The ALICE Inner Tracker Upgrade

R. Santoro
On behalf of the ALICE ITS Collaboration
Outlook

- Current Inner Tracking System (ITS)
  - Design and performance
- ITS upgrade
  - Physics motivation and detector requirements
  - Expected performances
  - Technology and R&D
    - Detector technologies
    - Mechanical support, cooling and material budget

Current ITS performance has been shown at this conference by S. Bufalino

Details on the ITS upgrade can be found in the recent CDR CERN-LHCC-2012-013 (LHCC-P-005)
The ITS role in ALICE

- Improve primary vertex reconstruction and momentum resolution
- Secondary vertex reconstruction (c, b decays)
  - Good track impact parameter resolution (< 60 \( \mu \text{m} \) \((r_\phi)\) for \( p_T > 1 \text{ GeV/c} \) in Pb-Pb)
- Tracking and PID of low \( p_T \) particles
- Prompt L0 trigger capability (<800 ns) with the first 2 layers

Barrel Tracking requirements (\(|\eta| < 0.9 \))

- Robust tracking for heavy ion environment
- Wide transverse momentum range (100 MeV/c – 100 GeV/c)
- PID over the large momentum range based on several techniques: dE/dx, TOF, transition, calorimetry and Cherenkov radiation

ITS: six layers based on 3 different silicon detector technologies

The ALICE experiment

Dedicated heavy ion experiment at LHC

- Study of the behavior of strongly interacting matter under extreme conditions of energy density and temperature
A key factor to quote the tracker performance is the transverse impact parameter (allows the secondary vertex reconstruction)
ALICE Upgrade

- **Requirements**
  - Improve vertexing and tracking at low $p_T$ while preserving the excellent particle-identification of the current detector
  - Readout all Pb-Pb events at an interaction rate of 50 kHz
  - Timeline: target for installation and commissioning LS2 (2018)

- **Physics targets** …
  - Identification of secondary vertices from charm and beauty decay
  - Increase statistical accuracy of channels already measured by ALICE e.g. displaced $D^0$, $J/\Psi$
  - Measurement of new channels:
    - e.g. charmed baryon $\Lambda_c$
    - or even more exotic channels: $\Lambda_b$

  … which will allow ALICE to study
  - The thermalization of heavy quarks in QGP
    - Measure baryon over meson ratio for charm and beauty ($\Lambda_c/D$ or $\Lambda_b/B$)
    - $D$ mesons down to very low $p_T$
  - Quark mass dependence of in-medium energy loss
    - Study separately nuclear modification factor ($R_{AA}$) of the $p_T$ distribution of $D$ and $B$ mesons down to low $p_T$
  - Comprehensive measurement of low-mass dileptons
    - Yield of low mass $e^+e^-$ (virtual $\gamma$)
    - Spectral function of $\rho$-meson - $e^+e^-$ effective mass spectrum down to 200 MeV
Requirements for the new ITS

- Improve impact parameter resolution by a factor of \( \sim 3 \)
  - Get closer to IP
  - Reduce material budget
  - Reduce pixel size

- High standalone tracking efficiency and \( p_T \) resolution
  - Increase granularity
  - Increase radial extension

- Moderate radiation hardness
  - Expected radiation level for the first layer: 700 krad and \( 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2 \) (safety factor \( > 4 \) already considered)

- Fast readout
  - Readout of all Pb-Pb interactions (50 kHz)

- Fast insertion/removal for yearly maintenance
  - Possibility to replace nonfunctioning detector modules during yearly LHC winter shutdown
Two upgrade options under discussion

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Inner Barrel</th>
<th>Outer Barrel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beampipe outer radius (mm)</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Beampipe wall thickness (mm)</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td>Detector Technology</td>
<td>Pixel</td>
<td>Pixel–Strip</td>
</tr>
<tr>
<td>Number layers</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Mean radial positions (mm)</td>
<td>22, 28, 36</td>
<td>200, 220, 410, 430</td>
</tr>
<tr>
<td>Stave length in z (mm)</td>
<td>270, 270, 270</td>
<td>843, 843, 1475, 1475</td>
</tr>
<tr>
<td>Power consumption (W/cm²)</td>
<td>0.3 (\div) 0.5</td>
<td>(\leq 0.5) mW/strip</td>
</tr>
<tr>
<td>Total material budget per layer (% of (X_0))</td>
<td>(\approx 0.3)</td>
<td>(\leq 1.0)</td>
</tr>
<tr>
<td>Working temperature (°C)</td>
<td>(\approx 30)</td>
<td>(\approx 30)</td>
</tr>
</tbody>
</table>

Option A: 7 layers of pixels
- Pixels: \(O(20 \times 20 \mu m^2 – 50 \times 50 \mu m^2)\)

