ALICE Upgrades

C. Lippmann
for the ALICE collaboration
ALICE in Run 1 and Run 2

Run 1 (2009 – 2013)

- Pb-Pb @ $\sqrt{s_{NN}} = 2.76$ TeV
- p-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV
- pp @ $\sqrt{s} = 0.9, 2.76, 7$ and $8$ TeV

Run 2 (2015 – 2018)

- Pb-Pb @ $\sqrt{s_{NN}} = 5.02$ TeV
- Xe-Xe @ $\sqrt{s_{NN}} = 5.44$ TeV
- p-Pb @ $\sqrt{s_{NN}} = 5.02$ and $8.16$ TeV
- pp @ $\sqrt{s} = 5$ and $13$ TeV

- Tracking and PID over large kinematic range
- High resolution vertex reconstruction
- Central barrel: $-0.9 < \eta < 0.9$
- Muon spectrometer: $-4.0 < \eta < -2.5$
- Forward detectors: trigger, centrality, luminosity, reaction plane
ALICE strategy for **Run 3** and **Run 4**

- 50 kHz Pb-Pb event readout rate (previously ~1 kHz in the central barrel)
- Integrated luminosity targets:

<table>
<thead>
<tr>
<th>Collision system</th>
<th>Integrated luminosity</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb-Pb @ $\sqrt{s_{NN}} = 5 - 5.5$ TeV</td>
<td>$\mathcal{L}_{\text{Pb-Pb}} = 13 \text{ nb}^{-1}$</td>
<td>Plus pp reference data</td>
</tr>
<tr>
<td>p-Pb @ $\sqrt{s_{NN}} = 8 - 8.8$ TeV</td>
<td>$\mathcal{L}_{\text{p-Pb}} = 0.6 \text{ pb}^{-1}$</td>
<td>Plus pp reference data</td>
</tr>
<tr>
<td>pp @ $\sqrt{s} = 14$ TeV</td>
<td>$\mathcal{L}_{\text{pp}} = 200 \text{ pb}^{-1}$</td>
<td>With focus on high multiplicity and rare signals</td>
</tr>
</tbody>
</table>

Programme is presented in CERN Yellow Report ([link](#)), LHC schedule ([link](#)), Future high-energy pp programme with ALICE ([link](#))
ALICE upgrade roadmap (2)

Run 3: ALICE 2
GEM TPC, ITS2, ...

Run 4: ALICE 2.1
Upgrade proposals: ITS3, FoCal

Run 5 and beyond: ALICE 3
All-Si tracker and PID

ALICE 3: Proposal for a new generation heavy-ion experiment for LHC Run 5
• See slide 36
Runs 3 and 4: Physics goals

- Heavy-flavour mesons and baryons (down to very low $p_T$)
- Charmonium states
- Dileptons from QGP radiation and low-mass vector mesons
- High-precision measurement of light and hyper nuclei

No dedicated trigger possible!

→ Need minimum-bias readout at highest possible rate
Runs 3 and 4: Implementation (1)

Runs 3 and 4: Physics goals

- Heavy-flavour mesons and baryons (down to very low $p_T$)
- Charmonium states
- Dileptons from QGP radiation and low-mass vector mesons
- High-precision measurement of light and hyper nuclei

Implementation

1. Untriggered data sample
   - Record all Pb-Pb interactions at 50 kHz through continuous readout
   - Collect a factor 50 – 100 more min bias data wrt Run 2

   \[ \Rightarrow \text{Continuous readout TPC} \]

\[ \text{No dedicated trigger possible!} \Rightarrow \text{Need minimum-bias readout at highest possible rate} \]
Runs 3 and 4: Implementation (2)

Runs 3 and 4: Physics goals

- Heavy-flavour mesons and baryons (down to very low $p_T$)
- Charmonium states
- Dileptons from QGP radiation and low-mass vector mesons
- High-precision measurement of light and hyper nuclei

Implementation

1. Untriggered data sample
   - Record all Pb-Pb interactions at 50 kHz through continuous readout
   - Collect a factor 50 – 100 more min bias data wrt Run 2

2. Improve tracking efficiency and momentum resolution at low-$p_T$
   - Increase tracking granularity
   - Reduce material thickness
   - Minimise the distance to IP

No dedicated trigger possible!

