4. Ionisationsmessung

4.1 Ionisationskammer

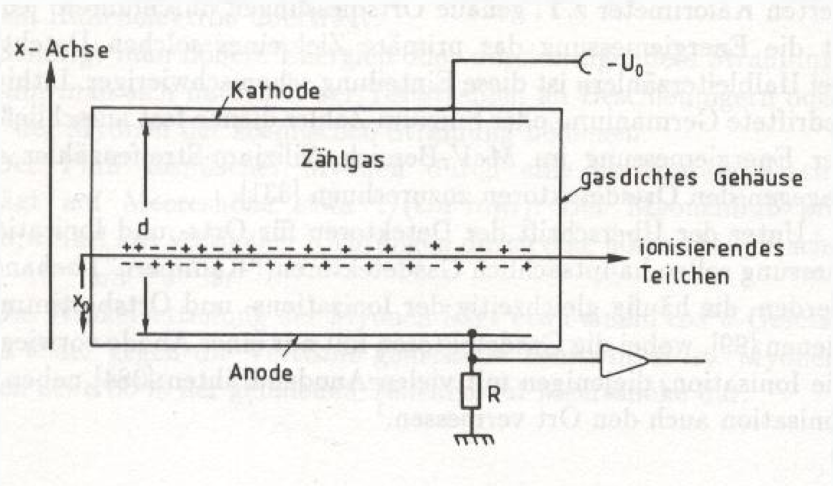
4.2 Ionisationsausbeute

4.3 Proportionalzähler

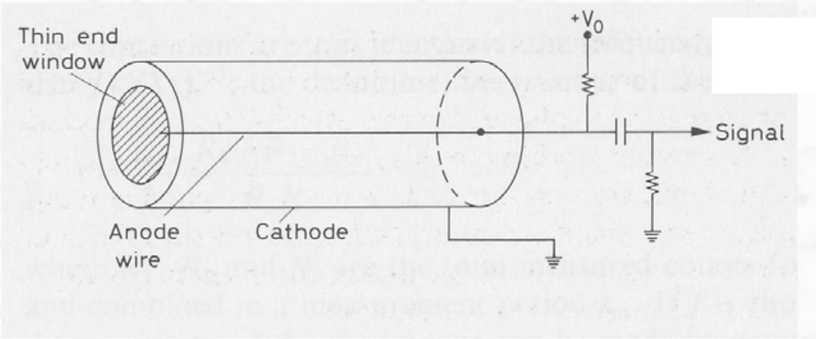
4.4 Auslösezähler, Geiger-Müller Zählrohr

4.5 Anwendungen zur Ortsmessung
- Vieldrahtproportionalkammer
- Driftkammer
- Silizium Halbleiterdetektoren

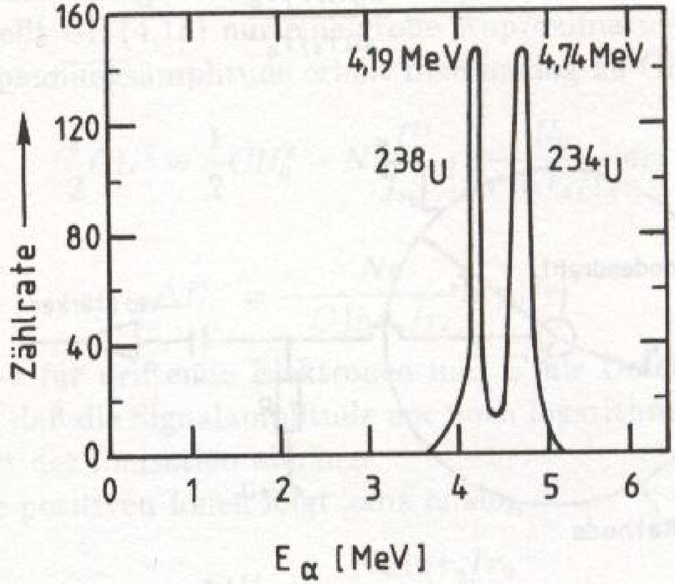
Abbildungen zu Kap 4.1



Prinzip einer planaren Ionisationskammer
[Ref. C. Grupen]



Prinzip eines zylindrischen Ionisationsrohres
[Ref. W.R. Leo]



Impulshöhendiagramm von a-Teilchen eines ^{234}U / ^{238}U Nuklidgemisches;   [Ref. Grupen]

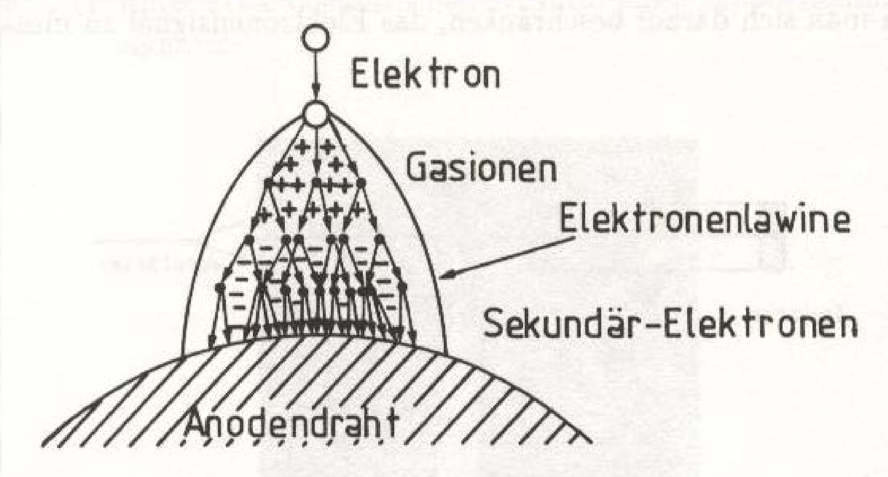
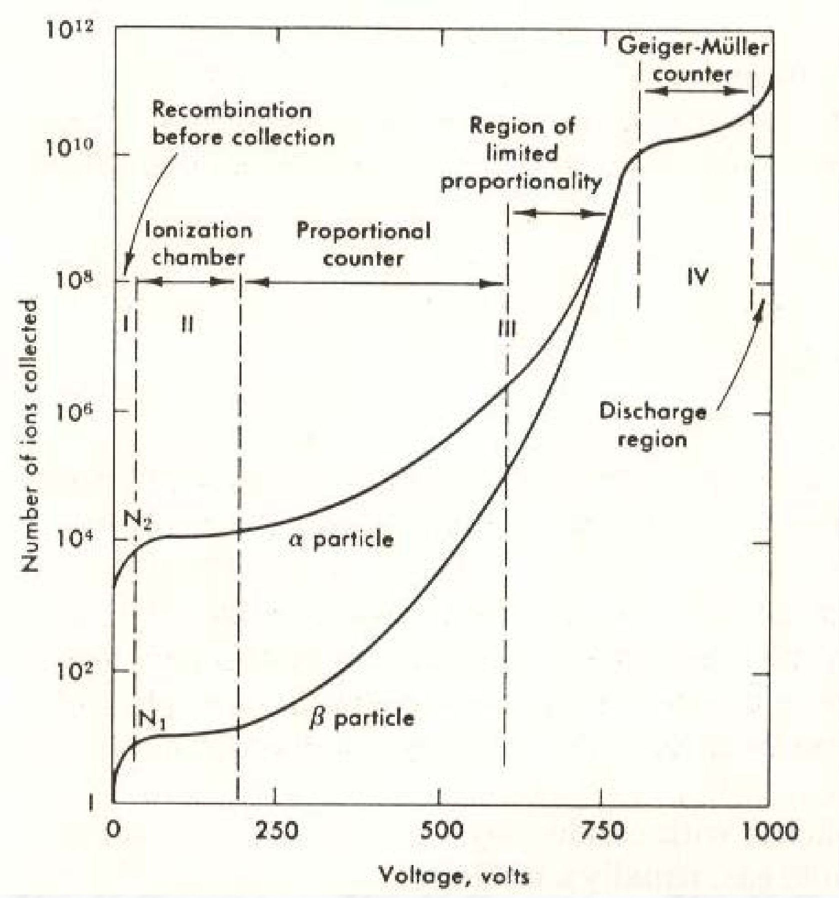


Illustration der Lawinenbildung an einem Anodendraht in einem Proportionalzählrohr. Durch laterale Diffusion entwickelt sich eine tropfenartige Lawine [Ref. Grupen]

Abbildungen zu Kap 4.2

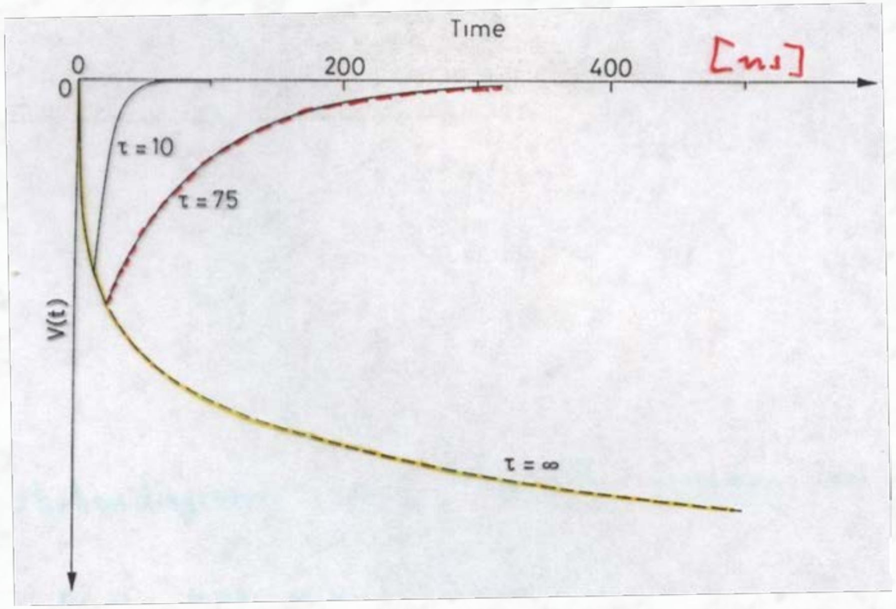
Gas	Dichte $\varrho[g/cm^3]$	$I_0[eV]$	$W[eV]$	$n_p[cm^{-1}]$	$n_T[cm^{-1}]$
H_2	$8.99 \cdot 10^{-5}$	15.4	37	5.2	9.2
He	$1.78 \cdot 10^{-4}$	24.6	41	5.9	7.8
N_2	$1.25 \cdot 10^{-3}$	15.5	35	10	56
O_2	$1.43 \cdot 10^{-3}$	12.2	31	22	73
Ne	$9.00 \cdot 10^{-4}$	21.6	36	12	39
Ar	$1.78 \cdot 10^{-3}$	15.8	26	29	94
Kr	$3.74 \cdot 10^{-3}$	14.0	24	22	192
Xe	$5.89 \cdot 10^{-3}$	12.1	22	44	307
CO_2	$1.98 \cdot 10^{-3}$	13.7	33	34	91
CH_4	$7.17 \cdot 10^{-4}$	13.1	28	16	53
C_4H_{10}	$2.67 \cdot 10^{-3}$	10.8	23	46	195

Tabelle 1.2: Zusammenstellung einiger Eigenschaften von Gasen. Angegeben sind der mittlere Energieverlust W pro erzeugtes Ionenpaar, das mittlere effektive Ionisationspotential pro Hüllen-Elektron I_0, die Anzahl der primär (n_p) und insgesamt (n_T) gebildeten Elektron-Ion-Paare pro cm bei Normaldruck für minimalionisierende Teilchen [94, 32, 104, 8]. [Ref. C. Grupen]



