The Upgrade of the ALICE Experiment at LHC

Vito Manzari (INFN Bari), for the ALICE Collaboration
(vito.manzari@cern.ch)
Outline

- ALICE at present
- Present and Future Experimental programme
- The Upgrade of ALICE
  - Physics motivation
  - Detector strategy
- Inner Tracking System (ITS) upgrade
- Time Projection Chamber (TPC) upgrade
- Online Systems upgrade
- Conclusions
ALICE and the "Little Bang"

- Compress a large amount of energy in a very small volume
  - Produce a “fireball” of hot matter
  - Temperature \(O(10^{12} \, ^\circ K)\)
    - \( \sim 10^5 \times T \) at centre of Sun
    - \( \sim T \) of Universe 10 \( \mu \)s after Big Bang

- Study nuclear matter under extreme conditions of temperature and density
  - Produce a state of the matter where quarks and gluons are deconfined (Quark Gluon Plasma) and study its properties

- Lattice QCD calculations predict a phase transition
  - \( T_c \approx 170 \, \text{MeV} \Leftrightarrow \varepsilon_c \approx 0.6 \, \text{GeV/fm}^3 \)
ALICE, only dedicated HI experiment at LHC

What do we measure?

- **global observables:** multiplicities, rapidity distributions
- **geometry of the emitting source:** HBT, impact parameter via zero-degree energy flow
- **early state collective effects:** elliptic flow
- **chiral symmetry restoration:** neutral to charged ratios, resonance decays
- **fluctuation phenomena - critical behavior:** event-by-event particle composition and spectra
- **degrees of freedom as a function of T:** hadron ratios and spectra, dilepton continuum, direct photons
- **deconfinement:** charmonium and bottomonium spectroscopy
- **energy loss of partons in QGP:** jet quenching, high $p_t$ spectra, open charm and open beauty

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Experimental Challenges & ALICE Solutions

- Extreme particle densities \((\text{Pb+Pb } \frac{dN_{\text{ch}}}{d\eta} \sim 2000)\)
  - 1000 times pp at LHC, 2-4 times Au+Au at RHIC
  - ALICE solution for particle densities: high granularity 3D tracking, long path-length from interaction vertex (e.g. EMCal at 4.5m)

- Large dynamic range in \(p_T\)
  - from very soft (0.1 GeV) to fairly hard (>100 GeV)
  - ALICE solution to extend \(p_T\) range: thin detectors, modest fields (low \(p_T\)), large lever arm for tracking & resolution at large \(p_T\)
    - ALICE: < 10% \(X_0\) inside \(r < 2.5\text{m}\), \(B=0.5\text{T}\), \(BL^2 \sim \text{CMS}\)

- Measure & ID many hadrons
  - requires: secondary vertices, leptons ID, hadron ID
  - ALICE solution for extended particle ID: employ many technologies \(dE/dx\), Cherenkov & transition rad, TOF, calorimeters, muon filter, topological, ...

- Modest luminosity and interactions rates
  - 8 kHz \((\text{Pb+Pb})\)
  - ALICE rates allow slow detectors (TPC, SDD) and moderate radiation hardness
The ALICE Detector

Central Barrel tracking & PID $|\eta| < 1$

Muon Spectrometer
$-4 < \eta < -2.5$

ACORDE (cosmics)
V0 scint. (centrality)
$\eta$: -1.7–-3.7, 2.8–5.1
T0 (timing)
ZDC (centrality)
FMD ($N_{ch} < 3.4 < \eta < 5$)
PMD ($N_{\gamma}, N_{ch}$)

Detector:
Length: 26 meters
Height: 16 meters
Weight: 10,000 tons

Collaboration:
> 1200 Members
> 132 Institutes
> 36 countries
Events in ALICE

<table>
<thead>
<tr>
<th>year</th>
<th>system</th>
<th>energy $\sqrt{s_{NN}}$ TeV</th>
<th>integrated luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Pb – Pb</td>
<td>2.76</td>
<td>~ 10 mb$^{-1}$</td>
</tr>
<tr>
<td>2011</td>
<td>Pb – Pb</td>
<td>2.76</td>
<td>~ 200 mb$^{-1}$</td>
</tr>
<tr>
<td>2013</td>
<td>p – Pb</td>
<td>5.02</td>
<td>~ 30 nb$^{-1}$</td>
</tr>
</tbody>
</table>
ALICE Physics Programme
Approved and Upgrade

