Lecture 11, 13.02.2019

Tracking detectors

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FROM MGA TO NUST MISIS 100 YEARS 1918-2018 OPENING A NEW CENTURY

MISIS National University of Science and Technology

SHiP Search for Hidden Particles

LHCb

University of Zurich UZH

Olaf Steinkamp

Born in Bremen (Germany)

Studied physics in Bonn (D)

PhD thesis work at CERN (GE)

1st PostDoc at CEA Saclay (F)

NA48 experiment at CERN

2nd PostDoc at NIKHEF Amsterdam (NL)

HERA-B experiment at DESY (Hamburg)

Since 2000 at University of Zurich:

LHCb experiment at CERN (new: also Mu3e at PSI)

Lectures on data analysis & experimental techniques

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Particle Physics Experiments

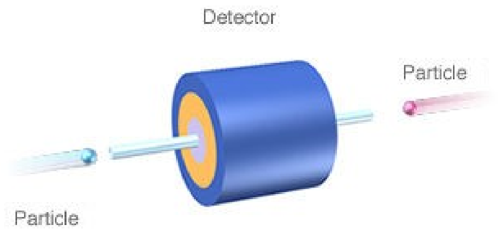
Accelerate a beam of (stable & charged) particles to high energies

- electrons/positrons, protons/antiprotons, heavy ions

Bring them into collision with

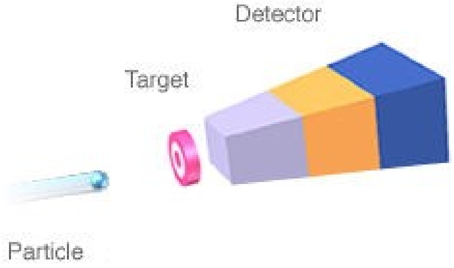
- **another beam of particles (“collider experiment”)**

  e.g. ATLAS, CMS



- **a target at rest (“fixed-target experiment”)**

  e.g. SHiP



Measure the properties of long-lived particles created in the collision

Reconstruct short-lived particles using relativistic kinematics

Particle Physics Experiments

Detector-components of a particle-physics experiment

- production & decay vertices
- flight paths
- momenta

position-sensitive detectors (in magnetic field)

- speed – **Cherenkov detectors**

charged particles only

- energy – **calorimeters** | charged and neutral

(momentum + speed → mass → particle type)

Momentum measurement

Moving charge in magnetic field → Lorentz force

$$\vec{F}_L = q \cdot \vec{v} \times \vec{B}$$

→ forces particle onto circular trajectory around field lines

$$\frac{m \cdot v^2}{r} = q \cdot v \cdot B$$

$$\boxed{p = q \cdot B \cdot r}$$

→ measure bending radius of particle trajectory in a known magnetic field

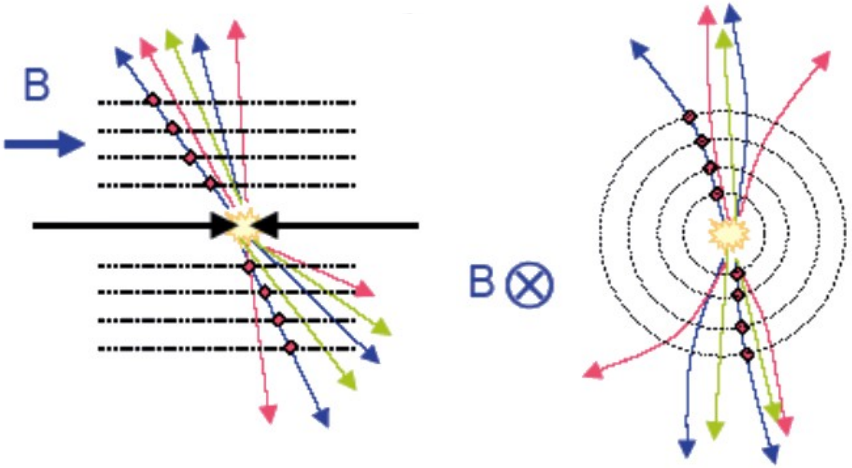
Momentum measurement

Typical collider experiment

- **solenoid/toroid magnet**

→ field lines parallel to beam axis

- **cylindrical tracking layers inside the magnet**

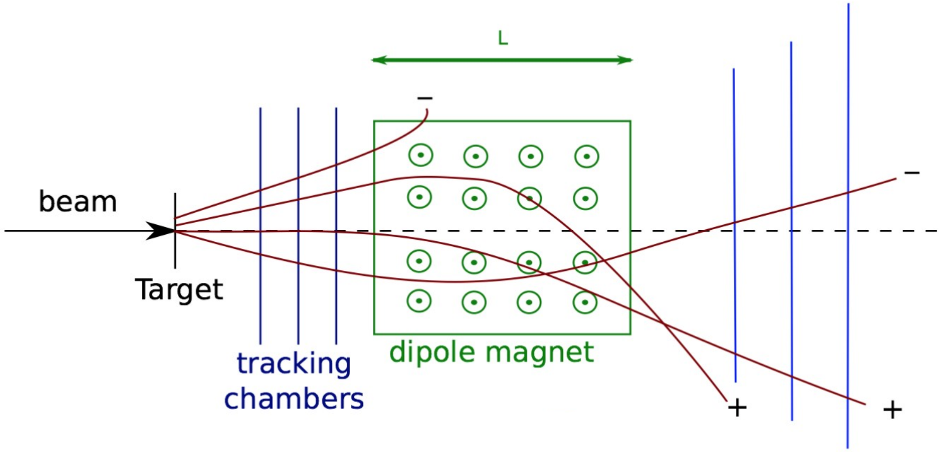


Typical fixed-target experiment

- **dipole magnet**

→ field lines orthogonal to beam axis

- **planar tracking detectors before and after the magnet**



Momentum resolution (I)

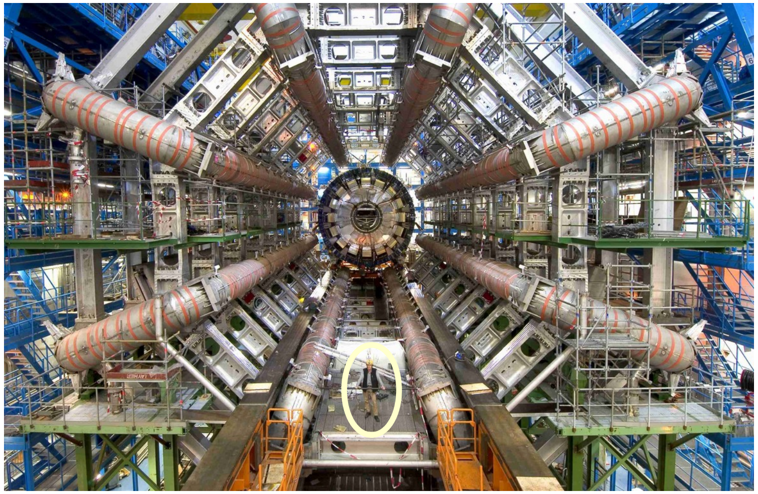
For *N* equidistant measurements (*N* ≥ 10)

$$\frac{\sigma(p)}{p} = \sqrt{\frac{720}{N+4}} \cdot \sigma_x \cdot \frac{p_T}{0.3\, B\, L^2}$$

[Gluckstern, NIM 24 (1963) 381]

Relative momentum resolution

- **improves linearly with spatial resolution of the detector**
- **improves linearly with the strength of the magnetic field**
- **improves <u>quadratically</u> with the length of the measured track segment**



⇒ main reason for the large size of high-energy particle physics experiments

Momentum resolution (II)

Particle trajectory disturbed due to multiple scattering in the material of the detector

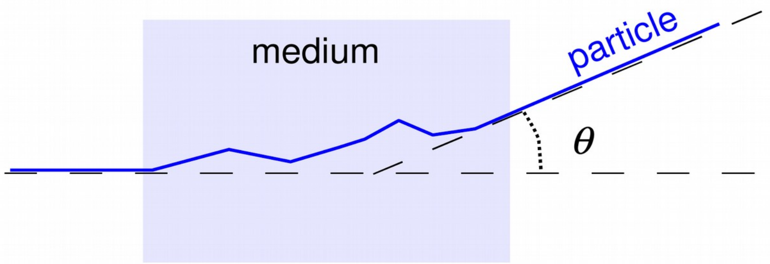
Causes deterioration of momentum resolution

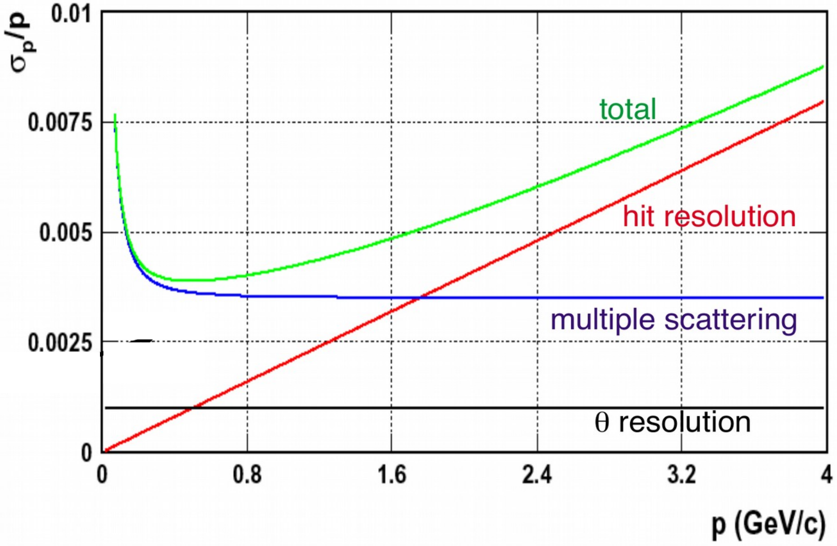
$$\frac{\sigma(p)}{p} = \frac{0.2 \cdot \sqrt{L/X_0}}{\beta \cdot B \cdot L}$$

(→ Richard Jacobson's lecture)

Important to minimize material

- especially if measuring particles at low momenta (small β = *v*/*c*)
- also "dead" material from supports, cables, etc





First tracking detectors

Cloud chamber (Wilson, 1912**):**

Vessel filled with supersaturated water vapour

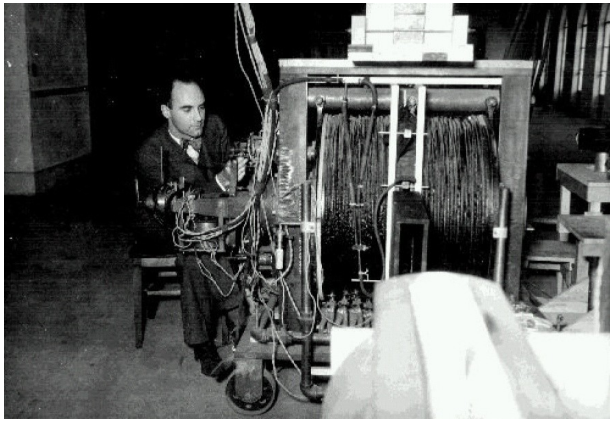
- charged particle creates ionisation clusters
- ionisation clusters act as condensation nuclei
- trail of water droplets along particle trajectory

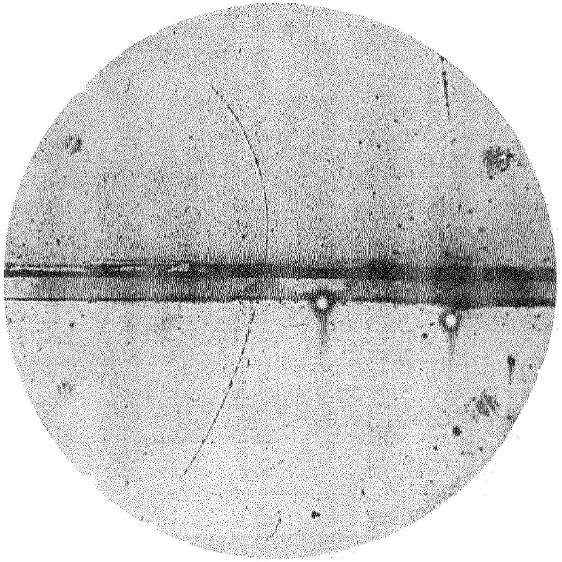
Photograph trails through windows in the vessel

- spatial resolution ~ 100 μm
- estimate particle energy from density of droplets

Most important experimental tool until 1950s, but

- low rate capability
- photographs require manual analysis



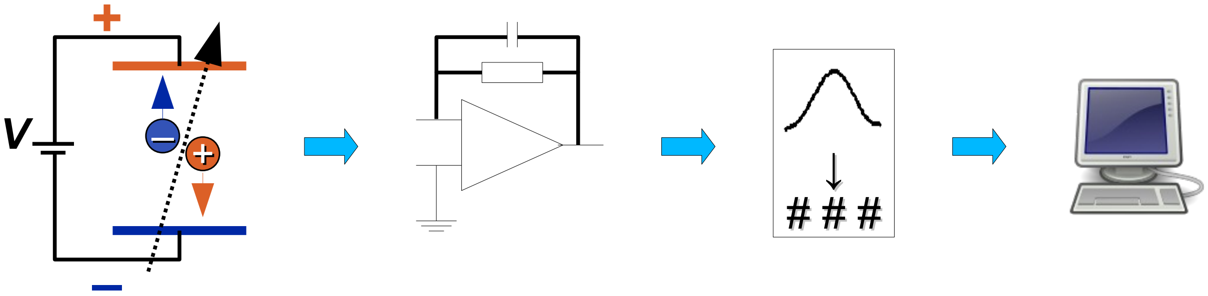


discovery of positron
(Anderson, 1932)

Modern tracking detectors

Electronic readout of detector signals

- **apply electric field across detector volume, collect charges on electrodes**
- **electronically integrate & amplify signal pulse**



- **digitize the signal:**
  - discriminator ⇒ binary information (hit / no hit)
  - analog-to-digital converter (ADC) ⇒ encode pulse height
  - time-to-digital converter (TDC) ⇒ encode signal arrival time
- **transfer digital data to a computer farm for processing and storage**

Need to know WHEN to read out the detector → trigger

(→ Lea Caminada's lecture**)**

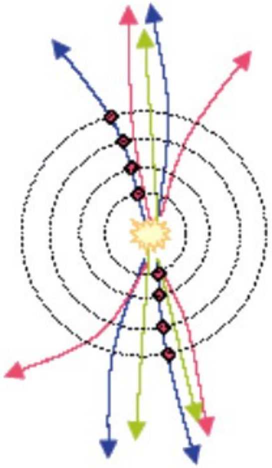
Modern tracking detectors

Position information from finely segmented readout electrodes

- **granularity determined by particle density and required spatial resolution**
  - close to interaction point: high particle density, small tracking volume

    → need fine granularity and excellent position resolution
  - further away: large tracking volume, but lower particle density

    → can afford coarser granularity, lower position resolution



Other requirements

- **rate capability**
  - charge collection time in detector
- **material budget**
  - including cables, support structures
- **radiation hardness**
  - degradation of detector material
- **cost**
  - including readout electronics

Gaseous tracking detectors

Thin-walled cylindrical tube,
filled with a gas mixture

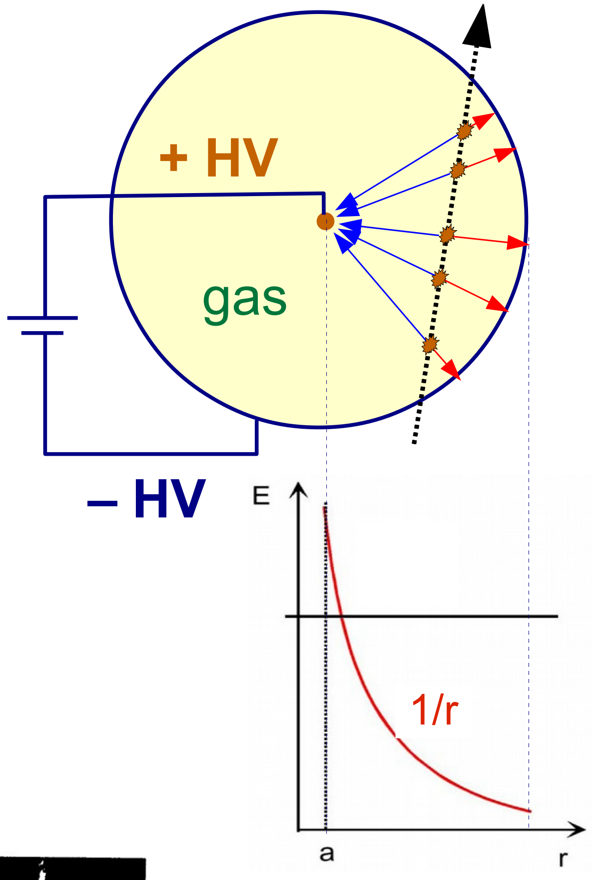
Thin wire along the centre of this tube

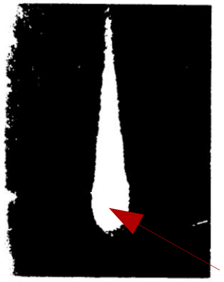
Apply a high voltage (typically 1– 2 kV)
between wire and outer wall of the tube

Charged particle ionizes atoms in the gas
electric field: electrons drift towards the wire

Very high electric field close to the wire
electrons gain enough energy
to ionize secondary atoms