- Need minimum-bias readout at highest possible rate

Continuous readout TPC

New Inner Tracking System ITS2 and Muon Forward Tracker MFT
Runs 3 and 4: Implementation (3)

Runs 3 and 4: Physics goals

- Heavy-flavour mesons and baryons (down to very low $p_T$)
- Charmonium states
- Dileptons from QGP radiation and low-mass vector mesons
- High-precision measurement of light and hyper nuclei

Implementation

1. Untriggered data sample
   - Record all Pb-Pb interactions at 50 kHz through continuous readout
   - Collect a factor 50 – 100 more min bias data wrt Run 2

2. Improve tracking efficiency and momentum resolution at low-$p_T$
   - Increase tracking granularity
   - Reduce material thickness
   - Minimise the distance to IP

3. Preserve particle identification (PID)

No dedicated trigger possible!
→ Need minimum-bias readout at highest possible rate

→ Continuous readout TPC

→ New Inner Tracking System ITS2 and Muon Forward Tracker MFT

→ Consolidate and speed-up main ALICE PID detectors
Runs 3 and 4: Physics goals

- Heavy-flavour mesons and baryons (down to very low $p_T$)
- Charmonium states
- Dileptons from QGP radiation and low-mass vector mesons
- High-precision measurement of light and hyper nuclei

No dedicated trigger possible!

- Need minimum-bias readout at highest possible rate

Implementation

1. Untriggered data sample
   - Record all Pb-Pb interactions at 50 kHz through continuous readout
   - Collect a factor 50 – 100 more min bias data wrt Run 2
   - Continuous readout TPC

2. Improve tracking efficiency and momentum resolution at low-$p_T$
   - Increase tracking granularity
   - Reduce material thickness
   - Minimise the distance to IP
   - New Inner Tracking System ITS2 and Muon Forward Tracker MFT

3. Preserve particle identification (PID)

4. Synchronous data processing (reconstruction, calibration)
   - Consolidate and speed-up main ALICE PID detectors
   - New Online/Offline (O²) farm
Detector upgrades for Run 3

**Inner Tracking System 2 (ITS2)**
- CMOS pixel, Monolithic Active Pixel Sensor (MAPS) technology
- Improved resolution, less material, faster readout

**New Muon Forward Tracker (MFT)**
- CMOS pixel, MAPS technology
- Vertex tracker at forward rapidity

**New TPC Readout Chambers (ROCs)**
- Gas Electron Multiplier (GEM) technology
- New electronics (SAMPA), continuous readout

**New Fast Interaction Trigger (FIT) Detector**
- Centrality, event plane, luminosity, interaction time

**Integrated Online-Offline system (O²)**
- Calibrate and reconstruct minimum-bias Pb-Pb data at 50 kHz

**Readout upgrade for all other detectors**
- TOF, TRD, MUON, ZDC, calorimeters
Inner Tracking System (ITS2)
ITS2 in CERN Courier

- Largest pixel detector so far
- Article in July/August 2021 issue
ITS2 layout and specifications

- 10 m² active silicon area, 12.5×10⁹ pixels
  - 7 layers (3 inner, 4 outer)
  - 192 staves (48 inner, 144 outer)

<table>
<thead>
<tr>
<th></th>
<th>ITS1</th>
<th>ITS2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance to IP (mm)</td>
<td>39</td>
<td>22</td>
</tr>
<tr>
<td>$X_0$ (innermost layer) (%)</td>
<td>~ 1.14</td>
<td>~ 0.35</td>
</tr>
<tr>
<td>Pixel pitch (µm²)</td>
<td>50 x 425</td>
<td>27 x 29</td>
</tr>
<tr>
<td>Spatial resolution ($r_{\phi} \times z$) (µm²)</td>
<td>11 x 100</td>
<td>5 x 5</td>
</tr>
<tr>
<td>Readout rate (kHz)</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>

-> Improved resolution, less material, faster readout
ITS2 sensors

- Based on the ALPIDE chip (Monolithic Active Pixel Sensor, MAPS)
- In-pixel amplification, shaping, discrimination and multi-event buffers (MEB)
- In-matrix data sparsification
- High detection efficiency: > 99%
- Low fake-hit rate: << $10^{-6}$/pixel/event
- Radiation tolerant: > 270 krad total ionising dose (TID), > $1.7 \times 10^{12}$ 1 MeV/n$_{eq}$ non-ionising energy loss (NIEL)
ITS2 timeline

