VII. Position-Sensitive Detectors

Position-sensitive detectors can be implemented in two basic architectures

1. Direct Readout

    1 readout cell per resolution element

    Example: 2D array of small pixels, with one readout channel per pixel

2. Interpolating Readout

    Large area sensor, designed so that a measurement parameter (signal magnitude, time) is dependent on position

    Example: Charge division
    Delay line readout

Since the direct readout requires a large number of readout channels, interpolating schemes are attractive for large area coverage.

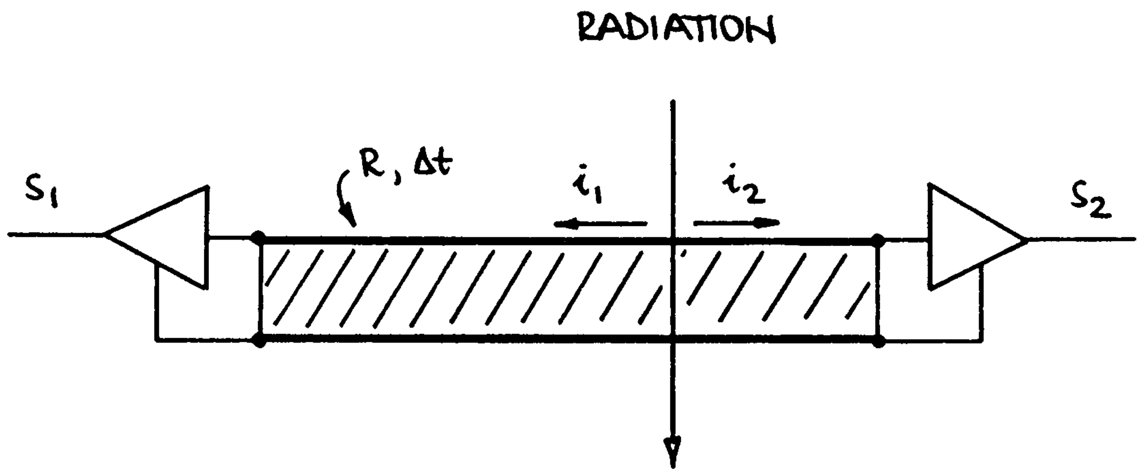
Furthermore, in “simple” experiments the complexity of a direct readout scheme may be prohibitive, so many techniques for interpolation have been developed.

These basic architectures can be applied to different detection media:

semiconductors
gases (ionization and proportional chambers)
liquid ionization chambers

or can be used within the sensor, e.g. to provide position sensing at the output of a photomultiplier or microchannel plate.

1. Interpolation



Possibilities:

a) Charge Division

Electrode is made resistive with low-impedance amplifiers at each end. The signal current divides according to the ratio of resistances presented to current flow in the respective direction

$$\frac{i_1(x)}{i_2(x)} = \frac{R_2(x)}{R_1(x)}$$

The obtainable position resolution depends on the precision of the relative signal measurement at the two ends, i.e. the signal to noise ratios of the two measurements.

The resistive electrode introduces

a) Noise due to its resistance. Viewed from any of the two ends, the amplifier at the opposite end connects the electrode resistance to ground, as the amplifiers have a low input impedance. Thus, the electrode resistance is effectively in parallel with the input of an amplifier, so the noise charge

$$Q_{nR} = i_{nR} F_i T_S = \frac{4k_B T}{R_D} F_i T_S$$

In principle, the noise can be reduced arbitrarily by reducing the shaping time T_S, but a lower limit is imposed by the signal dispersion introduced by the resistive electrode.

b) Signal dispersion, i.e. an increase in pulse duration, because the resistive electrode together with the detector capacitance forms an RC transmission line, i.e. sequential RC integrators.

The dispersion will depend on position. A signal originating at one end will suffer the greatest dispersion, proportional to

$$\tau_D = R_D C_D$$

Since the signal dispersion depends on the position of the incident signal, it will vary from event to event, so the shaper must be designed to reduce variations in the ballistic deficit to not significantly affect the position resolution.

Although the exact relationship between the detector time constant and the optimum shaping time T_S depends on detector signal shape and the type of shaper, the shaping time constant will be proportional to the detector time constant, so for simplicity we'll assume

$$T_S = \tau_D$$

To optimize the signal-to-noise ratio, we'll assume that the amplifier noise is negligible, so the dominant noise contributor is the electrode resistance.

Then the position resolution

$$\frac{\Delta l}{l} \propto \frac{1}{S/N} = \frac{Q_n}{Q_s} = \frac{1}{Q_s}\sqrt{\frac{4k_B T}{R_D} F_i R_D C_D} \approx \frac{\sqrt{k_B T C_D}}{Q_s}$$

The obtainable position resolution is independent of electrode resistance and depends only on detector capacitance and the magnitude of the signal.

Example:

$$C_D = 10 \text{ pF and } Q_s = 10^6 \; el \quad \Rightarrow \quad \frac{\Delta l}{l} \approx 10^{-3}$$

The above result only obtains if the electronic noise from the amplifier is negligible.

For C_D= 10 pF

$$\sqrt{k_B T C_D} = 1270 \, el$$

so if the degradation is to be less than 10%, the amplifier noise may not exceed 270 el.

Since the voltage noise of the amplifier

$$Q_{nv}^2 = v_n^2 C_D^2 \frac{F_v}{T_S}$$

for a given capacitance C_D and equivalent input noise voltage v_n , the amplifier noise contribution can only be reduced by increasing the shaping time T_S , which means that the electrode resistance must be increased to scale $R_D C_D$ to the required T_S .

The detector time constant $R_D C_D$ also imposes a limit on the rate capability of the detector. High-rate applications often require a compromise that yields a position resolution inferior to the above limit.

b) Delay Line Readout

In a delay line readout the detector electrode is used as a transmission line. The position is determined by the difference in propagation times from the point of incidence to the respective ends.

If the electrode has a group velocity v_g

$$t_1 = \frac{x}{v_g} \quad \text{and} \quad t_2 = \frac{l-x}{v_g}$$

$$t_1 - t_2 = \frac{x}{v_g} - \frac{l-x}{v_g} = \frac{2x-l}{v_g}$$

so the position

$$x = \frac{1}{2}(t_1 - t_2)v_g + l$$

and the position resolution

$$\Delta x = \frac{v_g}{2}\Delta(t_1 - t_2)$$

The position resolution can be improved by improving the time resolution.

In a low-loss transmission line, the signal magnitude at both ends will be the same. If the transmission line is sufficiently fast, i.e. non-dispersive, the rise times of the signals at the two ends will also be the same, so the time resolutions

$$\Delta t_1 = \Delta t_2$$

and

$$\Delta(t_1 - t_2) = \sqrt{2}\,\Delta t_1 = \sqrt{2}\,\Delta t_2 \equiv \sqrt{2}\,\Delta t$$

Thus, the position resolution is

$$\Delta x = \frac{v_g}{\sqrt{2}} \Delta t$$

If we use a simple RC low-pass filter as a shaper in the timing channel, matched to the rise time of the signal t_r to maximize the slope-to-noise ratio, the time resolution of a single channel

$$\Delta t = \frac{C}{Q_s} v_n \sqrt{\frac{t_r}{2}}$$

where v_n is the spectral noise voltage density of the amplifier.

With this result the position resolution is

$$\Delta x = \frac{v_g}{\sqrt{2}} \Delta t = \frac{v_g}{2} \frac{C}{Q_s} v_n \sqrt{t_r}$$

The remaining parameter is the velocity of signal propagation v_g.

In a pair of electrodes with an intermediate medium of dielectric constant ε

$$v_g = \frac{c}{\sqrt{\varepsilon}}$$

so increasing the dielectric constant will decrease the group velocity, increase the delay time and would seem to improve the position resolution.

