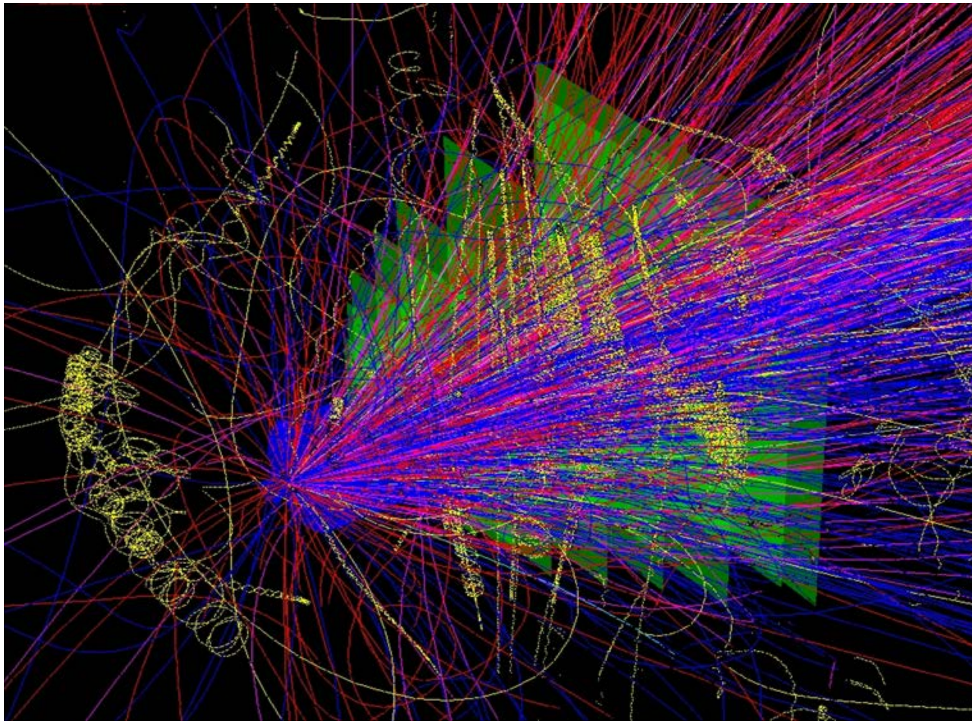
FAIR Facility for Antiproton and Ion Research

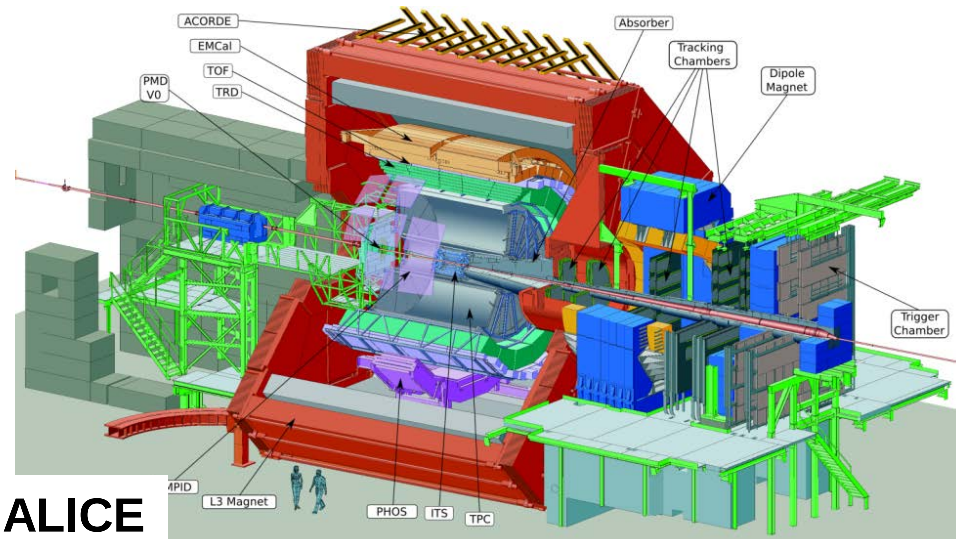
GSI

Lecture on Particle Detectors and Electronic Readout

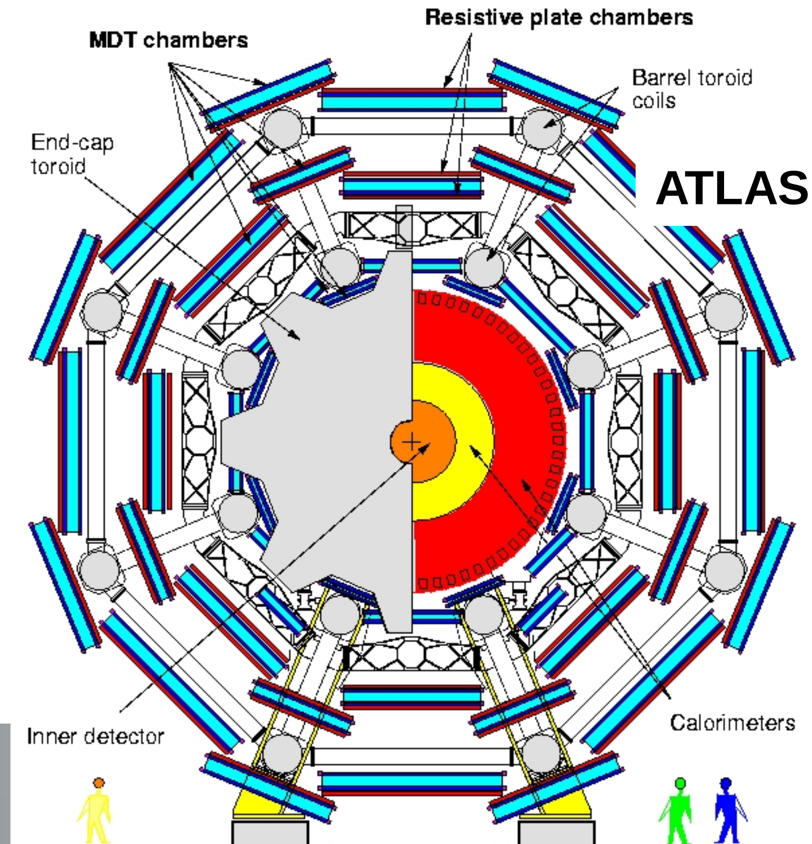


5th International FAIR School
Riva del Sole
Castiglione della Pescaia
Sept. 4 – 10, 2017

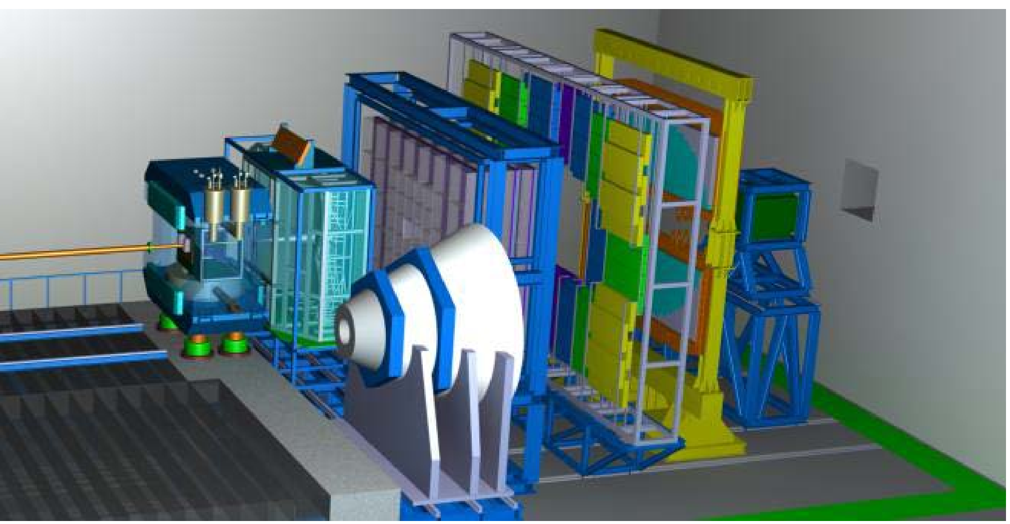
Christian J. Schmidt,
GSI Darmstadt



ALICE



ATLAS



CBM@FAIR

Very Large Structures

→ **Engineering**
→ **Electronics**
→ **Services, Cooling**

Finally → Resolution limits are still defined by the fundamental detector physics processes …

Plan

- Ionization Detectors
- Charged particle tracks, interaction and energy loss
- Electronic detection and the detection process
- Signal formation on electrodes
- Fluctuations in energy loss

Detection of Radiation

Goal: Measurement of 4-momentum and position in space of particles

Methods:

• Position-sensitive detectors ⇨ direction and position of momentum vector

• Bending in magnetic field ⇨ magnitude of p

• Absorption in calorimeter ⇨ energy

• Cherenkov radiation, time of flight ⇨ velocity β

• Transition radiation ⇨ γ

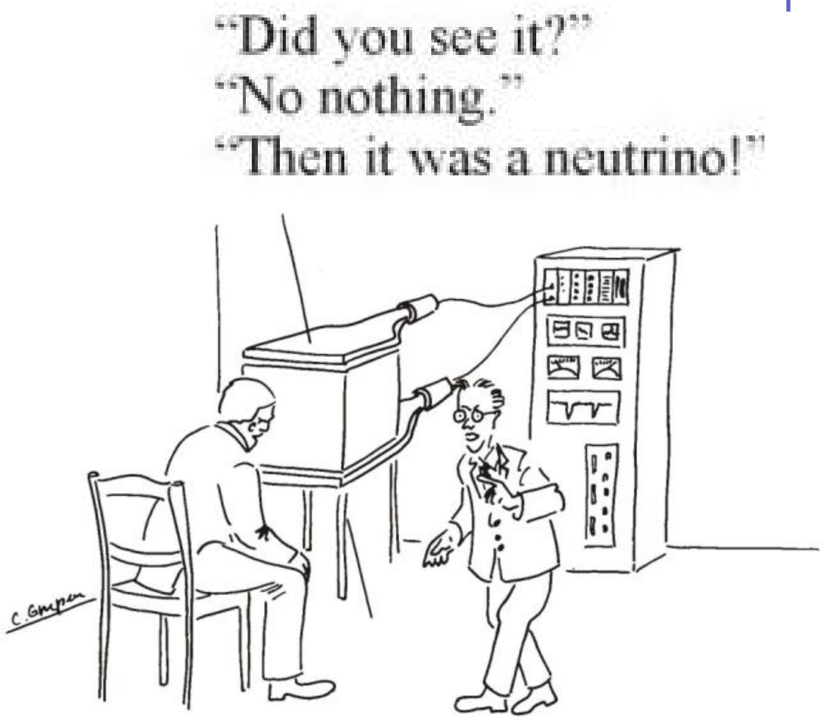
• Energy loss ⇨ β, γ

• Characteristic decay of a particle,
detection of secondaries ⇨ m

Detection by interaction with detector mater

• electromagnetic interaction with $\Delta E << E$

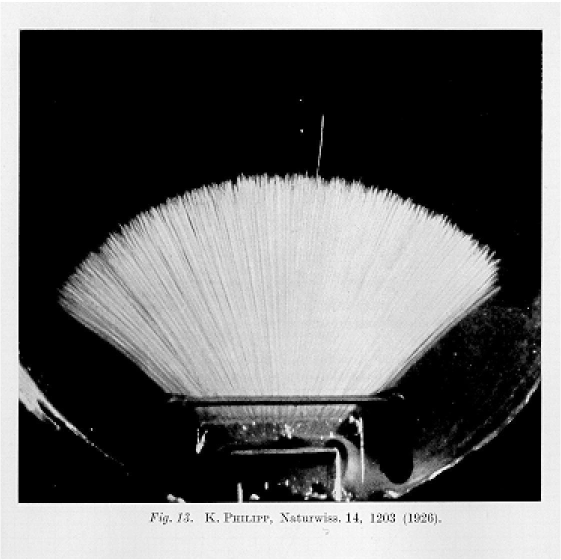
• interaction with $\Delta E \sim E$ (calorimtery)



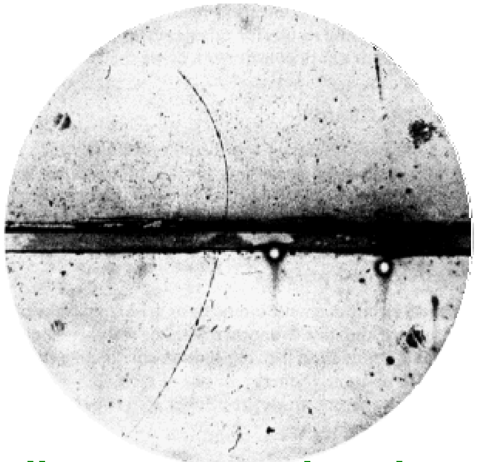
[Claus Grupen, Particle Detectors, Cambridge, 1996]

Cloud Chamber, C.T.R. Wilson 1910

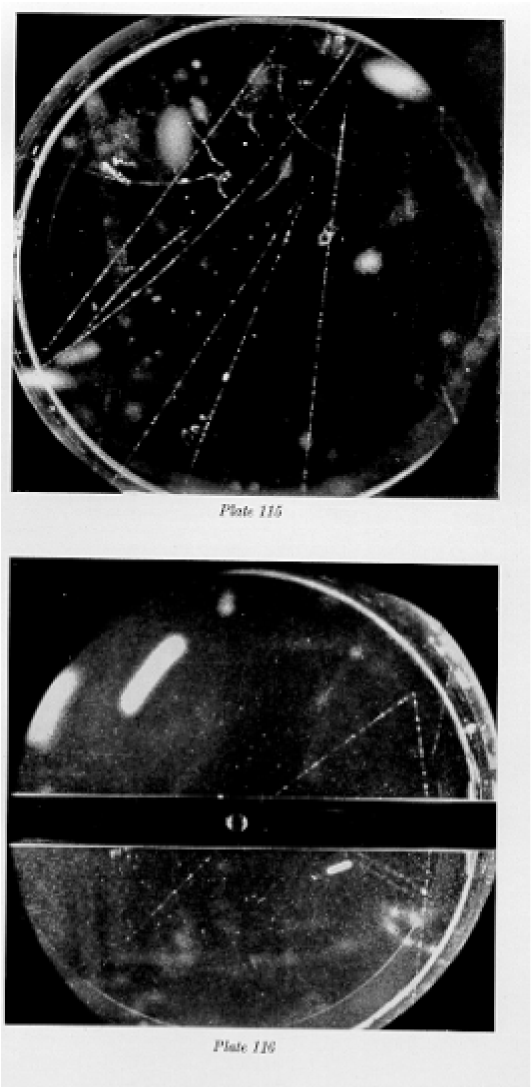
Charges act as condensation nuclei in supersaturated water vapor



Alphas, Philipp 1926



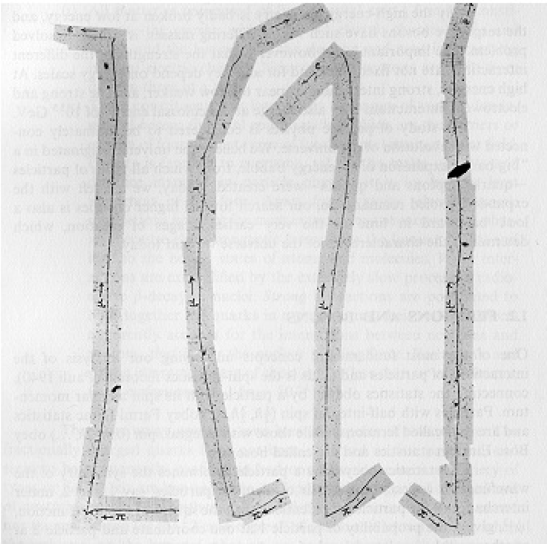
Positron discovery, Carl Andersen 1933

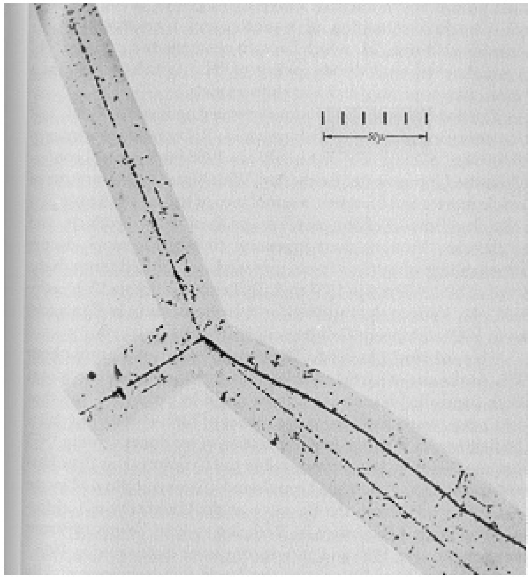


V- particles, Rochester and Wilson, 1940ies

Nuclear Emulsion, M. Blau 1930`ies

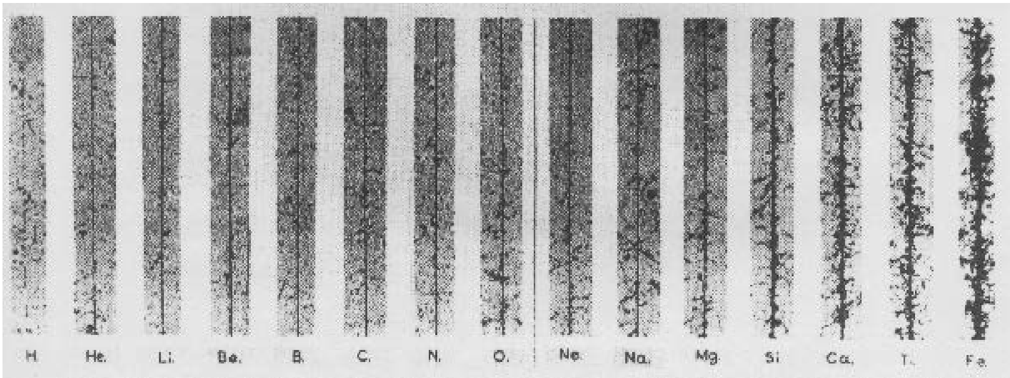
Charges initiate a chemical reaction that blackens the emulsion (photographic film)





C. Powell, Discovery of muon and pion, 1947

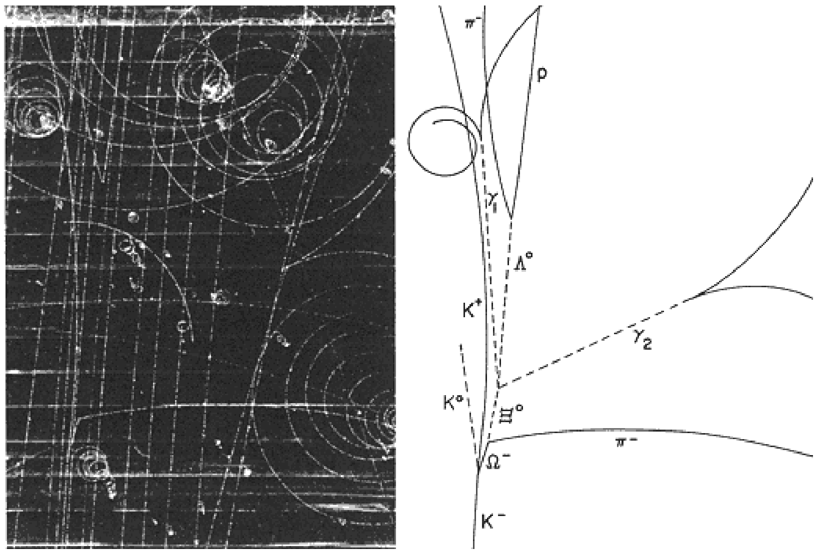
Kaon Decay into 3 pions, 1949



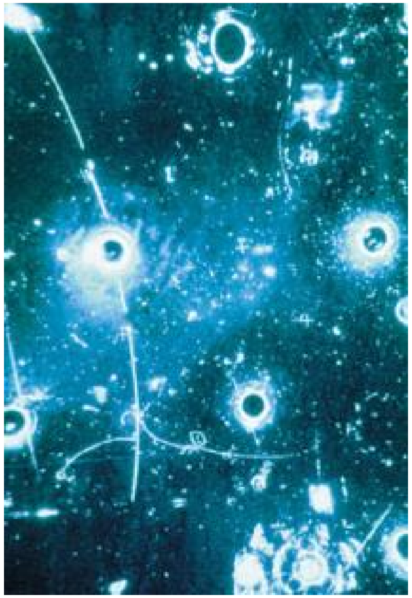
Cosmic Ray Composition

Bubble Chamber, D. Glaser 1952

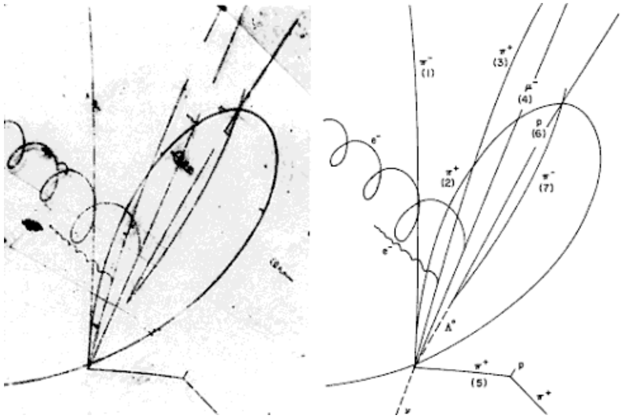
Charges create bubbles in superheated liquid, e.g. propane or Hydrogen (Alvarez)



Discovery of the ϕ^- in 1964



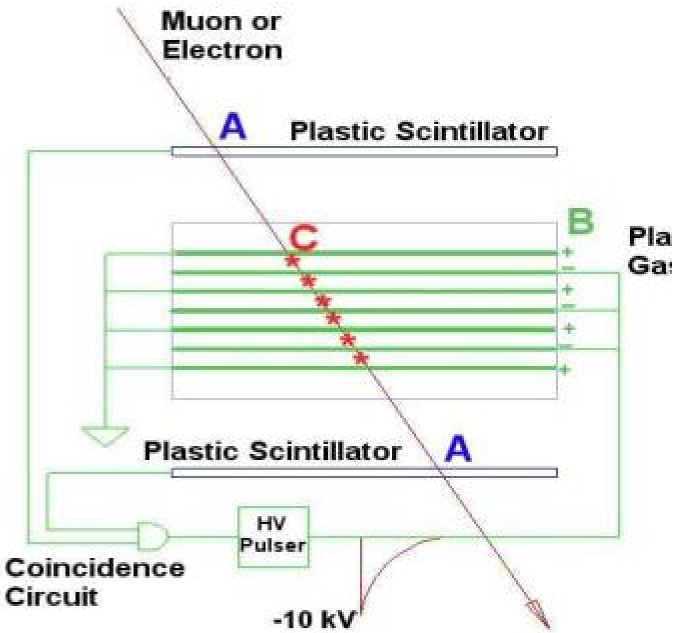
Neutral Currents 1973

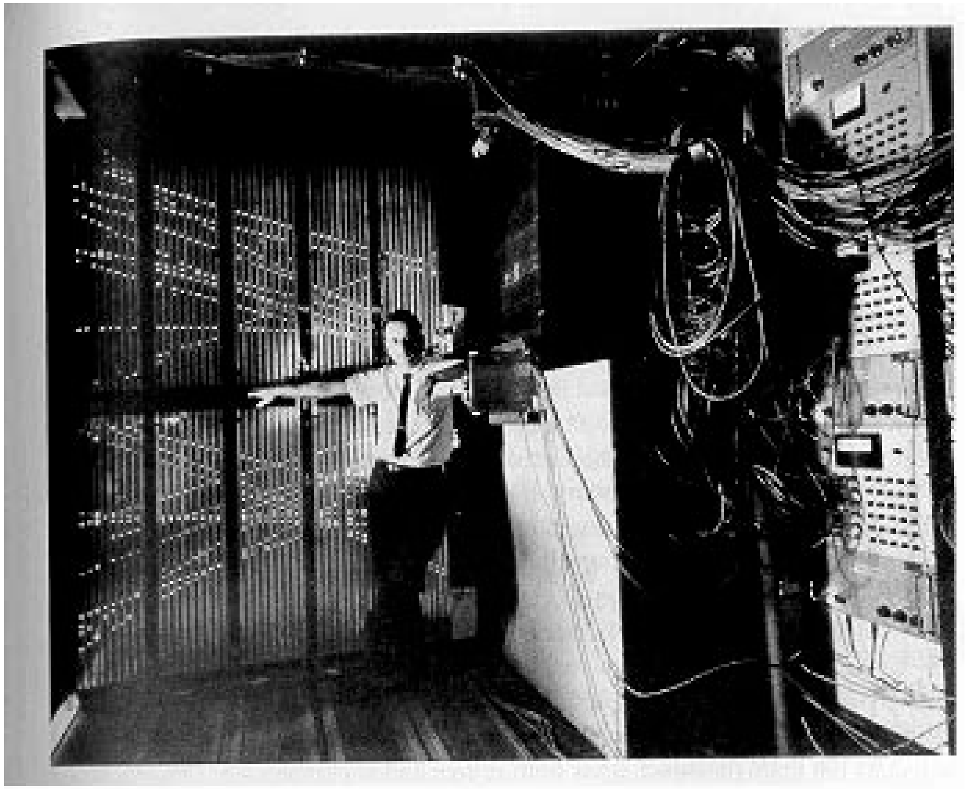


Charmed Baryon, 1975

Spark Chamber, 1960ies

Charges create 'conductive channel' which initiates a spark in case HV is applied.

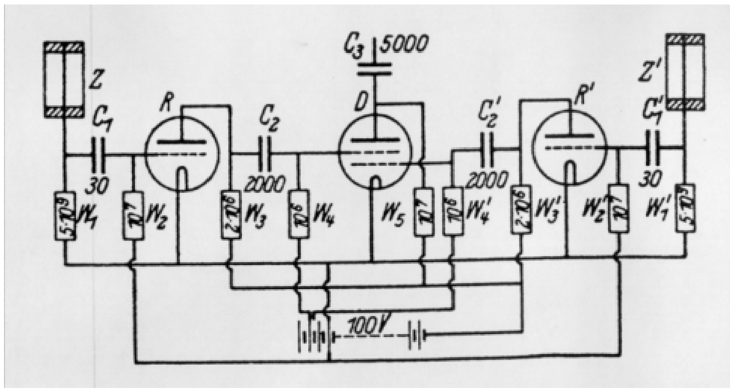




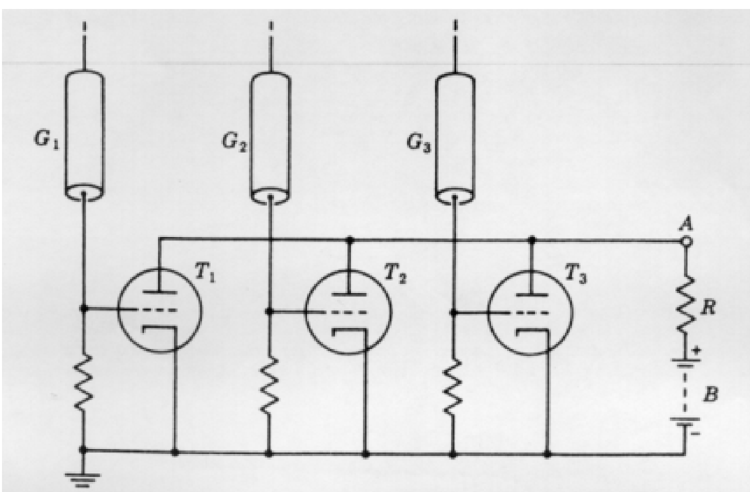
Discovery of the Muon Neutrino 1960ies

Electric Registration of Geiger Müller Tube Signals

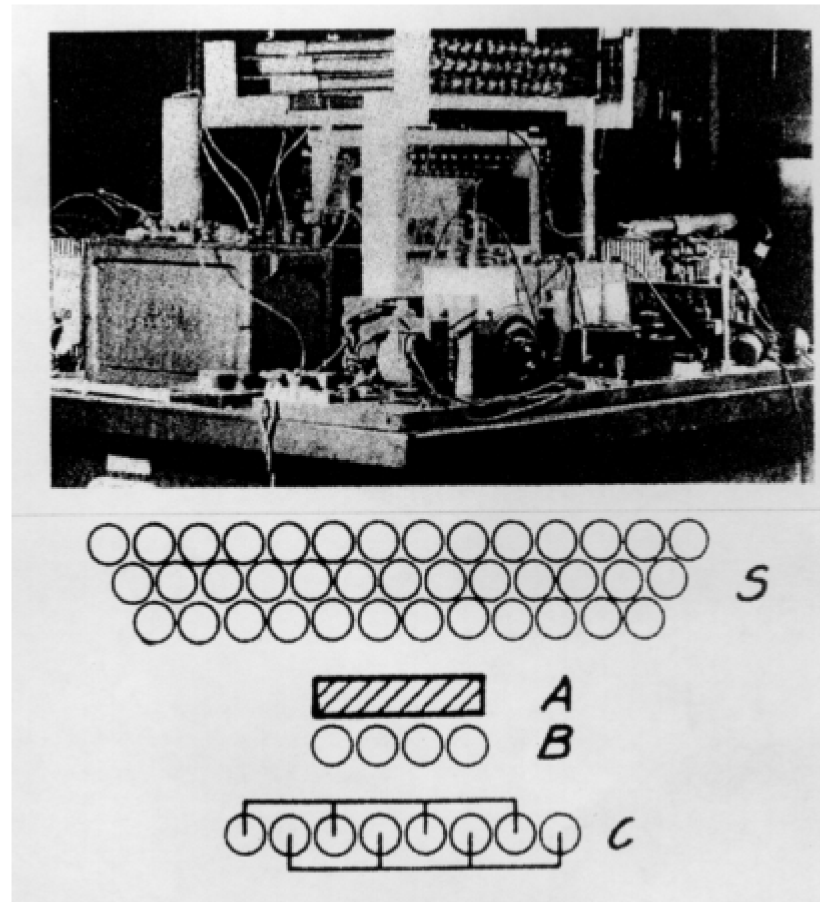
Charges create a discharge in a cylinder with a thin wire set to HV. The charge is measured with a electronics circuit consisting of tubes → electronic signal.



