

# A machine called ALICE

The ALICE experiment at the Large Hadron Collider will explore the universe as it was in the first few microseconds after its birth, explain **Jürgen Schukraft**, **Yves Schutz** and **Urs Wiedemann**

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In the small French village of St Genis, a few kilometres away from the CERN laboratory, a dozen or so physicists are crowded around a computer screen. The atmosphere is tense. After turning a few knobs and typing a few commands, an image comprising a few nondescript straight lines appears. It is greeted with cheers and relief: the date is early June 2006, and the huge “TPC” tracking detector of the ALICE experiment has just recorded its first particle ever, a passing cosmic ray. With champagne corks popping in the background, this event marked another milestone in the life of the largest and most complex detector ever devoted to the study of nuclear collisions.

ALICE – A Large Ion Collider Experiment – is unlike any of the other three large experiments at the Large Hadron Collider (LHC). Its purpose is to explore matter under extreme densities and temperatures, which demands collisions of entire nuclei rather than just protons as in ALICE, CMS and LHCb. The “matter” in question is that which fills the universe around us, made from quarks and gluons that are held together in protons and neutrons by the strong nuclear force.

The theory of the strong force, quantum chromodynamics or QCD, is very good at describing the interactions of quarks and gluons at high energies because the strong force becomes weaker with energy. However, it is fiendishly difficult to solve the equations of QCD under the conditions relevant, say, outside a particle accelerator. As a result, two of the most striking manifestations of the strong force – the tight confinement of quarks and gluons in composite particles and the fact that these composite particles are so much heavier than the sum of their parts – are still shrouded in mystery.

Theorists believe that the answer to these questions can be found by studying the ground state of the strong interaction: the QCD vacuum. Since Dirac’s work in the late 1920s, we have known that the vacuum is not merely empty space but rather is filled with short-lived particle–antiparticle pairs. Then in the 1960s, quantum field theory showed us that the vacuum is also filled with “condensates” of various particles or fields.

Condensates can be easily understood by considering the microscopic behaviour of a magnet. Here, electron spins are collectively oriented in an arbitrary but distinct direction, thus breaking the directional symmetry of the system. Similarly, condensates filling the vacuum consist of quantum fluctuations that break more abstract symmetries present in the underlying theory. Moreover, just as electrons in magnets lose their collective orientation above a certain temperature due to thermal fluctuations, the condensates of the vacuum are expected to “melt” above a critical temperature.

Symmetry breaking can have drastic consequences.

For instance, a condensate called the Higgs field is thought to be responsible for the mass of all the elementary particles by breaking the so-called electroweak symmetry of the vacuum. Likewise, the breaking of a QCD condensate called a chiral condensate increases the small mass of quarks due to electroweak symmetry breaking by almost two orders of magnitude, thus giving rise to most of the ordinary mass in our universe.

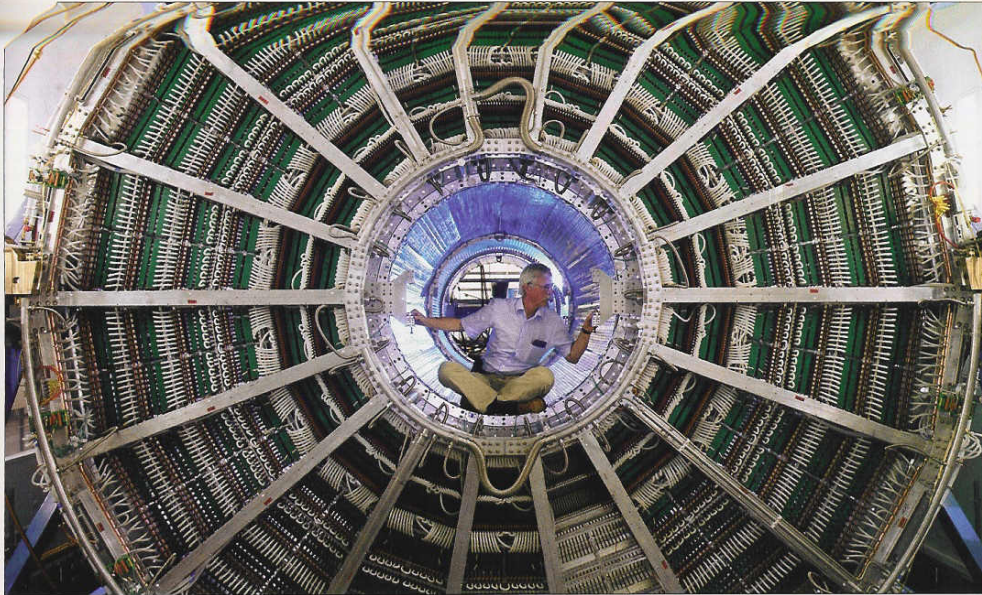
The LHC will be able to address symmetry breaking and mass generation for both elementary and composite particles. For instance, by concentrating the energy of the LHC’s proton beam in a single point, researchers on CMS and ATLAS may discover the famous Higgs boon – the excitation of the Higgs condensate. By colliding large nuclei, the LHC’s energy is distributed over a sizeable volume, thus filling a region of space with the densest and hottest matter ever produced in the laboratory. Because the energy scales relevant for QCD are sufficiently low, ALICE can now go one step further and experiment directly with the QCD condensate and the structure of the vacuum itself.