Charge avalanche, voltage pulse on wire

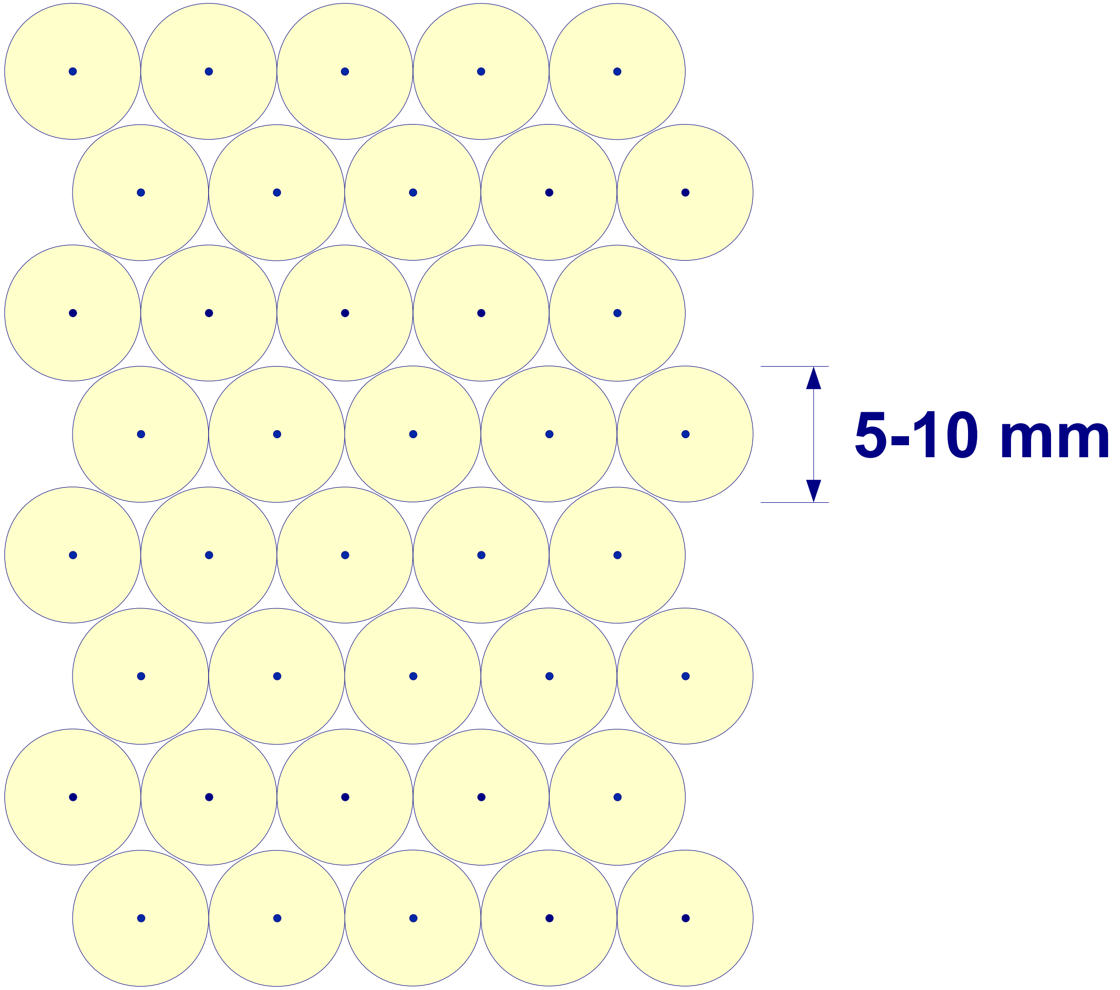




photograph of a
charge avalanche

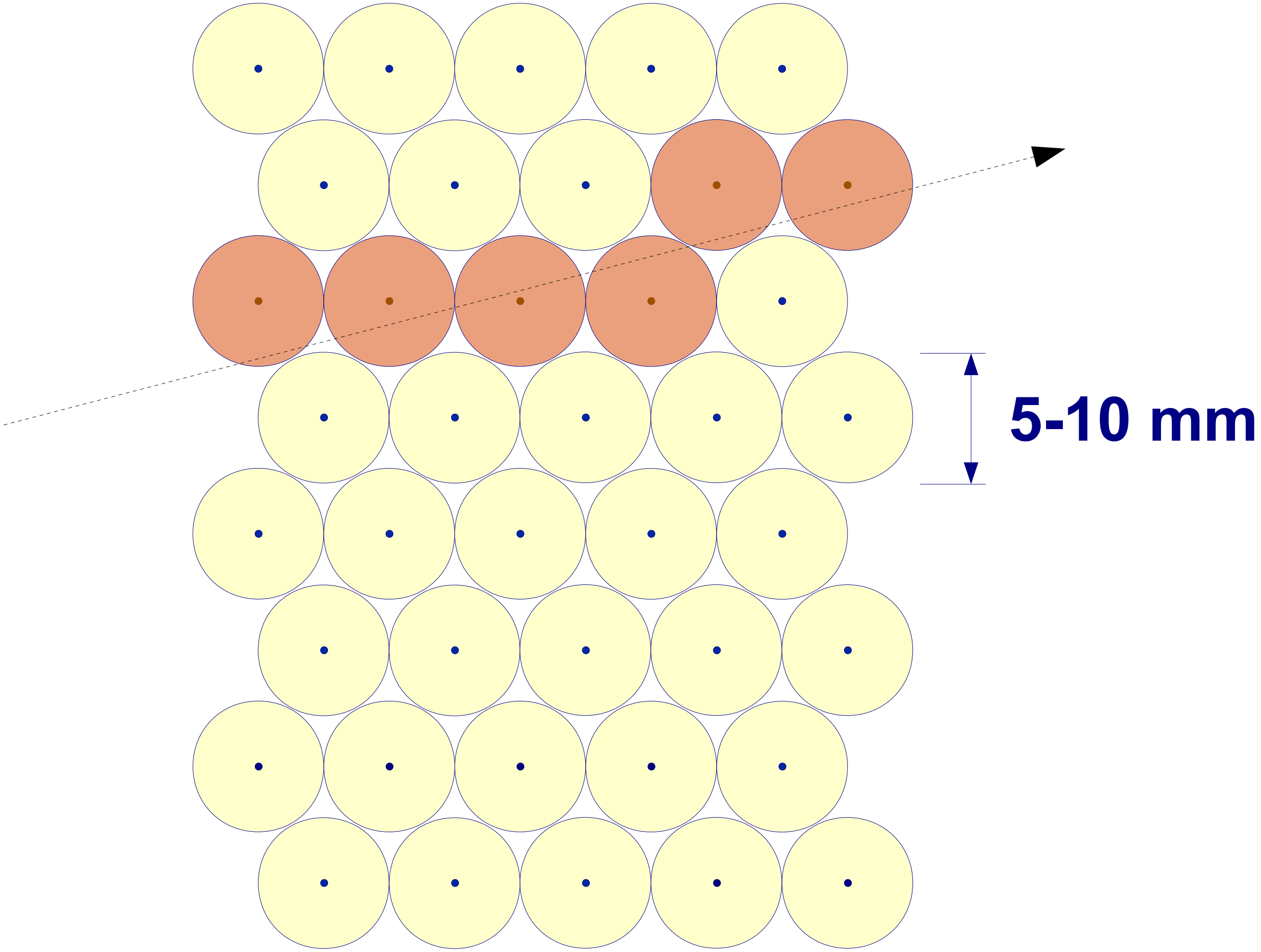
Gaseous tracking detectors

Tracking detector: several layers of such drift tubes



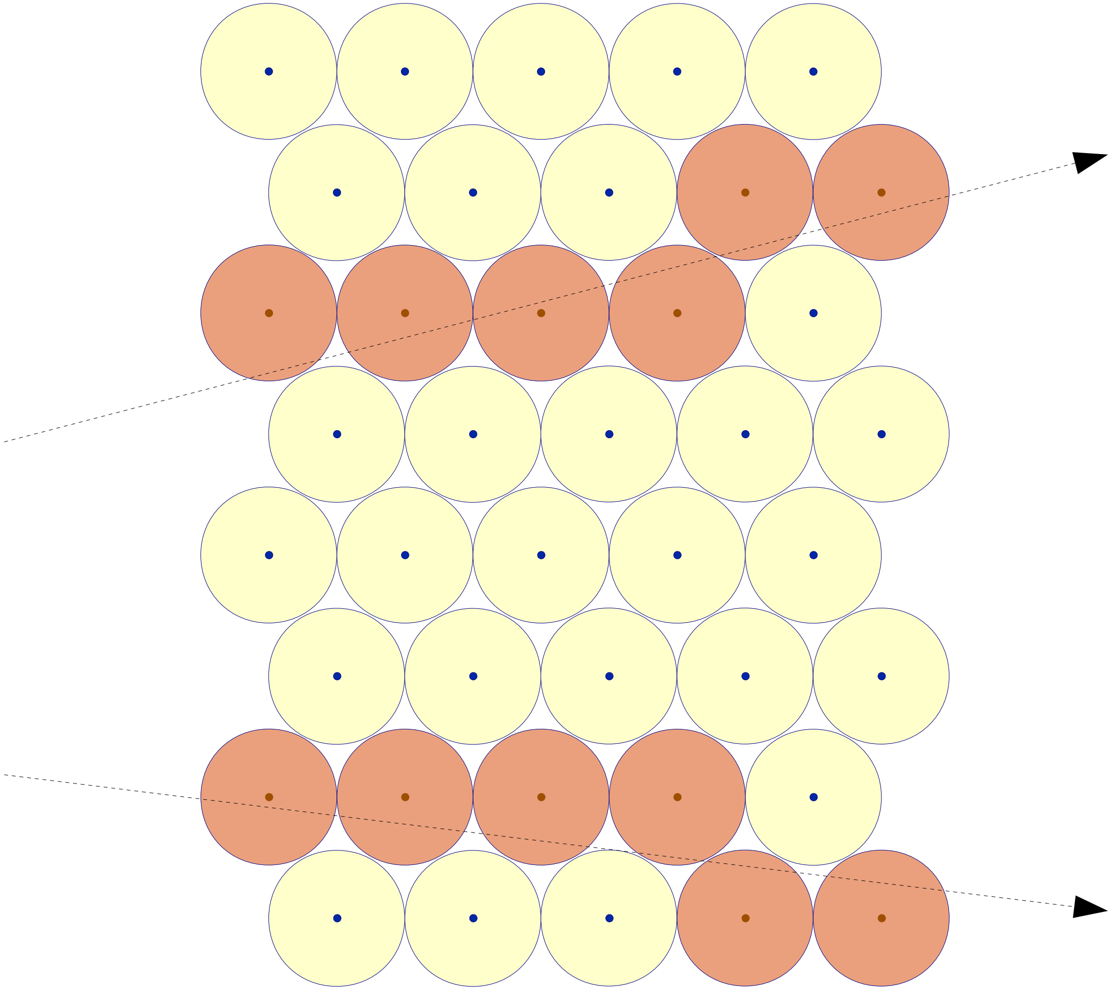
Gaseous tracking detectors

Tracking detector: several layers of such drift tubes



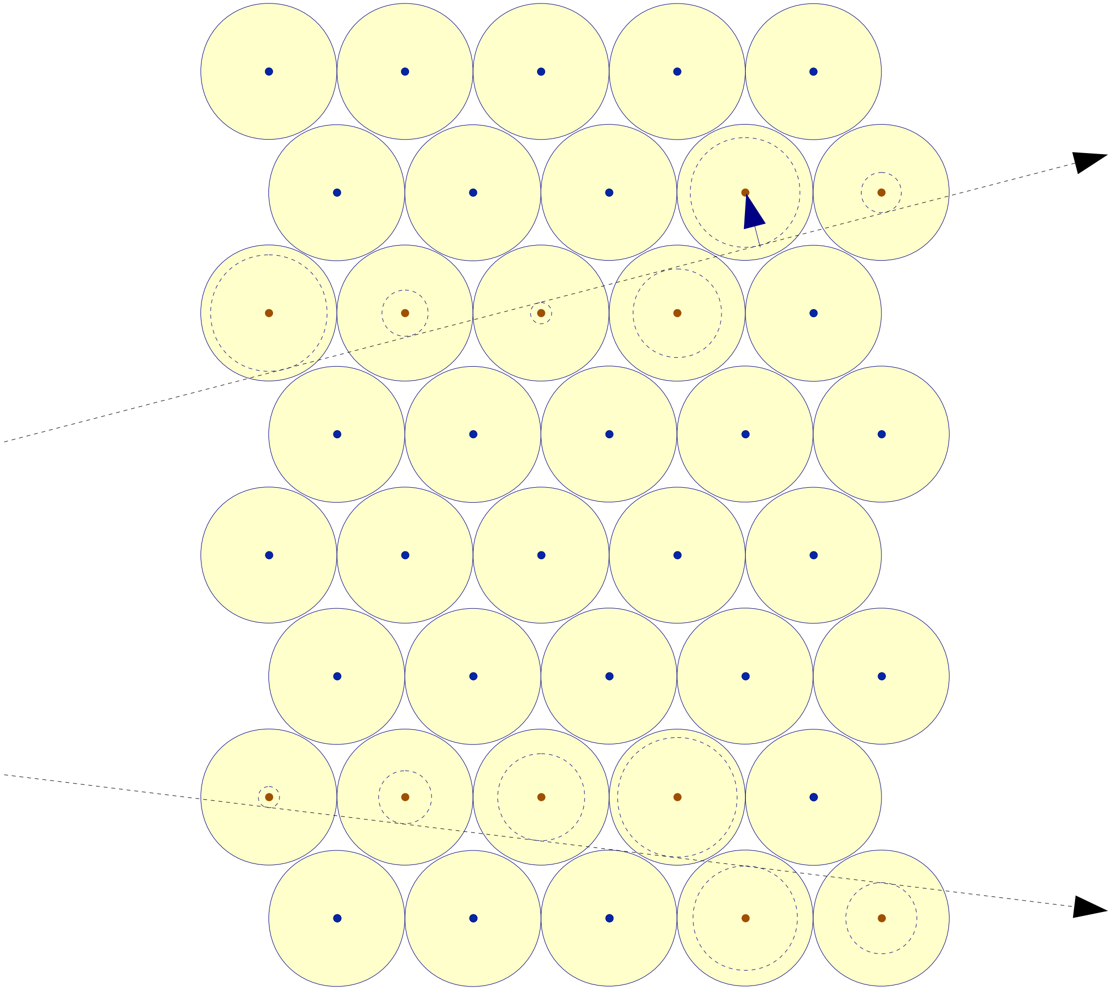
Gaseous tracking detectors

Tracking detector: several layers of such drift tubes



Gaseous tracking detectors

To improve spatial resolution: measure drift time of electrons



Gaseous tracking detectors

+ spatial resolution < 200 µm, appropriate for many applications

+ easy to cover large surfaces

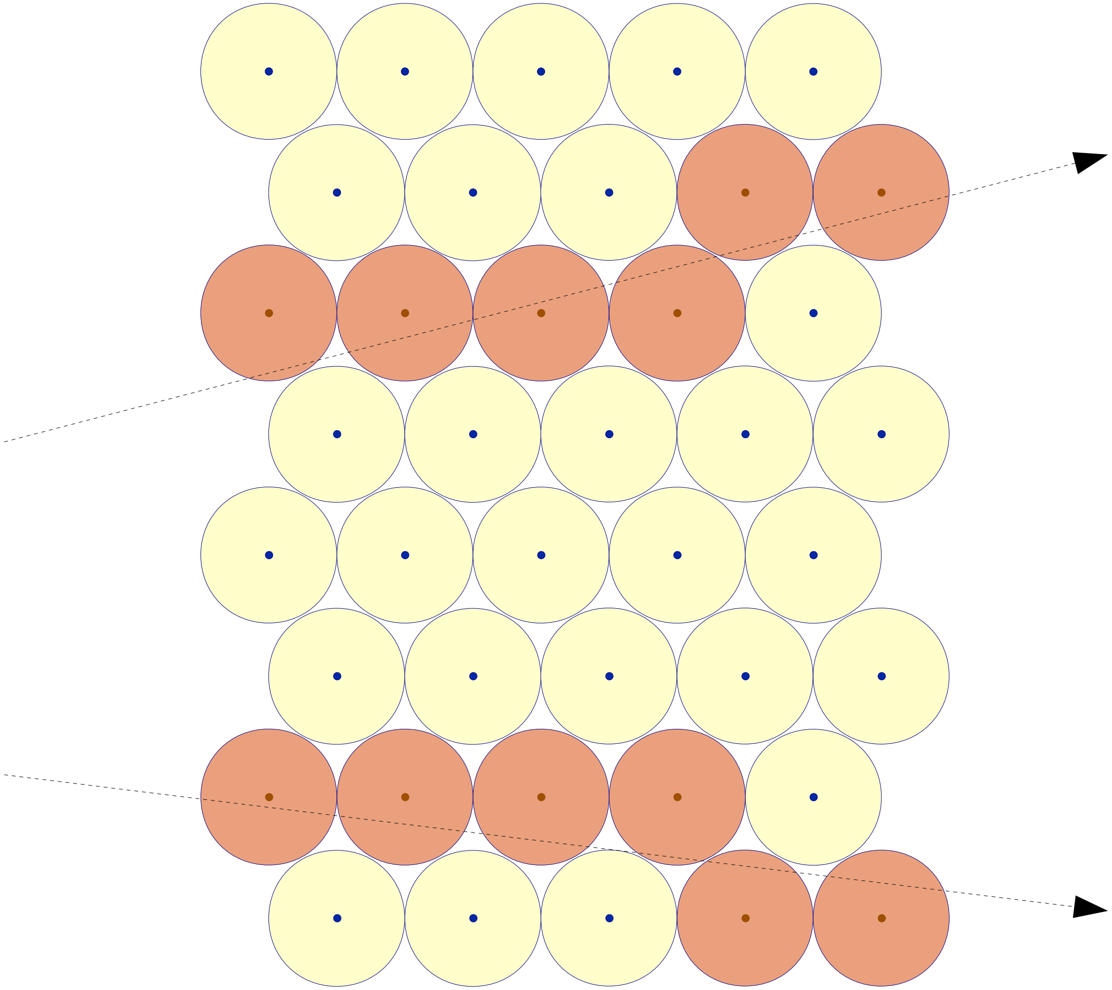
+ cost effective

But: granularity, rate capability and radiation hardness reaching their limits at the LHC

