Construction of the Phase I upgrade of the CMS pixel detector

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on behalf of the CMS collaboration
Pixel Phase-1 upgrade project

- Original detector not suited for operation at $L \sim 2 \times 10^{34} \text{cm s}^{-1}$
  - limited bandwidth readout chip to backend
- Upgrade detector
  - Faster digital readout chip
  - One extra layer for more robust tracking closer to the interaction point
  - Reduced material budget with CO$_2$ cooling system
  - Use DC-DC converters to avoid replacing power cables
- Will operate until LS3
Scope of the presentation

- The detector has been installed at the beginning of March and it is now being commissioned.
  - Commissioning details in the next presentation by Benedikt Vormwald.
- In this presentation, review the design and technology choices:
  - Upgrade in the readout system
    - Sensor modules with newly developed digital readout ASIC and transmitter
    - Backend control and readout system based on μTCA framework
  - No increase in material budget despite additional tracking layer
    - Lightweight carbon fiber supports
    - Two phase CO₂ cooling system
    - DC-DC converters
Detector and services

Four layers of sensor modules
1184 sensor modules

ROC: analog (40 MHz) --> digital (320Mbps)
Backend: VME --> $\mu$TCA
Controls largely unchanged

Sensor modules
- digital readout chip (ROC)
- data transmitter

Service electronics
- distribution of clock, trigger, and controls
- optical Rx/Tx

$\mu$TCA system
- electronics control
- sensor configuration, clock, trigger
- Readout

Barrel Pixel (BPIX)
Forward Pixel (FPIX)

Three disks of sensor modules
672 modules+spares

DCDC converter
Optical Rx/Tx
Sensor modules

- Sensor design unchanged relative to original detector
  - Only 1 sensor geometry through entire detector
  - n+ in n sensors, 66560 pixels with 100x150 μm² size
  - Total active area 16.2 x 64.8 mm² covered with 16 readout chips

- New digital readout chips (ROCs) used
  - Layer 1 requires dedicated chip to meet data transmission needs.
  - Each ROC transmits data at 160 Mbps

- Data from ROCs merged in single output stream in token bit manager ASIC (TBM) on each module with 320 Mbps (parallel readout):
  - 1 single data stream per module in FPIX and BPIX Layer-3/L4 (1 "TBM8" chip)
  - 2 data streams per module in BPIX L2 (1 "TBM9" chip)
  - 4 data streams per module in BPIX L1 (2 "TBM10" chips)
Digital readout chips

BPIX L2-L4 and FPIX use "psi46dig v2.1"

- Evolution of ROC of previous detector
- Double column drain architecture
- 8bit ADC on chip, data transmission at **160 Mbps**
- Larger buffers to reduced inefficiency at high occupancy
- **Lower threshold**: from 3500 e- (current detector) to ~1800 e-
- Redesigned power distribution to reduce cross talk noise
- Faster comparators to reduce time-walk
- Data streams from 2 ROC banks merged inside the TBM

BPIX Layer 1 uses "PROC600"

- Handles hit rate of 600 MHz/cm^2
- **Improve data throughput** by building 2x2 clusters in the double columns and transmitting cluster information
- Further increase in buffer sizes in ROC periphery
- Performance not degraded well beyond dose expected for Layer 1 (120 MRad)
Readout system

- FC7 mother board with mezzanine boards with Fitel optical receivers.
  - a μTCA compatible Advanced Mezzanine Card for generic data acquisition/control applications equipped with a Xilinx Kintex 7 FPGA.
- Firmware ready for LHC collisions.
  - current design allows handling data rates expected for 2017 (100 kHz L1 trigger rate, with PU=65)
- Control backend also moved to μTCA boards
- Stability of high bandwidth readout requires reduction of clock jitter, obtained by adding QPLL filter in the services electronics inside the supply tube / service cylinders.

Data signal without QPLL

Data signal with QPLL
DCDC converters

- The upgrade detector has factor 1.9 more channels, and it requires more power than the previous.
- To avoid replacing power supply cables and large voltage drops:
  - Adopt powering scheme with DC-DC converters
  - Power supplies deliver 10 V to the detector
  - DC-DC converters inside the support structure convert
  - Voltages to 2.5-3.6V (depending on application)
  - Radiation hard DC-DC converters used (CERN FEAST2 chip)
  - No impact on sensors / readout noise
Mechanics

- Detector supports built with carbon fibers / foam and graphite.

- Thanks to CO$_2$ cooling and DC-DC converters, no increase in material budget despite additional tracking layer.

- Material moved to higher rapidities.
CO2 cooling system

- Two-phase CO\textsubscript{2} cooling system replaced single phase C\textsubscript{6}F\textsubscript{14}.
- Modules are mounted on carbon fibre plates, which are thermally connected to the cooling pipes.
- Less flow required by exploiting the latent heat, which can enable the radius of pipes smaller (diameter of 1.6-3.0mm, wall thickness of ~0.1-0.2mm).
- Cooling lines and connections pressure tested at 150 bar, leak tests at 100 bar, operating pressure at -20°C is 20-30 bar.
Detector construction

- Various module production chains
- Single set of qualification criteria.
- Results of module calibrations from test stands used as starting point for commissioning after installation
- Module production done in ~1 year

Detector assemblies (integration of modules, mechanics and electronics) in Switzerland (PSI+Zurich) for BPIX, in the US (Fermilab) for FPIX

- After transport to CERN full test of detectors on the surface prior to installation (see next talk)
Summary

❖ Upgraded pixel detector was installed to CMS at the beginning of March,
  ❖ detector designed to remove bottleneck in readout and to provide improved performance.
❖ Readout system has been changed from 40MHz analogue-encoded to 320Mbps digital-encoded, with larger buffers.
  ❖ Two types of digital readout chips have been developed.
❖ Detector and backend ready for data taking.
❖ Better tracking performance expected with additional tracking layer and reduced material in the tracker acceptance.

This is a significant improvement of the CMS detector that will enable future discoveries / high precision measurements.