The LHCb Upgrades

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on behalf of the LHCb collaboration

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The LHCb LS2 Upgrade

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LHCb Motivation

- primary goal: “indirect” search for New Physics
  - new heavy particles can enter in internal loops and have sizeable effect on observables
- \( CP \) violating phases, rare \( FCNC \) decays
- \( B^0 \) and \( B^0_s \) systems are an ideal hunting ground
  - rich phenomenology, precise predictions from theory
- LHCb: confront predictions with precise measurements
[see also Ulrik Egede’s talk on Wednesday]

- \( b\bar{b} \) production at LHC peaks at small polar angles
  - LHCb layed out as forward dipole spectrometer
- forward geometry offers additional advantages:
  - larger Lorentz boost → better decay time resolution
  - higher momentum for same \( p_T \) → lower \( p_T \) thresholds
- extra benefit: unique potential for production studies in forward direction
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Requirements

- impact parameter resolution
  - to identify secondary vertices
- proper time resolution
  - to resolve fast $B^0_s - \bar{B}^0_s$ oscillations
- momentum & invariant mass resolution
  - to suppress combinatorial backgrounds

- $K/\pi$ separation
  - to suppress peaking backgrounds
  - for flavour tagging
- selective and efficient trigger, also for hadronic final states

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15 Aug 2014  LHC and Beyond – LHCb upgrade (5/28)  O. Steinkamp
**Run I/II Detector**

**VErtex LOcator**

$\sigma_{IP} \sim 20 \, \mu m$

for high-$p_T$ tracks

**RICH detectors**

$\varepsilon(K\rightarrow K) \sim 95 \%$

for 5 \% $\pi \rightarrow K$ mis-id

**Muon system**

$\varepsilon(\mu \rightarrow \mu) \sim 97 \%$

for 1-3 \% $\mu \rightarrow \pi$ mis-id

**Tracking system**

$\Delta p/p = 0.4 \% @ 5 \, GeV/c$ to

$0.6 \% @ 100 \, GeV/c$

**Calorimeters**

ECAL: $\sigma_E/E \sim 1 \% \otimes 10 \% / \sqrt{E} (GeV)$

**Acceptance**

$2 < \eta < 5$

[**JINST 3 (2008) S08005**]
**2012 Trigger**

**40 MHz bunch crossing rate**

**L0 Hardware Trigger**: 1 MHz readout, high \( E_T/P_T \) signatures

- **450 kHz** \( h^\pm \)
- **400 kHz** \( \mu/\mu \mu \)
- **150 kHz** \( e/\gamma \)

**Software High Level Trigger**
- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

**5 kHz Rate to storage**

- **2 kHz** Inclusive Topological
- **2 kHz** Inclusive/Exclusive Charm
- **1 kHz** Muon and DiMuon

**Hardware level (L0):**
- Maximum output rate 1 MHz
- Typical thresholds:
  - \( E_T(e/\gamma) > 2.7 \text{ GeV} \)
  - \( E_T(h) > 3.6 \text{ GeV} \)
  - \( p_T(\mu) > 1.4 \text{ GeV} \)

**Software level (HLT):**
- Event reconstruction similar to offline

**Combined efficiency L0+HLT (2012):**
- ~ 90 % for di-muon channels
- ~ 30 % for multi-body hadronic final states

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[LHCb run II trigger: Karol Hennessy's talk earlier today]
LHCb designed to operate at lower instantaneous luminosity than ATLAS/CMS

- very high particle density in forward region
- large pile-up could affect reconstruction performance (e.g. $B$ decay length, flavour tagging)

achieved by displacement of LHC beams

- luminosity leveling: adjust displacement throughout fill, operate at constant instantaneous luminosity
- optimal use of beams + stable operation conditions

2011: 1 fb$^{-1}$ pp at 7 TeV
2012: 2 fb$^{-1}$ pp at 8 TeV
2013: 1.6 nb$^{-1}$ $pPb / Pbp$

[run I performance: Giacomo Graziani's talk on Monday]
[run I operation: Clara Gaspar's talk on Monday]
Run I Physics Output

• 200+ submitted papers and counting
  • CP violating phases, rare heavy-quark decays
  • production & spectroscopy, exotics searches, Lepton Flavour Violation, …

[NJP 15 (2013) 053021]

[arXiv:1407.6127]

[arXiv:1406.2885]

[PRL 111 (2013) 101805]

[PRD 87 (2013) 112010]

[PRL 111 (2013) 191801]
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[PRD 87 (2013) 112010]

