LHCb Upgrade: Scintillating Fibre Tracker

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On behalf of the LHCb Upgrade SciFi Tracker group

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Netherlands (Nikhef) - Russia (Kurchatov, ITEP, INR) - Spain (Barcelona, Valencia) - Switzerland (CERN, EPFL)

Overview

[CERN-LHCC-2014-001](#)

- Introduction to LHCb.
 - Current detector.
 - Upgrade detector.
- Scintillating Fibre Tracker.
 - Requirements.
 - Scintillating fibres.
 - Silicon photomultipliers.
 - Electronics.
 - Module production.
 - Schedule.
- Conclusions.

Introduction

Current LHCb:

- Described in talk by Albert Puig (today @ 12.20).
- Data taking conditions:
 - Instantaneous luminosity = $4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$.
 - # visible interactions / crossing, $\mu \approx 1.7$.
- Hardware trigger reduces rate from 40 MHz to 1.1 MHz.

LHCb Upgrade:

- Upgrade conditions:
 - Instantaneous luminosity = $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ and $\mu = 5.2$.
 - Re-design some detectors to cope with higher occupancies.
- Full software trigger for every 25 ns bunch crossing.
 - See talk by Antonio Falabella (28th May @ 16.50).
 - Replace nearly all front-end electronics.
- Collect integrated luminosity $\approx 50 \text{ fb}^{-1}$.

Upgraded LHCb detector

Requirements on Upgrade Tracker

- Detector performance:
 - Hit efficiency $> 98\%$
 - Noise rate $< 10\%$ signal rate (in same region).
 - Resolution $\approx 100 \mu\text{m}$ (in bending plane).
- Material: $X/X_0 \leq 1\%$ per layer.
- 40 MHz read-out.
- Integrated luminosity $\approx 50 \text{ fb}^{-1}$.

Scintillating Fibre Tracker

- Redesign and replace IT+OT.
 - Occupancy too high in OT in upgrade conditions.
 - Electronics designed for 1 MHz.
- SciFi Tracker:
 - Scintillating fibres read out with Silicon Photomultipliers (SiPMs).
 - Single fast and light technology.
 - Read-out electronics and services outside acceptance.

Detector design

- 12 modules per detection plane.
- Scintillating fibres.
 - 2.4 m long, 250 μm diameter.
 - Mirrored at one end.
 - Six layers of fibres in each module.
 - 10,000 km needed for full detector.
- Total active area is 360 m^2 .
- SiPMs and front-end electronics inside light-tight read-out box.

Cross-section of fibre mat

10,000 km (ish)

Radiation environment

NIEL (neutrons):

- SiPMs at ± 250 cm
 - $9.5 \times 10^{11} n_{eq} / \text{cm}^2$ (T1).
 - $13 \times 10^{11} n_{eq} / \text{cm}^2$ (T3).
- Shielding of SiPMs.
 - Polyethylene with 5% boron.
 - $6 \times 10^{11} n_{eq} / \text{cm}^2$.

Ionising dose:

- 35 – 25 kGy (fibres).
- 40 – 80 Gy (SiPMs).

Challenges

- Procurement of scintillating fibres:
 - High light yield.
 - High attenuation length.
- Radiation hardness of fibres & SiPMs.
- Mechanical design and construction.
- Fast read-out / data reduction.
- Cooling requirements.
- Timescale.
 - Installation in Long Shutdown 2 (2018/19).

Scintillating fibres

Baseline fibre: Kuraray SCSF-78MJ

- Polystyrene core with two wavelength shifting dyes.
- Around 300 photons / MIP.
- Only a few photons after 2.4 m.
- Fibres must have long attenuation length (> 300 cm).

Irradiation effects in fibres

- Irradiation test at CERN PS with 24 GeV protons.
 - 3 m long SCSF-78 fibres ($\varnothing$ 0.25 mm).
 - Embedded in glue (EPOTEK H301-2).
- Other irradiations with X-ray, gamma, electrons.

Silicon Photomultipliers

Co-development with:

- Hamamatsu (Japan).
- KETEK (Germany).