However, increasing the dielectric constant also increases the capacitance. If C_0 is the capacitance for $\varepsilon = 1$,

$$\Delta x = \frac{v_g}{2} \frac{C}{Q_s} v_n \sqrt{t_r} = \frac{c}{2\sqrt{\varepsilon}} \frac{\varepsilon C_0}{Q_s} v_n \sqrt{t_r}$$

$$\Delta x = c\sqrt{\varepsilon} \frac{v_n C_0}{2Q_s} \sqrt{t_r}$$

so the position resolution will not improve by increasing the dielectric constant of the transmission medium to reduce the group velocity, as the attendant increase in capacitance decreases the time resolution and cancels the benefit of increased propagation time.

For the non-dispersive delay line the position resolution improves with

- increasing signal Q_s
- decreasing rise time $\sqrt{t_r}$
- decreasing capacitance C
- decreasing amplifier noise v_n

and is

- independent of the length of the delay line.

The other technique to increase the delay time is to introduce distributed series resistance, which also makes the delay line dispersive.

Since time resolution depends on the slope-to-noise ratio, i.e. the time derivative of the signal, the detector electrode must be designed to minimize dispersion, while maximizing the delay time x/v_g.

In an RC transmission line the delay time is proportional to the resistance $R' = R/l$ and capacitance $C' = C/l$ per unit length, so analogously to the propagation delay of cascaded integrators, the group velocity

$$v_g = \frac{l}{RC} \;,$$

whereas the rise time increases with the square root of length.

$$t_r = RC\sqrt{\frac{x}{l}}$$

The bandwidth of the electronics can be restricted to match the maximum rise time $t_r = RC$, so for a simple RC low-pass filter the time resolution is

$$\Delta t = \frac{C}{Q_s} v_n \sqrt{\frac{RC}{2}}$$

where v_n is the spectral voltage noise density of the amplifier.

Thus, the position resolution

$$\Delta x = \frac{v_g}{\sqrt{2}} \Delta t = \frac{l}{\sqrt{2}RC} \frac{v_n}{Q_s} C \sqrt{\frac{RC}{2}}$$

$$\frac{\Delta x}{l} = \frac{1}{2} \frac{v_n}{Q_s} \sqrt{\frac{C}{R}}$$

As to be expected, the position resolution improves with increasing signal-to-noise ratio and decreasing capacitance.
The dispersive delay line determines a relative resolution $\Delta x/l$, unlike the non-dispersive line where the absolute resolution for a given capacitance is independent of length

To a degree, increasing the electrode resistance will improve the position resolution, as long as its noise contribution does not become significant.

Including the noise from the electrode resistance,

$$\frac{\Delta x}{l} = \frac{\sqrt{v_n^2 + 4k_B TR}}{2Q_s}\sqrt{\frac{C}{R}}\ .$$

If the electrode resistance dominates the noise

$$4k_B TR >> v_n^2\ ,$$

then

$$\frac{\Delta x}{l} = \frac{\sqrt{4k_B TR}}{2Q_s}\sqrt{\frac{C}{R}} = \frac{\sqrt{k_B TC}}{Q_s}\ ,$$

which is the same as the result for charge division.

Example:

Non-dispersive delay line readout with

C_D= 10 pF, Q_s= 10^6 el, v_n= 0.9 nV/Hz$^{1/2}$, t_r= 10 ns and ε = 1

$$\Delta x = c\sqrt{\varepsilon}\,\frac{v_n C_0}{4Q_s}\sqrt{t_r} = 0.4\,\text{mm}$$

which for a 1 m long electrode corresponds to

$$\frac{\Delta x}{l} = 4\cdot 10^{-4}$$

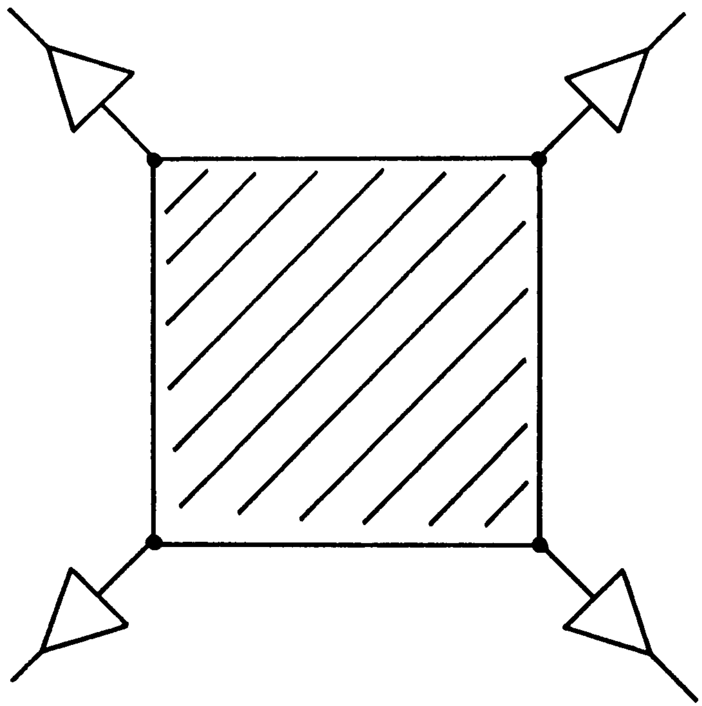
In practice, charge division tends to provide better results for short electrodes, whereas delay line readout is better for long electrodes.

> This is because, for a given capacitance, non-dispersive delay lines yield a constant resolution Δx, whereas charge division or dispersive delay lines yield a constant relative resolution $\Delta x / l$.

Some implementations use specially designed delay lines to increase the propagation time. Frequently, they sacrifice S/N, which may be acceptable. If the electronics have not been optimized, for example if the timing is dominated by pulse shape variations, rather than S/N, the degradation in S/N may not be that critical.

On the other hand, the optimization outlined above is the most direct approach.

Interpolation schemes can be extended to two dimensions:
(... in principle)



Although interpolation schemes allow a relatively large area to be read out with a small number of readout channels, they do this at the expense of multi-hit capability, i.e.

> only one hit is allowed within the readout area and required analysis time.

For optimum results the electronics must be rather sophisticated

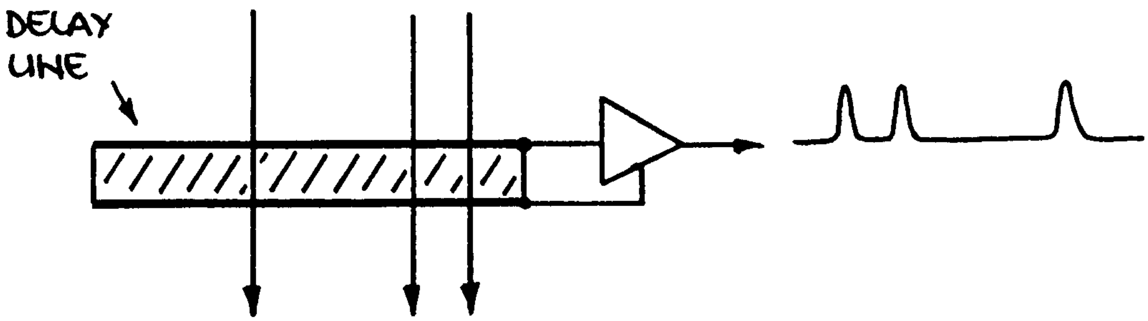
- low noise
- optimized pulse shaping
- calculation capability (hardware or software)

