Karlsruher Institut für Technologie

Institut für Experimentelle Teilchenphysik

Hochratenstudien der Auslesekette von 2S-Modulen für das Phase-2 Upgrade des CMS-Experiments

T 60.8

Tobias Barvich, Alexander Dierlamm, **Alexander Droll**, Ulrich Husemann, Stefan Maier, Thomas Müller, Jan-Ole Müller-Gosewisch, Marius Neufeld, Andreas Nürnberg, Hans Jürgen Simonis, Pia Steck, Julian Stanulla | 17.03.2021

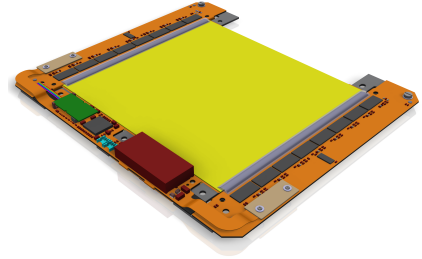
The Phase-2 Outer Tracker Upgrade

Requirements on High Luminosity Operation:

- increased granularity to cope with pileup up to 200 (PU200)
- improved radiation tolerance
- reduced material budget
- contribution to level-1 trigger

→ p_T modules

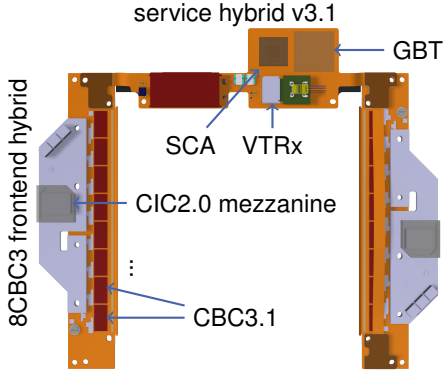
- identify high p_T particles on module level
- spatial correlation of hits in two sensors
- two flavors: pixel-strip (PS) and strip-strip (2S) modules



The 2S readout chain

Two 8CBC3 frontend hybrids each with:

- 8 x CMS Binary Chips[1](CBCs):
  - version 3.1
  - binary detection of sensor signals
  - identification of stubs
- 1 x Concentrator Integrated Circuit[2](CIC):
  - version 2.0
  - sparsification of CBC data
  - ordering and priorisation of stub data



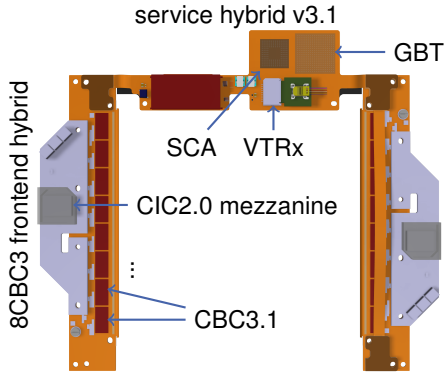
[1] Prydderch et al., *CBC3: a CMS microstrip readout ASIC with logic for track-trigger modules at HL-LHC*, CMS-CR-2017-383

[2] CMS Tracker Group, *First results from the CIC data aggregation ASIC for the Phase 2 CMS Outer Tracker*, DOI 10.22323/1.370.0102

The 2S readout chain

One service hybrid v3.1 with:

- 1 x GigaBit Transceiver[1] (GBT)
  - serialization of 2 x CIC data
- 1 x VTRx[2]
  - optical transmission to DAQ system



[1] Moreira et al., *The GBT Project*, DOI 10.5170/CERN-2009-006.342

[2] Amaral, *The versatile link, a common project for super-LHC*, DOI: 10.1088/1748-0221/4/12/P12003

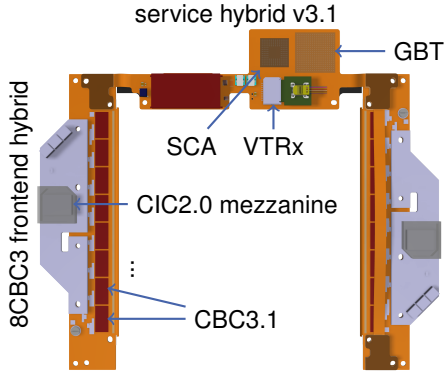
The 2S readout chain

Stub data stream:

- stub information send to L1-trigger
- stub data streamed at 40 MHz

L1 data stream:

- triggered full hit information
- sent on trigger reception
- bandwidth designed for 750 kHz trigger rate



Bandwidth requirements for 2S modules

- hit occupancy: up to 1.42 % at PU200
- average #clusters/FE/event: up to 13 at PU200
- mean trigger rate of 750 kHz
- bunch crossing rate of 40 MHz

Common Test System:

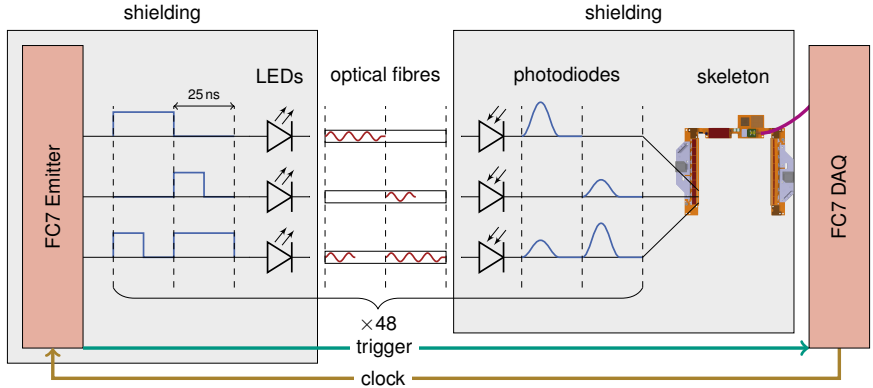
- beam test (DESY) $f_T = \mathcal{O}(1\,\text{kHz})$
- ^{90}Sr lab tests $f_T = \mathcal{O}(10\,\text{kHz})$, no tracking
- pulsed IR-LEDs $f_T = \mathcal{O}(10\,\text{kHz})$, wide beam spot

KArlsruhe high **RA**te **TE**st (KARATE)

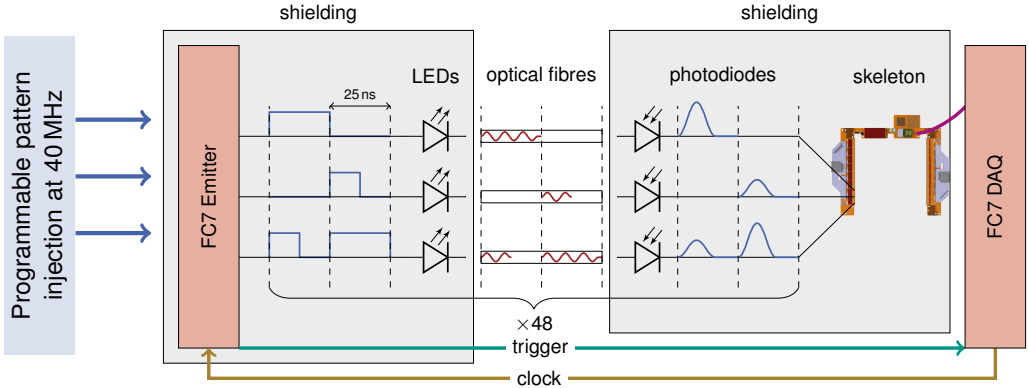
- developed for CBC tests by Stefan Maier (PhD Thesis[1])
- lab-based high-rate setup to test the 2S readout chain

[1] Maier, *Assembly and qualification procedures of 2S modules and high rate tests of the CMS Binary Chip for the Phase 2 Upgrade of the CMS Outer Tracker*, ETP-KA/2019-17

