Heavy-ion physics with the ALICE experiment at the CERN Large Hadron Collider

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After close to 20 years of preparation, the dedicated heavy-ion experiment A Large Ion Collider Experiment (ALICE) took first data at the CERN Large Hadron Collider (LHC) accelerator with proton collisions at the end of 2009 and with lead nuclei at the end of 2010. After a short introduction into the physics of ultra-relativistic heavy-ion collisions, this article recalls the main design choices made for the detector and summarizes the initial operation and performance of ALICE. Physics results from this first year of operation concentrate on characterizing the global properties of typical, average collisions, both in proton–proton (pp) and nucleus–nucleus reactions, in the new energy regime of the LHC. The pp results differ, to a varying degree, from most quantum chromodynamics-inspired phenomenological models and provide the input needed to fine tune their parameters. First results from Pb–Pb are broadly consistent with expectations based on lower energy data, indicating that high-density matter created at the LHC, while much hotter and larger, still behaves like a very strongly interacting, almost perfect liquid.

Keywords: heavy-ion physics; quark–gluon plasma; ALICE; Large Hadron Collider

1. Introduction

(a) Ultra-relativistic heavy-ion physics

The subject of ultra-relativistic heavy-ion physics is the study of strongly interacting matter under extreme conditions of high temperature and/or high matter density. The matter under study is the one that fills the Universe today with the elements of the periodic table, essentially made from quarks, the basic building blocks of matter, and held together by gluons, the carriers of the strong (nuclear) force. Under normal conditions, i.e. the ones currently prevailing in the Universe, the quarks are bound (‘confined’) into composite objects called baryons (bound states of three quarks, with the proton and the neutron being the most prominent examples) and mesons (bound states of a quark and anti-quark pair). Quantum chromodynamics (QCD), the theory of strong interactions, predicts that at a sufficiently high energy density, there will be a transition from ordinary nuclear or hadronic matter to a plasma of free (‘deconfined’) quarks and gluons—a transition that took place in the early Universe a few microseconds after the Big Bang and which might still play a role today in compact stellar objects.

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One contribution of 15 to a Discussion Meeting Issue ‘Physics at the high-energy frontier: the Large Hadron Collider project’.

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discovery and characterization of this new high-temperature phase of matter, called the ‘quark–gluon plasma’ (QGP), require a sufficiently large volume of hot matter and are therefore pursued in collisions of heavy nuclei at the highest possible energy.

The QGP is thought to be the ground state of QCD, where quarks and gluons are deconfined and chiral symmetry is (approximately) restored, i.e. the quarks are no longer bound into composite particles (collectively called ‘hadrons’) and are approximately massless, retaining only the bare mass associated with the Higgs mechanism. The transition from normal matter to the QGP is expected to happen at a critical temperature of the order of the QCD energy scale parameter $\Lambda_{\text{QCD}}$, which is approximately 200 MeV (more than $10^{12}$ K). At such an energy scale, the standard method of solving the equations of QCD by perturbative approximations is not very reliable. The theoretical description is therefore in need of—as well as a unique testing ground for—new approaches to QCD in the regime where the strong interaction is truly strong. A large number of these have been brought to bear on the subject, from numerical solutions on large computers (‘lattice QCD’), statistical and thermodynamical formulations, classical solutions in the high-density limit (‘colour glass condensate’), up to string theory and quantum gravity (‘conformal field theory in Anti-de Sitter Space or AdS/CFT’).

This study of the phases of nuclear matter is relevant also beyond the specific context of QCD, as phase transitions and symmetry breaking are central concepts in the Standard Model of particle physics and the predicted QCD transition is the only one directly accessible to laboratory experiments. It may also provide some insight into the properties of large and complex systems involving elementary quantum fields, indicating how the microscopic laws of physics (the ‘QCD equations’) give rise to macroscopic phenomena such as phase transitions and critical behaviour.

Using methods and concepts from both nuclear and high-energy physics, it constitutes a new and interdisciplinary approach in investigating matter and its interactions. In high-energy physics, interactions are derived from first principles (gauge theories), and the matter concerned consists mostly of single particles (composite or elementary). In contrast, on nuclear physics scales, the strong interaction is shielded and can, to date, only be described in terms of effective theories, whereas the matter under investigation consists of extended and interacting systems with collective many-body features. Ultra-relativistic heavy-ion physics combines the elementary interaction aspect of high-energy physics with the macroscopic matter aspect of nuclear physics.

