Upgrade of the ALICE Inner Tracking System (ITS)

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ALICE is a heavy-ion experiment at the CERN LHC with a main goal to study strongly interacting matter, in particular the properties of the Quark-Gluon Plasma, using Pb-Pb, p-Pb and pp collisions.

ALICE consists of a central barrel, a forward muon spectrometer, several dedicated detectors for triggering and event characterization.
ALICE upgrade

Motivation

High precision measurements of rare probes at low $p_T$, which cannot be selected by a hardware trigger

Target

Recorded luminosity of $10 \text{ nb}^{-1}$ in Pb-Pb (plus pp and p-Pb data)

- Increased statistics by a factor of 100 compared to LHC Run 1 and 2 (2009 - 18)
- Improved vertexing, tracking and read-out rate capabilities

Upgrades (LHC Long Shutdown 2 – 2019-20)

ALICE readout (of several detectors) and online systems

- Read out all Pb-Pb interactions at a maximum rate of 50 kHz with a minimum bias trigger
- Perform online data reduction

New silicon trackers: Inner Tracking System (mid-rapidity), Muon Forward Tracker (forward rapidity)
Requirements for ALICE ITS upgrade

Improve impact parameter resolution (≈ factor of 3 (6) in r-φ (z) at 500 MeV/c)

First layer closer to interaction point: \( r_0 = 39 \text{ mm} \rightarrow 22 \text{ mm} \)

Smaller beam pipe radius: \( 29 \text{ mm} \rightarrow 18.2 \text{ mm} \)

Reduce \( X / X_0 / \) layer: \( 1.14 \% \rightarrow 0.3 \% \) (inner layers)

Smaller pixel size: \( 50 \mu \text{m} \times 425 \mu \text{m} \rightarrow 28 \mu \text{m} \times 28 \mu \text{m} \)

Improve tracking efficiency and \( p_T \) resolution at low \( p_T \)

Increase the number of layers \( 6 \rightarrow 7 \)

All layers pixel chips

Fast readout: \( 50 \text{ kHz} \) in Pb-Pb, \( 200 \text{ kHz} \) in pp (currently \( 1 \text{ kHz} \))

Easier maintenance: replacement of faulty detector components during the yearly LHC technical stop
Expected performance of new ITS

Pointing resolution

~ 40 μm at $p_T = 500$ MeV/c

Tracking efficiency
Requirements for the ITS upgrade

7 layers of pixel sensors
\((r = 22 - 400 \text{ mm})\)

10 m\(^2\) of silicon with
12.5 Gpixels

\(|\eta| < 1.22\) for tracks from
90% of the most luminous region

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Inner barrel</th>
<th>Outer barrel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon thickness</td>
<td>50 \text{ (\mu)m}</td>
<td>10 \text{ (\mu)m}</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>5 \text{ (\mu)m}</td>
<td>10 \text{ (\mu)m}</td>
</tr>
<tr>
<td>Power density</td>
<td>&lt; 300 mW/cm(^2)</td>
<td>&lt; 100 mW/cm(^2)</td>
</tr>
<tr>
<td>Event resolution</td>
<td>&lt; 30 \text{(\mu)s}</td>
<td></td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>&gt; 99%</td>
<td></td>
</tr>
<tr>
<td>Fake hit rate</td>
<td>&lt; 10(^{-5}) per event per pixel</td>
<td></td>
</tr>
<tr>
<td>Average track density</td>
<td>15 - 35 \text{ cm}^{-2}</td>
<td>0.1 - 1 \text{ cm}^{-2}</td>
</tr>
<tr>
<td>TID radiation *</td>
<td>2700 \text{ krad}</td>
<td>100 \text{ krad}</td>
</tr>
<tr>
<td>NIEL radiation *</td>
<td>1.7 \times 10^{13} \text{ 1 MeV n}_{eq}/\text{cm}^2</td>
<td>10^{12} \text{ 1 MeV n}_{eq}/\text{cm}^2</td>
</tr>
</tbody>
</table>