[PRL 111 (2013) 101805]

[arXiv:1407.6127]

[arXiv:1406.2885]
LHCb Upgrade

- run 1 has been a great success for the LHC, LHCb, ... and the Standard Model
  - but current measurement precision in the flavour sector still allows significant contributions from New Physics
- precision of most LHCb results will still be limited by statistics after run 2
  - leading systematic uncertainties will often decrease with available statistics
- after run 2 would need > 10 years with current LHCb to double precision again

LHCb upgrade after run 2
increase annual event yields by
- increasing instantaneous luminosity
- increasing trigger efficiencies

<table>
<thead>
<tr>
<th>Year</th>
<th>Run</th>
<th>Data Rate</th>
<th>Energies</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>run 1</td>
<td>0.037 fb⁻¹ @ 7 TeV</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td></td>
<td>1 fb⁻¹ @ 7 TeV</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td>2 fb⁻¹ @ 8 TeV</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>LS 1</td>
<td>minor maintenance work</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>run 2</td>
<td>5 fb⁻¹ @ 13 TeV</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2018</td>
<td>LS 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2021</td>
<td>run 3</td>
<td>15 fb⁻¹ @ 14 TeV</td>
<td></td>
</tr>
<tr>
<td>2022</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2023</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2024</td>
<td>LS 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2026++</td>
<td>run 4</td>
<td>5 fb⁻¹ / year @ 14 TeV</td>
<td></td>
</tr>
</tbody>
</table>
**“Physics” Goal**

- approach theory uncertainties in quark flavour sector, e.g.:

<table>
<thead>
<tr>
<th></th>
<th>LHCb up to LS2</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run 1</td>
<td>Run 2</td>
<td>Run 3</td>
</tr>
<tr>
<td>Integrated lumi</td>
<td>3 fb⁻¹</td>
<td>8 fb⁻¹</td>
<td>23 fb⁻¹</td>
</tr>
<tr>
<td>$\frac{Br(B_d \rightarrow \mu\mu)}{Br(B_s \rightarrow \mu\mu)}$</td>
<td>-</td>
<td>110%</td>
<td>60%</td>
</tr>
<tr>
<td>$d_0^2 A_{FB}(B_d \rightarrow K^{*0}\mu\mu)$</td>
<td>10%</td>
<td>5%</td>
<td>2.8%</td>
</tr>
<tr>
<td>$\phi_s(B_s \rightarrow J/\psi\phi, B_s \rightarrow J/\psi\pi\pi)$</td>
<td>0.05</td>
<td>0.025</td>
<td>0.013</td>
</tr>
<tr>
<td>$\phi_s(B_s \rightarrow \phi\phi)$</td>
<td>0.18</td>
<td>0.12</td>
<td>0.04</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>7°</td>
<td>4°</td>
<td>1.7°</td>
</tr>
<tr>
<td>$A_{T}(D^0 \rightarrow KK)$</td>
<td>$3.4 \times 10^{-4}$</td>
<td>$2.2 \times 10^{-4}$</td>
<td>$0.9 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

[M.H. Schune at Heavy Flavour in the HL-LHC Era, Aix les Bains, 2013]

- ALSO: reinforce LHCb as a general purpose forward detector
  - e.g. electroweak boson production, exotic searches, proton-ion physics
Collect them all ...

Final Upgrade TDR submitted and under review – all others are approved

[CERN-LHCC-2011-001]  ➞  [CERN-LHCC-2012-007]

• to collect 5 fb⁻¹/year: operate at up to 5 × higher instantaneous luminosity
• final states with muons: event yields scale linearly with luminosity
• fully hadronic final states: in current trigger scheme have to increase $p_T$ thresholds to stay within 1 MHz limit of L0 trigger → no further gain in yield

- Readout full detector at 40 MHz
- Full software trigger with 20 kHz output rate
40 MHz Readout

Clock, Commands, ECS → Timing & Fast Control

Event-Builder Software LLT

EB LAN → Event Building Network

~10'000 optical links, 300 m long

~500 PCs

~1000 PCs

40 MHz

20 kHz

40 MHz Readout

LHC and Beyond – LHCb upgrade (15/28) O. Steinkamp

[status: ECFA-Workshop 10/2013]