(b) Heavy-ion physics at lower energies

The study of heavy-ion collisions is a rapidly evolving field. After the pioneering experiments at the Lawrence Berkeley National Laboratory in Berkeley and the Joint Institute for Nuclear Research in Dubna in the 1970s with relativistic heavy ions (energy/rest mass, $E/m \approx 1$), the first experiments at ultra-relativistic energies ($E/m \gg 1$) started in 1986 with light ions almost simultaneously at the Brookhaven Alternating Gradient Synchrotron (AGS) and the CERN Super Proton Synchrotron (SPS) fixed target accelerators. Really heavy ions ($A \approx 200$) have been available in the AGS since the end of 1992 and at the SPS since the end of 1994.
The turn of the century (2000) was an extremely important milestone. It started with an appraisal of the CERN SPS Pb beam results [1], which concluded that ‘compelling evidence has been found for a new state of matter’ featuring many of the characteristics expected for a QGP. Later that year, the Relativistic Heavy-Ion Collider (RHIC) and its four experiments at the Brookhaven National Laboratory began operation with Au–Au collisions at 130 GeV per nucleon. Already, the first short run produced a wealth of interesting and novel data, and the RHIC has kept producing exciting and at times surprising results ever since. A ‘Heavy-Ion Standard Model’ (HISM) began to emerge that characterizes the new high-density state created in high-energy nuclear collisions as an extremely strongly interacting and almost perfect fluid [2], sometimes called the ‘sQGP’ (where the ‘s’ stands for ‘strongly interacting’). It is almost opaque and absorbs much of the energy of any fast parton (quark or gluon), which travels through this matter—a process referred to as ‘jet quenching’—and it reacts with pressure gradients by flowing almost unimpeded and with very little internal friction (i.e. very small viscosity).

When the LHC came into operation with ion beams in November 2010, the available energy in the centre of mass system has increased by four orders of magnitude in a little over 25 years [3]. This rapid progress was only possible by re-using accelerators, and initially even detectors, built over a longer time scale for particle physics; the RHIC remains to be the only dedicated facility. Today, with more than 2000 physicists active worldwide in this field, ultra-relativistic heavy-ion physics has moved, in less than a generation, from the periphery into a central activity of contemporary nuclear physics.

2. The ALICE experiment

(a) Designing ALICE

ALICE, which stands for A Large Ion Collider Experiment, is very different in both design and purpose from the other experiments at the LHC [4,5]. It is specifically optimized to study heavy-ion reactions, but data-taking with proton–proton (pp and later p–nucleus) is equally part of the programme primarily to collect comparison data for heavy ions [6,7].

ALICE was ‘born’ in December 1990, when a first meeting took place between a few dozen physicists to contemplate how, and in fact if, to build a detector dedicated to heavy-ion physics at the LHC. Designing a dedicated heavy-ion experiment in the early 1990s for use almost 20 years later posed some significant challenges: in a field still in its infancy—with the SPS lead programme yet to start—it required extrapolating the conditions to be expected by a factor of 300 in energy and a factor of 7 in beam mass. The detector therefore had to be both ‘general purpose’—able to measure most signals of potential interest, even if their relevance may become apparent only later—and also flexible, allowing additions and modifications along the way as new avenues of investigation would open up. In both respects, ALICE did very well, as it included a number of

1Because of confinement, even a fast (high momentum) parton cannot be observed directly. It will fragment into a number of hadrons that can be detected as a narrow ‘jet’ of particles around the original parton direction.
observables in its initial physics menu whose importance became clear only after results were obtained from the RHIC (e.g. reconstructing secondary decay vertices for heavy quarks, particle identification (PID) up to large transverse momentum), and various major detection systems were added to the experiment over time to match the evolving physics goals, from the muon spectrometer in 1995, the transition radiation detector (TRD) in 1999, to a large jet calorimeter (EMCal) added as recently as 2008.

Other challenges relate to the experimental conditions expected for nucleus–nucleus collisions at the LHC. The most difficult one to meet is the extreme number of particles produced in central head-on collisions, which at the time were thought to be up to three orders of magnitude larger than in typical pp interactions at the same energy, and a factor 2–5 above the highest multiplicities expected at the RHIC. The tracking of these particles was therefore made particularly safe and robust by using mostly three-dimensional hit information with many points (up to 200) along each track in a moderate magnetic field \( B = 0.5 \text{T} \) to ease the problem of recognizing and measuring charged particles. In addition, a large dynamic range is required for momentum measurement, spanning more than three orders of magnitude from tens of MeV to well over 100 GeV. This is achieved with a combination of detectors with very low material thickness (to reduce scattering of low-momentum particles) and tracking particles over a large distance \( L \) of up to 3.5 m, which gives a figure of merit for momentum resolution, \( BL^2 \), quite comparable with those of the other LHC experiments. In addition, the vertex detector with its six silicon planes, four with analogue read-out, can be used as a stand-alone spectrometer with momentum and particle-type information to measure particles that do not reach the outer tracking detectors.

