SEE in HGCROC and H2GCROC
Radiation-Hard Front-End ASICs for the CMS HGCAL
FTCF 2025

G. Bombardi, F. Bouyjou, E. Delagnes, P. Dinaucourt, F. Dulucq, M. El Berni, M. Firlej, T. Fiutowski, J. Gonzalez, F. Guilloux, M. Idzik, C. de La Taille, A. Marchioro, J. Moron, L. Raux, K. Swientek, D. Thienpont, T. Vergine

November 25, 2025

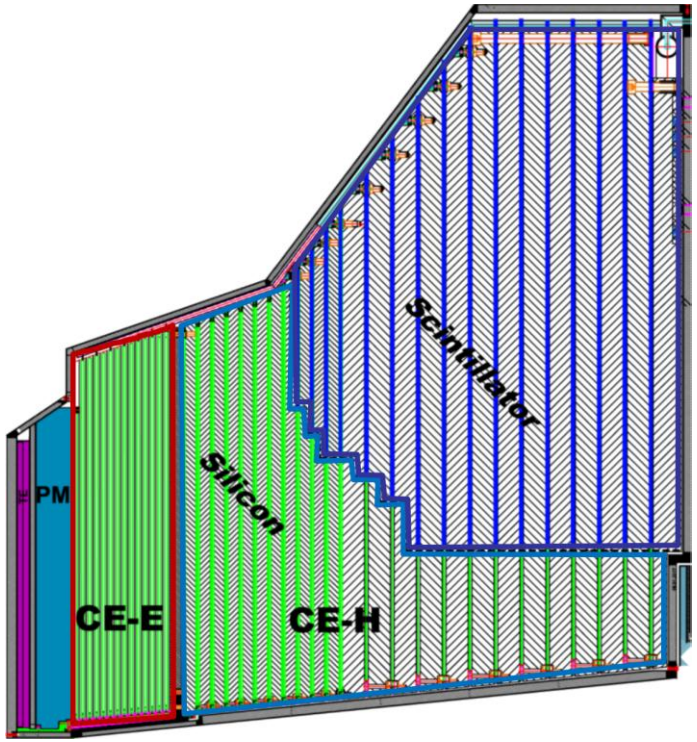
Sébastien EXTIER

Outline

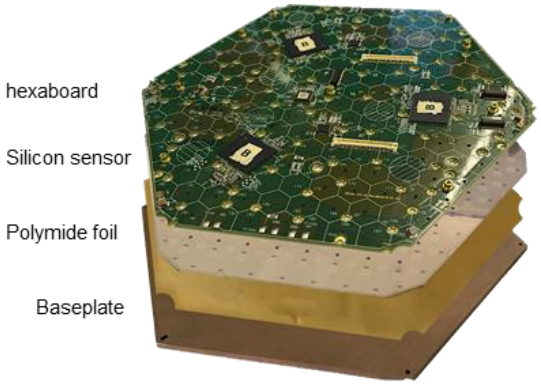
- Introduction
  - HGCAL for the HL-LHC Upgrade Phase II
  - HGCAL radiation exposure
  - Radiations effect in a chip
- HGCROC a RadHard ASIC
  - Triplication
  - Encoding
- Irradiation tests
  - Total Ionizing Dose
  - SEE with heavy ions
  - SEE with proton
- Productions tests
  - Robots, tests sequence, yield
- Summary

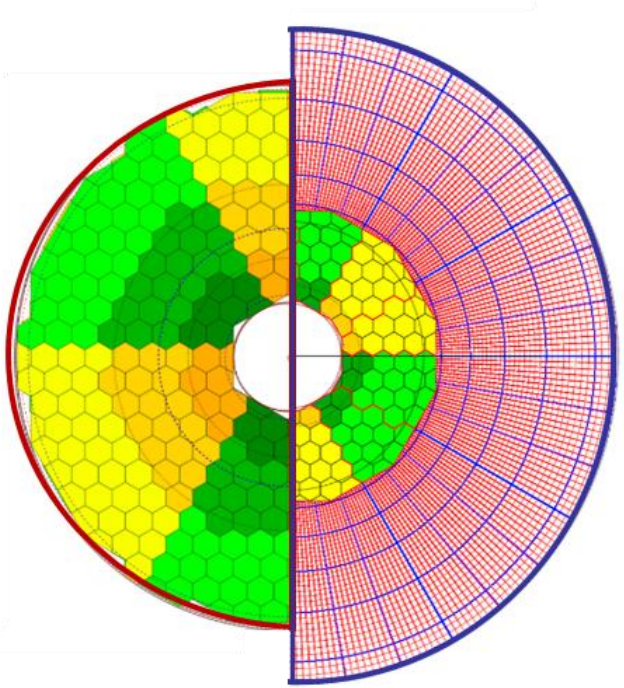
HGCAL: The High Granularity Calorimeter

- The High-Granularity Calorimeter will replace the existing endcap calorimeters of CMS detector for the High-Luminosity phase of LHC
  - Silicon-based modules for electromagnetic (CE-E) and part of the hadronic (CE-H-Si) section
  - Plastic scintillators tiles for the low-radiation hadronic section (CE-H-SiPM)
- Sampling silicon based calorimeter to sustain severe radiation conditions
- Unprecedented transverse and longitudinal granularity
  - 6M channels and 120k chips

