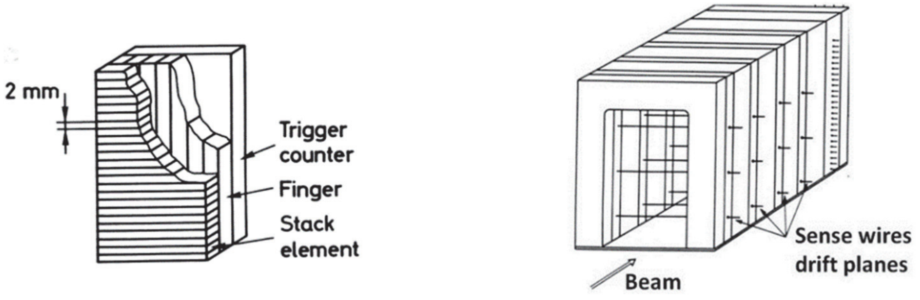


Fig. 4.14. Left: the small hodoscope of scintillation counters used by the CERN-Rome group at the ISR. Right: sketch of a special drift chamber used by the UA4 group at the CERN p–p̄ collider. The U-shaped frame of the chamber allowed the sensitive region of the chamber to approach the beams to within a few mm. An improved pot with a flat bottom plate was used for this experiment [48].

## 4.8 The Gas Detector (R)evolution

Fabio Sauli

The physics models current at the time of the conception of the ISR favoured the design of experimental setups optimized for detection of particles generated by proton-proton collisions in the forward direction. This required a detector design capable of bringing the sensitive area as close as possible to the vacuum chamber of the machine, and able to handle very high particle fluxes. None of the devices used in the sixties could meet these requirements. The invention in 1968 at CERN by Georges Charpak of the Multi-Wire Proportional Chamber (MWPC) [Box 4.4] completely changed the scenario [51]. Capable of detecting and electronically recording particle positions at a high rate, and permitting the coverage of large areas, they could be tailored to be sensitive a few cm from the vacuum chamber. It started a revolution in particle physics, recognized with the Nobel Prize to Charpak in 1992. The choice of this novel technology as main tracker of the Split-Field Magnet Detector (SFMD) was natural, albeit daring. A large-size MWPC prototype built by Charpak and collaborators is shown in Fig. 4.15 [52].

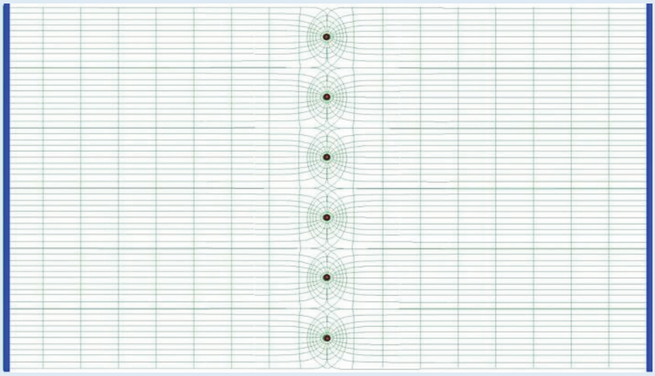
The original MWPC design, making use of heavy frames to tension and hold the stretched wires, was found to be ill-suited for installation within a magnet, where the ratio of sensitive to total detector area is a premium. An alternative assembly offered a much improved aspect ratio: light honeycomb plates tailored to cover the sensitive area, with the wires soldered to slender frames glued to the support plates [53]. This structure is very light and easy to handle, and has since been used for a large number of experiments.

**Multi-wire proportional chambers** **Box 4.4**

The multi-wire proportional chamber (MWPC), is a gas-filled radiation detector made with a grid of parallel and closely spaced thin metal wires (the anodes) stretched between two electrodes (the cathodes), see figure below. The typical wire spacing is one to few millimetres with a distance between cathodes of the order one cm. On application of a voltage between the electrodes, electrons released in the gas by ionizing radiation drift towards the anodes, where in the increasing electric field they collide with and ionize the gas molecules, resulting in charge multiplication, in a process called an electron-ion avalanche.

Even though multiplication factors of several tens of thousands can be reached in most gases, in order to detect small ionization yields it was necessary to use rather expensive electronics. This requirement made it problematic at the time to implement the large systems needed for particle physics. Discovered by Charpak and collaborators, filling with so-called "magic gas", a mixture of three or four component gases, permitted to reach gains above a million, and was paramount in the choice of the technology to equip the first large all-electronic detectors.

The MWPC localization accuracy, limited by the wire spacing of one or two millimetres, can be improved by an order of magnitude by measuring the charge distribution induced by the ion avalanches hitting the suitably segmented cathode planes.



