SciFi Tracker Upgrades

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Outline

- Expected aging of the SciFi after Run 3 & 4
- Replacement and upgrade
- Upgrade the performance of the SciFi
  - Micro-lens enhancement of SiPMs
  - Thinner SciFi
  - Cryo-cooling
- Conclusion for Upgrade 1b, Upgrade II
SiPM aging

SiPM nominal design:

- **Design luminosity** $50 \text{fb}^{-1}$
  - Neutron radiation: $6 \times 10^{11} \text{n}_{\text{eq}}/\text{cm}^2$
  - Charged: 50Gy, responsible for 15-20% of SiPM DCR increase after neutron shielding

- **Fluka simulation with neutron shield yields the values for the most exposed regions in T1 and T3:**
  - **T1**: $8.1 \times 10^{11} \text{n}_{\text{eq}}/\text{cm}^2 \Rightarrow 3.3 \times 10^{11} \text{n}_{\text{eq}}/\text{cm}^2$ (reduction of 2.5 after shielding)
  - **T3**: $14 \times 10^{11} \text{n}_{\text{eq}}/\text{cm}^2 \Rightarrow 4.2 \times 10^{11} \text{n}_{\text{eq}}/\text{cm}^2$ (reduction of 3.4 after shielding)

- **Fluka simulation uncertainty** for the absolute values of the neutron fluence is a **factor 2**
SiPM aging

SiPM after Run 3 of 40fb⁻¹:
- T1: $2.6 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$ (worst case $5.2 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$)
- T3: $3.3 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$ (worst case $6.6 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$)

SiPM after Run 3&4 of 80fb⁻¹:
- T1: $5.2 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$ (worst case $10.4 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$)
- T3: $6.6 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$ (worst case $13.2 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$)

In red, values beyond the design fluence which is the limit of acceptable dark count rate (DCR) and has a consequence the noise cluster rate (NCR).

To maintain NCR<10MHz, the noise threshold cut has to be increased and the efficiency is dropping rapidly.
Neutron fluence is responsible for 80-85% of DCR increase of the SiPM after shielding.

3.3*10^{11} \text{n}_{\text{eq}}/\text{cm}^2

4.2*10^{11} \text{n}_{\text{eq}}/\text{cm}^2

Neutron fluence with neutron shield.
Dose due to charged tracks, makes up 15-20% of the DCR increase for the SiPMs

Decrease to the edge is slow

Radiation dose profile in the x-y plane
Irradiated detector with $6 \times 10^{11} \text{n}_{\text{eq}}/\text{cm}^2$

Reducing $\Delta V$ by 1V reduces DCR by a factor 1.58!

DCR as a function of temperature at 3 different possible operation points
Light emitted by the SciFi is centered around 475nm.

Reducing $\Delta V$ by 1V reduces PDE by a factor 1.12!
Noise cluster rate (NCR) expected for the current SciFi

For “high” DCR only increasing the threshold can reduce NCR.
Noise cluster rate for different seed thresholds

Integration window (Pacific 25ns)
Noise cluster rate expected for the current SciFi

Pacific integration time 25ns

Exponential behaviour of NCR

Irradiated detector to $3 \times 10^{11} \, n_{eq}/\text{cm}^2$
Radiation damage of the fibre results in lower photon survival probability.

Linear law model ratios:

\[
\frac{LY_{50 fb^{-1}}}{LY_0} = \frac{12\text{PE}}{18\text{PE}} = 67\%
\]

\[
\frac{LY_{100 fb^{-1}}}{LY_0} = \frac{8.5\text{PE}}{18\text{PE}} = 47\%
\]

Power law model ratios:

\[
\frac{LY_{50 fb^{-1}}}{LY_0} = \frac{10\text{PE}}{18\text{PE}} = 56\%
\]

\[
\frac{LY_{100 fb^{-1}}}{LY_0} = \frac{6.7\text{PE}}{18\text{PE}} = 38\%
\]
Reduceing ΔV by 1V reduces DCR by a factor 1.58!

Radiation damage reduces the LY

The selection at the production allows to obtain LY>18PE before irradiation
Cutting or “not using” 30cm of the inner-most part of the module

\[
\frac{LY_{50 fb^{-1}}}{LY_0} = \frac{12 \text{PE}}{18 \text{PE}} = 67\% \\
\frac{LY_{100 fb^{-1}}}{LY_0} = \frac{8.5 \text{PE}}{18 \text{PE}} = 47\%
\]
Inefficiency as a function of noise cut and LY

End of Run 4, >20%

End of Run 3, 2-3%
Micro-lens enhanced SiPMs

Goal 1: Reduce pixel size without loosing light to reduce:
• optical x-talk
• gain and therefore bias current and self heating
• recovery time (dead time) and after-pulsing
• DCR for irradiated devices

Goal 2: Improve sensitivity (PDE)
• use micro-lenses to focus light in the center of the pixel avoiding dead and low-field region

Pro:
• Expected improvement of the LY is larger than 20%
• Same detector geometry and package size as current SiPM array

Cons:
• High cost for micro-lenses and through silicon via (TSV) package
• No cleaning possible anymore
Higher GFF technology between 2017 and now

Implementation example from FBK: High geometrical fill factor (GFF) due to thin trenches, NUV-HD has 20% higher GFF than the previous NUV design.