W. Bothe, 1928



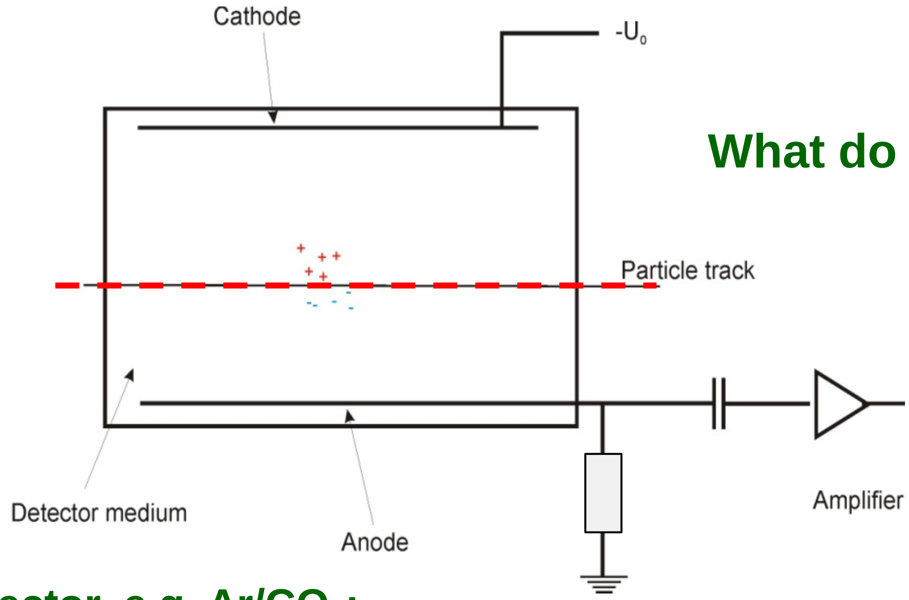
B. Rossi, 1932



Cosmic Ray Telescope 1930ies

... more modern: collect signals as electronic charges

- electronic signals can be read out electronically → computers
- can go to higher...
  - granularity (millions of very small pixels)
  - faster and faster signal readout → higher intensities reveal rarest effects



What do we need to make a detector?

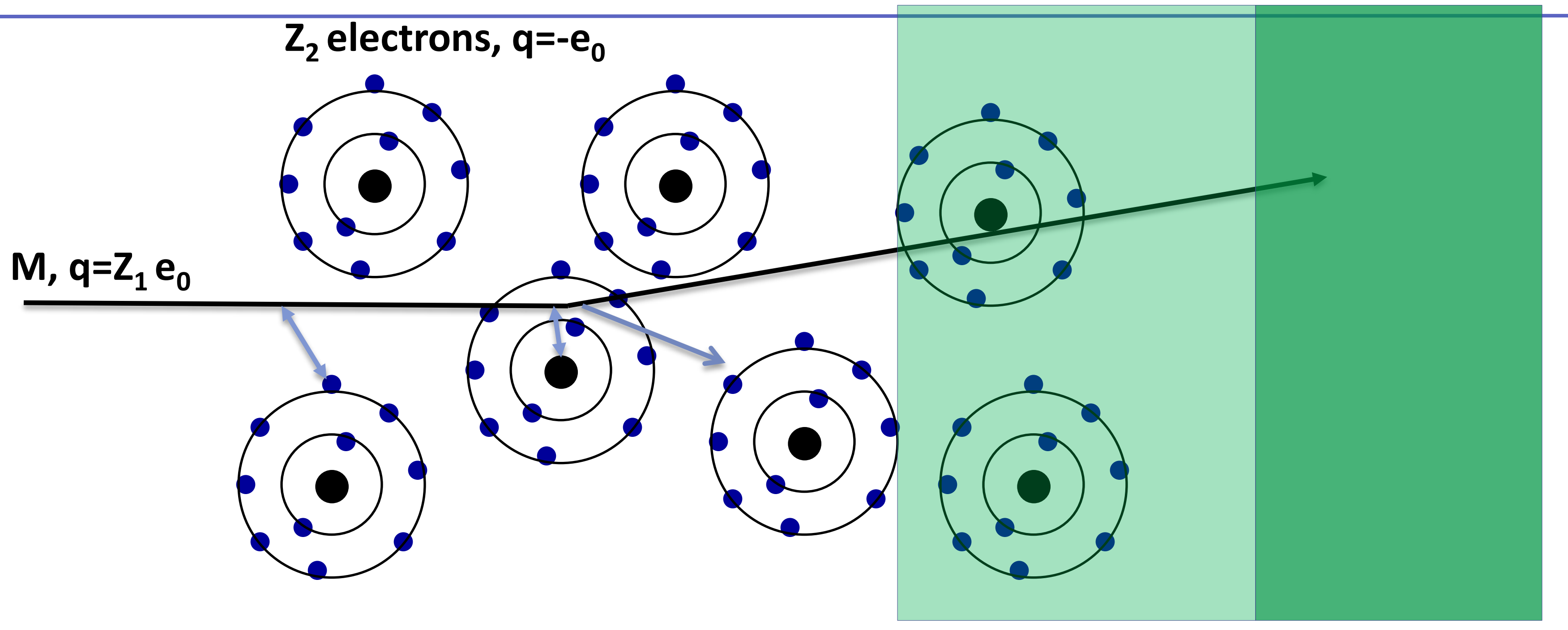
Gaseous detector, e.g. Ar/CO_2:

- q ~ 100 e^-/cm (MIP)
- internal amplification necessary
- quencher gas necessary

Solid state detector → Silicon, Diamond etc.:

- q~10000 e^-/100 μm (MIP)
- detectable with low-noise amplifier

Electromagnetic Interaction of Particles with Matter



Interaction with atomic electrons.
The incoming particle loses energy and the atoms are excited or ionized.

Interaction with atomic nucleus.
The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produced and X ray photon, called Transition radiation.

Particle Detection based on Ionization

Charged particles leave a trail of primary and secondary charges (and excited atoms) along their path:

Electron-Ion pairs in gases and liquids, electron hole pairs in solids.

The produced charges can be registered → Position measurement → Time measurement → Tracking Detectors ....

Cloud Chamber: **Charges create drops → photography.**

Bubble Chamber: **Charges create bubbles → photography.**

Emulsion: **Charges 'blacken' film.**

Spark Chamber: **Charges produce a conductive channel that creates a discharge → photography**

Electronic Detection of Ionization

Gaseous and Solid State Detectors:

Moving Charges (electric fields) induce electronic signals on metallic electrodes that can be read by dedicated electronics.

→ In solid state detectors the charge created by the incoming particle is sufficient for detection.

→ In gaseous detectors (e.g. wire chamber, GEM-chamber) charges are internally multiplied in order to provide a measurable signal.

Detector material:

- gas ⇨ fast collection of e- and ions, e.g. Ne, Ar
- liquid ⇨ higher density, e.g. liquid Ar
- solid ⇨ higher density, self-supporting, e.g. semiconductor

Statistics of Electron-Ion Pair Creation

Characteristic length: mean free path between ionizing collisions

	λ (cm)
He	0.25
air	0.053
Xe	0.023

$$\lambda = 1/n\sigma$$

σ = cross section for ionization
n = number density

efficiency of gaseous detector allows to find λ and thus $\sigma_i \rightarrow \sigma_I = 10^{-22}$ cm^2 or 100 b

Encounters with gas atoms are purely random, probability small

⇨ Poisson distribution of number k of ionizing collisions over length L

$$P(L/\lambda;k) = \frac{(L/\lambda)^k}{k!} e^{-L/\lambda}$$

L/λ = mean number of ionizing collisions in L

= mean number of primary e$^-$-ion pairs n_P

Total number of e$^-$-ion pairs: primary and secondary ionization

$$n_T = \frac{\bar{\Delta}}{W} \sim \frac{\xi L}{W}$$

ξ = 1st term of Bethe-Bloch equation

Δ = mean energy loss in thickness L

W = effective average energy to produce one e$^-$-ion pair, usually $W>I$, since part of energy lost by excitation, empirical determination

$$\frac{n_T}{n_P} \sim 2.5 - 3$$

the total number is larger than the number of primary charges

Properties of Gases

W = mean energy for electron-hole pair

Gas	Z	A	δ	E_{ex}	E_i	I	W	dE/dx		n_P	n_T
			(g/cm^3)	(eV)	(eV)	(eV)	(eV)	(MeV/g cm^{-2})	(keV/cm)	(ip/cm)	(ip/cm)
He	2	4	1.66E-4	19.8	24.5	24.6	41	1.94	0.32	5.9	7.8
N_2	14	28	1.17E-3	8.1	16.7	15.5	35	1.68	1.96	(10)	56
Ne	10	20.2	8.39E-4	16.6	21.5	21.6	36	1.68	1.41	12	39
Ar	18	39.9	1.66E-3	11.6	15.7	15.8	26	1.47	2.44	29.4	94
CO_2	22	44	1.86E-3	5.2	13.7	13.7	33	1.62	3.01	(34)	91
CH_4	10	16	6.70E-4		15.2	13.1	28	2.21	1.48	16	53

[F. Sauli, CERN 77-09 (1977)]

Properties of some Semiconductors and solid materials

Si	2,3	3,6
Ge	5,3	2,8
Diamond	3,5	5,8

Energy Loss of Charged Particles

Inelastic collisions

- ⇨ statistical process (quantum mechanics!)
- ⇨ mostly small energy losses (< 100 eV in 90% of all collisions)
- ⇨ rare events with large single-collision energy loss e.g. delta electrons
- ⇨ total energy loss fluctuates!

Number of collisions per macroscopic path length large

- ⇨ fluctuations in total energy loss small
- ⇨ characteristic parameter: average energy loss per unit pathlength

$$\left\langle -\frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle$$ “stopping power”

towards dE/dx

- Wish to know, how a charged ionizing particle interacts with detector.

- Photo-Absorption Ionization model: PAI model

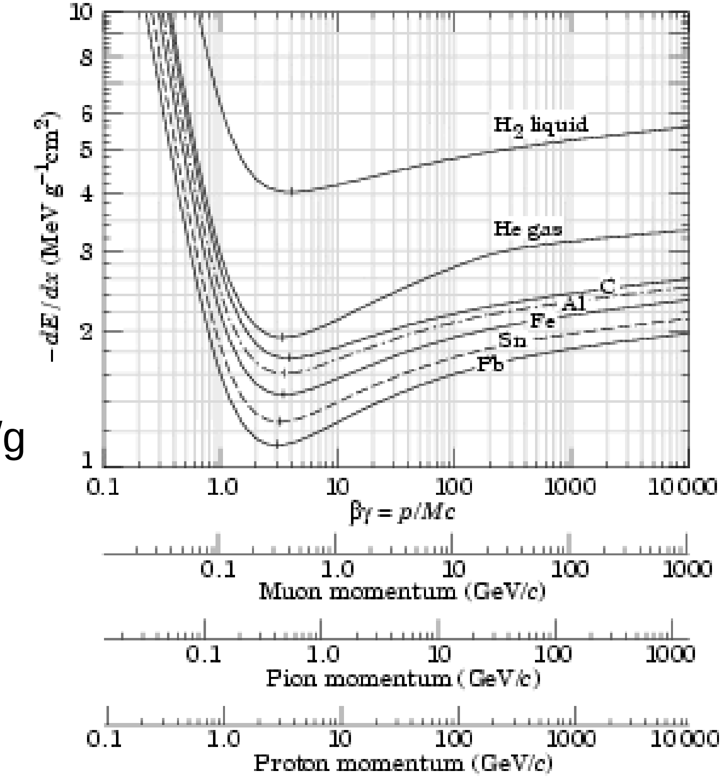
[W.W.M Allison, J.H. Cobb, Ann. Rev. Nucl. Part. Sci. 30, 253 (1980)]

- What is the energy loss dE in an infinitesimally thin disk of detector material dx? (dx is typically a mass density dx = ρdz)

Bethe-Bloch Formula for Mean Energy Loss dE/dx

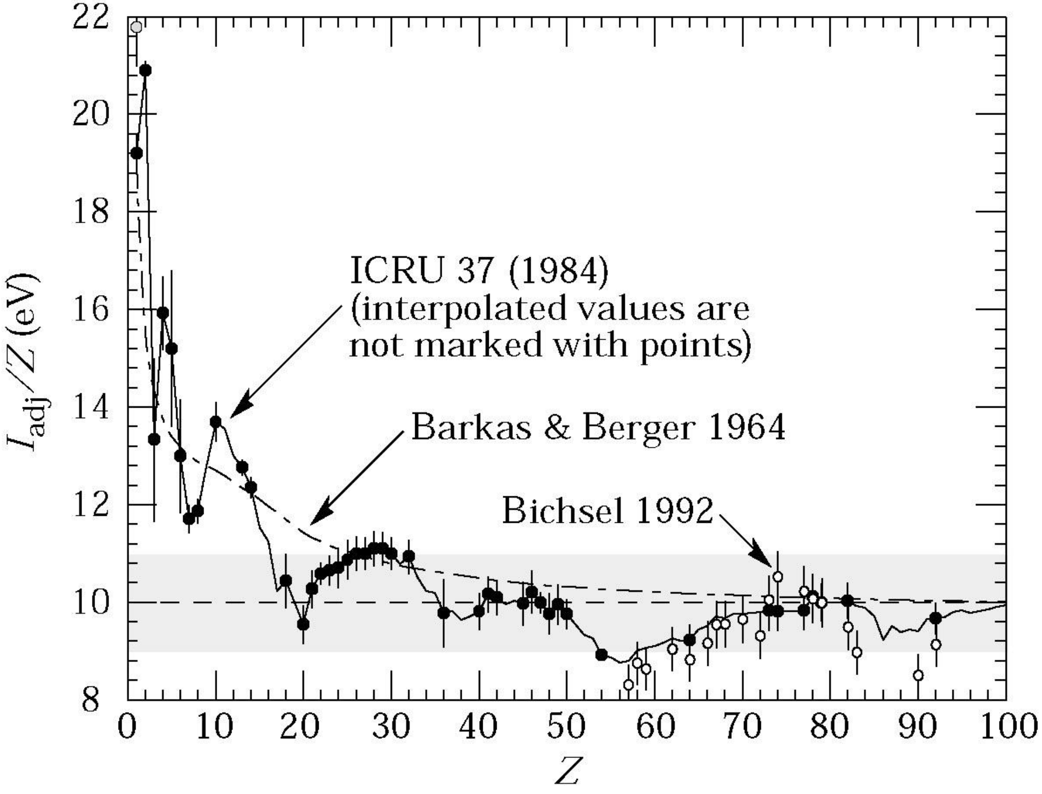
$$\left\langle -\frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = \frac{4\pi}{(4\pi\varepsilon_0)^2} \frac{z^2 e^4 n_e}{mc^2 \beta^2} \left[\frac{1}{2} \ln \frac{2mc^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

- independent of mass of incident particle
- depends only on velocity of inc. particle and on I, the mean exitation energy
  ⇨ main parameter
- low energies ⇨ $\left\langle -\mathrm{d}E / \mathrm{d}x \right\rangle \propto 1/\beta^2$
- minimum at $\beta\gamma \approx 3.5$: "MIP" dE/dx$|_{min}$ ~ 1,5 MeV cm^2/g
- high energies ⇨ $\left\langle -\mathrm{d}E / \mathrm{d}x \right\rangle \propto \ln \beta^2\gamma^2$: relativistic rise
- mass stopping power: $\left\langle -\mathrm{d}E / \rho\mathrm{d}x \right\rangle \propto z^2 \left(Z/A \right) \cdot f(\beta, I)$
  ⇨ almost independent of material
- density effect: polarization of atoms along track
  ⇨ partly compensates relativistic rise



[K. Nakamura *et al.* (PDG), J. Phys. G **37**, 075021 (2010)]

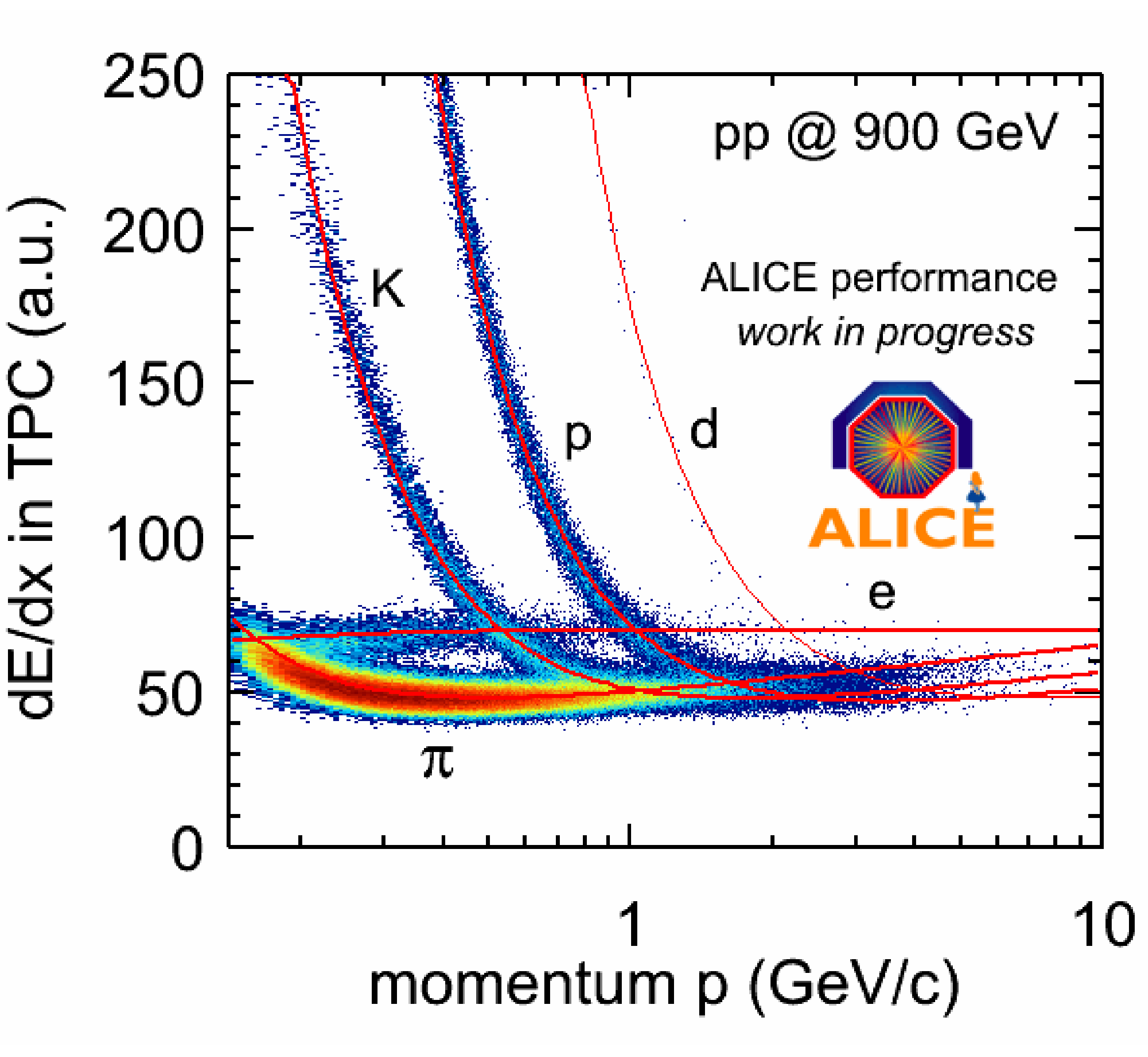
Mean Excitation Energy



[Review of Particle Physics, S. Eidelmann et al., Phys. Lett. B 592, 1 (2004)]

I = Z 10eV

dE/dx can be used for particle ID if plotted vs E or p

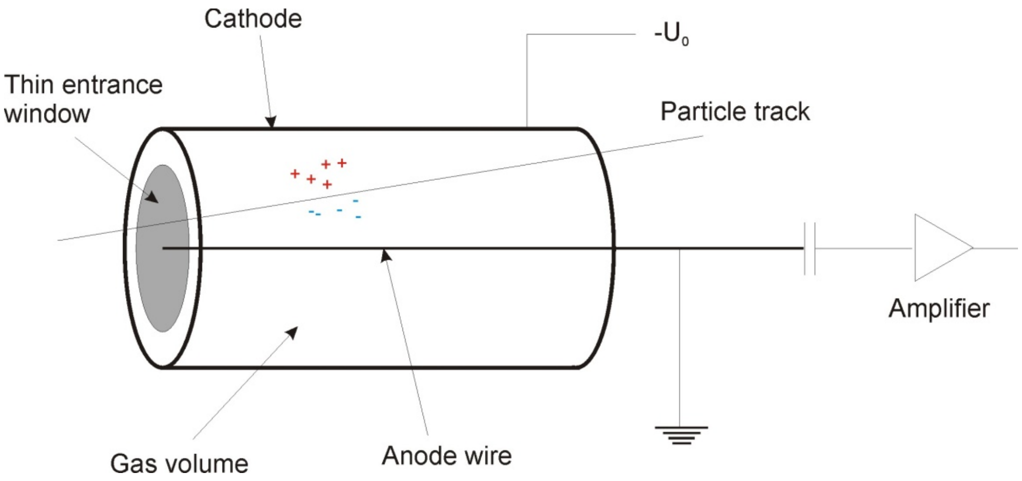


Detection process

- Primary interaction of ionizing particle with detector material
- Second: charges drift in electric fields towards electrodes and create (very small) induced signals
  - drift velocity for electrons in gas at decent drift fields ~ 1 to 6 cm/μs
  - drift velocity for ions ~ 1 cm/ms, smaller by four orders of magn.

- Drift time can be used for resolution enhancement
  - Drift chamber: invented by A. Walenta, J. Heintze, 1970 at Phys. Inst. U. Heidelberg (NIM 92 (1971) 373)
- Some charges trapped along drift path
  - solid state detectors → impurities, lattice defects, radiation damage
  - gaseous detectors → loss by electron attachment on electro-negative atoms → Oxygen, SF6 contamination
- High field region may be employed for final gain boost (wire chamber, GEM chamber)

Need signal amplification: Proportional Wire Counter

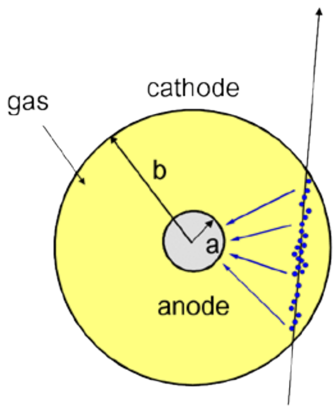


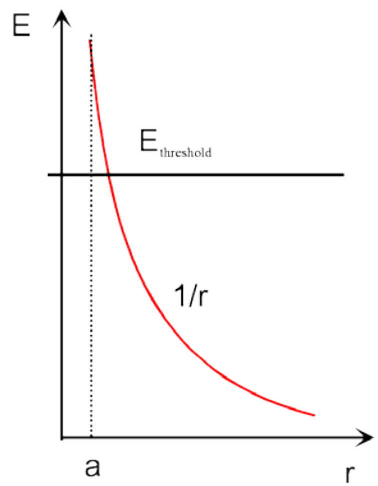
Charge gain:

$$G = \frac{N}{N_0} \approx e^{\mathrm{const} \cdot U}$$

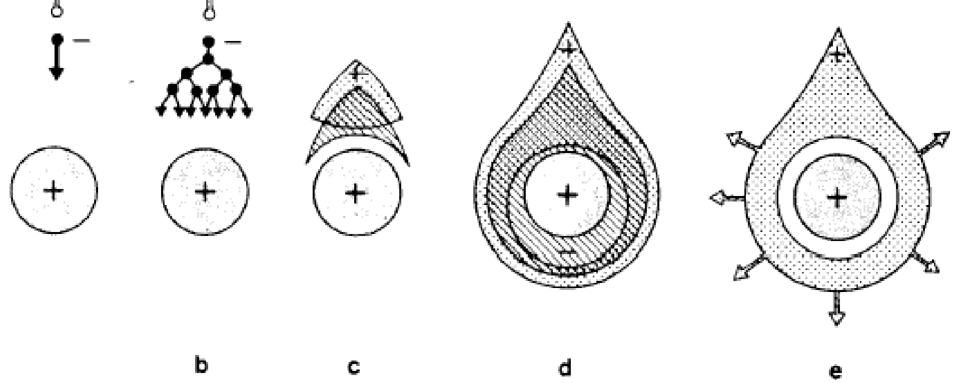
Typical values:

- Proportional wire counter: $G \sim 10^4 - 10^6$
- GEM: $G \sim 10^3 - 10^5$





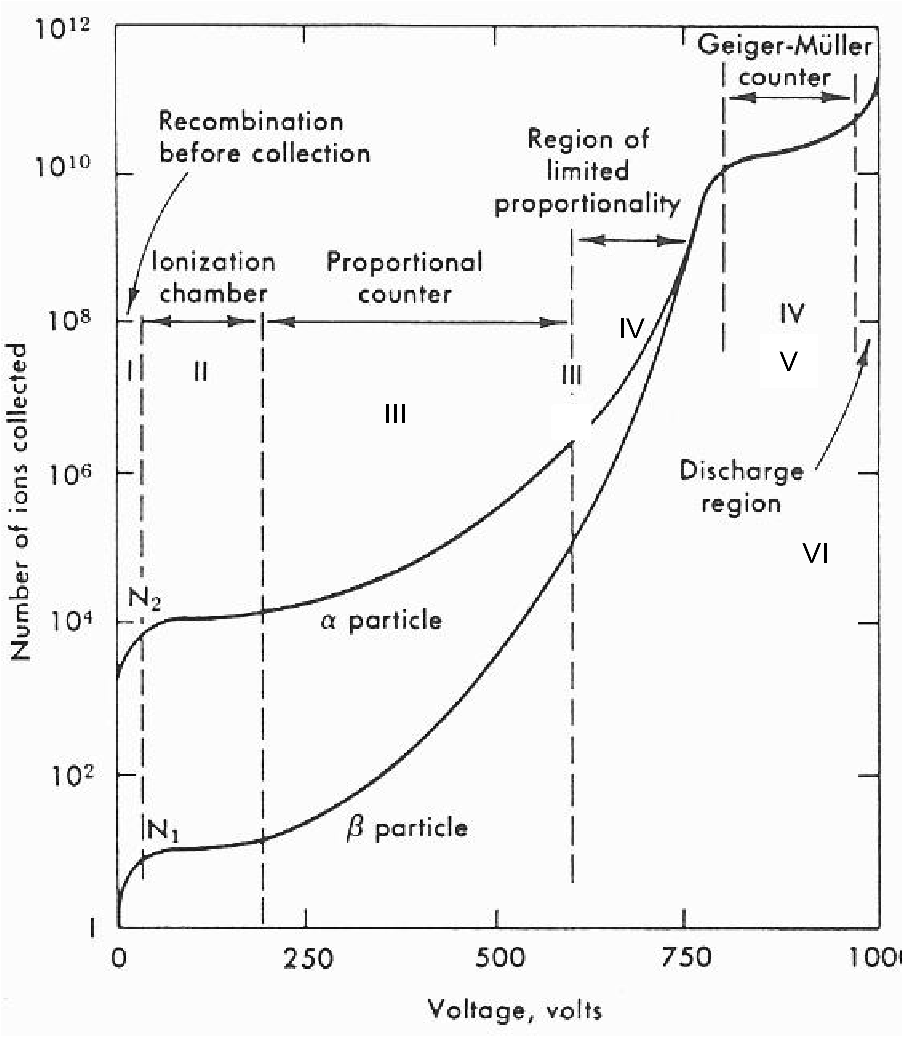
(F. Sauli, CERN 77-09)



Amplification starts at r~5a

⇨ negligible spatial dependence of pulse height

I-U Characteristics



Modes of operation of gas detectors
(after F. Sauli 1977, lecture notes)

