EDIT 2015

Excellence in Detectors and Instrumentation Technologies
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Silicon Detectors

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Outline

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Lecture 1

Introduction and Motivation

- Break-throughs in particle detection
- Vertex measurement

Fundamentals of Semiconductor Detectors

- The signal and the noise
- Spatial resolution with structured electrodes

Lecture 2

Semiconductor Detectors

- Microstrip Detectors
- Silicon Drift Chambers
- Hybrid Pixel Detectors
- Monolithic Pixel Detectors

Content Lecture 1

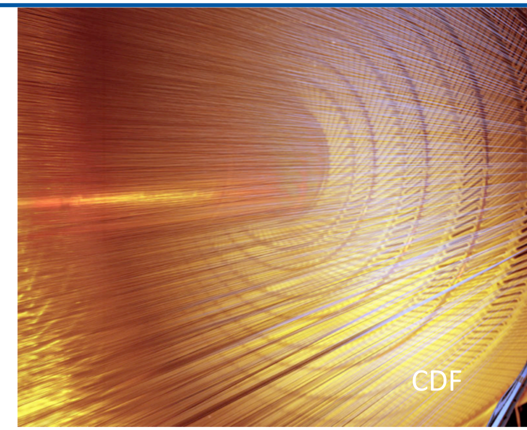
- Tasks of semiconductor tracking detectors

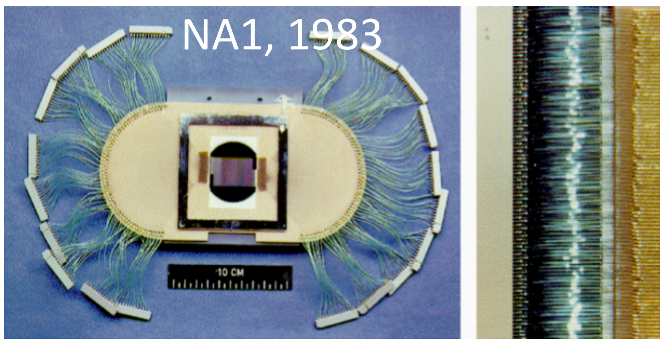
- Fundamentals of semicond. detectors
  - pn and other junctions
  - single and double sided detectors
  - signal and noise
  - (δ electrons)
  - Shockley-Ramo theorem
  - Lorentz angle
  - Spatial Resolution
  - Other semiconductor materials

Break through advances in experimentation

Wire chambers

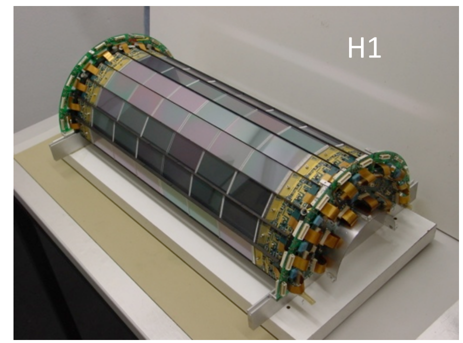
→ electronic recording of particle tracks
→ electronic recording of tracks
→ σ = mm –> 50 μm, 0.05 channels / cm^2

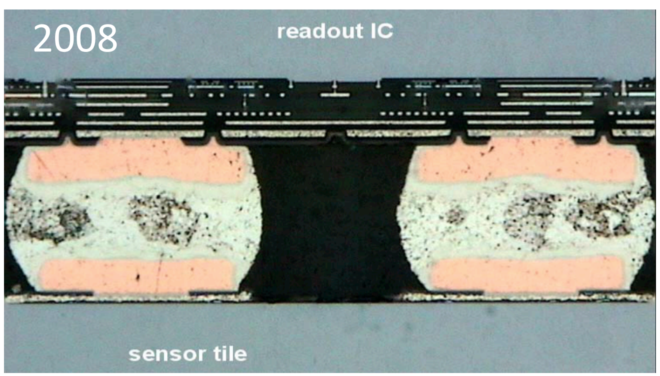




Silicon strip detectors

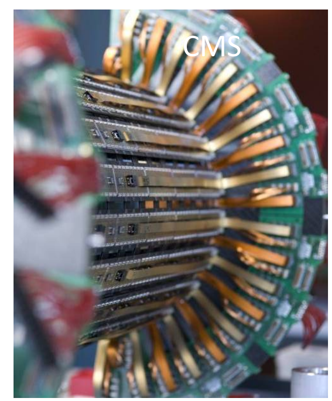
→ measurement of ps – lifetimes and heavy quark "tagging"
→ σ < 5 μm, 50 channels / cm^2

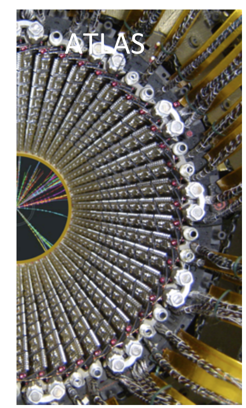




Pixel detectors

→ 3-dim point measurement in high rate environments like LHC
→ σ ~ 10 μm -> 2 μm,
→ 10 000 channels / cm^2





Looking back at 3 years of LHC (25 /fb) ...

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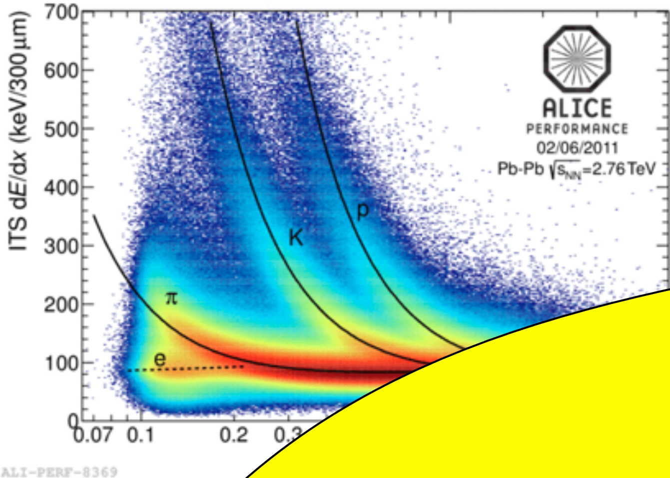
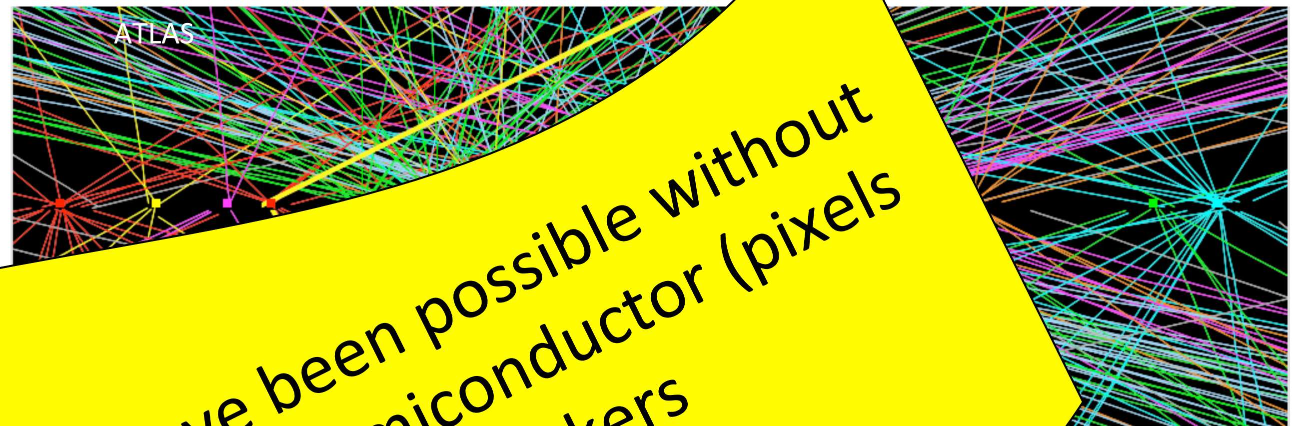
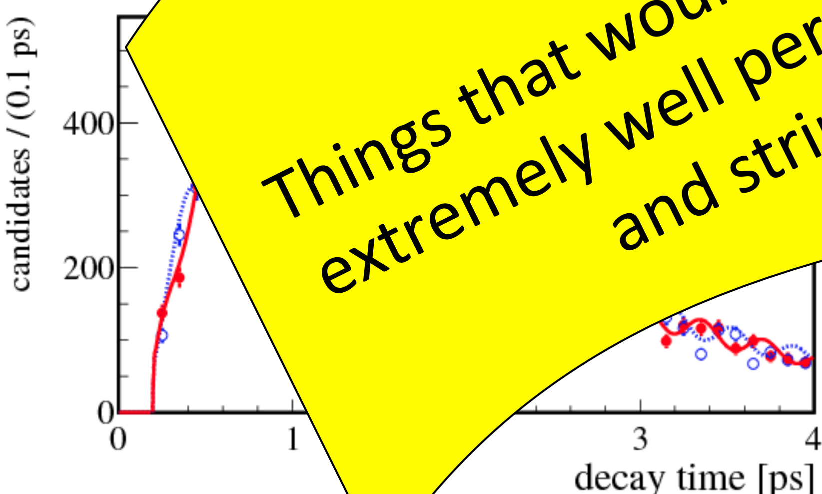
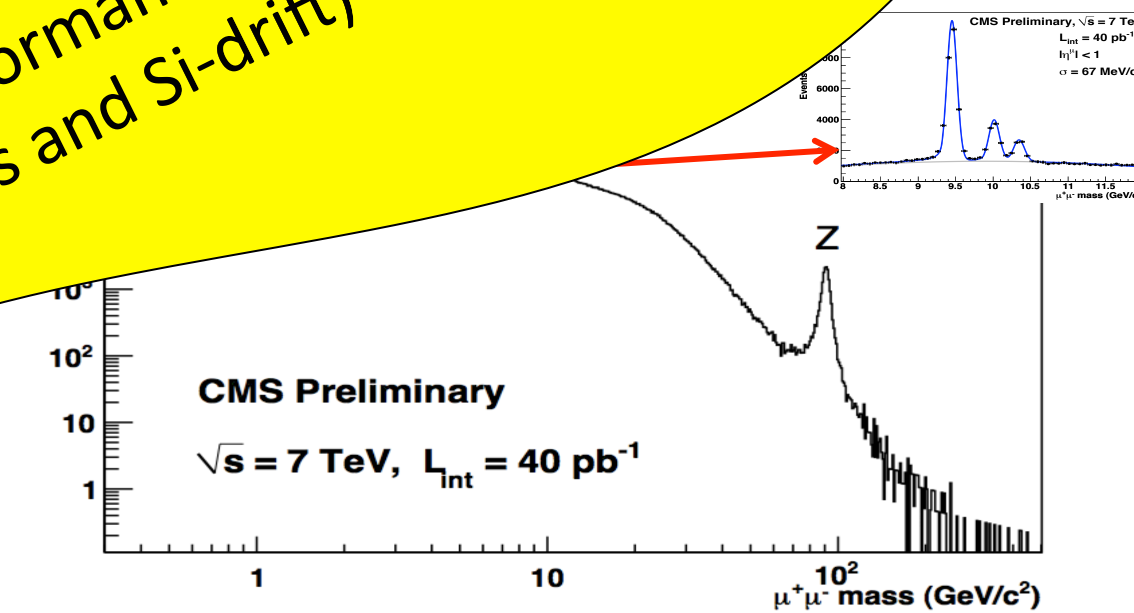
- This is a definitively a success story !

~70 interaction /BX









Things that would not have been possible without extremely well performant semiconductor (pixels and strips and Si-drift) trackers

Tracking in pp collisions at 13 TeV (LHC)

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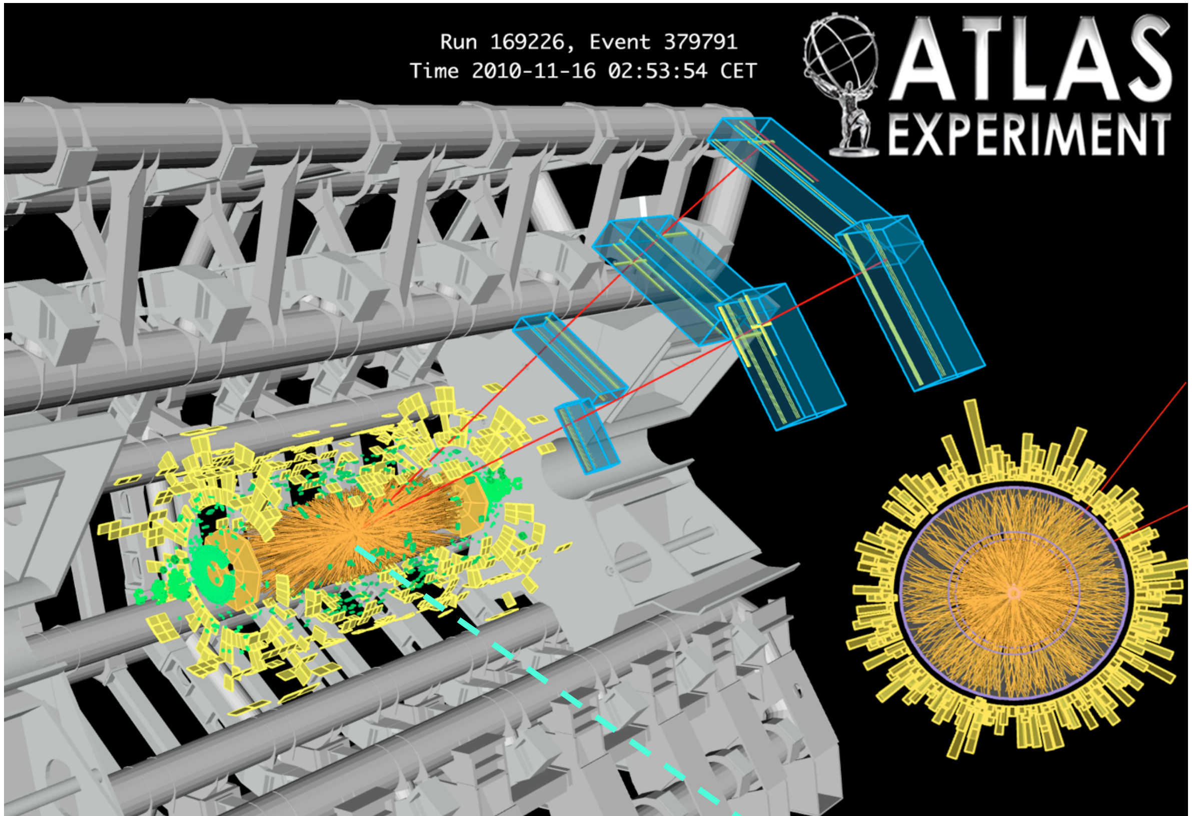


~1200 tracks every 25 ns
or ~ 10^{11} per second

⇒ high radiation dose

10^{15} n_{eq} / cm^2 / 10 yrs @ LHC

or

600 kGy (60 Mrad)
through ionisation of particles

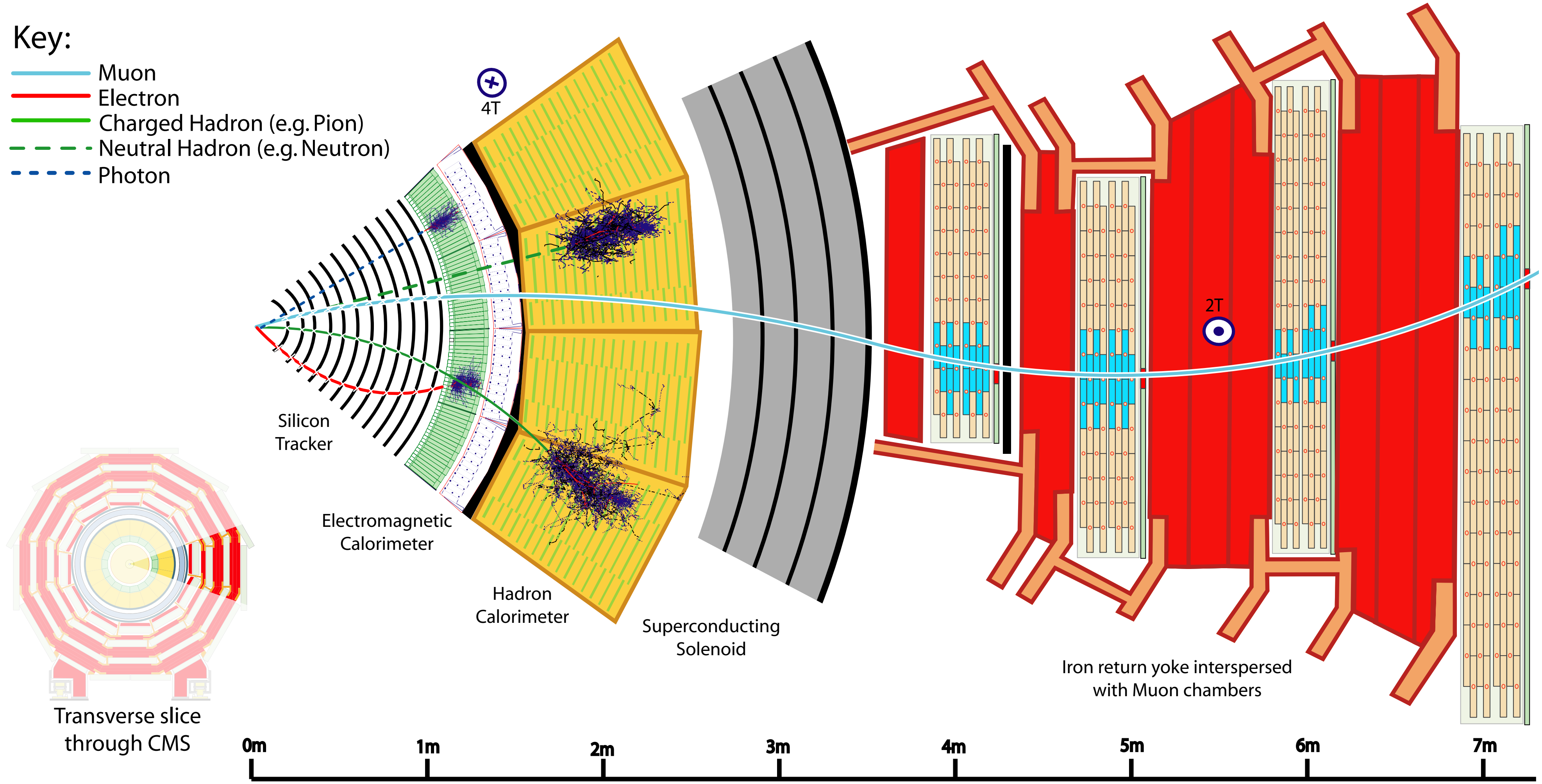
position of
tracking detector (pixels, strips, straw tubes)

DEMANDS

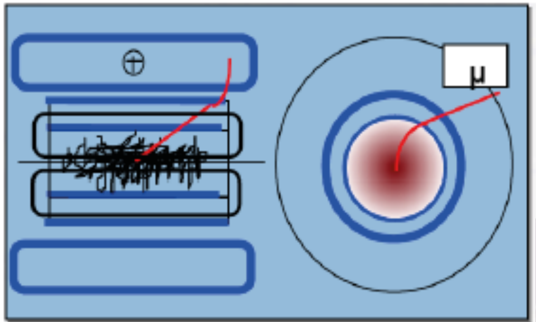
LHC ≅ 10^6 x LEP in track rate !

Note: LHC Upgrade (2026): HL–LHC = LHC x 10 !

