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Technical Notes

The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events

J. Alme [a], Y. Andres [d], H. Appelshäuser [g], S. Bablok [a], N. Bialas [a], R. Bolgen [a], U. Bonnes [f], R. Bramm [h], P. Braun-Munzinger [f,h,m,n], R. Campagnolo [d], P. Christiansen [j], A. Dobrin [j], C. Engster [d], D. Fehlker [a], Y. Foka [h,*], U. Frankenfeld [h], J.J. Gaardhøje [e], C. Garabatos [h], P. Glässel [i], C. Gonzalez Gutierrez [d], P. Gros [j], H.-A. Gustafsson [j], H. Helstrup [b], M. Hoch [d], M. Ivanov [h], R. Janik [c], A. Junique [d], A. Kalweit [f], R. Keidel [o], S. Kniege [g], M. Kowalski [k], D.T. Larsen [a], Y. Lesenechal [d], P. Lenoir [d], N. Lindegaard [e], C. Lippmann [d], M. Mager [d], M. Mast [d], A. Matyja [k], M. Munkejord [a], L. Musa [d], B.S. Nielsen [e], V. Nikolic [l], H. Oeschler [f], E.K. Olsen [e], A. Oskarsson [j], L. Osterman [j], M. Pikna [c], A. Rehman [d], G. Renault [e], R. Renfordt [g], S. Rossegger [d], D. Röhrich [a], K. Røed [b], M. Richter [a], G. Rueshmann [g], A. Rybicki [k], H. Sann [h,1], H.-R. Schmidt [h], M. Siska [c], B. Sitár [c], C. Soegaard [e], H.-K. Soltveit [i], D. Soyk [h], J. Stachel [i], H. Stelzer [h], E. Stenlund [j], R. Stock [g], P. Strmeň [c], I. Szarka [c], K. Ullaland [a], D. Vranic [h], R. Veenhof [d], J. Westergaard [e], J. Wiechula [i], B. Windelband [i]

[a] Department of Physics, University of Bergen, Bergen, Norway
[b] Faculty of Engineering, Bergen University College, Bergen, Norway
[c] Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
[d] European Organization for Nuclear Research (CERN), Geneva
[e] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[f] Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany
[g] Institut für Kernphysik, Johann-Wolfgang-Goethe Universität Frankfurt, Frankfurt, Germany
[h] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[i] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[j] Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
[k] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[l] Rudjer Bošković Institute, Zagreb, Croatia
[m] ExtreMe Matter Institute, EMMI, GSI, Darmstadt, Germany
[n] Frankfurt Institute for Advanced Studies, J.W. Goethe University, Frankfurt, Germany
[o] Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany

Acronyms: AC, alternating current; ACORDE, ALICE COsmic ray DEtector; ADC, analog to digital converter; ALEPH, apparatus for LEP PHysics; ALICE, a large ion collider experiment; ALTRO, ALICE TPC ReadOut chip; BC, board controller; CAD, computer aided design; CAN, controller area network; CCD, charge-coupled device; CERN, Conseil Européen pour la Recherche Nucléaire (European Organization for Nuclear Research); CFD, computational fluid dynamics; CMOS, complementary metal–oxide-semiconductor; CSA, charge sensitive amplifier; CTP, central trigger processor; CU, control unit; DAC, digital to analog converter; DAQ, data acquisition system; DC, direct current; DCS, detector control system; DDL, detector data link; DIM, distributed information management system; DNL, differential non-linearity; D-RORC, DAQ RORC data ReadOut receiver card; DU, device unit; ECS, experiment control system; EEPROM, electrically erasable programmable read only memory; ELMB, embedded local monitor board; EMCAL, ElectroMagnetic CALorimeter; ENC, equivalent noise charge; ENOB, equivalent number of bits; FEC, front-end card; FEE, frond-end electronics; FEM, finite element method; FET, field-effect transistor; FMD, forward multiplicity detector; FPGA, field programmable gate array; FSM, finite state machine; FWHM, full width half maximum; GEM, gas electron multipliers; GTL, gunning transistor logic (FEE-bus technology); HCMOS, high-speed CMOS; HF, high frequency; HLT, high level trigger; HMPID, high momentum particle identification detector; HV, high voltage; INL, integral non-linearity; IROC, inner ReadOut chamber; ITS, inner tracking system; L0, level 0 trigger; L1, level 1 trigger; L2(a,r), level 2 trigger (accept, reject); L3, magnet used by LEP-L3 experiment; LAN, local area network; LDC, local data concentrator; LEP, large electron positron collider; LHC, large hadron collider; LSB, least significant bit; LV, low voltage; LVCMOS, low-voltage CMOS; MEB, multiple event buffer; MSPS, mega-samples per second; MTBF, mean time between failures; MWPC, multi-wire proportional chamber; NMOS, N-type metal–oxide-semiconductor field effect transistors; NTP, normal temperature and pressure; OCDB, offline conditions data base; OLE, object linking and embedding; OPC, OLE for process control; OROC, outer ReadOut chamber; PASA, PreAmplifier ShAper; PCB, printed circuit board; PEEK, polyaryl-ether-ether-ketone; PHOS, PHOton spectrometer; PID, proportional–integral-derivative; PLC, programmable logic controller; PMD, photon multiplicity detector; PMEM, pedestal MEMory; PMOS, P-type metal–oxide-semiconductor field effect transistors; PS, power supply; PVSS, prozessvisualisierungs- und steuerungs- system; RCC, ring cathode chamber; RCU, readout control unit; RHIC, relativistic heavy ion collider; RICH, ring imaging Cherenkov; RMS, root mean square; ROC, ReadOut chamber; SCADA, supervisory controls and data acquisition; SEL, single event latchup; SEU, single event upset; SFDR, spurious-free dynamic range; SIU, system interface unit; *S/N*, signal-to-noise ratio; SRAM, static random access memory; SSW, service support wheel; STAR, solenoidal tracker At RHIC; TCF, tail cancellation filter; TCP/IP, transmission control protocol/internet protocol; TDR, technical design report; TID, total ionization dose; TOF, time-of-flight detector; TP, technical proposal; TPC, time projection chamber; TQFP, thin quad flat pack (chip package); TRD, transition radiation detector; TRG, TRigGer system; TTC, timing, trigger and control; UPS, uninteruptible power supply; UV, ultra violet; ZDC, zero degree calorimeter.

* Corresponding author. Tel.: +41 76 487 4387; fax: +41 22 767 7910.
E-mail address: Yiota.Foka@cern.ch (Y. Foka).

[1] Deceased.

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ABSTRACT

The design, construction, and commissioning of the ALICE Time-Projection Chamber (TPC) is described. It is the main device for pattern recognition, tracking, and identification of charged particles in the ALICE experiment at the CERN LHC. The TPC is cylindrical in shape with a volume close to 90 m^3 and is operated in a 0.5 T solenoidal magnetic field parallel to its axis.

In this paper we describe in detail the design considerations for this detector for operation in the extreme multiplicity environment of central Pb–Pb collisions at LHC energy. The implementation of the resulting requirements into hardware (field cage, read-out chambers, electronics), infrastructure (gas and cooling system, laser-calibration system), and software led to many technical innovations which are described along with a presentation of all the major components of the detector, as currently realized. We also report on the performance achieved after completion of the first round of stand-alone calibration runs and demonstrate results close to those specified in the TPC Technical Design Report.

1. Introduction

The ALICE [1,2] Time-Projection Chamber (TPC) [3] is the main device, in the ALICE 'central barrel', for tracking of charged particles and particle identification.

The main goal of the ALICE experiment at the CERN Large Hadron Collider (LHC) is the investigation of Pb–Pb collisions at a center-of-mass energy of 5.5 TeV per nucleon pair. Tracking of charged particles in such an environment can only be performed with a detector which can cope with unprecedented densities of charged particles: the maximum expected rapidity density in Pb–Pb collisions at LHC energy is about 3000 [4]. Furthermore, a comprehensive experiment needs to cover full azimuth and provide a significant acceptance in pseudo-rapidity $\eta = -\ln\tan\theta/2$ with θ the polar angle. In addition, the detector should provide excellent momentum and energy-loss resolution and run at extremely high rates (>300 Hz for Pb–Pb central collisions, >1.4 kHz for proton–proton collisions).