I. Recombination during drift

II. Collection of all created e⁻-ion pairs: ionization chamber

III. Avalanche creation: proportional counter

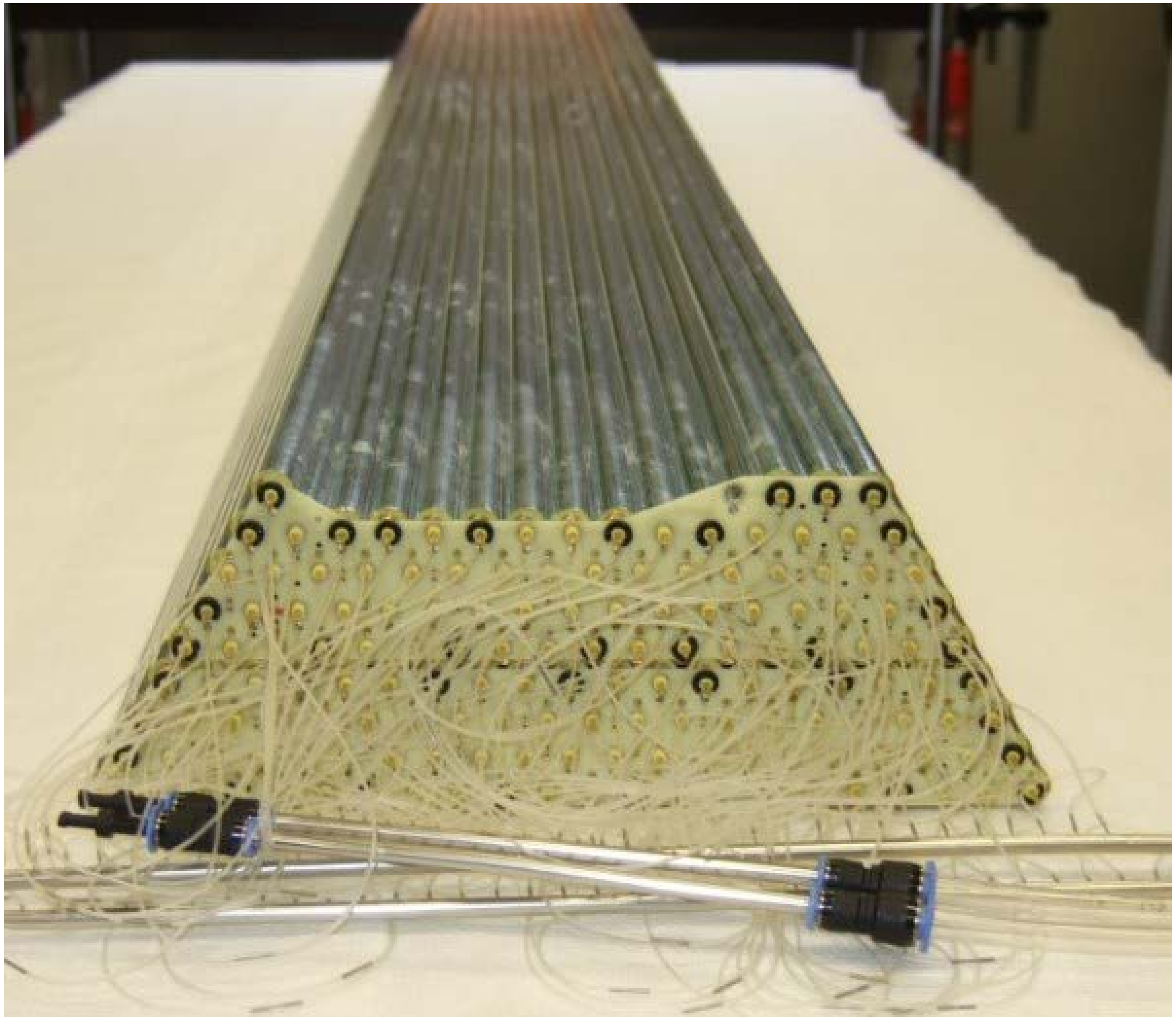
IV. Distortion of electric field around anode
  - ⇨ screening of electric field
  - ⇨ loss of proportionality

V. Propagation of avalanche over full length of anode (photon emission)
  - ⇨ electric discharge
  - ⇨ saturation of output current

  Termination: quench gas or lower U

VI. Continuous breakdown even without radiation

PANDA Straw Tracker, one submodule

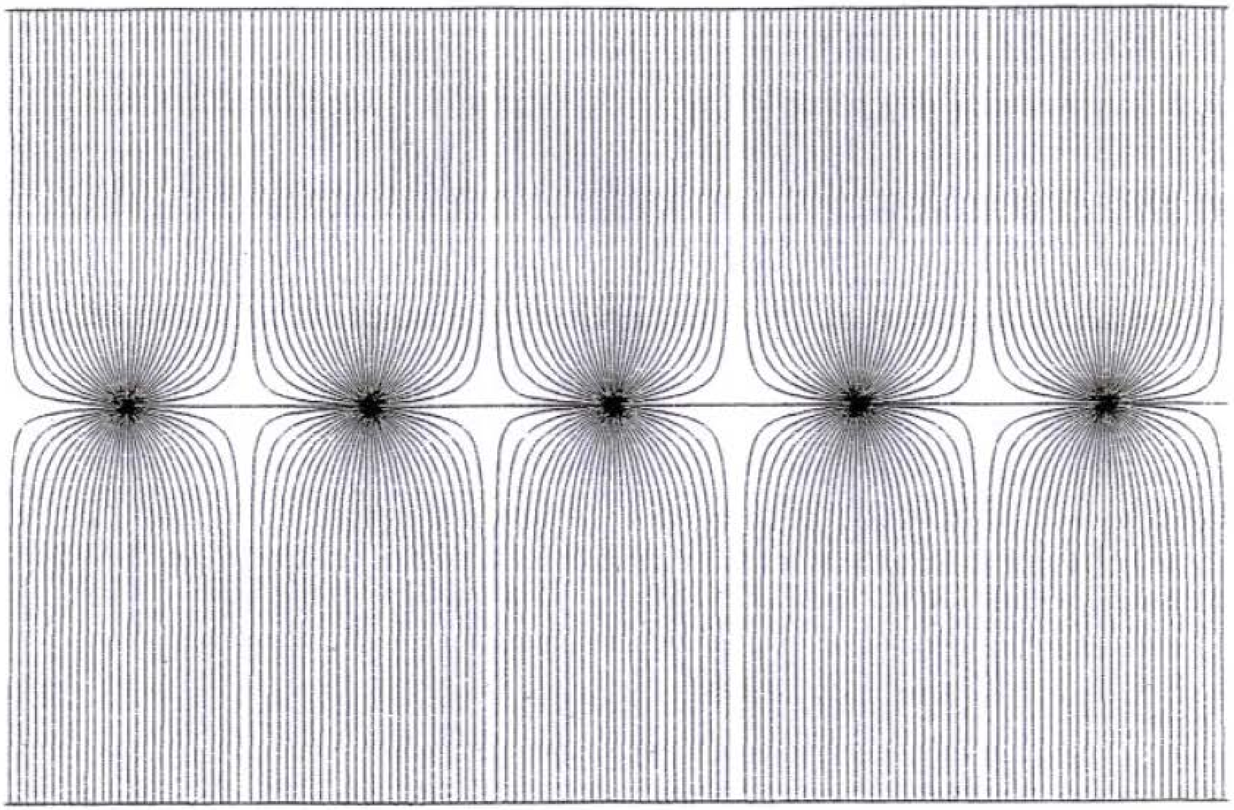


Straws are of 20µm Coated Polyimide Foil, pressurized to 2bar.

Charpak´s Multi-Wire Proportional Chamber MWPC

G. Charpak et al. NIM 62 (1968) 202
Nobel prize 1992, Rev. Mod. Phys. 65 (1993) 591

as compared to cylindrical arrangement field geometry somewhat different



typical geometry of electric field lines in multi-wire proportional chamber

typical parameters:

$d = 2 - 4$ mm

$r_i = 15 - 25$ μm

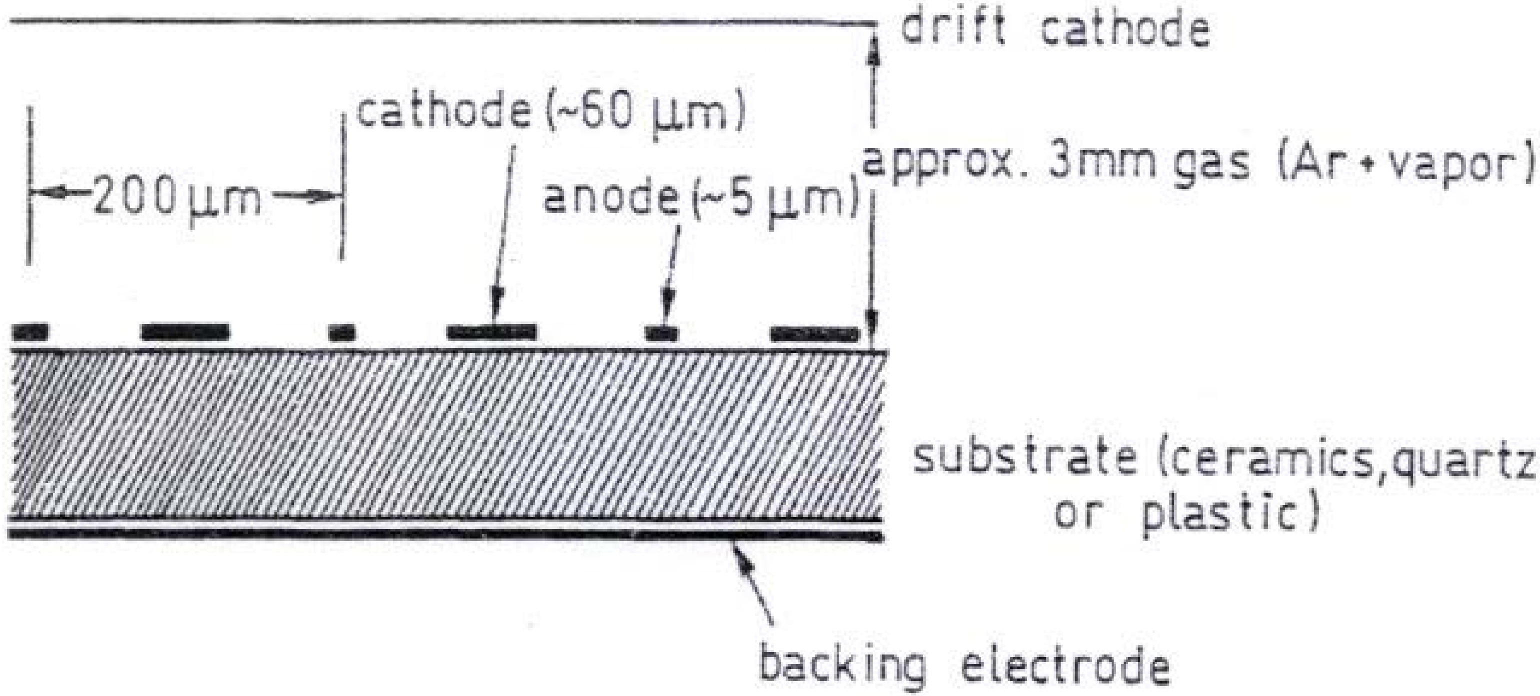
$L = 3 - 6$ mm

$U_0 =$ several kV

total area: many m^2

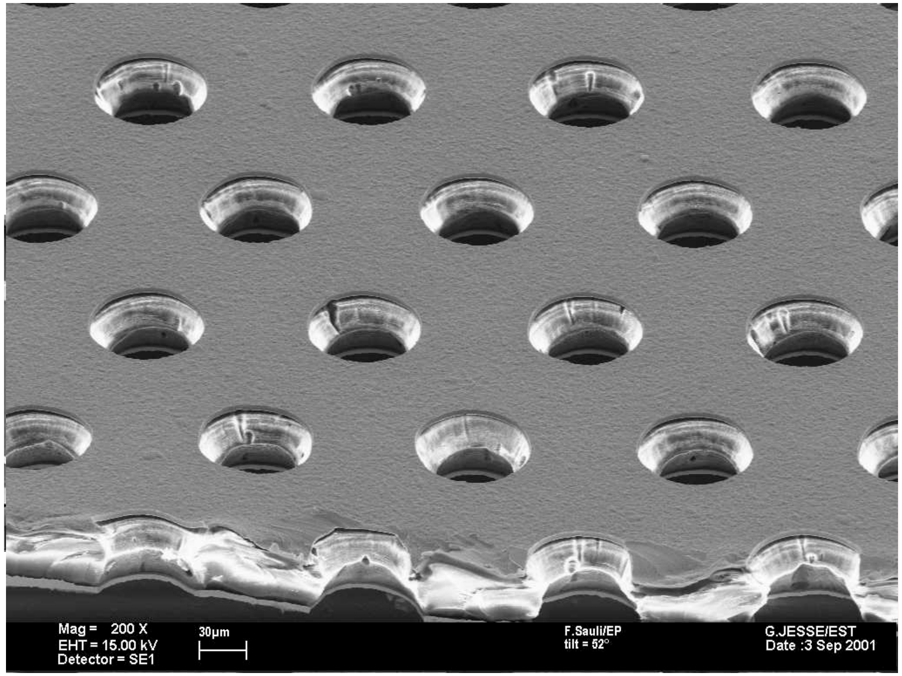
in vicinity of anode wire: radial field
far away homogeneous (parallel-plate capacitor)

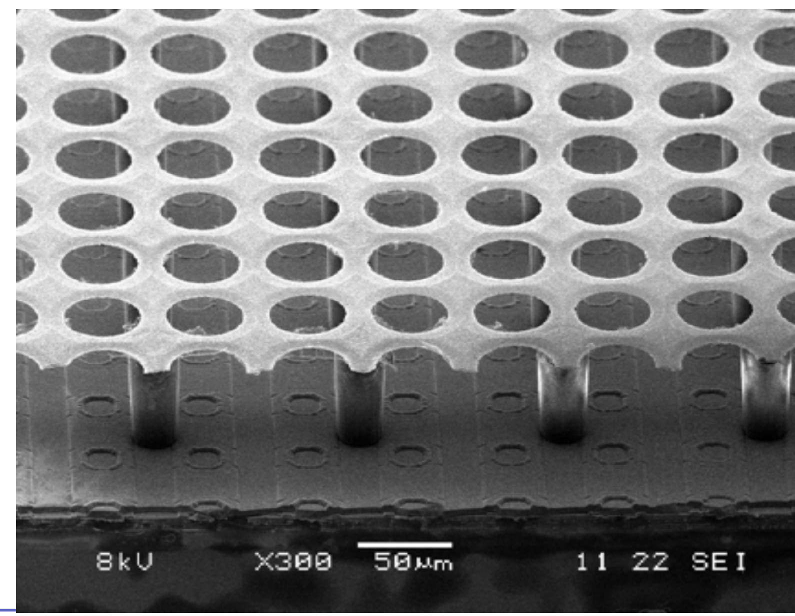
Anton Oed´s MSGC (Microstructured Gas Chamber)



On resistive glas substrate

Microstructured Amplification Stages: GEM, InGrid





- GEM: **G**as **E**lectron **M**ultiplier
  [F. Sauli, NIM A386, 531 (1997)]
- Photolithography: ~ 10.000 holes/cm^2

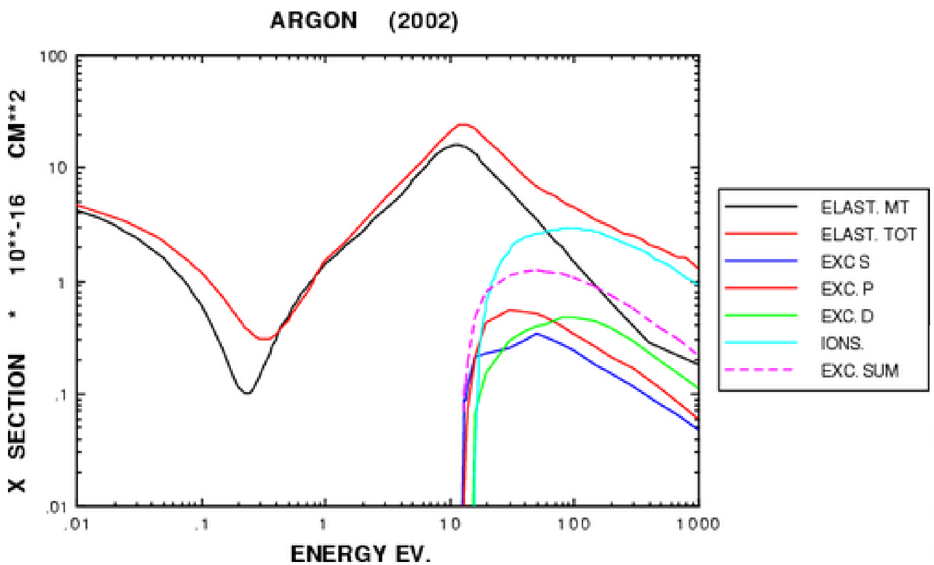
amplified charge clouds rain onto readout pixels

Microstructures: Ions travel very short → rate capability

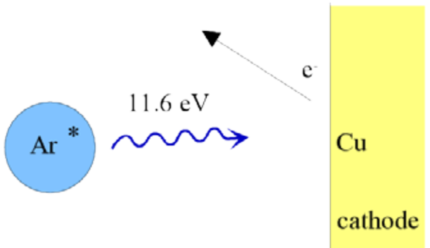
[J. Timmermans, VCI 2007]

Choice of Detector gas

Noble gases: Energy dissipation mainly through ionization

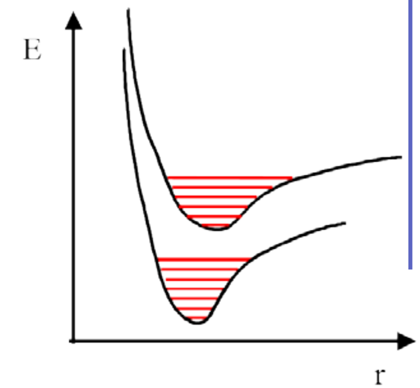


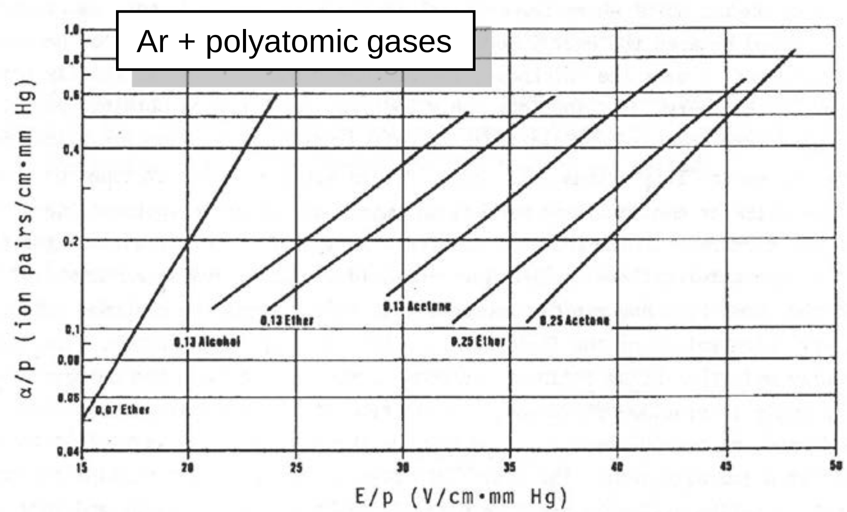
Deexcitation through photon emission



Polyatomic molecules:

Absorption of photons in broad energy range

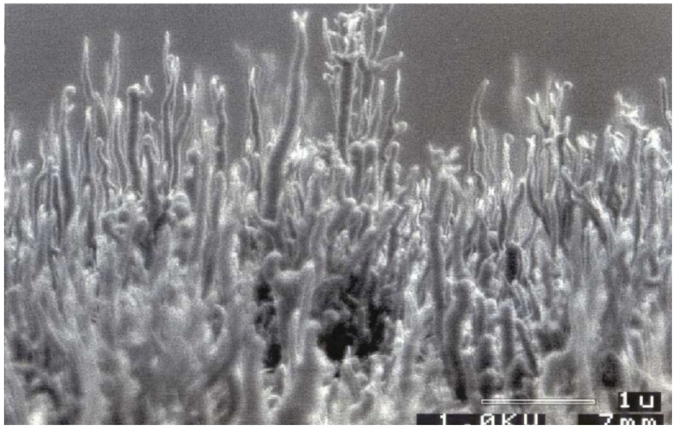


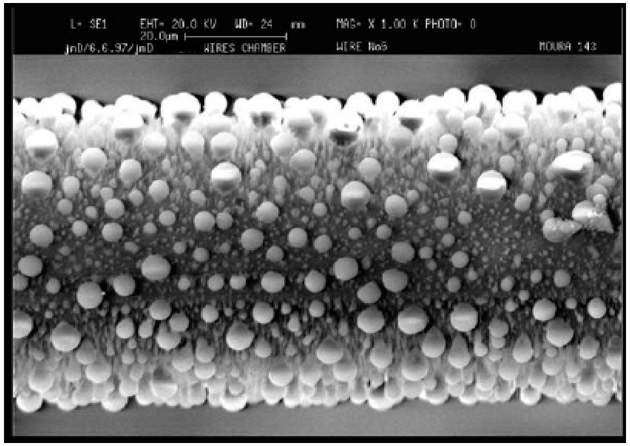


[O.K. Allkofer, Spark Chambers, Thiemig, München, 1969]

Polyatomic quencher gas essential for stable operation!

Aging

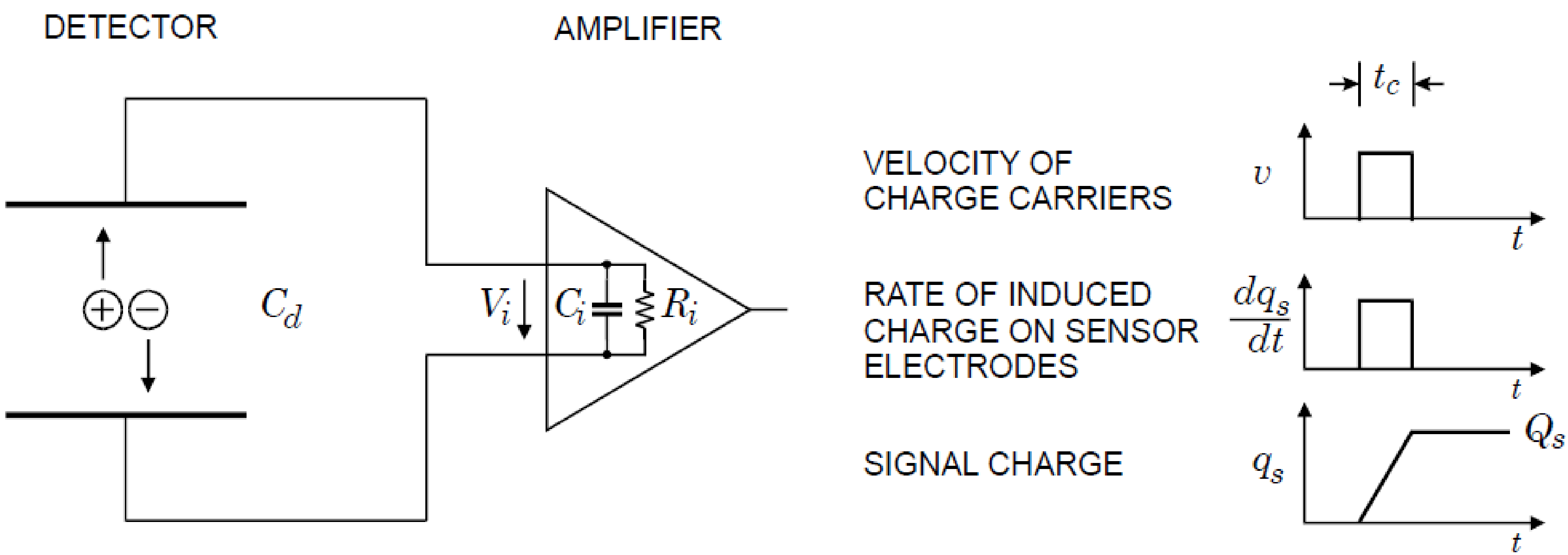




Let us take a three minute break!

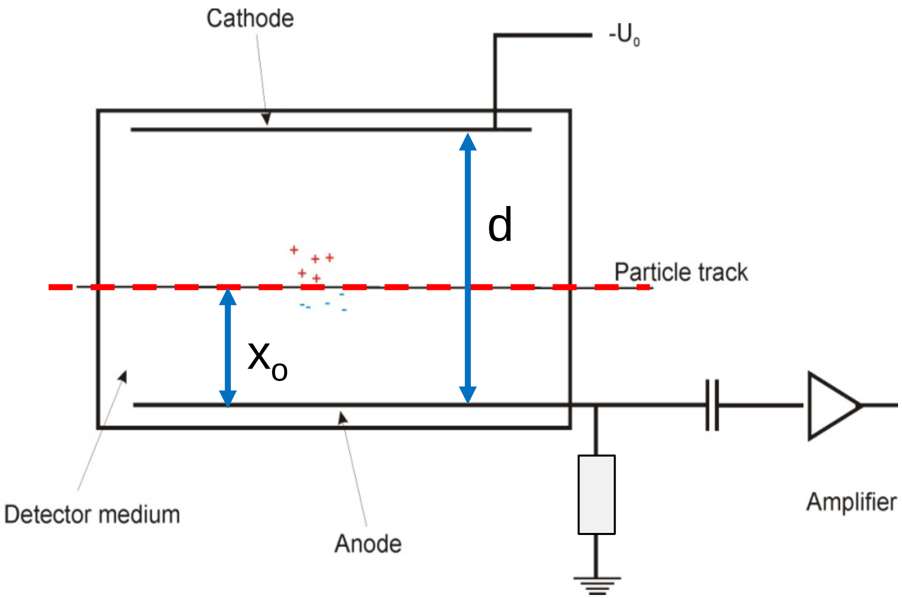
Electronic Signal Formation

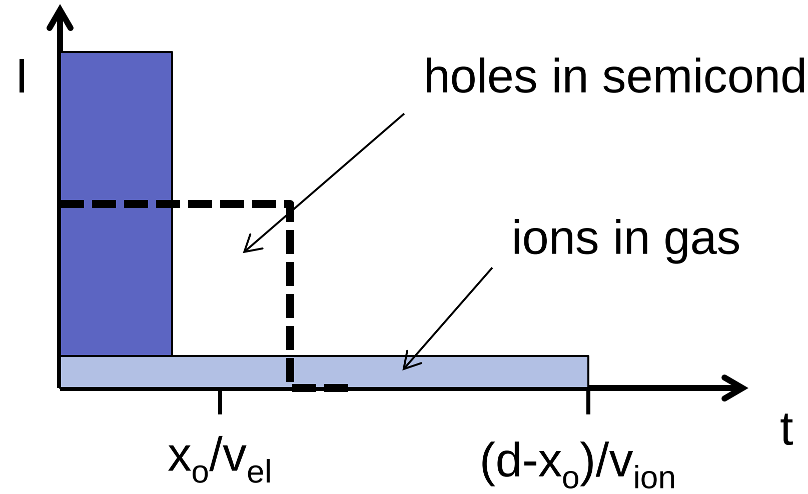
- Moving charges induce current in electrodes. Currents proportional to drift velocity.
- Simple case: Ionization chamber, no gain