=> well suited for Monolithic Active Pixel Sensors

* including a safety factor of 10
Choice of sensor technology

Monolithic Active Pixel Sensors (MAPS) using Tower Jazz 0.18 μm CMOS imaging process:

- Very thin sensors
- Very high granularity
- Large area to cover
- Modest radiation levels

Parameter comparison for mainstream MAPS architectures

<table>
<thead>
<tr>
<th></th>
<th>ALPIDE</th>
<th>MISTRAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel pitch</td>
<td><strong>28 μm x 28 μm</strong></td>
<td><strong>36 μm x 64 μm</strong></td>
</tr>
<tr>
<td>Event time</td>
<td>$&lt; 2 \mu s$</td>
<td>$\sim 20 \mu s$</td>
</tr>
<tr>
<td>resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power consumption</td>
<td><strong>39 mW/cm²</strong></td>
<td><strong>97 mW/cm²</strong></td>
</tr>
</tbody>
</table>

Baseline solution $\rightarrow$ ALPIDE

Both architectures have the same dimensions, identical physical and electrical interfaces.
Pixel sensor characterizations

Laboratory

- **Noise and threshold** scans
- **Radioactive source** measurements
- **Noise occupancy** measurements

Intensive efforts in a number of institutes to characterize pixel sensors

Test beam

- Tracking by a stack of 3 + 3 pALPIDE-1 chip around Device Under Test

Readout and analysis is done using the EUDAQ/EUTelescope framework (created by DESY)

- **Several campaigns** from 60 MeV to 120 GeV (PS, SPS, DESY, BTF, PAL)

Measurement of detection efficiency and spatial resolution

Example of pALPIDE test setup
**Selected performance**: Efficiency & Fake-Hit rate

Reverse substrate bias $V_{BB} = -6$ V, epitaxial layer and spacing comparison

- **Project goal**: Detection efficiency for MIP increases with increasing epitaxial layer thickness
- **Goal of the project**: Efficiency $> 99\%$
  - Fate-Hit rate $< 10^{-5}$ per pixel and event
- **Measurements meet the requirements**
- **Detection efficiency improves with larger back bias voltage**

Reverse substrate bias comparison, 30 µm epitaxial layer, 4 µm spacing

- Measurements meet the requirements
Irradiated prototypes: Efficiency & Position resolution

Reverse substrate bias VBB = −6 V, 25 µm epitaxial layer, 2 µm spacing

- Deterioration of the detection efficiency & position resolution is tolerable up to the maximal expected dose

Reverse substrate bias VBB = −6 V, 30 µm epitaxial layer, 4 µm spacing

- Cluster size is not affected by radiation

Project goal
Summary and outlook

- The **Inner Tracking System** of ALICE will be replaced during the second long LHC shutdown (2019/20)

- 7 layers of monolithic active **pixel sensors** will be used

- Expected track impact parameter resolution, tracking resolution and $p_T$ resolution at low $p_T$ will improve significantly

- First full scale prototypes show **good performance** and large operational margin

- Project is advancing according to schedule

![Timeline Diagram](image)
Backup slides
Pixel Specifications

Pixel choice: Monolithic Active Pixel Sensors (MAPS) using Tower Jazz 0.18 μm

- Chip size: 15 mm x 30 mm
- Pixel pitch ~ 30 μm
- Si thickness: 50 μm
- Spatial resolution ~ 5 μm
- Power density < 100 mW/cm²
- Integration time < 30 μs
- Fake-hit rate < 10⁻⁵ per pixel per event
Performance Example

pALPIDEfs: first full scale prototype of ALPIDE, pixel size: 28 x 28 mm²

Sector 3, \(V_{\text{casn}} = 150\)

- **Cluster size is consistent for data, measured at Frascati & on PS**
- **Cluster size does not depend on multiplicity**
- **20 most noisy pixels masked**
- **Wide operating range with efficiency ~99% and noise occupancy < 10^{-5} /event/pixel**
- **Noise occupancy increases after irradiation**

**Beam tests at Frascati (450 MeV e-) & on PS (6 GeV π-)**