The KARATE Setup

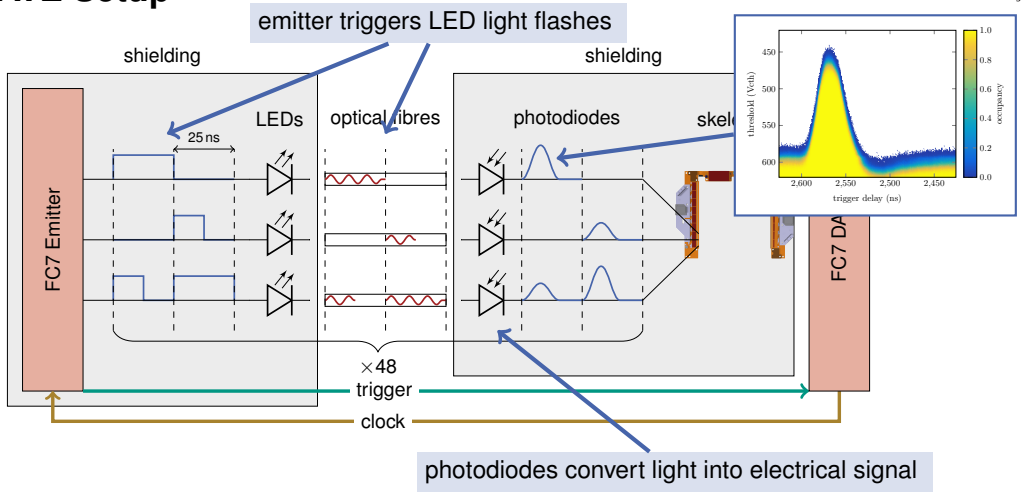


The KARATE Setup

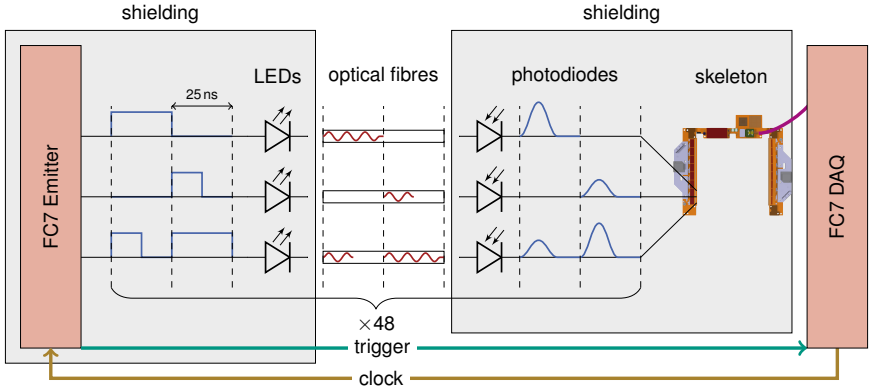


clock synchronisation and trigger

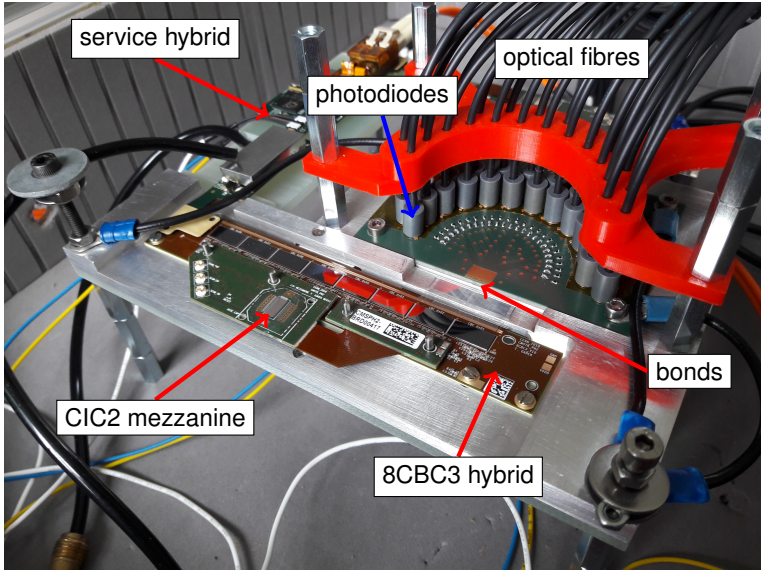
The KARATE Setup



The KARATE Setup



efficiency measurements by comparing injected and recorded pattern

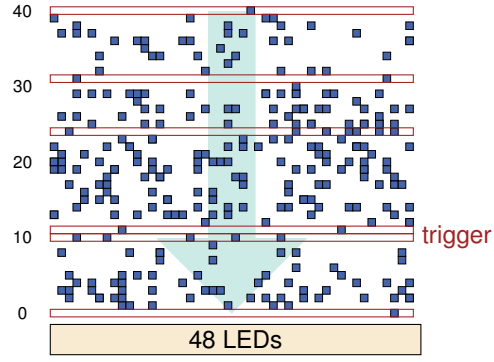

service hybrid
optical fibres
photodiodes
bonds
CIC2 mezzanine
8CBC3 hybrid

Pattern Injection

- individual pattern in 25 ns steps (bunch crossing rate of LHC)
- for each BX select channel and pulse length
- for each BX choose whether triggered or not

KARATE limits

- array of 48 equipped channels
- up to 24 clusters per event
- more clusters by shifting channels offsets (to noise)
- noise clusters in second FE to fill bandwidth



How to stress the readout chain?

CBC:

- unsparsified readout
- independent from occupancy!
- readout time 38 BX/event

→ $f_{T,max} = 1.05\,\text{MHz}$

