PROGRESS OF THE ALICE EXPERIMENT*

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The ALICE experiment, under construction at the Large Hadron Collider, has been designed to study the behavior of nuclear matter under extreme conditions of energy density and temperature, via a simultaneous measurement of many observables. The ALICE setup comprises a multipurpose complex of tracking and particle-identification devices installed in a large solenoid magnet and a muon detection arm in the forward rapidity region. Characteristics and construction status of the main ALICE sub-detectors will be discussed.

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1. Introduction

The Large Hadron Collider (LHC), providing heavy nucleus collisions at energies up to 5.5 TeV in the nucleon-pair center-of-mass, is a powerful tool to investigate the behavior of nuclear matter at densities higher than that of the ground state. The relevance of this study is based on the lattice-QCD calculations, which predict [1] that nuclear matter under extreme conditions of compression and heating evolves into a plasma of quarks and gluons (QGP), a state of matter that prevailed in the early Universe, just after the Big Bang. Inside this bulk phase of strongly interacting matter, chiral symmetry is approximately restored and colour freely propagates.

The interpretative difficulties met in drawing conclusions from the analysis of SPS and RHIC data indicated that understanding the results of energetic collisions between ultra-relativistic nuclei is a painstaking task requiring many simultaneous observations because of the non-perturbative features of the phase transition to QGP. The unique possibility offered by LHC to

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collide heavy nuclei at unprecedented energies will allow investigating a hotter, larger and longer-living QGP state than those achieved at the present heavy-ion facilities. At LHC energies, cross sections of very high momentum transfer processes will be large enough to make available additional signatures providing valuable information and insights on the early and thermalized stages of the collision. Such hard probes (heavy flavors, direct photons, jets and dijets) occur on so small temporal and spatial scales to entail that any modification of their known properties is caused by the medium they have subsequently traversed. The baryon content of the system after the collision is expected to be concentrated rather near the rapidity of the two colliding nuclei. Consequently, mid-rapidity nuclear matter at LHC will be much more baryon-free than at RHIC and closer to the conditions simulated in lattice QCD for a vanishing baryo-chemical potential allowing a more direct comparison with theory predictions.

In conclusion, at LHC, the more favorable conditions will likely provide a consistent and uncontroversial experimental evidence of the phase transition.

Currently, more than 1000 physicists from 80 institutions in 30 countries are involved in building ALICE (A Large Ion Collider Experiment) [2], the main experiment at LHC specifically devoted to study the physics of heavy ion collisions. The experiment was approved in February 1997, and the final designs of the various detector sub-systems were comprehensively described in the Technical Design Reports (TDR) [3–14], since mid 1998. The last TDR [14], devoted to the computing was approved by the LHCC in March 2006. Physics performance studies are reported in [15–16].

2. Basic design issues of the ALICE layout

In contrast to p–p physics, which requires high luminosity to search for rare events produced with cross-sections of the order of the pb, the measurement of observables related to the deconfined plasma of quarks and gluons and its time evolution can be performed in nuclear collisions at relatively low luminosity. LHC design luminosity for Pb beams is $L = 10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ corresponding to an interaction rate of about 10^4 Hz of which only a small fraction, approximately 5%, accounts for the most interesting central collisions with maximum particle production. Since fluences and doses roughly scale with luminosity, it follows that requirements on detector electronics and radiation damage issues are much less relevant than those in pp experiments thus allowing to exploit the outstanding tracking capability of slow devices like the time projection chamber (TPC) and the silicon drift detector. On the other hand, nuclear cross-sections ranging between 10 mb and the barn entail the production of a large amount of particles in Pb–Pb collisions.

The high multiplicities anticipated at LHC combined with the large rapidity range to be covered have represented the main technical challenges in designing the ALICE apparatus. The average charged-particle multiplicity per unit of rapidity plays an important role not only in assessing the detector performance but also physics-wise, because it largely determines the accuracy with which many observables can be measured, especially in the event-by-event studies of fluctuations.