Option B: 4 layers of strips
- 4 strips

3 layers of pixels
- Pixels: \(O(20 \times 20 \mu m^2 – 50 \times 50 \mu m^2)\)
- Strips: 95 \(\mu m\) x 2 cm, double sided
How to improve the impact parameter resolution

- Get closer to IP
  - Beampipe outer radius = 20 mm (presently 29.8 mm)
  - First detection layer at 22 mm (presently 39 mm)
- Reduce material budget
  - Target value for the first 3 layers: 0.3 X/X₀ per layer (current SPD: 1.14 X/X₀)
- Reduce pixel size for the first layers
  - Spatial precision ≈ 4 µm in both direction (current SPD: 12 µm in rφ and 100 µm in z)

ITS standalone pointing resolution for charged pions as a function of pₜ

- Current ITS
- New ITS (Option A and Option B)
How to improve the tracking efficiency and $p_T$ resolution

- Increase and redistribute the number of layers
  - **Current ITS**: 6 layers, optimized for track matching with TPC
  - **New ITS**: 7 layers, optimized also for standalone tracking

- Increase layer granularity
  - **Option A**: pixels 20µm x 20µm with spatial precision of 4µm x 4µm
  - **Option B**: combination of pixels (20µm, 20µm) and strips (95µm, 20mm, stereo angle 35mrad with a spatial precision of 20µm, 830µm)

- Increase radial extension
  - **Current ITS**: 39mm – 430mm
  - **New ITS**: 22mm – 430mm(*) (value used in the simulation)
  - (*) increasing outer radius to 500mm results in a 10% improvement in $p_T$ resolution
Examples of Physic Performance

\[ D^0 \rightarrow K\pi \]
Benchmark channel at low \( p_T \)

\[ \Lambda_c \rightarrow pK\pi \]
Benchmark channel in Pb - Pb

\( \Lambda_c \) requires both a very precise and fast readout tracker.
This will allow a measurement down to 2 GeV/c in central Pb-Pb collisions.

\[ p_T \text{ bin } 0 – 2 \text{ GeV/c accessible for the first time} \]
Technology and R&D:
Detector technologies
Mechanical support, cooling and material budget
Pixel detector technologies

Several technologies are being considered:

- Hybrid pixel detectors
  - Edgeless sensors (100µm) + front-end chip (50µm) in 130nm CMOS

- Monolithic pixel detectors
  - MIMOSA like in 180nm CMOS
  - INMAPS in 180nm CMOS
  - LePix in 90nm CMOS

Tower/Jazz
Deep submicron technology (i.e. IBM)
Hybrid Pixel Technology

- **Features**
  - CMOS chip + high resistivity sensor (~80 kW·cm)
  - Bump-bonding connections
  - Charge collection by drift
  - Proven radiation resistance to the expected ALICE levels
  - Mature technology

- **Some considerations**
  - Larger material budget: 0.5% X0 target
  - Larger pixel size: 30 µm x 30 µm target
  - High cost per m² (limited to inner layers)

- **R&D focus**
  - Sensor thinning (down to 100µm)
  - Edgeless sensors (to reduce the dead area along z)
  - Low cost bump-bonding
  - Low power FEE chips
  - Kapton-Al bus interconnection with BGA technique

First prototype with standard BGA balls (500 µm diameter) and standard soldering technique (oven) using two polyimide foils.

BGA balls of smaller diameter are being considered as well as different soldering techniques (i.e. laser).

General Features
- Sensing layer integrated into the CMOS chip
- Charge mainly collected by diffusion
- Have shown significant progress in recent years and will be installed in STAR (HFT)
- Radiation resistance is under study for the ALICE scenario: 700 krad and $10^{13}$ neq/cm²

Some considerations
- Small material budget: 0.3% of $X_0$ (target)
- Small pixel size: 20 µm x 20 µm
- Low cost per m²: some chances to equip the full tracker

**R&D with Tower/Jazz 0.18 µm CMOS technology:**
- Improved TID resistance due to smaller technology node
- Available with high resistivity (~1k Ω·cm) epitaxial layer up to 18 µm
- Special quadruple-well available to shield PMOS transistors (allows in-pixel truly CMOS circuitry)
Monolithic Pixel: evaluation of Tower/Jazz technology

MIMOSA 32 (IPHC Strasburg)
- Rolling shutter readout (following development for STAR HFT)
- Double-sided readout
  - Reduction of integration time down to 20-40 \( \mu \)s (target)
  - Double power consumption (more columns active at the same time)
- Submitted structures and performed tests
  - Digital and analog blocks
  - 100 circuits delivered Jan 2012
  - Test with Fe55 source
  - Irradiation tests (X-ray, neutron)
  - Beam-test

MONALICET1 (CERN and CCNU – Wuhan, China)
- Submitted structures and performed tests
  - Single transistors
  - Breakdown structures
  - Memories
  - Digital structures
  - Shift register
  - Delivered July 2012
  - Irradiation test (X-ray)

