Detectors

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In the domain of elementary particle physics, the detectors and detector systems have evolved from single Geiger counters, proportional counters, and scintillation counters covering small areas ($\cong$ cm^2) and solid angles, to the enormous ($\cong$ 50 m^2) 4π detectors of today. This evolution has been brought about by the need to study elementary particle collisions at ever higher centre-of-mass energies, made possible by advances in accelerator technology.

Fixed-Target Detectors — Past

Prior to colliding-beam accelerators (*ca* 1970), all experiments were of the fixed-target variety. A representative experiment consisted of a forward spectrometer (see Fig. 1) which covered a limited forward solid angle (4π in centre of mass) and which tracked all charged particles, emerging from an interaction, through many planes of multiwire proportional chambers (MWPCs). Ionization electrons, produced by a charged particle traversing the gas in the chambers, are amplified and collected on fine wires. Such detectors are the lineal descendants of the early proportional counters. They gave projective space-point resolutions of 500 μm in the detector plane. Many such planes allowed particle tracks to be reconstructed both before and after a dipole magnetic field region; hence particle momentum and charge were measured. Typical dimensions of the MWPC planes were 1 m $\times$ 1 m. Electromagnetic particles (e, γ) were detected and their energy was measured in sampling electromagnetic (e.m.) shower counters (e.m. calorimeters), composed typically of alternate layers of plastic scintillator and lead viewed by photomultipliers (PMs). The resolution obtained was about $\Delta E/E$ = 0.2 GeV$^{1/2}/\sqrt{E}$. In addition to tracking and e.m. calorimetry, a third type of detector, often present, was devoted to charged-particle identification (e, μ, π, K, p), and consisted of one or more threshold Cherenkov counters. Cherenkov radiation is produced by a charged particle traversing an optical medium (refractive index *n*) if the particle velocity $\beta > 1/n$. Observation of such radiation was effected by reflection of the Cherenkov light from ellipsoidal mirrors onto PMs placed at an ellipsoid focus. Combining the measured momentum with the Cherenkov velocity limit(s) sometimes allowed unambiguous particle identification. For low values of β, such identification could be achieved by time-of-flight measurements.

The physical processes utilized in these detectors are ionization *(dE/dx)*, scintillation, and Cherenkov light emission, and the energy deposition required to produce the ultimately detected electrons are 25 eV, 700 eV, and 50 keV, respectively.

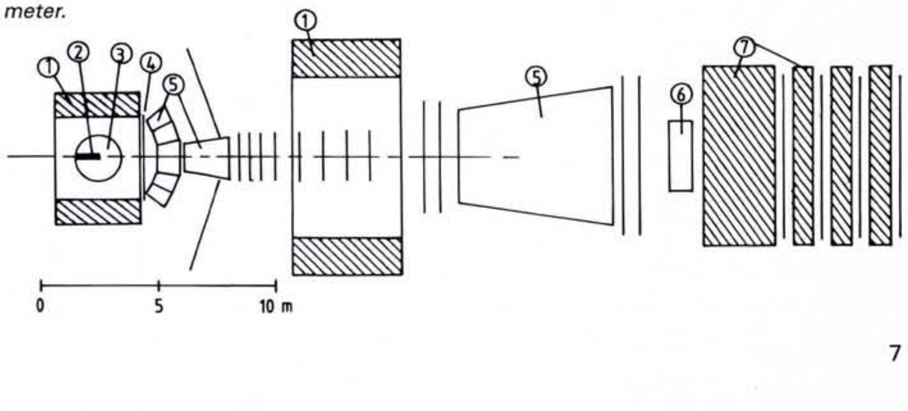
Colliding-Beam Detectors — Present

With the advent of colliding-beam accelerators (e^-, e^+) and (p, p) in the early 70's, and (p, $\bar{p}$) in the early 80's, an enormous increase in centre-of-mass energies was achieved, which necessitated a new generation of detectors to cope with the increased multiplicity and complexity of the collisions. A typical detector of this period (see Fig. 2) covered almost 4π sr, had cylindrical symmetry, and included a solenoidal coil and an iron flux-return yoke.

A gas-tracking central detector imaged the charged particle trajectories curving in the solenoidal magnetic field, allowing particle momentum and charge to be measured. One imaging method used very long drift ($\cong$ 1 m) of the ionization electrons, in an axial electric field, to a two-dimensional detection plane composed of anode wires and cathode pads. The electron drift-time gave the third (axial) coordinate. Another imaging method used concentric cylindrical layers of long ($\cong$ 2 m) proportional wires. The axial coordinate was measured by charge division between both ends of the resistive wire; the other coordinates were drift-time (short) and wire address. These drift-tracking detectors have very high granularity, typically 10^7 picture elements (pixels), which is necessary for resolving high-multiplicity events. The long-drift method is however not always practicable because of the accelerator time-structure and/or interaction rates. A space-point precision of 100 to 300 μm is typical for drift detectors.

