The readout electronics of the SciFi Tracker for LHCb detector upgrade

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Brazil (CBPF) - China(Tsinghua) - France (LPC, LAL, LPNHE) - Germany (Aachen, Dortmund, Heidelberg, Rostock) - Netherlands (Nikhef) - Russia (Kurchatov, ITEP, INR) - Spain (Barcelona, Valencia) - Switzerland (CERN, EPFL)



Figure : The LHCb detector

LHCb downstream tracker upgrade

Upgrade in 2018-19 Based on scintillating fibres readout by SiPMs

Detector performance:

- 40MHz readout
- ► resolution < 100µm in bending plane
- high hit efficiency; low noise (< 10% of the signal rate)
- ► minimize budget material in acceptance (X/X₀ ≤ 1% per layer)
- ▶ operations up to 50 fb⁻¹

Constrains:

- ► geometry
- radiation environement (≤ 80Gy at the location of the photo-detector, ≤ 35kGy peak dose for the scintillating fibres)

SC F



Figure : One station of the SciFi tracker

Scintillating Fiber tracker layout

- 3 stations
- 4 detection planes (XUVX) per station
- 12 modules per detection plane
- Fibers read out at top and bottom
- SiPMs, FE electronics and services in a *Readout Box*
- ▶ 32 SiPMs per module (width ≈ 530mm)
- ► 250µm channels
- ► 590k channels
- ► 4608 SiPMs

TDR:

https://cds.cern.ch/record/1647400/files/LHCB-TDR-015.pdf

Read-Out Box





Read-Out Box

- SiPM cold volume
- FE warm volume
- Connected to the fibre at one side and to the experiment data-acquisition, control system and services on the other

Characteristics

Fibre:

- ► Double-cladded scintillating fibers (Kurukay, SCSF-78, Ø250µm)
- Radiation studies: fast damage, recovery (annealing) and shift spectrum to the green

Multichannel SiPMs well suited for this application:

- Fast signal response
- Fast recovery

But need cooling at -40°C

Light yield

- Mirror in the middle to improve light yield
- Module will have 6 layers
- ► ≈ 16 PE expected for a MIP after 50 fb⁻¹





Figure : Picture of the fibre mat and the Hamamatsu SiPM

- Interaction of a particle with the scintillating fibres modelled in Geant4
- Each pixel of the SiPM can detect one photon
- The signal is proportional to the total number of triggered pixels
- The particle position can be calculated with a weighted mean value of the channel signal
- Note The fibres are not aligned to the detector channels and the photons can arrive at the detector outside the fibre area.



Figure : Simulation of the intercation of a particle with the scintillating fibres and the SiPM

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Front-End data path



Main components

- SiPM are connected to the FE chip (PACIFIC) using a flex cable
- PACIFIC: 64 channel ASIC with the analog processing and digitization
- Clusterization FPGA to handle the digital processing (zero-suppression)
- GBT: CERN ASICs (GBTx, GBT-SCA, GBLD) handling the electrical to optical conversion, the slow control and the timing
- TELL40: Standard DAQ board for LHCb

Front-end board design



Figure : Possible front-end board design

Description

- 2 Front-end board/Read-Out Box
- Modular design (maintenance and test)
- Each clusterization board handles 2 SiPM
- Clusterization FPGA: IGLOO2

- 8 optical links for the TELL40 (VTTx based)
- 2 optical links for the slow control, clocks, synchronisation (VTRx based)
- DC/DC converter to provide the needed voltages

The Front End Chip: PACIFIC



Figure : Synoptic of PACIFIC3

Description

- 64 channels ASIC dedicated to the SiPM readout, 130 nm TSMC
- ► Fast shaping (< 10*ns*)
- 3 thresholds digitization, 1/4 photo-electron resolution
- 160MHz single-ended serialized output

TWEPP'2015 presentation:

https://indico.cern.ch/event/357738/session/9/contribution/83



Description

- Common LHCb development for the back-end (PCIe board)
- GBT frame decoding and PCIe encapsulation
- ► 24 or 48 optical inputs: up to 220 Gb/s input bandwidth
- 110 Gb/s output bandwidth



PC farm

Figure : Bandwidth available at each processing stage

Available bandwidth

- ► PACIFIC digitization 2 × 2b × 64@40MHz
- ► Zero suppression (ZS) algorithm: 20.48Gb/s → 4.48Gb/s
- ▶ GBT: 112b@40MHz → 4.48Gb/s
- TELL40: 24 or 48 GBT inputs
- ► 16× PCIe v3.0 output allowing 110Gb/s

Constains

- FE board size and power consumption
- Cluzterization FPGA size (IGLOO2 with up to 120kLE)
- TELL40 FPGA size (has to handle 24 or 48 inputs and the PCIe output)

Solution used

- Barycentre processing done in the FE
- ADC data lost in ZS mode

ADC value



Figure : Example of clusters

Hardware

- The clusterization algorithm in the FE FPGA
- 128 inputs×2b (SiPM size, the gap between SiPM forbid overlapping algorithm)
- Target: Microsemi IGLOO2

Algorithm

- Mostly no cluster of size > 4 (simulation) ⇒ maximum cluster size, larger cluster will be merged by software
- Simple barycenter computation
- 4 thresholds: seed, neighbour and high in PACIFIC, sum in clusterization FPGA
 - Seed threshold: Candidate for a cluster
 - Neighbour threshold: With a seed, included in a cluster
 - High threshold: Cluster, no others conditions
 - Cluster sum threshold: Confirm a cluster (seed+neighbour)



Figure : 1 cluster detected

Figure : Multiple clusters found

Test beam

- Test beam events acquired in test beam using SPIROC readout in 2014
- Un-irradiated detectors



