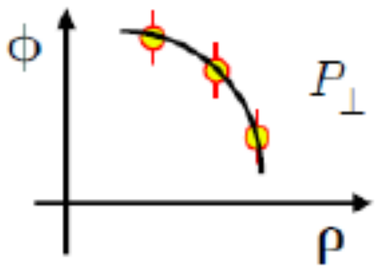
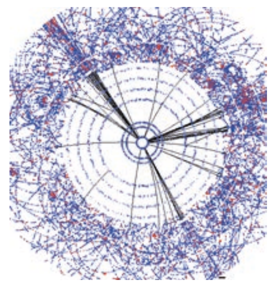
SLAC Summer Institute 2016

"New Horizons on the Energy Frontier"





Tracking Detectors
(Lecture 2)

Norbert Wermes
University of Bonn

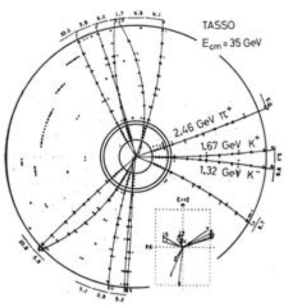
universitätbonn

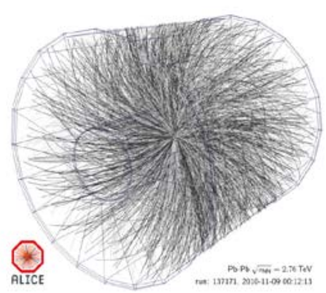
SI LAB
Silizium Labor Bonn

Outline

Lecture 1

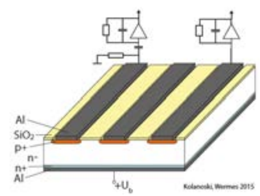
- ❑ Requirements on tracking detectors
- ❑ Gas/semiconductor detectors in comparison
- ❑ How the signal develops
  - Shockley-Ramo theorem
  - Weighting fields in various configurations
- ❑ Diffusion and drift (short)
- ❑ Space resolution w/ patterned electrodes
- ❑ Gas-filled detectors
  - Gas amplification (streamers and sparks)
  - The drift chamber
  - The “Time Projection” chamber
  - What is different at LHC experiments?

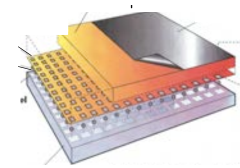


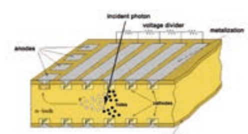


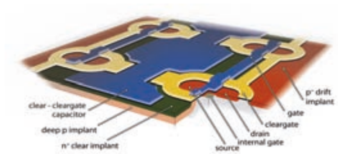
Lecture 2

- ❑ How to make a silicon detector?
- ❑ The nuisance of δ-electrons
- ❑ Radiation damage: NIEL and IEL (TID)
- ❑ What to do for High-Lumi LHC?
- ❑ Alternatives to “Hybrid” Pixels
  - DEPFET Pixels
  - DMAPS: Monolithic CMOS Pixels
- ❑ 4D with LGADs?



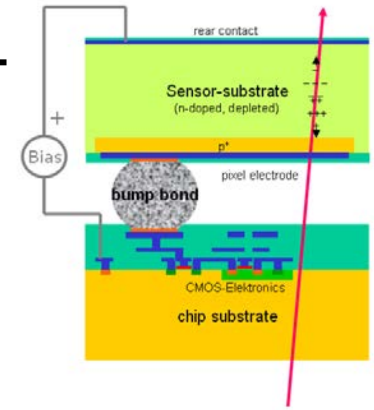


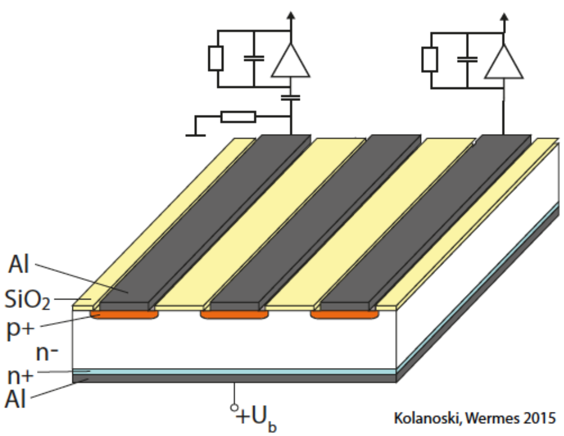


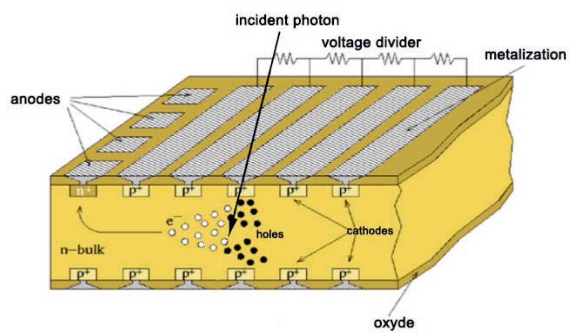


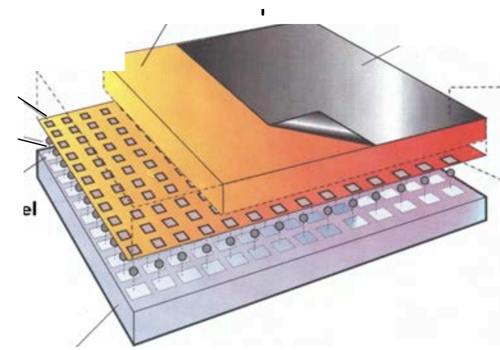
Semiconductor Tracking Detectors

Hybrid Pixel









Microstrip Detector

Silicon Drift Detector

Pixel Detector

Semiconductors suited for detectors

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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	3.65	1450	505	100μs
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	$\sim$ μs
CdS	2.42		48 + 16	6.3	340	50	
HgI_2	2.13		62	4.2	100	4	$\sim$ μs
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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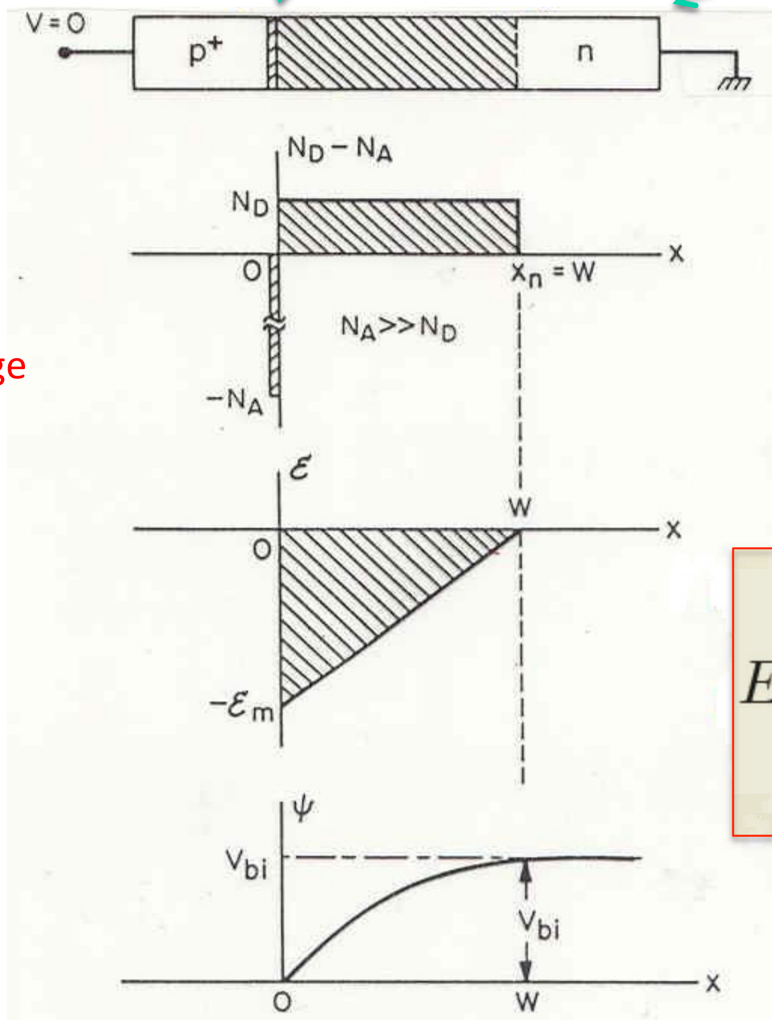
thin (~µm), highly doped p^+ (~10^{19} cm^{-3}) layer on lightly doped n^- (~10^{12} cm^{-3}) substrate

Space charge region

(depleted of mobile charge carriers)

Electric field

Potential



reverse biased junction

$$N_A x_p = N_D x_n$$

neutrality condition

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

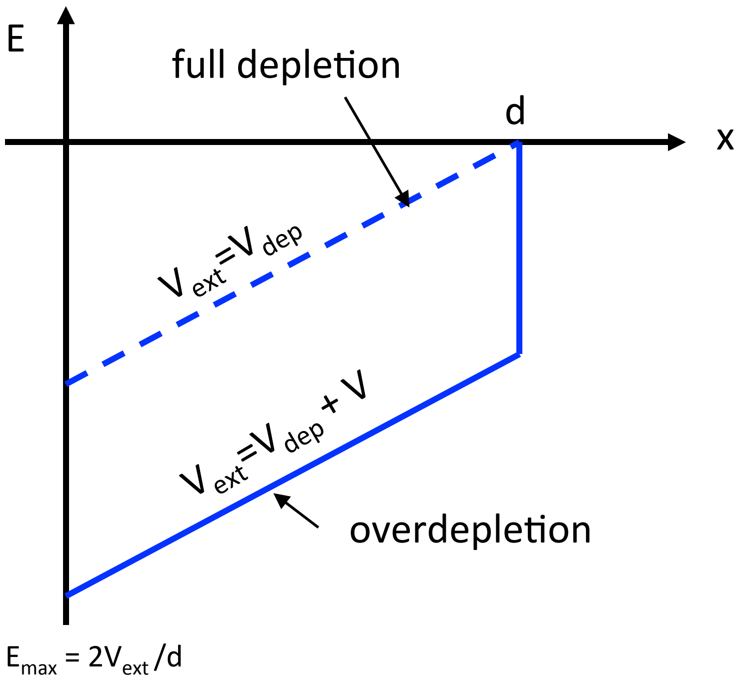
Maxwell

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

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

The Si pn junction as a particle detector

junction side "back" side



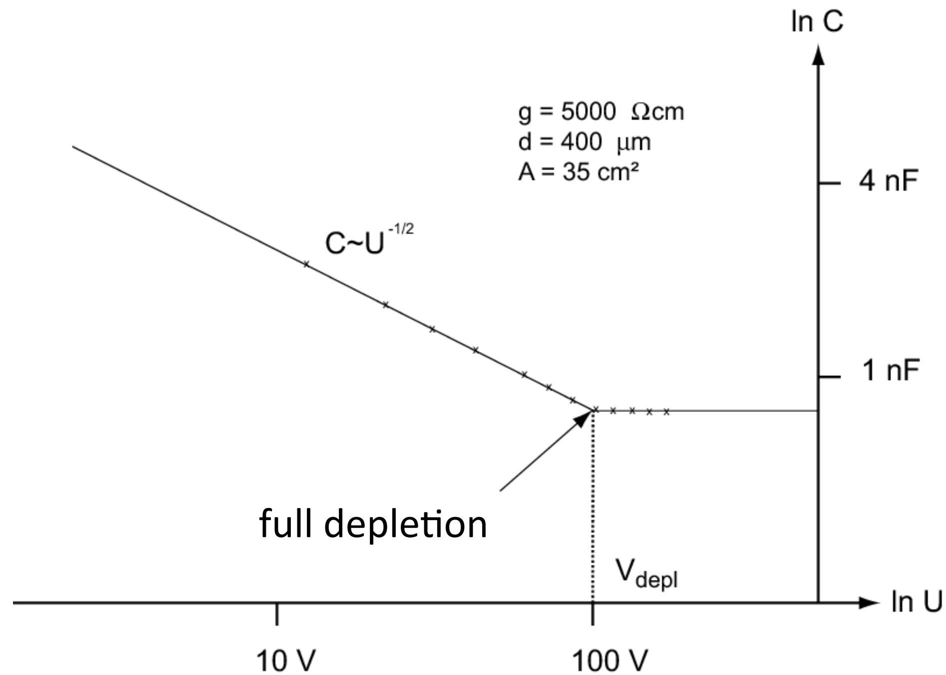
with applied external bias voltage

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

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

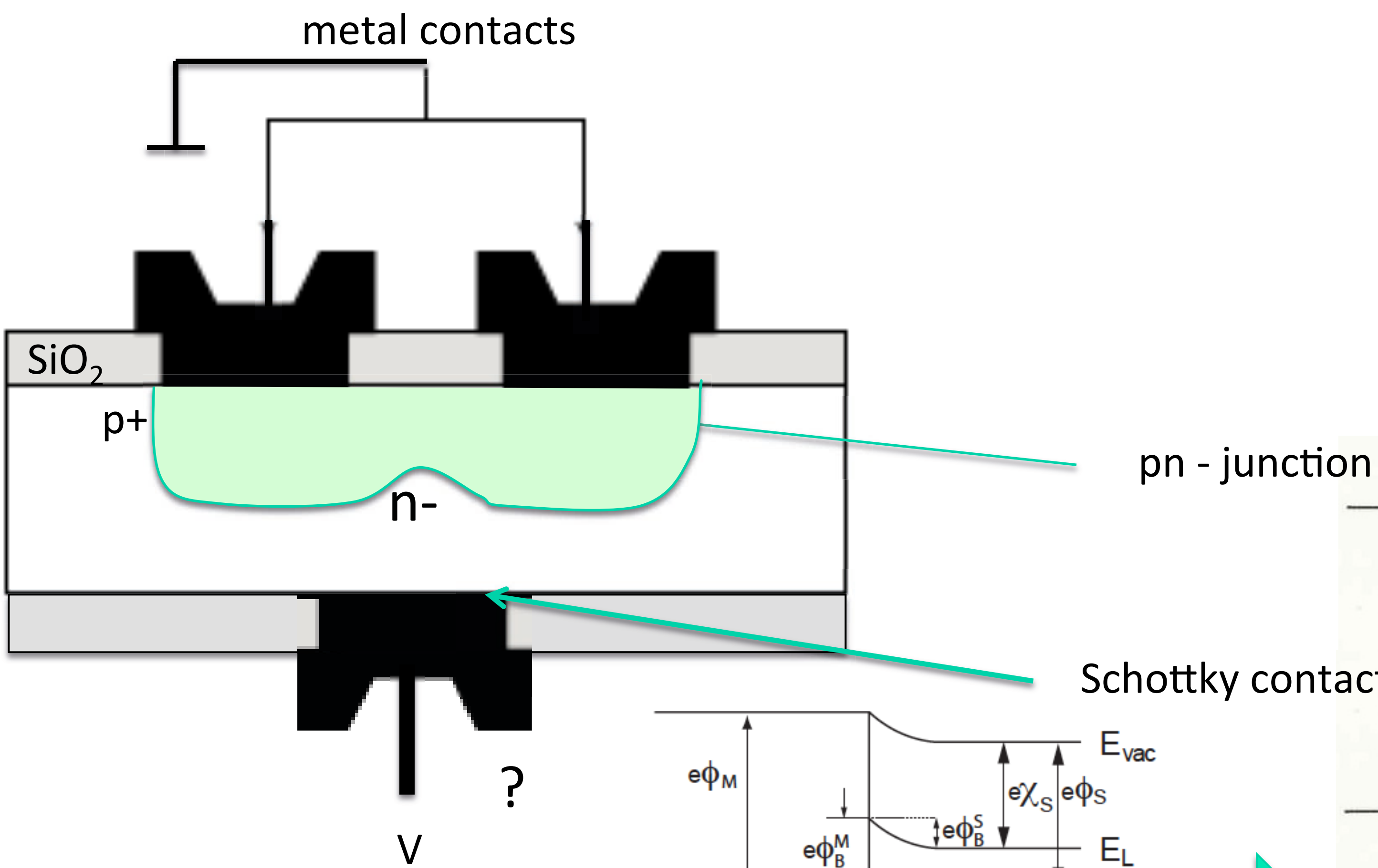
capacitance

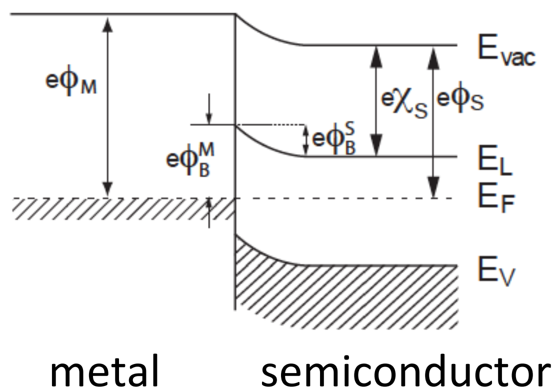
$$\frac{\mathrm{C}}{\mathrm{A}} = \frac{1}{\epsilon\epsilon_0}\frac{1}{d} \propto \frac{1}{\sqrt{V_{ext}}}$$

