4 July 2001

Thomas Ruf

- Introduction
- Sensors
- Physics Performance

Jo van den Brand

- Mechanics & Vacuum
- Electronics
- Planning
**Introduction**

**VErtex LOcator of the LHCb experiment**

**LHCb**: Systematic studies of $\mathcal{CP}$ in the beauty sector by measuring particle - antiparticle time dependent decay rate asymmetries.

**LHCb requirements:**

- Reconstruction of pp-interaction point
- Reconstruction of decay vertex of beauty and charm hadrons
- Decay time measurements
- Standalone and fast track reconstruction in second Level trigger (L1)
**Introduction**

**VErtex LOcator of the LHCb experiment**

**LHCb requirements:**
- Angular coverage of the downstream detectors
- Minimum amount of material in the acceptance

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VELO Overview

Number of silicon sensors: 100
Area of silicon: 0.32m²
Number of channels: 204,800

Precise vertexing requires, to be:
- as close as possible to the decay vertices
- with a minimum amount of material between the first measured point and the vertex

⇒ silicon sensors are placed in vacuum

~1 m
Introduction

VELO Setup

Length of the VELO defined by:
- Track reconstruction with 3 hits/track down to 15 mrad for 95% of the interactions.

Cross section at \(x=0\):

Spacing of sensors defined by:
- The 250 mrad x 300 mrad acceptance of the downstream detectors.
- Outer radius of the sensors.
**VELO Setup**

**Number of stations defined by:**
- Spread of interaction region and spacing of sensors
- Partial backward coverage for improved primary vertex measurement

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**Introduction**

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**VELO Setup**

**Number of stations defined by:**
- Spread of interaction region and spacing of sensors
- Partial backward coverage for improved primary vertex measurement

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**Small overlap between left and right halve**
Sensor Design

Azimuthal symmetry of the events suggests sensors which measure $\phi$ and $R$ coordinates.

Advantages of $R\phi$ geometry:

- **Resolution**: Smallest strip pitch where it is needed, optimizing costs/resolution.
- **Radiation**: Short strips (strixels) close to beam, low noise.
- **L1**: Segmented R-sensor information is enough for primary vertex reconstruction and impact parameter measurement.

- Inner radius is defined by the closest possible approach of any material to the beam: 8 mm $\Leftarrow$ LHC machine
- Outer radius is constrained by the practical wafer size: 42 mm
Sensor Design

- Strips are readout by using a double metal layer
- Analog readout for better hit resolution and monitoring
Radiation

◆ Sensors have to work in a harsh radiation environment:

max. fluences:

\[ 0.5 \times 10^{14} - 1.3 \times 10^{14} \ \text{n}_{\text{eq}}/\text{cm}^2/\text{year} \]

⇒ Requires simple access to sensors for replacement

\[ N \cdot r^{-\alpha} \]

\[ \alpha = 1.6 - 2.1 \]
**Silicon R&D**

**VELO Design Challenges**
- Varying strip lengths
- Double metal layer
- Regions of fine pitch
- Large and non-uniform irradiation

**VELO Technology Choices**
- Thickness
- Oxygenation
- Cryogenic Operation
- Segmentation p or n strips?

**Tested Prototypes**

**Double sided DELPHI sensor**

- strip pitch = 25 µm
- readout pitch = 50 µm
- pitch = 42 µm
- thickness: 310 µm

**Double sided DELPHI sensor**

- thickness: 310 µm
Silicon R&D

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Tested Prototypes

Hamamatsu n-on-n

thickness: 300 µm

radius = 49.88 mm

PR01 R-sensor

2*192+1*256+1*366 = 1006 strips

pitch

60 µm

40 µm

40 µm

40 µm

10.00 mm

27.92 mm

17.68 mm

10.00 mm

radius = 49.88 mm

PR01 φ-sensor

1*256+1*768 = 1024 strips

pitch

44 – 79 µm

45 – 126 µm

radius = 49.88 mm

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**Silicon R&D**

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**VELO Technology Options**
- Thickness
- Oxygenation
- Cryogenic Operation
- Segmentation p or n strips?