Finally, PID over much of this momentum range is essential, as many phenomena depend critically on either particle mass or particle type. ALICE therefore employs essentially all known PID techniques in a single experiment, including energy loss in silicon and gas detectors, Cherenkov and transition radiation, time-of-flight, electromagnetic calorimeters, as well as topological decay reconstruction.

As the intensity of heavy-ion beams in the LHC is rather modest, with interaction rates of order 10 kHz or less with Pb beams, rather slow detectors can be employed, such as the time-projection chamber (TPC) and silicon drift detectors. Only moderate radiation hard electronics and trigger selectivity are required and most of the read-out is sequential and not pipelined (i.e. only one single event can be processed at a time in ALICE). However, because the amount of information produced in heavy-ion interactions is huge (up to 100 Mbyte per event) and the statistics has to be collected in a short time (the LHC runs with ions only one month every year), the data acquisition system has been designed for a very high bandwidth of over 1 Gbyte s\(^{-1}\) to permanent storage, larger than the throughput of all other LHC experiments combined.

The ALICE design evolved from the Expression of Interest (1992) via a Letter of Intent (1993) to the Technical Proposal (1996) and was officially approved in 1997. The first 10 years were spent on design and an extensive effort in research and development (R&D). It became clear from the outset that the challenges of heavy-ion physics at the LHC could neither be met nor paid for with the existing technology. Significant advances, and in some cases a technological breakthrough, would be required to actually build what physicists had dreamt on paper for their
Figure 1. ALICE uses 18 different detector systems, indicated in the figure with their acronyms. The central detectors are located inside a large solenoid magnet (left-hand side), and the forward muon arm spectrometer with its dipole magnet is located on the right. The insert top right is a blow-up of the interaction region showing the six layers of the silicon vertex detector (inner tracking system) and the forward trigger and multiplicity detectors (T0, V0, FMD). Reproduced with permission from the ALICE Collaboration. (Online version in colour.)

experiments. The initially very broad and later more focused, well-organized and well-supported R&D effort, which was sustained over most of the 1990s, has led to many evolutionary and some revolutionary advances in detectors, electronics and computing [5].

(b) The ALICE detector

ALICE is usually referred to as one of the smaller detectors, but the meaning of ‘small’ is very relative in the context of the LHC: the detector stands 16 m tall, 16 m wide and 26 m long, and weighs approximately 10 000 tonnes. It was designed and built over almost two decades by a collaboration that currently includes over 1000 scientists and engineers from more than 100 institutes in some 30 different countries. The experiment consists of 18 different detection systems, each with its own specific technology choice and design constraints. A schematic view of ALICE is shown in figure 1. It consists of a central part, which measures hadrons, electrons and photons, and a forward single-arm spectrometer that focuses on muon detection. The central ‘barrel’ part covers the direction perpendicular to the beam from 45° to 135° and is located inside a huge solenoid magnet, which was built in the 1980s for the L3 experiment at CERN’s Large Electron Positron accelerator. As a warm resistive magnet, the maximum field
at the nominal power of 4 MW reaches 0.5 T. The central barrel contains a set of tracking detectors, which record the momentum of the charged particles by measuring their curved path inside the magnetic field. These particles are then identified according to mass and particle type by a set of PID detectors, followed by two types of electromagnetic calorimeters for photon and jet measurements. The forward muon arm (2°–9°) consists of a complex arrangement of absorbers, a large dipole magnet and 14 planes of tracking and triggering chambers.

(i) Tracking detectors

Tracking in the central barrel is divided into the inner tracking system (ITS), a six-layer, silicon vertex detector and the TPC. The ITS locates the primary vertex (where the interaction took place) and secondary vertices (decay points of unstable particles) with a precision of order of a few tens of micrometres. Because of the high particle density, the four innermost layers need to be high-resolution devices, i.e. silicon pixel and silicon drift detectors, which record both $x$ and $y$ coordinates for each particle hit (the third coordinate being fixed by their radial position in the experiment). The outer layers are equipped with double-sided silicon micro-strip detectors. The total area covered with silicon detectors reaches 7 m$^2$ and includes almost 13 million individual electronic channels.

The need for efficient and robust tracking has led to the choice of a TPC as the main tracking detector. In spite of its drawbacks concerning slow recording speed and huge data volume, a TPC can provide reliable and redundant momentum and PID information. The large TPC (5 m length, 5.6 m diameter) has been specifically optimized for heavy-ion physics in terms of very low mass and good performance up to extremely high particle densities.