→ stressed by high trigger rates

CIC:

- hit clustering
- up to 127 clusters/event
- dynamic event size

→ $f_{T,max}$ depends on occupancy

→ stressed by high occupancy + high trigger rates

⇒ scan over occupancy and trigger frequency

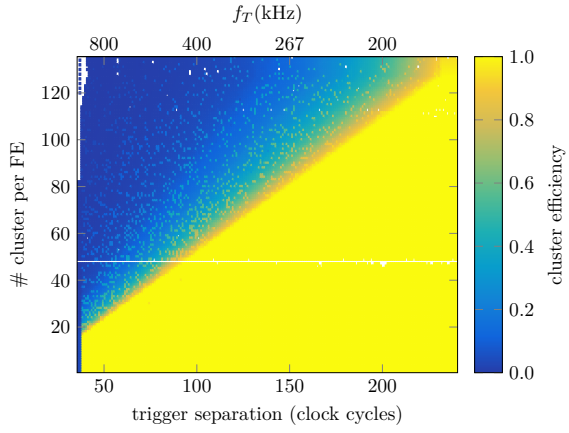
High Rate Measurements

constant trigger rate and occupancy

- inject pulses with fix length
- clear environment to indentify ultimate limits of the system
- scan over trigger separation and number of clusters per frontend and event
- 27 675 measurements, with 20k events each

Definitions

- $f_T = \frac{40\,\text{MHz}}{S}$
- events including an error (CBC or CIC) are inefficient
- cluster matching: seed is detected
- cluster efficiency: $\eta_{cl} = \frac{n_{matched}}{n_{inj}}$

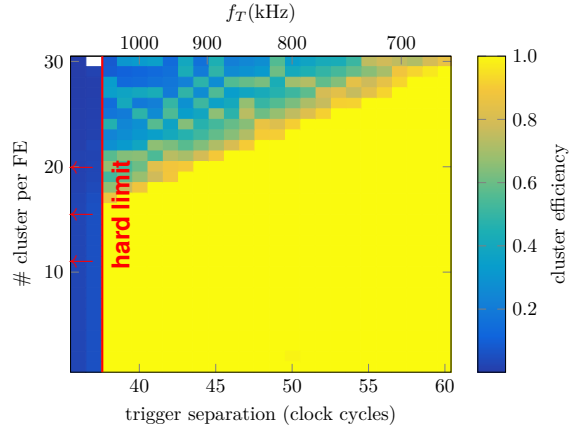


Hard limit:

- CBC readout bandwidth limitation: $S \geq 38$ BX
- Error: buffer overflow of the CBC