ALICE heavy-ion approved programme for $L_{\text{int}} \sim 1 \text{ nb}^{-1}$ (triggered):

✓ 2011 Pb–Pb at $\sqrt{s}_{NN} = 2.76 \text{ TeV}$ (~0.1 nb$^{-1}$, 10% of programme)
✓ 2013–14 Long Shutdown 1 (LS1)
    ✶ Detector Consolidation
✓ 2015 Pb–Pb at $\sqrt{s}_{NN} = 5.1 \text{ TeV}$
✓ 2016–17 (maybe combined in one year) Pb–Pb at $\sqrt{s}_{NN} = 5.5 \text{ TeV}$
✓ 2018 Long Shutdown 2 (LS2)
✓ 2019 probably Ar–Ar high-luminosity run
✓ 2020 p–Pb comparison run at 8.8 TeV
✓ 2021 Pb–Pb run at 5.5 TeV to reach 1 nb$^{-1}$
✓ 2022 Long Shutdown 3 (LS3)

ALICE proposed upgrade programme for $L_{\text{int}} \sim 10 \text{ nb}^{-1}$ (min. bias):

✓ 2018 Long Shutdown 2 (LS2): DETECTOR & LHC-Pb-lumi UPGRADE
✓ 2019-2021: Ar–Ar, p–Pb, Pb–Pb as above but at higher lumi
✓ 2022 Long Shutdown 3 (LS3)
✓ 2023-~2025: Pb–Pb at 5.5 TeV till 10 nb$^{-1}$ + pp reference at 5.5 TeV
ALICE Upgrade

- After almost three years of operation with LHC beams, ALICE has demonstrated its excellent capabilities to measure high energy collisions at the LHC

  - More than 30 articles published or submitted since January 2012
  - See E. Vercellin’s talk at this Conference for “Recent Results from ALICE”

- Physics objective

  - Focus on observables for which ALICE is unique: low-\(p_T\) heavy flavour, charmonia, and di-leptons (all have very high background conditions)
  - A phase transition of the high-energy heavy-ion physics from the exploring phase to the high-precision measurement phase
Precision measurement of the QGP parameters to fully exploit scientific potential of the LHC
- Large cross sections for hard probes
- High initial temperature

Main physics topics, uniquely accessible with the ALICE detector:
- Measurement of heavy-flavour transport parameters
  - Study of QGP properties via transport coefficient
- Measurement of low-mass and low-$p_T$ di-leptons
  - Study of chiral symmetry restoration
  - Space-time evolution and Equation of State of QGP
- $J/\Psi$, $\Psi'$, and $\chi_c$ states down to zero $p_T$ in a wide rapidity range
  - Statistical hadronization versus dissociation/recombination
- Jet quenching and fragmentation
- Heavy nuclear states
ALICE Upgrade
Build on Demonstrated Strengths ... and More

- Particle identification (practically all known techniques)
- Extremely low-mass tracker ~ 10% of $X_0$
- Very good vertexing capability
- Efficient low-momentum tracking – down to ~100 MeV/c
ALICE Upgrade Strategy

- High precision measurements of rare probes at low $p_T$, which cannot be selected with a trigger due to the low S/B, require:
  - a large sample of events recorded on tape
    - Pb-Pb recorded luminosity $\geq 10 \text{ nb}^{-1}$ ⇒ $8 \times 10^{10}$ events
    - pp (reference data) recorded luminosity $\geq 6 \text{ pb}^{-1}$ ⇒ $1.4 \times 10^{11}$ events
  - significant improvement of vertexing and tracking capabilities