→ drift time for electrons typically 100 ns, bunch crossings at LHC every 25 ns

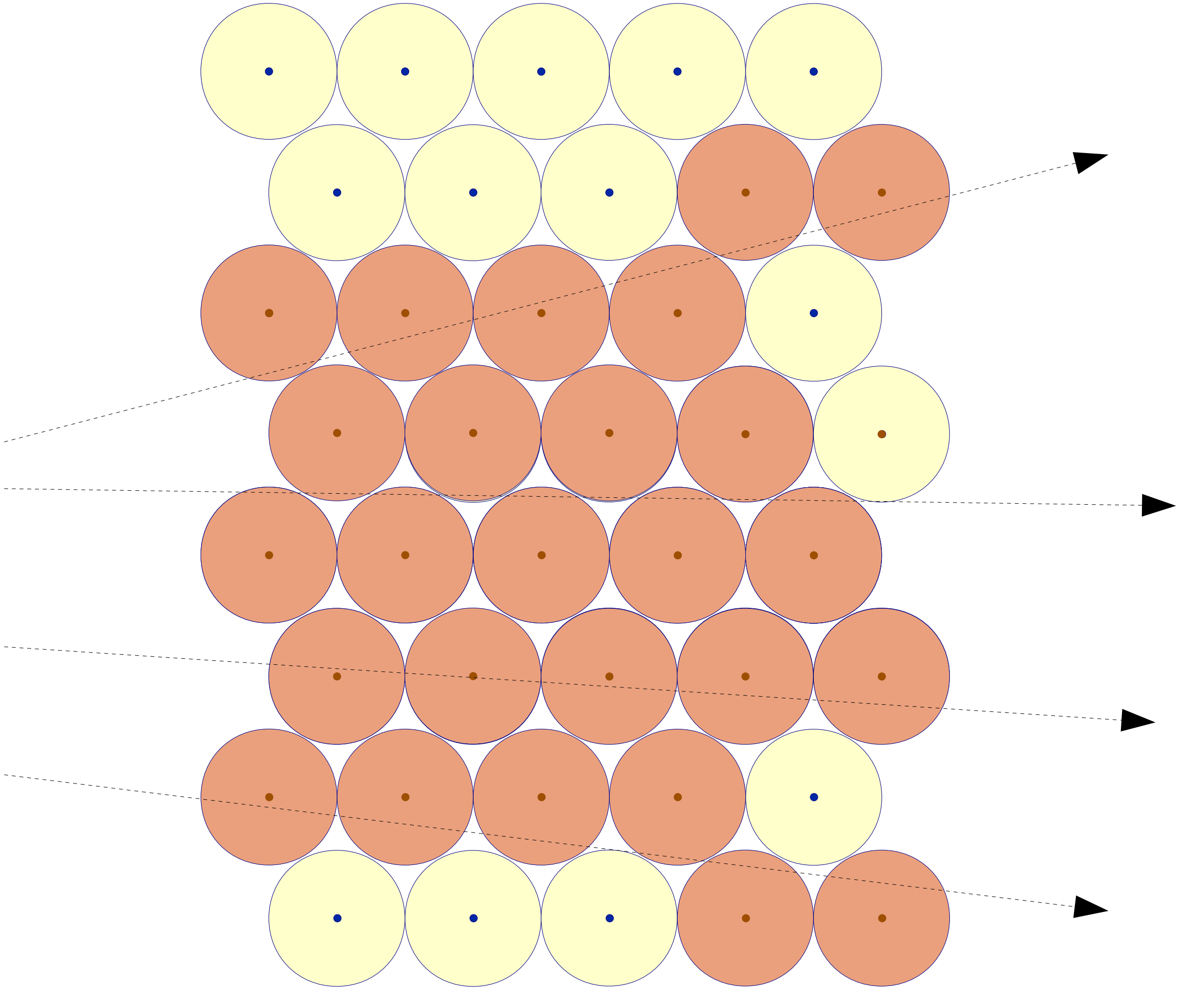
Gaseous tracking detectors

Too high occupancy: increasingly difficult to find the tracks



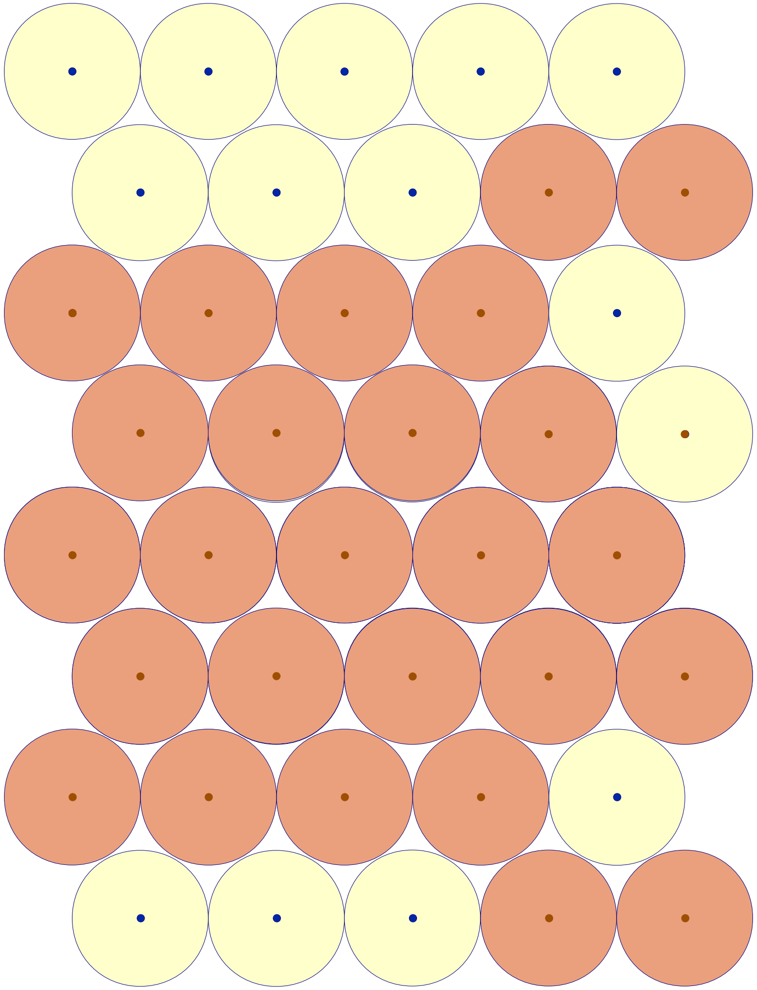
Gaseous tracking detectors

Too high occupancy: increasingly difficult to find the tracks



Gaseous tracking detectors

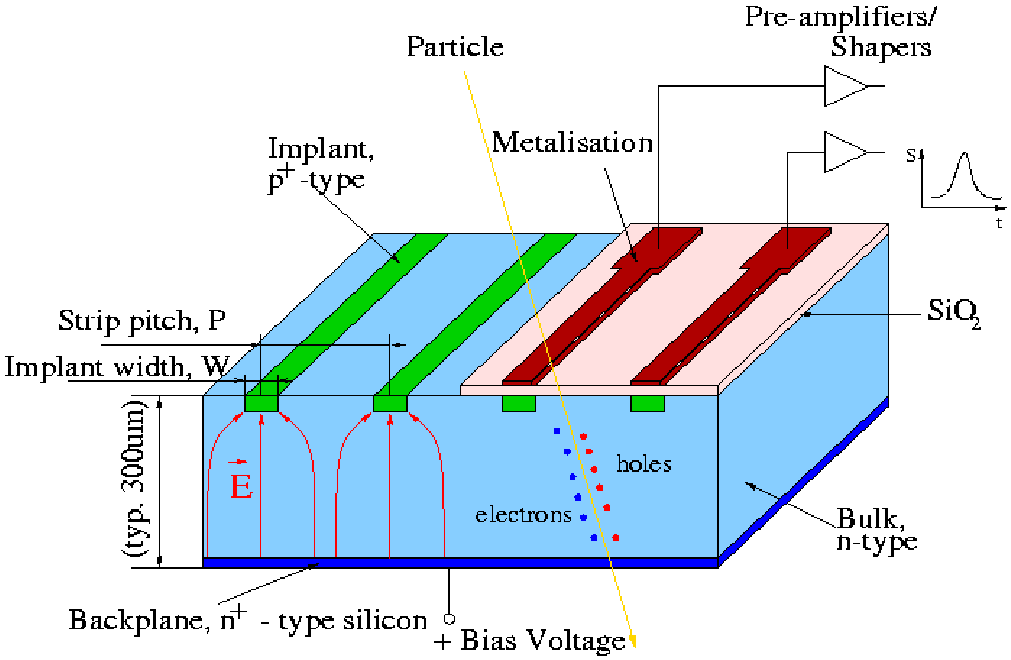
Too high occupancy: increasingly difficult to find the tracks



Silicon tracking detectors

Segmented reverse biased *p*–*n* junction (diode)

- ***n*–doped silicon wafer with segmented *p*–doped implants**
  - strips with pitch 250 – 20 µm
    ⇒ spatial resolution 50 to a few µm
  - or pixels for even finer granularity
- **apply reverse bias voltage**
  - fully deplete bulk, create electric field
- **ionizing particle creates electron-hole pairs in silicon lattice**
  - electrons and holes drift in electric field, induce signal on *p*-doped implants



Silicon tracking detectors

+ spatial resolution down to few μm,
much better than gaseous detectors

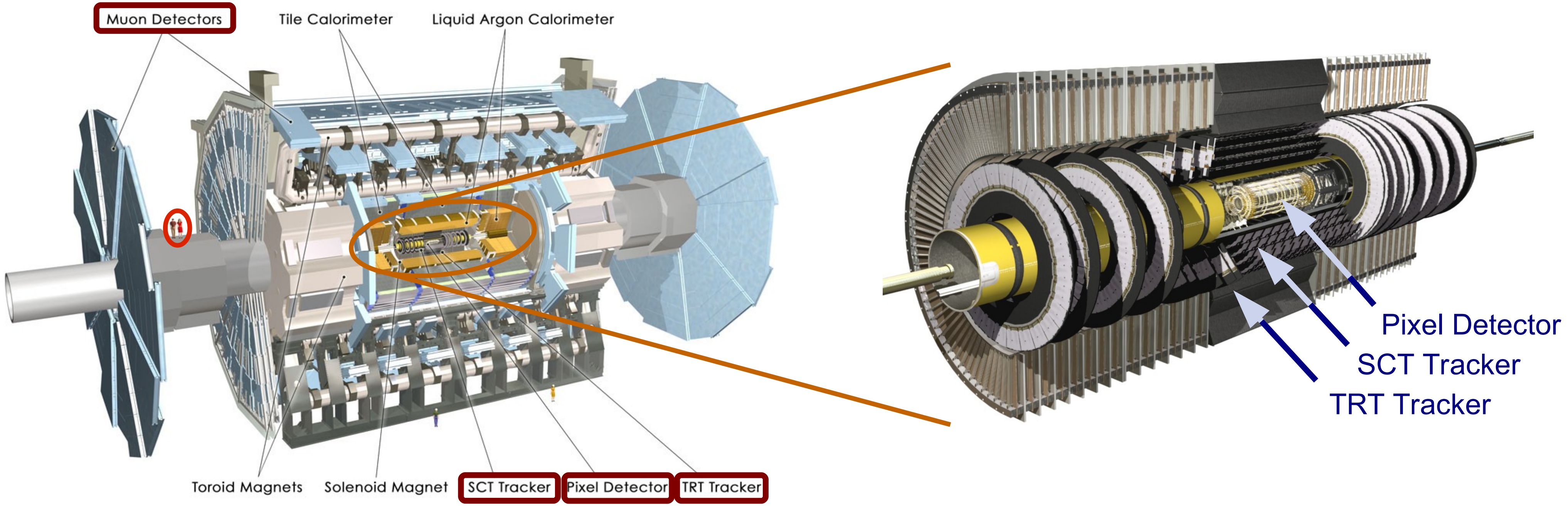
+ faster signal collection,
higher rate capability

+ much better radiation hardness

But: much more expensive than gaseous

→ use gaseous detectors where possible,
silicon detectors where needed

Example: ATLAS detector at LHC



radius	technology	cell size	area
5-12 cm	silicon pixels	50 x 400 μm	1.8 m²
30-50 cm	silicon strips (SCT)	80 μm x 13 cm	60 m²
56-107 cm	drift tubes (TRT)	4 mm x 75 cm	(680 m²)
500-1000 cm	drift tubes (MDT)	3 cm x 6 m	5500 m²

Gaseous Detectors

Problem: also excitation of gas atoms in the avalanche close to the wire

→ creation of UV photons

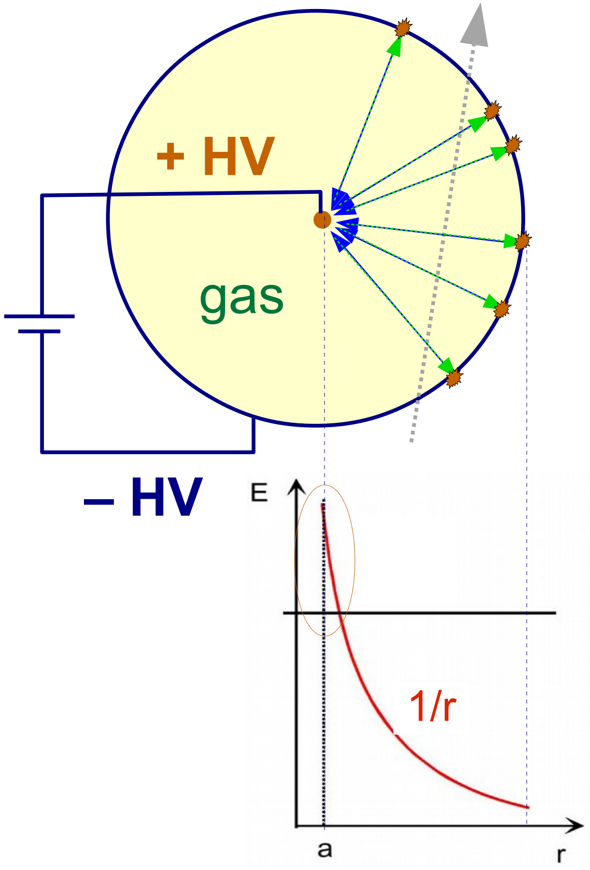
If UV photons hit cathode, they cause photo-emission of electrons

→ electrons drift to amplification region, create UV photons, etc.

→ breakdown

→ need to absorb UV photons before they reach the cathode

→ choice of gas !

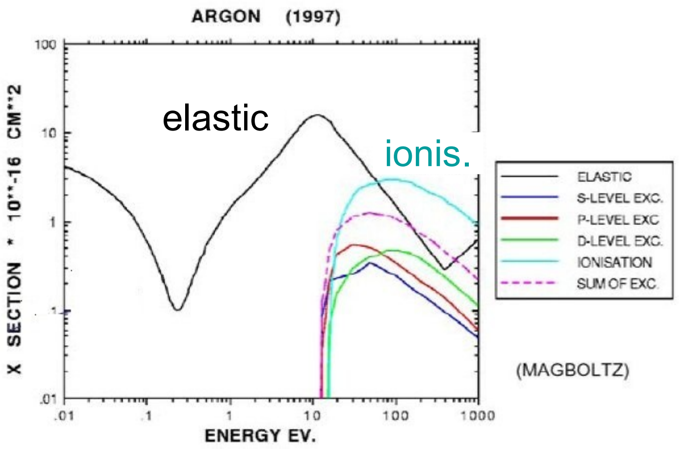


Gas Mixtures

Main gas component: noble gas

- **elastic collisions at low electron energies**
- **ionisation dominates at high electron energies**

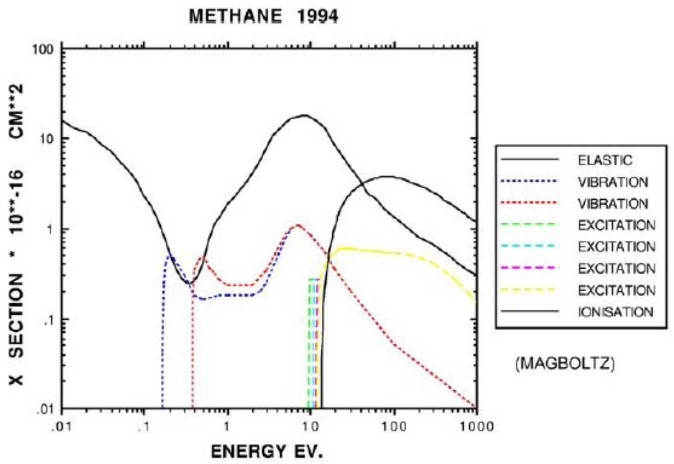
  → efficient gas amplification
- **usually use Argon (**availability, low cost**)**



"Quencher": complex molecular gas

- **rotational and vibrational excitation bands**

  → efficient absorption of UV photons
- **classic choices: CH_4, C_2H_6, iC_4H_{10}, alcohols**
  - but polymerization under irradiation → "wire ageing"
- **in high-radiation environment (**e.g. LHC**) use CO_2**



Signal Formation (I)

Signal on wire is created by electrons and ions drifting in electric field

- **potential and electric field in a cylindrical cell**

$$\phi(r) = -\frac{V_0}{\ln(b/a)}\cdot\ln\left(\frac{r}{a}\right) \quad\Leftrightarrow\quad E(r) = \frac{V_0}{\ln(b/a)}\cdot\frac{1}{r}$$

