Optimising the LHCb VELO detector

M. McCubbin
Liverpool University

VERTEX2000, 10th - 15th September, 2000

Outline:

• LHCb overview
• VELO tasks
• VELO layout
• Required VELO performance
• Updates to VELO design
• Simulation of new VELO designs
• Outlook
Aim: study CP violation in $B$ meson decays

LHC: $pp$ collisions at c.o.m. energy 14 TeV

$L = 2.0 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$

bunch-crossing (interaction) rate 40 (15) MHz

$\sigma_{\text{inel}} = 100 \text{ mb}, \sigma_{b\bar{b}} = 500 \mu \text{b}$

$\rightarrow 10^{12} \, b\bar{b}$ produced per LHC year ($10^7 \text{ s}$)

$\rightarrow$ high statistics samples for precision measurements of CP asymmetries, $B$ oscillations and rare $B$ decay studies

Experimental needs:

a) efficient trigger for leptons, hadrons and displaced vertices ($B$ meson selection)

b) particle ID ($\pi/K$ separation, flavour tagging)

c) good mass resolution (background rejection)

d) good decay time resolution ($\Delta m_s, \Delta \Gamma_s$)
Single-arm spectrometer covering $\theta = 15$ mrad to 300 mrad ($\eta = 1.88$ to 4.89)

Main features:

VErtex LOcator (VELO) — vertex detector

usual complement of tracking chambers, RICH, ECAL, HCAL, muon chambers and magnet
VELO has 2 main tasks:

a) precise track measurement near interaction region $\rightarrow$ good resolution on track impact parameters (IP), primary (PV) and secondary (SV) vertices and $B$ decay length

b) use in LHCb trigger to enrich $B$ sample

L0: input rate 40 MHz, output rate 1 MHz
based on high $p_t$ leptons, hadrons and photons
+ “pile-up” veto

L1: input rate 1 MHz, output rate 40 kHz
based on vertex (VELO) and track triggers

L2 and L3 reduce rate to 200 Hz (final sample mostly $\bar{b}b$, $c\bar{c}$ events)
At time of Technical Proposal (1998)...

17 disks (stations) of $r$ and $\phi$ detectors
upper-lower halves retract during LHC injection
upper-lower overlap for alignment
Strip layout:

LHCb

$61^\circ$ silicon vertex detector elements

$\phi$-detector

$r$-detector

(strips not to scale)

$256 + 640 = 896$ strips

$2'384 + 256 + 241 = 1265$ strips

$\phi$-detector

$r$-detector

Si thickness $= 150 \, \mu m$

module overlap for alignment

channel occupancy less than $0.5\%$
RF shielding:
beam in primary LHC vacuum, detector and electronics protected from beam RF pick-up in secondary vacuum

Al (100 $\mu$m thick) caps round Si

Al thick — withstand any differential pressure, provide enough shielding
Al thin — not degrade resolution

Vacuum tank:
VELO mounted on support structures in cylindrical vacuum tank
alignment, retraction of VELO, mechanical stress from heat load, maintain vacuum with signal feed-throughs
low mass in acceptance region
Simulated resolutions:

primary vertex — $\sigma = 40\mu m$

secondary vertex — $\sigma = 180\mu m \ (B \to \pi\pi)$

Proper-time resolution for $B_s \to D_s^- \pi^+$ events = $43 \text{ fs} \to 5\sigma$ measurement of $\Delta m_s$ up to $48 \text{ ps}^{-1}$ (in one year)
Required VELO performance (cont’d)

L1 vertex trigger:

a) 2D track search in \( r - z \) projection
b) estimate of PV using 2D tracks
c) for 2D tracks not from PV add \( \phi \) information \( \rightarrow \) 3D tracks
d) search for SV using pairs of 3D tracks

output — probability based on number of SV and distance from PV

---

**Signal efficiency vs. background retention**

- \( B \rightarrow \pi^+\pi^- \)
- \( B \rightarrow D_\pi \)
- \( B \rightarrow D_0K^* \)