(ii) Particle identification detectors

PIDs with large acceptances and for many different particles are an important design feature of ALICE with several detector systems dedicated to PID: the time-of-flight (TOF) array measures the flight time of particles from the collision point out to the detector; together with the momentum, this time determines the mass. It covers the central barrel over an area of 140 m$^2$ with 150,000 individual cells at a radius close to 4 m. The requirement for an affordable system with a large number of channels, as well as state-of-the-art time resolution better than 100 ps, was solved with the development of a novel type of gas detector, the multi-gap resistive plate chamber. The TOF method, which is limited to lower energy particles with a Lorentz factor $E/m \lesssim 3–6$, is complemented by two technologies that measure the electromagnetic radiation emitted by highly relativistic particles which travel through media: Cherenkov radiation in the electron volt energy range and transition radiation in the kiloelectron volt range. The HMPID detector is a single-arm, 10 m$^2$ array of ring imaging Cherenkov counters with a liquid radiator and a solid CsI photocathode evaporated on the segmented cathode of multi-wire proportional chambers. It extends the PID capabilities towards higher momenta in about 10 percent of the barrel acceptance. The TRD will identify electrons above 1 GeV to study production rates of heavy quarks (charm and beauty mesons). It consists of six layers of Xe/CO$_2$-filled time-expansion chambers following a composite foam and fibre radiator and includes a distributed tracking processor in the front-end electronics to select (i.e. trigger on) interesting events in real time.
(iii) **Calorimeters**

Photons, spanning the range from thermal emission to hard QCD processes, as well as neutral mesons are measured in the small acceptance, high-resolution and high-granularity PHOS electromagnetic calorimeter. It is located far from the vertex (4.6 m) and made of dense scintillating crystals (PbWO$_4$) in order to cope with the large particle density. A set of multi-wire chambers in front of PHOS helps in discriminating between charged and neutral particles. The interaction and energy loss of high-energy partons in dense matter will play an essential role in the study of nuclear collisions at the LHC. In order to enhance the capabilities for measuring jet properties, a second electromagnetic calorimeter (EMCal) was installed in the ALICE by the end of 2010. The EMCal is a Pb-scintillator sampling calorimeter with longitudinal wavelength-shifting fibres, read out via avalanche photodiodes. Much larger than PHOS, but with lower granularity and energy resolution, it is optimized to measure jet production rates and jet characteristics in conjunction with charged particle tracking in the other barrel detectors.

(iv) **Forward and trigger detectors**

A number of small and specialized detector systems are used for event selection or to measure global features of the reactions. The collision time is measured with extreme precision (<20 ps) by the ‘T0’ detector; two sets of 12 Cherenkov counters (fine mesh photomultipliers with fused quartz radiator) mounted tightly around the beam pipe. Two arrays of segmented scintillator counters, called ‘V0’ detector, are used to select interactions and to reject beam-related background events. An array of 60 large scintillators (ACORDE) on top of the L3 magnet triggers on cosmic rays for calibration and alignment purposes, as well as for cosmic ray physics. The forward multiplicity detector (FMD) provides information about the number and distribution of charged particles emerging from the reaction over an extended region, down to very small angles. These particles are counted in rings of silicon strip detectors located at three different positions along the beam pipe. The photon multiplicity detector measures the multiplicity and spatial distribution of photons in each single heavy-ion collision. It consists of two planes of gas-proportional counters with cellular honeycomb structure, preceded by two lead plates to convert the photons into electron pairs. Two sets of small, very compact calorimeters (ZDC) are located far inside the LHC machine tunnel (>100 m) and very close to the beam direction to record neutral particles that emerge from heavy-ion collisions in the forward direction.

Figure 2 shows the front of the ALICE barrel detectors and the magnet during detector installation in 2009.

(v) **Muon spectrometer**

On one side behind the central solenoid and at small angles between 2° and 9° relative to the beam direction is a muon spectrometer, which includes a dipole magnet generating a maximum field of 0.7 T. Several passive absorber systems (a hadron absorber close to the interaction point, a lead–steel–tungsten shield around the beam pipe and an iron wall) shield the spectrometer from most of the reaction products. The penetrating muons are measured in 10 planes of cathode
Figure 2. Front view of the ALICE magnet, with its doors fully open. A bridge guides services, power cables, fluids and gases into the central detector. The silicon tracker is no longer visible and even the large TPC is mostly obscured. The stainless steel space frame structure that supports most of the central detectors is partially filled with EMCal, TOF and TRD modules. Reproduced with permission from CERN. (Online version in colour.)

