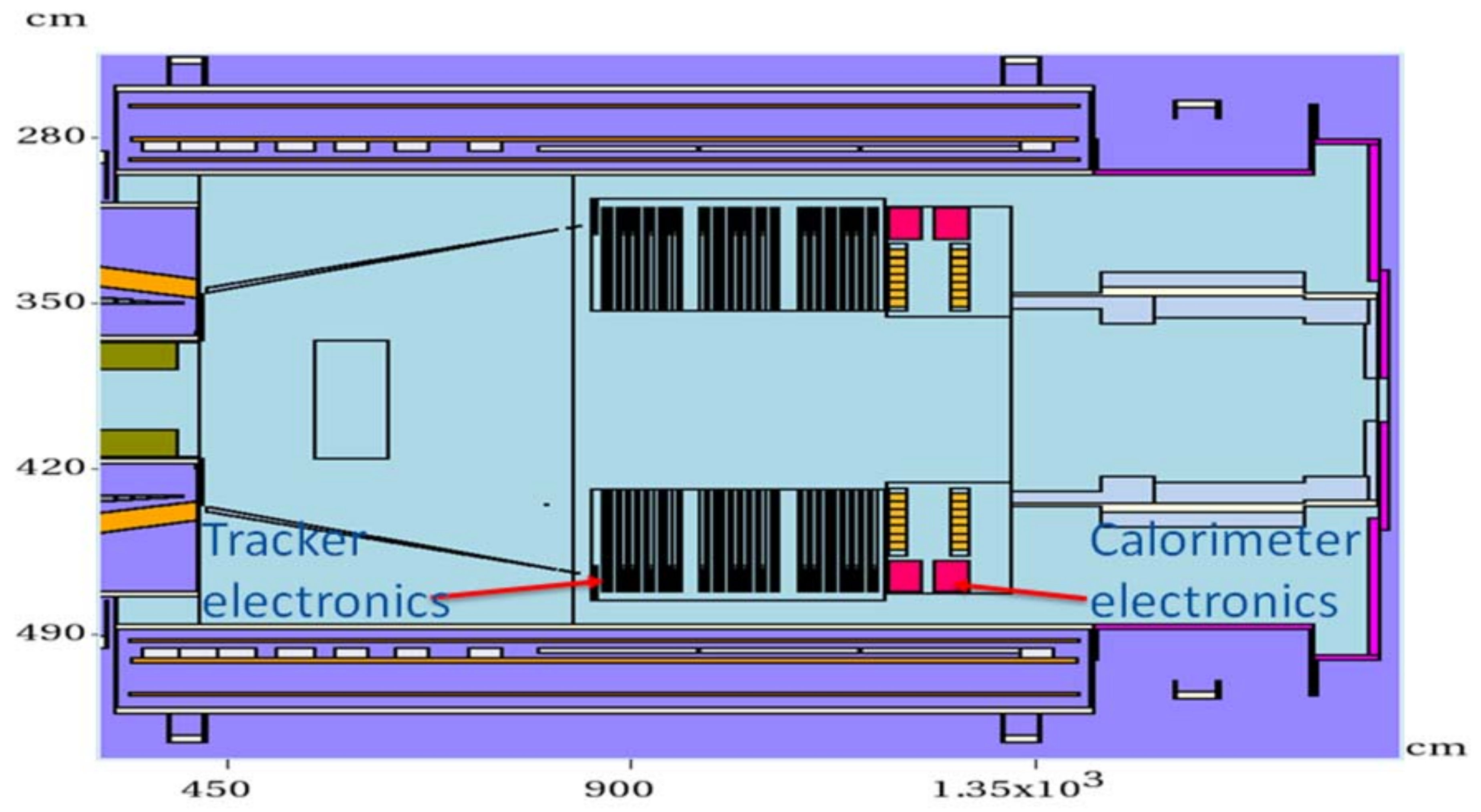
Mu2e radiation environment

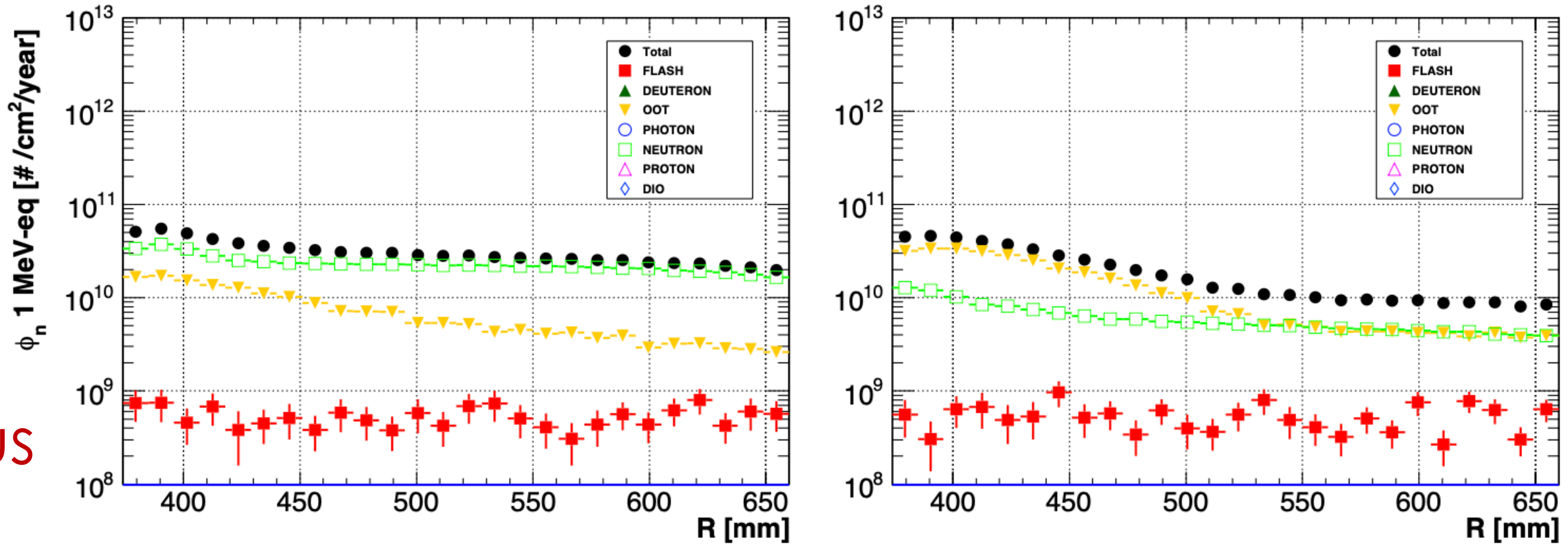
Radiation environment

- Mu2e detector solenoid simulation via MARS15

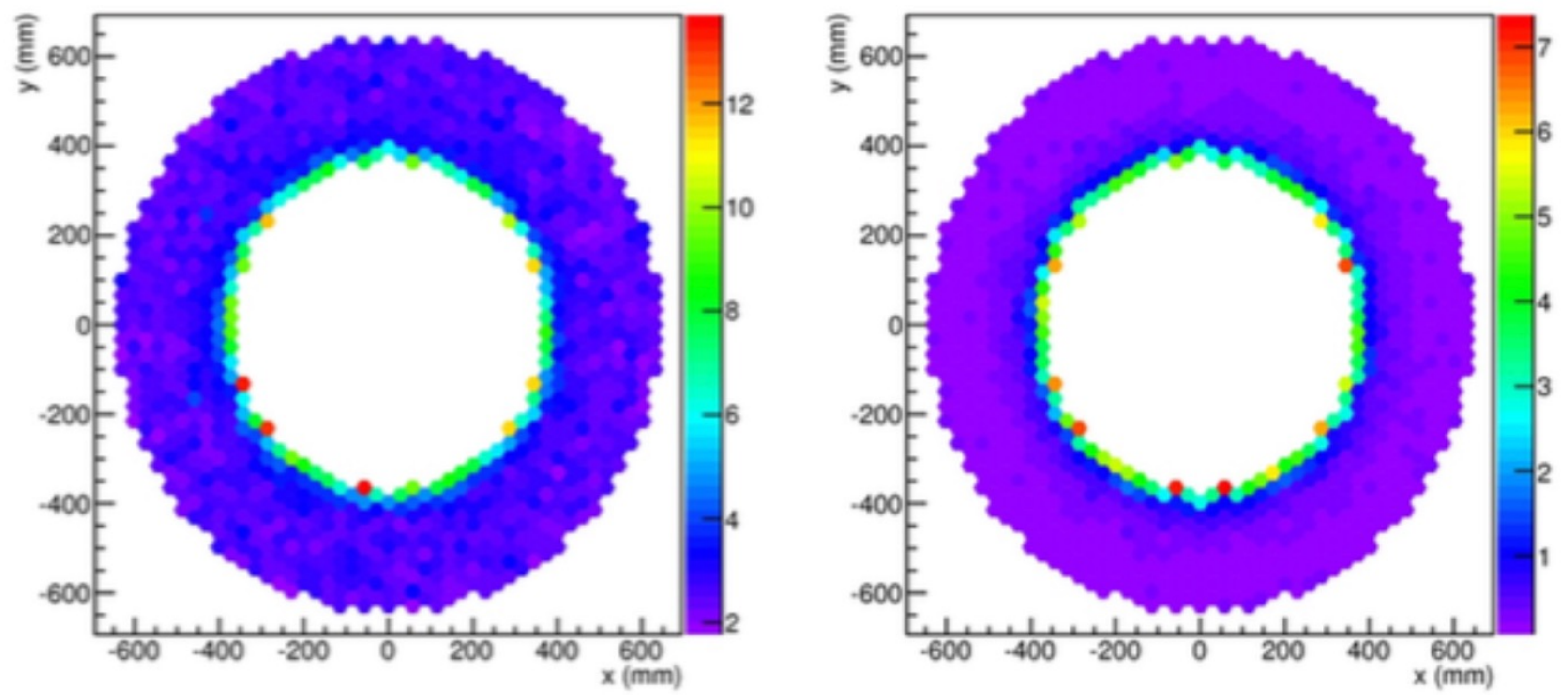
- Simulated events
  - beam flash (all particles within the beam other than a muon stopped either in the stopping target or in the beam dump);
  - DIO electrons
  - neutrons, protons and photons due to nuclear capture
  - Out-of-target particles produced by muons stopped outside the stopping target