Preliminary results from the July 2012 beam test (IPHC Strasbourg)
- Two values of temperature: 15° and 30°
- Radiation dose up to 1Mrad and 10^{13} \( n_{eq} \)/cm\(^2\)

<table>
<thead>
<tr>
<th>Irradiation Dose</th>
<th>SNR (MPV)</th>
<th>Detection efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15°C</td>
<td>30°C</td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Mrad &amp; 1 \times 10^{13} n_{eq} /cm(^2)</td>
<td>30.9 ± 0.4</td>
<td>29.7 ± 0.4</td>
</tr>
<tr>
<td></td>
<td>22.6 ± 0.4</td>
<td>19.3 ± 0.2</td>
</tr>
</tbody>
</table>
Silicon Strip R&D

- Sensor design based on current ALICE SSD
  - Standard 300 µm double-sided micro-strip sensors
  - 768 strip/side, 35 mrad stereo angle
- Reduced strip length down to 20 mm
  - Half cell-size: 95 µm x 20 mm
    - Higher granularity
    - Better ghost hit rejection
  - Doubled channel density
    - Challenging interconnection layout
    - Power consumption
- New ASIC design:
  - 0.18 µm technology (rad. hard)
  - Low power and fast ADC (10 bits)
  - Preserve 20 MIP range and 0.1 MIP resolution
External constraints

- Get closer to the IP
  - New beam pipe (20mm outer radius)
  - First detector layer very close to the beam pipe wall (2mm target value)
- Fast extraction to allow for an access to the detector during the LHC winter shutdown
  - No TPC displacement
  - Services only at one side

Preliminary studies of the new ITS installation sequence
Internal constraints

- Very demanding target for material budget (0.3 % of X0)
- Power dissipation (0.3 – 0.5 W/cm²)
- Operating temperature at around 30°C

This requires to evaluate different options of an integrated mechanical support and cooling system

Cooling system with integrated mechanical support

- Air cooling
  - Preliminary studies shown reasonable results with power dissipation lower than 0.3 W/cm²
- Cold plate
  - Microchannels etched in silicon or polyimide with an ultra-light carbon fiber mechanical support
- Cooling pipes
  - Pipes embedded in CFRP with a design optimized to guarantee adequate heat removal and reduced material budget
Cold plate

- Polyimide micro-channels:
  - Multilayer composite
    - 1 layer of LF110 (50 µm thick), 4 layers of PC1020 (50 µm thick each) and a cover layer hot pressed on the top
    - Micro-channels (200µm x 800µm) obtained with photolithography
  - Performed tests
    - Water compatibility, pressure test and long term test
    - Cooling performance

- Silicon micro-channels
  - Cooling technique developed by CERN/PH-DT with Microsystems Laboratory (EPFL) and CSEM (Neuchatel). Considered by NA62 for the Giga-Tracker detector
    - Micro-channels (200µm x 200µm) etched on a silicon plates (4 inches) covered with Si-plate by fusion bonding
    - Opening in the middle to reduce the material budget
  - Performed tests
    - Single frame test with C4F10
    - R&D on frames interconnection is ongoing

Mechanical support

- Different prototypes are being considered to guarantee adequate stiffness and very low material budget

R. Santoro
Vertex, Jeju (Korea)
Different material and layup to obtain good thermal and mechanical properties

The sample 2 has been used for thermal and mechanical test
Cooling pipe (II)

High thermal conductivity Carbon fibers wound around polyimide tubes

Carbon fiber K13D-2U 2K

~1,1 gram

Different optimization steps to improve the thermal performance

~1,4 gram

Winding angle <23° to avoid fiber break during winding due to fiber High Modulus

E=560MPa, X_t=2.2Gpa, K~450 W/mK

t=70 µm

Limit on fiber bending radius

23°
Cooling performances: cold plate

- Good cooling performance with the higher value of power consumption
- The total material budget estimate fulfills our stringent requirements

Test condition:
- Water @ 15°C and flow rate 4.8 l/h
- Power consumption = 0.5 W/cm²

Material budget assumptions:
- Monolithic pixel detector technology (50µm thick)
- Double layer polyimide – Al Electrical bus
Cooling performances: cooling pipe (I)

- Good cooling performance with the higher value of power consumption
  - Quite uniform temperature in the center
  - Two hotter areas in correspondence with the tube (to be investigated)
- The total material budget estimate fulfills our stringent requirements

Test condition:
- Water @ 15°C and flow rate 8 l/h
  - Good performances also shown with flow rate down to 3 l/h
  - Power consumption = 0.5 W/cm²

Material budget assumptions:
- Monolithic pixel detector technology (50µm thick)
- Double layer polyimide – Al Electrical bus
Cooling performances: cooling pipe (II)

This structure shows acceptable performance with the lower value of power consumption.
- It is a compromise between cooling and material budget.
- The material budget estimate is 0.26 % of $X_0$.

