The ALICE experiment upgrades for LHC Run 3 and beyond: contributions from mexican groups

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Abstract. The ALICE experiment at the LHC was designed and built to study the Quark-Gluon Plasma, a state of matter where quarks and gluons are not confined to hadrons and that can be recreated using high-energy heavy-ion collisions. The plans for ALICE after 2020 include the collection of more than 10 nb$^{-1}$ of heavy-ion collisions at luminosities up to 6x10$^{27}$ cm$^{-2}$ s$^{-1}$, corresponding to collision rates of 500 kHz. Such scenario imposes stringent constraints to the detector performances, forcing a major upgrade of the experiment. In this proceeding the main characteristics of the detector upgrades are presented, in particular the contributions from mexican groups are highlighted.

1. Introduction
Quantum Chromodynamics (QCD) is the correct gauge theory to describe the interactions among partons, but it is not enough, as it is also necessary to study the phases of the quark matter. Since equilibrium and phase transitions involve quarks and gluons interacting over a large distance scales, perturbative QCD cannot be applied. The solution to this problem is provided by lattice QCD, a non perturbative treatment of QCD formulated on a discrete lattice of space-time coordinates, where the extraction of the corresponding thermodynamic variables is possible.

Lattice QCD predicts that, at very high temperature and energy densities, ordinary nuclear matter undergoes a phase transition where quarks and gluons are no longer confined into hadrons. This new state of matter is called Quark-Gluon Plasma (QGP) and existed during the early Universe, a few microseconds after its formation. It is also believed to exist in the core of compact stars.

Theoretical calculations indicate that the transition between hadronic matter and the QGP at zero baryo-chemical potential ($\mu_B$) and high temperature is not a sharp phase transition, but rather a smooth cross-over. Nowadays it has been established that the critical temperature where this transition occurs is $T_c \approx 150$ MeV [1]. By increasing $\mu_B$ lattice QCD predicts the existence of a Critical End-Point, where the phase transition is expected to become of first order. This picture of strongly-interacting matter is called QCD phase diagram.

In the laboratory the only way to recreate the QGP is through high-energy heavy-ion collisions. Different regions of the QCD phase diagram can be accessed by changing the center of mass energy of the collision. Indeed, as the energy increases, the initial temperature of the system increases and its baryo-chemical potential decreases.

The LHC provides the optimal experimental conditions to study the QGP because [2]:

[1] Name of reference.
[2] Name of reference.
• The net baryon density in the central (mid-rapidity) region is very small, corresponding to the conditions of the early Universe.
• The initial temperature and energy density are the highest achievable in the laboratory.
• The large collision energy ensures an abundance of perturbatively calculable hard QCD processes.

The study of the strongly-interacting matter in the second generation of the LHC heavy-ion studies following the Long Shutdown 2 (2020-2021) will focus on rare probes and the study of their coupling with the medium and hadronization processes. Major highlights of the proposed program focus on the following physics questions [3]:

• Heavy flavour. Precise characterization of the quark mass dependence of in-medium parton energy loss; study of the transport and possible thermalization of heavy quarks in the medium; study of heavy quark hadronization mechanisms in a partonic environment. These studies require measurements of the production and azimuthal anisotropy of several charm and beauty hadron species, over a broad momentum range, as well as of \( b \)-tagged jets. ALICE will mainly focus on the low-momentum region, down to zero \( p_T \) and on a reconstruction of several heavy-flavour hadron species (including baryons). ATLAS and CMS will focus on \( b \)-tagged jets and D and B mesons at higher \( p_T \). LHCb has a strong potential for all these measurements, although the detector performance in central Pb-Pb collisions is still not clear.

• Quarkonia. Study of quarkonium dissociation and possible regeneration as probes of deconfinement and of the medium temperature. ALICE will carry out precise measurements, starting from zero \( p_T \), of \( J/\psi \) yields and azimuthal anisotropy, \( \psi(2S) \) and \( \Upsilon \) yields, at both central and forward rapidity. ATLAS and CMS will carry out precise multi-differential measurements of the \( \Upsilon \) states to map the dependencies of their suppression pattern. They will also complement the charmonium measurements to high momentum. Also in this case LHCb has a strong potential but the detector performance in central Pb-Pb collisions is still not clear.

