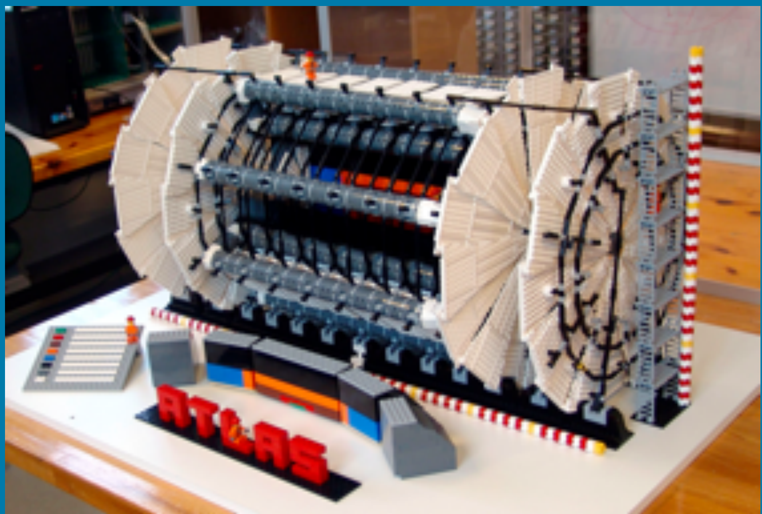
Detectors for High Energy Physics

Ingrid-Maria Gregor, DESY



DESY Summer Student Program 2018
Hamburg
July 26th/ Aug 1st

Overview

I. **Detectors for Particle Physics**

II. **Interaction with Matter**

III. **Calorimeters**

} *Thursday*

IV. **Tracking Detectors**
- Gas detectors
- Semiconductor trackers

V. **Examples from the real life**

} *Wednesday*

IV. Tracking Detectors

Tracking

- “tracking” in google image search:

Tracking

- "tracking" in google image search:

Tracking

- “tracking” in google image search:

Tracking Detector

- “tracking detector” in google image search

GPS Tracking Detector

Tracking Detector

- “tracking detector” in google image search

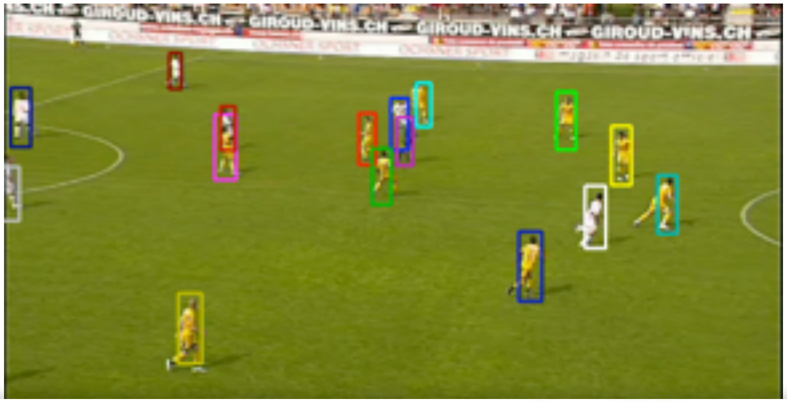
GPS Tracking Detector

Online Multi-Person Tracking-by-Detection from a Single, Uncalibrated Camera

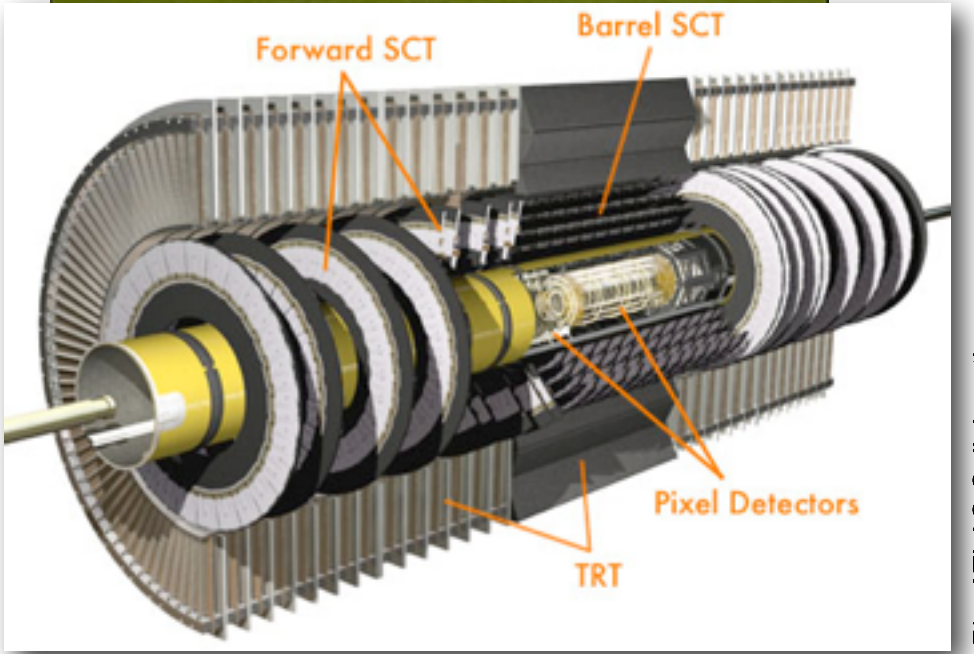
Tracking Detector

- "tracking detector" in google image search

GPS Tracking Detector



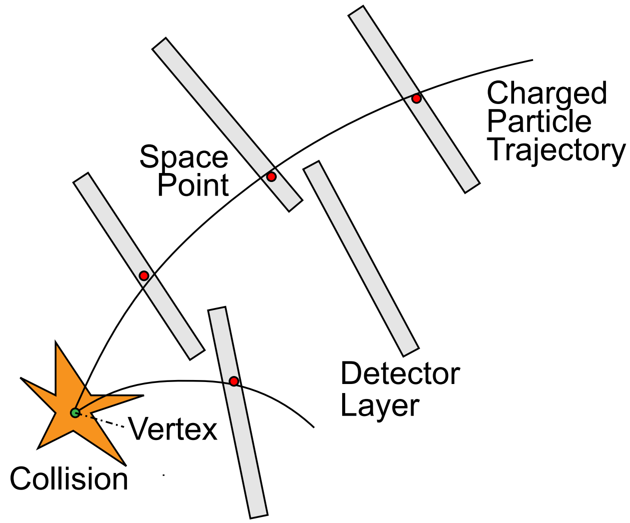
But the 1st image on list is:



Pic: ATLAS Collaboration

Tracking Detectors

- Precise measurement of track and momentum of charged particles due to magnetic field.
- The trajectory should be disturbed minimally by this process (reduced material)



Pictures: U. Husemann

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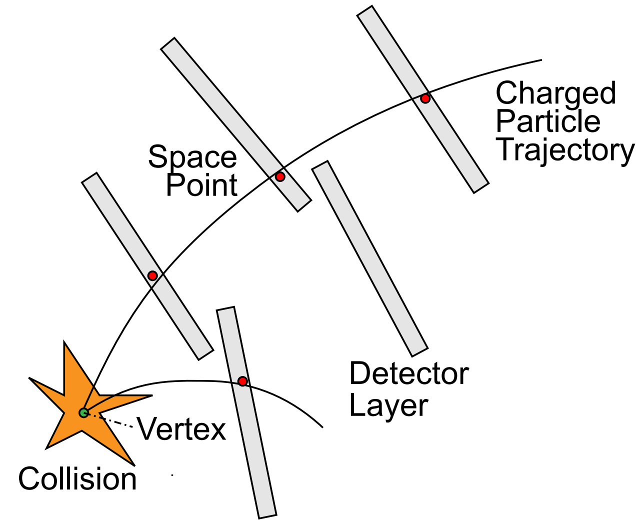
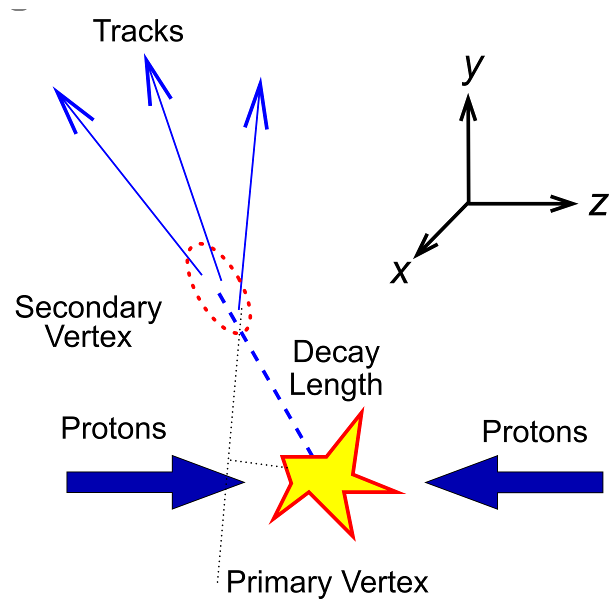


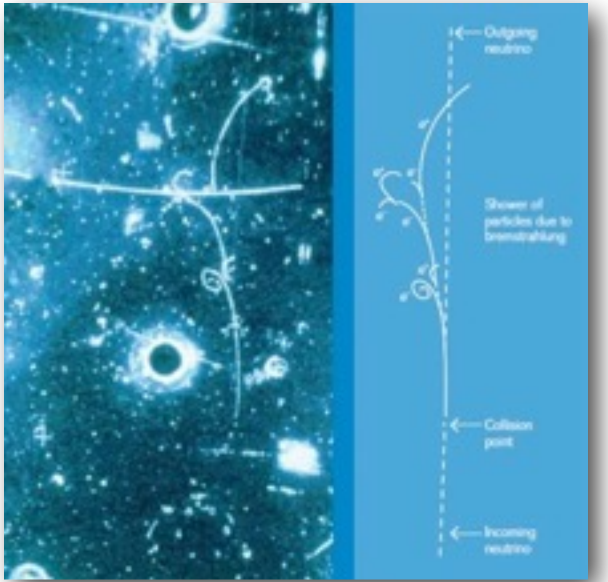
- Charged particles ionize matter along their path.
  - Tracking is based upon detecting ionisation trails.
  - An “image” of the charged particles in the event



Pictures: U. Husemann

Tracking Detectors - Technologies

- **"Classic"**: Emulsions, cloud, and bubble chambers
  - Continuous media
  - Typically very detailed information but slow to respond and awkward to read out
- **"Modern":** Electronic detectors, wire chambers, scintillators, solid state detectors
  - Segmented
  - Fast, can be read out digitally, information content is now approaching the "classic" technology
  - Mostly used solid state detector -> Silicon (pixels and strips)

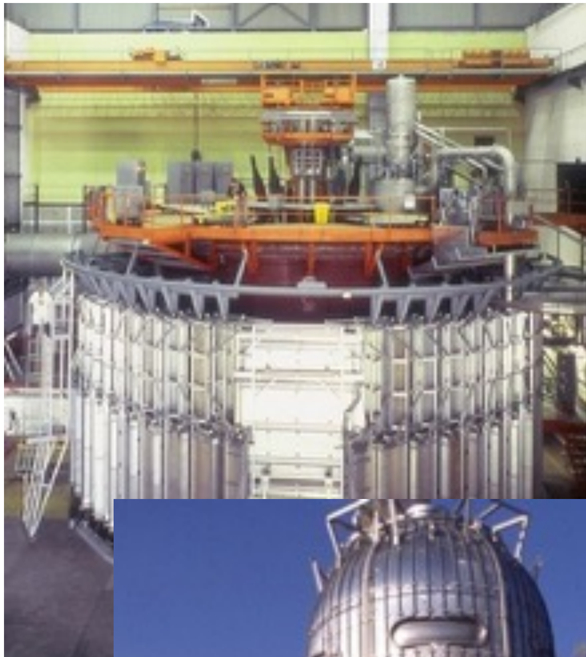


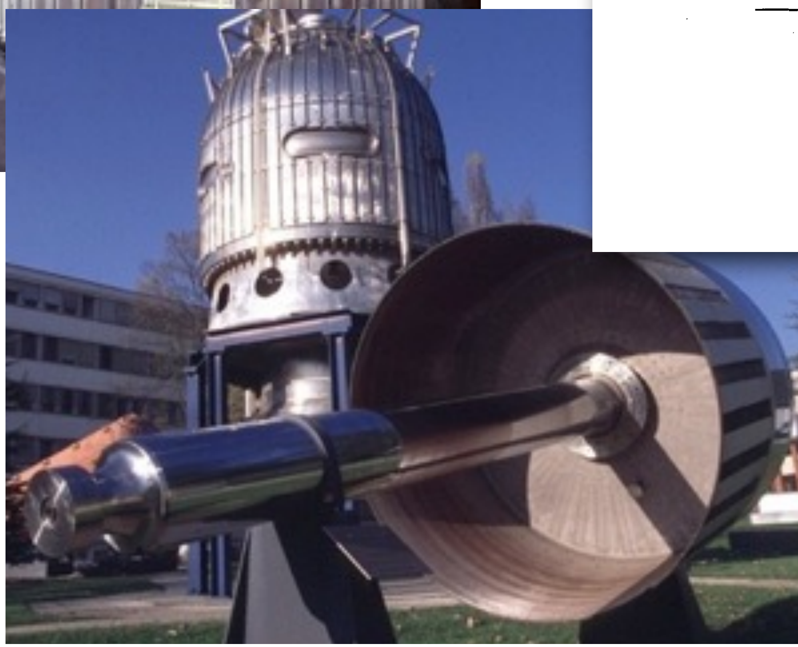
Discovery of neutral currents
Gargamelle, 1972

CMS Inner barrel Si Tracker:
Single-Sided Si-Strip

Pictures: CERN

Very "Classic": Bubble Chamber





- The biggest: Big European Bubble Chamber
  - 3.7 m diameter
  - Until 1984 used at CERN for the investigation of neutron hadron interactions

Early report on bubble chamber analysis:

Second United Nations
International Conference
on the Peaceful Uses of
Atomic Energy

A/CONF.15/P/730
U.S.A.
June 1958

ORIGINAL: ENGLISH

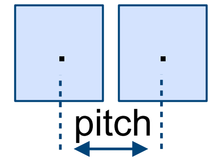
ON THE ANALYSIS OF BUBBLE CHAMBER TRACKS

Hugh Bradner and Frank Solmitz

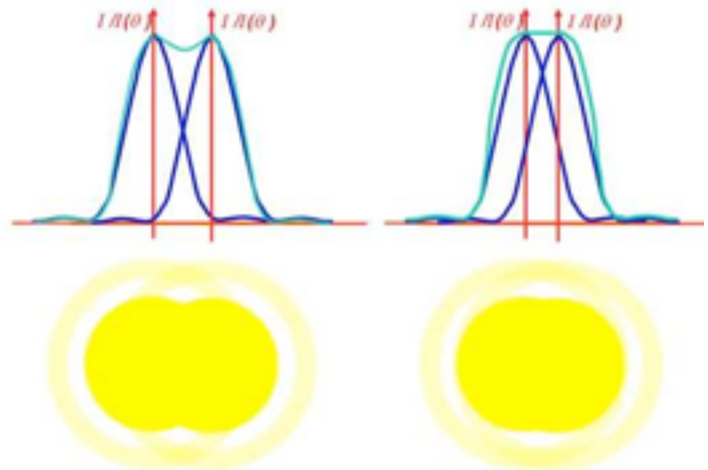
"… the large number of possible reactions, the variability of appearance of interaction, and the importance of being alert to possible new phenomena make it very important for a **trained physicist** to look at the bubble chamber pictures…."

Tracker: Important Parameter

- An important figure of merit is the **spatial resolution** of a tracking detector
- Depending on detector geometry and charge collection
  - Pitch (distance between channels)
  - Charge sharing between channels



can be tubes, strips, wires, pixels ….