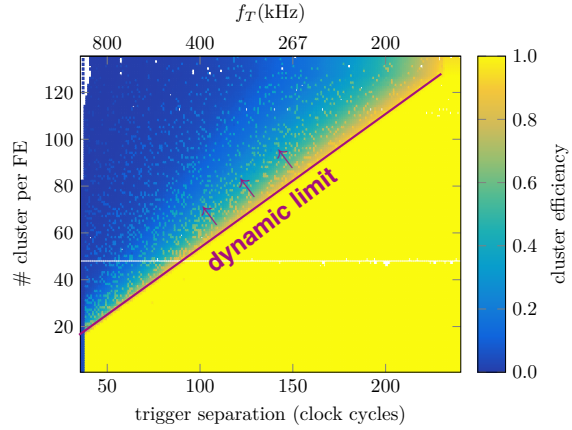
$\Rightarrow$ expected hard limit by CBC confirmed

$\Rightarrow$ trigger rules to prevent CBC buffer overflow



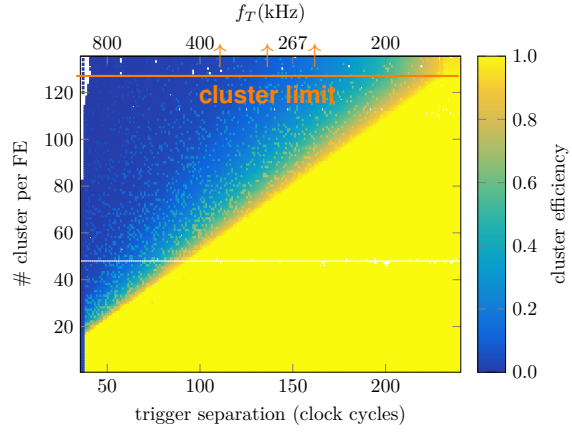
Dynamic limit:

- CIC bandwidth limit: 320 MBit s^{-1}
- soft overflow error if limit is reached (all CBC error flags + CIC error flag)
- number of clock cycles S to readout one event: $S(n_{cl}) = \frac{eventsize}{bandwidth} = \frac{52\,\text{Bit} + n_{cl} \cdot 13\,\text{Bit}}{8\,\text{Bit/clock cycle}}$
- linear dependence expected
- observation perfectly fits to what is expected



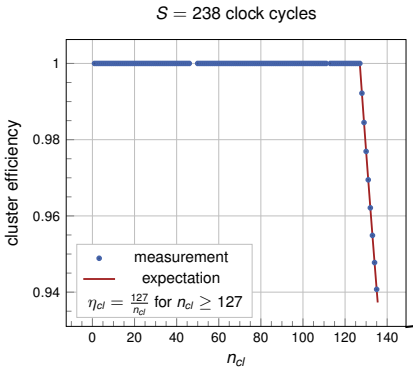
Cluster limit:

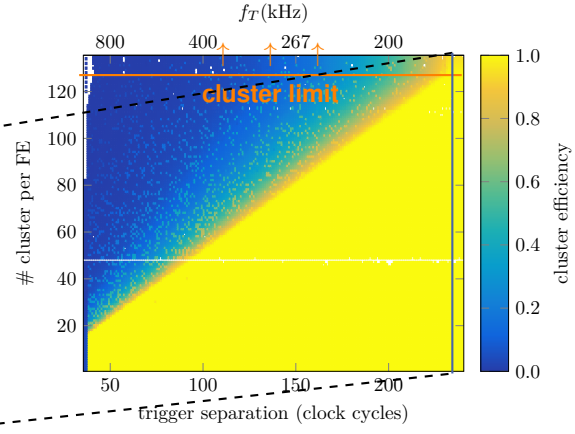
- CIC event format only allows $n_{cl,max} = 127$
- CIC drops clusters with lowest strip position
- loss of clusters as expected



Cluster limit:

