VI. Position-Sensitive Detectors

Position-sensitive detectors can be implemented in two basic architectures

1. Direct Readout

> 1 readout channel 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.

1. Interpolation
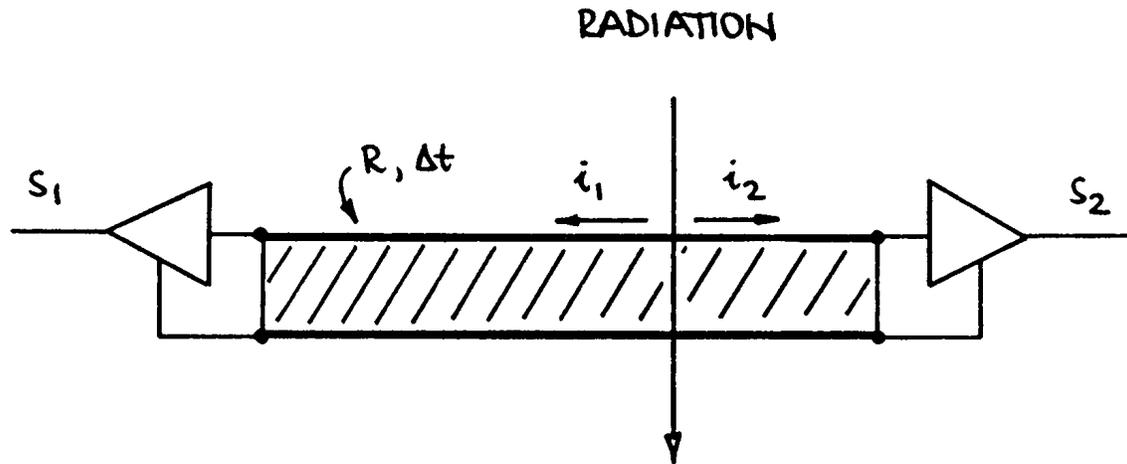
Possibilities:

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. Since the amplifiers have a low input impedance, 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.

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, the rise times of the signals at the two ends will also be the same, so the time resolutions

$$\Delta t_1 = \Delta t_2$$

so

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

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

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

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

With this result the position resolution is

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

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 increase the delay time and would seem to improve the position resolution.

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

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

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

so the resolution will not improve by increasing the dielectric constant of the transmission medium.

The other technique to increase the delay time is to introduce resistance to make 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 the group velocity

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

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 $\tau = RC$, so for a simple RC low-pass filter the time resolution is

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

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

Thus, the position resolution

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

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

As to be expected, the position resolution improves with increasing signal to noise ratio and decreasing capacitance.

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

If we include the noise from the electrode resistance:

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

If the electrode resistance dominates the noise

$$4k_B TR \gg v_n^2$$

then

$$\frac{\Delta x}{l} = \frac{1}{2\sqrt{2}} \frac{\sqrt{4k_B TR}}{Q_s} \sqrt{\frac{C}{R}} = \frac{1}{\sqrt{2}} \frac{\sqrt{k_B TC}}{Q_s}$$

which is practically 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 $\varepsilon = 1$

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

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.

Some implementations use specially designed delay lines to increase the propagation time. Frequently, they sacrifice S/N. 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)
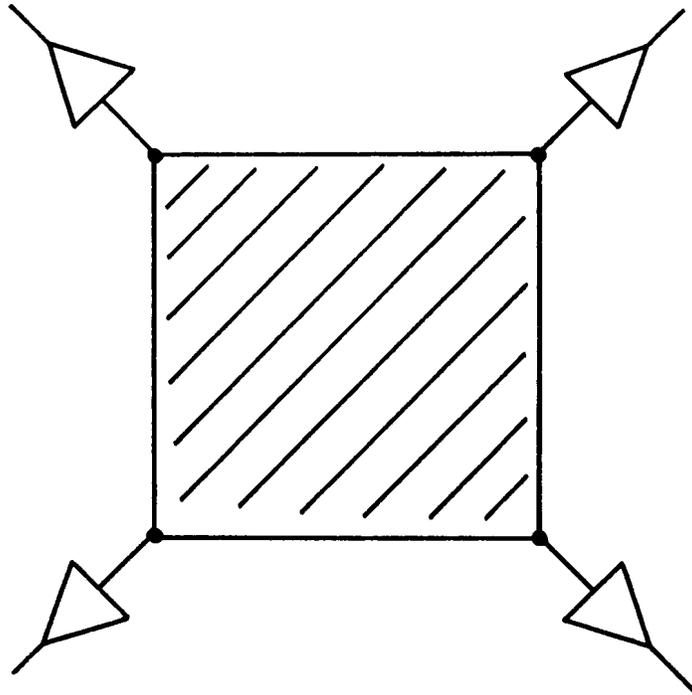
Although interpolation schemes allow a relatively large area to be read out with a small number of readout channels, they do this at the expense of multi-hit capability, i.e.

