ATLAS Track Reconstruction
Challenges for HL-LHC

Wolfgang Liebig
(CERN and University of Bergen, Norway)
on behalf of the ATLAS collaboration

Connecting the Dots 2015, Berkeley CA
The ATLAS Detector Upgrades
seen from track detector perspective

- Current LHC programme expected to deliver $300 \, fb^{-1}$ by end 2022
- Followed by High-Luminosity phase “HL-LHC”
  - *levelled* $L = 5 \times 10^{34} \, cm^{-2}s^{-1}$ (peak $L = 7.5 \times 10^{34}$)
  - $300fb^{-1}$ *per year* at $\sqrt{s}=13$ TeV
    - $\Rightarrow$ 3000 $fb^{-1}$ total over 10y
  - pileup of $\mu=140$ collisions/event
    (average, levelled, 25ns mandatory)
    - $\Rightarrow$ foresee events with $\mu \sim 200$
  - increased trigger rate
- Current inner tracker will be **completely replaced**, due to:
  - radiation hardness
  - occupancy limitation
  - bandwidth limitation
- muon spectrometer – challenge of its own in charged particle tracking
  - new “small wheel” (LS2, before HL-LHC)
  - new read-out electronics (HL-LHC)
**ITk Detectors**

- All-silicon arrangement of Pixel and strip modules
  - no more transition radiation tracker

- **Pixel:**
  - hybrid approach: planar+3D
  - baseline $50 \times 250\mu m^2$ and $25 \times 150\mu m^2$
  - R&D with 65nm ASICs could give $50 \times 50\mu m^2$ or $25 \times 100\mu m^2$

- **Strip:**
  - barrel: $75\mu m$ pitch,
    - 2 designs (short+long)
  - endcap: var. pitch, 6 designs
  - double-sided layers rotated by 40 mrad (z-coord.)

*Test chip in 65nm CMOS technology 16×32 pixels of size 25×125m²*

*Strips in endcap configuration*
Timeline for HL-LHC and ITk

- 2014: initial design review, ECFA
- 2015: layout, re-costing
- 2016–17: technical design rep.
  - strips (large surface) earlier than Pixel
- 2017-2019: pre-production
- 2019–2021: module production
- 2021-2023: integration and commissioning

Big challenge: precise simulation and reconstruction needed at early stage
**ITK Layout**

- Benchmark layout from Letter of Intent (LoI):
  - 4 layers pixel
  - 5 layers strip + stub
  - $|\eta|<2.7$ (match muon spectro)

- Known deficiencies
  - Engineering of services around disks
  - Active surface not yet rigorously optimized
  - Areas of high occupancy

- Examining many different and innovative layouts

- Optimization for
  - Tracking performance
  - Cost optimization
  - Ease of construction/installation
  - Ease of maintenance

### ATLAS ITk Reference Layout in r-z View

- **Si area**
  - Pixel: 8.2 m$^2$, 638×10$^6$
  - Strip: 190 m$^2$, 71×10$^6$

---

10-FEB-2015
Innovative Layouts

- Tracking performance: extension to $|\eta| < 4.0$
- Engineering: end-cap rings
- Active surface optimization:
  - "Conical" layout
  - "Alpine" layout
- Re-costing in 2015
- Ideally have accurate tracking performance simulation for all conceived layouts
  - Task force in ATLAS
Options for far forward muons

- Studied for extending MS to match far forward ITk range
  - ID+MS combination (here statistical)
  - complemented by muon tagging
Physics Goals at HL-LHC

- general physics goals
  - deeper examination of Std. Model, esp. Higgs boson properties
  - explicit searches for New Physics
- examples: NP mass reach extended, dark matter sensitivity from Higgs couplings to WIMPs
- follow-up of 300fb$^{-1}$ from phase 1
  - if discovery measure properties
  - if not: new ideas for searches may involve signatures beyond design
- additional challenges to reconstruction
  - pile-up mitigation: tracks enter jet and missing-E reconstruction,
  - object ID (e, μ, γ, jets) under pile-up
  - more non-standard signatures (slow&heavy particles, late decays)
Expected Occupancies

- Occupancy studied at high expected pileup ($\mu=200$)
- High occupancies in layers facing interaction point and with long strip length
- Challenging to clustering and pattern recognition

**Figure 7.34.** Rejection versus efficiency curves for left: $c$–jets and right: $l$–jets for both the SV0 and IP3D taggers at $\mu=140$, $\mu=250$, and $\mu=300$ pileup scenarios. A secondary vertex is required for a SV0 weight. The degradation at higher pileup is clearly seen for both taggers.

