Tracking performance and alignment of the upgraded CMS tracker

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On behalf of the CMS Collaboration

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Motivation for pixel upgrade

- More layers both in Barrel (BPix) and Forward (FPix) pixel in the same detector volume
  - BPix 48 M → 79 M; FPix 18 M → 45 M
- Detector and services in the same mechanical envelope
- Maintain the same or better material budget
- Quick replacement during extended TS in 2017

- Previous detector designed to operate at $10^{34}$ cms$^{-2}$s$^{-1}$ @ 25 ns bunch spacing
- LHC expects to reach 2.5 times that and 70 PU before LS3

Goals
- Sustain data-taking
- Maintain and improve performance
- Keep the original design wherever possible
Advantages of Phase 1 geometry

- Increased event PU $\rightarrow$ larger multiplicity
  - More primary vertices to resolve
  - Higher hit rate in the chip
  - Increased processing time and fake-rate due to combinatorics

- Extra layers at no cost on material budget
  - Redundancy for hit loss
  - Quadruplet seeding possible
  - Better $p_T$ resolution

- The new layout
  - Inner layer closer to beam – better impact parameter resolution
  - Outer layer closer to outer tracker – easier track propagation from pixels to first outer tracker layer
Hit reconstruction in the upgraded pixel

- Same sensor as before the upgrade: n+-in-n, 285 µm thick, 100x150 µm pixel size

- Read out in zero-suppression mode
  - Low noise, thresholds generally lower than in previous detector
  - More radiation tolerant

- Cluster parameterization
  - Thick sensors + magnetic field
    - significant charge sharing
    - but beneficial for resolution
  - BPix geometry fairly simple (perp. E- and B-fields)
  - FPix complicated, requires LA description in 8 different E-field configuration w.r.t the B-field
Tracking algorithm and seeding

- **Track reconstruction**
  - inside-out, starting from hit-multiplet seeds formed in the pixel
  - outer tracker-only and muon seeds

- **Trajectory building in the outer (strip) tracker using Kálmán filter**

- **Iterative tracking:** earlier steps reconstruct better quality tracks, then remove used clusters
  - High-pt, good quality, tracks at small production radius first
  - Worse quality tracks and secondary interactions in latter steps

- **New seeding algorithm developed**
  - Novel approach based on Cellular Automaton (CA) techniques
**Expected tracking efficiency**

- Performance in ttbar events at $\sqrt{s}=13$ TeV at average expected PU of 35

- Increased tracking efficiency especially at low-$p_T$

- Increased efficiency more significant in the forward region
  - Better eta-coverage due to additional FPix disk

- Significant reduction of fake-rate at barrel-forward transition region
  - Layer 1 has larger overlap with FPix disks

- Improvements mostly due to layout and hit detection efficiency not relying on better resolution...
PU dependence

- Robust tracking efficiency as function of PU
  - Only tracking algorithm; hit-efficiency and bad modules are not simulated

- PU affects mostly the fake-rate

- 2016-level seeding time is preserved by CA despite increased number of layer combinations

- CA needs fewer and simpler calculations that are localized in memory
Bad components and SEU-s

- Permanently bad components presented on Monday by Jory
  - Tracking marks modules inactive for the whole run
  - trajectory is propagated further
  - or fall-back on triplet seeding

- „Stuck TBM”-s are marked by FEDs in raw data
  - Unpacker marks chips temporarily inactive in the event

TBM core: 4 ROCs in Layer 1
Alignment

- $\chi^2$ of all hits in all tracks are summed up and minimized by moving positions of all modules and refitting tracks
  - Multi-dimensional fit: $O(10^5)$ alignment parameters and up to $O(10^6)$ track parameters
  - Two algorithms used in CMS:
    - Millepede
    - Hippy
  CMS Collaboration "Alignment of the CMS tracker with LHC and cosmic ray data" 2014 JINST 9 P06009 doi:10.1088/1748-0221/9/06/P06009

- Internal constraints defined by the construction hierarchy of the detector structure
  - Pixel/Strip detector $\rightarrow$ Pixel Half-shells $\rightarrow$ inner/outer modules within layers $\rightarrow$ individual modules

- Higher-level structure adjustment $\rightarrow$ fix overall detector movement
- Inner/outer module alignment $\rightarrow$ cluster position bias
- Individual module $\rightarrow$ manufacturing spread, module curvatures

Assumed (ideally aligned) geometry reconstructs hit at wrong position
Track is biased $\rightarrow$ trying to cure it by minimizing

$$\chi^2 = \sum_j \sum_i \frac{r_{ij}^2}{\sigma_{ij}^2}$$
Alignment strategy at start-up

- Pixel detector inserted in „left” and „right” halves placed around the beam-pipe

- Seeding of cosmic rays in the muon system
  → pixel is just an observer

- Based on earlier experiences, assumed no movement in strips

- Finding position of pixel
  - Cosmic ray muons → high-level structure, limited module alignment
  - Collisions → module alignment
  - When high-stat cosmics and muon-resonances available → full Tracker alignment
**BPix: 0T cosmic ray alignment**

