A new Readout Control System for the LHCb Upgrade at CERN

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The upgrade of the LHCb experiment

LHCb in 2012

- ✓ Instantaneous luminosity in IP of $4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ (factor 50 less than nominal LHC lumi)
- ✓ Expected $\int \mathcal{L} = 5\text{-}10 \text{ fb}^{-1}$ collected after 5 years of operations
- Probe/measure NewPhysics at 10% level of sensitivity
- Measurements limited by statistics and detector itself
- World best measurements in flavor physics and rare decays already performed in 2011-2012

↓ **Upgrade!** (During LHC Long Shutdown 1 in 2018)

S-LHCb in 2018-19

- ✓ Collect $\int \mathcal{L} = 50 \text{ fb}^{-1}$ → a factor 10 increase in data sample and in reasonable time
 - probe NewPhysics down to a percent level
- ✓ Increase luminosity by a factor 10 @ LHCb, up to $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
 - 28 MHz S-LHCb effective collisions rate vs. 1 MHz LHCb
 - 1 MHz bb-pair rate @ S-LHCb vs. 100 KHz @ LHCb

More than:

- Excellent vertexing resolution
- Excellent mass resolution
- Excellent particle identification
- Efficient trigger
- Low background

The challenges of the LHCb upgrade

- ✓ **Pile-up (N)**: number of interactions per LHC bunch-bunch crossing
 - LHCb designed for $\langle N_{\text{max}} \rangle = 1$
 - $\langle N \rangle = 1$ @ $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ / $\langle N \rangle = 4$ @ $20 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- ✓ **Higher radiation damages** over time
- ✓ **Spill-over** not minimized
- ✓ Current **first-level trigger limited for hadronic modes** at $> 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
 - **25% efficiency vs. 75% for muonic modes**
- ✓ Full readout of 28 MHz of bunch-bunch crossing
 - current first level trigger selects only 1 MHz of events

Upgrade!

- ✓ **New technologies for sub-detectors to be replaced**
 - More radiation hard, Reduced spill-over, Improved granularity
- ✓ **Continuous 40 MHz *Trigger-free* Readout Architecture**
 - all detector data passed through the readout network
 - fully software trigger analyzing events at 40 MHz

Upgraded LHCb Readout System

Upgraded LHCb Readout System

Fully trigger-free
40 MHz readout
architecture!

LHC clock

Timing &
Fast
Control
System

MEP Request

Output rate of processed events
20kHz
(currently is 4.5 kHz)

Use of **bidirectional** links
to/from FE
Based on CERN GigaBit
Transceiver (GBT)

~400 Readout
Boards
(TELL40)

multi-Terabit/s
Event Building
network

>5000 CPU
processing multi-core
nodes
O(50k cores)

Upgraded LHCb Readout System

Fully trigger-free
40 MHz readout
architecture!

LHC clock

New Timing and Fast
Readout Control
System for the LHCb
upgrade

System and functional requirements of the new Readout Control system

1. Bidirectional communication network
2. Clock jitter, and phase and latency control
 - ✓ At the FE, but also at the Readout Boards and between S-TFC boards
3. LHC interfaces
4. Low-Level-Trigger input
5. Events rate control
6. Destination control for the event packets
7. Event data bank
 - ✓ Information about transmitted events
8. Sub-detectors calibration triggers
9. Partitioning to allow running with any ensemble and parallel partitions
10. Support for old Timing and Trigger based distribution system
11. Test-bench support + flexibility as it should be ready for testing!

A new LHCb Readout Control System

A new LHCb Readout Control System

Readout Supervisor
(called S-ODIN)
+
a set of **Interface boards**
(called **TFC+ECSInterface**)
=
S-TFC system
(S - Timing and Fast Control system)
for the LHCb upgraded readout architecture

The physical S-TFC system

LHC clock, LHC interfaces

TFC on backplane

Entire architecture
based on **ATCA**
technologies and
common electronics
(developed at CPPM, Marseille)

TFC+ECS

RS → common **AMC card**
LLT → common **AMC card**
Readout board → common **AMC card**
LHC Interfaces → common **AMC card**
with special mezzanine

S-TFC system concept

✓ **Readout Supervisor** multi-master in one single FPGA (multi-cores)