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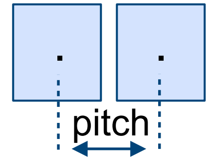

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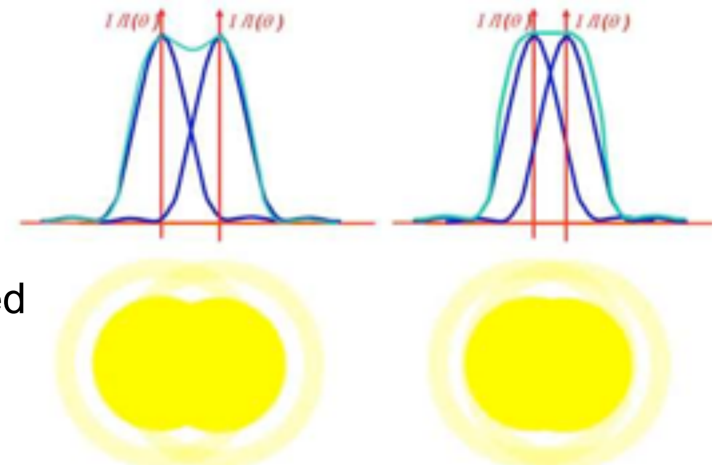
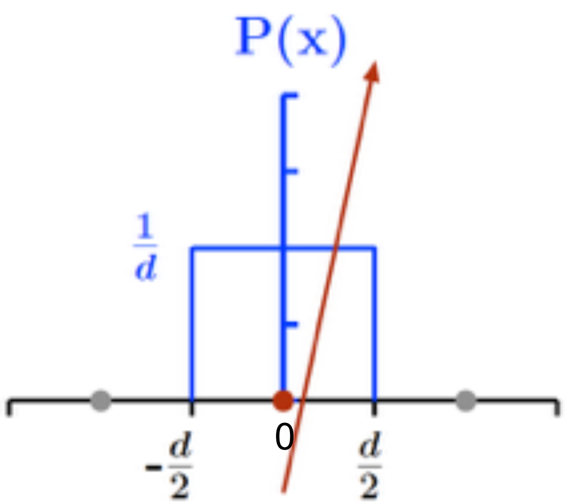


- Simple case: all charge is collected by one strip
- Traversing particle creates signal in hit strip (binary)
- Flat distribution along strip pitch; no area is pronounced
- ➔ Probability distribution for particle passage:



$$P(x) = \frac{1}{d} \qquad \Rightarrow \int_{-d/2}^{d/2} P(x)\,dx = 1$$

The reconstructed point is always the middle of the strip:

$$\langle x \rangle = \int_{-d/2}^{d/2} x\,P(x)\,dx = 0$$

Tracker: Important Parameter

- Calculating the resolution orthogonal to the strip:

$$\sigma_x^2 = \langle (x - \langle x \rangle)^2 \rangle = \int_{-d/2}^{d/2} x^2 \, P(x) \, dx = \frac{d^2}{12}$$

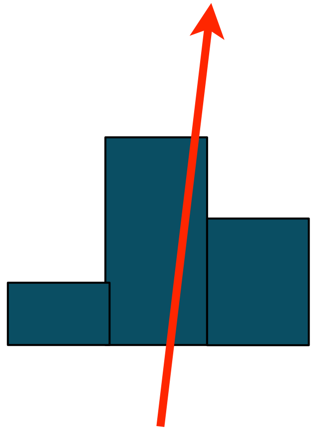
- Resulting in a general term (valid for tracking detectors with a pitch d):

$$\sigma = \frac{d}{\sqrt{12}}$$

very important !

- For a silicon strip detector with a strip pitch of 80 µm this results in a minimal resolution of ~23µm
- In case of charge sharing between the strip (signal size decreasing with distance to hit position) and information about signal size
  - resolution improved by additional information of adjacent channels

$$\sigma \propto \frac{d}{(S/N)}$$



Tracking: Determination of the Momentum in Magnetic Field

- A tracking detector is typically placed within a B-field to enable momentum measurements
- Charged particles are deflected in a magnetic field:
  - takes only effect on the component perpendicular to the field

$$F = qvB$$

$$ma = qvB$$

$$m(\frac{v^2}{r}) = qvB$$

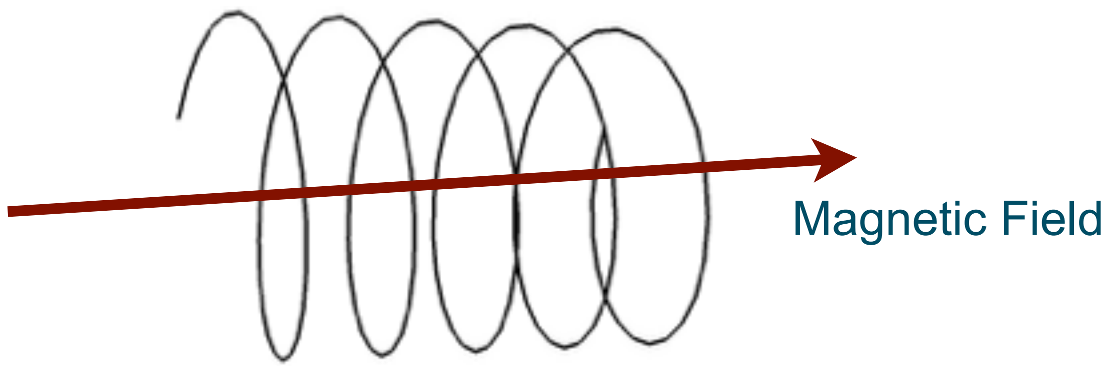
$$p = 0.3Br$$

Radius of the circular path is proportional to the transversal momentum

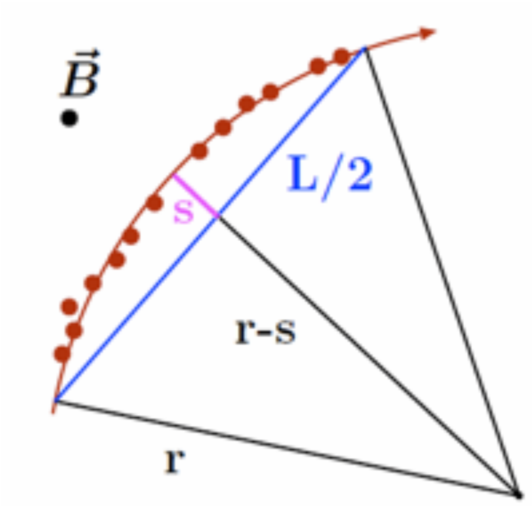
when converting in HEP units and assuming that all particles have the |electron charge|

- parallel to the field is no deflection:

➩ particle is moving on a helix, the radius is determined by the field and p_T



Determination of the Momentum in Magnetic Field II



- In real applications usually only slightly bent track segments are measured
  - Figure of merit: sagitta

Segment of a circle: $$s = r - \sqrt{r^2 - \frac{L^2}{4}}$$

$$\Rightarrow r = \frac{s}{2} + \frac{L^2}{8s} \approx \frac{L^2}{8s} \quad (s \ll L)$$

With the radius-momentum-B-field relation: $$r = \frac{p_T}{0.3\,B} \Rightarrow s = \frac{0.3\,B\,L^2}{8\,p_T}$$

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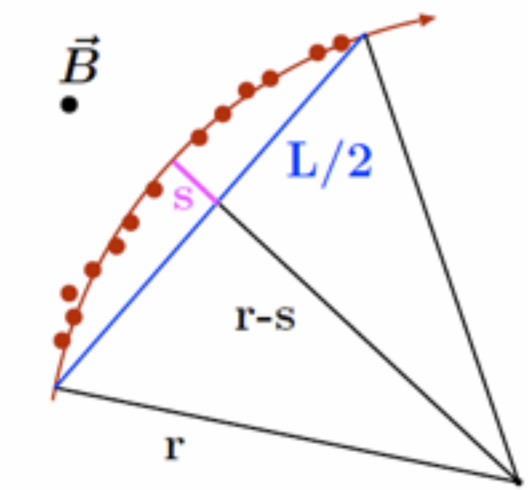

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Momentum resolution due to position measurement:

Gluckstern $$\frac{\sigma_{p_T}}{p_T} = \frac{\sigma_s}{s} = \sqrt{\frac{720}{n+4}}\frac{\sigma_y p_T}{0.3BL^2}$$

NIM, 24, P381, 1963

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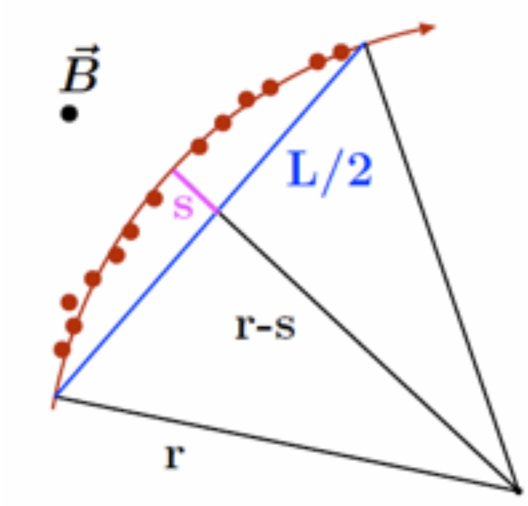

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NIM, 24, P381, 1963

➠ The larger the magnetic field **B**, the length **L** and the number of measurement points n, and the better the spatial resolution, the better is the momentum resolution

Impuls resolution: Spatial resolution and multiple scattering

- More components are influencing the momentum resolution $\sigma(p_T)/p_T$ of a tracking system:
  - Inaccuracy of the tracking detector: $\sigma(p_T) \propto p_T$
  - Influence of the particle due to MS: $\sigma(x)_{MS} \propto \frac{1}{p}$
  - The angular resolution of the detector

Multiple scattering angle: $\theta \propto \frac{1}{p}$

$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = \left(\sqrt{\frac{720}{n+4}}\frac{\sigma_y p_T}{0.3BL^2}\right)^2 + \left(\frac{52.3\times 10^{-3}}{\beta B\sqrt{LL_y\sin\theta}}\right)^2 + (\cot\theta\sigma_\theta)^2$$

Position resolution — Multiple scattering — Angular resolution

- p_T resolution improves as 1/B and depends on p as $1/L^2$ or $1/L^{-1/2}$
- For low momentum (β→0), MS will dominate the momentum resolution.
- Improving the spatial resolution (σ_y) only improves momentum resolution if the first term is dominate.

Tracker: Important Parameter

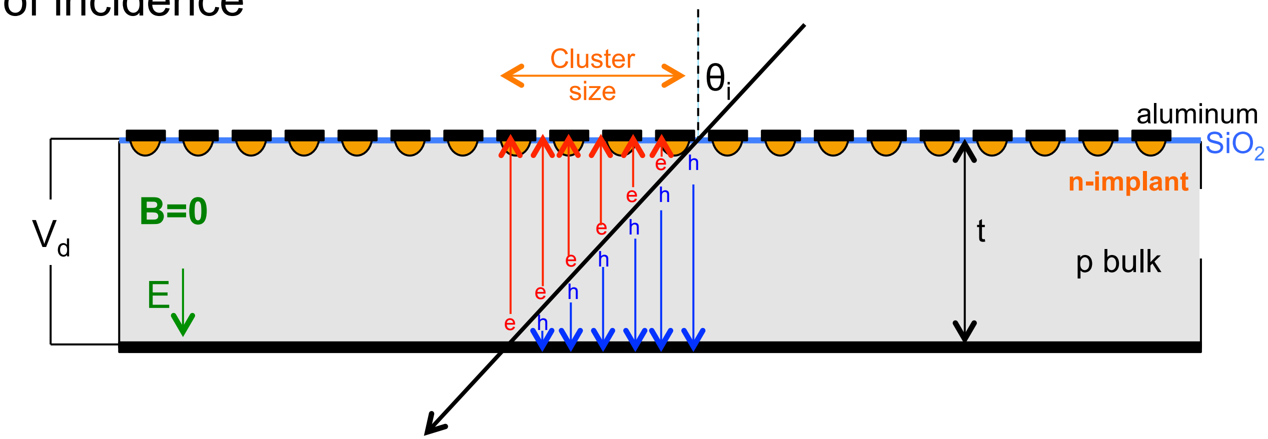
- **Detector efficiency** ϵ: probability to detect a transversing particle
  - should be as close to 100% as possible
  - i.e. 12 layer silicon detector with 98% efficiency per layer -> overall tracking efficiency is only 78%
  - needs to be measured in test beam

$$\epsilon_{\text{track}} = \left(\epsilon_{\text{layer}}\right)^n$$

n = number of layer is tracking system

- **Cluster size** : number of hit pixels/strips belonging to one track
  - usually given in unit of strips or pixels
  - depending on angle of incidence

Optimally measured in test beam ….



Tracker: Important Parameter

- **Signal/noise ratio**: signal size for a certain input signal over the intrinsic noise of the detector
  - parameter for analog signals
  - good understanding of **electrical noise charge** needed
    - leakage current (ENC_I)
    - detector capacity (ENC_C)
    - det. parallel resistor (ENC_{Rp})
    - det. series resistor (ENC_{Rs})

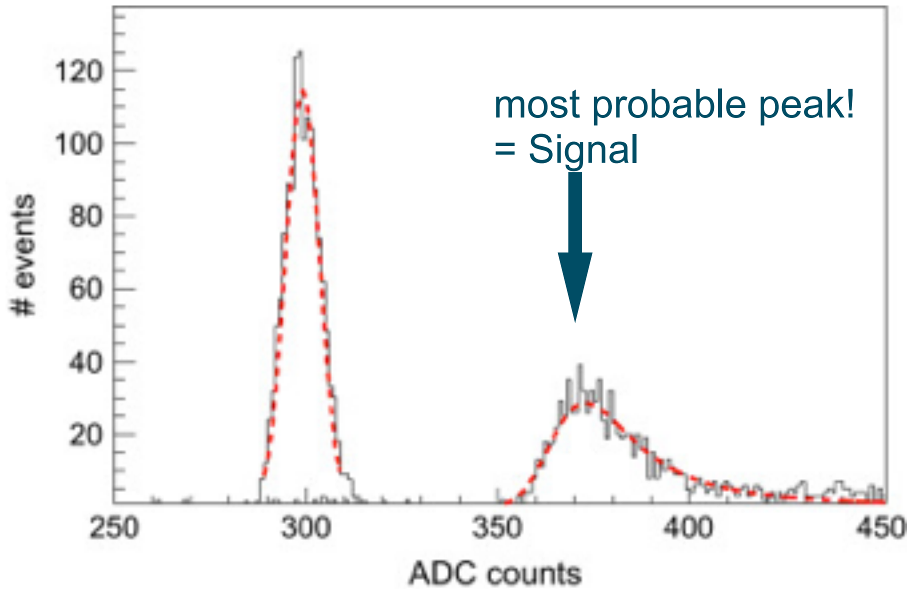
$$\mathrm{ENC} = \sqrt{\mathrm{ENC}_C^2 + \mathrm{ENC}_I^2 + \mathrm{ENC}_{R_p}^2 + \mathrm{ENC}_{R_s}^2}$$

example for silicon detector

  - signal induced by source or laser (or test beam particles)
  - optimal S/N for a MiP is larger than 20

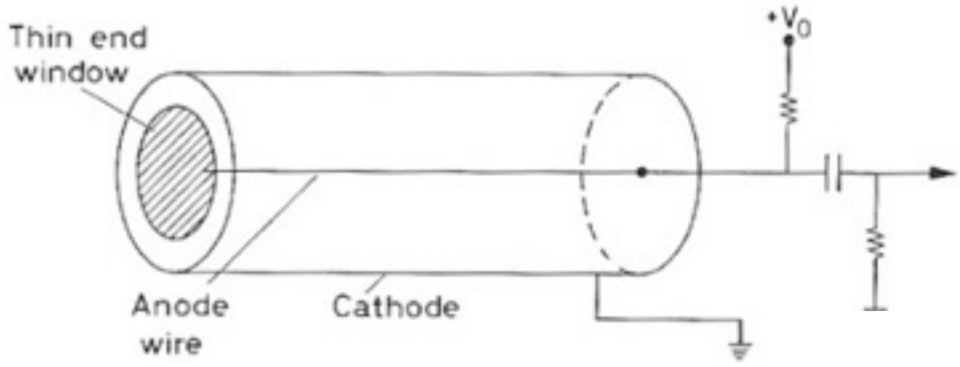
With analog readout:

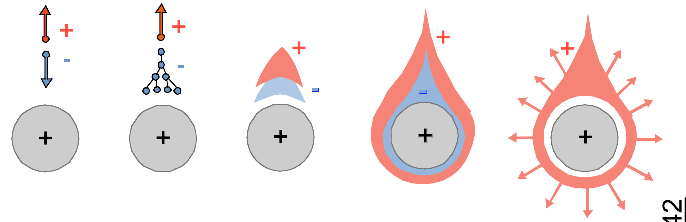
Gaussian distributed "non-signal"
= sigma -> noise