- Expected ~1000 µm high-level, ~500 µm ladder, and ~100 µm module misalignment w.r.t initial geometry

- Cosmic ray illumination (from „top”) constraints well all high-level positions
  - Found a global horizontal position mismatch of ~2 mm
  - r-dependent spread implies additional rotation

- Local coordinates (top plots)
  - x = global rφ direction
  - y = global z direction (beam axis)

- Global coordinates (bottom plot)
  - x = in the LHC plane
  - z = beam axis
  - r = radius perp. to z
**FPix: 0T cosmic ray alignment**

- Expected mismatch from initial geometry model
  - up to \(~500 \, \mu m\) in transverse plane
  - up to \(~4 \, mm\) along beam axis

- **Cosmic ray illumination constraints** \(z\) position
  - well (a weak mode for collision tracks)
  - Found a larger mismatch in FPix \(-Z\)

- **Local coordinates** (top plots)
  - \(x\) = global \(r\phi\) direction
  - \(y\) = global \(r\) direction (beam axis)

- **Global coordinates** (bottom plot)
  - \(x\) = in the LHC plane
  - \(z\) = beam axis
  - \(r\) = radius perp. to \(z\)


Accuracy of detector insertion

- Reference frame: barry center of the strip TOB (Tracker Outer Barrel)

- Plots show barry centers for previous and upgrade detectors
  - BPix: off horizontally w.r.t previous detector, better centered in other directions
  - FPix: at least as well or better centered in any directions
Alignment with collisions

- Median of the residual distribution is computed for each module
  → spread of this value (DMR) quantifies goodness of alignment

- Great improvements in BPix
  - Sigma of DMR already much better than intrinsic resolution
  - Expect some more improvements in end-of-year, ultimate calibration
Alignment with collisions

- Collision tracks closer to perpendicular in FPix → very accurate positioning in local x,y
- Sigma of DMR reached alignment of ideal Monte Carlo geometry (!)
  - Negligible w.r.t intrinsic resolution

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Performance and alignment
Full tracker alignment

- Last step of commissioning: a full strip+pixel alignment was performed

- Weak modes in alignment: movements that leave $\chi^2$ sum invariant
  - E.g. Coherent dislocation of layers at different radii
  - Distortions

- Weak modes lead to systematic errors in track momentum $\rightarrow$ can be constrained by muon-pairs from Z-decays

- Final alignment eliminates $\phi$-dependency of Z-mass

(plots from N. Bartosik’s thesis)
Alignment validation

- Mean impact parameter w.r.t primary vertex (PV) should be zero
  - Systematic deviation is a sign of remaining biases

- 6-fold structure vs global $\phi$
  - Clue: Layer 1 is composed of 6 inner + 6 outer ladders
  - Bias comparable to expected single hit resolution

- Similar bias seen also with the previous detector right after commissioning
Layer 1 resolution

- Resolution is quantified as the residual in the hit-triplet method: tracks from 2 hits are analytically propagated to the 3rd layers
  - Large systematics on Layer 1 being the last (first) hit, but should be reproduced by MC

- Resolution so far 50-70% worse than expected

- Resolution is determined by
  - Accuracy of charge-sharing description
  - Read-out threshold
  - Hit-pixel efficiency
  - Charge collection efficiency
  - Timing
Layer 1 resolution

- In the transverse plane: prime suspect is the incorrect LA in reco, not fixed by alignment
  (Note: LA is short for Lorentz force induced charge sharing – a single value is actually not sufficient to describe the mechanism)

- LA is measured with the grazing angle method: displacement of charges originating at different depths
  - Used same model for the entire layer in previous detector
  - Already large variations within Layer 1 modules after 15.5 fb⁻¹

- Inconsistent LA leads to non-zero mean residual in alternating directions
  → in symmetric case to wider residual

- Effect seems to reduce by sufficient over-depletion
Layer 1 resolution

- Cross-talk in Layer 1 demands a higher threshold than designed → estimate \( \sim 4000 \text{ e}^- \)

- Dynamic efficiency causes loss of pixels in clusters → affecting cluster shoulders and cluster splitting

- Already considerable radiation damage by the end of commissioning → signs of charge collection inefficiency even in farther layers → made bias voltage adjustment necessary (L1: 350V, L2: 250V, L3-4: 200V, FPix: 300V)
Timing effect on resolution – Layer 2

- Hit pixel pulses are buffered asynchronously along with time-stamps in units of bunch-crossing
  - Time-stamp assignment affected by clock-phase difference between chip and LHC collisions
  - Clock-phase adjusted per clock-distribution group: Layer 1+2 and Layer 3+4
  - In clock-phase scan, observed a 10-12 ns relative shift between Layer 1 (PROC600) and Layer 2 (PS146dig) chips.