- **moving charges in electric field → work**

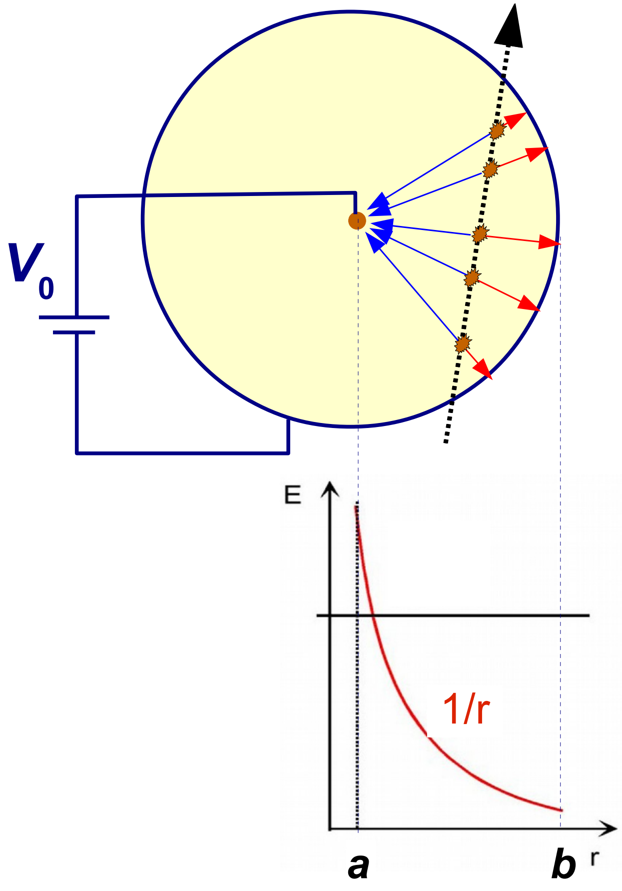
$$dW = q\cdot E(r)\,dr = C\cdot V_0\,dV$$

→ voltage pulse on wire

$$dV = \frac{q}{C V_0}\cdot E(r)\,dr$$

- **total signal from charge *q* drifting from radius r_0 to r_1**

$$\Delta V = \frac{q}{C V_0}\cdot\int_{r_0}^{r_1}\frac{-V_0}{\ln(b/a)}\,\frac{dr}{r} = -\frac{q}{C\cdot\ln(b/a)}\cdot\ln\left(\frac{r_1}{r_0}\right)$$

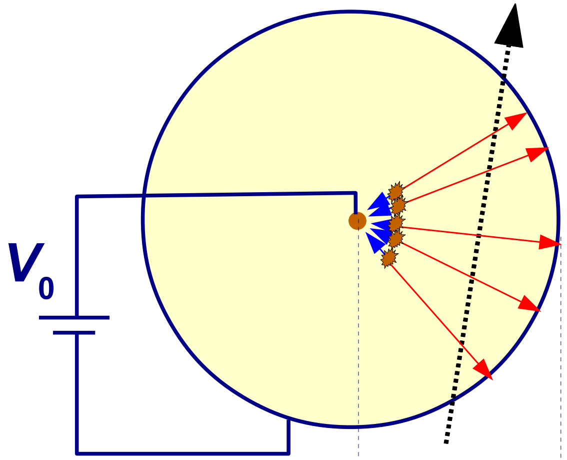


Signal Formation (II)

Almost all charges are created in the avalanche close to the wire

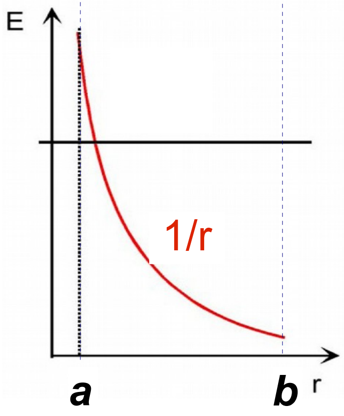
- $r_0 = a + \varepsilon$
- **electrons drift to the wire surface** $\Rightarrow r_1 = a$

$$\Delta V^{(-)} = -\frac{q}{C \cdot \ln(b/a)} \cdot \ln\left(\frac{a+\varepsilon}{a}\right)$$



- **ions drift to the cathode** $\Rightarrow r_1 = b$

$$\Delta V^{(+)} = \frac{q}{C \cdot \ln(b/a)} \cdot \ln\left(\frac{a+\varepsilon}{b}\right) = -\frac{q}{C \cdot \ln(b/a)} \cdot \ln\left(\frac{b}{a+\varepsilon}\right)$$



- $a + \varepsilon \ll b \Rightarrow$ **signal dominated by ions drifting away from wire**
- **example:** for b = 5 mm, a = 12.5 µm, r_0 = 15 µm

$$\Delta V^{(+)} / \Delta V^{(-)} \approx 32$$

Signal Length

Induced signal as a function of time **(** for an ion created at $r_0 = a$ **)**

$$V^{(+)}(t) = -\frac{q}{C \cdot \ln(b/a)} \cdot \ln\left(\frac{r(t)}{a}\right)$$

- **drift velocity for ions is proportional to the electric field**

$$\frac{dr}{dt} = \mu \cdot E(r) = \frac{\mu \cdot V_0}{\ln(b/a)} \cdot \frac{1}{r}$$

μ = “ion mobility”
[μ] = (cm/s)/(V/cm)

$$\Rightarrow \quad r(t) = a \cdot \sqrt{1 + \frac{2\mu \cdot V_0}{a \cdot \ln(b/a)} \cdot t}$$

- **total drift time (** $r(t_{max}) = b$ **)**

$$t_{max} = \frac{a \cdot \ln(b/a)}{2\mu V_0} \cdot \frac{(b^2 - a^2)}{a^2}$$

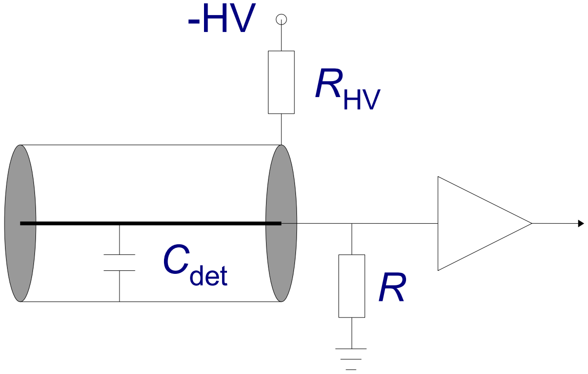
- e.g. for μ = 1.7 cm²/V/s, b = 5 mm, a = 12.5 μm, V_0 = 1500 V

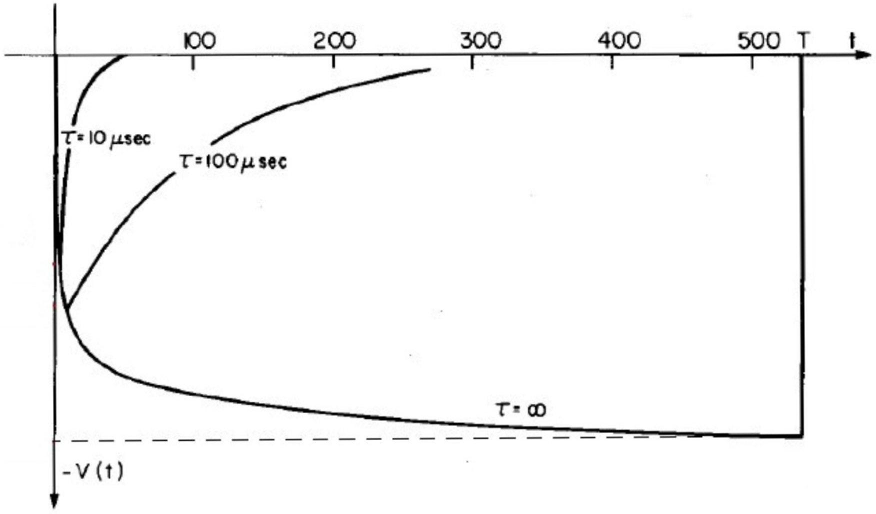
$$t_{max} \approx 300\ \mu\text{s}$$

Signal Length (II)

Electronic readout differentiates detector signal

- **time constant τ = $R \cdot C_{det}$**





[F.Sauli - CERN report 77-09]

- **shorten pulse length with acceptable loss of signal amplitude**
  - shorter signals ⇒ higher rate capability
- **limitation of rate capability: electric charges drifting inside detector volume**
  - electric charges screen electric field ⇒ reduce gas amplification
  - need short drift distances, fast drift gases, high electric field

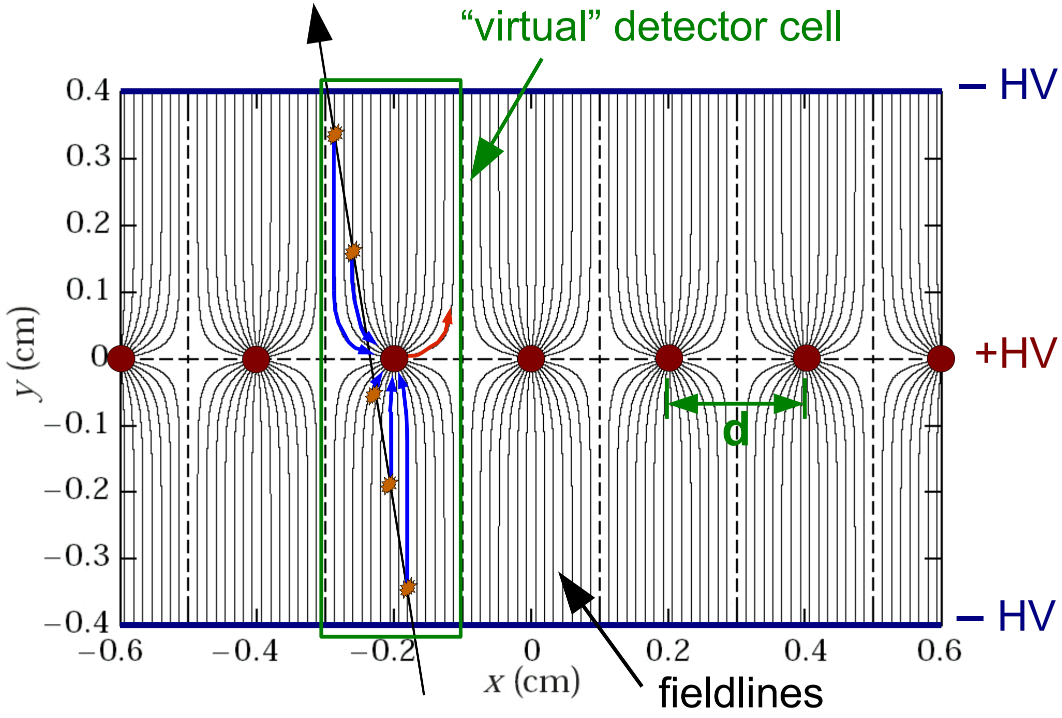
Multi Wire Proportional Chamber

Array of signal wires in between two planar cathodes (Charpak, 1968)

- **each wire connected to a readout amplifier and a discriminator**
  - register a "hit" if signal on the wire is above discriminator threshold
  - "binary readout" (hit or no hit)
- **spatial resolution given by distance *d* between wires**

$$\sigma \approx d / \sqrt{12}$$

  - typically $d \approx 2$ mm ⇒ $\sigma \approx 600$ μm

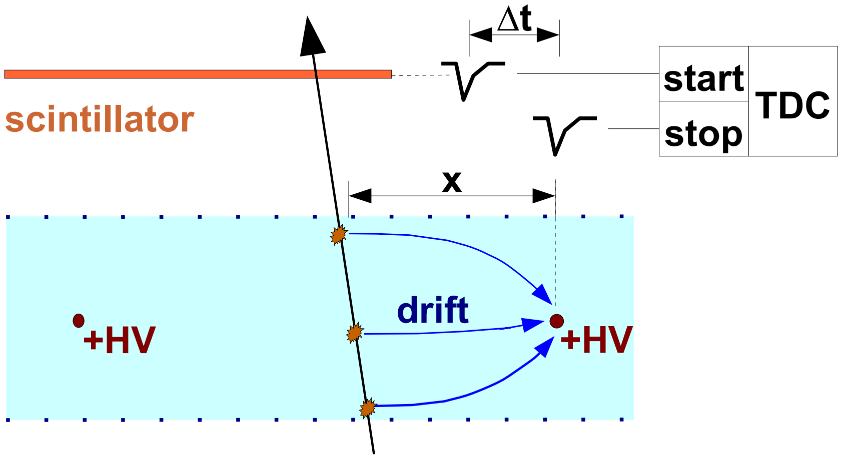


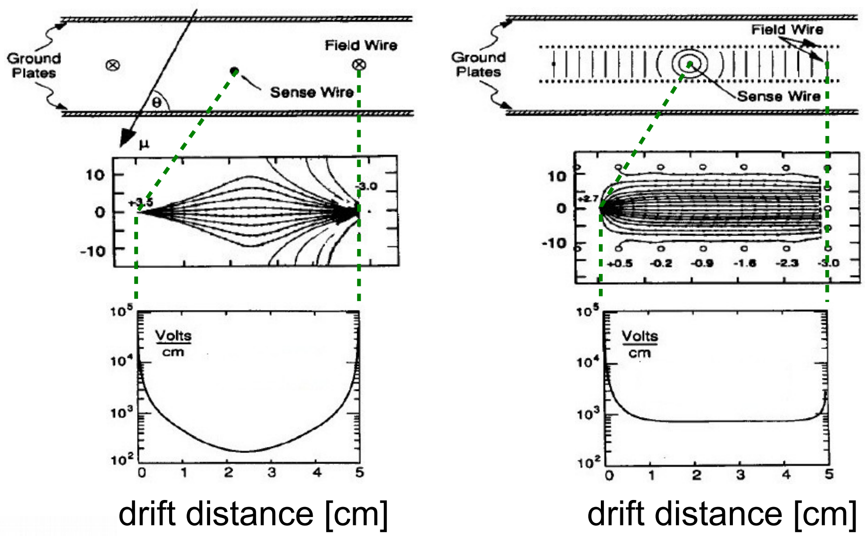
- **rate capability up to 10^6 /s**

Drift Chamber

Measure the time it takes electrons to drift from particle trajectory to wire

- **need to know when the particle passed:**
  - fast, external detector (e.g. scintillator)
  - at LHC, know the time of the *pp* collision
- **allows readout pitch of up to several cm**
  - much smaller number of readout channels
  - but requires TDC readout of sense wires
- **can reach spatial resolution < 200 μm**
- **electron drift velocity varies strongly with the strength of the electric field**
  - field-shaping wires to make field as homogeneous as possible





Cylindrical Drift Chambers

Collider experiments need barrel geometry

- ”open geometry”: one large gas volume with wires for anode, cathode and field shaping

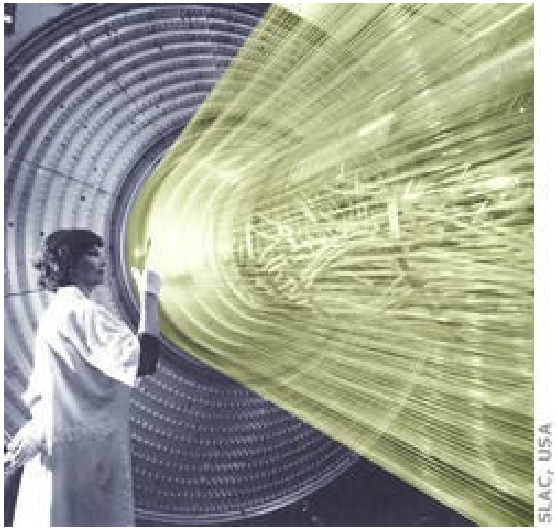
+ low material budget inside tracking volume

  – **difficult to avoid regions of low field**
  (build-up of space charge, rate capability)

