A scintillating fiber tracker for the LHCb upgrade

Fred Blanc (EPFL)

Clermont-Ferrand
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Proposed tracker

- 3 tracking stations downstream of the LHCb magnet
- 250 µm scintillating fibers
- readout with multi-channel Silicon photo-multipliers (SiPM)
LHC and the LHCb experiment
The CERN accelerator complex
The CERN accelerator complex
The LHC accelerator at CERN

- The LHC is installed in the old 27km circular LEP tunnel
- Accelerates protons to a maximum energy of 7TeV
  - 3TeV in 2011; 4TeV in 2012; expect 6.5-7TeV in 2015
- Interaction rate: (up to) 40MHz ⇒ 25ns bunch crossings
- Revolution frequency: 11kHz
- Main operation since 2010
- Currently stopped to bring the beams to nominal performance by 2015
LHC: beam energy

- 7 TeV protons ⇒ $2 \times 7$ TeV center of mass energy
  $[1 \text{TeV} = 10^{12} \text{eV} \quad \text{with} \quad 1 \text{eV} = 1.6 \times 10^{-19} \text{Joules}]$
  ⇒ kinetic energy of a 1mg mosquito at 1.5m/s

- $10^{11}$ protons per bunch

- ~1400 bunches per beam in 2012 data taking period

- Total beam energy
  
  - $E_{\text{beam}} = 1400 \times 10^{11} \times 7 \times 10^{12} \text{ eV}$
  $\approx 10^{27} \text{ eV} = 1.6 \times 10^8 \text{ J}$

  - equivalent to the kinetic energy of a 40-ton truck at 300km/h
    $E_{\text{kin}} = \frac{1}{2}mv^2$ ⇒ $v = (2E_{\text{kin}}/m)^{1/2} = (3.2 \times 10^8 / 40000)^{1/2} = 90\text{m/s} = 324\text{km/h}$
Les particules du “modèle standard”

**LEPTONS**

<table>
<thead>
<tr>
<th>Composants de la matière</th>
<th>Électron</th>
<th>Neutrino-Électron</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Muon</th>
<th>Neutrino-Mu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Très proche de l’électron, mais plus lourd ; il a une durée de vie de 2 millionièmes de secondes.</td>
<td>Créé en même temps que les muons quand certaines particules se désintègrent.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tau</th>
<th>Neutrino-Tau</th>
</tr>
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</table>
Les particules du “modèle standard”

<table>
<thead>
<tr>
<th>Composants de la matière</th>
<th>QUARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Up</strong></td>
<td><strong>Down</strong></td>
</tr>
<tr>
<td>Sa charge électrique est + ( \frac{2}{3} ) e ; les protons en contiennent deux, les neutrons en contiennent un.</td>
<td>Il a une charge électrique de -( \frac{1}{3} ) e ; les protons en contiennent un, les neutrons en contiennent deux.</td>
</tr>
<tr>
<td><strong>Charmé</strong></td>
<td><strong>Étrange</strong></td>
</tr>
<tr>
<td><strong>Top</strong></td>
<td><strong>Beauté</strong></td>
</tr>
<tr>
<td>Encore plus lourd ; découvert en 1995.</td>
<td>Encore plus lourd ; mesurer les quarks beauté est un test important de la théorie électro-faible.</td>
</tr>
</tbody>
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**Les particules du “modèle standard”**

### Quarks

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LHCb: the physics goals

• Main LHC experiments (ATLAS & CMS)
  - search for new heavy particles ($M \approx 100-1000\text{GeV/c}^2$)
  - candidate Higgs particle observed at $126\text{GeV/c}^2$
    ⇒ confirmation of the standard model of particle physics

• LHCb
  - study the matter-antimatter asymmetry and rare processes
  - precision measurements in heavy-flavor systems
    - particles containing heavy quarks (beauty or charm)
  - new physics (i.e. heavy particles) can enter loops and modify the behaviour of the standard model predictions
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![Diagram of B meson production in pp collision](image)
Comment détecte-t-on les particules ?

