The LHCb VELO Upgrade

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LHCb is an experiment designed to study the CP violation and rare decays of B and D mesons.

**VELO**:
- Silicon detector surrounding the collision region
  - Provides excellent vertex resolution and identification of secondary vertices.
  - helps in tracking.
  - provides partial information about tracks that falls outside the LHCb acceptance.

The Current VELO

- Si microstrip n-in-n detector (R, Φ sensors)
  - 300 μm thick, 0.22 m² area.
  - Semicircular geometry.
  - 2048 strips per sensor.

- 42 modules in total
- Modules are placed in 2 retractable halves.
- Closest distance of active Si is 8.2 mm far from the beam.
- Operates in secondary vacuum.
- 300 μm thick RF foil separates VELO from beam vacuum.
- Evaporative CO₂ cooling.
The LHCb Upgrade

LHCb have accumulated ~9.6 fb$^{-1}$ data. Run 2 is about to end.

Need more statistics to increase the precision of the analysis results.

Goal:

- Collect 50 fb$^{-1}$ data
- Increase operational luminosity from $4 \times 10^{32}$ cm$^{-2}$ sec$^{-1}$ → $2 \times 10^{33}$ cm$^{-2}$ sec$^{-1}$
- Many hadronic channels saturate due to $p_T$ cuts in the L0 hardware trigger.
  - Improve trigger efficiency by removing hardware trigger.
  - 1 MHz → 40 MHz readout
- Upgrade various sub-detectors, electronics and DAQ system.
- Sensors and electronics need to be radiation hard, have low material density and faster.

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<th>Run 2</th>
<th>LS 2</th>
<th>Run 3</th>
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Module construction and installation of upgrade.
The VELO Upgrade

- Enhanced track reconstruction speed and precision.
- Pixel detector bump-bonded to 3 ASICs.
- Thinner, smaller sensors (200 µm, 0.12 m²)
- Closer to the beam: (8.2 mm → 5.1 mm)
- 52 L shaped modules:
  - Highly non-uniform radiation dose.
- New improved electronics.
- Evaporative CO₂ cooling through micro-channels.
- Thinner RF foil 250 µm at 3.5 mm radius

Integrated Radiation Dose per fb⁻¹ (in 1 MeV neq cm⁻²)
The VELO Upgrade

VeloPix ASICs and front-end hybrids.
Data Link Tape.
Vacuum Feedthrough.
Opto and Power Board (OPB).

Cables:
**Dark Brown**: Readout/data cables.
**Green**: Data tapes.
**Light Brown**: Control/interconnecting cables.
**Grey/Red-Black**: LV power cables.
HV cables not shown.
Sensors

CERN SPS Testbeam:
Extensive testing before/after irradiation (upto full fluence radiation) with TimePix3 telescope:

- VELO sensors must tolerate 1000 V.
- Sensors must collect at least 6000 e-.
- Efficiency should be at least 99 %

Cluster Collection Efficiency:
35-39 microns implants tested.

- Larger implants improves efficiency at the corners.
- Efficiency reaches 99% (target) before 1000 V.
- Production choice: 39 µm.
Sensors

- Sensors tested could tolerate high bias voltage upto 1000 V.
- Charge collection efficiency > 6000 e- (target) with bias voltage < 1000 V.

- 200 μm thick n-in-p Si sensor chosen based on charge collection after irradiation, material budget, bias voltage and mechanical handling constraints.

Sensors are bump-bonded to 3 ASICs.
VeloPix ASICs

- 130 nm CMOS technology (TSMC). Derived from TimePix3.
- Highly radiation hard.
- ASIC size = 14.08 \times 14.08 \text{ mm}^2, thickness = 200 \mu \text{m}.
- 256 \times 256 pixels matrix of size 55 \times 55 \mu \text{m}^2
- Continuous, trigger-less, binary, data driven readout.
- Packet-based architecture (super pixel = 2 \times 4 pixels):
  - 30 \% reduction in data rate
- 20 M packets/s/double column
- Timing resolution consistent with LHC bunch crossing time (25 ns).
- Power consumption : < 2-3 W per ASIC.
CO$_2$ Cooling through Micro-channels

- Sensors need to be kept below -20 °C to prevent radiation damage.
- Evaporative CO$_2$ cooling through 500 µm thick Si micro-channel substrate (same CTE as sensors).
  - 19 parallel $120 \times 200 \mu m^2$ channels, 260 mm long
  - High impedance input restrictions $60 \times 60 \mu m^2$, 40 mm long.
    - Dominant Pressure drop.
    - Prevents instabilities among channels.
- Front tiles overhanging (5mm) to minimise material budget.
- Cooling is exactly under the ASIC surface.

![Thermal map from simulation (°C)](image-url)
RF Foil Enclosure

- Separates primary (LHC) and secondary vacuum.
- Properly accommodate the (~1m long) modules.
- Thinner and lightweight (250 µm thick).
- Corrugated structure.
- Can withstand $\Delta P = 10$ mbar.
- Close to beam ~ 3.5 mm.
- Thermally stable, radiation hard.

Half RF enclosure prototype

Total material: $21.3 \times X_0$

Total amount of material for the VELO upgrade broken down by component.
Module Construction and Mechanical Tests

Connecting Substrate and Capillaries

Si metallized with Ti + Ni + Au.

Connector metallized with Ni + Au.

Micro-channel Si substrate

capillaries

Alignment

Soldering

QUALITY ASSURANCE :

- Visual Inspection, X ray tomography.
- Leak test (under vacuum).
- Cooling and pressure test : -40 to +40 °C, 186 bar
- Planarity measurement.

X-ray image
Module Construction and Mechanical Tests

Bare Module Assembly

The cooling substrate is connected to the VELO base with the help of module foot, CF legs and mid-plate. Alignment precision needed: 50 µm in z and 20 µm in x and y.

Tilt, Sag and Bow: Flatness of prototypes measured using a smartscope.
Module Construction and Mechanical Tests

Tiles and hybrids attachment

Turn plate holding the bare module

Screws and dowel pin hold the substrate and the module foot

Movable stages

The tile alignment system

The positions for each tile w.r.t. the LHCb frame is measured with the smartscope and then translated w.r.t. the turnplate. The parameters are fed to alignment code
Tiles and hybrids attachment

The jigs holding the sensors and the bare module are sandwiched.

Tiles placement precision: < 10 µm in x and y.
Hybrid placement precision: < 50 µm in x and y.
Module Construction and Mechanical Tests

Wire-Bonding and cables attachment

3 movable vacuum chucks to support the hybrids.

Microscopic images of wire-bonds

Pull Tested.
Required bond strength > 6g pull force.
The VELO upgrade will operate at higher luminosity and data rates.

- Microstrip detectors will be replaced by pixel detectors to operate at higher occupancy.
- CO$_2$ cooling will be through micro-channels.
- Module assembly procedure is almost optimized.
- 2 assembly sites. 1 electrical prototype is already made and tested at each assembly site.
- Production expected to start after site readiness review in Nov end.
- All modules expected to be finished within a year. Install VELO in 2020.
Electrical Tests

Electrical tests with CO\textsubscript{2} cooling: Noise maps of all VeloPix chips, DAC scan.