2. Time-Projection Structures

Transform the position axis to the time axis

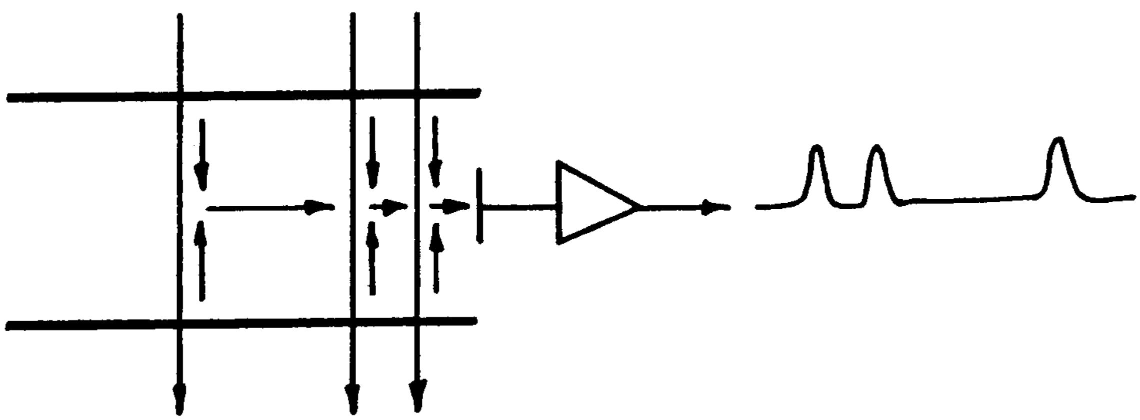
– use multi-hit capability to record multiple events occurring simultaneously at different positions within the sampling volume

Example 1: Delay line readout with external trigger



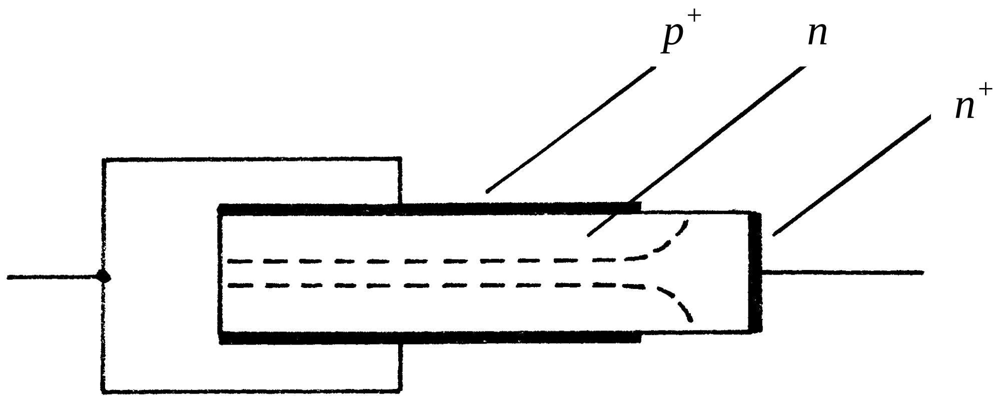
Example 2: Semiconductor Drift Chamber

Use detector material as delay element

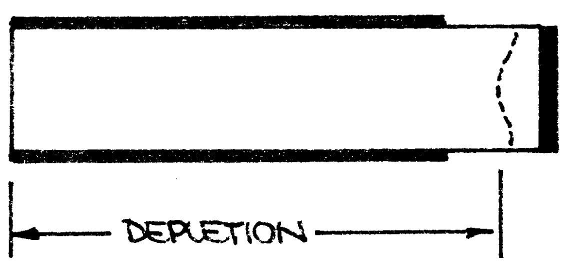


Semiconductor Drift Chamber

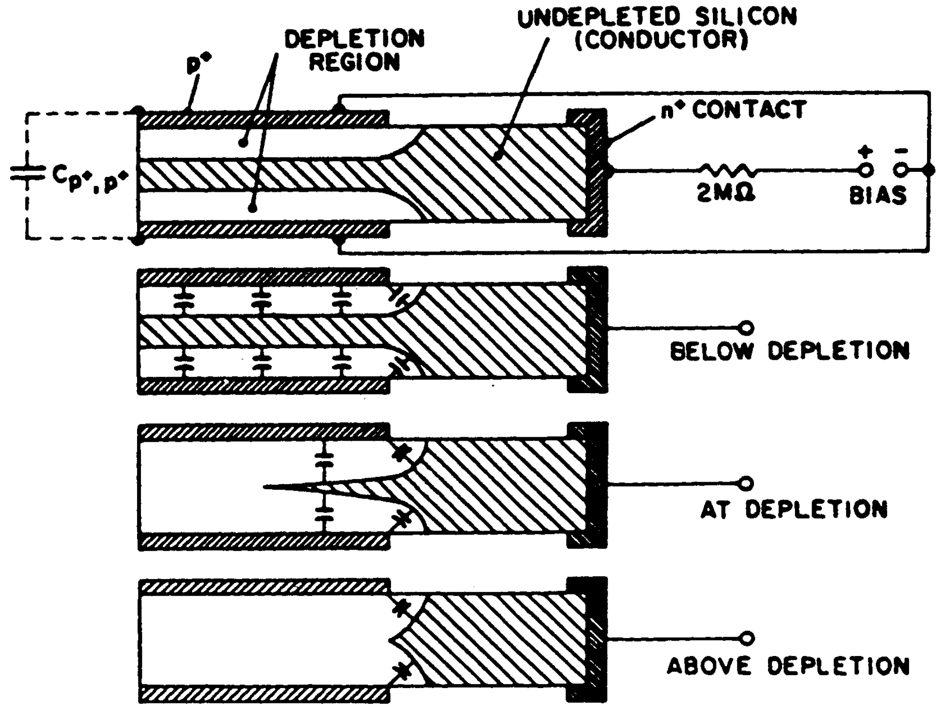
1st Ingredient: depletion from edge of detector

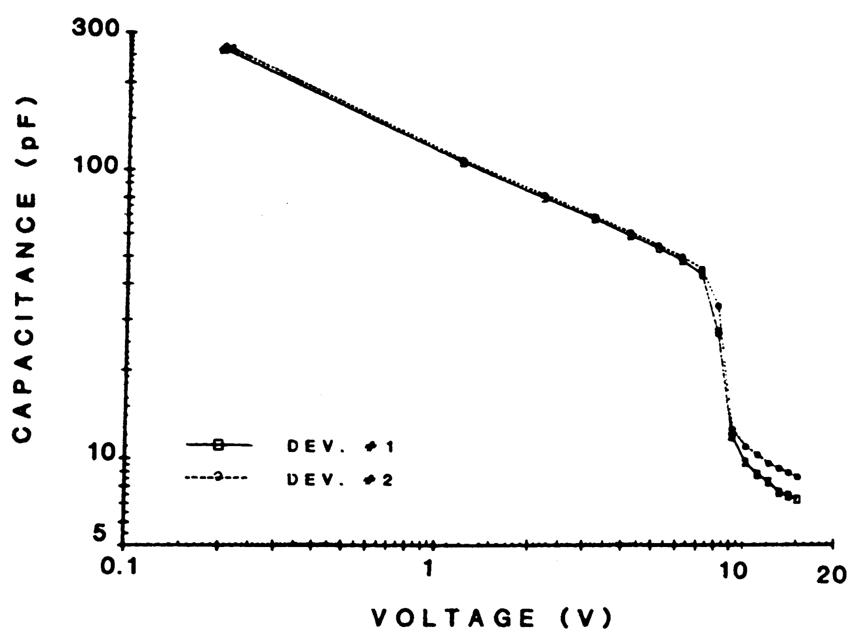


INCREASE REVERSE BIAS:



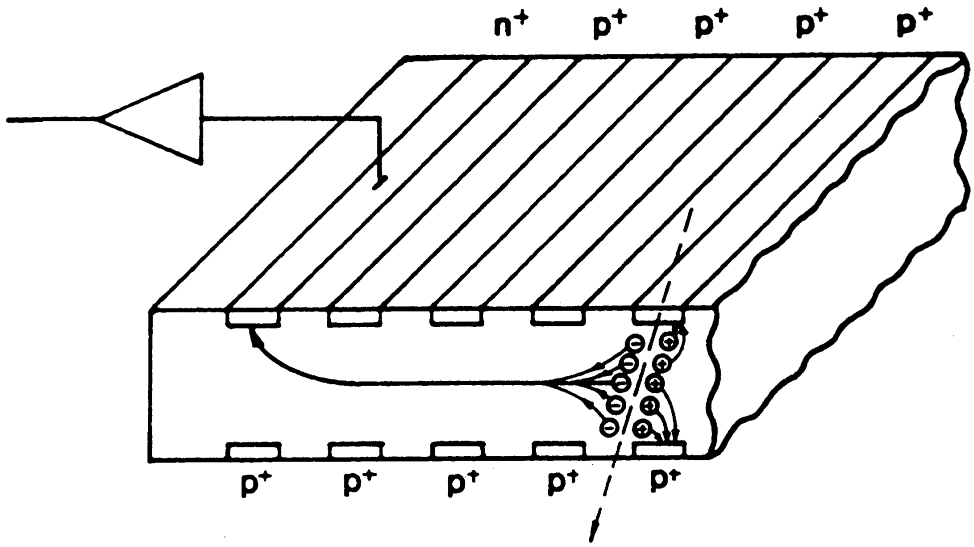
Depletion vs. Reverse Bias Voltage
(from Gatti et al. IEEE Trans. Nucl. Sci. **NS-32** (1985) 1204)



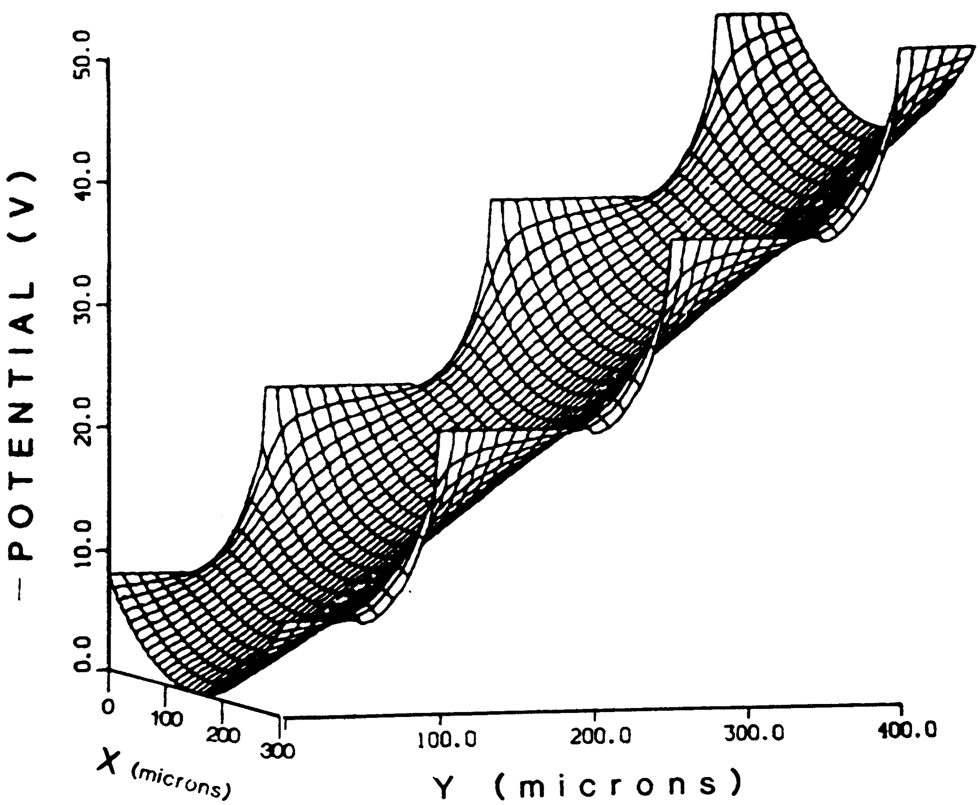


2nd Ingredient:

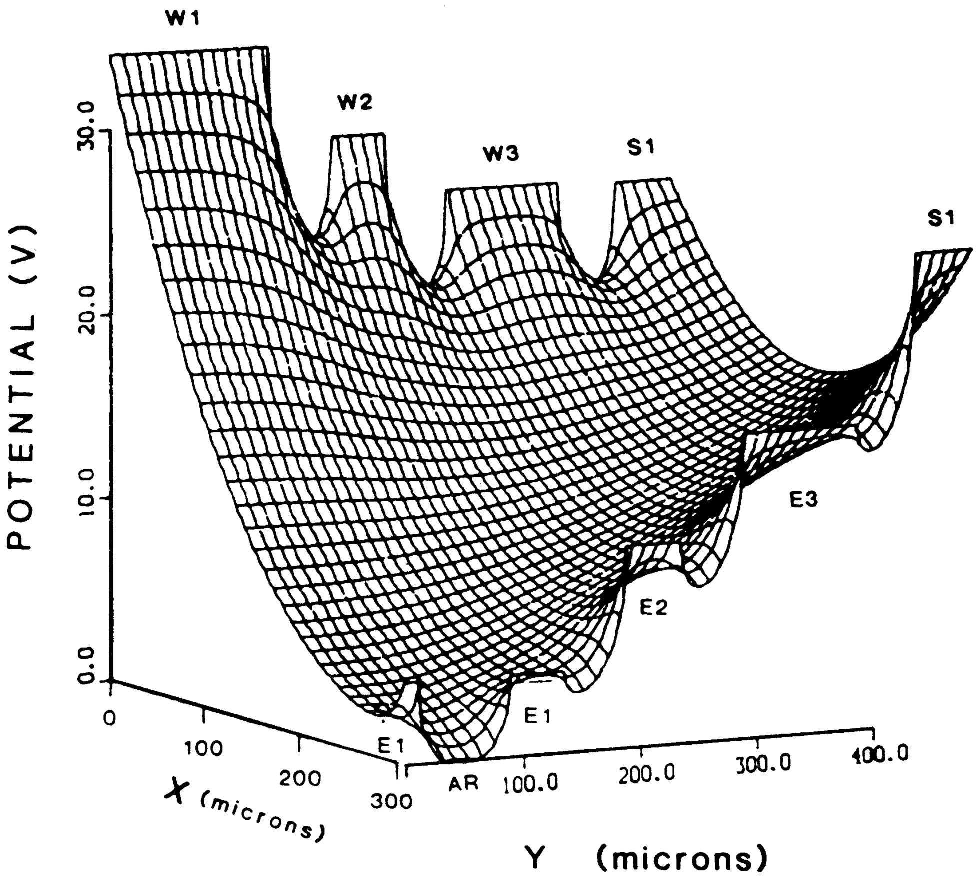
Add additional electrodes to form drift field parallel to surface



Potential Distribution



The potential trough can be skewed to direct the charge to a readout electrode on the surface.



Silicon drift chamber has advantage that the collection electrode is decoupled from the large track-acceptance area.

⇒ capacitance can be very small, even on a large area detector (C~ 50 – 100 fF for A= 10 cm^2)

⇒ ~ 10 µm resolution over 5 – 10 cm drift distance

Drift velocity must be predictable.
Trapping must be low for long drift distances (~ cm)

⇒ problem with radiation damage.

Electronics optimized for timing – multi-hit capability requires fast time digitization.