**Figure 7.35.** Expected percentage hit occupancy map for $\mu=200$ pileup for a. pixel detector b. strip detector.
Expected Performance
as of ECFA 2014

- Pixel+Strip hits over full range up to forward direction of $\eta \sim 2.6$
- Examining “VF” option to place Pixel modules in far forward
- Momentum resolution
  - Example using full simulation

![Graphs showing expected performance](image)
Challenges in Upgrade Studies

progressive set of tools:

- “IDRes”: analytical calculation of basic numbers
  - resolution, hermeticity, rough material
  - NOT: fake rates, hadronic interaction
  - layouts quickly defined with few params

- fast track simulation
  - in standard ATLAS software
  - simulation and reco use same tools
    (propagation, geometry, material...)

- truth vs. full tracking
  - ability to decouple pattern recognition by tracking only truth associated hits

- full simulation
  - Geant4 simulation & track reco as tuned for current Inner Detector

New level: fast but precise comparison of layouts
Challenges in Upgrade Studies

- “IDRes”: analytical calculation of basic numbers
  - resolution, hermeticity, rough material
  - NOT: fake rates, hadronic interaction
  - layouts quickly defined with few params

- fast track simulation
  - in standard ATLAS software
  - simulation and reco use same tools
    (propagation, geometry, material... )

- truth vs. full tracking
  - ability to decouple pattern recognition
    by tracking only truth associated hits

- full simulation
  - Geant4 simulation & track reco as
    tuned for current Inner Detector

Technical challenges:

- Integration in “live” ATLAS run-2 software
- support of additional geometries
- developments for high-lumi tracking
  needed already now
ATLAS Track Reconstruction
Inner Detector Strategy for run-1 (and run-2)

Pre-processing:
• clusterization
• TRT DriftCircle creation
• SpacePoint formation

Ambiguity Solver:
• precise track fit with:
  – full hit calib (incidence angle, ...)
  – precise geometry & material
• score and rejection using
  – fit quality
  – hit content, shared hits, holes
• brem recovery

Combinatorial track finding:
• iterative (ordered list!):
  – Pixel seeds
  – 2-Pixel+SCT seeds
  – SCT seeds
• extend seeds to full roads
• bookkeeping against duplicates
• brem recovery

Extension into TRT:
• Si-seeded road search
• precise track fit, scoring
• brem recovery

TRT-Seeded “back-tracking”
• TRT pattern reco on unused hits
• road search back to SCT+Pixel
• track fit, scoring

Post-Processing:
• primary vertexing
• conversion and V0 search
ATLAS Track Reconstruction
Strategy for HL-LHC

- ITk version: re-configure current algorithm chain
- high modularity on purpose – collisions, cosmics, ..., upgrade!
- most detector dependent: geometries, track finding
- similarly modular chain in muon spectrometer, common tracking tools w/ID
- CPU perf recently optimized

(simplified!)

![Diagram of ATLAS track reconstruction algorithm chain]

Figure :: Time per event as measured in seconds to reconstruct Monte Carlo top $t\bar{t}$ pair production events $t\bar{t}$ as a function of the ATLAS software release version. These events are generated at LHC collision energy of 14 TeV with conditions of a bunch crossing spacing time of 25 ns and an average number of interactions per BC of 4. Two sets of data are displayed: the full reconstruction time fired; and the reconstruction time used for the Inner Detector sub-system reconstruction only which is the dominant sub-component to the full reconstruction time. The simulation is performed for the run: ATLAS detector geometry. Measurements were performed on a machine with a HS. scaling factor of 11.95. The data processing time of interest here is the time taken to process Raw Data Object files into Event Summary Data files in what is known as the reconstruction step.