- 1 core master for main readout
- others for local tests

✓ **Switching fabric inside FPGA**

✓ **Use of bidirectional links**
→ ALTERA GX transceivers

✓ **TFC+ECSInterface** contains fan-in/fan-out timing and trigger logic to FE and Readout Boards

- Optionally can act on as master for local tests

✓ **Manages ECS configuration and monitoring of FE**

✓ **Uses backplane** to connect to Readout Boards

Clock distribution and phase/latency control

✓ LATENCY

- Alignment with LHC bunch crossing identifier (BXID)

✓ FINE PHASE

- Alignment with best sampling point

✓ 3 types of links to be studied

Clock distribution and phase/latency control

1. at the FE: CERN GBT

→ *Does the job for us*

→ control of fine phase + latency at the FE + minimize jitter

→ No problem in ECS monitoring

- Simply decoding GBT protocol in TFC+ECSInterface FPGA

→ No need of fine phase or latency control for ECS.

Clock distribution and phase/latency control

2. ATCA backplane

→ *Does the job for us*

- control of latency
- jitter and fine phase less of an issue
- Effectively is an FPGA-to-FPGA link on backplane dedicated lines
- To be tested: jitter on backplane!

Clock distribution and phase/latency control

3. FPGA to FPGA transceivers

→ Special studies on latency and phase alignment
→ (see later for preliminary tests)

→ control of fine phase and latency
→ minimize jitter

Validation tests

First preliminary tests on phase/latency control using:

1. First AMC prototype with ALTERA Stratix IV
2. First Stratix IV low level interfaces

→ Nios + board resources interfaces

✓ **8b/10b protocol: no problem**

- Using «word alignment» from Altera GX buffer + «deterministic latency»
- Simply add Ctrl word for the 8b/10b encoder: 2bits more
- Full reproducibility upon power-up and resets and reconfiguration

✓ **FPGA-to-FPGA GBT protocol: ok, but needs special frame alignment**

- No deterministic latency if no special words are sent!
- Needs a special word (10 bits minimum) at power-up/after reset/after reconfiguration for the GX buffer to realign to the beginning of the frame + «deterministic latency»
 - First preliminary tests were ok, *but needs more validation*

TFC and ECS over the same link

Relay/merge block logic:

Generic approach:

- control FE from the uplink
- addressing map and GBT-busses protocol drivers
 - ✓ No need of special protocol, simply address the right chip with the right bus using the CERN GBT generic protocol
 - ✓ Same for every sub-detector → needs simply configuration

Running a «*hybrid*» system

Suggested the idea of an **hybrid system**:

reminder: some first-level trigger electronics relying on TTC protocol

- part of the system runs with old Timing and Trigger system
- part of the system runs with the new architecture

How?

1. Need bidirectional connection between new Readout Supervisor (S-ODIN) and old Readout Supervisor (ODIN)
 - use dedicated PICMG 3.8 compatible RTM board
2. In an early commissioning phase ODIN is the master, S-ODIN is the slave
 - S-ODIN task would be to distribute new commands to new FE, to new TELL40s, and run processes in parallel
 - ODIN tasks are the ones today + S-ODIN controls the upgraded part
 - ✓ In this configuration, upgraded slice will run at 40 MHz, but positive triggers will come only at maximum 1.1MHz...
 - Great testbench for development + tests
3. In the final system, S-ODIN is the master, ODIN is the slave
 - ODIN task is only to interface the L0 electronics path to S-ODIN and to provide clock resets on old Timing and Trigger protocol

Conclusions

Outlined new Timing, Trigger and Readout Control system for the LHCb upgraded readout electronics:

- ✓ Based on **FPGAs** and **bidirectional optical links**
- ✓ Based on **ATCA technologies** and **common readout electronics**
- ✓ To **control the readout** by transmitting:
 - **Synchronous commands**
 - **Timing and clock** with a **controlled phase** and **fixed latency**
 - **Trigger decisions**
 - **Trigger throttle** in case of back-pressure or readout load
 - **Events destination**
- ✓ To **configure and monitor the FE electronics over the same link**
 - By using the **CERN GBT protocol**
 - By having an **addressing scheme** and **bus driving protocol** directly into FPGAs
- ✓ To allow running a **hybrid system**
 - **Old and new together!**
- ✓ Complete **simulation and verification testbench** under development
- ✓ **First version of the system** to be ready by end of 2012 and **first readout slice** to be tested in 2013