> 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. TPC-like 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

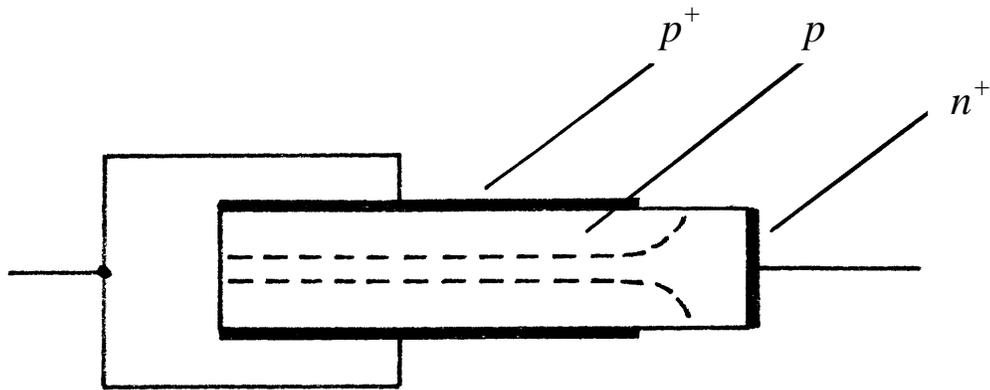Example 1: Delay line readout with external trigger
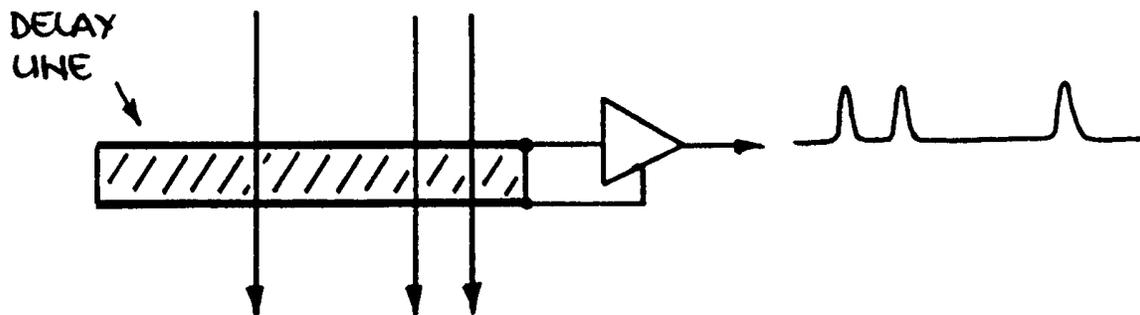
Example 2: Semiconductor Drift Chamber
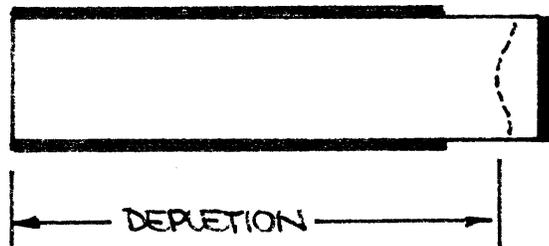
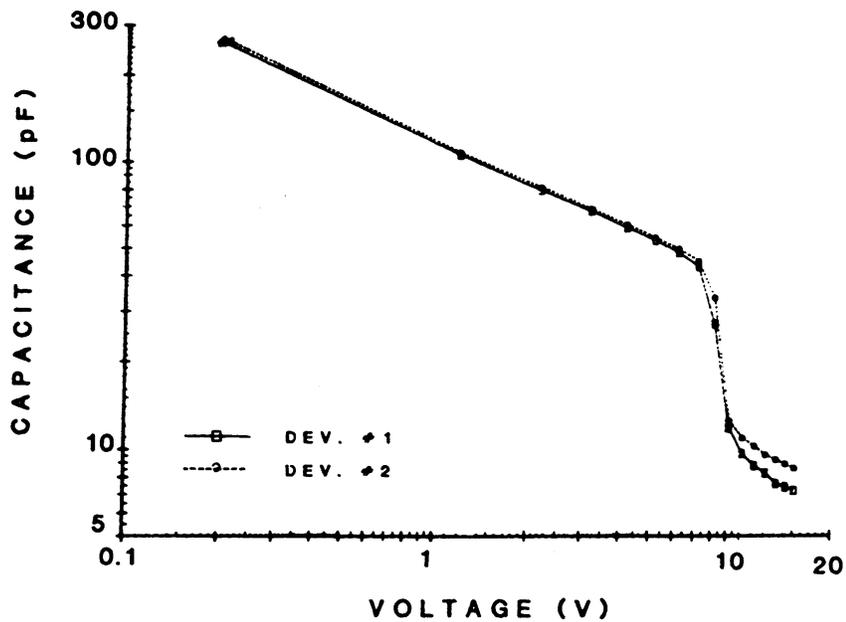Use detector material as delay element
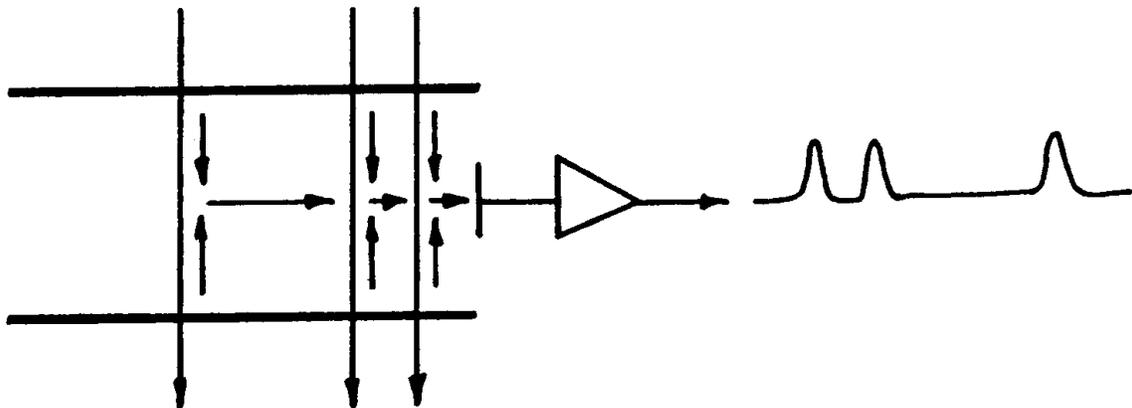
Semiconductor Drift Chamber

