Radiation Testing of New Readout Electronics for the CMS ECAL Barrel

Nico Härringer
On behalf of the CMS collaboration
30. September – 4. October 2024, Glasgow

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- General purpose detector located at the LHC, CERN

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  - Hadronic Calorimeter (HCAL)
  - Muon stations

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  - Upgrade of ECAL and HCAL «barrel»

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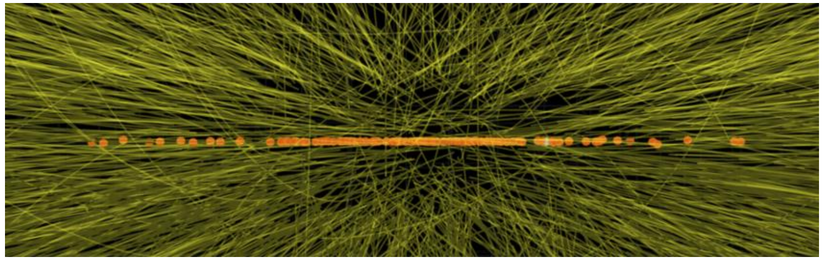
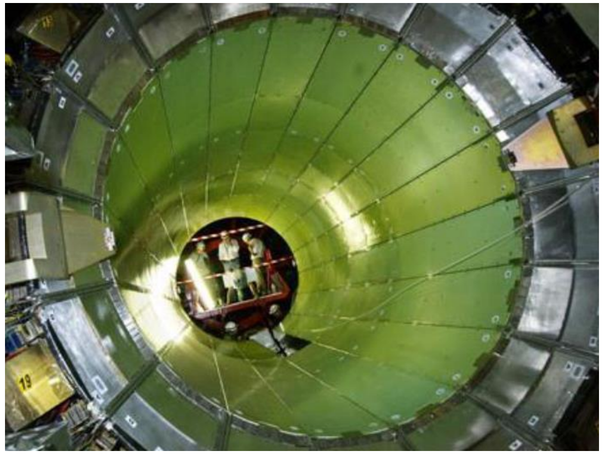
Focus on the ECAL barrel

Upgrading the (sub)detector

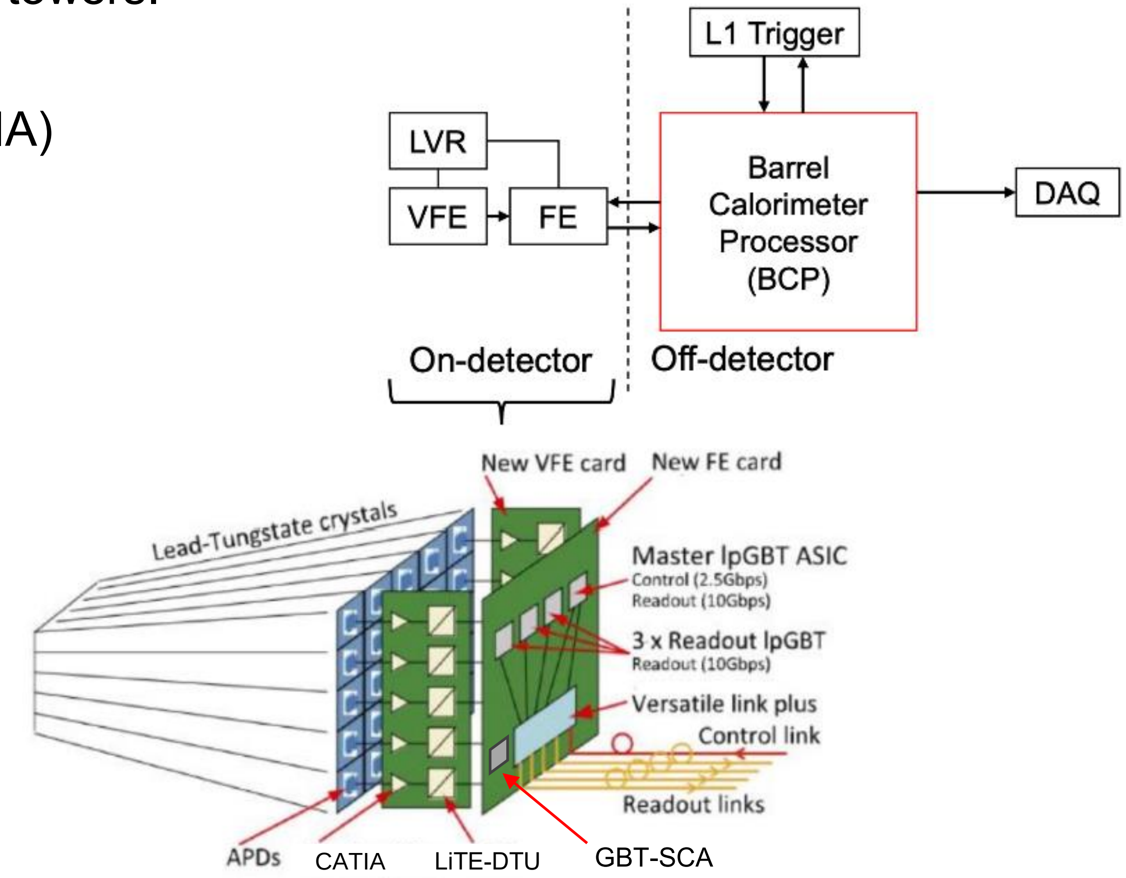
- Why do we do this upgrade of the ECAL barrel?
  - 🚀 **Increase in pileup (from ~40 to 150/200)**
    - Implement faster electronics (sampling at 160 MHz)
  - 🔄 **Redesigning the Trigger system**
    - Increased trigger rates from 100 kHz to 750 kHz and higher hardware-level trigger latency (12.5 us)
  - ❄️ **Mitigating APD Dark Current**
    - Lower cooling temperature from 18°C to 9°C





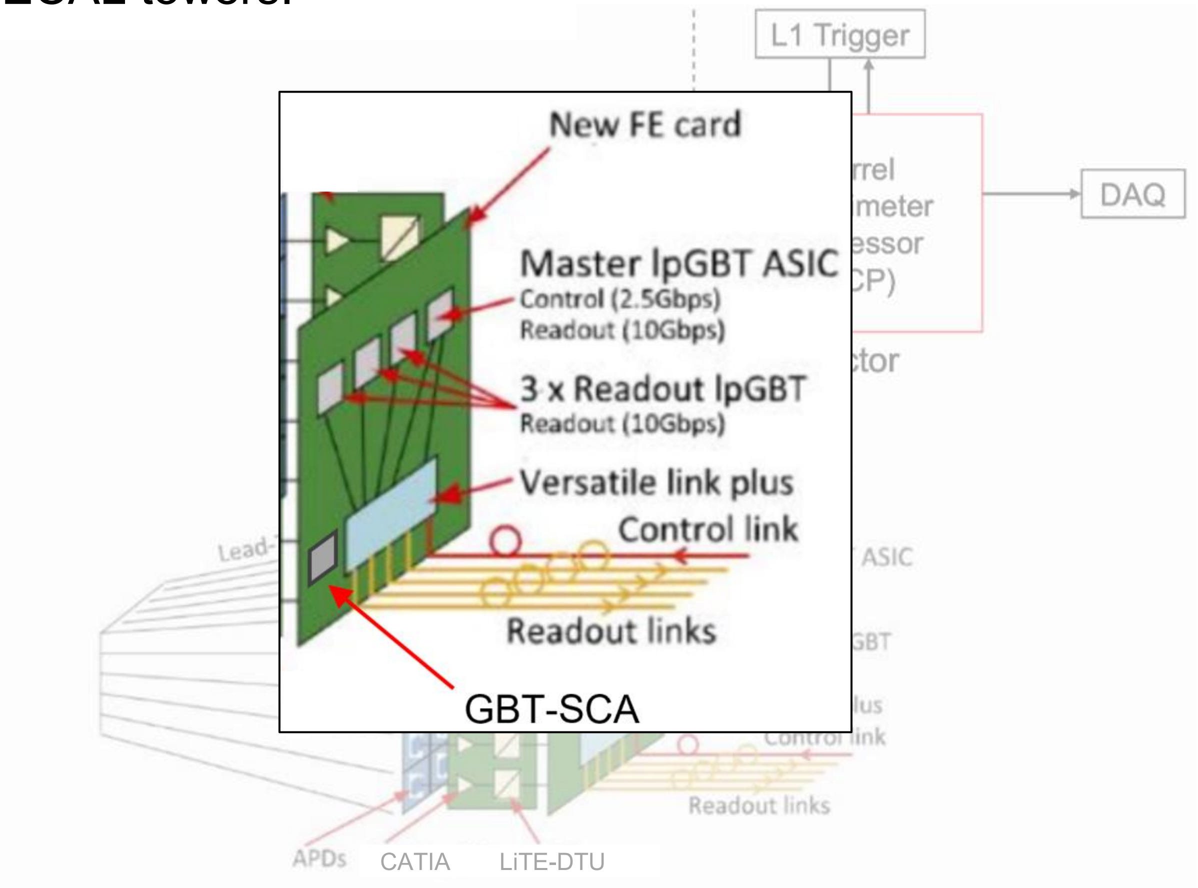
Upgrading the (sub)detector

- Upgrade of readout electronics for all 2,448 ECAL towers.
  - **V**ery **F**ront **E**nd card (VFE)
    - Calorimeter Transimpedance Amplifier (CATIA)
      - Two gain stages
        - High gain (HG), low gain (LG)
      - Internal test pulses
    - Lisbon-Torino ECAL Data Transmission Unit (LiTE-DTU)



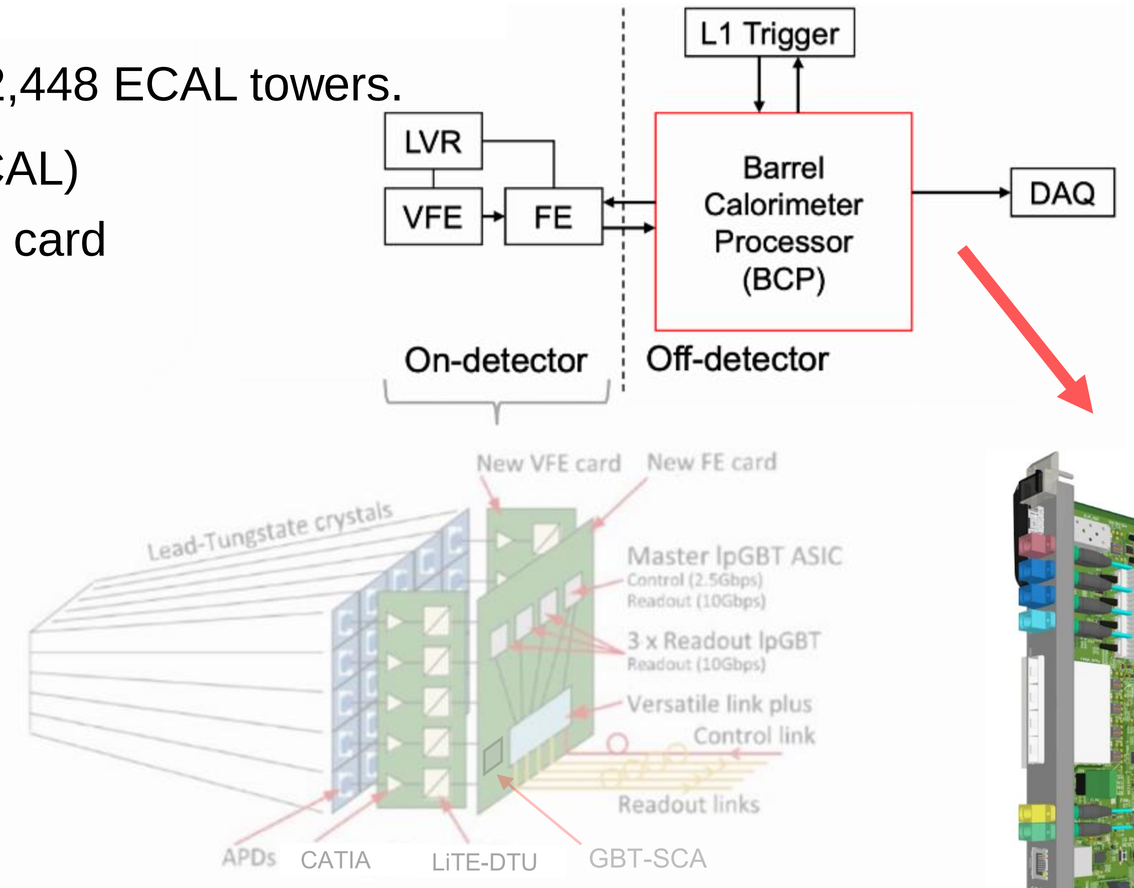
Upgrading the (sub)detector

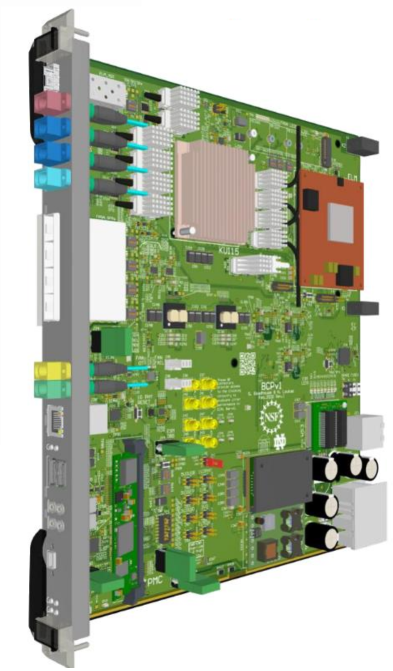
- Upgrade of readout electronics for all 2,448 ECAL towers.
  - **F**ront **E**nd card (FE)
    - Four Low Power Gigabit Transmission chips (LpGBT)
      - Master-Slave arrangement
    - Optical interface (Versatile link plus)
    - Slow Control Adapter (GBT-SCA)
  - **L**ow **V**oltage **R**egulator card (LVR)
    - Four DC-DC converters
    - Low Dropout Regulator (LDO)
      - Powers GBT-SCA



Upgrading the (sub)detector

- Upgrade of readout electronics for all 2,448 ECAL towers.
- … and the back end (for ECAL <u>and</u> HCAL)
  - **B**arrel **C**alorimeter **P**rocessor (BCP) card
    - Analyze received data
    - Trigger primitive generation
    - APD spike rejection algorithm
    - FE clock and control signals





Test objectives

System test of EB electronics in radiation

Functionality

- Connection
- Register triplication
- Dark current
- Readout

Stability

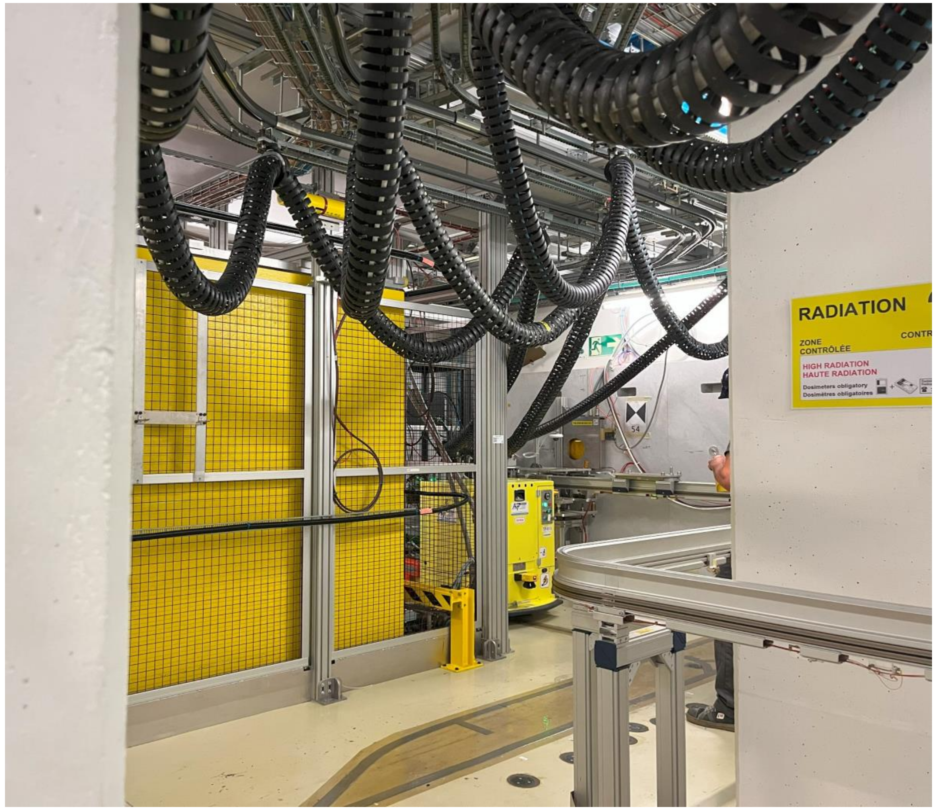
- Readout invariant under radiation?
- RMS Noise evolution

Stress testing

- System performance with higher fluxes?