• Jets. Detailed characterization of the in-medium parton energy loss mechanism, that provides both a testing ground for the multi-particle aspects of QCD and a probe of the QGP density. The relevant observables are: jet structure and di-jet imbalance at TeV energies, \( b \)-tagged jets and jet correlations with photons and \( Z^0 \) bosons. These studies are crucial to address the flavour dependence of the parton energy loss and will be the main focus of ATLAS and CMS, which have unique high-\( p_T \) and triggering capabilities. ALICE will complement in the low-momentum region, and carry out measurements of the flavour dependence of medium-modified fragmentation functions using light flavour, strange and charm hadrons reconstructed within jets.

• Low-mass dileptons and thermal photons. These observables are sensitive to the initial temperature and the equation of state of the medium, as well as to the chiral nature of the phase transition. The study will be carried out by ALICE, which will strengthen its unique electron and muon reconstruction capabilities down to almost zero \( p_T \).

2. The ALICE experiment upgrade strategy
ALICE is the only experiment at the LHC that was designed and built to study the QGP created in high-energy heavy-ion collisions. However the physics program also includes in-depth research on proton-proton and proton-ion collisions. The ALICE experiment and its detectors during LHC Run 2 (2015-2018) are shown in figure 1.

The plans for the ALICE experiment before Long Shutdown (LS) 2 include collecting 1 \( \text{nb}^{-1} \) of Pb-Pb collisions at a peak luminosity of \( L = 10^{27} \text{cm}^{-2} \text{s}^{-1} \), corresponding to a collision rate
of 8 kHz [4]. During LHC Run 1 (2009-2013), the maximum readout rate was limited to 500 Hz of Pb-Pb events.

The ALICE upgrade strategy beyond LS2 is based on collecting more than 10 nb$^{-1}$ of Pb-Pb collisions at luminosities up to 6x10$^{27}$ cm$^{-2}$ s$^{-1}$, corresponding to collision rates of 50 kHz. In this scenario each collision is shipped to the online systems, either upon a minimum bias trigger or in a self-triggered or continuous fashion. This will result in the collection and inspection of a data volume of heavy-ion events roughly 100 times greater than that of Run 1, implying an upgrade strategy also for the online and offline computing system.

The plan also considers the collection of 6 pb$^{-1}$ of pPb collisions, both at a leveled collision rate of 200 kHz.

The operation of the Time Projection Chamber (TPC) is one of the limiting factors to achieve the desired readout rate. Actually, the TPC is based on a gated readout with Multi Wire Proportional Chambers (MWPC) [5]. The electron drift time of 100 μs from the central electrode to the readout chambers, together with the ion drift time of 180 μs from the sense wires to the gating grid, limits the readout rate to less than 3.5 kHz.

Operating the TPC in ungated mode, this is, leaving the gating grid continuously open, would result in a severe build up of space charge in the drift volume due to back drifting ions. At a minimum bias event rate of 50 kHz this would lead to a sustained ion accumulation from several thousand collision events piling up in the drift volume. Under such conditions, the space charge would distort the electron drift paths in such a way that a meaningful reconstruction of the particle trajectories would no longer be possible. In addition, the anticipated particle rates at the wire chambers would reach 100 kHz/cm$^2$, for which space charge effects in the amplification region result in a few percent gain drop, thus deteriorating the dE/dx performance of the detector.

In view of the challenging scenario for LHC Run 3 (2021-2023) and beyond, the ALICE Collaboration has scheduled an important upgrade of the experiment during LS2.
3. Upgrades
The upgrades are driven by the following requirements:

- Increase the readout capabilities in order to record all the Pb-Pb interactions (each collision will be shipped to the online systems).
- Improve the track reconstruction performance, in particular for low-$p_T$ particles.
- Enhance particle identification (PID) capabilities.

Although not a detector itself, the beam pipe will also be replaced. Indeed, the reduction of the beam pipe diameter in the center of the experiment is one of the main ingredients in view of the improvement of the impact parameter resolution.

3.1. Inner Tracking System
The present Inner Tracking System (ITS) consists of six cylindrical layers of silicon detectors placed coaxially around the beam pipe [6]. The main tasks of the ITS are to determine the interaction vertex, to track and identify particles at low-$p_T$, to measure the distance of closest approach of charged particles to the interaction vertex and to the Particle IDentification (PID). The inner radius is the minimum allowed by the radius of the beam pipe and the outer one is determined by the necessity to match tracks with those from the TPC. The impossibility to access the present ITS detector for maintenance and repair interventions during the yearly shutdowns, together with the limited read-out rate of 1 kHz are key priorities in the design of the new ITS.