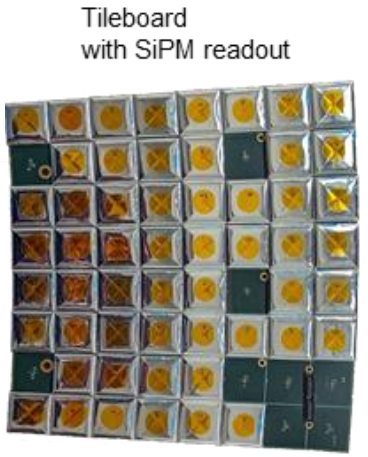


3/6 HGCROC3 chips / HB





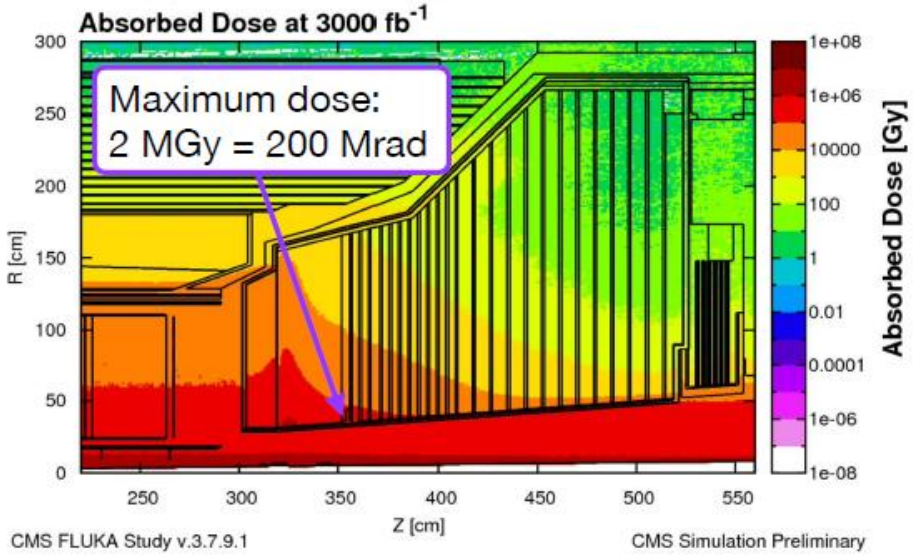
1 H2GCROC3 chip / TB



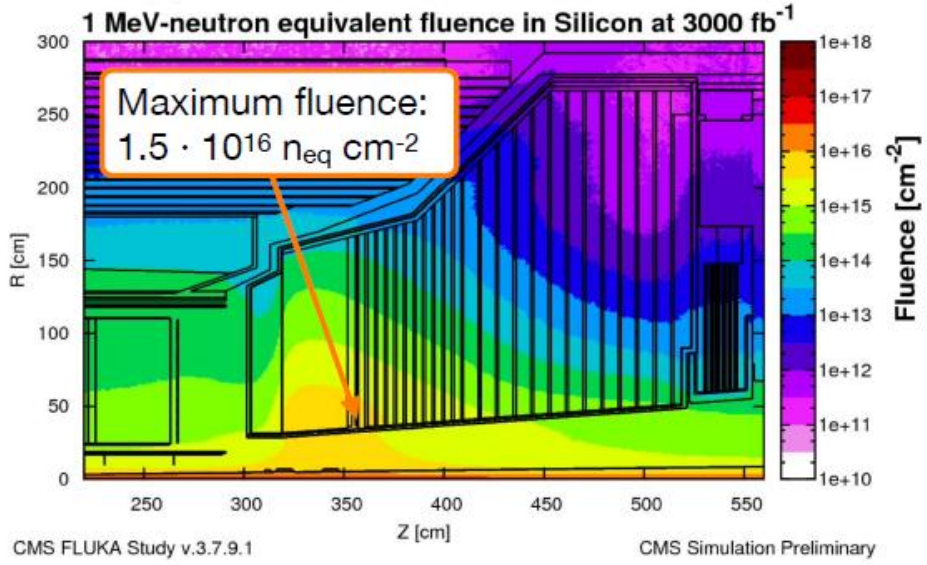
Radiation exposure in HGCAL

- According to FLUKA simulations, the CMS forward region will be exposed to:
  - A total integrated dose of up to **~ 200 Mrad**
  - A hadron fluence up to **$1{,}5.10^{16}$ n_{eq} cm^{-2}**

- Irradiation campaigns required to demonstrate that HGCROC3 withstands such harsh radiation environments



Total Ionising Dose (TID): test the cumulative damage of ionising particles



Single Event Effect (SEE): test the non-cumulative damage induced by single particles

HGCROC3 overview

Readout ASIC for calorimetry with external triggering

- Read 72 channels
- Event validation by Level 1 Trigger

Charge measurements

- Peak measurement: 10 bits ADC @ 40 MHz (AGH)
- Time over Threshold: 12 bits TDC, LSB = 50 ps (IRFU)

Time measurement

- Time of Arrival: 10 bits TDC, LSB = 25 ps

Two data flows

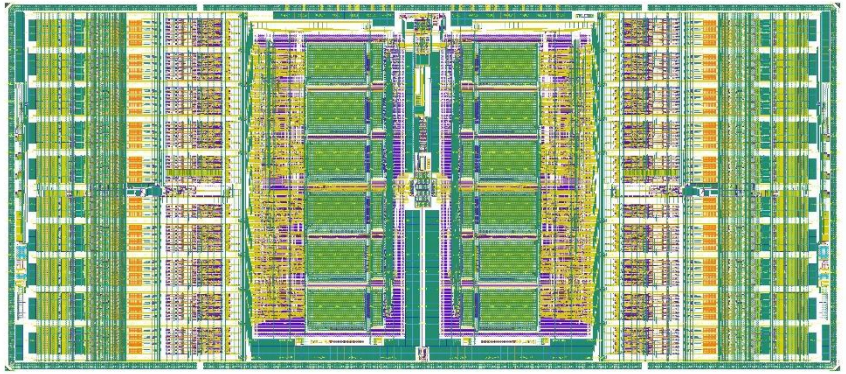
- Trigger path
  - Sum of 4(9) channels, linearization, compression over 7 bits
  - 4 Trigger 1.28 Gbps links
- DAQ path
  - Store all event data (512 depth circular buffer)
  - Derandomize buffer for hit congestion (32 depth FIFO)
  - 2 DAQ 1.28 Gbps links