Irradiation facilities

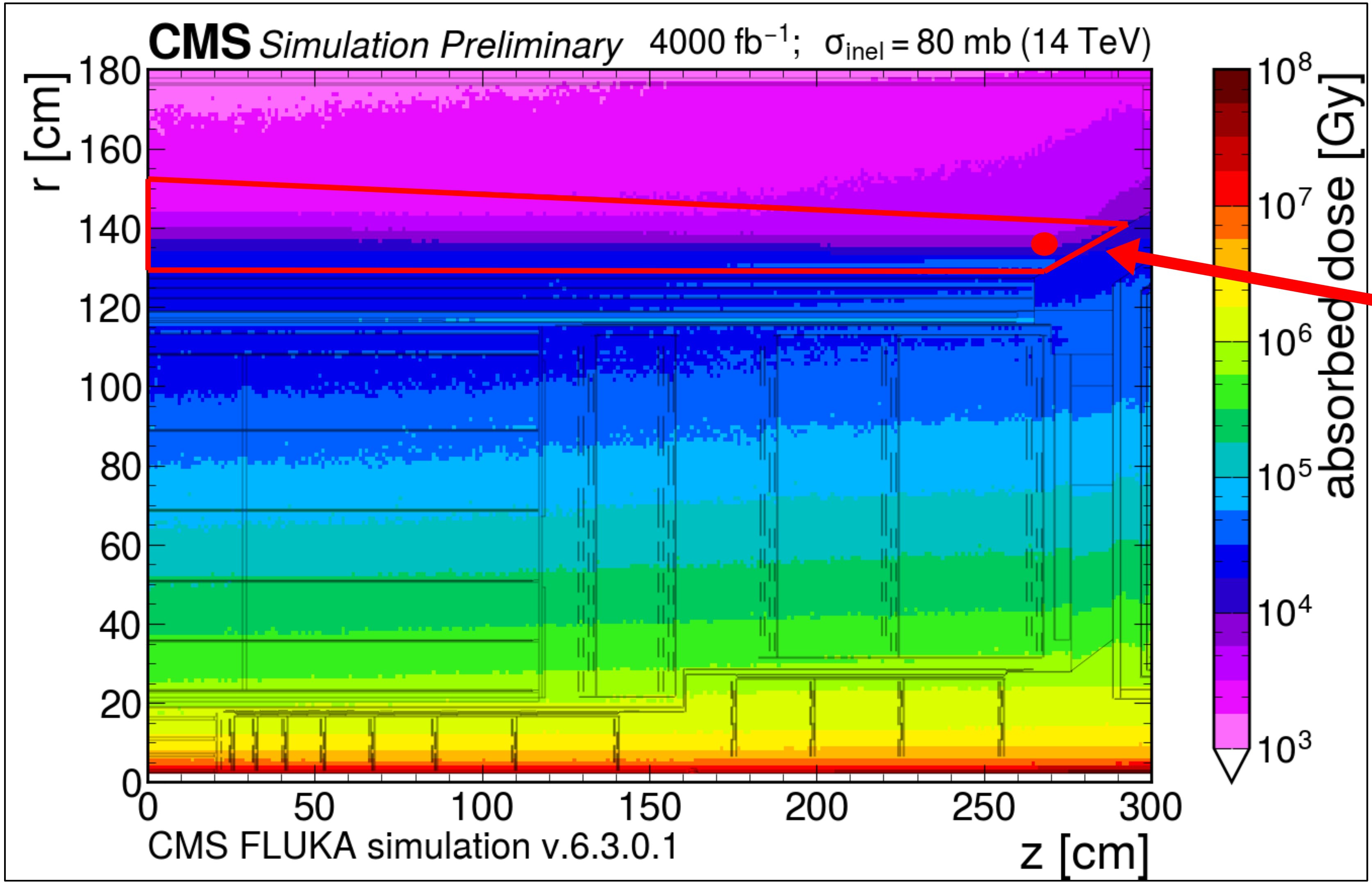
- First irradiation campaign done in **C**ERN **H**igh energy **A**ccele**R**ator **M**ixed field (CHARM) in July 2023
  - 17 days of irradiation, access times included
  - Uniform radiation field



Irradiation facilities

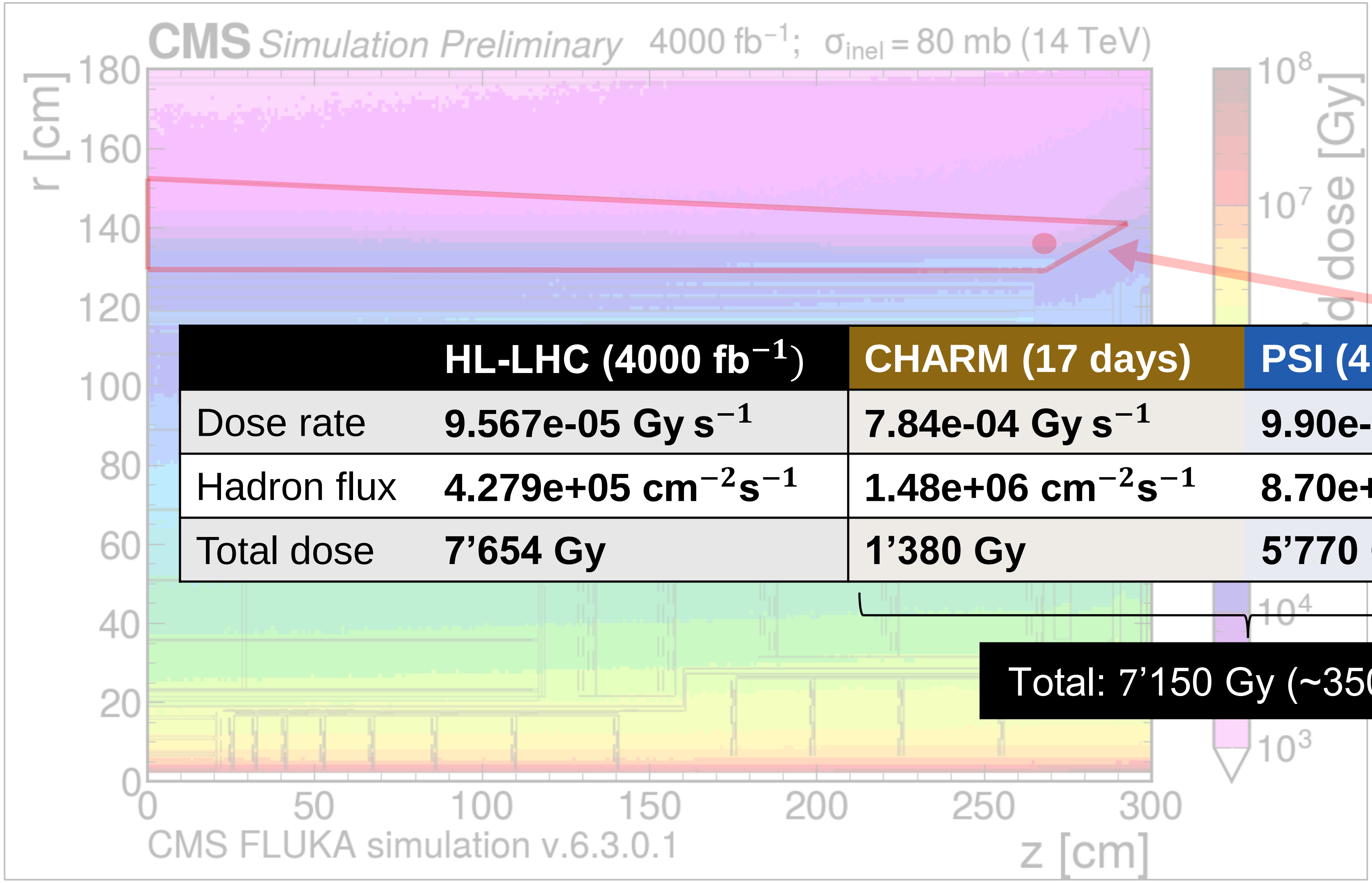
- First irradiation done at the **C**ERN **H**igh energy **A**ccele**R**ator **M**ixed field (CHARM) facility in July 2023
  - 17 days of irradiation, access times included
  - Uniform radiation field
- Second irradiation done using the Proton Irradiation Facility (PIF) at the Paul Scherrer Institute, CH
  - About 16 hours of irradiation (distributed over 4 nights)
  - Non-uniform irradiation (Gaussian profile)

Irradiation facilities



Most stressed readout towers @ $|\eta| = 1.431$

Irradiation facilities



Most stressed readout towers

	HL-LHC (4000 fb^{-1})	CHARM (17 days)	PSI (4 nights)
Dose rate	**9.567e-05 Gy s^{-1}**	**7.84e-04 Gy s^{-1}**	**9.90e-02 Gy s^{-1}**
Hadron flux	**4.279e+05 cm^{-2}s^{-1}**	**1.48e+06 cm^{-2}s^{-1}**	**8.70e+07 cm^{-2}s^{-1}**
Total dose	**7'654 Gy**	**1'380 Gy**	**5'770 Gy**

Total: 7'150 Gy (~3500 fb^{-1})

Results

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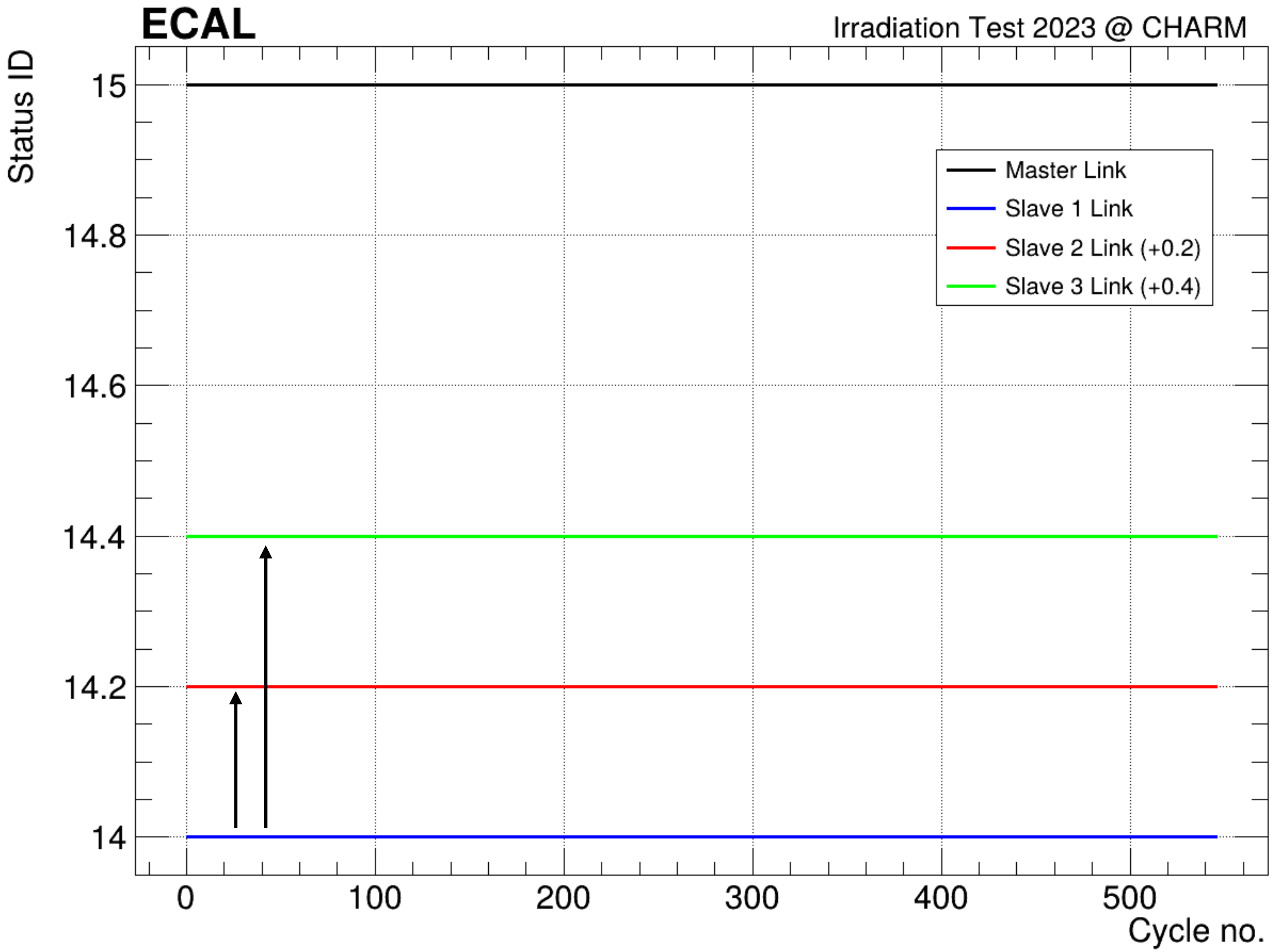
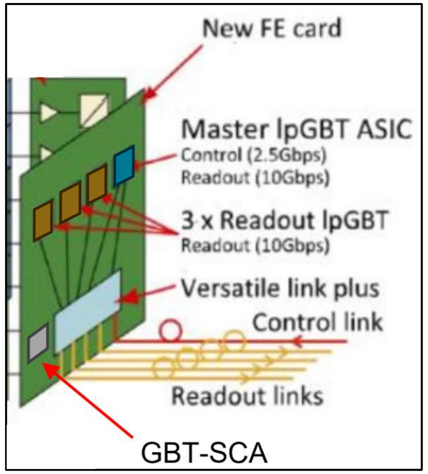
Communication - CHARM