1st Ingredient: depletion from edge of detector

p^+ p n^+

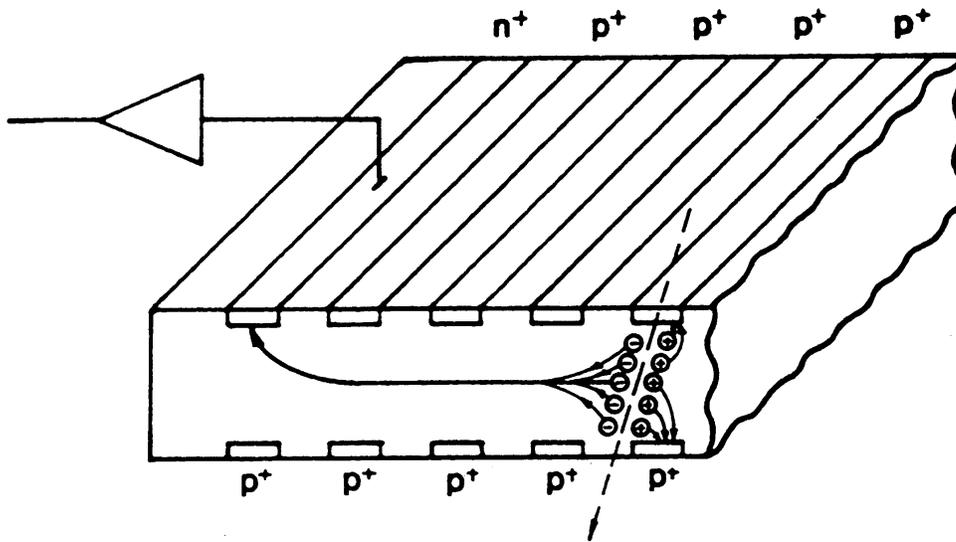INCREASE REVERSE BIAS:

|← DEPLETION →|

Depletion vs. Reverse Bias Voltage
(from Gatti et al. IEEE Trans. Nucl. Sci. **NS-32** (1985) 1204)
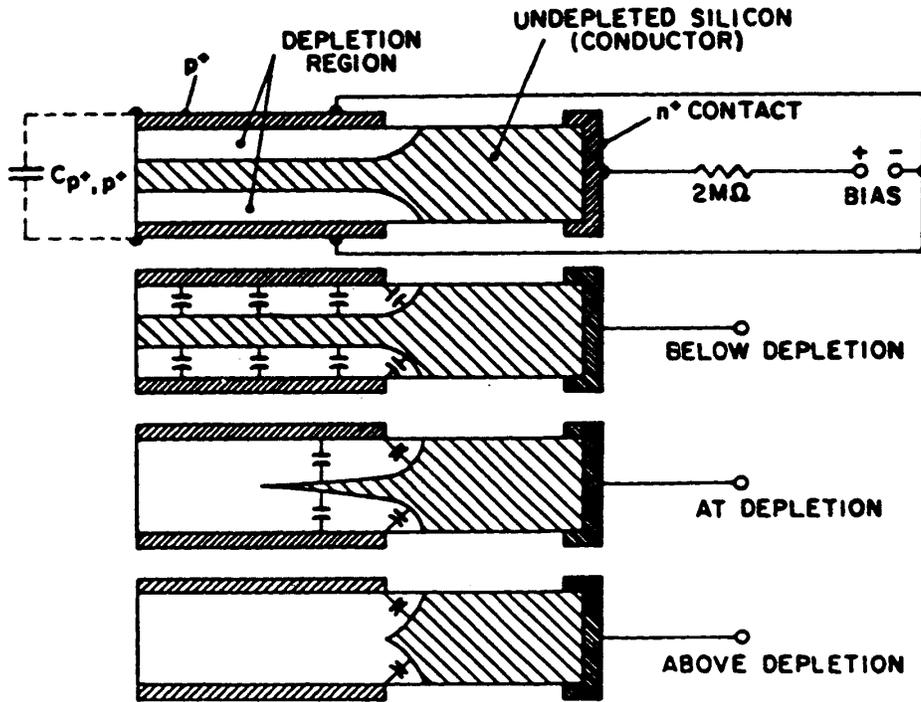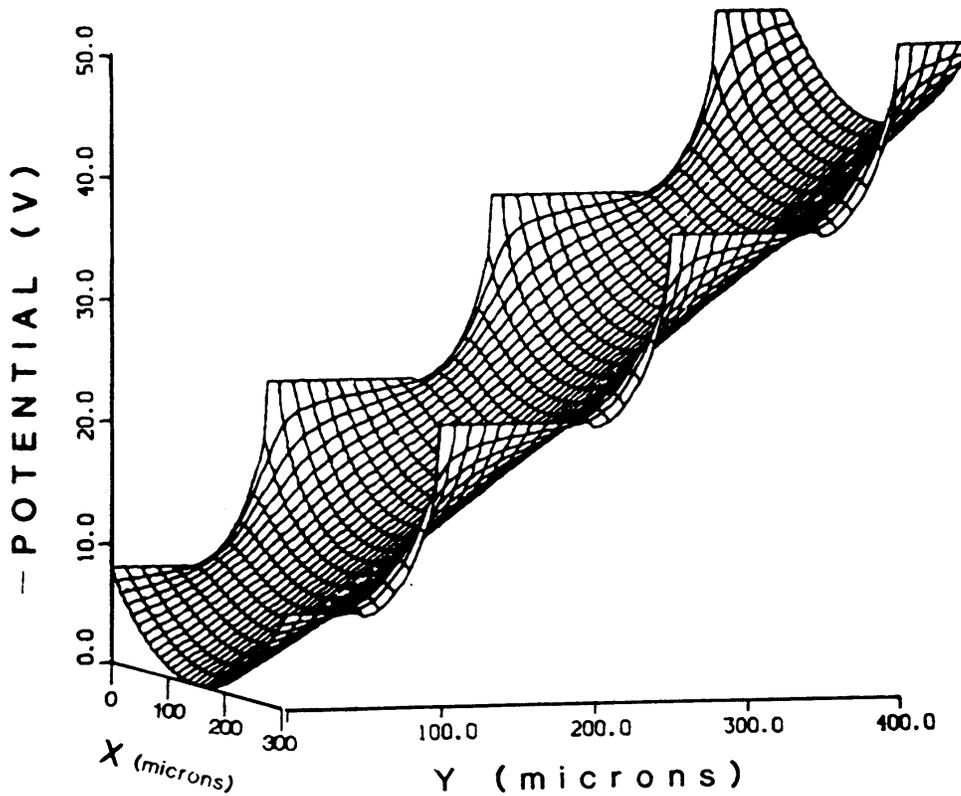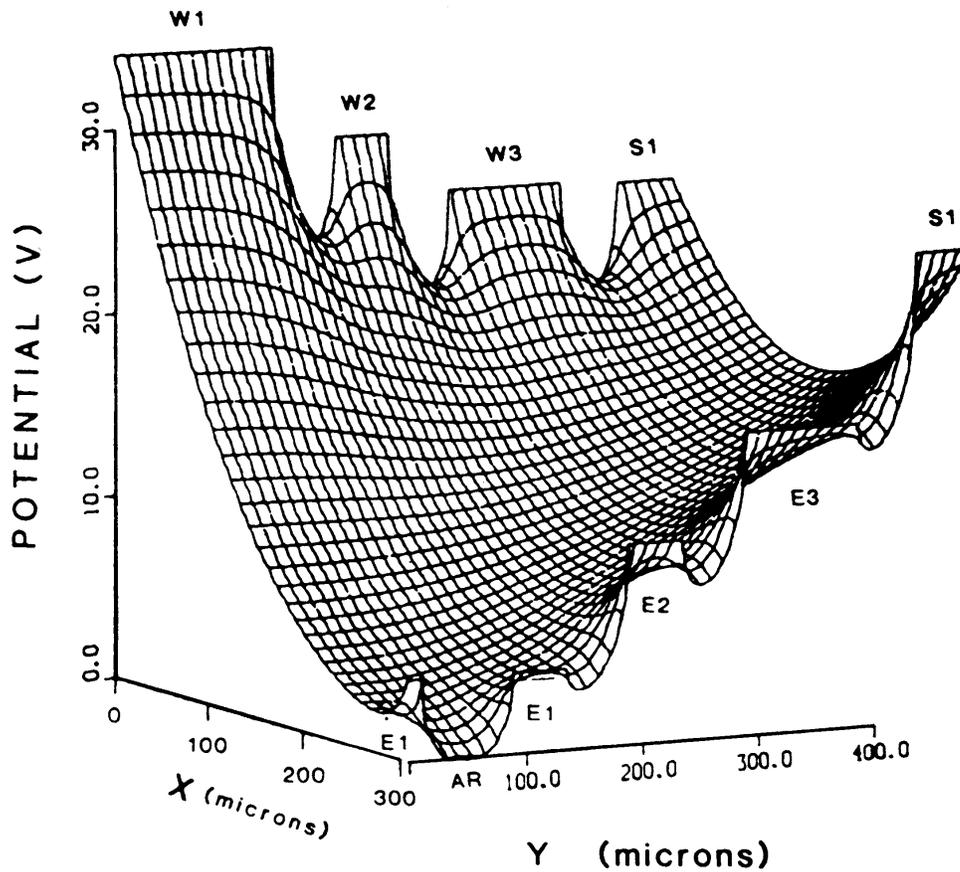
2nd Ingredient:

Add additional electrodes to form drift field parallel to surface

Potential Distribution

Potential trough can be skewed to direct charge to readout electrode on surface.