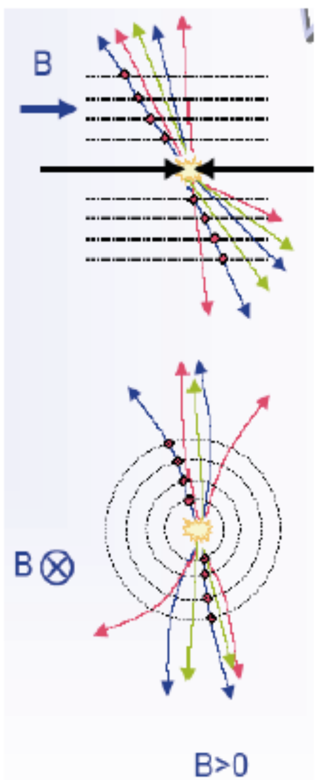
A spectrometer -> momentum measurement in B-field

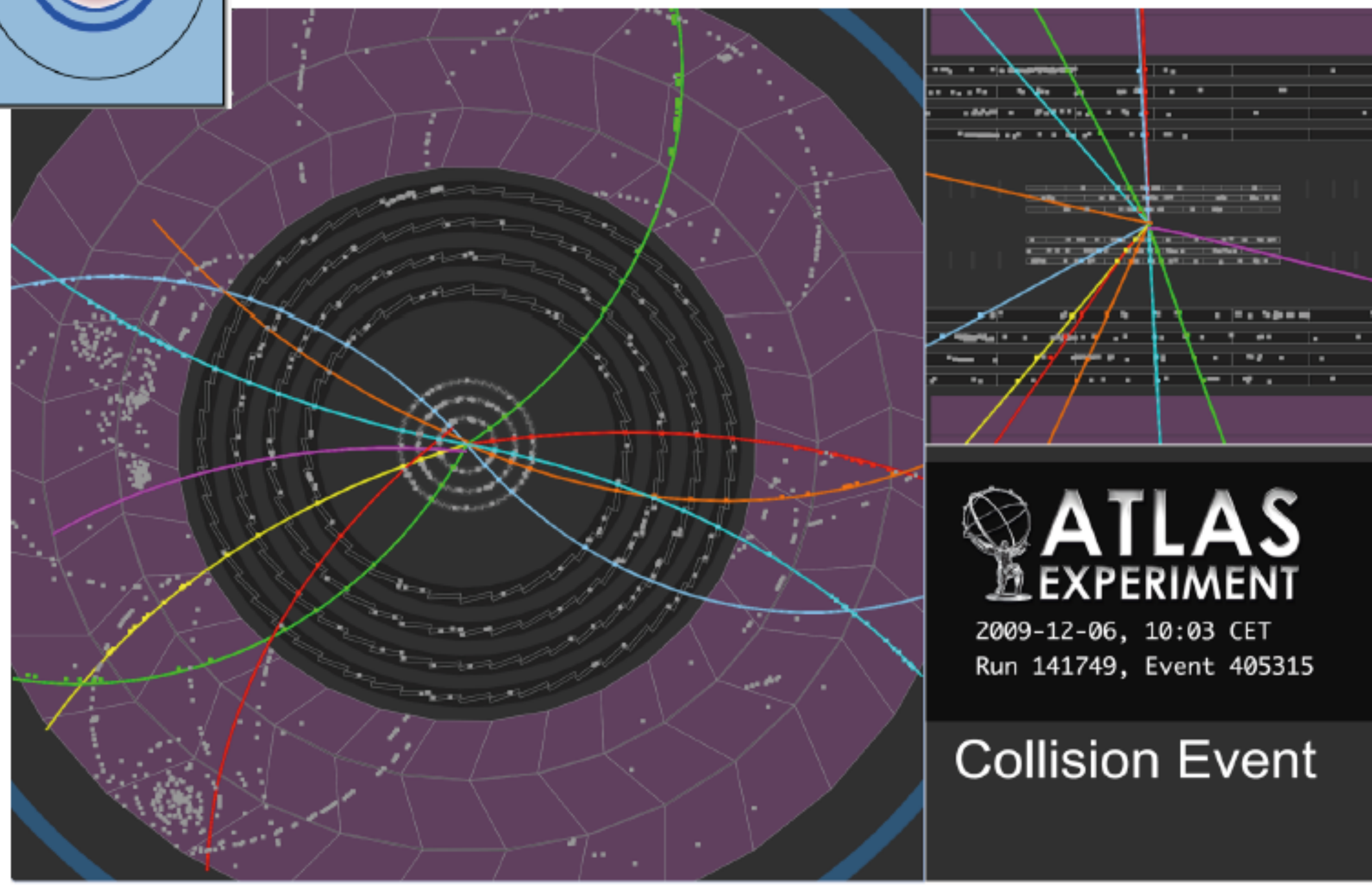


Tracking in ATLAS



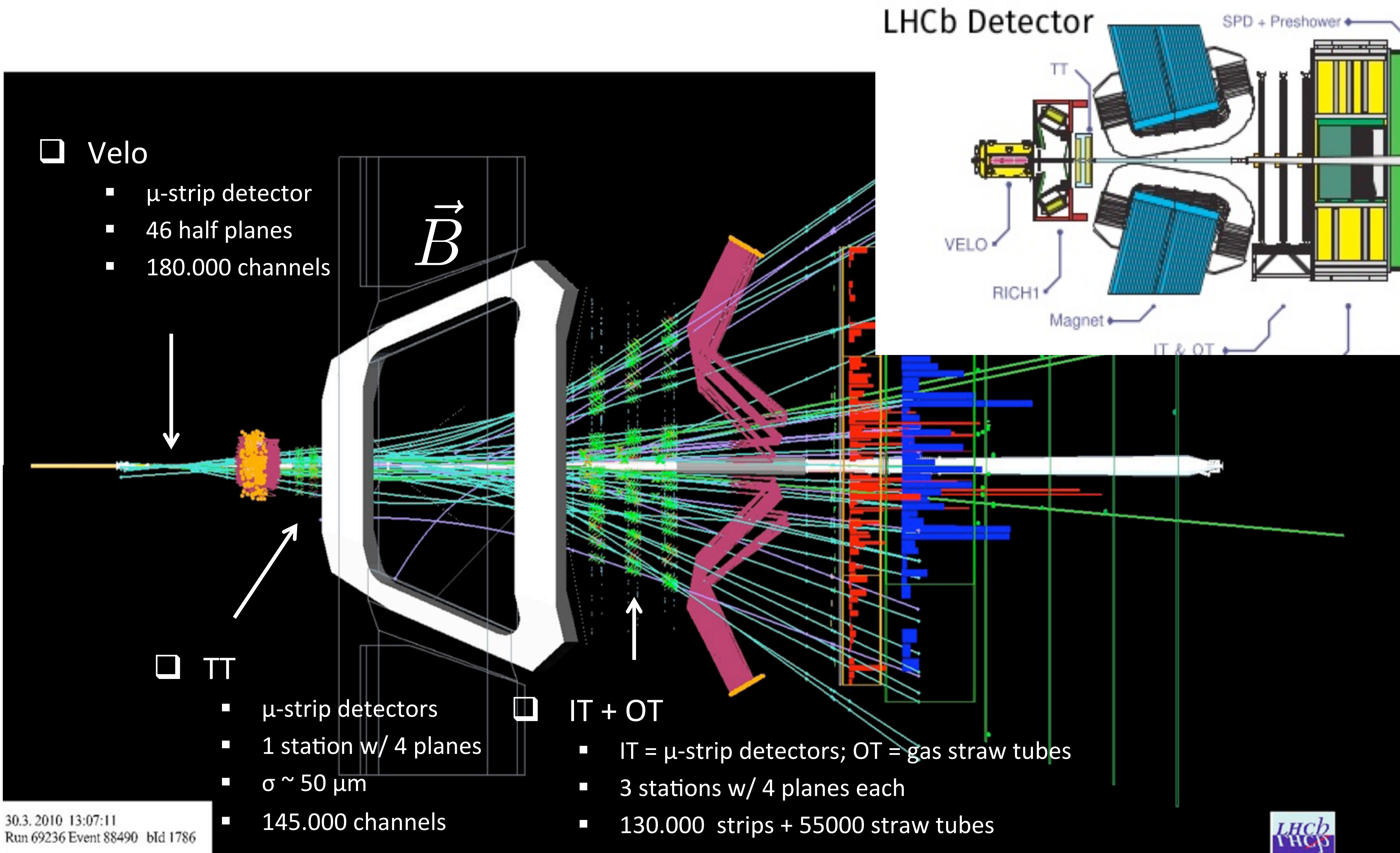
ATLAS: (air-core) toroid magnet
+ inner solenoid





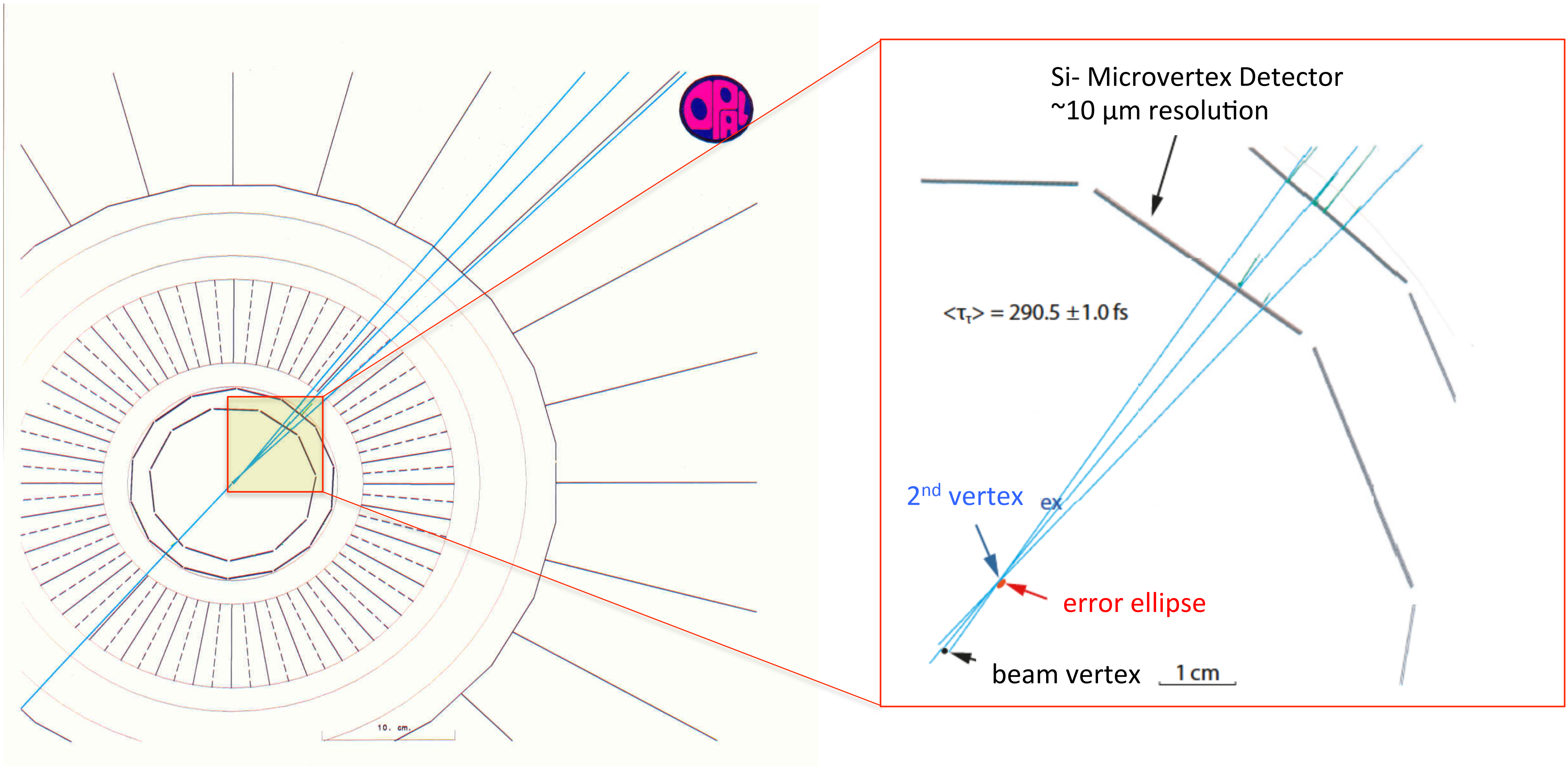
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

Example: Tracking in LHCb (Dipole)



- Velo
  - μ-strip detector
  - 46 half planes
  - 180.000 channels
- TT
  - μ-strip detectors
  - 1 station w/ 4 planes
  - σ ~ 50 μm
  - 145.000 channels
- IT + OT
  - IT = μ-strip detectors; OT = gas straw tubes
  - 3 stations w/ 4 planes each
  - 130.000 strips + 55000 straw tubes

Extrapolation to the (primary) vertex



Tasks of semiconductor strip and pixel detectors

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1. Pattern Recognition and Tracking
   - precision tracking points in 3D → track seeding
   - 1 pixel layer ←→ 3-4 strip layers (x,y & u,v for ambiguities)

2. Vertexing (primary and secondary vertex) [1)]

• impact parameter resolution	~10µm (rφ), ~70µm (z)
• secondary vertex resolution	~50µm (rφ), ~70µm (z)
• primary vertex resolution	~11µm (rφ), ~45µm (z)
• (life) time resolution	~70 fs

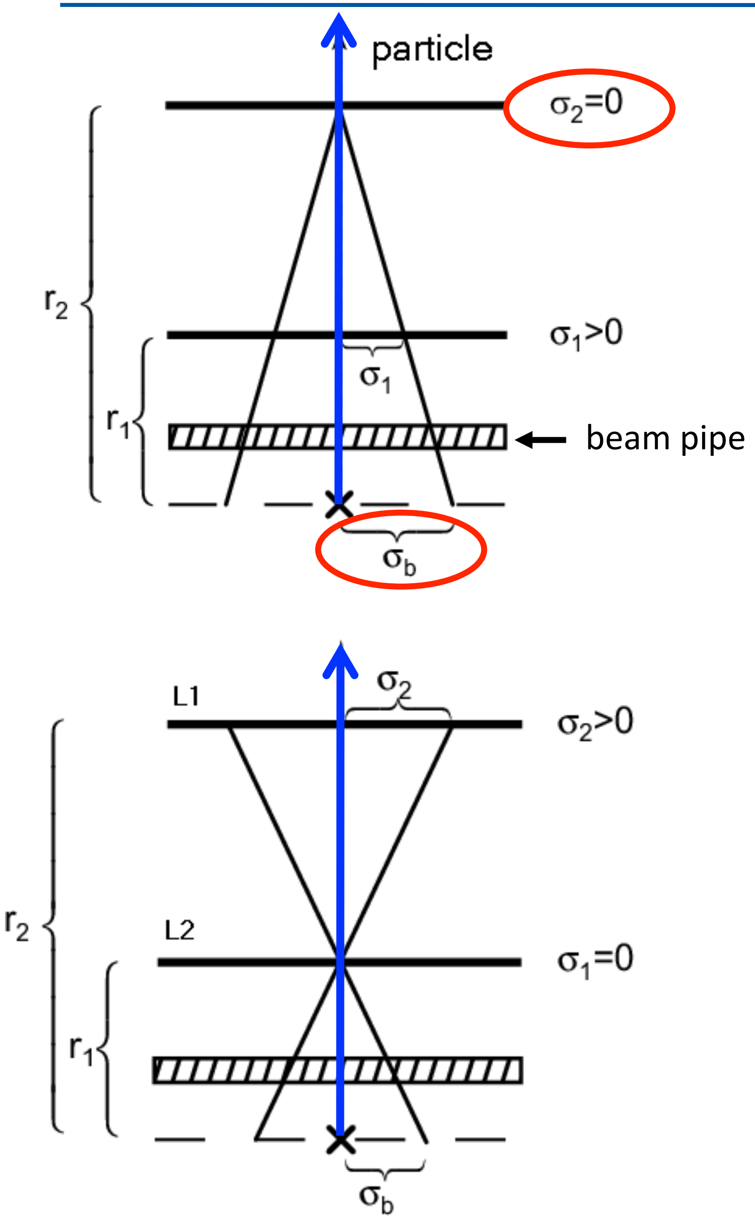
3. Momentum measurement [1)]

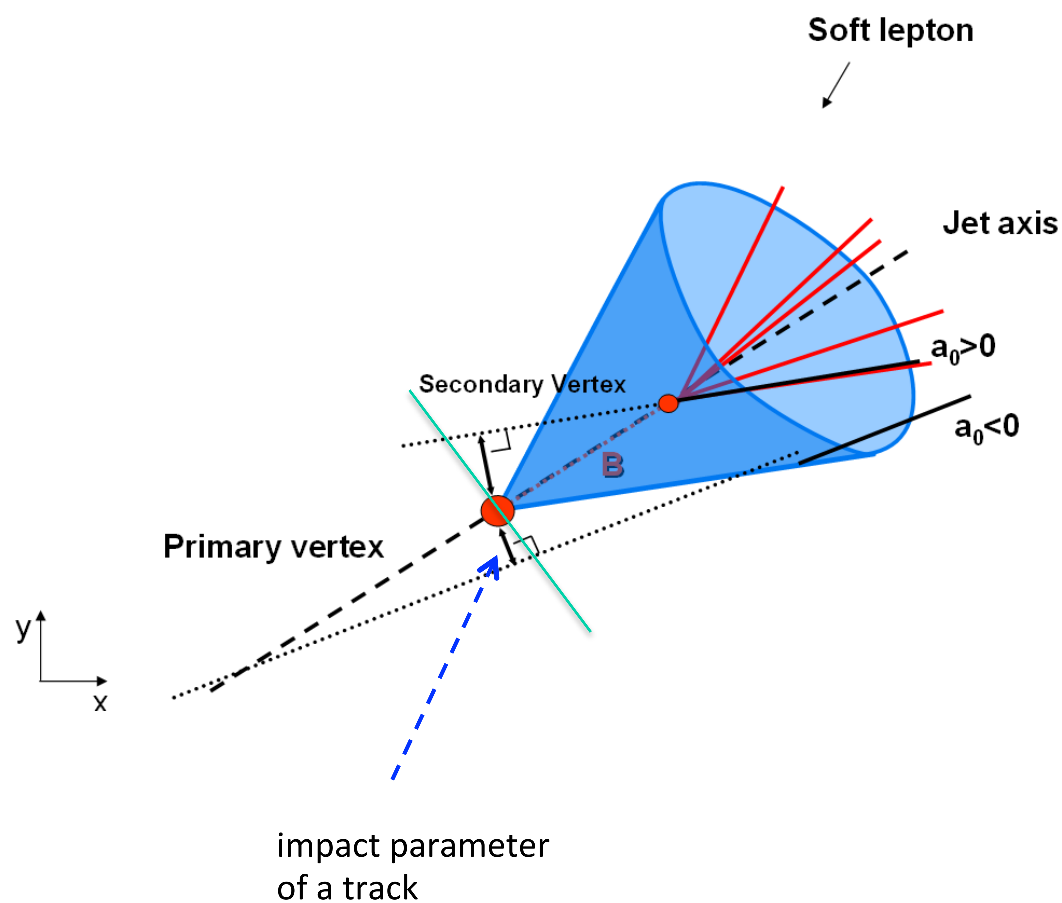
$$\frac{\sigma_{p_T}}{p_T} = 0.03\%\ p_T\,(\mathrm{GeV}) \oplus 1.2\%$$

(inner detector)

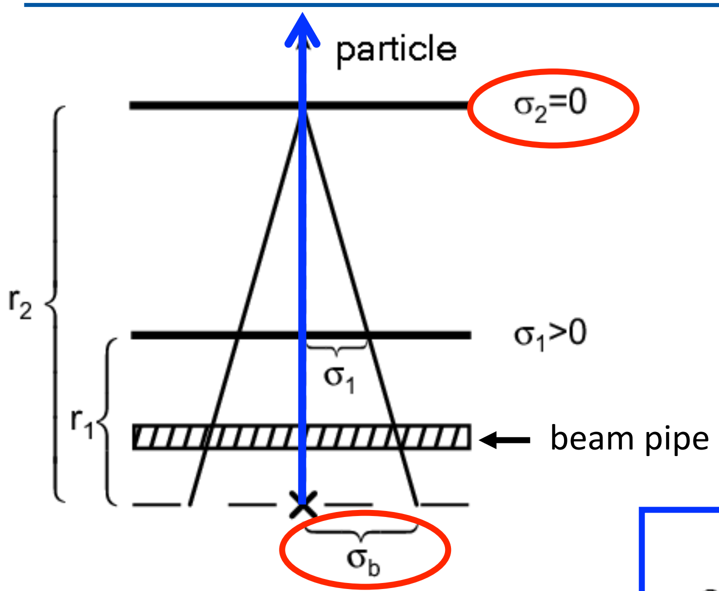
[1)] values for ATLAS

Impact parameter resolution (simplified)





Impact parameter resolution (simplified)



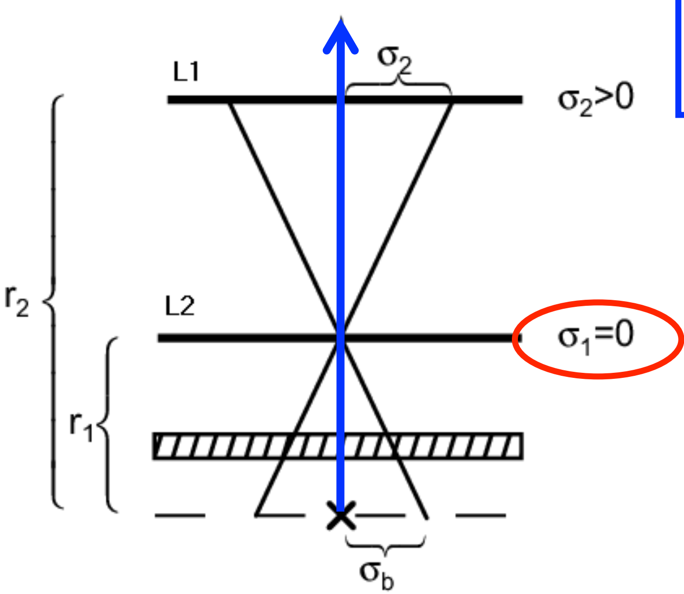
$$\frac{\sigma_b}{\sigma_1} = \frac{r_2}{r_2 - r_1}$$

small !

small !

