The Performance and Radiation Hardness of the Outer Tracker Detector for LHCb

Evelina Gersabeck

Ruprecht-Karls-Universität Heidelberg
on behalf of the LHCb OT collaboration

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THE LHCb DETECTOR

- ❖ Single arm spectrometer designed for heavy flavour physics measurements
- ❖ Consists of Vertex Locator (VeLo), 2 RICH detectors, silicon trackers, dipole magnet, outer tracker, ECAL, HCAL, muon system

OUTER TRACKER

- ❖ Gaseous straw tube technology detector
- ❖ 3 stations each with 4 layers of modules in X - U (+5°) - V (-5°) - X geometry
- ❖ One detector layer is built of 14 long and 8 shorter modules
- ❖ Covers area of approximately 5 x 6 m²

OT STATIONS

- ❖ Each station is split into two halves, retractable on both sides of the beam line (on C-frames)
- ❖ Number of modules: 216
- ❖ Long module length: 5 m
- ❖ Module width: 340 mm
- ❖ Inner region around the beam pipe: instrumented with Si strip detectors

OT MODULES

- ❖ Each module consist of 2 staggered straw tube monolayers
- ❖ Numbers of straws in a monolayer: 64
- ❖ Total number of straws: 53760
- ❖ Inner diameter of straw tubes: 4.9 mm
- ❖ Straw tube length: 2.4 m
- ❖ Glue: Araldite AY103-1

OT STRAWS

- ❖ Straw tube material: Kapton XC / Kapton / Aluminium
- ❖ Anode wire diameter: 25 μm
- ❖ Material of the anode: Gold plated Tungsten
- ❖ Anode at +1550 V
- ❖ Gain: 5×10^4

TR-RELATION

- ❖ The position of the hits in the OT is determined by measuring the drift-time to the wire of the ionisation clusters
- ❖ The drift-time -distance relation (TR-relation) is used to convert the drift time to particle position.

$$t_{\text{drift}}(r) = 20.5 \text{ ns} \cdot \frac{|r|}{R} + 14.85 \text{ ns} \cdot \frac{r^2}{R^2}$$

- ❖ The TR-relation is **calibrated on data** by fitting the distribution of drift-time as a function of the reconstructed distance of closest approach between the track and the wire
- ❖ First iteration: TR-relation obtained from beam tests

OT ELECTRONICS

- ❖ Modular design of the FE electronics
- ❖ The main components:
 - the high voltage (HV) board
 - the ASDBLR amplifier chip: the complete analog signal processing (amplification, shaping, baseline restoration, and discrimination)
 - the OTIS drift time digitization chip
 - the GOL auxiliary (GOL/AUX) board: the power connection, the interface to the fast - control (beam crossing clock BX, triggers, resets) and the interface to the slow-control

The drift times are digitized for each 25 ns (the LHC design value for the minimum bunch crossing interval) and stored in a digital pipeline (4 μ s) to await the lowest-level trigger (Lo) decision.

On a positive Lo decision, the digitized data in a window of 75 ns is transmitted via optical links (1.6 GBit/s) to TELL1 boards in the LHCb DAQ system

THRESHOLD AND DELAY SCANS

- ❖ Possibility to inject a test pulse at the ASDBLR test input
- ❖ 2 kinds of test runs:
- ❖ Test pulse at varying threshold settings: check the threshold uniformity and cross-talk
- ❖ Test-pulse (at fixed threshold) at increasing test-pulse delay settings: determine the time-linearity
- ❖ Relative variation is well within expected values

NOISE

- ❖ Noise due to: dark pulses from the detector, bad FE -electronics shielding, or bad grounding
- ❖ Check occupancy at increasing values of the amplifier threshold (nominal value 800 mV):
 - Using random triggers
 - About 2% of the FE boxes exhibited noise pattern
 - At the nominal threshold of 800 mV only 0.2% of the channels exhibited a noise occupancy larger than 0.1% (usual occupancy $\sim 10^{-4}$)
- ❖ Completely negligible for data taking

GAS SYSTEM

- ❖ Ar / CO₂ / O₂ (70 / 28.5 / 1.5): fast drift time below 50 ns
- ❖ OT continuously flushed: no recycling of gas
- ❖ Gas quality constantly analysed and monitored
- ❖ Level of impurities (H₂O) monitored: low and stable
- ❖ Pre-mixed bottles containing in total about 100 m³ of Ar/CO₂/O₂, is automatically activated in case of electrical power failures of the main gas system, or during various interventions
- ❖ Back-up system is used regularly, and is well working

GAS GAIN TRENDS

- ❖ Gas gain is monitored with two custom built OT modules, of 1 m length, which are irradiated by a ^{55}Fe source (K- α ^{55}Mn line used as calibration reference)
- ❖ Take pulse height spectrum (every 15 min)
- ❖ Fit peak position ($\sim$ gain)
- ❖ Correction for air pressure

GAS GAIN TRENDS

- ❖ Data for ~ 3 months from the last year's running period
- ❖ Gas gain stability is within $\pm 2\%$
- ❖ All the spikes are due to known interventions