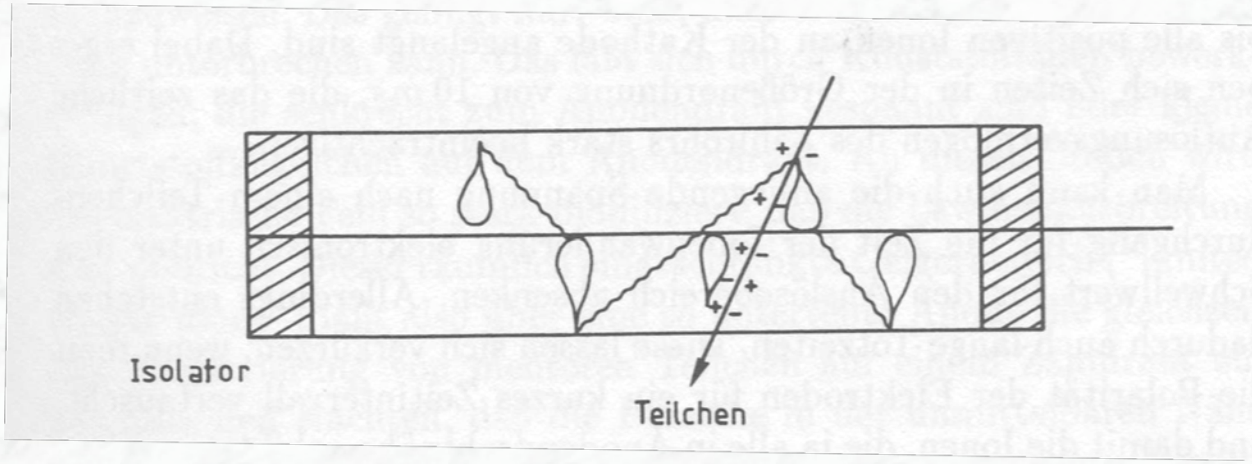
Anzahl der gesammelten Ladungsträger (Ionen) als
Funktion der angelegten Spannung in einem Gas-Zählrohr
[Ref. W.R. Leo]

Abbildungen zu Kap 4.3



Spannungspuls in einem zylindrischen Proportionalzählrohr,
Für verschiedene Zeitkonstanten der nachfolgenden
Elektronik [Ref. W.R. Leo]

Abbildungen zu Kap 4.4



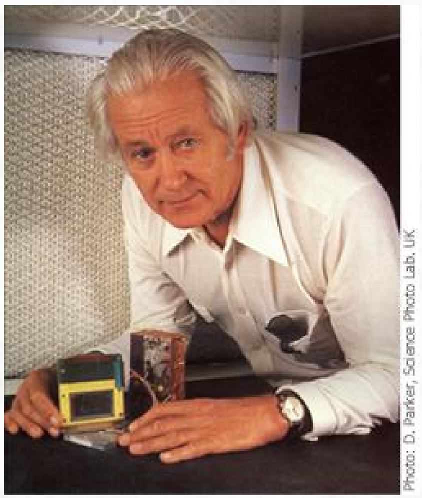
Zur Illustration der transversalen Lawinenausbreitung in einem Geiger-Müller-Zählrohr [Ref. C. Grupen]

4.5.1 Multi-wire proportional chamber

- In order to extract space / coordination information efficiently, Multi-Wire-Proportional Chambers (MWPCs) were used for long time

  G. Charpak (Nobel prize,1992)

Principle:
Put many anode wires in parallel, in one volume



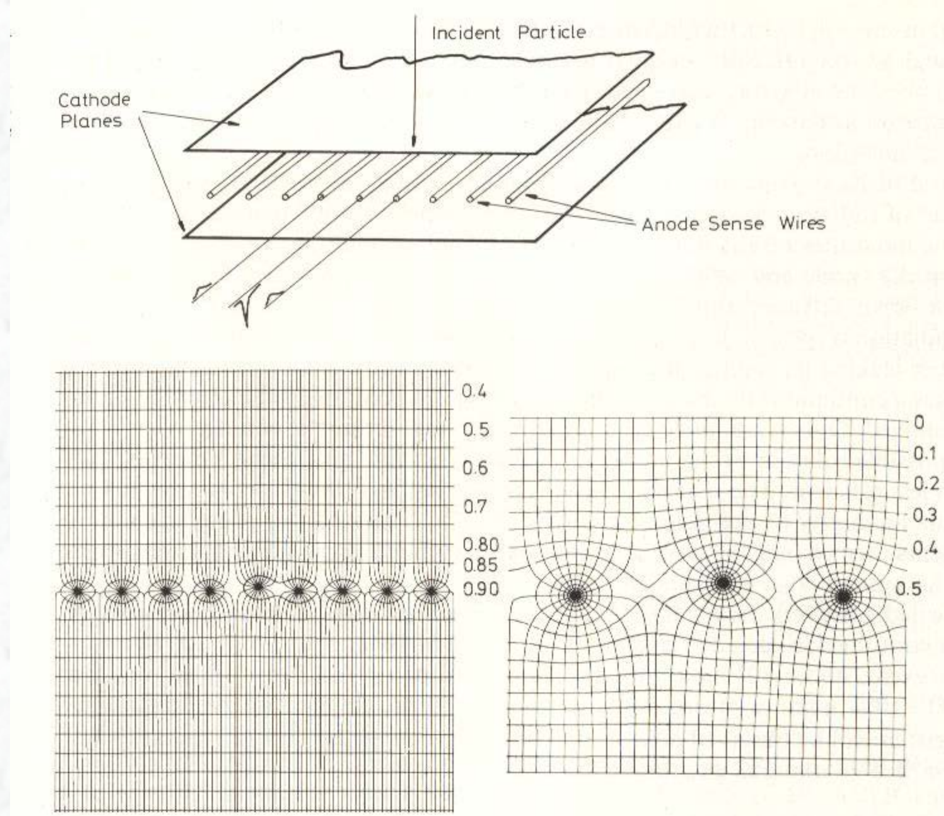
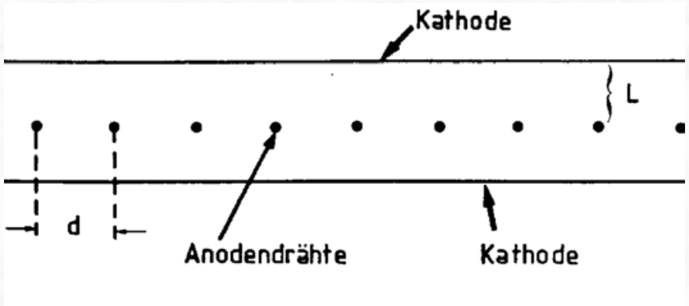


Fig. 6.8. Electric field lines and potentials in a multiwire proportional chamber. The effect of a sli displacement on the field lines is also shown (from *Charpak* et al. [6.16])

- Every wire acts as an independent proportional tube

  → every anode wire is read out separately → space information



- Typical parameters: distance between wires: d = 2 mm
  distance anode-cathode: L = 7-8 mm
  diameter of anode wires: 10 – 30 μm

- Achievable coordinate resolution: $\sigma = d / \sqrt{12}$ ~ 600 μm

Can they be used for the LHC ??

No ! they are too slow, and the precision is not good enough !

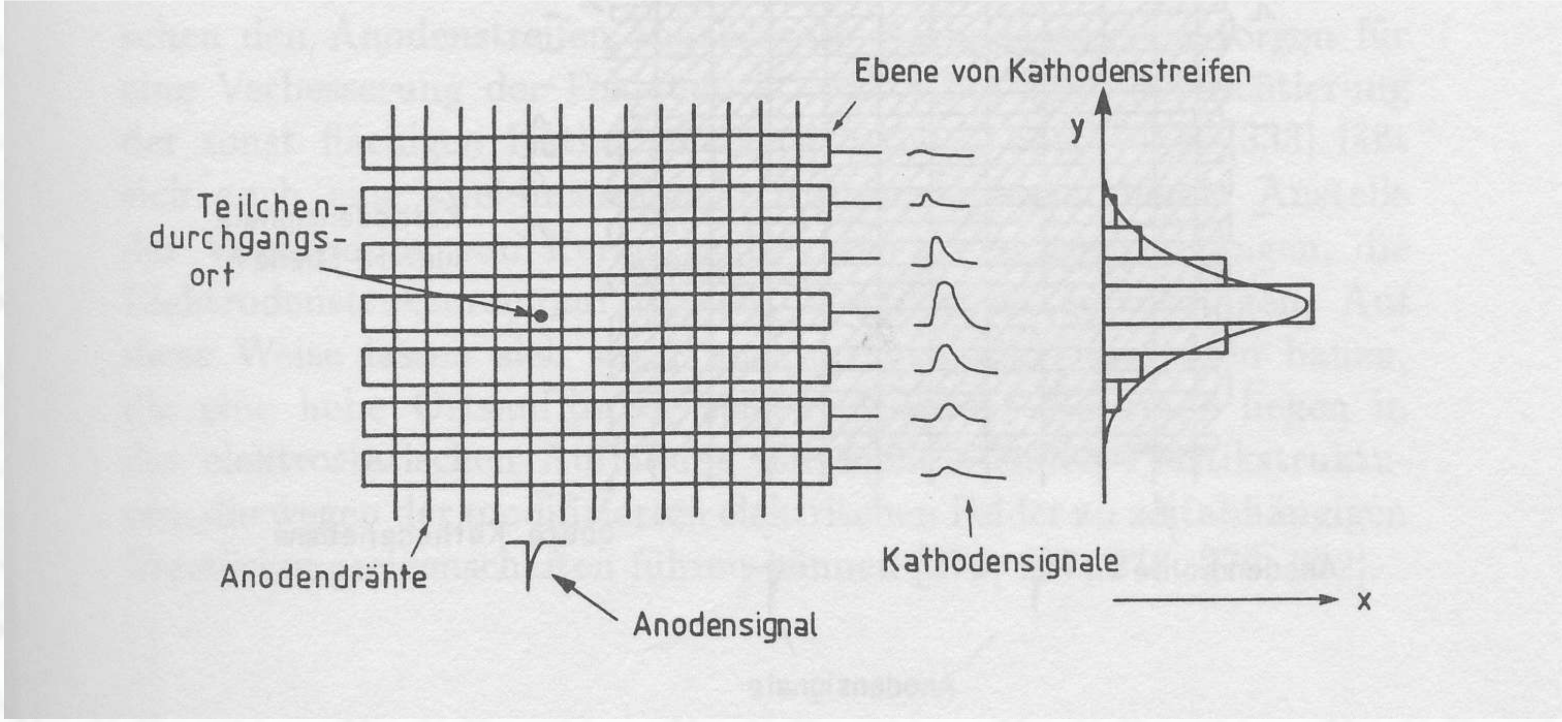
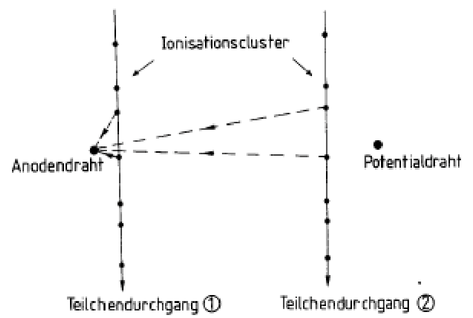
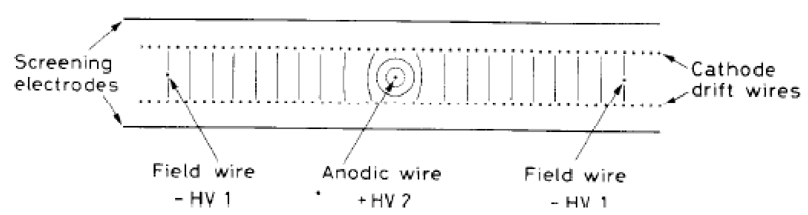


Illustration der Kathodenauslese in einer Vieldrahtproportionalkammer
[Ref. C. Grupen]

4.5.2 Drift chambers

- Measure not only pulse height, but also the time when a signal appears with respect to an external trigger signal