Backup

CERN

Readout Supervisor, specs

Board with one big central FPGA (Altera Stratix IV GX or alt. Stratix II GX for R&D)

- Instantiate a set of TFC Master cores to guarantee partitioning control for sub-detectors
- TFC switches is a programmable patch fabric: a layer in FPGA
 - no need of complex routing, no need of “discrete” electronics
- Shared functionalities between instantiations (less logical elements)
- More I/O interfaces based on bidirectional transceivers
 - depend on #S-ROBs crates
- No direct links to FE
- Common server that talks directly to each instantiation:
 - TCP/IP server in NIOS II
- Flexibility to implement (and modify any protocol)
 - GX transceiver as IP cores from Altera
- Bunch structure (predicted/measured) rate control
- State machines for sequencing resets and calibrations
- Information exchange interface with LHC

TFC+ECSInterface, specs

Board with FPGA entirely devoted to fan-out TFC information/fan-in throttle info

- Controlled clock recovery
- Shared network for Throttling (Intelligent) & TFC distribution
- All links bidirectional
 - 1 link to S-TFC Master, 2.4 - 3.0 Gb/s, optical
 - 1 link per S-ROB, 20 max per board (full crate)
- Technology for S-ROBs links could be backplane (ex. xTCA) or copper HI-CAT
- Protocol flexible: compatibility with flexibility of S-TFC Master
 - We will provide the TFC transceiver block for S-ROBs' FPGA to bridge data to FE through readout link S-FE → S-ROB
- For stand-alone test benches, the Super-TFC Interface would do the work of a single TFC Master instantiation

First Readout Supervisor HW implementation

First TFC+ECSInterface HW implementation

- Clock fully recovered from data transmission (lock-to-data mode)
 - Phase adjusted via register on PLL
- Jitter mostly due to transmission over fibres, could be minimized at sending side

- ## 2. Scan the phase of clock within “eye diagram”

Still investigating feasibility and fine precision

Simulation

→ Full simulation framework to study buffer occupancies, memories sizes, latency, configuration and logical blocks

Event Destination and Farm Load Control

The current system operates in a powerful mixture of *push and pull protocol* controlled by ODIN :

- ✓ Asynchronous pull mechanism
- ✓ “Push” driven by trigger type and destination command

→ 4 years faultless operation

Similar proposal for upgrade

Event Destination and Farm Load Control

Central FPGA based implementation

- Extreme reliability, flexibility, speed, controllable latencies

→ Central event packing control

- Different trigger types and destination types
- Variable MEP packing factor

→ Dynamic rate regulation as function of farm rate capacity

- Accounts for statistical variations in processing time

→ Dynamic handling of farm nodes in-flight

- Processing blockages, failures, interventions
- All impacts on rate capacity handled automatically
- As soon as nodes are recovered, included automatically in-flight by event request mechanism

→ Minimal event loss and accurate dead-time counting

Contrary to conventional pull scheme, this is robust against event request packet losses

Event Destination and Farm Load Control

Buffer requirement trivia

- Readout boards: ~1.5 MEPs per link
- Network: Some naïve assumptions
 - Rate: 30 MHz
 - MEP packing factor 10 → 3 MHz MEPs and 3 MHz MEP Requests
→ Current ODIN can handle 1.8 MHz of MEP Requests (ODIN ↔ FARM is 1 GbE...)
 - Event size 100 kB → 1 MB / MEP
 - Farm nodes 5000 → 600 MEPs/node/s → 1.7ms / MEP
 - Switch subunit sharing resources: 50 links / subunit → 100 subunit
→ 30 kHz of MEPs per switch subunit
→ Every 1.7ms, 50 MEPs to juggle with → <buffer> = O("50 MB")
→ True need of memory depends on statistical variation of HLT processing time and "local farm derandomizer"
- Farm nodes: few MEPs in local derandomizing buffer

In our view, this looks like a straight-forward implementation...