$$\sigma_b^2 = \left(\frac{r_1}{r_2 - r_1}\,\sigma_2\right)^2 + \left(\frac{r_2}{r_2 - r_1}\,\sigma_1\right)^2 + \sigma_{MS}^2$$

small x/X_0

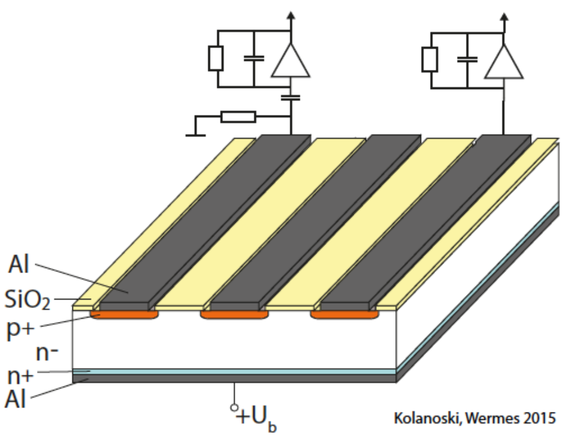


$$\frac{\sigma_b}{\sigma_2} = \frac{r_1}{r_2 - r_1}$$

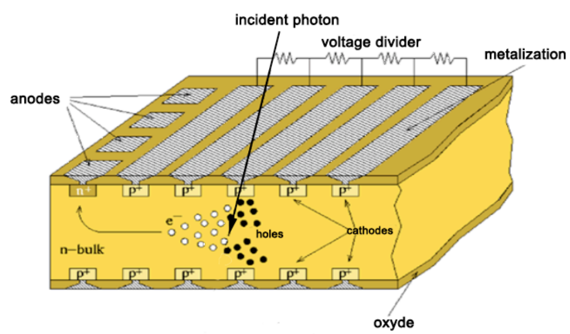
$$\sigma_{MS} \sim \frac{1}{p}\sqrt{\frac{x}{X_0}}$$

Fundamentals of Semiconductor Detectors

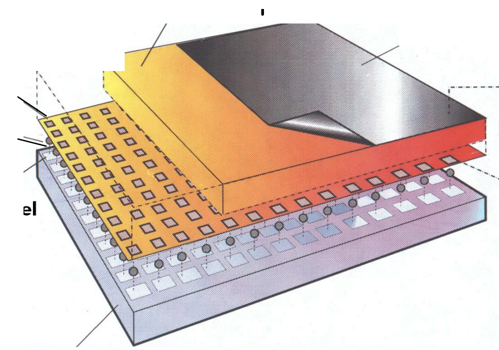
(with emphasis on particle detectors for tracking)



Microstrip Detector



Silicon Drift Detector



Pixel Detector

Gas-filled versus Semiconductor Detectors

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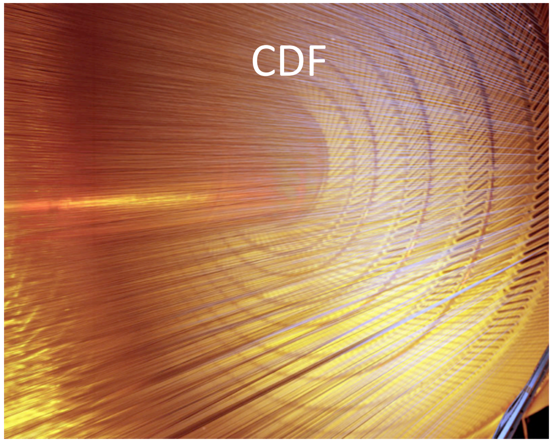
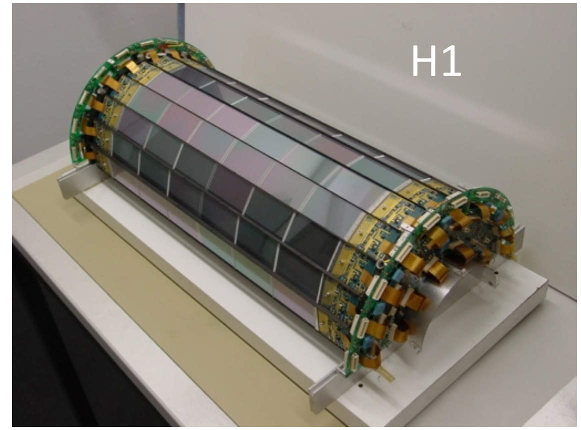
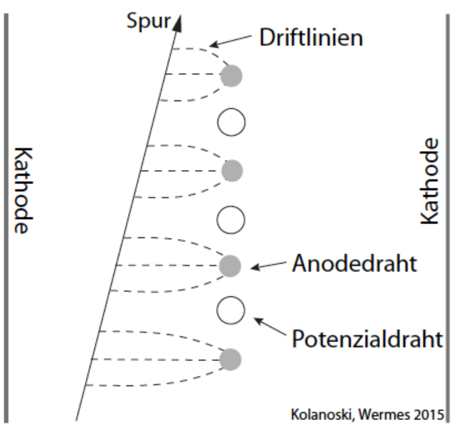


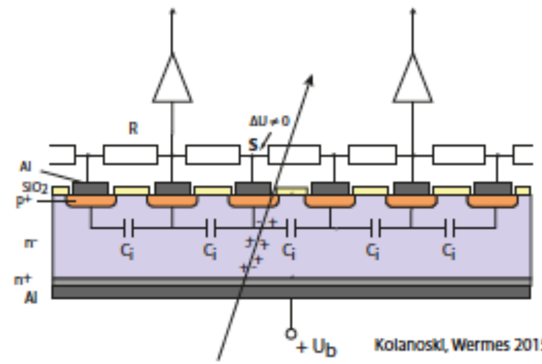
++	material	-
+	N_{meas}	--
low	cost	high
--	rate/speed	++
100 µm	resolution	10 µm



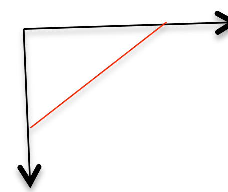


field near wire
$E(r) \sim 1/r$

$\Rightarrow$ gas amplification



linear E



26 eV needed (Ar) per e/ion pair
94 e/ion pairs per cm
intrinsic amplification typ. 10^5
typ. noise: > 3000 e- (ENC)

3.65 eV (Si) needed per e/h pair
~10^6 e/h pairs per cm (20 000/250µm)
no intrinsic amplification
typ. noise: 100 e- to 1000 e- (ENC)

cf. lecture by Fabio Sauli

Semiconductors suited for detectors

Semiconductor	band gap (eV)	intrinsic carrier conc. (cm^{-3})	average Z	w_{eh} (eV)	mobility cm^2/Vs e	h	carrier life time
Si	1.12	$1.45 \cdot 10^{10}$	14	3.61	1450	505	100 μs
Ge	0.66	$2.4 \cdot 10^{13}$	32	2.96	3900	1800	
GaAs	1.42	$1.8 \cdot 10^{6}$	32	4.35	8800	320	1-10 ns
CdTe	1.44	10^{7}	50	4.43	1050	100	0.1-2 μs
CdZnTe	$\sim$1.6		49.1	4.6	$\sim$1000	50-80	$\sim \mu s$
CdS	2.42		48 + 16	6.3	340	50	
HgI_2	2.13		62	4.2	100	4	$\sim \mu s$
InAs	0.36		49 + 33		33000	460	
InP	1.35		49 + 15		4600	150	
ZnS	3.68		30 + 16	8.23	165	5	
PbS	0.41		82 + 16		6000	4000	
Diamond	5.48	$<10^3$	6	13.1	1800	1400	$\sim$1 ns

photon absorption by photo effect $\sim Z^{(4-5)}$

The pn junction as a semiconductor particle detector

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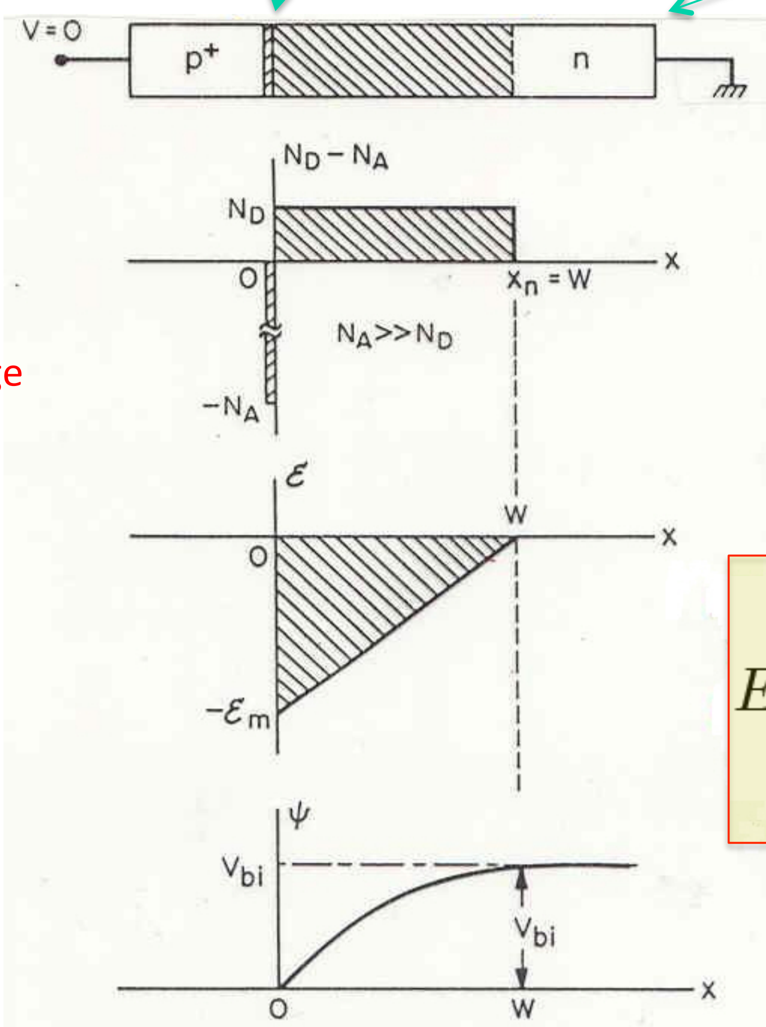
typical: thin (~µm), highly doped p^+ (~10^{19} cm^{-3}) layer on lightly doped n^- (~10^{12} cm^{-3}) substrate

Space charge region
(depleted of mobile charge carriers)

Electric field

Potential



reverse biased junction

$$N_A x_p = N_D x_n$$ neutrality condition

$$\frac{dE}{dx} = \frac{1}{\epsilon}\rho(x)$$ Maxwell

$$E(x) = \begin{cases} \frac{-eN_A}{\epsilon}(x + x_p)\ ; -x_p < x < 0 \\ \frac{+eN_D}{\epsilon}(x - x_n)\ ; 0 < x < x_n \end{cases}$$

$$V_{bi} = \frac{e}{2\epsilon}\left(N_A x_p^2 + N_D x_n^2\right)$$

The pn junction as a semiconductor particle detector

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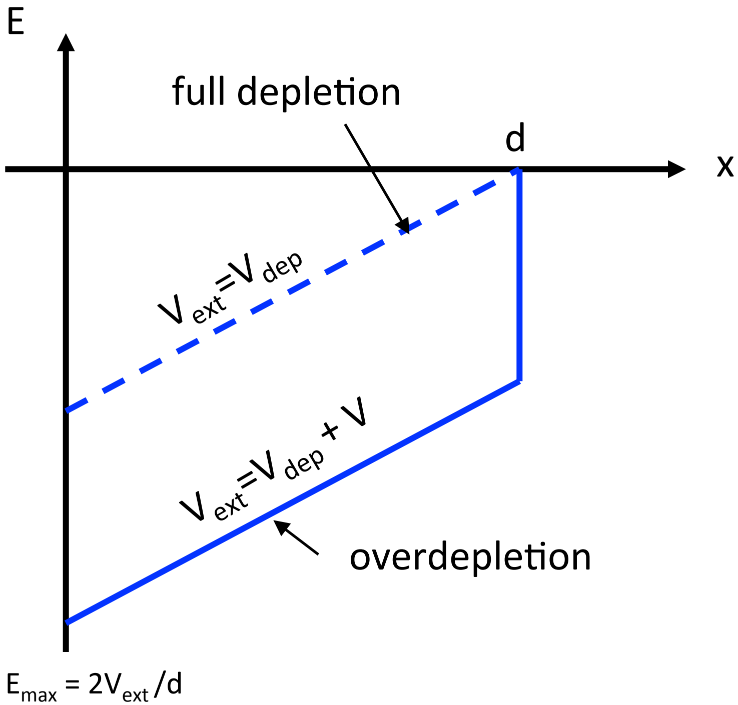


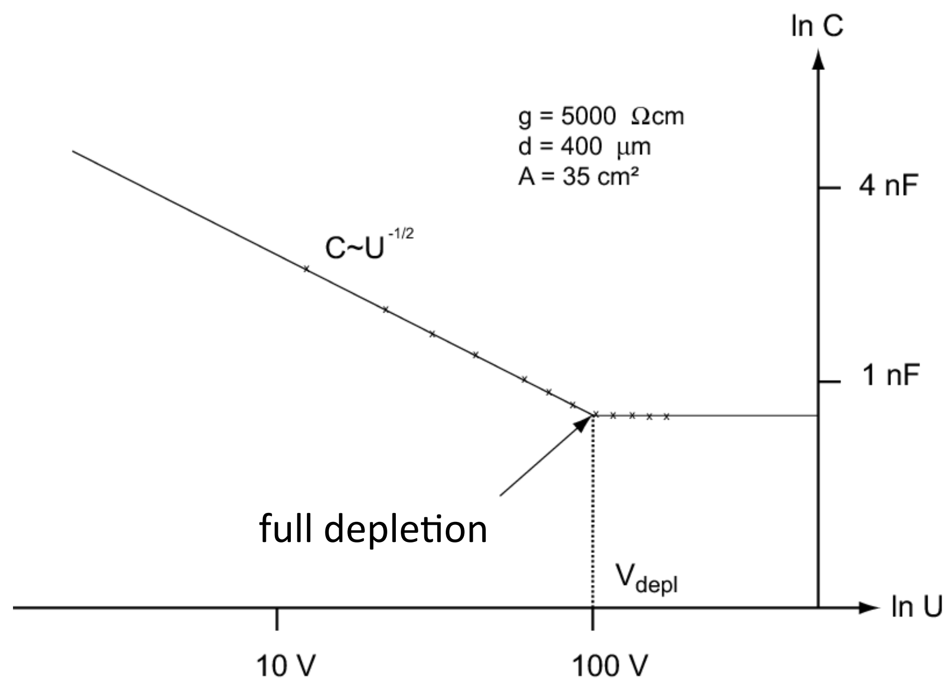
with applied external bias voltage

$$E(x) = -\frac{V + V_{dep}}{d} + \frac{2V_{dep}\,x}{d^2}$$

$$d = x_n = \sqrt{\frac{2\epsilon}{e}\frac{1}{N_D}\left(V_{bi} + V_{ext}\right)} \propto \sqrt{V_{ext}}$$

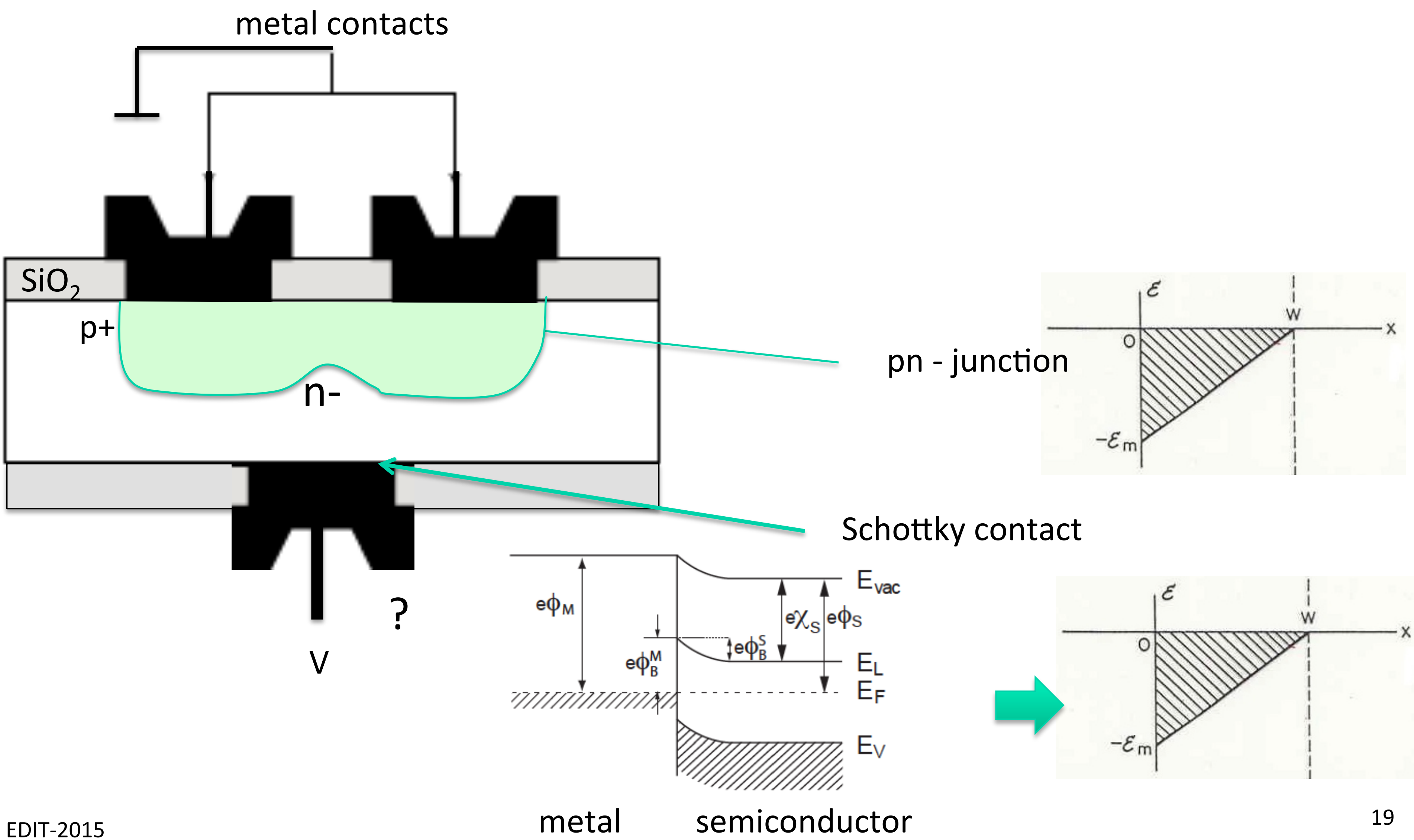
capacitance

$$\frac{C}{A} = \frac{1}{\epsilon\epsilon_0}\frac{1}{d} \propto \frac{1}{\sqrt{V_{ext}}}$$



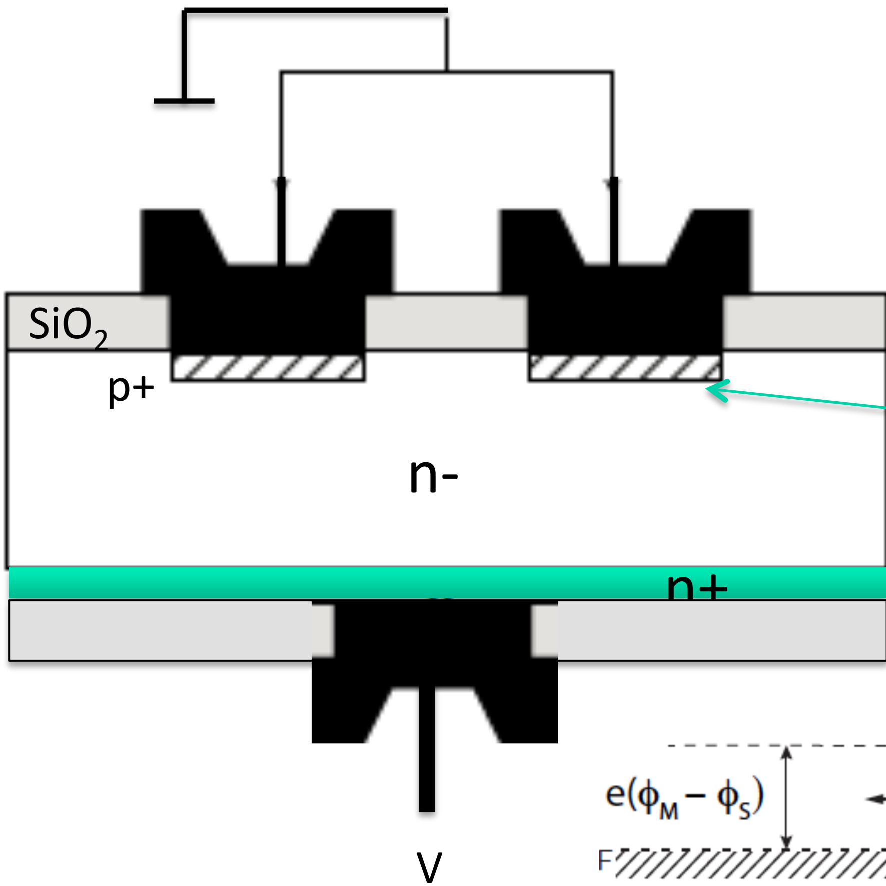
depletion zone grows from the junction into the lower doped bulk