Initial theoretical estimates for the rapidity density of produced charged hadrons for central Pb+Pb collisions ranged from 2000 to 8000 per unit of rapidity at mid-rapidity. The high multiplicities in central nucleus–nucleus collisions typically arise from the large number of independent and successive nucleon–nucleon collisions, occurring when many nucleons interact several times on their path through the oncoming nucleus. A scaling function, based on the parton saturation and classical QCD, was successfully used for evaluating the multiplicity at full RHIC energy (200 GeV) based on the 130 GeV data [17]. Extrapolation of this model to LHC energies yields a multiplicity density at the lower end of the predicted range (2000 particles per unit of rapidity or less). However, since the difference in energy between SPS to RHIC is smaller than that between RHIC to LHC, extrapolation to the center-of-mass energy per nucleon pair of $\sqrt{s_{\mathrm{NN}}} = 5.5\,\mathrm{TeV}$ is quite inaccurate and evenly ranges between 1500 and 3000 charged particles per unit of rapidity. In view of this uncertainty, the ALICE detector granularity has been optimized to provide the best performance at a charged particle rapidity density of 4000, assuring a large safety margin, and to maintain the occupancy at the highest predicted multiplicity at such a level to still allow the event analysis.

An irrenounceable feature of heavy ion experiments is the capability to identify the charged hadrons in the full range of momentum because it allows to investigate many new event-by-event observables and plays an important role in the study of the properties of the quark-gluon plasma during its dynamical evolution toward the freeze-out phase when the re-hadronization occurs. At LHC energies, more than 97% of the particles will be produced with a $p_{\mathrm{t}} < 2\,\mathrm{GeV}/c$, the bulk of the remaining 3% will be in the range 2–5 GeV/c although a not negligible fraction (0.02 %) will have $p_{\mathrm{t}} > 5\,\mathrm{GeV}/c$. Therefore, ALICE employs more than one method to perform an efficient and unambiguous particle identification (PID) and envisages two dedicated and complementary systems for di-electrons (a Transition Radiation Detector, TRD) and dimuons (a forward muon arm spectrometer).

Other design considerations are dictated by the need for special physics triggers to select the events of interest for storage [12]. The trigger capabilities become indispensable for the most interesting rare probes in view of the large data volume and slow readout of the central TPC detector (about 25 Hz for central Pb+Pb collisions).

3. Detector layout overview

The ALICE experiment will be located 45 m below ground level, at the Intersection Point 2 of the LHC tunnel, in the underground cavern previously used by the LEP L3 experiment. Conceived as a general-purpose experiment, ALICE features a single set-up optimized to study the full spectrum of observables (hadrons, photons and leptons) together with a global survey of the events over a large phase space. The design of the apparatus has also been optimized to study interactions between protons, at lower luminosity than the other LHC experiments, and between protons and nuclei, to be used as reference data for the Pb–Pb collisions. Collisions between lighter nuclei than Pb are also envisaged to investigate the influence of the energy density and volume on the phase transition properties.

As shown in Fig. 1, the ALICE layout consists of two main components: a 2π barrel detector system at mid-rapidity (polar angles from 45° to 135°) embedded within the 0.2–0.5 T uniform solenoid field provided by the large magnet inheredited from the L3 experiment, and a forward muon spectrometer (from 2° to 9° polar angles). Charged particles will be tracked and identified over a wide range of momenta (from 100 MeV/c up to 100 GeV/c) by the following state of the art detectors featuring a high performance even at the highest density anticipated for Pb–Pb collisions:

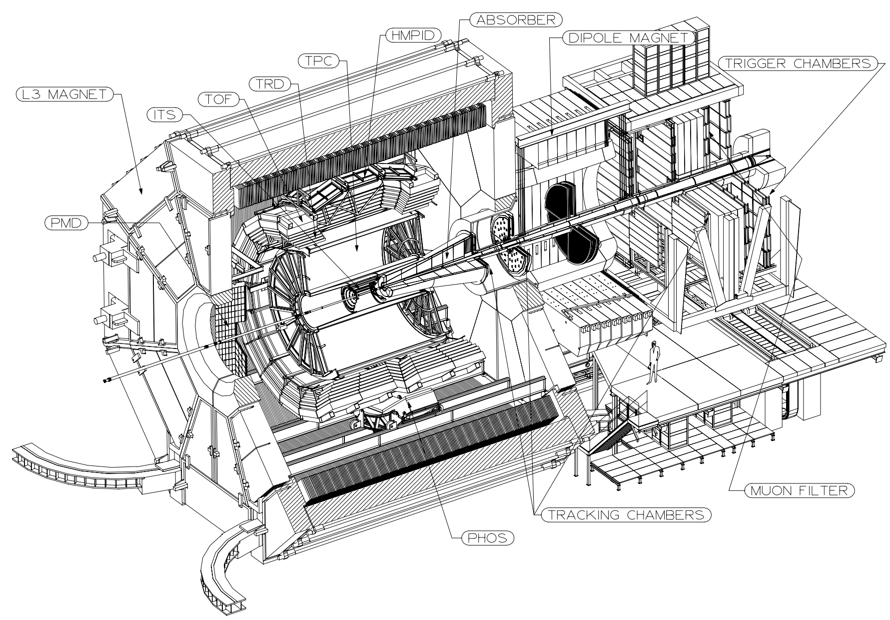

Fig. 1. Axonometric view of the ALICE layout.

- an inner tracking system (ITS) [6] with six cylindrical layers of highly accurate position-sensitive silicon detectors designed to track charged particles emerging from the main interaction vertex and to identify decay products of short-lived secondary particles having strange and charm quark content;
- a cylindrical, large volume TPC [9] envisaged to determine the charged particle trajectories curving in the magnetic field, allowing particle momentum and charge to be measured;
- two highly segmented particle identification barrel arrays for hadrons (by means of Time Of Flight, TOF) [10] and electrons (by means of a TRD) [11];
- a single arm array of seven Ring Imaging CHerenkov detectors (RICH) optimized to perform an inclusive identification of high momentum charged hadrons (High Momentum Particle Identification Detector, HMPID) [3];
- a single arm high resolution electromagnetic calorimeter (PHOton Spectrometer, PHOS) [4], consisting of 17 k lead tungstate crystals ($PbWO_4$) readout by silicon photodiodes, designed to search for direct photons and to measure π° and η spectra at high momenta. It is located in the bottom part of the central barrel region ($-0.12 < \eta < 0.12$ and $40^\circ < \phi < 140^\circ$), at 4.6 m from the vertex and covers $8\,\mathrm{m}^2$. A charged-particle veto detector, placed in front of the PHOS, tags charged particles reaching the calorimeter.

Within a few years, the capability of ALICE to measure the energy of gammas will be enhanced. In fact, several US groups have recently expressed interest to join ALICE by submitting a financial request to DOE for building a large acceptance lead-scintillator sampling calorimeter (EMCAL) consisting of $\sim 13\,000$ towers arranged in 11 super modules. With an acceptance of 110° in azimuthal angle and ± 0.7 units in η, EMCAL will significantly extend the measured momentum range for photons and electrons to provide a measurement of jet energy and jet fragmentation functions and to allow the study of dijets. The corresponding Technical Proposal [18] has been submitted to the LHCC in April 2006.

The forward muon spectrometer [7], featuring measurements of quarkonia states with a Υ mass resolution of about $100\,\mathrm{MeV/c}^2$, consists of a complex arrangement of absorbers (reaching totally about $18\lambda_{\mathrm{int}}$), a large dipole magnet (3 Tm integral field), ten stations of thin multi-wire proportional chambers (MWPC) equipped with highly segmented cathode planes for tracking and four Resistive Plate Chambers (RPCs) for muon identification and triggering.

Four small and very dense zero degree calorimeters [5], made of tungsten and lead with embedded quartz fibres read out by photomultipliers, are located about 100 m downstream the machine tunnels on both sides of the interaction region to infer and trigger upon the impact parameter.

A pre-shower detector called PMD (Photon Multiplicity Detector) [8] has been designed to measure photon multiplicity in the forward region. It consists of a lead converter sandwiched between two planes of high granularity gas proportional counters. Additional detectors [13], designed to provide fast trigger signals and event multiplicity at large rapidity and an array of scintillators (ACORDE) on top of the L3 magnet, envisaged to trigger on cosmic rays, complete the ALICE set-up.