~72000 chips ~280 staves
>10 production sites worldwide
~ 30 institutes involved

Start detector construction and assembly
Dec 2016

Start on-surface commissioning with final services
May 2019

ITS outer barrel installation
Mar 2021

ITS inner barrel installation
May 2021

ITS IB Bottom

~72000 chips ~280 staves
>10 production sites worldwide
~ 30 institutes involved
Muon Forward Tracker (MFT)
Muon Forward Tracker (1)

High pointing accuracy
• Matching muon tracks with MFT tracks
• Charm/beauty separation via secondary vertex reconstruction
Muon Forward Tracker (2)

High pointing accuracy
- Matching muon tracks with MFT tracks
- Charm/beauty separation via secondary vertex reconstruction

- A new high-resolution Si tracker (2.5 < $\eta$ < 3.6) based on ALPIDE chips
  - 5 disks, 0.4 m²
- Detector installed in Dec 2020
- **Excellent noise performance:** < $10^{-8}$ fake hits / pixel / event
Time Projection Chamber (TPC)
**TPC readout chambers**

**TPC upgrade specifications**
- Continuous readout
- Nominal gain = 2000 in Ne-CO$_2$-N$_2$ (90-10-5)
- Ion back-flow (IBF) < 1%
- Preserve dE/dx performance
- Stable operation under LHC Run 3 conditions

- Adopted solution: 4–GEM stack, combination of standard (140 μm) and large hole pitch (280 μm) GEM foils, optimized HV configuration
- Unprecedented challenges: e.g. distortions from remaining space charge

Max. drift time: ~100 μs

Previous detector (Run 1, Run 2):
- 72 MWPCs
- Wire gating grid (GG) to minimize Ion Back-Flow (IBF)
- Rate limitation: few kHz

The upgrade of the ALICE TPC with GEMs and continuous readout (link)
TPC readout electronics

Newly developed FE ASIC **SAMPA** (130 nm TSMC CMOS)
- 32 channels with preamplifier, shaper and 10 bit ADC
- Readout mode: continuous or triggered
- Also used in the ALICE Muon spectrometer

Front-End Cards (FECs)
- 5 SAMPA chips per FEC (3276 FECs in total)
- Continuous sampling at 5 MHz
- All ADC values read out at 3.3 TB/s
- Readout link: CERN GBT / Versatile link system
- FPGA-based readout card receives the data: Common Readout Unit (CRU)

Excellent noise figure: 670 e⁻ @18 pF on detector
TPC upgrade timeline

- **Start GEM ROC installation**: May 2019
- **Start pre-commissioning**: Sep 2019
- **Transportation to LHC P2**: Aug 2020
- **Connection and commissioning**: Dec 2020

**Timeline Dates:**
- **Aug 2016**: Start GEM production
- **March 2017**: Start GEM ROC production
- **May 2019**: Start installation FEE and services
- **Aug 2020**: Start pre-commissioning
- **Dec 2020**: Connection and commissioning
TPC cosmic muon tracks

From TPC installed in cavern
Fast Interaction Trigger (FIT)
# Fast Interaction Trigger

<table>
<thead>
<tr>
<th>Detector</th>
<th>Purpose</th>
<th>Distance from collision point</th>
<th>Technology</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDD-A</td>
<td>Measurements of diffractive cross sections and studies of ultra-peripheral collisions</td>
<td>17 m</td>
<td>BC420 scintillator pads, wavelength shifters, fibers, Hamamatsu H8409-70 PMTs</td>
<td>To be installed mid July</td>
</tr>
<tr>
<td>FDD-C</td>
<td>-19.5 m</td>
<td></td>
<td></td>
<td>Installed</td>
</tr>
<tr>
<td>FV0</td>
<td>Min bias and multiplicity triggers, centrality and event plane measurement</td>
<td>3.2 m</td>
<td>EJ-204 scintillators, fibers, Hamamatsu R5924-70 PMTs</td>
<td>To be installed end of June</td>
</tr>
<tr>
<td>FT0-A</td>
<td>3.3 m</td>
<td>Quartz Cherenkov radiators, Photonis XP85002/FIT-Q MCP photomultipliers</td>
<td></td>
<td>To be installed end of June</td>
</tr>
<tr>
<td>FT0-C</td>
<td>-0.8 m</td>
<td></td>
<td></td>
<td>Installed</td>
</tr>
</tbody>
</table>

- **FDD-C in the LHC tunnel**
- **FV0**
- **Half of FT0-A**
- **Half of FT0-C**
Online & Offline (O\(^2\)) processing
O\textsuperscript{2} processing