MWPC schematic showing electric field lines between anode (centre) and cathode wires (sides).

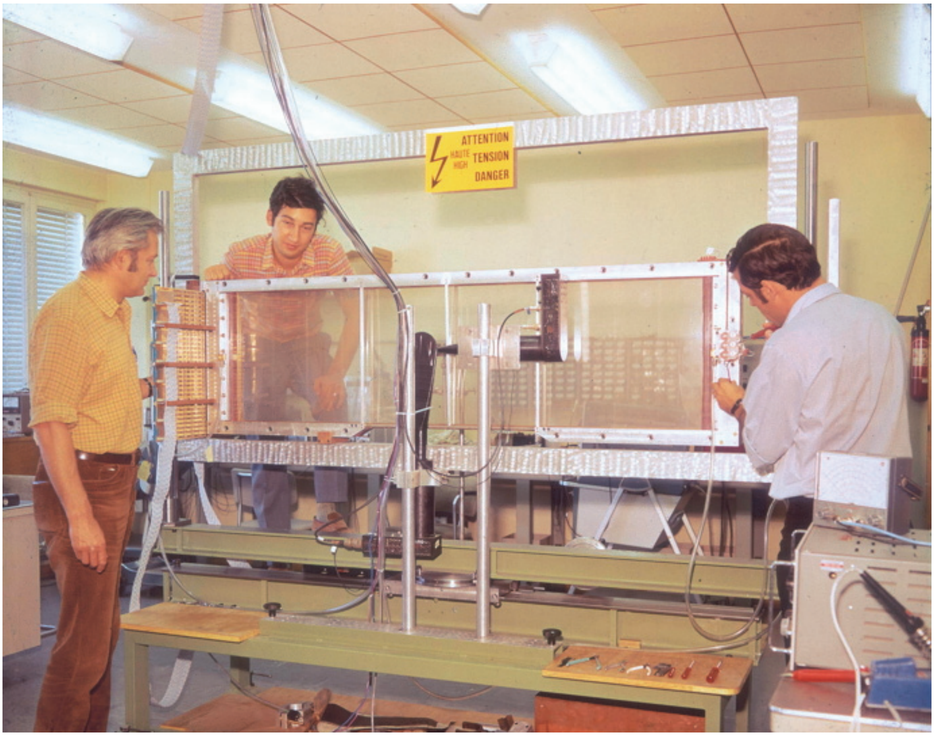


Fig. 4.15. Georges Charpak (left) and collaborators with one of the first large MWPCs.

A system of 40 MWPCs of this light-weight design with around 50,000 sense wires and the electronics to read the signals was completed in record time, and in 1972 the SFMD was ready to take data (Fig. 4.16). With one coordinate provided by the wire hit, and a coarser information given by pickup strips on the cathode planes, the detectors provided two-dimensional space points for the measurement of particle momenta from their bending radius in the magnetic field. The SFMD took data along the operating lifespan of the ISR, producing many results of relevance for fundamental physics.

The quest for free quarks, one of the physics motivations to build the ISR, was not successful, despite the demonstration that the single-electron sensitivity achieved using the "magic gas" filling permitted to efficiently detect the hypothetical particles. It became clear later that "confinement", a fundamental property of the strong interaction, prevents the existence of free quarks and hence their direct observation in the laboratory.

There were many derivatives of the revolutionary MWPC concept. In one frequently used form the drift time between the passage of a particle and the arrival time of the ionization charge on the anode wire is measured, providing much improved position information. These "Drift chambers" were widely used at the ISR [Box 4.5], the most advanced version being constructed for the Axial Field Spectrometer (AFS), shown in Fig. 4.17 [54]. Two half-cylinders around the central beam pipe were immersed in the field of the Axial Field Magnet [Highlight 4.11]. The full azimuth was subdivided into $4^0$ cells, each one being instrumented radially with 42 anode wires, measuring the drift time. This very high subdivision was instrumental in imaging events with highly collimated groups of particles. These were some of the first observations of "jets", the incarnation of quarks and gluons expelled from confinement.