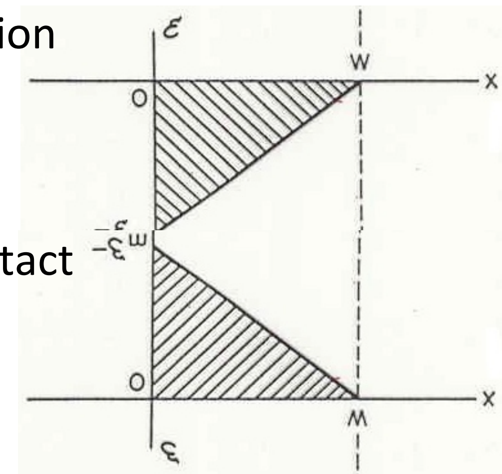


depletion zone grows from the junction into the lower doped bulk

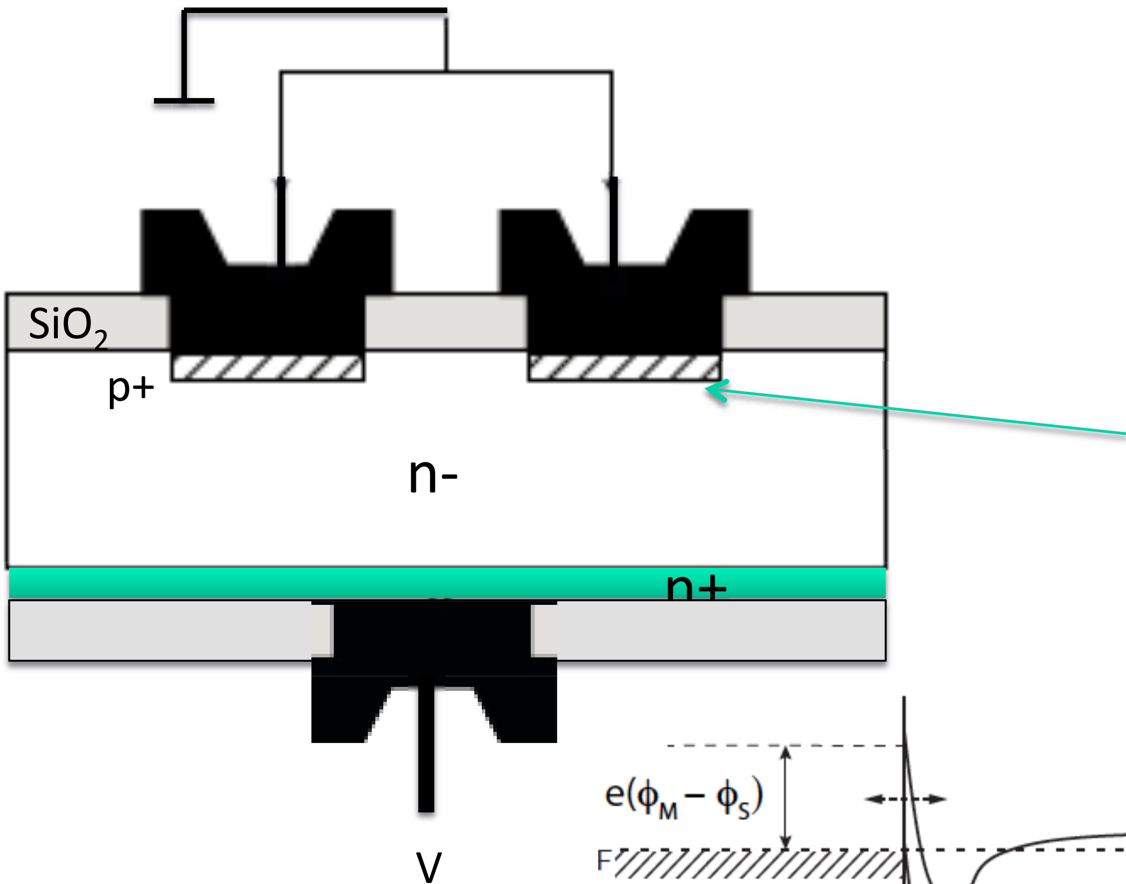
Contacts


metal contacts
SiO$_2$
p+
n-
pn - junction
Schottky contact
?
V

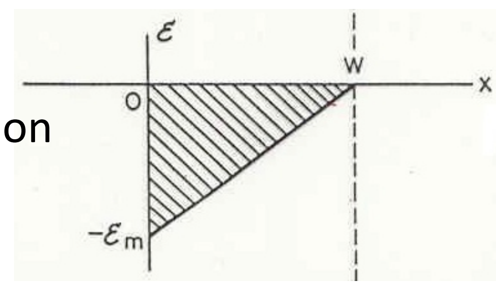

eφ$_M$
eφ$_B^M$
eχ$_S$
eφ$_S$
eφ$_B^S$
E$_{vac}$
E$_L$
E$_F$
E$_V$
metal
semiconductor