- 50 kHz Pb-Pb collisions $\Rightarrow$ ~ 3.5 TB/s continuous raw data flow
- Continuous data flow is chopped into (sub-)time frames on the FLPs
- Data volume reduction in two steps
ITS3 for Run 4
(from 2027)
ITS3 material budget

Material budget ITS2 inner-most layer

Material budget Si only

- Only about 15% of the total material is silicon!
- Irregularities due to support and services

Removal of water cooling ➔ power consumption below 20 mW/cm² (➔ 65 nm technology)
Removal of circuit board ➔ Integrate power and data buses on chip
Removal of mechanical support: Benefit from increased stiffness of bent Si wafers
New inner layers (3 out of 7) for the ITS

Key ingredients:
- 300 mm wafer-scale chips, 65 nm CMOS process
- thinned down to 20-40 μm, making them flexible
- bent to the target radii
- mechanically held in place by carbon foam ribs

The whole detector will comprise six chips (current ITS2 inner barrel: 432) – and barely anything else!
• Data based on analysis of test beam data using bent, 50 μm thick ALPIDEs from ITS2
• No deviation from flat performance observed
• Important milestone for ITS3

Bent chips just continue to work!

See also [link](#)
Proof of concept (2)

- Three layers with bent ALPIDEs
- Mimics ITS3 (same radii)
FoCal for Run 4
(from 2027)
FoCal (from 2027)

- A new high granularity Forward Calorimeter
  - High-precision inclusive measurement of direct photons and jets
  - Coincident $\gamma$-jet and jet-jet measurements
- 7 m from interaction point, $3.4 \leq \eta \leq 5.8$
- FoCal-E: Si-W electromagnetic calorimeter (w/ pads and 2 high-granularity pixel layers)
- FoCal-H: A conventional sampling calorimeter (Cu + scintillating fibres)

Simulated longitudinal shower profile for 2 photons

LOI: CERN-LHCC-2020-009
ALICE 3 for Run 5 and Run 6
(from 2032)
• A next-generation HI experiment
• **Ultra-lightweight silicon tracker:** ~12 tracking barrel layers + disks based on CMOS sensors
• New physics opportunities due to improved detector performance + increased luminosity
• Kinematic range down to very low $p_T$: 50 MeV/c (central barrel), 10 MeV/c forward (dedicated detector)
• Different options for PID under study
• LOI under preparation

Expression of interest: [link]
Summary

- Major ALICE upgrade for Run 3 in its final steps: ITS2, MFT, TPC, FIT, O² and readout electronics
- Last detector installation to be completed in July
- ALICE global commissioning from July
- New upgrade proposals for Run 4: ITS3, FoCal
- Preparation for a new generation, heavy-ion experiment for Run 5 ongoing

Thank you for your attention!
Thank you for your attention!

Summary

- Major ALICE upgrade for Run 3 in its final steps: ITS2, MFT, TPC, FIT, $O^2$ and readout electronics
- Last detector installation to be completed in July
- ALICE global commissioning from July
- New upgrade proposals for Run 4: ITS3, FoCal
- Preparation for a new generation, heavy-ion experiment for Run 5 ongoing

See also (at this conference):
- Ivan Ravasenga: New ITS commissioning and impact on vertexing in Run 3. Thursday
- Ernst Hellbär: Reconstruction and TPC calibration in Run 3. Monday
- Giacomo Contin: Novel detector concepts for ALICE for Run 4 and beyond. Wednesday
- Stefania Bufalino: PID and tracking with timing detectors in ALICE and LHCb in Run 5. Tuesday
- Antonio Uras: Physics prospects for ALICE in Run 5 and beyond. Monday
Detector performance in Runs 3 and 4

**Tracking efficiency vs $p_T$**

- **ITS1** (old)
- **ITS2** (new)

**Momentum resolution vs $p_T$**

- **MWPC** (old)
- **ITS1** (old)
- **ITS2** (new)

**GEM** (new)

**ITS2**
- Improved tracking efficiency
- Improved tracking resolution
- Pointing accuracy 3 times better in transverse plane (6 times along beam axis)

**GEM TPC**
- Preserve momentum resolution for TPC+ITS tracks
- Preserve particle identification ($dE/dx$)
Performance gain with ITS3

- Pointing resolution 2x better
- Improved tracking efficiency for low momenta
- Improved physics performance for heavy-flavour baryons and low-mass dielectrons