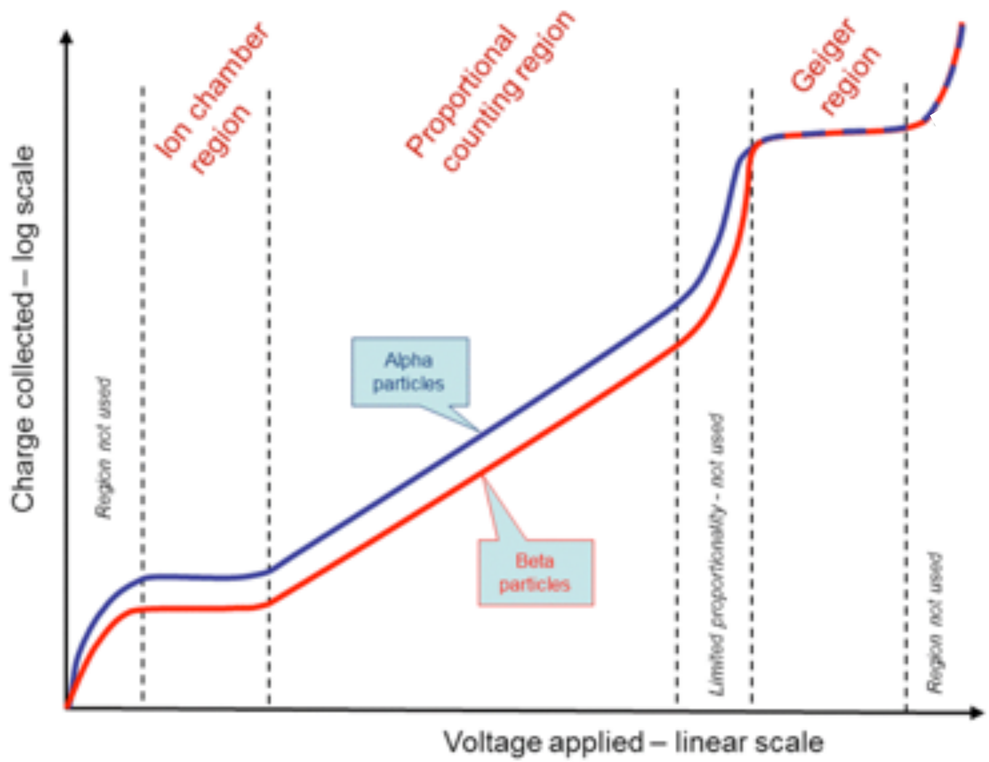
IV.a Gas-Detectors

Another Classic: Ionisation Chamber





Variation of ion pair charge with applied voltage

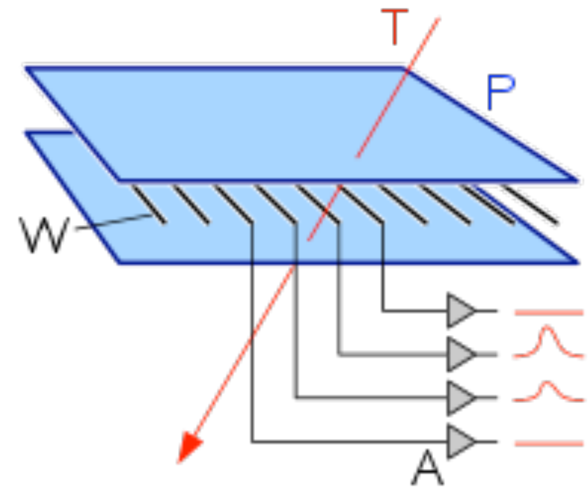


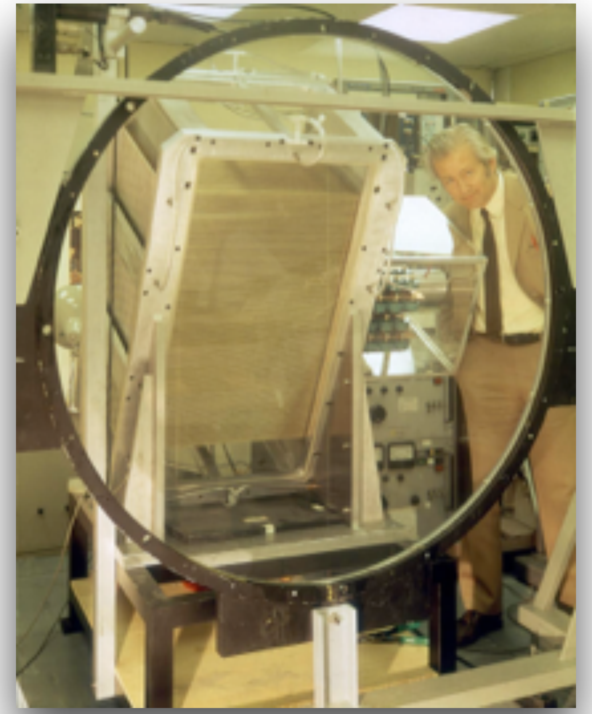
- Passage of particles creates within the gas volume electron-ion pair (ionisation)
- Electrons are accelerated in a strong electric field -> amplification
- The signal is proportional to the original deposited charge or is saturated (depending on the voltage)

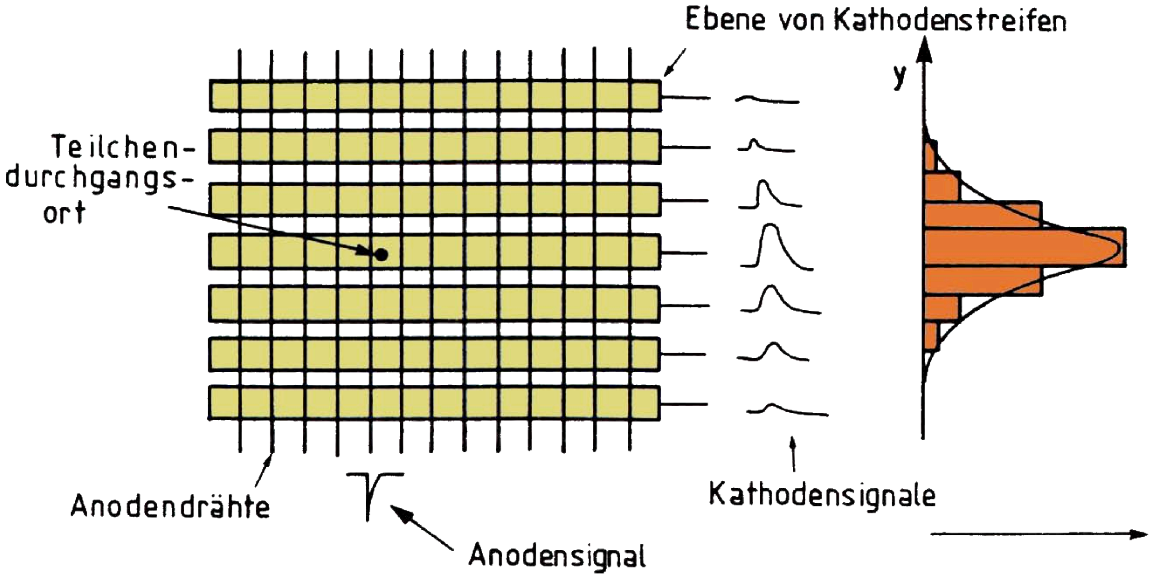
By Doug Sim - https://commons.wikimedia.org/w/index.php?curid=19789442

Continuation of Ionisation Chambers

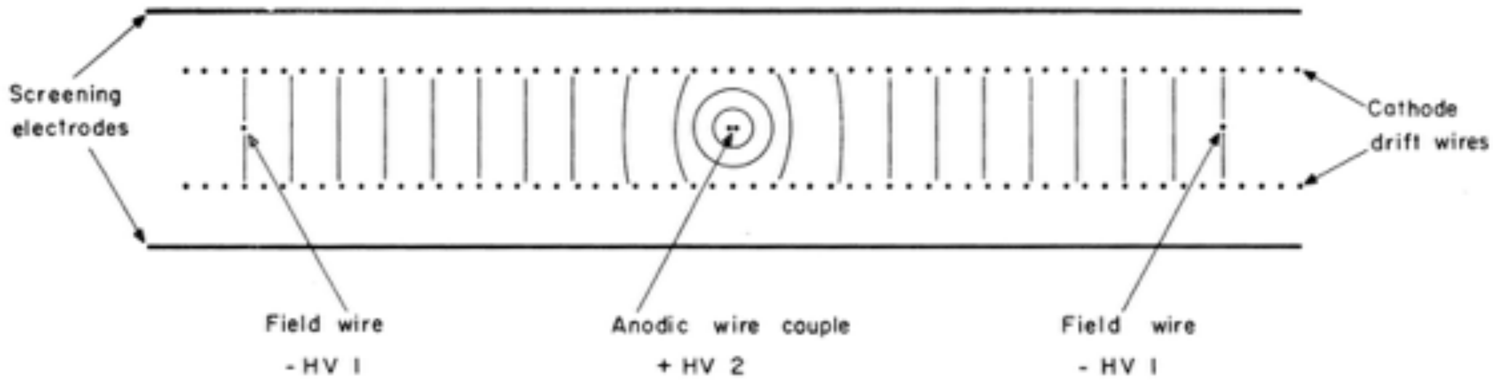
- Extreme successful approach to improve the spatial resolution of gas detectors
- Multi wire proportional chamber (MWPC)
- Gas-filled box with a large number of parallel detector wires, each connected to individual amplifiers
- G. Charpak 1968
  (Nobel-prize 1992)



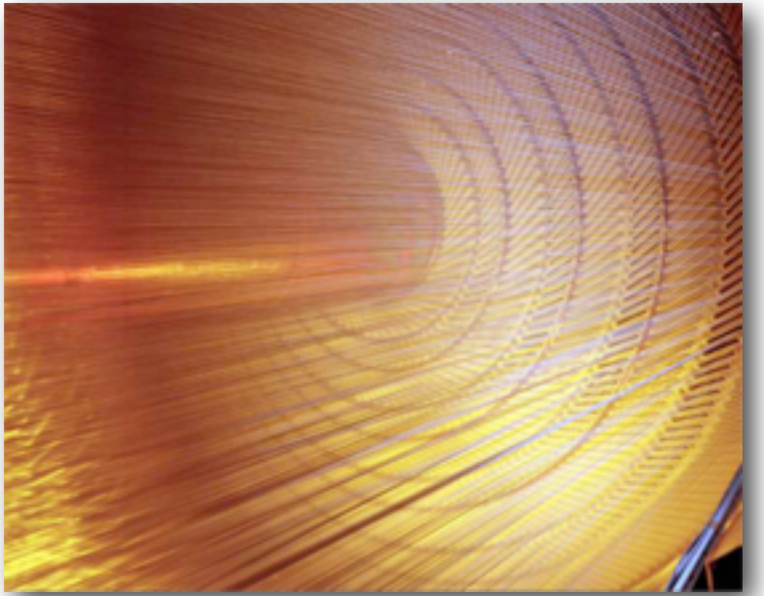




Adding the Time: Drift chamber

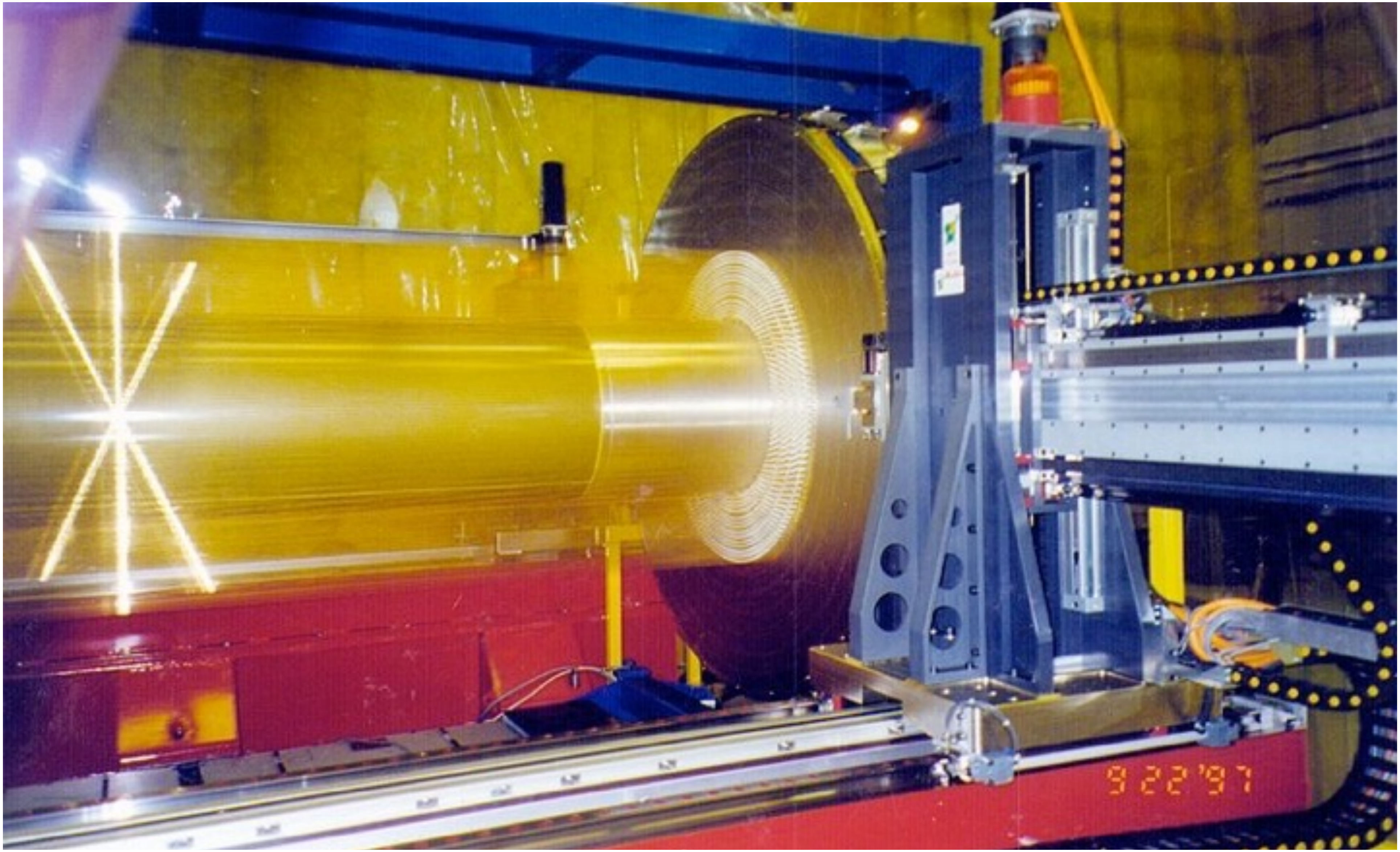


- Electric field is designed in a way that electrons drift with a constant velocity and only amplify very close to the wire
- If time of arrival of a particle is known (trigger), one can derive from the signal arrival time at the anode the position of the track
- Condition: the HV field distribution and therefore the drift velocity within the gas is well known