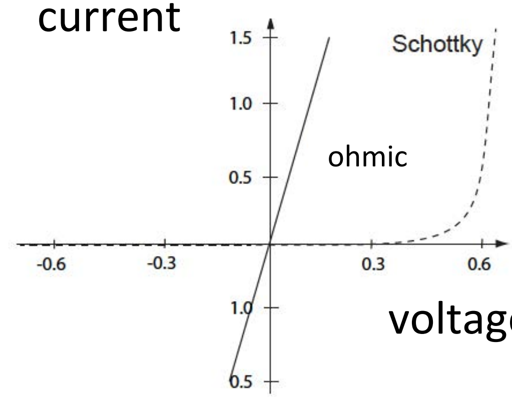
Contacts



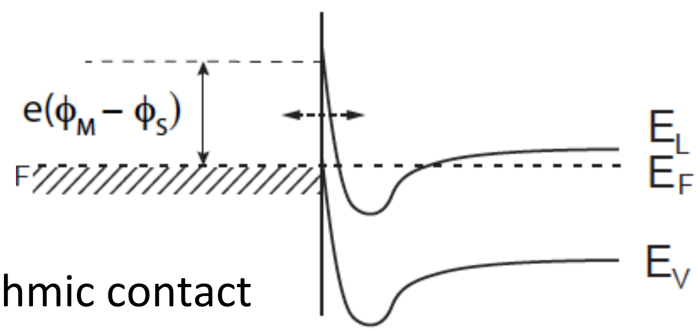
pn - junction



current

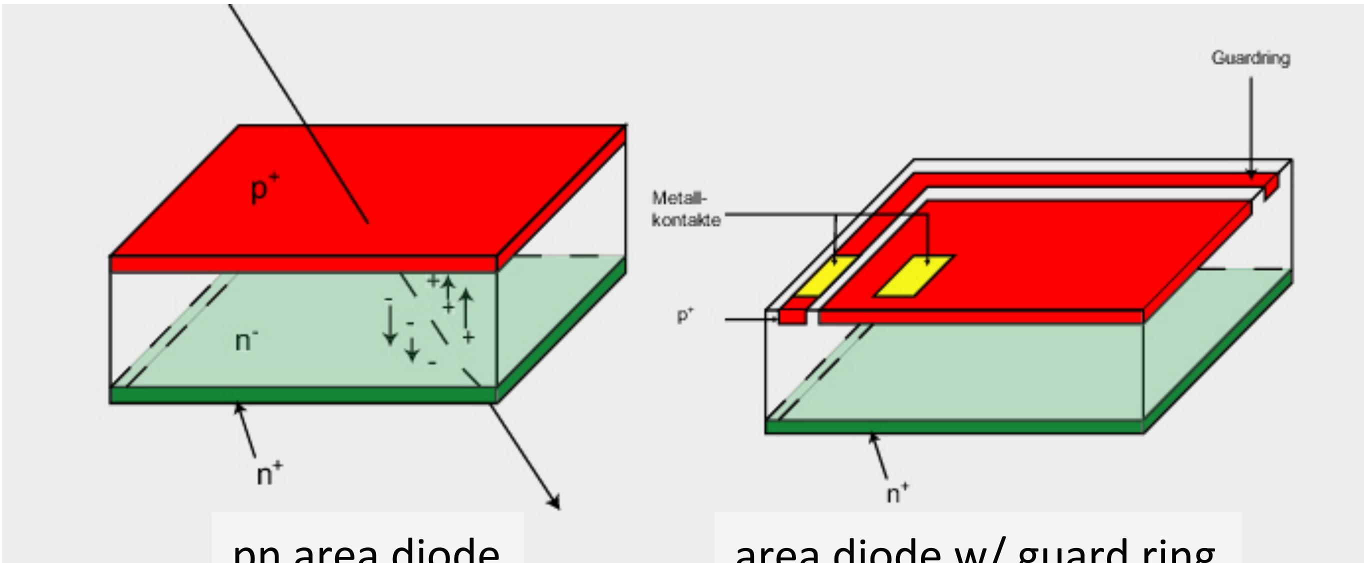


voltage



ohmic contact

Detector biasing

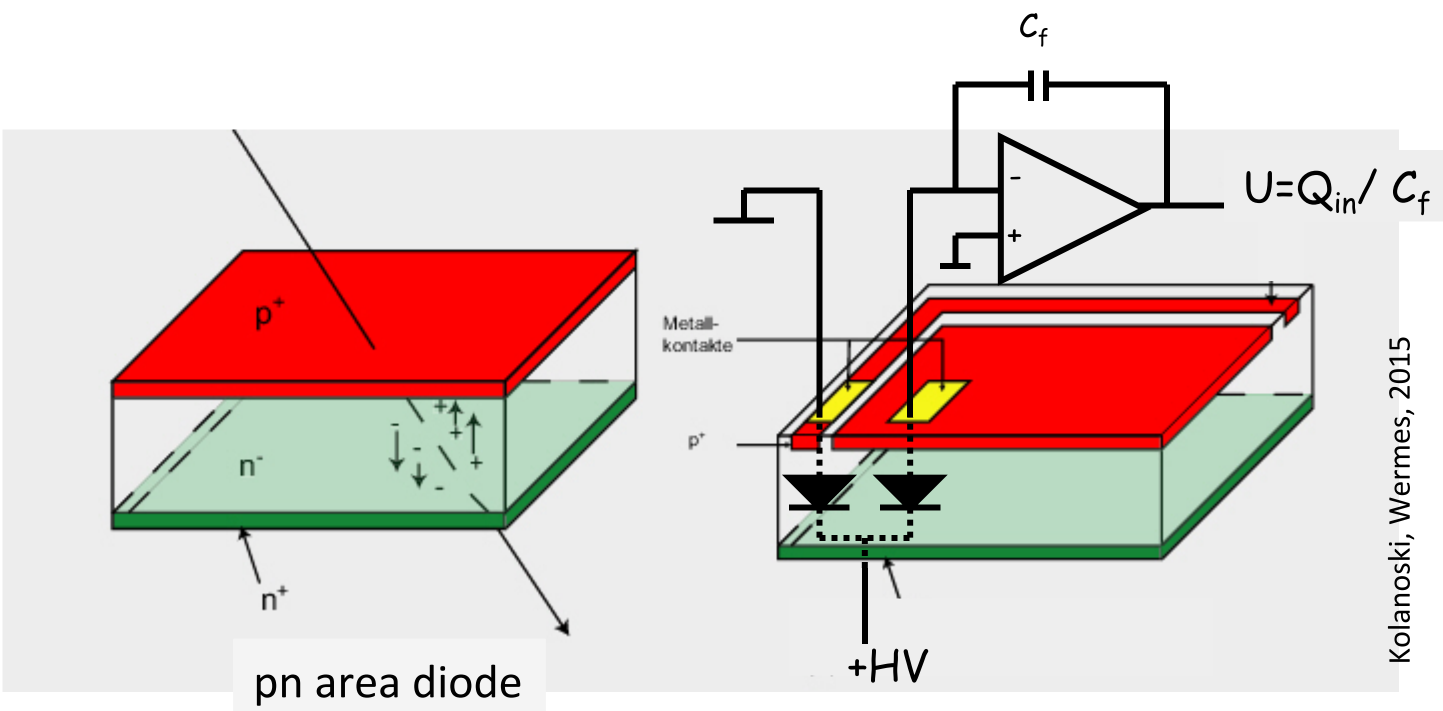


pn area diode

area diode w/ guard ring

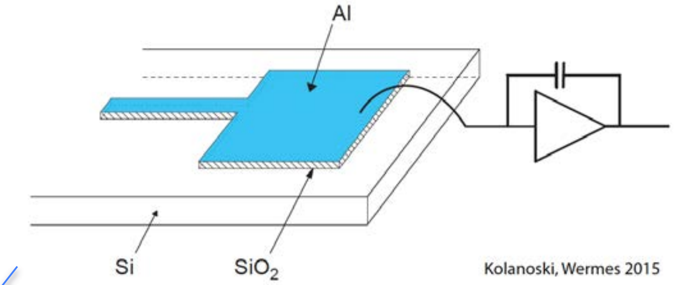
Kolanoski, Wermes, 2015

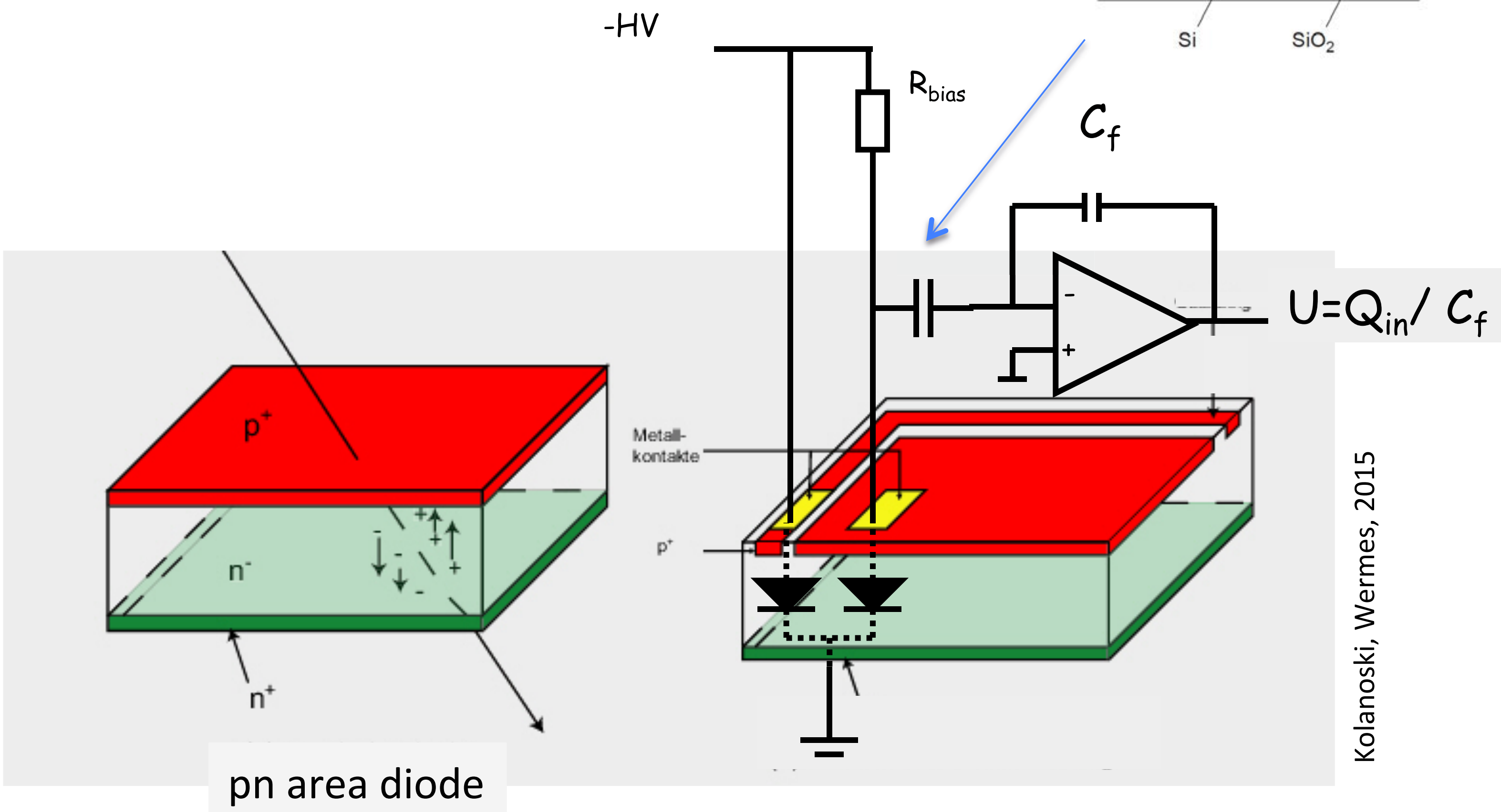
Detector biasing



DC - Coupling

Detector biasing





AC - Coupling

The Signal in pixel detectors => particle tracks

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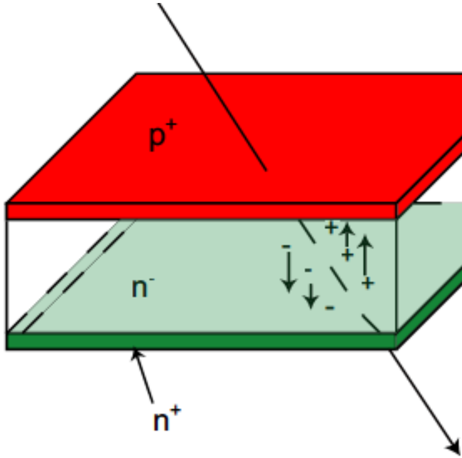
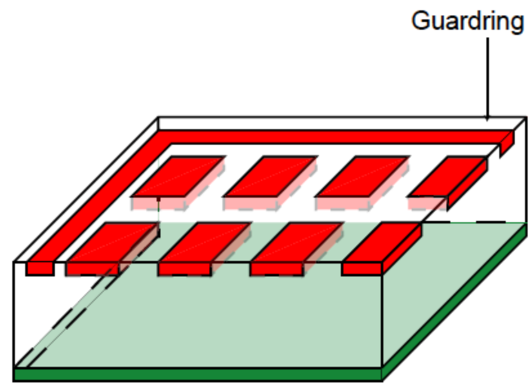
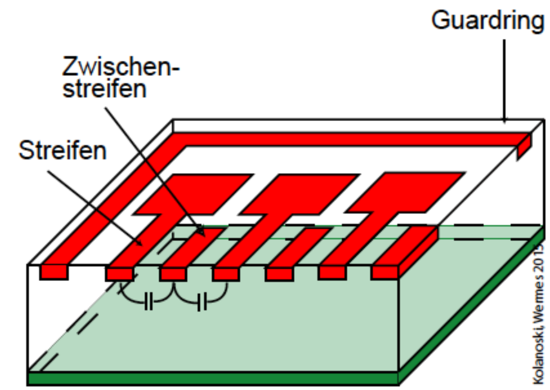






in Si bulk fully depleted

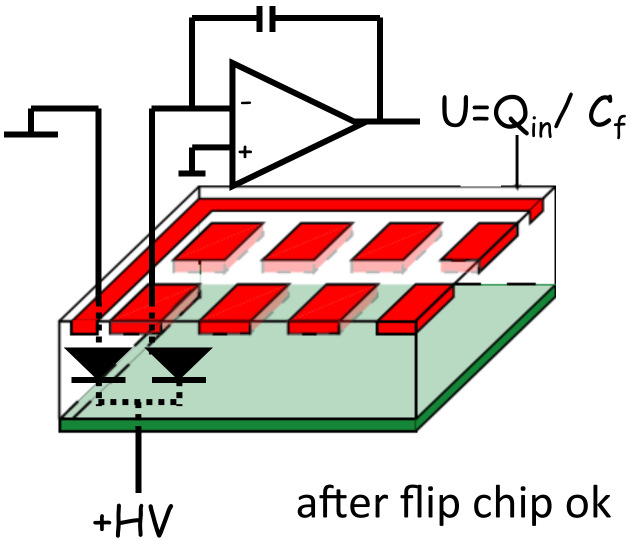
- w_i = 3.65 eV per e/h
- a high energy particle
  → ~ 80 e/h per μm
- all charge collected
- ~ 20 000 e/h per 250 μm
  = 3 fC

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

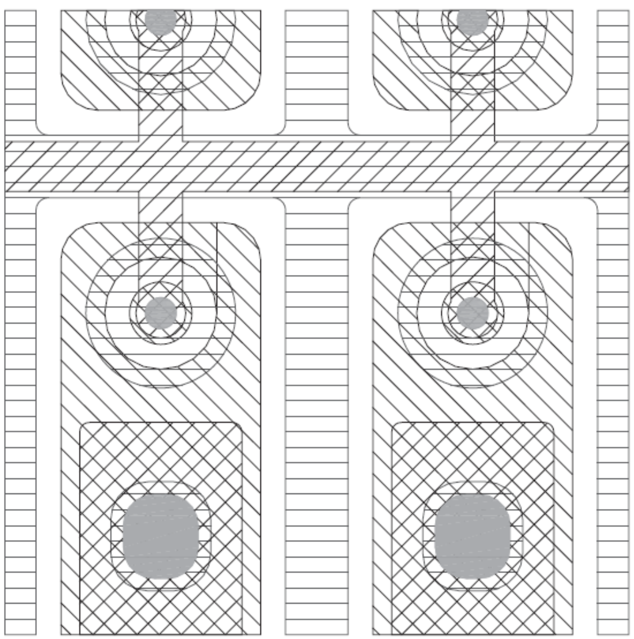
- pixel or strip pattern
- typical pixel cells: 100 x 150 μm²
  50 x 400 μm²
- charge drift in E-field
- charge diffusion σ ~ 8-10 μm
  → charge spreads over 2-3 pixels/strips

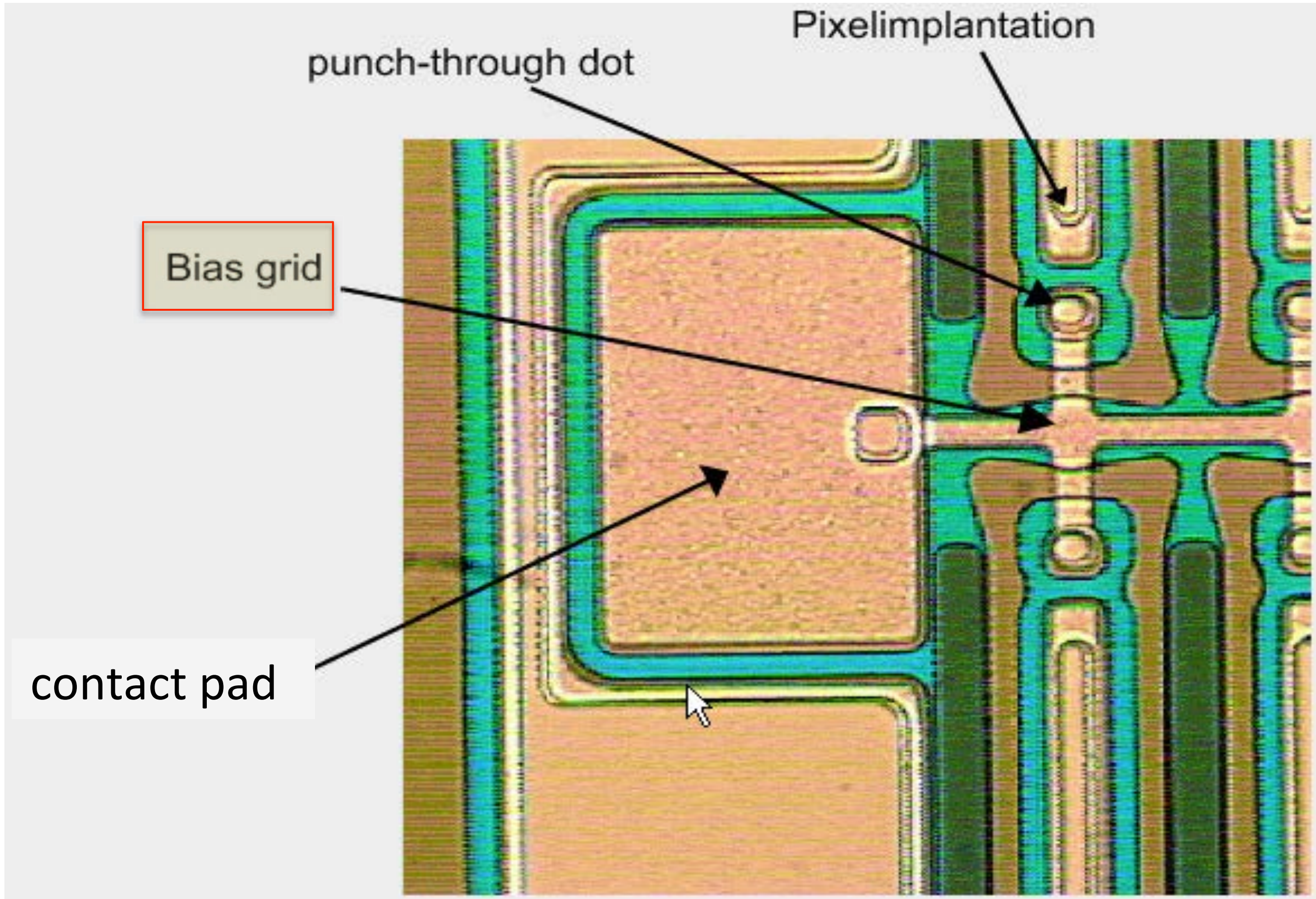
note: photo effect ~$Z^{(4-5)}$
Si → CdTe, CZT, HgI_2, …

How to bias a pixel detector … with many many channels?

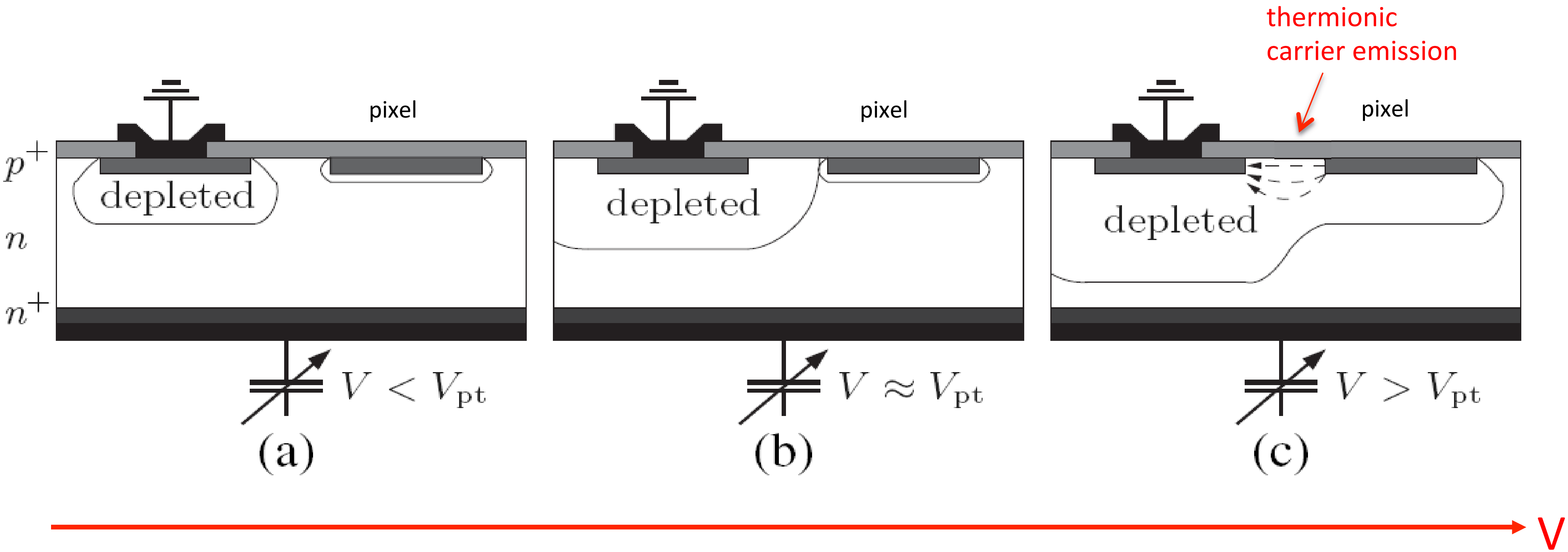


- ❑ answer: through the virtual ground of the preamplifier
- ❑ but one wants to test the sensor w/o chip, i.e. <u>before</u> you put R/O chips on (yield!)