The central gas detector was usually surrounded by a coil and an e.m. calorimeter. If the coil preceded the calorimeter, its detection elements were outside the magnetic field and so PMs could be used. Transparent (totally active) Pb glass blocks, each viewed by a PM, gave the best energy resolution of $0.05/\sqrt{E}$. Lead sheets interleaved with sampling scintillators and viewed by PMs gave resolutions of about $0.15/\sqrt{E}$. In this case the coil was usually superconducting in order to minimize the inert material before the calorimeter to less than one radiation length. In some detectors the calorimeter came before the coil, hence detectors which worked in a magnetic field were necessary. Liquid-argon sampling ionization chambers have this property. Ionization electrons produced in very clean (impurities < 0.10 ppm) liquid argon (23 eV per ion pair) are drifted in an electric field to collection electrodes. Drift velocities of 4 mm/μs are obtained at 10 kV/cm drift field. The advantage of this method is that spatial granularity can be achieved simply by segmenting the collection electrodes. Small-area towers looking at the interaction point can be hard-wired and used in the trigger. Typical energy resolutions of $0.07/\sqrt{E}$ have been achieved. Gas sampling detectors have also

Fig. 1 — A representative fixed-target spectrometer (EMC, FNAL Muon Spectrometer): 1 = Magnet iron; 2 = Target material; 3 = Streamer chamber; 4 = MWPC detector planes; 5 = Cherenkov threshold counters; 6 = e.m. calorimeter; 7 = Iron absorber in hadron calorimeter.



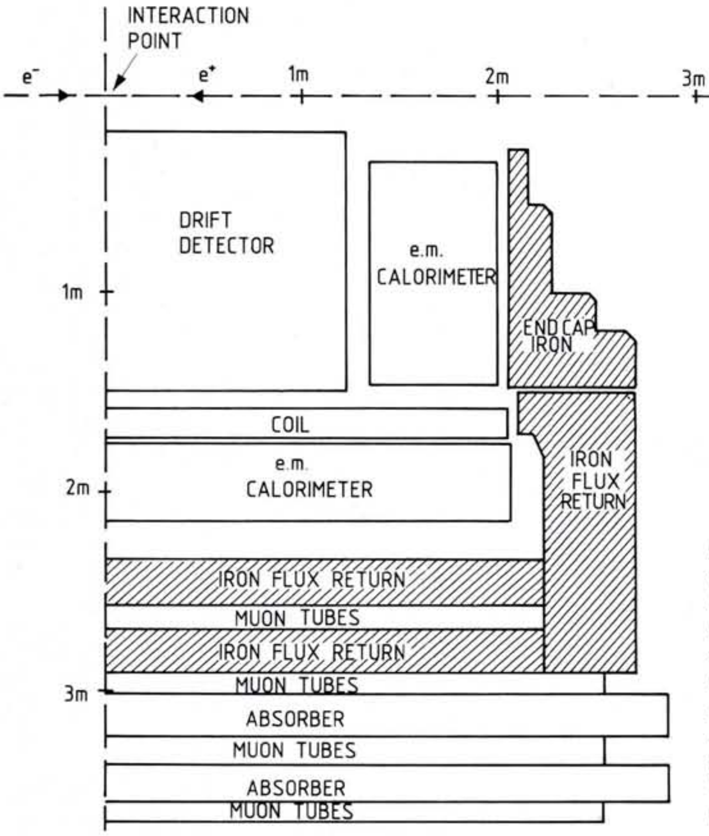


Fig. 2 — A representative colliding-beam detector facility (MARK II). The detector has cylindrical symmetry about the e^+,e^- axis and left-right symmetry about the interaction point.

been used inside the magnetic field with however, about a factor of three less resolution than the liquid-argon sampling detectors.

Following the coil and the calorimeter is the iron return yoke. This magnetized iron is used as a hadron (π, K, p) absorber. Particles which emerge from the yoke are mostly muons (μ), which are detected with large-area drift chambers or proportional counter tubes. Deflection of the muon in the magnetized iron yoke allows measurement of the muon momentum.