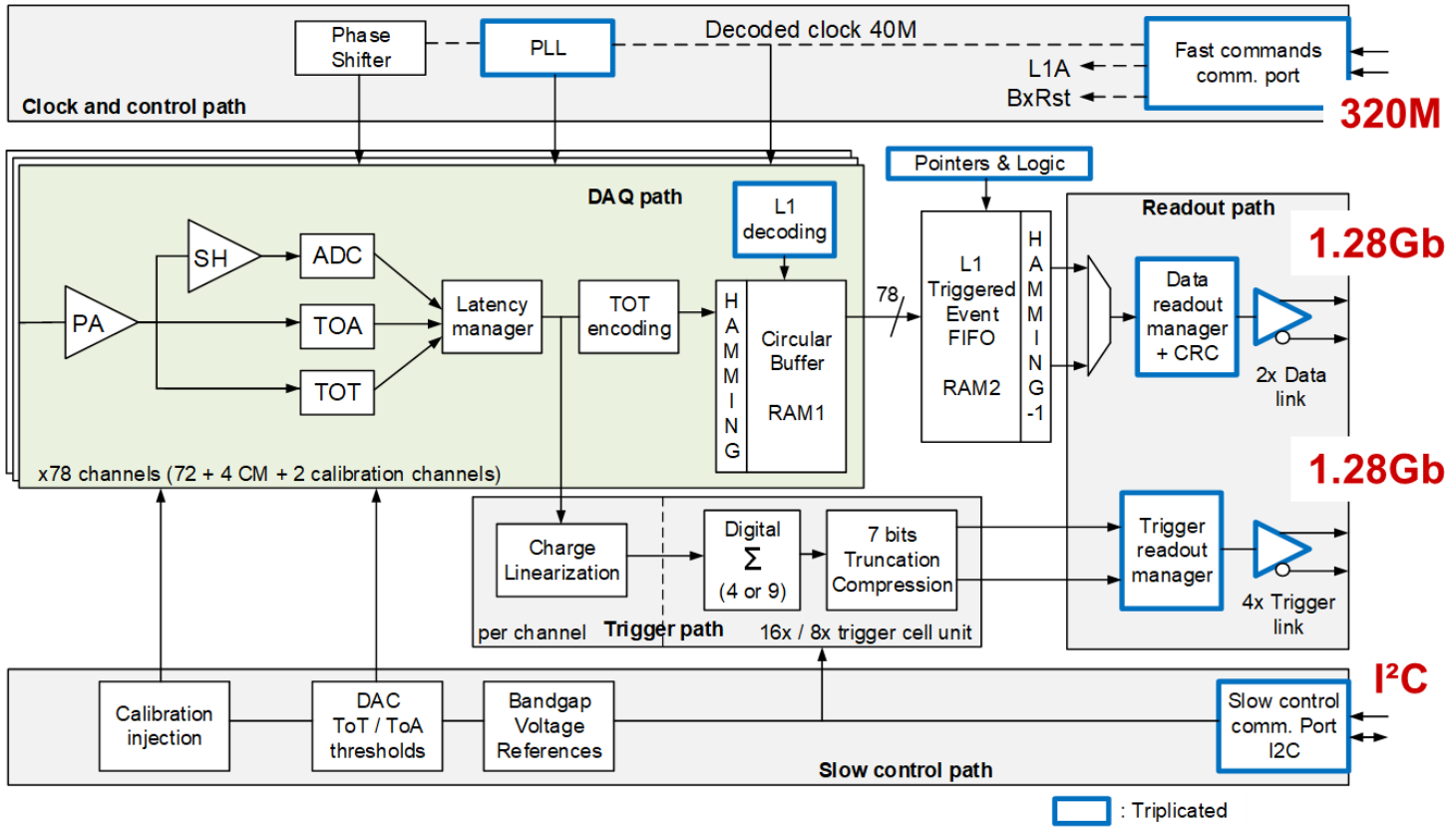
Control

- Fast commands
  - 320 MHz commands
  - 40 MHz synchronous clock extracted

Configuration

- I²C protocol for slow control





Introduction to radiations effects in a chip

TID: Total Ionizing Dose

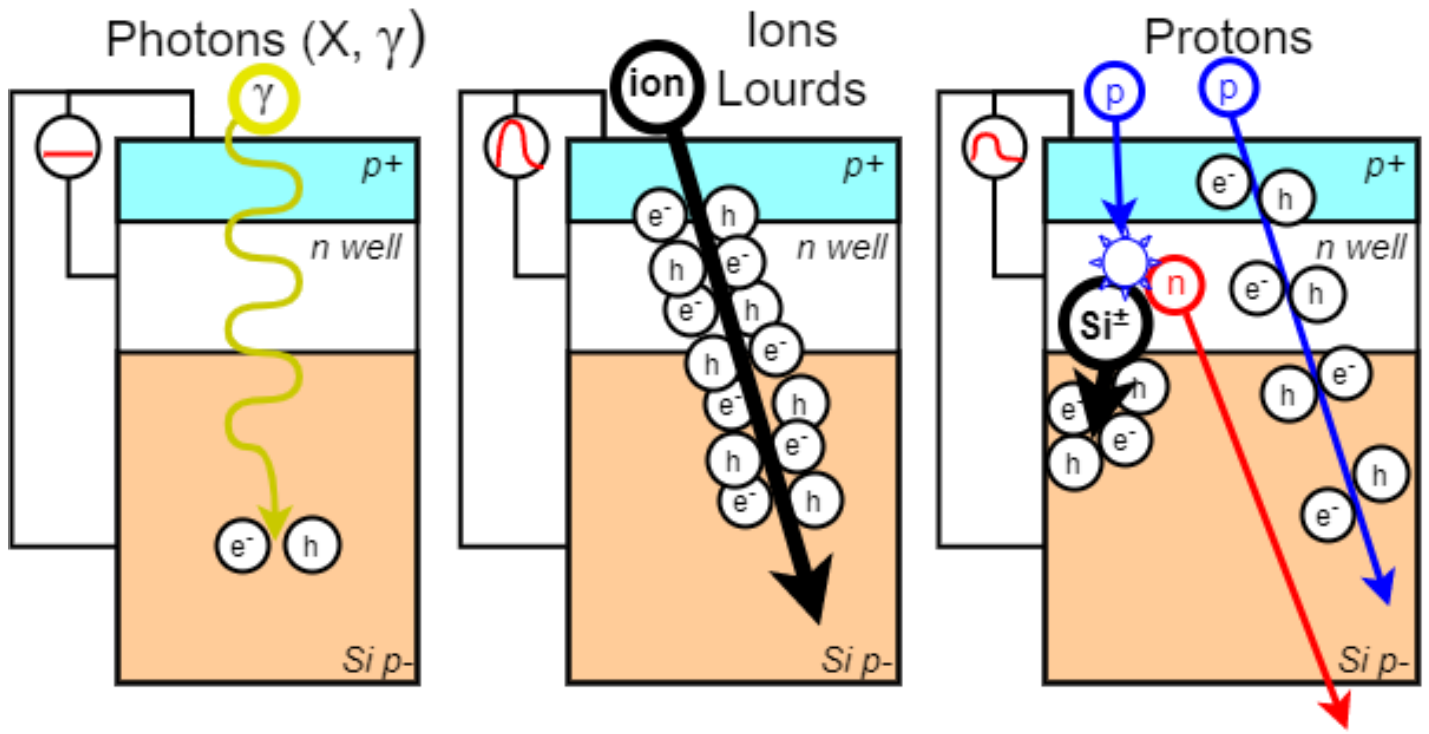
- Photon (X, Gamma)
- Proton (direct)

➔ Cumulative effect
  - Leakage current
  - Increase power consumption
  - Voltage threshold shifting

SEE: Single Event Effect

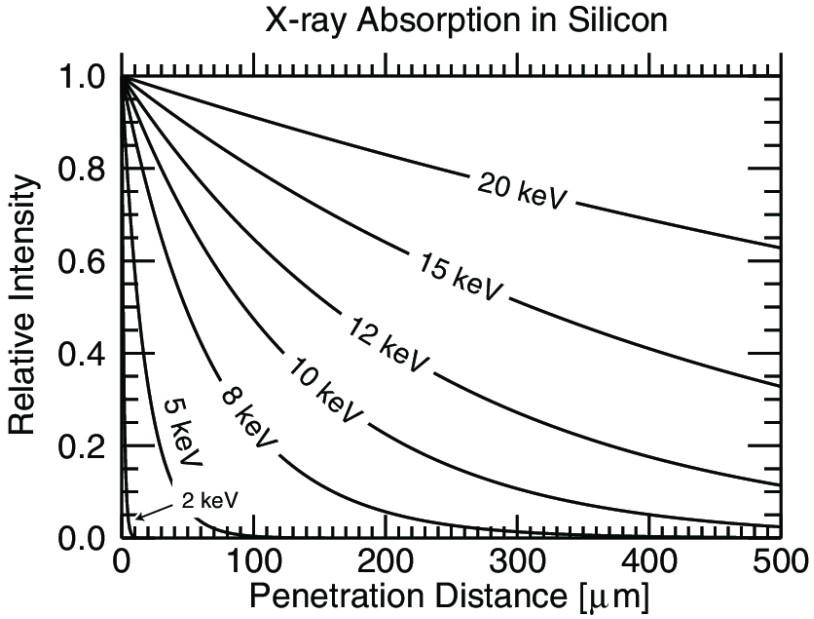
- Heavy ions
- Protons (Indirect)