**Tested Prototypes**

**MICRON p-on-n**

<table>
<thead>
<tr>
<th>PR02-Φ sensor</th>
<th>PR02-R sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2048 strips read out</td>
<td>2048 strips read out</td>
</tr>
<tr>
<td>1024 outer strips</td>
<td>256 strips</td>
</tr>
<tr>
<td>1024 inner strips</td>
<td>256 strips</td>
</tr>
<tr>
<td>256 strips</td>
<td>256 strips</td>
</tr>
<tr>
<td>pitch 24 µm</td>
<td>pitch 32.5 µm</td>
</tr>
<tr>
<td>pitch 55 µm</td>
<td>pitch 32.5 µm</td>
</tr>
<tr>
<td>pitch 124 µm</td>
<td>pitch 50 µm</td>
</tr>
<tr>
<td>thickness: 200/300 µm</td>
<td>thickness: 200/300 µm</td>
</tr>
</tbody>
</table>

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Silicon R&D

Test-beam Results

40MHz readout chip
SCT128A

~5% of VELO sensors tested with beam

Trigger performance

Resolution vs angle and pitch
Best resolution: 3.6 µm simulation

First confrontation with alignment issues

Results of irradiated sensors

see the TDR!

Results of irradiated sensors
**n-on-n Prototypes**

Variable irradiation with 24 GeV protons at the CERN-PS

Sensor readout with 25ns electronics (SCT128A)

Most irradiated region corresponds to 2 years of LHCb operation for the innermost sensor part.

Disadvantages for n-on-n:
- strip pitch limited by space needed for p-stops / n-strip
- requires double sided processing
Irradiated p-strip sensor

Depletion voltage vs. radiation

Fully depleted

Underdepleted

Cluster spread
Silicon R&D

**Irradiated p-strip sensor**

Depletion voltage vs. radiation

**Fully depleted**

- p side signal
- routing lines on 2nd metal layer
- dielectric
- hole drift
- electron drift

**Underdepleted**

- p side signal
- routing lines on 2nd metal layer
- dielectric
- hole drift
- electron drift

**Active region**

- Undepleted insulating region
- n⁺ implants
- dielectric
- traversing MIP
- electron drift

**Cluster spread AND charge loss**

**Depletion voltage vs. radiation**

- RD48
- standard FZ
- oxygen rich FZ

- Neff [10¹² cm⁻³]
- n_eq [10¹⁴ cm⁻²]

- Neff [10², 10³, 10⁴, 10⁵ cm⁻³]
- n_eq [1, 2, 3, 4, 5 cm⁻²]

- Vdep [V] (300 µm)

- Neutrons
- Pions
- Protons

- Neutrons
- Pions
- Protons

- Oxygen rich FZ
- Standard FZ

Additional problem

- Cluster spread
- AND charge loss
Results with DELPHI Prototype

Drastic effect on resolution observed if the sensor is underdepleted.

Irradiated up to $3.5 \times 10^{14}$ protons/cm$^2$

Empirical model, thickness of undepleted region

Charge Collection Efficiency

Size of boxes proportional to efficiency
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Results with DELPHI Prototype

Irradiated up to $3.5 \times 10^{14}$ protons/cm$^2$

Reference plaquette
Irradiated plaquette

Size of boxes proportional to efficiency

Other result:

Cryogenic operation:
Recovery of CCE after biasing sensor, BUT effect disappears after few minutes.
Irradiated with 24 GeV protons at the CERN-PS

Beam profile $\sigma = 6\text{mm}$, max. fluence $10 \times 10^{14}$ protons/cm$^2$ measured with Aluminium

Aim of tests:
- Measure resolution and efficiency

Repeater card

Sensor readout with 25ns electronics (SCT128A)

3-chip hybrids

Temperature probes

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$p$-on-$n$ Prototypes with LHCb design

Non irradiated reference area

Irradiated test area

Al calibration pieces

Beam

[cm]
Charge loss in double metal region

Size of boxes proportional to efficiency

Efficiency in outer region at 300 V

- S/N > 3
- S/N > 5
- S/N > 10

Efficiency [%]

Irradiation [x 10^{14} p/cm^2]

PP--on--

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Summary

VELO Design Challenges

- Varying strip lengths ✓
- Double metal layer ✓
- Regions of fine pitch ✓
- Large and non-uniform irradiation ✓

VELO Technology Choices

- Thickness: 300 µm, OK for radiation hardness and material budget
- Oxygenation: nice to have, but not mandatory, less of interest for p-on-n
- Operating temperature: -50°C
- Segmentation: n strips
  - Safest solution: sensors can be operated underdepleted
  - Smaller strip pitch doesn’t justify the use of p-strip sensors
Sensor Design

3 views: R and +/- stereo $\phi$

- **R**: 4 inner and 2 outer sectors, smallest pitch for $r < 18.5$mm.
  - $r > 18.5$mm: pitch increases with $r$
- **$\phi$**: 1 inner and 1 outer sector
- 2048 strips / sensor