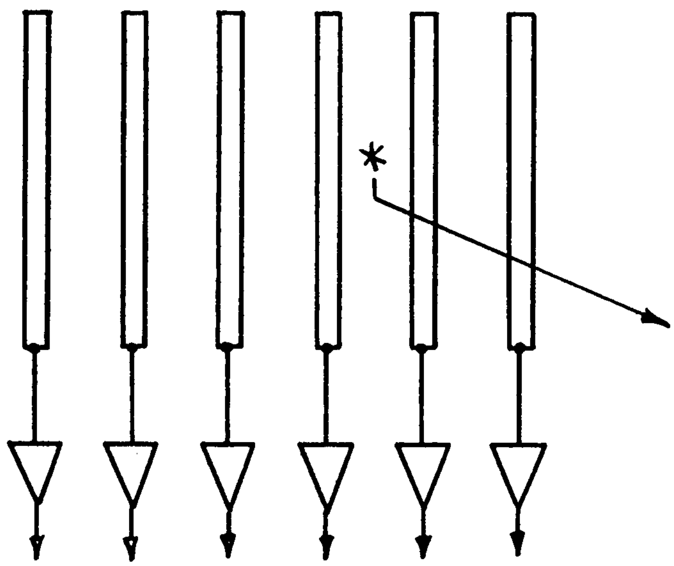
3. Parallel Readout

One readout channel per resolution element

Example: Strip Detectors – electrode segmented as strips

Two options:

Binary Readout



to discriminators

Position resolution determined directly by pitch

$$\sigma_x = pitch/\sqrt{12}$$

Analog Readout

Interpolation yields resolution < pitch

Relies on transverse diffusion

$$\sigma_x \propto \sqrt{t_{coll}}$$

e.g. in Si

$t_{coll} \approx$ 10 ns

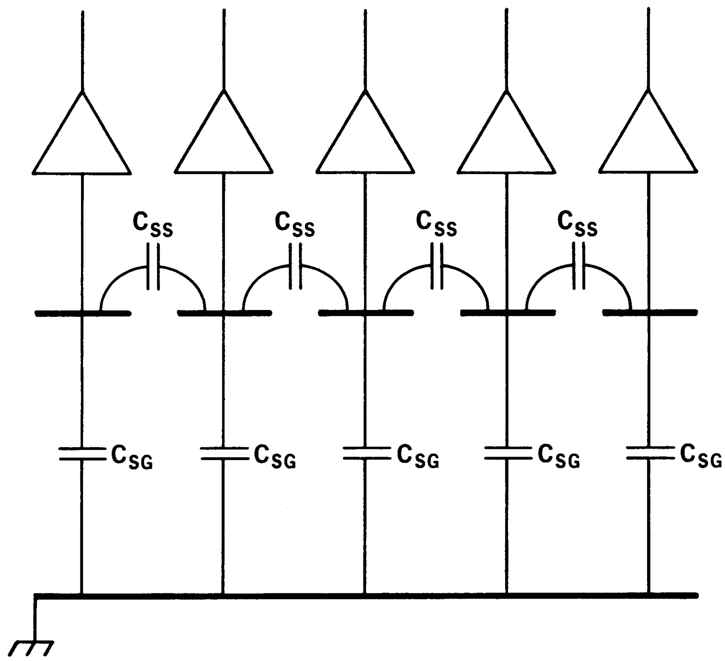
$\Rightarrow \quad \sigma_x$ = 5 µm

Interpolation precision depends on S/N and p

p = 25 µm and S/N=50

$\Rightarrow$ 3 – 4 µm resolution

Amplifiers must have a low input impedance to reduce transfer of charge through capacitance to neighboring strips



The capacitance is dominated by the fringing capacitance to the neighboring strips C_{SS}.

Typically: 1 – 2 pF/cm for strip pitches of 25 – 100 μm.

The capacitance to the backplane C_{SG} is simple to calculate

$$C_{SG} = \varepsilon \frac{A}{d} = \varepsilon \frac{pl}{d}$$

where A is the area subtended by a strip element, d is the substrate thickness, p is the strip pitch (not width!) and l the strip length.

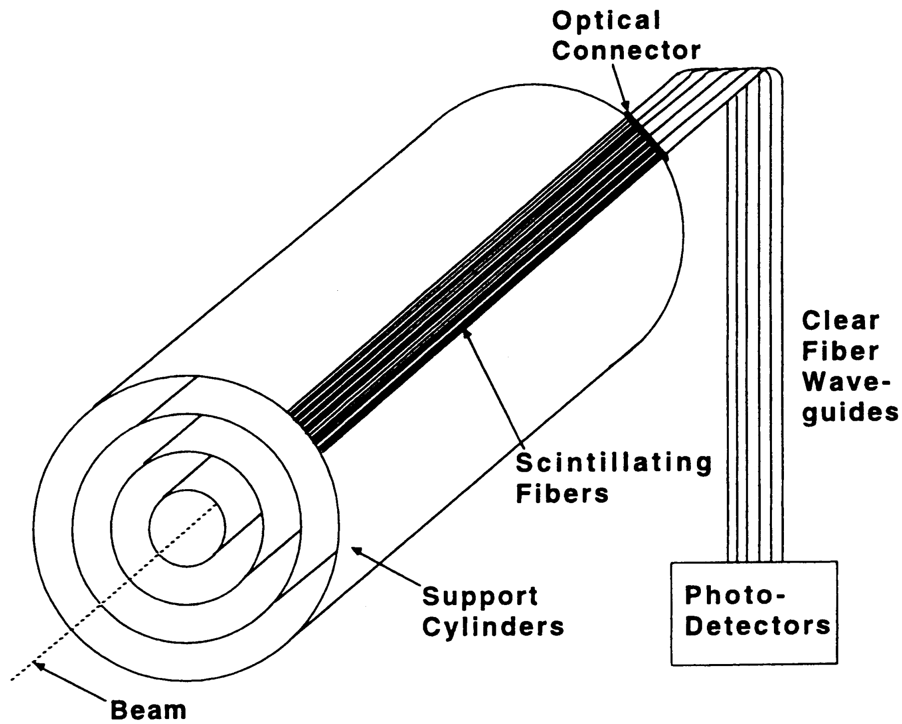
The presence of the adjacent strips limits the fringing field to the centerline between two strips, i.e. width = strip pitch.

For strip pitches of 25 – 100 μm the backplane capacitance is typically 20% of the strip-to-strip capacitance.

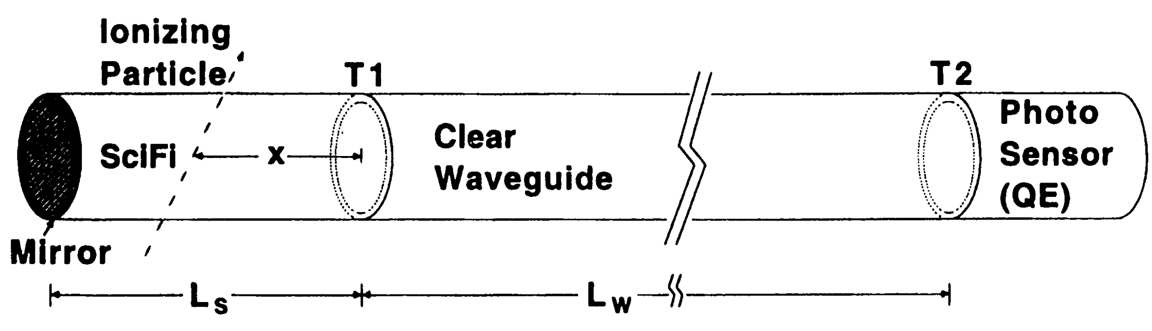
Scintillating Fiber Tracker

Array of small-diameter cylindrical scintillators (fibers)

(see R. Ruchti, Scintillating Fibers for Charged-Particle Tracking, Ann. Rev. of Nuclear and Particle Science **46** (1996) 281-319)