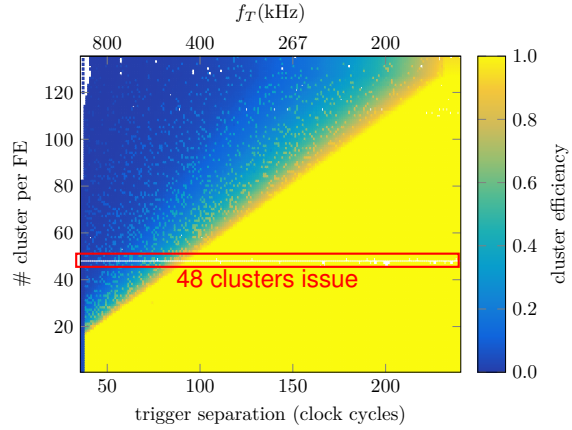
- CIC event format only allows $n_{cl,max} = 127$
- CIC drops clusters with lowest strip position
- loss of clusters as expected





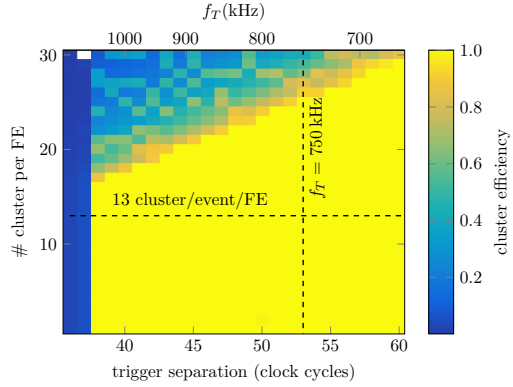
48 clusters issue:

- DAQ crashes in case an event contains 48 clusters
- DAQ developers expect firmware bug
- still to be confirmed/fixed!



Summary

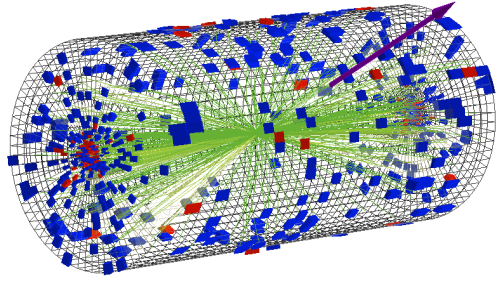
- high rate studies on the 2S module readout chain for the Phase-2 Outer Tracker Upgrade of the CMS experiment
- using the FPGA based KARATE system for pattern injection at LHC bunch crossing rate (40 MHz)
- efficiency by comparing injected and recorded hits
- commisioning with 2D scan constant trigger rates and occupancy
- observing the expected limits of CBC and CIC
- fully efficient for specified HL-LHC limits
- discovered hints to otherwise hidden problems



Outlook

- realistic pattern injection
- based on CMSSW simulation
- check different pileup scenarios
- scan over module positions within tracker