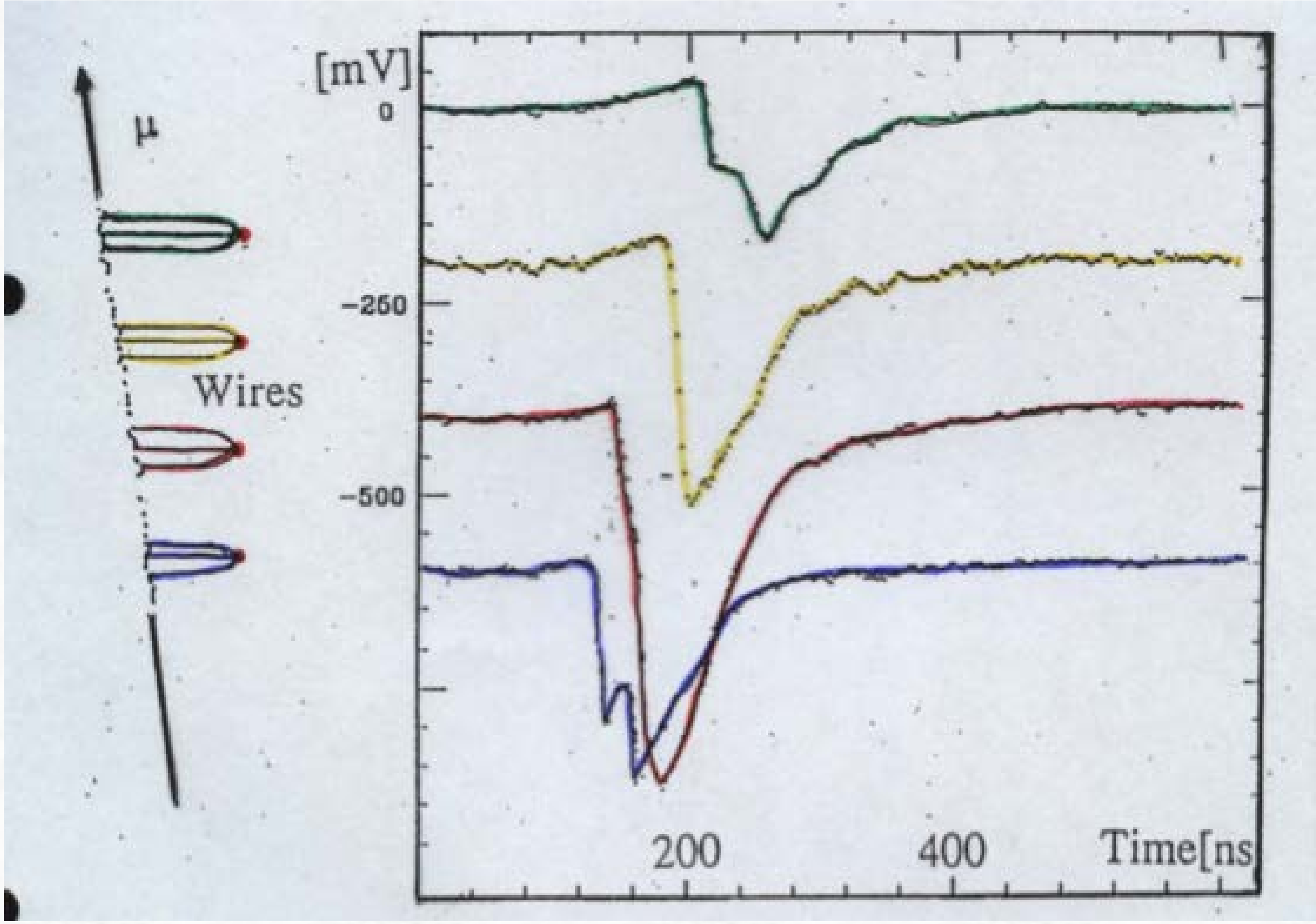
- Position perpendicular to the anode wire can be extracted from a space-drift-time relation
  (has to be known, it is linear if the drift velocity is constant over the drift volume)

- Typical drift distances: 5 – 10 cm → more economical, less readout channels

- Improved coordinate resolution, typical values: $\sigma \sim 50 - 200\ \mu m$

  limited by diffusion of the drifting electron clouds, electronics (time measurements)

Measured signals in a drift chamber



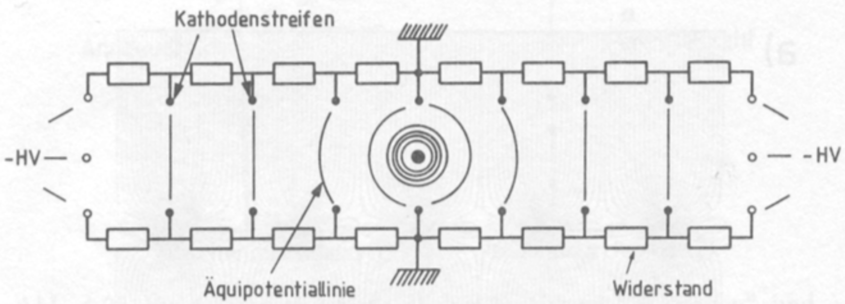


Abb. 4.36 Illustration der Feldformung in einer großflächigen Driftkammer.

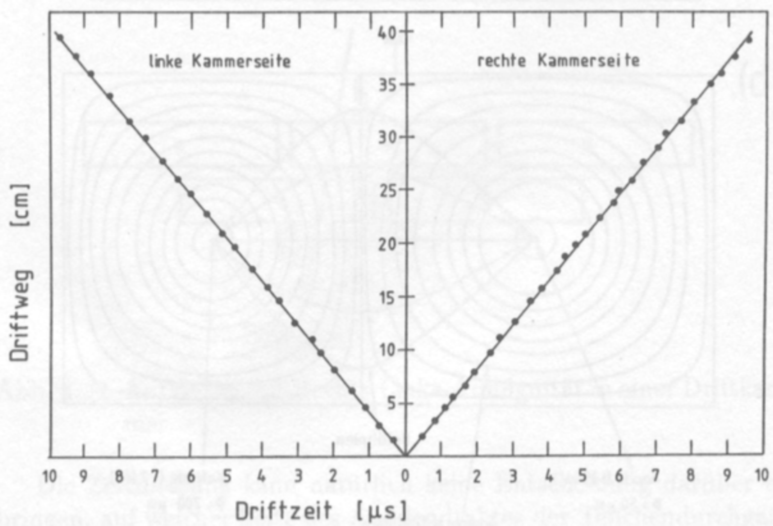


Abb. 4.37 Driftzeit-Driftwegbeziehung in einer großen Driftkammer ($80 \times 80\, cm^2$) mit nur einem Anodendraht [130].

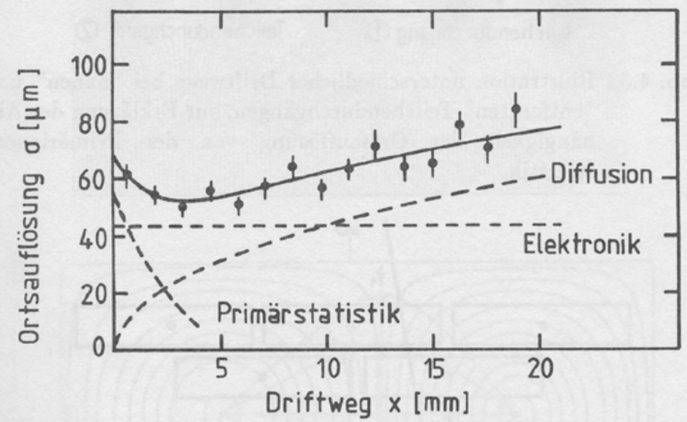


Abb. 4.32 Ortsauflösung in einer Driftkammer als Funktion des Driftweges [104].

[Ref. C. Grupen]

Drift chamber of the CDF experiment (Fermilab)

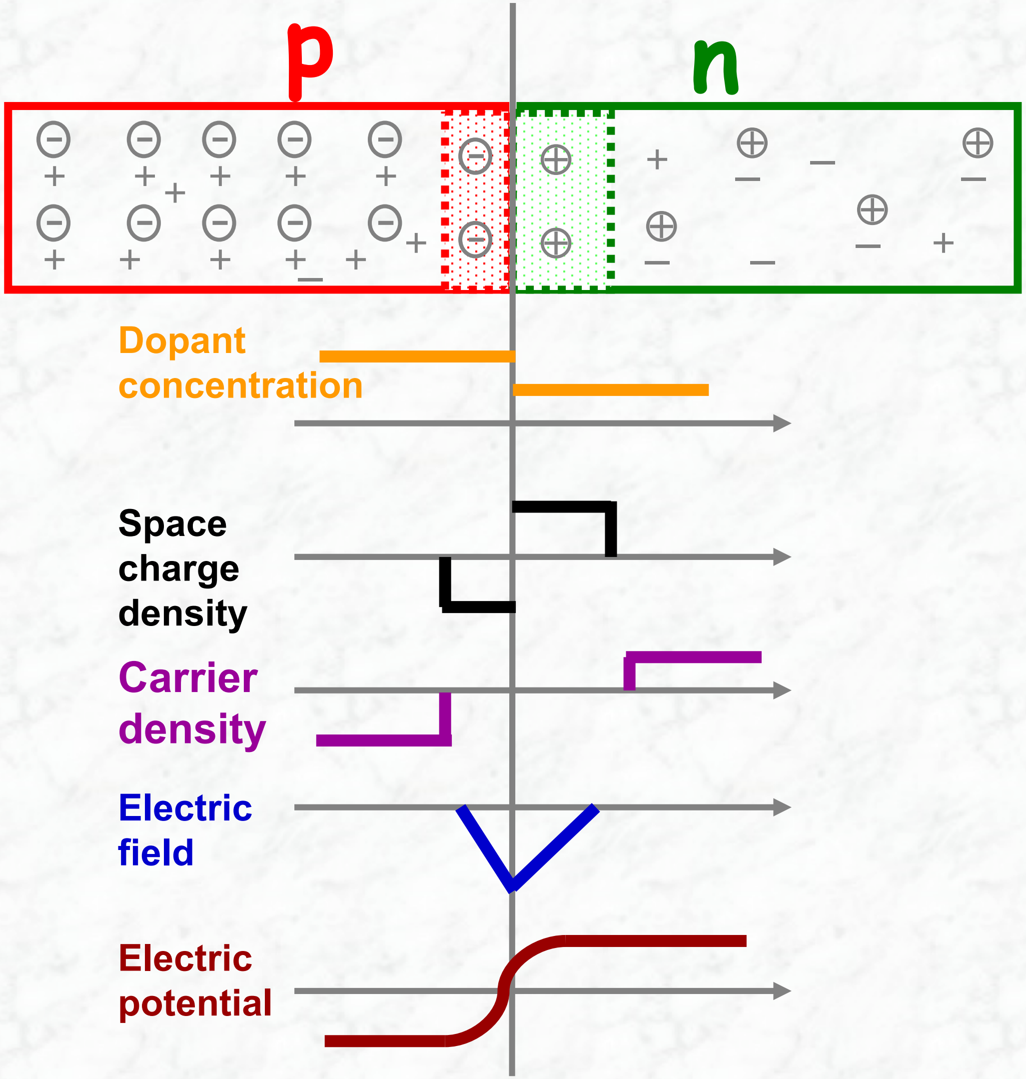
4.5.3 Silicon Semiconductor detectors

- Silicon detectors: a kind of solid-state ionisation chamber
- Si-detector concepts started in the 80s, but expensive and difficult at first
- Increased commercial use of Si-photolithography and availabilty of VLSI electronics lead to a boom for Si-Detectors in the 90s – and it still goes on;
- Nearly all high energy physics experiments use Silicon detectors as innermost high-precision tracking device
- High energy physics experiments are now exporting Si-technology back to the commercial world (Medical Imaging