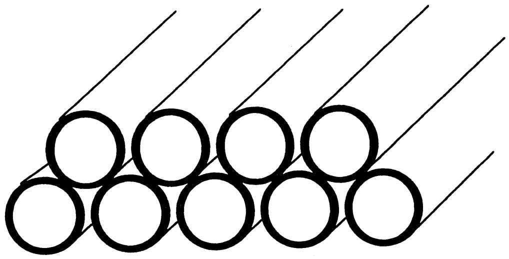


Detail of individual fiber



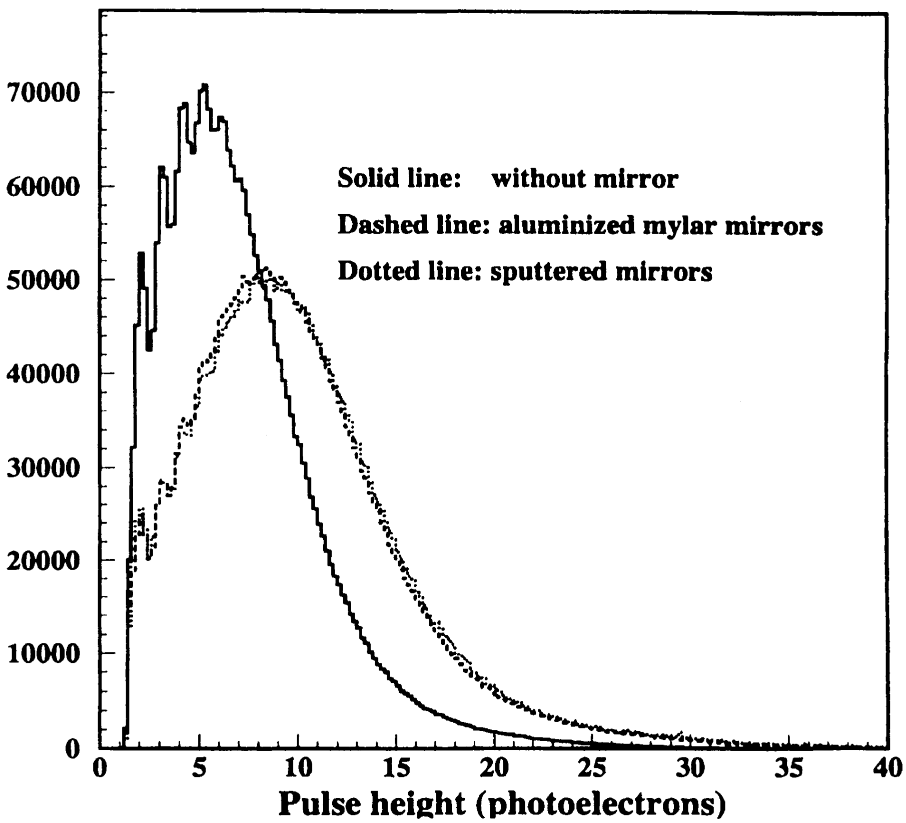
Fiber diameter: 10 - 100 μm

Fibers arranged as two-layer ribbons to assure full-efficiency coverage.



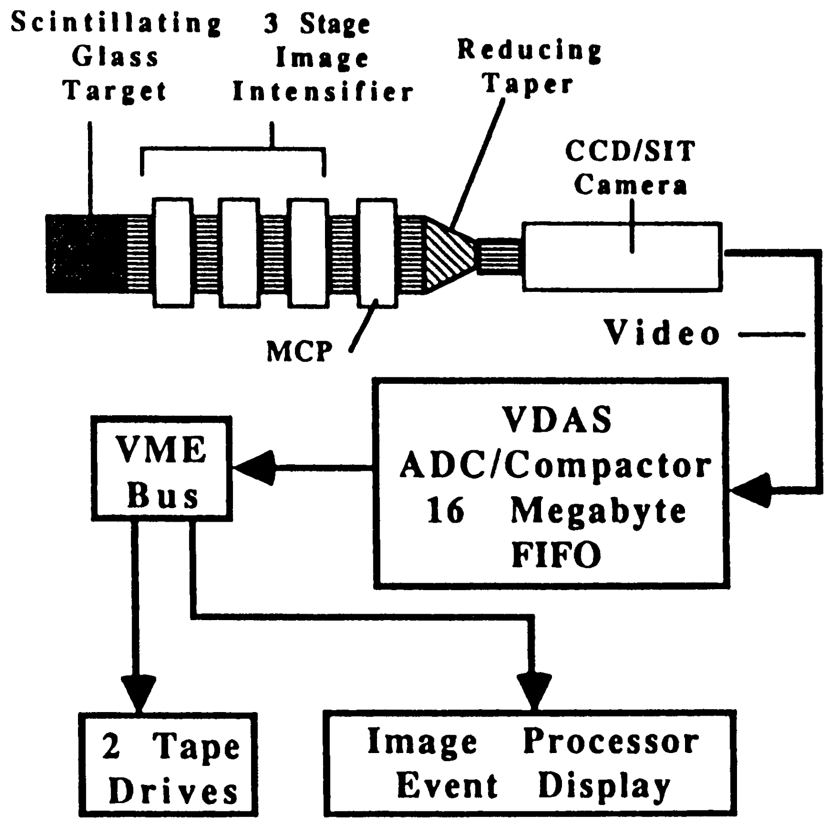
Small fibers $\Rightarrow$ deposited energy small
+ light attenuation in light-guide

$\Rightarrow$ small number of photons



Requires photodetectors with high quantum efficiency.

Example: Image Intensifier + Microchannel Plate (MCP)
+ Charge Coupled Device (CCD)

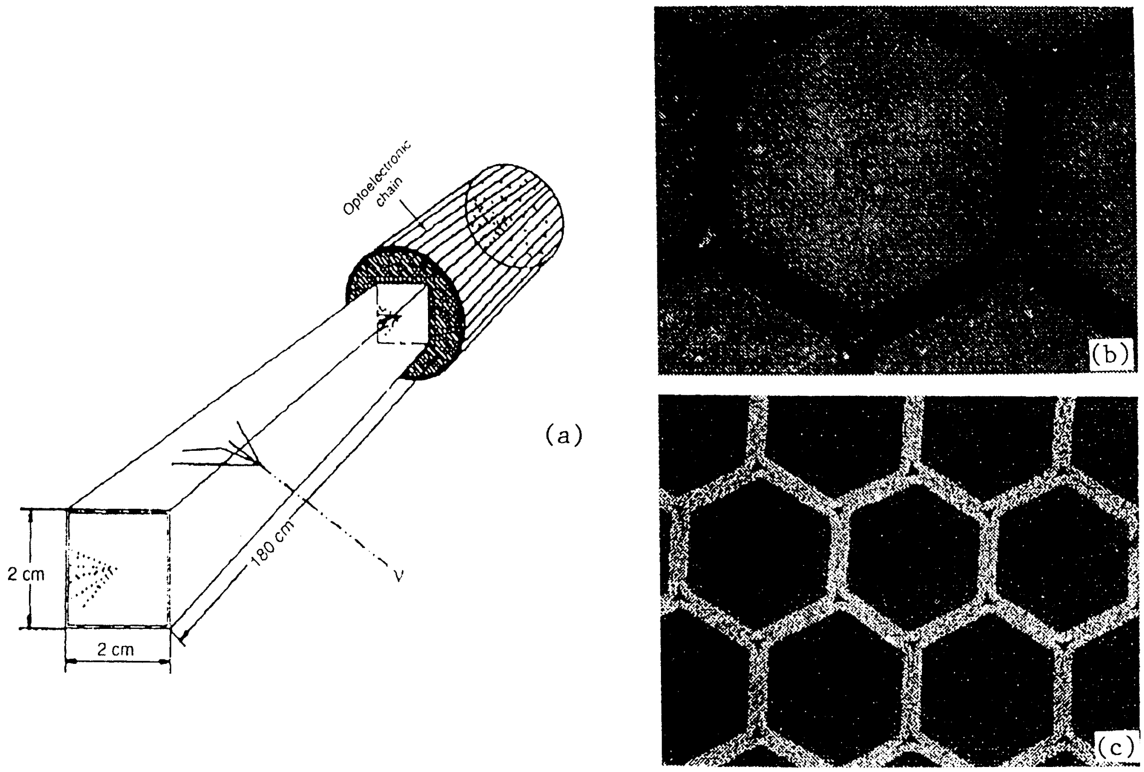


Scintillating fiber tracker under construction for DØ at FNAL uses special semiconductor devices operating at cryogenic temperatures (Visible Light Photon Chamber – VLPC)

⇒ high quantum efficiency coupled with high gain.