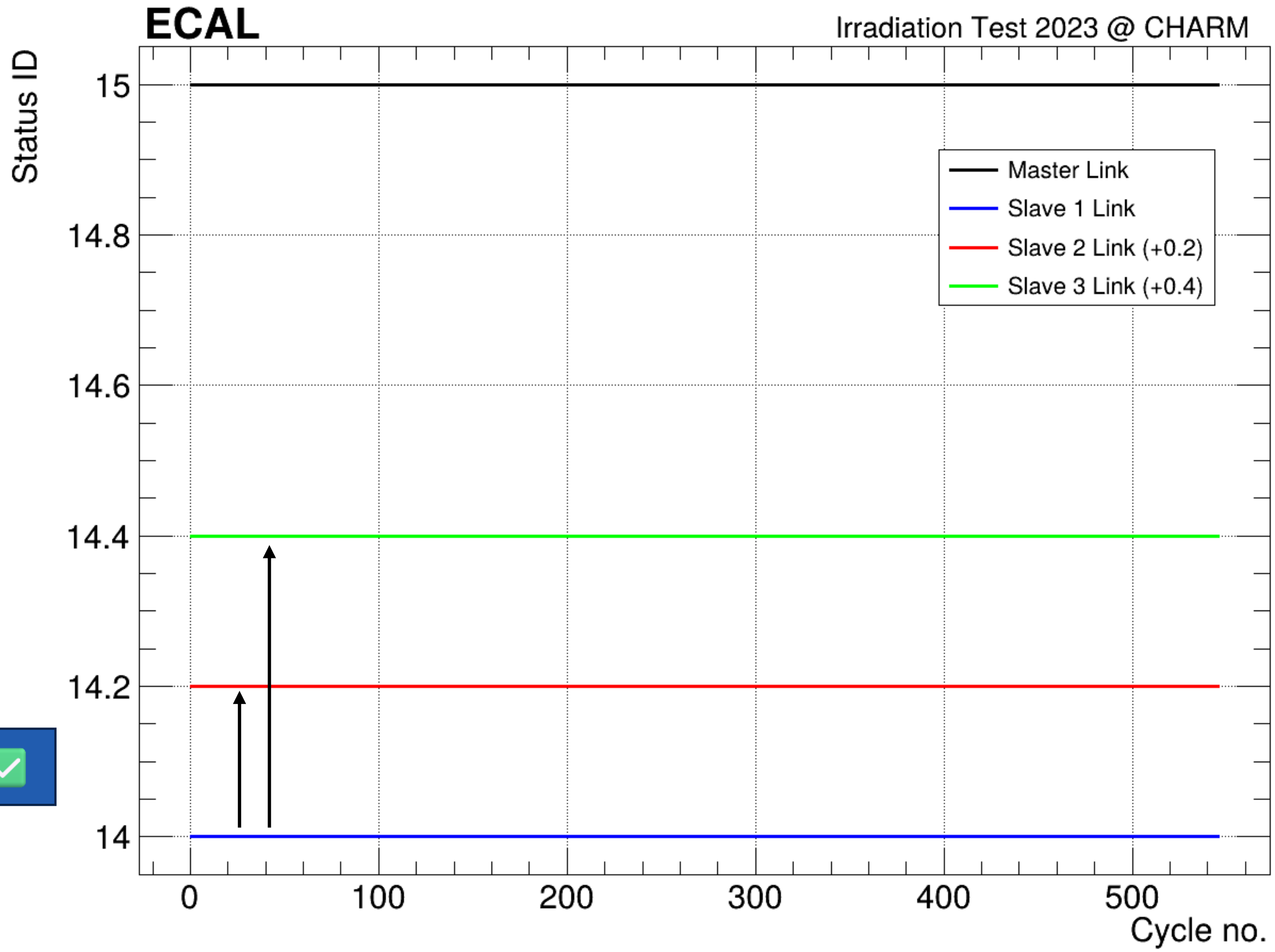


Master mode: Status ID 15



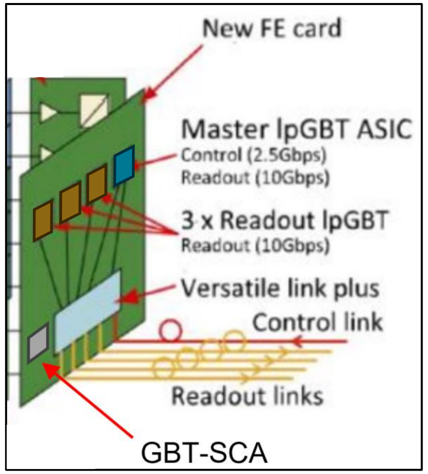
Slave mode: Status ID 14

Communication - CHARM



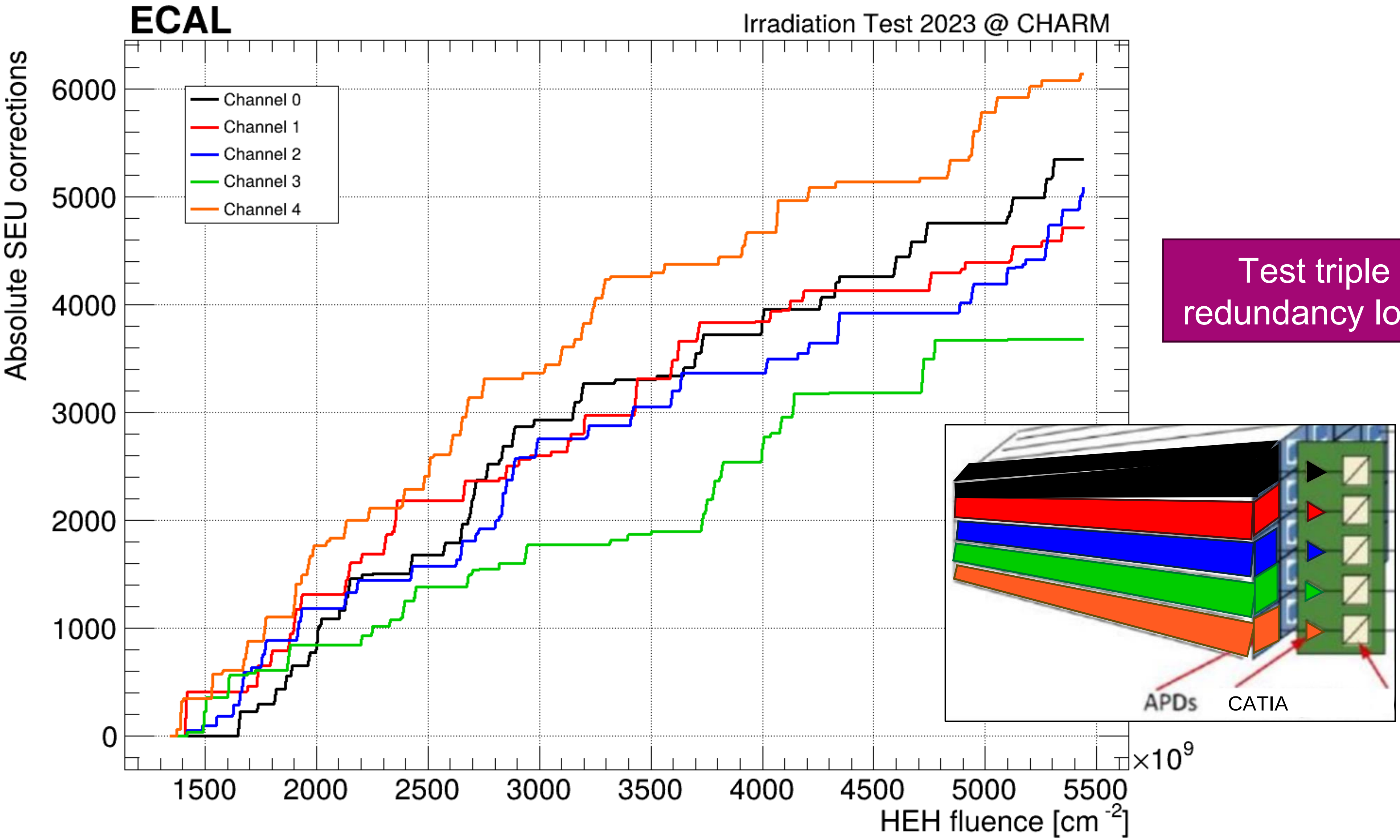
Connection ✅

Master mode: Status ID 15



Slave mode: Status ID 14

SEUs (CATIA) - CHARM



Test triple redundancy logic

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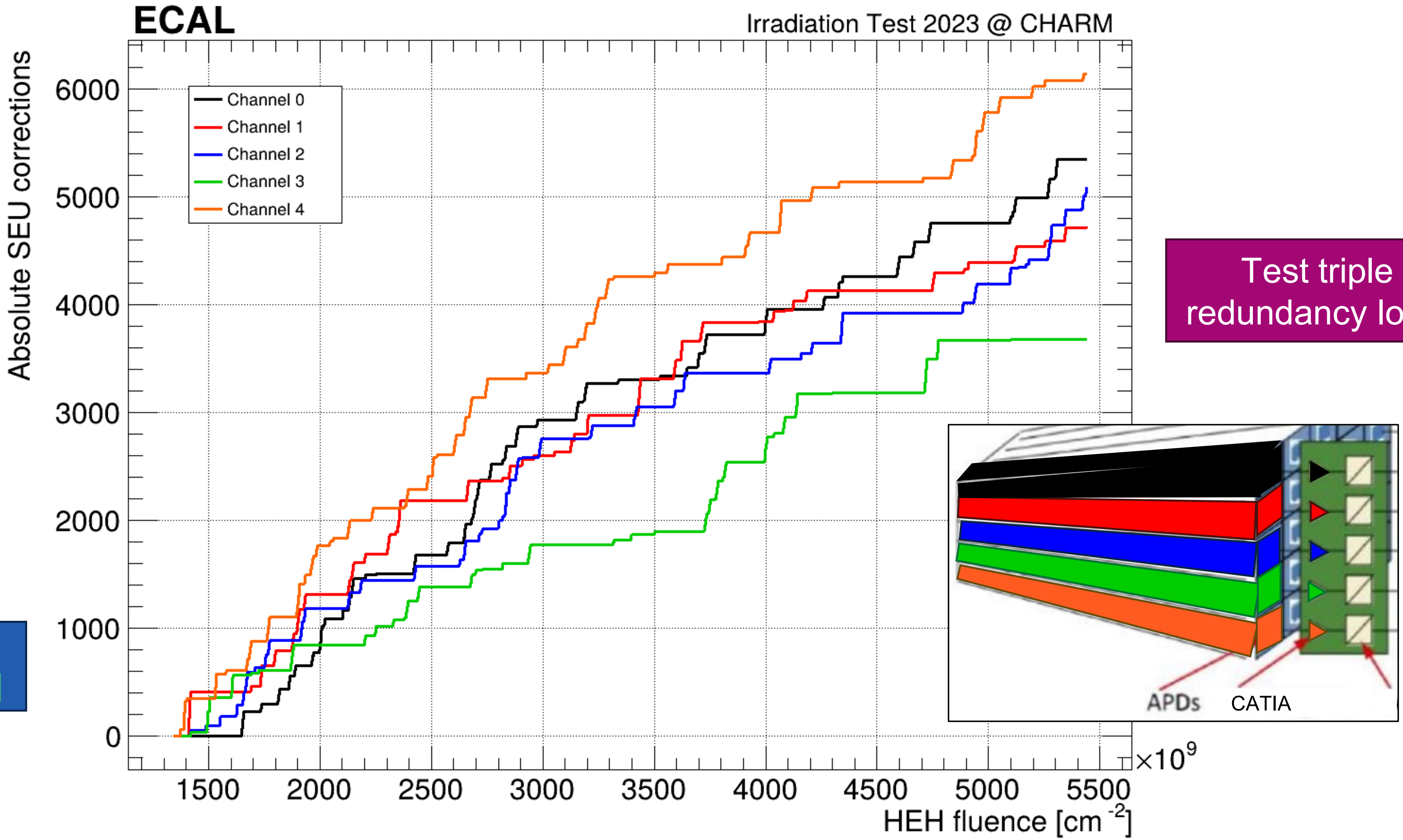
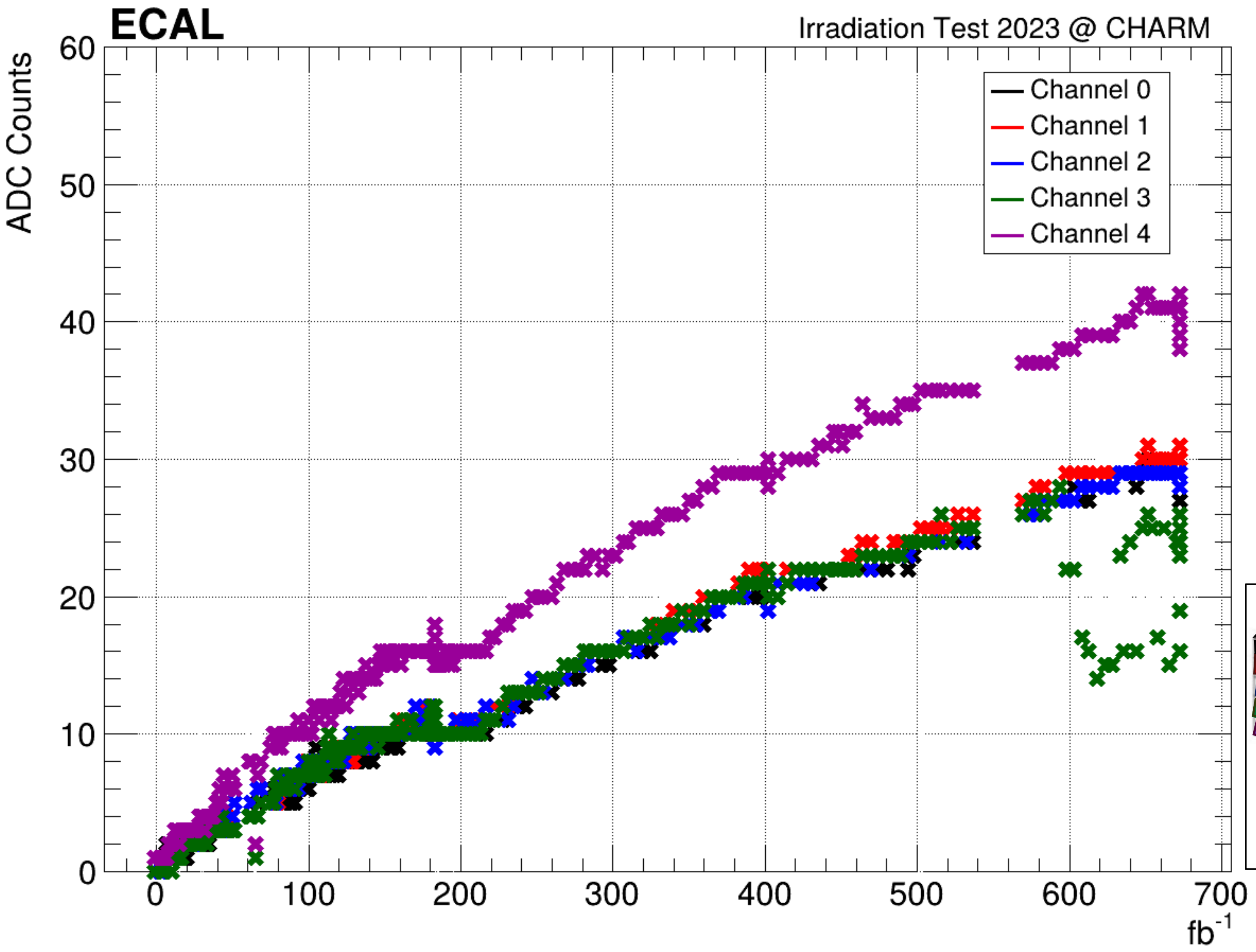
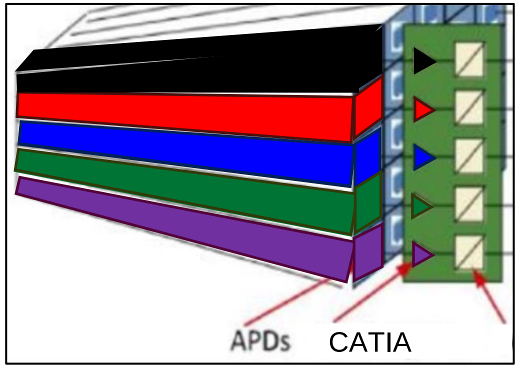