- 128 channels / array.
- ~ 100 pixels connected in parallel /channel.
- Avalanche photo-diode operated in Geiger mode.
- Channel width: 250 µm.
- 147m instrumented:
 - 590k channels.
 - 4608 SiPMs.
- Connected to read-out electronics via flex PCB.

Many different devices:

- Various pixel sizes.
- With/without trenches.

Characterisation of SiPMs

Non-irradiated

- High gain: 10^6 — 10^7 .
- High PDE at $\Delta V=3.5V$!
— 39% @ 490 nm.
- Dark count rate.
- Cross-talk.
- Temperature dependent.

Irradiated to 25 fb^{-1}

Signal (TDR)

Fibres:

- Emission spectra.
- Measured at different distances from detector.

SiPMs:

- $PDE = QE \times GF \times \epsilon_{AT}$
 - PDE: Photon detection efficiency.
 - QE: Quantum Efficiency.
 - GF: Geometrical factor.
 - ϵ_{AT} : Avalanche trigger probability.
- Single channel device.
- 50 μm pixels.

Signal Clusters

Clusters:

- Signals shared over two (or more) channels.

SiPMs:

- Dark noise increases with neutron radiation.
- Cooling and annealing.

Fibres:

- Darken after irradiation.
- Six layers of fibres to maximise light yield.

Expected signal:

- $\sim 12 - 16$ photo-electrons after irradiation.

Channel pitch < fibre pitch.

Cluster charge and size measured in cosmic ray telescope.

- Trigger-less read-out.
 - Zero-suppression in front-ends.
 - Development of custom front-end ASIC.
- PACIFIC:
 - 64 channels, 130 ns CMOS (TSMC).
 - Three hardware thresholds = 2-bit.
 - Bandwidth: ~ 300 MHz.
 - Low input impedance: $20 - 40 \Omega$.
 - Low power ~ 8 mW / channel.
 - Fast shaping with zero dead-time.

Clustering on FPGA (sum threshold).

Fibre mat production

Measure fibre diameter

1. Optical cut ends
2. Attach mirror
3. Machine cut sides

Read-out Box

- Every module has one read-out box at each end.
 - Light tight and gas tight.
- Ensures precise optical coupling of cold (-40°C) SiPMs to fibres.
- Houses warm front-end electronics.
- Provide mechanical coupling to support structure.

Cold part of box (illustrative).
Coolant: C6F14 or Novec 649.
Heat load: 20 W / box.

Test beam

- Test beam at CERN SPS:
 - October / November 2014.
 - May 2015 – ends at 7am tomorrow!
- Goals:
 - Attenuation length.
 - Hit efficiency.
 - Resolution.
- Compare with measurements made in the lab and with the simulation.

5-layer HD module without mirror

- Four DUTs.
- 5 and 6 layer mats.
- ~ 2.5 m long.
- Hamamatsu SiPMs.

Schedule / timeline

SciFi Tracker

R & D

Production

Installation

(More) New Physics?

LHC LS1

LHC Run II

• *pp* runs 13 TeV @25 ns

LHC LS2

LHC Run III

• *pp* runs 14 TeV @25 ns

LHC LS3
HL-LHC

- Installation during LS2.
- Collect 50 fb⁻¹ after upgrade.

LHCb Upgrade:

- Instantaneous luminosities up to $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$.
- Trigger-less read-out system.
- New tracking system with scintillating fibres.

SciFi Tracker:

- Scintillating fibres produced by Kuraray.
 - High attenuation length and light yield.
- Silicon photomultipliers:
 - Co-development with Hamamatsu and Ketek.
 - High PDE and low cross-talk.
- Radiation damage studied up to 50 fb^{-1} .
 - Six layers of fibres to ensure sufficient light yield.
 - Shielding required for SiPMs.
- Module production will start at end of 2015.

