A 3D CAD rendering of the LHCb detector upgrade. The image shows a complex arrangement of detector components, including a large blue rectangular structure on the left, a yellow frame-like structure in the center, and a series of stacked, multi-layered detector modules on the right. Various cables and smaller components are visible throughout the assembly.

100Gbps PCI-Express Readout for the LHCb Upgrade

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Overview

- ▶ PCIe40 board architecture
- ▶ PCIe DMA controller architecture
- ▶ PCIe DMA results

LHCb experiment at CERN (in 2020)

Hadron & Electromagnetic Calorimeters ($\sim 6\text{Tb/s}$)

Vertex Locator
 ($\sim 2\text{Tb/s}$)

Upstream Tracker
 ($\sim 4\text{Tb/s}$)

RICH 1&2
 ($\sim 5\text{Tb/s}$)

SciFi
 ($\sim 5\text{Tb/s}$)

Muon Chambers
 ($\sim 2\text{Tb/s}$)

High-level readout architecture

PCIe-40 architecture

- ▶ 24 inputs in nominal DAQ configuration
- ▶ Up to 48 inputs for low occupancy sub-detectors
- ▶ Up to 48 bidirectional links for SOL40 configuration

PLX switch performance

- ▶ Altera PCIe IP only implements Gen3 x8
- ▶ Use two and bond them with a PCIe switch
- ▶ nVIDIA does it with their dual GPGPUs, and it works!
 - ▶ Sustained 112.8 Gbps observed downstream from switch

PCIe DMA controller architecture

- Data path: 256bits @ 250 MHz → 64 Gbps

DMA descriptors

- ▶ DMA engine tuning for Stratix V
 - ▶ 16 descriptors
 - ▶ Leaves headroom to absorb traffic bursts
 - ▶ 4 KiB per descriptor
 - ▶ PCIe MPS is 256B, no advantage in overloading DMA engine
 - ▶ Matches MMU page size in event builder address space

DMA timing

DMA performance & stability

- ▶ Good performance
 - ▶ 55.49 Gbps on average
 - ▶ 96.9% of theoretical max
- ▶ Good stability
 - ▶ ± 0.1 Gbps avg. deviation
 - ▶ Driver and firmware stable over days of operation
- ▶ FPGA: Altera S5 (Bittware)
- ▶ CPU: Intel i7-3820 (Sandy)

Logic utilization

- ▶ Dynamic segment allocation minimizes on-chip buffering
 - ▶ 64 KiB per instance
- ▶ Hardened IP minimizes reconfigurable logic resources
 - ▶ 5% per instance
- ▶ MiniDAQ firmware is still heavy but constantly improving!
 - ▶ Gen X devices are coming!

Control system interface

- ▶ The PCIe link will be used also by the control system
 - ▶ Monitor and control internal state of readout board
- ▶ Instantiate an additional BAR to access firmware
- ▶ Is this going to create issues?

Control system overhead

- ▶ Implement control traffic emulator
- ▶ Evaluate different reads/writes ratio
- ▶ Performance still consistently over 54 Gbps!

Conclusions

- ▶ DMA performance is close to maximum link capacity
- ▶ PCIe output stage is more efficient wrt Ethernet readout
- ▶ Control & status traffic over PCIe does not disrupt DAQ
- ▶ DMA kernel driver and library are ready for integration in future event building software
- ▶ PCIe switch tested on GPGPU but not yet on FPGA

Thank you!
どうもありがとうございました

Modeling a PCI-e Gen3 link (1 / 2)

► Protocol parameters

- Signaling speed: 8 GT/s
- Encoding overhead: 128b / 130b
- TLP header overhead: 20 Bytes
- Maximum payload size: 256 Bytes

► From the above we can readily obtain

- Packet efficiency: 92%
- Symbol time: 1.016ns / Byte
- TLP (256B+20B) transfer time: $\sim 35\text{ns} (\times 8) \sim 17.5\text{ns} (\times 16)$
- DLLP (8B) transfer time: $\sim 1\text{ns} (\times 8) \sim 0.5\text{ns} (\times 16)$

Modeling a PCI-e Gen3 link (2/2)

- ▶ Descriptor size: 4 KiB
- ▶ TLPs per descriptor: $4096/256=16$
- ▶ DLLP traffic parameters
 - ▶ Assume 1 ACK every 5 TLPs
 - ▶ Assume 1 Flow Control update every 4 TLPs
- ▶ Descriptor transfer time
 - ▶ 8 lanes: $(16 \times 35\text{ns}) + (16/5 \times 1\text{ns}) + (16/4 \times 1\text{ns}) = 572.2\text{ns}$
 - ▶ 16 lanes: $(16 \times 17.5\text{ns}) + (16/5 \times 0.5\text{ns}) + (16/4 \times 0.5\text{ns}) = 283.6\text{ns}$
- ▶ Theoretical Bandwidth
 - ▶ 8 lanes: $4096\text{Bytes} / 572.2\text{ns} = \mathbf{57.267\ Gbps}$
 - ▶ 16 lanes: $4096\text{Bytes} / 283.6\text{ns} = \mathbf{115.54\ Gbps}$

DMA buffering requirements

- ▶ Events are committed to buffer in 32 Byte chunks
- ▶ Event header parsing + pass-through memory write
- ▶ FPGA buffer is divided in DMA sections
 - ▶ 4KiB sections → 88% bandwidth
 - ▶ $\geq$ 8KiB sections → 87% bandwidth
- ▶ 16 sections → just 64 KiB on the FPGA
 - ▶ DMA does not need an external memory interface

DMA descriptor format

- ▶ To every DMA section corresponds a descriptor
 - ▶ Source (QSYS) address: 64bits
 - ▶ Destination (Host) address: 64bits
 - ▶ DMA length (dwords): 12bits
 - ▶ Descriptor ID: 8bits

- ▶ At most 4 descriptors can be queued at once

MSI generation

- ▶ Asynchronous signal to driver (and event builder)
- ▶ Triggered by Posted Write TLP at special host address

- ▶ ~56 Gbps / 4 MiB
 - ▶ Interrupt rate $\rightarrow \leq \underline{1.67 \text{ kHz}}$ (no losses observed up to 5kHz)

Readout/Builder-Unit architecture

Full events to farm

Event fragments
 from/to rest of EB net

Event fragments
 from detector