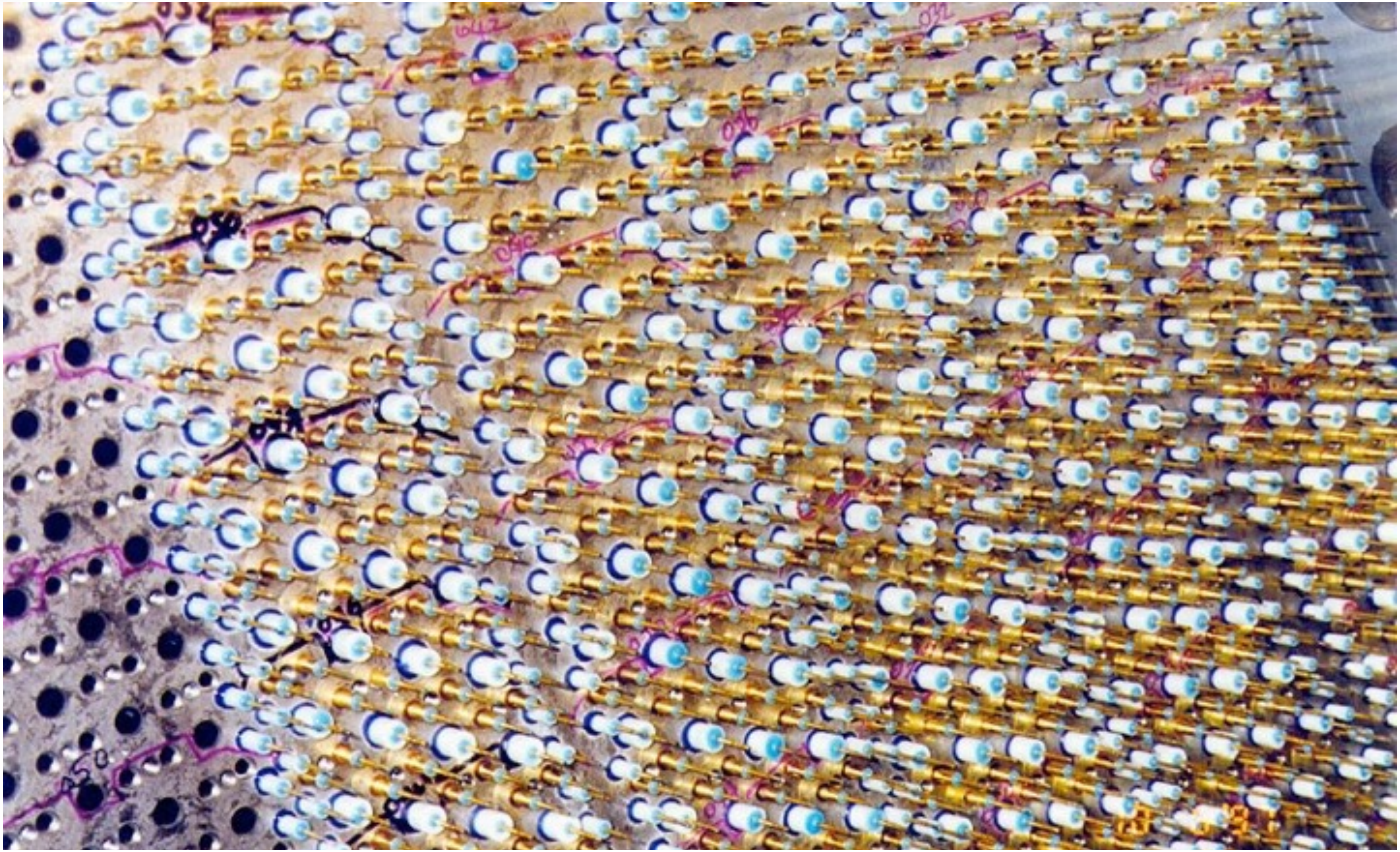


Wire chamber CDF (@Tevatron)

Wire Stringing In Progress

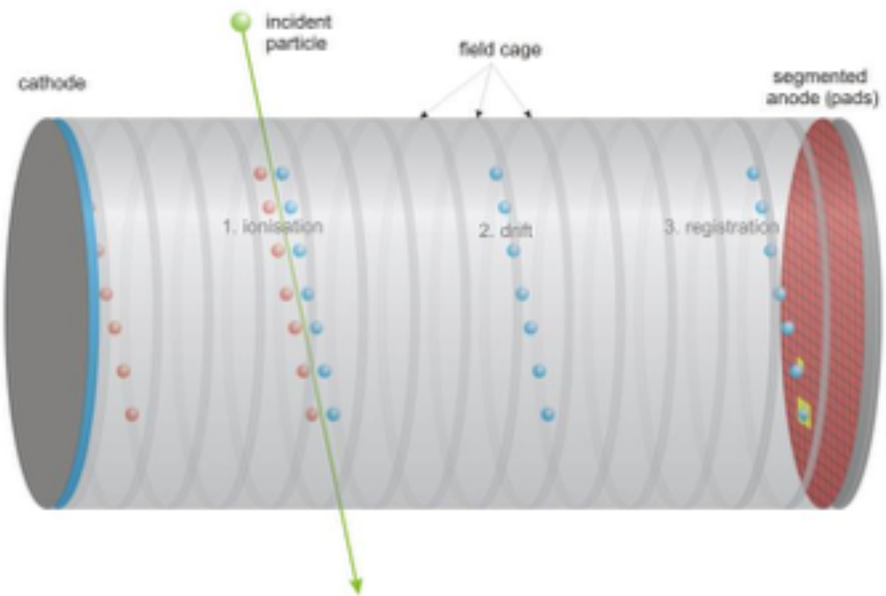


End Plate Close Up



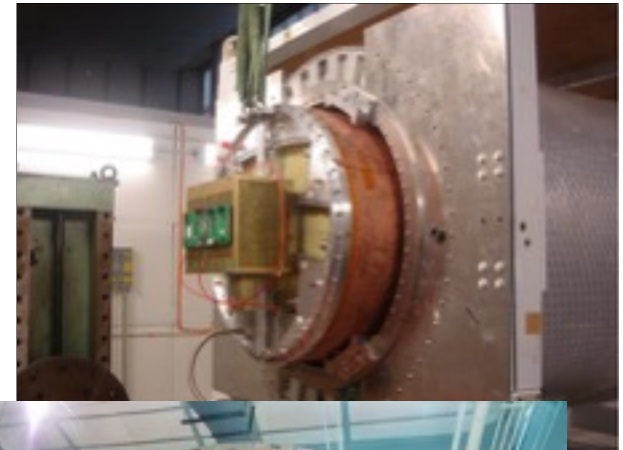
TPC- Time Projection Chamber: 3D

- Combination of the the 2D track information and the time results in a real 3D point

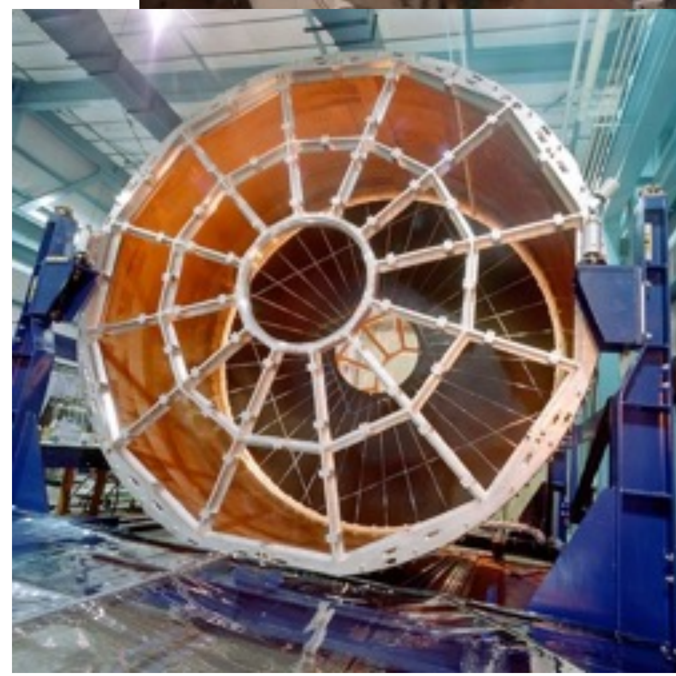


Pic: O. Schäfer

- Readout of the anode usually with multi wire projection chambers
- Nowadays new developments under way.



Pic: DESY



Pic: ALICE Collaboration

New Developments

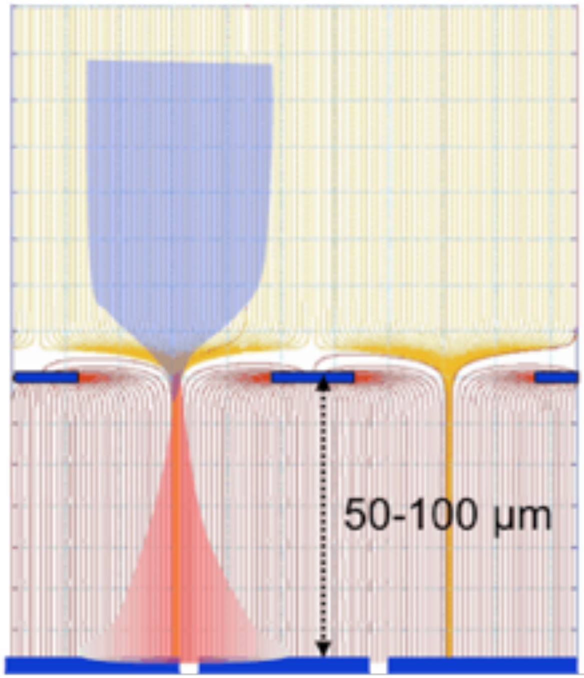
- Largely improved spacial resolution and higher particle rates:

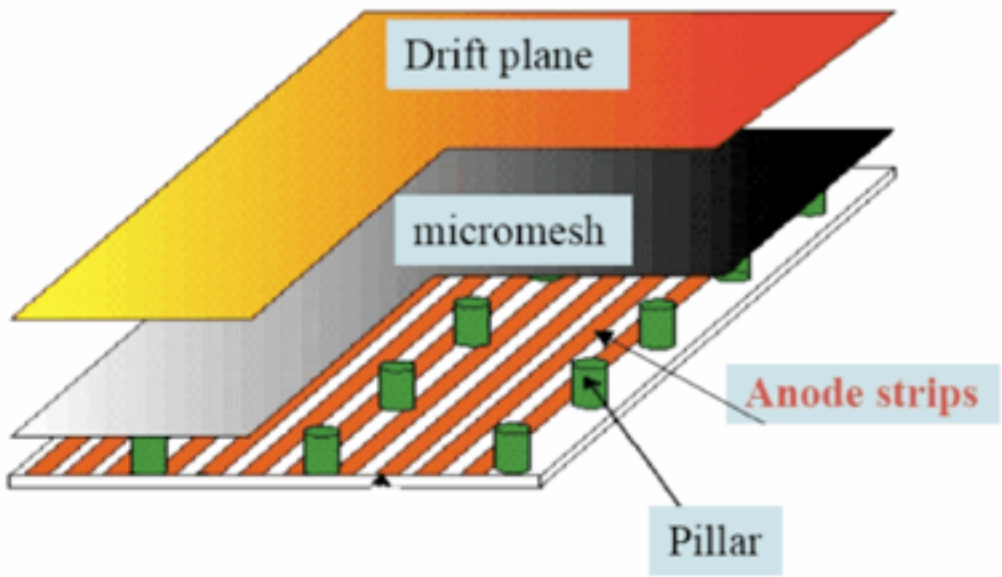
Micro-Pattern Gas Detectors

- a number of developments were started, some with a lot of problems
- two technologies are currently the most successful: GEMs and MicroMegas

- MicroMegas: Avalanche amplification in a small gap

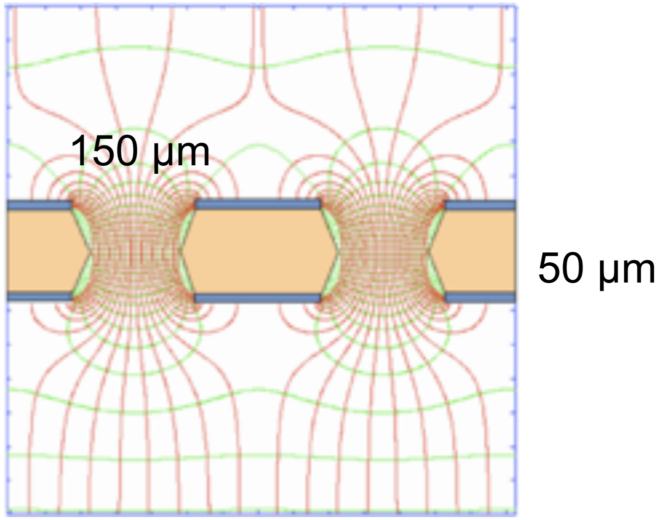
Y. Giomataris et al, NIM A376, 29(1996)

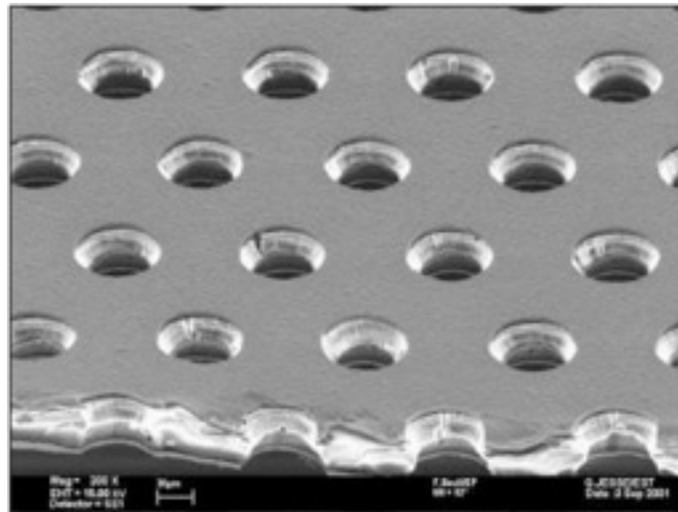


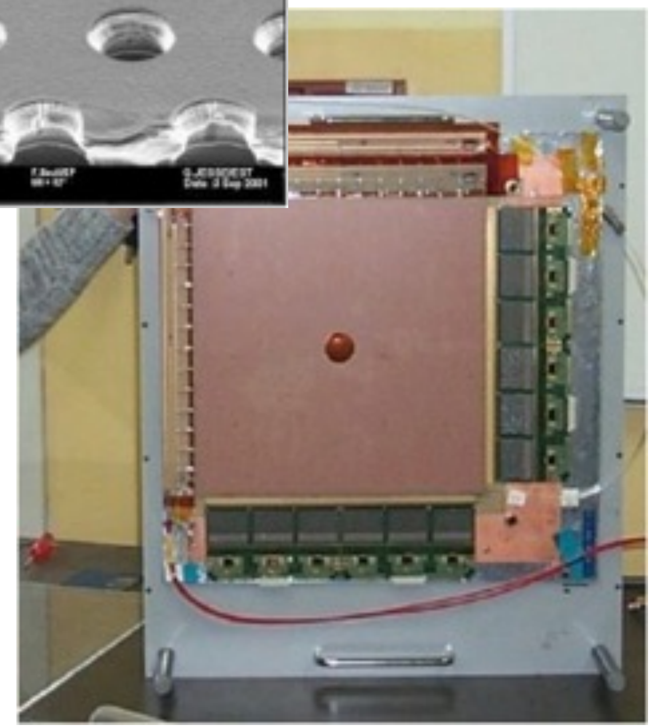


New Developments

- GEM: Gas Electron Multiplier: Gas amplification in small holes in a special foil







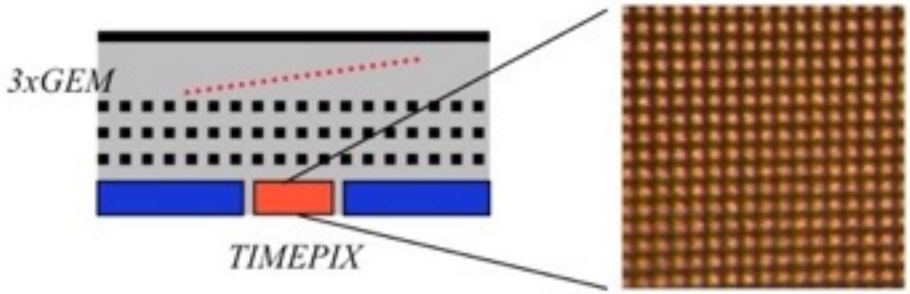
F. Sauli, NIM A386, 531(1997)