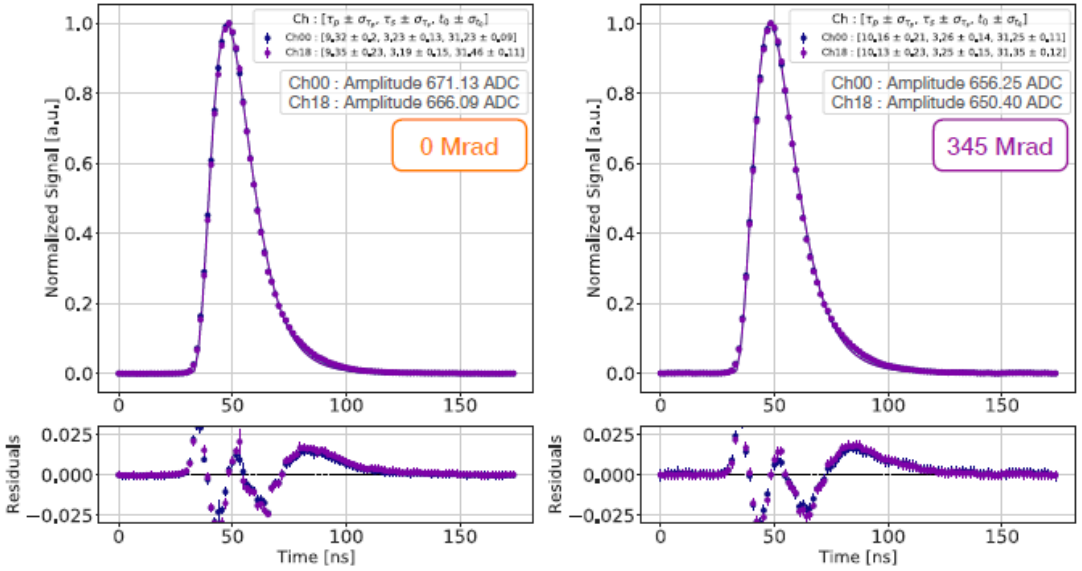
➔ Singular effects:
  - Upset: Corrupt data in storage
  - Transient: Corrupt data in node
  - Latchup: Destructive short

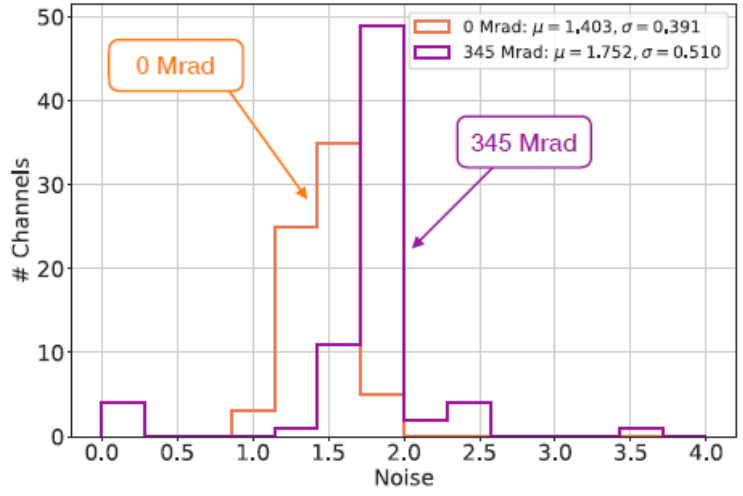


TID tests

- All versions of the chip have been tested against TID
  - CMS forward region will be exposed to a total integrated dose of up to **~ 200 Mrad**
- The chip is placed on a **mezzanine** and **thinned down** to **~ 70 µm**
  - *Beam*: 10 keV X-rays (Obelix facility at CERN)
  - *Temperature*: -10° C
  - *Dose rate*: 0.35 and 3.5 Mrad/h
  - *Total integrated dose*: **345 Mrad**
- **No big impact** observed on any part of the chip:
  - *No change in the **charge** and **time** measurement (linearity and jitter)*
  - *No misbehavior in **DRAM***
  - *Preamplifier **noise** slightly increase with dose: ~20 % (1800 e- to 2200 e-)*
  - ***PLL, e-links** and **digital** part maintain the good performance as expected*

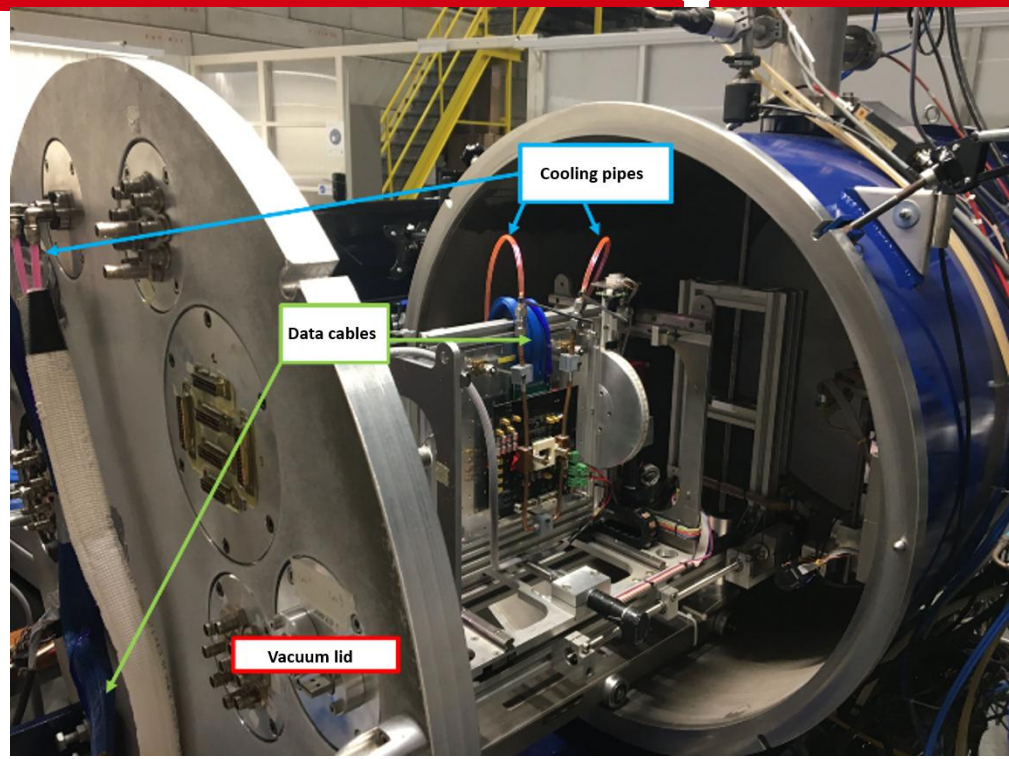






SEE testing: Heavy Ions facilities

- **Heavy ions** campaign at the HIF of **UCL** at Louvain, Belgium
  - 1 campaign in 2022