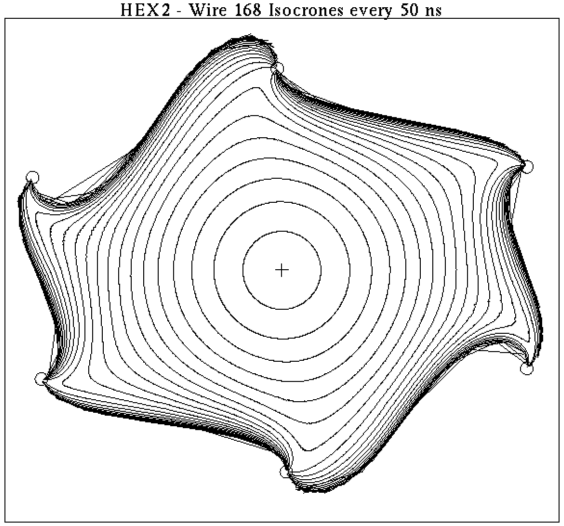
  – **risk if a single wire breaks**

  – **massive end plates to hold wires in place**

  e.g. 50 g wire tension × 20’000 wires
  → force of 1 ton pulling on end-plates

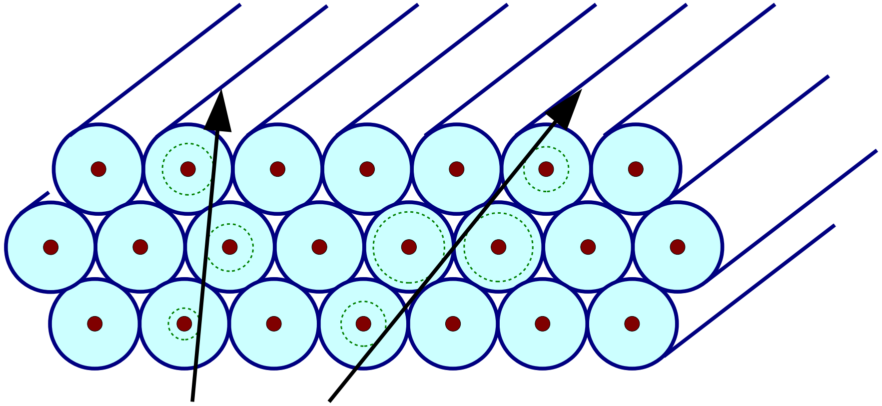

SLAC, USA

HEX2 - Wire 168 Isocrones every 50 ns



Straw Drift Tubes

Individual drift cell for each anode wire

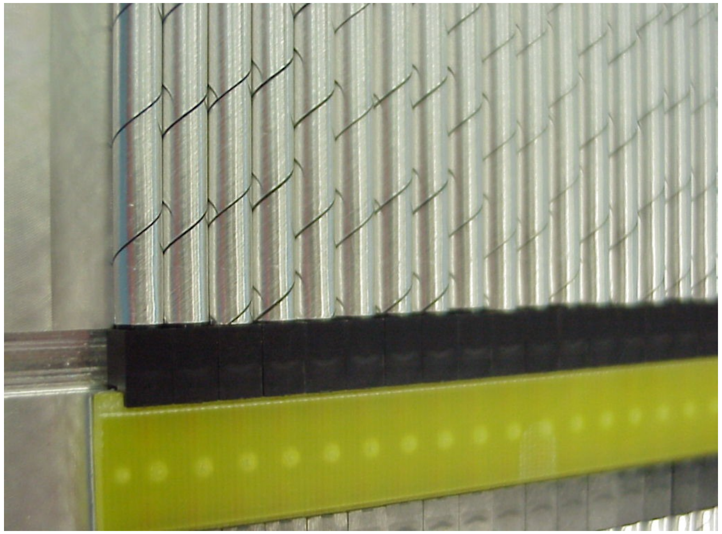


– slightly more material in tracking volume

+ self-supporting structure, no need for massive end plates

+ well defined electric field, no low-field regions

+ reduced risk if a wire breaks

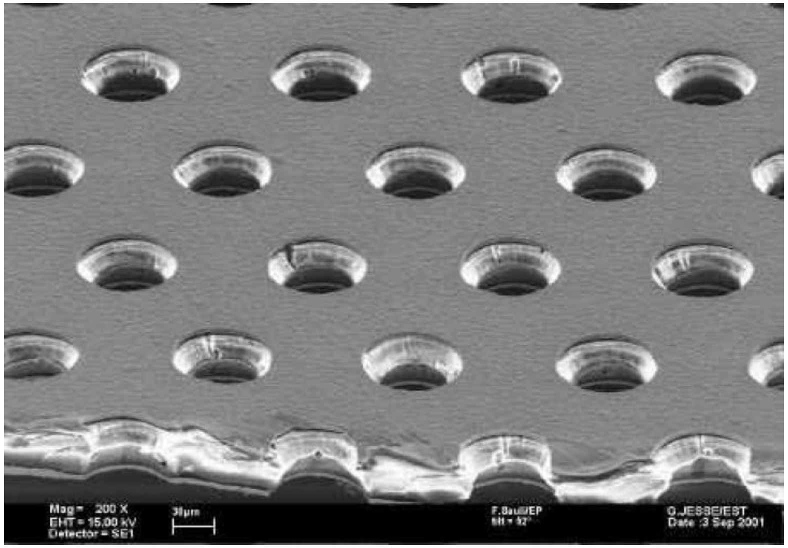


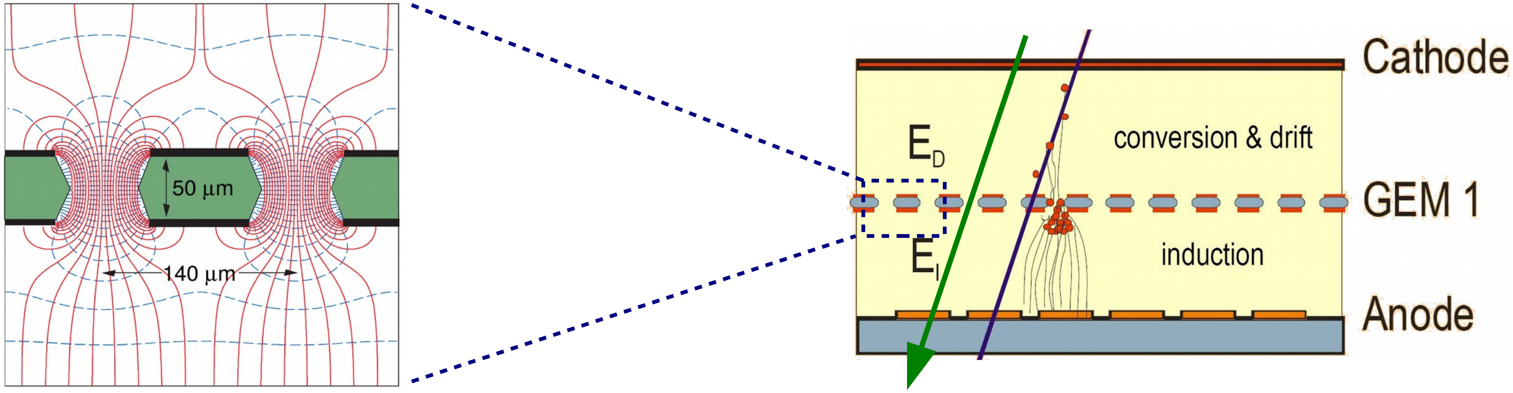
Micro-Pattern Gaseous Detectors

Gas Electron Multiplier (Sauli, 1996)

- **thin Kapton foil (**electrically insulating)
  - copper coating on both sides
- **etch regular array of fine holes**
- **apply voltage between the two sides**
  - high electric field inside the holes

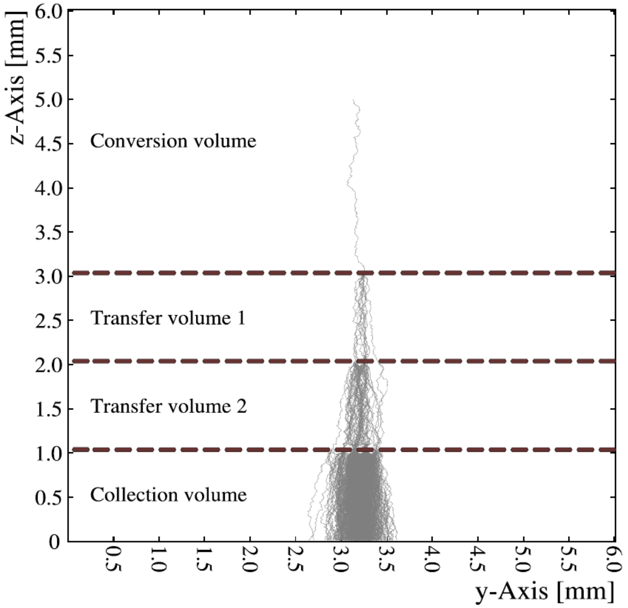
→ gas amplification





Micro-Pattern Gaseous Detectors

- **problem: gas gain from a single GEM not high enough for good efficiency**
  - high electric field inside the holes → high discharge probability through the holes
- **idea: stack several GEM foils**
  - high total gain with low field per GEM foil
- **triple-GEM detectors e.g. employed in innermost part of LHCb muon system**
  - 415 V per GEM foil → total gain ~ 4’300
  - Ar/CO_2/CF_4 gas mixture (45/15/40)



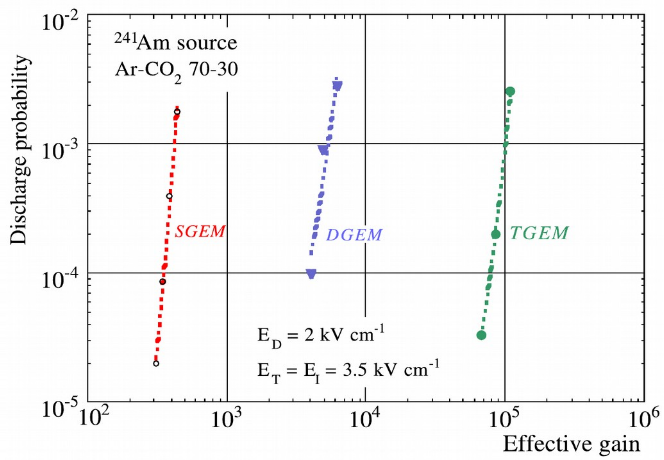
gas gain, e.g.

~ 20

~ 20

~ 20

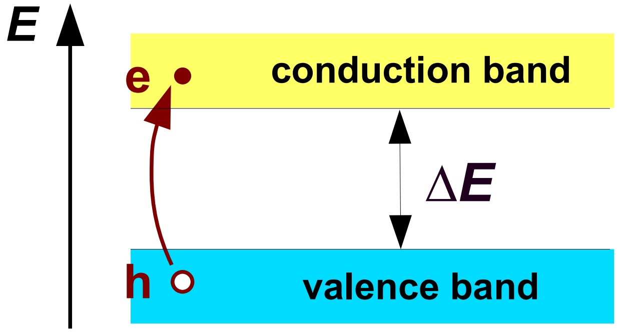
~ 8000



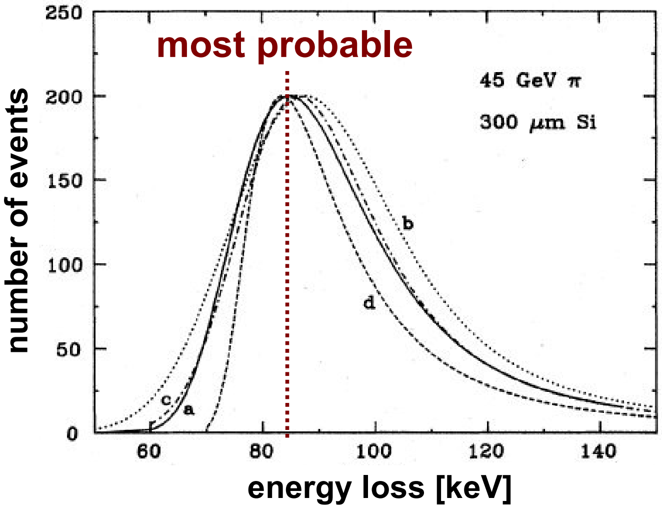
Silicon Detectors

Monocrystalline silicon is a semiconductor

- **valence and conduction band separated by band gap energy Δ*E* = 1.12 eV**



- **ionizing particle can excite electrons from valence band to conduction band**
  - creation of electron/hole (*e*/*h*) pairs
- **number of *e*/*h* pairs follows Ландау distribution**
  - most probable signal from a minimum ionizing particle in 300 µm of silicon is 22'500 *e*/*h* pairs

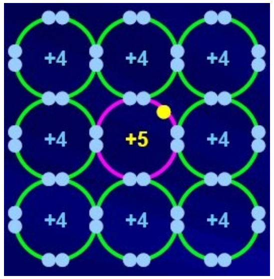


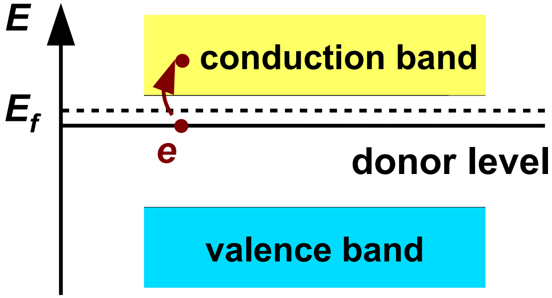
- create electric field across the detector volume to collect created electrons or holes on segmented electrodes on the surface (strips or pixels)

p-*n* Junction

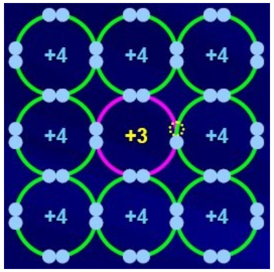
To generate electric field, create reverse biased *p*-*n* junction

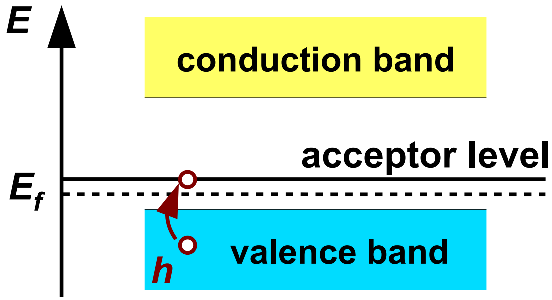
- **_n_-doping: introduce small fraction of group-V “donor” atoms (As, P)**
  - loosely bound excess electrons





- **_p_-doping: introduce small fraction of group-III “acceptor” atoms (B)**
  - loosely bound missing electrons (holes)





- **excess electrons/holes can move through the lattice**
- **create junction between _p_- and _n_-doped regions → density gradient**
  - excess electrons diffuse into *p*-doped region, holes diffuse into *n*-doped region

p-*n* Junction (II)

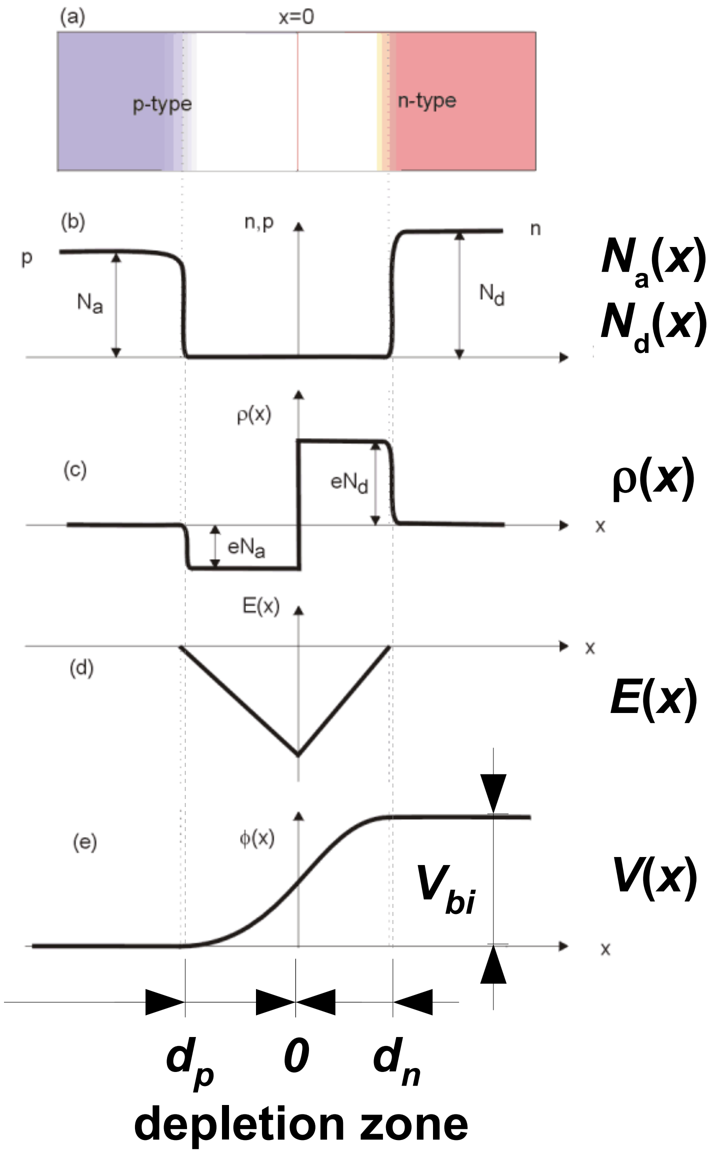
Diffusion of charge carriers across junction

- **depletion zone without free charge-carriers**
  - *p*-side: electrons absorberd by acceptor atoms
  - *n*-side: holes absorbed by donor atoms
- **but also net movement of electric charge**
  - creation of electric field across the junction
- **equilibrium of diffusion and Coulomb force**
  - electric field from Poisson equation:

$$-\frac{d^2V}{dx^2} = \frac{dE}{dx} = \frac{\rho(x)}{\varepsilon}$$

⇒ intrinsic potential barrier

$$V_{\text{bi}} = \frac{e}{2\varepsilon}\cdot\left(N_{\text{d}}\,d_n^2 + N_{\text{a}}\,d_p^2\right)$$