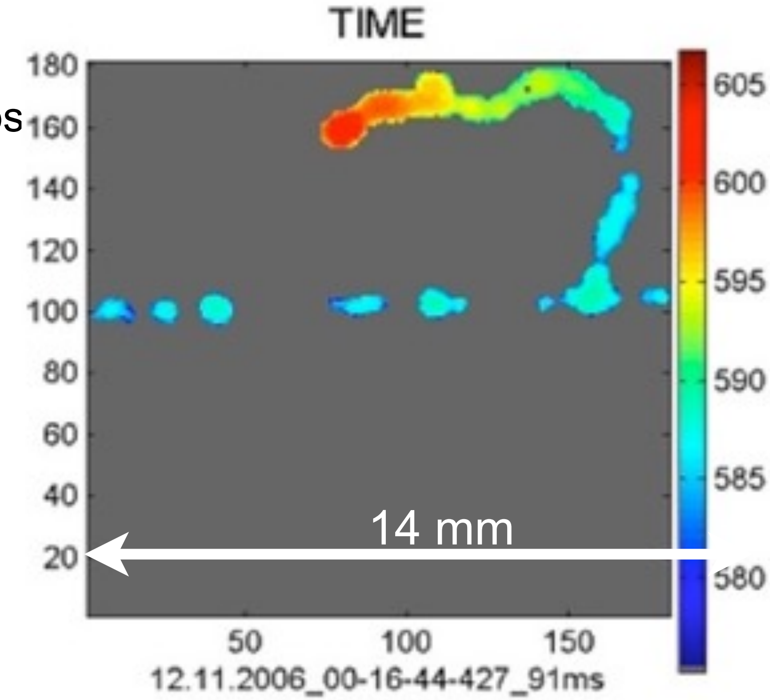
Charge collection on two separate levels: 2D structure possible: separation of amplification and read out

Both technologies, MicroMegas and GEMs are used in experiments. Typical spacial resolution: ~70 um

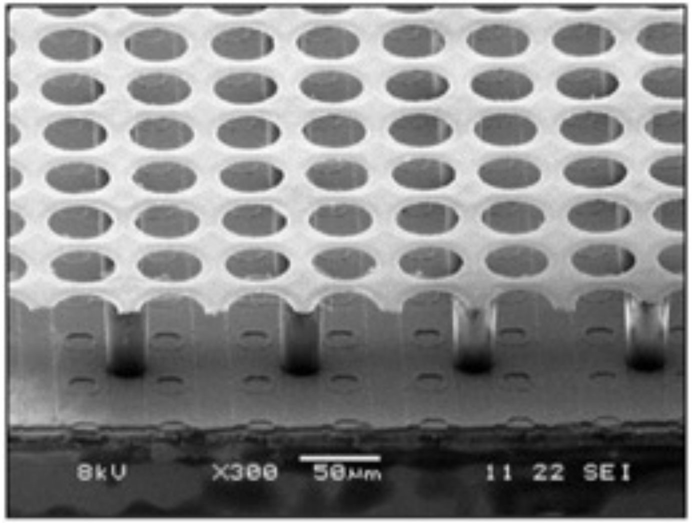
MPGDs as next generation detector

- Combination of gas detectors and Silicon
  - Integration of MPGDs with pixel read out chips





- Amplification and read out made of silicon



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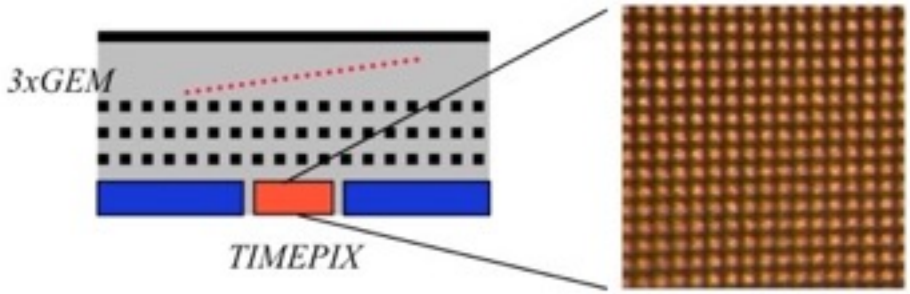

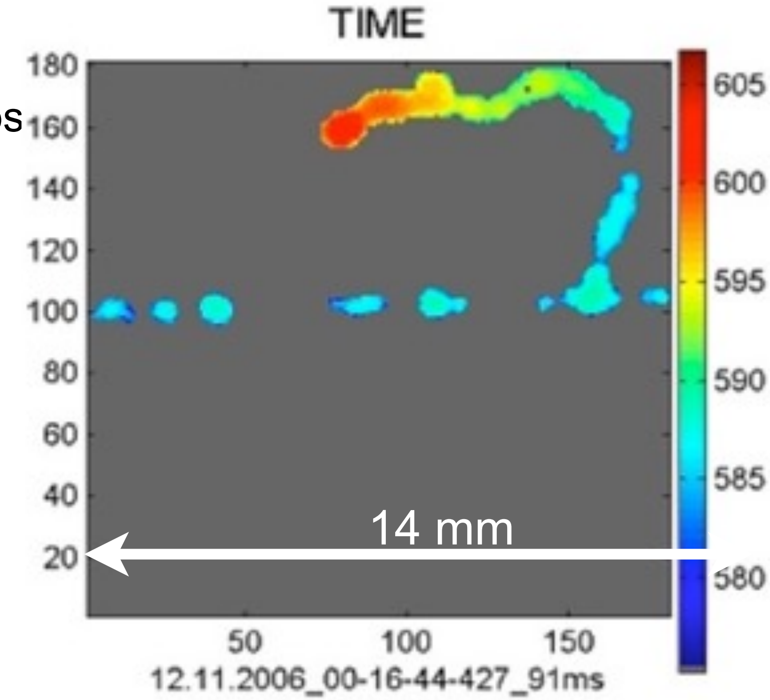

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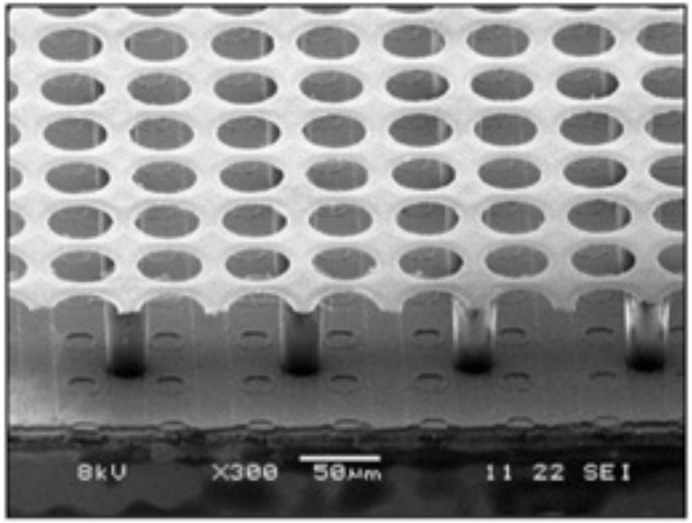
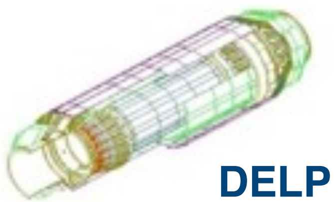


Advantages of gas detectors:
- Low radiation length
- Gas can be replaced regularly: Reduction of radiation damages!

V.b Semiconductor-Detectors

Large Silicon Systems

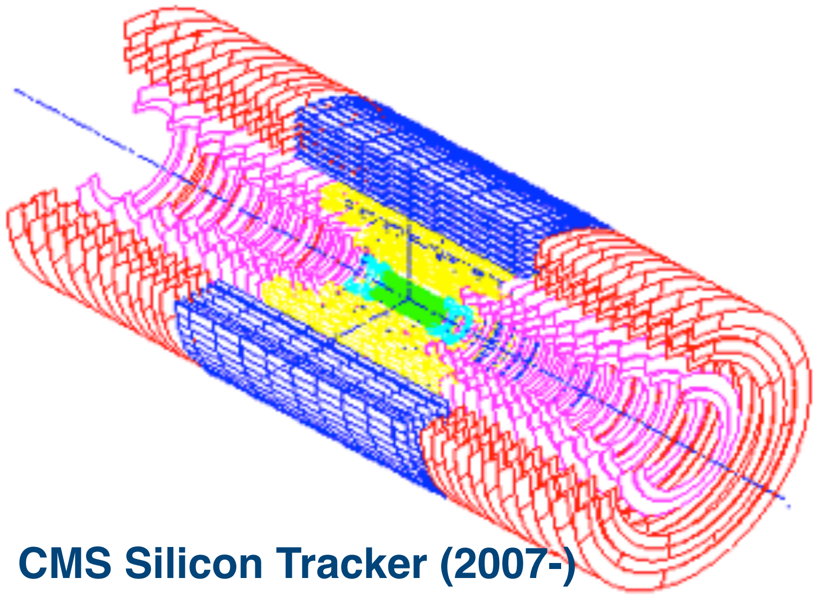
Since ~ 30 years: Semiconductor detectors for precise position measurements.



DELPHI (1996)

~ 1.8m² silicon area

~ 175 000 readout channels



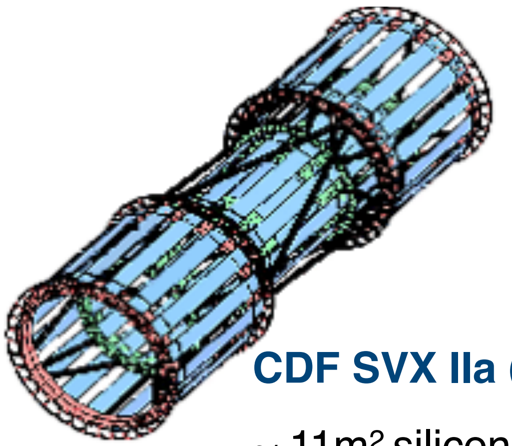
CMS Silicon Tracker (2007-)

~12,000 modules

~ 223 m² silicon area

~25,000 silicon wafers

~ 10M readout channels



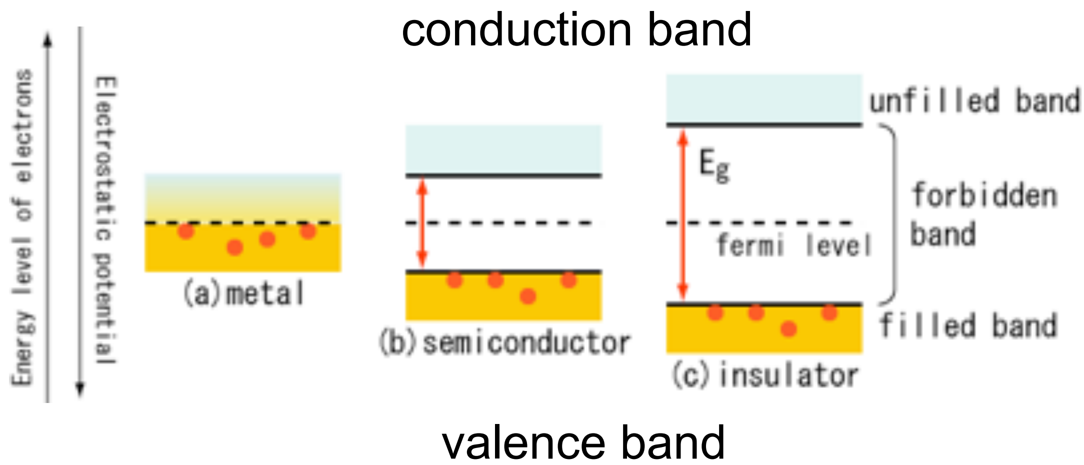
CDF SVX IIa (2001-2012)

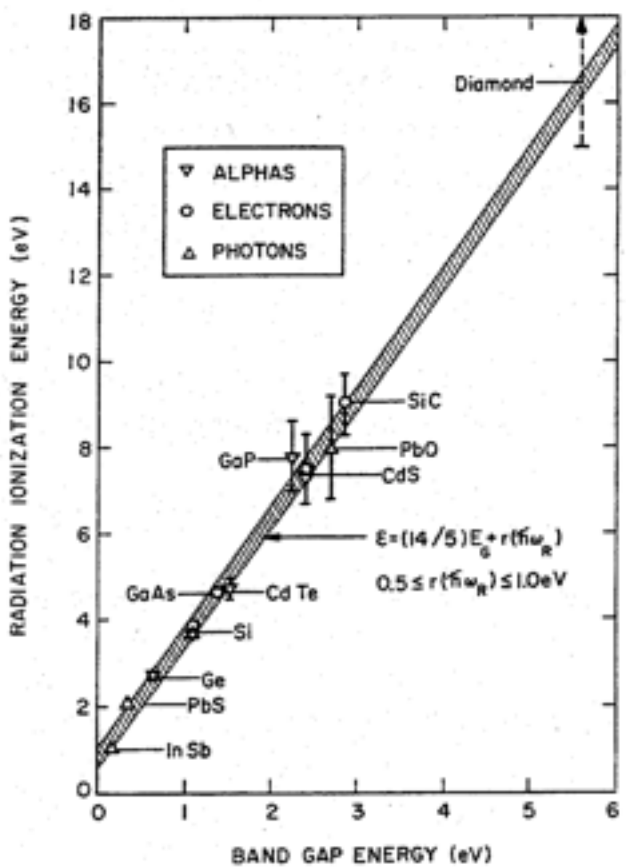
~ 11m² silicon area

~ 750 000 readout channels

Semiconductor Basics I

- In free atoms the electron energy levels are discrete.
- In a solid, energy levels split and form a nearly-continuous band.





C.A. Klein, J. Applied Physics 39 (1968) 2029

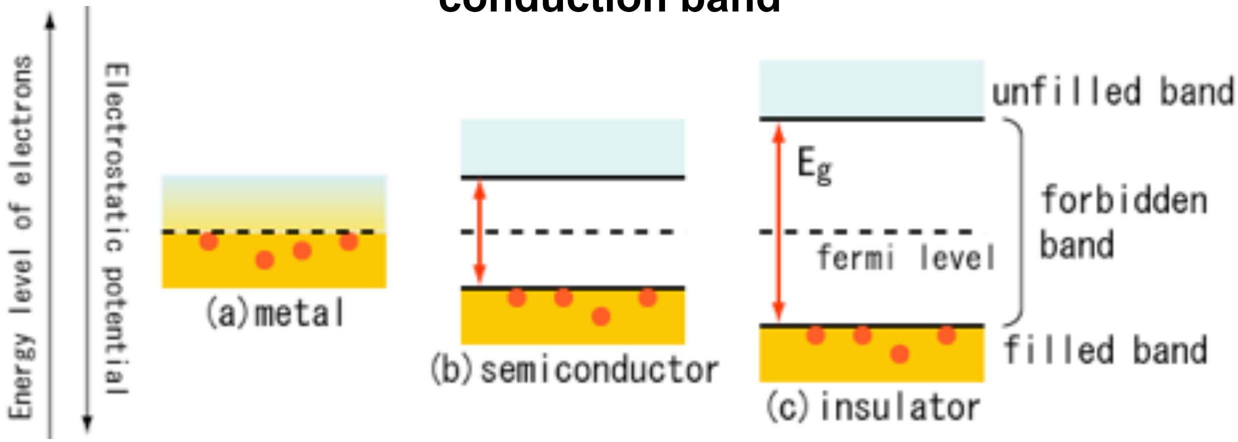
- Large gap: the solid is an insulator.
- No gap: it is a conductor.
- Small band gap: semiconductor

- For silicon, the band gap is 1.1 eV, but it takes 3.6 eV to ionize an atom -> rest of the energy goes to phonon excitations (heat).