Contacts

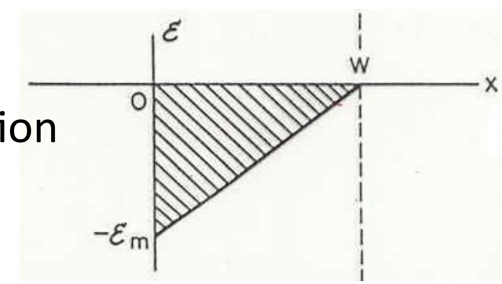


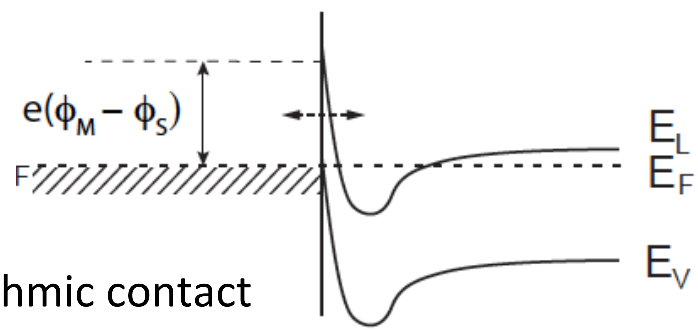
metal contacts
SiO$_2$
p+
n-
V
?
pn - junction
Schottky contact
$\mathcal{E}$
W
x
0
$-\mathcal{E}_m$
E_{vac}
$e\phi_M$
$e\chi_S$
$e\phi_S$
$e\phi_B^S$
$e\phi_B^M$
E_L
E_F
E_V
metal
semiconductor

Contacts

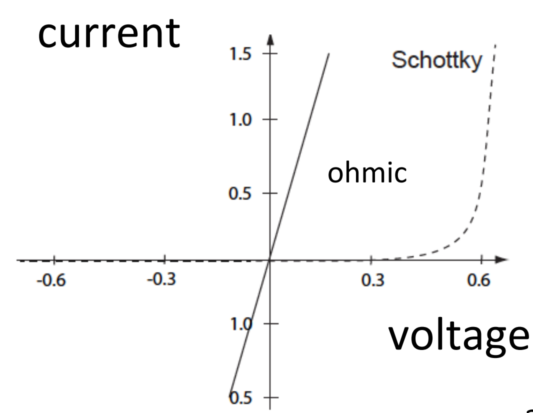


pn - junction

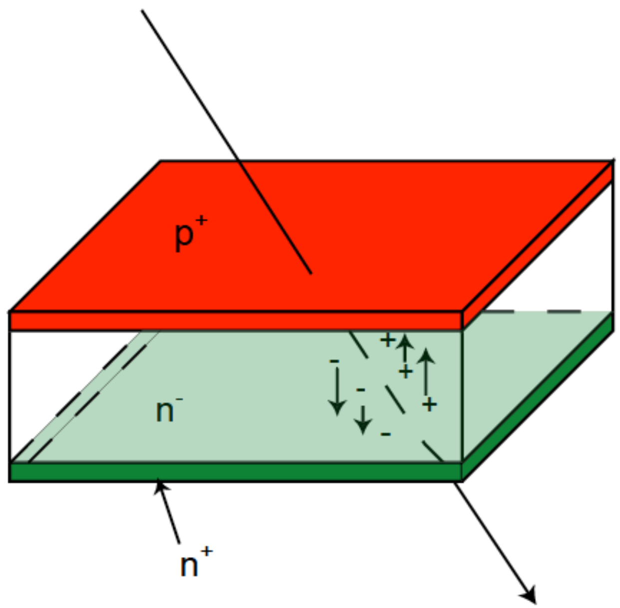




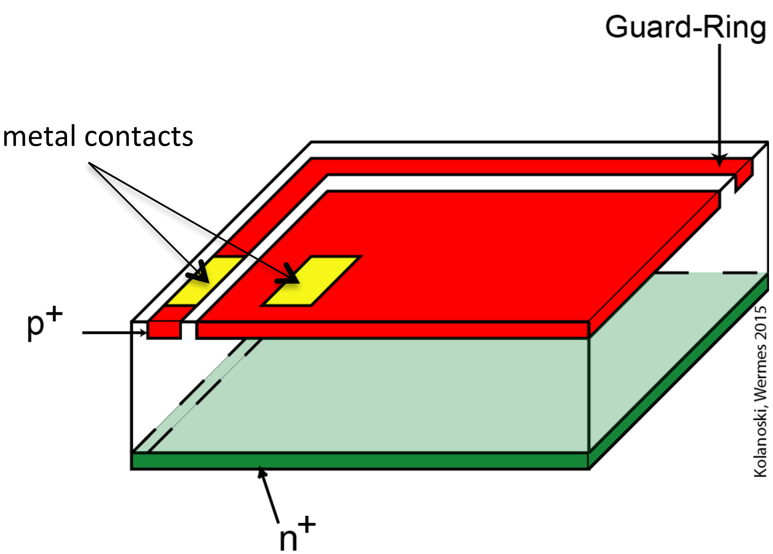
ohmic contact



Detector shapes

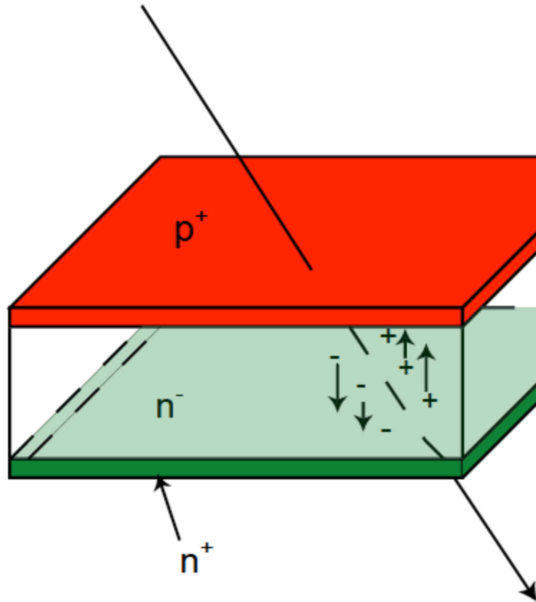


pn area diode

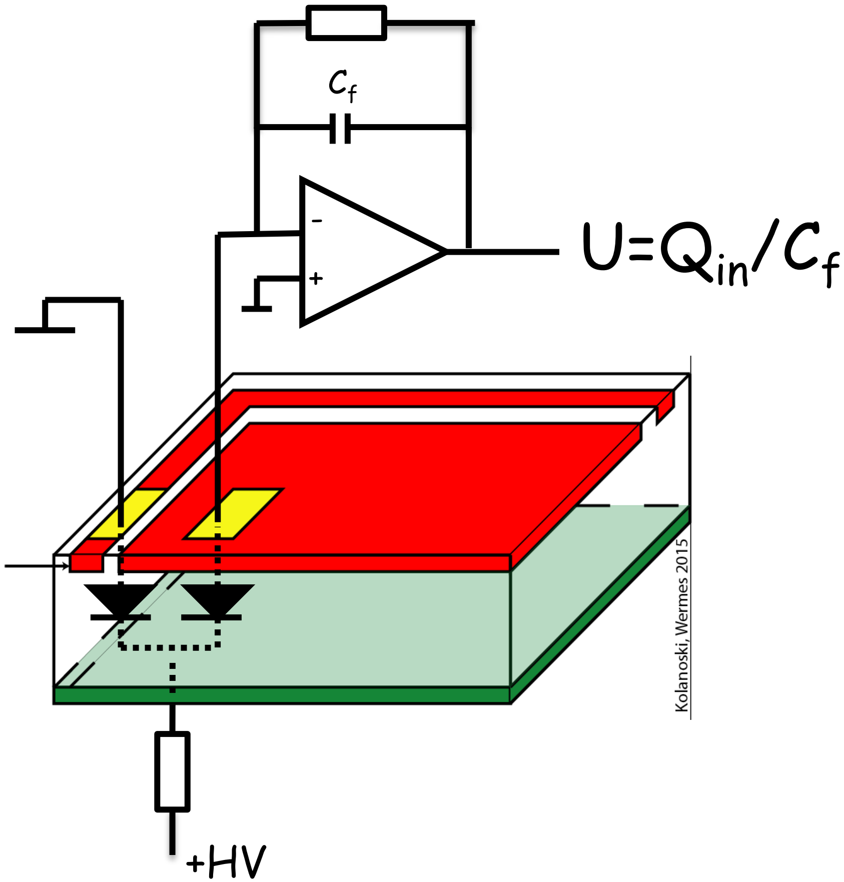


area diode w/ guard ring

Detector shapes

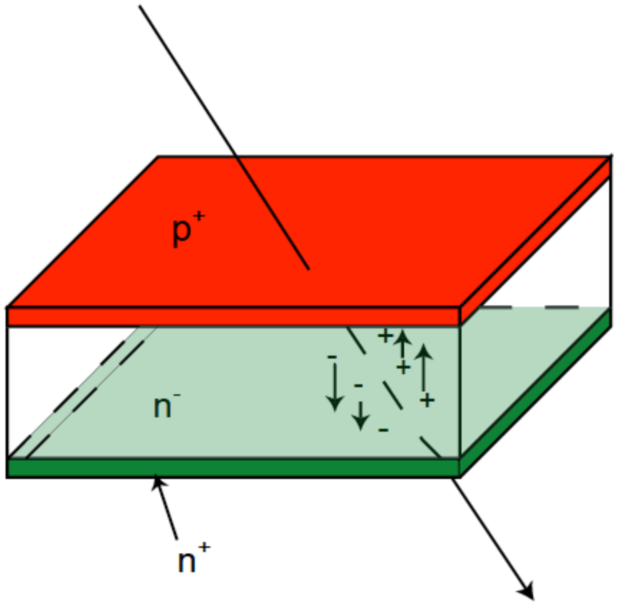


pn area diode

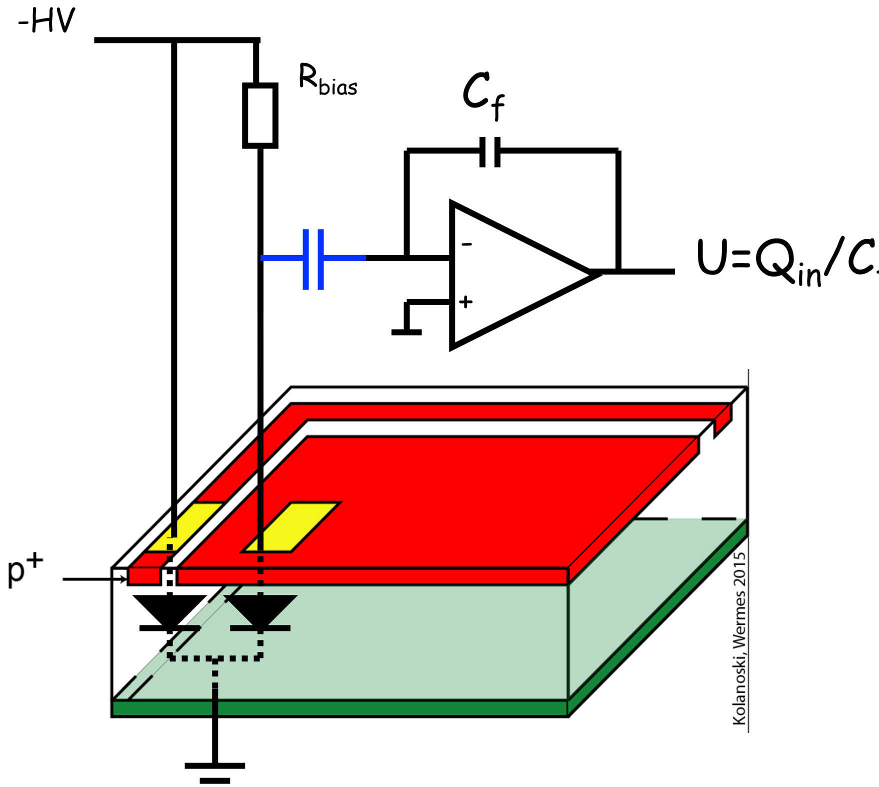


DC - Coupling

Detector shapes



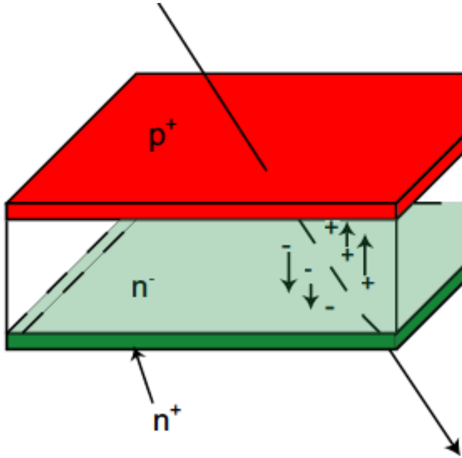
pn area diode

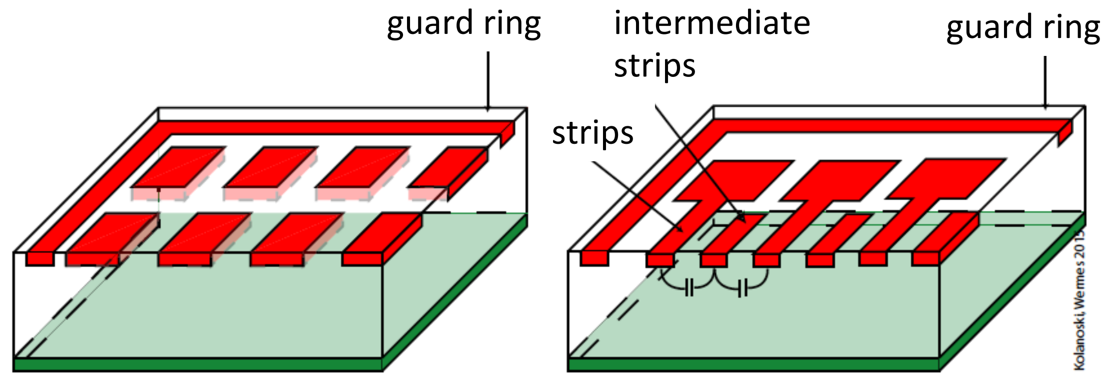


AC - Coupling

Detector shapes

an ionizing particle (or an X-ray photon) creates e/h pairs





in Si bulk fully depleted

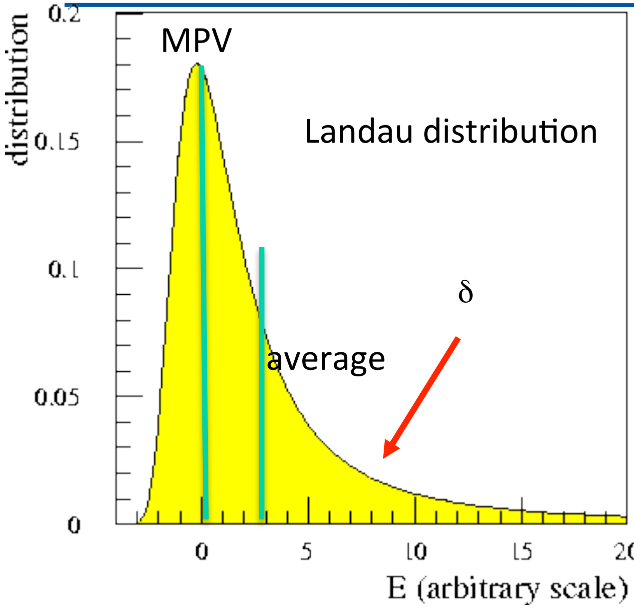
- w_i = 3.65 eV per e/h
- a high energy particle
  → ~ 80 e/h per µm
- all charge collected
- ~ 20 000 e/h per 250 µm
  = 3 fC

- radiation
  e.g. 10 keV X-ray: 3000 e/h
  ≈ 0.5 fC

- strip or pixel pattern
- typical strip pitch: 50 - 100 µm
- typical pixel cells: 100 x 150 µm²
  50 x 400 µm²
- charge drift in E-field
- charge diffusion σ ~8-10 µm
  → charge spreads over 2-3 pixels/strips

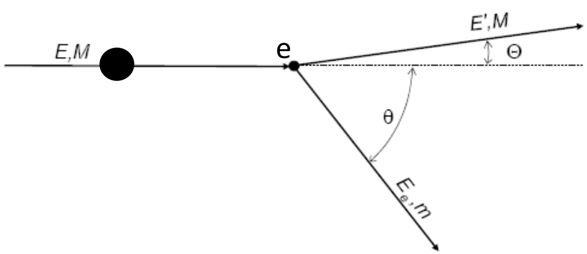
skip δ-electrons?

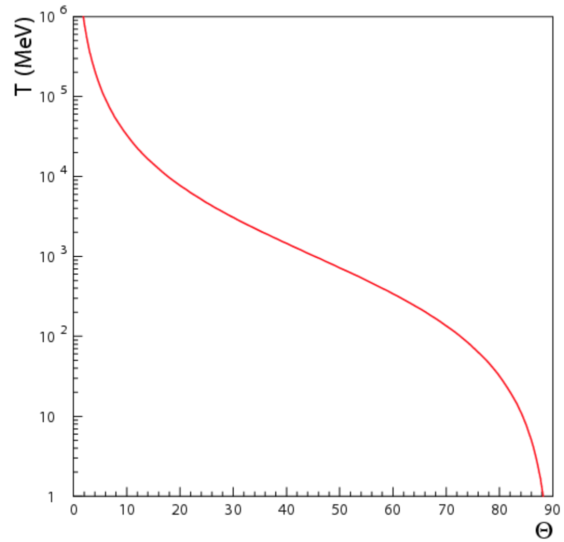
Charge distribution and delta electrons



kinematics: 1-1 relation between emission angle and kin. energy

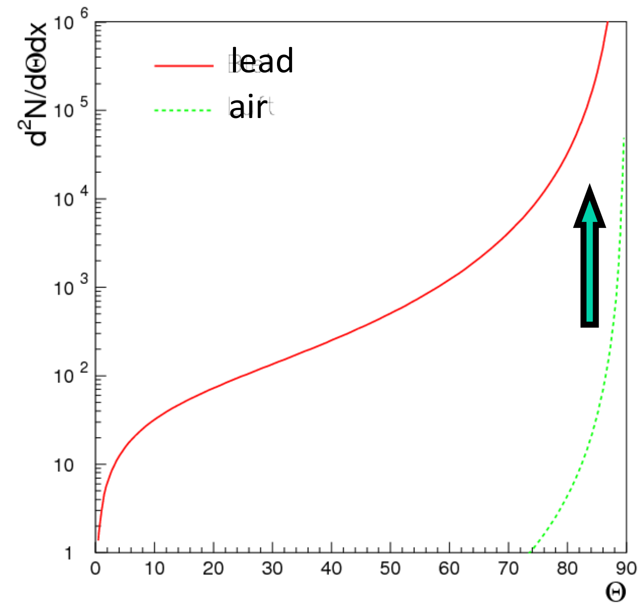
$$\Theta_e(T) = \arctan\left[\frac{1}{\gamma}\left(\frac{T_{\max}}{T}-1\right)^{\frac{1}{2}}\right] \simeq \arctan\sqrt{\frac{2m}{T}}$$





slow ones emitted at right angles
→ in $1/\beta^2$ part of BBF
→ highly ionizing

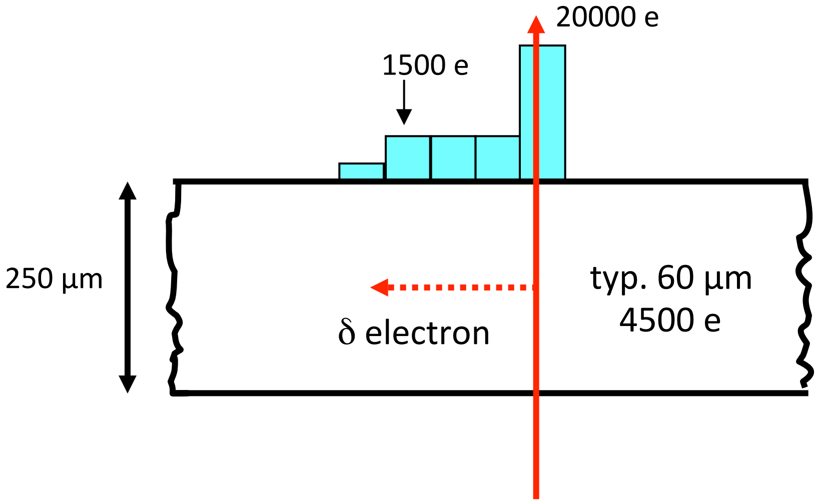
$$\frac{dN}{d\Theta} = \frac{1}{2} D z^2 \frac{Z}{A} \rho x \frac{\sin\Theta}{\cos^3\Theta}$$



for experimentalists

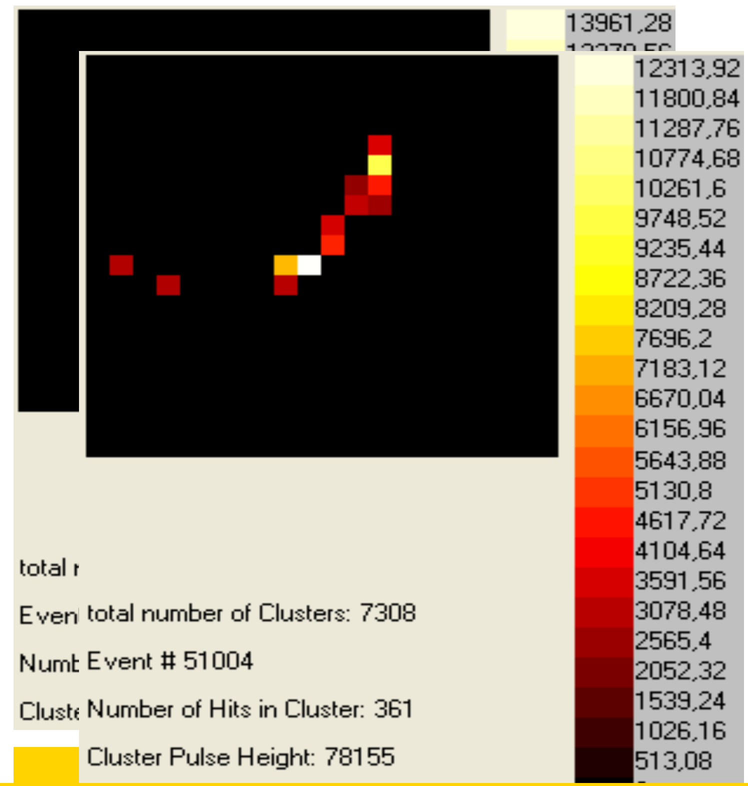
δ- electrons are "always" emitted at 90^0 and are highly ionizing