Figure : Simulated mean occupancy of one quarter of the the detector in the hottest layer

Occupancy simulation

- Maximum: 4.5 clusters/SiPM/event after the clusterization processing
- ► 0.05 hits / SiPM / event of noise

Probability of truncation



GBT frame : 112b/event

bits per cluster	Max. N ^o cluster		
	/ event (20b header)		
8	11		
9	10		
12	7		
16	5		

For each cluster, the minimal information for $\approx 70 \mu m$ precision is: SiPM channel ID (7b) + Inter-channel position (2b) = 9b

Figure : Probability of truncation / Maximum numbers of clusters

Truncation simulation

The simulation shows that:

- We can not cope with more than 9b
- In the hot zone (inner module): need to be able to sent > 10 clusters
- Cold zone (5 outer modules): 10 clusters is enough
- ⇒ Different frame formats

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Frame format: High occupancy

Reminder: A GBT frame = 112b@40MHz



Figure : Frame format in the high occupancy region

Description

- ► 20b header + 9b × number of clusters
- Max. number of cluster: 16
- Headers aligned on 28b (4 fragments/GBT frame) to ease the decoding
- '0' padding used for the 28b alignment
- A event can be split on several GBT frame
- Idle frame are sent when
- Very versatile frame format
- Used for the inner module

Reminder: A GBT frame = 112b@40MHz



Figure : Frame format in the low occupancy region

Description

- 20b header + 9b × number of clusters
- Max. number of cluster: 10
- 1 event/GBT frame
- '0' padding used for the 112b alignment
- Truncation when more than 10 clusters
- Easier decoding



Figure : Simulated data rate of the 1st inner module

High occupancy (inner module)

- ► 37.5Gb/s for the full module
- 16 links connected to 1 TELL40 (110Gb/s input bandwidth)



Figure : Simulated data rate of the 5 outer modules

Low occupancy (5 outer module)

- 40 links connected to 1 TELL40 (220Gb/s input bandwidth)
- 2 low occupancy TELL40/module: 50 Gb/s and 40 Gb/s used



One quarter of one plane of the detector

Figure : Simplified view of the optical links connection for one quarter of a detection plane

Description

- Factor 2 security margin
- 3 TELL40 / quarter of detector plane
- Actual connection may be optimized to average the links occupancy

Conclusion

The SciFi tracker generate 47.1 Tb/s of data:

- Software trigger: all the data have to be sent to the farm
- Zero-suppression algorithm
- Cluster processing on the FE FPGA
- Optimized frame format (20b header + 9b of data/cluster)
- \Rightarrow Sustainable bandwidth

Next steps

Prototyping:

- FE board prototype under test
- Full scale PACIFIC submitted to foundry
- Clustering algorithm optimization (test beam, simulation)

SPARES



Figure : Simulated hit map for minimum bias event (T1) with v = 2.5



Figure : 2013 SiPM dark noise at nominal voltage and -60°C, irradiated at $2\times10^{11} n_{eq}/cm^2$



Figure : 2013 Hamamatsu SiPM dark noise at nominal voltage and 25°C, non-irradiated



Standard Hamamatsu 2012 - Irradiation 50 fb-1

Figure : 2013 SiPM simulated cluster noise at nominal voltage irradiated at $2 \times 10^{11} n_{eq}/cm^2$

SiPM signals 1/3: Single cell

Hamamatsu SiPM:





Figure : Comparison between the SiPM for Ketek and Hamamatsu measurements (2013 samples) on 50Ω and the model

Single SiPM cell

- Two SiPM provider: Ketek and Hamamatsu
- Latest versions expected in 2015

Measurements on 50Ω (2013):

- Hamamatsu SiPM return to its baseline in \approx 50*ns*, while the Ketek SiPM needs \approx 250*ns*
- ► Amplitude: 1.4mV for the Ketek SiPM and 0.5mV for Hamamatsu SiPM





Figure : Mean photon time-of-arrival at x = 50 cm, x = 150 cm and x = 24.9 cm

Figure : Combining the Hamamatsu SiPM model with the photon time-of-arrival simulation at x = 60cm (left) and x = 250cm (right)

Simulation of the SiPM signal

- Convolution of the SiPM model with the simulation of time of arrival of the photon for 1MIP
- Generated from Geant4 simulation
- Simulations made from 0 to 250cm by step of 22cm (irradiated and no-irradiated)
- Second peak: mirror at the end of the fibre
- Signal shape dominated by large statistical fluctuation
- Signal in more than 25ns: effect decreased by the fast shaping, the remaining spill-over is handled by the software

Hit resolution



Figure : Hit resolution (linear 6 bits)





Study

- Resolution of the hit position with 6 bits digitization (linear scale) and 2 bits digitization (non-linear scale)
- Geant4 simulation
- No spill-over
- ► Study with 4 × 10⁶ clusters
- Resolution computed as the mean channel position from hit - mean channel position from clustering
- Thresholds used:

Neighbour	Seed	High	Sum
1.5PE	2.5PE	4PE	4PE

Results

6 bits digitization:

► RMS hit resolution: 64µm

3 thresholds (2 bits):

► RMS hit resolution: $69\mu m$

Both case show a resolution below the required $100 \mu m$



Figure : The expected dose in the x - y plane at T1



Figure : The expected 1-MeV neutron equivalent fluence per \mbox{cm}^2 at T1

Radiation

- ► Estimated using FLUKA simulation of the LHCb detector for the expected conditions
- For the SiPMs/FE electronics ($y = \pm 250 \text{ cm}$):
- \Rightarrow neutron fluence: $13 \times 10^{11} n_{eq}/cm^2$ (T3)
- \Rightarrow TID: 40-80 Gy (T1)
 - Neutron shield can reduce by a factor 2 the fluence for the SiPM