Punch through biasing

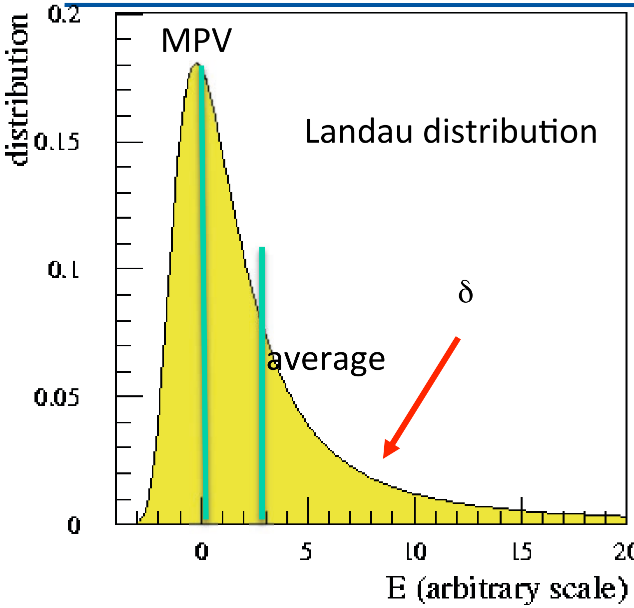


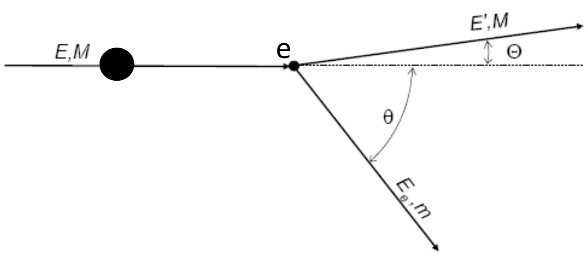
below $V_{\text{punch through}}$

equal $V_{\text{punch through}}$

above $V_{\text{punch through}}$

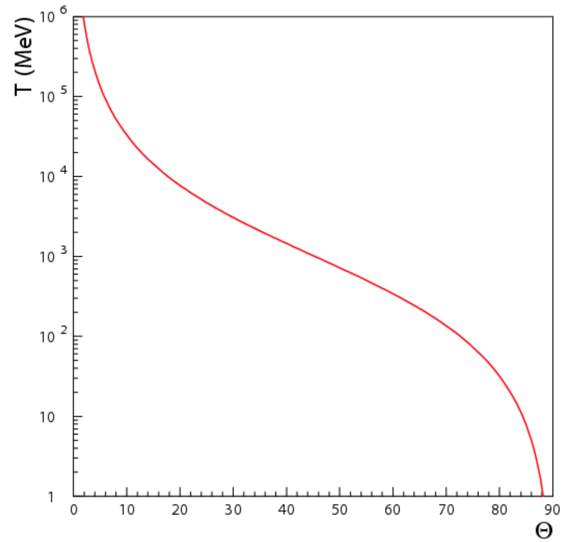
Charge distribution and delta electrons





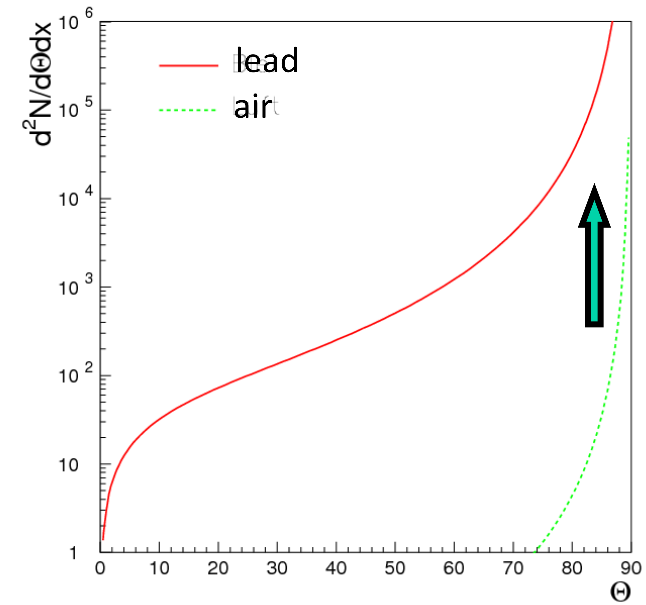
kinematics: 1-1 relation between emission angle and kin. energy

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



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

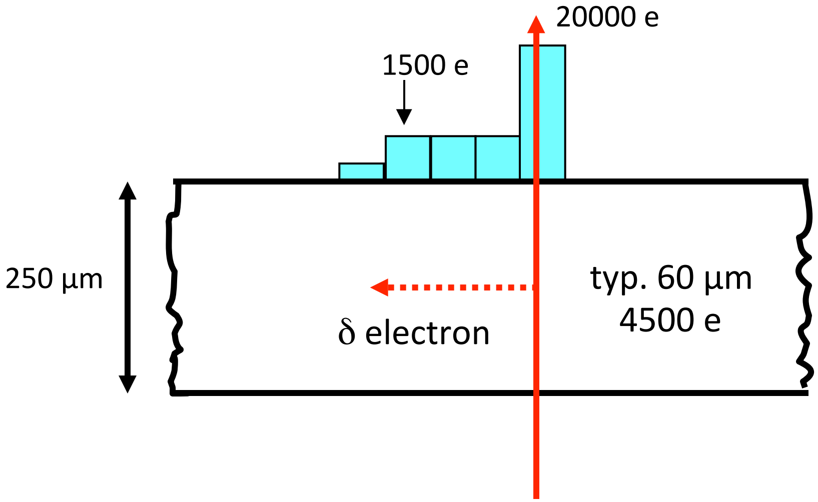
$$\frac{dN}{d\Theta} = \frac{1}{2} D z^2 \frac{Z}{A} \rho x \frac{\sin\Theta}{\cos^3\Theta}$$

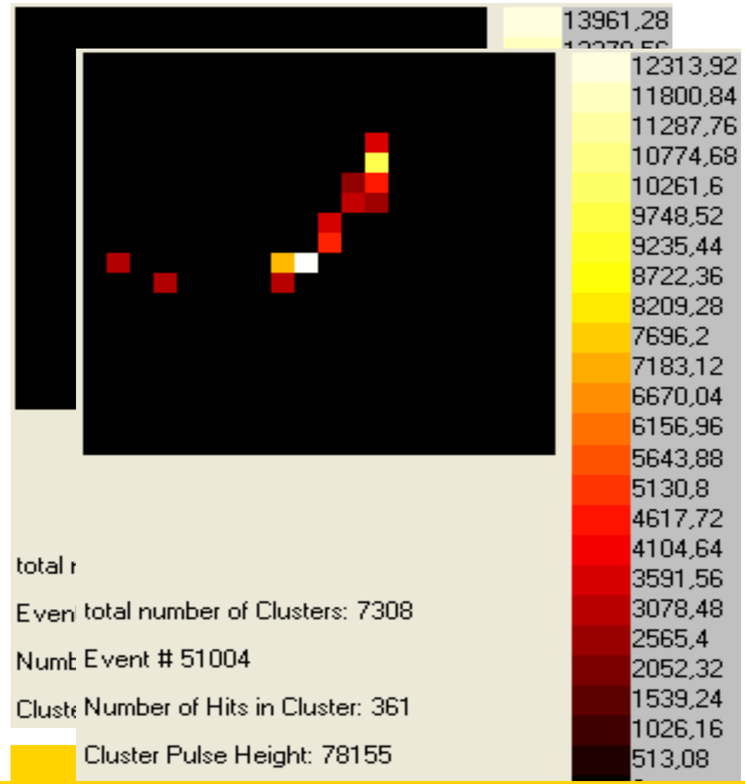


for experimentalists

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

Delta electrons





δ-electron with perpendicular emission

DEPFET pixels (25 µm x 25 µm)

<u>effect of δ -electrons</u>

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

The typical S/N situation (... here ATLAS)

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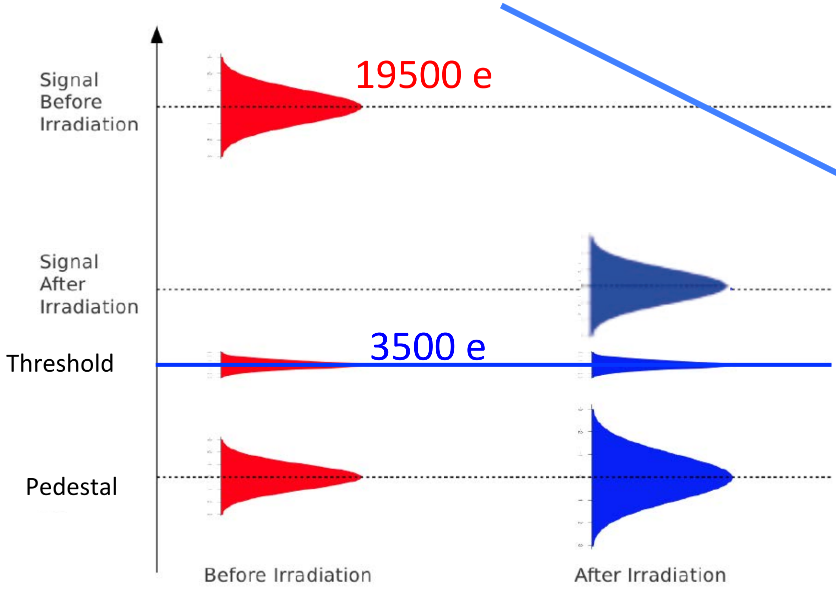
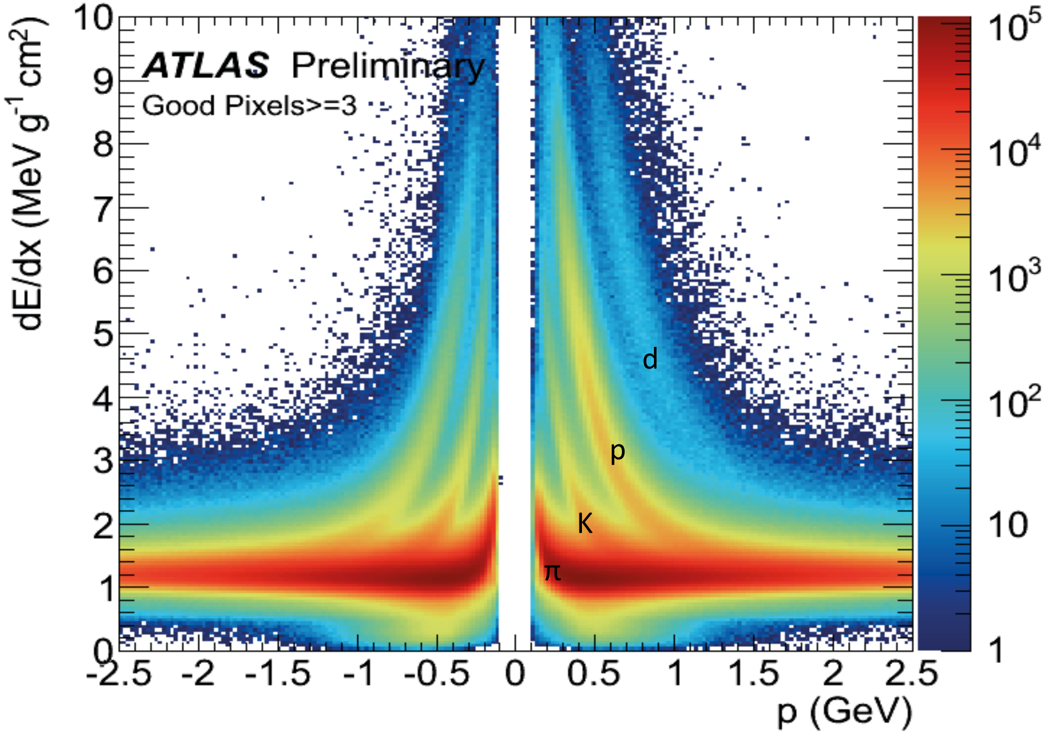
Signal of a mip in 250µm Si ≙ 19500 e^- → <10000 e^- after irradiation

Charge on more than 1 pixel => S/N > 30 → S/N ~ 10

- ❑ Discriminator thresholds = 3500 e, ~40 e spread, ~170 e noise
- ❑ 99.8% data taking efficiency
- ❑ 95.9% of detector operational
- ❑ ca. 10 µm x 100 µm resolution (track angle dependent)
- ❑ 12% dE/dx resolution





C. Gemme et al., ATLAS-CONF-2011-016

Radiation Damage

- From defect investigation -> defect engineering (example: oxygen enrichment)

Recipe

- Readout at n^+ electrodes (e^- collection)
- Operate at high bias voltages
- Carefully plan the annealing scenario
- Do proper electrode design (no high-E regions)
- Use p-substrates (or n -> p inversion)

Silicon Sensors in the LHC radiation environment

particle interactions with lattice nuclei

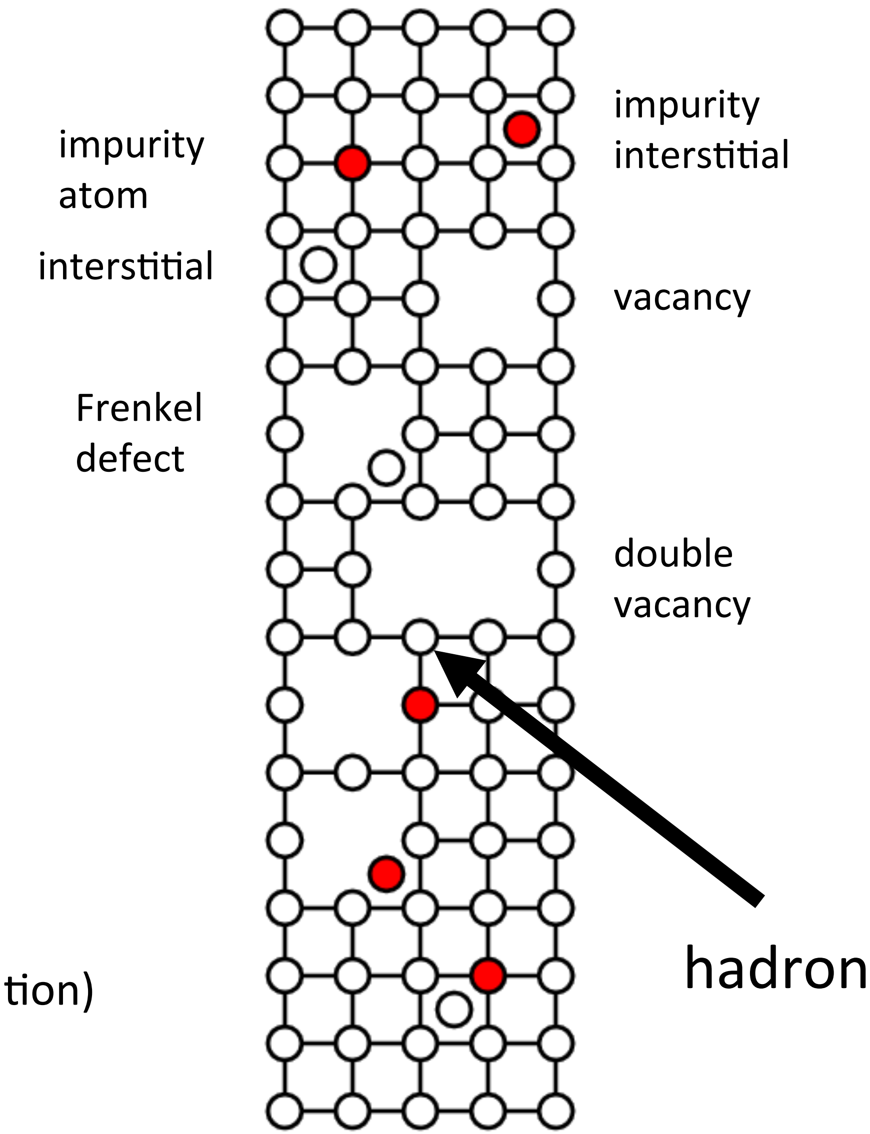
↓

NIEL — non-ionizing energy loss (not reversible) normalized to 1 MeV neutron damage

recoiling Si-atom can cause further defects
→ defect clusters (10nm x 200nm)