Basic Silicon Properties

- Silicon: type IV element, 1.1eV band gap
- Intrinsic conductivity very low $\boldsymbol{\sigma_i = e \cdot n_i (\mu_e + \mu_h)}$
  - Carrier density at 300 K:
    - $1.5 \cdot 10^{10}$ cm^{-3} compared to $5 \cdot 10^{22}$ Si-Atoms per cm^{-3}
    - often dominated by impurities
- "Doping": Small admixtures of type III or type V elements increase conductivity
  - Donors like Phosphorous give extra electron -> n-type Si
  - Acceptors (e.g. Boron) supply extra hole -> p-type Si
  - Contact between p- and n-Si forms p-n-junction
  - Doping dominates conductivity as $\boldsymbol{n_i \ll n_D}$
  - for n-type Si: $\boldsymbol{\sigma_D = e \cdot n_D \cdot \mu_e}$

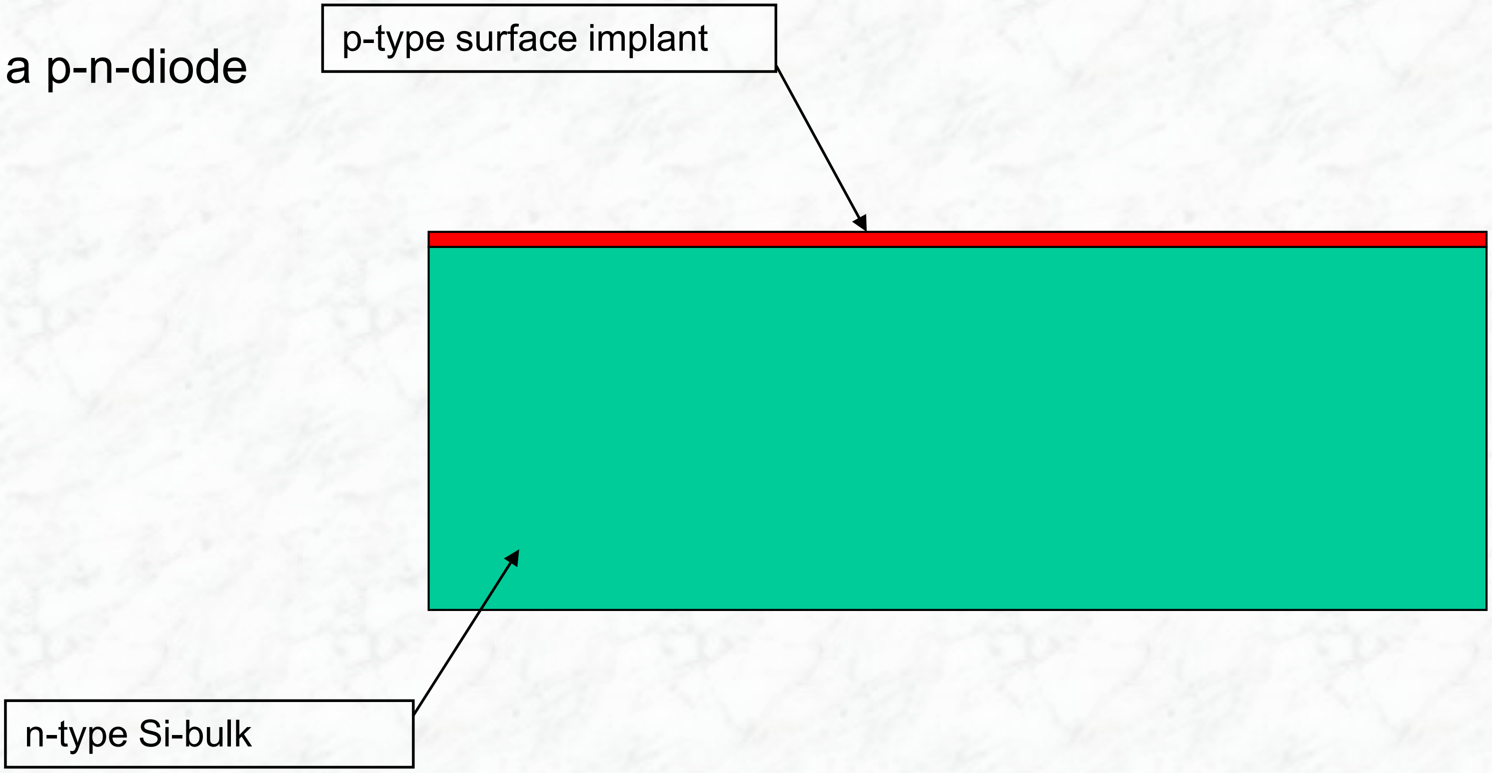
p-n-Junction



- Diffusion of e^- from n-side and h^+ from p-side
- Recombination on other side, free charges disappear around junction ("depletion")
- Neutral p- or n-Si becomes charged → E-Field
- External field can increase or decrease depletion zone
- Depletion is what we want for detectors!