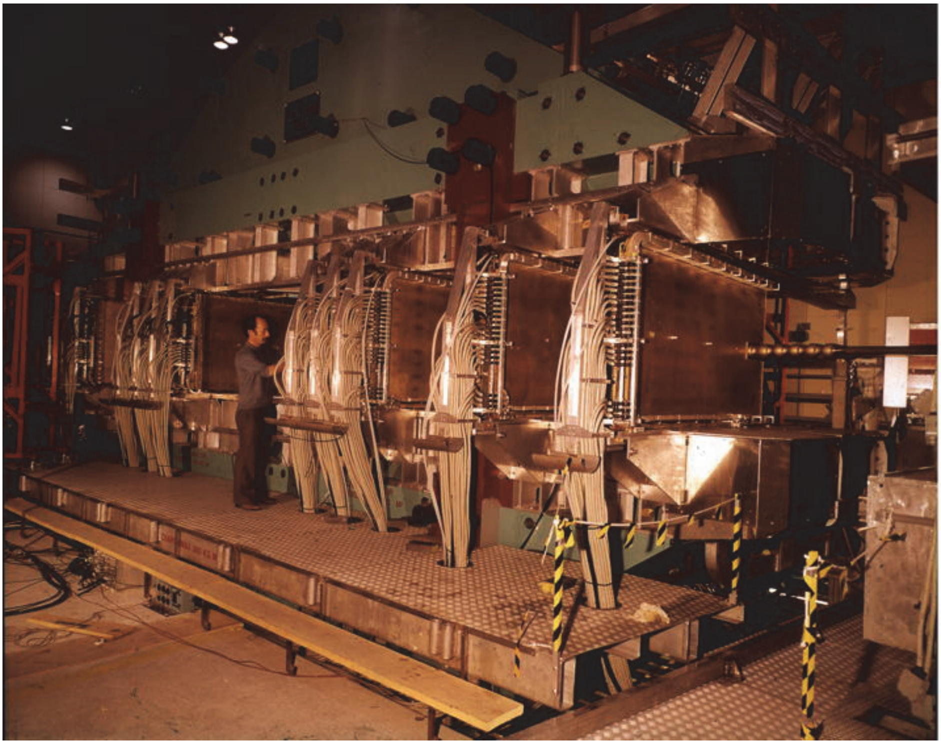
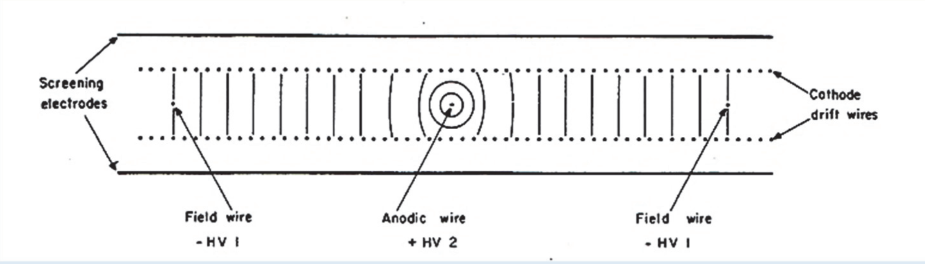


Fig. 4.16. The Split-Field Magnet Detector with the MWPCs of the novel light-weight design installed between the poles of the magnet.

**Multi-wire drift, imaging and time projection chambers** **Box 4.5**

A measurement of the time taken by the electrons released in the gas to reach the anodes, together with a precise knowledge of their drift velocity permits to infer the distance of the track from the wires with sub-mm accuracy. Developed in a wide variety of designs, from planar to cylindrical structures with cell sizes of several centimetres, multi-wire drift chambers provide localization accuracies of a few hundred microns or better with a relatively small number of measurement channels. Examples of large drift chamber systems are the cylindrical AFS detector used at the ISR (see main text), and the UA1 imaging drift chambers at the CERN proton-antiproton collider [Highlight 6.5].

In the time projection chamber, first used at SLAC and then in two LEP experiments and presently in ALICE at the LHC, the sensitive volume is a large gas vessel where ionisation trails are produced by the particles; the vessel is instrumented at one end with MWPCs. A measurement of the drift time gives the distance of the tracks from the wires, while a recording in short time intervals of the charge induction profiles on one cathode, stripped or padded, provides the other two orthogonal coordinates.



Schematic drawing of the high accuracy drift chamber.

Widely used in particle physics experiment and other applied research fields, MWPCs have several intrinsic drawbacks. The slow positive ions created in the multiplication process accumulate in the drift volume, causing field distortions and efficiency losses at high radiation fluxes; more serious, the formation in the avalanches of molecular aggregates of the main gas or of pollutants, coating the thin wires, results in permanent damages after long exposure to radiation (a process called “ageing”). A new family of gaseous devices, named micro-pattern gas detectors, (MPGD) solves many of these problems [55]. One frequently used detector in this family is the gas electron multiplier (GEM) [Box 4.6] introduced in 1997 [56]. Manufactured with a high-quality printed circuit technology developed at CERN, GEM electrodes can be tailored to the experimental requirements, and assembled using light yet sturdy honeycomb supporting frames.