Pour chaque collision, l'objectif du physicien est de compter, de suivre et de caractériser toutes les différentes particules produites, de manière à reconstituer l'ensemble du processus. La trace laissée par la particule fournit de nombreuses informations utiles, surtout si le détecteur est placé dans un champ magnétique : la charge de la particule, par exemple, est clairement détectable, puisque les particules à charge électrique positive sont déviées dans un certain sens et celles à charge négative dans le sens opposé. De même, il est possible de déterminer l'impulsion de la particule (la « quantité de mouvement » égale au produit de la masse par la vitesse) : les particules à impulsion élevée se propagent en ligne presque droite, tandis que les particules à faible impulsion décrivent des spirales serrées.

Les détecteurs :

- Trajectographe électromagnétique
- Calorimètre électromagnétique
- Calorimètre hadronique
- Détecteur de muons

<table>
<thead>
<tr>
<th>Photons</th>
<th>Électrons ou positons</th>
<th>Muons</th>
<th>Pions ou protons</th>
<th>Neutrons</th>
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LHCb: the detector

- In proton-proton collisions, the B mesons are predominantly produced in the direction of the beams
  ⇒ build the detector along the beam line (forward spectrometer)

- Short B meson lifetime
  ⇒ high precision vertex detector near interaction point

- Kinematics reconstruction of the processes
  ⇒ tracking system with bending magnet

- Multiple types of detected charged particles ($\pi^\pm$, $K^\pm$, $p$, $e^\pm$, $\mu^\pm$)
  ⇒ particle identification (Cherenkov + calorimeters)

- Detection of neutral particles (photons)
  ⇒ electromagnetic calorimeter

- Muon ($\mu^\pm$) identification
  ⇒ muon detectors placed after the calorimeters
...zoom on the tracker

Tracker Turicensis (TT)
Si strips
σ≈50μm

Interaction point (IP)

Vertex Locator
Si strips
σ≈5-25μm
vertexing + tracking

B field ≈4Tm

Vertex Locator

Outer Tracker (OT)
Straw tubes
σ≈250μm

Inner Tracker (IT)
Si strips
σ≈50μm

Clermont-Ferrand seminar, 23/05/2013
LHCb: selected physics results

- Measurement of the oscillations of $B_s^0$ mesons

- Observation of the CP (matter-antimatter) asymmetry in $B_d^0$ decays
LHCb: the need for an upgrade

• Adding 2fb\(^{-1}\) of data every year is significant in the first years
  - statistical uncertainties are proportional to the square root of the integrated luminosity \(\sim (L)^{1/2}\)

• Expect \(\sim 7fb\^{-1}\) by 2016; 2017 will add 30%
  ⇒ only \(\sim 13\%\) improvement on the statistics

• A significant increase is necessary to justify the effort of operating the detector
  ⇒ upgrade of the LHCb detector

• LHCb upgrade plans:
  - replace several sub-detectors
  - change all electronics to allow 40MHz readout
  - install new detector during the 2018 LHC shutdown
LHCb tracker upgrade
LHCb detector upgrade

- LHCb upgrade: replace several detectors, and R/O electronics
- Discuss here the replacement of the tracker, downstream of the magnet
Tracking detector requirements

• High hit detection efficiency ($\geq 98-99\%$)
• Spatial hit resolution at the level of 60–100µm
• Minimize material in the acceptance
  - to limit the effects of multiple scattering and energy loss
• Readout electronics to operate at 40MHz
• Rate of reconstructed noise clusters $< \sim 2\text{MHz} / 128$-channels

• The above requirements must be fulfilled over the full lifetime of the experiment (up to $50\text{fb}^{-1}$)
Comments on the hit resolution

- Hit resolution is driven by multiple scattering
  - each station (TT, IT, OT): \(x/X_0 \approx 3-4\%\)
    \[\theta_{ms} = \frac{13.6 \text{ MeV}}{\beta c p} \sqrt{x/X_0 [1 + 0.038 \ln (x/X_0)]}\]
  - \(p \approx 20 \text{ GeV/c} ; \beta \approx 1 \Rightarrow \theta_{ms} \approx 0.12 \text{ mrad}\)
  - \(0.12 \text{ mrad} \times 0.6 \text{ m} = 72 \text{ µm}\)
    \[\Rightarrow \text{uncertainty due to multiple scattering from a tracking station to the next}\]
    \[\Rightarrow \text{do not need better than } \approx 60 \text{ µm measurement accuracy}\]
  - effect across the magnet: \(0.12 \text{ mrad} \times 5.5 \text{ m} = 660 \text{ µm}\)
    \[\Rightarrow \text{necessity to minimize the material in the acceptance!}\]
Options for the LHCb tracker upgrade