<table>
<thead>
<tr>
<th></th>
<th>Event-size [kB]</th>
<th>Rate [kHz]</th>
<th>Bandwidth [Gb/s]</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>20 000</td>
<td>50</td>
<td>8 000</td>
<td>2019</td>
</tr>
<tr>
<td>ATLAS</td>
<td>4 000</td>
<td>200</td>
<td>6 400</td>
<td>2022</td>
</tr>
<tr>
<td>CMS</td>
<td>4 000</td>
<td>1000</td>
<td>32 000</td>
<td>2022</td>
</tr>
<tr>
<td>LHCb</td>
<td>100</td>
<td>40 000</td>
<td>32 000</td>
<td>2019</td>
</tr>
</tbody>
</table>

~500 PCs

underground

on surface
- upgrade to 40 MHz front-end electronics
- need to replace sub-systems with embedded front-end electronics
- adapt where needed to maintain excellent performance at 5× higher luminosity
Vertex LOCator

Run I/II: silicon micro-strip detectors

- $r/\phi$ strip geometry, strip pitch 83-101 $\mu$m

Operating in secondary vacuum inside LHC vessel

- 300 $\mu$m Al foil separates detector from beam vacuum

Two retractable halves

- silicon at 7 mm from beam during data taking

Upgrade challenges and goals:

- cope with increased radiation level
  - up to $8 \times 10^{15} \text{n}_{eq} / \text{cm}^2$ for 50 fb$^{-1}$, highly non-uniform across surface

- improve current performance
  - decrease material budget (thinner Al foil)
  - get even closer to beam ($\rightarrow$ 5.5 mm)

55×55 $\mu$m$^2$ silicon pixel detector

- Velopix readout chip
  (evolution of TimePix chip)
- micro-channel CO$_2$ cooling
Expected Vertexing Performance

Expect superior performance in essentially every aspect compared to current VELO operating at high luminosity

- better impact parameter resolution due to reduced material budget
- reduced ghost rate due to pixels
- improved efficiency over full range in $p_T, \phi, \eta$
Main Tracker

Run I/II: silicon micro-strips upstream of magnet, silicon and 5 mm Ø straw drift tubes downstream

- granularity / segmentation across detector surface adjusted to forward peaked particle densities
- excellent momentum resolution due to small material budget → crucial for background suppression

Upgrade challenges and goals:
- cope with increased particle density
  - too high in inner region of straw detector
- improve speed of track reconstruction
  - crucial for trigger performance
- improve forward acceptance in upstream station
  - approach closer to beam pipe

keep current setup with 1+3 stations
upstream: silicon strip detector with finer readout granularity
downstream: scintillating fibres
Main Tracker - Upstream

Upstream Tracker (UT)

- four layers of 250 μm thin silicon micro-strip detectors
- three readout strip geometries, adapted to particle densities across detector surface
- new 40 MHz readout chip
- silicon sensors and readout chips mounted on 130 cm long “staves”
- detectors on both sides of stave to avoid gaps in acceptance
- bi-phase CO₂ cooling
- thin cooling pipes in stave supports
Main Tracker - Downstream

Scintillating Fibres (SciFi) with Silicon Photo-Multiplier (SiPM) readout

- 2.5 m long fibres with 250 µm Ø
- each detection plane = five fibre layers to ensure full efficiency
  - typically 15-20 photo-electrons
- single technology advantageous for fast track reconstruction in trigger
  - uniform material distribution
  - avoid “left-right ambiguities” of straws
- region close to beam pipe might need further optimization for occupancy
- SiPM need to be cooled to –40°C to mitigate effects of radiation damage
- fibres look okay up to 50 fb⁻¹
Expected Tracking Performance

Improved efficiency from SciFi compared to existing Silicon/Straw combination

- Reduction of rate of fake tracks (ghosts) from use of UT hits in track reconstruction

![Graph showing efficiency comparison between Silicon, Straws, and Scintillating Fibres](image)

Track reconstruction fits into 50% of estimated HLT time budget of 13 ms

- Assumes 10 × current CPU farm
- Option to further speed up by applying Global Event Cuts (GEC) on hit multiplicities to veto small fraction of very high multiplicity events

<table>
<thead>
<tr>
<th>Tracking Algorithm</th>
<th>CPU time [ms] No GEC</th>
<th>CPU time [ms] GEC = 1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>VELO tracking</td>
<td>2.3</td>
<td>2.0</td>
</tr>
<tr>
<td>VELO-UT tracking</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Forward tracking</td>
<td>2.5</td>
<td>1.9</td>
</tr>
<tr>
<td>PV finding</td>
<td>0.40</td>
<td>0.38</td>
</tr>
<tr>
<td>Total @29 MHz</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td><strong>6.6</strong></td>
<td><strong>5.4</strong></td>
</tr>
</tbody>
</table>
Run I/II: Hybrid photon detectors (HPD) with embedded 1 MHz front-end readout electronics

