The ATLAS tracking system for HL-LHC

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The future of ATLAS: Run 3 and HL-LHC

LHC proton-proton collisions \[ \sqrt{s} = 7/8/13 \text{ TeV (2011-2018)} + 13/14 \text{ TeV (2021-2023)} \]

High Luminosity LHC (HL-LHC) \[ \sqrt{s} = 14 \text{ TeV (2026-20XX)} \]

Instantaneous Luminosity a factor 5 to 7 higher than LHC: \[ \mathcal{L} = 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]

Expect up to 200 pile-up events

At HL-LHC, harder conditions for the ATLAS detector (especially for the tracking system):
- increase in occupancy → finer granularity
- larger readout bandwidth → faster detector readout
- radiation damage → better radiation hardness
The current ATLAS tracking system

Composed by 3 subsystems:

- TRT (Transition Radiation Tracker) $\rightarrow$ Gas mixture straw tubes
- SCT (Semi-Conductor Tracker) $\rightarrow$ Micro strips
- Pixel Detector & IBL (Insertable B-Layer) $\rightarrow$ Pixels

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The future ATLAS tracking system: Inner Tracker (ITk)

Composed by 2 subsystems:
- Strip Detector → Micro strips
- Pixel Detector → Pixels
Inner Tracker detector layout

- Inner Tracker
- New all-silicon detector
- Tracking coverage up to $|\eta| = 4$
- Inner pixel det. (13 m², 5 M channels)
- Outer strip det. (160 m², 160 M channels)
- First two pixel layers will be replaced (after 2000 fb⁻¹)

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Layout, material budget, pseudorapidity coverage

- Extended coverage up to $|\eta| = 4$
- Up to 13 hits per crossing particle
- Reduced material w.r.t Inner Detector
- Inclined modules in Pixel Detector
  - Maximize resolution
  - Minimize material

**Current Pixel Detector**

**ITk**

**ITk radiation lengths**

**Inner Detector radiation lengths**

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Despite the increase in complexity of the project and the tougher conditions

- ITk detector will maintain good track reconstruction efficiency (up to $|\eta| = 4$)
- And lower fake rates compared to the Run 2 Inner Detector performance

**Track reconstruction efficiency**

**Track fake rate**

Simulation on $tt$ events at HL-LHC ($\langle \mu \rangle = 200$) compared to LHC Run 2 ($\langle \mu \rangle = 20$)
Pixel detector Outer EndCap

➢ Two EndCaps
  ➢ Two Half Cylinders
    ➢ 11+8+9 Rings (x 2 Half Rings)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Radius [mm]</th>
<th>Z [mm]</th>
<th>Rings</th>
<th>Sensors per Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>154.50</td>
<td>1145-2850</td>
<td>11</td>
<td>32 (8 quad)</td>
</tr>
<tr>
<td>3</td>
<td>214.55</td>
<td>1145-2850</td>
<td>8</td>
<td>44 (11 quad)</td>
</tr>
<tr>
<td>4</td>
<td>274.60</td>
<td>1145-2850</td>
<td>9</td>
<td>52 (13 quad)</td>
</tr>
</tbody>
</table>

➢ Effort shared by Italian and UK institutes
  ➢ Italy: Milano, Udine, Trento, Genoa, Bologna, Frascati, Lecce

Italian organization
Module assembly: Milano, Genova
Module tests: Bologna, Trento, Udine
Module loading: Genova, Lecce
Local supports: Genova
Integration in Half Cylinders: Frascati

Half Ring (support and cooling):
  ➢ Sandwiches of carbon-fiber, carbon foam and titanium cooling pipe
  ➢ Modules directly attached on Half Rings

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Pixel Detector module

Pixel hybrid-module concept

- Flex Hybrid, with SMDs
- Solder/Indium Bumps
- Local Support
- Encapsulated wire bonds
- Sensor
- FE chips
Planar/3D sensor + RD53 chip

Pixel hybrid-module concept

3D in the innermost layer

Planar everywhere else

Pixel size: 50x50 or 25x100 µm²
Thickness: 100-150 µm
Reduced pixel size & thickness → higher radiation hardness

New Front-End chip developed within the RD53 Collaboration
65nm CMOS technology
RD53A prototype: 3 Analog FE flavours
RD53B chip design in few months

Analog FE choice is approaching

Final size: 2x2 cm²
Total of about 160 k pixels
Bump density: 4·10⁴ pixels per cm²
Data rates and radiation fluences

With such a high granularity
Expect high data rates (2.6 Gb/s) at $\langle \mu \rangle = 200$
Simulation with RD53B readout chip
Pixel Detector barrel section

![ATLAS Simulation graph]

To hold such a high data rate:

- Developing high speed readout
- 4 x 1.28 Gb/s links (single/quad-mod.)

![Pixel and Strip fluences graph]

Pixel: up to $10^{16}$ $1 \text{ MeV} n_{eq} / \text{cm}^2$ fluence
Strip: up to $10^{15}$ $1 \text{ MeV} n_{eq} / \text{cm}^2$ fluence

Check survival to high radiation environment:

- Built and test Pixel module prototypes
- Irradiation campaigns at $10^{16} n_{eq} / \text{cm}^2$

Test beams confirmed efficiency $> 97%$
Primary vertex reconstruction, Vertexing resolution

Tougher conditions:
need to ensure high quality tracking performance

From simulation studies:
expect better efficiency and higher resolution in tracking and vertexing

Primary vertex reconstruction efficiency for $tt$ events

Resolution on $z$ coordinate of the primary vertex for $tt$ events

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Pile-up jet rejection, b-tagging performance

Tougher conditions:
need to ensure high quality tracking performance

From simulation studies:
expect similar or improved pile-up rejection and b-tagging performance

Pile-up jets rejection as a function of the jet reconstruction efficiency

B-tagging performance (light-jet rejection) as a function of b-jet efficiency
Pixel detector R&D phase: prototyping and tests

**Outer barrel layers: Longerons**
- Tilted cell
- Longeron
- Barrel cell
- Longeron with 44 silicon heaters

**Outer EndCap: Rings**
- Half ring with heaters and temp. sensors

**Inner System Barrel: Staves**
- Staves for layers 0 and 1
- Inner system ring with temperature sensors

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Summary and outlook

The current Tracking System of the ATLAS experiment (ID: Inner Detector) will be replaced by a new all-silicon detector (ITk: Inner Tracker) to cope with the harsher HL-LHC conditions.

- A challenging detector with Strips (160 m²) + Pixels (13 m²)
- Layout is being refined, carefully checking the tracking performance
  - New results form simulation: ATLAS-PHYS-PUB-2019-014
- ITk detector is expected to have similar or better tracking performance compared to ID
  - Comparable tracking efficiency, lower fake rate
  - Lower material budget, higher pseudorapidity coverage (up to |\(\eta| = 4\))
  - Improved primary vertex reconstruction, better vertexing resolution
  - Higher pile-up jets rejection, comparable b-tagging performance

- The ITk Pixel detector will be composed by hybrid Pixel modules (sensor + FE chip)
- Reduced pixel size (50x50 or 25x100 µm²) and thickness (100-150 µm) compared to ID mod.
  - Confirmed hit detection efficiency higher than 97% after \(10^{16} \text{n}_{eq} / \text{cm}^2\) irradiation
- New Front-End chip: RD53A prototype being tested, RD53B being designed
  - High speed links (4 x 1.28 Gb/s), low consumption

- For ITk Pixel detector, 3 main sections are identified: Inner System, Outer Barrel & EndCaps
  - R&D effort is shared by many institutes: currently prototyping and testing
  - The Italian community is committed to build one EndCap

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