Pad-tracking chambers, located between 5 and 14 m from the interaction, with a precision of better than 100 μm. Again, the relative low momentum of the muons of interest and the high particle density are the main challenge; therefore, each chamber has two cathode planes, which are both read out to provide two-dimensional space information, and the chambers are made extremely thin and without metallic frames. The individual cathode pads range in size from 25 mm² close to the beam up to 5 cm² further away and cover 100 m² of active area with over $1 \times 10^6$ active channels. Four trigger chambers are located at the end of the spectrometer, behind a 300 tonne iron wall to select and trigger on pairs of muons, including those from the decay of heavy quark particles (of main interest for ALICE are the $J/\psi$ and $\Upsilon$ mesons). The chambers are made in the ‘resistive plate’ technology widely used by LHC experiments, and of modest granularity (20,000 channels covering 140 m²).

The layout of the ALICE detector and its various subsystems were described in more detail in earlier studies [5,8].

3. Initial operation and performance

The very first pp collisions were observed in ALICE on 23 November 2009, when the LHC, during the very early commissioning phase, provided an hour of colliding beams for each of its four large experiments [4]. Such was the enthusiasm of

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‘real data’, after years of simulation exercises, that this first harvest of some 300 events, significantly less than the number of ALICE collaborators, was analysed right away and made it into a physics publication only 5 days later [9]; well before stable beams were declared on 6 December and sustained data taking could start.

The many years of preparation, analysis tuning with simulations, and detector commissioning with cosmic rays during much of 2008–2009 paid off quickly with most of the detector components working ‘out of the box’ and rather close to performance specifications. Within a few days, all experiments were showing first qualitative results and the first phase of LHC physics, often referred to as the ‘rediscovery of the standard model’, was getting underway [10]. The various members of the ‘particle zoo’ created in pp collisions made their appearance in ALICE in rapid succession, from the easy ones (π, K, p, Λ, Ξ, φ, etc.) in 2009 to the more elusive ones when larger datasets were accumulated in early 2010 (K∗, Ω, charmed mesons, J/ψ, etc.).

However, precise results and small systematic errors need more than large statistics and a good detector performance; they require a precise knowledge and understanding of the detector as well. The next months were therefore spent on ‘getting to know’ the experiment in greater detail, including calibration, alignment, material distribution and detector response, which are all crucial ingredients for the analysis and correction procedures. For example, the amount of material of the detector ‘as built’ (rather than ‘as designed’) had to be measured with the help of photons that convert in the material into electron–positron pairs. With this method, the material thickness was determined to about 5 per cent relative accuracy. Such a precision is important, e.g. for the measurement of the antiproton to proton ratio, because annihilation of antiprotons in the detector material is one of the dominating factors of the systematic error.

Measuring the precise position of the many millions of detection elements inside the experiment is a crucial prerequisite for accurate momentum determination. To improve on the initial information provided by geometrical survey, this ‘detector alignment’ started with cosmic rays and continues to date with beam, quickly reaching an accuracy of less than 10µm for the innermost layers of the vertex detector, about 200–300µm for the TPC, and the millimetre level in the outer detectors required for track matching. Likewise, accurate gain and pulse height calibrations are needed in particular for the PID using energy loss (dE/dx). The energy-loss distribution in the TPC, which has reached its design resolution of better than 6 per cent relative accuracy in dE/dx for long tracks, is shown in figure 3 versus rigidity, separately for positive and negative charges. Different particle species and light nuclei are clearly separated in the non-relativistic momentum region. Note that the apparent asymmetry between nuclei and anti-nuclei production rates in this plot is an instrumental effect. Here, tracks are not required to point precisely back towards the vertex and therefore many secondary particles knocked out from the detector material are included. Even in pp collisions, anti-nuclei as heavy as anti-tritium can be produced. In heavy-ion reactions, even a handful of anti-Helium candidates, the heaviest anti-nuclei ever produced in the laboratory, have been identified by a combined energy loss and TOF measurement.
4. Results with proton–proton collisions

Data taking with proton beams was focused during most of 2010 on collecting a large sample ($>10^9$) of average (so-called ‘minimum bias’) collisions and measuring their global event properties, which are needed for comparison with the heavy-ion data [11]. Both the average number of charged particles ($dN_{\text{ch}}/d\eta$) as well as their multiplicity distributions in different acceptance windows were measured at 0.9, 2.36 and 7 TeV for inelastic and non-single diffractive collisions [9,12,13]. The dependence of the average multiplicity on the centre-of-mass energy $\sqrt{s}$ is well described by a power law, $s^{0.11}$, and increases significantly faster than predicted by most QCD-based simulation programmes (‘event generators’). Most of this stronger increase happens in the tail of the multiplicity distribution, i.e. for events with much larger than average multiplicity. Likewise, neither the transverse momentum ($p_T$) distribution at 900 GeV nor the dependence of average $p_T$ on charged particle multiplicity is well described by these generators [14], in particular, when including low-momentum particles ($p_T < 500$ MeV). The shape of the $p_T$ spectrum as a function of multiplicity hardly changes below 0.8 GeV (which includes the large majority of all particles), whereas the high-momentum power-law tail typical of hard QCD scattering increases rapidly with event multiplicity above about 1–2 GeV.