- Calorimeter electronics requirements
  - TIDs up to 100 krad (SF = 12)
  - NIEL fluences up to 3E+10 1MeV-neq(Si)/cm^2 (SF = 6)
  - High-energy hadrons (> 20 MeV) fluence up to 1E10 p/cm^2

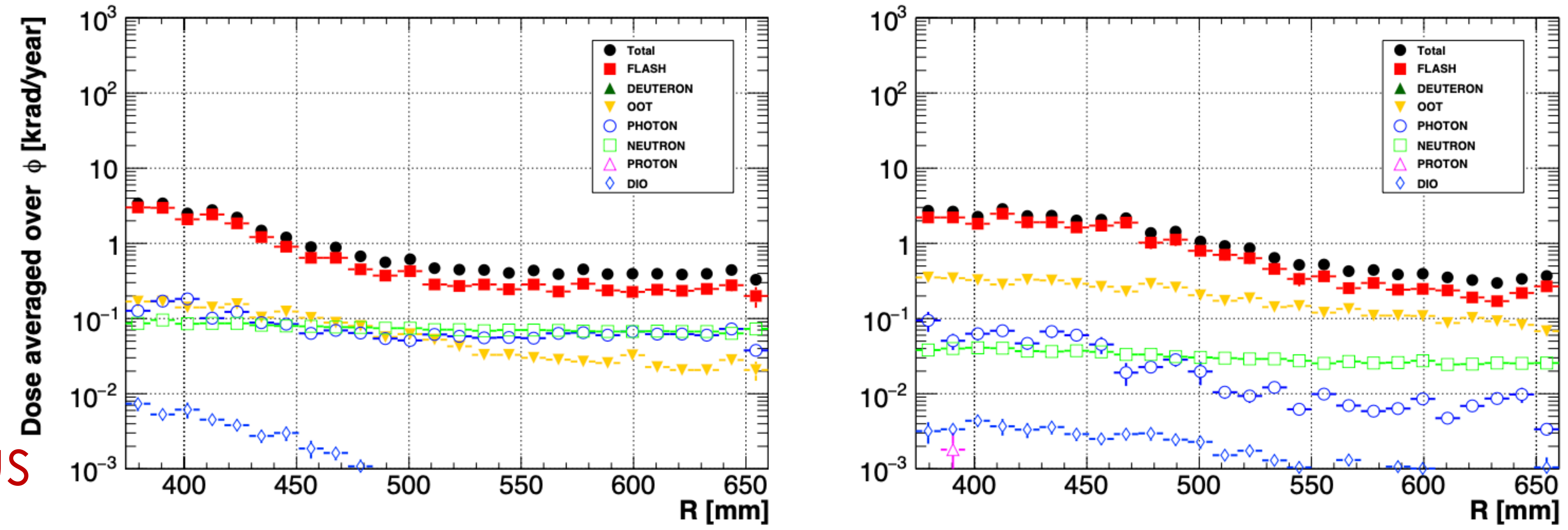




NIEL vs radius

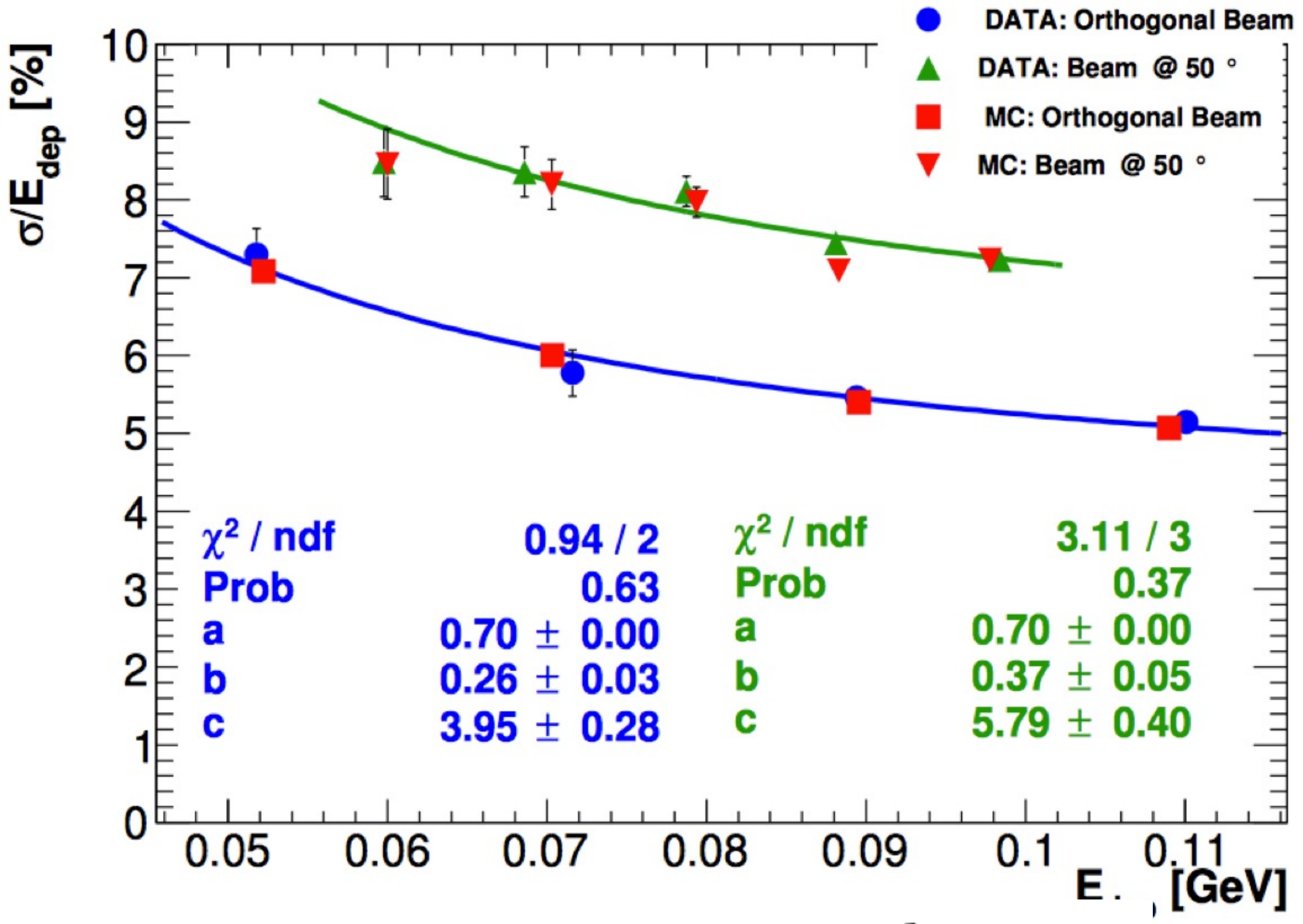


TID heatmap

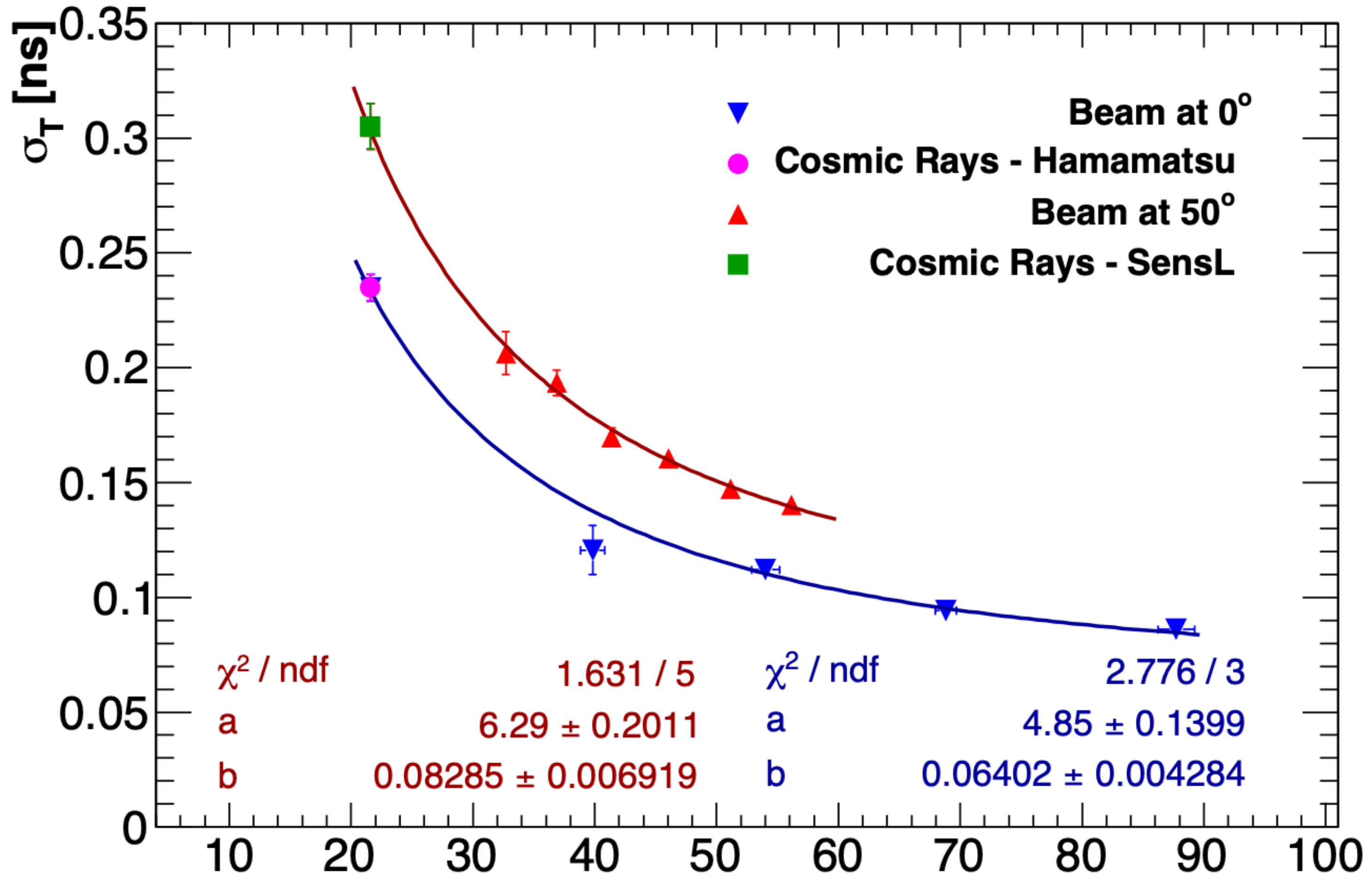