Test triple redundancy logic

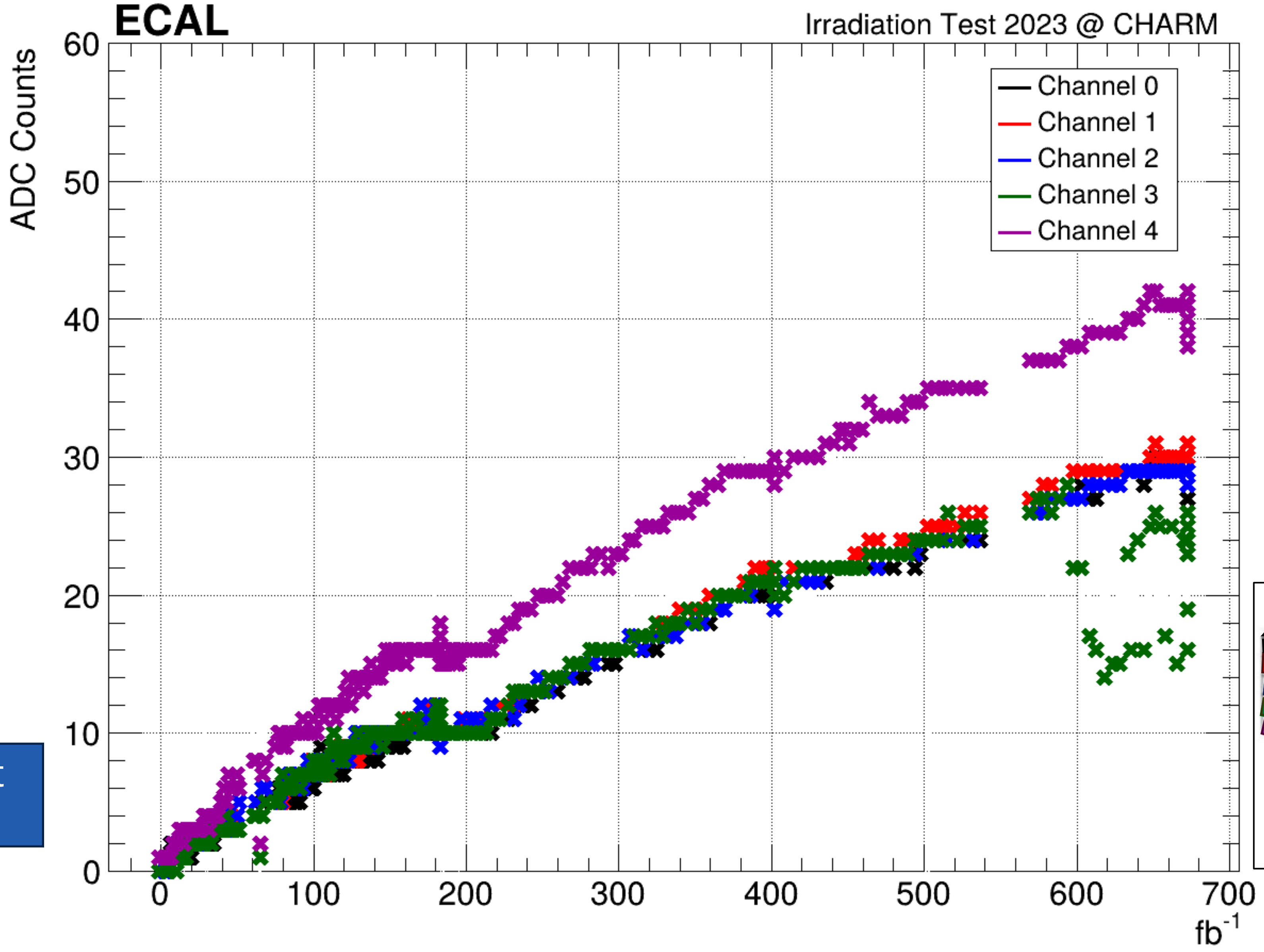
Register triplication ✅

Dark current - CHARM

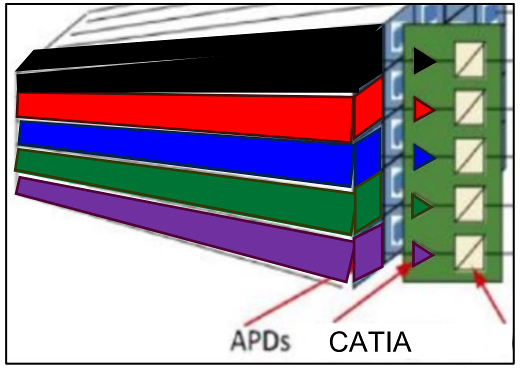




Dark current - CHARM



Dark current readout ✅



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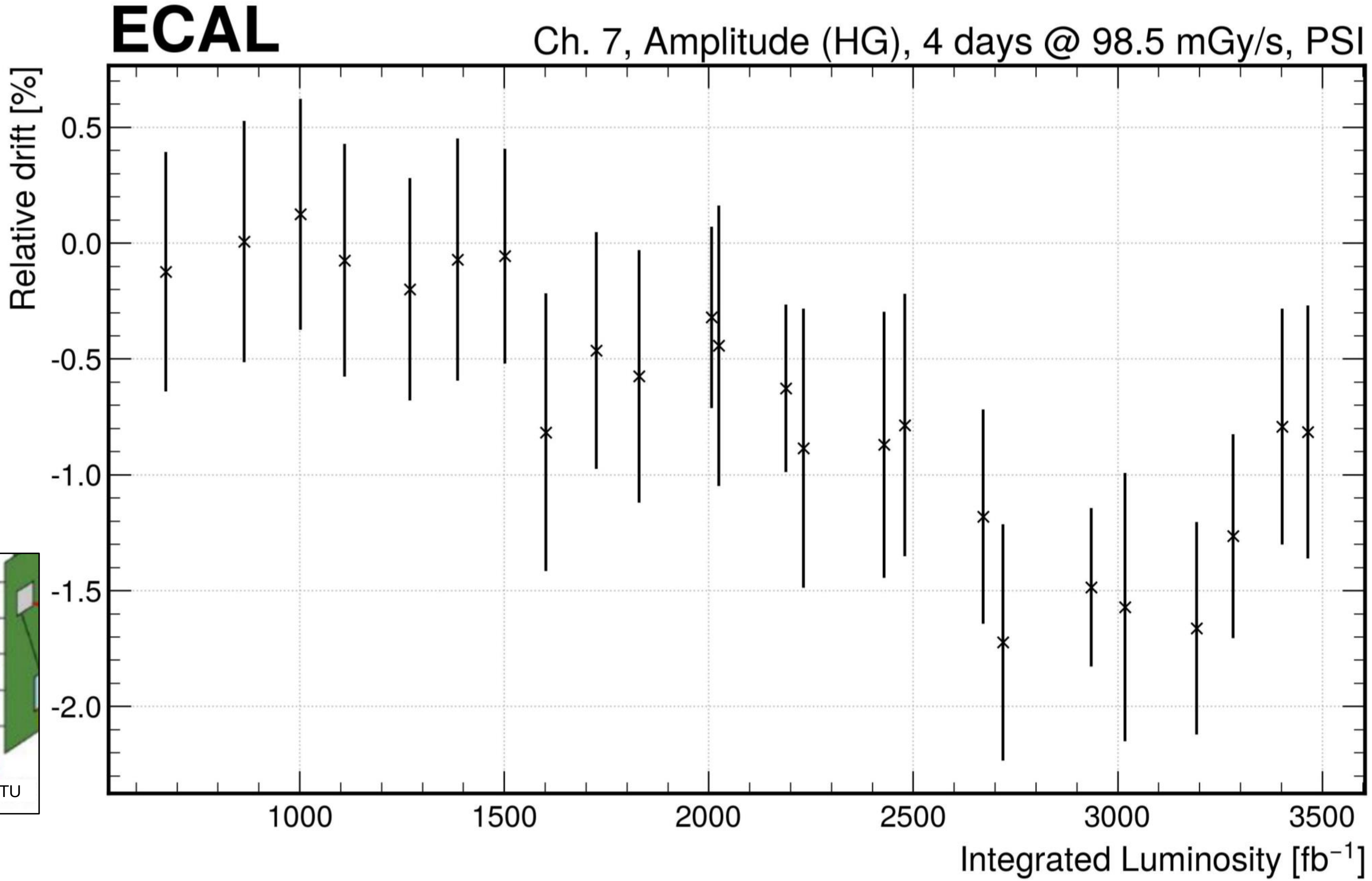
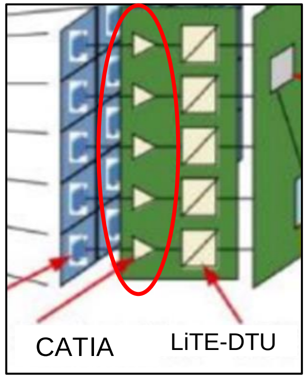
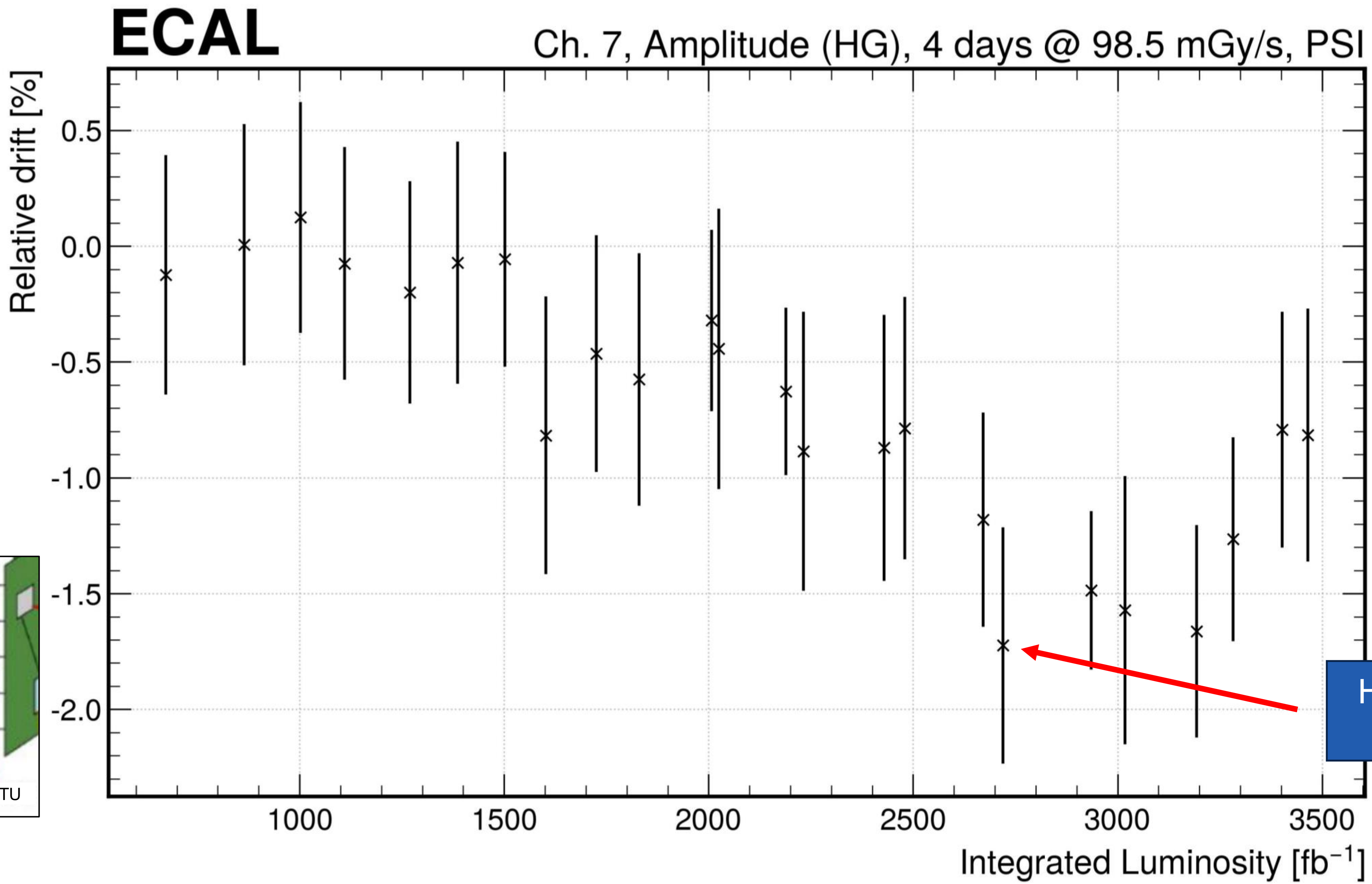
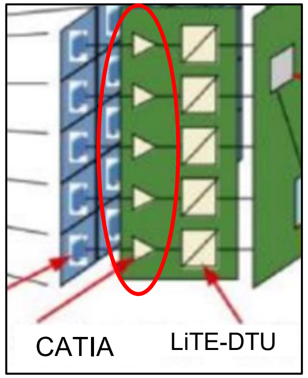
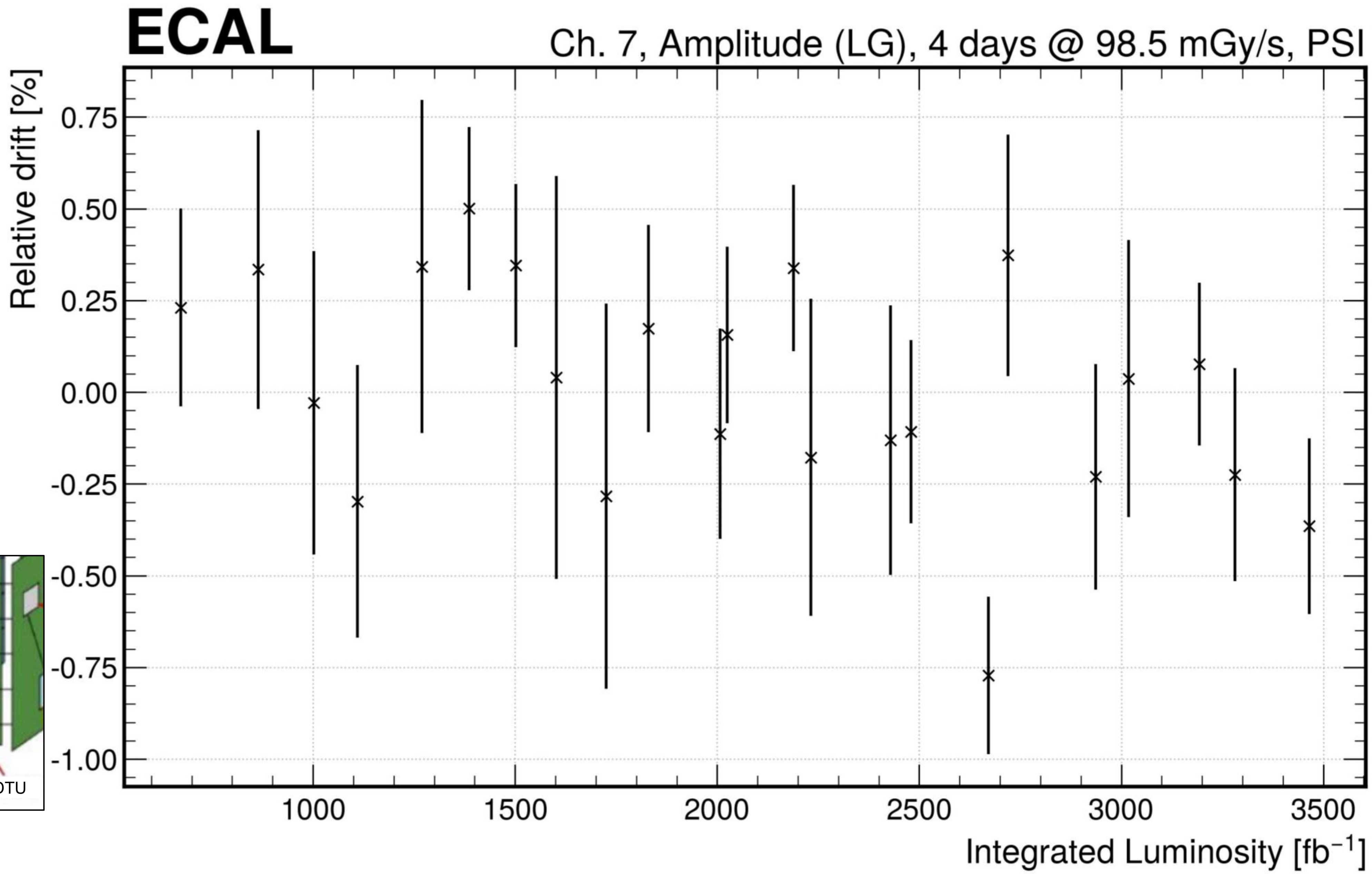

ECAL
Ch. 7, Amplitude (HG), 4 days @ 98.5 mGy/s, PSI
Relative drift [%]
0.5
0.0
-0.5
-1.0
-1.5
-2.0
1000
1500
2000
2500
3000
3500
Integrated Luminosity [fb^{-1}]