↓

1. generation/recombination levels in band gap
   → increase of leakage current
2. change of space charge in depleted region
   → change of effective doping concentration (VP creation)
3. trapping centers created
   → trapping of signal charge



Pixel Sensors in the LHC radiation environment

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particle interactions with lattice nuclei

NIEL

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1. generation/recombination levels in band gap
   → increase of leakage current
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   → change of effective doping concentration
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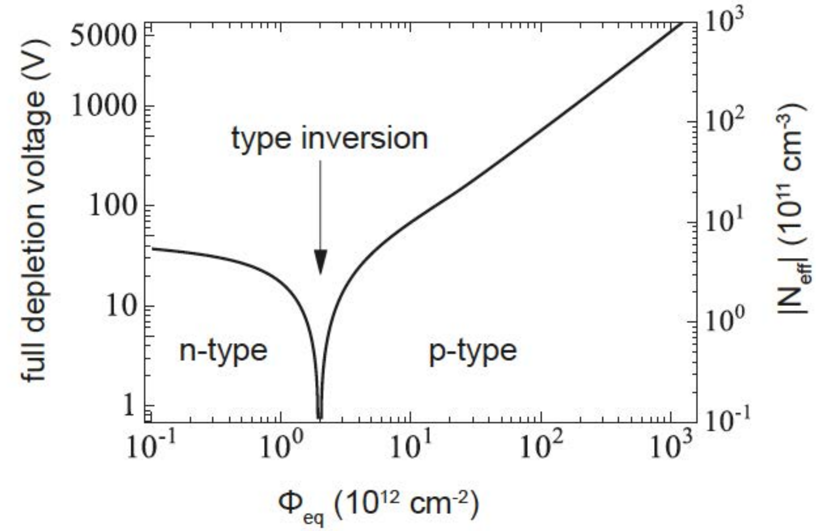
- Change of Depletion Voltage V_{dep} (N_{eff})

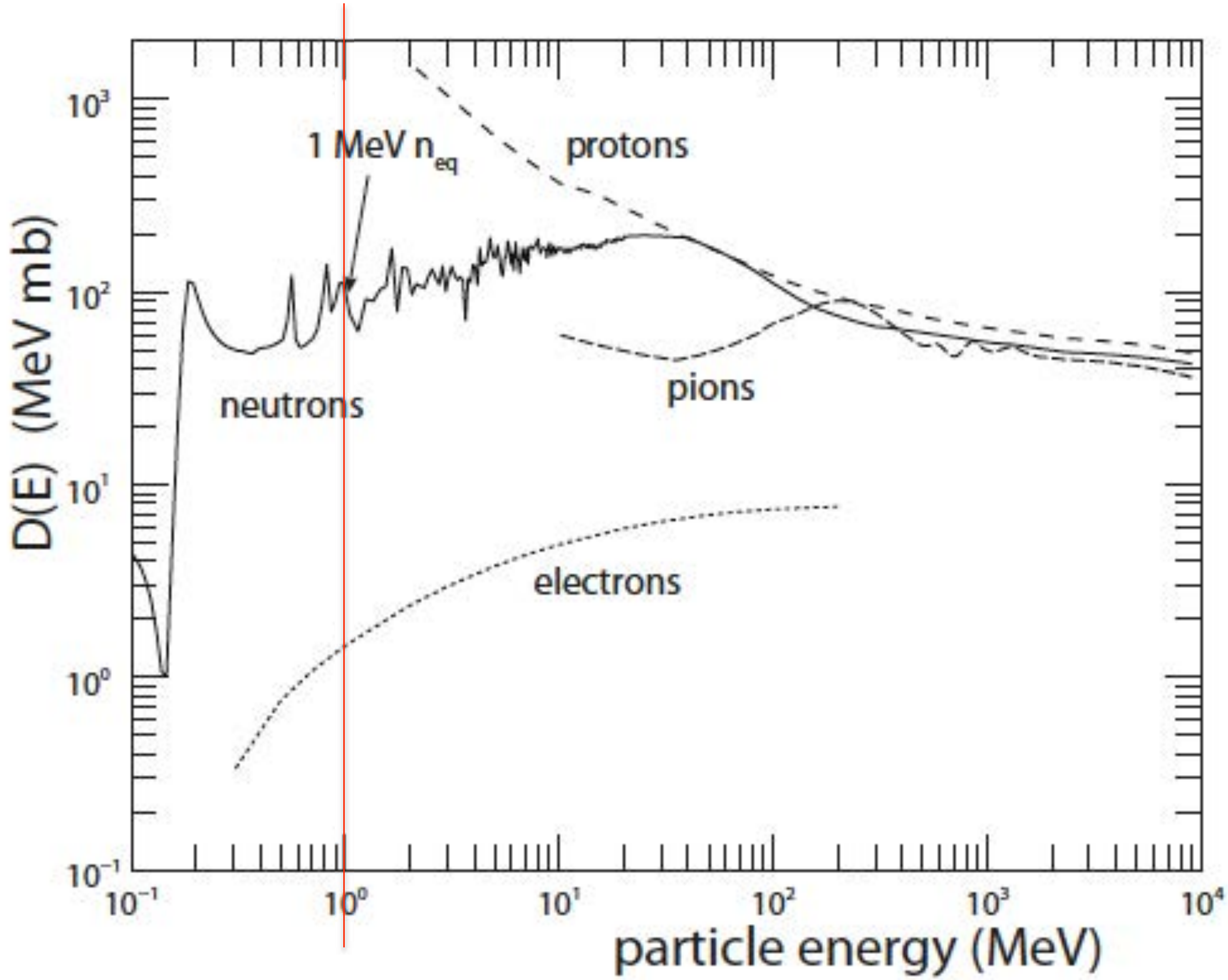
.... with particle fluence:



- "Type inversion":
  N_{eff} changes from positive to negative
  (Space Charge Sign Inversion)

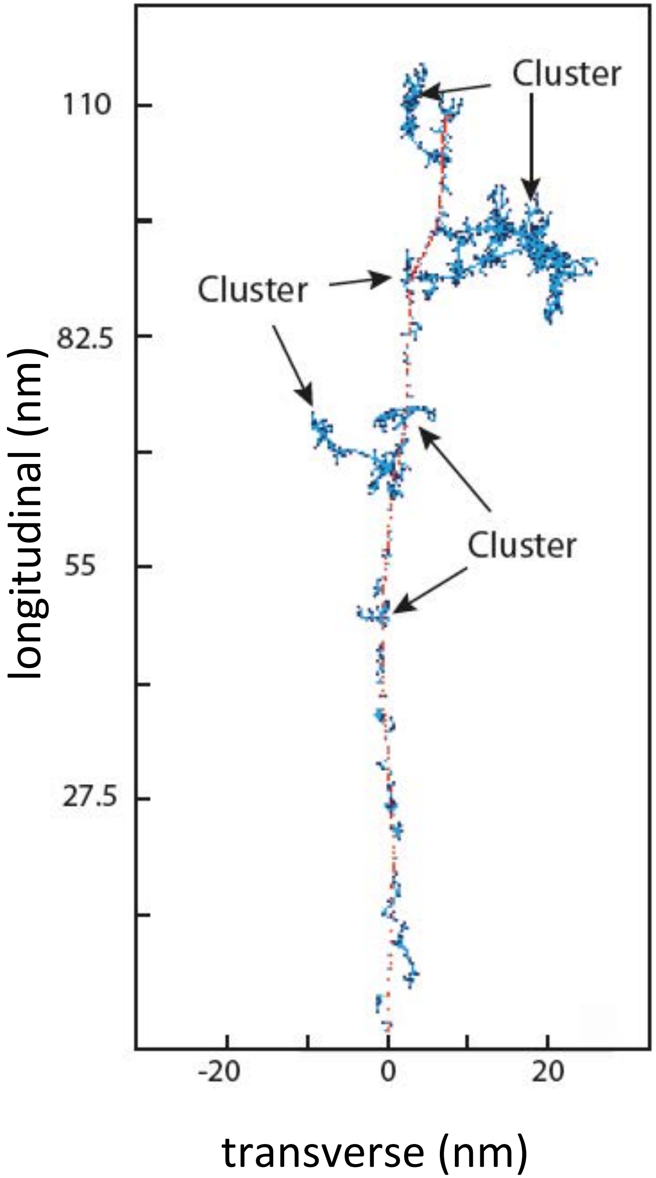
NIEL fluence > 10^{15} n_{eq}/cm^2

× 10 for HL-LHC

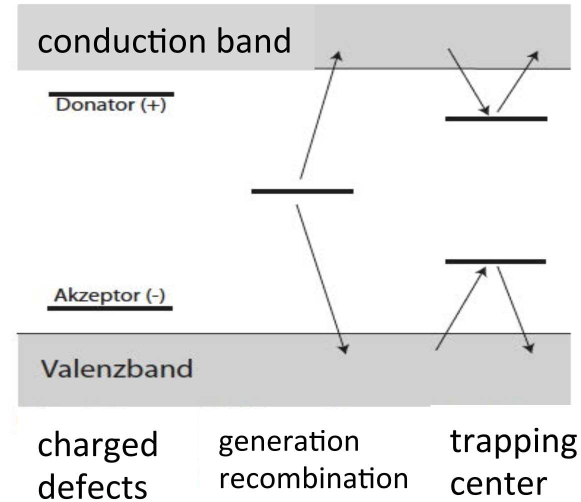


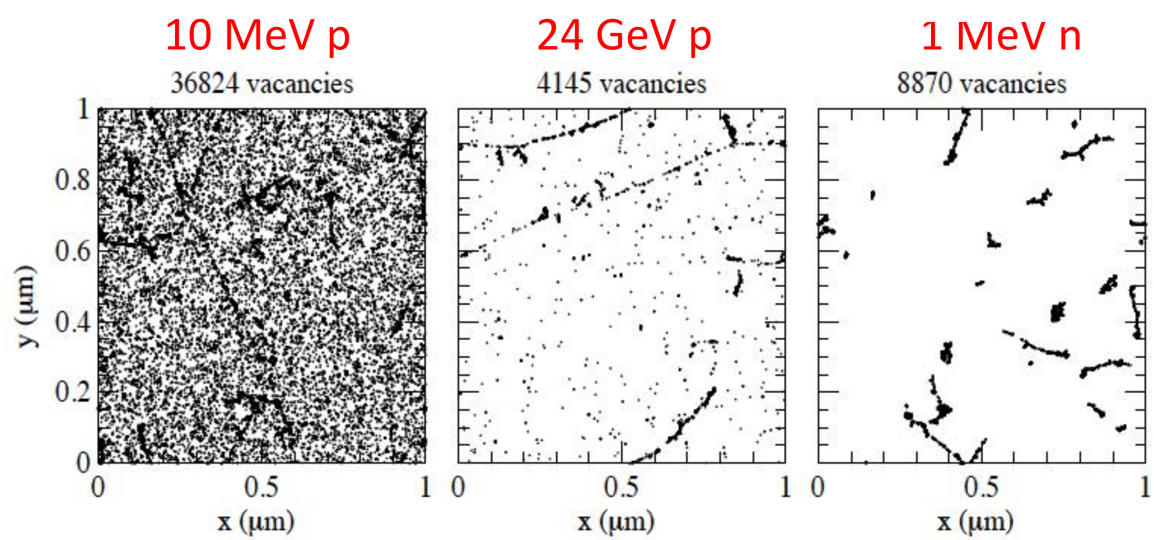
1 MeV n_{eq}
protons
neutrons
pions
electrons
D(E) (MeV mb)
particle energy (MeV)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

Radiation Damage (NIEL)