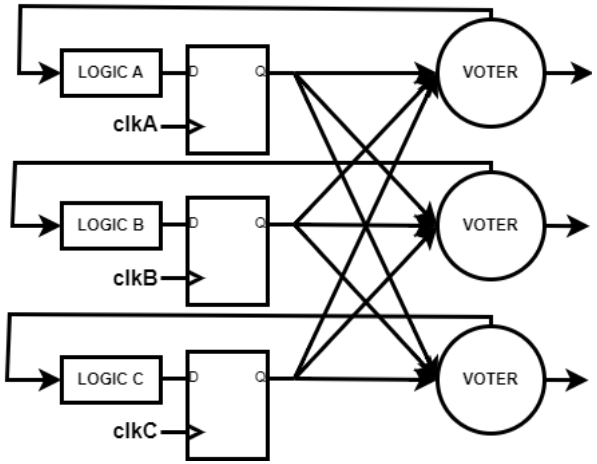


Digital RadHard Methodology:

- Triple Modular Redundancy (TMR)
- Hamming Encoding Memories
- Checksum data transmit (CRC-32)

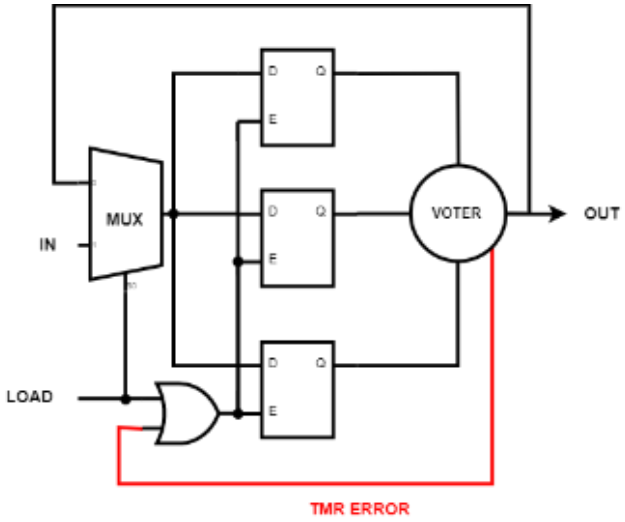
Full TMR:

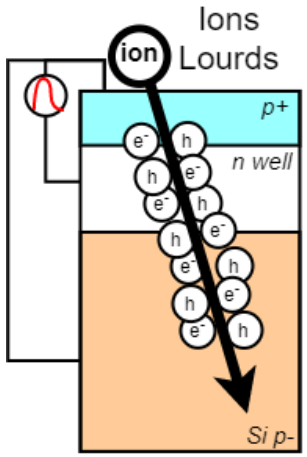
Synchrous refresh



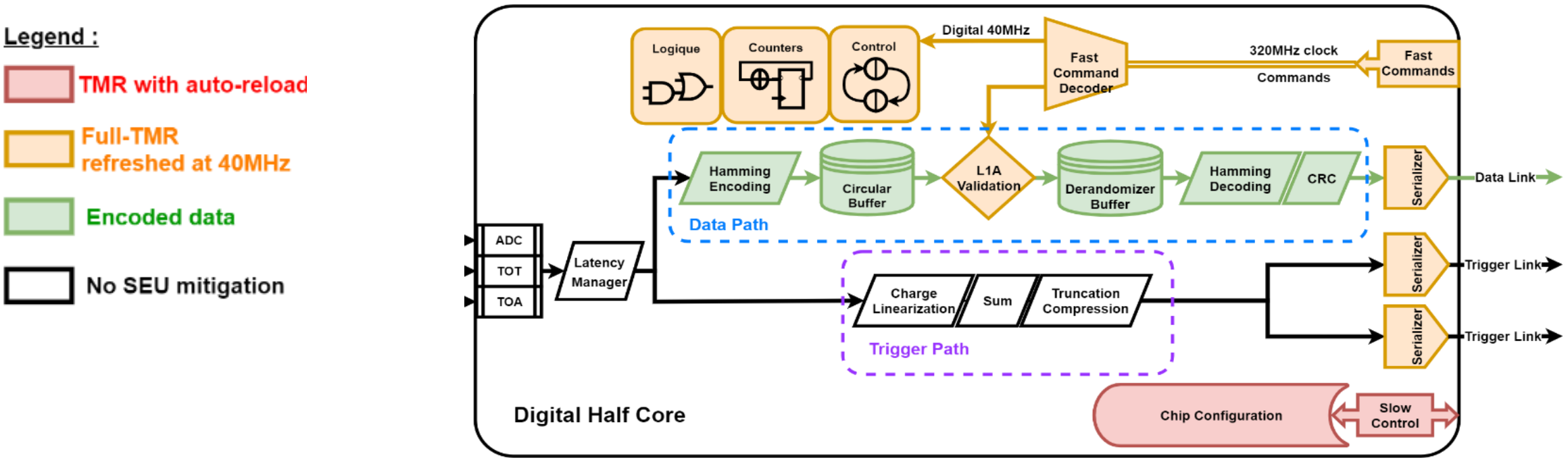
TMR:

Asynchrous refresh





SEE: Heavy ions testing result



Digital core

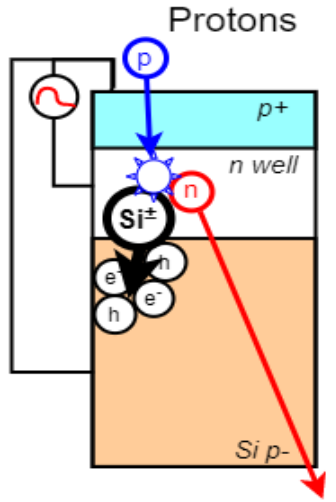
IONS	LET	EXPOSITION	LOGIQUE TMR	TRIGGER	CRC	DAQ	TOTAL
Ne	3.3	1512	-	-	-	-	0
Al	5.7	932	-	-	1	-	1
Ar	9.9	934	-	1	1	-	3
Cr	16.1	873	-	-	-	1	5
Ni	20.4	911	-	-	-	2	12
Kr	32.4	457	-	-	-	-	18
Xe	62.5	128	-	-	-	-	10
TOTAL			0	1	2	3	49