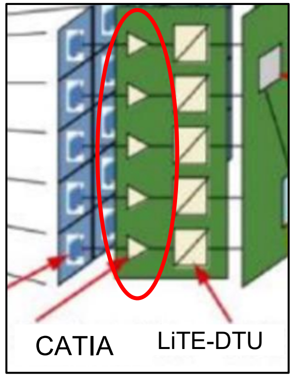

CATIA
LiTE-DTU



Highest drift
-1.72%




ECAL
Ch. 7, Amplitude (LG), 4 days @ 98.5 mGy/s, PSI
Relative drift [%]
0.75
0.50
0.25
0.00
-0.25
-0.50
-0.75
-1.00
1000
1500
2000
2500
3000
3500
Integrated Luminosity [fb⁻¹]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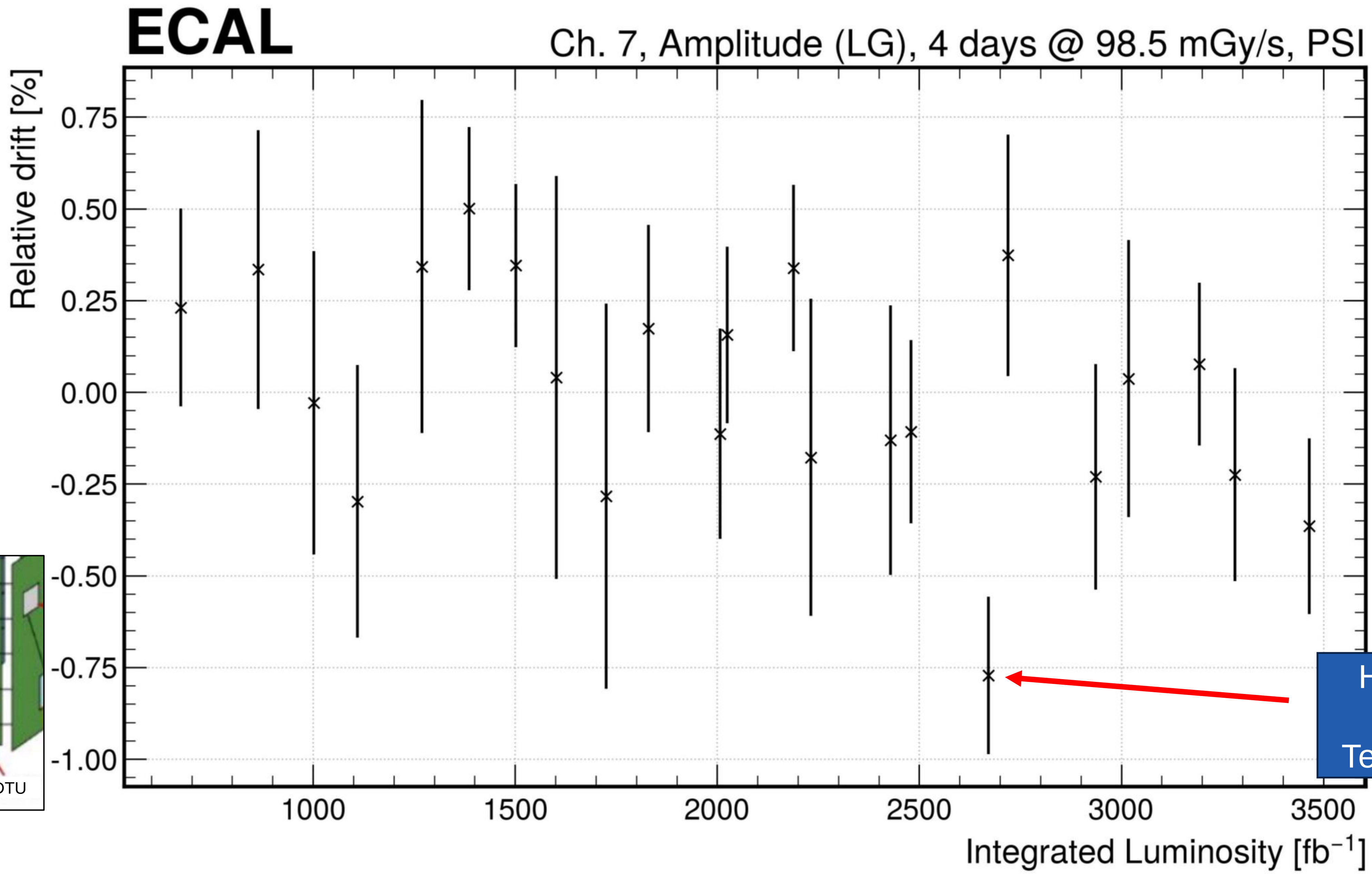
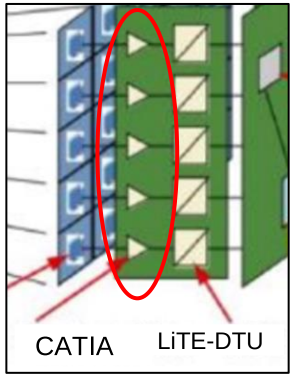
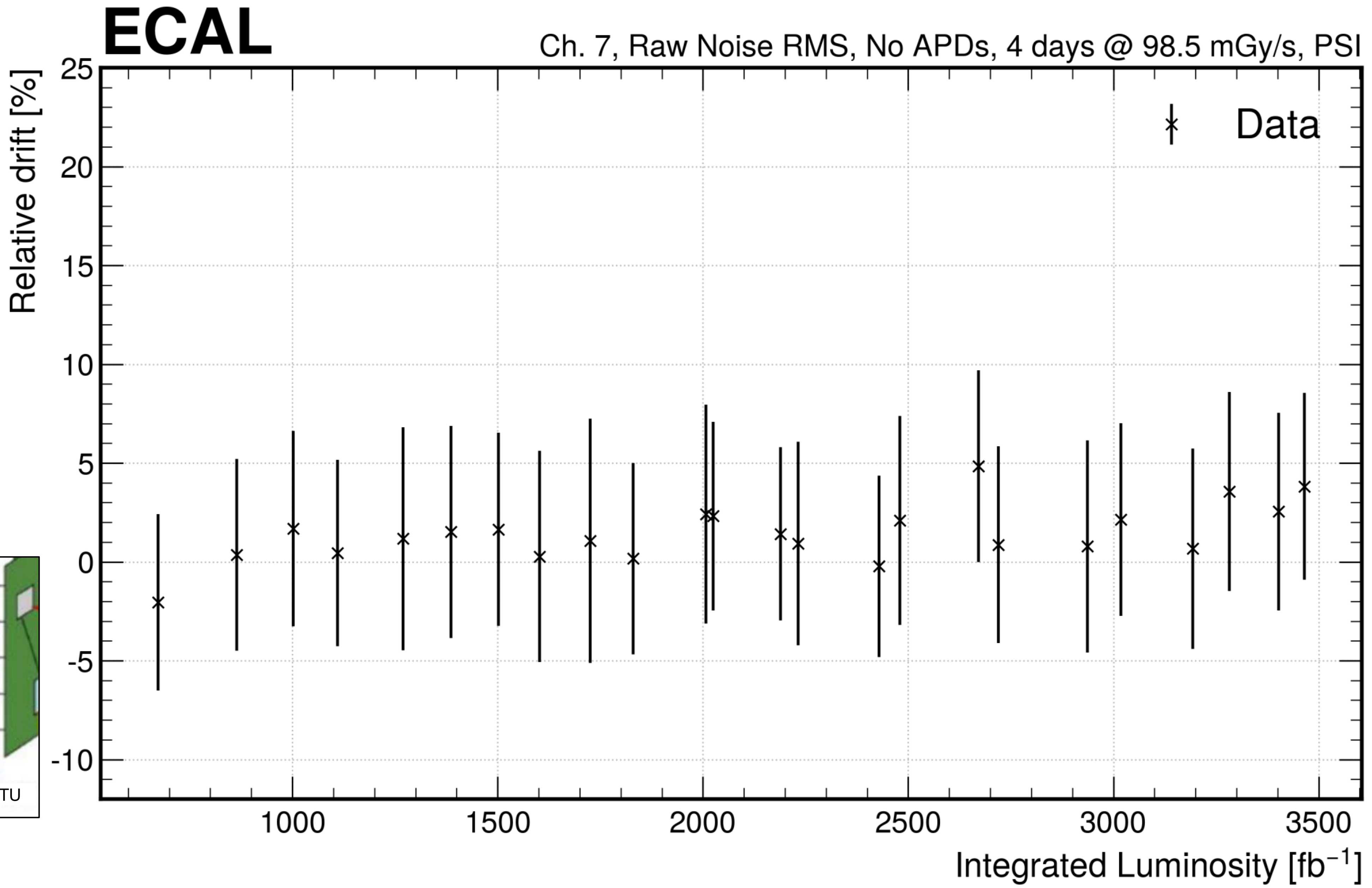
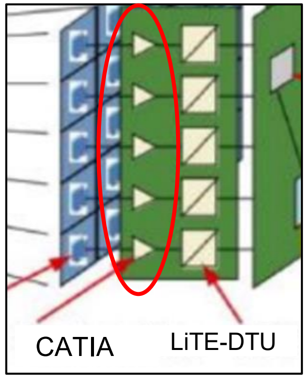




Highest drift
-0.77%
Test pulses ✅


ECAL
Ch. 7, Raw Noise RMS, No APDs, 4 days @ 98.5 mGy/s, PSI
Relative drift [%]
Data
Integrated Luminosity [fb^{-1}]
25
20
15
10
5
0
-5
-10
1000
1500
2000
2500
3000
3500


CATIA
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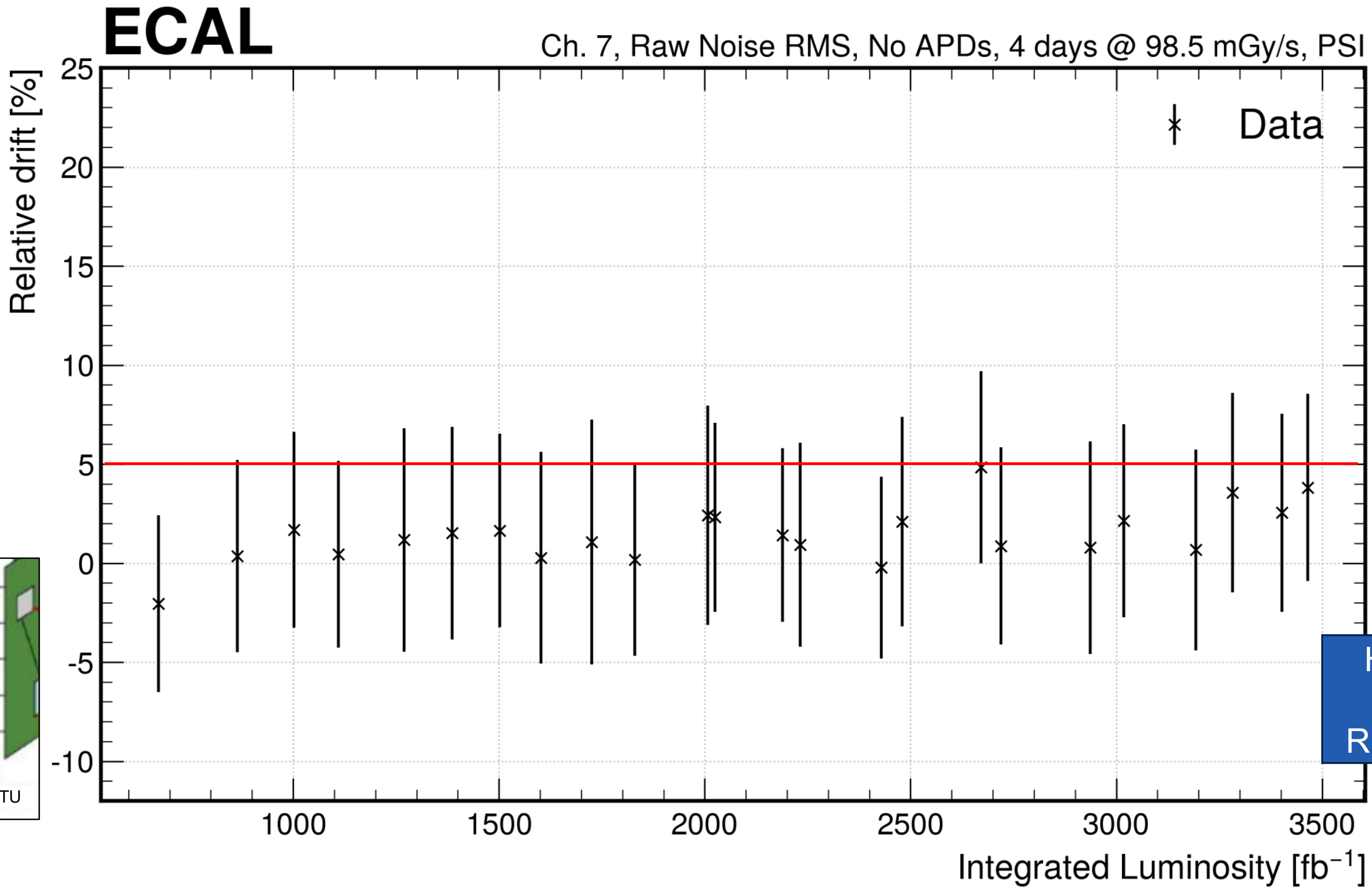
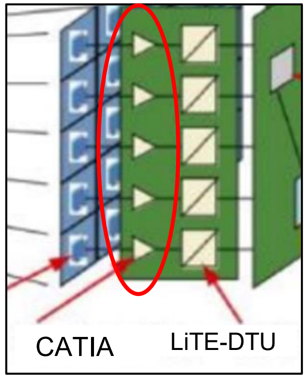
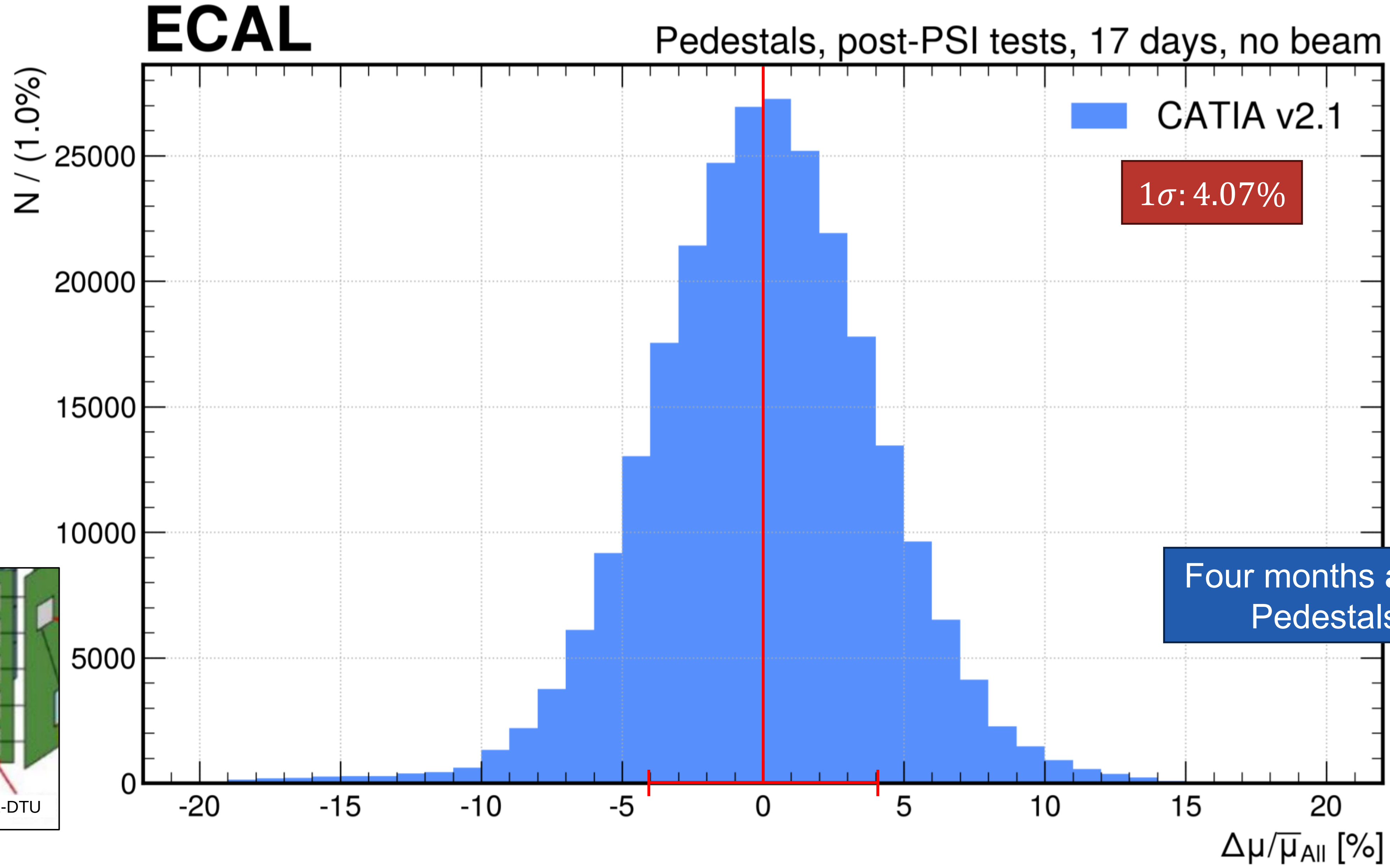
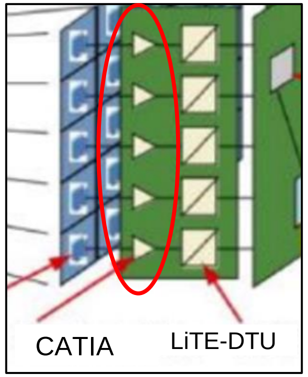




Highest drift
+4.84%
RMS Noise ✅



Four months **after** PSI
Pedestals ✅



Summary

🛠️ Functionality

- ✅ Connection
- ✅ Register triplication
- ✅ Dark current
- ✅ Readout

☢️ Stability

- ✅ Pedestals
- ✅ Test pulses within 2%
- ✅ RMS Noise: Relative drift within 5%

💪 Stress testing

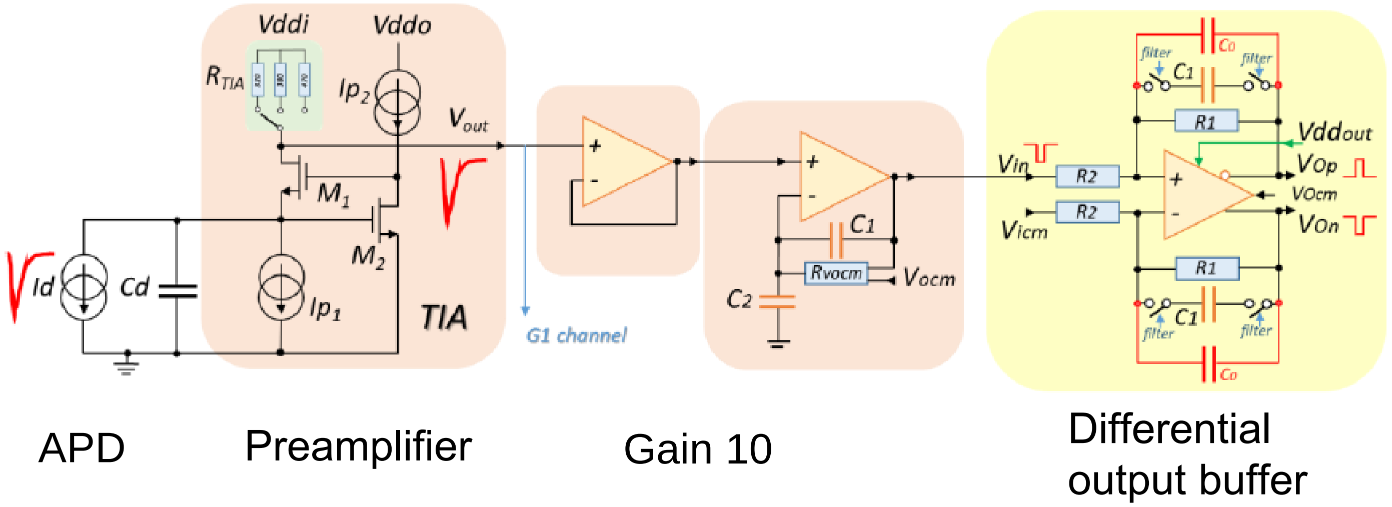
- ✅ Survived dose rates >1000x higher than foreseen in HL-LHC
- ✅ Hadron fluxes >200x higher

Thank you for listening!