Frontier Detectors for Frontier Physics

13th Pisa meeting on
advanced detectors

La Biodola • Isola d'Elba • Italy
May 24 - 30, 2015

Istituto Nazionale
di Fisica Nucleare

Università di Pisa
Dipartimento di Fisica

Università di Siena
Dipartimento di Fisica

TOPICS

New ideas on detection techniques
Trends in tracking, calorimetry and particle identification
Ground, sea and space based detector systems
Detectors for astroparticle physics and cosmic radiation
Detectors for fundamental physics and gravitational waves
Neutrino detectors
Synchrotron radiation, X-ray and photon detectors
Frontend electronics and trigger systems
DAQ and data management
Techniques for simulations and data analysis
HEP techniques in medicine, biology and related fields
Application to cultural heritage, environment monitoring
and homeland security
Applied superconductivity in HEP
Acceleration techniques and detectors for beam monitoring
Technology transfer and industrial application
Aim of the meeting is to review the progress
in detector technology with emphasis on
applications in future experiments.

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Grazie mille!

More?

BACK UP

Why upgrade?

- No evidence for New Physics in LHC Run 1.
 - Look for deviations from Standard Model.
 - Most measurements still limited by statistics.
- Limited by Level-0 hardware trigger.
 - Maximum rate is 1.1 MHz.
- Increase luminosity:
 - Already ran well above design.
 - Trigger yield saturates.
 - No real gain in statistics.
- Higher occupancy.
 - Degraded detector performance.
 - Radiation damage of detectors.

Fibre diameter

- Measure diameter every 3 mm with laser micrometer.
- Once per km, diameter goes above limit (300 μm).
- Manually remove during winding process.

Radiation damage in fibres

(a) Logarithmic x-axis

(b) Linear x-axis

Figure 3.16: The combined attenuation length data shown with statistical errors versus dose from three fibre irradiation studies and fits to 4 models. Model 1 assumes a linear damage with dose effect ($\Lambda'(D)/\Lambda_0 = 1/(1 + (D/A))$). Model 2 assumes a power law function ($\Lambda'(D)/\Lambda_0 = 1/(1 + (D/A)^B)$). Model 3 is the logarithmic function $\Lambda'(D)/\Lambda_0 = \alpha + \beta \text{Log}(D)$. Model 4 has an exponential-like behaviour ($\Lambda'(Dose)/\Lambda_0 = \exp((D/\alpha)^\gamma)$). The LHCb-Pit data are not yet included in these fits as they likely have much larger systematic errors that are currently being determined.

Irradiation effects in fibres

KETEK Microcell Construction

Standard technology

Trench technology

<http://www.ketek.net/products/sipm-technology/microcell-construction/>

Dark noise

- Standard hamamatsu.
- Non-irradiated.
- Nominal voltage.
- Temperature: 25°C.

- $2 \times 10^{11} n_{eq} / \text{cm}^2$.
- Nominal voltage.
- Temperature: -60°C.
- Ratio between 1st and 2nd p.e. peaks is same.
 - Cross-talk unchanged.

Annealing in SiPMs

- Multi-channel hamamatsu arrays without trenches.
- Irradiated with neutrons up to 50 fb^{-1} .
- Dark current increases linearly with fluence.

- Hamamatsu with trenches.
- Different annealing scenarios.

Summary of SiPM measurements

Detector type	H. S10262-11-050C	H. with trench (2013)	K. W1C2, with trench	K. W9C2, with trench	K. W7C3, double trench
Surface [mm ²]	1	1	1/3	1/3	1/3
Pixel size [μm ²]	50×50	50×50	60×62.5	60×62.5	82.5×62.5
T _c [mV/K]	56	53	15	26	22
Over-voltage [V]	1.3	3.5	3.5	3.5	3.5
X-talk + After-pulsing	17%	7%	8%	9%	3%
V _{BD} [V]	69	55	23.5	23.5	32.4
Gain [e/PE]	0.75×10 ⁶	2.0×10 ⁶	8.5×10 ⁶	6.4×10 ⁶	9.5×10 ⁶
PDE @peak	30%	37%	42%	41%	40%
Weighted PDE integral	1.26	1.61	1.44	na	1.47
Scaled DCR in [MHz] at -40°C, 2×10 ¹¹ n _{eqv} /cm ² , 1/3mm ²	1.5	6	22	3.8	12

Module Production