- Clock-phase is optimized to reduce time-walk effect (read-out as low charge/late pixels as allowed by the time-window)
  - Needed to optimize for Layer 1
  - A bit early for Layer 2

- Layer 2 threshold ~2500 – 3000 e- mostly due to timing
  - 1000 e- $\rightarrow$ ~1 µm worsening (seen in test beam)

- Average threshold in module testing was ~1600 e- (average 100-200 e-)
  $\rightarrow$ indeed achieved in Layer 3-4 and FPix
Resolution of Layer 2-4

- Compare triplet residual measurements in data and simulation
  - MC assumes perfect detector (no radiation damage, threshold 2000 e-, no pixel efficiency loss)
  - intrinsic resolution 6-7 µm (simhit-rechit residual width)

- Comparisons imply optimal performance of Layer 2-4

- Layer 2 still compatible with MC
  - seem to have no sensitivity to the timing issue
  - but need to keep an eye on the issue...
Resolution of FPix

- Triplets fully in FPix
  - result independent of Layer 1
- Resolution of data in the rφ direction outperforms simulation!
  - 2000 e- in simulation is probably too pessimistic
B-tagging expectations

- Expected performance in simulation shown

- **Blue vs magenta**: improvement due to upgrade as seen in preliminary simulation (similar to TDR)

- **Magenta vs green**: training and retraining tagging with upgrade detector before and after finalizing reconstruction in simulation
  - Proper handling of E-field direction w.r.t the B-field
  - More accurate reco geometry
  - Updated material budget in tracking (duplicate rate seems to be rather sensitive)
  - New seeding
  - Final tuning of tracking
B-tagging in data

- Not yet at ultimate performance just being right after commissioning
- Still a bit better performance seen in 3D impact parameter
- And in one of the basic b-tag discriminator values
Summary

- Challenging times with installation and commissioning of the new Phase 1 detector: unusually short time available

- Encountered some unexpected issues, major ones being:
  - Higher threshold in Layer 1 due to cross-talk
  - Clock-phase difference between PROC600 and PSI46dig
  - Unexpected level and trend of hit efficiency loss
  - SEU-s in the TBM
  - ...each is manageable, but they all came at the same time while significant radiation damage received already while in commissioning

- Despite challenges, performance is already as good or better than the previous detector
  - Big fraction of improvement purely due to new geometry already present
  - Chips also perform better → the Phase 0 would have not taken $1.7 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ well
  - Commissioning has concluded successfully, we have a good prospect on reaching the design performance
Extra slides
Expected initial misalignment

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<td>StripModule</td>
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</tr>
</tbody>
</table>
The Phase 1 detector system

- Inner layer is at smaller radius, requires more clearance
- Beam pipe changed from 59 mm to 45 mm during LS1
- Beam pipe position was checked in 2015 running
- Nuclear interactions reconstructed by tracking; multiplicity clearly shows beam pipe and Layer 1 of the current detector

Tracker material measurement

Barrel off-centered w.r.t beam pipe
The Phase 1 detector system

- Supply tubes on two ends of the detector provide the services to the detector

- Power distribution, optical read-out, detector programming and trigger control

- Reusing the same power cables, fiber optic lines from patch panel

- Installation with minimum impact on the other CMS subsystems

- But, constraints imposed on electronics design
Powering and read-out

- Doubling the read-out is achieved with more modules, need more power

- Analog 3.0V and digital 2.5 V by DC-DC converters (80%) from 10 V input

Electronics

- Distributes clock signal synchronized to TOF within 1 ns
- Equally distributes data-load among back-end FPGA-s

8 slots per half-shell, servicing a sector of up to 39 modules

- 6 layers of 20 mm wide PCB-s and a bundle of 56 fiber optic cables stacked within a 20 mm deep slot
Material budget

- Light mechanical support
- Smaller coolant mass
- Supply tube has much more components, but shifted away from the interaction point

- Reduced mass, less multiple scattering and nuclear interactions
- Factor of two decrease in photon conversion between 1.1 and 2.6 in pseudo-rapidity w.r.t. current detector
Hit efficiency

- Present detector operated at $\sim$75 MHz/cm² in 2012
- 2-3% loss of measured hit finding efficiency, $\sim$6-9% dcol loss – complicated relationship between beam test and real LHC conditions
- Performance of new Layer 2 chip is also expected to be stable with irradiation

- TS and Buffer overflows, the major sources of inefficiency currently, entirely eliminated
- Typical expected rate 120 MHz Layer 2
- Chip to handle Layer 1 rate of 580 MHz is under testing
Module testing – Threshold and noise

- Colors show results of grading (~90% bare and ~74% detector grade module yields)
- Average threshold ~1600 electrons (35 VCal units) from 3200 e

- Very stable with irradiation way beyond the dose expected after 500 fb$^{-1}$ (1.2 MGy)
- Noise for modules qualified as detector grade (dark brown) much below threshold
- Noise stable with irradiation
Resolution

- Cluster position resolution much better than pixel pitch due to Lorentz drift induced charge sharing
  - LA angle $\sim 21^\circ$

- Lorentz angle decreases with higher bias voltage (moving the „wrong” way)

- Lower threshold beneficial effect is clearly visible

- Improvements of cluster position resolution is expected from $\sim 10.6$ microns to $5$ microns