Backup

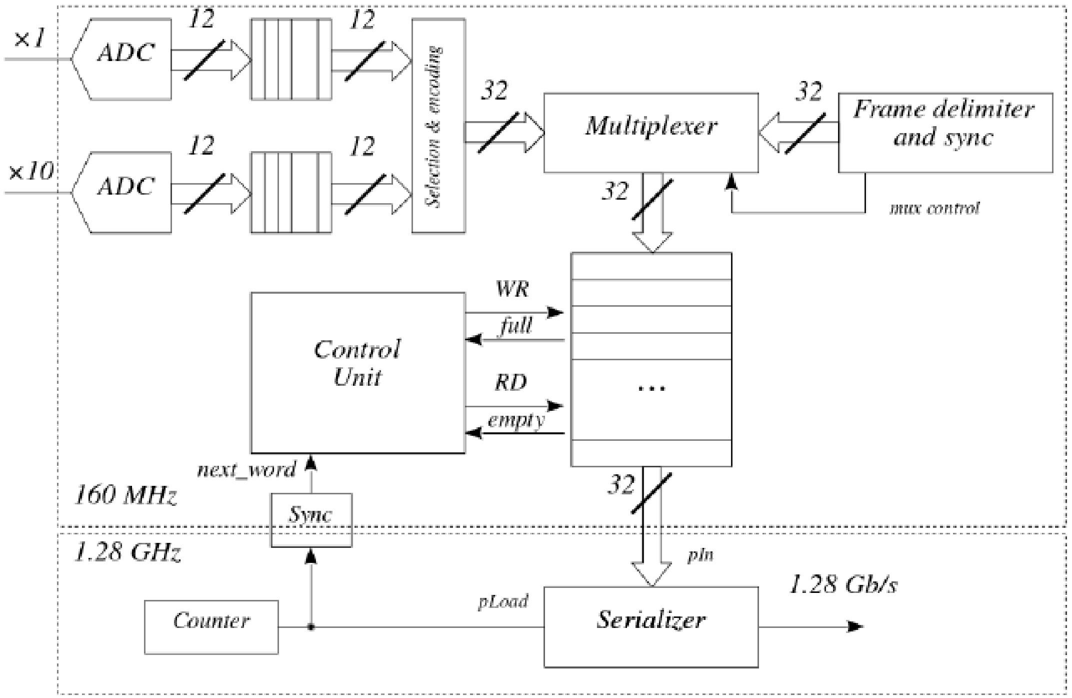
CATIA

- **CA**lorimeter **T**rans**I**mpedance **A**mplifier (CATIA)
  - Amplifies scintillation pulse collected from the APD
  - Two gain stages: G10 (high gain) and G1 (low gain)
  - I2C interface
  - Has a current source for internal test pulses to test readout electronics



LiTE-DTU

- **Li**sbon-**T**orino **E**CAL **D**ata **T**ransmission **U**nit (LiTE-DTU)
  - Digitizes CATIA-amplified pulse with two dedicated 12-bit ADCs at 160 MHz in parallel
  - Data Compression and Transmission Unit
    - Internal PLL
    - Gain selection
      - If G10 ADC is saturated, all G1 samples in a window around the saturated ones are taken
    - Data compression and formatting in 32-bit words
    - Data serializing and streaming (1.28 Gb/s)



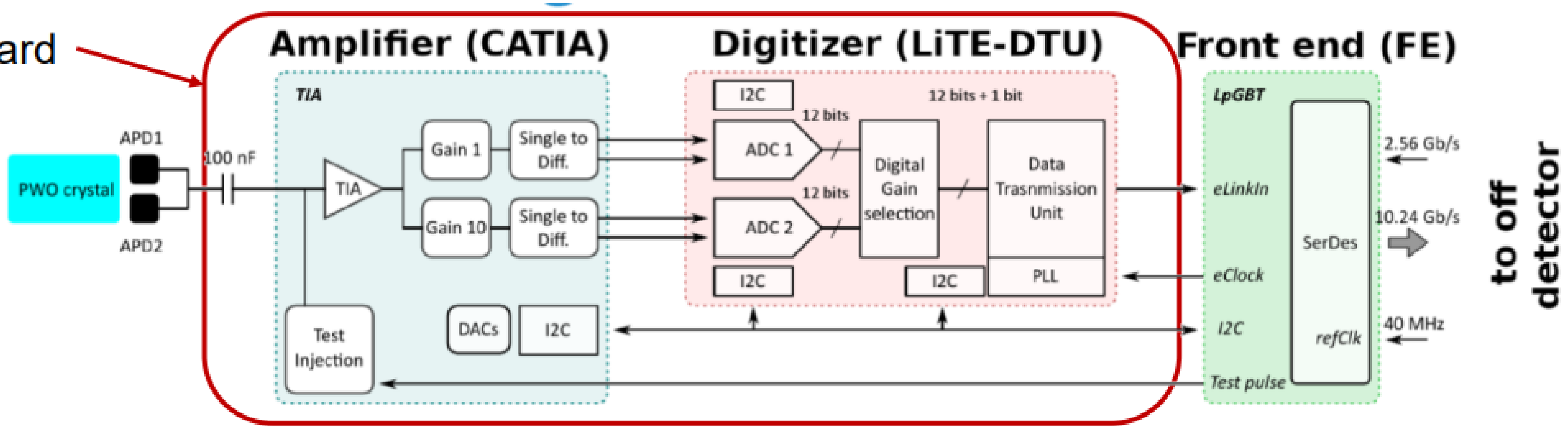
VFE card functionality - ASICs

Slide from W. Lustermann

New electronics – why:

- Longer level 1 trigger latency (12.5μs)
- Mitigates problems induced by high radiation levels at HL-LHC
- Introduces precision time measurement into ECAL: resolution 30 ps for E > 50 GeV
- Introduces data streaming: trigger primitives generation off-detector

VFE card



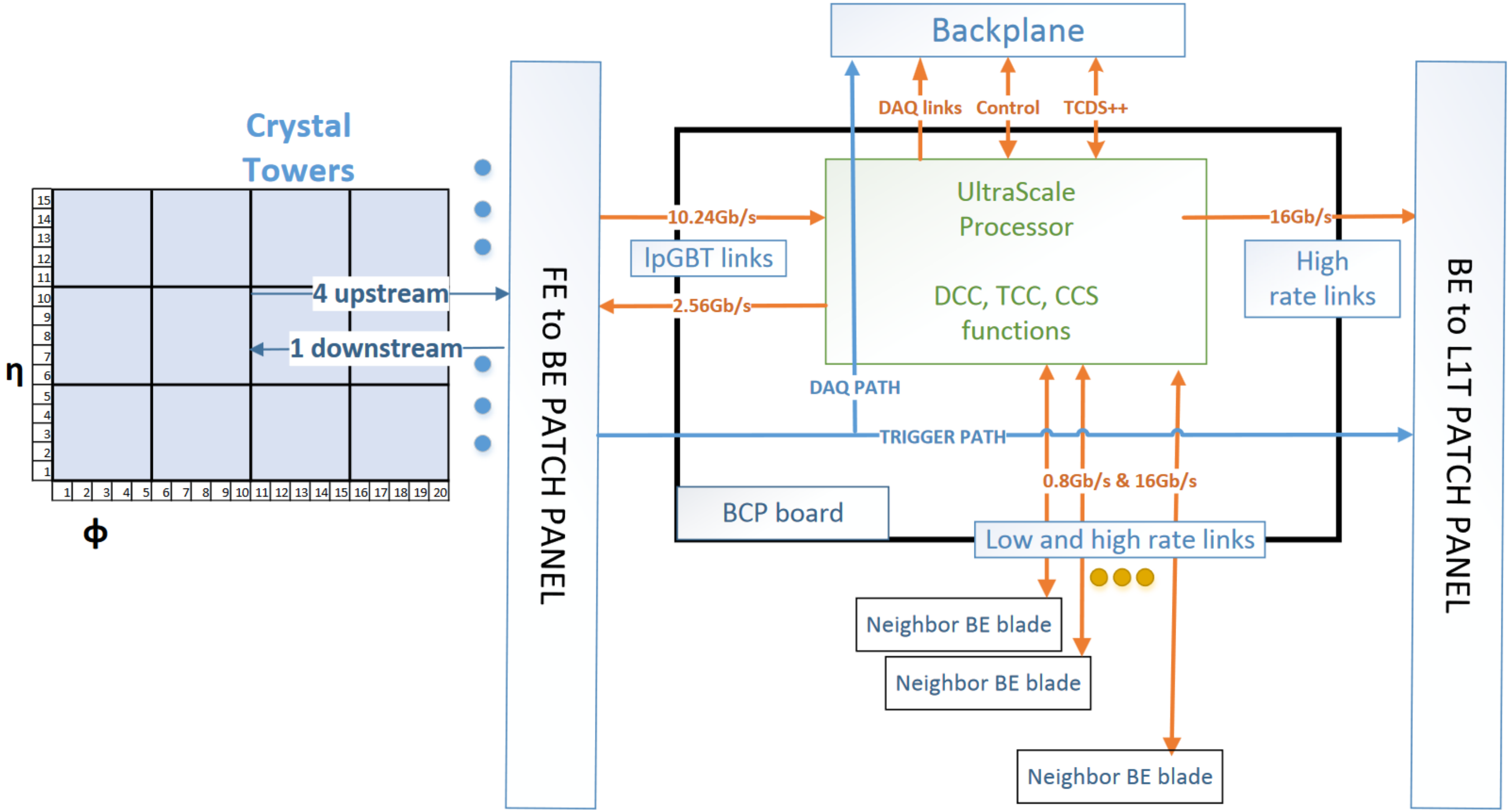
CATIA (CEA Saclay)

- Trans-impedance amplifier ~35 MHz bandwidth
- Two gains differential outputs: 1 and 10
- Pedestal adjustment
- Internal test-pulse generator
- Internal temperature sensor
- I2C interface

LiTE-DTU (INFN Torino, LIP Lisbon)

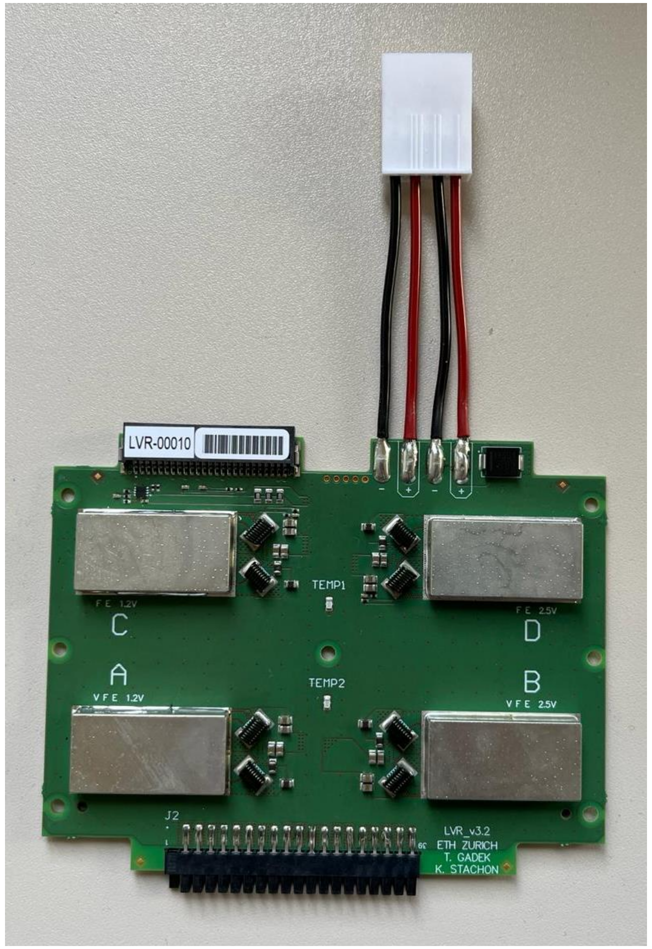
- Dual 12bit ADC, sampling at 160 MS/s
- 160 MHz CLK and fast control input
- internal PLL
- Lossless data compression
- Data streaming at 1.28 Gbit/s
- I2C interface

Barrel Calorimeter Processor - Layout



Low Voltage Regulator (LVR) card

- Low voltage for VFE and FE
  - VFE:
    - CATIA: 2.5 V
    - LiTE-DTU: 1.2 V
  - FE:
    - LpGBT + Optical Link: 2.5 V and 1.2 V
    - GBT-SCA: 1.5 V
- Hosts four DC-DC converters
  - bPOL12V
  - linPOL12V
- Calculated power consumption per Readout Tower: 40 W
- Amount needed: 2448
  - Thermal cycling, Burn-In and testing (external company)



Pedestals optimization procedure

Slide from G. Cucciati

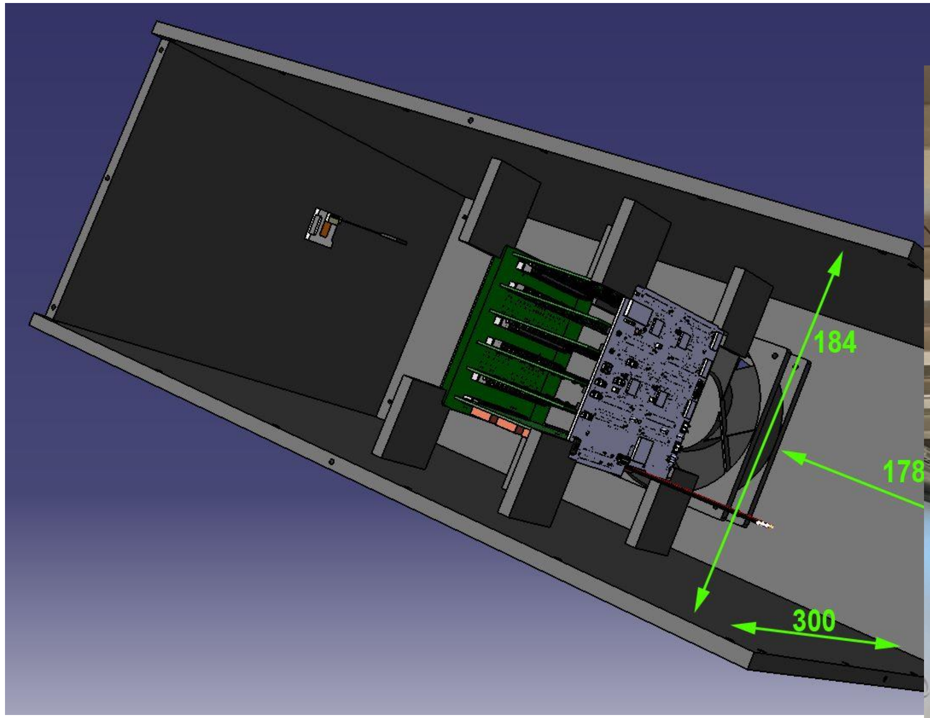
Steps HG Optimization:

- Loop:
  - set a value of CATIA input common mode voltage (Vicm)
  - acquire pedestals and check if average is between 20 and 40 ADCs
    - yes: break the loop
    - no: move to the next Vicm value
- All channels have now pedestals between 20 and 40 ADCs
- Apply a digital subtraction to move all channels to avg of 20 ADCs