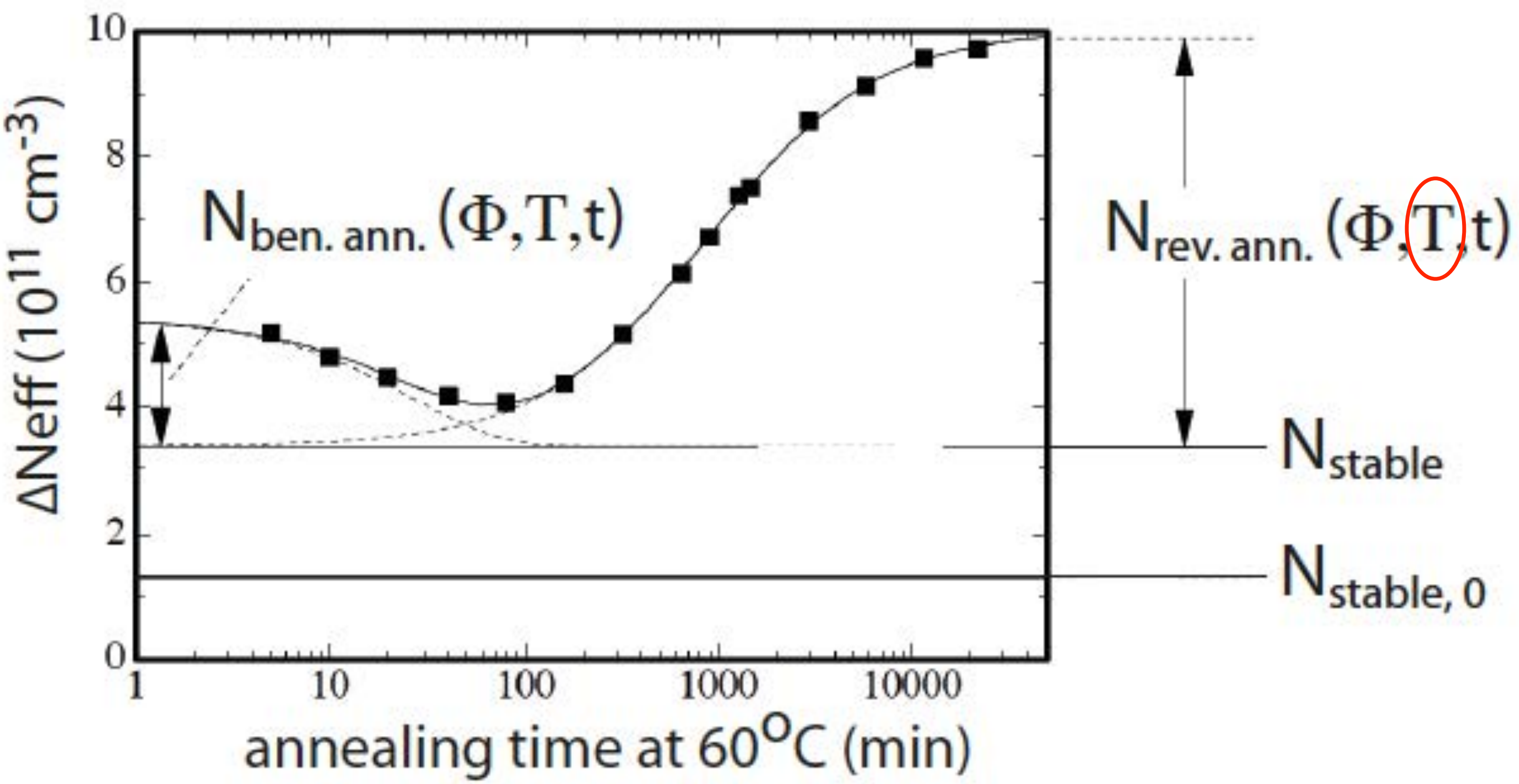


threshold energy to remove a Si-atom from the lattice:
Si: 25 eV, diamond: 43 eV





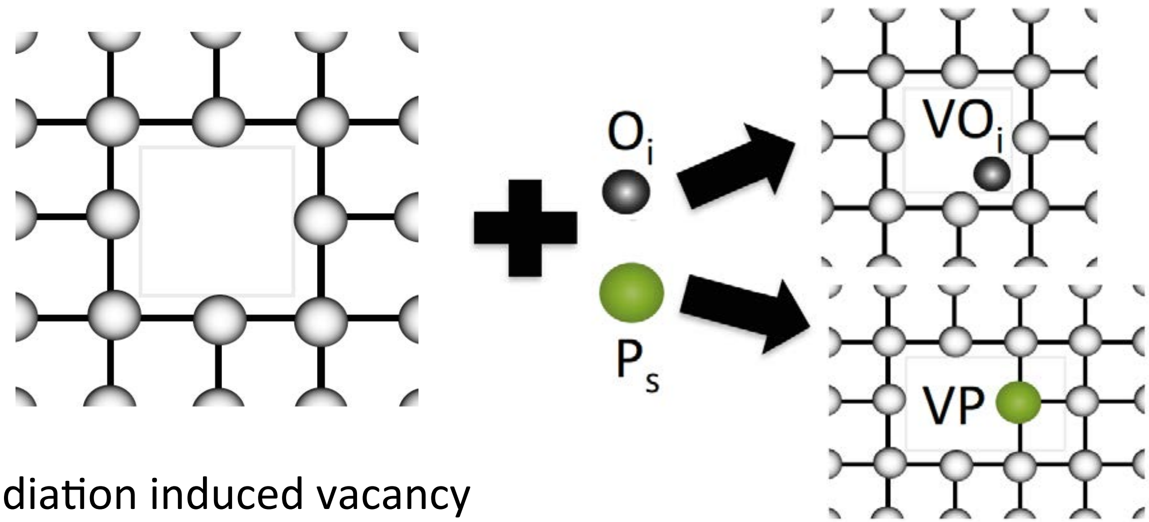
Annealing



- shaking the lattice => beneficial annealing
- too long at a high temperature => defects, that did not harm so far, become electrically active => reverse annealing

… and cures (defect engineering example)

- low temperature (-10 °C) operation
- oxygenated silicon



radiation induced vacancy
(mobile even below RT)

harmless
VO_i defect

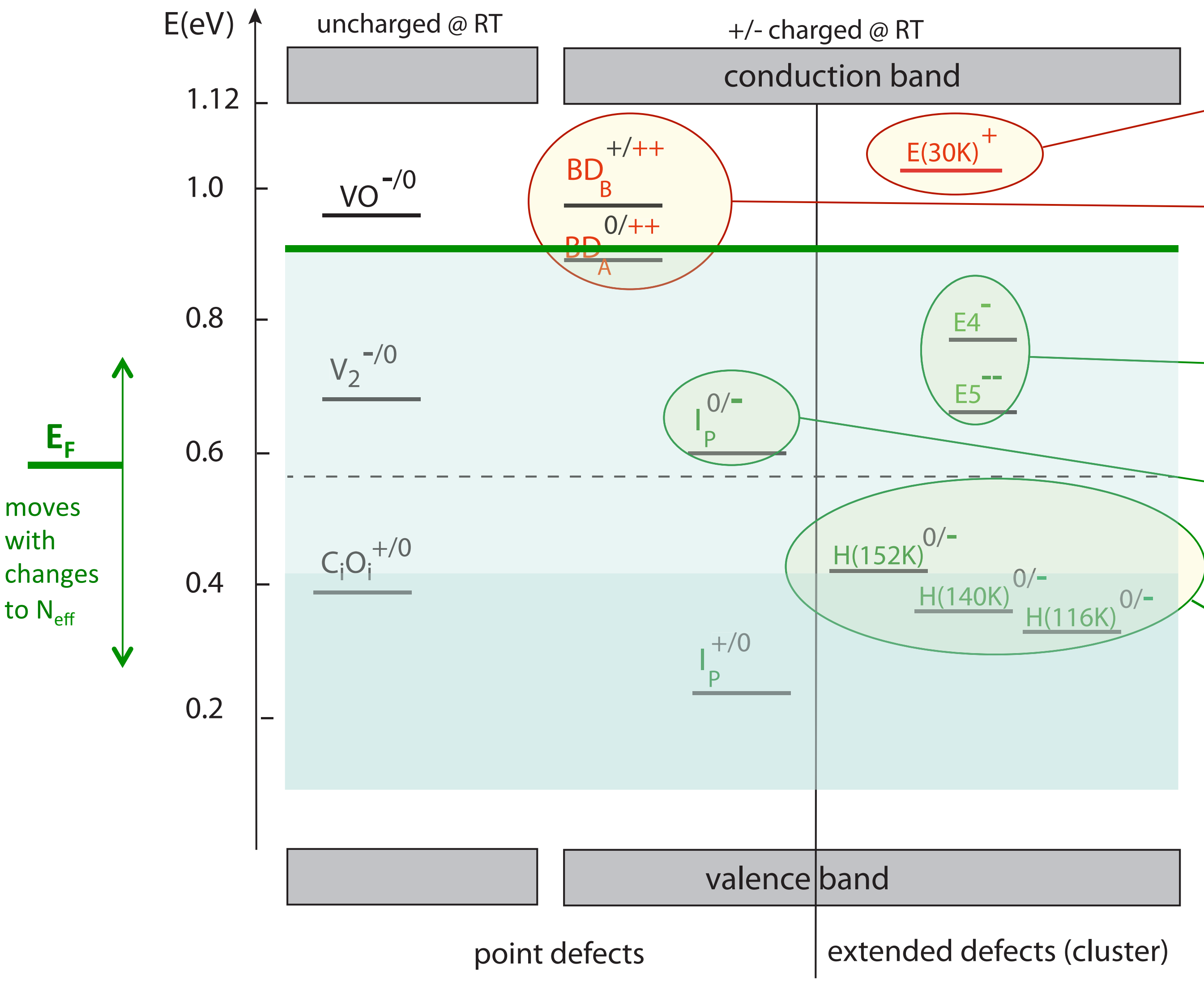
harmful
removes donor (P)
decreases N_{eff}

⇩

$[O] \gg [P]$

A. Junkes, PoS Vertex 2011 (2011) 035
I. Pintilie et al., Nucl.Instrum.Meth. A611 (2009) 52-68

Much progress in understanding radiated Si-sensors



e- trap
positive space charge
higher conc. after proton than neutron irradiation
depends on oxygen content

BD=bistable donor (e- trap)
positive space charge
strongly produced in oxygen rich DOFZ material

triple vacancy, small cluster
negative space charge
-> **high leakage current**

V_2O complex (?)
negative space charge
causes **leakage current**,
strongly produced in oxygen lean STFZ

extended acceptor defects produced equally by n,p
negative space charge
-> **reverse annealing**

- most defects show linear fluence dependence
- cooling helps to keep I_{leak} and rev. annealing smaller
- N_{eff} changes

Radu et al., J. Appl. Phys. 117, 164503 (2015)
RD50, M. Moll et al., PoS (Vertex 2013) (2013) 026

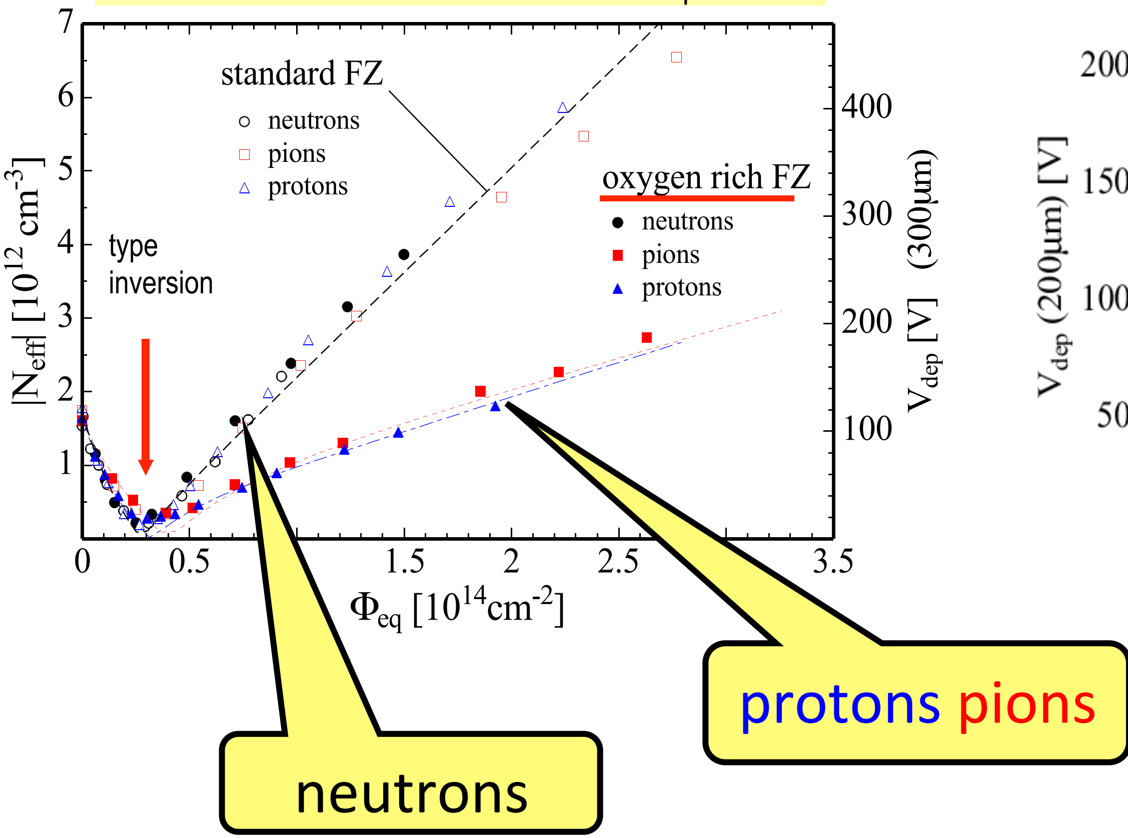
- most studies with n-type material

Pixel Sensors in the LHC radiation environment

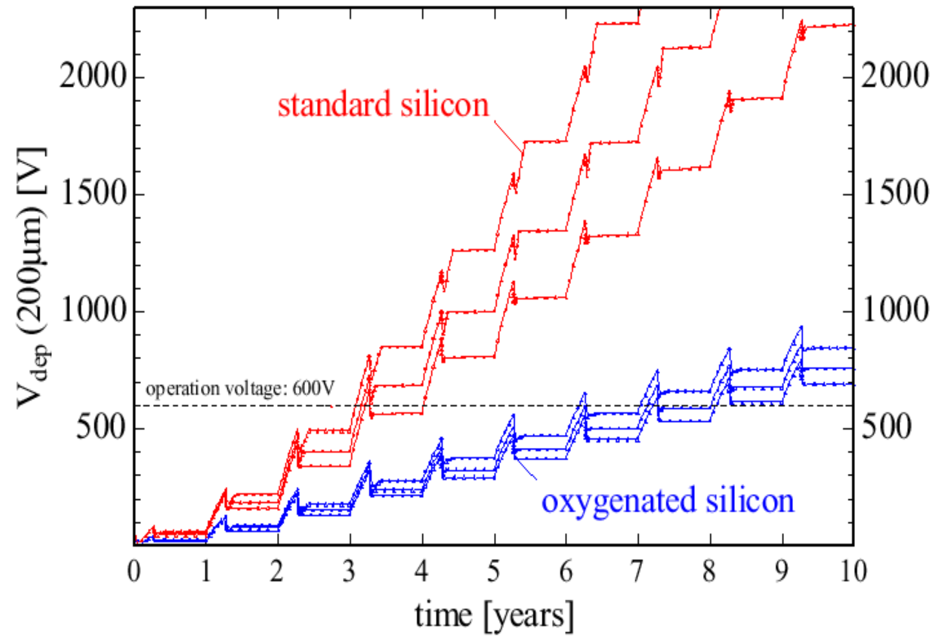
universitätbonn

solution: oxygenated FZ silicon

radiation tolerant to > 10^{15} n_{eq} / cm^2



necessary voltage for full depletion



RD50, G. Lindström et al.
NIM-A 465 (2001) 60-69

reason: complex interaction of various (point+cluster) defects: "shallow donor" (BD point defect) in oxygen enriched silicon replaces donor removal. For neutrons => only cluster defects contribute.