$n$-on-$n$, AC coupling, polysilicon biasing, double metal layer
R sensors: charge sharing due to inclined tracks
⇒ improved resolution

φ sensors: tracks are always perpendicular
⇒ resolution = strip pitch / \sqrt{12}

⇒ use floating strips

Sensor Design

Ultimate φ Sensor

- R sensor
- φ sensor
- 2048 strips
- read out
- strips
- routing lines
- floating strips
- rz view
- θz view
- telescope resolution, 40 µm pitch
- test-beam simulation
- telescope resolution, 60 µm pitch
- test-beam simulation

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Sensor Design

Occupancy

Low occupancy: < 1% per channel

~ 1.5 tracks in the seeding region
(innermost 45° sectors of R-sensors)

⇒ track reconstruction is straightforward

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Detector Lifetime

- Fully depleted for >2 years, $U_{\text{bias}} < 400 \, \text{V}$
  Prototype $n$-on-$n$ detectors even for 4 years
- With $n$-on-$n$, can accept 40% under-depletion
  → extending the lifetime even further

Operation model:
- 100 days constant fluence
- 14 days at $+22^\circ \text{C}$

Operation at $-5^\circ \text{C}$

Prototype $n$-on-$n$ sensors behaved much better than expected for “standard” silicon
Physics Performance

**Impact Parameter Resolution**

- Due to the forward geometry, contribution of multiple scattering is proportional to $1/p_t$.
- Material in front of first measured point is important, average $= 3.8\% x/X_0$, $\Rightarrow$ shape of secondary vacuum container.

- Resolution for most B decay tracks is below $50\mu m$.

(Primary Vertex resolution: $42\mu m$)
Physics Performance

Invariant mass, decay length and decay time resolutions

**Invariant mass resolutions**

<table>
<thead>
<tr>
<th>decay mode</th>
<th>( \sigma ) [MeV/c^2]</th>
<th>( \sigma_p ) [MeV/c^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_d^0 \rightarrow \pi^+ \pi^- )</td>
<td>17.8 \pm 0.2</td>
<td>6.1 \pm 0.1</td>
</tr>
<tr>
<td>( B_s^0 \rightarrow D_s^- \pi^+ )</td>
<td>12.0 \pm 0.2</td>
<td>9.1 \pm 0.2</td>
</tr>
<tr>
<td>( D_s^- \rightarrow K^+ K^- \pi^- )</td>
<td>5.4 \pm 0.1</td>
<td>4.2 \pm 0.1</td>
</tr>
</tbody>
</table>

**Decay length resolutions**

<table>
<thead>
<tr>
<th>event type</th>
<th>( \sigma_{\text{av}} ) [( \mu m )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_d^0 \rightarrow \pi^+ \pi^- ) [102]</td>
<td>224 \pm 22</td>
</tr>
<tr>
<td>( B_s^0 \rightarrow D_s^- \pi^+ ) [102]</td>
<td>310 \pm 30</td>
</tr>
<tr>
<td>( B_d^0 \rightarrow J/\psi K^0_s (\mu \mu) ) [4]</td>
<td>373 \pm 66</td>
</tr>
</tbody>
</table>

**Decay time resolution:** 40 fs

\( \Delta m_s \) reach in one year: 54 ps\(^{-1} \)
The Velo is well designed to reconstruct beauty mesons.
Damage in silicon is normalized to the damage of neutrons of 1 MeV kinetic energy.
One word about oxygenated silicon

A higher CCE is reached for a lower bias voltage with oxygenated silicon compared to standard silicon.

HOWEVER, the voltage, where maximum CCE is reached, is not so much different between oxygenated and standard silicon.

Oxygen could help in case of n-strip sensors.
Cryogenic Operation

Recovery of CCE after biasing sensor, BUT effect disappears after few minutes.

Reason:

Irradiation creates holes in the silicon crystal structure:

\[ n\text{-type} \iff p\text{-type} \]

Depletion voltage increases because of increased effective doping density

Holes can be filled by a current pulse (switching on bias voltage), reducing the effective doping density

Trapping and De-trapping times at room temperature \(~\text{ns}\)

Trapping and De-trapping times at cryogenic temperatures are much longer. HOWEVER, still not long enough to ensure stable operation.

Continuous current injection could be a solution, but requires much more R&D to become a reliable way of operating silicon sensors.