Engineering challenges included the stabilization of the temperature of about 100 t of crystals and 130 000 APDs to 0.1°C (achieved by water cooling) and stabilizing the bias voltage of the APDs to some tens of mV. This was necessary because the APD gain has large temperature (−2.4%/°C), and bias voltage dependence (3%/V). The goal was to keep these contributions to the energy resolution at the ‰ level. The crystals were supported by specially developed, lightweight carbon-fibre or glass-fibre structures and integrated with high performance electronics. The performance of the lead tungstate calorimeter in test beams is illustrated in Fig. 8.18(c). Figure 8.18(d) shows the installed barrel part of the crystals calorimeter in the CMS underground cavern. The result related to the physics benchmark reaction (that of the di-photon mass spectrum) clearly showing the presence of the Higgs boson, is illustrated in [13].

Concluding remarks
It is remarkable, if not surprising, that the ATLAS and CMS Collaborations have chosen two very different techniques for their electromagnetic calorimeters, yet addressing and meeting overall the same physics goals. This did not happen by design or by a committee decision. It happened, because even in these 3000-plus strong collaborations the physicists and engineers use their experience, familiarity, conviction and "taste" in selecting an experimental approach and shaping the decisions. In each of the two collaborations members were familiar with the respective technology and were able to convince their collaborations that the technology could be honed to achieve the required performance. "Required" means achieving a measurement accuracy which approaches the intrinsic performance limited only by the fundamental aspects. There was little room for even the slightest degradation, lest the discovery of the Higgs boson be jeopardized. That both collaborations reported, on the same day of July 4, 2012, the discovery of the Higgs boson with the same experimental significance is a tribute to the foresight, intuition, perseverance and dedication of many hundreds of students, technicians, engineers and physicists worldwide.

8.9 Multigap Resistive Plate Chamber: Chronometry of Particles

Crispin Williams

The ALICE experiment at the CERN LHC is designed to study nuclear matter under extreme conditions of temperature and density produced in collisions of heavy ions. Knowledge of the identity of the particles emerging from such a collision is crucial for this research. That this is not a trivial task can be appreciated by observing Fig. 8.19, which displays a typical heavy ion collision. Among the thousands of particles, which are, for example, the protons, pions or kaons?

Most of these particles are produced with momenta less than a few GeV/c. For these particles a frequently used technique is the "Time-of-Flight" (ToF) velocity measurement. The curvature of the tracks in a magnetic field determines the particle momentum (i.e. "relativistic" mass × velocity). If the velocity is also measured, its mass can be determined; hence its identity is inferred. All that is needed is to surround the central tracker with a detector capable of precisely measuring the arrival time of the particles. This, together with the time the collision occurred and the distance to the point of collision gives the time-of-flight (and its velocity) and thus, with the momentum measurement, its mass. The detector must be highly segmented, so that each of the thousands of particle tracks has its own individual time stamp. This detector must also work in a strong magnetic field.

In the late 1990s ALICE started to develop its experimental concept. ToF-identification was an essential part, but none of the existing techniques were remotely close to meeting the novel and stringent specifications: a new detector was needed. The breakthrough was the "The Multigap Resistive Plate Chamber" [42].

The principle of this detector is as simple as it is elegant. It is a derivative of the time-honoured gaseous parallel plate detector. A single gap Resistive Plate Chamber (RPC) is shown in cross section in Fig. 8.20. A strong electric field is applied across this gap. A charged particle traversing the gap ionizes the gas molecules producing positive ions and electrons. Typically, a few primary ionisation collisions occur in the 2 mm gap. The electrons are accelerated in the strong electric field, collide with and further ionize the gas molecules leading to

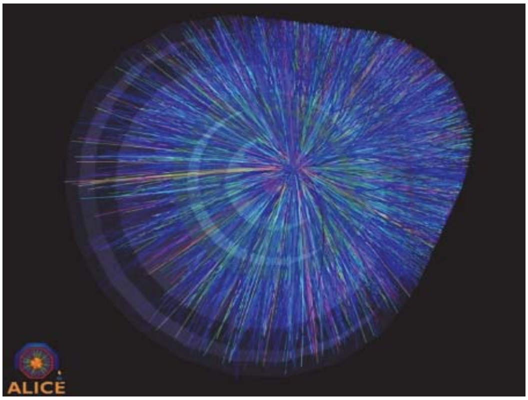

Fig. 8.19. A lead-lead collision observed in the ALICE experiment. Each of the lines represents a particle track. (Source: ALICE).

an avalanche [Highlight 4.8]. The movement of these charges induces signals at the pick-up electrodes. Registering the induced signal provides a measurement of the position of the particle and the arrival time. The time resolution is quite respectable being typically 2×10^{-9} sec (2 ns). But this was not good enough for ALICE where a time resolution of < 0.1 ns (100 ps) was required.