## Probing the vacuum

ALICE will study how the presence of this ultra-dense matter changes the structure of the vacuum. The matter will be so dense that the QCD condensate will melt away and, in a small region and for a short time, the vacuum will revert back to its primordial symmetric structure. In other words, we will be able to study the state of the universe as it was a few microseconds after the Big Bang.

This new phase of matter is known as the quark–gluon plasma (QGP). The Standard Model of particle physics – which embodies electroweak theory and QCD – predicts that the minimum energy density required for this new state of matter to appear is about 10 times the density of the nucleus. Quarks and gluons are also expected to be able to roam freely in the QGP, and should be essentially massless because the chiral condensate has been removed from the vacuum. Because of its high internal pressure, this ultra-dense system will expand and cool rapidly, with the condensate reappearing once the energy density has dropped be-

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low a critical value.

On its way back to normal matter, the system will evolve as a “little bang” through a sequence of stages very similar to the Big Bang. And in the same way that measurements of, say, galaxies give us an insight into the collective expansion of our universe, the abundance of different composite particles and their relative motions in a heavy-ion collision tell us about the state of the ultra-dense QCD matter produced.

ALICE will observe this little bang with unprecedented accuracy. It will record up to 8000 lead-lead collisions per second, each of which will produce tens of thousands of particles. Imprinted in the properties of these particles are the telltale signatures of both the fiery birth and the complex history of expansion and cooling (which lasts about the same time it takes for light to cross a few nuclear diameters). Recording each particle and measuring its energy, mass and direction with great accuracy is an enormous challenge.

**A class of its own**

The roots of ALICE go back to 1990, when physicists first seriously considered the rather challenging prospect of filling the LHC with heavy nuclei from time to time. Since then the ALICE collaboration has grown into an interdisciplinary team of about 1000 nuclear and high-energy physicists from over 90 institutes in 30 different countries. While similar scientific goals were previously tackled by a dozen or so other experiments at CERN’s Super Proton Synchrotron (SPS), and are currently covered by four large detectors at the Relativistic Heavy Ion Collider at Brookhaven in the US, ALICE will do this all in one. ALICE therefore requires a large number of distinct detector systems. Many of these, such as the specific particle-identification arrays, are com-

pletely novel and have been developed specifically for heavy-ion physics in recent years. Others are state-of-the-art implementations of tried and tested technologies, scaled up to the huge sizes required at the LHC.

While ALICE is one of the two smaller LHC experiments, “small” has taken on a new meaning at CERN these days. Weighing 10 000 tonnes and measuring 16 m in height by 26 m in length, ALICE is larger and more complex than any previously built collider detector. Most of its size is due to the barrel detectors, which are arranged as concentric cylinders around the LHC beam pipe and are embedded in a huge solenoid magnet.

Wrapped tightly around the beam line at the smallest radii is a six-layer silicon “vertex detector”, which will pinpoint the origin of each particle with a precision of better than 100 μm. At the outer radius of the detector lie some 150 000 individual “time of flight” detectors that pinpoint the arrival time of particles to within 100 ps. In between sits the huge, gas-filled time projection chamber (TPC), which will allow us to reconstruct the paths of particles to within a fraction of a millimetre. And there are a host of other detectors in place to identify photons, electrons and high-energy hadrons.

After more than 15 years of preparation, the experiment is steadily building up in its final location 50 m underground. The TPC crew has stowed away the champagne bottles and rejoined its many colleagues in the painstaking task of assembling, checking and bringing to life the myriad pieces of the puzzle named ALICE. Before the end of 2007 the detector will be ready to observe its first particle collisions and therefore open the next chapter of its life: trying to unlock the secrets of matter and the vacuum to see what the world was like in the first few microseconds after its birth in the Big Bang some 14 billion years ago. Let the sparks fly.

**The little bang**

Physicists working on the ALICE Time Projection Chamber recently celebrated the successful tracking of a cosmic ray.



**Colourful quarks**  
Protons and neutrons are more than the sum of their parts.