4. Characteristics of the main sub–detector systems

4.1. The Inner Tracking System

At the heart of ALICE, the ITS consists of six cylindrical layers (Fig. 2): the four innermost ones are made of truly bi-dimensional devices, pixel and drift detectors, owing to the high particle density expected and the necessity to achieve an impact parameter resolution below 100 μm, whereas the two outer planes are made of double-sided silicon microstrip detectors. The main parameters of the constituent subdetectors are shown in Table I. The first layer of pixel detectors, located at only 4 cm from the beam axis, covers almost four units of pseudo-rapidity to provide, together with the forward multiplicity detectors, a continuous coverage in rapidity for the measurement of charged particle multiplicity. In order to keep the average layer thickness, all included, below 1% of X_0, a lightweight (28 g/m) but very stiff support structure in carbon fiber has been designed to maintain the sagitta below 100 μm over a meter.

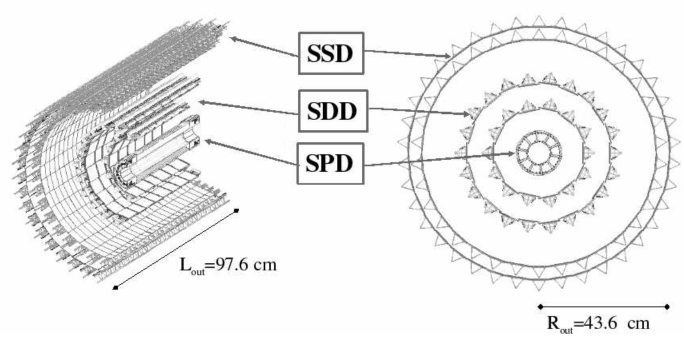

Fig. 2. Artist view of the six cylindrical layers of the Inner Tracking System.

TABLE I

Parameters of the various silicon detector types. A module represents a single detector.

	Pixel	Drift	Strip
Spatial precision $r\,\phi$ (μm)	12	38	20
Spatial precision z (μm)	100	28	830
Two track resolution $r\,\phi$(μm)	100	200	300
Two track resolution z (μm)	850	600	2400
Cell size ($\mu\,\mathrm{m}^2$)	50×425	150×300	$95 \times 40\,000$
Active area per module (mm^2)	12.8×69.6	72.5×75.3	73×40
Total number of modules	240	260	1698
Total number of cells (M)	9.84	23	2.6
Average occupancy (inner layer)	2.1%	2.5%	4%

Drift and strip silicon layers are equipped with an analog readout for independent particle identification via dE/dx in the $1/\beta^2$ region. In order to assure the thermal uniformity required by the TPC and the two silicon drift layers, the about 8 kW of power dissipated by the over 12 M of electronics channels are removed by a very efficient cooling system based on a hybrid approach that combines the forced circulation of the liquid C_6F_{14} with a moderate air flow.

4.2. The Time Projection Chamber

The TPC is the main tracking detector in the central barrel of the ALICE experiment. Together with the ITS and the TRD, it has to provide charged particle momentum measurement and vertex determination with sufficient momentum resolution (better than 2.5 % for electrons with momentum of about 4 GeV/c), tracking efficiency (larger than 90 %) and two-track separation (resolution in relative momentum below 5 MeV/c) in the p_{t} region up to several 10 GeV/c and pseudo-rapidity $|\eta| < 0.9$. Furthermore, the TPC has to allow the inspection and tracking of electron candidates identified in the TRD, at central collision rates of up to 200 Hz and to provide dE/dx measurements for charged particles with pseudo-rapidities in the range $-1 < \eta < +1$. Although large size TPCs have been successfully employed by the NA49 and STAR experiments for the study of heavy ion collisions at SPS and RHIC, respectively, the extreme particle densities expected at LHC energies and the large drift volume of the ALICE TPC, the biggest ever built, required a careful design, leading to many individual innovative aspects. As shown in Fig. 3, it consists of a 88 m^3 cylindrical field cage, divided in two drift regions, back-to-back, by a central membrane.

This membrane is a high voltage central electrode which defines in each of these two regions a uniform electrostatic field, to transport the primary electrons over a distance of 250 cm towards the readout end plates. The readout chambers are conventional multi-wire proportional chambers with cathode planes segmented in pads equipped with an electronics chain to amplify, digitize and pre-process the signal before transmission to the DAQ. Each of the 570 000 channels includes a custom digital circuit that, with an innovative approach, performs tail cancellation, digital baseline restoration, data compression and multi-event buffering for event de-randomization. The azimuthal segmentation of each readout plane consists of 18 trapezoidal sectors, each covering 20°.