Delta electrons



<u>effect of δ -electrons</u>

100 keV δ-electron occurs in 300 µm Si with 6% probability and has a “range” of 60 µm

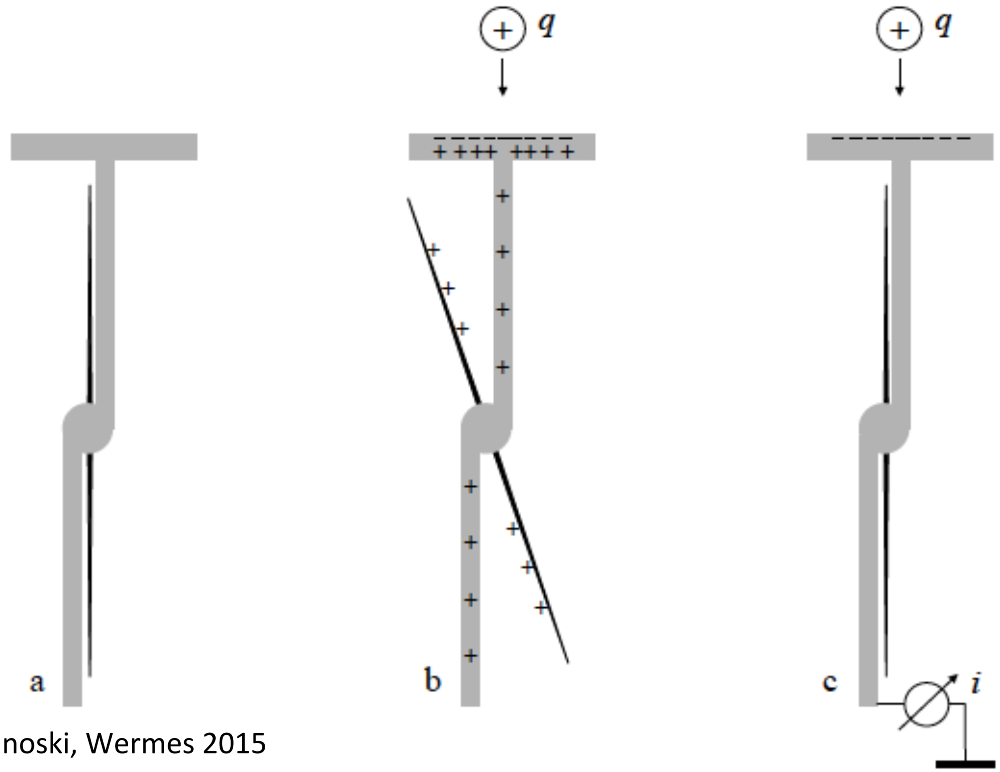


δ-electron with perpendicular emission

DEPFET pixels (25 µm x 25 µm)

How the signal develops

by "electrostatic induction" (influenza elettrica, influence electrique, elektrische Influenz)



Kolanoski, Wermes 2015

a current is generated

Signal generation in an electrode configuration

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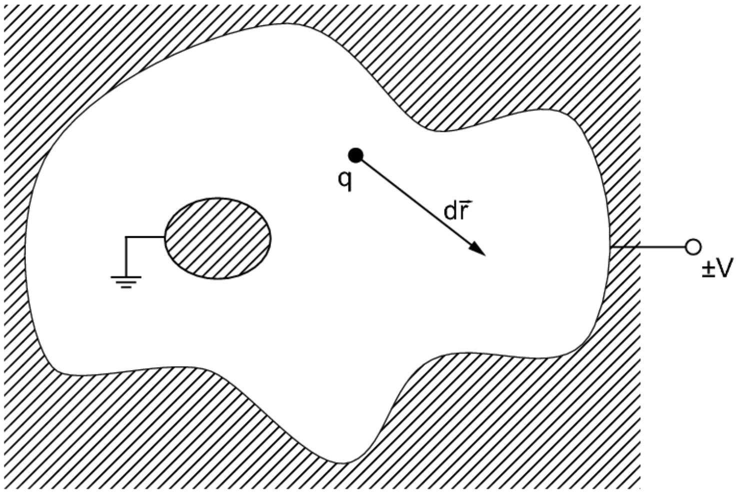


how does a moving charge couple to an electrode ?

- respect Gauss' law and find

Shockley- Ramo theorem
(Shockley J Appl.Phys 1938, Ramo 1939)

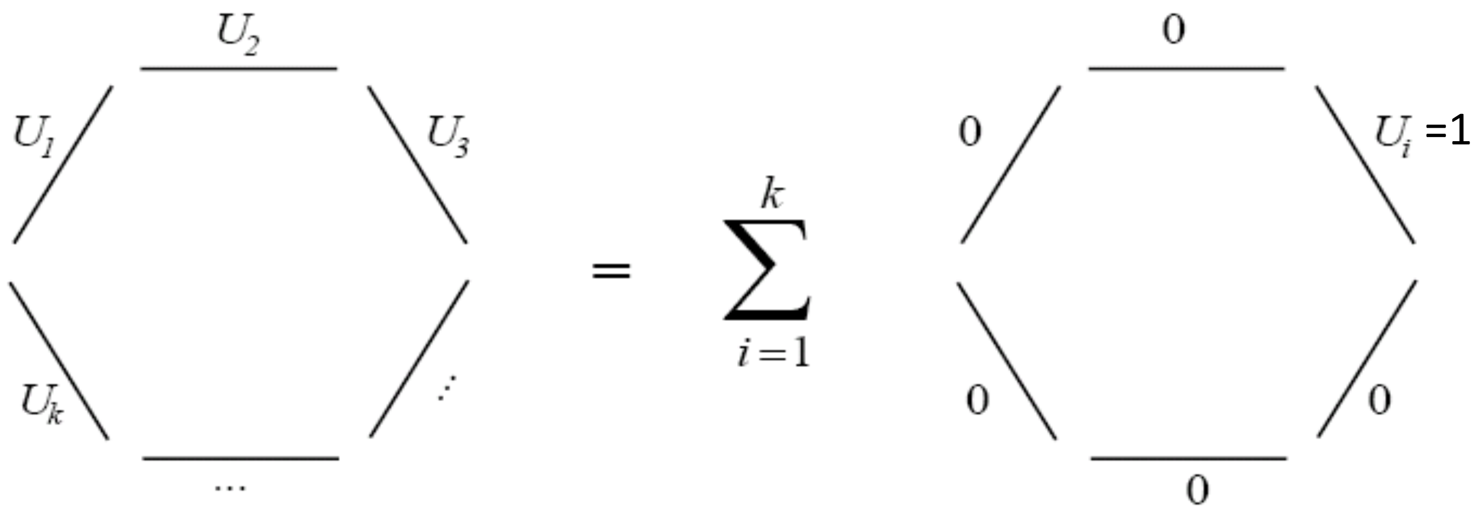
weighting field
determines how charge movement couples to a specific electrode

$$i_S = -\frac{dQ}{dt} = q\,\vec{E}_w\,\vec{v}$$

$$dQ = q\vec{\nabla}\Phi_W\,d\vec{r}$$

induction (weighting) potential
determines how charge movement couples to a specific electrode

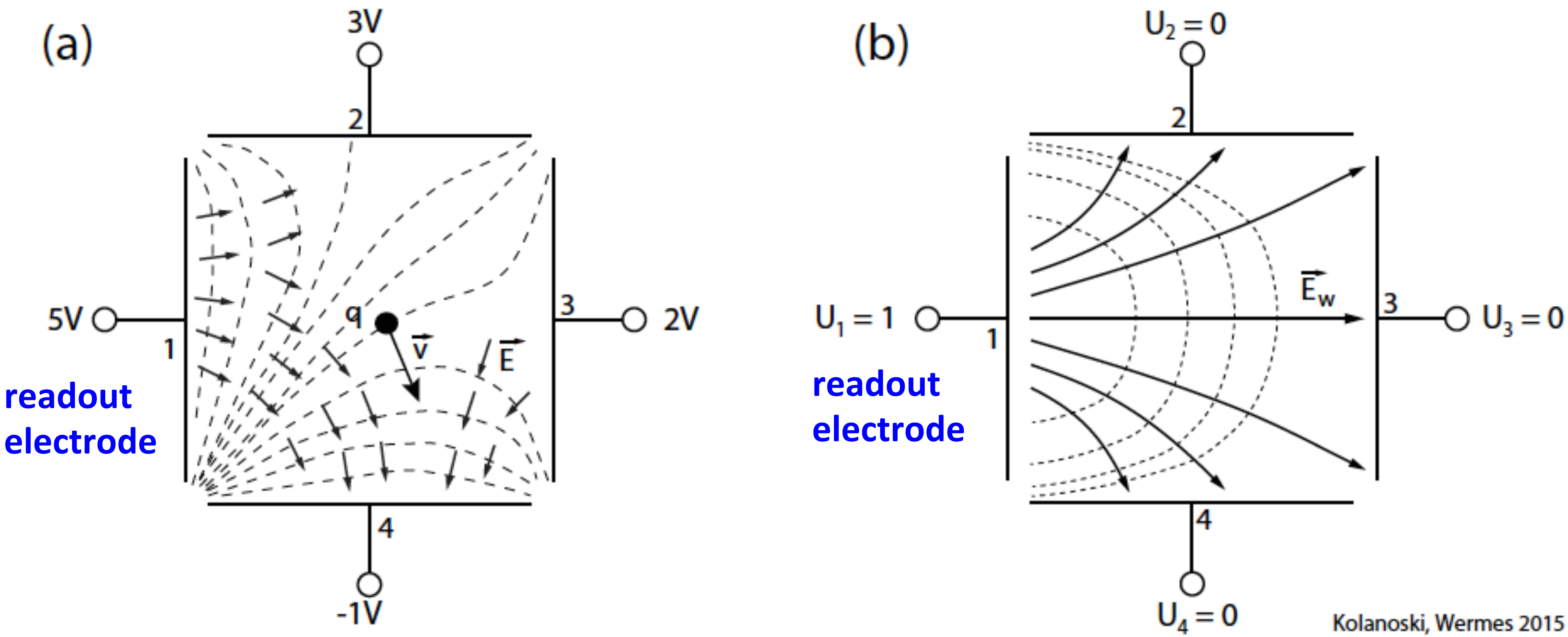
Ramo Theorem in a many electrode configuration



$$dQ_i = -q\,\vec{E}_{w,i}\,d\vec{r}$$

Recipe: To compute the weighting field of a readout electrode i, set voltage of electrode i to 1 and all other electrodes to 0.

Normal Field and Weighting Field



Kolanoski, Wermes 2015

$$i_S = -\frac{dQ}{dt} = q\,\vec{E}_w\,\vec{v}$$

A detector is a **current source**

delivers a current pulse
independent of the load

one can convert current into
charge (integral) or voltage (via R or C)

A parallel plate detector (capacitor)

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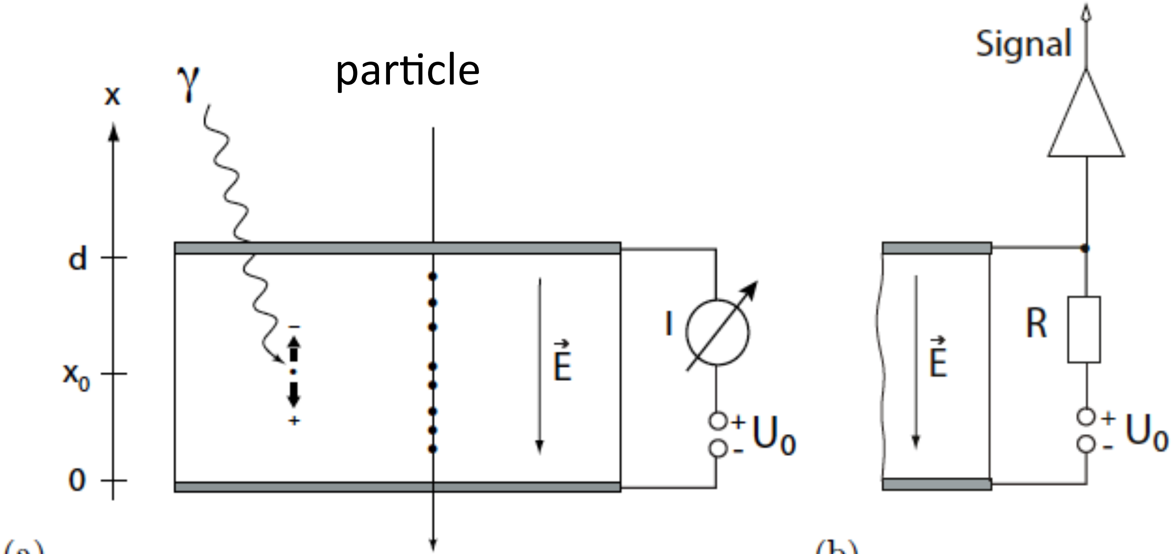


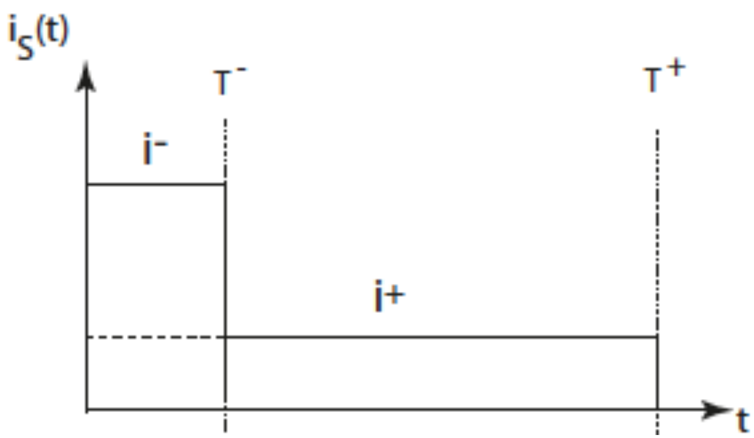
Kolanoski, Wermes 2015

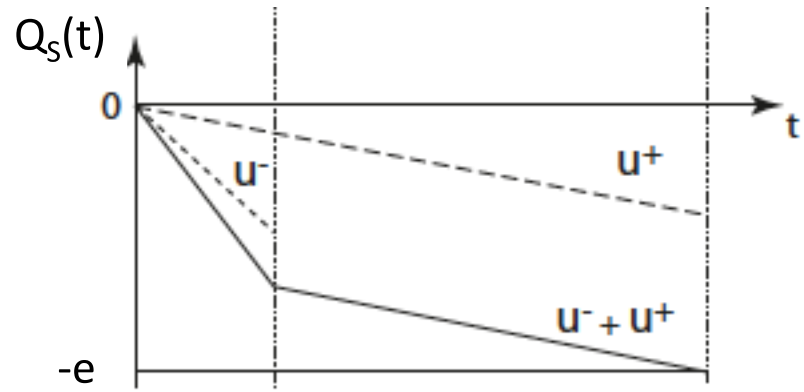
$$\vec{E} = -\frac{U_0}{d}\vec{e}_x \quad ; \qquad C = \frac{\epsilon\epsilon_0 A}{d}$$

- constant E-field
- almost constant velocity (v=μE)
- weighting field simple

$$dQ = -q\,\frac{\vec{E}_0}{U}\,d\vec{r}.$$

$$\vec{E}_w = -\frac{1}{d}\vec{e}_x$$





$$i_S^{\pm} = q^{\pm}\vec{E}_w\,\vec{v}^{\pm} = -\frac{q^{\pm}}{d}\,\vec{e}_x\,\vec{v}^{\pm} = \frac{e}{d}v^{\pm}$$

$$Q_S^{tot} = Q_S^- + Q_S^+ = -\frac{e}{d}\left(\int_0^{T^-} v^- dt + \int_0^{T^+} v^+ dt\right)$$

$$= -\frac{e}{d}v^-\left(\frac{d-x_0}{v^-}\right) - \frac{e}{d}v^+\left(\frac{x_0}{v^+}\right) = -e\,.$$

Signal in a Silicon detector (= parallel plate w/ space charge)

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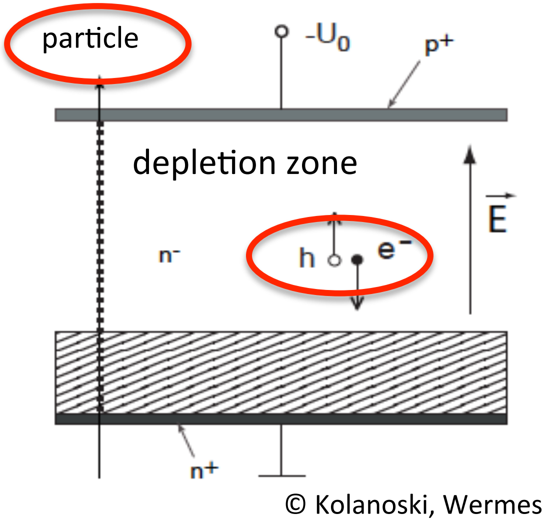
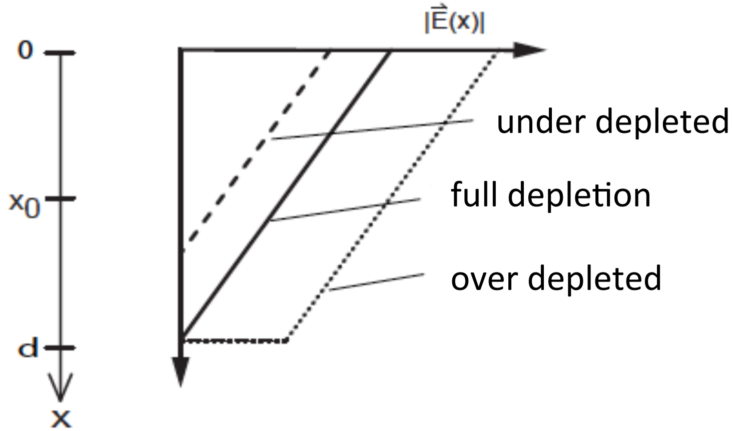