The yields and $p_T$ spectra of identified stable-charged ($\pi, K, p$) and neutral strange particles ($K_S^0, \Lambda, \Xi, \phi$) have been measured for the small 900 GeV dataset taken in 2009 [15,16]. Most event generators predict yields well below the data—by factors of 2 to almost 5—and more so at high $p_T$ and for the heavier particles ($\Lambda, \Xi$). The ratio of $\Lambda$ to $K_S^0$ agrees very well with pp data at 200 GeV from the RHIC, but is significantly below the ratio measured at the pp bar colliders at CERN and Fermilab. This discrepancy merits further investigation; it could be owing to differences between the experiments in the acceptance, triggers or...
correction for feed-down from weak interaction decays. The relative production ratios of baryons to mesons (e.g. the proton-to-pion ratio) are of particular interest, as they rise well above unity in nuclear collisions at the RHIC. This ‘meson–baryon’ anomaly has been interpreted as an indirect sign of the QGP, in which case, it would not be obvious why similar ratios should be reached already in minimum bias pp interactions.

Baryon number (which counts the number of baryons minus anti-baryons) is a conserved quantity in the high-energy physics Standard Model because quarks, which make up baryons, are created (and annihilated) always in particle–anti-particle pairs. In high-energy pp collisions (two incoming baryons), the projectiles in general break up into several hadrons including two excess baryons (which may or may not be protons). The outgoing baryons retain only a fraction of the original beam energy and emerge under a finite angle (finite rapidity\(^2\)) with respect to the original beam particles. The deflection and deceleration (or ‘baryon stopping’) of the incoming projectile, or more precisely of the conserved baryon number associated with the beam particles, are often called ‘baryon-number transport’. At the LHC, by far the highest energy pp collider, ALICE has studied the distribution of net baryon number along the beam direction over very large rapidity intervals (large deflection/large deceleration) by measuring the antiproton-to-proton ratio at mid-rapidity \(^{[17]}\) (i.e. perpendicular to the beam) in order to discriminate between various theoretical models of baryon stopping. Baryon number transport over large distances in rapidity is often described in terms of a nonlinear three-gluon configuration called ‘baryon string junction’. The dependence of this process on the size of the rapidity gap has been a long-standing issue (for large gaps, where it should be dominant), with advocates for both very weak and rather strong dependencies. In either case, the \(\bar{p}/p\) ratio at the LHC is expected to be very close to unity, with the difference between various models only of the order of a few per cent. So this ratio must be measured with high precision. While, in the ratio, many instrumental effects cancel, the very large difference between \(p\) and \(\bar{p}\) cross section for both elastic (track changes direction and can get lost) and inelastic (particle can be absorbed) reactions with the detector material lead to corrections of order 10 per cent, even in the very thin central part of ALICE. As the corrections are much larger than the effect, a very precise knowledge of the detector material as well as of the relevant cross-section values at low momentum is required. The former was measured with the data via photon conversions; the latter had to be cross-checked with the experimental data as all available versions of the standard computer program used to simulate detector response overestimated the \(\bar{p}\) cross sections by up to a factor of 5. The \(\bar{p}/p\) ratio was found to be compatible with 1 at 7 TeV and 4 per cent below 1 at 900 GeV, with an experimental uncertainty of about 1.5 per cent, dominated by the systematic error. This result favours models that predict a strong suppression of baryon transport over large gaps; they agree very well with standard event generators, but not with those that have implemented enhanced proton stopping.

\(^2\)Rapidity \((y)\) is a relativistic and convenient measure of the polar angle, invariant under Lorentz boost along the beam direction. For massless (or highly relativistic) particles, it coincides with the pseudorapidity \((\eta)\), defined as \(\eta = -\ln \tan \theta/2\), where \(\theta\) is the polar angle with respect to the beam line.