---

Martin McCubbin

VERTEX2000, 10th - 15th September, 2000
Updates to VELO design

Si thickness:

thin — decrease depletion voltage, lower bulk leakage current (less cooling required), reduced signal and S/N needing better electronics

thick — increased multiple scattering, larger operating voltage $\rightarrow$ breakdown, more heating

availability (thickness) depends on technology and manufacturer — p-in-n generally thinner and cheaper than n-in-n

choice: 220 $\mu$m with 300 $\mu$m as backup

(TP: 150 $\mu$m)
Strip pitch:

hit resolution $\approx$ SP/12 with low noise analog electronics and charge-sharing technology choice affects SP —
n-strip with p-stops: min. 40 $\mu$m
p-strip: min. 20-25 $\mu$m

resolutions from simulation studies —

$\rightarrow$ strip pitch important for SV resolution

choice: 20/30/40 $\mu$m for $r$ detectors (backup as TP: 40/60/80 $\mu$m)
Si inner/outer radius:

reducing inner radius improves IP resolution

→ reduce outer radius to maintain number of electronics channels

6”/4” facilities and flexibility of options —

180° sensors on 4” wafers: max. radius 4.5 cm

not all manufacturers moved to 6”

choice: IR 0.8 cm, OR 4.5 cm (TP: 1.0 cm and 6.0 cm)
Number of Si stations:

tracks in LHCb — at least VELO 3 hits

increase from 17 — further improve tracking capabilities → cost, complexity, space

fast optimisation —

PYTHIA+beam-spot+MS+inefficiencies

choice: 25 stations (TP: 17)
Updates to VELO design (cont’d)

RF design:

TP shielding thickness not sufficient

wake field suppressors needed — 4 strips along VELO length →

problems — thickness, cooling, mechanics

Al box acts as wake field suppressor

corrugation needed for upper-lower overlap

minimise multiple scattering

choice: “toblerone” design, Al 250µm (TP: 100µm)
Si radiation tolerance:

extreme environment — damage degrades performance

technology — n-in-n more “rad. hard”

results from irradiated detectors + work with oxygenated detectors, thinner detectors

→ better understanding of effects allowing Si closer to beam

Overall material budget:

minimise effect of changes on rest of LHCb
Simulation of new VELO designs

Simulated new VELO design parameters with standard LHCb simulation (SICB: PYTHIA + GEANT)

Use MAP facility at Liverpool (http://www.ph.liv.ac.uk/map/)

Quantities investigated:

- RMS distance between the true and reconstructed PV
- RMS distance between the true and reconstructed SV
- double-Gaussian fits to (true − rec.) decay lengths
- $B$ decay selection efficiencies and backgrounds
- charged and neutral particle multiplicities
- number of hits per event in other LHCb detectors
- number of VELO hits per track
- particle flux versus radius
- L0 selection efficiency
- number of high IP tracks — for L1
- L1 efficiency versus min. bias retention
Simulation of new VELO designs (cont’d)

Multiparameter problem — investigate performance for many combinations of VELO design parameters

→ large event samples used for this study:

<table>
<thead>
<tr>
<th>study</th>
<th>event type</th>
<th>n. events</th>
</tr>
</thead>
<tbody>
<tr>
<td>resolution</td>
<td>$B \rightarrow \pi\pi$</td>
<td>378k</td>
</tr>
<tr>
<td></td>
<td>$B \rightarrow J/\psi(\mu\mu)K^0_s$</td>
<td>440k</td>
</tr>
<tr>
<td>event selection</td>
<td>$B \rightarrow \pi\pi$</td>
<td>771k</td>
</tr>
<tr>
<td></td>
<td>$B \rightarrow J/\psi(\mu\mu)K^0_s$</td>
<td>730k</td>
</tr>
<tr>
<td>trigger, multiplicity</td>
<td>$B \rightarrow \pi\pi$</td>
<td>364k</td>
</tr>
<tr>
<td>and other</td>
<td>minimum bias</td>
<td>987k</td>
</tr>
</tbody>
</table>

Over 10 million fully simulated LHCb events in total for this and other studies
## Simulation of new VELO designs (cont’d)