Asymmetric Junction

Detector: junction between bulk and implants

- **bulk few 100 μm thick, implants few μm thin**
  - simplest setup: *p*-implants in *n*-bulk (→ later)
- **want depletion zone to extend into bulk**

$$\boldsymbol{d_n}\,(\text{bulk}) \gg \boldsymbol{d_p}\,(\text{implant})$$

  - to achieve this, use charge conservation

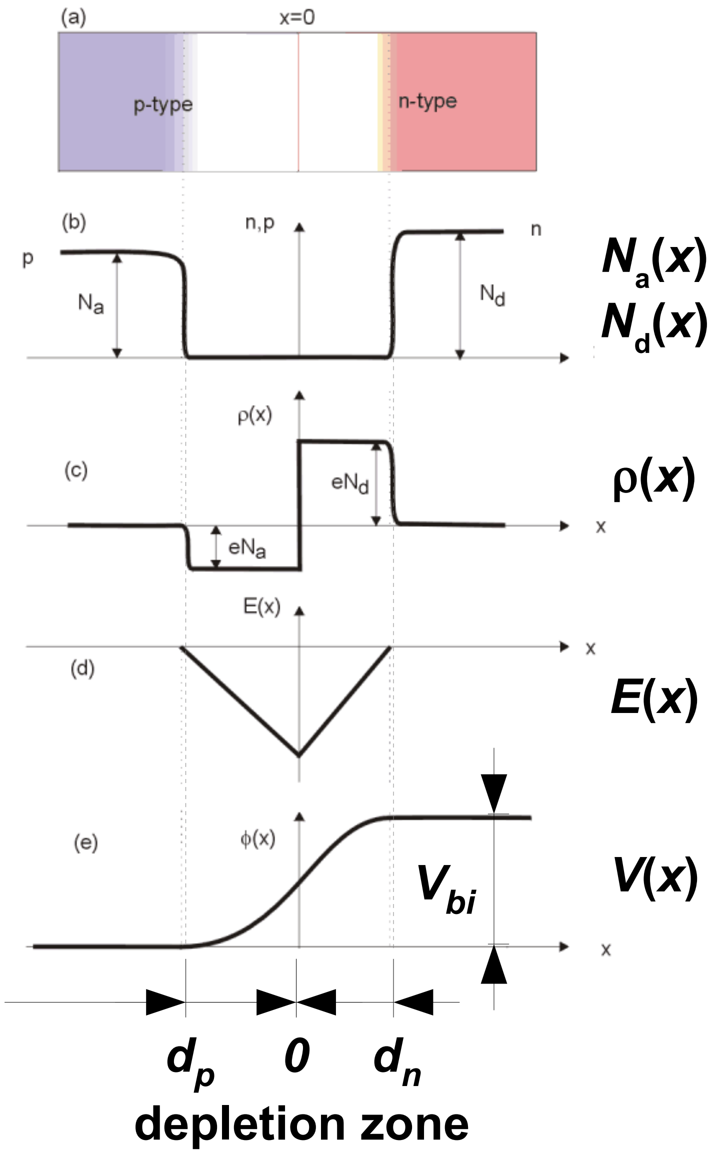
$$\boldsymbol{N_\text{d}\, d_n = N_\text{a}\, d_p}$$

  - and make

$$\boldsymbol{N_\text{a}}\,(\text{implant}) \gg \boldsymbol{N_\text{d}}\,(\text{bulk})$$

  - e.g. for $N_a \approx$ few × 10^{17} / cm³, $N_d \approx$ few × 10^{12} / cm³

$$\mathbf{V_{bi} = 0.65\ V\ \ ;\ \ d_n \approx 25\ \mu m}$$



Reverse-Biased Junction

Apply external voltage to increase thickness of depletion zone

- for $d_n \gg d_p$

$$V_{\text{bi}} = \frac{e}{2\varepsilon} \cdot N_{\text{d}}\, d_n^2 \Leftrightarrow d_n = \sqrt{\frac{2\varepsilon\, V_{\text{bi}}}{e} \cdot \frac{1}{N_{\text{d}}}}$$

- apply external voltage V_{b}

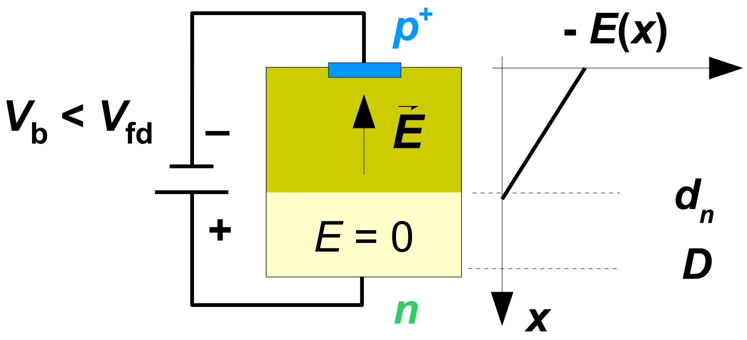
$$d_n = \sqrt{\frac{2\varepsilon\,(V_{\text{b}} + V_{\text{bi}})}{e} \cdot \frac{1}{N_{\text{d}}}}$$

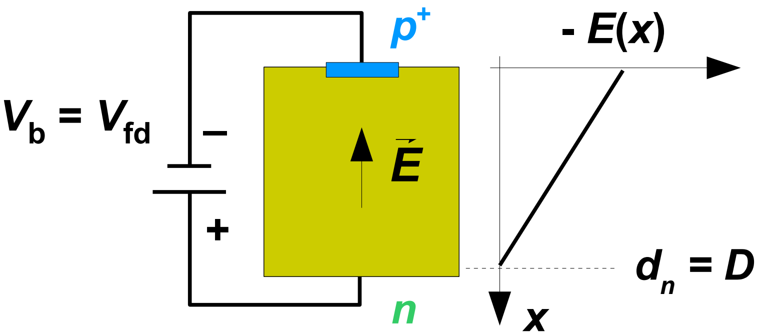
- to fully deplete a detector of thickness *D*

$$V_{\text{fd}} = \frac{e}{2\varepsilon} \cdot N_{\text{d}} \cdot D^2$$

  - e.g. for $D = 300\ \mu\text{m}$, $N_{\text{d}} = \text{few} \times 10^{12} / \text{cm}^3$

$$V_{\text{fd}} \approx 100\ \text{V}$$



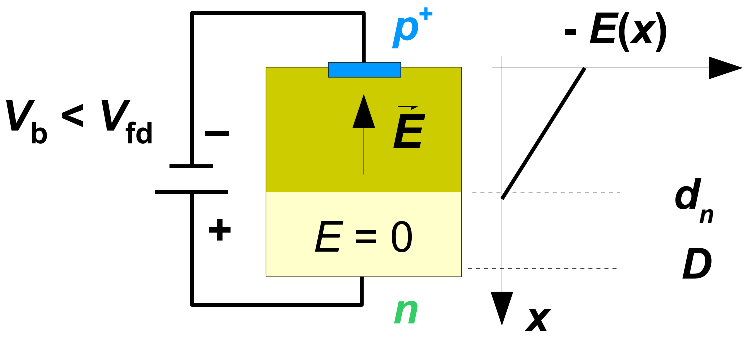


Full-Depletion Voltage

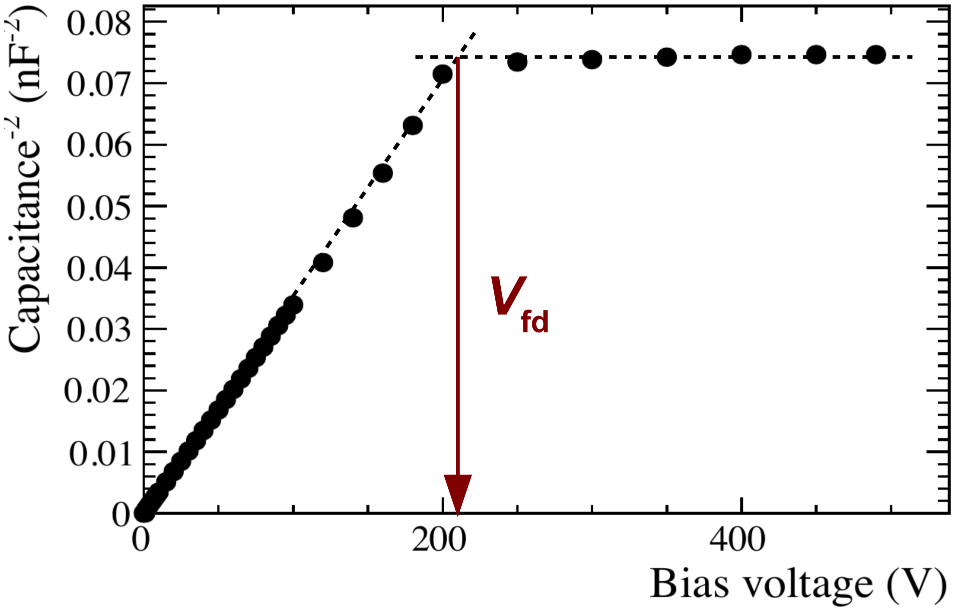
Determine V_{fd} from measurement of detector capacitance

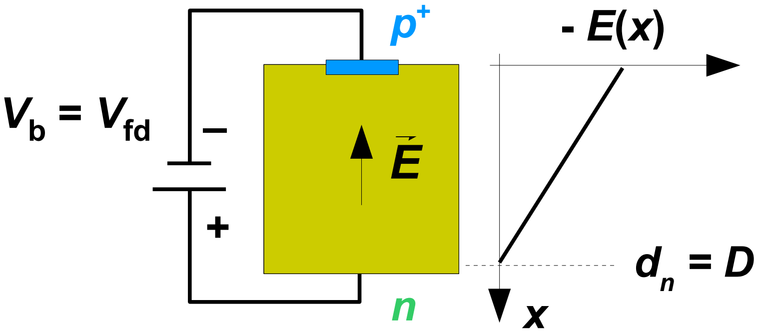
- detector ~ parallel-plate capacitor

$$C = \begin{cases} \dfrac{\varepsilon \cdot A}{d} \propto \dfrac{1}{\sqrt{V_b}} & \text{for } V_b < V_{fd} \\[2ex] \dfrac{\varepsilon \cdot A}{D} = \text{const} & \text{for } V_b \geq V_{fd} \end{cases}$$



- measure C as a function of V_b, plot $1/C^2$ vs V_b





Signal Creation

Moving charge carriers induce signal on readout strips

- **drift velocity of charge carriers is proportional to electric field *E*(*x*)**

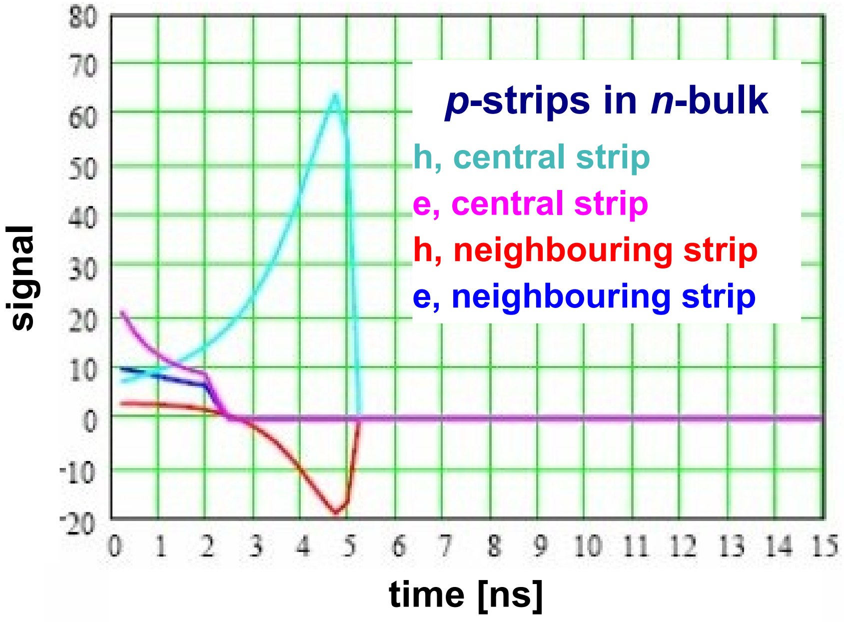
$$\boldsymbol{v}(\boldsymbol{x}) = \mu \cdot \boldsymbol{E}(\boldsymbol{x}) \qquad \text{with mobility } \mu \approx \begin{cases} 1500\ \text{cm}^2/\text{Vs} & \text{for electrons} \\ 450\ \text{cm}^2/\text{Vs} & \text{for holes} \end{cases}$$

- **maximum drift time** (for $V_b \gg V_{fd}$)

$$t_{\text{max}} = \frac{D^2}{2\,\mu \cdot V_b}$$

- e.g. for $D = 300\ \mu\text{m}$, $V_b = 200\ \text{V}$

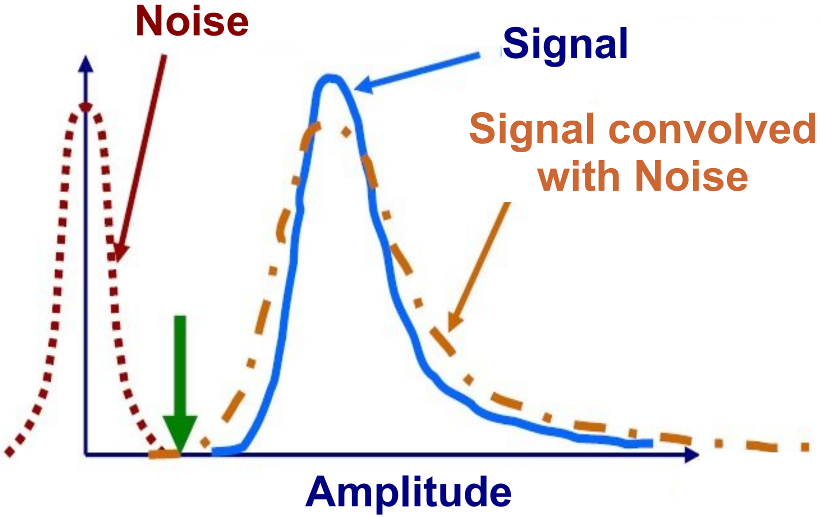
$$t_{\text{max}} = \begin{cases} 3.5\ \text{ns} & \text{for electrons} \\ 11\ \text{ns} & \text{for holes} \end{cases}$$



Signal and Noise

Critical parameter for particle detection efficiency

- **creation of *e*/*h* pairs is a statistical processes**
  - signal amplitude follows Landau distribution
- **electronics noise generates random signals**
  - Gaussian distribution with mean zero
- **measured signal amplitude is also smeared by electronics noise**
  - Landau convolved with Gaussian



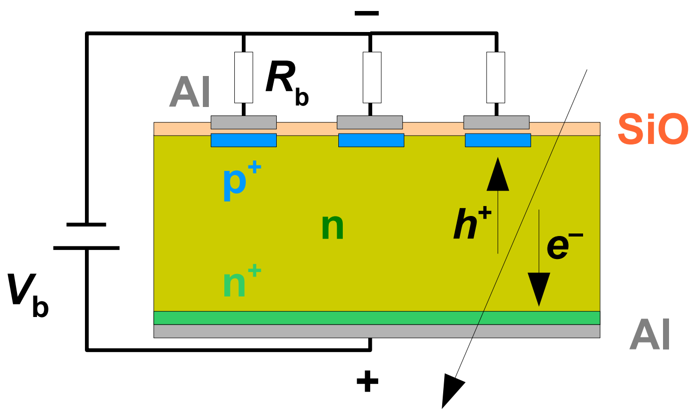
- **cut on the measured amplitude to distinguish signal from noise**
- **for high detection efficiency need clean separation between the distributions**

figure of merit: $$S/N \equiv \frac{\text{most probable signal for mip}}{\text{rms of noise distribution}}$$

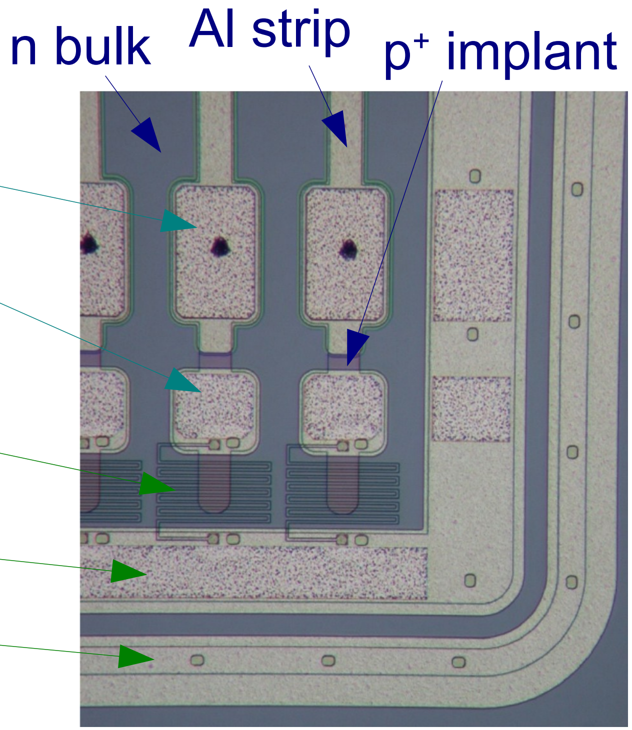
- **rule of thumb: need $S/N > 10$ to obtain full particle detection efficiency**

Silicon Strip Detector

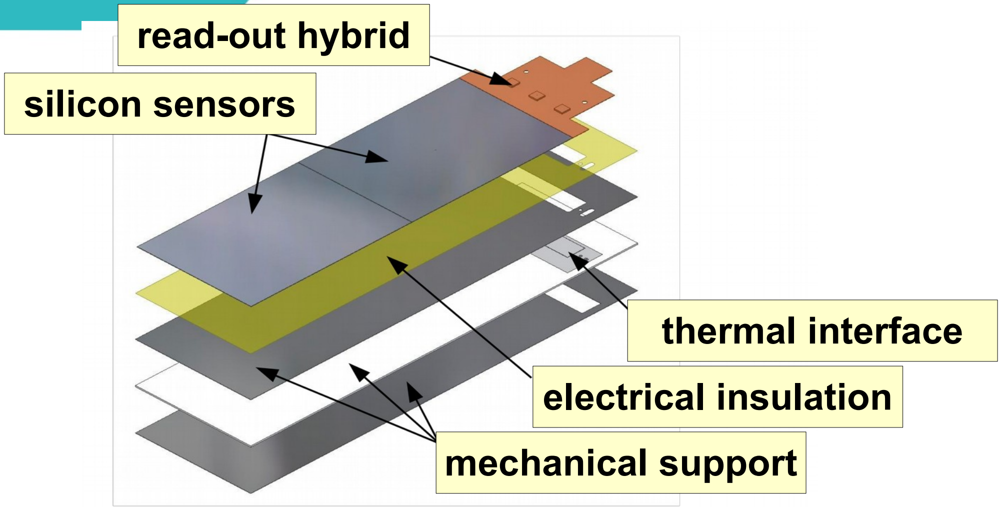
Basic features of a *p*-in-*n* strip sensor