- How this can be achieved?
  - Upgrade the present readout and online systems to
    - Read out all Pb-Pb interactions at a maximum rate of 50kHz (i.e. $L = 6 \times 10^{27} \text{ cm}^{-1}\text{s}^{-1}$), with a Minimum Bias (MB) trigger
    - Perform online data reduction based on reconstruction of clusters and tracks (tracking used only to filter out clusters not associated to reconstructed tracks)
  - Improve vertexing and tracking at low $p_T$ ⇒ ITS and TPC upgrade
ALICE Upgrade Strategy (cont’d)

- The ALICE upgrade plans entails building
  - New beam pipe with smaller diameter
  - New high-resolution and low-material ITS
  - Upgrade of TPC with replacement of MWPCs with GEMs and new pipelined readout electronics
  - Upgrade of readout electronics of TRD, TOF, PHOS and Muon Spectrometer
  - Upgrade of the forward trigger detectors and ZDC
  - Upgrade of the online systems
  - Upgrade of the offline reconstruction and analysis framework and code

- Targets 2018 (LHC 2nd Long Shutdown)
Furthermore, three major proposals are under consideration to extend the scope of ALICE: MFT, VHMPID and FOCAL (a decision will be taken by the end of 2012)

- b-tagging for low $p_T$ $J/\Psi$ and low-mass di-muons at forward rapidities
  - complement muon arm with tracking in front of absorber: secondary vertex measurement, better background rejection, improved mass resolution
- New high momentum PID capabilities: $\pi$, $K$ and $p$ well beyond 10 GeV/c
- Low-x physics with identified $\gamma/\pi^0$ at large rapidity

**Further Detector Upgrades**

**MFT**
5 layers of high-granularity pixel detectors

**VHMPID**
Focusing RICH with CSI photocathodes combined with DCAL

**FOCAL**
High-granularity SiW Calorimeter of $\approx 2$ m$^2$ at a distance of 3.5 m coverage: $2.5 < \eta < 4.5$
ITS Upgrade
Design Goals

- Improve impact parameter resolution by a factor of ~3
  - Get closer to IP: 39mm → 22mm
    - Radius of innermost layer constrained by beam pipe radius: 29.8mm + 0.8mm → 19.8mm + 0.8mm
  - Reduce material budget: X/X₀ per layer ~1.14% → ~ 0.3%
    - Reduce mass of silicon, electrical bus (power and signals), cooling, mechanics
  - Reduce pixel size: 50μm x 425μm →
    - O(20μm x 20μm) monolithic pixels or O(30μm x 30μm) hybrid pixels

- High standalone tracking efficiency and pₜ resolution
  - Increase granularity: 6 layers → 7 layers, reduce pixel size
  - Increase radial extension: 39 - 430 mm → 22 - 430 (500) mm

- Fast readout
  - Readout of Pb-Pb interactions at > 50 kHz and pp at ~several MHz

- Fast access for yearly maintenance
  - Insertion/removal to replace non functioning detector modules during yearly shutdown
ITS Upgrade on the Web

http://aliceinfo.cern.ch/ITSUpgrade/
Hybrid pixels

- State-of-the-art in LHC experiments
- 2 components: CMOS chip and high-resistivity (~80 kΩcm) sensor connected via bump bonds
- Optimize readout chip and sensor separately with in-pixel signal processing
- Charge collection by drift
- R&D: Thinning (100μm sensor + 50μm FEE), edgeless detectors, low-cost bump bonding, low pc FEE chip in 130nm CMOS
- Cost, Yield

Monolithic pixels

- All-in-one, detector-connection-readout
- Very cheap: sensing layer (moderate resistivity ~1kΩcm epitaxial layer) included in the CMOS chip
- Charge collection mostly by diffusion (MAPS), but some developments based on charge collection by drift
- R&D: MIMOSA like & INMAPS (180nm CMOS Tower-Jazz), LePix (90nm CMOS IBM)
- Radiation hardness, PID capability, Fast readout
Two detector options are being studied

A. 7 layers of pixel detectors
   - better standalone tracking efficiency and $p_T$ resolution
   - worse PID

B. 3 inner layers of pixel detectors and 4 outer layers of strip detectors
   - worse standalone tracking efficiency and momentum resolution
   - better PID
Simulation study of the two layout options