For the ITS upgrade, the first detection layer will be closer to the interaction point, as the reduction of the beampipe diameter in the center of ALICE is one of the main ingredients to improve the measurement of the impact parameter resolution [7]. The new detector will use Monolithic Active Pixel Sensors (MAPS) that will reduce the material budget and will allow the tracking performance and momentum resolution to be significantly improved. Also a new layer will be added, enhancing even more, the physics performance capabilities of the upgraded ITS. For example, simulations show that the pointing resolution provided by this detector in Pb-Pb will be improved, with respect to the current ITS, by a factor of 5 and 3 along the $z$ axis and in the $r\phi$ plane, respectively (left plot of Figure 2). Another important point is that the new ITS is designed to be able to read the data related to each individual interaction up to a rate of 100 kHz for Pb-Pb and 400 kHz for pp collisions, a factor two higher than the ALICE upgrade requirements.

3.2. Muon Forward Tracker
The Muon Spectrometer is composed of tracking and trigger chambers, a dipole magnet, a rear absorber, an iron wall, a beam shield and a front absorber [8]. The latter is made out of different materials and its goal is to absorb the large flux of particles resulting from the collision. The distance from the interaction point is constrained by the ITS dimension along the $z$ axis.

However, the current ALICE muon physics program suffers from various limitations, basically because of the multiple scattering induced on the muon tracks by the front absorber. In this way the details of the vertex region are completely smeared out, and as a consequence it is very difficult to reject muons coming from semi-muonic decays of pions and kaons, representing an important background (specially at low-$p_T$). Besides this, the degradation of the kinematics, imposed by the presence of the hadron absorber, plays a crucial role in determining the mass resolution for the resonances (in particular in the region of the $\phi$ and $\omega$ mesons). Finally the lack of details in the vertex region prevents to differentiate between prompt and displaced $J/\psi$ production, as well as to disentangle open charm and open beauty production without making assumption relying on physics model.
The Muon Forward Tracker (MFT) will be used to overcome these limitations. This new element in ALICE will be a silicon pixel detector (identical to that of the new ITS) that will be located upstream the front absorber and in the acceptance of the Muon Spectrometer [9]. The idea is to match the extrapolated muon tracks, coming from the tracking chambers after the absorber, with the clusters measured in the MFT before the absorber. In this way the muon tracks will gain enough pointing accuracy to allow a reliable measurement of their pointing resolution with respect to the interaction vertex.

The MFT consists of two half cones, each one in turn is made of five half-disks positioned along the beam axis. A half-disk includes a disk spacer, a disk support, two printed circuit boards and sensors. Current simulations of Pb-Pb collisions indicate that at low-$p_T$ the pointing resolution has an important dependence on the material budget (right plot of Figure 2).

3.3. Other detectors

The Muon Chamber System is presently limited to 1 kHz readout rate and will change the entire readout electronics using the SAMPA chip to digitize the detector signals. The Muon Trigger detector is also limited to the same readout rate, and as the upgrade strategy does not foresee a muon trigger, all events will be read upon the interaction trigger. Consequently the detector will be called Muon IDentifier (MID).

The Transition Radiation Detector (TRD) is presently limited to a few kHz readout rate. By reducing the data volume from the detector, using tracklets and increasing the data throughput of the off-detector electronics, a readout rate of 100 kHz for Pb-Pb and pp collisions can be achieved. However, since the front-end electronics does not support the use of multi event buffers, a 50 kHz trigger rate in Pb-Pb events corresponds to 75% of the collisions being read-out. Going beyond this threshold is not conceivable because a change of the on-detector electronics would be needed, which requires a removal and disassembly of the TRD modules.

The readout rate of the Time Of Flight detector is at present limited to 40 kHz by the throughput of the VME system located in the crates at the end of the detector modules. An upgrade of this element will increase, by a factor five, the readout rate capabilities.

The Zero Degree Calorimeter will change the readout electronics, it will also be able to
provide trigger information that can be used to clean the interaction trigger.

The PHOtton Spectrometer (PHOS) and ElectroMagnetic CALorimeter (EMCAL) use the same readout electronics and was already upgraded during Long Shutdown 1. These systems accomplish the desired performance.