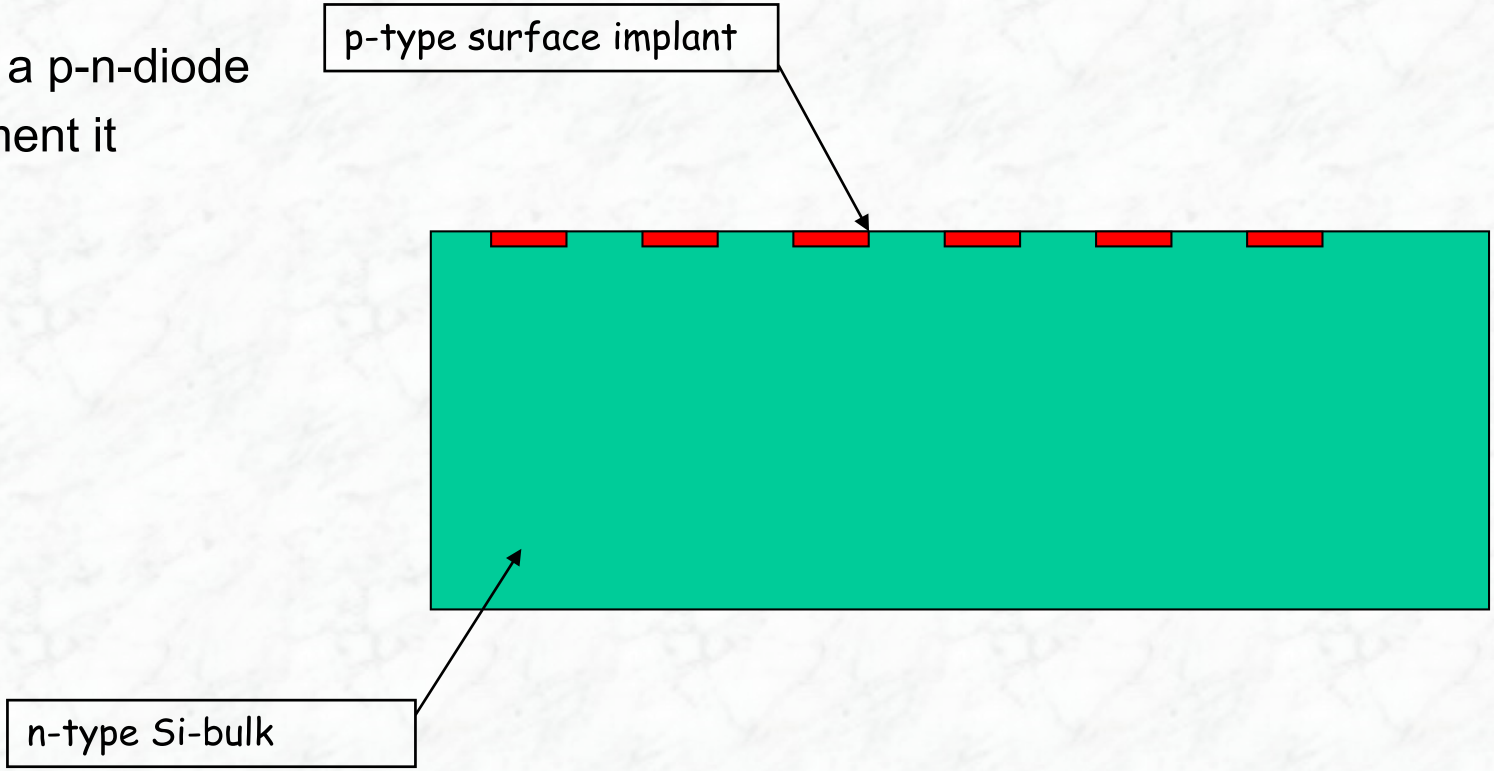
A Basic Silicon Detector

- Take a p-n-diode



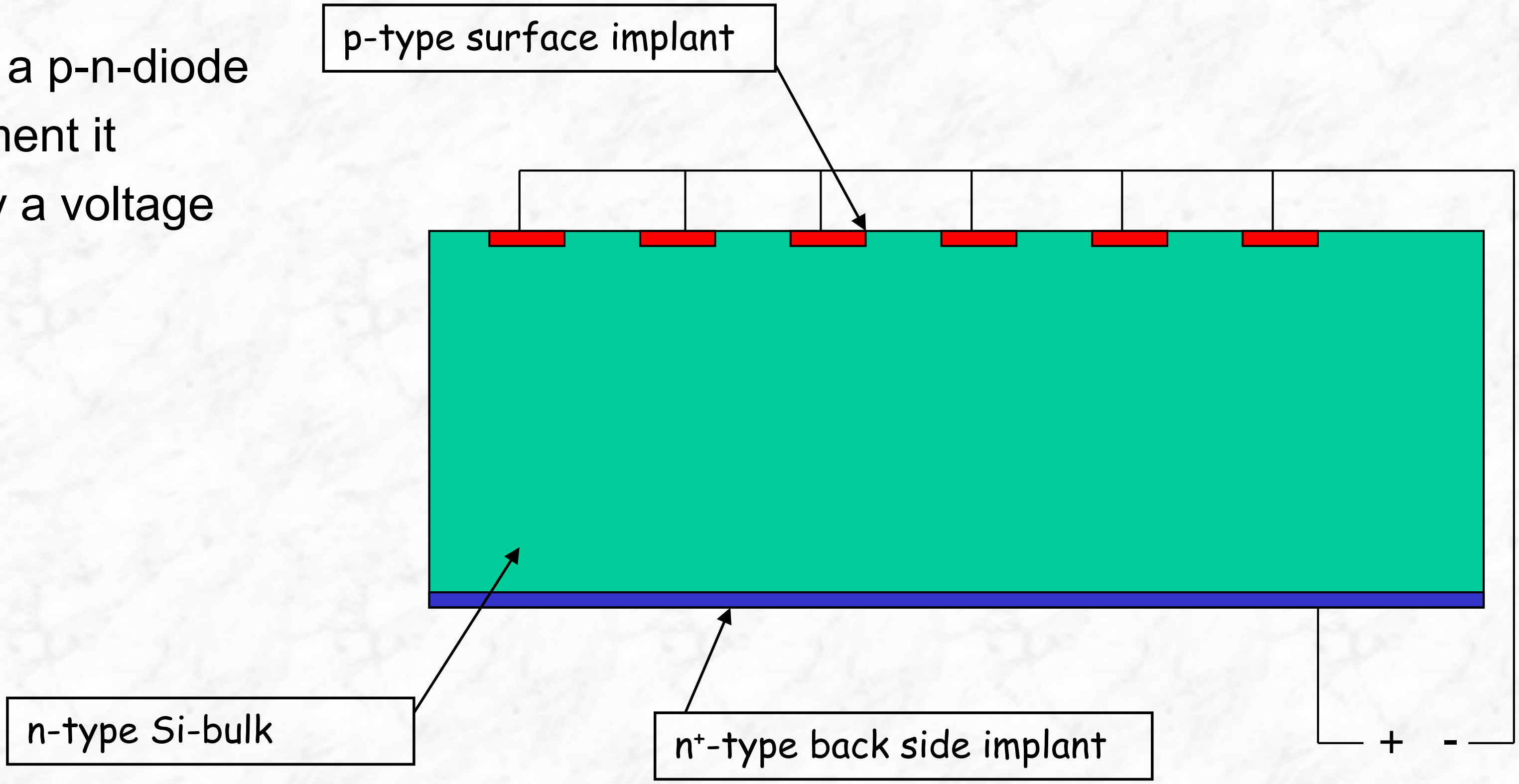
A Basic Silicon Detector

- Take a p-n-diode
- Segment it



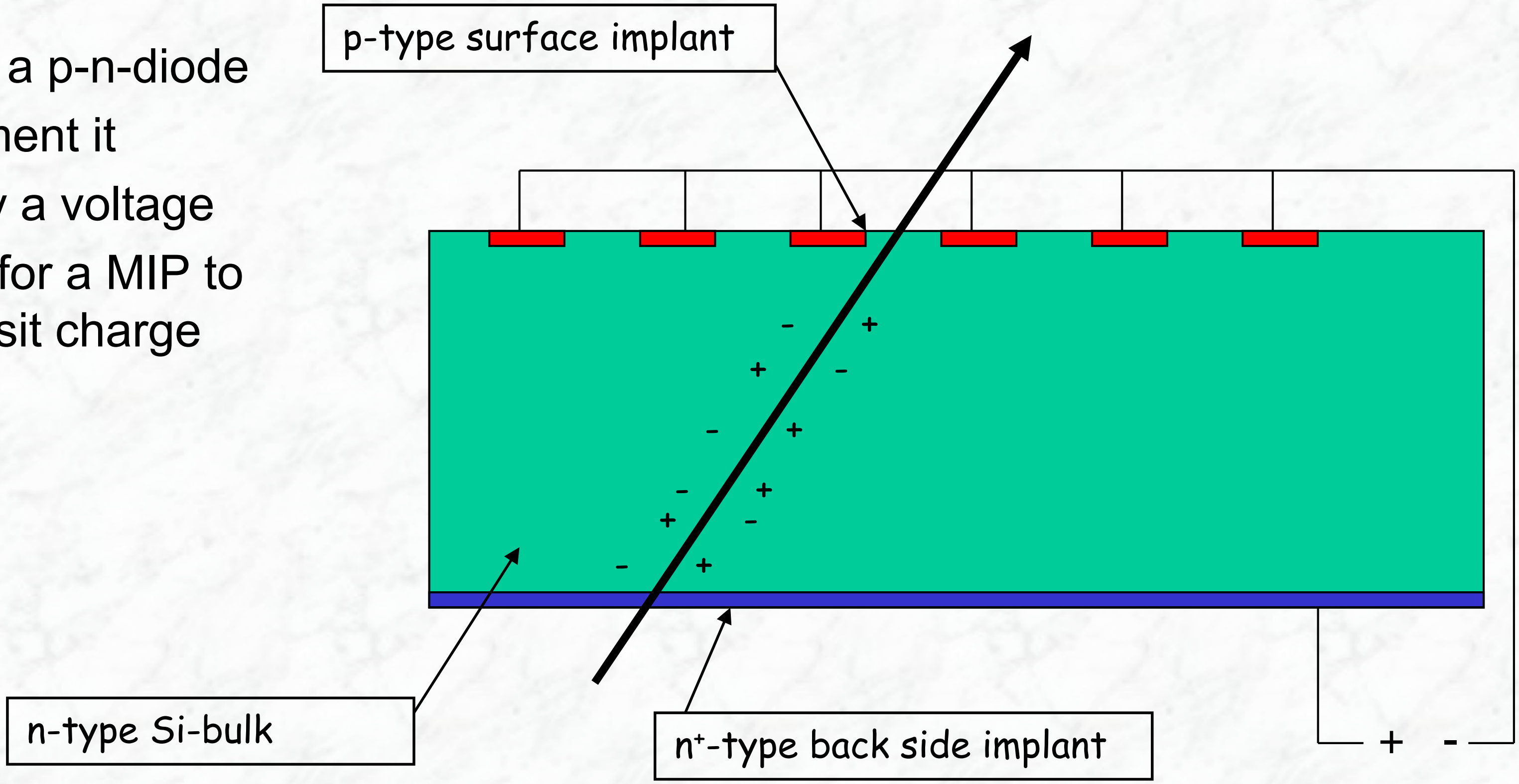
A Basic Silicon Detector

- Take a p-n-diode
- Segment it
- Apply a voltage



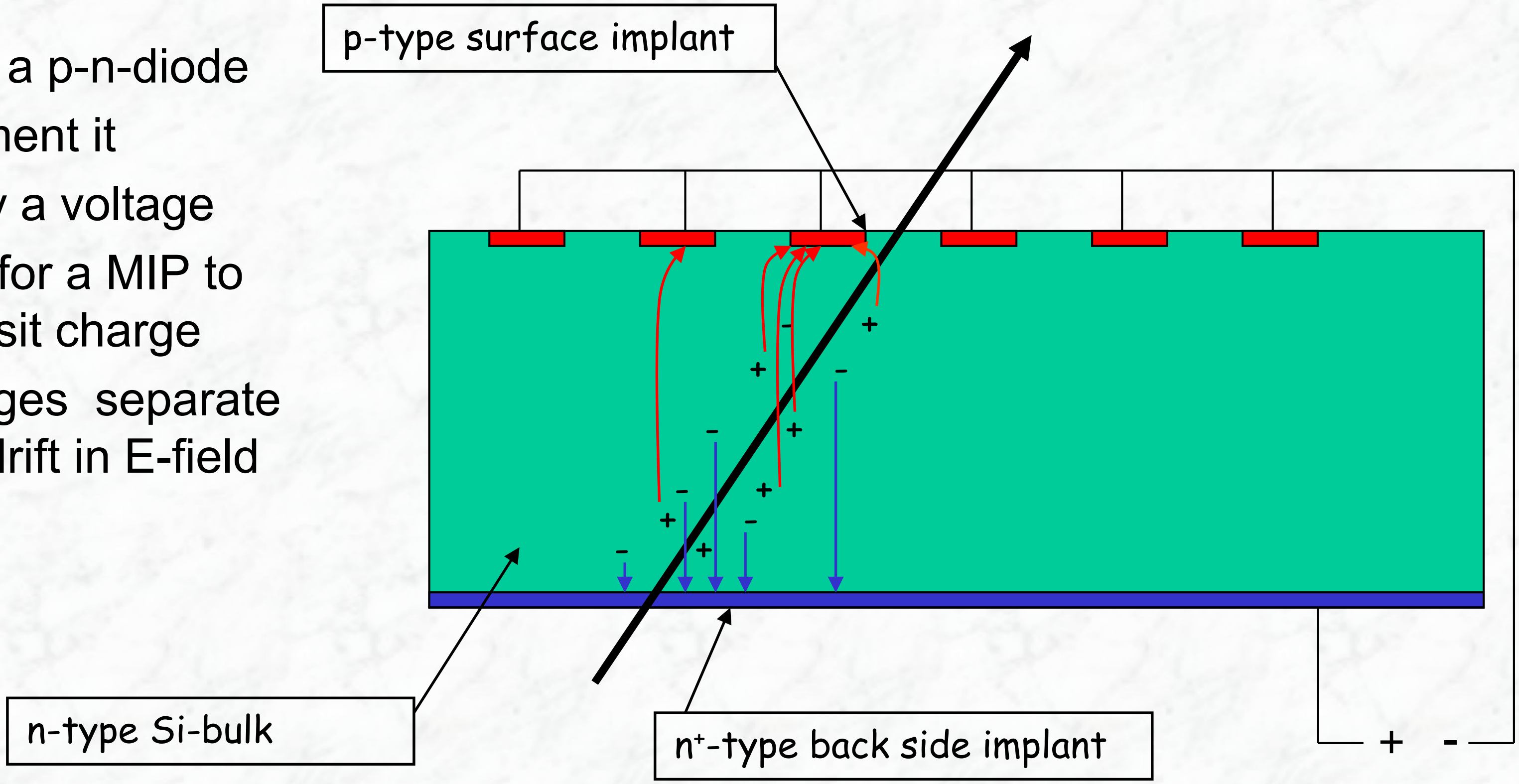
A Basic Silicon Detector

- Take a p-n-diode
- Segment it
- Apply a voltage
- Wait for a MIP to deposit charge



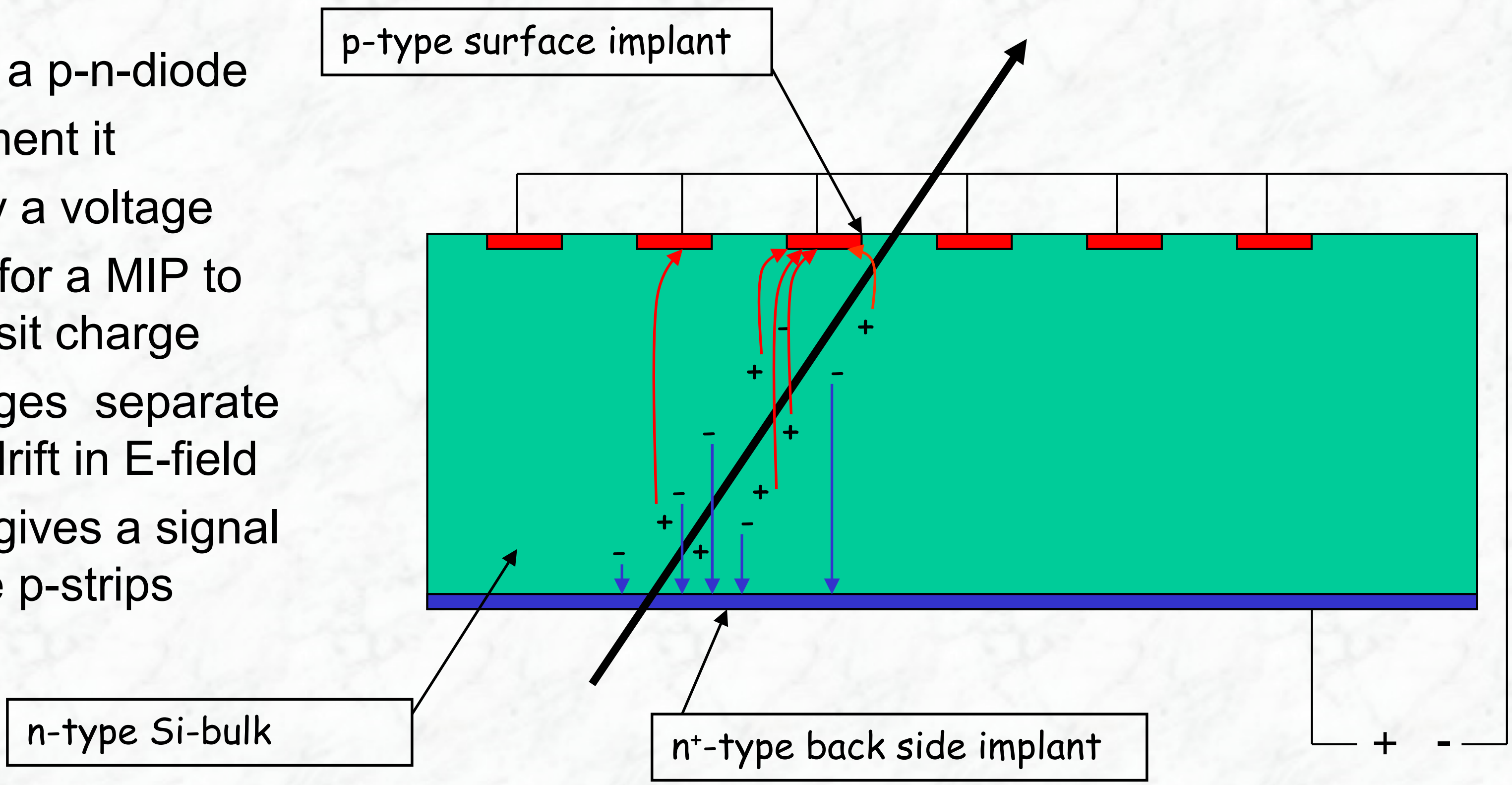
A Basic Silicon Detector

- Take a p-n-diode
- Segment it
- Apply a voltage
- Wait for a MIP to deposit charge
- Charges separate and drift in E-field