The resulting detector choice was a large-volume TPC with overall 'conventional' lay-out but with nearly all other design parameters beyond the state of the art. This manuscript describes in detail the resulting detector and outlines the path from design considerations to construction and commissioning.

In outline the ALICE TPC consists of a hollow cylinder whose axis is aligned with the beams from the LHC and is parallel to the ALICE detector's solenoidal magnetic field. The active volume has an inner radius of about 85 cm, an outer radius of about 250 cm, and an overall length along the beam direction of 500 cm. A conducting electrode at the center of the cylinder, charged to 100 kV, provides, together with a voltage dividing network at the surface of the outer and inner cylinder, a precise axial electric field of 400 V/cm. The detector is filled with a counting gas consisting of a Ne–CO_2–N_2 mixture at atmospheric pressure. Charged particles traversing the detector ionize the gas. The ionization electron drift, under the influence of the electric field, to the endplates of the cylinder, where their arrival point in the cylinder plane is precisely measured. Together with an accurate measurement of the arrival time (relative to some external reference such as the collision time of the beams from the LHC) the complete trajectory in space of all charged particles traversing the TPC can be determined with precision.

The ALICE set-up is shown in Fig. 1. The TPC surrounds the Inner Tracking System (ITS) which is optimized for the determination of the primary and secondary vertices and precision tracking of low-momentum particles. On the outside the Transition Radiation Detector (TRD) is designed for electron identification. The outermost Time-Of-Flight (TOF) array provides pion, kaon, and proton identification. In addition, there are three single-arm detectors: the Photon Spectrometer (PHOS), the Electro-Magnetic CALorimeter (EMCAL) and an array of RICH counters optimized for High-Momentum Particle IDentification (HMPID).

The 0.5 T magnetic field in the central barrel is provided by the L3 solenoidal magnet previously used by the L3 experiment.

The ALICE TPC was designed to cope with the highest conceivable charged particle multiplicities predicted, at the time of the Technical Proposal (TP), for central Pb–Pb collisions at LHC energy [1,5,6], i.e. rapidity densities approaching $dN_{ch}/dy = 8000$ at center-of-mass energy of 5.5 TeV.[2] Its acceptance covers 2π in azimuthal angle and a pseudo-rapidity interval $|\eta| < 0.9$. Including secondaries, the above charged particle rapidity density could amount to 20 000 tracks in one interaction in the TPC acceptance.

Furthermore, the design of the readout chambers, electronics, and data handling allows inspection of up to several hundred such events per second with a maximum interaction rate of 8 kHz for Pb–Pb collisions, implying special precautions to minimize the effects of space-charge built-up in the drift volume of the TPC on the track reconstruction.

To realize a detector which performs efficiently in such an environment required the development of many new components and procedures. A summary of the design parameters is presented in Tables 1–3. A summary and system overview can be found in Ref. [2].

In this paper we describe the major components of the detector as currently realized and report on the performance achieved after completion of the first round of calibration runs.

The first major challenge was the design and construction of the field cage, whose overall thickness should not exceed 5% of a radiation length while providing, over a volume of nearly 90 m^3, an axial electric field of 400 V/cm with distortions in the 10^{-4} range. The realization of this device is described in Section 2.

The readout chambers are installed at the two endplates of the cylinder. Their design is based on the Multi-Wire Proportional Chamber (MWPC) technique with pad readout. To ensure low diffusion of the drifting electrons and a large ion mobility, Ne was chosen as the main component of the counting gas. Furthermore, the size of the readout pads had to be adapted to the expected large multiplicities, implying pad sizes as small as $4 \times 7.5\ mm^2$ in the innermost region. As a consequence, the readout chambers have to be operated safely at gains near 10^4. In Section 3 we describe the technical implementation and report on the first operating experience of these detectors.

In Section 4 we discuss the design and implementation of the electronics chain. Because of the high granularity (557 568 readout channels) special emphasis was placed on very low power consumption. To cope with the large dynamic range needed to track particles from very low to high momenta, and to

[2] More recent estimates [4] put this number at $dN_{ch}/dy < 3000$.