The LHCb upgrade and the Scintillating Fibre Tracker

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ON BEHALF OF THE LHCb COLLABORATION

Presented at:
EUROPEAN PHYSICAL SOCIETY
HEP2015
LHCb and the Upgrade (briefly)
- The Scintillating Fibre Tracker (SciFi)
  - Detector Basics
  - Challenges
Two other LHCb Upgrade talks at EPS-HEP:
- Upgrade of the LHCb VELO detector by Mark Williams (Friday @ 15:30)
- The LHCb Upgrade: Plans and Potential by Franz Muheim (Saturday at 9:45)

Main points:
1. We want to collect up 50 fb\(^{-1}\) of integrated luminosity in 10 years to reduce statistical uncertainties to near theory levels
2. The current 1MHz readout is a bottle neck to collect more data at higher luminosity
   - Remove the L0 hardware trigger and read out everything at 40 MHz; software trigger
3. The granularity of the gas straw tube tracker is too low and must be replaced to handle the occupancy at higher luminosity; the silicon tracker was only designed for 10 fb\(^{-1}\)
   - Replace the central tracking stations with the Scintillating Fibre tracker

The LHCb Upgrade
In the LHCb luminosity upgrade (not tied to LHC luminosity upgrade)

- Without a detector upgrade:
  - OT occupancy would grow to 40% at the higher luminosity

- Replace Inner and Outer tracker with a single technology
  - Higher granularity and resolution to handle occupancy
  - Light and uniform weight
  - High rate capability

OT tracking efficiency degrades above 25% occupancy

OT($\sigma_x=200\mu m$)
IT($\sigma_x=50\mu m$)
The Scintillating Fibre Tracker...
Scintillating Fibre Tracker

Scintillating fibres

Image from Kuraray

Cross-section of a fibre mat

Silicon Photomultipliers (SiPM)

60μm pixel

128 channel array

Kapton flex-pcb

Ø 0.250 mm

32.59 mm

1.62 mm

1.35 mm

0.250 mm

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BASIC PRINCIPLE

Scintillating Fibres
(0.250mm diameter)

SiPM array

250μm

6 layers of fibre per plane

Typically, one observes 3-4 photoelectrons per layer of fibre

Position resolution:
\[ \sigma(x) = 65 \text{ μm} - 85 \text{ μm} \]
PRODUCTION

1% $X_0$ / module

Interfaces

5m length

Carbon-fibre/Honeycomb Fibre modules

Fibre winding

Fibre mats

C-frame

Interfaces

5m length

6m
• 144 modules in 12 layers
• 360 m² total area
• more than 10,000 km of fibre
SiPM Ch. 0                                                    19            …           127

SiPM clusters

Old gas straw tube detector

5mm straws

pitch 5.25 mm

Track
Polystyrene core with 2 dyes, PTP + TPB

Only a few photons after 2.5m

300 photons per MIP produced (only 5% of those are captured)

Also investigating nanostructured NOL-fibres. Promises better light yield, but still in development.

S. A. Ponomarenko et al., Nature Scientific Reports 4, Article number: 6549.
Light transmission of scintillating fibre decreases under irradiation up to 35 kGy expected near the beam pipe over the upgrade lifetime.

A mix of low dose, low rate xray, gamma, and high rate, high dose proton irradiations.

As measured by PIN diode.

Expect a 40% loss of transmitted light created near the beam pipe after 10 years.

Expected ionizing dose for LHCb Upgrade.

Transmission losses from radiation.
Light transmission of scintillating fibre decreases under irradiation up to 35 kGy expected near the beam pipe over the upgrade lifetime.

A mix of low dose, low rate x-ray, gamma, and high rate, high dose proton irradiations.

As measured by PIN diode.

Expect a 40% loss of transmitted light created near the beam pipe after 10 years.

Transmission losses from radiation.
Many technology improvements in the last two years related to LHCb

- Pixel crosstalk reduced to <11% via trenching, <5% for next generation
- Photon detection improvements (PDE > 40%) by increased fill factor
- More stable vs temperature changes (operate at 3.5V overvoltage)
- Lower dark noise (improved silicon)

Large area (2 x 64 channel)

Figure 15: Cross-talk for the 128 channels at five different ΔV.

