The electronics of the upgraded LHCb calorimetry system

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on behalf of the LHCb collaboration
The LHCb detector

Forward arm spectrometer: study of CP violation, physics of b-quark, B-mesons, charm and heavy hadrons
The LHCb detector

- Vertexing
- RICH detectors
- Calorimeters
- Muon
- Tracking

2008 JINST 3 S08005
Run 1-2 LHCb calorimetry system

- Solid angle coverage 300x250 mrad
- Distance from interaction point ~12.5 m
- Four sub-detectors: SPD, PS, ECAL, HCAL
- Based on scintillator/WLS (with PMTs)

- L0 trigger on high $p_T$, $e^\pm$, $\pi^0$, $\gamma$, hadron
- Precise energy measurement for $e^\pm$ and $\gamma$
- Particle identification: $e^\pm/\gamma$/hadron, and contributes to Muon ID (HCAL)
LHC upgrades timeline

**LHC roadmap: according to MTP 2016-2020 V2**

- **LS2** starting in 2019 => 24 months + 3 months BC
- **LS3** LHC: starting in 2024 => 30 months + 3 months BC
- **Injectors:** in 2025 => 13 months + 3 months BC

| Year | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
|------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 2015 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 2016 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 2017 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 2018 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 2019 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 2020 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 2021 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

**Phase 1**
- **Run 2**
- **LS 2**

**Phase 2**
- **Run 3**
- **LS 3**
- **Run 4**
- **LS 4**
- **Run 5**
Phase-I LHCb upgrade

The 1 MHz L0 trigger saturates physics processes yield with increasing luminosity

➔ At high luminosity, need to increase $p_T$ threshold to remain within 1 MHz
➔ Rate reduced, fraction of events of interest remains the same
➔ Rate of physics processes saturates
Phase-I upgrade strategy

**SOLUTION**: remove the first level hardware trigger

Electronics need to be redeveloped
Phase-I upgrade strategy

- Control boards fully redesigned (now called 3CU)
- Crates modified
- Power supplies kept and adapted to new requirements

➔ Part of trigger calculation (LLT)
➔ Front end data
Calorimeters & front end electronics

Front end electronics of calorimeters

Calorimeters

Protons
Calorimeter crates

On gantry above calorimeter: 18 crates

- 18 crates for ECAL and HCAL:
  - Control unit (3CU)
  - Up to 16 FEBs

- Each 3CU receives (1 bi-dir. link)
  - The clock
  - The fast command
  - The slow control
  - ... and distributes them on the backplane

- Each FEB receives clock, commands and configuration from 3CU (backplane) and provides data on 4 optical links (mono-dir)

- Data from 1 FEB is made of
  - ADC values of the 32 channels
  - The Low Level Trigger (LLT), i.e. the result of a sum/comparison that can be used by the software trigger in the PC farm
Run 1-2 analog signal processing

Specifications
- Pulse shaping in 25 ns
- Spill-over (residual signal) < 1% after 25ns
- Integrator plateau: 4ns
- Linearity < 1%
- Rise time ~5ns

Clipping
- Reduce signal tail
- Reduce spill over

Integrator discharge
- Clipped signal
- Delayed negative clipped signal

Detector cells
Before clip
After clip

5ns
50Ω
12m cable

Analog Chip

PMT

R_f = 12MΩ

C_f = 4pF

BUFFER

INTEGRATOR

100nF

22nF

12b ADC

BiCMOS 0.8um integrated circuit
8 channels per chip
Electronics upgrade motivation

Reduction of PMT gain needed:
→ FE electronics gain has to be increased...
→ …but FE noise should not be increased in the process!

Proposed solution is to design a new ASIC: ICECAL chip
→ Increased gain
→ Reduced noise
→ Integration/shaping
FEB processing @ 40 MHz

- Signals from 32 PMTs
FEB processing @ 40 MHz

- Signals from 32 PMTs
- Shaping and integration of the analog signal on ICECAL chip
FEB processing @ 40 MHz

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- 12-bit conversion on commercial ADCs
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- Processing of signal in radiation tolerant FPGA-Microsemi (ACTEL) Igloo2 family:
  - Pedestal subtraction and low frequencies noise cancellation
  - Numerical correction and event formatting
  - LLT calculation
FEB processing @ 40 MHz

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- Data transmission to neighbouring FEBs and to TELL40
ICECAL chip architecture

- Very difficult to integrate HQ delay lines
- Switching noise
- Active termination at input to avoid resistor noise

2 switched alternate paths
Fully differential
ICECAL: how does it work?
ICECAL: how does it work?

