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The Silicon Inner Tracker for LHCb

Olaf Steinkamp

- **Requirements and Layout**
- **Silicon Sensors and Ladders**
- **Read-Out Chip**
- **Outlook**

Physik Institut der Universität Zürich
Winterthurerstrasse 190 CH-8057 Zürich
olaf.steinkamp@physik.unizh.ch

LHCb Experiment

Dedicated experiment for B-physics at LHC

CP Violation and rare decays

$b\bar{b}$ production at LHC strongly forward peaked

⇒ forward spectrometer $250 \text{ mrad} \times 300 \text{ mrad}$

Special attention on:

- vertexing: VELO (→ talk by J.Libby)
- particle identification: RICH detectors (→ talk by C.Matteuzzi)
- triggering: VELO, calorimeters, muon detector
- tracking, momentum reconstruction: **dipole spectrometer**

LHCb Spectrometer

4 Tm dipole magnet (bending plane horizontal)

Nine planar tracking stations

- positions optimized for “upstream” tracking

Each station four detection layers

- wire/strip orientation vertical, $+5^\circ$, -5° , vertical
- optimized for momentum resolution, pattern recognition

– track reconstruction efficiency $> 95\%$ for B decay tracks

– average momentum resolution $\approx 0.4\%$, dominated by mult.scatt. up to 100 GeV

$\Rightarrow$ **watch material budget!**

Tracking Stations

(largest station $6\text{ m} \times 5\text{ m}$)

Track density strongly forward peaked

- up to 10^6 charged part./ cm^2 near beam pipe
- falling off with $\approx 1/r$

⇒ each station: two detector technologies

- borderline determined by track density
- “Outer Tracker”: straw drift chambers
- **“Inner Tracker”: silicon-strip detector**

Inner Tracker: cross-shaped layout

- four detector boxes
- each box four detection layers
- each layer seven silicon ladders
- each ladder two 6” silicon sensors
- total surface 9 stations $\approx 14\text{ m}^2$

Detector Simulation

GEANT description of active and dead material
Digitization within LHCb *Gaudi* framework:

- signal generation
- charge sharing (from laser tests)
- amplifier response (from Beetle prototype)
- gaussian noise
- clustering

eta function

signal shape

cluster size

occupancies

Radiation Dose and Particle Fluxes

Detailed Fluka description of detector and cave

- careful analysis of Inner Tracker region to be done

From previous study:

- integrated dose 20 Mrad
 - 5×10^{13} 1-MeV equiv. neutrons / cm²
- after 10 years of operation in hottest spot

Silicon Sensor Design

Cost read-out electronics:

- “long” ladders, “large” pitch

Tracking performance, station layout:

- 22 cm long ladders
- readout pitch about $250\ \mu\text{m}$

Material budget:

- “thin” sensors

LHC bunch crossing frequency:

- shaping time $\approx 25\ \text{ns}$ to avoid pile-up
- small w/p to minimize capacitance

Radiation environment:

- 5×10^{12} 1-MeV equiv. $\text{n/cm}^2/\text{year}$
locally ($\Rightarrow$ not our biggest worry ...)

Technology	p ⁺ -on-n
Thickness	320 μm
Sensitive	108 mm $\times$ 76 mm
Number strips	320 (384)
Strip pitch	237.5 μm (198 μm)
Implant width	$0.2 < w/p < 0.3$

Ladder Design

Design aims:

- simple, robust construction
- modularity
- material budget
- cooling (sensors at -5°C)

Layout:

- U-shaped carbon-fibre support
- ceramic pitch adaptor
- kapton read-out hybrid
- cooling “balcony”

Detector Box Design

- one box for four detection layers
- common “cooling plate” carrying cooling pipe
- thermal contact and positioning via individual balconies
- cold, dry nitrogen atmosphere
- insulation box (not shown)
 - light-weight foam for thermal insulation
 - thin aluminium foil for electrical shielding

Ladder Prototype

- four-layer Amoco K1100 shelf
 - dummy silicon sensors and hybrid
 - Kapton heat elements
 - temperature probes / thermal camera
- ⇒ test mechanical and thermal properties

Detector Box Prototype

First prototype for thermal tests:

- box from mold-injected polyurethane foam
- C_6F_{14} liquid cooling
- aluminium cooling plate / balconies
- mock-up ladders with kapton heat elements

⇒ validate cooling concept

Next: identify low-weight materials

- balconies magnesium matrix composite (magnesium-infiltrated carbon fibres)
- cooling plate carbon-carbon material

1st Prototype Sensors from SPA-Detector, Kiev

- p^+ -on-n, 300 μm thick
- 64 strips, 6.66 cm long, 240 μm pitch
- implant width 48, 60, 72 μm
- fast turnaround, attractive price!
- sensors work fine, except junction breakdown at too low bias voltages