TID vs radius

Test beam validation



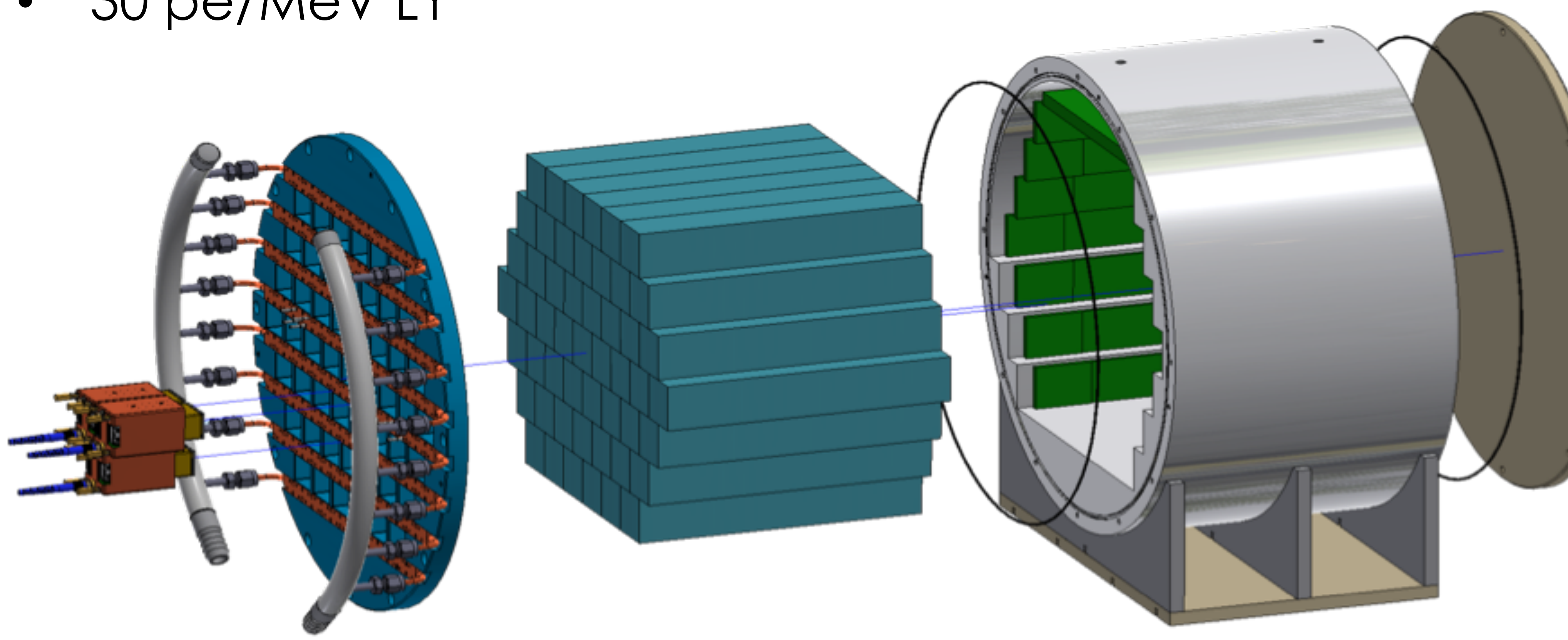
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[GeV]}} \oplus \frac{b}{E[GeV]} \oplus c$$