simulated PU200 event

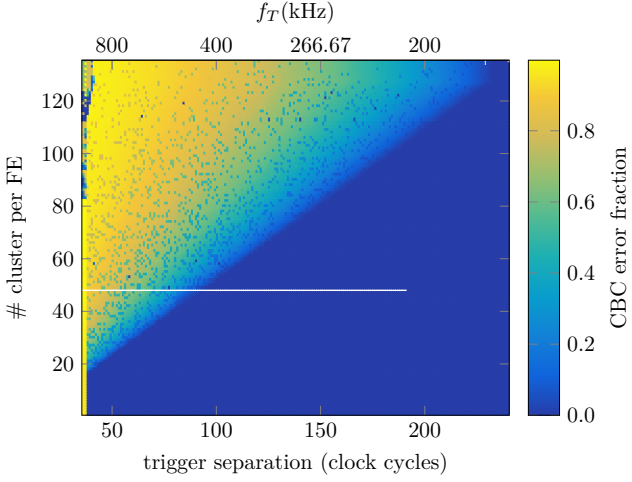


BACKUP

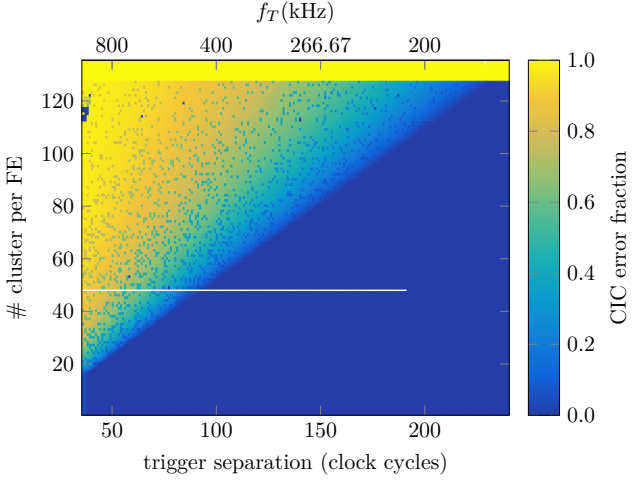
CIC Data Format

header												payload			
start sequence		error / status bit								L1 ID	nb clust		chip ID	Sclust address	width	
start séquence with 27 bits at '1'	**0**	CBC 8	CBC 7	CBC 6	CBC 5	CBC 4	CBC 3	CBC 2	CBC 1	CIC		**0**				.....
28 bits		9 bits								9 bits	7 bits	1 bit	3 bits	8 bits	3 bits	
52 bits																

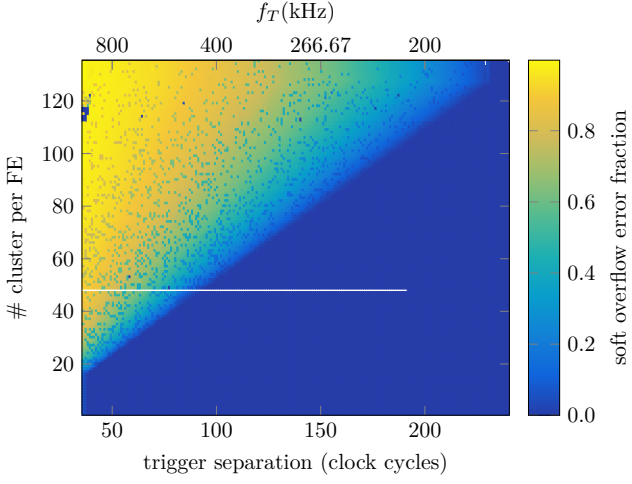
CBC Errors


f_T(kHz)
800
400
266.67
200
120
100
80
60
40
20
cluster per FE
50
100
150
200
trigger separation (clock cycles)
0.8
0.6
0.4
0.2
0.0
CBC error fraction

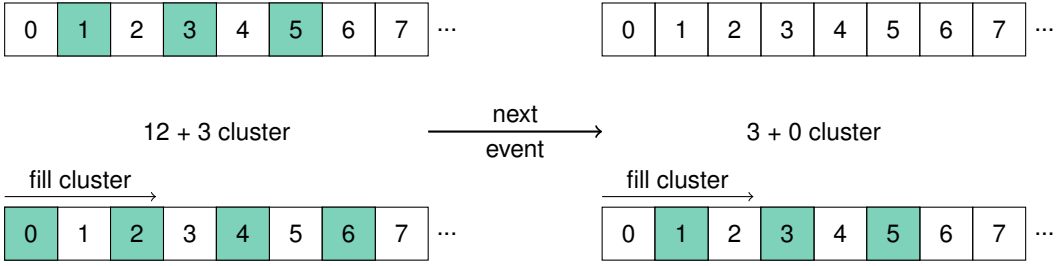
Cic Errors


f_T(kHz)
800
400
266.67
200
cluster per FE
120
100
80
60
40
20
50
100
150
200
trigger separation (clock cycles)
1.0
0.8
0.6
0.4
0.2
0.0
CIC error fraction

