Introduction to LHCb I
Introduction to LHCb II

- $O(10^{12})$ bb pairs/year
- $\sigma_{bb} \sim 500\mu b$
- $\sigma_{bb} / \sigma_{inelastic} \sim 5 \times 10^{-3}$
- Pairs produced at small angles
- Modest luminosity
LHCb VELO concept

- Offline reconstruction of B vertices
- Vertex trigger

25 VELO stations
1 station = 1 left and 1 right detector module
1 module = 1 R- and 1 φ-measuring sensor

Left and right halves are retracted from the beam axis by 3 cm during LHC injection.

Top view:

Cross section at x=0:

LHC beam
LHCb VELO concept

Foil protects the VELO and the LHC beams from each other.
LHCb VELO concept

Putting it all together:
Detector Design

Phi sensor

R sensor

Minimum pitch

Readout Chips
Detector requirements

Driving arguments for a technology choice are:

- Resolution
- Signal / Noise
- Radiation hardness
- Availability
- Material Budget

Problem: Cannot get all the good things at the same time.
Find a solution which we are convinced will work.
Improvements are still possible at a later time.
Radiation issues

- Sharp gradient in dose
- Highest dose in place where best precision is needed
- Sensors MUST function when partially underdepleted
- Sensors will be replaced after 3 years

LHCb VELO

![Graph showing radiation levels](image)
Material issues

- multiple scattering
  \(~\sqrt{d}\~
  
  optimization study:
  d=300\mu m: acceptable
  d=500\mu m: effect seen

<table>
<thead>
<tr>
<th>Detector</th>
<th>TDR</th>
<th>lite a</th>
<th>lite b</th>
<th>lite c</th>
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<tbody>
<tr>
<td>Silicon</td>
<td>6.1</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
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<tr>
<td>Hybrid and supports</td>
<td>1.6</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>RF-foil</td>
<td>9.0</td>
<td>10.4</td>
<td>6.4</td>
<td>8.8</td>
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<tr>
<td>RF-box sides</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
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<tr>
<td>Wake-field cone</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Vacuum tank</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Beam Pipe</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Total (&lt; X_0 &gt;)</strong></td>
<td>20.6</td>
<td>18.7</td>
<td>14.7</td>
<td>16.8</td>
</tr>
<tr>
<td>(&lt; X_0 &gt;) before 1st hit</td>
<td>3.1</td>
<td>4.0</td>
<td>2.5</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Effect on downstream detectors with respect to occupancies under study.
Multipl. scattering:
\[ \delta(\vartheta) \sim \frac{1}{p} \]
distance to first material:
\[ l \sim \frac{1}{\sin(\vartheta)} \]
\[ \Rightarrow \text{error on impact parameter} \quad \sigma \sim \frac{1}{p_t} \]

Average decay length errors

- **Conservative detector**
  - \( B \Rightarrow \pi \pi: 176 \mu m \quad B \Rightarrow K_s J/\psi: 236 \mu m \)

- **Ultimate detector**
  - \( B \Rightarrow \pi \pi: 138 \mu m \quad B \Rightarrow K_s J/\psi: 176 \mu m \)
Efficiency issues

L1 trigger of LHCb based on VELO impact parameter

Many channels have multihadronic final states: - tracking efficiency crucial

$B_d^0 \rightarrow \pi^+ \pi^-$  
$B_d^0 \rightarrow \rho \pi$

$B_d^0 \rightarrow D_0 K^*$  
$B_S^0 \rightarrow D_S K$

$B_d^0 \rightarrow D^* \pi,$

$3\pi$

$B_S^0 \rightarrow D_S \pi$

$B_d^0 \rightarrow J/\psi K_S^0$

$B_S^0 \rightarrow J/\psi \phi$
Cost issues

Experiments using silicon strip detectors

Area in squared meters

- Space
- Tevatron
- LHC
- LEP-like

LHCb VELO is here
R&D trends for LHCb

- Lazarus effect
  - go cold?
  - consequence: p-on-n vs n-on-n decision

- Oxygenated silicon

- p spray

for the future…

- Czochralski detectors, 3d etc.
The Lazarus effect

LHCb was one of the first large experiments to very seriously consider cryogenic operation when it was first proposed in 1998. Test program set up in collaboration with RD39

Finally we didn’t choose cryogenic operation, but as a consequence of the system test many important and useful issues came up
The Lazarus effect (at “moderate irradiation levels”)

COLD is COOL – as Rembrandt knew

- Cool detectors have little leakage current
- Cool detectors don’t reverse anneal
- Possible to control doping – hence underdepleted detectors magically become depleted

It’s all about space charge!

\[ V_{\text{depl}} \propto | \text{space charge} (N_{\text{eff}}) | \]
Irradiation: strips for LHCb

• Reminder from Ramo (1939)

Irradiated detectors

\[ Q = e \times \frac{d}{w} \quad V_{\text{bias}} \]

Underdepletion has two bad consequences

Charge loss

Charge spread:
A killer for fine pitch detectors!