Repeat same procedure for LG Optimization

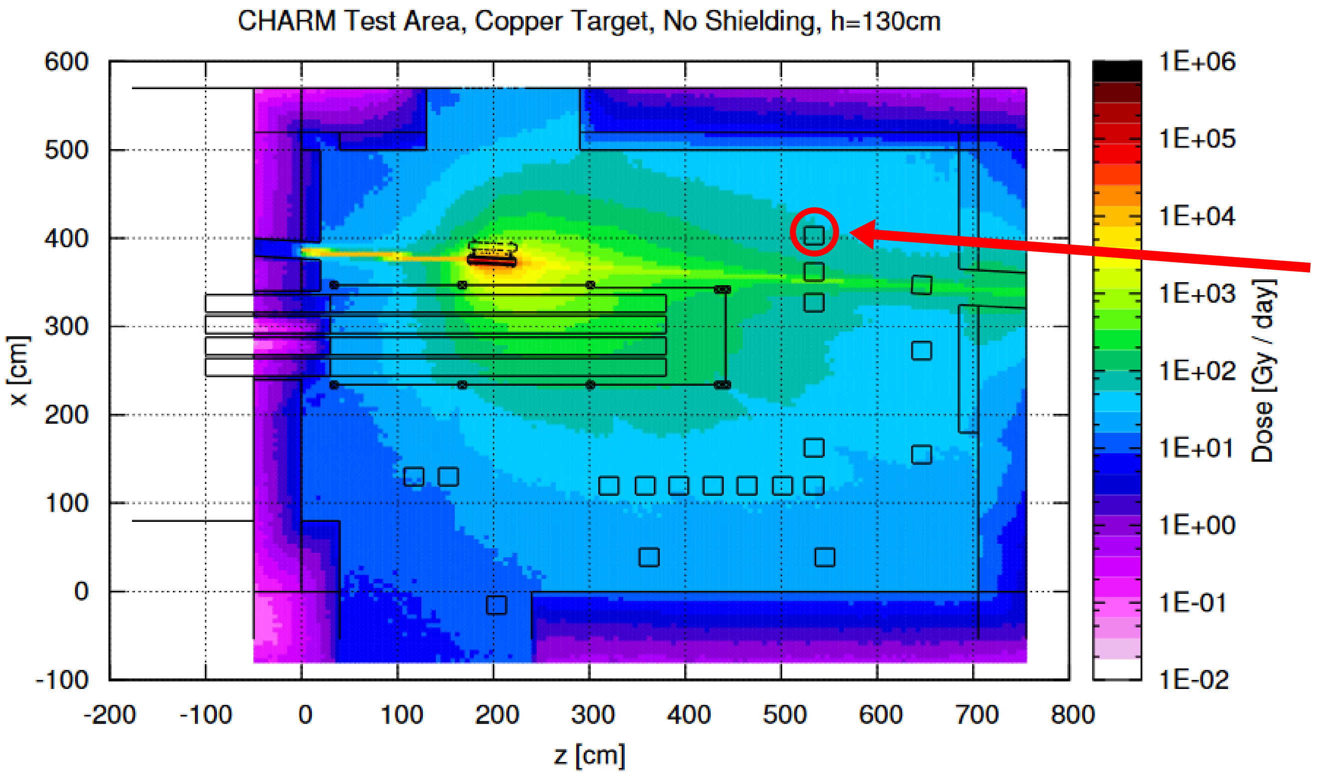
2

Test setup



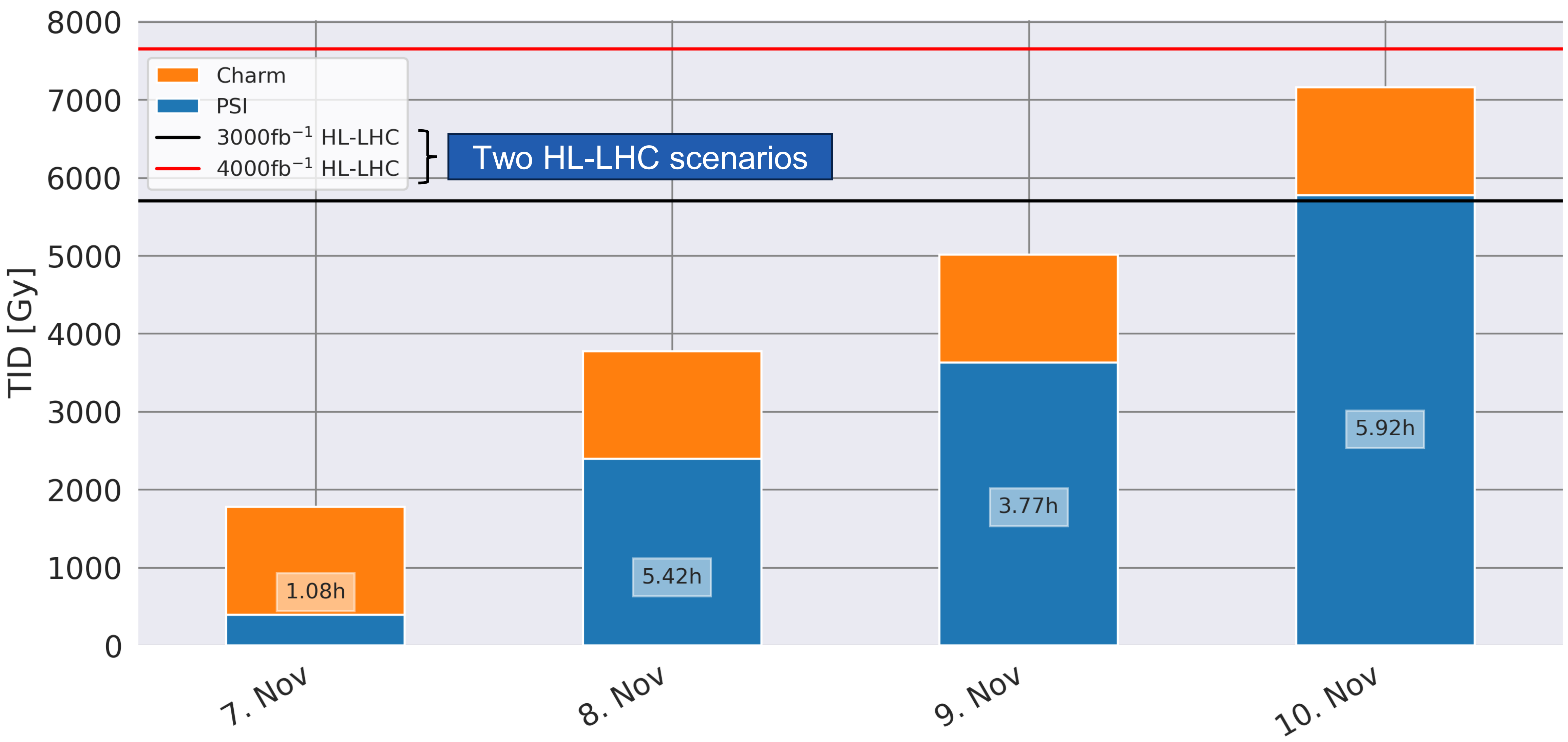
CHARM – FLUKA Simulation

- First irradiation campaign done in **C**ERN **H**igh energy **A**ccele**R**ator **M**ixed field (CHARM) in July 2023
  - 17 days of irradiation, access times included
  - Uniform radiation field



Dose rate: $67.7\ \mathrm{Gy\ day}^{-1}$
HEH fluence: $1.28 \times 10^{11}\ \mathrm{cm}^{-2}\mathrm{day}^{-1}$

Dose goals



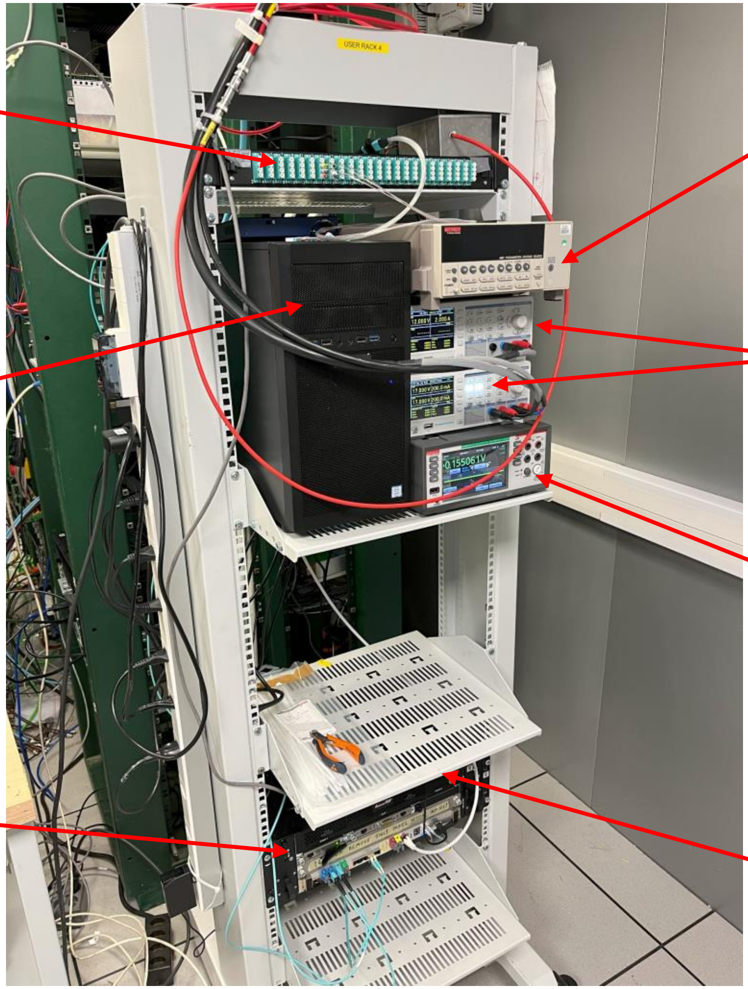
8000
7000
6000
5000
4000
3000
2000
1000
0
TID [Gy]
Charm
PSI
3000fb^{-1} HL-LHC
4000fb^{-1} HL-LHC
Two HL-LHC scenarios
1.08h
5.42h
3.77h
5.92h
7. Nov
8. Nov
9. Nov
10. Nov

Readout equipment

Optical patch panel

Tower readout PC
- Controls tower readout (connected to BCP)
- Controls power supplies and DAQ6510
- Stores data on HDD

Mini ATCA crate with BCP
- Converts optical pulses to digital data
- Decompresses data and sends it to readout PC

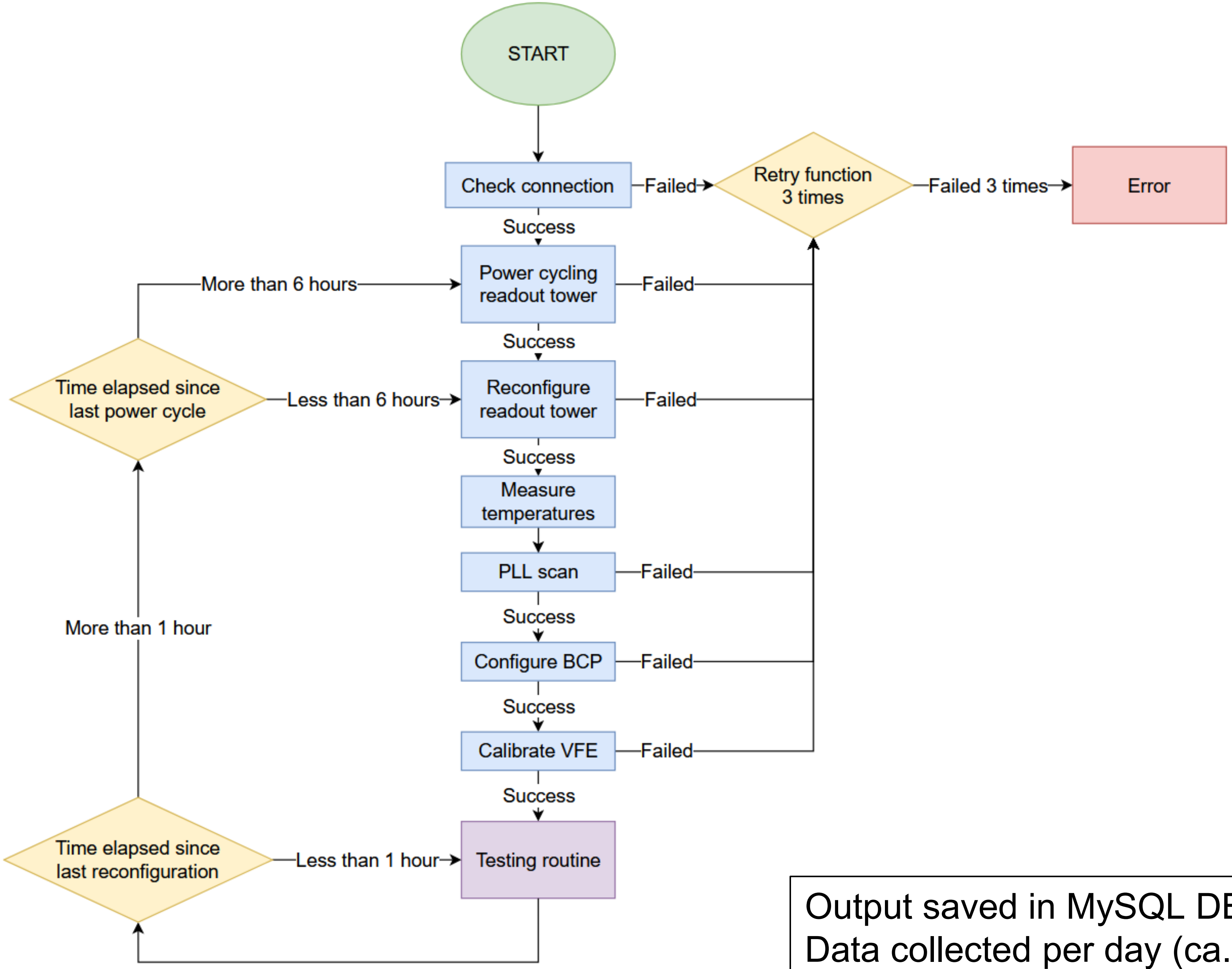


Keithley 2401 Source/Meter
- Provides +400V bias voltage for APDs
- Measures Dark Current

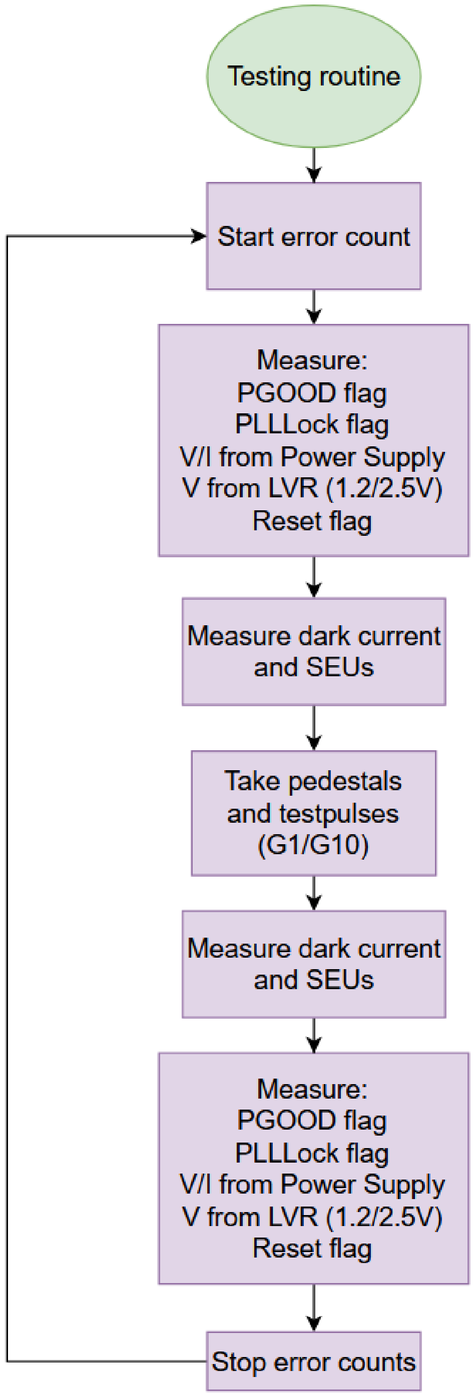
R&S HMC804x Power Supplies
- Powers tower and two cooling fans

Keithley DAQ6510
- Measures output voltages of LVR

Dark Current readout PC (not visible)
- Controls Keithley 2401
- Stores data on HDD