Other form of scintillating “fiber”

Liquid scintillator in capillary (CHORUS experiment at CERN)



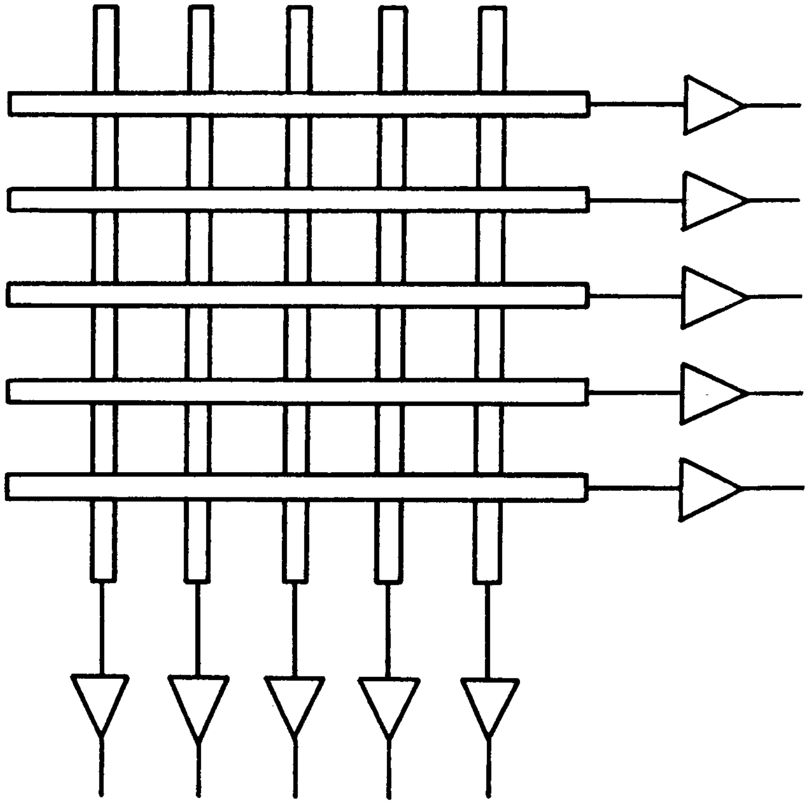
Pitch in the direction of opposite corners is 23 μm.

Capillaries are bundled to form 2 x 2 cm^2 arrays.

Two-Dimensional Detectors

1. Two-Dimensional Projective Devices

Example: Crossed strips on opposite sides of Si wafer



n readout channels $\Rightarrow$ n^2 resolution elements

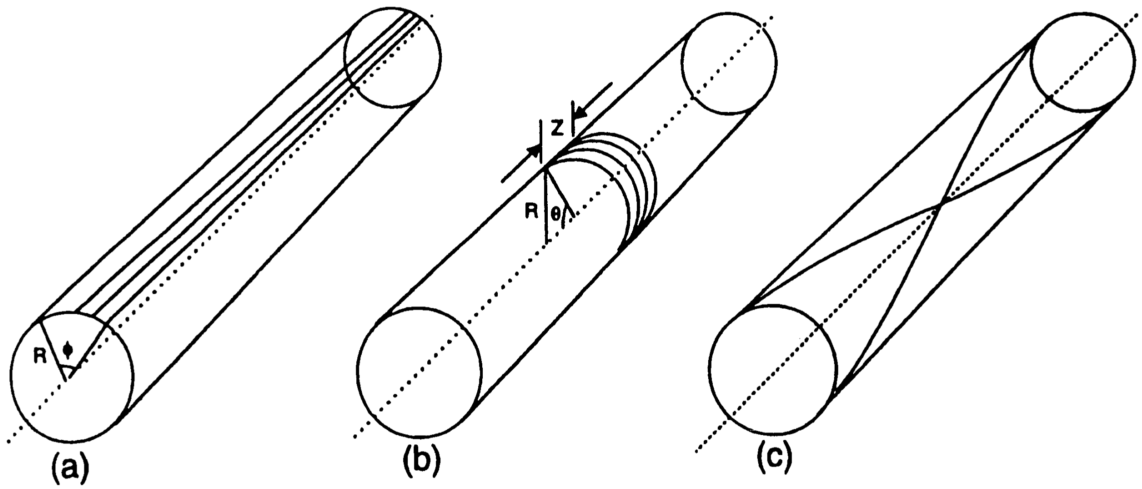
Problem: ambiguities with multiple hits

n hits in acceptance field $\Rightarrow$ n x-coordinates
n y-coordinates

$\Rightarrow$ n^2 combinations

of which
$n^2 - n$ are "ghosts"

Projective 2D sensing applied to scintillating fibers:



(from Ruchti)

a) and b) can be combined to provide two-dimensional position sensing, where the resolution in the two dimensions is determined by the respective fiber pitch.

a) and c) combined form “small-angle” stereo layers that provide two-dimensional information with reduced “ghosting”

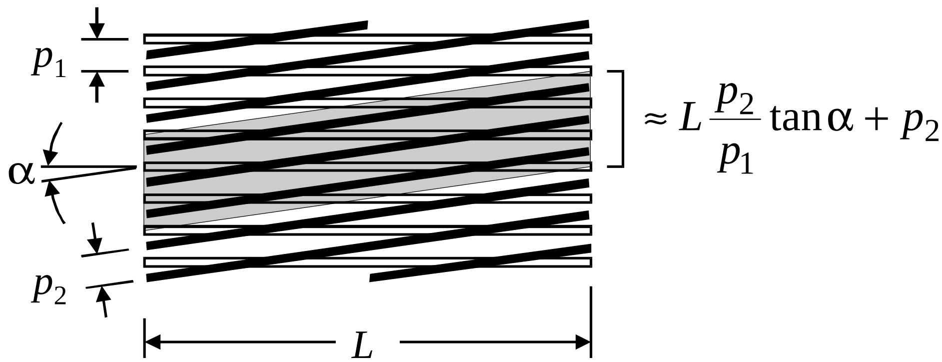
Reduces area subtended by fibers (strips) that registered signal.

Small-Angle Stereo

The area subtended by two sensing elements (strips) of length L_1 and L_2 arranged at an angle 90º is $A = L_1 L_2$, so a hit in a given strip can form combinations with hits on all of the transverse strips – the probability of "ghosting" is maximal.

However, if the angle α subtended by the two strip arrays is small (so that their lengths L are approximately equal), then the capture area

$$A \approx L^2 \frac{p_2}{p_1} \tan\alpha + L p_2$$



Consider a given horizontal strip struck by a particle. To determine the longitudinal coordinate all angled strips that cross the primary strip must be checked and every hit that deposits on these strips adds a coordinate that must be considered in conjunction with the coordinate defined by the horizontal strip.

Since each strip captures charge from a width equal to the strip pitch, the exact width of the capture area is an integer multiple of the strip pitch.

The probability of multiple hits within the acceptance area, and hence the number of "ghosts", is reduced as α is made smaller, but at the expense of resolution in the longitudinal coordinate.

$$\Delta z = \frac{p_1}{\tan\alpha} + p_2 \sin\alpha$$

2. Two-Dimensional Non-Projective Devices

Example: Pixel Devices

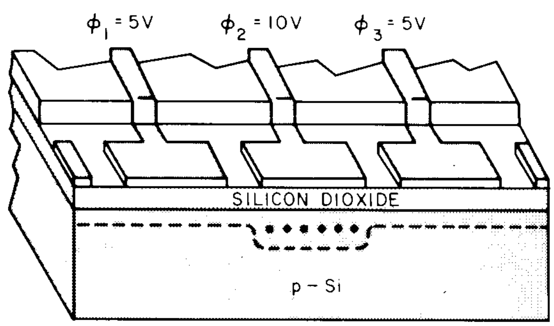
"Checkerboard" of detector elements than can be read out as discrete signal packets

Implementations:

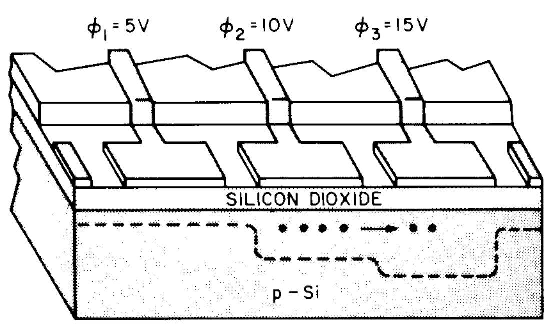
a) CCDs Array of MOS Capacitors – applied potential forms potential well that collects signal charge from bulk.