Semiconductor Basics

- In free atoms electron energy levels are discrete.
- In a solid, energy levels split and form a nearly-continuous band.

conduction band



valence band

300µm

- Large gap: the solid is an insulator.
- No gap: it is a conductor.
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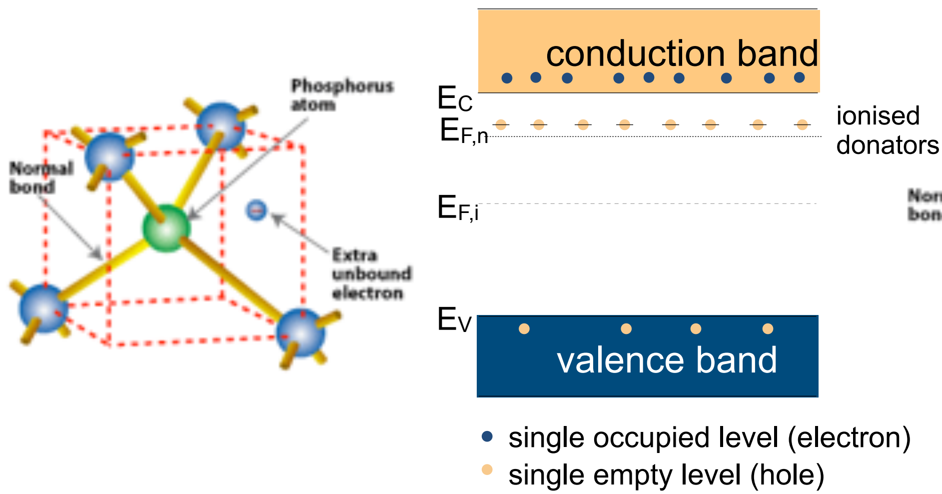
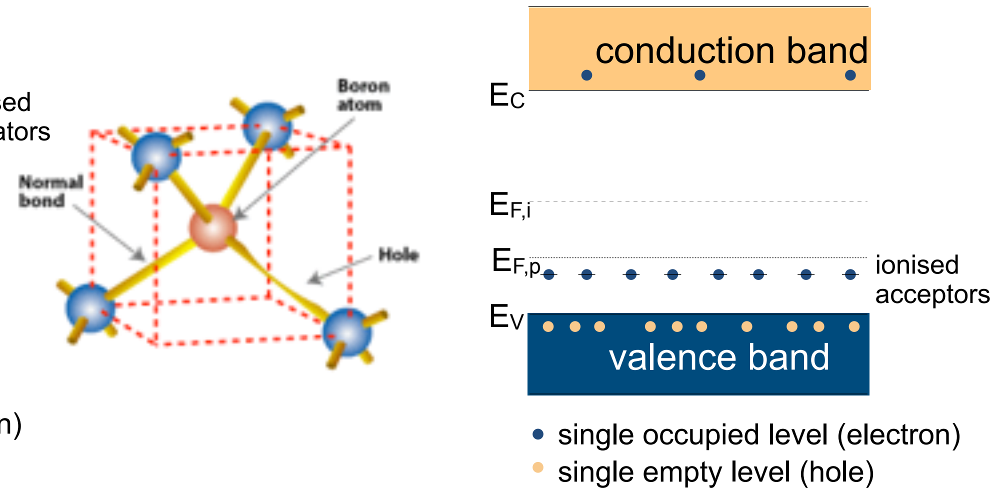
Signal of charged particle:
~3 x 10^4 electron/hole pairs
Intrinsic charge carrier
~4 x 10^8 electron/hole pairs

- For silicon, the band gap is 1.1 eV, but it takes 3.6 eV to ionise an atom
  - Remaining energy goes to phonon excitations (heat).

Doping Silicon





n type semiconductor:

- **N**egative charge carriers (electrons) by adding impurities of donor ions (e.g. Phosphorus (type V))
- **Donors** introduce energy levels close to conduction band thus almost fully ionised (E_F closest to CB)

Electrons are the majority carriers.

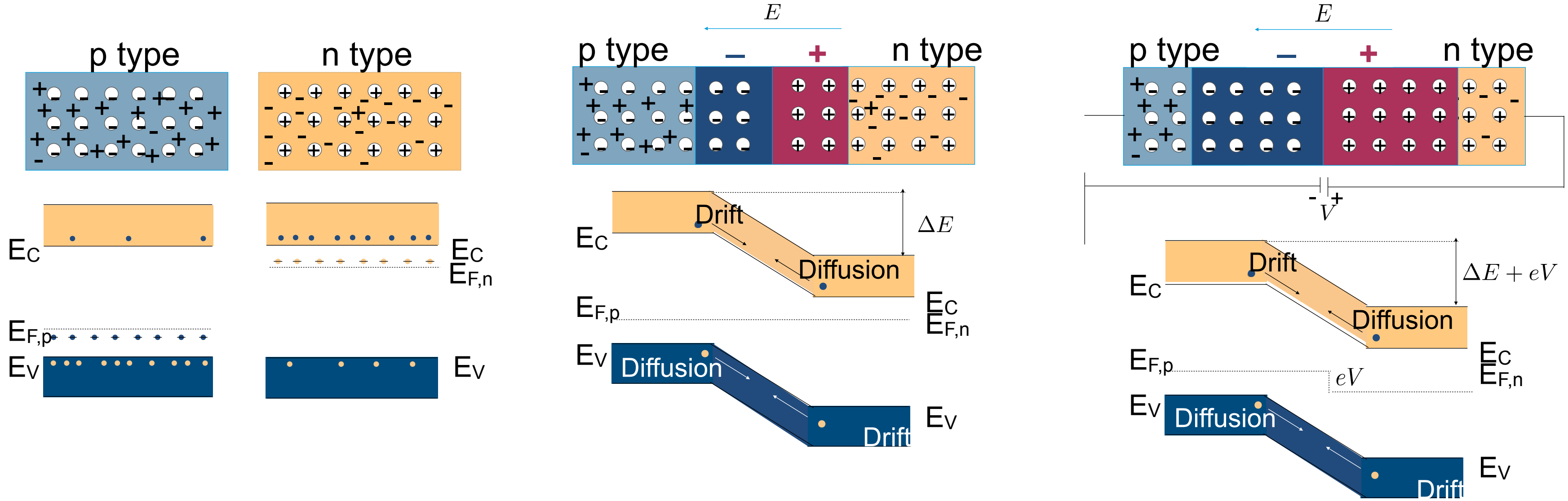
p type semiconductor:

- Positive charge carriers (holes) by adding impurities of acceptor ions (e.g. Boron (type III)).
- Acceptors introduce energy levels close to valence band thus ‘absorb’ electrons from VB, creating holes (E_F closest to VB).

Holes are the majority carriers.

Basis of Silicon Detector: PN Junction

- At interface of p type and n type semiconductor difference in the Fermi levels causes diffusion of excessive carriers to the other material until thermal equilibrium is reached.
- Stable space charge region free of charge carriers is called **depletion zone**.
- Typical current-voltage of a p-n junction: exponential current increase in forward bias, small saturation in reverse bias.



Applying an external voltage V with the cathode to p and the anode to n (reverse biasing), e-h pairs are pulled out of the depletion zone. ➔ **larger depletion zone** ➔ suppress current across the junction

pn-junction with reverse bias

Principle of Semiconductor

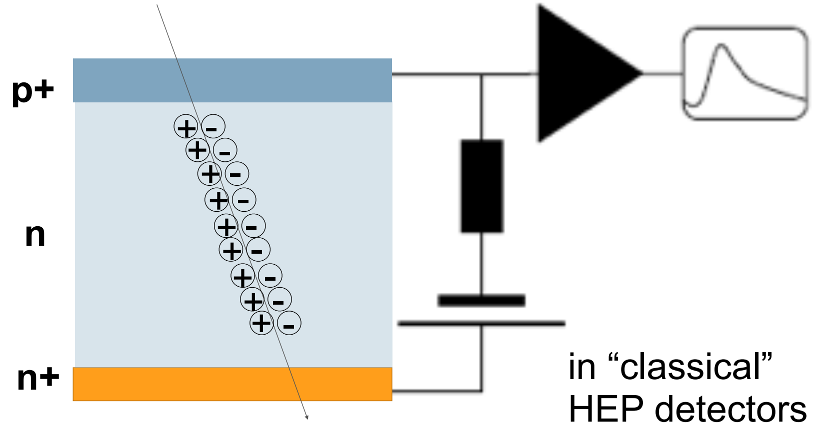
- Creation of electric field: voltage to deplete thickness d

with $n_A >> n_D$ $$d = \sqrt{\frac{2\epsilon\epsilon_0 V_{dep}}{e n_D}}$$

for $d = 300\mu m$ $V_{dep} \approx 160V$

- Passage of a charged particle: Electron-hole pairs
formed in the depletion zone
  - Drift under the influence of the electric field
  - Signal depends on width of depletion zone

> The signal is induced by the motion of charge after incident radiation (not when the charge reaches the electrodes).



Typical numbers

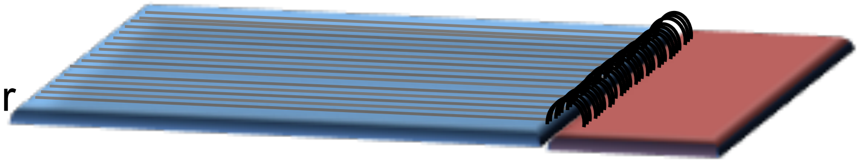
Doping concentration

$n_A \approx 10^{19} cm^{-3}$ Acceptors

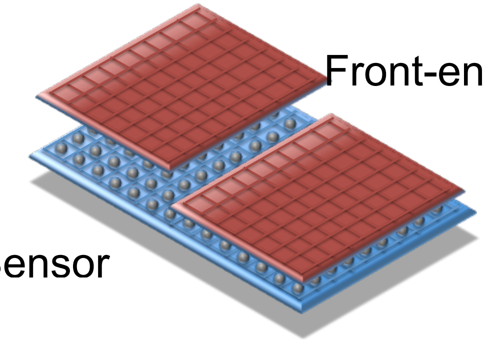
$n_D \approx 2 \cdot 10^{12} cm^{-3}$ Donators

Strips and Pixels

- **Strips detector:** charge sensed by long narrow strips
  1D information (typically 20 - 100µm)
  - 2D information by double sided processing or adding back to back second layer slightly rotated (stereo angle)
- In regions with higher track density one dimensional measurements can lead to ambiguities.
- **Pixel detector:** charge sensed by small pixels on one side of sensor
  - Hybrid pixels: sensors and readout joined via bump bonds
  - Monolithic pixels: sensor and readout on one substrate



Microstrips detector



Hybrid pixel detector

Strips and Pixels

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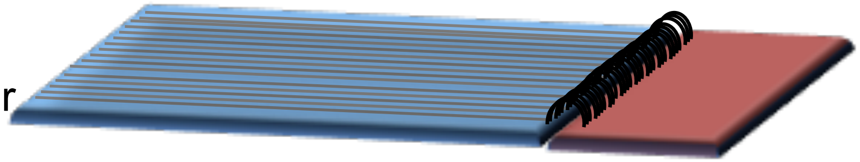

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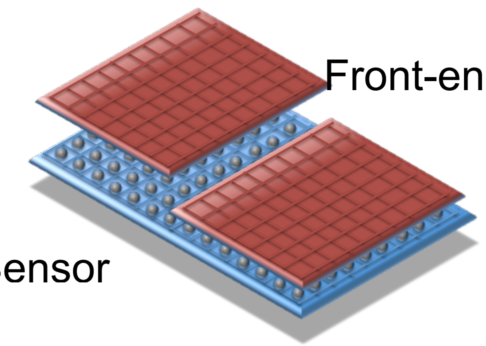


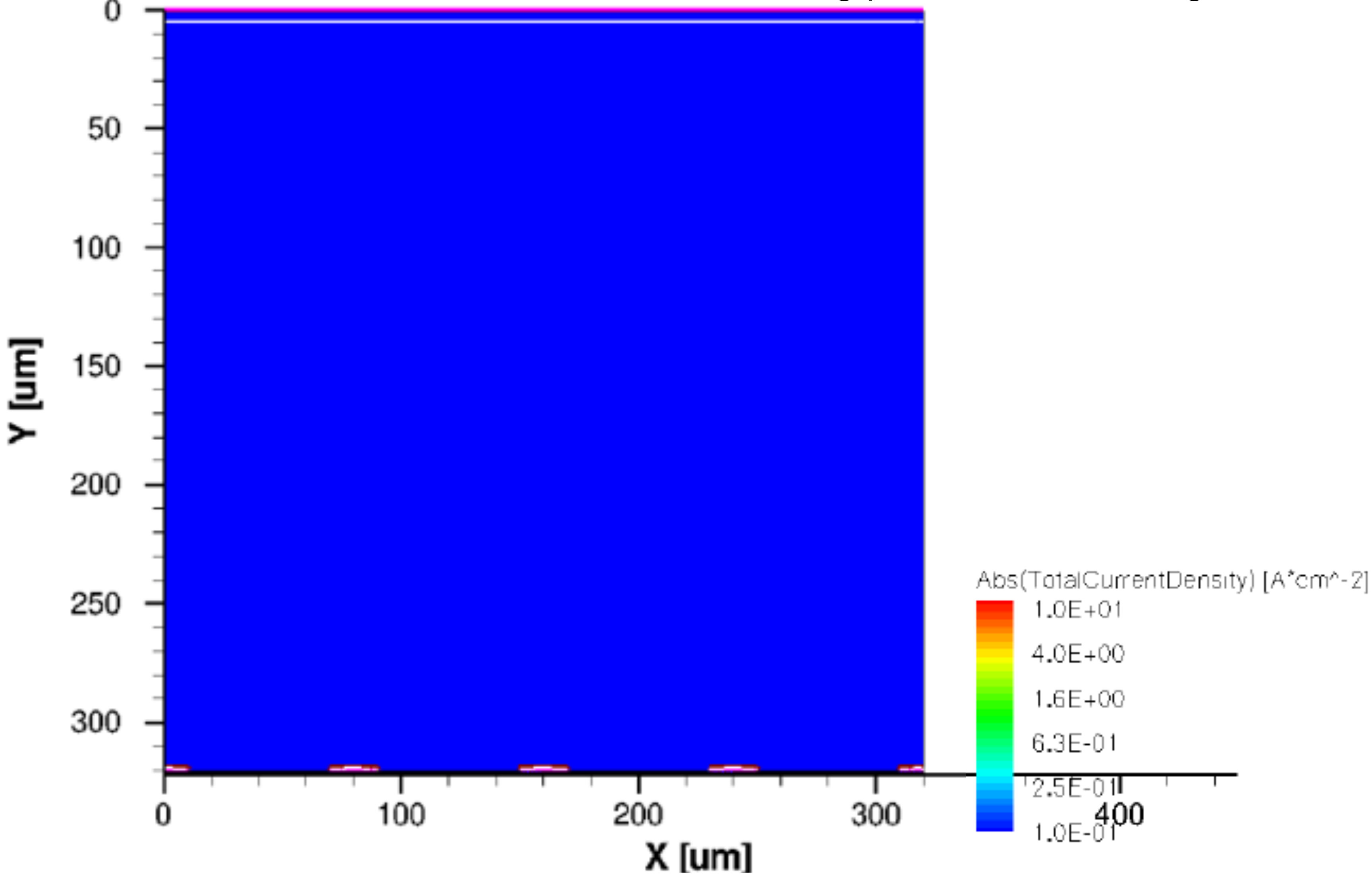
Hybrid pixel detector

Signal creation → Signal processing

- Signals created in silicon by charged particle
  - Very small signals (fC): need amplification
  - Measurement of amplitude/hit and/or time
  - Several thousands to millions of channels