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5. Results with lead–lead collisions

With the fantastic results from the RHIC and the emergence of the HISM mentioned earlier, the search for the QGP is essentially over and the characterization of the new high-temperature phase is well underway. However, precision measurements of QGP parameters are just starting (precision is meant here in the context of non-perturbative QCD, where a factor of 2 is already respectable). At up to 30 times higher energy, the LHC has some unique advantages compared with the RHIC and is complementary in other aspects. Significant differences are expected at the higher energy in terms of energy density, lifetime and volume of the state of matter created in the collisions, and rare ‘hard probes’ (jets, heavy flavours) will be produced abundantly. In this new environment, the HISM can be tested and validated. Once it has been verified that the global event characteristics (e.g. energy density, volume, lifetime) of matter at the LHC are indeed rather different, but that evolution and intrinsic properties are still well described by the HISM, one can embark on the programme of precision measurements of the QGP parameters (e.g. viscosity, equation-of-state, transport coefficients, Debye screening mass, etc.) [18].

The first, and most anticipated, results concerned global event characteristics. When ALICE was conceived in the early 1990s, the charged particle density predicted for central Pb–Pb collisions at the LHC was extremely uncertain, varying between 2000 and more than 4000 charged particles per unit rapidity. With RHIC results, the uncertainties came down substantially, as did the central value, with most predictions clustering in the range 1000–1700 [19]. The value finally measured at the LHC, \( \frac{dN_{\text{ch}}}{d\eta} \approx 1600 \) [20], was right in this range, if somewhat on the higher side. From the measured multiplicity in central collisions, one can derive a rough estimate of the energy density, which gives at least a factor 3 above the RHIC; the corresponding increase of the initial temperature is about 30 per cent. This is indeed matter under extreme conditions, reaching a temperature that is 200,000 times hotter than the centre of our Sun and an energy density 50 times larger than in the core of a neutron star!

When combined with lower energy data, the charged particle production per participant, \( N_{\text{part}} \), rises stronger with energy than in pp, approximately with \( s^{0.15} \) (figure 4a). Therefore, a central collision between Pb nuclei (\( N_{\text{part}} \approx 400 \)) at the LHC produces not 200, but 400 times the particle multiplicity of a typical pp collision (\( N_{\text{part}} = 2 \)). Even more surprising is the fact that the centrality dependence of \( \frac{dN_{\text{ch}}}{d\eta} \) [22] is practically identical to the one of Au–Au at the RHIC (at least for \( N_{\text{part}} > 50 \)), despite the fact that impact parameter-dependent nuclear modifications would be expected to be much stronger at the LHC.

Various notations and measures are used to classify nuclear collisions: in ‘central’ collisions, the two nuclei collide head-on (impact parameter close to 0), in ‘peripheral’ ones, they only touch at the edges (impact parameter close to twice the nuclear radius). The collision geometry is captured more quantitatively by the number of ‘participating nucleons’ \( N_{\text{part}} \), which are contained in the nuclear overlap volume at a given impact parameter and therefore participate in the collision. ‘Centrality’ measures the fraction of the total interaction cross section in bins of a variable that is directly related to the impact parameter; e.g. the ‘10 per cent most central events’ correspond to the 10 per cent of events with the highest multiplicity. Centrality is experimentally measured, whereas \( N_{\text{part}} \) is derived indirectly and in a slightly model-dependent way.
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Figure 4. (a) Charged particle pseudorapidity density $dN_{ch}/d\eta$ per colliding nucleon pair ($0.5 N_{part}$) versus centre of mass energy for pp and AA (nucleus–nucleus) collisions. (b) Elliptic flow coefficient $v_2$ versus transverse momentum when compared with RHIC data from the STAR experiment. Reproduced with permission from Aamodt et al. [20,21]. (Online version in colour.)

Figure 5. (a) Local freeze-out volume as measured by identical pion interferometry at the LHC when compared with central gold and lead collisions at lower energies. (b) The decoupling time $\tau_f$ compared with results from lower energies. Reproduced with permission from Aamodt et al. [23]. (Online version in colour.)

Indeed, models with either strong nuclear modifications or different saturation-type calculations (‘colour glass condensate’-based models) do describe the impact parameter dependence best.