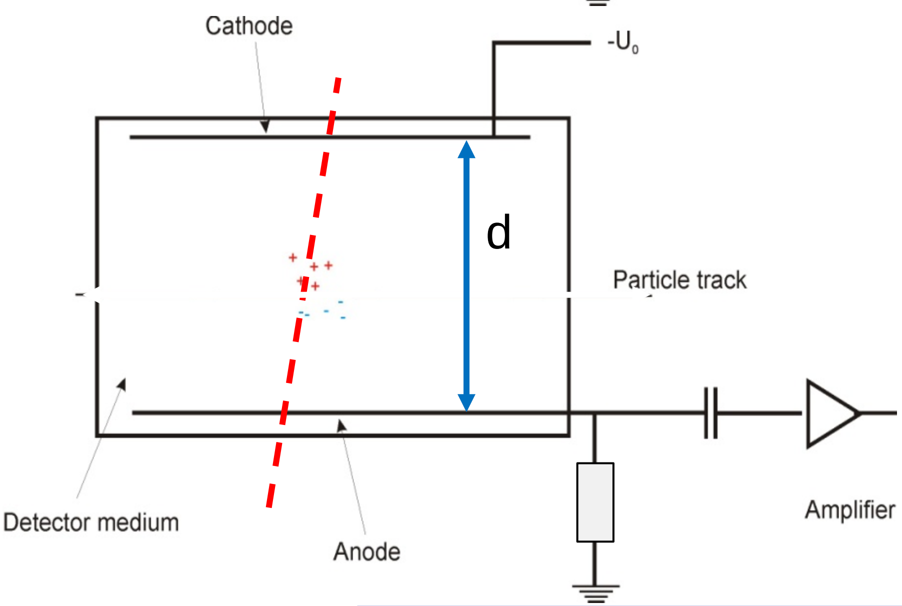


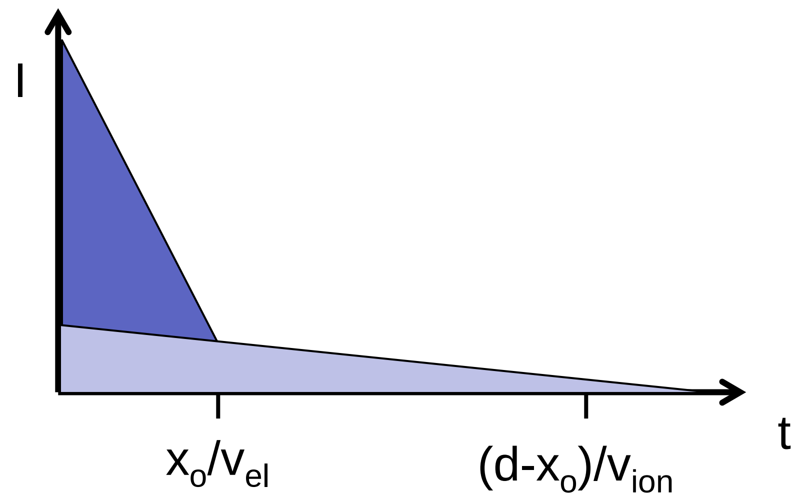
If $R_i \cdot (C_d + C_i) \gg$ collection time t_c the peak voltage at the amplifier input $V_s = \dfrac{Q_s}{C_{\mathrm{det}} + C_i}$

Varying Signal Formation

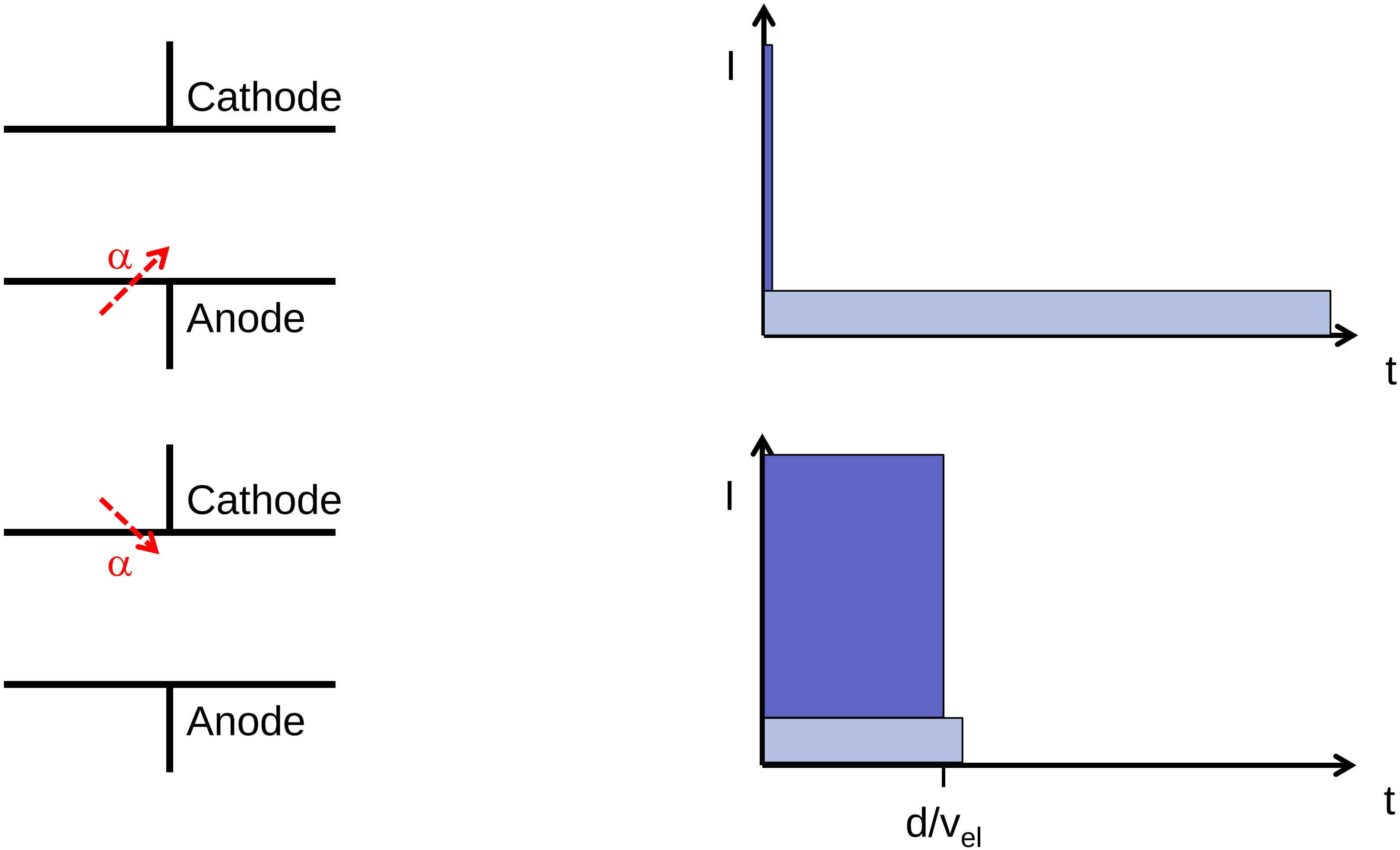








localized charge injection: one charge carrier only



→ realized to study mobility and drift velocity

More complicated detector geometries→ need Ramo´s Theorem

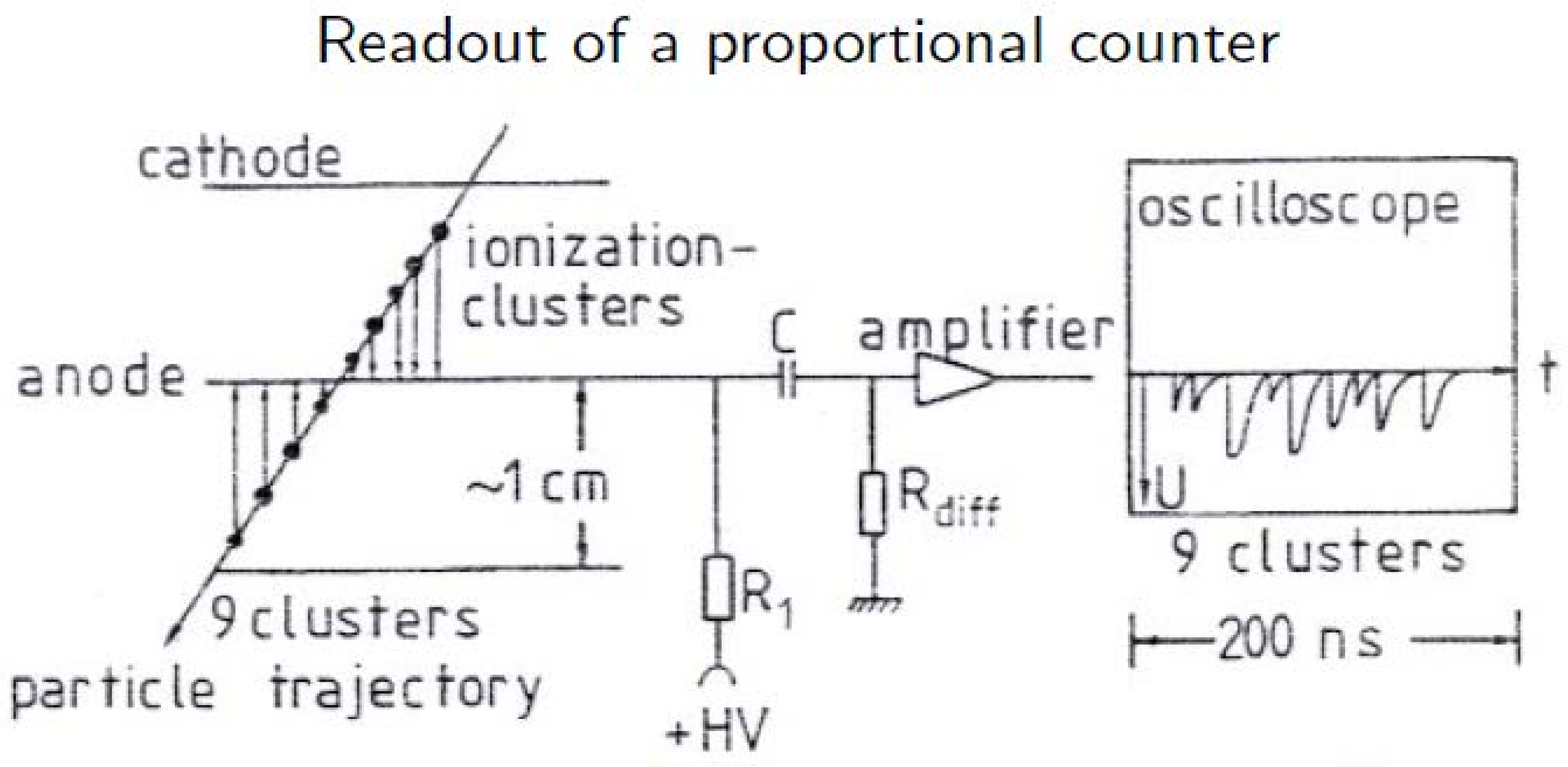
Mostly focus on fast, electron component

- Charge sensitive amplifier integrates signal current to measure the full signal charge

  → (electronically low pass filter, integrate onto capacitor)

- Ion drift in multi wire proportional chambers creates a long $1/(t + t_o)$ tail which leads to signal pile-up. A following shaper amplifier has high-pass filter characteristic that removes slow, ion-drift components

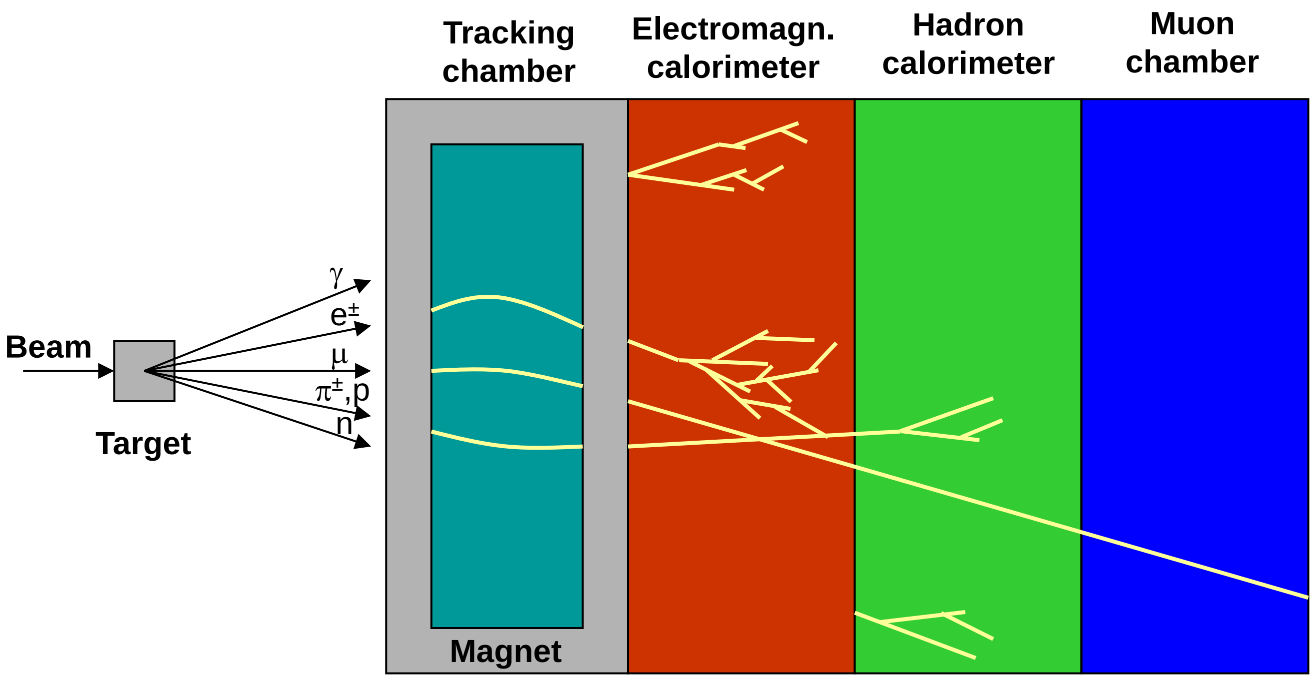
- Ion tail nevertheless limits rate capability

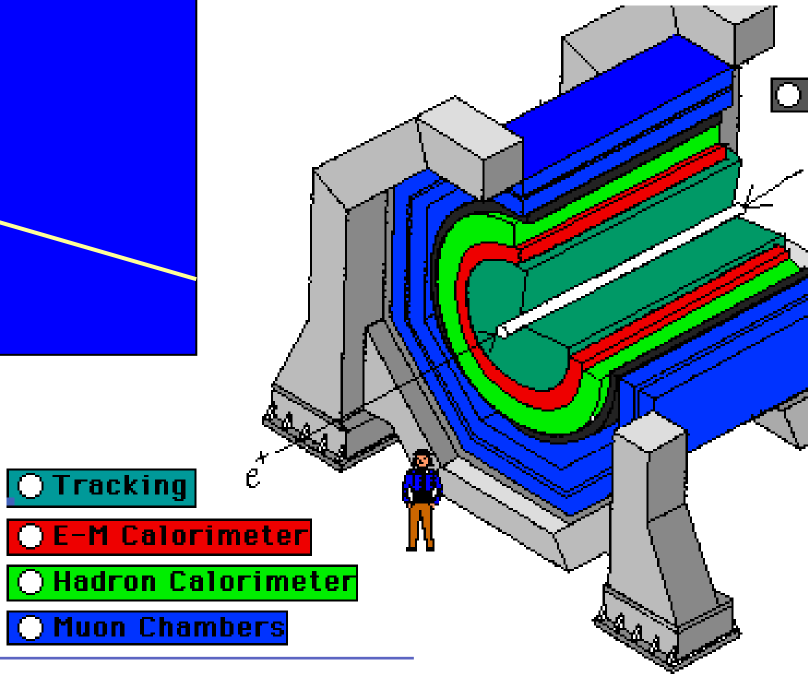


Since charge clusters need to drift to anode for amplification, time delay proportional to drift distance → Drift chamber

Modern Experiments Comprise a Detector System

Different **components**, measuring different **aspects** of reaction products: track, charge, energy, momentum, particle type, ...

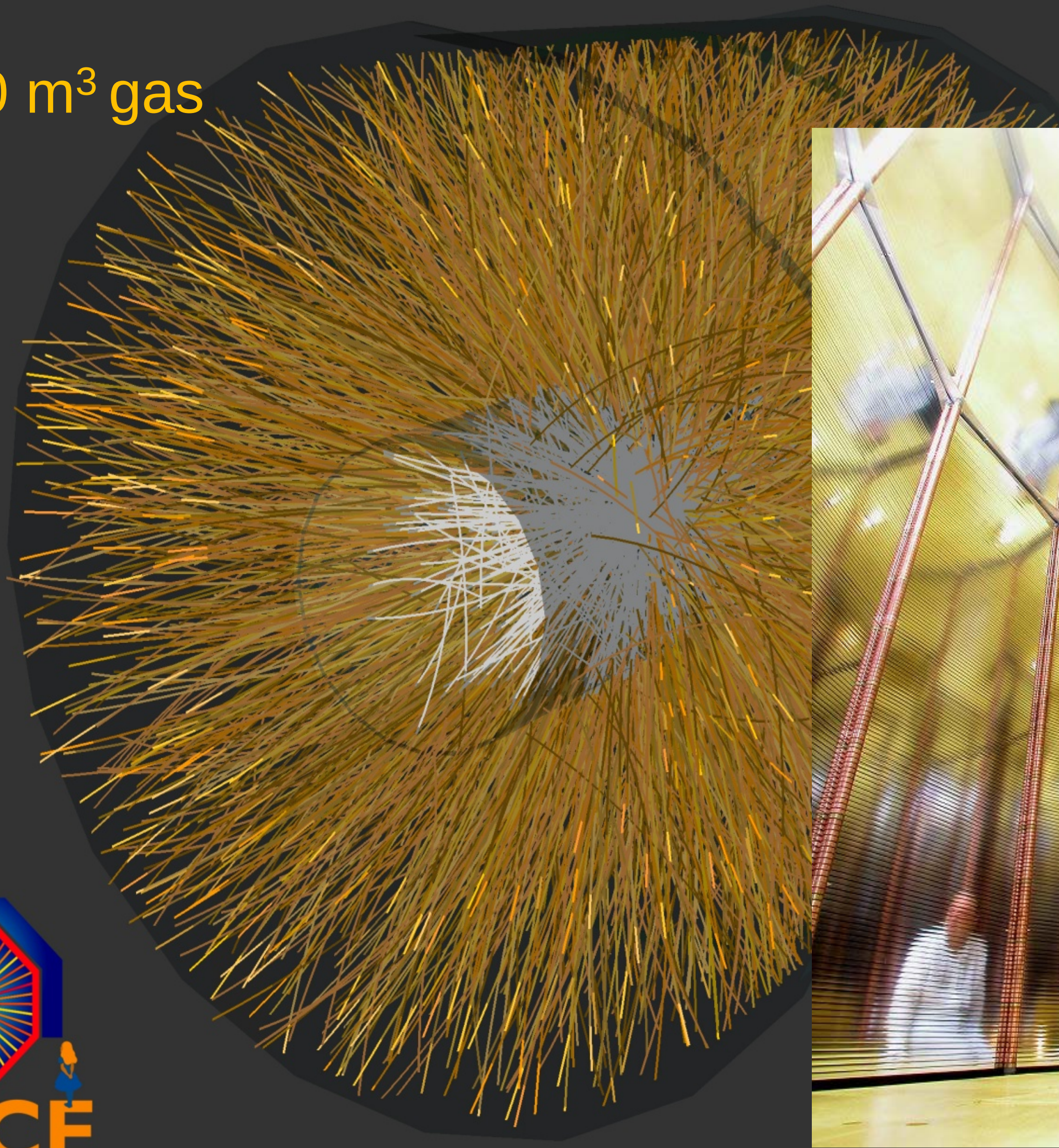


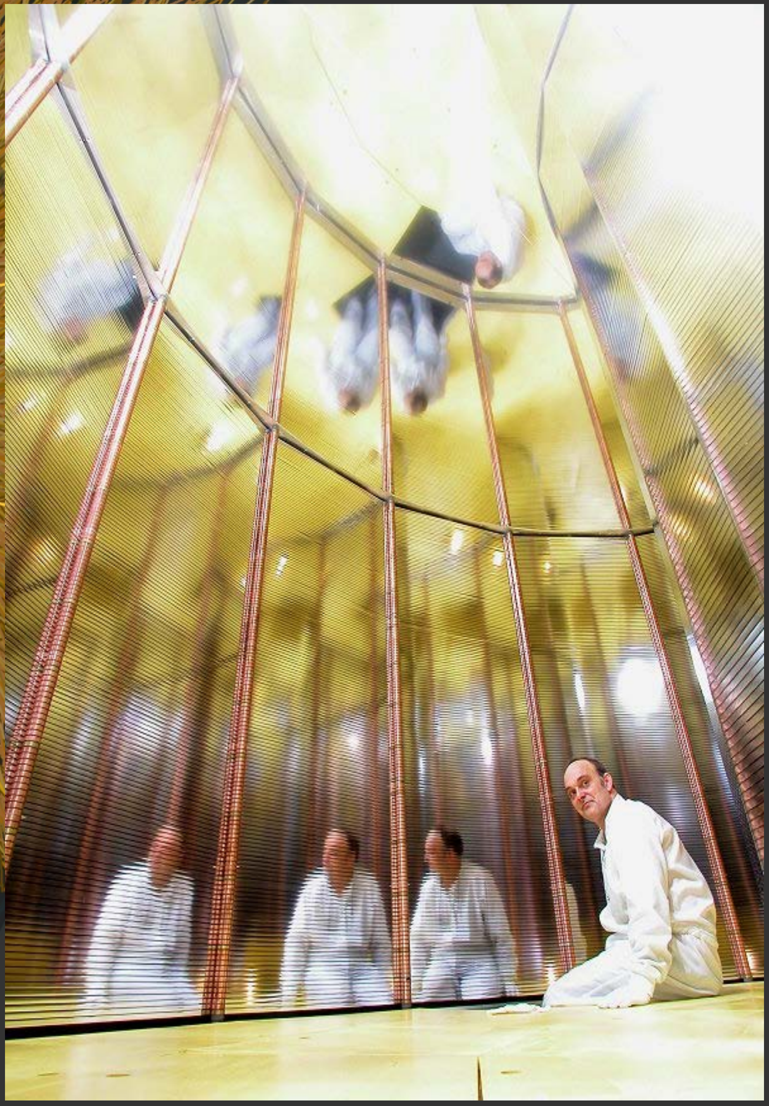


The tracking detector is to see everything....
.....but consist of nothing

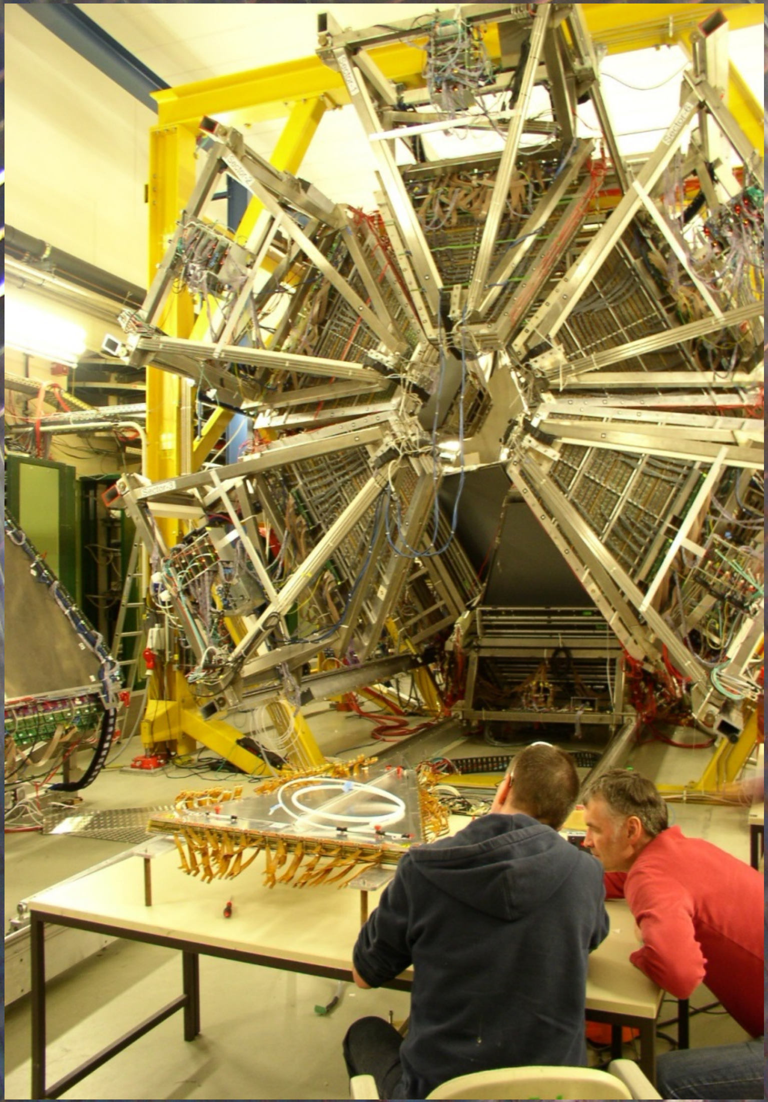
Time Projection Chamber, the Queen of Trackers