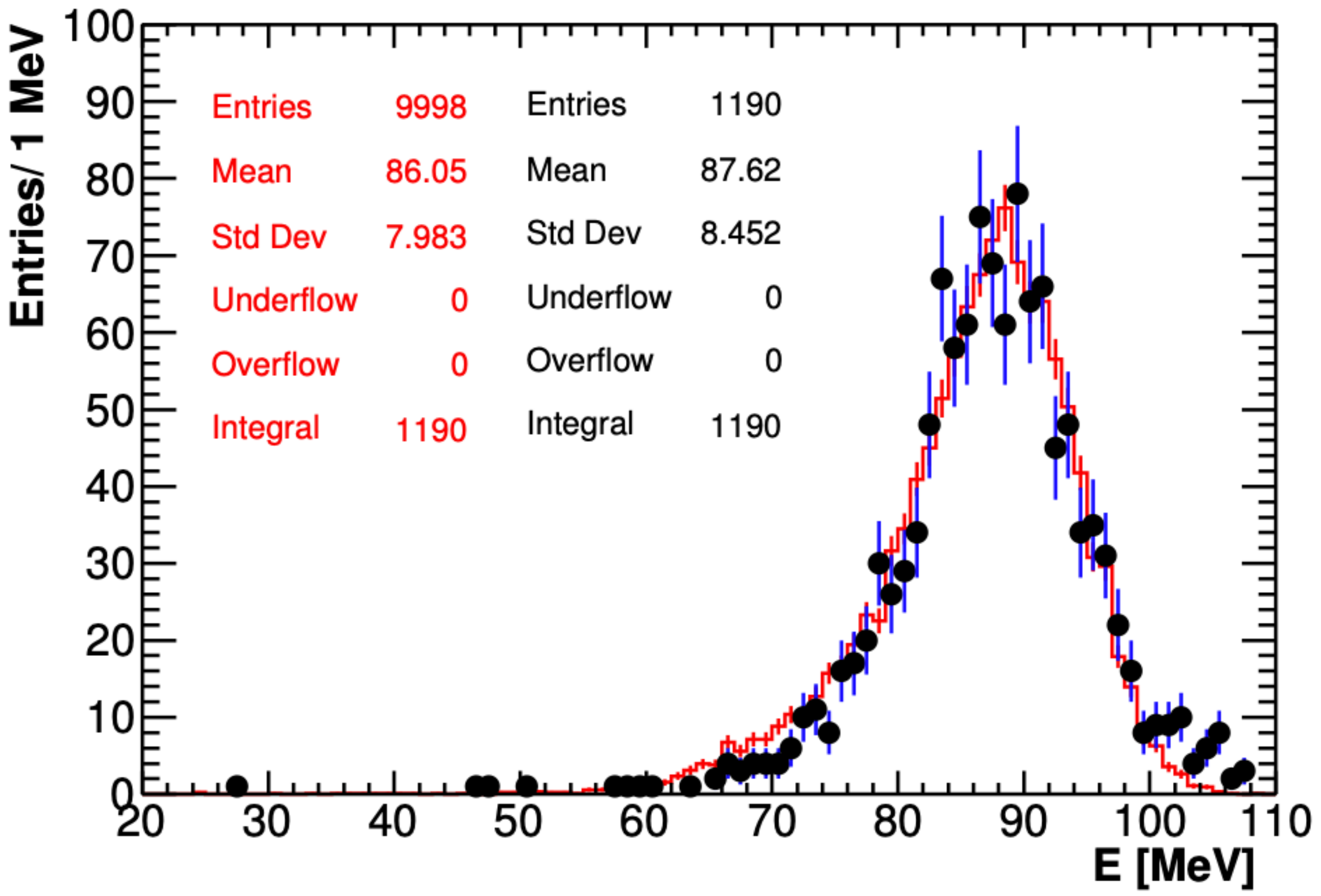