NIM A 412 (1998) 238

Similar story for trapping...
Mr. Ramo

I co-invented the electron microscope

I pioneered microwave technology

I founded TRW

I had a theorem
Irradiation: strips for LHCb

• Reminder from Ramo (1939)

Irradiated detectors

\[ Q = e \times d/w \times V_{bias} \]

Underdepletion has two bad consequences

Charge loss

Charge spread: A killer for fine pitch detectors!

NIM A 412 (1998) 238
Testing the Lazarus effect

n-on-n detectors from HAMAMATSU
- Thickness: 300 μm, Smallest strip pitch: 40 μm

p-on-n detectors, DELPHI module, double sided readout:
- Thickness: 310 μm, Smallest strip pitch: 42 μm n-side
  25 μm p-side

p-on-n detectors from MICRON:
- Thickness: 150/200/300 μm
- Smallest strip pitch: 32.5/24.4 μm for the phi-detector

+ measurements from ATLAS, CMS, ROSE, …

But LHCb is special: Small strip pitch!
Irradiation: strips for LHCb

Charge spread causes problems on the p side only
Up to $\sim 10^{14}$ underdepletion is still more important than trapping

For LHCb
n-on-n detectors are the technology choice

Resolution [µm]

Efficiency

NIM A 450 (2000) 297
NIM A 440 (2000) 17
Back to the thin detector issue

Suppose, one cannot deplete the detector throughout the lifetime of LHC. Thinner silicon detectors could be at an advantage.

Example for $V_{bias}/V_{depletion} = 50\%$ for 300 $\mu$m thick irradiated detector, which needs 800V to deplete.

Remember Ramo: $\Delta q = e \frac{q}{w}$

<table>
<thead>
<tr>
<th>$w$</th>
<th>300$\mu$m thick</th>
<th>210$\mu$m thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{depletion}$</td>
<td>800 V</td>
<td>400 V</td>
</tr>
<tr>
<td>$V_{bias}$</td>
<td>400 V</td>
<td>400 V</td>
</tr>
<tr>
<td>$d$</td>
<td>210$\mu$m</td>
<td>210$\mu$m</td>
</tr>
<tr>
<td>$e/h$</td>
<td>19000</td>
<td>19000</td>
</tr>
<tr>
<td>$\Delta q$</td>
<td>13300</td>
<td>19000</td>
</tr>
</tbody>
</table>
Radiation Hardness summary

max. dose:
~ $1 \times 10^{14}$ n/cm$^2$/year at
r=8mm

in general:
Not limited by increasing current
(small strip length)
BUT limited by maximum voltage
Therefore, detector will slowly
die from inside to outside.

\[ \text{pn: detector needs to be fully depleted (100%), otherwise} \]
\[ \text{resolution degrades drastically.} \]
\[ \text{Even worse, charge could also be lost to the double metal layer.} \]

\[ \text{nn: detector can run under depleted, loose only in CCE.} \]
\[ \text{Resolution is conserved.} \]
What about a different detector design?

For \( r \)-detectors:

- Cluster resolution saturates at \(~25\text{-}30\mu m\) and \( \vartheta > 100\text{mrad} \)
- Cluster resolution still improves at low angles, but there the multiple scattering contribution becomes larger.

For \( \Phi \)-detectors:

- Track angle is always \(~0\text{ mrad} \) (for no or small stereo angle, with \( 20^\circ \text{ stereo angle} = 35\text{mrad} \))
- Cluster resolution profits from smaller strip pitch.
- Add floating strips:
  - improves resolution without increasing readout channels
  - avoid very large strip pitches
Floating strips

Beautiful concept: needs checking for n-on-n detectors under irradiation – part of LHCb program
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 detectors.
What can p-strip detectors offer? 
Or why consider p-strip detectors after all?

**p-strip detectors can have smaller strip pitches**

n-strips need to be isolated. Done by using p-stops, p-spray. Limits minimal strip pitch.

**p-strip detectors can be made thinner**

Hamamatsu produces n-strip detectors with 300μm thickness only. BUT, MICRON accepted order for 200μm thin detectors.

**p-strip detectors are cheaper**

expected saving ~30% (ATLAS). But money is not an issue. Sensor cost is only 10-15% of total VELO cost.

⇒ Physics Study
Czochralski silicon

- Received from Helsinki
- Collaboration with RD50 & Glasgow
- Hope is that Czochralski-Si could be particularly radiation hard
  - high Oxygen concentration
- Parameters:
  - 50 µm pitch
  - 380 µm thick
  - read with SCTA128-HCs
- Parasitic running during SCTA_VELO TB period – tested up to 700 V

First landau distribution…
Conclusions

LHCb VELO is on the lookout for new ideas

Our collaborating institutes are actively involved in silicon R&D (rad-hard, new devices etc)

Our main requirements are good (ultimate silicon!) precision and noise performance in harsh radiation environments

Going to a real system is a challenge

We will work closely with RD50 to evaluate new technologies in the VELO context