uses pixel-to-pixel charge transfer for signal "bussing"

charge accumulation due to photon or particle



charge transfer to neighboring pixel



Typically, charge transferred to end of column and then across row to single readout amplifier per chip.

serial readout $\Rightarrow$ long readout times

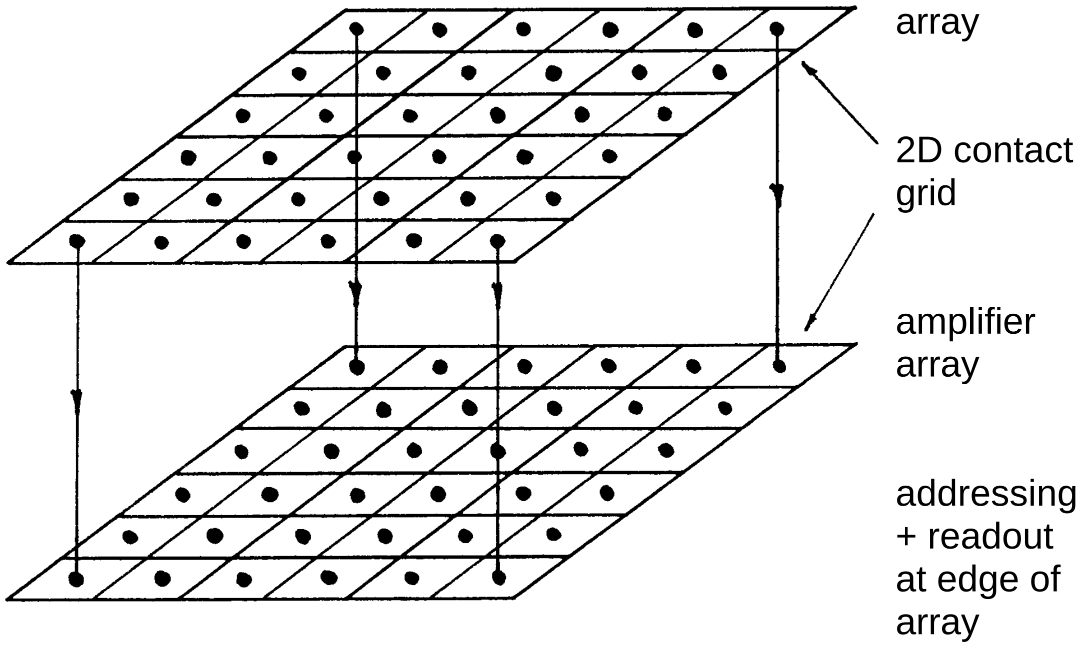
at clock rate of 10 MHz

50 µm pixel size $\Rightarrow$ 20 µs/cm

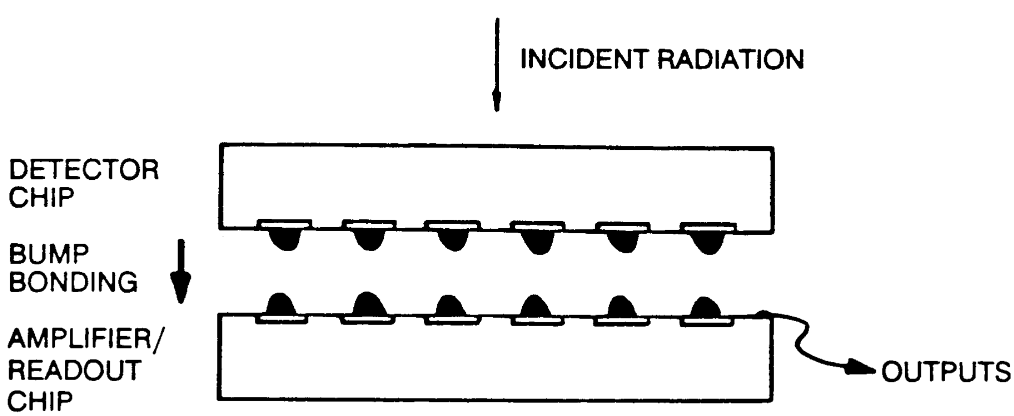
b) Random–Access Pixel Arrays

Amplifier per pixel

Address + signal lines read out individually addressed, i.e. single, pixels



2D contact via “bump bonds”

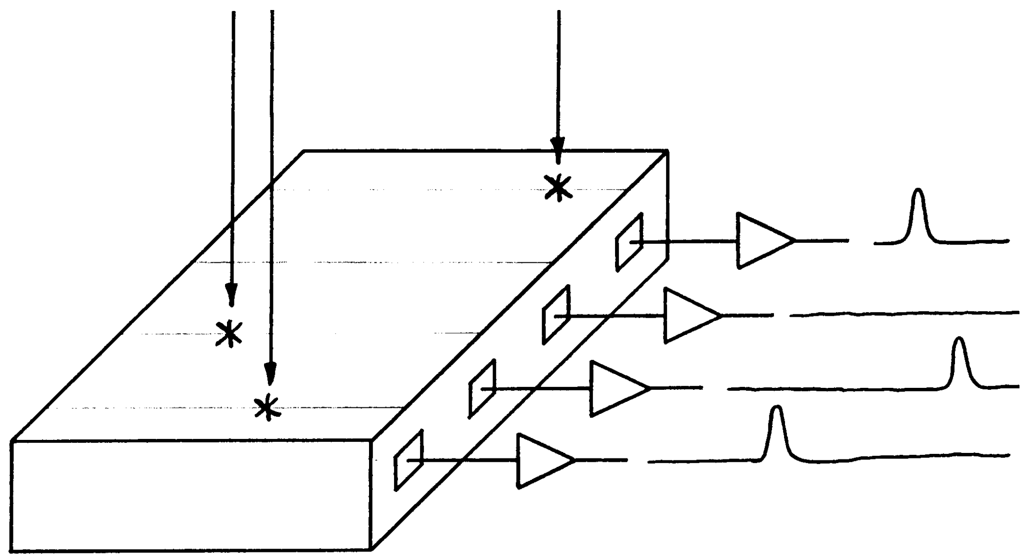


3. Hybrid Arrays

CCD with readout amplifier per row or column

or

Semiconductor drift chamber with segmented anode



Readout time dependent on hit coordinate.

Drift time ~ µs/cm

⇒ At high rates multiple spills within readout time

⇒ Event timing must be reconstructed

No problem at long bunch intervals, e.g. RHIC

Is the Power Dissipation of a Random Access Pixel Array Prohibitive?

If a strip readout for the LHC requires 2 mW per strip on an 80 µm pitch, i.e. 250 mW/cm width, is it practical to read out 15000 pixels per cm^2?

strip detector:	n strips
pixel detector:	n x n pixels

The capacitance is dominated by the strip-strip or pixel-pixel fringing capacitance.

$\Rightarrow$ capacitance proportional to periphery (pitch p and length l)

$$C \propto 2(l+p) \;\Rightarrow\; C_{pixel} \approx \frac{2}{n} C_{strip}$$

In the most efficient operating regime the power dissipation of the readout amplifier for a given noise level is proportional to the square of capacitance (to be discussed in IX.10)

$$P \propto C^2$$

$\Rightarrow$
$$P_{pixel} \approx \frac{4}{n^2} P_{strip}$$

n times as many pixels as strips

$\Rightarrow$
$$P_{pixel,tot} \approx \frac{4}{n} P_{strip}$$

$\Rightarrow$ Increasing the number of readout channels can reduce the total power dissipation!

The circuitry per cell does not consist of the amplifier alone, so a fixed power P_0 per cell must be added, bringing up the total power by $n^2 P_0$, so these savings are only realized in special cases.

Nevertheless, random addressable pixel arrays can be implemented with overall power densities comparable to strips.