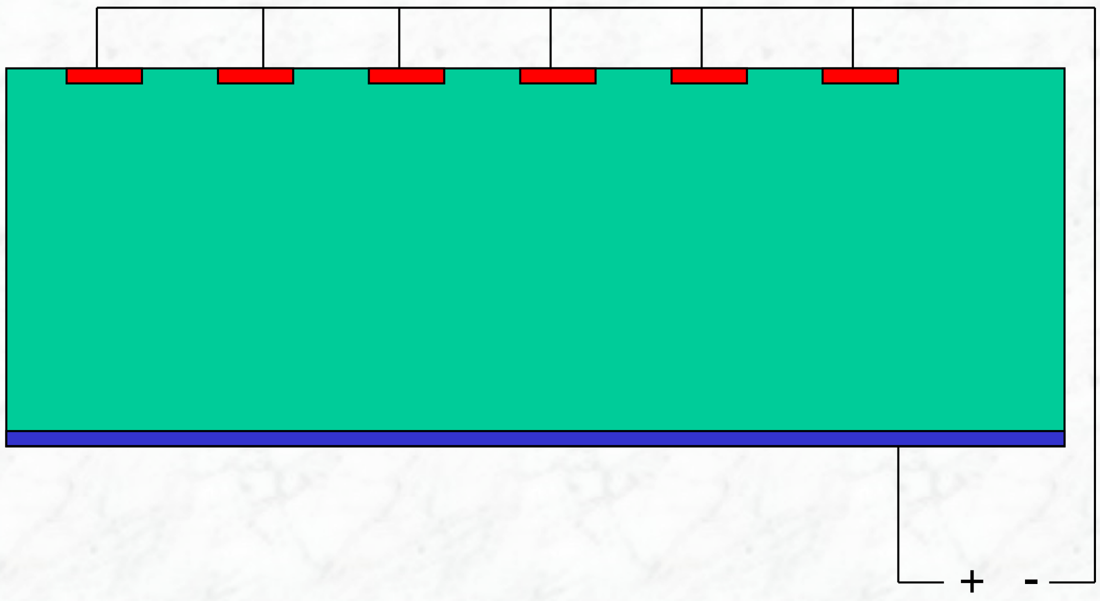
A Basic Silicon Detector

- Take a p-n-diode
- Segment it
- Apply a voltage
- Wait for a MIP to deposit charge
- Charges separate and drift in E-field
- This gives a signal in the p-strips



Depletion

- MIP charge in 300 µm Si is 4fC (22.000 e^-h^+-pairs)
- Free charge in 1 cm^2 Si-Detector 10^4 times larger (T=300K), so signal is invisible. Options:
  - Cryogenic operation
  - E-field to get rid of free charge
- Apply external Voltage to deplete Si from charges
- Depletion zone grows from p-n-junction towards the back side



$$w_{depletion} = \sqrt{2\varepsilon\rho\mu V_{bias}}$$

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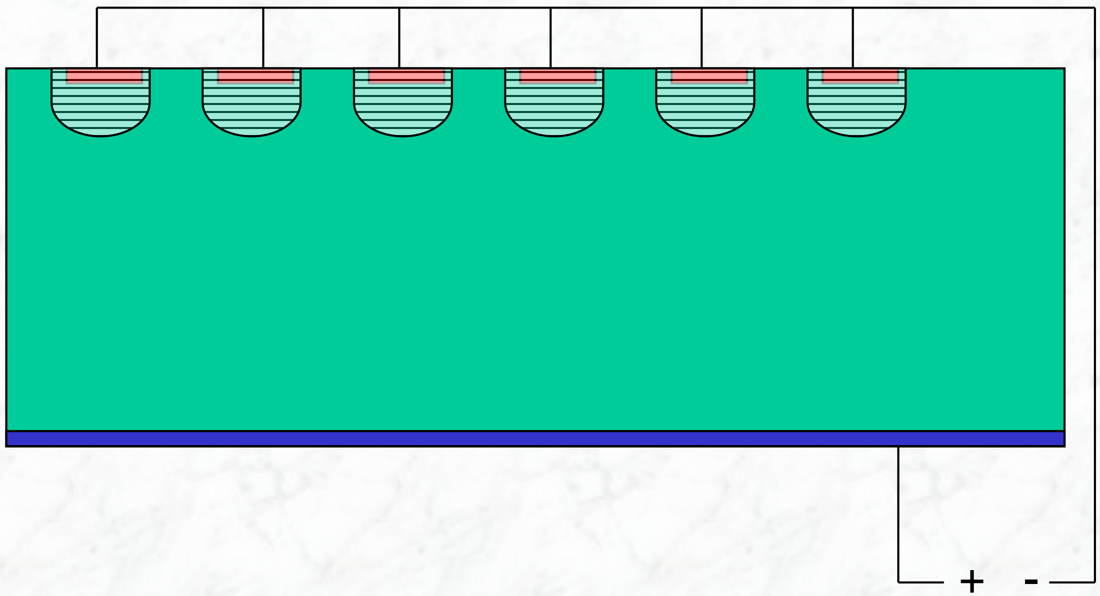

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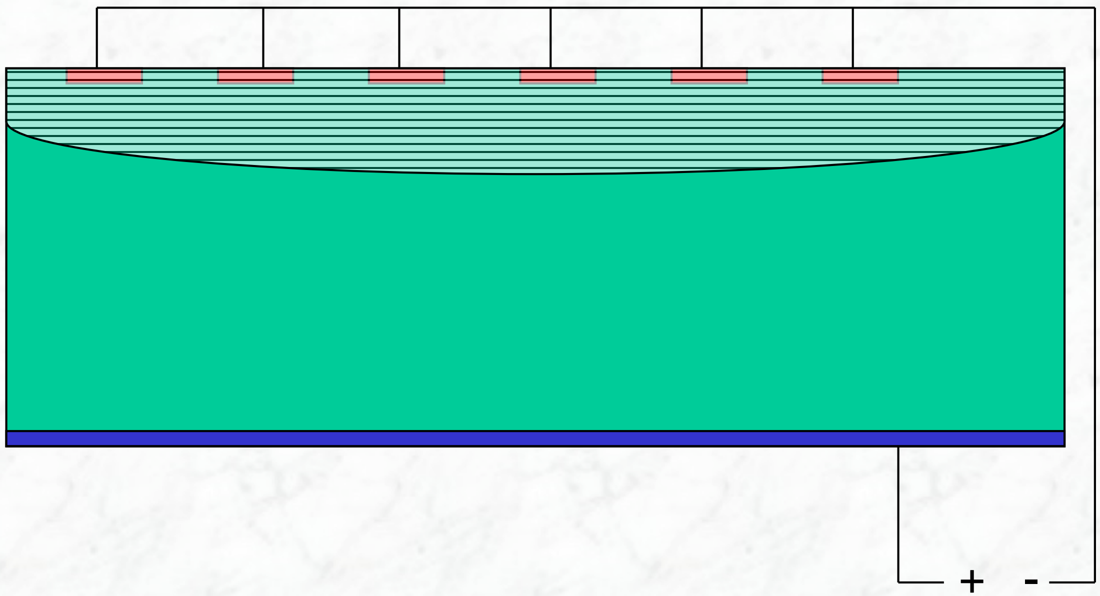

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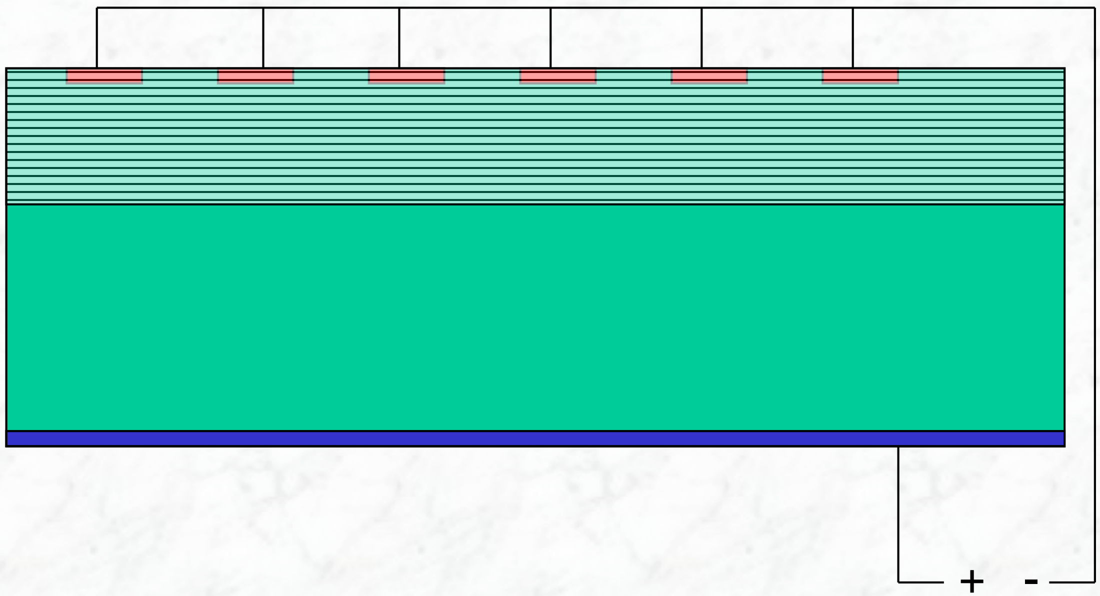

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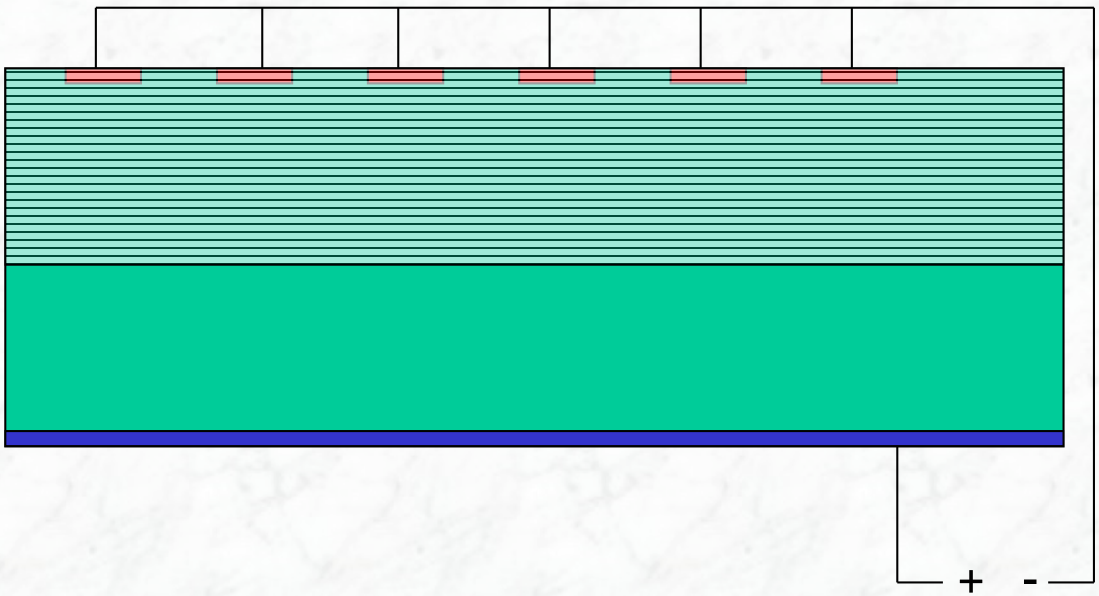