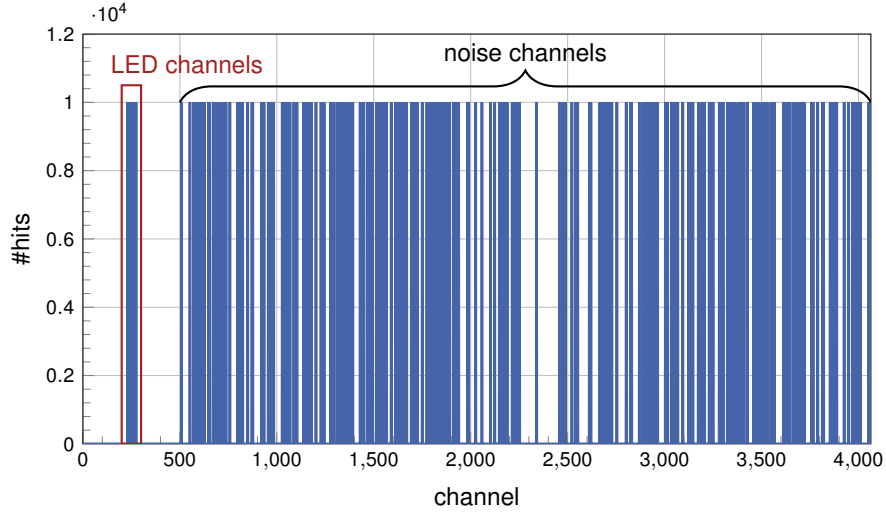
Soft Overflow Errors



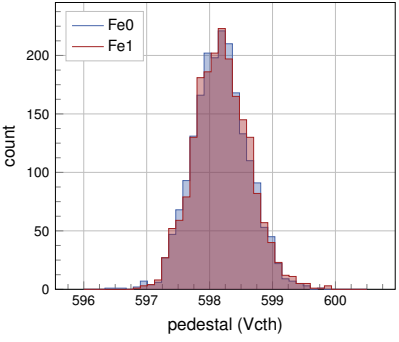
Cluster Injection

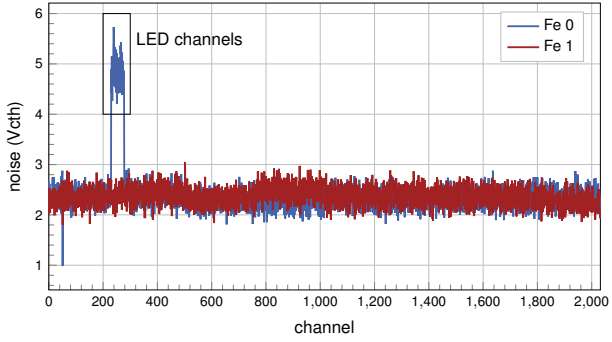


Hit map


·10^4
1.2
1
0.8
0.6
0.4
0.2
0
#hits
LED channels
noise channels
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
channel

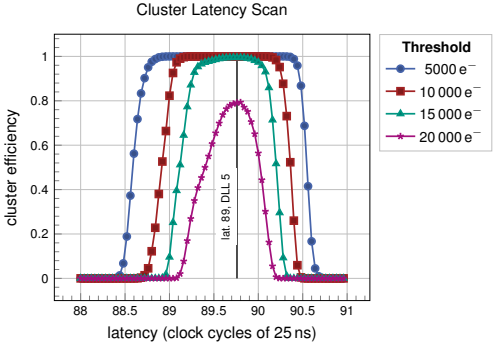
Offset calibration and noise measurements

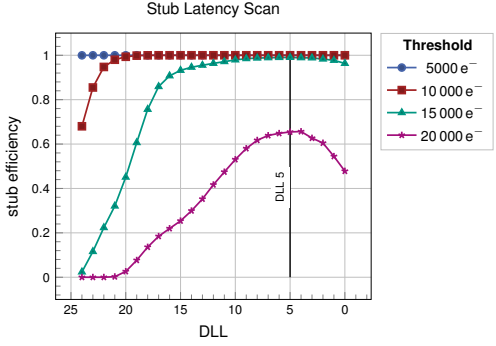




- pedestals sharp at $\approx$ 598 VCth
- noise of LED channels at $\approx$ 5 VCth
- unbonded channels at $\approx$ 2.5 VCth (one dead channel)

Latency Scans





- scan latency with hit injection for different thresholds
- pulse height $\approx 18\,000\,e^-$
- operation point for DAQ at 89 latency and 5 DLL