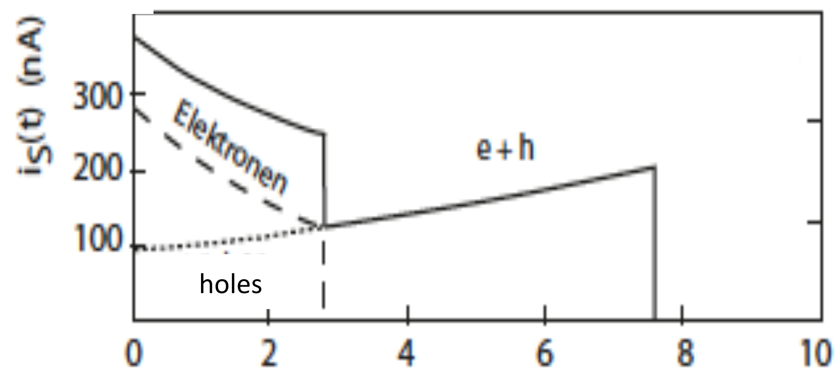


- E-field not constant
- velocity not constant
- weighting field still the same

$$\vec{E}_w = -\frac{1}{d}\vec{e}_x$$

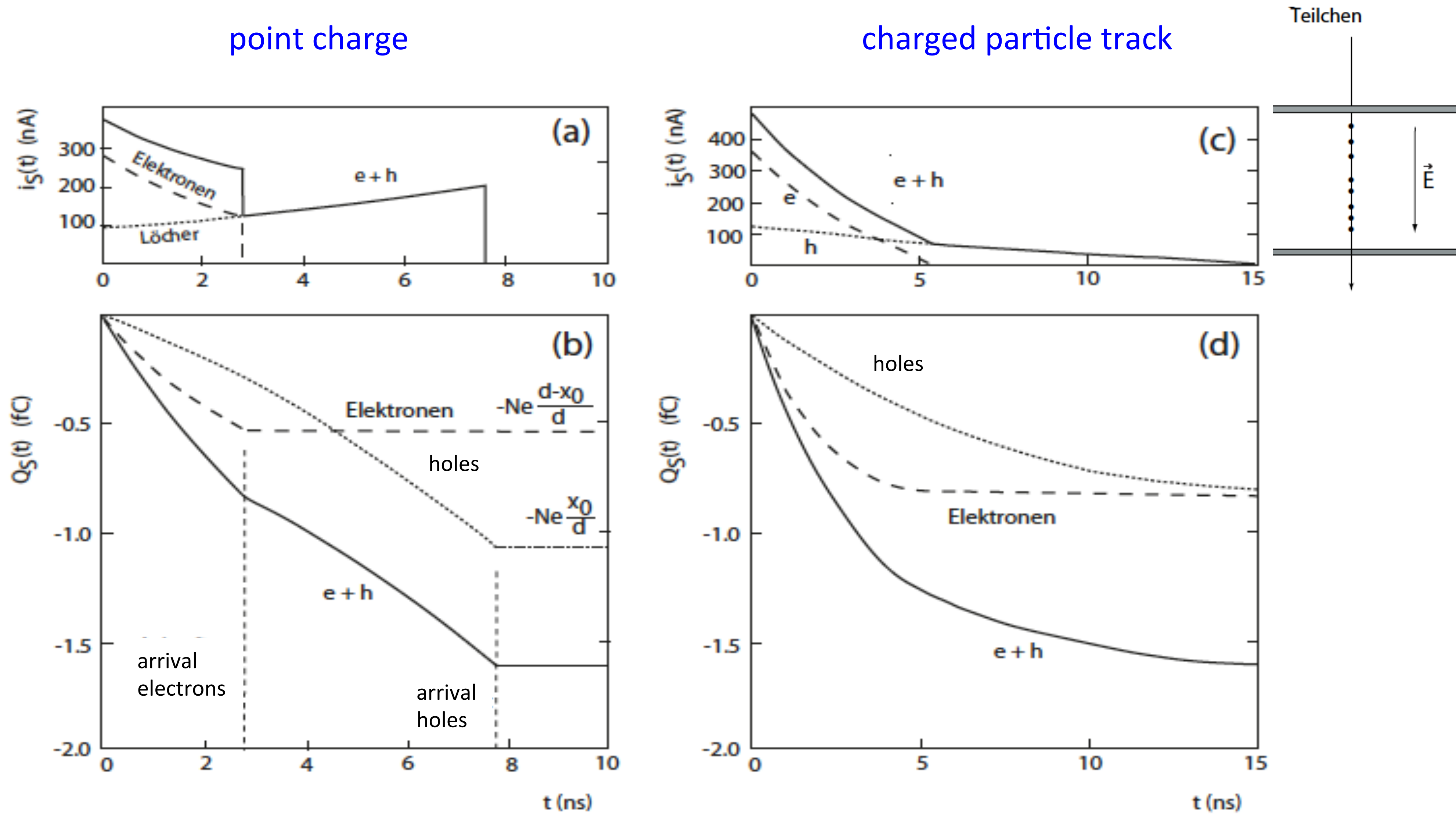
$$E(x) = -\left[\frac{2U_{\text{dep}}}{d^2}(d-x) + \frac{U-U_{dep}}{d}\right] = -\left[\frac{U+U_{dep}}{d} - \frac{2U_{dep}}{d^2}x\right] = -(a-bx)$$

$$v_e = -\mu_e E(x) = +\mu_e(a-bx) = \dot{x}_e$$
$$v_h = +\mu_h E(x) = -\mu_h(a-bx) = \dot{x}_h$$



$$i_S(t) = i_S^e(t) + i_S^h(t)$$
$$= -\frac{e}{d}\left(\frac{2U_{dep}}{d^2}x_0 - \frac{U+U_{dep}}{d}\right)$$
$$\times\left\{\mu_e \exp\left(-2\mu_e\frac{U_{dep}}{d^2}t\right)\Theta(T^- - t) - \mu_h \exp\left(+2\mu_h\frac{U_{dep}}{d^2}t\right)\Theta(T^+ - t)\right\}$$

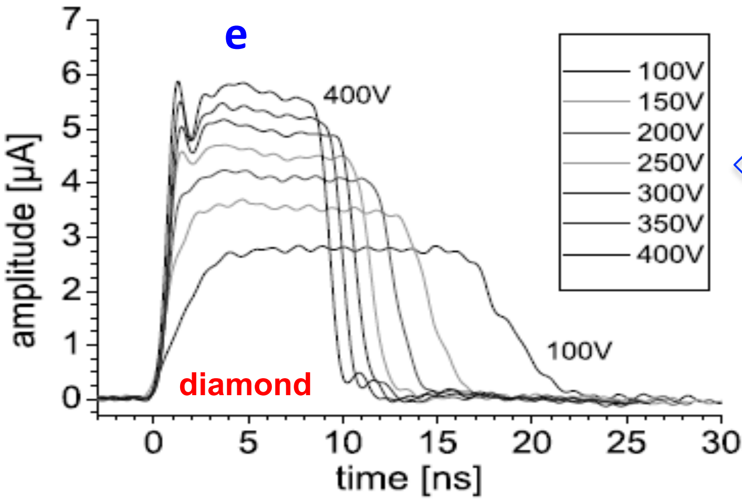
Current and charge signals



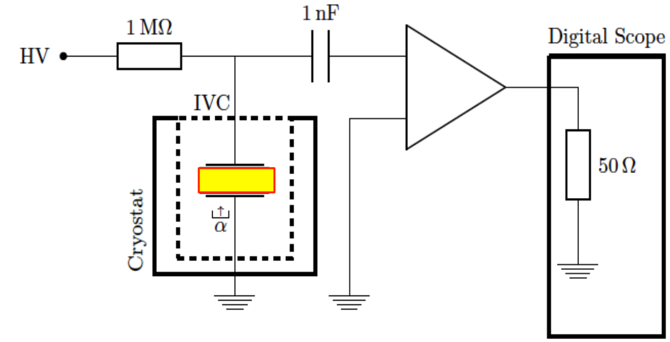
Kolanoski, Wermes 2015

transient current

Current pulse measurements: TCT technique

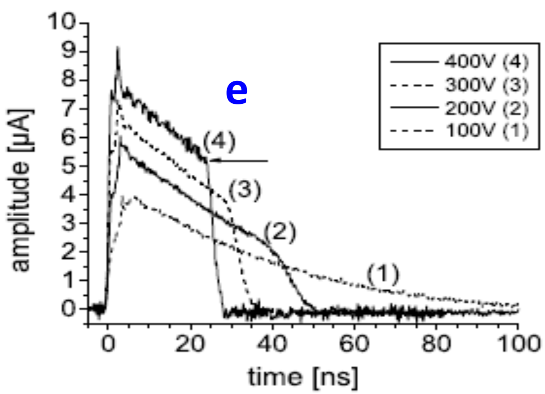


single crystal **diamond** is like a parallel plate detector filled with a dielectric w/o space charge

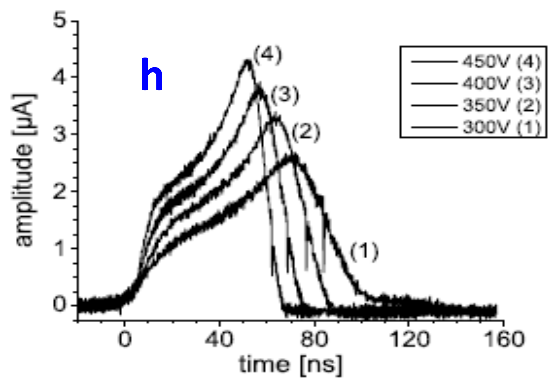


1mm pn – Diode **silicon**

- same weighting field
- different electric field



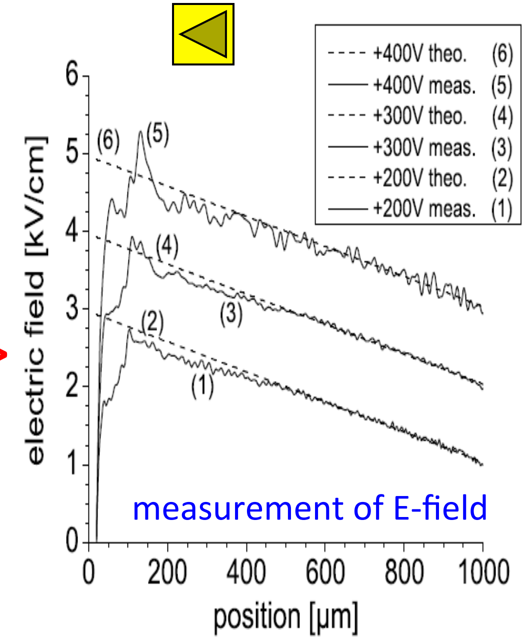
Si



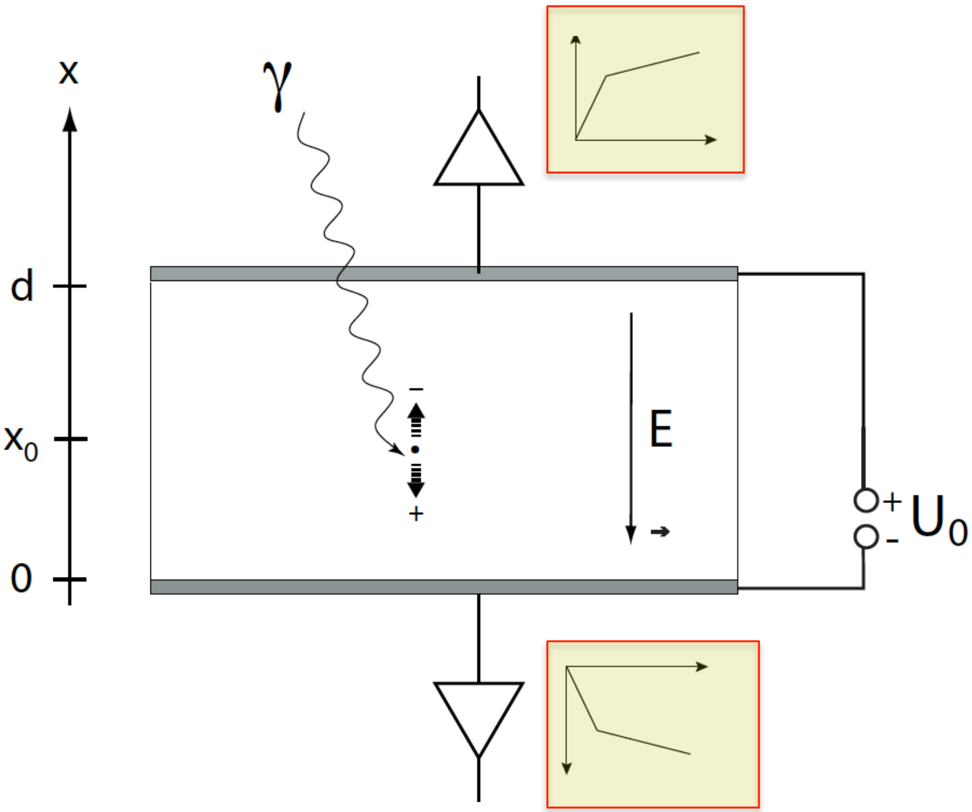
(a) Electron signals from α-particles impinging on the cathode.

(b) Hole signals from α-particles impinging on the anode.

=>



Note

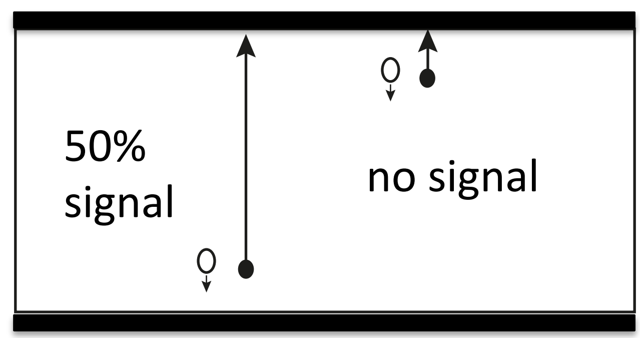


- movement of both charges create signals on both electrodes.
- on every electrode a total charge of

$$Q_S^{tot} = Q_S^- + Q_S^+ = -Ne$$

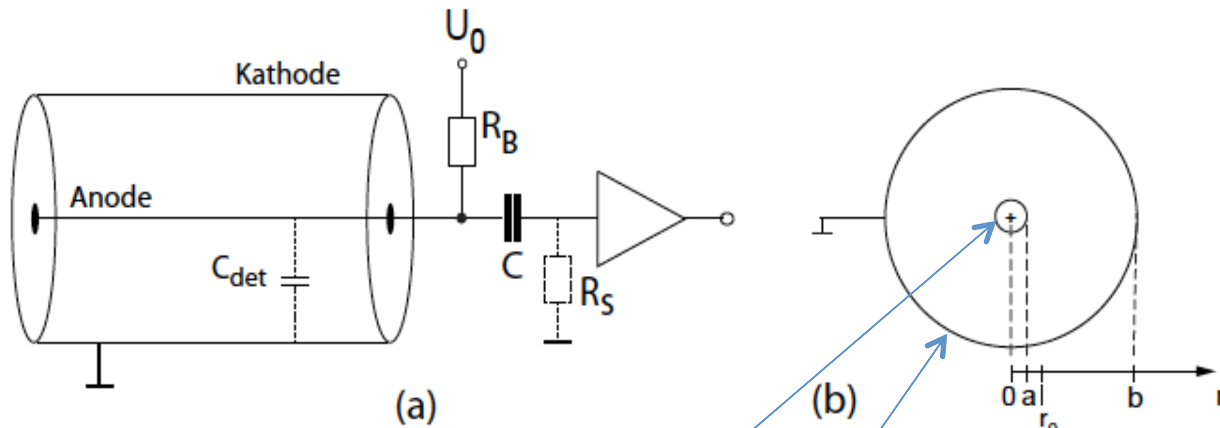
  is induced.

- if a material the produced charges have very different mobilities (like CdTe) e.g. with $\mu_h \approx 0$, then part of the signal is lost and the signal becomes dependent on where the charge was deposited.



Signal development in a wire configuration

configuration



$$\vec{E}(r) = \frac{1}{r}\frac{U_0}{\ln b/a}\frac{\vec{r}}{r}, \qquad \phi(r) = -U_0\frac{\ln r/b}{\ln b/a}, \qquad C_l = \frac{2\pi\epsilon_0}{\ln b/a}.$$

- we follow our Shockley-Ramo-recipe: find weighting field E_W or the weighting potential Φ_W by setting

$$\phi_w(a) = 1\,, \quad \phi_w(b) = 0 \qquad (*)$$

- we know already the shape of $\Phi_W \sim \ln r$, since $E(r) \sim 1/r$
- hence

$$\vec{E}_w(r) = \frac{1}{r}\frac{1}{\ln b/a}\frac{\vec{r}}{r}, \qquad \phi_w(r) = -\frac{\ln r/b}{\ln b/a}$$

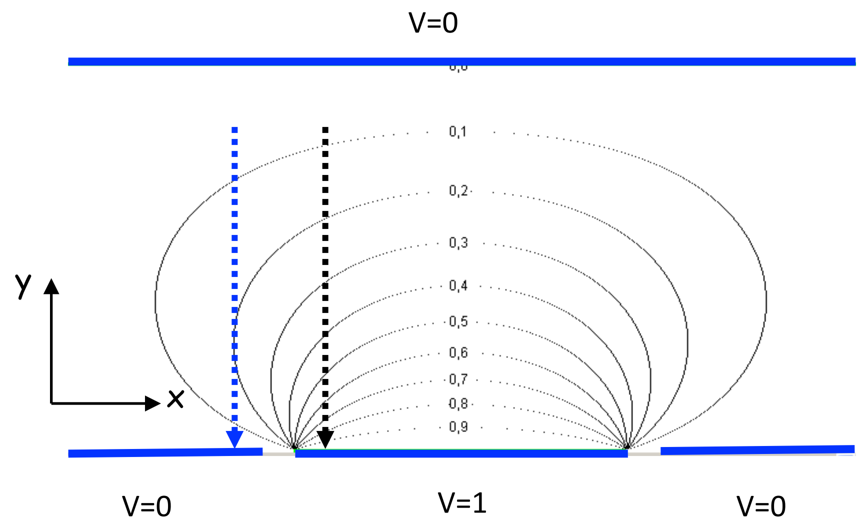
which fulfils (*)

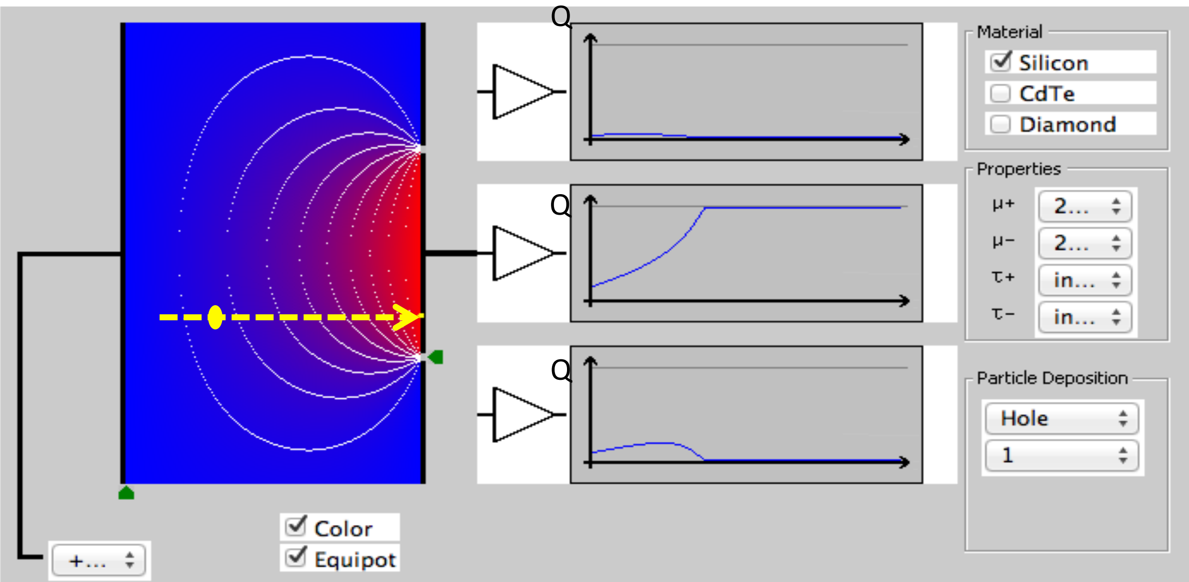
Signal generation in a pixellated detector (1-dim)

Φ_W for a strip/pixel geometry

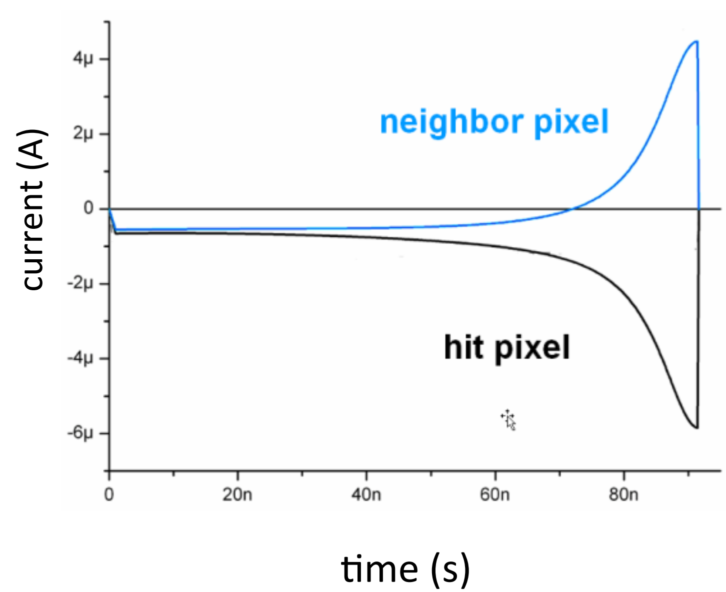
$$\Phi(x,y) = \frac{1}{\pi}\arctan\frac{\sin(\pi y)\cdot\sinh(\pi\frac{a}{2})}{\cosh(\pi x) - \cos(\pi y)\cosh(\pi\frac{a}{2})}$$

(can be calculated e.g. by using "conformal mapping")





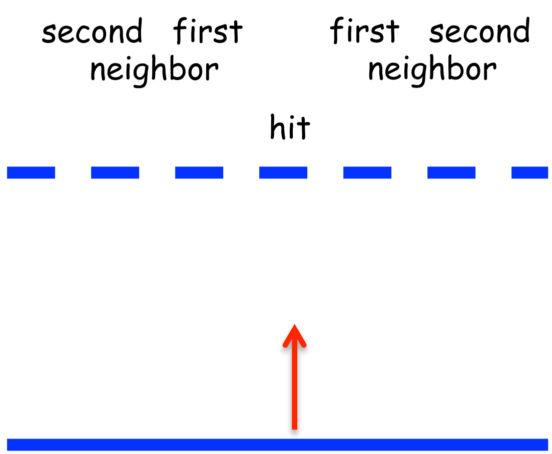
"small pixel effect" !