Current Density

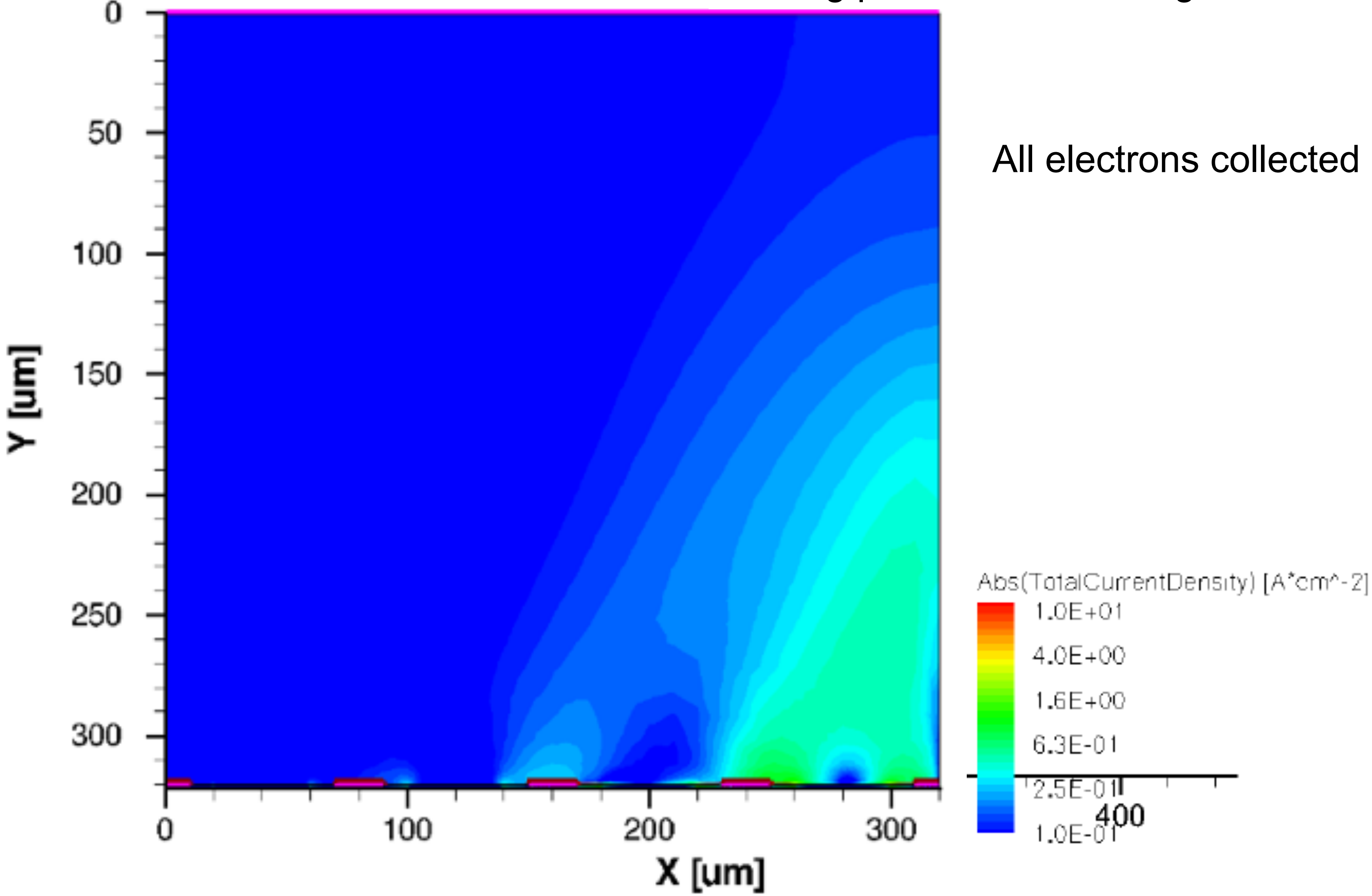
Ionizing particle with 45° angle t=0ns



Simulation: Thomas Eichhorn

Current Density

Ionizing particle with 45° angle t=7ns



All electrons collected

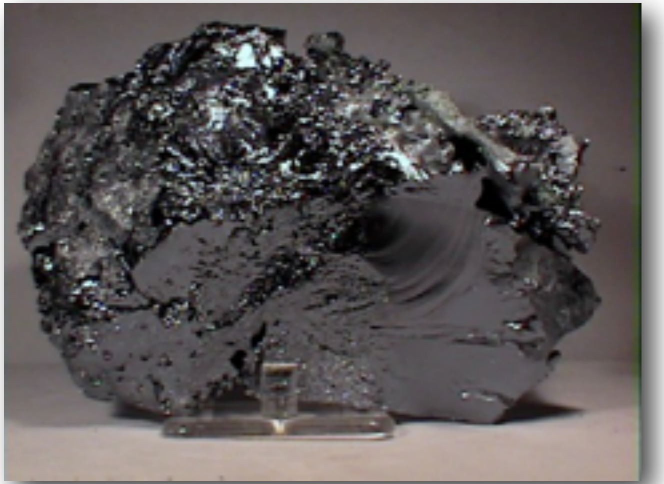
Simulation: Thomas Eichhorn

Material Properties

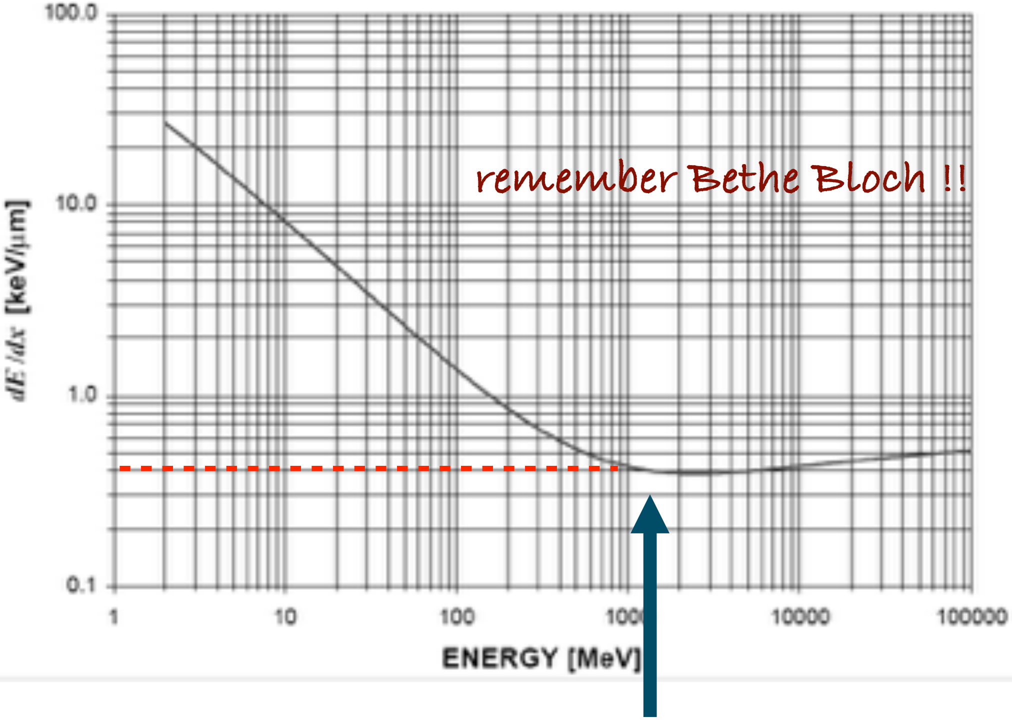
	Si	Ge	GaAs	CdTe	Diamond	SiC
band gap	1.12	0.67	1.42	1.56	5.48	2.99
energy for e-p pair [eV]	3.6	2.9	4.2	4.7	13.1	6.9
e- for MIP (300µm)	24000	50000	35000	35000	9300	19000
Z	14	32	31+33	48+52	6	14+6

Why is silicon used more often ?

- Silicon is the only material which can be produced in larger areas in high quality
- compare to kT = 0.026 eV at room temperature -> dark current under control
- high density compared to gases: $\rho = 2.33 g/cm^3$
- good mechanical stability -> possible to produce mechanically stable layers
- large charge carrier mobility
- fast charge collection $\delta t \sim 10ns$
- well understood -> radiation tolerant



Protons in Silicon



remember Bethe Bloch !!

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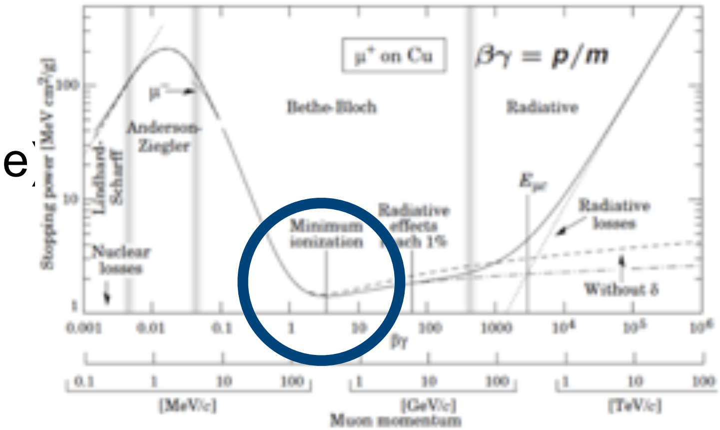
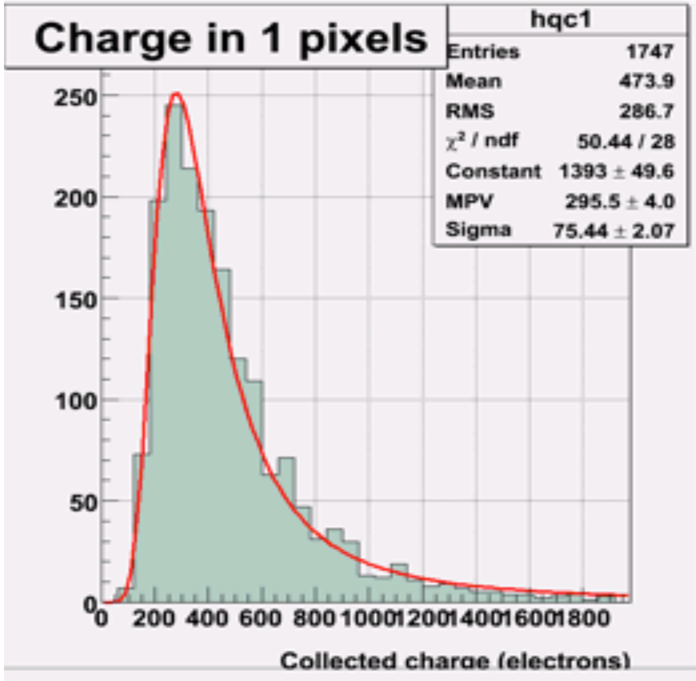
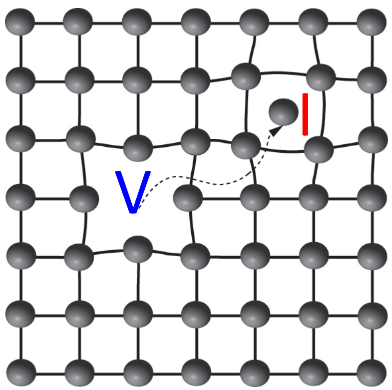




Problem: Radiation Damage

- Radiation damage the silicon on atomic level significantly leading to macroscopic effect.
- **Bulk effects:** displacement damage and built up of crystal defects due to Non Ionising Energy Loss (NIEL) **(main problem for sensors).**

  unit: 1MeV equivalent n/cm^2 (up to 10^{15} n_{eq}/cm^2)



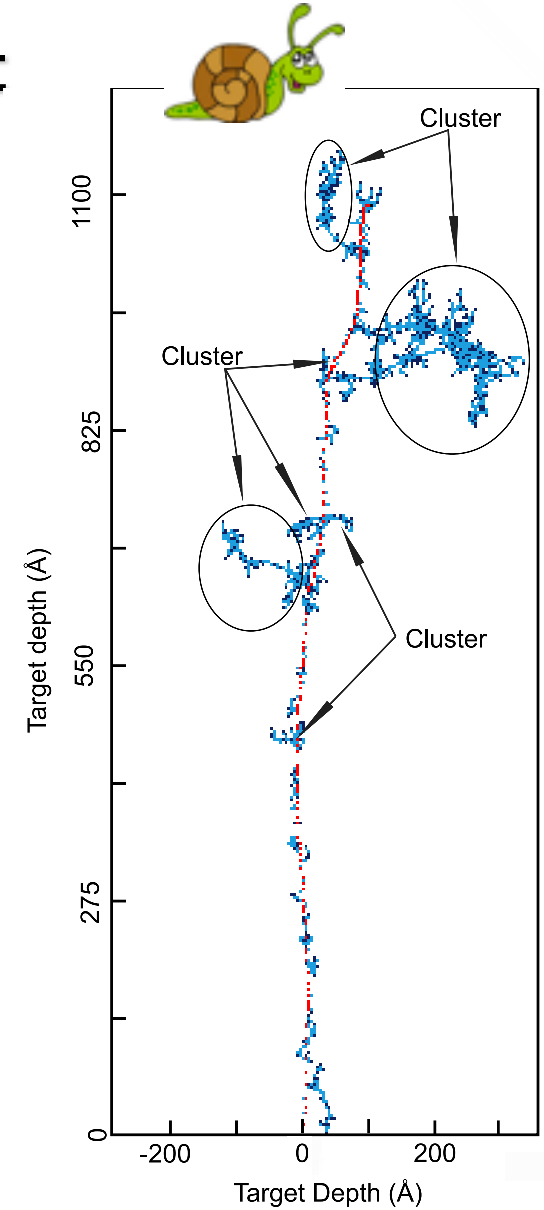
Defects composed of:
Vacancies and **I**nterstitials

Compound defects with impurities possible!

- **Surface effects:** Generation of charge traps due to ionizing energy loss (Total ionising dose, TID)

  (main problem for electronics).

  unit: Rad (up to 100 MRad)

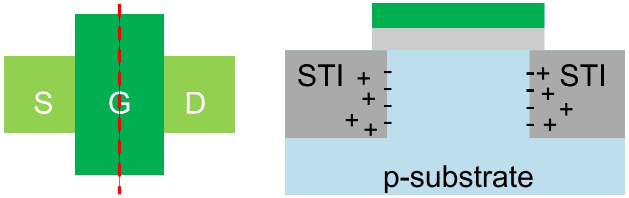


Simulation of 50 keV PKA damage cascade (1 MeV n)

Problem: Radiation Damage

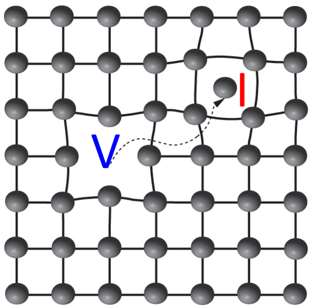
- Radiation damages the silicon on atomic level significantly leading to macroscopic effects.

- **Surface effects:** Generation of charge traps due to ionising energy loss — Total ionising dose, TID **(problem for sensors and readout electronics).**
  - Cumulative long term trapping of positive charge
  - Increase of leakage current and oxide breakdown



STI = shallow trench interface

- **Bulk effects:** displacement damage and build up of crystal defects due to non ionising energy loss (NIEL) **(main problem for sensors).**
  - Unit: 1MeV equivalent n/cm^2



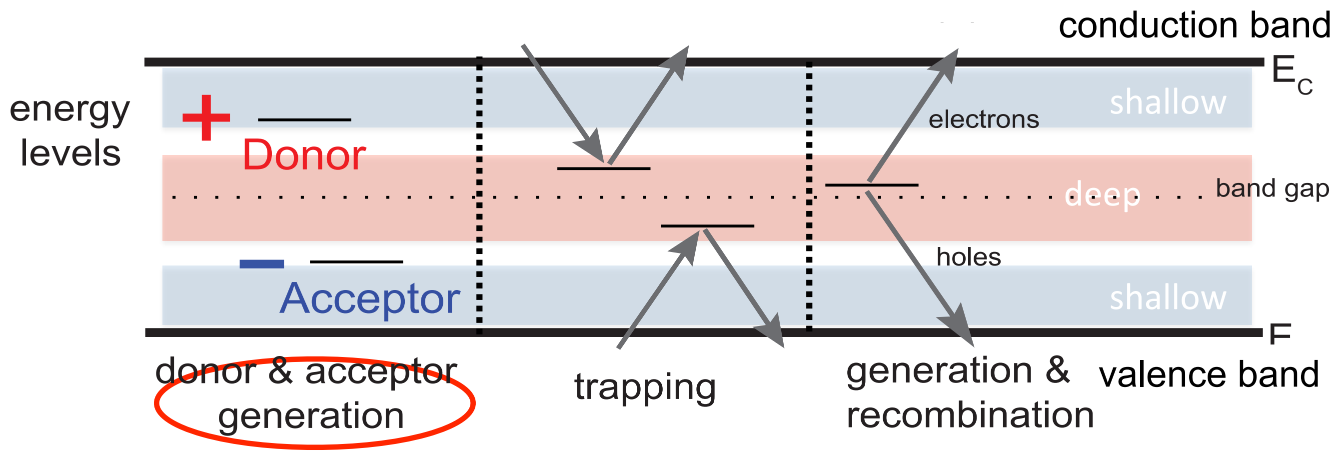
Defects composed of:
Vacancies and Interstitials

Compound defects with impurities possible!