Comparison with H2017:

GFF=70% for H2017 62x57.5 μm² vs GFF>80% for FBK 40x40 μm²
Reducing occupancy

Typical cluster for an orthogonal track has a size of 3 channels.

Maximum occupancy depends not only on the number of tracks per linear distance but also on the cluster size.
Reducing occupancy

3 ch

5 ch
Reducing occupancy with thinner SciFi mats (less layers = less signal)

Less light, this can work with cryogenic cooling!
Reducing occupancy with thinner SciFi mats and or segmenting channels in height

Requires 2x the number of channels, this will be simulated for evaluation.
Reducing noise drastically with cryogenic cooling (LN2) in a vacuum chamber

Note:
- **Flexible interface with clear fibre**, expected light loss <15%
- Total width of vacuum vessel allows space between modules. Sufficient space for services for the Si-pixel detector is available
- Vacuum feedthrough with clear fibres
Reducing noise drastically with cryogenic cooling (LN2) in a vacuum chamber

FBK cryo version of SiPMs

Cell size = 25 µm

DCR (Hz/mm²)

-40°C

120K -> 1/4000 DCR of the current level

2017
Reducing noise drastically with cryogenic cooling (LN2) in a vacuum chamber

Noise reduction for FBK SiPMs optimized for cryogenic operation:

• pessimistic assumption for noise reduction slope (10K instead of 8K for a factor 2)
• Limited range of valid slope
• Upgrade II conditions, 10 x radiation level $6 \times 10^{12} \text{n}_{eq}/\text{cm}^2$ of current Upgrade
• 5x higher DCR than Hamamatsu for the same neutron fluence

⇓ Cryocooling allows to reduce DCR to a level of $5 \times 10^7 \text{ Hz per SiPM array}$
⇓ **Noise cut is as low as 1.5PE** producing less NCR than for the current detector

Cryogenic cooling is currently the only solution to operate the SciFi tracker beyond Run 4! It can compensate for the reduction of LY due to the fibre irradiation.
Conclusion

- Large uncertainties for radiation level simulated by Fluka (Factor 2), neutron shield and neutron fluence.
- **Uncertainties for efficiency** are large when the LY is close to 10 photons, steep rise
- **Uncertainties in LY from the fibre** module at large irradiation level, annealing and aging of scintillator
  
  *We need to operate the detector to gain detailed knowledge*

**Upgrade 1b:**

**Optimistic scenario:**
- Replace the 12 0° central modules (6 layers) with Si-pixel + SciFi modules.
- Keep fibre modules with 5° angles without exchange of fibres
- Replace SiPMs for all 24 central modules after Run 3 (avoid 80fb⁻¹ of radiation for central SiPMs)
- Develop and produce advanced micro-lens enhanced SiPMs for this replacement

**Pessimistic scenario:**
- All replacements needed for the optimistic case plus replacing also the 5° central fibre modules

**Upgrade 2:**
- Replace all modules and SiPMs
- Replace cooling with cryogenic LN2 cooling and develop a clear fibre interface
• Development of radiation optimized SiPMs
  – Study optical focusing system on pixels with micro-lens to increase overall PDE.
  – Study more radiation hard SiPM implementations (silicon structures) and the use of smaller pixels (Hamamatsu, Ketek, FBK, SensL, …).
• Development of a clear fibre interface required for cryogenic cooling (vacuum feedthrough) and to reduce SciFi length for segmented readout.
• Development of fast, high light yield, green fibres to reduce light transport loss (radiation) with possible application in LHCb SciFi Upgrade 1b or II.
• Reduced hit detection efficiency is the “aging” effect of the SciFi and is directly coupled to the S/N ratio.
• For 50 fb\(^{-1}\) a reduction of efficiency of 1-2% is expected. Precise numbers are difficult to obtain before a few years of operation.

Light loss of fibres decreases signal, green fibres help.

Increase luminosity increases noise

Reduce pixel size to improve x-talk, AP DCR, current induced self-heating

Decrease the number of fibre layers in mat to reduce occupancy!

Decrease active surface of SiPM reduces noise

Increase PDE of SiPM increases signal