300 μm thick silicon detector is about 4 fC (25000 electrons). Readily available photodiodes have quantum efficiences > 70% for wavelengths between 600 nm and 1 μm. UV extended photodiodes have useful efficiency down to 200 nm. In applications in which photodiodes detect light from scintillators, care must be taken so that signal from the scintillator is larger than that produced by particles going through the photodiode.

Collection time decreases with increased depletion voltage, and can be reduced further by operating the detector with "overbias," *i.e.*, a bias voltage exceeding the value required to fully deplete the device. The collection time is limited by velocity saturation at high fields; at an average field of 10^4 V/cm, the collection times is about 15 ps/μm for electrons and 30 ps/μm for holes. In typical strip detectors of 300 μm thickness, electrons are collected within about 8 ns, and holes within about 25 ns.

Position resolution is limited by transverse diffusion during charge collection (typically 5 μm for 300 μm thickness) and by knock-on electrons. Resolutions of 3–4 μm (rms) have been obtained in beam tests. In magnetic fields, the Lorentz drift can increase the spatial spread appreciably (see "Hall effect" in semiconductor textbooks).

Radiation damage occurs through two basic mechanisms:

1. Bulk damage due to displacement of atoms from their lattice sites. This leads to increased leakage current, carrier trapping, and changes in doping concentration. Displacement damage depends on the nonionizing energy loss, *i.e.*, particle type and energy. The dose should be specified as a fluence of particles of a specific type and energy.
2. Surface damage due to charge build-up in surface layers, which leads to increased surface leakage currents. In strip detectors the inter-strip isolation is affected. The effects of charge build-up are strongly dependent on the device structure and on fabrication details. Since the damage is determined directly by the absorbed energy, the dose should be specified in these units (rad or Gray).

The increase in leakage current due to bulk damage is $\Delta i = \alpha\phi$ per unit volume, where ϕ is the particle fluence and α the damage coefficient ($\alpha \approx 2\times10^{-17}$ A/cm for minimum ionizing protons and pions after long-term annealing; roughly the same value applies for 1 MeV neutrons). The doping concentration in n-type silicon changes as $n = n_0\exp(-\delta\phi) - \beta\phi$, where n_0 is the initial donor concentration, $\delta \approx 6\times10^{14}$ cm^2 determines donor removal, and $\beta \approx 0.03$ cm^{-1} describes acceptor creation. This leads to an initial increase in resisitivity until type-inversion changes the net doping from n to p. At this point the resistivity decreases, with a corresponding increase in depletion voltage. The safe operating limit of depletion voltage ultimately limits the detector lifetime. Strip detectors have remained functional at fluences beyond 10^{14} cm^{-2} for minimum ionizing protons. At this damage level, charge loss due to recombination and trapping also seems to become significant.

12.6. Proportional and drift chambers

Proportional chamber wire instability. The limit on the voltage V for a wire tension T, due to mechanical effects when the electrostatic repulsion of adjacent wires exceeds the restoring force of wire tension, is given by (SI units) [22]

$$V \le \frac{s}{\ell C}\sqrt{4\pi\epsilon_0 T}\ , \tag{12.10}$$

where s, ℓ, and C are the wire spacing, length, and capacitance per unit length. An approximation to C for chamber half-gap t and wire diameter d (good for $s \lesssim t$) gives [23]

$$V \lesssim 59T^{1/2}\left[\frac{t}{\ell} + \frac{s}{\pi\ell}\ln\left(\frac{s}{\pi d}\right)\right]\ , \tag{12.11}$$

where V is in kV, and T is in grams-weight equivalent.

Proportional and drift chamber potentials The potential distributions and fields in a proportional or drift chamber can usually be calculated with good accuracy from the exact formula for the potential around an array of parallel line charges q (coul/m) along z and located at $y = 0$, $x = 0, \pm s, \pm 2s, \ldots,$

$$V(x,y) = -\frac{q}{4\pi\epsilon_0}\ln\left\{4\left[\sin^2\left(\frac{\pi x}{s}\right) + \sinh^2\left(\frac{\pi y}{s}\right)\right]\right\}\ . \tag{12.12}$$

Errors from the presence of cathodes, mechanical defects, TPC-type edge effects, *etc.*, are usually small and are beyond the scope of this review.

12.7. Calorimeters

Electromagnetic calorimeters. The development of electromagnetic showers is discussed in the "Passage of Particles Through Matter" section (Sec. 10 of this *Review*). Formulae are given for the approximate description of average showers, but since the physics of electromagnetic showers is well understood, detailed and reliable Monte Carlo simulation is possible. EGS4 has emerged as the standard [24].

The resolution of sampling calorimeters (hadronic and electromagnetic) is usually dominated by sampling fluctuations, leading to fractional resolution σ/E scaling inversely as the square root of the incident energy. Homogenous calorimeters, such as solid NaI(Tl), will in general not have resolution varying as $1/\sqrt{E}$. At high energies deviations from $1/\sqrt{E}$ occur because of noise, pedestal fluctuations, nonuniformities, calibration errors, and incomplete shower containment. Such effects are usually included by adding a constant term to σ/E, either in quadrature or (incorrectly) directly. In the case of the hadronic cascades discussed below, noncompensation also contributes to the constant term.

In Table 12.4 we give resolution as measured in detectors using typical EM calorimeter technologies. In almost all cases the installed calorimeters yield worse resolution than test beam prototypes for a variety of practical reasons. Where possible actual detector performance is given. For a fixed number of radiation lengths, the FWHM in sandwich detectors would be expected to be proportional to $\sqrt{t}$ for t (= plate thickness) ≥ 0.2 radiation lengths [25].

Given sufficient transverse granularity early in the calorimeter, position resolution of the order of a millimeter can be obtained.

Table 12.4: Resolution of typical electromagnetic calorimeters. E is in GeV.

Detector	Resolution
NaI(Tl) (Crystal Ball [26]; 20 X_0)	$2.7\%/E^{1/4}$
Lead glass (OPAL [27])	$5\%/\sqrt{E}$
Lead-liquid argon (NA31 [28]; 80 cells: 27 X_0, 1.5 mm Pb + 0.6 mm Al + 0.8 mm G10 + 4 mm LA)	$7.5\%/\sqrt{E}$
Lead-scintillator sandwich (ARGUS [29], LAPP-LAL [30])	$9\%/\sqrt{E}$
Lead-scintillator spaghetti (CERN test module) [31]	$13\%/\sqrt{E}$
Proportional wire chamber (MAC; 32 cells: 13 X_0, 2.5 mm typemetal + 1.6 mm Al) [32]	$23\%/\sqrt{E}$

Hadronic calorimeters [33,34]. The length scale appropriate for hadronic cascades is the nuclear interaction length, given very roughly by

$$\lambda_I \approx 35\ \mathrm{g\ cm^{-2}}A^{1/3}\ . \tag{12.13}$$

Longitudinal energy deposition profiles are characterized by a sharp peak near the first interaction point (from the fairly local deposition of EM energy resulting from π^0's produced in the first interaction), followed by a more gradual development with a maximum at

$$x/\lambda_I \equiv t_{\rm max} \approx 0.2\ln(E/1\ \mathrm{GeV}) + 0.7 \tag{12.14}$$

as measured from the front of the detector.