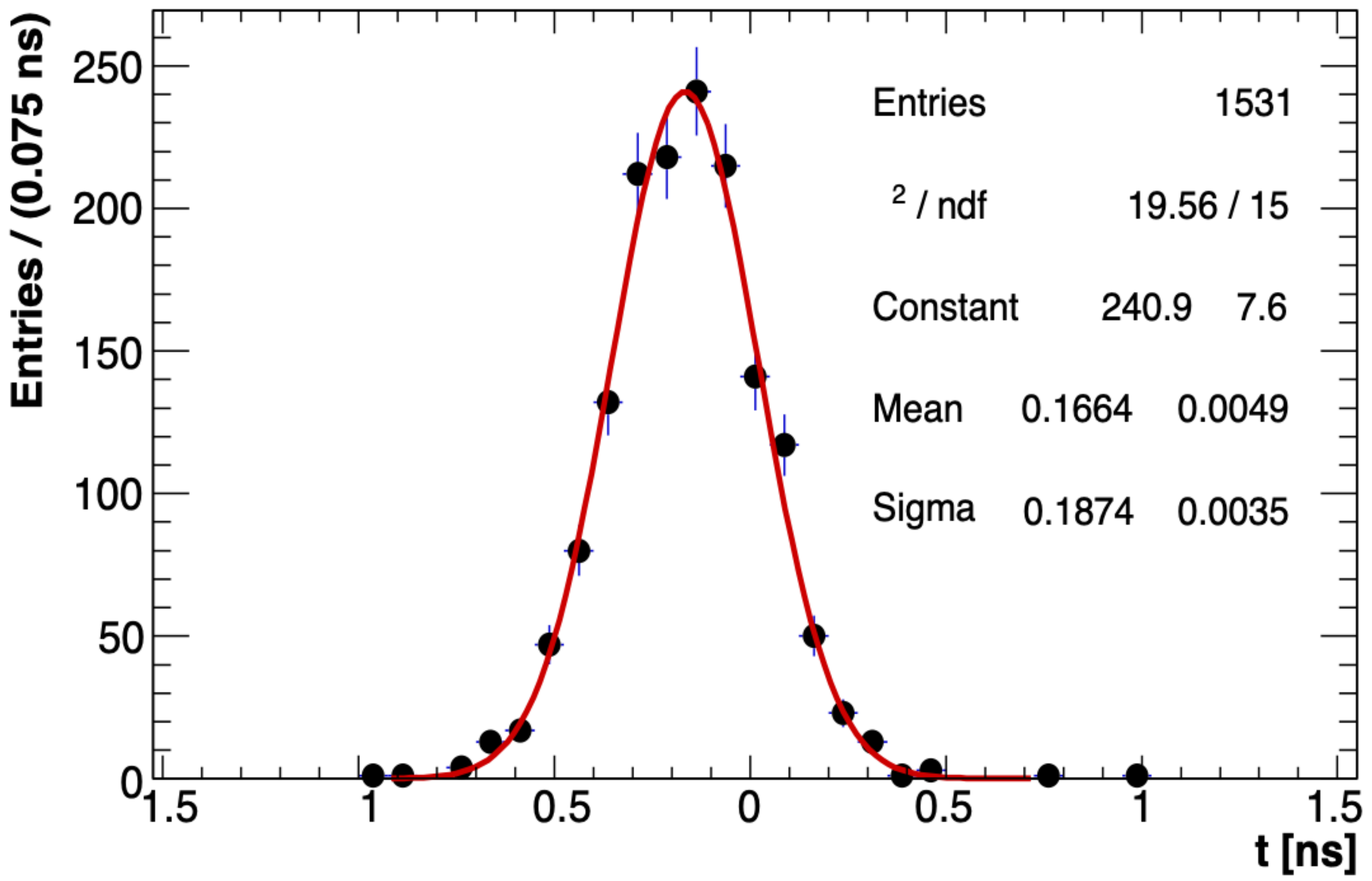
$$\sigma_T = \frac{a}{E[GeV]} \oplus b$$