Test condition:
- Water @ 15°C and flow rate 8 l/h
- Power consumption = 0.3 W/cm²

Material budget assumptions:
- Monolithic pixel detector technology (50µm thick)
- Double layer polyimide – Al Electrical bus

<table>
<thead>
<tr>
<th>Material</th>
<th>Surface (%)</th>
<th>Thickness (µm)</th>
<th>$X_0$ (cm)</th>
<th>$X/X_0$ (%)</th>
<th>Contribution to the total $X/X_0$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP filament</td>
<td>100</td>
<td>70</td>
<td>25</td>
<td>0.035</td>
<td>12.6</td>
</tr>
<tr>
<td>Polyimide Tubes</td>
<td>19</td>
<td>70</td>
<td>28.6</td>
<td>0.005</td>
<td>1.8</td>
</tr>
<tr>
<td>Water</td>
<td>19</td>
<td>1450</td>
<td>36.1</td>
<td>0.06</td>
<td>22.8</td>
</tr>
<tr>
<td>Glue (CFRP - silicon)</td>
<td>50</td>
<td>100</td>
<td>44.4</td>
<td>0.01</td>
<td>4.4</td>
</tr>
<tr>
<td>Silicon</td>
<td>100</td>
<td>50</td>
<td>9.36</td>
<td>0.054</td>
<td>20.7</td>
</tr>
<tr>
<td>Glue (silicon - bus)</td>
<td>100</td>
<td>100</td>
<td>44.4</td>
<td>0.022</td>
<td>8.7</td>
</tr>
<tr>
<td>Electrical bus</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>0.075</td>
<td>29.0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>≈ 0.26</td>
<td></td>
</tr>
</tbody>
</table>
The new ALICE Silicon Tracker will allow one to address new physics topics (i.e.)
- The thermalization of heavy quarks in QGP
- Quark mass dependence of in-medium energy loss
- Comprehensive measurement of low-mass dileptons

New Tracker composed of 7 silicon layers characterized by:
- Impact parameter resolution improved by factor 3x
- First detecting layer at 22 mm from the beam line
- Demanding material budget ~ 0.3-0.5 % of X0 in the first layers
- Fast access for maintenance

R&D ongoing - To be built and installed by 2018
Thanks for your attention

R. Santoro
On behalf of the ALICE ITS Collaboration
PID over the large momentum range based on several techniques: dE/dx, TOF, transition, calorimetry and Cherenkov radiation
Carbon Fleece

M55j- 6k
E=540 MPa, X_T=4,2 Gpa
K= 150 W/mK

M60j- 3k
E=588 MPa, X_T=3,9Gpa
K= 140 W/mK

Carbon Roving

Polyimide tubes

1,5mmx32 µm (ODxwt)

Amec FGS_003

Carbon Unidirectional Prepreg

E=560MPa, X_T=2.2Gpa, K~ 450 W/mK

Carbon Paper

t=70 µm

t=30 µm, w=50g/m²

K13D-2U 2K

t=20 µm

t=100 µm, E_fiber =230 MPa,

t=20 µm

Carbon Fabric (0° /90°)

Carbon Fiber (0° /90°)

Glass fiber fabric

t=20 µm
Mechanical tests

- Steel tube vs. Aluminum tube
- Deformation in working condition
- Total distributed load = 5 grams
- First natural frequency = 596 Hz
Mechanical tests

### Design and Production Validation: Mechanical test

<table>
<thead>
<tr>
<th>Pressure Test Results</th>
<th>Carbon Fleece</th>
<th>Glass fabrics</th>
<th>Carbon Fleece</th>
<th>Carbon Fleece</th>
<th>Carbon Fleece</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Paper K13D2U</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Fleece K13D2U</td>
<td>1.0/5.0</td>
<td>1.8/4.0</td>
<td>4.4/6.0</td>
<td>6.0/6.5</td>
<td></td>
</tr>
<tr>
<td>Glass fabrics K13D2U</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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~0.3 bar Operating Pressure

Failure Initial / Final (bar)

<table>
<thead>
<tr>
<th>Initial</th>
<th>Final</th>
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</thead>
<tbody>
<tr>
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</table>

Final

Tube up to 11 bar (test set-up limit) with no failure
Inner Barrel layout
The ITS upgrade targets the shutdown in 2018:

- **Until end 2014: R&D**
  - Finalization of specifications
  - Evaluation of technologies using prototypes
  - Selection of technologies and full validation of prototypes
  - Final design and validation
- **2015/16: production, construction and test of modules**
- **2017: assembly and pre-commissioning in clean-room**
- **2018: installation in ALICE**