- Two options are being considered:

Silicon strips + Straw tubes

Silicon strips ("Inner Tracker")

Straw tubes ("Outer Tracker")
Options for the LHCb tracker upgrade

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  Silicon strips + Straw tubes

  Scintillating fibers + Straw tubes

- Scintillating fiber (SciFi) is a new technology in LHCb
  - Can a SciFi tracker fulfil the performance requirements?
  - Will the SciFi technology perform as required after the radiation dose received in the LHCb upgrade (50 fb⁻¹)?
Options for the LHCb tracker upgrade

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Main SciFi detector features

• 250μm diameter scintillating fibers
  - arranged in multiple layers for sufficient light collection

• Cover the acceptance with 2.5m long fibers
  - mirror at the center (beam pipe height)
  - light detected outside the acceptance
    ⇒ minimize “inactive” material in the acceptance
  - vertical (x) and stereo (u&v) ⇒ 12 layers

• readout with multi-channel Silicon photo-multipliers (SiPM)

• Readout: 40MHz front-end electronics
The SciFi tracking in numbers

- 12 layers of $5 \times 6 \text{m}^2$ \Rightarrow 360\text{m}^2

- 250\text{$\mu$m} diameter fibers arranged in 5 layers \Rightarrow 7200\text{km}

- readout at top and bottom of the detector stations

\Rightarrow 144\text{m} instrumented with 250\text{$\mu$m} channels

\Rightarrow 576\text{k channels}

\Rightarrow 4500\text{ SiPMs}
SciFi technology challenges

- Development needed for the LHCb SciFi tracker
  - fibers and SiPM radiation hardness studies
  - fiber module construction
    - how to produce 2.5m long fiber mats
    - how to obtain the necessary mechanical precision and rigidity
  - cooling for the SiPMs down to −50°C
    - what cooling system
    - how to control the mechanical stress
  - readout at 40MHz
SciFi R&D
LHCb upgrade: radiation environment

- **1MeV neutron-equivalent fluence**: At a position of ±250cm, the $n_{eq}$ fluence is $6 \times 10^{11}$ per cm$^2$.
- **Neutron fluence** could be reduced by a factor more than two for 1MeV neutrons using a shielding 10cm-thick.

- **Ionizing DOSE**: At a position of 9cm approx. from the beam axis, the peak dose is about 26kGy and average dose over the second and first rings gives 23kGy (10% stat. error)

**SiPM rad. environment**

**Fibers rad. environment**
Spectra close to the beam pipe at Fiberplate in front of IT1

**Careful:** Lethargy means multiplying fluence with Energy bin values in order to get more detail out of high energy regions in a logarithmic binning. Integration below the curve is no longer possible!
Scintillating Fibers

- Baseline fiber: Kuraray SCSF-78MJ
- The fibers have two roles:
  1. act as scintillator
     - 2.8ns scintillation decay time
     - light yield: ~1600 photons/mm/MIP×5.35% capture
       ⇒ 10’s of photons
     - scintillating dye is expected to be radiation hard
  2. transport the light to the SiPM
     - 5.3ns/m propagation time
     - attenuation length is an issue (radiation hardness)
- Alternative fiber: 3HF
  - expected to be more radiation hard
  - ...but slower decay time and lower light yield
Fiber emission spectrum after irradiation

Irradiation shifts the spectrum, observed at the fibre end, towards green/red. This has an impact on the specifications of the SiPM.