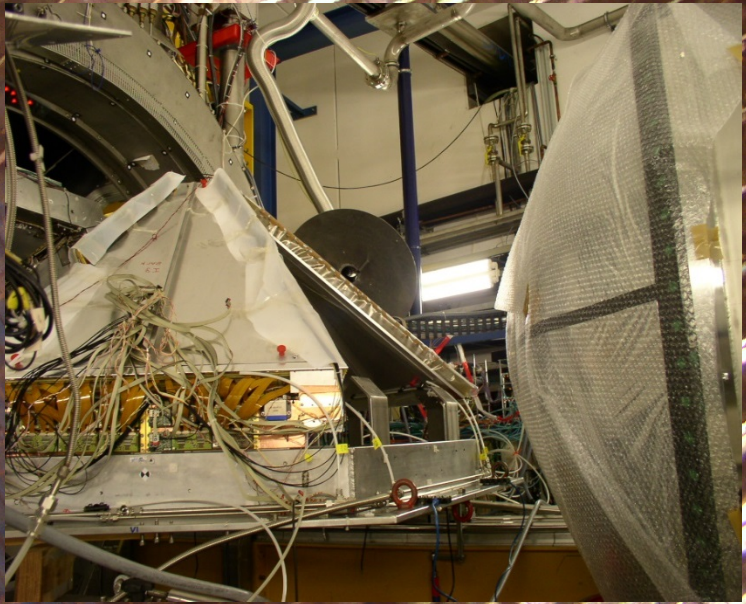
- 100 m^3 gas



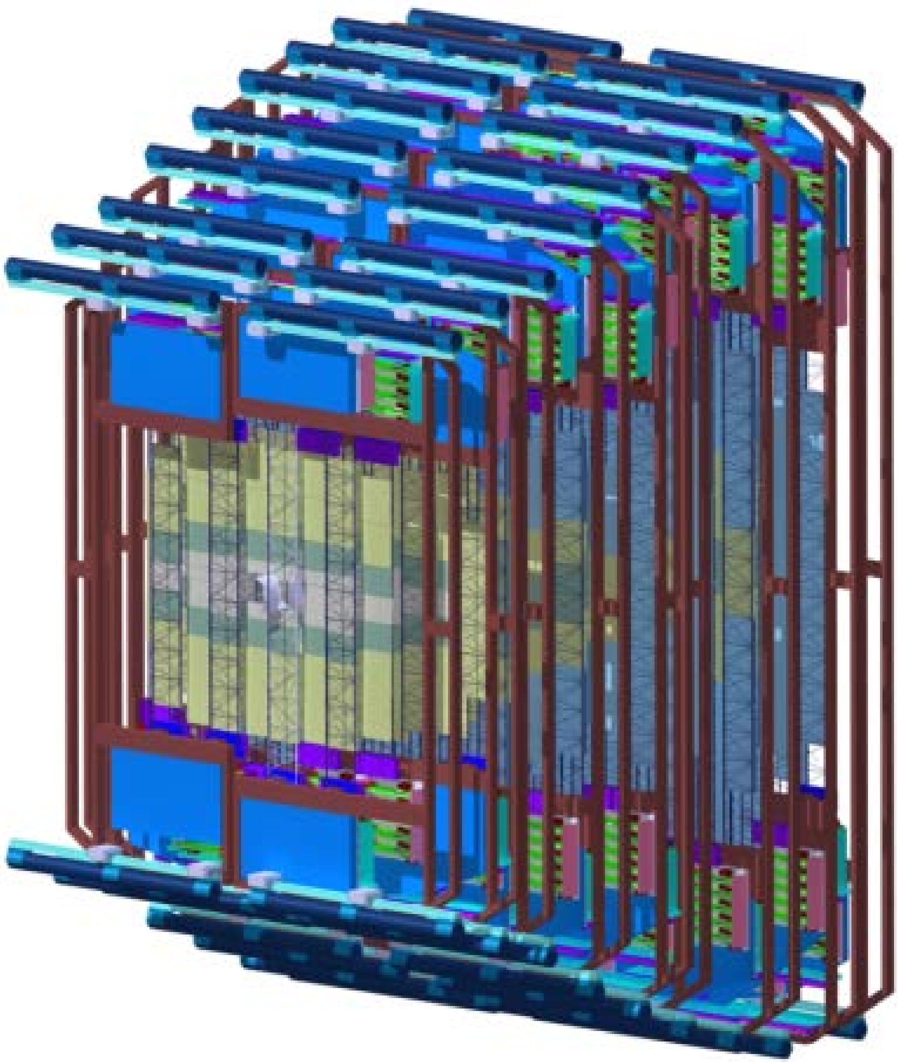


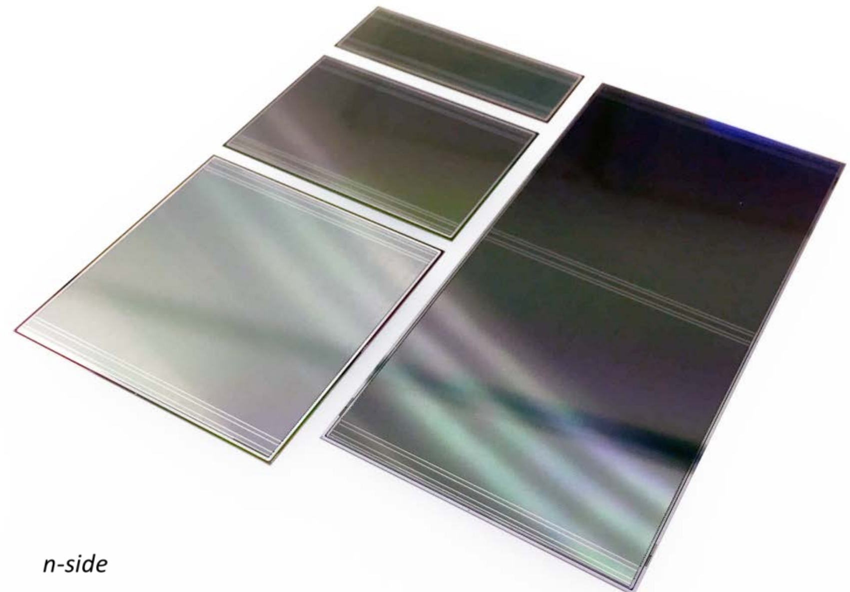
HADES- The GSI Dilepton Spectrometer

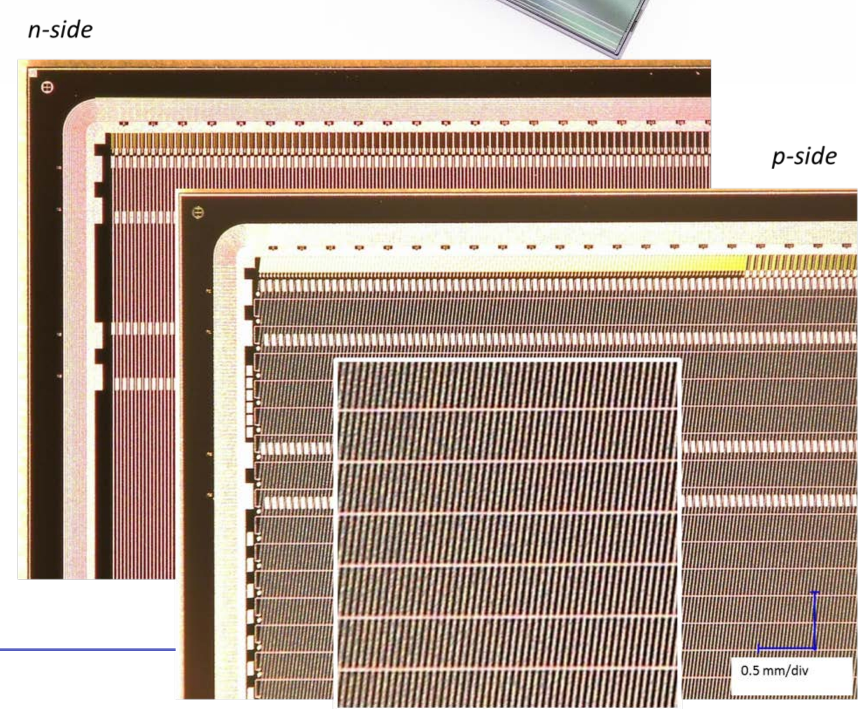




CBM Silicon Tracking System STS

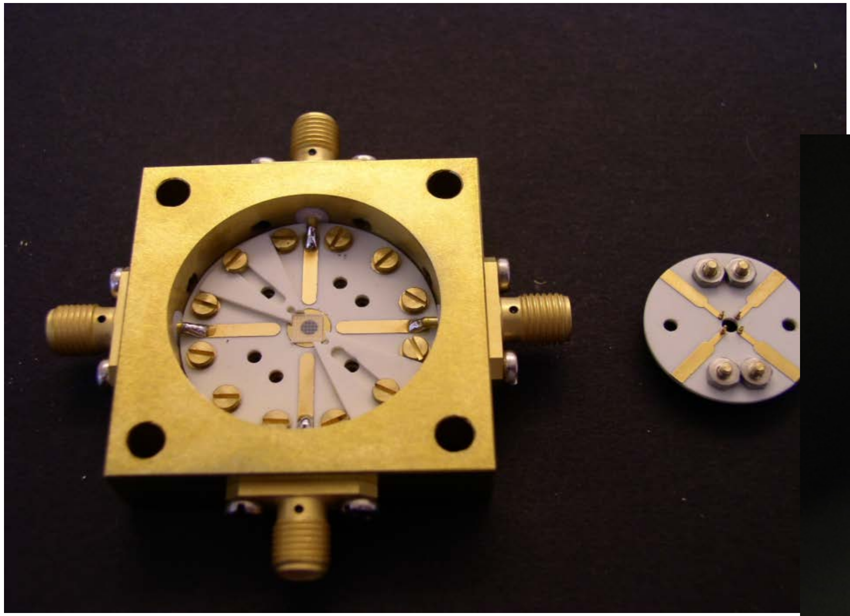


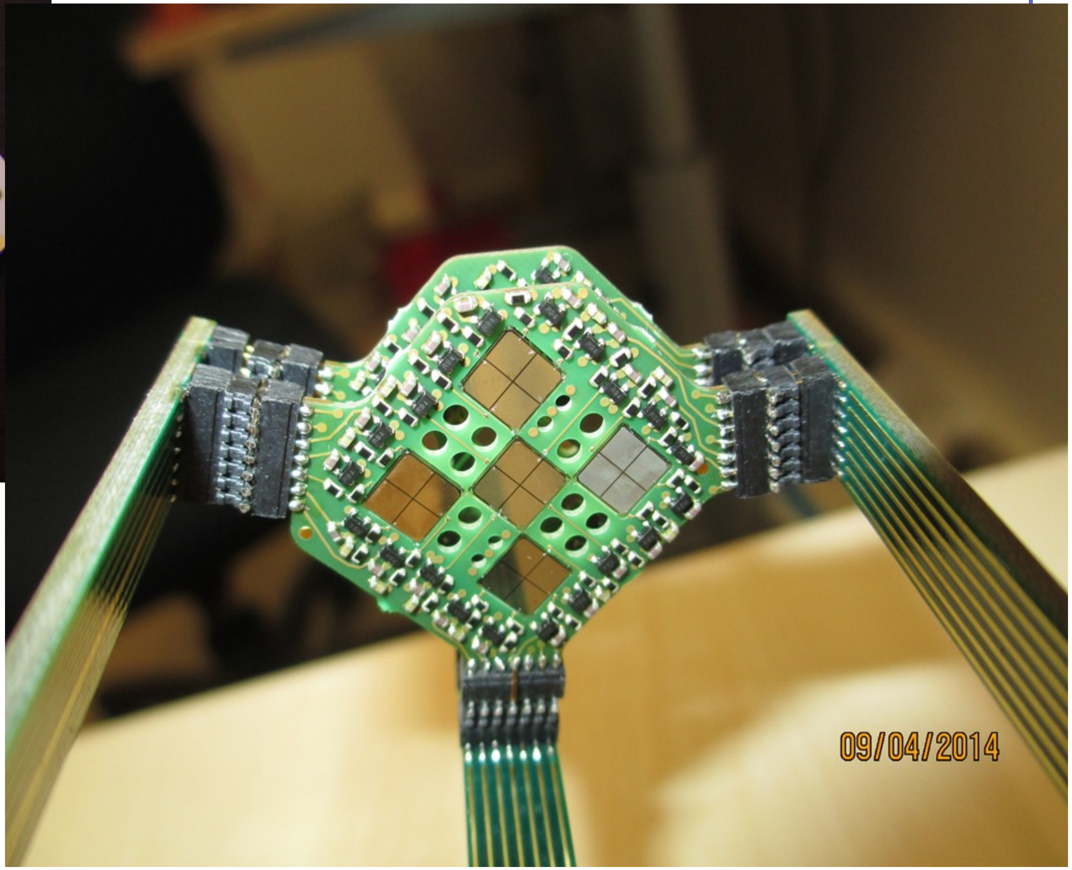




Very Small: Single Crystal- CVD Diamond Detectors

Particle Identification by Time of Flight



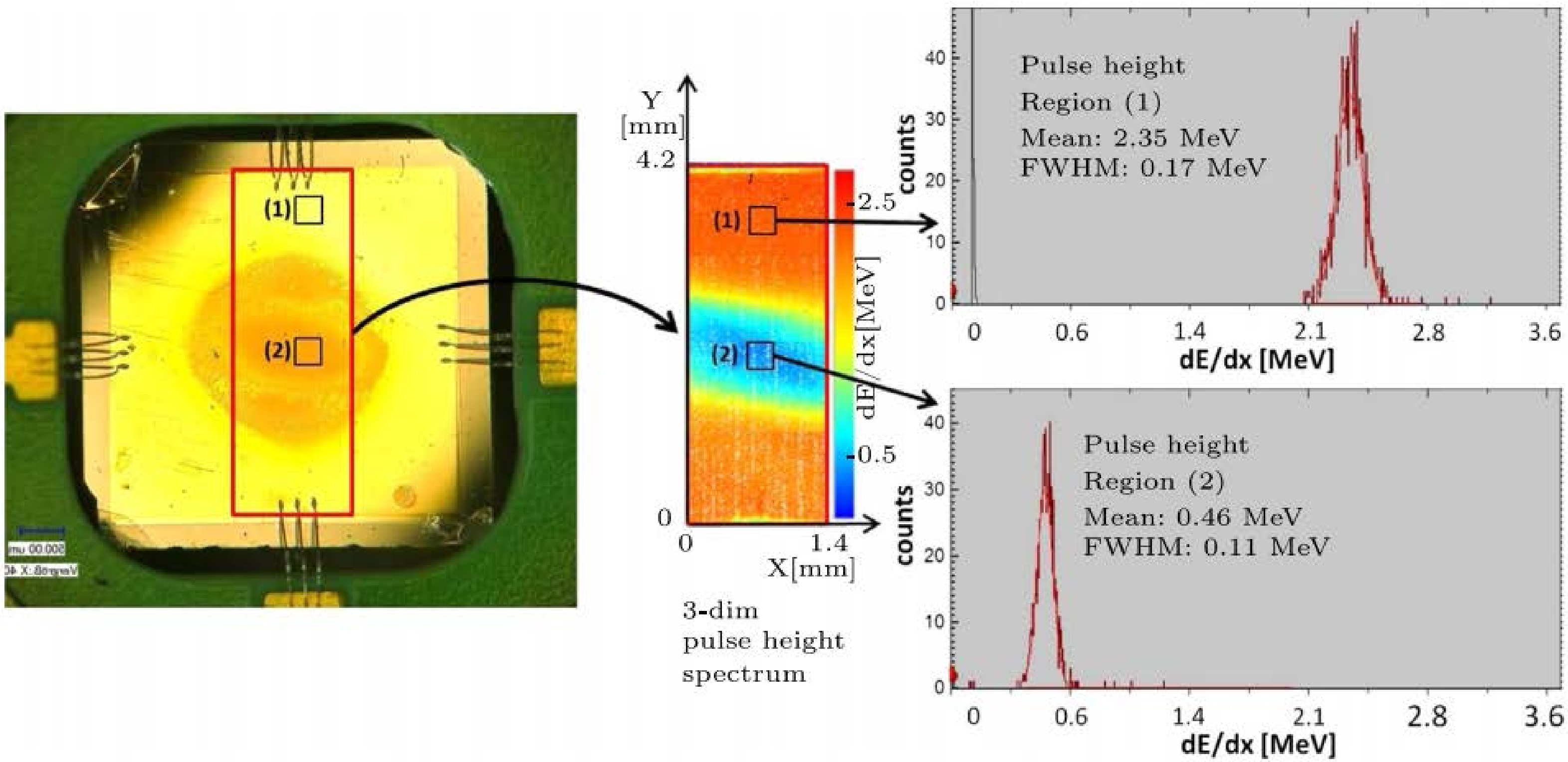


- time resolution better 50ps
- identify particles by speed

exceptional radiation hardness properties

HADES @ GSI

Radiation hard material (scCVD diamond)



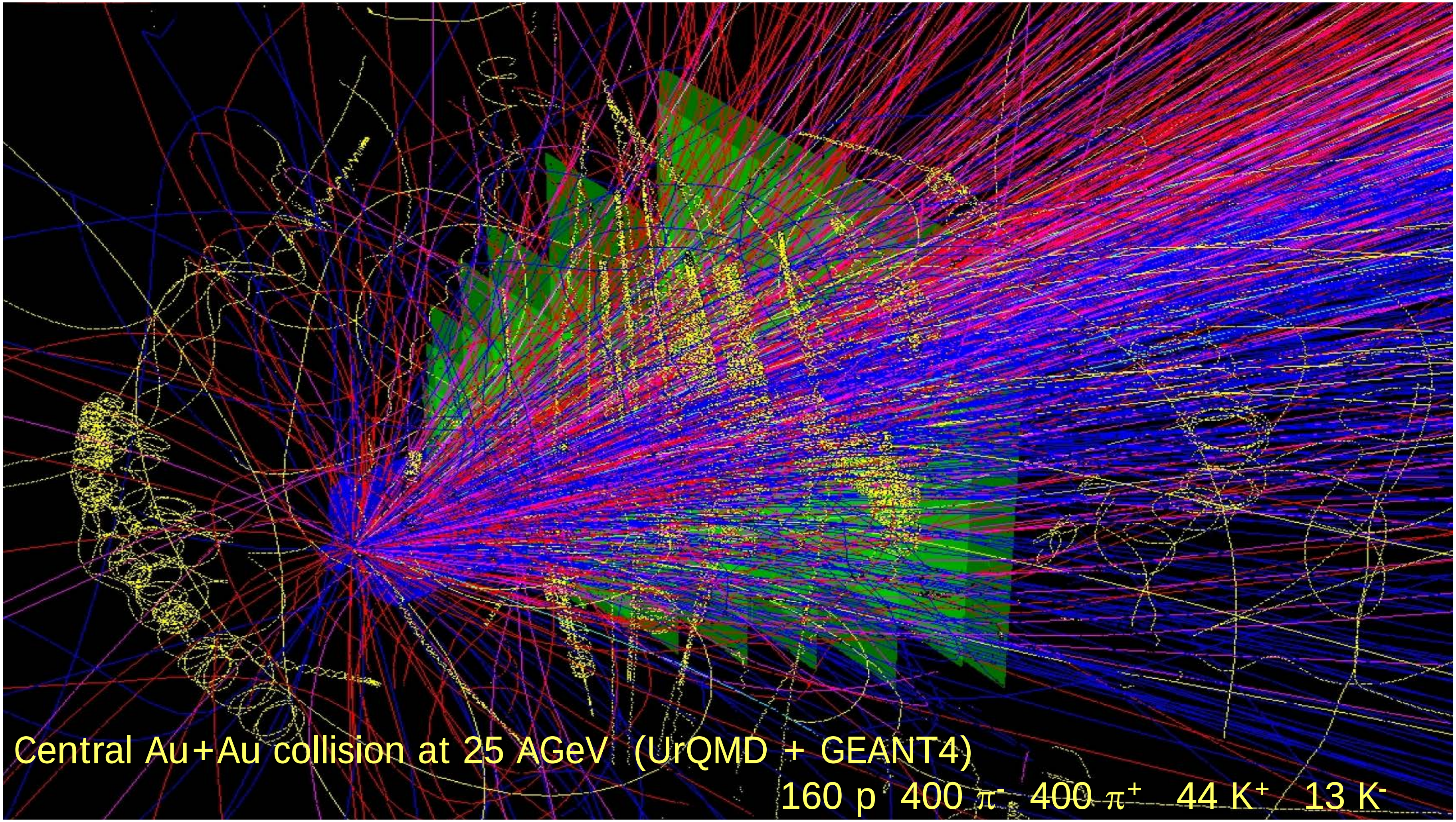
<u>3.04 x 10^{11} Au ions / mm^2 → total absorbed dose: 87 MGy !!!!</u>

→suffered amplitude reduction but still good timing < 70ps

Jerzey Pietrasco et al. at GSI for HADES

Ionization Chambers, Wire Chambers, Solid State Detectors

!The movement of charges in electric fields induces signals on readout electrodes (No discharge, there is no charge flowing from cathode to Anode) !



Signals induced in Detectors by moving Charges

Signals induced on grounded electrodes:

S. Ramo, Currents induced by electron motion, Proc. IRE 27 (1939)

W. Shockley, 1938, Currents to Conductors Induced by a Moving Point Charge, Journal of Applied Physics, vol. 9 (1938) 635

Signals induced on electrodes connected by impedance elements:

E. Gatti, G. Padovini and V. Radeka, Signal evaluation in multielectrode radiation detectors by means of a time dependent weighting vector, Nucl. Instr. and Meth. 193 (1982) 651

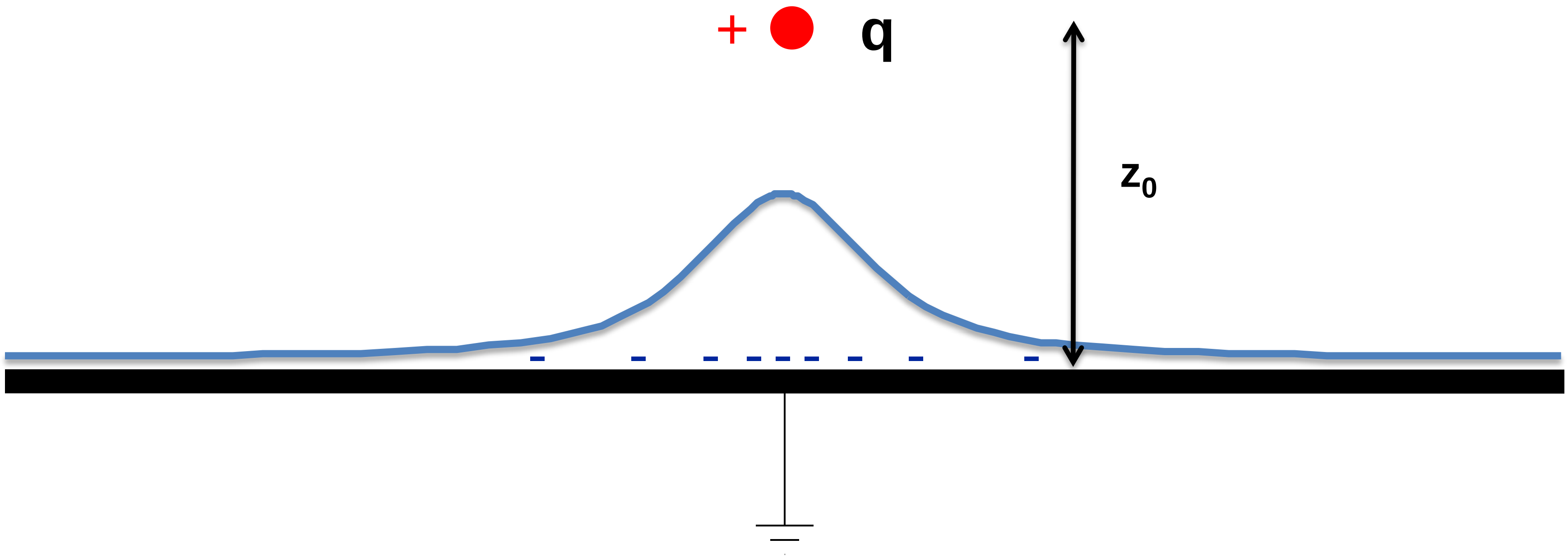
Signals induced on electrodes embedded in materials with finite conductivity and connected with arbitrary impedance elements:

W. Riegler, Extended theorems for signal induction in particle detectors, Nucl. Instr. and Meth. A 535 (2004) 287.

The Principle of Signal Induction on Metal Electrodes by Moving Charges

Induced Charges

A point charge q at a distance z_0 above a grounded metal plate 'induces' a surface charge.



Electrostatics, things we know

Poisson Equation:

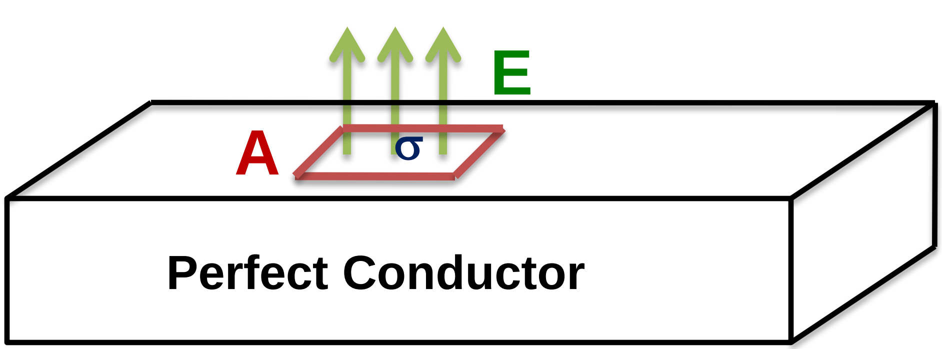
$$\Delta\varphi = -\frac{\rho}{\varepsilon_0} \qquad \vec{E} = -\vec{\nabla}\varphi$$

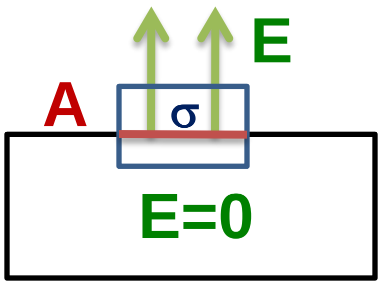
Gauss Law:

$$\oint \vec{E}\, d\vec{A} = \frac{1}{\varepsilon_0} \oint \rho\, dV$$

- → **Metal Surface: Electric Field perpendicular to surface.**
- → **Charges are only on the surface, no electric field in the conductor.**
- → **Surface Charge Density σ and electric E field on the surface are related by**

$$E\,A = \frac{1}{\varepsilon_0}\sigma\,A \qquad \rightarrow \qquad \sigma = \varepsilon_0 E$$





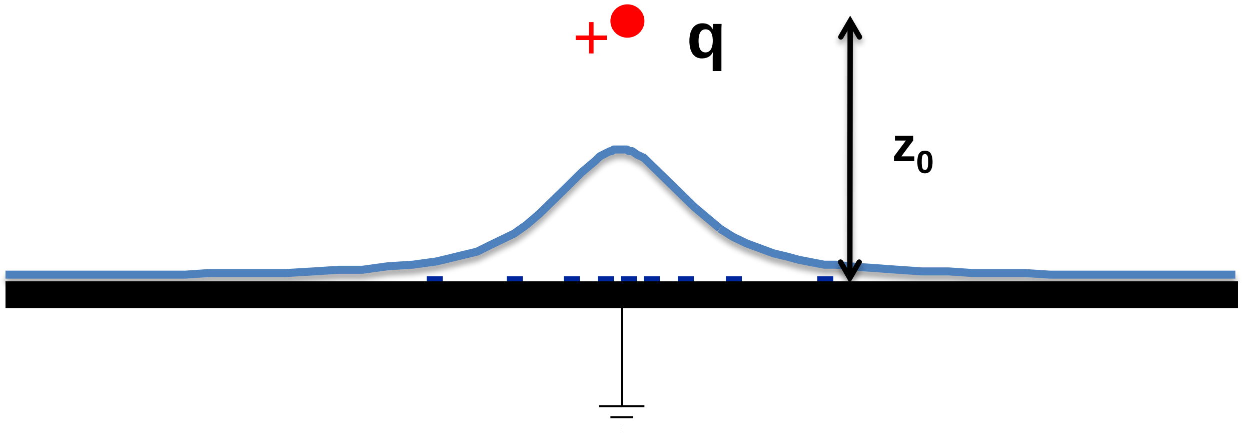
Induced Charges

In order to find the charge induced on an electrode we therefore have to

a) **Solve the Poisson equation with boundary condition that $\varphi = 0$ on the conductor surface.**

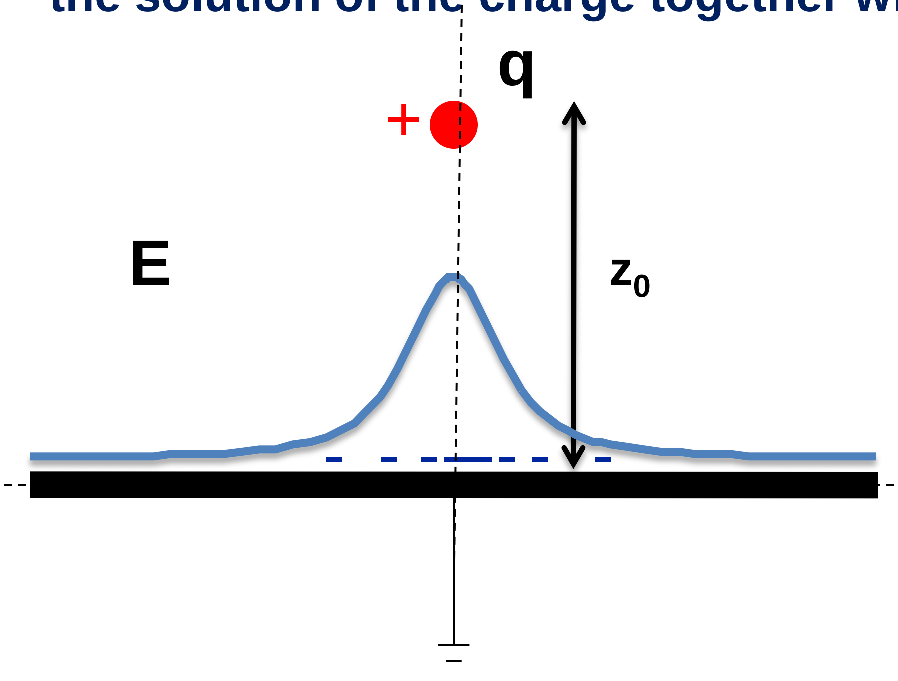
b) **Calculate the electric field E on the surface of the conductor**

c) **Integrate $\varepsilon_0 E$ over the electrode surface.**



Induced Charges

The solution for the field of a point charge in front of a metal plate is equal to the solution of the charge together with a (negative) mirror charge at z=-z_0.