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

$\Rightarrow$ capacitance can be very small, even on a large area detector ($C \sim 50 - 100$ fF for $A = 10$ cm^2)

$\Rightarrow$ ~ 10 μm resolution over 5 – 10 cm drift distance

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

$\Rightarrow$ problem with radiation damage.

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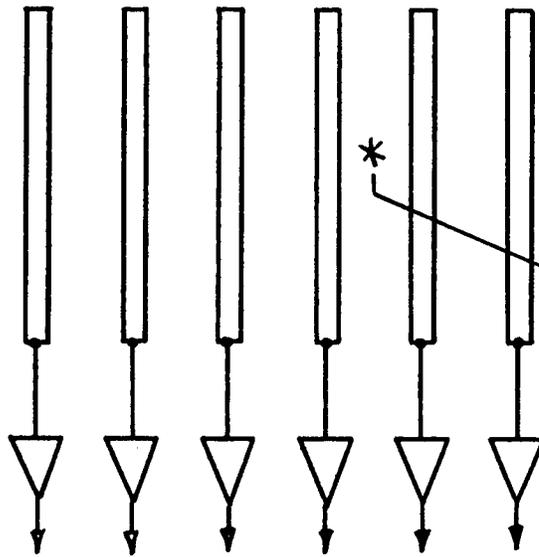
3. Parallel Readout

One readout channel per resolution element

Example: Strip Detectors

Two options:

<div style="display: flex;">
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Binary Readout

to discriminators

Position resolution determined
directly by pitch

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

</div>
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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