⇒ SiPM preferably mostly sensitive in the green wavelength
Attenuation length of irradiated fibers

- Irradiated fibers at the CERN PS with 24GeV/c protons

![Graph showing attenuation length and intensity over position for UV and Sr-90 data.](attachment:image.png)

- UV data
- 4-exp fit to UV data
- Sr-90 data

3.5 Discussion and conclusions

The irradiation of the Kuraray SCSF-78 fibre to fluences of up to $7.1 \times 10^{13}$ p/cm$^2$ (equivalent to 22 kGy) leads to a significant reduction of the optical absorption length. The primary scintillation and wavelength shifting mechanisms appear to be unaffected. On a time scale of 2 months, the measured absorption lengths are stable and no annealing effects were observed. Annealing is generally attributed to the oxidation of free radicals produced during the radiation exposure. The fact that our fibres are embedded in epoxy glue, which may act as a barrier for oxygen, is possibly suppressing a recovery of the optical transmission. It should be noted that a possible fast annealing component during the first 7 days after the irradiation would have remained undetected. The available data limits the time constant of such a component to about 3 days.

The measured damage, expressed as $K = \text{abs}_{0}/\text{abs}$, was fitted to a model proposed by Hara et al. [14]:

$$K = \alpha + \beta \cdot \log_{10}(D),$$

with $D$ being the dose in kGy. The fit yielded the parameters $\alpha = 0.381$ and $\beta = 0.196$ (see Fig. 17). The model appears to describe the absorption length:

- $\sim 0$ kGy: absorption length $400 \text{ cm}/20 \text{ cm}$
- $\sim 3$ kGy: absorption length $125 \text{ cm}$
- $\sim 22$ kGy: absorption length $52 \text{ cm}$
Scintillating fiber radiation hardness

- Damage due to radiations found to increase logarithmically with the dose

- Projected relative light yield loss:
  (without mirror & without timing cut)

\[ \text{Projected relative light yield loss:} \]
\[ (\text{without mirror} \& \text{without timing cut}) \]

![Graph showing expected relative light yield](image)

- Non-irradiated fibre (0.46)
- Damaged fibre after 50 fb\(^{-1}\) (0.28)
- 40% yield loss
Light detection time

Arrival time of photons at the detector as a function of y pos of injection.

- 500mm
- 1500mm
- 2500mm

SiPM
detection point

10 ns

mirrored light

longer tail

25 ns

with mirror
Light yield loss: with mirror and timing cut

- Effect of mirror and timing cut is to reduce light yield spread for all hits along the 2.5m long fiber
Detector performance from simulation

- Tracking on simulated data has been used to evaluate the performance of the SciFi tracker:
  - similar performance to current LHCb, even with ×5 luminosity!
  - faster thanks to single technology
- Estimated level of acceptable noise clusters: ~2MHz / SiPM
- Fibers must be straight over their full length
Fiber mat production

- Lay down fibers on a 96cm diameter cylinder
  - grooves give fibers 280µm pitch
  - each layer is glued to the previous layer (total = 5 layers)
- Fiber mat is cut and taken off the wheel before the glue is dry

Fiber quality is tested (diameter, cracks) before use
Fiber mats

• Fiber mat prototype

• Next steps:
  - improve fiber mat quality
  - R&D for cutting 2.5m long mats (sides and ends)
  - casting into a precise shape
Silicon Photo-Multipliers (SiPM)

- 0.25 × 1.3 mm² channels of 4×20 pixels
- Pixel size = 55µm
- 128 (2×64) channels grouped in a 32mm array

- Two manufacturers: Hamamatsu and Ketek
- Development in progress
Signal cluster detection with SiPM

1. Particle creates photons in the fibers
2. Pixel (red squares) detect photons propagated through the fibers
SiPM noise studies

- The thermal noise is the primary source of noise
- The noise cluster rate depends on
  - the primary noise frequency $f_p$ (thermal noise)
  - temperature $T$ ($f_p$ is reduced by a factor 2 every 10ºC)
  - neutron dose: $f_p$ increases linearly with the dose
  - pixel-to-pixel cross talk probability $P_{x\text{-talk}}$
  - after pulse probability $P_{\text{after}}$
  - integration and shaping time $\Delta t$
  - clustering algorithm $A$, which depends on selection thresholds
- A simulation was developed on this model

$$f_C = f \left( f_P(\Delta V, T, \text{Dose}), A(th_{\text{seed}}, th_{\text{neigh.}}, th_{\text{sum}}), p_{x\text{-talk}}(\Delta V), p_{\text{after}}(\Delta V), \int^{\Delta t} \right)$$
Simulation of the dark noise spectrum