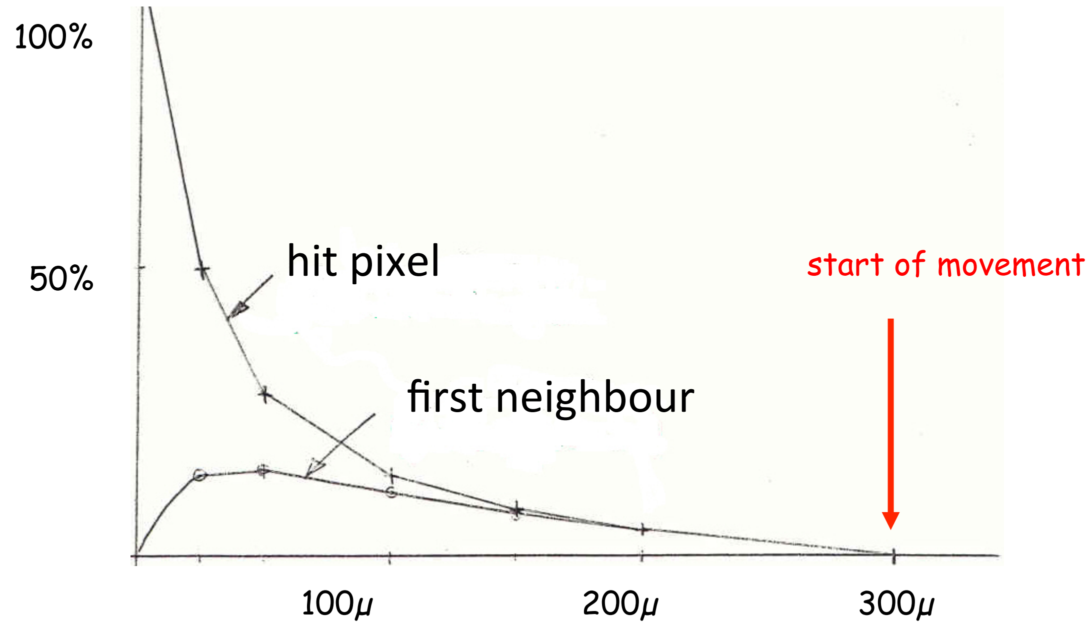


Concluding … consequences …

- The weighting field reaches also into regions of neighbor pixels → induced signals there as well
- At the beginning of the charge movement, neighbor pixels "see" almost as much signal as the "hit" pixel → no difference when electronics is (too) fast
- consequences for small electrodes is, that most of the charge is induced, when q is <u>near</u> the hit pixel → small pixel effect
- when charges drift only a short distance due to
  - $\mu_h << \mu_e$ (e.g. for CdTe)
  - trapping (e.g. for pCVD diamond)

  peculiar signal patterns may arise (worst case: holes do not move and electrons are trapped after 50 µm → several pixels "fire")





Transport of charges to the R/O electrode

generally described by the Boltzmann Transport Equation

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{d\vec{r}}{dt}\vec{\nabla}_{\vec{r}} f + \frac{d\vec{v}}{dt}\vec{\nabla}_{\vec{v}} f = \frac{\partial f}{\partial t}_{|coll}$$

with f(r, v, t) describing the probability distribution in phase space

$$dp(\vec{r},\vec{v},t) = f(\vec{r},\vec{v},t)\, d^3\vec{r}\, d^3\vec{v}$$

Which can treat arbitrary E and B-fields …

$$v^B_{D,1} = -\frac{4\pi}{3}\frac{qE}{m}\int_0^\infty \tau \frac{\omega_2\tau}{1+\omega^2\tau^2}\left(\frac{2\epsilon}{m}\right)^{3/2}\frac{\partial f_0}{\partial\epsilon}d\epsilon = \frac{qE}{m}\left\langle \tau\frac{\omega_2\tau}{1+\omega^2\tau^2}\right\rangle_\epsilon$$

$$v^B_{D,2} = \frac{4\pi}{3}\frac{qE}{m}\int_0^\infty \tau \frac{\omega_2\omega_3\tau^2}{1+\omega^2\tau^2}\left(\frac{2\epsilon}{m}\right)^{3/2}\frac{\partial f_0}{\partial\epsilon}d\epsilon = \frac{qE}{m}\left\langle \tau\frac{\omega_2\omega_3\tau^2}{1+\omega^2\tau^2}\right\rangle_\epsilon$$

$$v^B_{D,3} = \frac{4\pi}{3}\frac{qE}{m}\int_0^\infty \tau \frac{1+\omega_3^2\tau^2}{1+\omega^2\tau^2}\left(\frac{2\epsilon}{m}\right)^{3/2}\frac{\partial f_0}{\partial\epsilon}d\epsilon = \frac{qE}{m}\left\langle \tau\frac{1+\omega_3^2\tau^2}{1+\omega^2\tau^2}\right\rangle_\epsilon$$

with

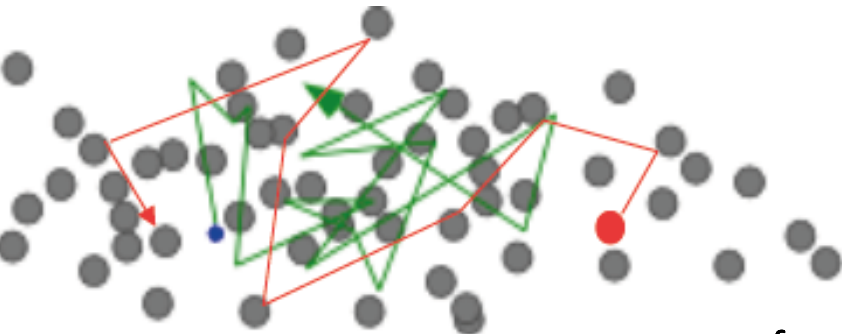
$\omega_i = qB_i/m$ = cyclotron frequencies

τ = mean collision time
ε = kin. energy

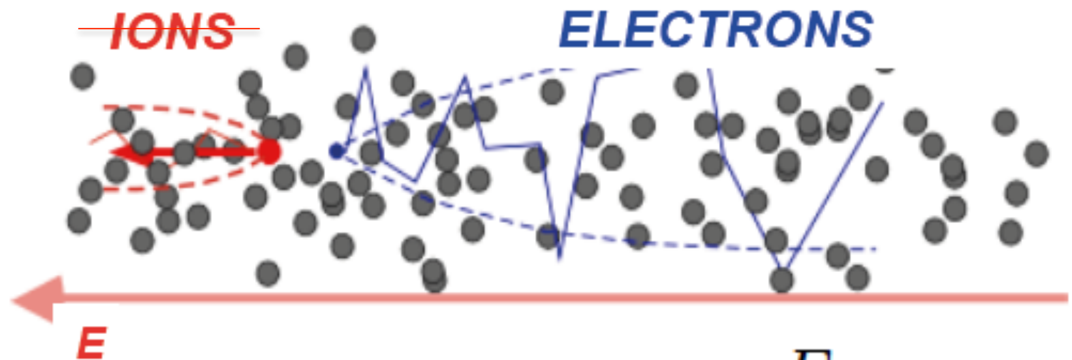
In detectors: usually either $\vec{E} \perp \vec{B}$ or $\vec{E} \parallel \vec{B}$

Diffusion and drift of charge cloud on way to electrode

E = 0, T > 0: diffusion



E > 0, T > 0: diffusion + drift



$$D = \frac{\langle \lambda v \rangle}{3} = \frac{1}{3\sigma p}\sqrt{\frac{8(kT)^3}{\pi m}}$$

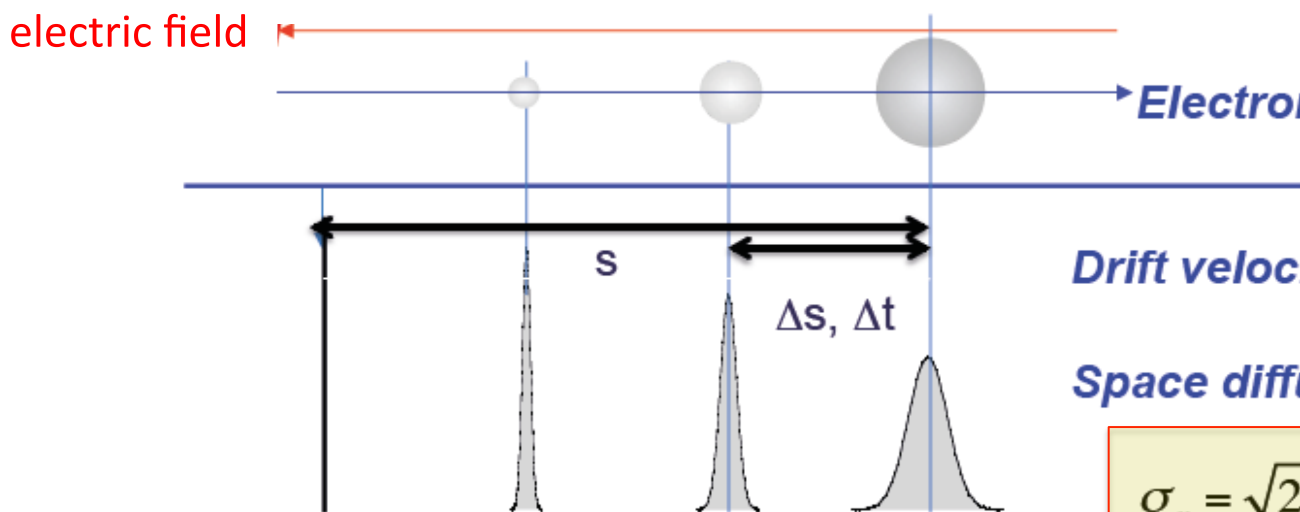
pressure for gas

density for semicond.

$$v_D = \mu(E)\,E = \frac{\mu_0 E}{\left[1 + \left(\frac{\mu_0 E}{v_{\mathrm{sat}}}\right)^{\beta}\right]^{1/\beta}}$$

Drude Ansatz (emp.)
(especially semicond.)

β~1-2

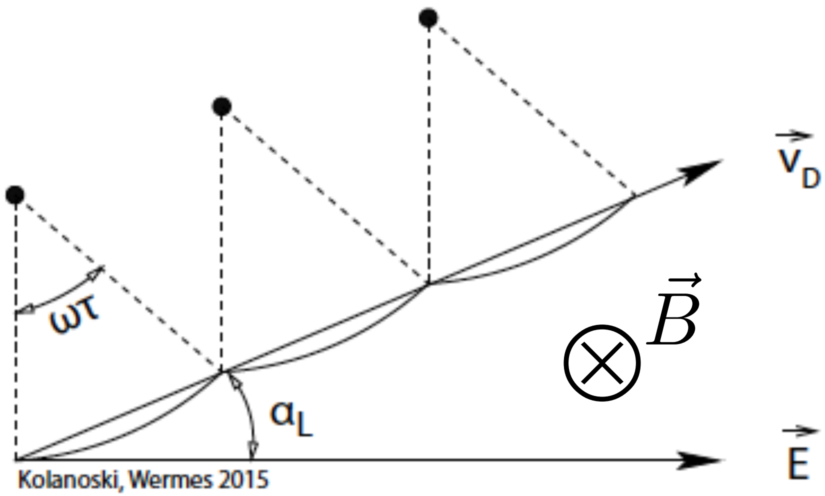


Drift velocity: $v_D = \frac{\Delta s}{\Delta t}$

Space diffusion rms:

$$\sigma_x = \sqrt{2Dt} = \sqrt{2D\frac{s}{v_D}}$$

Movement in the presence of a magnetic field



- if the electric field E is perpendicular to a magnetic field B then the charges drift on circle segments until they stop in a collision
- on average this results in a deflection of the drift path by an angle called

Lorentz angle

perp. to E

$$\tan \alpha_L = \frac{v_{D,\perp}}{v_{D,\parallel}} = \omega\tau$$

parallel to E

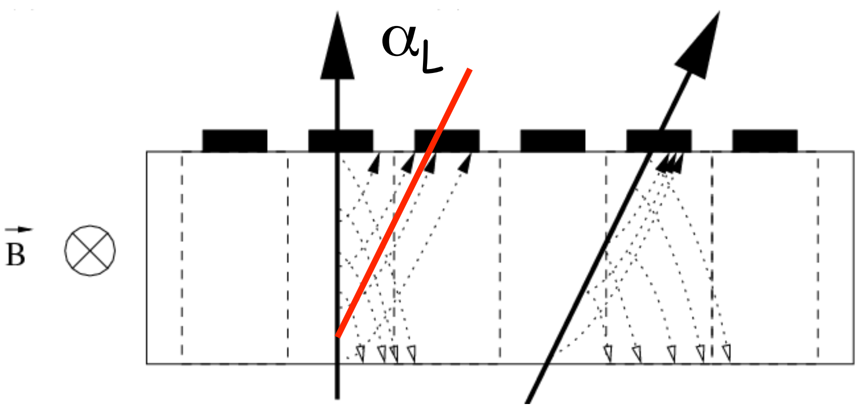
with

ω = qB/m = cyclotron frequency

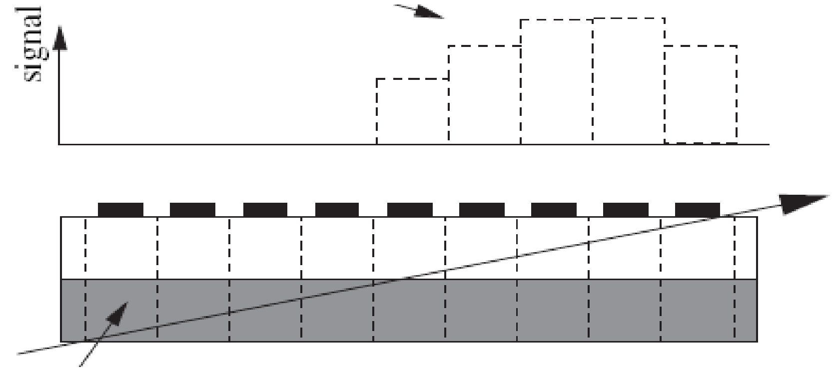
τ = mean collision time

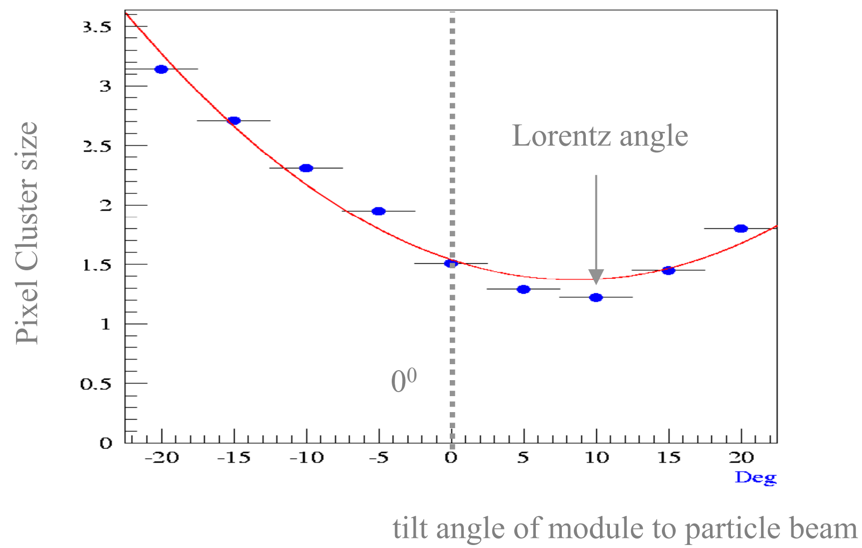
Signal generation in a magnetic field

Lorentz angle (= average deviation between collisions)



$$\tan\alpha_L = \mu_{Hall} B_\perp$$





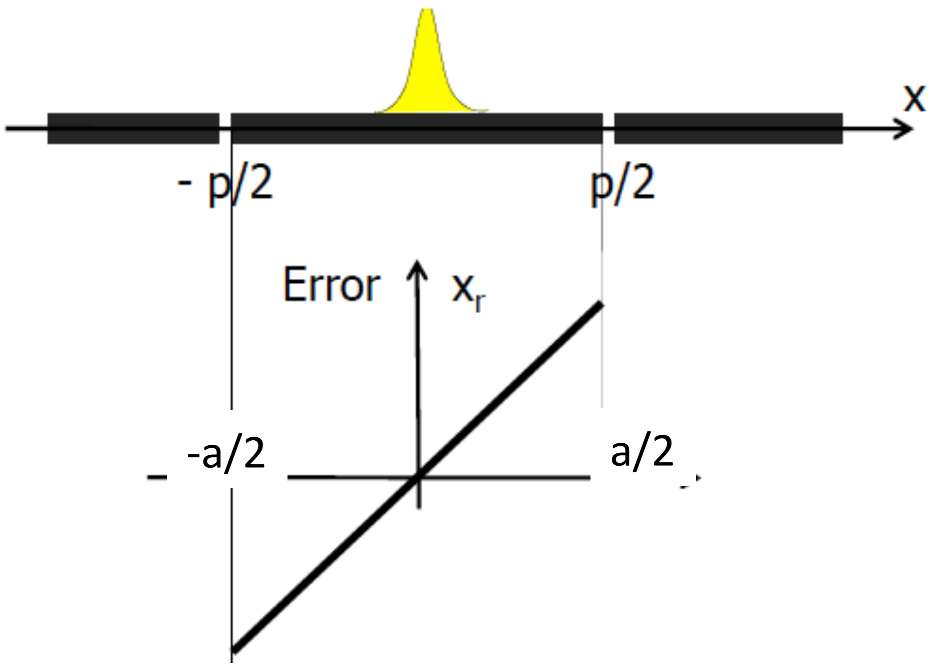
Measurement method: number of pixel hits is minimal when the particle incidence angle is equal to the Lorentz angle (ATLAS pixels)

skip hit space resol?

