ATLAS Inner Tracker Upgrade Simulation for High-Luminosity LHC

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Outline
- Introduction
- Design Considerations
- Tracking Performance
- New Detector Structures
- Conclusions
Large Hadron Collider at CERN

- p-p collider
- Center of mass energy $\sqrt{s} = 7$ TeV
  - $\sqrt{s} = 8$ TeV @ 2012
  - $\sqrt{s} = 13-14$ TeV after 2013-2014
- Multi-purpose experiments: ATLAS and CMS
The ATLAS Detector at LHC

- Muon Detector
- Tile Calorimeter
- Liquid Argon calorimeter
- Toroid Magnet
- Solenoid Magnet
- SCT
- Pixel Detector
- TRT

Weight: 7 000 T
Length: 42 m
Diameter: 25 m
Solenoid-Field: 2 T
**LHC Upgrade Schedule**

- **LHC startup, \( \sqrt{s} = 900 \) GeV**
  - \( \sqrt{s} = 7 \sim 8 \) TeV, \( L = 6 \times 10^{33} \) cm\(^{-2}\) s\(^{-1}\), bunch spacing 50 ns
  - \( \approx 20 \) months
- **Go to design energy, nominal luminosity (Phase-0)**
  - \( \sqrt{s} = 13 \sim 14 \) TeV, \( L = 1 \times 10^{34} \) cm\(^{-2}\) s\(^{-1}\), bunch spacing 25 ns
  - \( \approx 14 \) months
- **Injector and LHC Phase-1 upgrade to full design luminosity**
  - \( \sqrt{s} = 14 \) TeV, \( L = 2 \times 10^{34} \) cm\(^{-2}\) s\(^{-1}\), bunch spacing 25 ns
  - Need \( \approx 2 \) years
- **HL-LHC Phase-2 upgrade, IR, crab cavities?**
  - \( \sqrt{s} = 14 \) TeV, \( L = 5 \times 10^{34} \) cm\(^{-2}\) s\(^{-1}\), luminosity leveling

- \( \approx 20 \sim 25 \) fb\(^{-1}\)
- \( \approx 75 \sim 100 \) fb\(^{-1}\)
- \( \approx 350 \) fb\(^{-1}\)
- \( \approx 3000 \) fb\(^{-1}\)

as shown by Rolf-Dieter Heuer at the EPS conference
**Why Upgrade?**

- **Exploit the rich physics potential of the LHC**
  - Probing the Higgs sector
  - Fermion and weak gauge boson couplings?
  - Unitarity of vector boson scattering?
  - Measure self coupling?
  - Extending the reach for new physics beyond the standard model

- **The Means**
  - LHC demonstrated the ability to deliver beyond expectations
  - Future LHC upgrades offer the opportunity for an order of magnitude greater data samples
  - Improved detector technologies and strong R&D investments

- **The challenge**
  - Severe conditions: pile-up event increase by a factor of 4!
**Computing Challenge**

- Currently, Inner Detector track reconstruction of simulated event takes about 50% of the total CPU time
- ~88M channels in current tracker
- Reconstruction workload is close to 100% of capacity
- Memory usage is close to 4GB
- Strong dependence on pile-up conditions

For HL-LHC we need to simulate events with 140-200 pile up events.

Many efforts needed to mitigate this bottle neck.
Major effort in ATLAS under way to improve the data processing chain.
- both to improve its structure and performance.
- The design is modular you can have full or fast simulation with full or fast digitization -> more flexible

Can have full simulated upgrade samples and then use Fast Digitization to allow us to model different pixel granularities
- without the need for full digitization/reconstruction of different samples (w/wo pile up) with different pixel pitches.
- Estimated event time: few seconds per event !
- possibility for large scale MC production with substantially lower resources

"Preparing the Track Reconstruction in ATLAS for a high multiplicity future" - CHEP2013
ATLAS Simulation Framework

- ATLAS GeoModel framework used to build description of complex detector geometry
  - Interfaces to Geant4 to simulate particle interactions within the detector
  - Also used for building simplified detector description used in reconstruction
- Designed to deal with ATLAS geometry
  - Numerous changes required to allow extension to different tracker layouts
  - Modifications throughout core ATLAS software extending channel addressing, to accommodate increased number of readout channels

GeoModel

- Simulation
  - Uses Geant4 to model energy losses/energy deposition in sensors/generation of secondaries, etc

- Digitization
  - Models detector readout electronics, turning Geant4 energy deposits into ATLAS raw data format
  - Pile-up collisions added at this point

- Reconstruction
  - Uses hits in sensors to build tracks and vertices
**Inner Tracker Design Considerations**

- **Granularity:**
  - Good impact parameter resolution and separation of tracks/vertices
  - Efficient track finding
- **Material:** Minimize multiple scattering and Bremsstrahlung
- Maintain detector occupancy below % level

- **Hit Coverage:** High track efficiency with good rejection of combinatorial fakes
- **Detector Acceptance:** Match coverage to other ATLAS subdetectors and Physics aims
- **Momentum Resolution:** Maximize lever arm and uniformity

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**Figure 1.** A quarter panel radius (r) vs. z projection of the proposed LoI layout that will be used for detailed Geant4 simulations and engineering studies (see text).