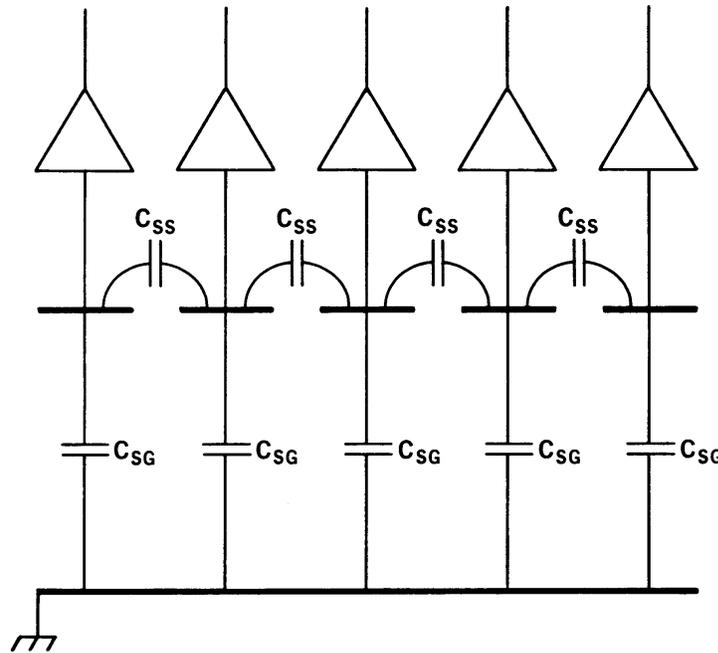$\Rightarrow$ $\sigma_x =$ 5 µm

Interpolation precision
depends on S/N and p

$p =$ 25 µm and $S/N = 50$

$\Rightarrow$ 3 − 4 µm resolution

</div>
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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.
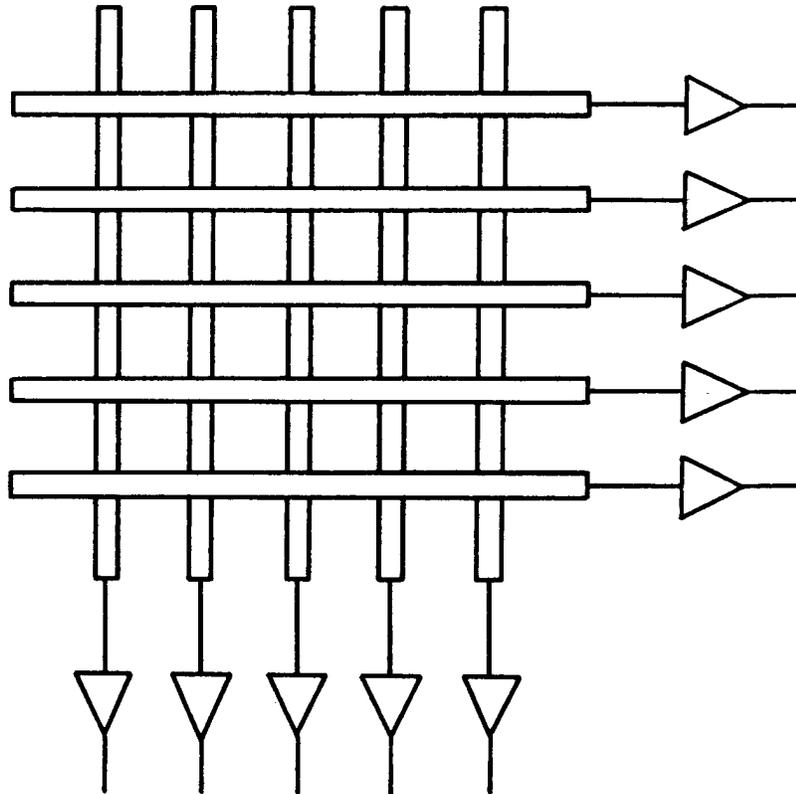
The presence of the adjacent strips limits the fringing field to the centerline bewteen two strips, i.e. width = strip pitch.

The backplane capacitance is typically 20% of the strip-to-strip capacitance.

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
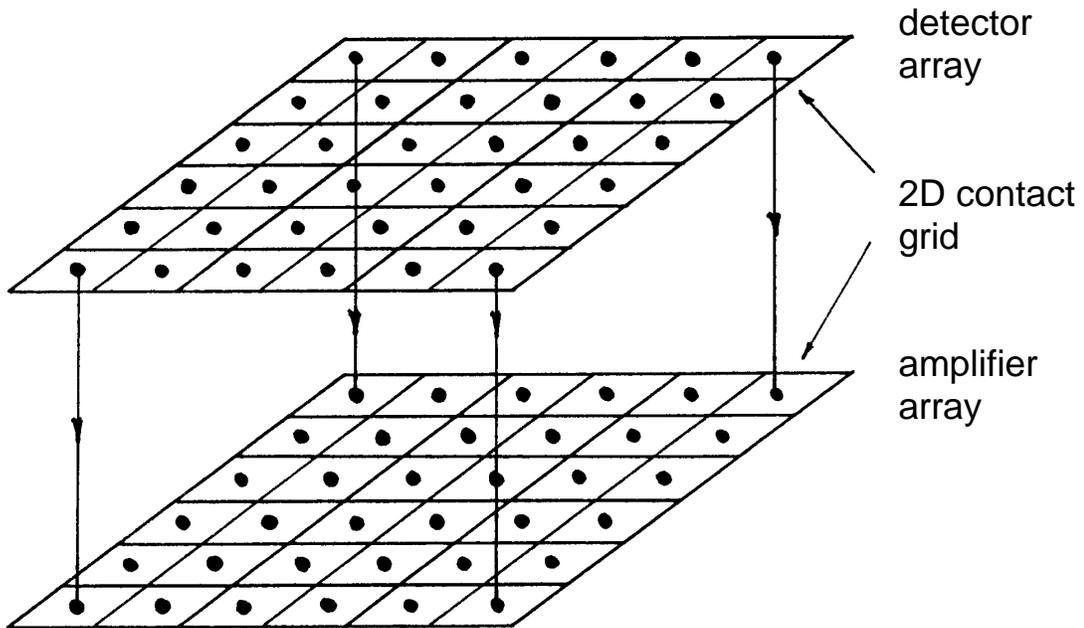 n y-coordinates