Progress came through a detailed understanding of the processes influencing the time resolution. Only avalanches that are initiated close to the cathode can grow to a sufficient size able to produce a detectable signal. Fluctuations in its initial growth give rise to time jitter (i.e. uncertainty) of the observed signal. Decreasing the width of the gap decreases the time jitter; but this also decreases the efficiency of the detector. The *Multigap Resistive Plate Chamber (MRPC)* is a solution invented and developed by the LAA project at CERN. The gas is divided into several small gas gaps (five in this example) with a single pair of readout electrodes, as shown in Fig. 8.21. The voltage is applied to the outer surfaces of the two external plates. The internal plates are allowed to float electrically, which considerably eases construction. The MRPC is made by stacking sheets of resistive material (window glass in the case of the ALICE TOF barrel). The gap size is controlled by running a fishing line (!) across the surface. This is the short version of a long story of heated debates between experts, on whether such a device would work and how exactly it should be constructed. Details are revealed in [42].

A crucial aspect of precise timing is the readout technique for a highly segmented large-area detector. Suppression of electronic noise is mandatory in order not to spoil the timing resolution. This is best achieved with a ‘differential’ readout, where both pickup electrodes are separated from the electrical ground of the system, and connected to a differential amplifier. An ultra-fast differential

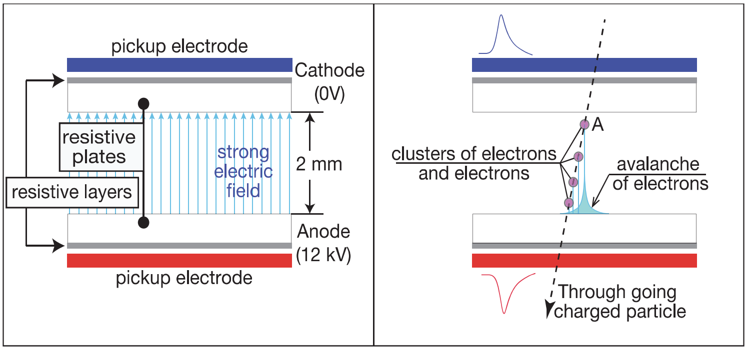

Fig. 8.20. Cross section of single 2 mm gap RPC. A traversing charged particle creates clusters of electrons and ions in the gas. The electrons avalanche across the gap due to the high electric field.

amplifier-discriminator, known as the NINO, was developed in 250 nm CMOS technology and has become the standard for precise timing. Together with these developments, MRPCs have been shown to be excellent high performance TOF detectors meeting the requirement of a systems time resolution below 100 ps [42].

For ALICE a TOF cylindrical detector of radius 3.7 m with a length of 7 m was built surrounding the Time Projection Chamber (TPC). The MRPCs have ten 250 micron gaps; the detector planes are segmented into $2.5 \times 3.5\ \mathrm{cm}^2$ pads, resulting in a total of 160,000 signal channels. All MRPCs are operated at the same applied voltage and the same discriminator threshold. Figure 8.22 shows a typical plot of $\beta = v/c$ (measured by the TOF) versus the momenta measured by the TPC. At low momenta, the dE/dx measurements from the TPC provide additional identification power [Box 5.2]. A similar detector based on these MRPCs has been built for the STAR heavy ion experiment at RHIC. A TOF barrel built from MRPCs will be installed for the BES III experiment at IHEP, Beijing. The CBM experiment at GSI/FAIR is planning to build a 120 m^2 wall of MRPCs for TOF measurements [43]. There are also proposals to build a neutron detector with precise timing with MRPCs embedded between iron plates. MRPCs are also being considered as detectors of 511 keV gamma photons for Positron-Emission-Tomography (PET), where its excellent time resolution would improve the imaging quality.

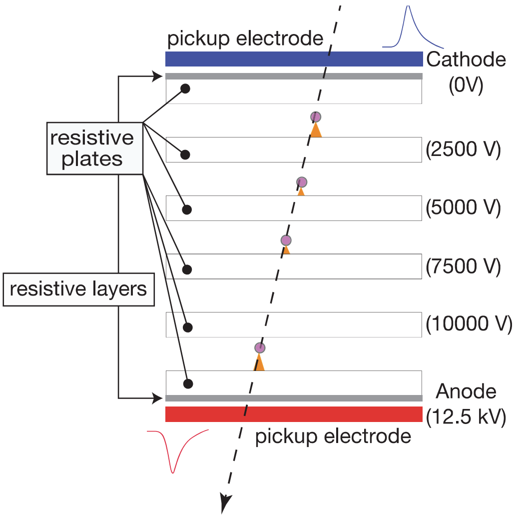

Fig. 8.21. Schematic cross-section of a Multigap Resistive Plate Chamber (MRPC). Voltage is only applied to the outer surface of the two external plates. All internal plates are electrically floating.