Silicon Sensors in the LHC radiation environment

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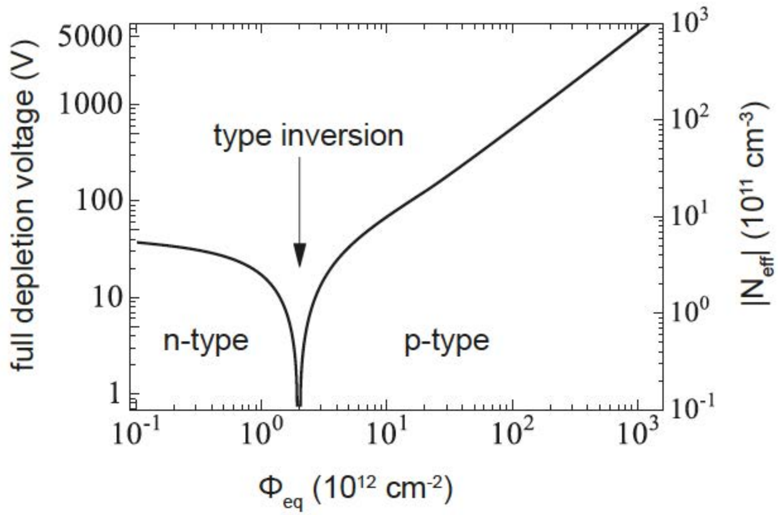
- Change of Depletion Voltage V_{dep} (N_{eff})

.... with particle fluence:



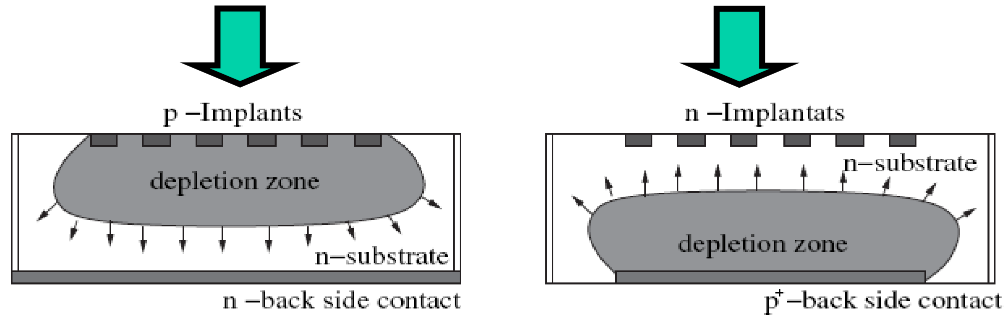
- "Type inversion":

  N_{eff} changes from positive to negative (Space Charge Sign Inversion)

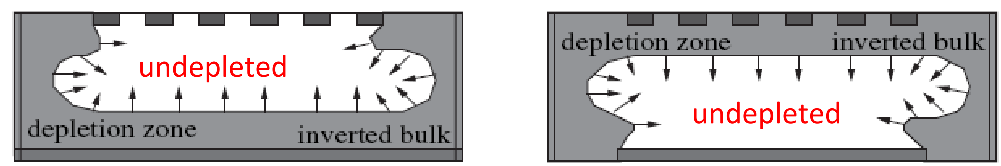
NIEL fluence > 10^{15} n_{eq}/cm^2

× 10 for HL-LHC

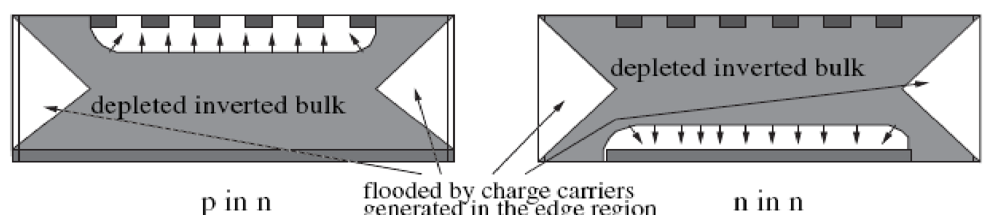
p^+ in n "normal" | n^+ in n (also n^+ in p)



before type inversion



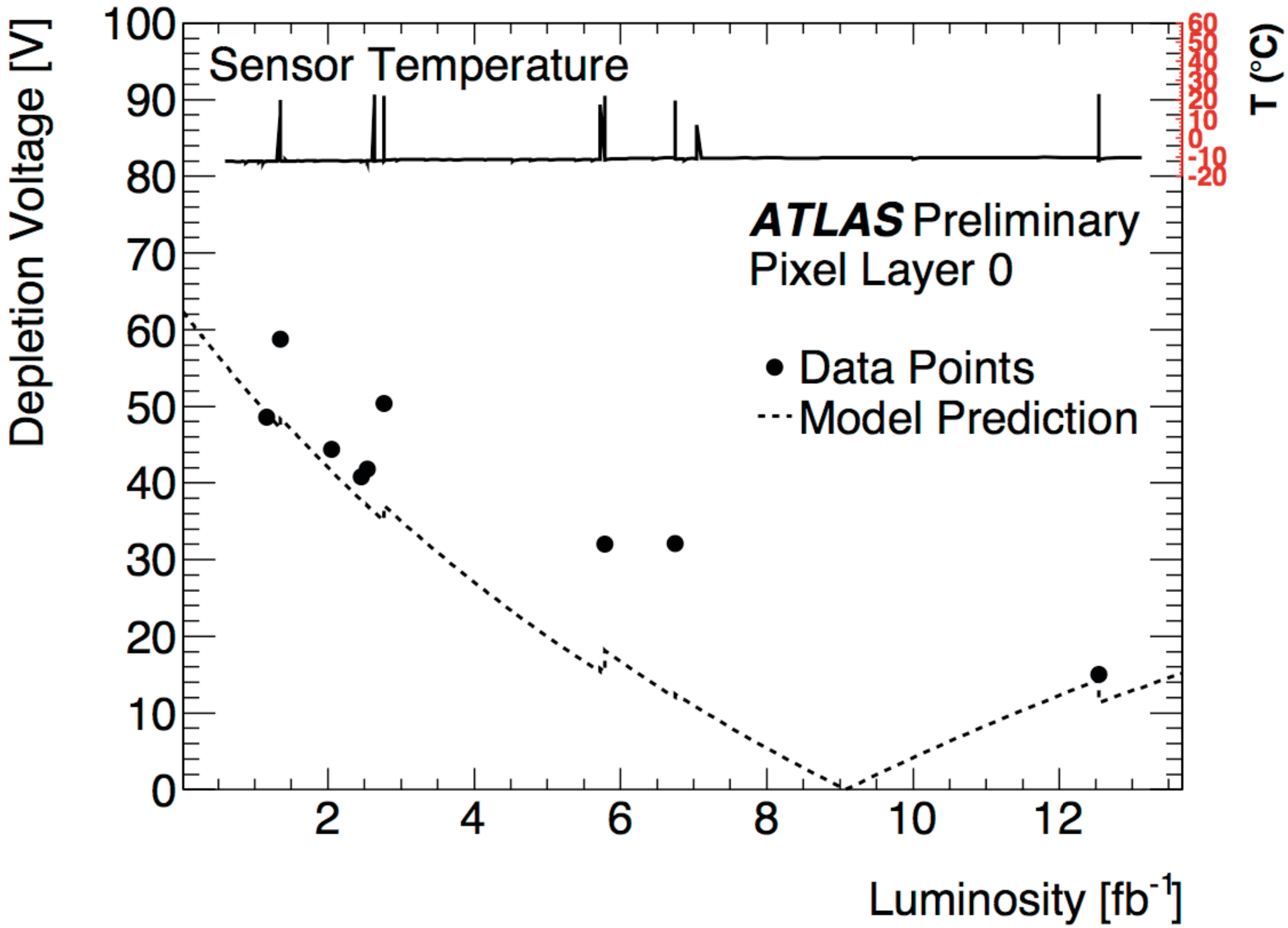
after type inversion



after heavy radiation damage

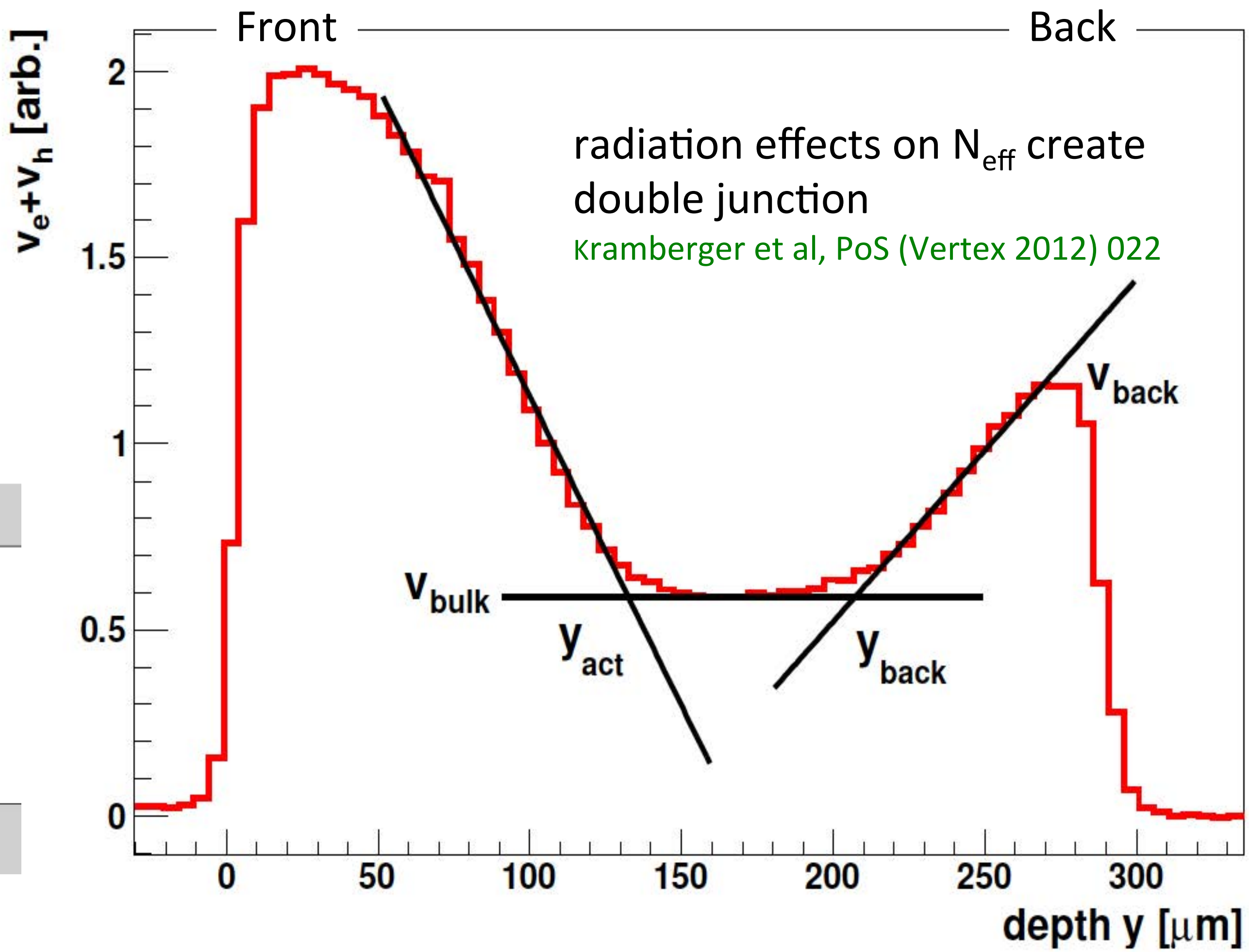
L. Andricek et al, NIM-A 409 (1998) 184-193

“Type inversion” seen

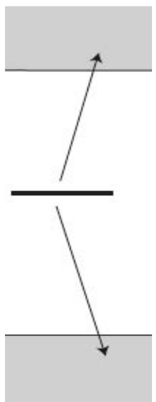


It is not "just" a type inversion ...

- change in N_{eff}
⇒ "type inversion"
⇒ "reverse annealing"
⇒ need higher V_{bias}
⇒ op. in partial depletion



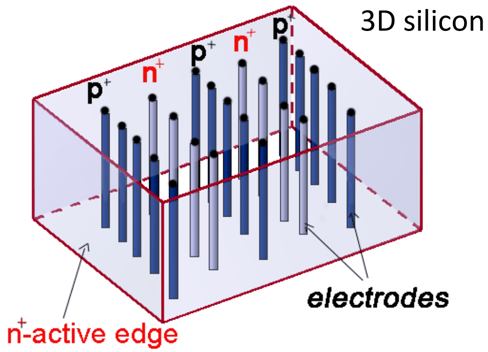
- change in I_{leak}
⇒ increased noise
⇒ increased power
⇒ thermal runaway
⇒ increased cooling
⇒ increased material

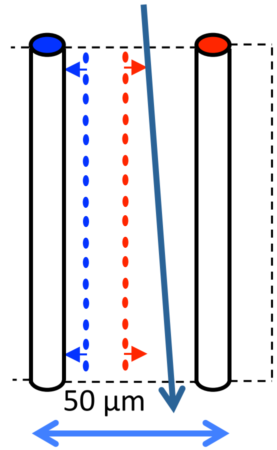


- for $\Phi > 10^{15}\, n_{eq}/cm^2$ → charge trapping important: $Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr}),\ 1/\tau_{tr} = \beta\Phi.$

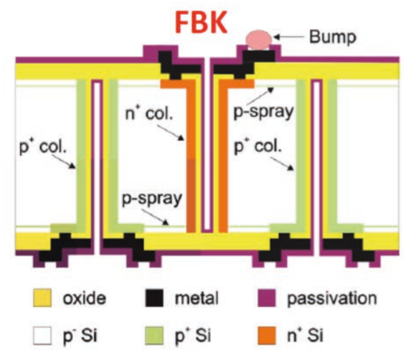
CCD becomes smaller than detector thickness (low Q) => need low noise @ high leakage current

3D-Si sensors for the innermost pixel layer(s)

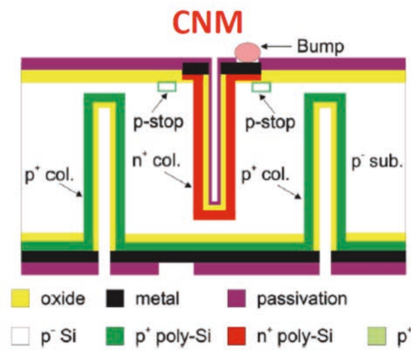




S. Parker, C. Kenney , J. Segal, ICFA Instrum.Bull. 14 (1997) 30-50
C. Da Via, et al., NIM A49 (2005) 122-125 and NIM A 699 (2013) 18

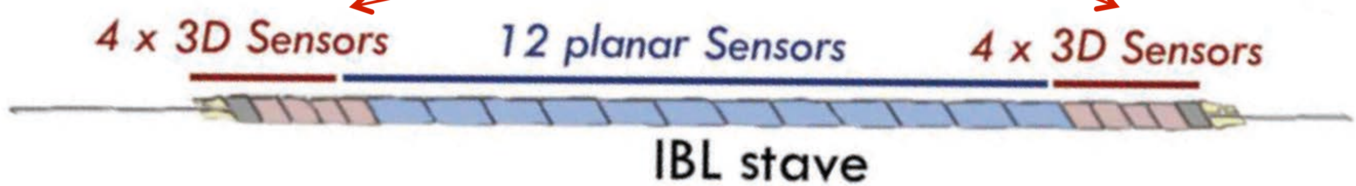


G.F. Della Betta et al.,
PoS Vertex2012 (2013) 014



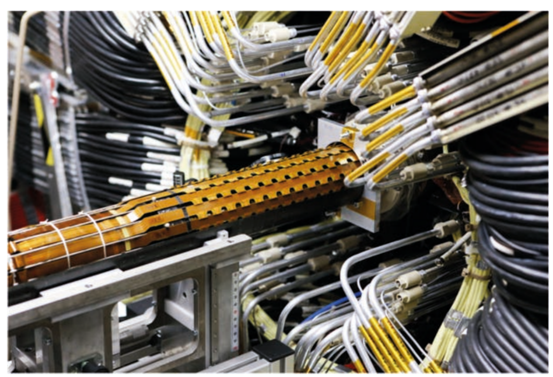
G. Pellegrini et al..
NIM A731 (2013) 198-200