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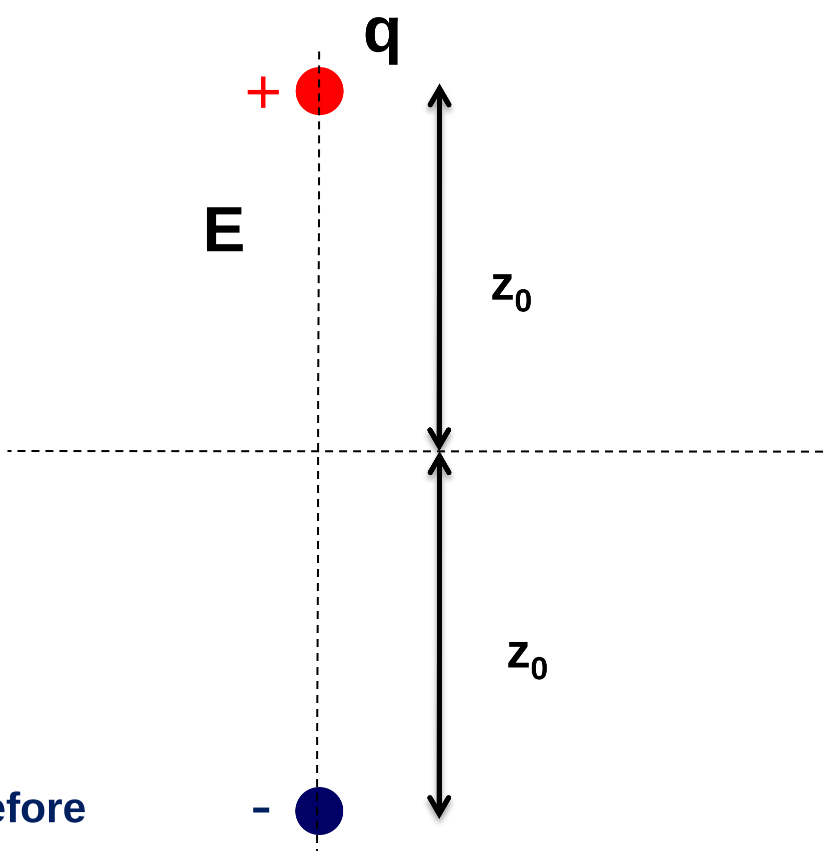


The field on the electrode surface (z=0) is therefore

$$E_z(x,y) = -\frac{q z_0}{2\pi\varepsilon_0 (x^2+y^2+z_0^2)^{\frac{3}{2}}} \qquad E_x = E_y = 0$$

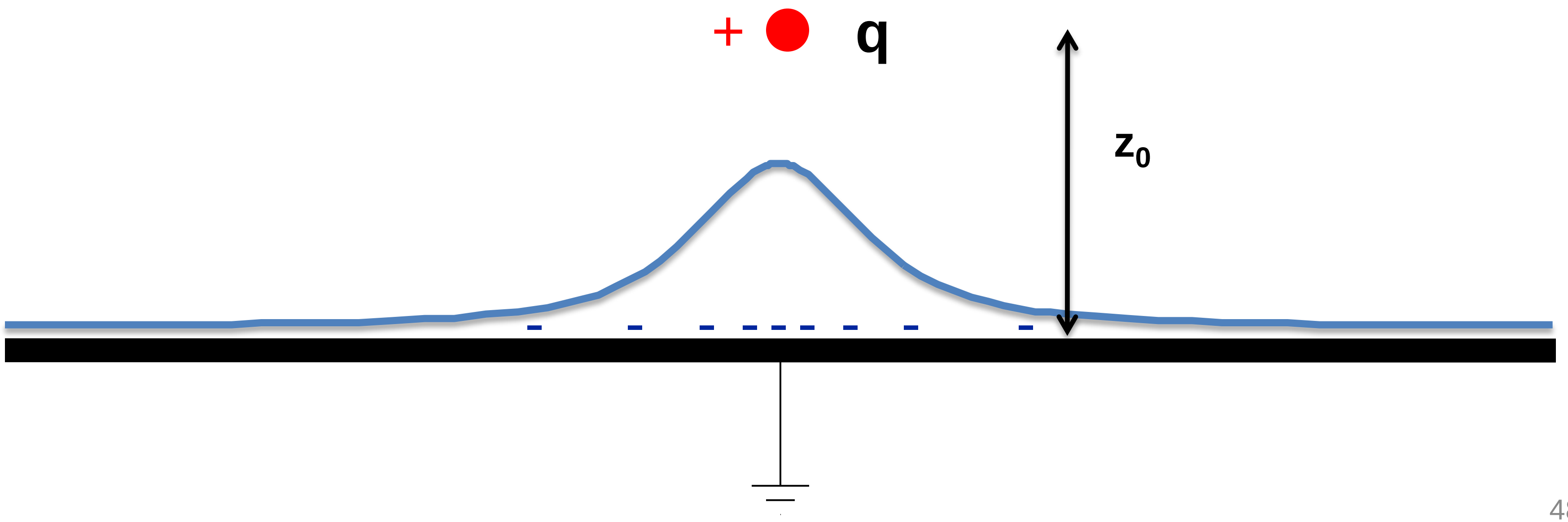
Induced Charges

We therefore find a surface charge density of

$$\sigma(x,y) = \varepsilon_0 E_z(x,y) = -\frac{q z_0}{2\pi(x^2+y^2+z_0^2)^{\frac{3}{2}}}$$

And therefore a total induced charge of

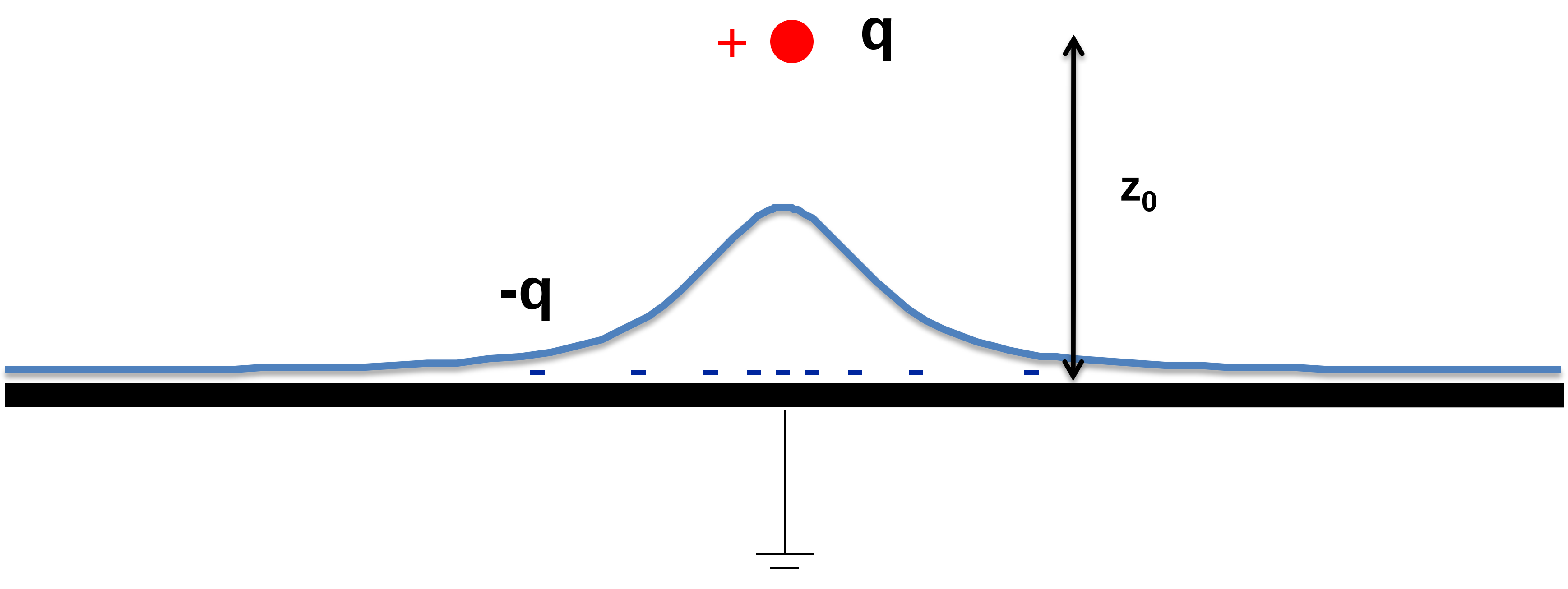
$$Q = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \sigma(x,y)dxdy = -q$$



Induced Charges

The total charge induced by a point charge q on an infinitely large grounded metal plate is equal to –q, independent of the distance of the charge from the plate.

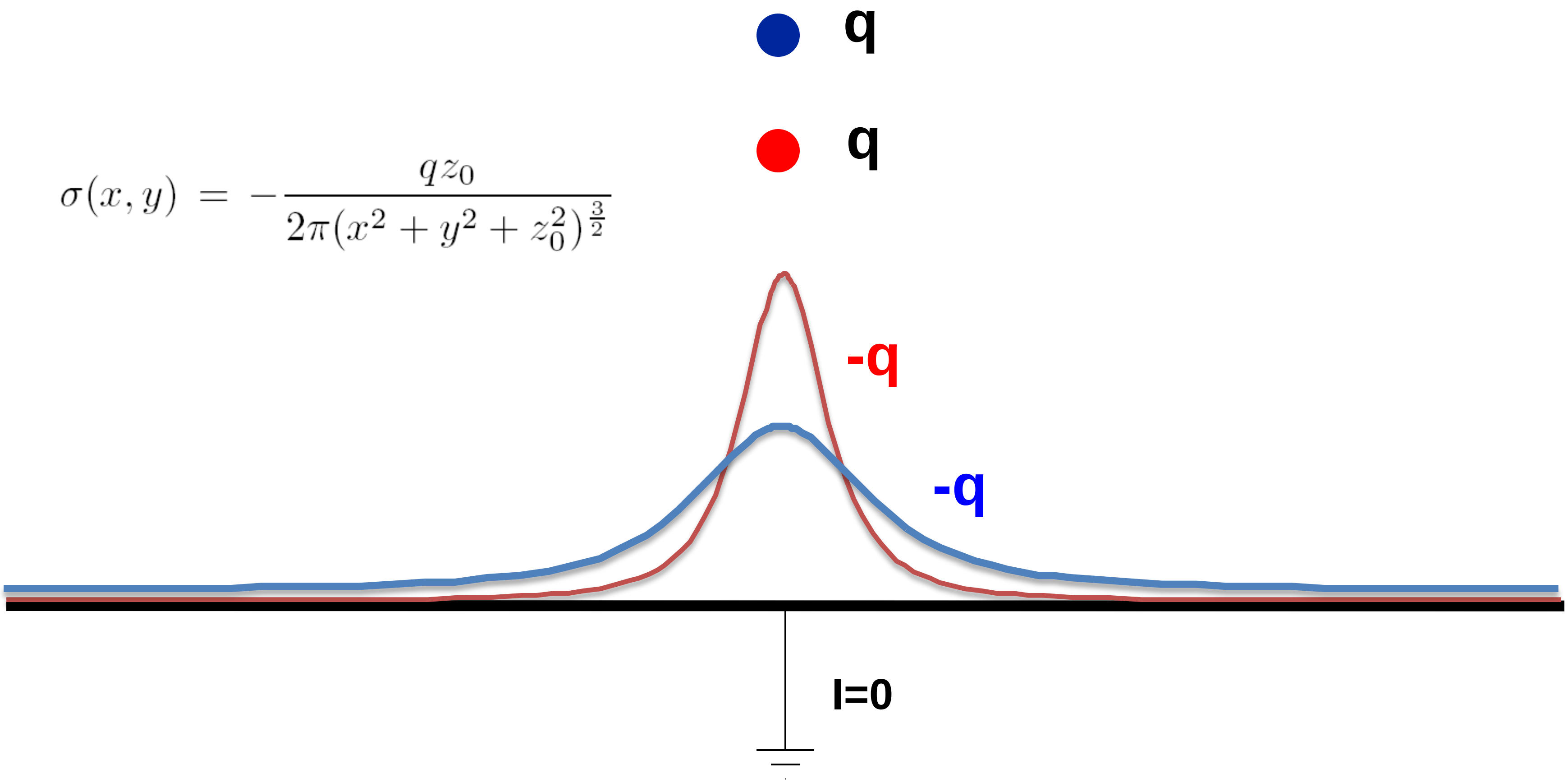
The surface charge distribution does however depend on the distance z_0 of the charge q.



Induced Charges

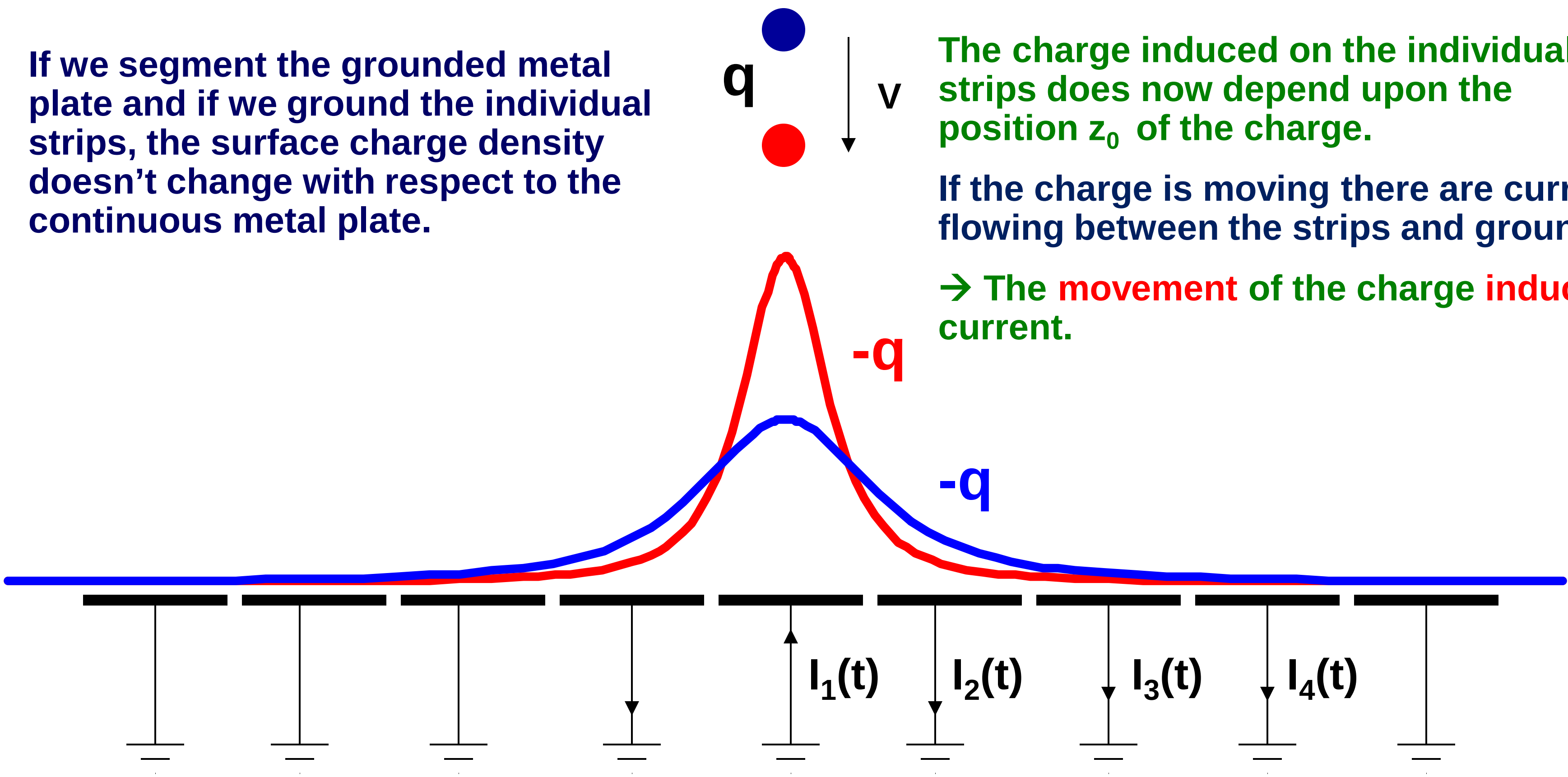
Moving the point charge closer to the metal plate, the surface charge distribution becomes more peaked, the total induced charge is however always equal to –q.

$$\sigma(x,y) = -\frac{q z_0}{2\pi(x^2+y^2+z_0^2)^{\frac{3}{2}}}$$



Signal Induction by Moving Charges

If we segment the grounded metal plate and if we ground the individual strips, the surface charge density doesn't change with respect to the continuous metal plate.



The charge induced on the individual strips does now depend upon the position z_0 of the charge.

If the charge is moving there are currents flowing between the strips and ground.

→ The movement of the charge induces a current.

$$Q_1(z_0) = \int_{-\infty}^{\infty}\int_{-w/2}^{w/2} \sigma(x,y)dxdy = -\frac{2q}{\pi}\arctan\left(\frac{w}{2z_0}\right) \qquad z_0(t) = z_0 - vt$$

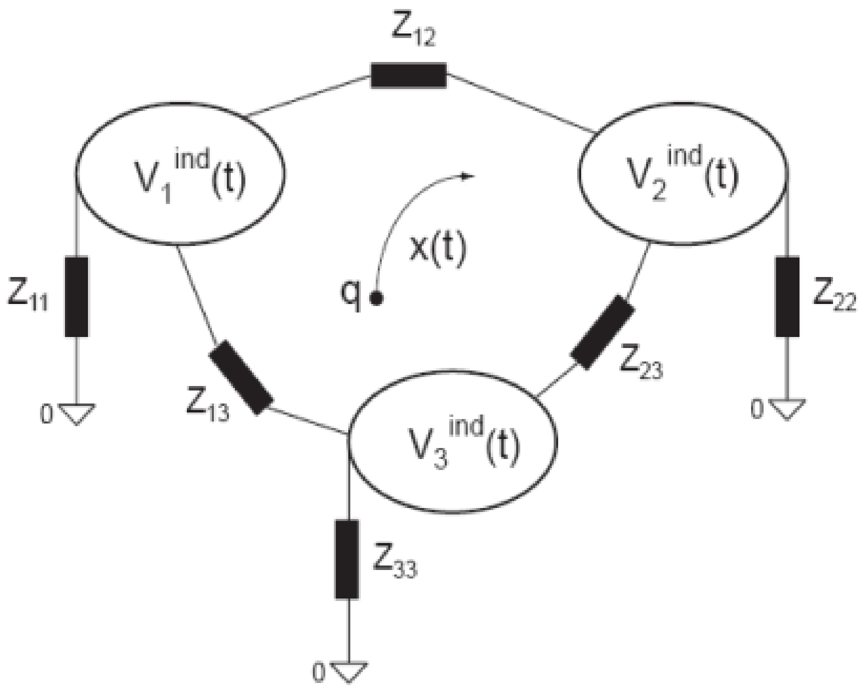
$$I_1^{ind}(t) = -\frac{d}{dt}Q_1[z_0(t)] = -\frac{\partial Q_1[z_0(t)]}{\partial z_0}\frac{dz_0(t)}{dt} = \frac{4qw}{\pi[4z_0(t)^2 + w^2]}v$$

a little more general, more practical

In a real particle detector, the electrodes (wires, cathode strips, silicon strips, plate electrodes …) are not grounded but they are connected to readout electronics and interconnected by other discrete elements and kept at different potentials.

We want to answer the question:

What are the voltages induced on metal electrodes by a charge q moving along a trajectory x(t), in case these metal electrodes are connected by arbitrary linear impedance components ?

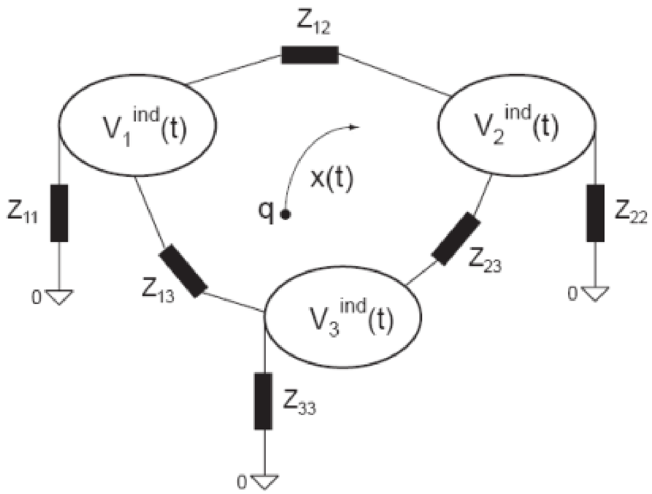


solution in two steps

We first calculate the currents induced on grounded electrodes.

We then insert the currents as ideal current sources,

shrink the electrodes to nodes and add all the inter-node impedances.



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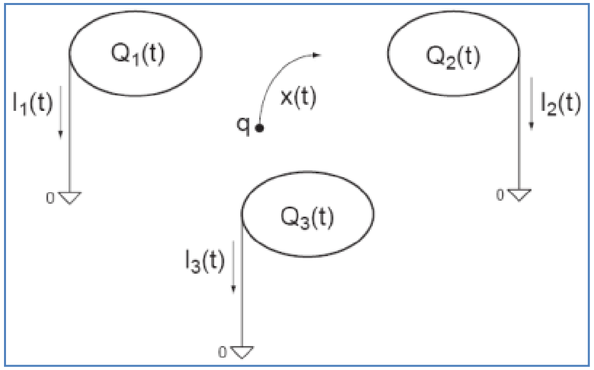

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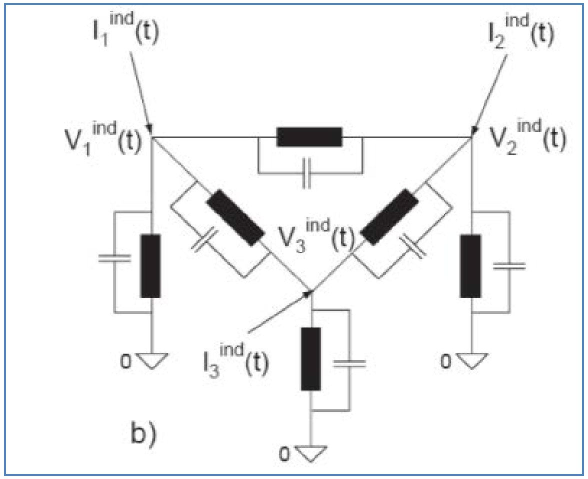
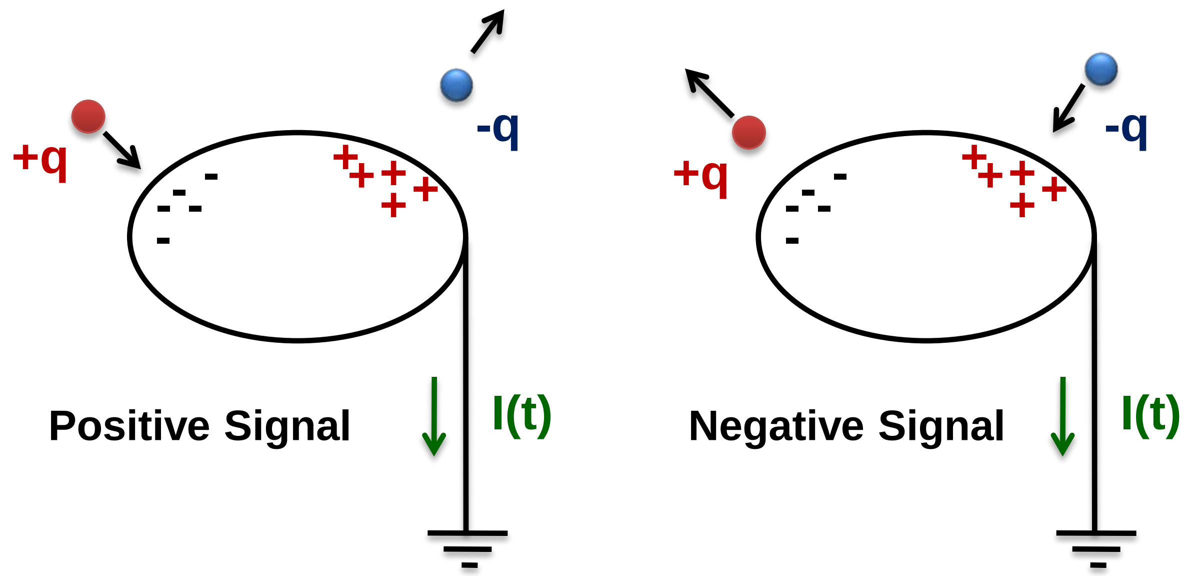


The second step is typically performed by using an analog circuit simulation program. We will focus on the induced currents.

Signal Polarity Definition

$$I(t) = -\frac{dQ(t)}{dt}$$



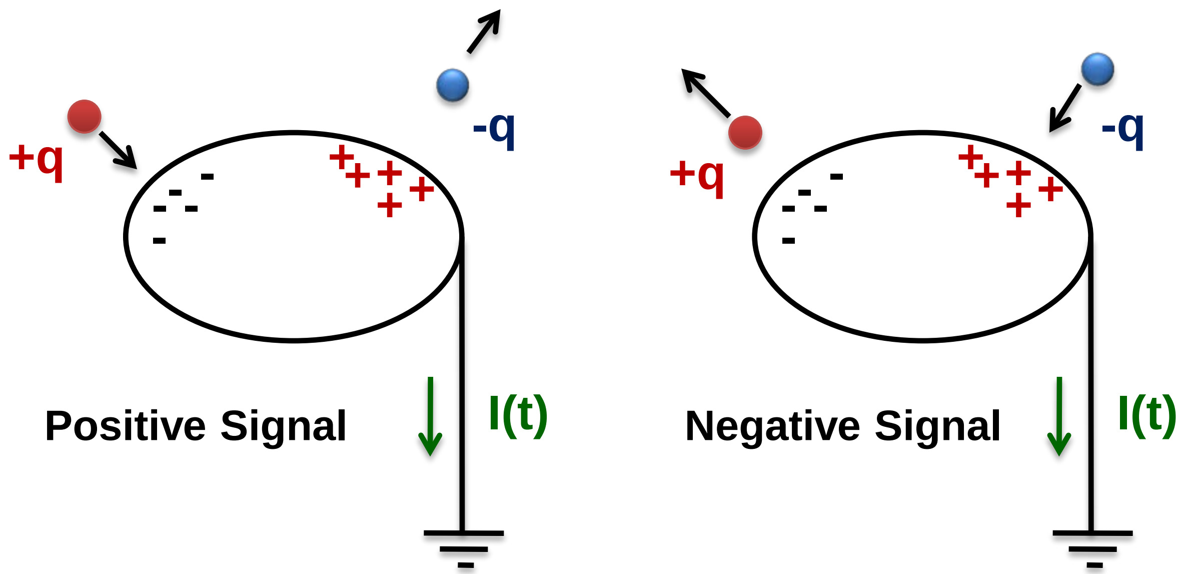
The definition of I = -dQ/dt states that the positive current is pointing away from the electrode.

The signal is positive if:
Positive charge is moving from electrode to ground or
Negative charge is moving from ground to the electrode

The signal is negative if:
Negative charge is moving from electrode to ground or
Positive charge is moving from ground to the electrode

Signal Polarity Definition

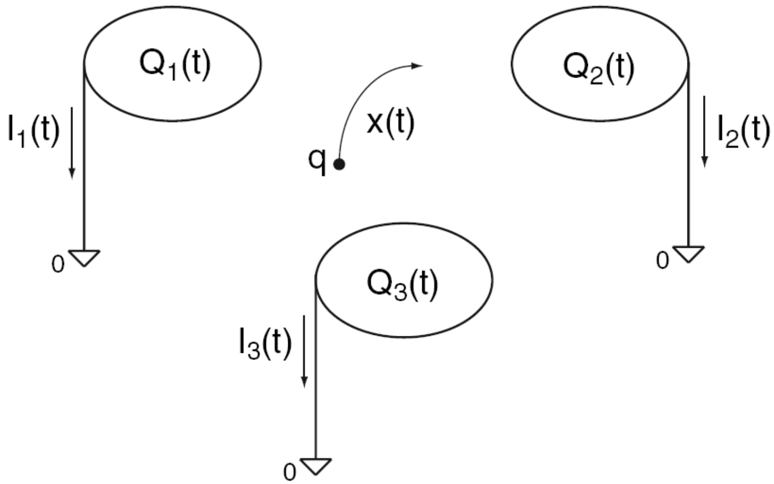
$$I(t) = -\frac{dQ(t)}{dt}$$

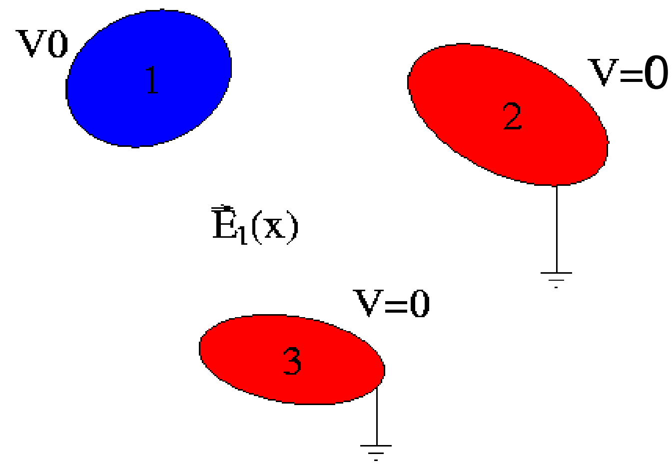


By this we can guess the signal polarities:

In a wire chamber, the electrons are moving towards the wire, which means that they attract positive charges that are moving from ground to the electrode. The signal of a wire that collects electrons is therefore negative.

Induced Current, Ramo Shockley Theorem
the general, arbitrary electrode case





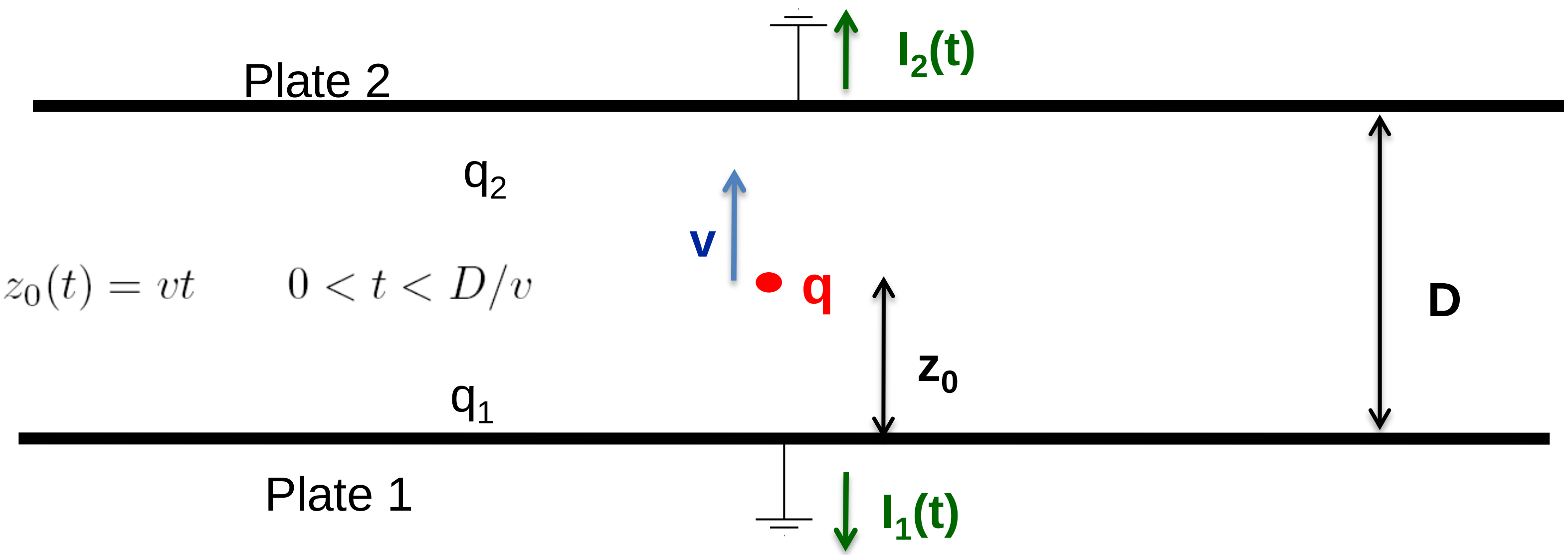
The current induced on a grounded electrode n by a moving point charge q is given by

$$I_n(t) == -\frac{q}{V_w} \vec{E}_n\left(\vec{x}(t)\right) \vec{v}(t)$$

Where the weighting field E_n is defined by removing the point charge, setting the electrode in question to potential V_w and keeping the other electrodes grounded.