PERFORMANCE

ALIGNMENT

- ❖ The design and construction of the OT detector guarantees a mechanical stability of $100(500)\mu\text{m}$ in the $x(z)$ direction.
- ❖ An optical survey measured the position of all modules after installation to $200\mu\text{m}$
- ❖ An optical alignment system measures relative displacements
 - detailed pattern mounted on the 4 corners of the C-frames
 - the position of the C-frames is unchanged after opening and closing within $\pm 10\mu\text{m}$, and unchanged within $\pm 20\mu\text{m}$ for data taking periods with opposite polarity of the LHCb dipole magnet
- ❖ Software alignment with reconstructed tracks (see the talk of M. Martinelli on 'Tracking and Alignment of the LHCb detector')

25-50-75 BUNCH CROSSING

- ❖ Three consecutive intervals of 25 ns are readout upon a positive L0-trigger.
- ❖ Only the first hit in the readout window is recorded
- ❖ Distributions obtained in the 75 ns bunch-crossing period are close to those observed with only one single bunch crossing: free of spillover
- ❖ Double pulse:
 - in 30 to 40% of all hits
 - 30 ns later
 - due to: multiple ionizations, reflections, photon feedback

Drift time spectrum understood,
and occupancy under control

OT OCCUPANCY

- ❖ In absence of spill over: 3 to 15% occupancy (at 50 ns)
- ❖ 30% of all hits are due to spillover
- ❖ Most of the hits originate from secondary charged particles produced in interactions with material
- ❖ Hits from tracks that originate from the genuine pp interaction or a subsequent particle decay are predominantly located close to the interaction region (T1 / T2 / T3 : 27.7% / 27.1% / 25.7%)
- ❖ **Despite the high occupancy: excellent tracking efficiency**

SINGLE HIT EFFICIENCIES

- ❖ A high single-hit efficiency is crucial, as it affects the tracking efficiency
- ❖ Efficiency is defined as the number of observed hits in a particular detector region over the number of expected hits in the same region
- ❖ Limited probability to ionise the gas at the straw tube edges
- ❖ Average efficiency for single hits at the center of the straw for a given module : 99.2%

OT HIT RESOLUTION

- ❖ For a given track, the drift-time and the hit position in a straw are predicted, and compared with the measured drift-time and position
- ❖ Drift-time residual distribution width: 3ns (dominated by the ionization and drift properties in the counting gas)
- ❖ Hit distance residual distribution width: 210 μm (close to the design value of 200 μm)
- ❖ Potential improvement: two monolayers within one detector module are allowed to be relatively displaced to each other in the alignment procedure

RADIATION HARDNESS

AGEING EFFECTS

^{90}Sr Source

- ❖ Irradiation of modules in the lab (before LHCb): ageing visible
- ❖ Radiation damage:
 - Half moon shape
 - The gain loss occurs mainly upstream the source position
 - Ozone created in avalanches protects the wires downstream
- ❖ Bachmann, et al., Nucl.Instrum.Meth. A 617 (2010) 202; N. Tuning, et al., Nucl.Instrum.Meth. A656 (2011) 45-50S.

Ageing seen in lab: due to outgassing of the plastifier of the **Araldite AY103-1** glue

AGEING TESTS IN SITU

- ❖ 2 methods to determine signal loss:
- ❖ Measure response to ^{90}Sr source
 - only a few modules at a time
 - only at shutdown periods
 - from hours to weeks
- ❖ Measure efficiency point with varying ASDBLR threshold for each of the 12 module layers individually with tracking.
 - entire OT
 - during nominal LHC operation
 - ~ 2 hours for scanning all layers
- ❖ D. van Ejik et al., Nucl.Instrum.Meth. A685 (2012) 62-69

SCANNING FRAME

- ❖ Using two ^{90}Sr source to measure gain
- ❖ Measure response to radioactive source (current profile) for each straw channel for each position along Y
- ❖ Correct for air pressure
- ❖ No beam induced ageing visible so far
- ❖ Test at each technical stop of the LHC with irradiation source
- ❖ Short irradiation tests during technical stop
- ❖ No sign of ageing: gain variation uniform within $\pm 5\%$

NO AGEING IN 4 MODULES

In 2012, LHCb received $\sim 2.2 \text{ fb}^{-1}$ of data and the hottest region received about 0.08 C/cm

(and 3.5 fb^{-1} of data; 0.12 C/cm in 2011+2012)

No ageing

THRESHOLD LAYER SCAN

- ❖ Measure hit efficiency with tracks by scanning threshold values per layer.
- ❖ Determine with S-curve for each 12x12 cm² bin half-efficiency point (HEP)
- ❖ Convert HEP to relative gain for each bin
- ❖ Correct relative gain by air pressure
- ❖ Take gain ratio for each OT bin
- ❖ Get ratio map for each layer
- ❖ So far no beam induced radiation damage observed for installed detector.

SUMMARY

- ❖ Very reliable operation during the 2010, 2011, 2012 LHC running periods
- ❖ No significant failures of the LV, HV and gas systems.
- ❖ The fraction of working readout channels was about 99.5%
- ❖ Excellent performance with a single-hit efficiency of about 99.2% near the center of the straw, and a single hit resolution of about 210 μm .
- ❖ No signs of irradiation damage have been observed.