3.4. Online-offline computing system

The computing upgrade concept consists on transferring all detector data to the computing system [10]. The data volume reduction will be performed by processing the data on the fly in parallel with the data collection and not by rejecting the complete events as the high-level triggers or event filter farms of most high-energy physics experiments do. The online-offline (O²) system will perform a partial calibration and reconstruction online and replace the original raw data with compressed data. The online detector calibration and data reconstruction will, therefore, be instrumental in keeping the total data throughput within an envelope compatible with the available computing resources. The main role of the O² system will be to perform detector calibration and data reconstruction concurrently with the data taking.

Figure 3 shows how the new detectors inside ALICE will look like after LS2 when looking to the direction of the front absorber of the Muon Spectrometer.

Figure 3. Schematic view of the of the new beam pipe, ITS, TPC, MFT and FIT detectors inside ALICE. IP stands for Interaction Point, IB for Inner Barrel and OB for Outer Barrel.
4. Contributions from Mexican groups

Mexican groups were involved in the design and/or construction of the following detectors: Alice COsmic Ray DEtector (ACORDE), Alice Diffraction (AD), TPC and V0A. So far there are no official plans for ACORDE and AD upgrades.

4.1. Time Projection Chamber

Limitations of the actual TPC have already been mentioned. The new TPC will use Gas Electron Multipliers (GEM) technology for the new readout chamber, since they feature intrinsic ion-blocking capabilities that avoid massive charge accumulation in the drift volume from the back-drifting ions, and prevent excessive space-charge distortions [11]. However GEMs do not feature the same opacity for ions as a gating grid. The requirement to keep the distortions at a tolerable level leads to an upper limit of 1% for the fractional ion backflow at a gas gain of 2000. The resulting space-charge distortions are less than 10 cm in most of the TPC drift volume and can be calibrated with sufficient precision. The replacement of the existing MWPC-based readout chambers by GEMs also implies the necessity for new readout electronics that accommodate the negative signal polarity and enable continuous data readout.

In this sense the contribution of a Mexican group in this project is the development of the new high voltage mechanism that will be used by the TPC.

4.2. Fast Interaction Trigger

Currently ALICE employs two forward detectors (T0 and V0) in order to provide minimum bias trigger, multiplicity measurements, beam-gas rejection, event plane determination and collision time for TOF. However for LHC Run 3 the upgrades of these detectors (T0+ and V0+) will be merged into a single system: the Fast Interaction Trigger (FIT) [12]. This new system will discriminate beam-beam interactions with 99% efficiency and will act as a Level 0 trigger, this is, it will provide a start signal for the rest of the ALICE detectors with a time resolution better than 30 ps.

Each T0+ module consists of a 2 cm thick quartz radiator coupled to a modified Planacon MCP-PMT, the size of the radiator matches that of the photocathode. In order to improve the detector performance at high particle multiplicities, the granularity of the sensors has been increased. The best performance of the T0+ has been reached by grouping the anodes and dividing the radiator into four sectors.

The V0+ will consist of a 4 cm thick ring made of plastic scintillation with an inner diameter of 8 cm and an outer one of 148 cm, it will be located at 330 cm from the interaction point on the opposite to the MFT. The plastic scintillator will be divided into five concentric rings and eight 45° sectors in the azimuthal angle direction. The light collection will be performed by 1 mm diameter optical fibers, assembled on a two-dimensional grid with 5 mm pitch. As compared to the actual V0 detector, V0+ will have 25% more readout channels, 3.2 times larger active area and an improved time resolution. Besides this, it is expected to diminish aging problems and after-pulses observed in the current V0.

The physics performance of both detectors has been simulated within the AliRoot package, that is the official software of the ALICE experiment. A sample of simulated Pb-Pb collisions at √sNN = 2.76 TeV was used to compute the event plane resolution (Figure 4 left) and the centrality resolution (Figure 4 right).

Mexican groups have an important role in the FIT group, as they are in charge of the design and construction of the V0+.
Figure 4. Left: Event plane resolution as a function of the centrality and for different detectors. Smaller values of the centrality indicate a more central collision. Right: Centrality resolution. Both plots are obtained from a Pb-Pb collisions event generator.

5. Summary
There are still many physics questions related to the QGP waiting for an answer, for this reason more data from high-energy heavy-ion collisions is needed. The ALICE experiment is looking forward to collect more than $10^{-1}$ nb of Pb-Pb collisions during LHC Run 3 and Run 4 at an interaction rate of 50 kHz, approximately 100 times the interaction rate during Run 1. In order to achieve this goal, the ALICE experiment is preparing a major upgrade of many detectors. Among these, mexican groups have an active contribution in this process, as they are deeply involved in the upgrades of the TPC and the V0+.

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