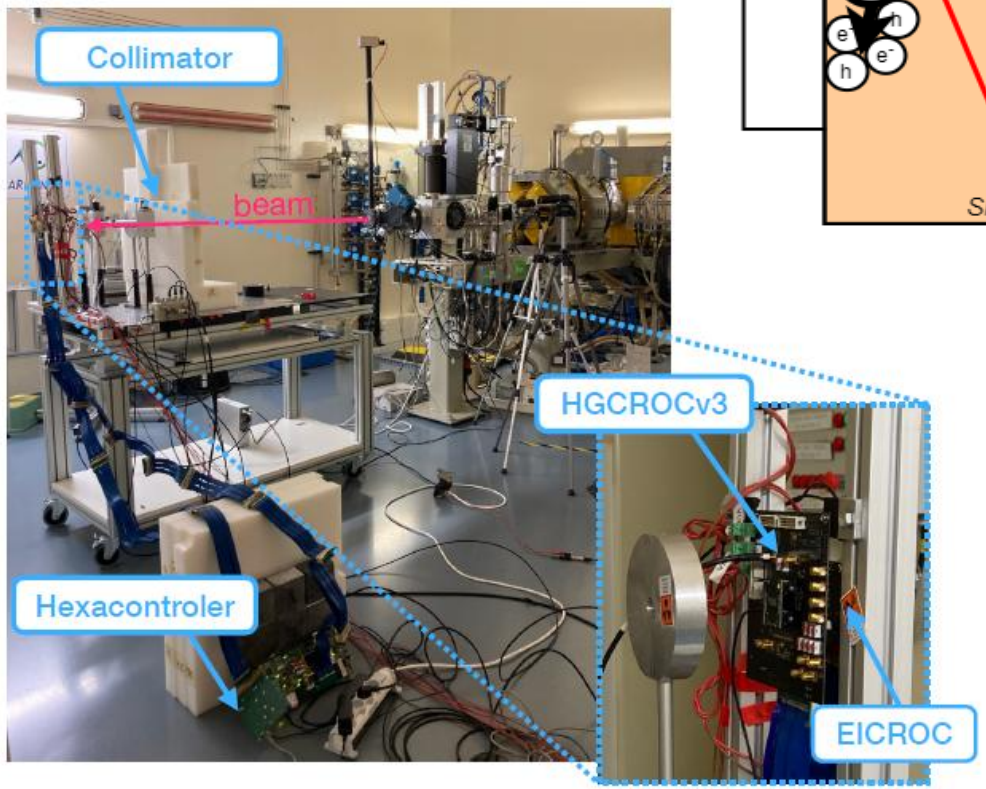
Chip Configuration

AUTO CORRECTION		OFF		ON	
ION	LETEFF [MeV/Mg/cm^2]	TEMPS [s]	TOTAL BIT FLIPS	TEMPS [s]	TOTAL BIT FLIPS
NE	4	490	55	1515	-
AL	8.26	674	213	1291	-
AR	14.76	699	316	1184	-
CR	25.2	687	559	879	-
NI	31.13	678	662	1289	-
KR	38.5	507	502	661	-
XE	< 10	641	130	127	-
TOTAL			2437		0

SEE testing: Protons facilities

- **Proton** irradiation campaigns at *Arronax* in Nantes, France
  - *More than 6 campaigns (3b, 3c and 3d)*
  - *Beam*: 70 MeV protons, flux from 10^8 to 10^{11} p/cm²/s
  - **HGCAL** radiation environment dominated by light hadrons
    → more **realistic** description of the HGCROC3 behaviour with proton
    → higher flux and more error **statistics**
  - **Complex** experimental **setup**:
    → Long cables to protect the Hexacontroller
    → No access to the cavern for days (activation)

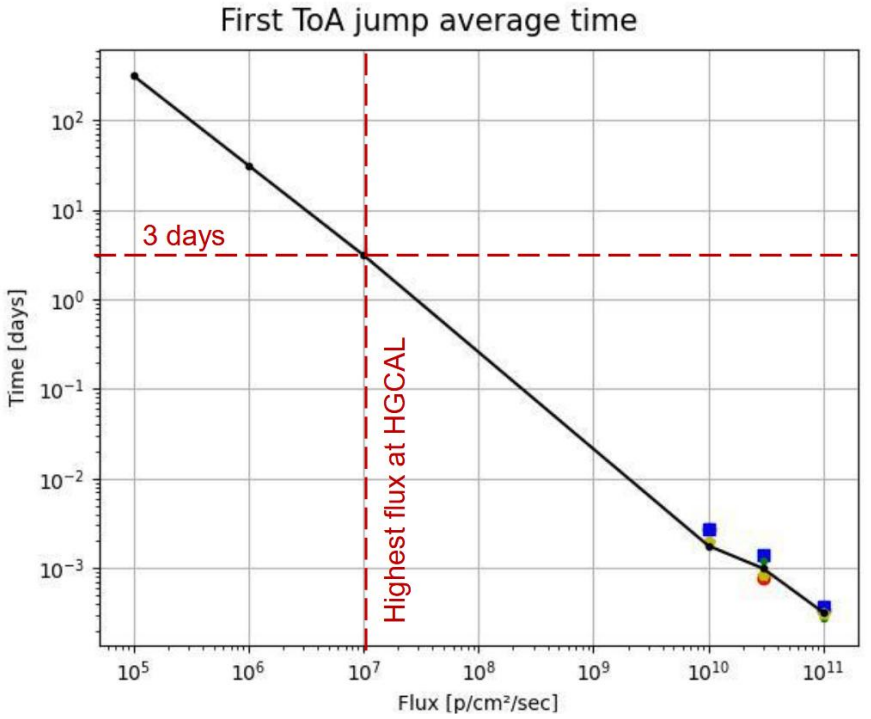




SEE: Proton testing results

- **Protons results**
  - Flux = **2.20 10^{10}** s-1·cm-2 , total time = **13 h**
    → ~ 10 years of HL-LHC (but for 1 chip)
  - Observation:
    - No I2C configuration error
    - No SEU in counter/FSM
    - A few SEU in non triplicated blocks → detectable by hamming encoding and/or CRC-32 information in the DAQ frame
    - About 5 errors per second in trigger data for the full detector
  - ToA jumps cross-section **4.10^{-13} cm^{-2}**
    → Average first ToA jump time about 3 days in the worst section of HGCAL (for 1 chip but without I2C reset)
  - Link loss cross-section due to SET in the PLL less than **1.10^{-14} cm^{-2}**