Removing the charge means that we just have to solve the Laplace equation and not the Poisson equation !

Parallel Plate Chamber



Weighting field E_1 of plate 1: Remove charge, set plate1 to V_w and keep plate2 grounded

$$E_1 = \frac{V_w}{D}$$

Weighting field E_2 of plate 2: Remove charge, set plate2 to V_w and keep plate1 grounded

$$E_2 = -\frac{V_w}{D}$$

So we have the induced currents

$$I_1 = -\frac{q}{V_w}\frac{V_w}{D}E_1 v = -\frac{qv}{D} \qquad I_2 = -\frac{q}{V_w}\frac{V_w}{D}E_2 v = \frac{qv}{D}$$

Signal Calculation in 3 Steps

What are the signals induced by a moving charge on electrodes that are connected with arbitrary linear impedance elements ?

1) Calculate the particle trajectory in the 'real' electric field.

2) Remove all the impedance elements, connect the electrodes to ground and calculate the currents induced by the moving charge on the grounded electrodes.

The current induced on a grounded electrode by a charge q moving along a trajectory x(t) is calculated the following way (Ramo Theorem):

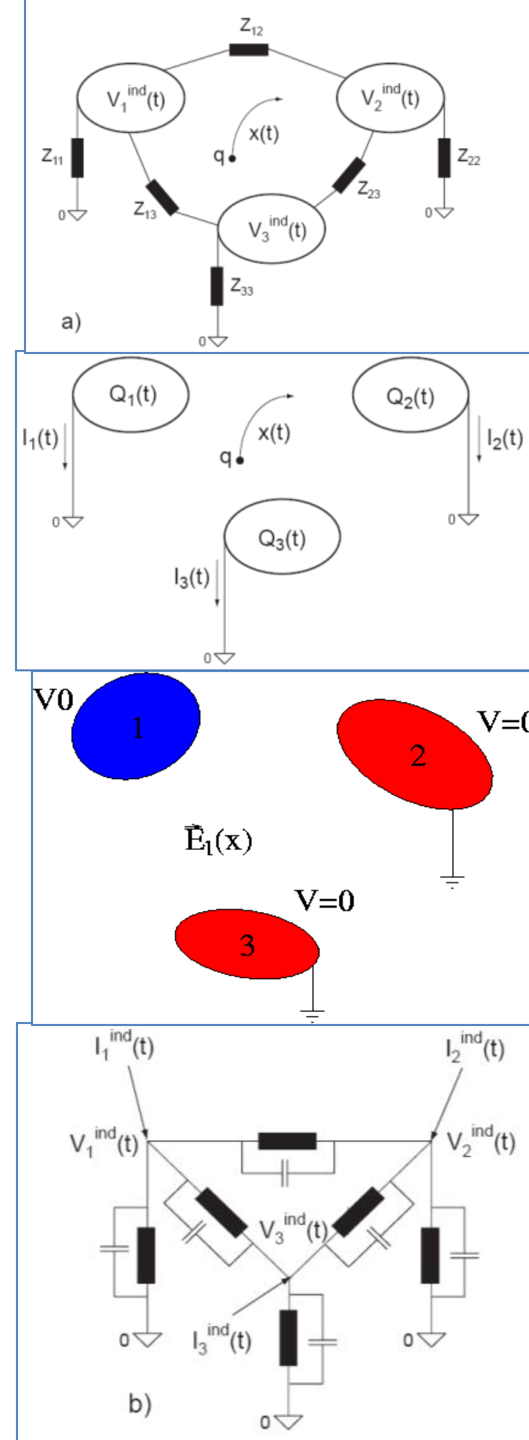
$$I_n(t) = -\frac{q}{V_0}\vec{E}_n[\vec{x}(t)]\frac{d\vec{x}(t)}{dt} = -\frac{q}{V_0}\vec{E}_n[\vec{x}(t)]\vec{v}(t)$$

Weighting Field E_n:

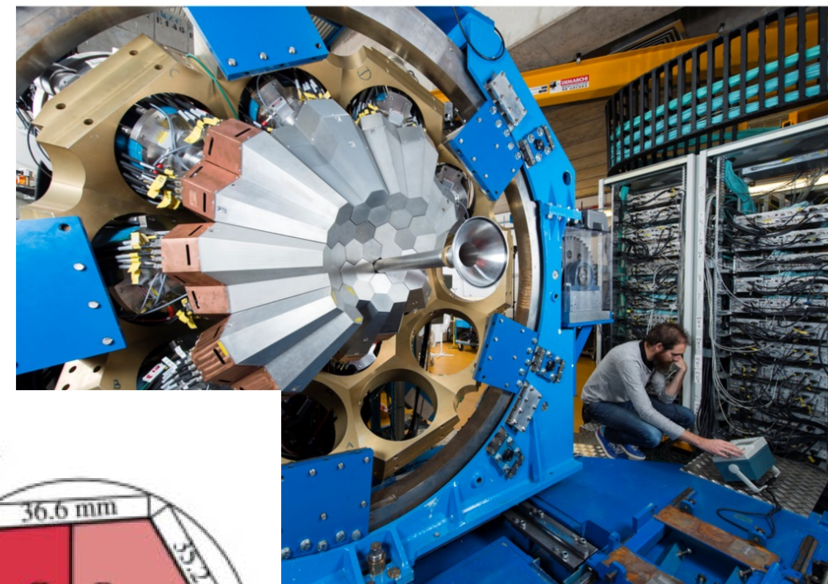
Remove q from the setup, set the electrode to voltage V_0 while keeping all other electrodes grounded. This results in an electric field $E_n(x)$, the Weighting Field

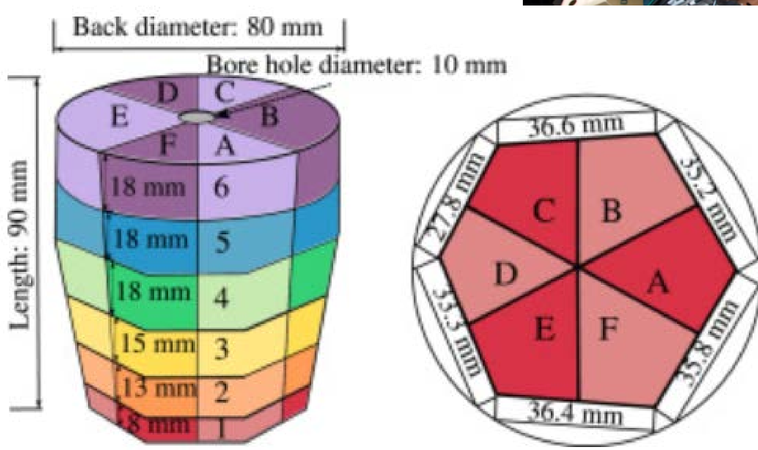
3) These currents are then placed as ideal current sources on a circuit where the electrodes are 'shrunk' to simple nodes and the mutual electrode capacitances are added between the nodes. These capacitances are calculated from the weighting fields by

$$c_{nm} = \frac{\varepsilon_0}{V_w}\oint_{\boldsymbol{A}_n}\boldsymbol{E}_m(\boldsymbol{x})d\boldsymbol{A} \qquad C_{nn} = \sum_m c_{nm} \qquad C_{nm} = -c_{nm} \quad n \neq m$$

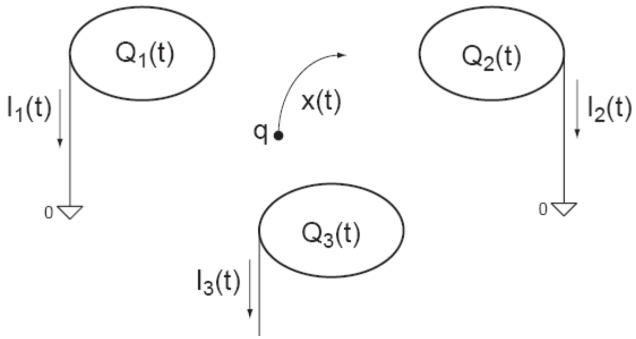


Careful design of multi-electrode, highly segmented Germanium Crystal Detectors and full understanding of the signals along Ramo, Shockley and the Weighting field were the basis for AGATA Gamma Tracking → Lecture by Andreas Heinz





General Signal Theorems

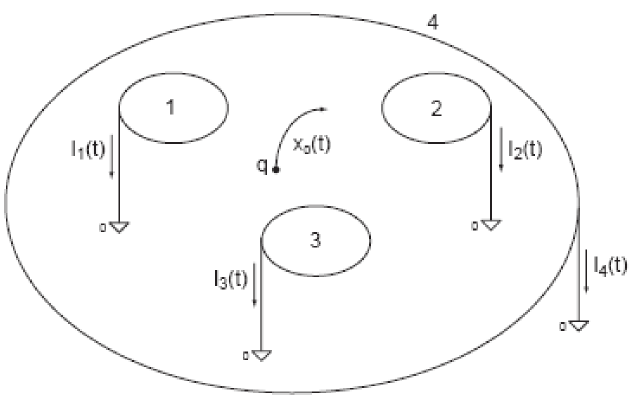


The following relations hold for the induced currents:

1) The charge induced on an electrode through a charge moving from a point x_0 to a point x_1 is

$$Q_n^{ind} = \int_{t_0}^{t_1} I_n^{ind}(t)dt = -\frac{q}{V_w}\int_{t_0}^{t_1} \boldsymbol{E}_n[\boldsymbol{x}(t)]\,\dot{\boldsymbol{x}}(t)dt = \frac{q}{V_w}[\psi_n(\boldsymbol{x}_1) - \psi_n(\boldsymbol{x}_0)]$$

and is independent of the actual path.



2) Once ALL charges have arrived at the electrodes, the total induced charge in the electrodes is equal to the charge that has ARRIVED at the particular electrode.

3) If there is one electrode enclosing all the others, the sum of all induced currents is zero at any time.

take a 3 min break

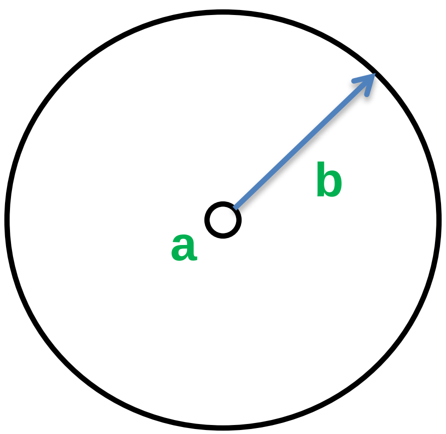
Wire Chamber Signals

People sometimes picture detector signals as ‘the charge entering the electrode and flowing through the amplifier’.

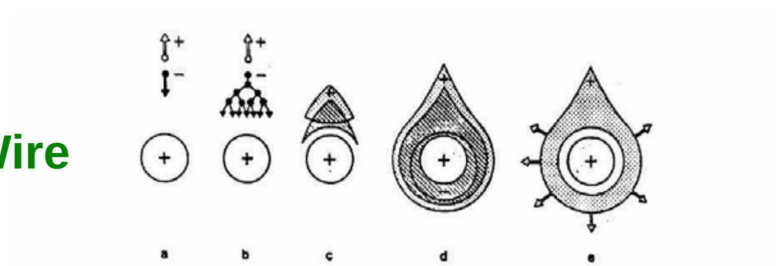
This is very misleading and gives incorrect results – once the moving charges have arrived at the electrodes the signal is over.

The shape of the signal is determined by the movements of the charges in between the electrodes.

Werner Riegler, CERN

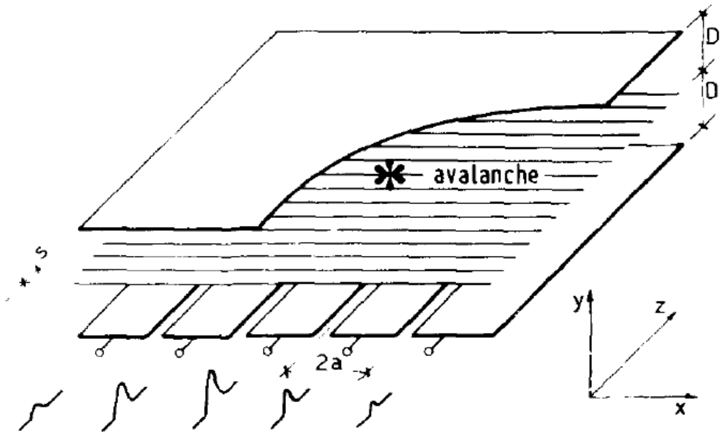


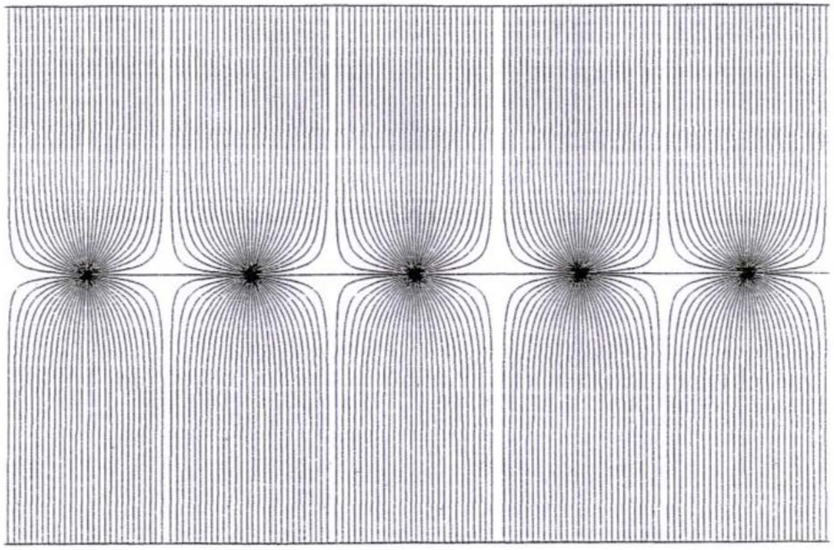
Wire

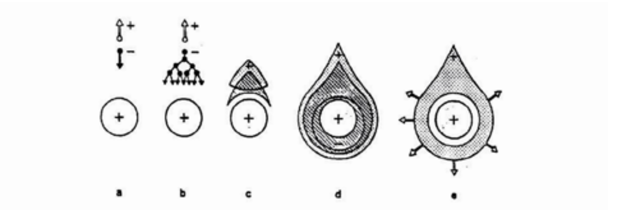


Consequences on wire chamber readout

- Primary charges become visible through avalanche amplification at the anode wire
- negative signals at anode
- induced positive signals at cathodes
- → localized avalanche



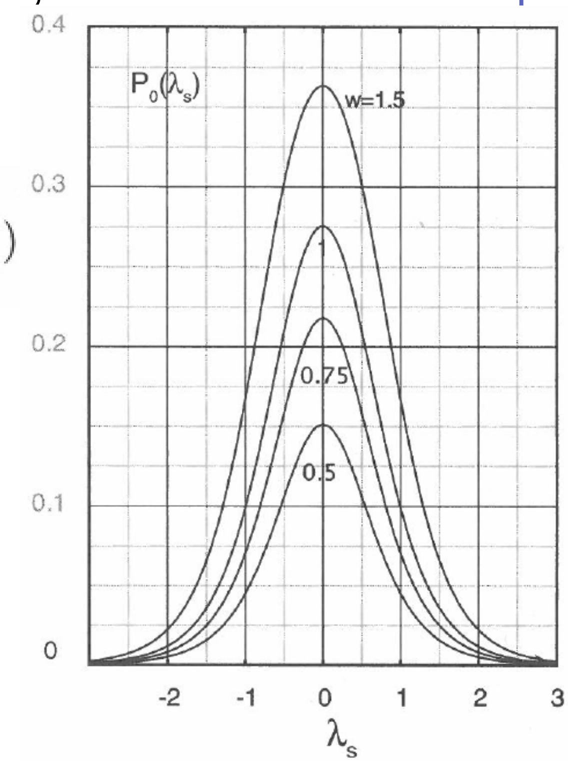


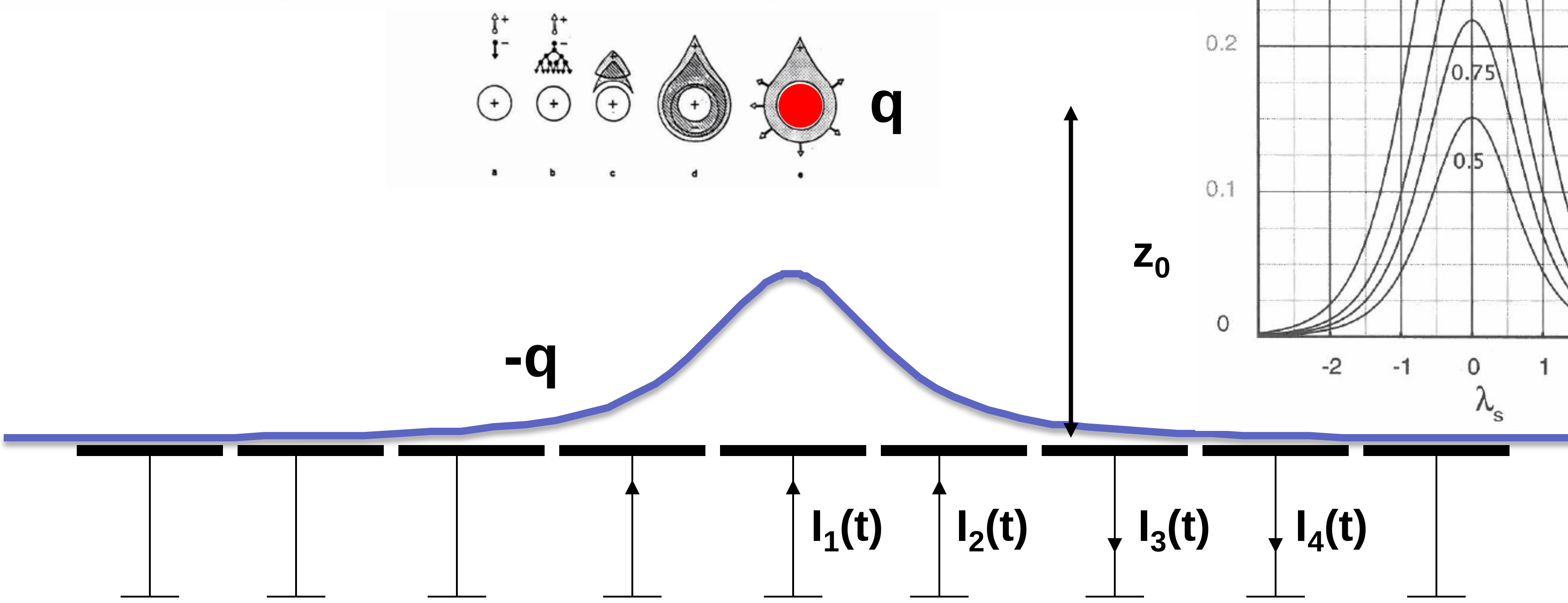


Cathode Pad Response Function $P_o(\lambda)$ in MWPC

- Electrons in avalanche do not travel far
- → surface charge distribution does not change for the fast, electron induced signals
- Signal factorizes into $I_{cathode}(t)$ x Pad Response Function

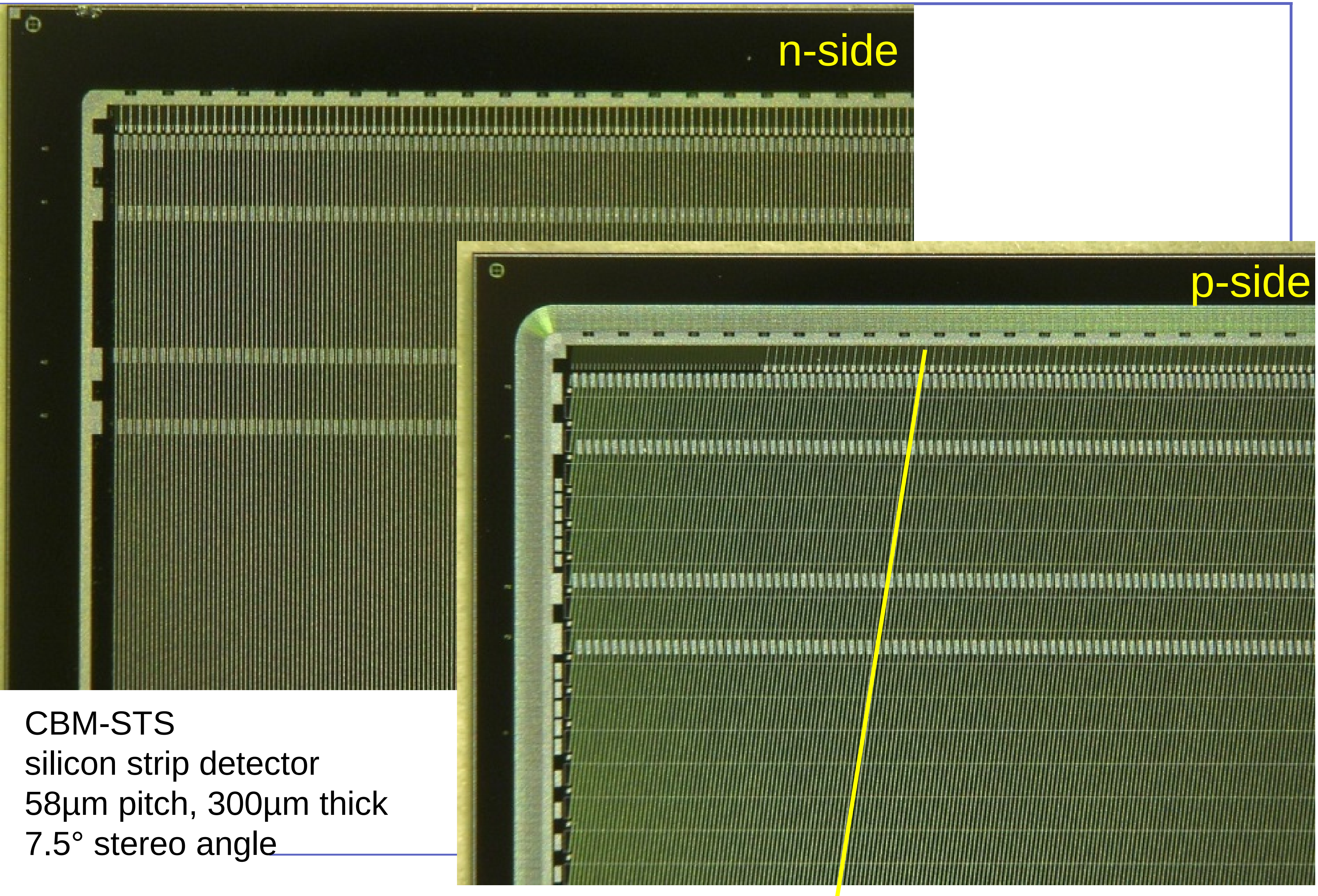
$$I(t,\lambda,w) = \int_{\lambda-w/2}^{\lambda+w/2} dI_{c1}(t,\lambda')d\lambda' = I_c(t)\int_{\lambda-w/2}^{\lambda+w/2} \Gamma(\lambda')d\lambda' = I_c(t)P_0(\lambda)$$





$$Q_1(z_0) = \int_{-\infty}^{\infty}\int_{-w/2}^{w/2} \sigma(x,y)dxdy = -\frac{2q}{\pi}\arctan\left(\frac{w}{2z_0}\right)$$

Further Example: Double Sided Silicon Strip Detector



CBM-STS
silicon strip detector
58µm pitch, 300µm thick
7.5° stereo angle

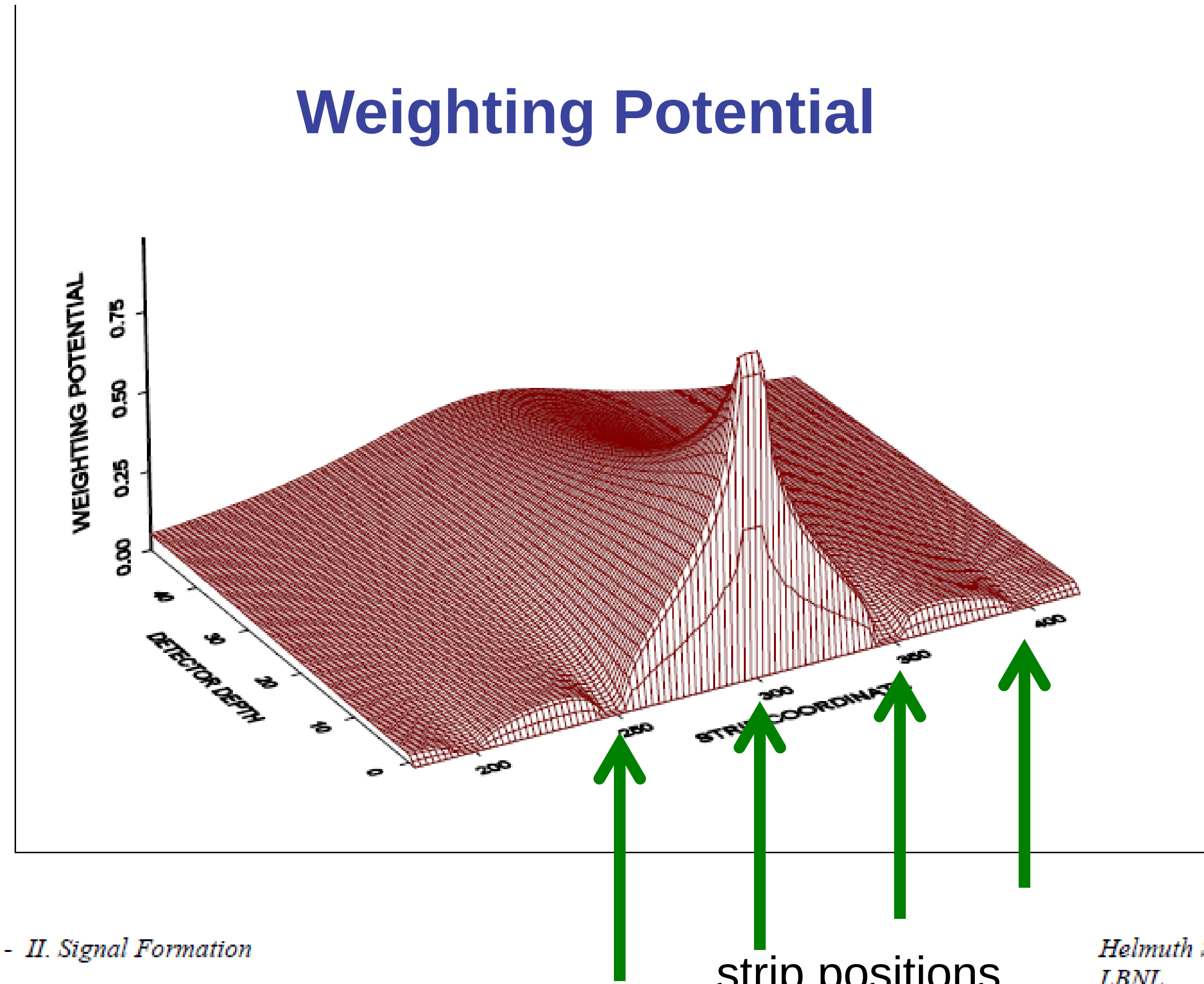
Further Example: Double Sided Silicon Strip Detector

The strip pitch is assumed to be small compared to the thickness.

The electric field is similar to a parallel-plate geometry, except in the immediate vicinity of the strips.

The signal weighting potential, however is very different.