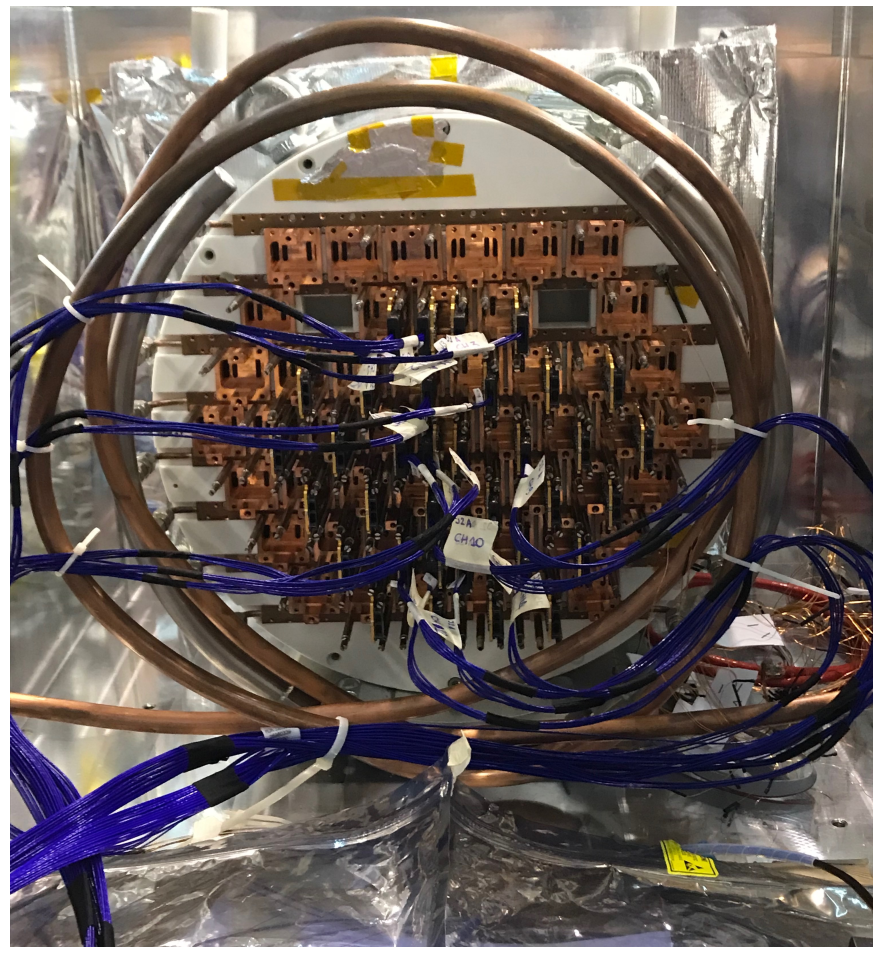
Beam test

- LNF-INFN Beam Test Facility
- e^- beam up to 100 MeV
- orthogonal and tilted beam runs
- Single particle selection
- Great data-MC agreement
- 30 pe/MeV LY









Module-0

- Large scale prototype
- 51 crystals
- Final Mu2e readout
- Final FEE
- Cooling system
- Laser calibration system