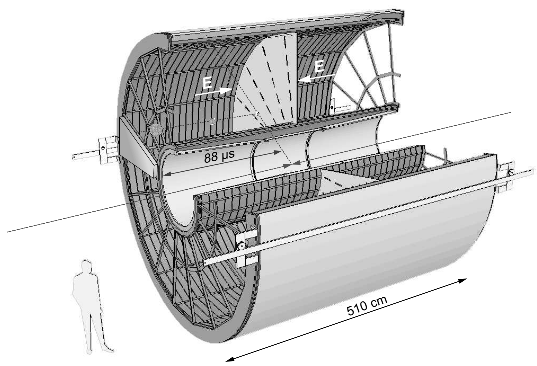

Fig. 3. Cut-away view of the ALICE TPC showing the central electrode and the field cage.

Charged particles traversing the field cage volume ionize the gas along their path, liberating electrons that drift towards the end plate of the chamber, where the signal amplification is provided through avalanche effect (gas gain of 2×10^4) in the vicinity of the anode wires. Moving from the anode wire towards the surrounding electrodes, the positive ions created in the avalanche induce a positive signal on the pad plane. The field cage and the containment volume are constructed from two concentric cylinders each, sealed by an annular disc (end plate) on either side. The inner radius ($r = 90$ cm) is given by the maximum acceptable density of hits in the inner TPC volume whilst the outer radius ($r = 250$ cm) is determined by the minimum track length required for achieving a dE/dx resolution better than 10 %. Good momentum resolution and the need to keep the distortions small, which are created by the space charge, require a drift gas with low diffusion, low Z and large ion mobility. Extensive investigation of different gas mixtures has been performed, leading to the choice of the adopted mixture (85% Ne–10% CO_2–5% N_2). This drift gas, however, requires a high drift field (400 V/cm) to secure an acceptable drift time of $\sim 88\,\mu$s.

Therefore, the high voltage on the central electrode has to be as high as 100 kV. An insulating envelope filled of CO_2 gas surrounds the actual field cage for operational safety reasons.

4.3. The Transition Radiation Detector

The TRD will identify electrons with momenta above 1 GeV/c, near mid-rapidity, to study the suppression of quarkonia decaying in electron pairs and the production of heavy quarks (charm, beauty) in their semi-leptonic decays. A pion rejection factor of 100 % at 90 % electron efficiency for momenta larger than 2 GeV/c is required.

The TRD consists of six layers of xenon-filled time expansion chambers with a radiator stack of carbon fibers optimized to provide the best compromise between TR yield, radiation thickness and mechanical stability. In order to keep the total anticipated radiation thickness X/X_0 below 15%, the radiator is made of polypropylene fibres mats of 3.2 cm total thickness, sandwiched between two Rohacell foam sheets of 0.8 cm thickness each. The foam sheets are reinforced by carbon fiber sheets laminated onto the surface with a thickness of 0.1 mm. 540 individual detector modules with a total active area of roughly 750 m^2 and 1.2 million read-out channels surround the TPC starting at a radius of 2.9 m and extending to 3.7 m. With an overall length of 7 m, the TRD barrel is azimuthally segmented in 18 sectors covering a rapidity range between −0.9 and 0.9. Each sector is subdivided in 5 stacks in the longitudinal direction.

The electronics has been designed to feature a fast local cluster recognition to produce a Level-1 trigger on high-p_t leptons or hadrons within 6μs after the collision, thus enriching the statistical sample of the observables under study. The tracking capability of the TRD, in junction with ITS and TPC, will valuably improve the predicted momentum resolution for charged particles as shown in Fig. 4. The results indicate that the ALICE tracking system will reach a good momentum resolution up to $\sim$ 100 GeV/c, even at the highest multiplicities, enabling detailed jet fragmentation studies.

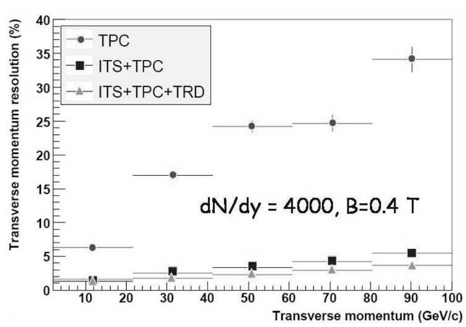

Fig. 4. Momentum resolution as a function of the transverse momentum.