Figure 8: $V_{bd}$ over the 128 channels. Green points correspond to Hamamatsu measurements. Typical pattern repeat itself after 64 channels.
Fibre wavelength spectra overlaid with Hamamatsu SiPM photon detection efficiency

![Graph showing fibre wavelength spectra overlaid with Hamamatsu SiPM photon detection efficiency.](image)

**Graph Details:**
- **X-axis:** Wavelength (nm)
- **Y-axis:** Intensity (a.u.)
- **Legend:**
  - ΔV = 2.5V (Ref.)
  - ΔV = 3.5V
  - ΔV = 4.5V

**Note:**
- SCSF-78MJ (0.25 mmØ) un-irradiated (excitation with UV LED)

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A. Kuonen et al., LHCb-Int-2015-00
- cross-talk between pixels makes 1 pixel avalanche into 2+
- Irradiation at Mains reactor to 3, 6 & $12 \times 10^{11} \text{n}_{1\text{MeV/cm}^2}$
- A few MHz of 1pe signals from radiation damage after 50 fb$^{-1}$ @ -40°C

Neutron eq. Damage

Top: plot from Frank Hönniger, DESY-THESIS-2008-002; reproduced from J. Stahl, DESY-THESIS-2004-028 (unavailable)
Bottom: plots from D. Gerick, Uni. Heidelberg (PhD student)
A manageable dark count rate requires cooling to \(-40^\circ C\)

150m of silicon arrays, without vacuum

Image from D. Gerick, presented at DPG Wuppertal, 11.03.2015

Neutron Eq. Damage and Cooling
The PACIFIC (Front-end ASIC)

- PACIFIC
  - TSMC 130nm
  - 64 channels
  - 2 bit/ch digital output
  - High Bandwidth (~300 MHz)
  - Low power (6.5 mW/ch)
  - Low input impedance (~50Ω)
  - Fast shaping
  - Dual gated integrators (zero deadtime)
  - 25ns peak resolution

- Front-end board development underway
Performance

- Successful test-beams of single mat fibre modules in November 2014 and May 2015

- @250cm from the photodetector
  - 16 photoelectrons (6 layers, with mirror)
  - 99% hit efficiency
  - $\sigma_x = 75 \mu m$

- Signal loss from fibre radiation damage will reduce hit efficiency
- But the good performance of the SiPMs and PACIFIC will allow us to keep the noise suppression thresholds low

Plans:

- Maximize the mirror reflectivity coefficient
- Study fibre recovery effects and radiation damage in a more LHCb-like scenario
- Investigate tracking performance from additional layers/modules
- Optimize some neutron shielding

![Graph showing light yield at 250cm from SiPM]
The SciFi tracker is crucial to scope with the upgrade requirements:
- Low mass (1% X0 per layer)
- Allows for fast tracking
- Good hit efficiency

Technology can cope with the higher radiation environment.

An extensive collaboration between 17 institutes* in 8 countries:
- Production begins in 2016
- Installation in 2019

* 17 institutions: Kurchatov, ITEP, INR (RUS), Aachen, Dortmund, Heidelberg, Rostock (GER), EPFL (SUI), Clermont-Ferrand, LAL, LPNHE (FRA), Nikhef (NL), Barcelona, Valencia (SPA), CBPF (BRA), Tsinghua (CN), CERN
Scintillating Fibres: The gory details

Back-up
- Apply clustering and threshold cuts to reject dark noise clusters due to irradiation in the front-end electronics.
- A balance between thresholds, hit efficiency and allowable noise clusters (ghost tracks and bandwidth).
- Clustering done on an FPGA after the PACIFIC; hit position output to data acquisition.
The LHCb upgrade

Letter of Intent
CERN-LHCC-2011-001

Upgrade Framework TDR
CERN-LHCC-2012-007

Trigger and Online
CERN-LHCC-2014-016

VELO
CERN-LHCC-2013-021

Tracker
CERN-LHCC-2014-001

PID
CERN-LHCC-2012-007
\[ I(x) = I_0 \left( A e^{-x/\Lambda_{\text{short}}} + (1 - A) e^{-x/\Lambda_{\text{long}}} \right) \]

- \( \Lambda_{\text{short}} \sim \text{few cm} \)
- \( \Lambda_{\text{long}} \sim 350 \text{cm} \)

- Data is typically fit to a single or double exponential; integrated over multiple effects

Scintillating Fibres
Fibres and Radiation Damage

- Different radicals are produced in the polystyrene matrix under ionizing radiation (few eV)
- Radicals are absorption centers which reduce the transmission of scintillation light
- Some radicals are unstable \((R+R→X)\), some react with oxygen \((R+O_2→RO_2)\), some are permanent damage
- Diffusion of oxygen plays an important roll in formation and annealing (dose rate and diffusion effects)
- Half lives of hours and weeks depending on temp and \(O_2\)

![Image](image_url)

Fig. 2. The additional absorption \(\Delta \mu\) induced in the scintillator BCF-12 during irradiation in argon atmosphere. The stable absorption centers \(P\) are responsible for the permanent damage \(\Delta \mu_p\), while the anneable damage \((\Delta \mu_1 + \Delta \mu_2)\) is caused by \(R_1\) and \(R_2\). Rapid annealing occurs after inlet of oxygen.