I. Gorelov et al. NIM A481:204-221,2002

Spatial Resolution in segmented electrode configurations

binary R/O



- binary readout (hit/no hit)
- analog readout (pulse height information)

- signal (charge) distributed on more than one electrode

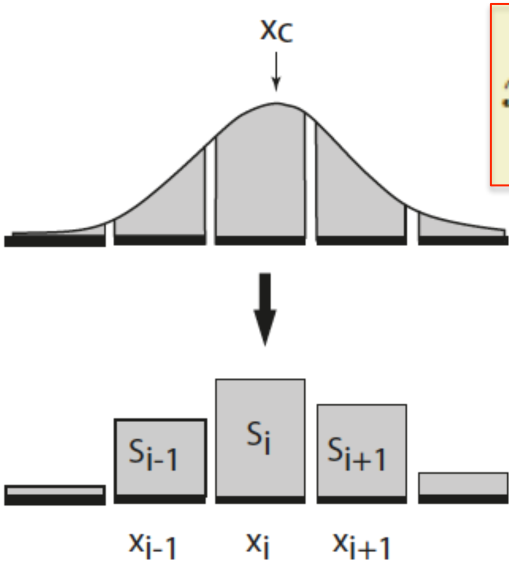
$$v = \int_{x_1}^{x_2} x^2 f(x) dx$$

$$\sigma_x^2 = \frac{1}{a}\int_{-a/2}^{a/2} \Delta_x^2 \, d(\Delta_x) = \frac{a^2}{12}$$

$$\sigma_x = \frac{a}{\sqrt{12}}$$

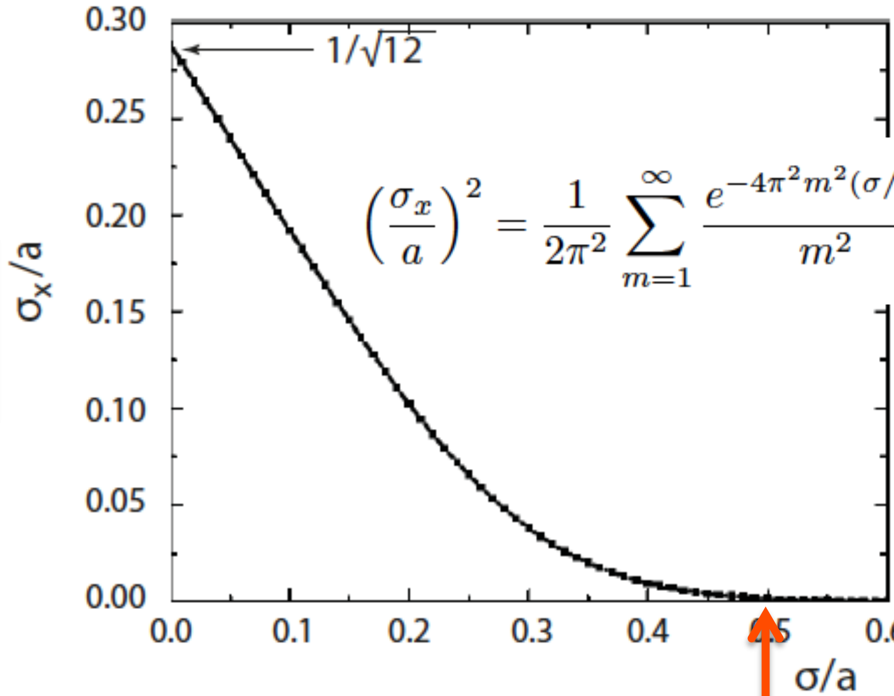
Spatial Resolution in segmented electrode configurations

with analog information and spread over more than one electrode



center of gravity

$$x = x_c = \frac{\sum S_i x_i}{\sum S_i}$$



$$\left(\frac{\sigma_x}{a}\right)^2 = \frac{1}{2\pi^2}\sum_{m=1}^{\infty}\frac{e^{-4\pi^2 m^2(\sigma/a)^2}}{m^2}$$

perfect resolution but only w/o noise

width of charge cloud

$$x_{rec} = \frac{\sum (S_i + n_i)\, x_i}{\sum (S_i + n_i)} = \frac{x + \sum n_i x_i}{1 + \sum n_i} = \left(x + \sum n_i x_i\right)\left(1 - \sum n_i + \mathcal{O}(n_i^2)\right)$$

with uncorrelated noise (normalized to signal and with S=1) $\langle n_i^2 \rangle = \sigma_n^2,$

$$\Rightarrow \sigma_x^2 = \sigma_n^2 \left[\left(\sum_{i=1}^{N} x_i^2\right) + N\langle x^2\rangle\right] + \mathcal{O}(\sigma_n^3)$$

P. Fischer publ. in prep

Observations

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formalism can be extended accordingly to 2D

$$\sigma_x^2 = \sigma_n^2 \left[\left(\sum_{i=1}^{N} x_i^2 \right) + N \langle x^2 \rangle \right] + \mathcal{O}(\sigma_n^3)$$

small number of electrodes good (because of noise)

good, if charge confined in small area -> circle like

Geometry	factor for (a = A = 1)
strips	0.816
pixel (square)	1.155
pixel (hexagonal)	0.491

hexagons least sensitive to noise contributions on electrodes

Example:

- two strips at x_1 = -a/2 and x_2 = +a/2 (N = 2)
- Signals for a hit at x are

$$S_1(x) = (x_2 - x)/a \text{ and } S_2(x) = (x + x_2)/a$$

- $S_1 + S_2 = 1$; $x_1 S_1 + x_2 S_2 = x$; $x_1 + x_2 = 0$ ✓

$$\left(\frac{\sigma_x}{\sigma_n}\right)^2 \approx x_1^2 + x_2^2 + \frac{2}{a}\int_{x_1}^{x_2} x^2 dx = \frac{2}{3} a^2$$

$$\sigma_x = 0.816\, a\, \sigma_n$$

- Thus the resolution for S/N = 10 (σ_n= 0.1) is

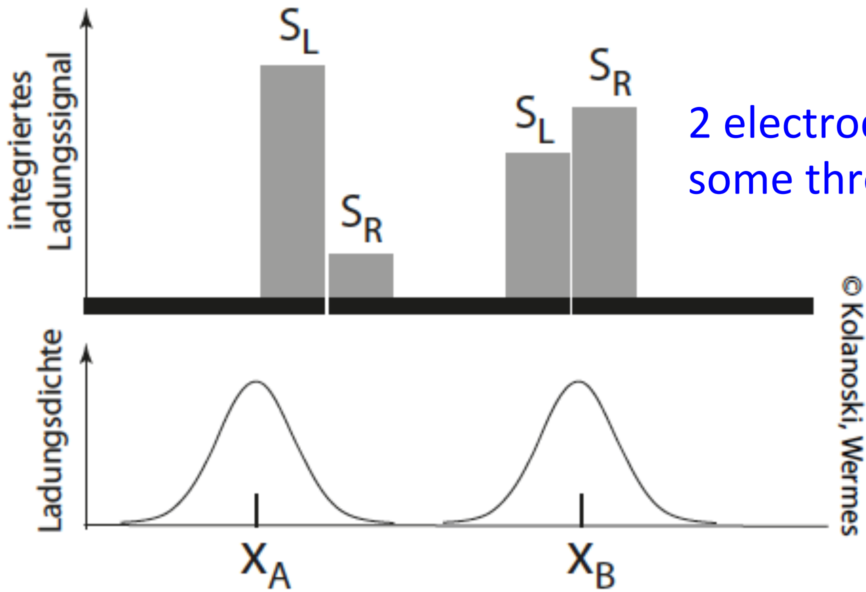
$$\sigma_x = 0.08a$$

It is better than binary (a/√12) as long as S/N > 2.8.

Arbitrary detector response

typical for semiconductor detectors
and patterned gaseous detectors

$N_{electrodes}$ = 2-3, S/N ~ 10



2 electrodes have signal over some threshold

$$S_L(x) = Q\,\eta(x)$$

$$S_R(x) = Q - S_L(x) = Q\,(1 - \eta(x))$$

η = response function, indep. of Q
can be determined from signals themselves

$$\eta = \frac{S_L}{S_L + S_R}$$

- assume a constant hit probability density
- => can build inverse of η-function (η -> x)
- pick best estimate of position from measured distribution
- algorithm can also be extended to three – electrode situations

$$x_{rec} = \eta^{-1}\left(\frac{S_L}{S_L + S_R}\right) = \frac{a}{N}\int_0^{\eta} \frac{dN}{d\eta'}\,d\eta'$$

Arbitrary detector response

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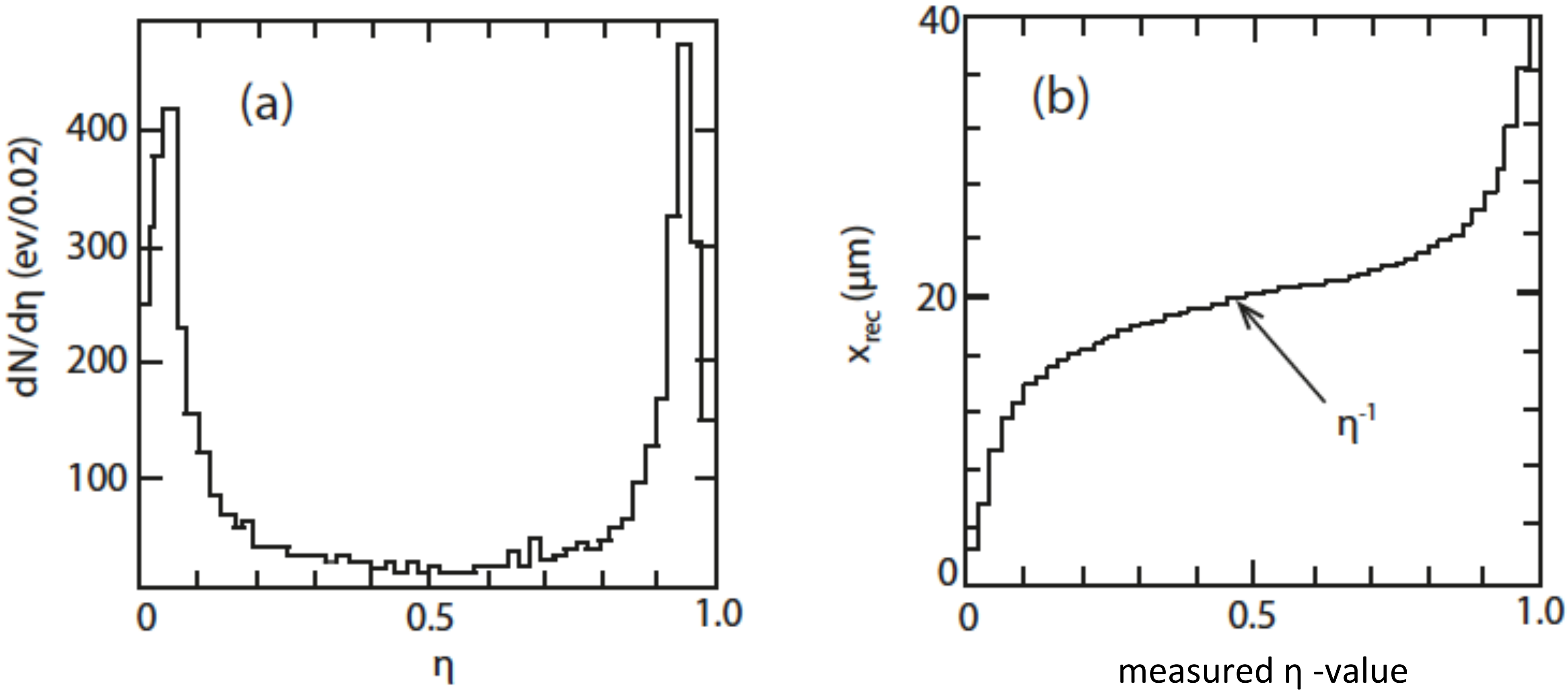
Belau, E. et al.: NIM 214 (1983) 253–260



measured η -value

including noise

$$x_{rec} \approx x + \left.\frac{d\eta^{-1}(s)}{ds}\right|_{\eta(x)} \cdot \Big(n_L(1-\eta(x)) - n_R\,\eta(x) \Big)$$

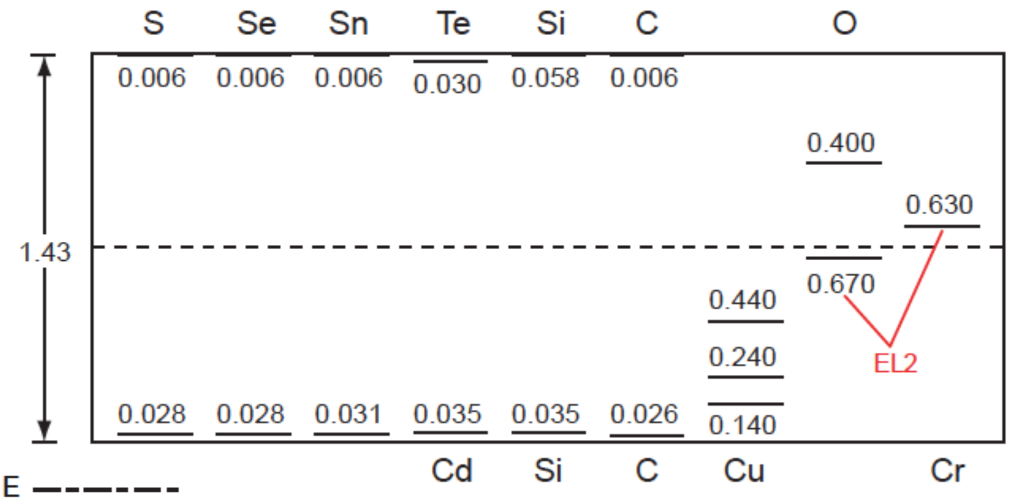
What is different in other semiconductors?

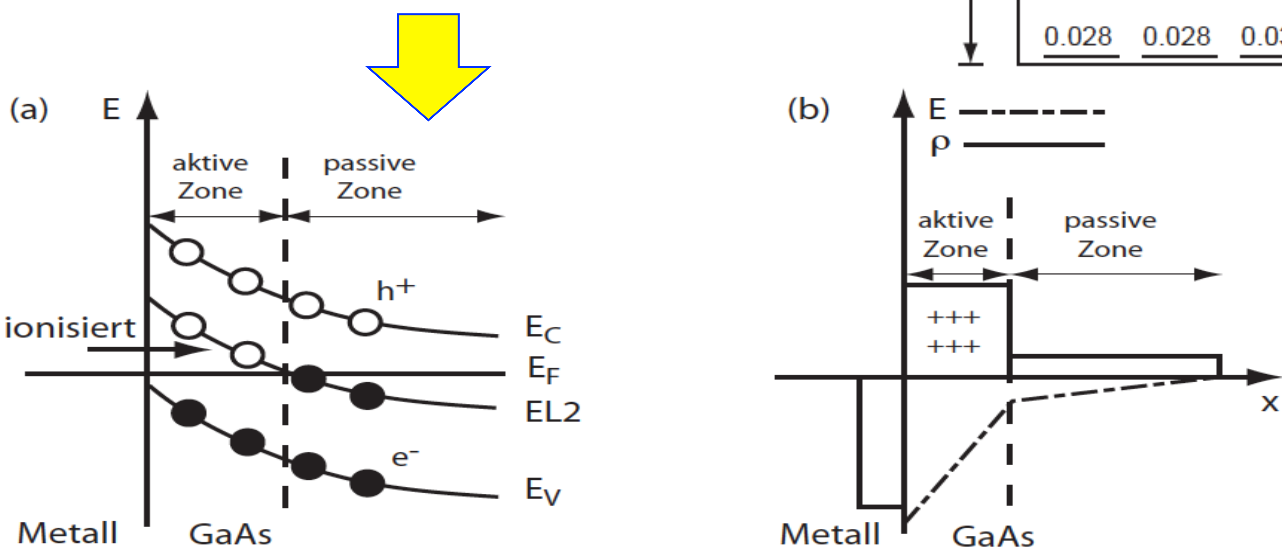
❑ Ge

- similar to Si (but larger Z = 32)
- smaller bandgap (Ge: 0.7 eV; Si: 1.12 eV),
  => smaller w_i needed per e/h-pair (2.96 vs 3.65 eV) => larger signal
  => but also: more thermally generated leakage current => needs cooling

❑ GaAs

- Z = 32
- larger bandgap than Si (radhard??)
- dangerous EL2 defect (Ga on As place which causes low field region





- in low field region only slow charge movement -> losses
- CCEs of >90% achieved
- currently not pursued for particle tracking

Kolanoski, Wermes 2015

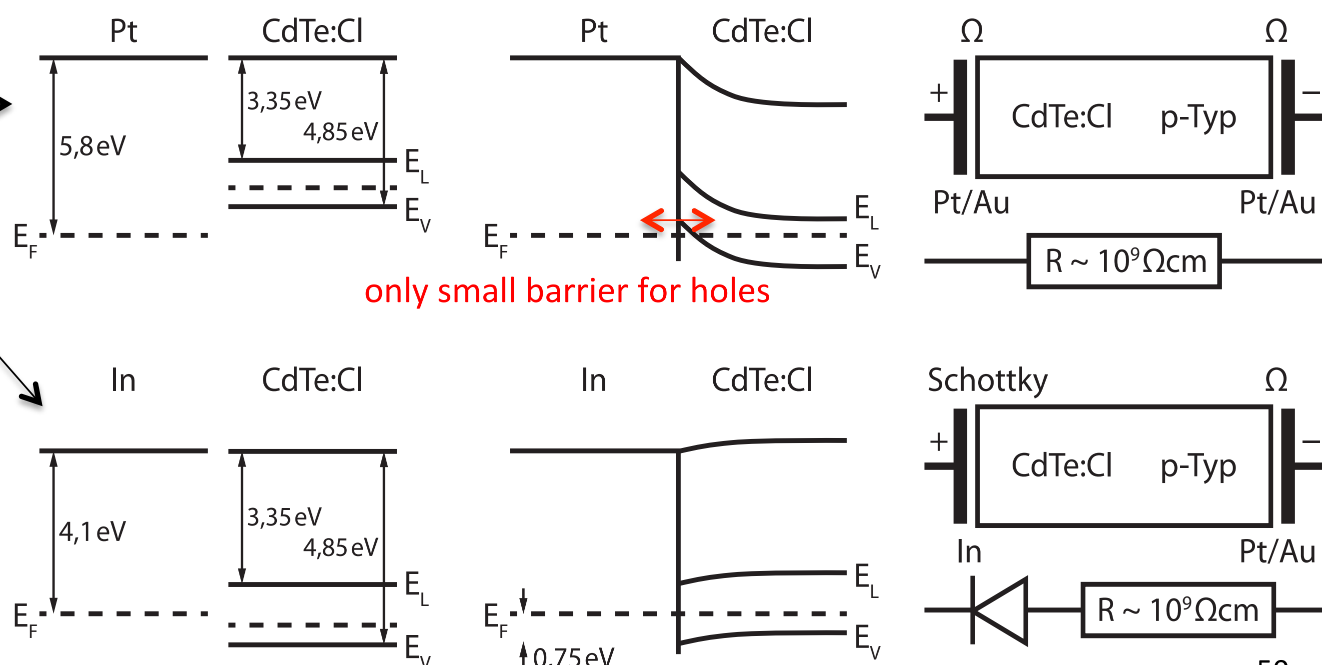
What is different in other semiconductors?

universitätbonn

- **CdTe and CZT (= $Cd_{(1-x)}Zn_xTe$)**
  - large Z ≈ 50 => interesting for imaging
  - larger bandgap (1.44 – 2.2 eV … typical 1.6 eV)
    => less signal
    => less leakage current
  - material is soft
  - small hole mobility and small μτ-product
    (2-3 orders of magnitude smaller than Si)
  - crystal defects often compensated by Cl or In (donors)
  - depending on the choice of metal CdTe can be operated in
    ohmic mode
    or Schottky mode
  - Schottky mode has o(10) smaller leakage current than ohmic, but develops a time dependent space charge

$$(\mu\tau)_e \approx 10^{-3}\,\mathrm{cm}^2/\mathrm{V}$$
$$(\mu\tau)_h \approx 10^{-4}\,\mathrm{cm}^2/\mathrm{V}$$

"holes don't move"
=> 50% signal
=> signal position dependent

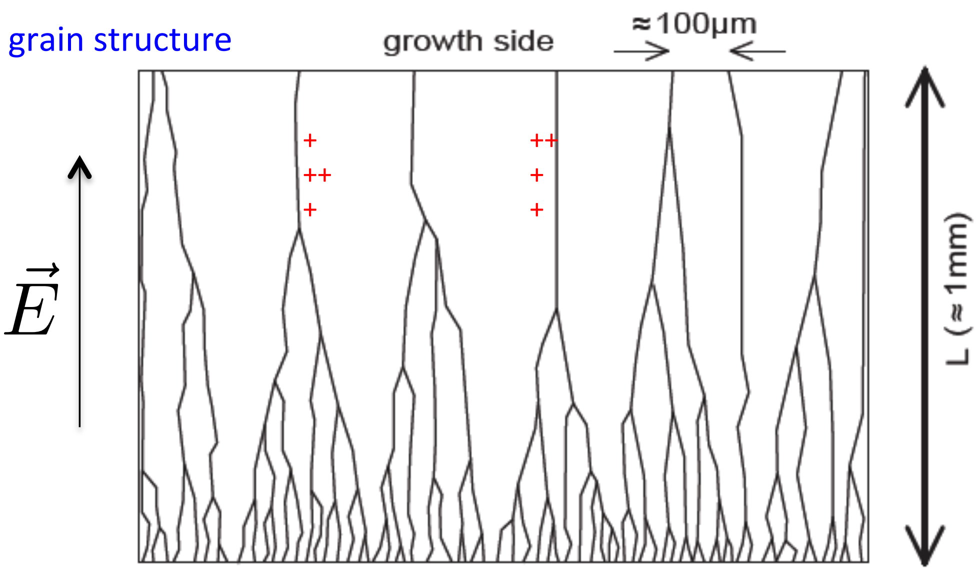


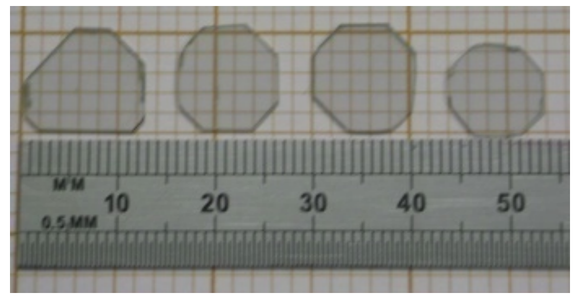
What is different in other semiconductors?

❑ CVD – Diamond

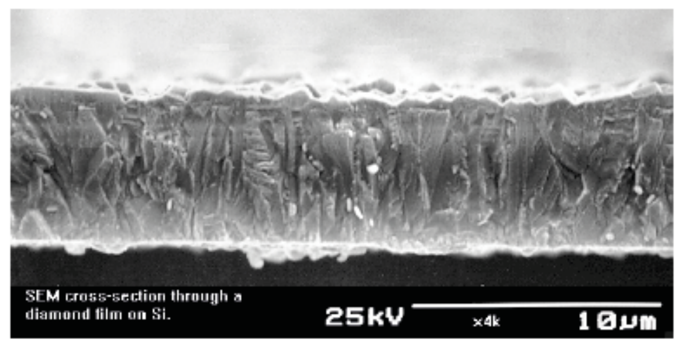
- actually an insulator (bad gap = 5.3 eV, w_i= 13.2 eV)
  => small signal ☹
  => zero leakage current (radiation hardness!!) ☺
  => free of intrinsic charge carriers (diamond is already "depleted") ☺
- energy need to knock out a crystal atom is 43 eV (Si: 25 eV)
  => radiation hard ☺
- CVD-grown in poly-crystalline (today's standard) and in mono-crystalline samples ☹ tedious
- high carrier mobility (fast)
- CCD ≈ 250µm reached ☺
- nice thermal features !! ☺

grain structure





mono-crystalline CVD diamond



poly-crystalline CVD diamond