Detector	NIEL [1MeV n_{eq}/cm^2]	TID [Mrad]
ALICE ITS	10^{13}	<1
Belle II (per year)	1.2×10^{13}	1.9
ATLAS/CMS Outer Tracker	10^{15}	<100
ATLAS/CMS Inner Tracker	10^{16}	1000

Radiation Damage: Macroscopic Effects

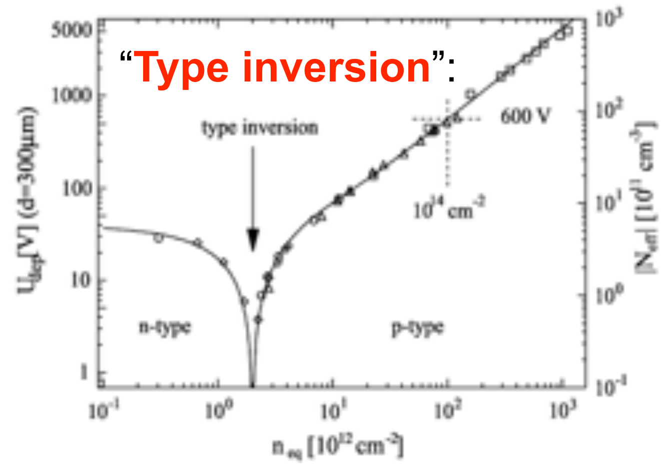
- Impact of defects on detector properties depends on defect level in band gap



Donor&acceptor generation:
Change of effective doping concentration (N_{eff})

$$V_{dep} = d^2 N_{eff} \frac{q}{e\epsilon\epsilon_0}$$

- Increase of depletion voltage
- Under-depleted operation



M. Moll, PhD thesis, Uni Hamburg 1999

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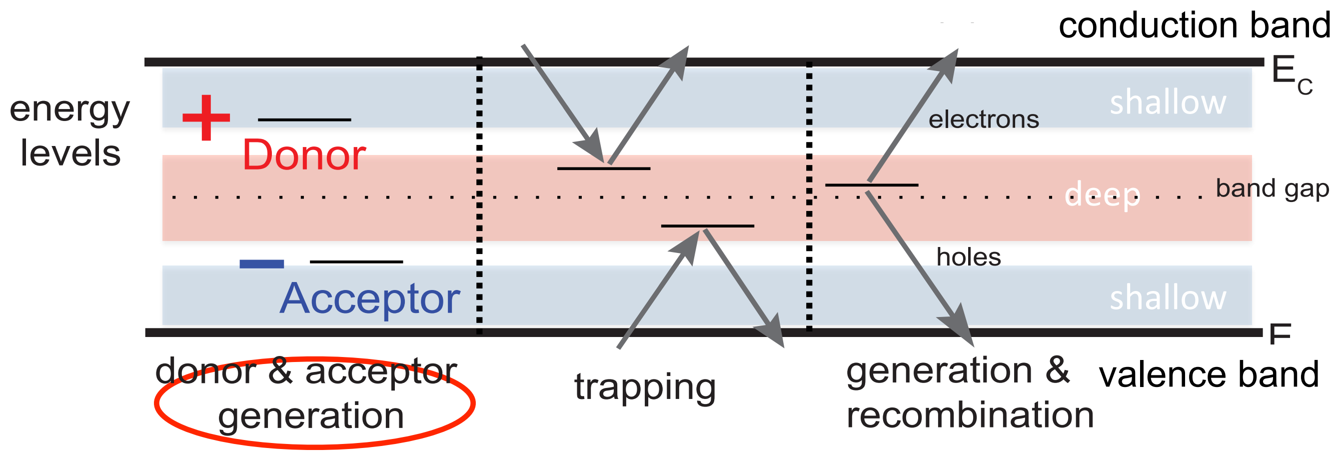

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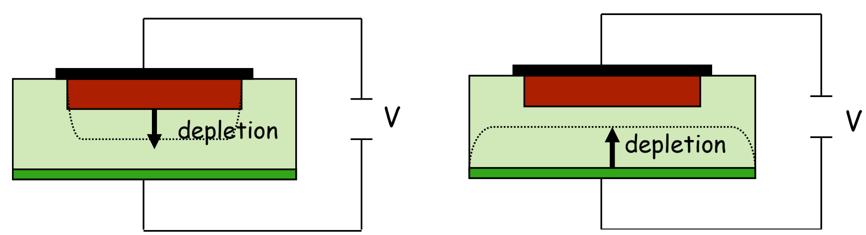
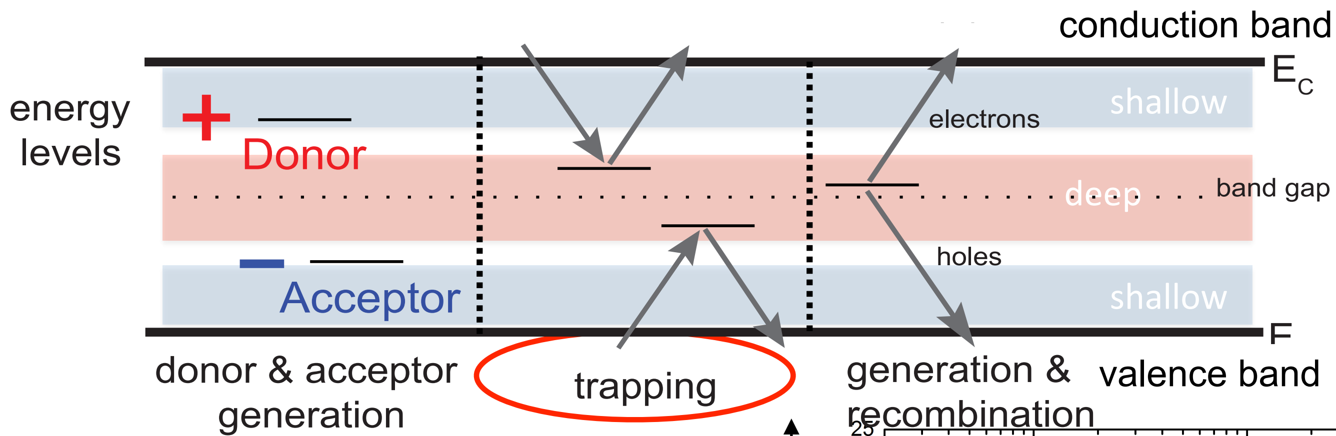


Before type inversion **After type inversion**

M. Moll, PhD thesis, Uni Hamburg 1999

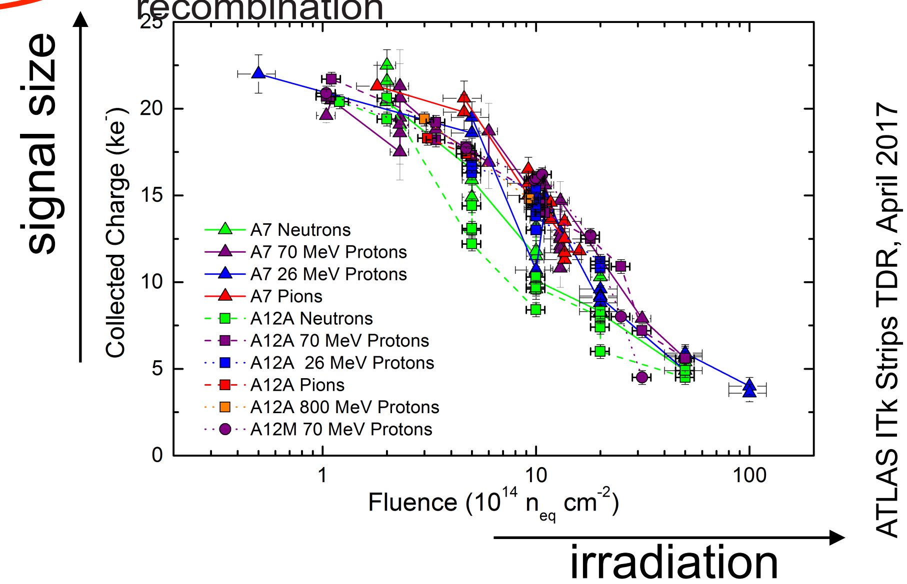
RADIATION DAMAGE: MACROSCOPIC EFFECTS

- Impact of defects on detector properties depends on defect level in band gap



Increased charge trapping

Lower signal (less charge)
Reduced charge collection efficiency



Radiation Damage: Macroscopic Effects

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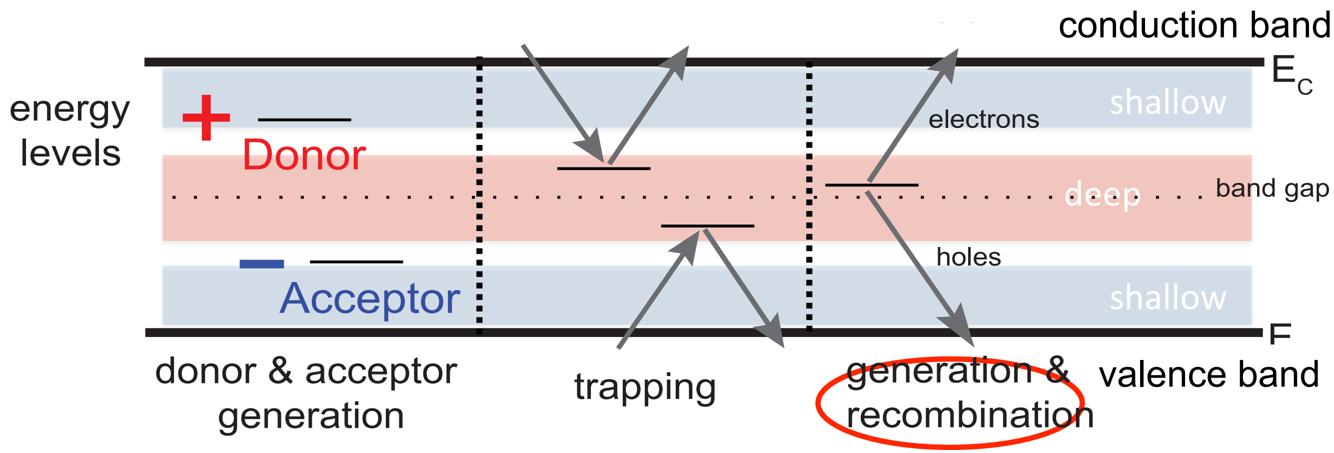
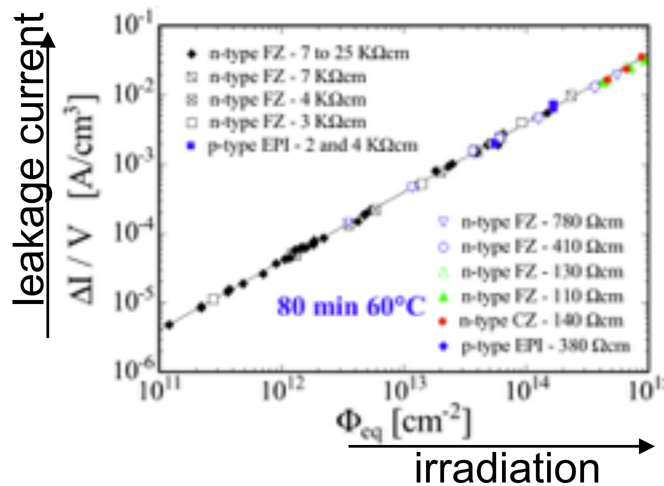


Increase of leakage current
higher shot noise; thermal runaway
→ Cooling during operation helps
(leakage current depends on T)

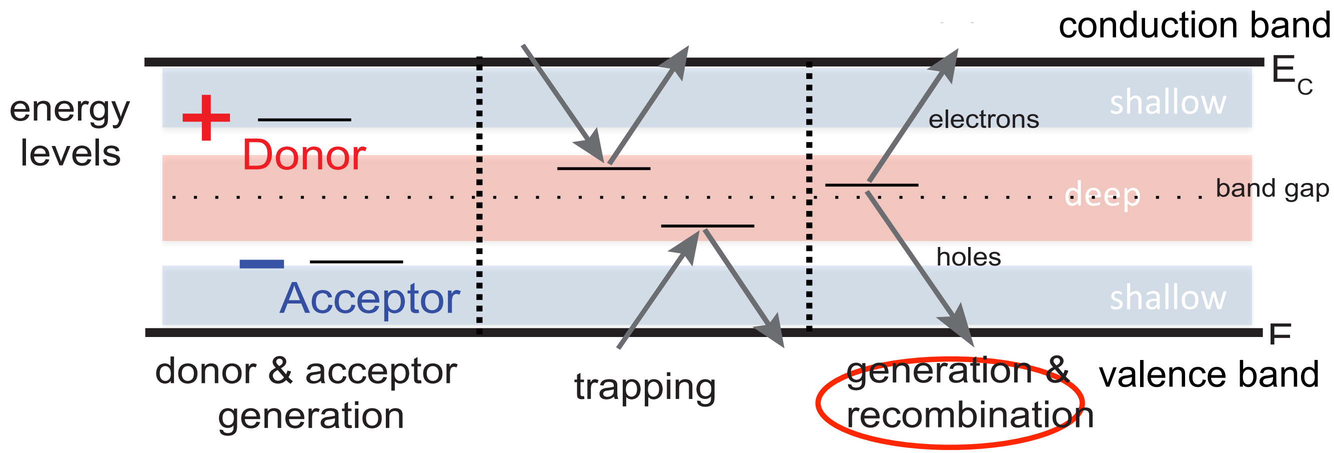


$$\alpha = \frac{\Delta I}{V \Phi_e}$$

α is constant over several orders of fluence and independent of

Radiation Damage: Macroscopic Effects

- Impact of defects on detector properties depends on defect level in band gap



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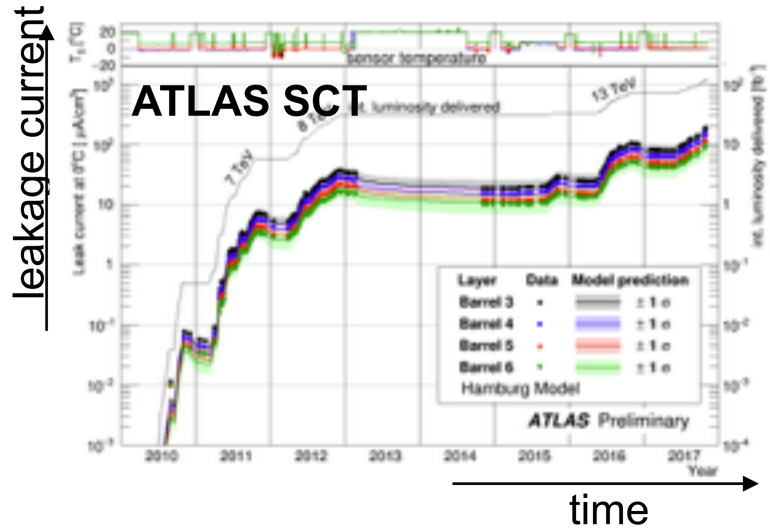
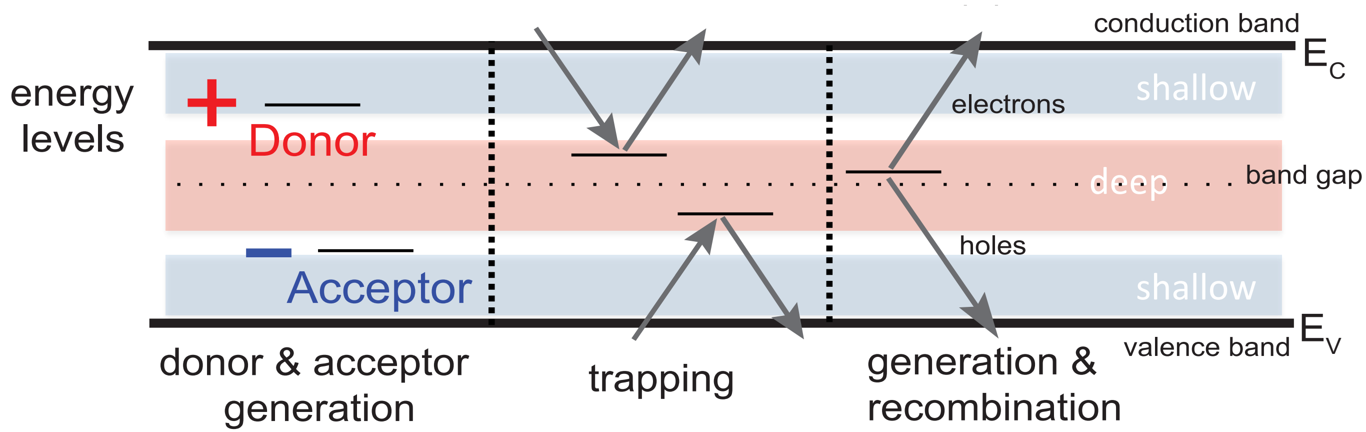


Radiation Damage: Bulk Defects

- Impact of defects on detector properties depends on defect level in band gap



Change of effective doping concentration (N_{eff})

Can contribute to space charge:
- increase of depletion voltage
- under-depleted operation

Increased charge trapping

Loss of signal (reduced charge collection efficiency)

Increase of leakage current
higher shot noise
thermal runaway

Coffee Break ??