![Graph showing reconstruction time per event]

$\sqrt{s} = 14$ TeV
$\langle n \rangle = 40$
25 ns bunch spacing
Run 1 Geometry
$pp \rightarrow t\bar{t}$
HS06 = 11.95

Figure ¯: ATLAS Inner Detector track reconstruction efficiency for true charged particles from $t\bar{t}$ that originate within an radius of 1 mm from the $z$-axis of the ATLAS detector, which is defined along the beam line. The true charged particle must have a true transverse momentum of greater than 8 GeV/c and create at least 7 hits in the silicon tracker. These events are generated at LHC collision energy of 14 TeV with conditions of a bunch crossing spacing time of 25 ns and an average number of interactions per BC of 4.
Pattern recognition

- fast and efficient pattern reco is a challenge in high pile-up
- PR biggest InDet CPU consumer
  - before and after LS1 software review
  - typically 3x more than track fitting
- up to now able to tune handles without cutting into physics
  - quality of seeds (3-cluster combin.)
  - vertex pre-constraints
  - latest development:
    seeds with 3+1 hits
  - see talk by A. Morley

Example from run-1 for ability to reduce combinatorics (here by vertex constraint)
Outside-in seeding, conversions

Open challenges and questions

- how to evolve TRT-seeded strategy for all-silicon tracker?
  - important for conversions, and subsequent electron/photon ID

- maintain good brem recovery achieved during run-1 for ID
  - see A. Morley's talk tomorrow
  - high pile-up: track-based measurement

one of several developments to improve brem recovery
**Tracking R&D: dense environment**

Run-1 inspired work with high relevance for HL-LHC

- “dense environment” = highly collimated jet
  - high $p_T$ b-jet, 3-track tau, boosted $t,W$
  - signals also at HL-LHC, convoluted with even higher pileup

- ATLAS WG to improve tracking in dense environments (TIDE)
  - ambi solver = main source of track loss
  - new version in place with in-algorithm treatment of shared hits

- directly addresses ITk challenges
  - improvement ~decoupled from pile-up or layout optimisation issues

- future perspectives
  - experience from run-2
  - beyond shared hit treatment, e.g. multi-track fitting

Public ATLAS note to appear see talk by A. Morley tomorrow
Vertexing R&D in run-1
Run-1 inspired work with high relevance for HL-LHC

- pile-up = challenge also for vertex reconstruction
- run-1 software subject to high vertex-merging rate
  - identified as limitation in seed strategy
- new seeding strategies being commissioned for run-2
  - medical imaging inspired
  - sliding window algorithms
  - ability to tune splitting vs merging rates
- pile-up suppression and correct identification of hard scatter PV will be a challenge in HL physics analyses
Evolution of Computing Aspects

- ~10 years to HL-LHC (20 to end) means innovations in computing
- make tracking software adapt to/profit from such innovations
  - LS1 example: new math library Eigen (>1000 packages touched)
  - ID reco sped up by more than $x^3$, but can not assume to redo that
- keep pace with architectures
  - increase in number of cores
  - availability of HPCs or GPUs
  - what else in 5, 10 years?
- number of cores: “athena-MP”
  - multi-threading at event level
  - shares all non-event memory
  - track-level difficult (cross-talk, ordered lists in current software)
- First studies to use GPU architectures
- Comes with organizational challenge
  - large disruptions, large code migrations
  - revive or retrain good number of experts
Conclusions

- All-silicon detector under design in ATLAS for HL-LHC
- Challenges to track reconstruction from many directions:
  - **harsh environment:** high hit occupancy, high pile-up, high local track densities
  - **early software integration:**
    1) need current software to now support HL-LHC
    2) HL-LHC deliverables improve also run-2 performance
  - **support for many different and innovative layouts**
  - **evolution of computing architecture**
- ATLAS addresses all these aspects within the given manpower (*manpower:* speaking of yet another challenge...)
- design decisions for the new detector in the coming 2 years

For ATLAS upgrade plans and expected performance follow
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
The end.