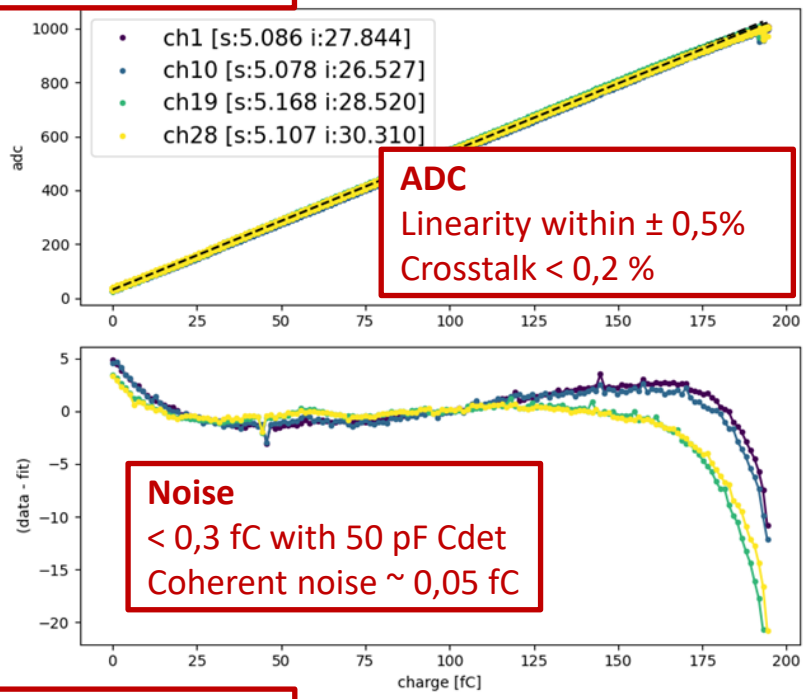
	Counters	Trigger	CRC	Memory	Hamming
Time [s]	46800	34,00	340,00	4352,00	89,70
# errors	1	38	30	127	24
rate [error / s]	0,0000	1,1176	0,0882	0,0292	0,2676
Cross-section	9,71E-16	5,08E-11	4,01E-12	1,33E-12	8,11E-12
$rate_{full_detector}$ (HL-LHC)	0,000	10,160	0,802	0,265	1,622



Performance snapshot

Data path

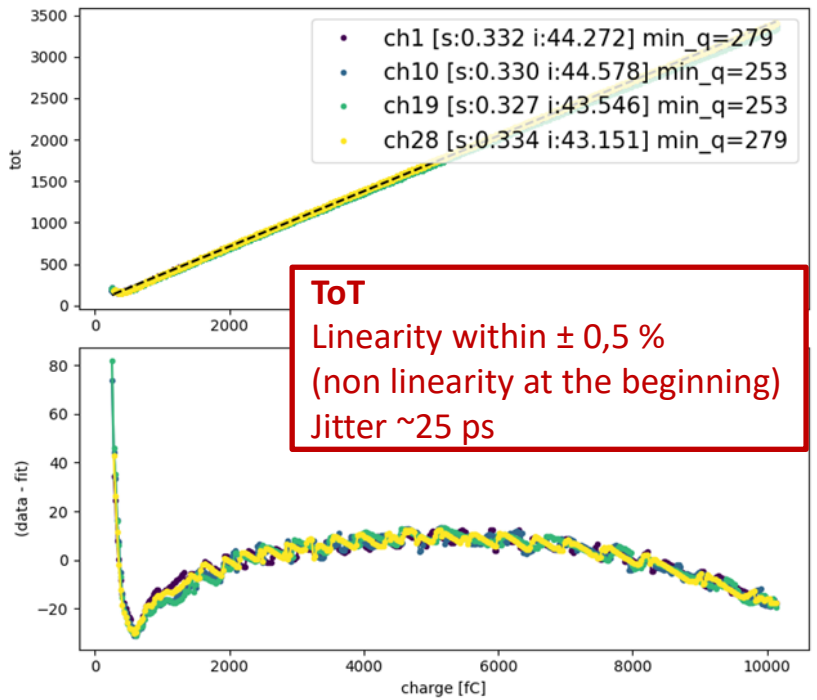
ADC



ADC
Linearity within ± 0,5%
Crosstalk < 0,2 %

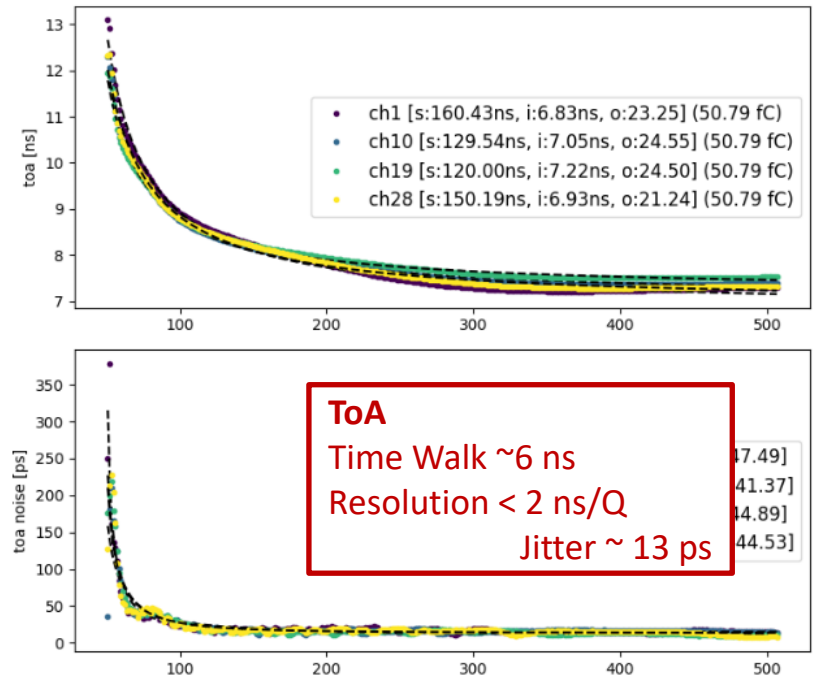
Noise
< 0,3 fC with 50 pF Cdet
Coherent noise ~ 0,05 fC

ToT



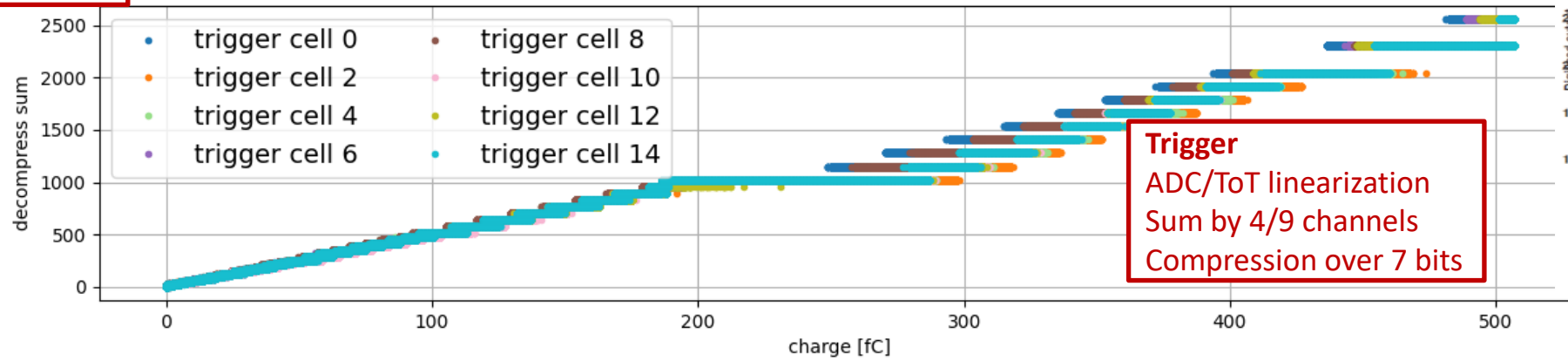
ToT
Linearity within ± 0,5 %
(non linearity at the beginning)
Jitter ~25 ps