The freeze-out volume (the size of the matter at the time when strong interactions cease) and the total lifetime of the created system (the time between collision and freeze-out) were measured with identical particle interferometry (also called Hanbury–Brown Twiss or HBT correlations) [23]. Compared with top RHIC energy, the local ‘comoving’ freeze-out volume (figure 5a) increases by a factor of 2 (to about 5000 fm$^3$), and the system lifetime (figure 5b) increases by about 30 per cent (to 10 fm$^{-1}$), pretty much in line with the predictions of the HISM.
The most critical test of the HISM, however, comes from the measurement of the elliptic flow\(^4\) at the LHC, the pillar that supports the ‘fluid’ interpretation of the QGP. Collective observables like particle flow are usually described in the framework of hydrodynamic models, where initial conditions (e.g. geometry and pressure gradients) and fluid properties (e.g. viscosity and equation-of-state) fully determine the observed pattern of collective motions. Assuming only small or no changes in the fluid properties between the RHIC and LHC, hydrodynamic models predict firmly that the elliptic flow coefficient \(v_2\), measured as a function of \(p_T\), should change very little. As shown in figure 4b, this prediction was confirmed very quickly and with good precision [21]. The \(p_T\)-integrated flow values however do increase when compared with the RHIC by some 30 per cent, because the average \(p_T\) is significantly higher at the LHC. While the average \(p_T\) increases also in pp with energy, because hard and semi-hard processes become more important, hydrodynamics predicts, in addition, an increase in the radial flow velocity leading to a characteristic \(p_T\) and mass dependence of the spectra. It will be very interesting to see, once identified particle spectra will be available, if this prediction is also borne out (as everyone assumes it is), and if the radial flow regime extends to even higher momentum than at the RHIC (here predictions are less firm).

With the HISM having passed its first tests (HBT, elliptic flow \(v_2\)) with flying colours, the programme of precision measurements is now starting at the LHC. For example, a major advance in quantifying the shear viscosity, which at the RHIC was measured to be within a factor 2–4 of the quantum limit of a perfect fluid as conjectured by AdS/CFT, will require a better estimate of the remaining non-flow contributions, as well as a better constraint on the initial conditions, i.e. the geometry of the collision zone (and its fluctuations) that drives the various flow components. Progress is already being made on both fronts, in particular, by looking in more detail at the centrality dependence and at higher Fourier components (\(v_3, v_4\), etc.).

The energy advantage of the LHC is most evident in the area of parton energy loss (or jet quenching, the ‘opaque’ aspect of the sQGP), where the kinematic reach vastly exceeds the one available at the RHIC. With high \(p_T\) jets easily visible above the soft background, jet quenching is qualitatively evident already by visual inspection of charged jets in the TPC, where a striking jet-energy imbalance develops for central collisions. A quantitative analysis will, however, take more time, in order to see how much energy is actually lost (i.e. measure the transport coefficient), how and where it is lost (multiple soft versus few hard scatterings), and if there is a response of the medium to this local energy deposit (shock waves, Mach cones). Eventually, an answer to all these questions will require comparing in detail how a fast parton fragments into hadrons when travelling through the medium rather than through the vacuum (as in pp collisions), down to low (<5 GeV) or even very low (<2 GeV) transverse momentum of the fragments.

\(^4\)Flow refers to a correlation between space and momentum variables, i.e. particles close in space show similar velocity in both magnitude and direction. Such a collective behaviour is in contrast to random thermal motion where space and momentum variables are generally not correlated. Different flow patterns are observed in heavy-ion collisions and quantified in terms of a Fourier decomposition. The second harmonic is called ‘elliptic’ flow and the zero-order (i.e. isotropic) harmonic is called ‘radial’ flow. Other harmonic components (e.g. first, third, etc.) can be measured as well.

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In the meantime, ALICE has measured the nuclear modification of charged particle momentum distributions out to 20 GeV [24], where the spectra are dominated by leading jet fragments. The change of the $p_T$ spectrum is most pronounced at around 6 GeV, where the suppression of high-momentum particles is modestly stronger than at the RHIC, but then rises again smoothly towards higher momentum. This latter feature is not evident in the published RHIC data, and while such a rise was qualitatively predicted by some models for the LHC [19], it looks stronger at first sight. However, initial state effects (shadowing/saturation), which presumably are very strong at the LHC and which should depend on both impact parameter and momentum transfer, can complicate a straightforward interpretation of the data and the comparison between different beam energies. It will be interesting to see how this result will fit into the overall picture of jet quenching.

All of the heavy-ion results summarized above have emerged within weeks of the first Pb–Pb collisions at the LHC. They paint a picture that is broadly consistent with the expectations based on lower energy results and confirm that ultra-relativistic heavy-ion physics has reached a remarkable level of stability and predictability. However, it should be kept in mind that these are still very early days for heavy ions at the LHC and surprises and unexpected results may yet turn out to require new ingredients ‘beyond the HISM’.

6. Summary

After two decades of design, R&D, construction, installation, commissioning and simulations, the ALICE experiment has had a remarkably smooth and efficient start-up since the LHC came into operation at the end of 2009. Most detector systems are fast approaching design performance, and physics analysis is well underway. With the first heavy-ion collisions, a new era has begun for ultra-relativistic heavy-ion physics, and one can look forward to at least a decade of exciting (and hopefully revealing) new results concerning matter and the strong interaction under conditions of extreme temperature and density.

References

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