Radial positions for both options: 2.2, 2.8, 3.6, 20, 22, 41, 43 cm

A. 7 pixel layers

- Resolutions: $\sigma_{r\phi} = 4 \, \mu m$, $\sigma_z = 4 \, \mu m$ for all layers
- Material budget: $X/X_0 = 0.3\%$ for all layers

B. 3 pixel layers + 4 strip layers

- Resolutions: $\sigma_{r\phi} = 4 \, \mu m$, $\sigma_z = 4 \, \mu m$ for pixels $\sigma_{r\phi} = 20 \, \mu m$, $\sigma_z = 830 \, \mu m$ for strips
- Material budget: $X/X_0 = 0.3\%$ for pixels $X/X_0 = 0.83\%$ for strips
Simulation study of the two layout options

- Radial positions for both options: 2.2, 2.8, 3.6, 20, 22, 41, 43 cm
- Central events at $\sqrt{s_{NN}} = 5.5$ TeV

A. 7 pixel layers
- Resolutions: $\sigma_{r\phi} = 4$ $\mu$m, $\sigma_z = 4$ $\mu$m for all layers
- Material budget: $X/X_0 = 0.3\%$ for all layers

B. 3 pixel layers + 4 strip layers
- Resolutions: $\sigma_{r\phi} = 4$ $\mu$m, $\sigma_z = 4$ $\mu$m for pixels $\sigma_{r\phi} = 20$ $\mu$m, $\sigma_z = 830$ $\mu$m for strips
- Material budget: $X/X_0 = 0.3\%$ for pixels $X/X_0 = 0.83\%$ for strips
**ITS Upgrade Mechanical Integration**

- Inner barrel: 3 layers of pixels
- Outer barrel: 4-layer structure
  - 4 pixel/strip layers mounted on 2 barrels
  - 3 beams made of carbon composite or beryllium are fixed between the two structures to provide rigidity and support/guide the inner part insertion
Carbon fabric
T300
M55J 6k
M60J 3k

Fiber T300, Young modulus = 230 GPa
Fiber M55J 6k, Young modulus = 540 GPa
Fiber M60J 3k, Young modulus = 588 GPa

~1.3 gram
~1.0 gram
~0.6 gram
~0.2 gram
~0.1 gram

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TPC upgrade
Replace MWPCs with GEMs
Why do we need to upgrade the TPC readout MWPC?

- **Space charge (no ion feedback from triggering interaction)**
  - Effective dead time $\sim 280\mu s \rightarrow$ max readout rate $\sim 3.5$ kHz
  - Maximum distortions for 50kHz interaction rate and $L1=3.5$kHz: $\Delta r \sim 1.2$mm

- **Space charge for continuous readout (GG always open)**
  - Max distortions for 50kHz interaction rate: $\Delta r \sim 100$cm

- **In addition space charge in the amplification region**
  - Particle rate 40-100 kHz / cm$^2$
  - Sizeable gain drop $\rightarrow$ deterioration of $dE/dx$

New readout planes and front-end electronics for continuous readout

- Replace MWPC with GEMs
  - Continuous readout (no gating)

- Faster gas $\sim 2$-3
  - Could be achieved by replacing Ne-CO$_2$ with CF4

**MWPC not compatible with 50 KHz operation**
Position resolution somewhat deteriorated, but momentum resolution recovered with inner (and outer) trackers.
Main requirements:

- Event readout, processing and (local) storage: 50 kHz (top inst. lumin.)
- Average rate during a fill: 20 kHz
- The system should be scalable by a factor 2: 100 kHz

Assumptions:

- 1 month of Pb-Pb running with 40% duty factor: $10^6$ s
- Minimum-bias events recorded in 1 Pb-Pb run: $2 \times 10^{10}$