S-TFC Protocols

- **TFC control** fully synchronous **60bits@40MHz**
 - 2.4 Gb/s (max 75 bits@ 40 MHz → 3.0 Gb/s)

BXID (12 bits)	TFC information (32 bits)	ReedSolomon-FEC (16 bits)
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- ✓ Reed Solomon-encoding used on TFC links for maximum reliability
 - based on CERN-GBT
 - ✓ Asynchronous data
 - TFC info carry Event ID
 - ✓ **24 bits of TFC information relayed to FE electronics (see later) by TFC+ECSInterface**
- **Throttle** protocol: each bit in Throttle is flagged by a Readout Board

BXID (12 bits)	THROTTLE information (20 bits)	OTHERS	ReedSolomon-FEC (16 bits)
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- ✓ Must be synchronous (currently asynchronous)
 - Protocol will require alignment between various input from Readout Boards
 - Done in TFC+ECSInterface for each readout cluster

S-TFC protocol

TFC Word to BE via TFC+ECSInterface:

→ 44 bits (60 with Reed-Solomon encoder) @ 40 MHz = 1.76 (2.4) Gb/s

Encoding	43 .. 32	31 .. 16	15 .. 12	11 .. 8
TFC Info	BID(11..0)	MEP Dest(15..0)	Trigger Type(3..0)	Calib Type(3..0)

7	6	5	4	3	2	1	0
Trigger	BX Veto	NZS	Header Only	BE reset	FE reset	EID reset	BID reset

Constant latency after S-ODIN

✓ **THROTTLE Information from BE:** 1 bit per board connected to TFC+ECSInterface.
Full set of bits sent to S-ODIN by TFC+ECSInterface.

S-TFC protocol to FE!

TFC Word to FE via TFC+ECSInterface:

→ 24 bits in GBT frame @ 40 MHz

Encoding	23 .. 12	11 .. 9	8 .. 5	4	3	2	1	0
TFC Info	BID(11..0)	Reserve	Calib Type(3..0)	BX Veto	NZS	Header Only	FE reset	BID reset

- ✓ 56bits leftover in GBT frame are dedicated to ECS configuration
- ✓ uplink of GBT is dedicated to ECS monitoring of FE

S-TFC FE commands

Crucial information: the decoding and sequencing (delays etc...) of these has to go in the FE design

“BXID” (+BXID Reset)

- Every TFC word carries a BXID for synchronicity of the system

“FE RESETS”

- Reset of Bunch Counter and Event Counter

“BX VETO”

- Based on filling scheme, processing of that particular event is rejected
 - ✓ Only header or basic bits sent from FE to TELL40s for that BXID
 - ✓ Allows “recuperating” clock cycles for processing “real” events

“HEADER ONLY”

- Idling the system: only header if this bit is set
 - Multiple purposes (Resets, NZS scheme, etc...)

“CALIBRATION PULSES”

- Used to take data with special pulses (periodic, calibration)
 - ✓ Associated commands at fixed latency to FE
 - ✓ S-ODIN overrides LLT decision

“NZS MODE”

- Allows to read out all channels in FE (or all channels connected to a GBT)
 - ✓ Subsequent BXIDs are vetoed to allow packing of data into GBT frames
 - ✓ Only header or basic bits sent: use “Header Only” function

«BX VETO»

@ 40 MHz

S-ODIN vetoes the readout of an event

Based on filling scheme

- Used to control the rate of readout while $< 30\text{MHz}$
- INDEPENDENT FROM LLT DECISION!

FE can use this info to recuperate time for processing events

- Only header for vetoed events
- Flexible packing of data into GBT frame

Sending a «LLTyes»

@ 40 MHz

S-ODIN receives decisions from LLT

Special triggers

S-ODIN aligns and applies priority scheme on trigger types

Rate regulation
(next slide)

S-ODIN sends out a «LLTyes» to TELL40 at
a fixed latency wrt BXID!

Rate regulation

@ 40 MHz

TELL40 raises the throttle bit

TFC Interfaces compiles a throttle word with BXID and sends it to S-ODIN

MEP request scheme
(next slide)

S-ODIN rejects event(s) until throttle is released

→ In practice: the subsequent “LLTyes”(s) become “LLTno”(s)!