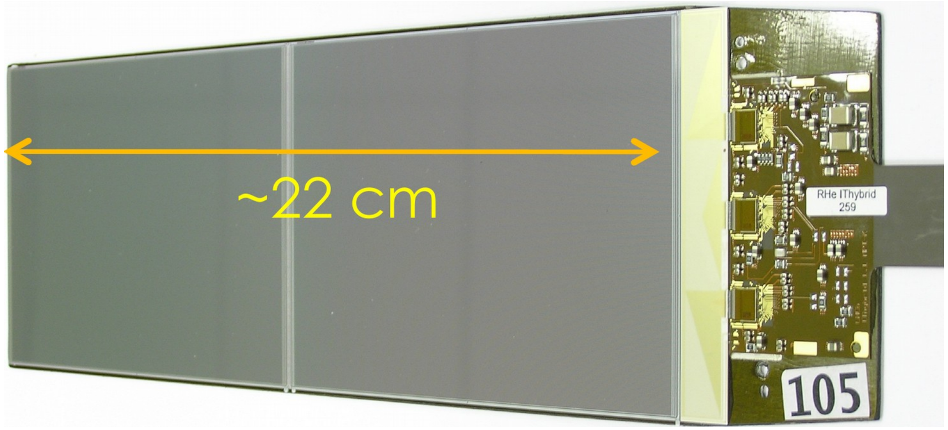


- **metallization of readout strips and backplane**
  - reduce electric resistance (R_s) along signal path
- **thin SiO layer between implants and metal strips**
  - isolate readout amplifier from leakage currents through detector bulk (“AC coupled readout”)
- **bond pads:** connect metal strip to readout electronics
- **DC pads:** ohmic contact to p^+ implant, for test purposes
- **bias resistors:** connect p^+ implants to bias ring, but insulate implants from each other
- **bias ring:** connect to external bias voltage
- **guard ring(s):** shape electric field close to the edge of the sensor, avoid discharges to backplane



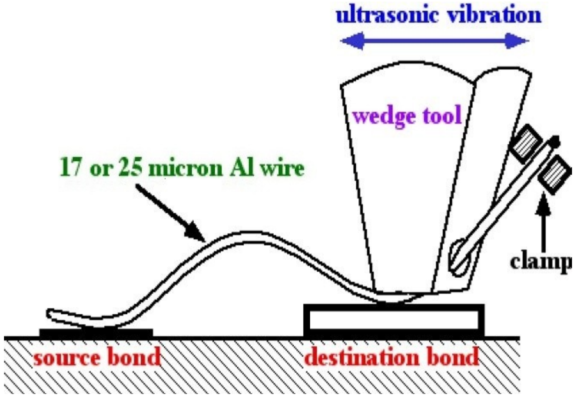
Silicon Strip Module

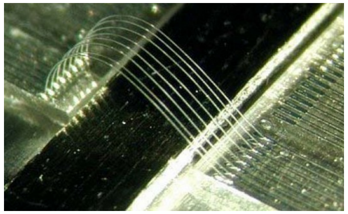


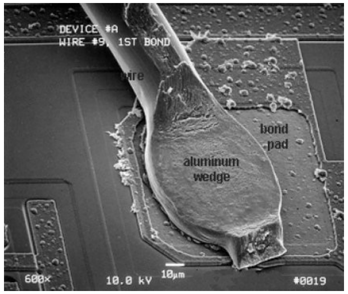


Silicon sensors + front-end readout electronics + mechanical support

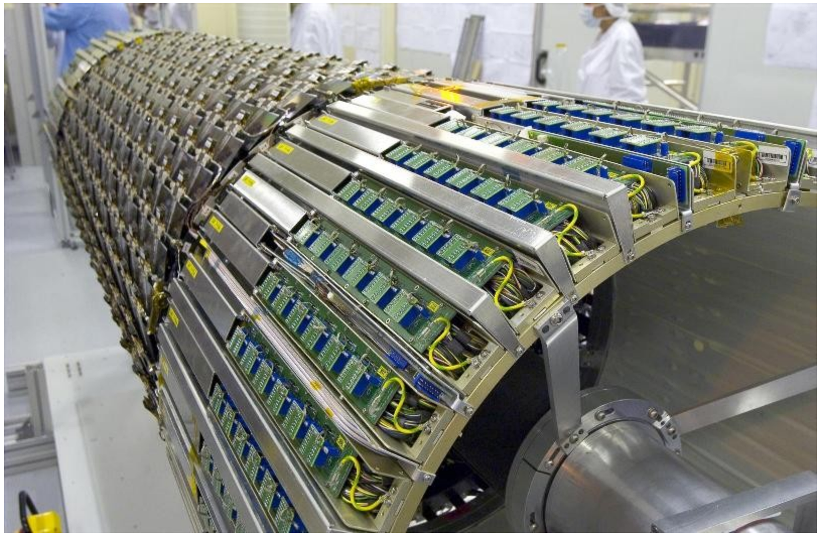
- **sensors usually produced from 6” silicon wafers**
  - typically 10 cm × 10 cm
  - connect sensors in series for longer strips
- **electrical connections by “wire bonding”**
  - ultrasonic welding of thin aluminium wire onto aluminium bond pads
- **light-weight support structures** (e.g. carbon fibre)



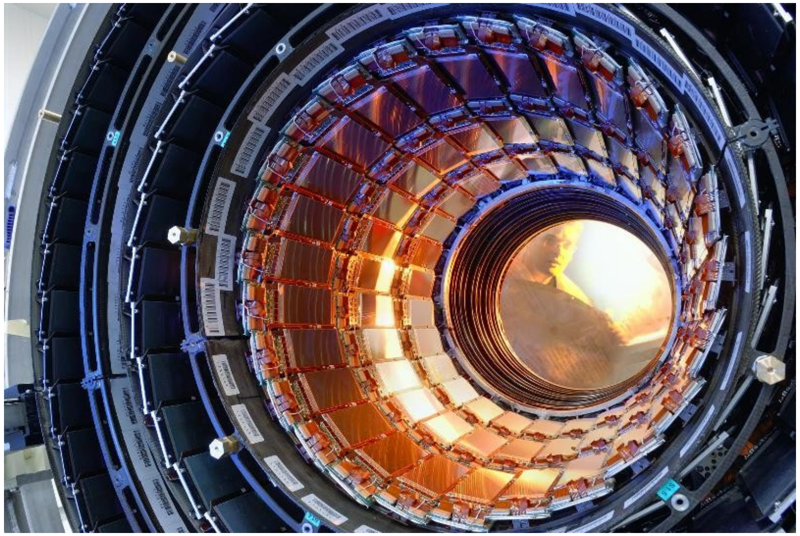




Silicon Strip Detectors



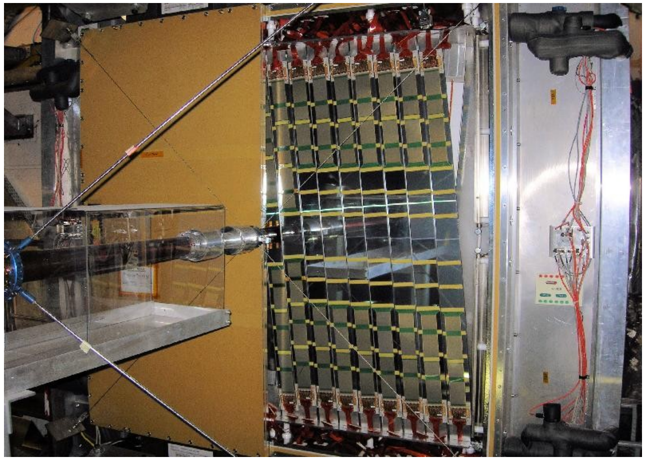
CMS Silicon Tracker (barrel)



ATLAS Silicon Tracker (barrel)

ATLAS (endcap)

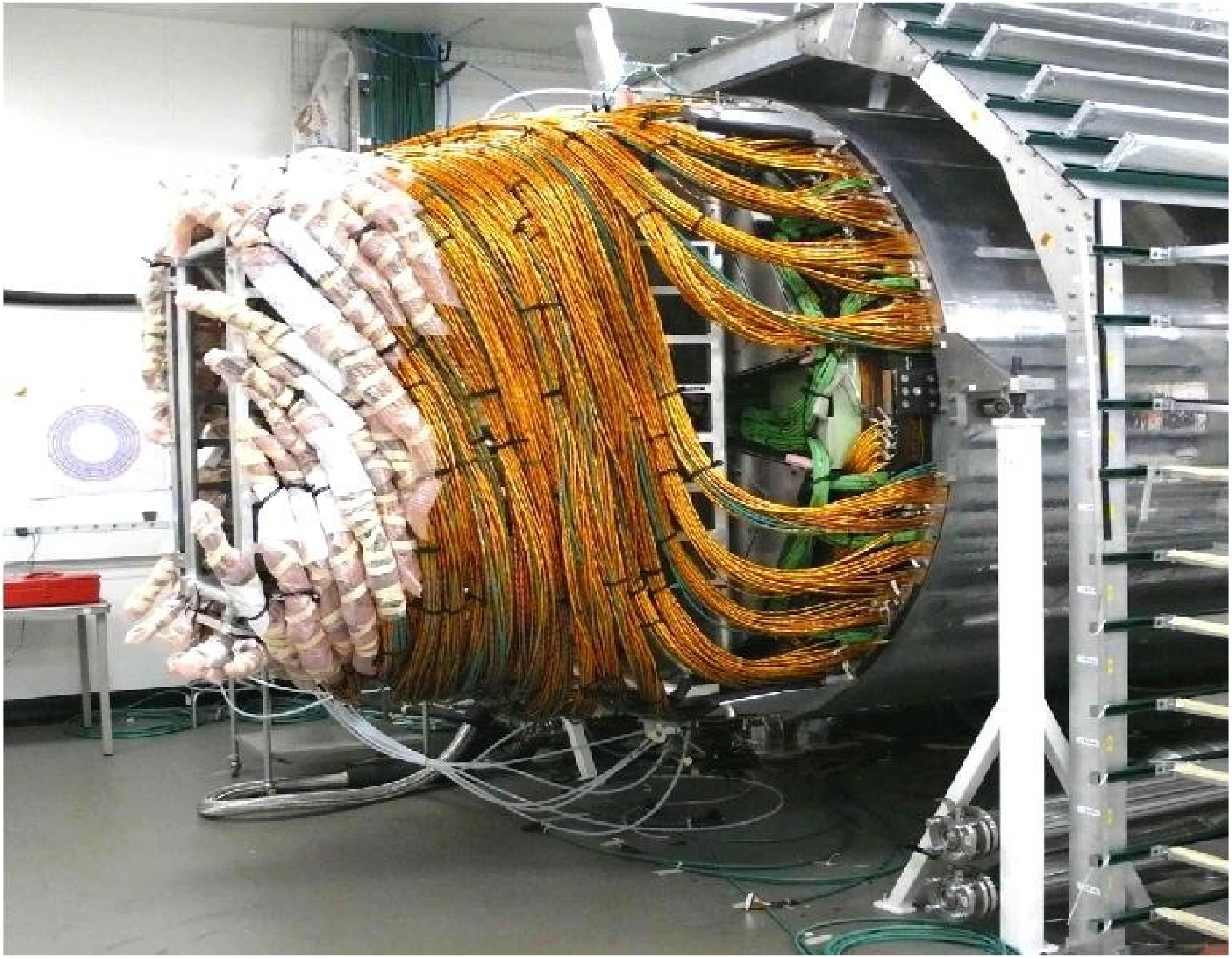
LHCb Vertex Locator



LHCb Tracker Turicensis

LHCb Inner Tracker

Silicon Strip Detectors

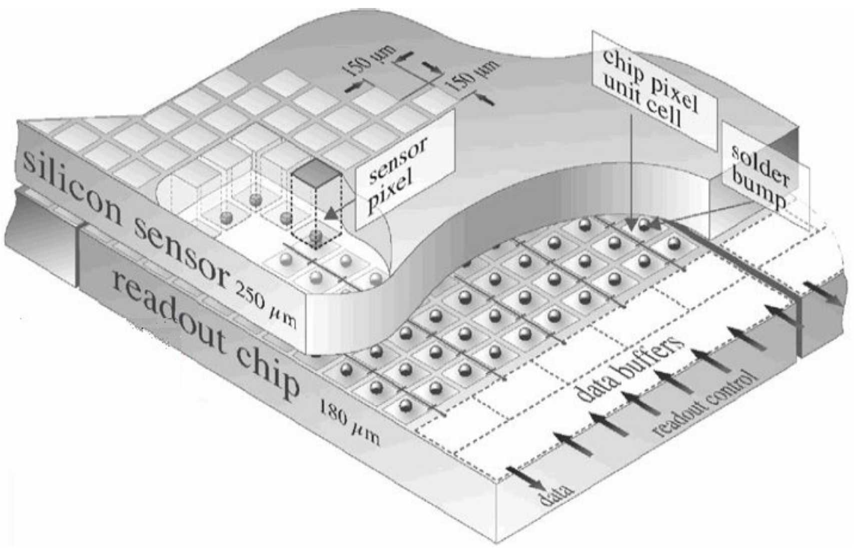


Cables of CMS Silicon Tracker Barrel

Pixel Detectors

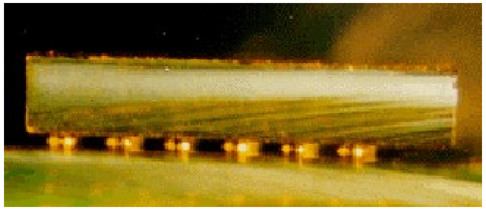
Readout implants segmented into pixels (typically ≈ 50 × 500 μm²)

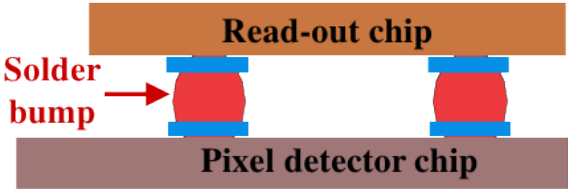
- **finer segmentation**
  → higher rate capability
- **smaller cell size**
  → small leakage current, low capacitance
- **measure both coordinates**
  → avoid ambiguities in track reconstruction
- **need readout amplifier for each pixel, located directly on top of the pixel**



Hybrid detector: two wafers mounted back-to-back

- **1st wafer: pixel sensor, 2nd wafer: readout electronics**
- **electrical connection by “bump bonding”**

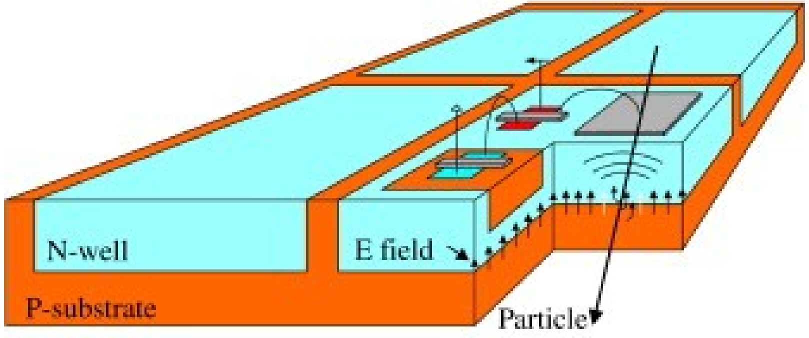




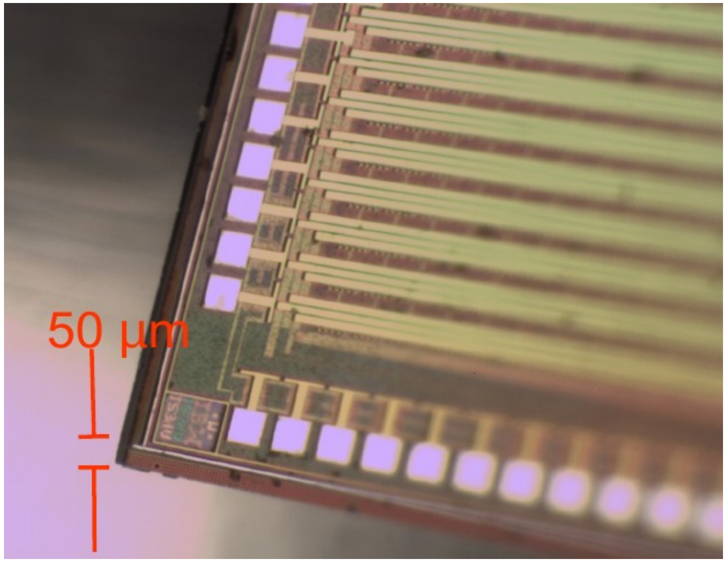
Pixel Detectors

Monolithic pixels: integrate detector and electronics in the same wafer

- **even smaller capacitance → lower noise**
  - do not need large signal to reach good S/N
  - can make detectors very thin
  - low material budget



- **use High-Voltage CMOS production process**
  - developed for automobile industry
  - allows to apply voltages up to 100 V
  - deplete substrate, fast signal collection

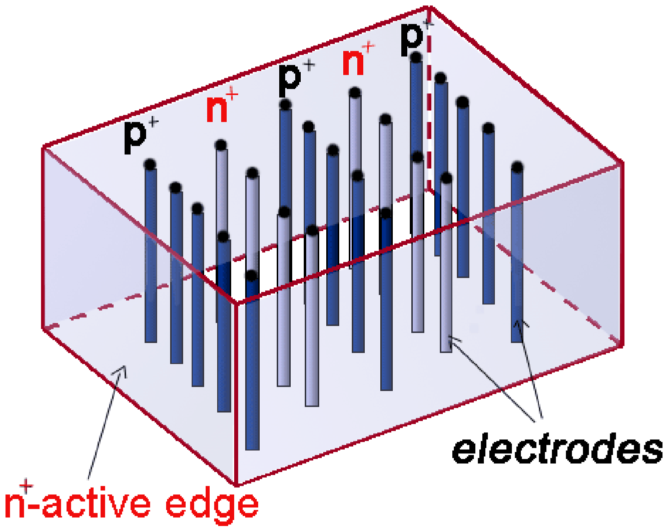


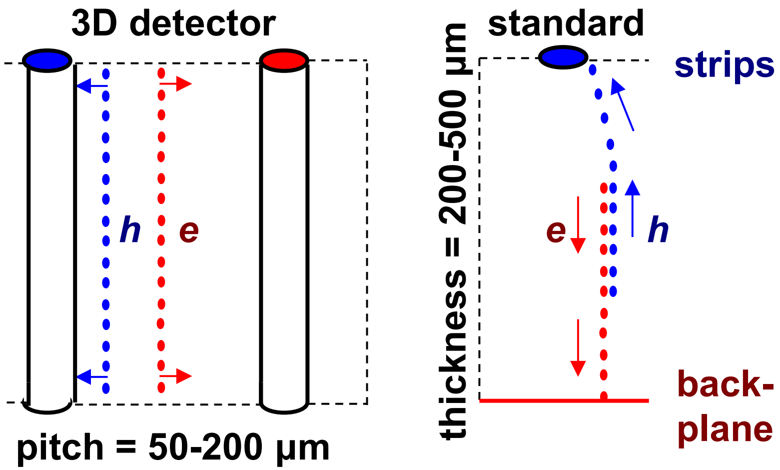
- **prototype detectors for µ3e experiment at PSI**
  - thickness 50 mum
  - pixel size ~ 80 x 80 mm
  - signal collection in < 15 ns

“3D Detectors”

Implants not at the surface of the detector, but penetrating the bulk

- **allows smaller distance between implants for same detector thickness**
  - faster charge collection → higher rate capability
- **lower bias voltages, smaller losses from charge trapping in radiation-induced defects**
  - better radiation hardness
- **production complex and expensive**
  - laser drilling or etching
- **first employed in new ATLAS Inner Barrel Layer, installed in 2013/2014**





Summary

Efficient and precise tracking of charged particles is a crucial ingredient for almost all particle physics experiments

- to determine production and decay vertices
- to measure momenta

Detection based on interaction of particle with detector material, e.g.