4.4. The Time of Flight detector

Low momentum hadron identification will be achieved via measurements of energy loss in the silicon layers and in the TPC gas, while above the $1/\beta^2$ region, identification will be performed by employing the TOF barrel. Based on 1638 double-stack multigap resistive plate chambers (MRPC) with an intrinsic time resolution of about 60 ps, the TOF barrel covers a surface larger than $160\,\mathrm{m}^2$ at a radius of about 3.7 m. It has been optimized for the identification, on a track-by-track basis, of hadrons with a transverse momentum below $2\,\mathrm{GeV}/c$, with a separation between pions and kaons better than 3 sigmas to keep the contamination below a 10 % level in presence of a huge bulk of hadrons at low momentum.

A cross section of the ALICE MRPC is shown in Fig. 5. Each resistive electrode is spaced one from the other with equal sized spacers creating a series of ten gas gaps, each $250\,\mu$m thin. Electrodes are connected to the outer surfaces of the stack of resistive plates reading out all gas gaps in parallel while all the internal plates are left electrically floating. The flow of positive ions and electrons generated in the avalanche processes maintain the correct voltage between the intermediate plates. Pickup pads (96 per strip), with an area of $3.5 \times 2.5\,\mathrm{cm}^2$ each, are arranged in two-row arrays.

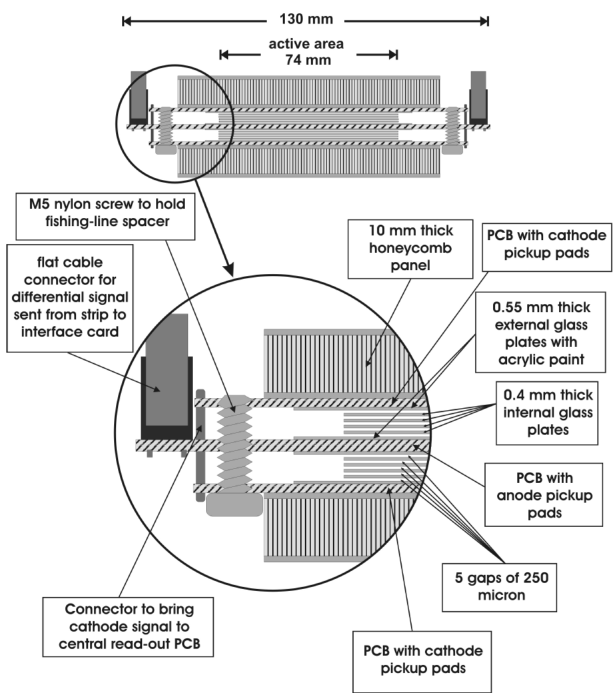

Fig. 5. Schematic description of the ALICE TOF.

Time resolutions as good as 65 ps have been achieved on large size prototypes. Lifetime and rate capability above 50 Hz/cm^2 have been measured at the CERN Gamma Irradiation Facility (GIF) and proved to be in excess of the ALICE requirements.

4.5. The High Momentum Particle Identification system

The HMPID, an array of seven proximity focusing Ring Imaging Cherenkov (RICH) detectors, located at 4.7 m from the beam axis, will further enhance the PID capability of the ALICE layout by exploiting the novel technology of manufacturing large area CsI photocathodes to identify particles beyond the momentum interval covered by the TOF. Namely, the HMPID has been optimised to extend the useful range for the identification of π/K and K/p, on a track-by-track basis, up to 3 GeV/c and 5 GeV/c, respectively. The single-arm geometry with a HMPID acceptance of 5 % of the central barrel phase space is motivated by the need to measure the spectra of particles with a momentum above 1 GeV/c in an inclusive manner, with the possibility to build classes of events using the event-by-event characterization performed at lower momenta by the barrel detectors.