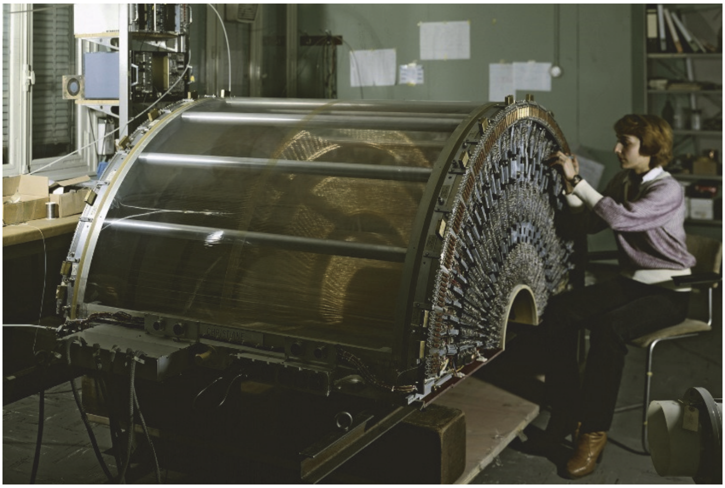
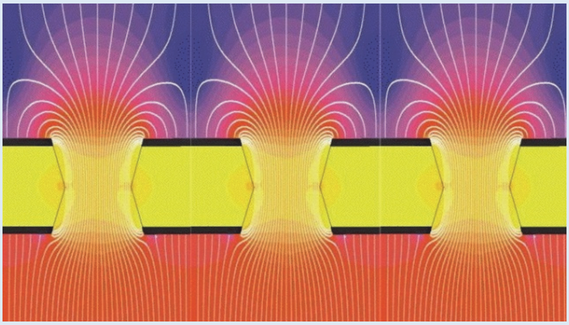


Fig. 4.17. One half of the AFS cylindrical drift chamber. The anode and cathode wires were strung coaxially with the beam between the endplates, which carried the readout electronics.

**The Gas Electron Multiplier (GEM)** **Box 4.6**

Introduced in the late nineties, the gas electron multiplier (GEM) provides charge amplification in closely spaced narrow holes, typically fifty to hundred per square millimetre, etched on a metal-clad polymer foil with a photolithographic process. Electrons released in the upper region drift downwards into the high field of the holes, multiply and proceed towards the lower region; unlike other gaseous counters, the charge amplified by a GEM foil can be multiplied further in one or more cascaded electrodes, permitting to safely attain very large overall gains and reach single electron detection. Owing to their high granularity, GEM detectors are efficient at very high radiation fluxes, and achieve excellent spatial localization and multi-track resolutions.



The electric field lines in the holes of a GEM electrode.

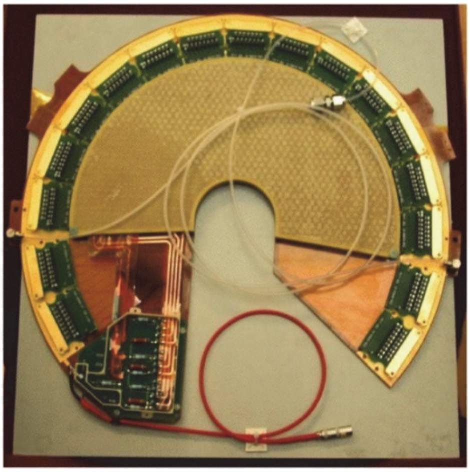


Fig. 4.18. A half-moon shaped GEM detector complete with its readout electronics.

Several hundred electrodes of this design have been produced at CERN for the construction of the tracker in the COMPASS spectrometer. Installed in 2001, the tracker is still in operation, demonstrating the reliability of this new detector technology. Figure 4.18 shows the half-moon shaped module developed for the TOTEM forward tracker.

Because of their superior performance, GEM detectors are foreseen to gradually replace wire-based devices in LHC experiments, e.g. the ALICE TPC end-cap MWPCs and the CMS muon detector, in order to better cope with increased interaction rates. Many other applications in medicine, biology, plasma diagnostics, neutron imaging are under development [56].

## 4.9 Transition Radiation: Imaging Relativistic Particles

Christian Fabjan

In the early years of research at the ISR the view emerged that «new» physics phenomena might reveal themselves through the observation of leptons, i.e. electrons and muons, not explainable with conventional physics. Such textbook examples are the discovery of the J/Ψ or the rare pion decay [Highlight 2.3]. But Nature likes to be cagy about revealing its secrets: These “new physics” leptons would be produced very rarely, if at all, and are difficult to detect. The ISR R209 collaboration, led by the co-discoverer of the J/Ψ and Nobelist S. Ting, developed a large Muon Spectrometer for this purpose. The R806 collaboration placed its bet on electrons. The stakes were high enough, daring the collaboration into