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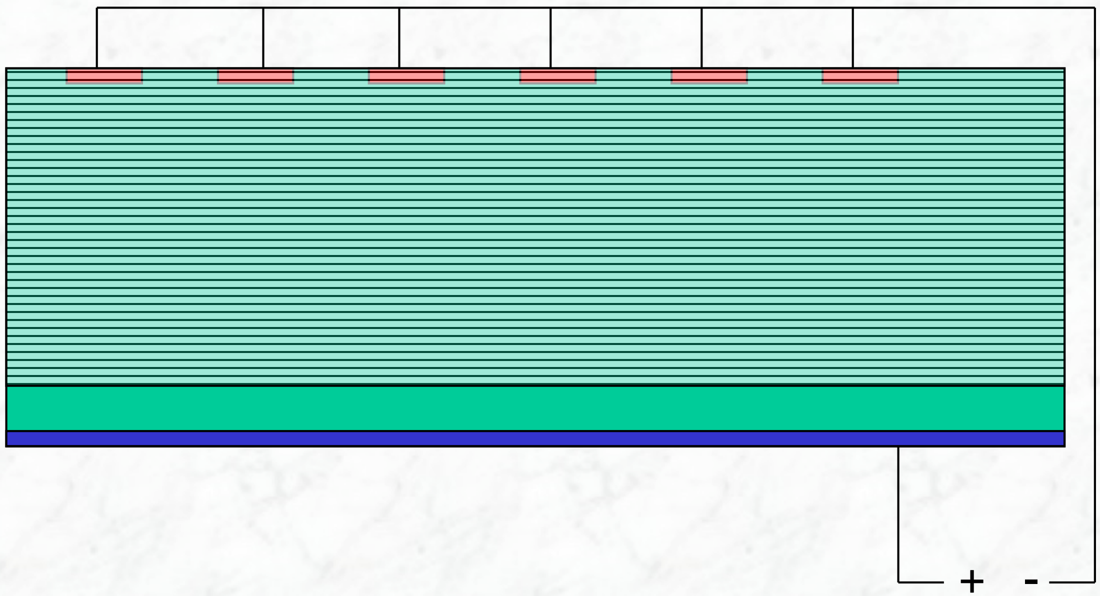

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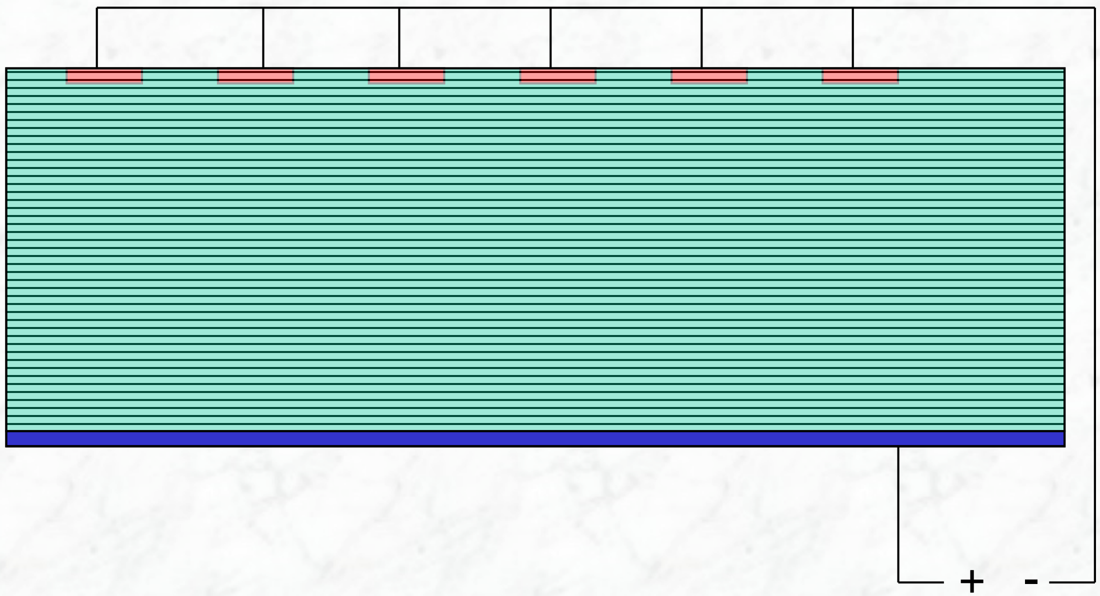
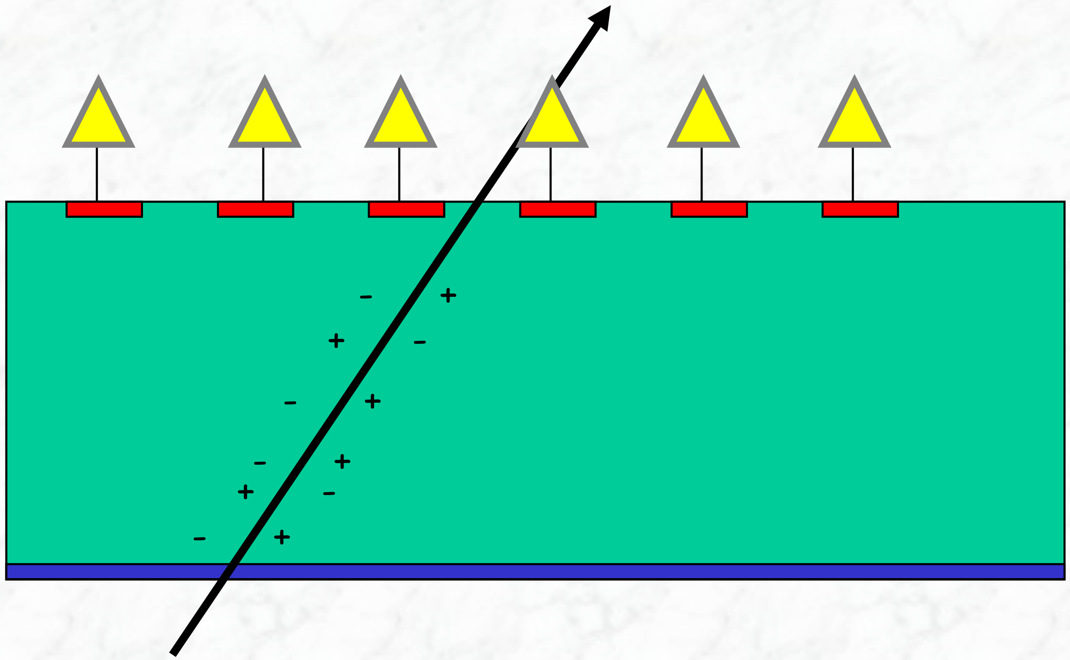


$$w_{depletion} = \sqrt{2\varepsilon\rho\mu V_{bias}}$$

Signal

- Depleted piece of Si, a MIP generates e^-h^+-pairs…
- e^-h^+-pairs separate in E-field, and drift to electrodes
- Moving charges -> electric current pulse
- Small current signal is amplified, shaped and processed in ASICs ("chips") on read-out electronics



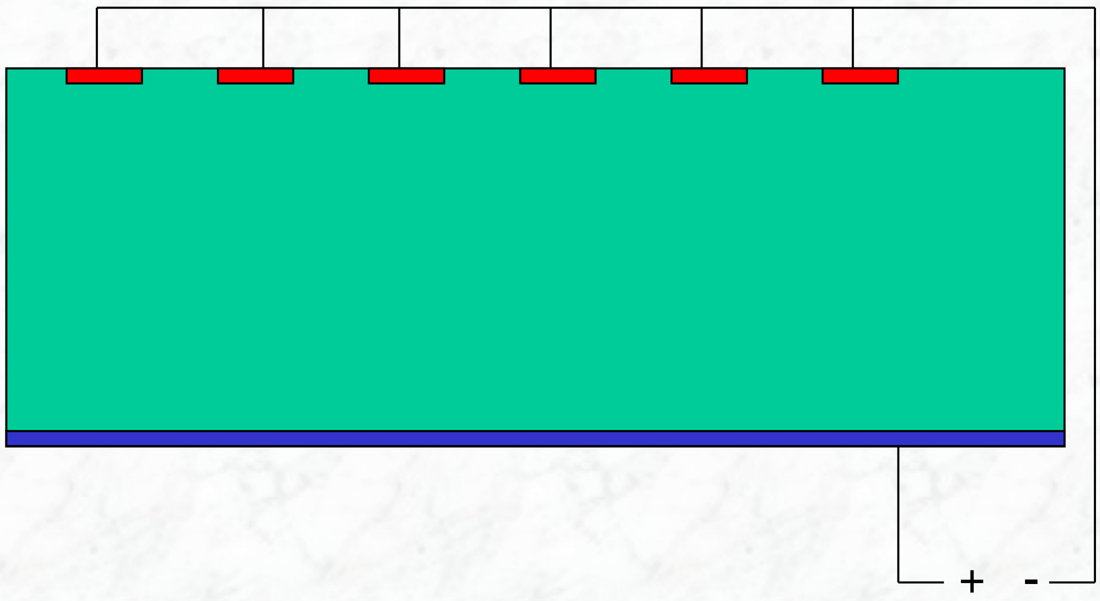
ASIC = application specific integrated circuit

Schematic Si-Detector

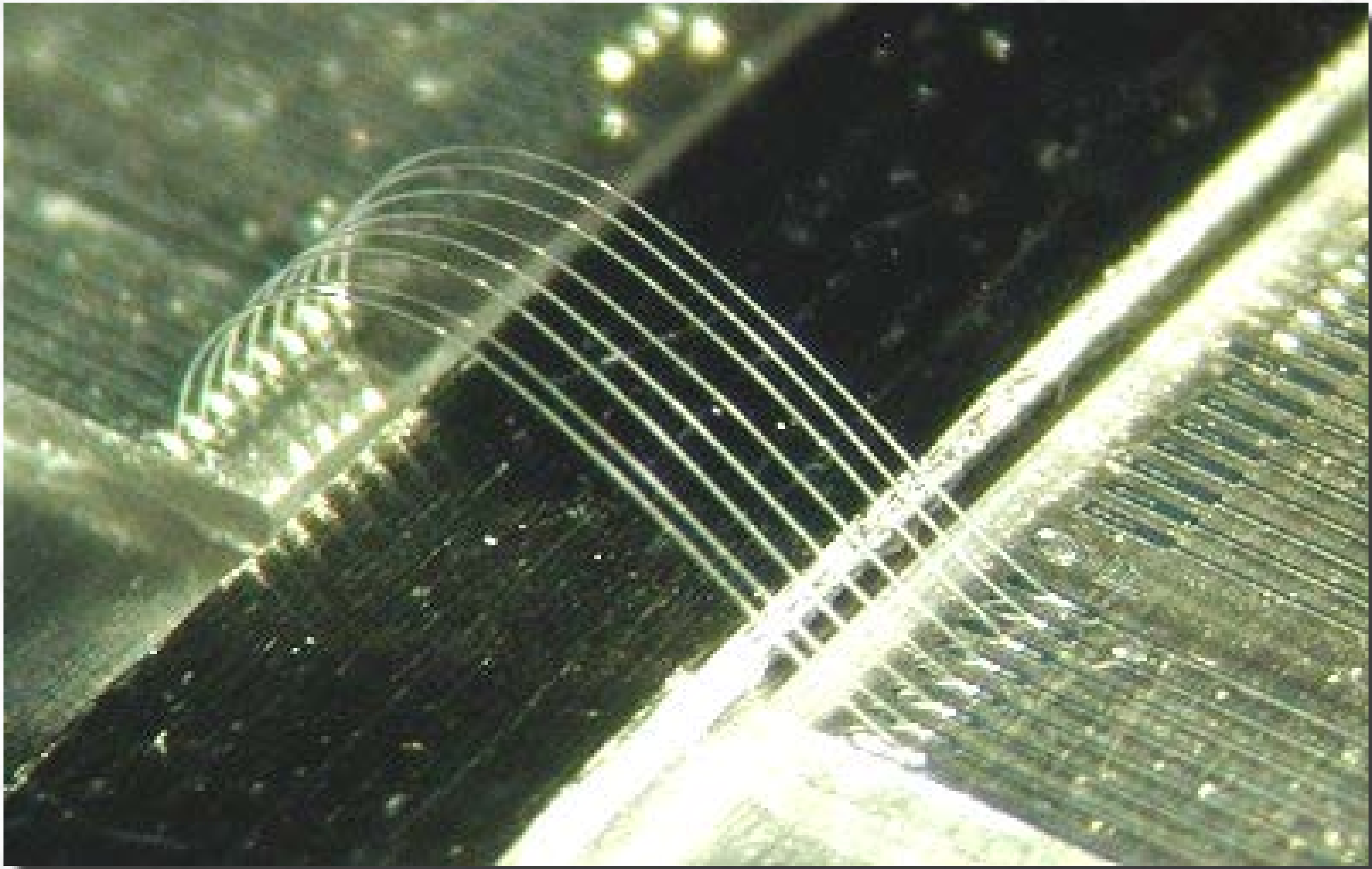
- This detector will deliver 2D information – we need one more coordinate:

- Take another detector and place it on top with orthogonal strips

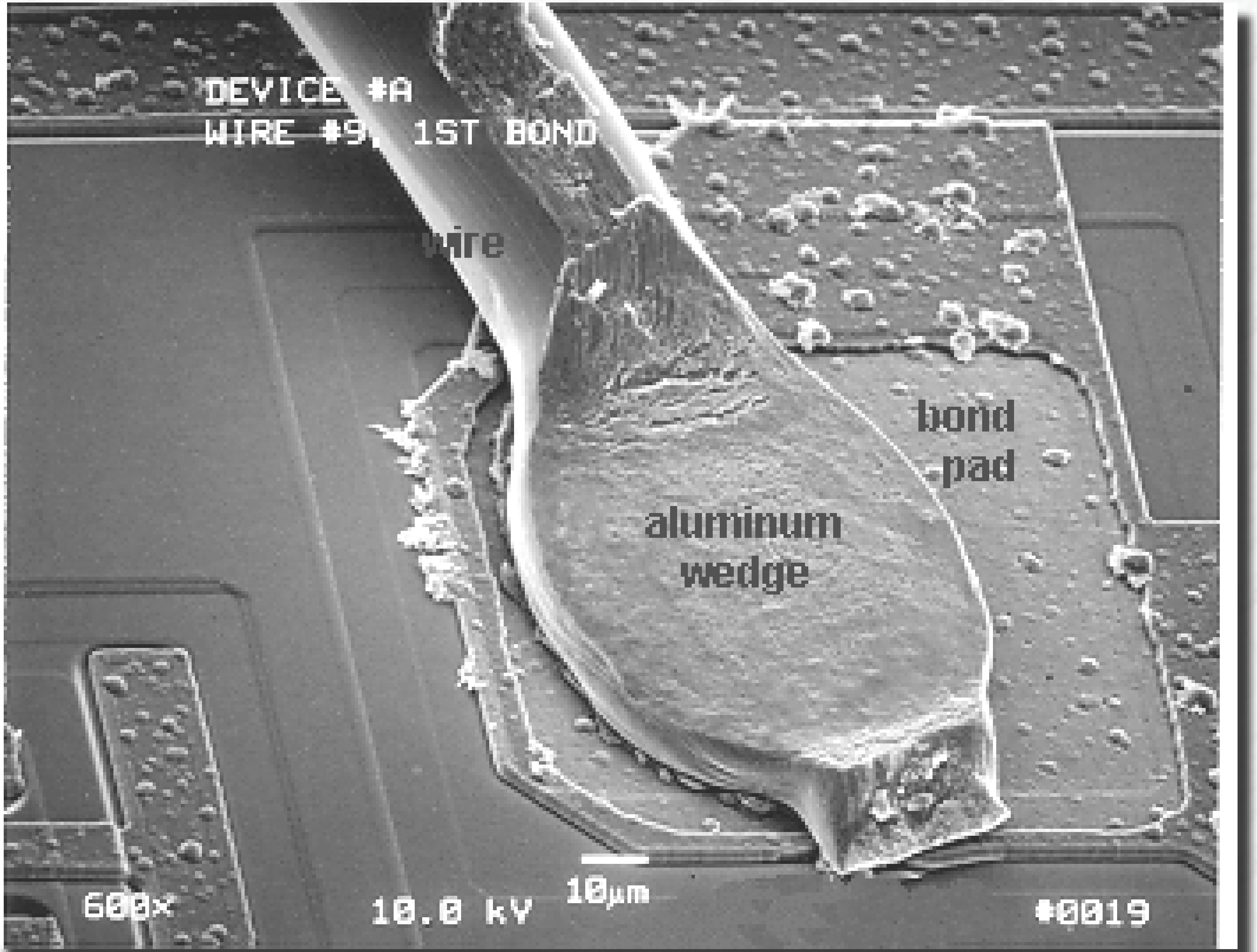
- Or segment the n-side (backside) as well
  -> double-sided detector



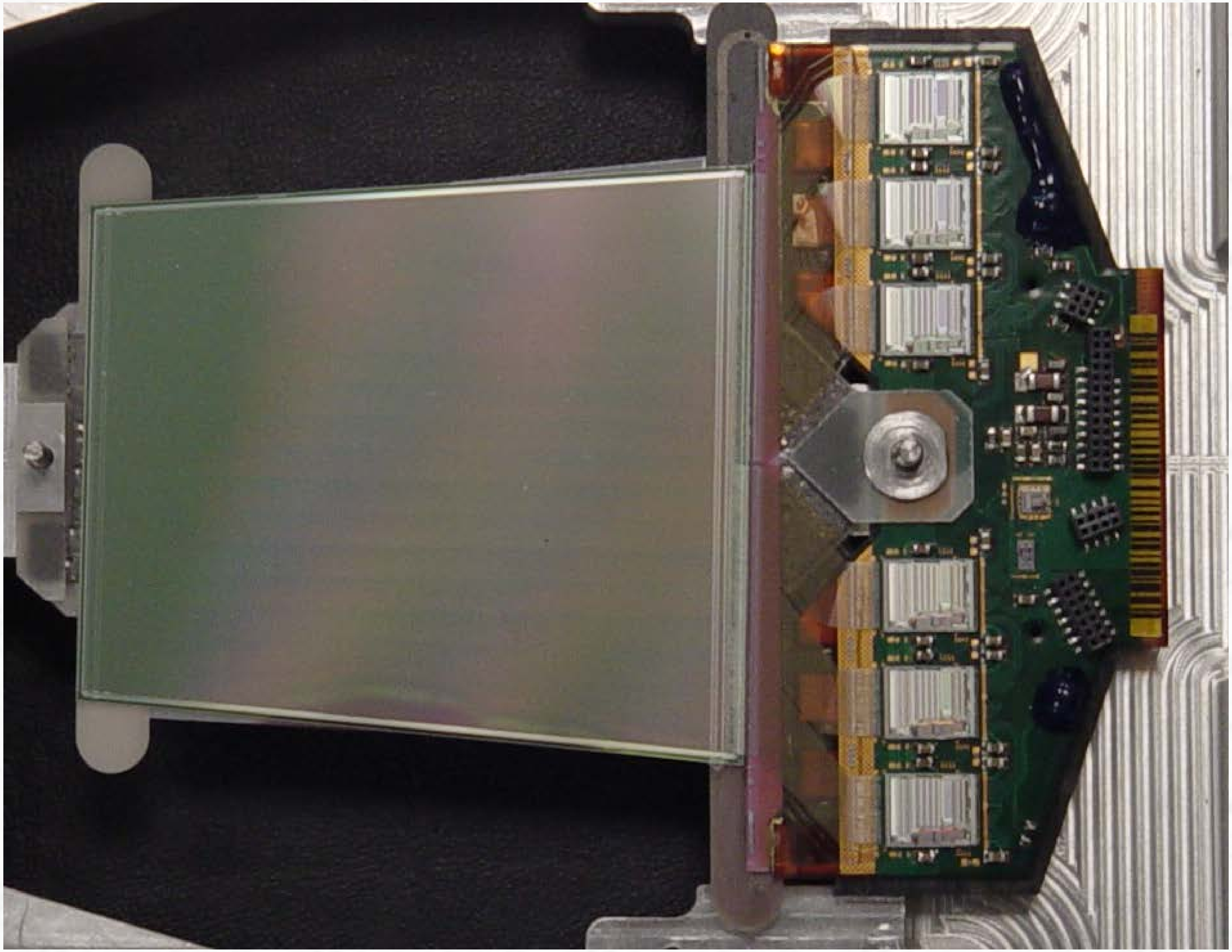
Wire Bonding



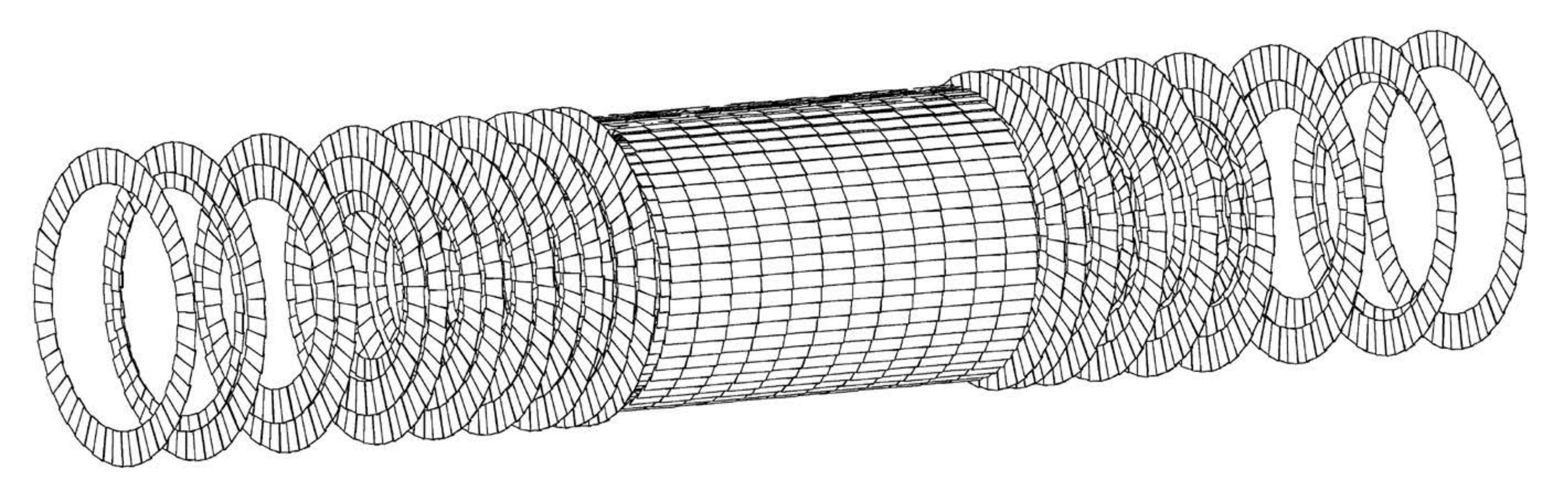
Single Wire Bond Foot



Example: ATLAS Semiconductor Tracker Module



Example: ATLAS Si-Tracker SCT



Example: ATLAS Semiconductor Tracker Endcap Wheel