4.6. The Forward Spectrometer

The Forward Spectrometer will measure the decay of heavy quark resonances into muons, both in proton–proton and in heavy-ion collisions, with a mass resolution (about 100 MeV/c^2 at quarkonia masses of 10 GeV and better than 70 MeV/c^2 in the J/Ψ region) and momentum precision (about 1%) sufficient to separate all states on a continuum due to B and D meson decays and Drell–Yan processes. It consists of a complex arrangement of absorbers (reaching totally about $18\lambda_{\rm int}$) to reduce as much as possible the hadron punch-through into the spectrometer and the back-splash into the TPC, a large dipole magnet (3 Tm integral field), ten stations of thin MWPC equipped with highly segmented cathodes for tracking and four Resistive Plate Chambers to identify and trigger on the muon tracks escaping from the muon filter through the dipole magnet.

A high-density small angle absorber with a central hole shields the spectrometer from the particles emitted at angles below 2° allowing the beam particles to traverse the spectrometer.

The construction of gas-filled chambers with pad read-out is based on a well known technology. However, the large total surface of the muon chambers, over 100 m^2, and the huge number of electronic channels employed, almost one million, required an intensive R&D activity to optimize cost and performance. Frameless modules, almost free of dead areas to maximize the acceptance, and low cost front-end chips were specifically designed and manufactured.

5. Construction status

The current LHC schedule, as approved by the CERN Council in the June 2006 meeting, envisages the start-up in November 2007 by colliding proton beams at a center-of-mass energy of 0.9 TeV, whereas the run at the full collision energy of 14 TeV and lead nucleus collisions will occur in Spring and Fall 2008, respectively.

The ALICE collaboration is fully committed to achieve a timely completion of the apparatus allowing early and full exploitation at the start of LHC. The construction is well advanced for all of the detector systems. The functionality and performance of the L3 solenoid magnet and of the muon arm dipole magnet has been checked and the magnetic field mapped accurately. The commissioning tests have confirmed the compliance to all design parameters and the long term stability of magnet operation. Ancillary systems have been put in place and most of the cables and pipes have been installed and commissioned. Platforms and gangways have been modified and adapted to the new cavern layout. Refurbishing of the counting rooms and the installation of racks has been completed.

The lowering of the main detectors into the underground cavern is scheduled to start by September this year. HMPID, being in a very advanced stage with the seven modules already in place onto the cradle and, having completed the commissioning successfully, will be the first detector to enter in the L3 magnet followed by the TPC. Owing to the complexity of the assembly operation, ITS will be the last detector to be integrated in the barrel. The installation of the modular barrel detectors (TOF and TRD) is envisaged to occur in steps for the twofold reason to balance the weight on the mechanical structure supporting the barrel detectors and the need to avoid any interference with the TPC and ITS integration phases.

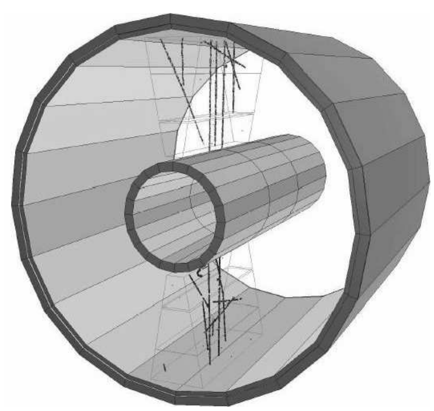

Fig. 6. Cosmic ray tracks reconstructed in two TPC sectors during the commissioning tests.

The construction of the main ALICE tracking system, the TPC, has been completed since long with all the wire chambers installed and equipped with the electronic cards. Analysis of recorded cosmic-ray events (Fig. 6) and laser induced tracks have indicated that the main parameters match the design values.

The muon spectrometer assembly has started in parallel to the barrel detector installation since April 2006 by placing in position the absorbers and the large support structures for the tracking and trigger chambers.

6. Conclusion

LHC, scheduled to start commissioning in fall 2007, will be the ultimate facility for searching the transition of hadronic matter to a short-lived state, called Quark–Gluon Plasma, by means of head-on collisions between ultra-relativistic heavy nuclei at energies about thirty times higher than at RHIC in BNL. A large international community of physicists is engaged in building the ALICE detector, which will exploit new signatures and likely draw conclusions on the character of the strong interaction and on the evolution of the early universe. The ALICE construction is steadily progressing towards the major milestone: completion of the installation and test of the detectors by August 2007 to be ready to record the first *pp* collisions at LHC start-up.

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