- need to be replaced for 40 MHz readout

Upgrade:

- replace HPDs with commercial Multi-Anode PMTs
- re-optimize RICH1 mirror optics
  - spread out rings to compensate for higher occupancy
  - but stay within current gas enclosure
Expected $K/\pi$ performance

- **GOOD:** high efficiency, low mis-id rate
- **BAD:** low efficiency, high mis-id rate

Comparing current and upgrade geometries:
- $4 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$, current geometry
- $1 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, current geometry
- $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, current geometry
- $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, upgrade geometry
Calorimeters

Run I/II: L0 trigger and e/γ reconstruction

- robust sampling calorimeters: absorber and scintillating fibres with photo-multiplier readout

Upgrade:

- remove pre-shower (PS) and scintillating pad detector (SPD)
  - not needed without L0 trigger
- replace readout electronics for 40 MHz
- compensate for higher occupancy
  - reduce photo-multiplier gains
  - revise cluster definition
- radiation damage
  - consider replacing innermost ECAL cells during LS3, otherwise okay up to 50 fb⁻¹
Muon System

Run I/II: L0 trigger and muon identification

- five detector stations (M1-M5) interleaved with absorber walls (M1 upstream of calorimeters)
- multi-wire proportional chambers, triple-GEMs in regions of highest particle density
- detectors read out at 40 MHz for L0 trigger

Upgrade:

- no need to change front-end readout ;-)
- remove M1 in front of calorimeters
  - too high occupancies, not crucial for muon ID
- add more shielding between HCAL and M2
  - to reduce background rate in innermost region
- possible replacement of detectors in innermost regions of M2 and M3 under consideration
Summary / Outlook

- excellent LHCb performance is leading to world best measurements in the beauty and charm quark sectors and many other interesting results

- expect to increase available data sample from $3 \text{ fb}^{-1}$ to $\sim 8 \text{ fb}^{-1}$ by 2018
  - will allow LHCb to find or rule-out large sources of flavour symmetry breaking at the TeV scale

- LHCb upgrade is then mandatory to reach measurement precisions of the order of current theoretical uncertainties
  - goal is to collect $\geq 50 \text{ fb}^{-1}$ within $\sim 10$ years, with improved selection efficiency
  - software-only trigger with access to the full detector information
  - detector upgrade to 40 MHz readout, able to sustain a levelled luminosity of $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ at 25 ns bunch spacing

- LHCb upgrade is fully approved, the last TDR is under review
  - to be installed in LS2 and operational at the beginning of 2020
THANK YOU!
Roadmap Towards the Upgrade

2011  LoI submitted & encouraged to proceed to TDRs
2012  “Framework TDR” submitted, endorsed & approved

- “LHCb upgrade approved to be part of
the long-term exploitation of the LHC”

2012  Submission of MoU for Common Projects
2012/13 R&D towards technical choices
2013  Technical reviews & choice of technologies
2013/14 Technical Design Reports & MoUs of sub-systems
2014  Prototype validation & Engineering Design Reviews
2014-16 Tendering & serial production
2016-17 Quality control & acceptance tests
2018/19 18 months installation during LS2

[A. Schopper at Heavy Flavour in the HL-LHC Era, Aix les Bains, 2013]
LHCb

- Rare decays: $B_{d,s} \rightarrow \mu\mu$
- $B_s$ system
- $b$-baryons

\textit{Spectroscopy}

- CKM phases ($\beta$, $\gamma$)
- Gluonic penguins
- EW penguins
- Charm physics
- Semileptonic: Mixing, $A_{SL}$

\textit{On-going}

- Semileptonic: $V_{xb}$
- $B \rightarrow \tau\nu, D\tau\mu,$
- $B \rightarrow K^{*}\nu\nu$
- $\tau$-physics

Belle II

ATLAS & CMS

* Caveat: I am probably missing “your” favored channel/field

\[\text{U. Uwer at Flavour Physics Conference, Quy Nhon, 2014}\]
## DAQ Numbers

<table>
<thead>
<tr>
<th>Event rate</th>
<th>40 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean nominal event size</td>
<td>100 kBytes</td>
</tr>
<tr>
<td>Readout board bandwidth</td>
<td>up to 100 Gbits/s</td>
</tr>
<tr>
<td>CPU nodes</td>
<td>up to 4000</td>
</tr>
</tbody>
</table>