1st Test Beam with SPA Prototype Sensors

- 9 GeV pions (CERN-T7 test beam)
- one-sensor and three-sensor ladders
 - ⇒ 6.7 cm and 20 cm long
- unirradiated sensors at room temp.
- Helix read-out chip (HERA-B)
 - ⇒ fastest shaping time ≈ 50 ns

Detection Efficiency 20 cm-long Ladder

As function of w/p (for $V_{\text{bias}} = 90 \text{ V}$):

$w/p = 0.2$

$w/p = 0.25$

$w/p = 0.3$

As function of V_{bias} (for $w/p = 0.2$):

$V_{\text{bias}} = 80 \text{ V}$

$V_{\text{bias}} = 90 \text{ V}$

$V_{\text{bias}} = 100 \text{ V}$

$V_{\text{bias}} = 110 \text{ V}$

Charge Collection Efficiency

one-strip clusters

two-strip clusters

Reduced charge collection efficiency in between strips

- effect decreases with increasing w / p
- effect decreases with increasing overbiasing

Interpretation:

- low-field region in between strips
- charges get trapped or arrive too late (fast shaping time!)
- (simulation in preparation)

Cure:

- optimized strip geometry
- higher overbiasing

⇒ new sensors with better HV performance !

Prototype Sensors from Hamamatsu

Full-size multi-geometry sensors:

- p^+ -on-n, 320 μm thick
- 198 μm and 237.5 μm pitch
- $0.2 < w / p < 0.3$

Sensors received last Friday:

⇒ testbeam at CERN end May

⇒ select strip geometry for LHCb

128-channel pipelined r/o chip, custom design at ASIC lab Heidelberg

- basic RD20 front-end architecture
- 0.25 μm CMOS
- analog and binary pipeline
- prompt binary readout
- programmable via I²C interface

LHCb front-end requirements

- 40 MHz sampling rate
- 1 MHz read-out rate
- 160 cell analog pipeline
- 16 event internal buffer
- 900 ns max. read-out time

Beetle 1.1 submitted March 2001

Beetle 1.1 Total Ionizing Dose Irradiation

Four chips irradiated at CERN X-ray facility

⇒ full functionality up to 45 Mrad

trigger / readout and slow control

⇒ performance degradation small

Pulse shape at $C_{load} = 3 \text{ pF}$

Amplitude remainder after 25 ns

1st Test Beam with Beetle 1.1 Read-Out Chip

- 120 GeV muons (CERN-X7 test beam)
- SPA prototype sensor ladders

6.7 cm and 20 cm long

⇒ successful, reliable operation of chips

(S / N limited by DAQ setup)

Beetle — Next Steps

Beetle 1.2, submission April 2002:

- few bug fixes
- SEU redundant logic
- fully differential output driver
- improved front-ends

Measured on test chips (Beetle-FE 1.1):

- remainder after 25 ns
 $< 30\%$ for C_{load} up to 30 pF
- ENC
 $\approx 520 \text{ e}^- + 40 \text{ e}^- \times C_{\text{load}} / \text{pF}$
 $\Rightarrow \text{S/N} \approx 13$ for 22 cm long ladder

Read-Out Hybrid

Four-layer kapton hybrid for three Beetle chips

1. digital/analog power
2. digital/analog ground
3. traces
4. components

Two-layer “tails” for control signals and read-out of analog signals

Separate pitch adaptor (thin-film ceramic?)

⇒ prototypes in production

Read-Out Link

Readout rate (L0-trigger accept rate): 1.1 MHz

⇒ Beetle output: 4×40 MHz analog

8-bit digitization:

⇒ 1.28 Gbit/s per Beetle, 3.84 Gbit/s per ladder, 134 Gbit/s per Box

Design criteria read-out link:

radiation hardness components, material budget, cost

“LHCb-Light”

Common effort for overall re-optimization of LHCb detector

Two major changes to tracking system under investigation:

a) reduce number of tracking stations

- improved performance due to lower material budget
- baseline scenario: four stations

⇒ very promising results

b) use 1st station in Level-1 trigger

- improved performance from momentum information
- may need all silicon (6.8 m²)

⇒ careful study still needed

Summary and Outlook

Main requirements:

- 22 cm long ladders,
- large pitch (80 μm resolution sufficient)
- fast shaping for 25 ns bunch crossing rate
- material budget!!!

Main R&D:

- sensors: 6" p^+ -on-n , 320 μm thick, 198 μm or 237.5 μm pitch
- readout chip: Beetle
- ladder supports, detector boxes: modular design, low-weight materials
- digital optical read-out link

Upcoming:

- May/June — testbeam with full-size prototype sensors
⇒ validation of sensor design, choice of strip geometry
- October — submission Technical Design Report