- Irradiation 8 fb⁻¹
  - \( T = -40^\circ\text{C} \)
  - Slow shaping

- Irradiation 8 fb⁻¹
  - \( T = -20^\circ\text{C} \)
  - Slow shaping

- Irradiation 50 fb⁻¹
  - \( T = -44^\circ\text{C} \)
  - Slow shaping

Very good agreement for the dark noise spectrum. Dark count rate can be compared with measured dark.

Change only the primary noise (higher \( T \)). Very good prediction of the dark noise spectrum.

Too slow readout, pile-up of random events create large noise.

Good predictive power \( \Rightarrow \) can be used to extrapolate to LHCb upgrade conditions.
Simulation of the cluster noise rate

- Irradiation 8fb\(^{-1}\)
  - T=\(-20^\circ C\), \(-40^\circ C\)
  - Slow and fast shaping
- Irradiation 25fb\(^{-1}\)
  - T=\(-40^\circ C\)
  - Fast shaping
- Irradiation 25fb\(^{-1}\)
  - T=\(-40^\circ C\)
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Shaping time

- Irradiation 25fb\(^{-1}\)
  - T=\(-40^\circ C\)
  - Fast shaping

2MHz rate

- Irradiation 25fb\(^{-1}\)
  - T=\(-40^\circ C\)
  - Fast shaping

X-talk

- Irradiation 25fb\(^{-1}\)
  - T=\(-40^\circ C\)
  - Fast shaping

After-pulse

Shorten the shaping time by a factor 8!
Cluster noise is dominated by random pile-up of noise pulses.

Keep x-talk probability below 2% to allow for a low noise cluster rate.

Keep after-pulse probability below 2% to allow for a low noise cluster rate.
SiPM radiation hardness

- Maximize the hit detection efficiency, while keeping the cluster noise at an acceptable level (< ~2MHz / 128-channels)

- Noise controlled by:
  - shielding, cooling, pixel-pixel cross-talk, integration time

- Results:
  - noise can be kept below 2MHz
  - photon detection efficiency: OK for the KETEK SiPM, and too low for Hamamatsu SiPM

- On-going R&D is expected to improve significantly the performance of the Hamamatsu detector

Note: This simulation needs to be verified further with the data from test beam and cosmics tests.
Detector modules

- Plan to build 16 SiPM wide modules (~52cm)
- Single or double fiber layers

- Development of a service box to hold
  - the SiPMs
  - the cooling system for the SiPMs
  - the readout electronics
  - the mechanical support
SiPM cooling (−50°C)

- Considering several cooling systems for SiPMs

1. liquid (single- or 2-phase)

2. thermoelectric cooling

3. chilled air cooling

4. cooling through the PCB

- Thermal analysis of the various options in progress
Front-end electronics

• 40MHz readout electronics
  - development in Clermont-Ferrand and Barcelona to meet the SciFi detector requirements
  - considering various options

- take into account SiPM response, occupancy distribution, etc...

• Short term testing with existing 40MHz *beetle* chip (LHCb)
Detector layout and integration (in progress)
Prototype engineering drawings for a double fiber layer design
Scintillating fibers
Support structure
Polycarbonate

Cooling pipe
SiPM

Gaps to minimize thermal connection
Conclusion (and next steps)

- A scintillating fiber detector readout with SiPMs is being developed for the upgrade of the LHCb experiment
- It is the first time this technology would be used at this size and in the high radiation environment of the LHC
- The next steps towards a Technical Design Report by the end of 2013 are in preparation:
  1. continuation of the SciFi and SiPM R&D
  2. construction of a demonstrator detector module with all functionalities
     - challenging engineering R&D
       (e.g. fiber mat production, integration of the cooling, ...)
  3. design of the front-end electronics
     - multiple solutions are being considered
  4. design of the global detector layout
  5. planning until installation and cost evaluation