This generation of detectors has had spectacular success in experimentally establishing the Standard Model of electroweak interactions. Strange, charm and bottom quark-content particles have been identified with these detectors. Hadronization of quark pairs has been inferred from observation of two-jet events and gluon bremsstrahlung from three-jet events. The quanta of the electroweak theory, Z^0 and $W^\pm$ particles, have been discovered, and some decay modes categorized. Three generations of leptons (e, μ, τ) and neutrinos (ν_e, ν_μ, ν_τ) have been observed, but only two and a half generations of quark pairs (u, d), (s, c), (b, t?). The discovery of the top-quark (t) and the Higgs boson are needed by the theory, but this will require higher-energy colliders. Other generations of electrons, neutrinos, and quarks may also be seen. Extensions of the standard theory (technicolour, supersymmetry, etc.) predict new phenomena.

Current Developments

The Tevatron (0.9 TeV p on 0.9 TeV $\bar{p}$), the SLAC Linear Collider (SLC) and the Large Electron-Positron storage ring (LEP) (50 GeV e^- on 50 GeV e^+), and the Hadron-Electron Ring Accelerator (HERA) (30 GeV e^- on 800 GeV p) — a new generation of colliders for exploring this higher-energy domain — will be coming on line during the next four years (1987-1991). These have spawned a new generation of colliding-beam detectors. They follow those of the previous generation in so far as they have solenoidal magnetic fields and gas-tracking central detectors with, however, improved spatial resolution (30 to 200 μm). New features include vertex detection, particle identification with ring-imaging Cherenkov (RICH) counters or transition radiation detectors (TRDs), and combined e.m. and hadronic calorimetry.

Silicon Detectors

Silicon vertex detectors have been developed during the past five or six years to identify short-lived secondary particles having charm, bottom, or top (c, b, t) quark content. The proper lifetime τ of these particles is in the 0.1 to 1 ps range with proper decay lengths $c\tau$ of 30 to 300 μm. In order to identify such particles, both the primary and secondary vertices must be measured. The required space-point precision of 3 to 10 μm has been achieved with silicon strip detectors (SSDs) as well as with charge-coupled devices (CCDs). Both devices operate as ionization detectors, which is extremely advantageous in silicon because only 3.6 eV of energy loss is sufficient to produce an electron-hole pair. A comparison with liquid-argon detectors shows that silicon gives more than 12 times the signal per centimetre. The SSDs are typically 300 μm thick, high-resistivity (≥ 10 kΩ • cm), silicon wafers with one surface subdivided into conducting strips (25 μm pitch) and the other surface uniformly conducting. An applied bias voltage of about 100 V achieves full depletion, which allows electron collection throughout the full thickness of the silicon. A signal of about 3×10^4 charges is deposited by a minimum-ionizing particle. Electron collection times are small (≤ 5 ns) and the signal-to-noise ratio is good (≅ 15).

A high density of channels (≅ 400 per cm) characterizes these devices, which has necessitated the development of VLSI silicon chips (128 × 2 channels per 6 mm). A full vertex detector, composed of two or three concentric cylinders of SSDs surrounding the collider beam pipe, consists of about 1 m^2 of silicon and has 5×10^4 readout channels. This illustrates the necessity for cheap VLSI chips. Readout through shift registers is achieved in about 150 μs per event. The SSDs give one-dimensional (25 μm pitch) information on the track coordinate, in contrast to CCDs, which have a two-dimensional array structure (20 × 20 μm^2 pixel size). These devices are much thinner than SSDs (15 μm rather than 300 μm) and have the readout circuitry on the same silicon wafer as the detector array. To achieve the same signal-to-noise ratio as that of the SSDs demands lower noise (20), with the consequence that readout times are much slower (≅ 10 ms). For the SLC at Stanford, this time agrees well with the machine repetition rate, allowing use of the CCDs with their enormously high granularity (2.5×10^9 pixels per m^2).

Ring Imaging Cherenkov Detectors

The RICH detectors have been developed to measure the Lorentz factor γ for each charged particle emitted in an interaction. The particle mass (e, μ, π, K, p) may be calculated from the knowledge of the momentum p and of γ. The geometry of RICH detectors has been adapted to the overall cylindrical symmetry of the full system. A thin (≅ 1 cm) cylindrical shell of UV-transparent, low refractive index (n = 1.28) liquid is located just outside the central tracking detector (radius ≅ 1 m). The Cherenkov light cone (670 mrad) produced in the liquid is intercepted by a cylindrical drift volume (radius 1.15 to 1.2 m). The drift volume has UV-transparent fused-quartz windows and is filled with methane and ethane at atmospheric pressure, with a small admixture (≅ 1 Torr) of an organic photoionizing vapour [TMAE: tetrakis(dimethylamine)ethylene]. This vapour acts as a gas-phase photocathode with high average quantum efficiency (≅ 30%) at photon energies above the threshold of 5.3 eV (230 nm) to the liquid transmission limit of 7 eV (177 nm). The photoelectrons produced (≅ 25) are drifted a maximum distance of 1.5 m, in an applied electric field, to a MWPC that is sensitive to single electrons. The three-dimensional position of the photoelectron is obtained from the measured drift-time, wire address, and wire charge division. Knowledge of the particle track position in the thin liquid radiator determines the photon emission point and allows the Cherenkov angle to be reconstructed with an error of about 2 mrad (out of 670). This accuracy is sufficient to discriminate (π, K, p) below 10 GeV/c. In order to identify particles of higher momenta, the cylindrical annulus between 1.2 and 1.7 m is filled with UV-transparent gas radiator ($n-1 = 18 \times 10^{-4}$), followed by a row of UV-reflective mirrors which focus the Cherenkov light back down to the drift volume at 1.2 m. The ring images are detected, as before, by photoionization and drift to the MWPC detector. These gas images contain about 15 points, allowing the Cherenkov angle determination of about 60 ± 1 mrad. Discrimination of (π, K, p) up to 35 GeV/c is achieved by these gas ring-images. Identification of K mesons is important in identifying strange and charm quark content.

