Alignment Challenge

at

LHCb

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LHCb Experiment

- Large Samples of $b$ decays for New Physics searches in CPV & rare $B$ (&$D$) decays
- $B$ production predominately at small polar angles
- LHCb optimized as a single forward arm spectrometer

LHCb Tracking System

- Vertex Locator
- Muon system

21 stations
R and $\phi$ sensors

~1.4 x 1.2 m$^2$

~6 x 5 m$^2$

M1
SPD/PS

M2

M3

M4

M5

Magnet

Bending Plane

ECAL

HCAL

Tracker

RICH1

RICH2

T1

T2/T3

T3

T4/T5

50 mrad

120 mrad

250 mrad

10 mrad
Tracking System Challenges

- Large track density

- Trigger uses tracking info
  - Requires good alignment
  - Online updating of constants if needed.

- Tracking algorithms need to be FAST, as they are executed online. Want offline pattern recognition very similar to online version, except for fine tuning of alignment & calibrations.

- Minimize material (no surprise here)
**21 tracking stations**

- 4 sensors per station with \( r/\phi \) geometry
- Overlap regions for L/R alignment
- Optimised for
  - Fast online 2D tracking
  - Vertex reconstruction
  - Offline track reconstruction

**R-sensors**
- 2048 strip in 45° sectors
- Strip pitch increase with \( R : 40\mu m \rightarrow 100\mu m \)

**Φ-sensors**
- 2048 strip in inner and outer regions
- Strip pitch increase with \( R : 36\mu m \rightarrow 97\mu m \)
Vertex Detector Challenges

- Most precise device in LHCb moves
  - Retracted by ~ 3 cm in-between fills
  - Reinserted to ~ 8 mm after stable beams

- Integral part of the trigger
  - RZ (2D) tracking/trigger scheme requires transverse alignment between modules <20 μm.
  - Internal alignment monitoring/updating as necessary (online vs offline), 2D vs 3D
  - Rest of tracking system (online vs offline)
    - Momentum estimate using VELO-TT in HLT.

- Need for “same” tracking in HLT and offline:
  - tradeoffs of speed/efficiency/ghost rate

~4% ghost rate (3D)
~7% ghost rate (2D)
Tracking Stations

Outer Tracker
- 5.0 mm Straws
- Double-layer straws

Silicon Strips
- 198 µm pitch
- 1-2 sensor ladders
- 4 layers: XUVX
- 336 ladders to be aligned

Silicon Strips
- 183 µm pitch
- 128 7-sensor ladders
- 128 ladders to be aligned

Overlap regions between IT/OT to facilitate relative alignment

Trigger Tracker (TT)

Inner Tracker

Outer Tracker

125.6 mm
Magnetic Field

\[ \int B \, dl = 0.12 \, Tm \]

Very small field in VELO

Non-uniform, non-negligible field in region of T Stations

\[ \int B \, dl = 4 \, Tm \]

Non-zero field in region of TT integral part of trigger: \( \Delta p/p \sim 30\% \)
Silicon Strips
- 183 μm pitch
- 128 7-sensor ladders
- 4 layers: X, U(5°), V(-5°), X
- 128 ladders to be aligned
- 2% occupancy, max.
Silicon Strips
- 198 μm pitch
- 1-2 sensor ladders
- 4 layers: XUVX
- 336 ladders to be aligned, 6 paras each
Outer Tracker

- Very large!
- 5.0 mm Straws
- Double-layer straws
- Single Hit Resolution ~ 200 μm.
- High occupancy

Detector is planar to within 0.9 mm
Hardware Alignment at LHCb

- Generally, the detector structures will be surveyed by the TS-SU group at CERN.
  - Precision is typically 0.3-0.5 mm ($1\sigma$) level in X, Y and Z, depending on the precision needed. VELO box surveyed to 0.3 mm.

- All points given with respect to the global LHCb frame nominal interaction point is (0,0,0).

- VELO is most critical.
  - 5 fiducials on each sensor
  - Surveyed during module production
  - Will also be re-surveyed after installation in supporting base.

- Practice with test beam telescope.
  - Metrological measurements within a few microns of final tracking alignment.

- Hardware Position Monitoring
  - RASNIKs for OT
  - Laser system for RICH mirrors
Software Alignment at LHCb

General Strategies

- Magnet OFF data crucial
  - Separate magnetic field effects from geometrical ones.
  - Commissioning
  - After access to service tracking system
  - Otherwise, periodically, based on unexplainable change in alignment

- Pre-selected track samples
  - Low multiplicity events
  - Isolation requirements around track (if necessary)
  - Magnet OFF: Use energy from calorimeter

- Magnet ON data
  - Tweak alignments from Magnet OFF
  - Cross-check with $K_s$, $J/\psi$, $Y$, $D \rightarrow K\pi$, $Z^0$, etc (after $dE/dx$ corrections and B field map validated)
General Flow of Alignment

- **VELO Alignment**
  - Align +X (-X) modules to one another
  - Align +X VELO to -X VELO

- **IT Alignment**

- **OT Alignment**
  - Align IT to OT using overlap regions and tracks with hits in both detectors

- **Detector Description & Conditions Database**

- **Align VELO to IT/OT System**
  - Long = segments in both VELO and T-stations

- **Align TT using long tracks**

- **After Tracking System Alignment**
  - Align RICH
  - Align ECAL
  - Align HCAL
  - Align MUON

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Tracking System, Expected Performance with Perfect Alignment

Momentum resolution

Impact parameter resolution

\[ \delta p/p = 0.35\% - 0.55\% \]

\[ \sigma_{pT} = 14\mu + 35\mu/p_T \]
Some Impacts of Misalignment
Random Velo Misalignment

Impact Parameter Resolution (in mm)

Mechanical placement, $\sigma < 20 \, \mu m$, S. Viret

Impact Parameter Resolution (in mm)

log $\left(1/Pt(\text{GeV}/c)\right)$
Misalignment of OT

- Tracking robust against misalignments up to ~500 μm, but:
  - ~20% degradation in momentum (not acceptable from physics view)
  - fewer hits per track
- Expect transverse alignment to be at the ~50 μm level, or better.

For misalignments larger than 3 mm the hits of T1 are ignored.

Toy MC, Gaussian Smearing of Momentum

\[ \overline{B}^0 \rightarrow K^+ \pi^- \]

\[ B \rightarrow K^+ \pi^- \]

\[ \sigma/p = 0.004 \quad \overrightarrow{\longrightarrow} \quad \sigma/p = 0.005 \]
VELO – TT Misalignment @ L1

- Fraction of tracks above 2.5 GeV $p_T$
- Double apparent rate at ~ 300 micron miss alignment
- Trigger requires X misalignment below ~100 micron

D. Hutchcroft
LHCb Trigger requires “good” online alignment.

Extraction/re-insertion of VELO every fill requires updating of some subset of alignment constants
- Probably default alignment constants from previous run to start off (aside from an overall $\Delta X$ ($\Delta Y$) from VELO motion controller between fills)
- Always update? Or only when significant change?

Large number of planes and overlap regions facilitate alignment between detectors

Magnet OFF data critical to decoupling geometry from B field effects
- More work needed on proving that dE/dx and B field mapping “issues” can be de-convoluted.

Fine tuning of alignment for final offline analysis.

Software Alignment Monitoring:
- Low-level: #Hits/track, $\chi^2$, IP, residuals, #tracks/event, etc
- High level: Masses, mass resolutions, relative particle yields.