- **Instantaneous luminosity**: $2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$
- **Pile-up**: 7.6
- **Input rate**: 30 MHz
- **Maximum processing time per event**: 13 ms
- **Output bandwidth**: $20 \text{ kHz} \times 100 \text{ kB} = 2 \text{ GByte/s}$

<table>
<thead>
<tr>
<th>Versatile Links for DAQ</th>
<th>8800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean nominal total event-size</td>
<td>100 kB</td>
</tr>
<tr>
<td>PCIe40 boards for DAQ</td>
<td>500</td>
</tr>
<tr>
<td>Versatile Links / readout board (DAQ)</td>
<td>up to 48</td>
</tr>
<tr>
<td>Event builder-PCs</td>
<td>500</td>
</tr>
<tr>
<td>PCIe40 boards for ECS and TFC (SOL40)</td>
<td>77</td>
</tr>
<tr>
<td>Core switch ports (100 Gbit/s)</td>
<td>500</td>
</tr>
<tr>
<td>Event-filter nodes</td>
<td>up to 4000</td>
</tr>
<tr>
<td>Output rate</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Nominal instantaneous output rate</td>
<td>2 GB/s</td>
</tr>
</tbody>
</table>

- LHC BX frequency
- PCIe Gen3 protocol
- Power, cooling, space constraints
- \( \langle \text{pp collisions} \rangle \) per BX
- Non-empty BX
- \# CPU \times \text{CPU power (assume 2011} \times 16)
Micro-Channel Cooling

Thermal pyrolytic graphite (TPG)

Sensor
ASIC

TPG
Hybrid

Cooling pipes

Heat sources  |  Cooling

Too much $\Delta T$ in simulations and thermal mock-up.
Too much thermal expansion difference (delamination).

Pablo Rodríguez Pérez

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Micro-Channel Cooling

New approach: the cooling is underneath the heat source

Pocofoam®
Cooling pipes surrounded by carbon foam

Micro-channel
CO$_2$ passes through channels etched in a silicon plate

Both satisfy the cooling requirements. 😃
Both acts as mechanical support.
Micro-channel showed better IP resolution:
  • Lower material budget.
  • Thinner modules.

Pablo Rodríguez Pérez

TIPP’14
Micro-Channel Cooling

Fabrication
- Etch trenches into the surface of silicon wafer.
- Atomic bond a cover wafer to create the capillaries.
- Practice exit and entry holes.
- Attach the connectors & electronics.

Advantages
- Cooling is exactly under the heat source.
- Large heat exchange surface (many parallel channels).
- Small thermal gradients across the module (no heat path through the hybrid/sensor plane).
- Minimal material budget (thin silicon layer).
- No CTE difference between heat source and heat sink.
Number of visible pp interactions per BX Poisson distributed with

- **2012:** $\langle \mu \rangle = 2$
- **upgrade:** $\langle \mu \rangle = 5$

Average number of tracks for $b\bar{b}$ events

- **2012:** 72
- **upgrade:** 180
Figure 2.6: Expected fluence profile (left) and dose profile (right) after 50 fb$^{-1}$ of total integrated luminosity as a function of the vertical coordinate $Y$ for $X=0$. (The LHCb coordinate system is a right handed Cartesian system with the positive $Z$-axis aligned with the beam line and pointing away from the interaction point and the positive $X$-axis following the ground of the experimental area, and pointing towards the outside of the LHC ring.) This slice represents the highest fluence region throughout the UT system.
Figure 2.19: The SALT ASIC block diagram.
Silicon Photo Multiplier

- The SiPM pixel is a photo-diode (reverse-biased, above breakdown)
- a single free electron/hole-pair can trigger an avalanche of electrons
- $10^6$—$10^7$ gain
- 40-50% photon detection efficiency

Sketches from Wei Shen, PhD Thesis Uni Heidelberg
SiPMs create single photo-electron signals from thermal electrons, cross-talk between pixels makes 1 photo-electron look like 2+

Neutron damage to silicon worsens thermal problem, expect $10^{12}$ neutrons/cm$^2$

Acceptable cluster rates require -40C cooling and +40C annealing

$\text{dark noise} \propto T^2 \exp\left(\frac{-E_g}{2k_B T}\right)$
Production of Fibre Mats

Fibre mats are produced from winding a single fibre onto a threaded wheel.

- Need about 8km of fibre for one mat of 6 layers 2.5 metres long
- 10,000 km of fibre in total...
The scintillating fibres darken with radiation (up to 35 kGy expected near the beam pipe over the upgrade lifetime)