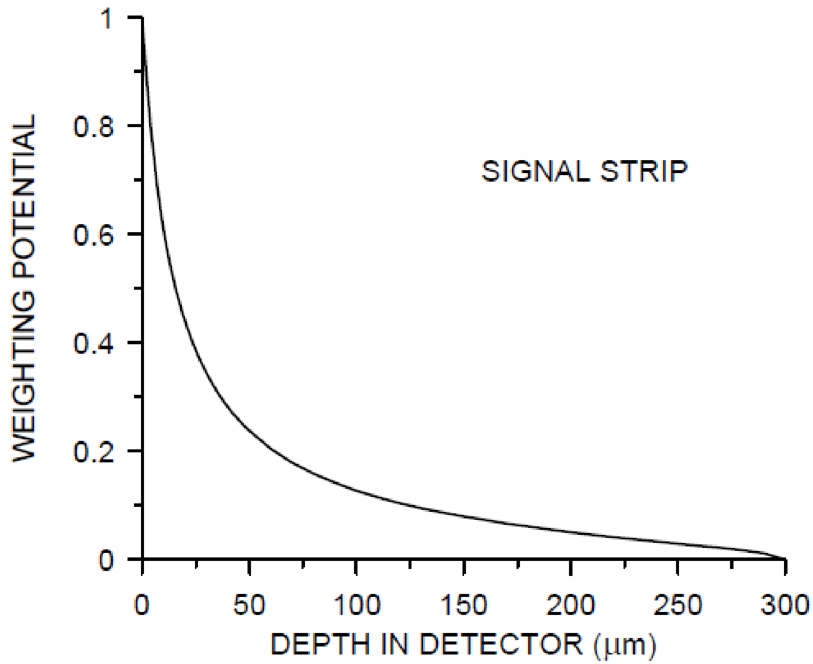
Weighting potential for a 300 µm thick strip detector with strips on a pitch of 50 µm. Only 50 µm of depth are shown.

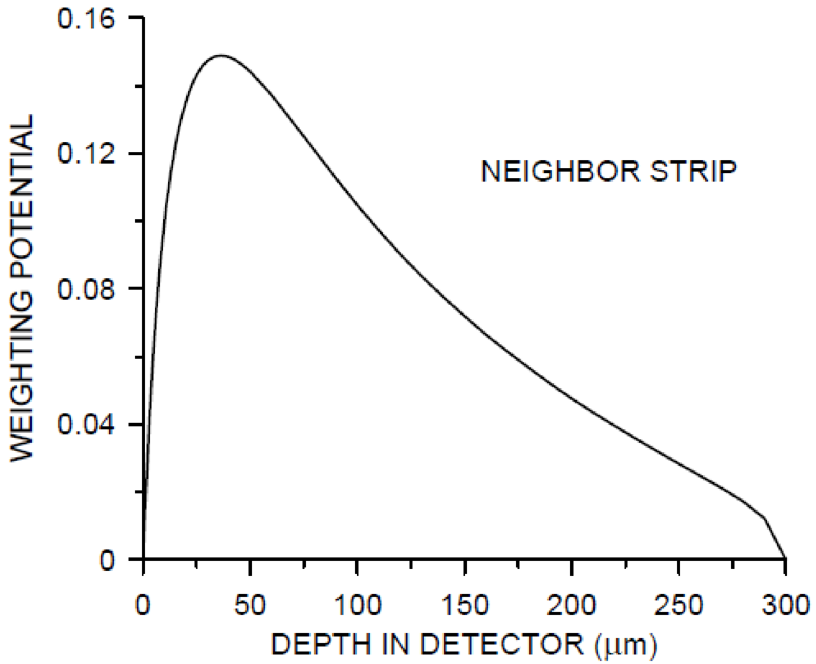


Helmuth Spieler
LBNL

Weighting Potential gives Total Charge Detected

Cuts through the weighting potential





$$Q_n^{ind} = \int_{t_0}^{t_1} I_n^{ind}(t)dt = -\frac{q}{V_w}\int_{t_0}^{t_1} \boldsymbol{E}_n[\boldsymbol{x}(t)]\,\dot{\boldsymbol{x}}(t)dt = \frac{q}{V_w}[\psi_n(\boldsymbol{x}_1) - \psi_n(\boldsymbol{x}_0)]$$

Conclusion on Signals

The principle of signal generation is identical for Solid State Detectors, Gaseous Detectors and Liquid Detectors.

The signals are due to charges (currents) induced on metal electrodes by moving charges.

The easiest way to calculate signals induced by moving charges on metal electrodes is the use of Weighting fields (Ramo – Shockley theorem) for calculation of currents induced on grounded electrodes.

These currents can then be placed as ideal current sources on an equivalent circuit diagram representing the detector.

An extended version of the theorem applies to detectors containing any resistive materials.

Conclusion on Ramo Shockley Theorem

- With the Ramo Shockley prescription we can fully understand signal formation
- ... even in an arbitrary detector volume with arbitrarily shaped electrodes

- Cannot be inverted i.e. from knowledge of all signals in all electrodes, the charge distribution cannot necessarily be reconstructed, but a hypothesis may be tested
- Prerequisit is the measurement of the actual signal shapes

Fluctuations in Energy Loss

Bethe-Bloch formula ⇨ mean energy loss,

i.e. statistical average over many collisions

Important quantity to understand the response of a detector:

$f(x,\Delta)$ probability distribution of energy loss Δ in material of thickness x, determined by

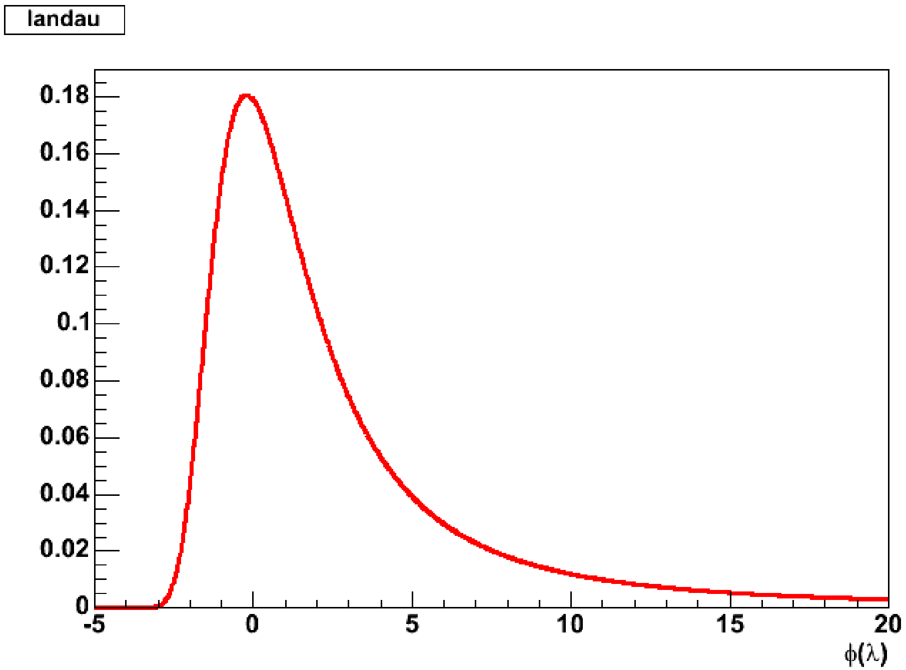
- cross section $\mathrm{d}\sigma/\mathrm{d}T$
- $n_e x$

Calculation of energy loss distribution: two approaches

- Convolution method
- Laplace transform method

[Allison, Cobb, Ann. Rev. Nucl. Part. Sc., 253 (1980)]

Landau Distribution



Universal Landau distribution:

$$\phi(\lambda) = \frac{1}{\pi}\int_0^\infty e^{-\pi u/2}\cos(u\ln u + \lambda u)\,\mathrm{d}u \quad ,$$

mit $\lambda = \dfrac{\Delta - \overline{\Delta}}{\xi} - (1 + \beta^2 - C) - \ln\kappa \quad ,$

$$\xi = \frac{2\pi}{(4\pi\varepsilon_0)^2}\cdot\frac{z^2e^4}{mv^2}\cdot n_e x \approx \overline{\Delta} \quad , \kappa = \frac{\xi}{T_{\max}} \quad ,$$

$C = 0.5772\ldots$ (Euler-Konstante) ,

$$\overline{\Delta} = 2\xi\left[\frac{1}{2}\ln\left(\frac{2mc^2\beta^2\gamma^2T_{\max}}{I^2}\right) - \beta^2 - \frac{\delta}{2}\right]$$

ξ is the scaling factor for the energy loss

Landau distribution in ROOT:

$$f(\Delta|p_1,p_2,p_3) = p_1 \times \phi\left(\frac{\Delta - p_2}{p_3}\right) \quad ,$$

mit p_1 Normierung (Integral)

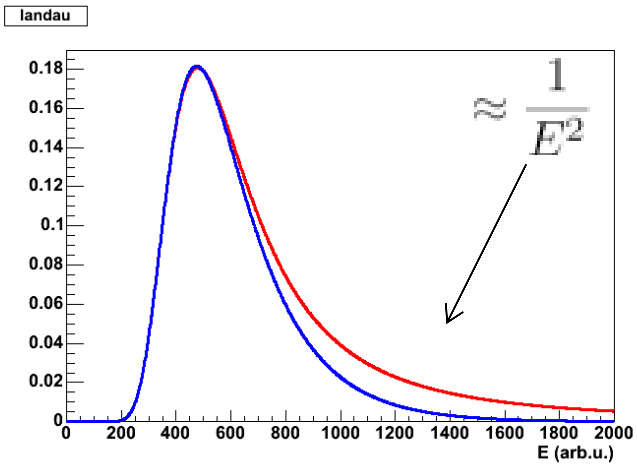
$\Delta_m = p_2 - 0.22278 \times p_3 \quad ,$

$\text{FWHM} = 2\sqrt{2\ln 2}\times\dfrac{p_3}{0.5860} \quad .$

Properties of $\phi(\lambda)$:

- asymmetric: tail up to T_{max}
- Maximum at λ= - 0.223
- FWHM = 4.02
- numerical evaluation

Analytical approximation: Moyal distribution [Moyal 1955]:

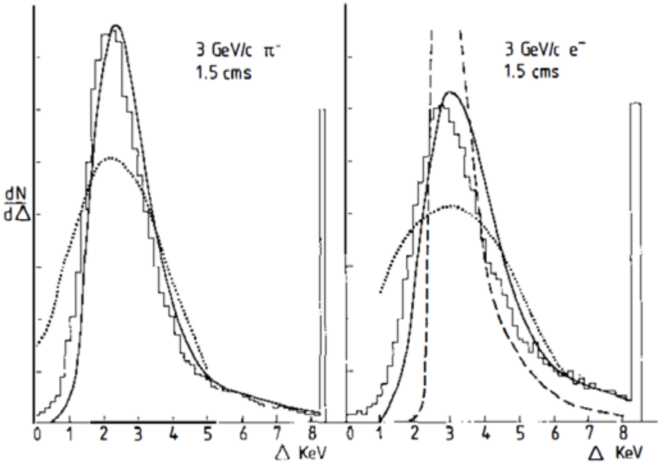


$$f_M(x,\Delta) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})}, \quad \lambda = \frac{\Delta - \Delta_m}{\xi}$$

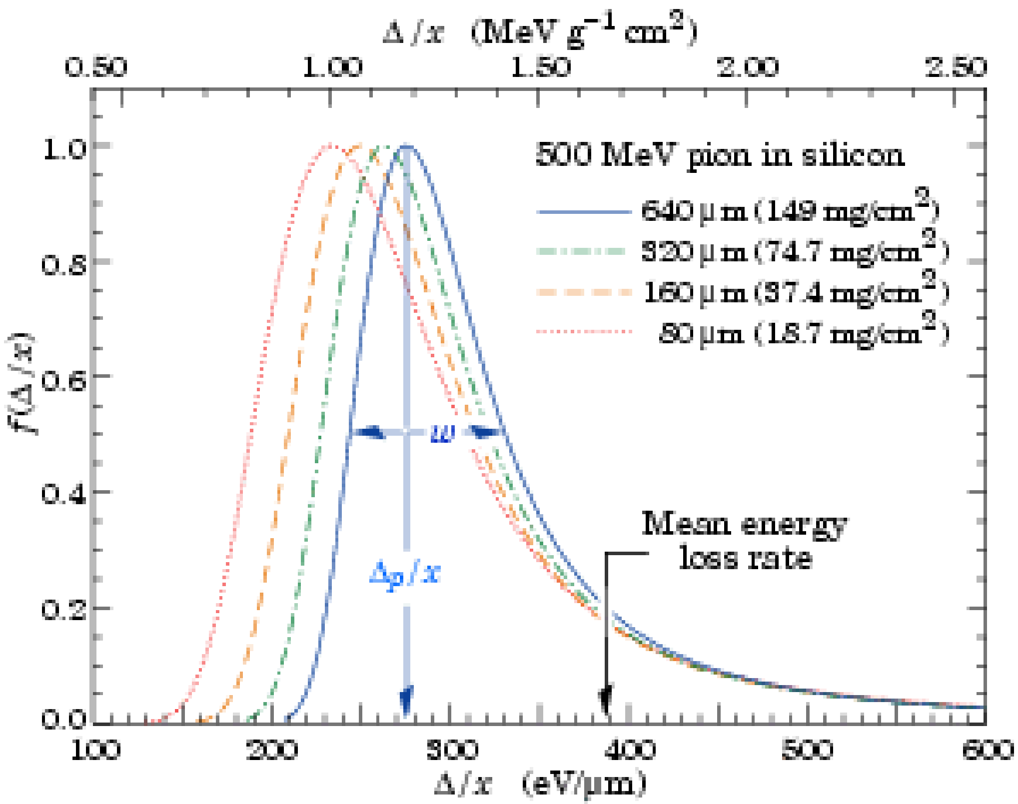
The Moyal tends to zero exponentially while the (correct, physical) Landau distribution decays as $1/E^2$.

Since the long tail of the Landau distribution has significant impact on detector resolution it is a very bad idea to use it – it is simply incorrect and gives wrong predictions ….

People worry a lot about the details of the energy deposit spectrum around the most probable value, but forget the long tail by cutting at low values – which will give very wrong predictions.



Landau Distribution does not follow Central Limit Theorem



[H. Bichsel, Rev. Mod. Phys. 60, 663 (1988)]

The tail does not vanish with increasing detector depth!

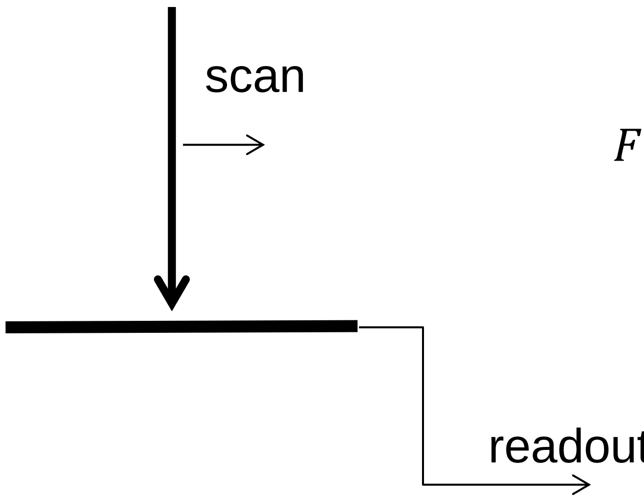
Mean and Variance of Landau distribution are infinite even though it is normalized!

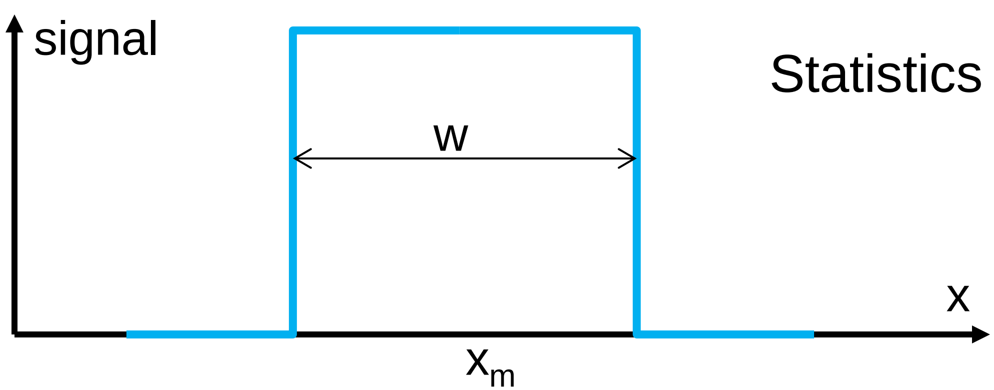
Small signal extend, read-out by single electrode: Position Resolution

- Resolution = Sqrt(Variance signal distribution)

$$\sigma = \sqrt{\frac{1}{w}\int_{-w/2}^{w/2} x^2\,dx} = \frac{w}{\sqrt{12}}$$

$$FWHM = 2.35\,\sigma = \frac{2.35\,w}{\sqrt{12}} = 68\%\,w$$





Statistics of the cylinder hat distribution...

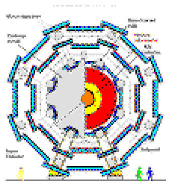
- same as digitization error

- Gausian of width σ has the same variance

Enhancement of Resolution

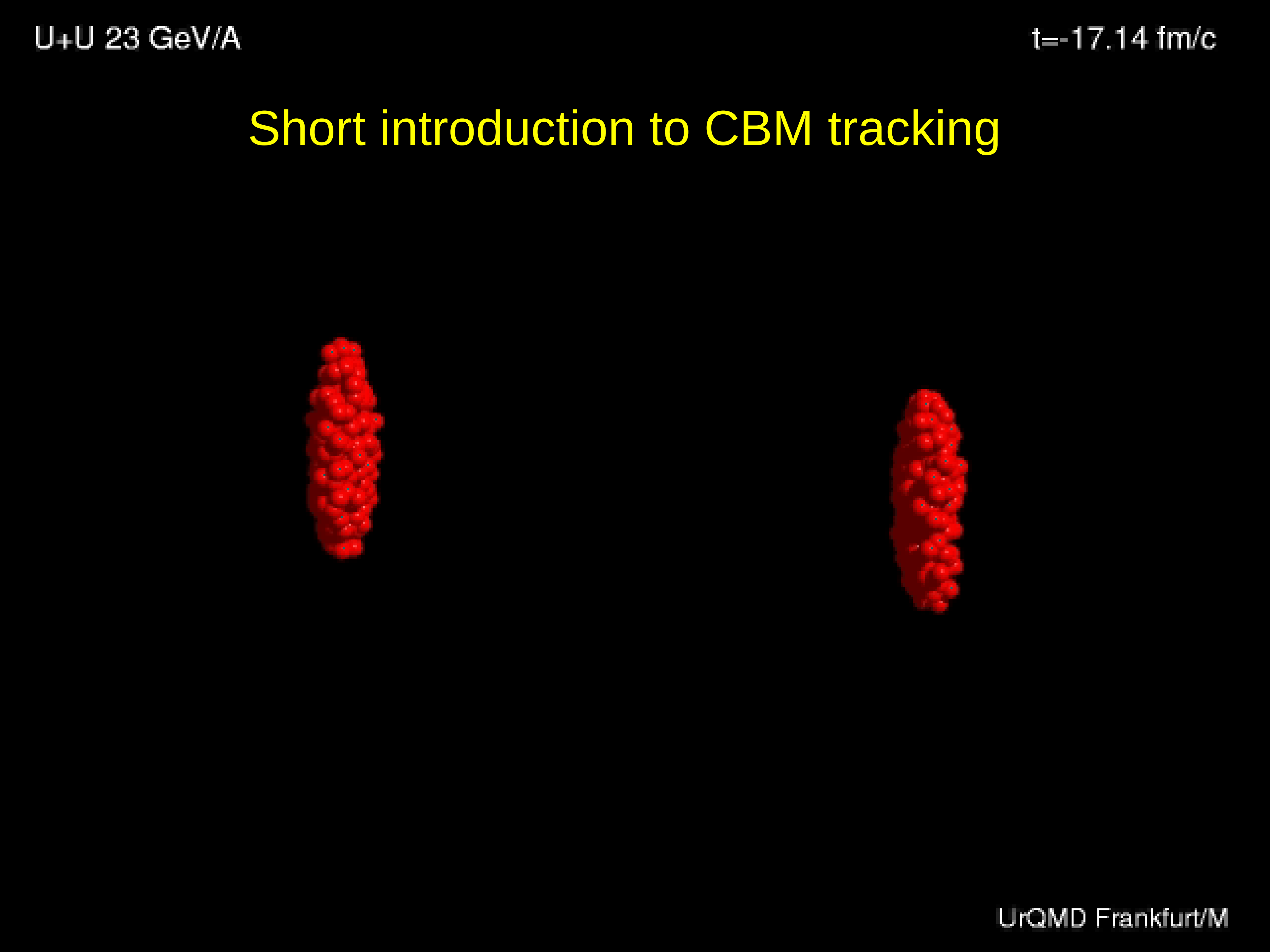
- spatial extension of induced cathode signals allow for high precision → the center of pad response function can be determined
- typical gaseous detector resolution ~ 150μm << pad size (~cm)
- Similarly: lateral diffusion enhances resolution on TPC with finite granularity
- → Detector granularity does not limit resolution as long as cluster sizes are larger than pad size.

Detector Simulation Tools available from CERN



- **Garfield (Rob Veenhof)**
  - **electric fields, particle drift, induced signals, electronics ….**
- **Magboltz (Steve Biagi)**
  - **transport properties of gas mixtures, driftvelocity, diffusion**
- **Heed (Igor Smirnov)**
  - **charge deposit of fast particles in gas mixtures with PAI model**
- **Very reliable simulation of all the chamber and signal processes**

Short introduction to CBM tracking



CBM technological challenges

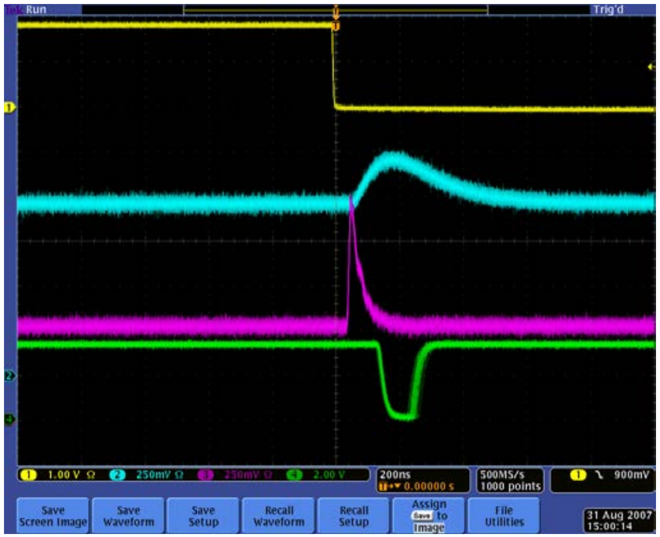
Central Au+Au collision at 25 AGeV (UrQMD + GEANT4):
160 p 400 π^- 400 π^+ 44 K^+ 13 K^-

- 10 million Au+Au reactions/sec
- determination of (displaced) vertices ($\sigma \approx 50\ \mu m$)
- identification of leptons and hadrons
- fast and radiation hard detectors
- free-streaming readout electronics
- high speed data acquisition and high performance computer farm for online event selection
- 4-D event reconstruction

ASICs - Pre-Amplifier Microchips made for FAIR

Self triggered, free streaming data generated with detector front-end chips

analogue signal sequence



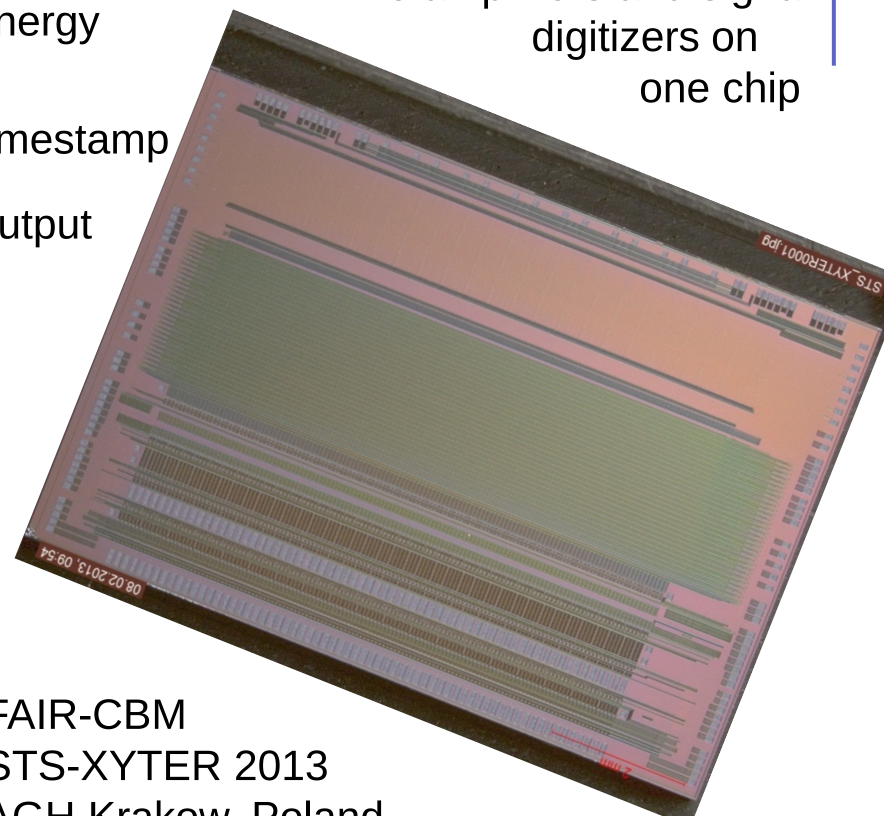
Testpulse Release

Slow Shaper: Energy

Fast Shaper: Timestamp

Discriminator Output

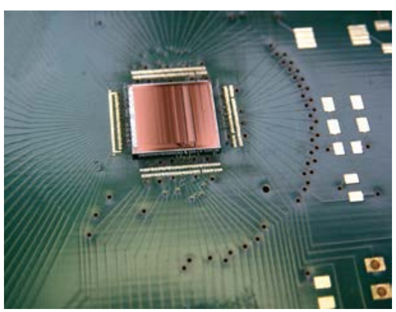
128 amplifiers and signal digitizers on one chip



FAIR-CBM
STS-XYTER 2013
AGH Krakow, Poland

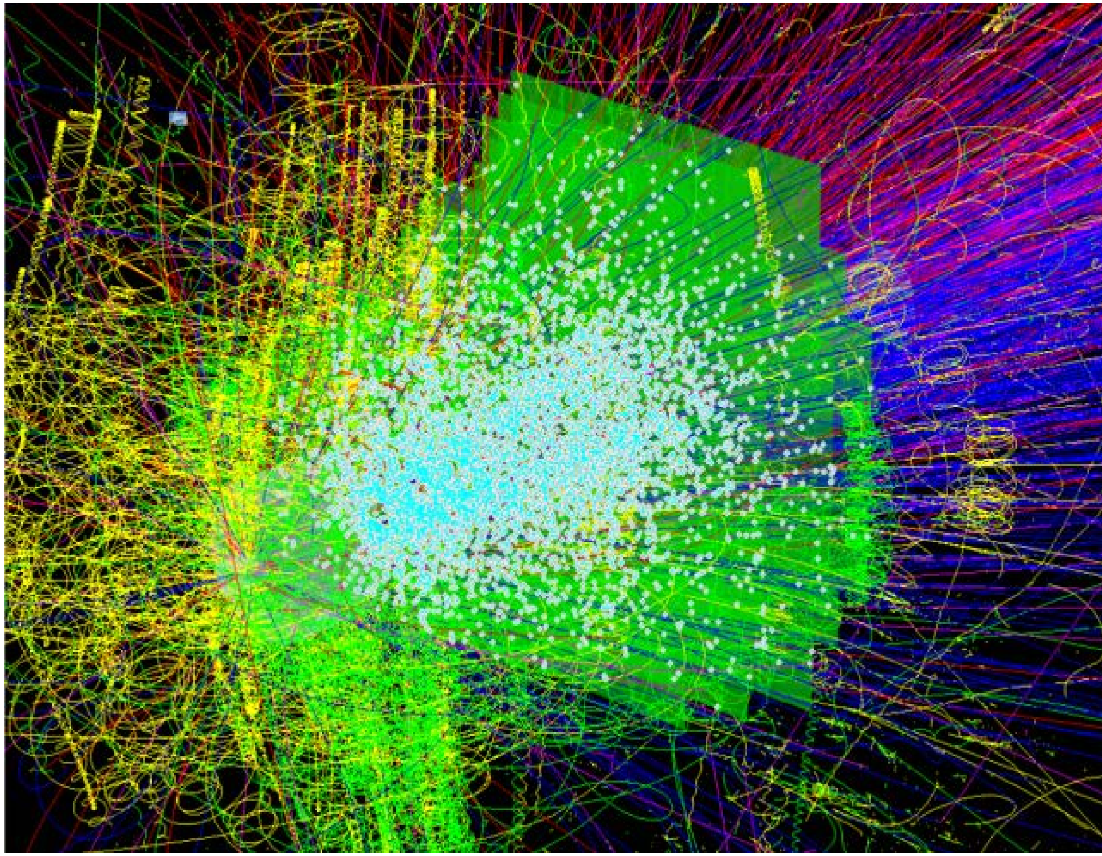
n-XYTER 2006 built for neutrons

DETNI



Game industry supplies computing power for physics!

- ...Computer graphics relies on ray-tracing



- particle tracking is not

  much different!

For the experiments:

- At 1000 Gbyte/s, there is

no time to store the data!

At FAIR, on-line event reconstruction will be realized by means of many thousands of Graphics-Chips operating in parallel!

Work at the GSI Detectorlab