ToA

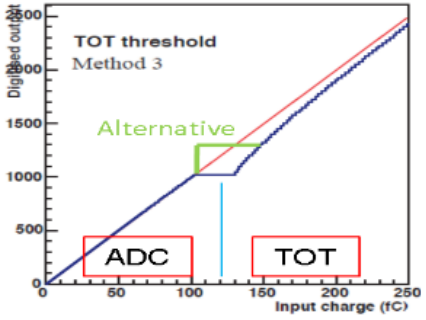


ToA
Time Walk ~6 ns
Resolution < 2 ns/Q
Jitter ~ 13 ps

Trigger path



Trigger
ADC/ToT linearization
Sum by 4/9 channels
Compression over 7 bits

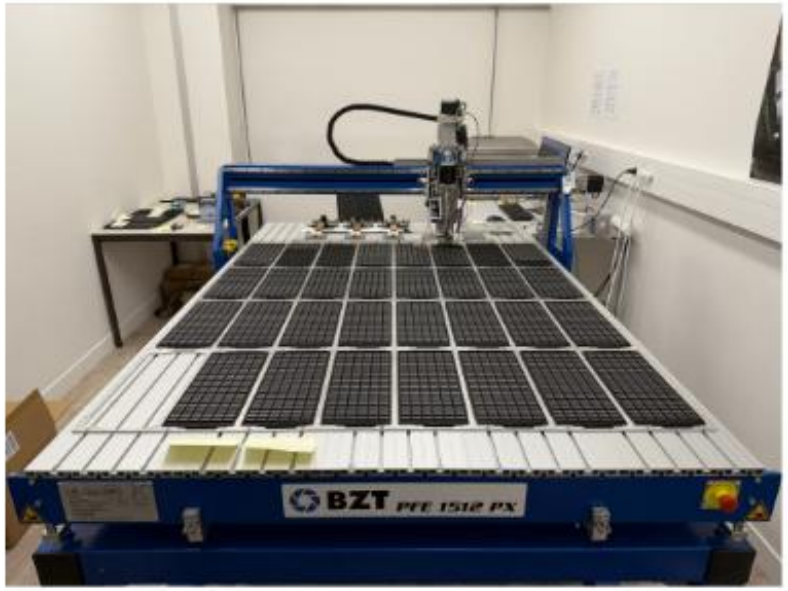


Production QC tests

- 2 robots: LLR and OMEGA
  - **High Density** (HD) and **Low Density** (LD) packages, QR code printed on package for tracking
  - 120k chips in total: 36k HD Si / 84k LD Si / 4.3 k LD SiPM
  - Chip test duration < 5 min
  - The rate of false positive should be 0
  - Results stored for long-term

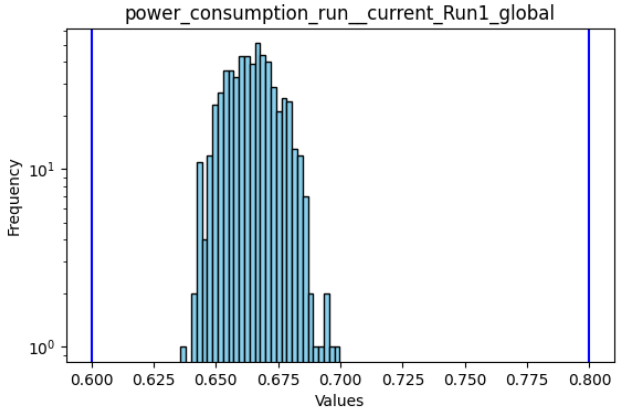
LRR robot (LD)

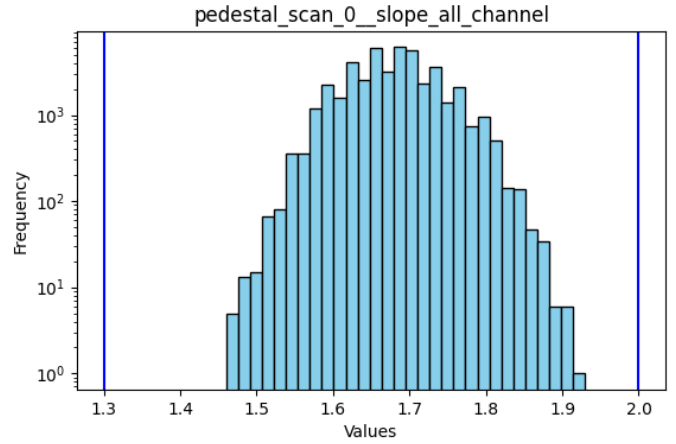
OMEGA robot (HD)

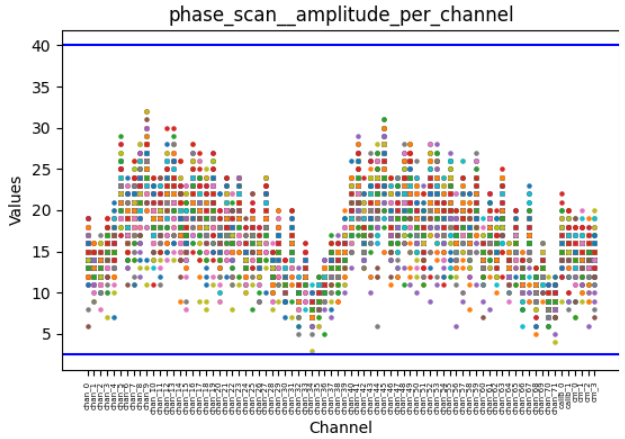


Production test yield

- Production quantity is based on ~ 80 % yield
- The effective yield varies between 85% and 92% depending on the runs
  - It was far below at the beginning because of a lot of crashes, poor socket connection, etc
- The two robots are now running every day
- Main cause of failures
  - 1 bad channels: ADC and/or TDC
  - Consecutives noisy channels: packaging issue
  - 1 bad half-chip because of something wrong in the bias
  - Surprisingly, incorrect default I2C parameters







Summary

- Developing a RadHard ASIC requires:
  - A hardening strategy based on the available resources and the expected radiation levels
  - Single-Event injection simulation for the digital part using the TRMG tool
  - Extensive irradiation testing for both TID and SEE

- More complicated for mixed part
  - Identify problems during radiation tests
  - Emulate problem in mixed simulation (difficult)
  - Resolve problem and validate solution by radiation testing

- The productions chip is actually HGCROC3d
  - Tested in batches 50 wafer by robots
  - Beam tests and Integration soon

Thank you for listening