The pixel (red) and silicon micro-strip (blue) subdetectors are independent. The pixel subdetector has four barrel layers with 6 pixel disks in each end-cap. The two inner pixel barrel layers are separately removable and supported on an Inner Support Tube (IST) of inner radius \( R_{\text{IST}} = 110 \text{ mm} \). The full pixel detector is supported on a Pixel Support Tube (PST) of inner radius \( R_{\text{PST}} = 345 \text{ mm} \).

The strip subdetector has 5 barrel layers, and in addition a barrel “stub” to maintain hermeticity at the barrel-forward boundary. The layout is complemented by 7 disks in each end-cap. Each strip layer or disk has back-to-back sensors that provide 2 hits with a nominal 40 mrad stereo angle.

Table 1 and 2 list the mean active radial and longitudinal boundaries for each layer and disk of the pixel and strip subdetectors.

The layout was guided by the requirement of at least 14 hits, including at least 4 pixel hits, in the range \(|\eta| < 2.5\).
Letter of Intent ITk Layout

- 4 Pixel and 5 double-sided strip layers + 6 pixel and 7 double-sided strip disks
- 14 hit system up to $\eta=2.5$
- 80 $\rightarrow$ 400 million pixels ($\sim 8m^2$), 6 $\rightarrow$ 45 million strips ($\sim 200m^2$)

Baseline layout optimized for tracking performance
- Full simulation of tracker with LoI layout including service layout

Biggest changes compared to current tracker:
- pixels system extends out to larger radii (better double track resolution)
- more pixel hits in forward direction to improve tracking
- smaller pixels and short inner strips to increase granularity
- outer active radius slightly larger to improve momentum resolution
- full coverage for $|\eta| < 2.5$, Pixels cover $|\eta| < 2.7$ (forward muon identification)
- minimize hit gaps: Strip disk $z_{\text{max}} = 3m$, small layer in barrel-endcap gap
**Geant4 Studies**

- **Simulated** variety of event types under expected HL-LHC pile-up conditions
- **Reconstructed** events using ATLAS software
- **Analysed** performance for fundamental tracking parameters
- **Significant improvements** observed compared to current ATLAS tracking detector

Hit occupancies for the ITk layout with 200 pile-up events

- **Occupancy**
  - <1% for strip detector
  - <0.25% for pixel detector
- Within operation limits of read-out electronics
Significant reduction in detector material within acceptance

New material estimation based on prototyping and current experience

Please note different scales!
**Performance $P_T$ resolution**

$P_T$ resolution as a function of $\eta$, for muons of different momenta from simulation of

- current ATLAS Inner Detector ("ATLAS" until 2013, IBL for 2015+)
- simulation of the ITk layout.
Performance $d_0$ and $Z$ resolutions

- Neural Network cluster splitting will further improve the impact parameter resolution
**New Detector Structures**

- **Current simulations** assume sensors and structures similar to those used in the current ATLAS Inner Detector.
- **Implementation** of detailed representations of new sensors and structures within the ATLAS simulation framework in progress.

End-cap has trapezoidal sensor shapes pointing to the centre of the beam -pipe -> \( r\phi \) resolution

=> work in progress
Ingrid-Maria Gregor, DESY - ATLAS ITK Simulations

Alternative Layouts

- In parallel to work on baseline design, other alternatives are being investigated.
- For example, the so-called “Conical” [8] layout, which uses barrel sensors tilted wrt z-axis in place of full disk system for high-$\eta$ tracking.
- Requires much more significant modifications of the ATLAS GeoModel and reconstruction framework in order to be fully implemented.
- Work is ongoing.
- Effort also going in to GeoModel description of strip end-cap structure and sensors.
- Fully detailed description of new sensor geometries.
- Currently verifying quantifying benefit for physics measurements.
Summary

- Detailed simulation studies of the baseline ITk layout for an upgraded ATLAS tracker to operate at HL-LHC have been performed, both in isolation and embedded within the rest of the ATLAS detector.
- These studies, which include the projected HL-LHC levels of pile-up collisions, demonstrate the excellent performance of this tracker layout.
- Work is ongoing to refine the description of this layout and to study further aspects of its performance, and in parallel to implement and study various alternatives to the baseline ITk layout.