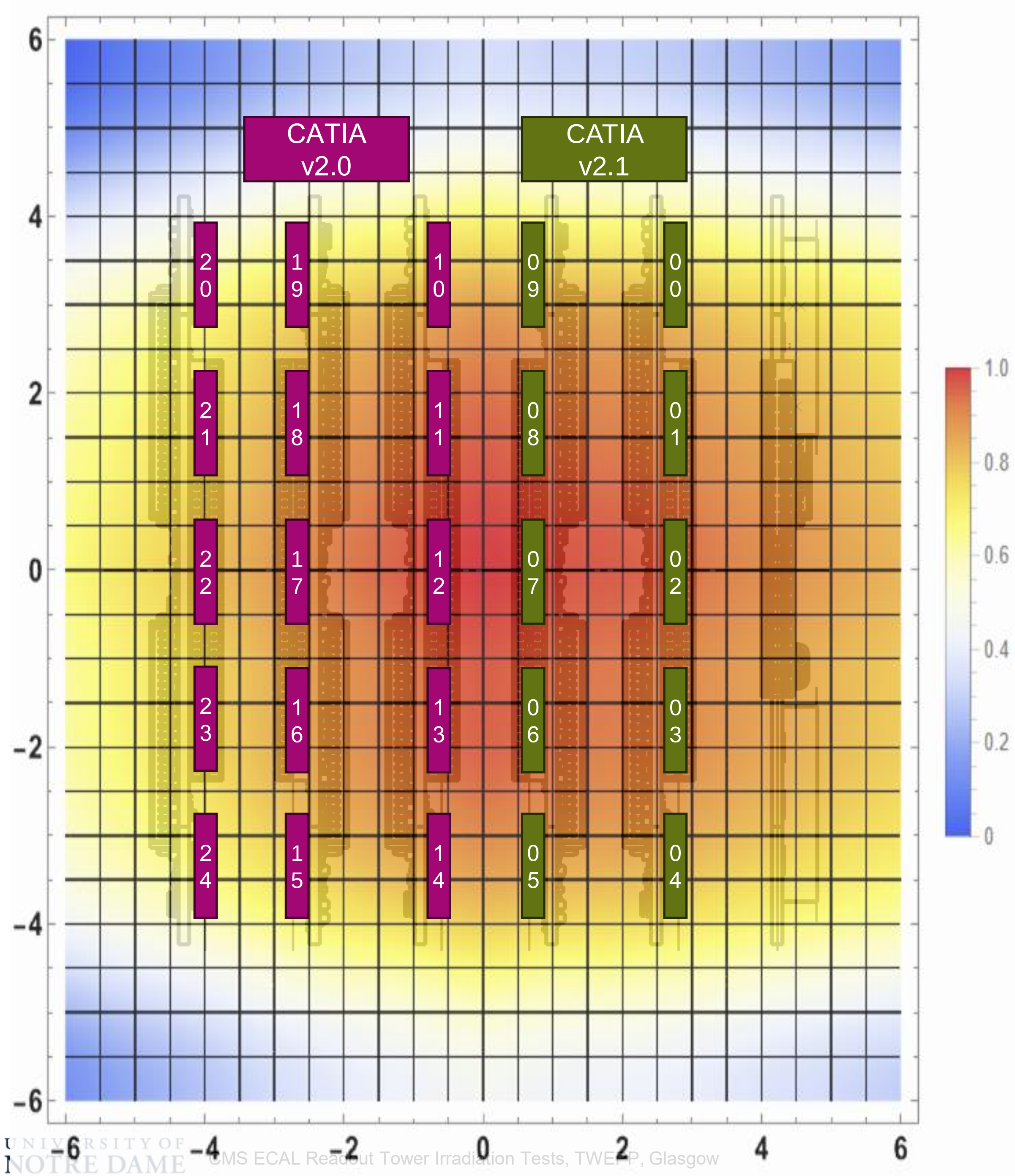


Output saved in MySQL DB + HDD
Data collected per day (ca. 1.5 GB)



Every ~12 seconds

Irradiation map



Data Processing Methodology for CATIA test pulses

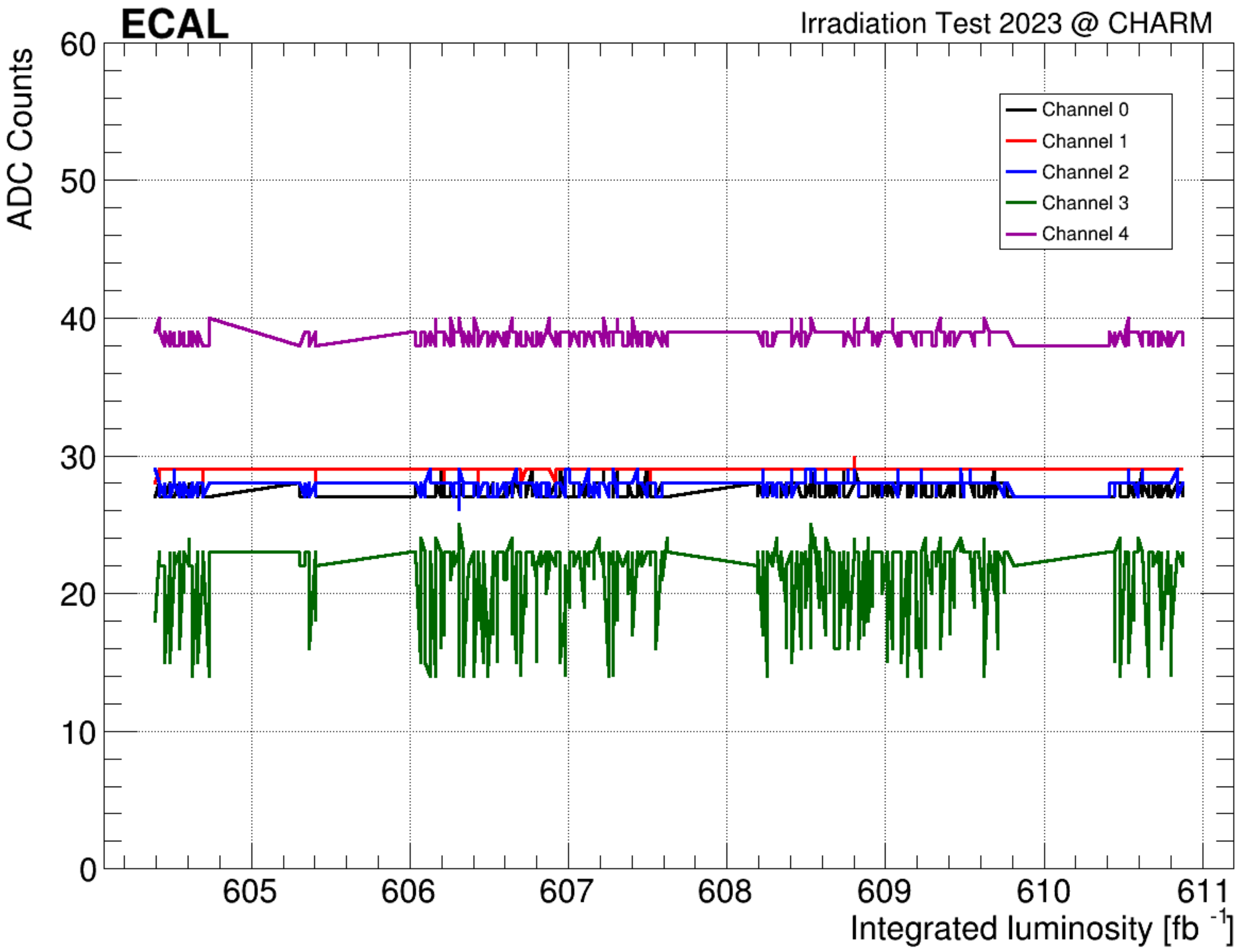
- **Steps in Data Processing**

1. **Amplitude Extraction** 📊
   1. Generate test pulses using CATIA.
   2. Record pulse shape and fit to determine the highest point as the amplitude.
2. **Skimming of Outliers** 🗑️
   1. For each cycle, form a set of amplitudes.
   2. Remove amplitudes further than 3 sigma (standard deviations) away from the mean of the dataset.
3. **Analysis Based on Trends** 📈 📉
   - **Clear Trend in Mean (Positive or Negative)**
     1. Use the mean of the first three skimmed datasets.
     2. Calculate the <u>relative deviation (drift)</u> of subsequent datasets from this mean.
   - **No Clear Trend:**
     1. Calculate an overall mean of all skimmed datasets.
     2. Determine the <u>relative deviation (drift)</u> for each dataset from this overall mean.

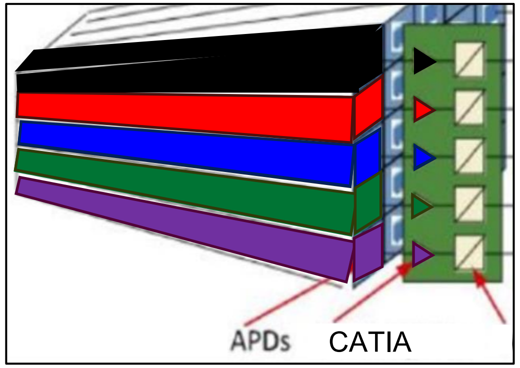
- Points 2 and 3 also applied when extracting the raw RMS Noise distribution

Backup - Results

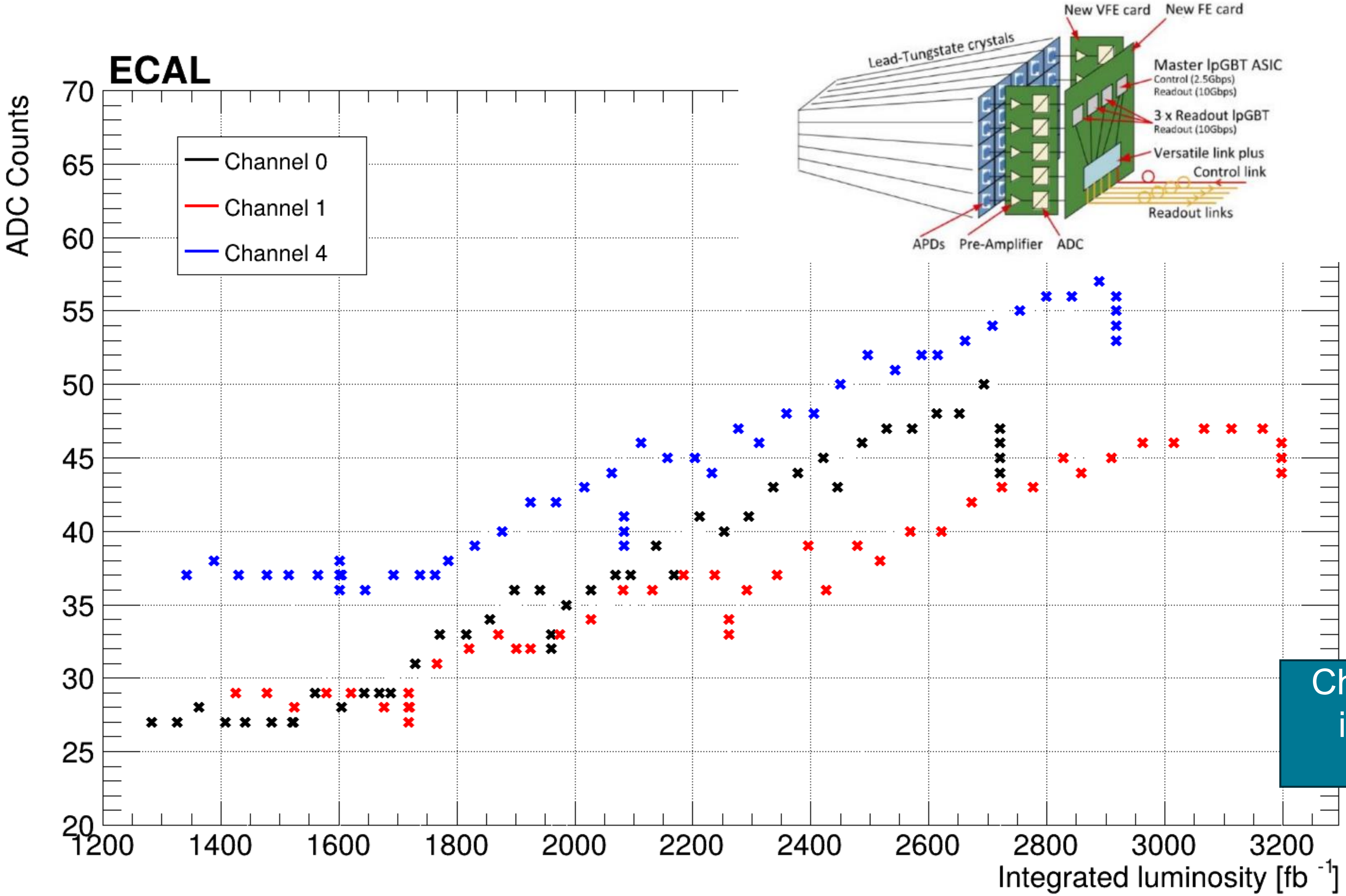
Dark current - CHARM



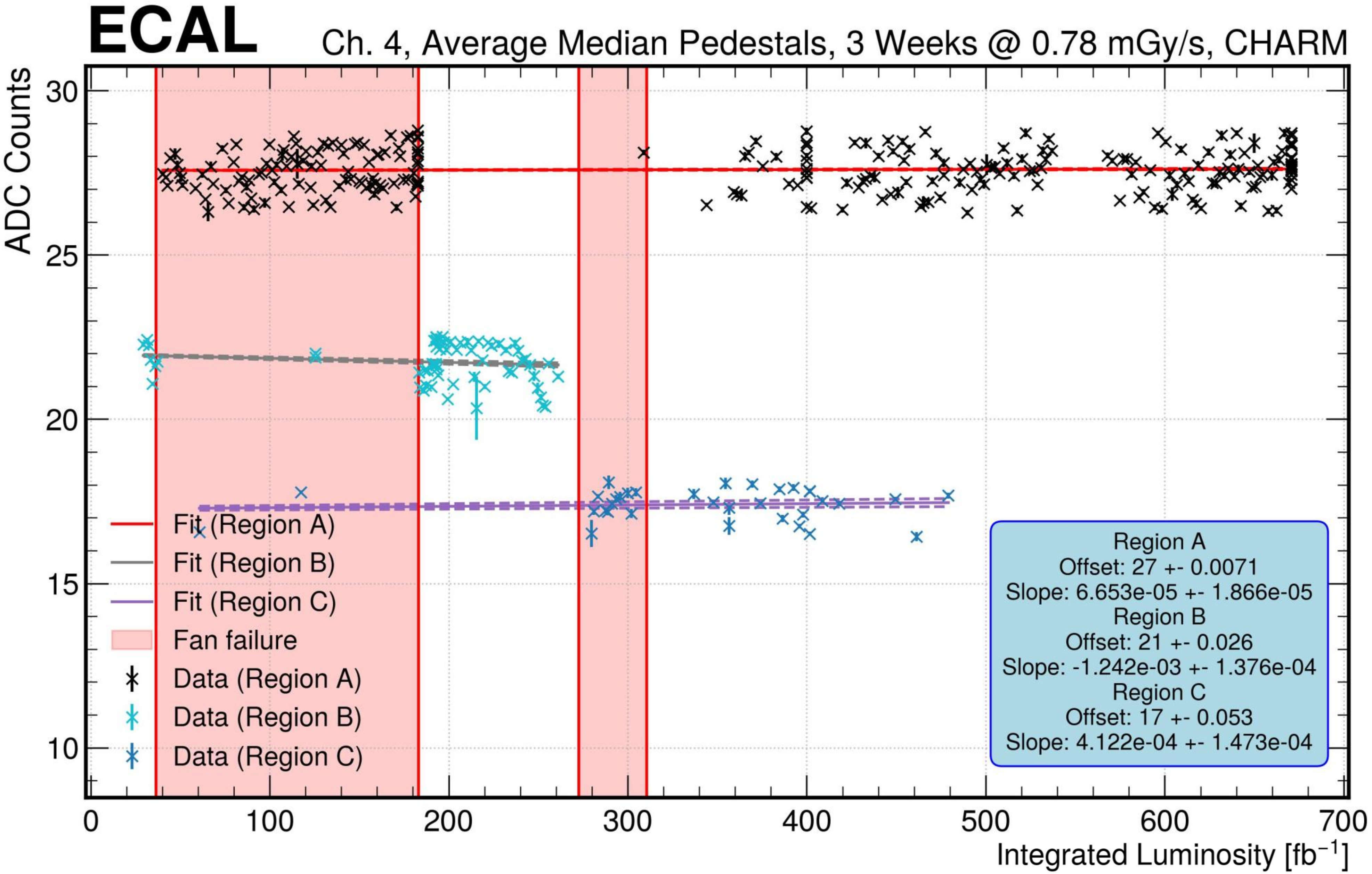
APD #3 oscillates.



Dark current - PSI



Ch 2 and 3: Not irradiated by beam


ECAL
Ch. 4, Average Median Pedestals, 3 Weeks @ 0.78 mGy/s, CHARM
ADC Counts
Integrated Luminosity [fb^{-1}]
Fit (Region A)
Fit (Region B)
Fit (Region C)
Fan failure
Data (Region A)
Data (Region B)
Data (Region C)
Region A
Offset: 27 +- 0.0071
Slope: 6.653e-05 +- 1.866e-05
Region B
Offset: 21 +- 0.026
Slope: -1.242e-03 +- 1.376e-04
Region C
Offset: 17 +- 0.053
Slope: 4.122e-04 +- 1.473e-04