<table>
<thead>
<tr>
<th>VELO design</th>
<th>number stations</th>
<th>Si parameters d (μm)</th>
<th>IR/OR (cm)</th>
<th>strip-pitch SPir/SPmr/SPor (μm)</th>
<th>RF shield design</th>
<th>ALth (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP</td>
<td>17</td>
<td>150</td>
<td>1.0/6.0</td>
<td>40/60/80</td>
<td>TP</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>I</td>
<td>25</td>
<td>220</td>
<td>1.0/4.5</td>
<td>40/60/80</td>
<td>TP</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>Ia</td>
<td>25</td>
<td>220</td>
<td>0.8/4.5</td>
<td>40/60/80</td>
<td>TP</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>II</td>
<td>17</td>
<td>220</td>
<td>1.0/6.0</td>
<td>40/60/80</td>
<td>tb</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>III</td>
<td>17</td>
<td>220</td>
<td>1.0/6.0</td>
<td>40/60/80</td>
<td>bp</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>IV</td>
<td>25</td>
<td>220</td>
<td>0.8/4.5</td>
<td>20/30/40</td>
<td>TP</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>250</td>
</tr>
<tr>
<td>Va</td>
<td>25</td>
<td>220</td>
<td>0.8/4.5</td>
<td>40/60/80</td>
<td>tb</td>
<td>250</td>
</tr>
<tr>
<td>Vb</td>
<td>25</td>
<td>220</td>
<td>0.8/4.5</td>
<td>20/30/40</td>
<td>tb</td>
<td>250</td>
</tr>
<tr>
<td>baseline</td>
<td>25</td>
<td>220</td>
<td>0.8/4.5</td>
<td>20/30/40</td>
<td>tb</td>
<td>250</td>
</tr>
<tr>
<td>backup</td>
<td>25</td>
<td>300</td>
<td>0.8/4.5</td>
<td>40/60/80</td>
<td>tb</td>
<td>250</td>
</tr>
</tbody>
</table>

tb — “toblerone” RF, bp — “beampipe” RF

+ TP with Si 500μm thick
Simulation of new VELO designs (cont’d)

Particle fluxes for min. bias:

\[ \sigma_{\text{inel}}, L \text{ and 1 LHC year as before:} \]

\[ 1.6 \times 10^{14} \text{ cm}^{-2} \text{ charged particles/year} \]

Mostly pions, fold with \( p \) and NIEL constants:

\[ 0.6 - 1.1 \times 10^{14} \text{ cm}^{-2} \text{ 1 MeV neutrons/year} \]

(at \( r = 1 \text{cm, depending on } z \))
Simulation of new VELO designs (cont’d)

Event selection efficiencies and backgrounds for $B \to \pi\pi$ and $B \to J/\psi(\mu\mu)K_S^0$:

No large systematic effects, cuts not tuned for each design
Simulation of new VELO designs (cont’d)

TP and baseline (backup) comparisons:

a) resolutions:

PV resolution — 5% worse
SV resolution — 15% better (no change)
decay length resolution — 20% better (no change)

- strip pitch, Si inner radius
+ Si thickness, RF thickness

b) multiplicities:

charged multiplicity up 7%
neutral multiplicity up 0.4%
number of hits in other dets. — up 5%

+ Si thickness, RF thickness
c) number of high IP tracks (L1):

IP > 50,100\,\mu m up 10(20)\% (B \rightarrow \pi\pi)

IP > 50,100\,\mu m up 20(40)\% (min. bias)

+ Si thickness, RF thickness and design

- strip pitch, Si inner radius

d) number of VELO hits per track — up 50\%

d) number of stations

e) L0 efficiency — down 7\%

RF design

f) particle densities at min. radius — up 50\%

Si inner radius
Chosen new design is “baseline”, with a conservative “backup” design (thicker Si, larger strip-pitch)

Main points:

a) need for increased RF shielding met
b) number of stations increased to 25 — average number of VELO hits per track 50\% higher \rightarrow greater standalone tracking capability for the VELO
c) $B$ decay length resolution improved
d) slight increase in material budget
e) $B$ decay selection performance maintained
f) number of high IP tracks (for the L1 trigger) close to the TP values