Event size and data throughput

<table>
<thead>
<tr>
<th>Detector</th>
<th>Event Size (MByte)</th>
<th>Input to online systems (GByte/s)</th>
<th>Peak output to local data storage (GByte/s)</th>
<th>Average output to computing center (GByte/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>After zero suppression</td>
<td>After data compression</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPC</td>
<td>20.0</td>
<td>1.0</td>
<td>1000</td>
<td>50.0</td>
</tr>
<tr>
<td>TRD</td>
<td>0.3</td>
<td>0.1</td>
<td>6</td>
<td>2.0</td>
</tr>
<tr>
<td>ITS</td>
<td>0.8</td>
<td>0.2</td>
<td>40</td>
<td>10.0</td>
</tr>
<tr>
<td>Others</td>
<td>0.5</td>
<td>0.25</td>
<td>25</td>
<td>12.5</td>
</tr>
<tr>
<td>Total</td>
<td>1.55</td>
<td></td>
<td>74.5</td>
<td></td>
</tr>
</tbody>
</table>

Note: - Peak rate has to be sustained in the whole Online System up to local storage
- Average rate has to be sustained all the way to the CERN computing center
Online Systems Upgrade
DAQ and HLT System Upgrade

\[ \sim 2500 \text{ DDL3s} \]
\[ 10 \text{ Gbit/s} \]

- ITS
- TPC
- TRD
- EMCal
- PHOS
- TOF
- Muon
- FTP

\[ \sim 250 \text{ FLPs} \]
\[ \sim 1250 \text{ EPNs} \]

\[ 2 \times 10 \text{ or 40 Gbit/s} \]
\[ 10 \text{ or 40 Gbit/s} \]

- RORC3
- FLP

- EPN

- Storage Network

- Data Storage

- Data Storage

L0
L1

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Combination of continuous and triggered readout

- L0: Minimum Bias trigger for every interaction
- L1: selective trigger (e.g. jet, muons)
- LHC clock and L0 trigger distributed for data tagging and test purpose

Detector triggering and electronics

- Continuous readout for TPC and ITS when average inter-events arrival time < TPC drift time
  - At 50 kHz, ~5 events in TPC during the TPC drift time of 92 µs
- TRD - MB L0 trigger. Max: 27 kHz (ADC data), 100-150 kHz (tracklet parameters).
- TOF - MB L0 trigger. max: 200 - 400 kHz
- EMCal - MB L0 trigger max: 25-50 kHz (after LS1 upgrade), or L1 rare trigger
- PHOS - (if upgraded) MB L0 trigger max: 50kHz
- Muon – L1 rare trigger (max R/O rate 5kHz)

Detector readout

- Interface and cluster finder in the same FPGA shared by DAQ and HLT

Event building and processing

- First Level Processors (FLP): clusters of sub-events for triggered detectors and time-windows for continuous readout detectors
- Event-building and Processing Nodes (EPN): tracking of time windows, association of clusters to events only possible after the tracking
The ALICE Upgrade is planned to be in operation after LHC Long Shutdown 2 (LS2) and has a programme that will extend into the HL-LHC era after LS3:

- Current LHC schedule: LS2 in 2018 and LS3 from 2022

Two installation scenarios depending on the duration of LS2:

- Scenario 1: Complete upgrade in an LS2 of at least 18 months
- Scenario 2: TPC removed during the “End of Year Technical Stop“ 2016/17, no operation 2017 and upgrade installation in an LS2 of at least 14 months.

To achieve the 1 nb⁻¹ integrated heavy-ion luminosity before LS2, an extended heavy-ion run in 2016 is mandatory.
Conclusions

- After almost three years of operation with pp and Pb-Pb collisions, ALICE has demonstrated its excellent capabilities to measure high energy collisions at the LHC
  - Tracking in very high multiplicity environment from very low to very high $p_T$
  - Particle identification over a wide momentum range

- ALICE general upgrade strategy described in the LoI recently submitted to LHCC
  - Minimum bias readout of all central detector at 50 kHz
  - Factor $\sim$3 improvement in secondary vertex resolution
  - Very high standalone tracking efficiency down to low $p_T$

- It entails
  - New beam pipe with smaller radius
  - New high-resolution and low-material ITS
  - TPC upgrade (replace MWPCs with GEMs + new readout electronics)
  - Upgrade of readout electronics of TRD, TOF, PHOS and Muon Spectrometer
  - Upgrade of the Online Systems
  - Upgrade of the offline reconstruction and analysis framework and code
Thank you for your attention!