                                      $\Rightarrow$ n^2 combinations

                                            of which
                                            n^2 - n are "ghosts"

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

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

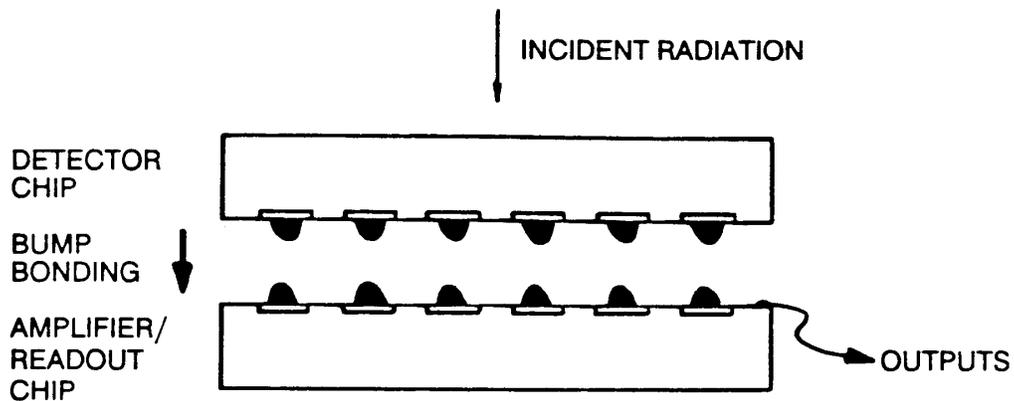at clock rate of 10 MHz
50 μm pixel size $\Rightarrow$ 20 μs/cm

b) Random–Access Pixel Arrays

Amplifier per pixel

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

detector array

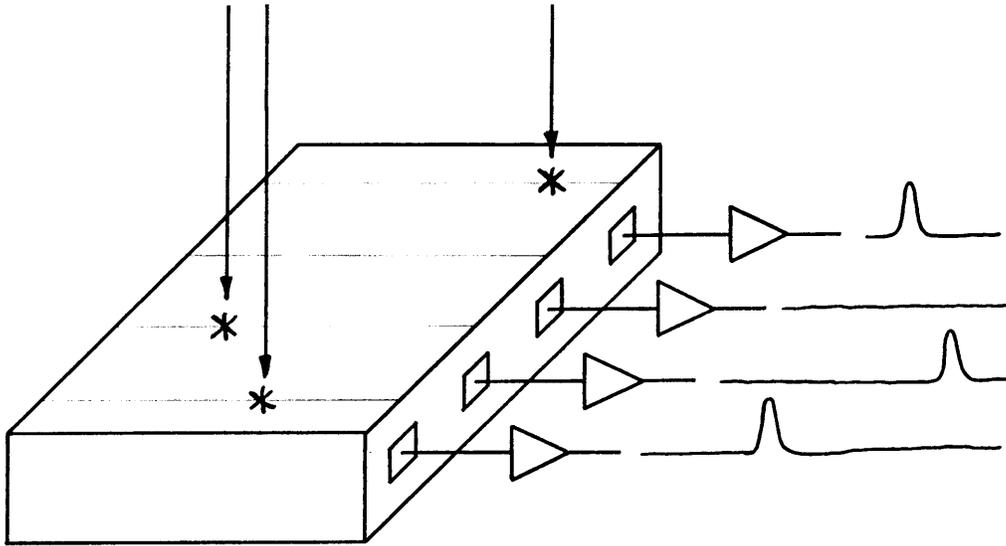2D contact grid

amplifier array

2D contact via "bump bonds"

INCIDENT RADIATION

DETECTOR CHIP

BUMP BONDING

AMPLIFIER/ READOUT CHIP

OUTPUTS

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

$\Rightarrow$ At high rates multiple spills within readout time

$\Rightarrow$ 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)

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

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 (discussed in VIII.5)

$$P \propto C^2$$

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

n times as many pixels as strips

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

$\Rightarrow$ 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.