Transition Radiation Detectors

Transition radiation detectors, used primarily to identify electrons, are only sensitive for $\gamma \gtrsim 10^3$. Transition radiation, in the X-ray region, occurs when a relativistic charged particle crosses the boundary between two media with different dielectric constants. The intensity of the radiation increases linearly with γ but is only about 1 X-ray (10 keV) per 100 crossings at $\gamma = 4000$ (2 GeV/c electron). Radiator stacks contain several hundred foils (Mylar, polyethylene, or lithium) limited by X-ray self-absorption. The radiation from a stack of foils is detected in a MWPC filled typically with a xenon + argon gas mixture. Since the X-rays are highly collimated along the particle track ($\theta \sim 1/\gamma$), the MWPC must detect the transition X-rays in a background of ionization charge *(dE/dx)* due to the particle. This limits its hadron (γ, K, p) rejection capability to about a factor of 100 for 40 cm of transition radiators and detectors. This factor is of great value in identifying electrons in jets containing many particles, where calorimeters do not have high enough granularity to identify the specific particle (e) causing an e.m. shower.

Combined Calorimetry

Combined e.m. and hadronic calorimetry is a most promising development for future high-energy colliders. The electromagnetic particles (e, γ) are converted into a shower of lower-energy photons and electrons, and the energy is totally contained in 20 to 30 radiation lengths, which for Pb is 11 to 17 cm. An e.m. calorimeter with an equal sampling fraction of Pb and scintillator thus requires 22 to 34 cm for e.m. containment. Hadronic particles (π, K, p) interact with an absorption mean free path *(λ)* of about 190 g/cm^2 in Pb, so full absorption occurs in 7 – 8λ, i.e. 120 to 130 cm of Pb and 240 to 260 cm of equal-sampling Pb/scintillator. The e.m. resolution is about $10\%/\sqrt{E}$ and the hadronic resolution is $60\%/\sqrt{E}$ with, however, a constant additive term which dominates at very high (TeV) energies. The bad hadronic resolution is due to the unequal response of the calorimeter to the e.m. (e) and hadronic (h) components of the shower. The resolution is thus sensitive to fluctuations in π^0 production in hadronic showers. The calorimeter can be tuned to have equal *e/h* response by varying the sampling fraction as well as the hydrogenous composition of the sampling material. The hydrogen makes the detector sensitive to spallation neutrons, which are highly correlated with nuclear binding-energy losses. Fully compensated Pb or U calorimeters should achieve a resolution of $30\%/\sqrt{E}$. So far, $35\%/\sqrt{E}$ has been attained for U and $41\%/\sqrt{E}$ for Pb. More important, compensated calorimeters scale as $1/\sqrt{E}$, so that at TeV energies, resolutions of 1% seem possible.

In the Future

The detectors used in the recent past and at present, and those for use in the near future, have been surveyed. Future detectors will certainly evolve from these. The development time for the realization of a new technique is at least 5 years. Future detectors will depend on the accelerator time-structure and interaction rates. High-luminosity (10^{33}/cm^2 s) hadron colliders, now being proposed, will exclude long-drift methods. Only fast detectors can be used in this environment. They will certainly include silicon for vertex detection and probably also for tracking. Fast RICH counters seem possible and are being developed. Compensated hadronic calorimetry with fast scintillator sampling will play an important part. For electron-positron colliders, where interaction rates are small, the gas-tracking and drift detectors are still viable. Nearly all the detectors discussed above are of interest. In general, the trends are towards the increasing use of silicon both as a detector element and for VLSI electronic components. This will allow the construction of detectors with much higher space-point precision and granularity.