- ionisation of a gas
- creation of electron/pair holes in a semiconductor

Apply electric field across detector volume, read out the signals induced by drifting charges on segmented electrodes

- wires, strips, pixels

Several (sometimes conflicting) performance parameters

granularity, spatial resolution, rate capability,
radiation hardness, material budget, cost

Summary

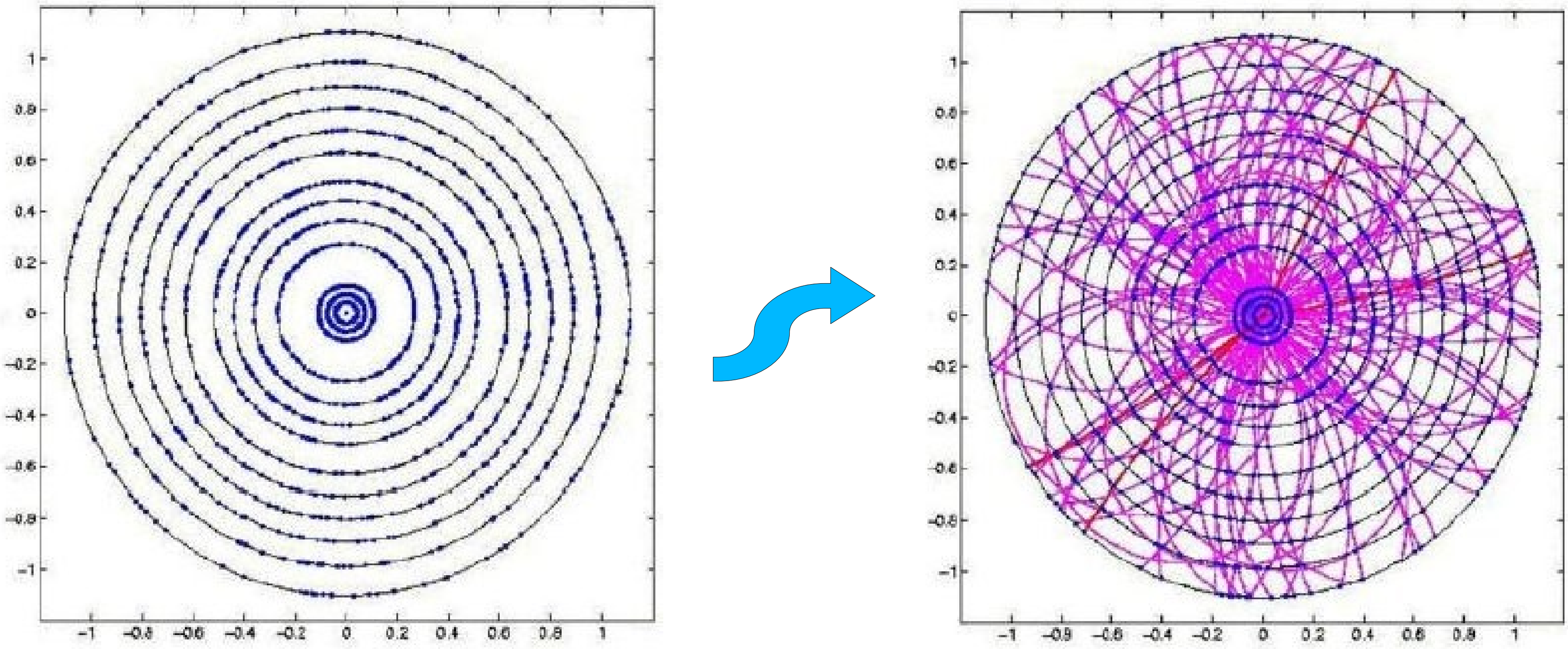
Did not talk about many, many very interesting things

e.g. use of scintillating fibres for tracking

$\left\{\begin{array}{c}\text{Scintillators and scintillating fibres play an important role}\\ \text{in calorimetry, I suspect this will be discussed in the lecture}\\ \text{by Giovanni de Lellis on March 20.}\end{array}\right\}$

Tutorial

After the break:
Tutorial on track reconstruction by Michele Atzeni



The slides of this lecture are available at

http://www.physik.uzh.ch/~olafs/pdf/190213_MISIS.pdf

Efficiency and Granularity

Primary ionization is a statistical process

- **discrete ionization clusters along particle trajectory**
- **number of clusters follows Poisson distribution**

$$P(k\,|\,\mu) = \frac{\mu^k}{k!}\, e^{-\mu}$$

  - probability to create at least one cluster is

$$\varepsilon = 1 - P(0\,|\,\mu) = 1 - e^{-\mu}$$

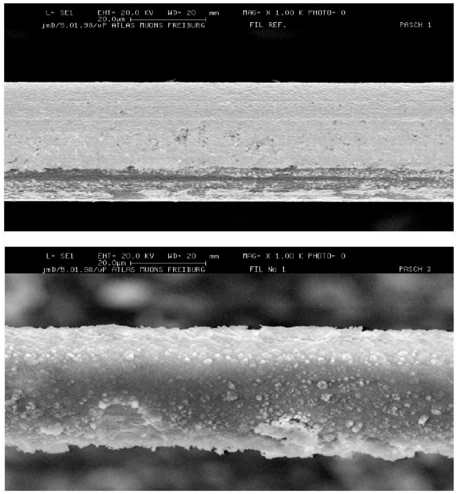
  - for detection efficiency ε > 99% need μ ≥ 5
- **e.g. Argon (**at 1 bar**):** μ **= 29 primary clusters / cm**
  - need ≥ 1.7 mm path length to reach ε ≥ 99%
- **cannot make cells smaller than that → limits possible granularity**

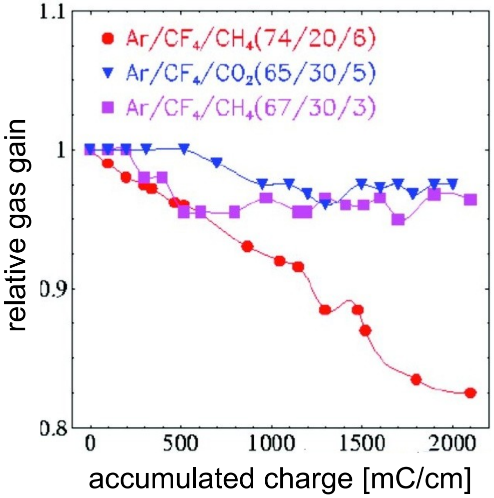
Gas	Density ρ [g/cm^3]	I_0 [eV]	W [eV]	n_P [cm^{-1}]	n_T [cm^{-1}]
H_2	8.99×10^{-5}	15.4	37	5.2	9.2
He	1.78×10^{-4}	24.6	41	5.9	7.8
N_2	1.23×10^{-3}	15.5	35	10	56
O_2	1.43×10^{-3}	12.2	31	22	73
Ne	9.00×10^{-4}	21.6	36	12	39
Ar	1.78×10^{-3}	15.8	26	29	94
Kr	3.74×10^{-3}	14.0	24	22	192
Xe	5.89×10^{-3}	12.1	22	44	307
CO_2	1.98×10^{-3}	13.7	33	34	91
CH_4	7.17×10^{-4}	13.1	28	16	53
C_4H_{10}	2.67×10^{-3}	10.8	23	46	195

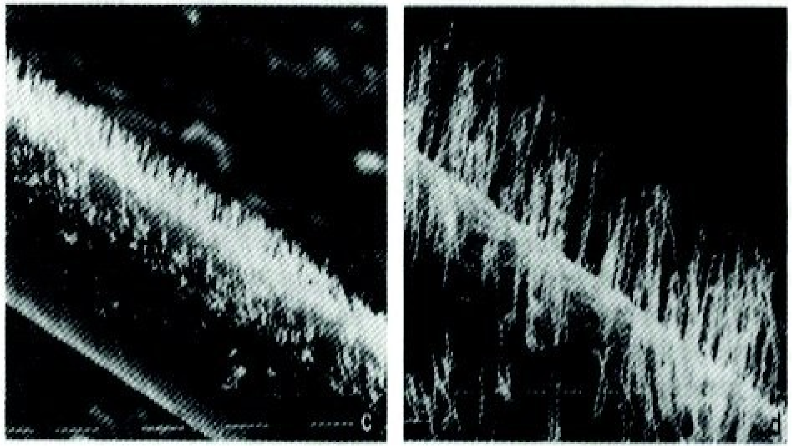
Wire Ageing

Deterioration of detector performance due to radiation damage

- **formation of radicals in gas avalanche, polymerization of carbohydrates**
- **formation of deposits on wires**
  - gradual reduction of gas gain
- **formation of whiskers**
- discharges, HV breakdown
- **very small contamination of the drift gas can have disastrous consequences**
  - typical problem: outgassing of glues
- **lots of dedicated research: qualification of materials and fundamental processes**



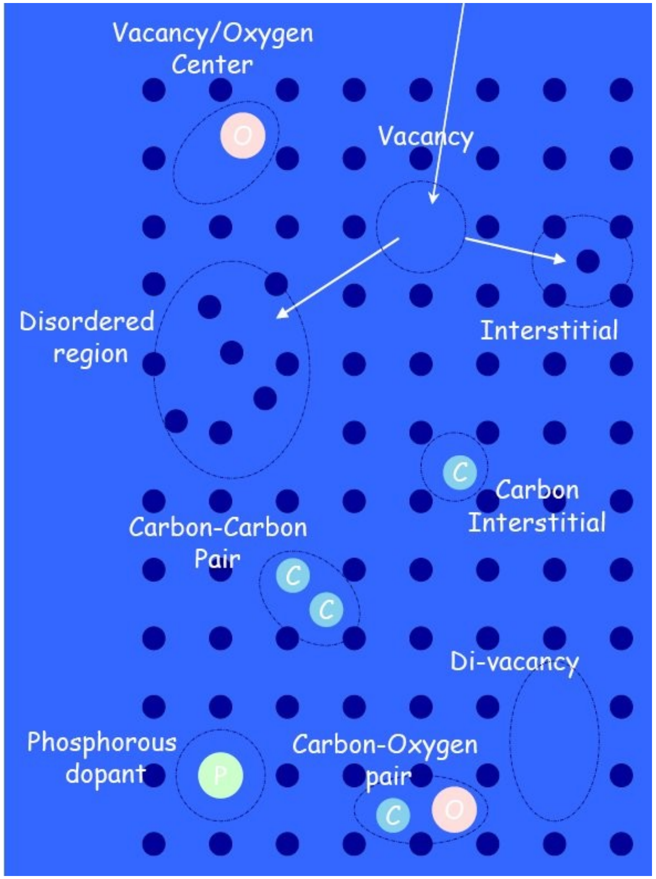




Radiation Damage

Most important: bulk damage from Non-Ionising Energy Loss (NIEL)

- **displacement of atoms in the lattice**
  - creation of vacancies and interstitials
- **defects can recombine** (beneficial annealing) **or combine to form stable defects** (reverse annealing)
- **defects create energy levels inside band gap**
  - increase of leakage current, noise
- **defects act like acceptors → change of "effective dopant concentration" $N_{eff} = N_d - N_a$ in silicon bulk**
  - "type inversion": bulk becomes *p*-type when $N_a > N_d$
  - $V_{fd} \propto |N_{eff}|$: increases steadily after type inversion



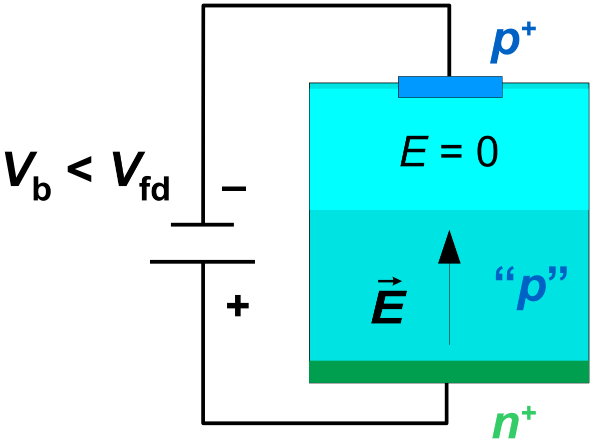
- **defects can "trap" drifting charge carriers**
  - reduction of collected signal

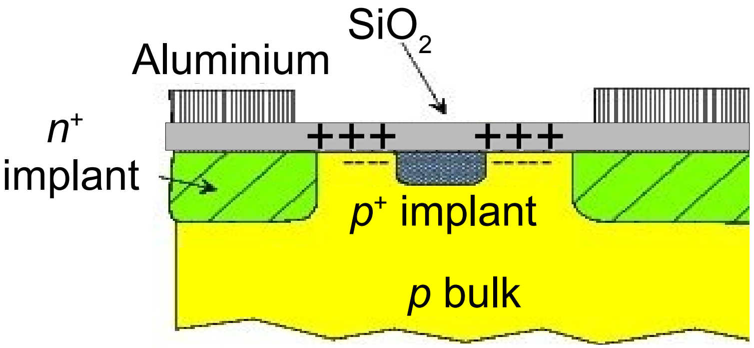
} becomes limiting factor at high-luminosity LHC upgrades

Radiation Damage

To increase radiation hardness of strip detectors

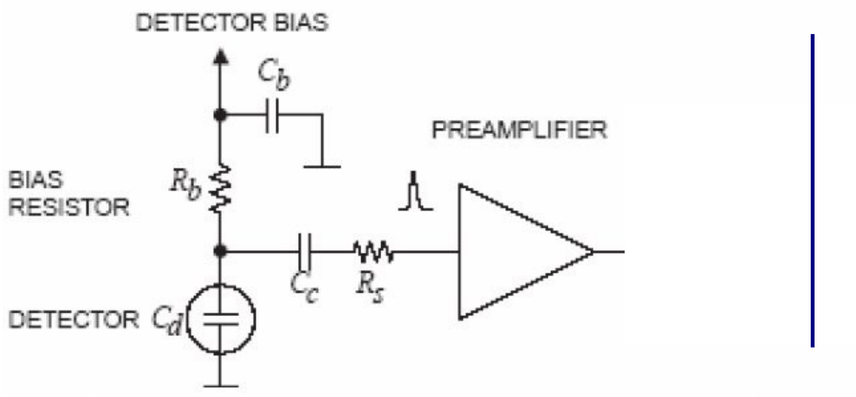
- **operate detectors at low temperatures**
  - suppress leakage currents & reverse annealing
- ***n*-type implants in *p*-type bulk:**
  - no type inversion: depletion zone grows from readout side also after irradiation
  - allows to operate detector partially depleted
  - problem: e^- get trapped at Si/SiO_2 interface in between implants → short-circuit
  - solution: add p^+-type implants, create insulating depletion zone in between the *n*-type implants
  - additional production step → more expensive





Noise Sources

Signal determined by thickness of detector ⇒ need to minimize noise



C_d: sensor capacitance to ground

R_b: bias resistor

C_C: AC coupling capacitance

R_s: serial resistance on signal path

- **“shot” noise: statistical fluctuations of detector leakage currents**
  - dominates for long signal integration times
- **thermal noise: current fluctuations in R_b, R_s**
- **capacitive noise: charge fluctuations in input transistor of readout amplifier**
  - dominates for short integration times (LHC)

(more in Lea Caminada’s lecture on April 13)