The diagram illustrates the ICECAL system flow, starting with input signals and proceeding through the following stages:

1. **Current amplifier** (PZ output)
2. **Filter**
3. **Offset**
4. **Switched Integrator**
5. **Track-and-Hold**
6. **Multiplexer**
7. **ADC driver**

The diagram also shows the clock input and the PMT signal at different stages of the system, including the current amplifier output and a time axis (time(ns)) from 60.0 to 200.0.
ICECAL: how does it work?

CLOCK
INPUT

INTEGR. OUTPUT

Main signal
Tail
ICECAL: how does it work?
ICECAL: how does it work?

CLOCK INPUT

CHANNEL OUTPUT

Main signal

Tail

Current amplifier
Filter
Offset
Switched Integrator
Track-and-Hold
Multiplexer

ADC driver

PZ

TH

I

time (ns)

V (V)

60.0 80.0 100.0 120.0 140.0 160.0 180.0 200.0

-0.8 0.0 0.8 1.6 3.4
ICECAL ASIC

➔ Complete 4 analog channels
➔ 4 DLL synchronization
➔ Slow control registers (SPI interface)
➔ Tunable parameters
ICECAL ASIC tests: non-linearity

Non linearity < 1%
ICECAL ASIC tests: Spill-Over

- Prev 1 ~ 0.5%
- Next 2 ~ 1.8%
- Next 3 ~ 1.2%
- Next 1 ~ -0.6%
ICECAL ASIC tests: Plateau

![Graph showing the normalized output signal (%) vs. relative time of arrival (ns). The graph indicates a plateau with a width of ±2ns and a variation of Δ ~ 1%.]
ICECAL ASIC tests: Noise

Noise = 1.1 LSB

Noise after pedestal subtraction = 1.3 LSB
ICECAL ASIC: Radiation hardness

**Electronics radiation levels expected exposure:**
- Dose: < 100 rad/fb\(^{-1}\) (5 krad for 50 fb\(^{-1}\))
- High energy hadrons: \(4.2 \times 10^{10}\) parts/cm\(^2\)
- Neutrons: \(2.55 \times 10^{12}\) parts/cm\(^2\)

**TID tests:**
- Use beam of 61 MeV protons
- Dose up to 55 krad on 4 chips
- Results:
  - No SEU or SEL was detected
  - No relevant variation on the chips characteristics

**SEE tests:**
- Irradiate with heavy ions: \(^{58}\text{Ni}^{+18}\)
  - LET = 20.4 MeV/mg/cm\(^2\)
- Two chips were irradiated: no SEU detected
- Equivalent expected limits for all channels in detector lifetime: 1.3 SEU and 0.9 SEL.
ICECAL ASIC: Production and test

**FE production requirements**

- FE production: 310 boards
  - ECAL+HCAL: 246 boards
  - + ~15% contingency
- Required chips: 2480

**Production**

- 3167 pieces

**Quality control passed**

- 2894/3167 pieces (91.4%)

- Motorized horizontal gantry system to move the chips from tray to the test PCB and to final tray.
- Motorized stage in the vertical direction.
- Pneumatic suction
- Pressure sensor
Conclusions

Major upgrade of LHCb detector for next data taking period of LHC, in 2021

- Removal of L0 HW trigger, switch to full software trigger running at 40 MHz
- Reduction of PMTs gain by a factor 5

The Calorimeter system of LHCb is part of the upgrade

- Replacement of electronics of ECAL and HCAL to send full data flow to counting room @ 40 MHz
- Partial compensation of PMTs gain in electronics necessary, but without increasing noise in the process

New Front End Boards developed

- Shaping and integration via customly designed ICECAL ASIC
- FPGA for pedestal sub., noise cancellation, numerical correction, event formatting, LLT calculation

Design and testing of analog circuit has been shown to fulfill the requirements

- Non linearity < 1%
- Very limited spill-over
- Low noise, around 1.3 LSB (corresponding to ~7 MeV)
- Excellent results in terms of radiation hardness
Acknowledgements

Thank you for your attention!
backup
Non-linearity