- particle path (signal) different from drift path
- high field w/ low voltage



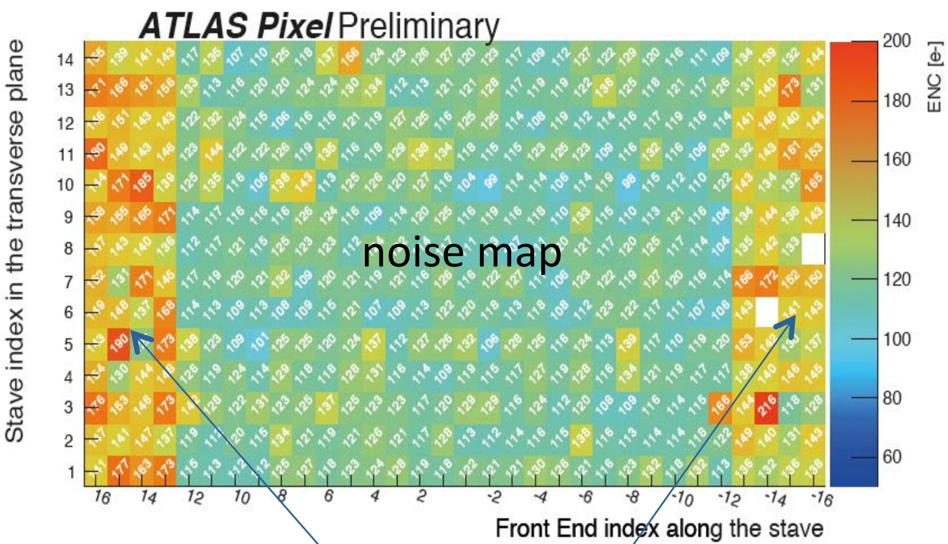
-> radiation tolerance
-> Q still 50% @ 10^{16} cm^{-2}

- good for inclined tracks
- slightly larger C_{in} (noise)
- now also in diamond, CdTe



- 3D sensors have been put to reality
- in ATLAS IBL for one year
- Let’s see how they performed

3D-Si sensors in ATLAS at 13 TeV and 0.5×10^{34} cm^{-2} s^{-1}

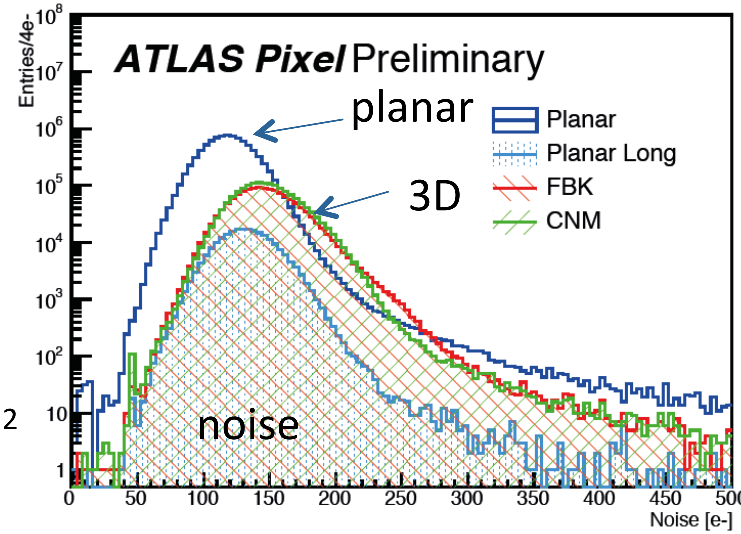


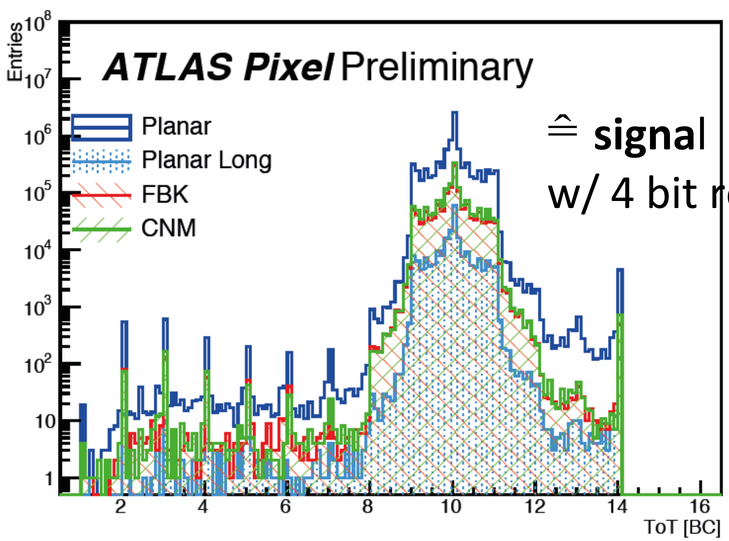
3D sensors

after 4.3 fb^{-1} radiation

1.3 Mrad

2.5 10^{13} n_{eq}/cm^2





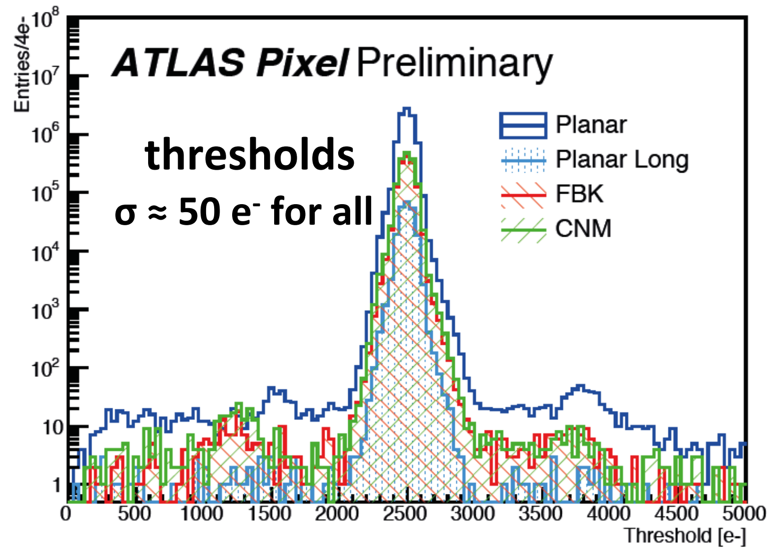
≙ **signal** w/ 4 bit res.

bias voltage

IBL 3D: 20 V

IBL planar: 80 V

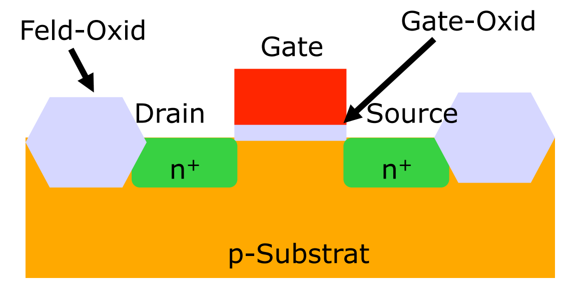
B-layer: 250 V



Conclusion: 3D-Si sensors seem suited for inner pixel layer(s) @ HL-LHC

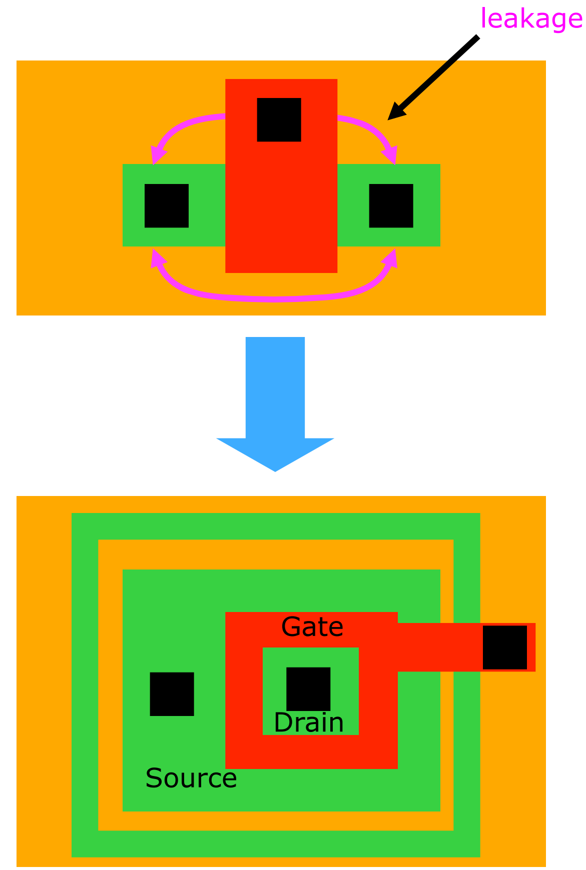
Radiation damage to the FE-electronics … and cure

Effects: generation of positive charges in the SiO_2
and defects in Si - SiO_2 interface



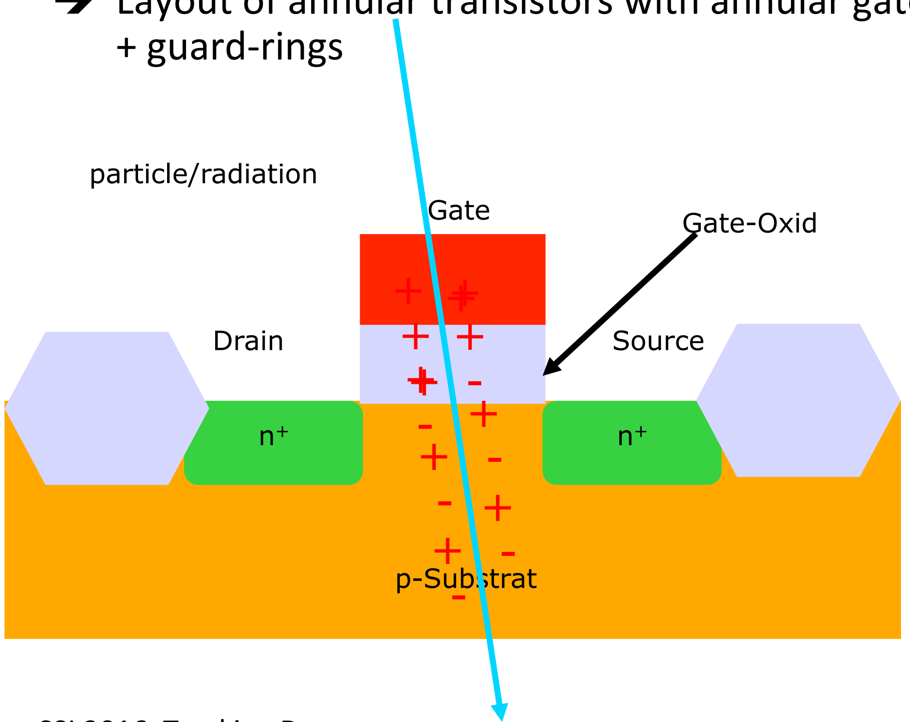
1. Threshold shifts of transistors

➔ Deep Submicron CMOS technologies with small structure sizes (≤ 350 nm) and thin gate oxides (d_{ox} < 5 nm) → holes tunnel out



2. Leakage currents under the field oxide

➔ Layout of annular transistors with annular gate-electrodes + guard-rings



Radiation damage to the FE-electronics … and cure

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radiation induced bit errors

("single event upsets" SEU)

large amounts of charge on circuit nodes
- by nuclear reactions, high track densities -
can cause "bit-flip"

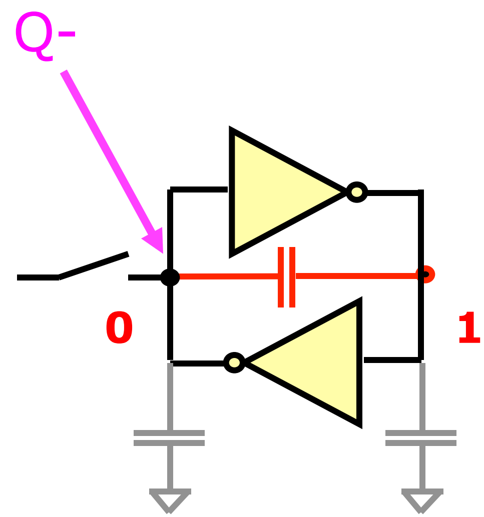
2 examples of error resistant logic cells

➔ enlarge storage capacitances in SRAM cells:

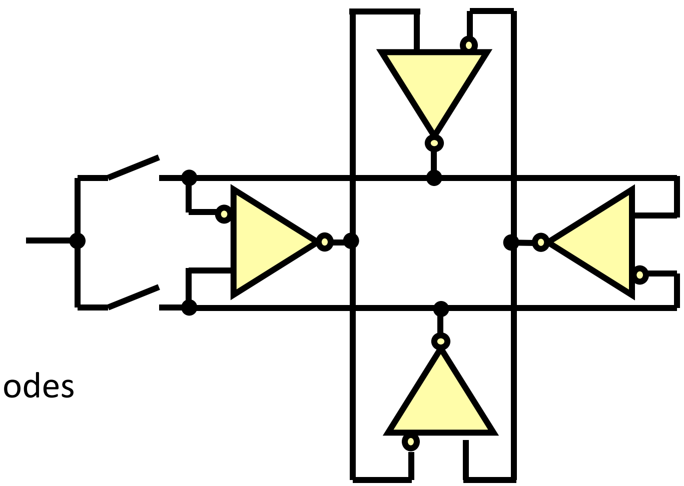
$Q_{crit} = V_{threshold} \cdot C$

➔ storage cells with redundancy (DICE SRAM cell)

information and its inverse stored on 2+2 independent and cross-coupled nodes
→ temporary flip of one node cannot permanently flip the cell.



standard SRAM cell


SEU tolerant DICE SRAM cell

Pixel R/O-Chip for HL-LHC rates (and radiation)

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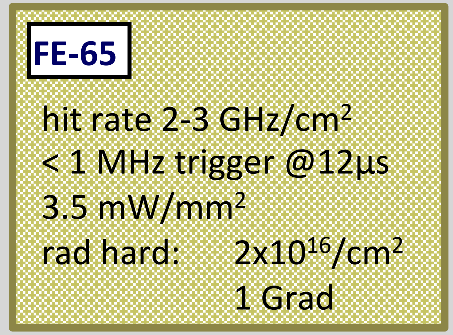
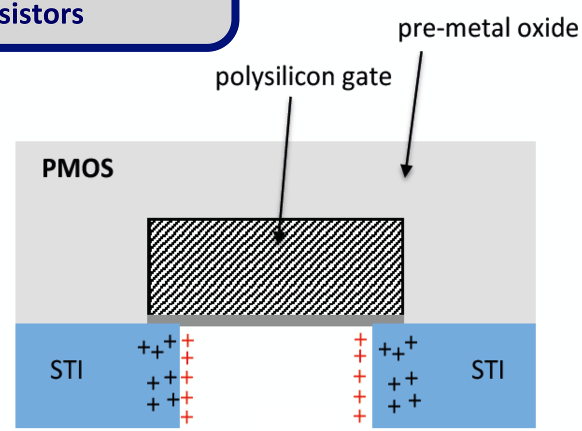
- effort and costs so large that joint approach (cross experiments) is needed -> **RD53** (20 Institutes)
- decide on technology w/ some probability of sustainability -> **65 nm TSMC**



FE-I3	FE-I4	FE-65
250 nm technology	**130 nm technology**	**65 nm technology**
pixel size 400 × 50 µm^2	**pixel size 250 × 50 µm^2**	**pixel size 50 × 50 µm^2**
3.5 M. transistors	**70 M transistors**	**~ 1000 M transistors**

- FE-65 first full-size prototype -> spring 2016
- Deep submicron (250 nm & 130 nm) saved LHC pixel R/O chips
- 65 nm has its own – geometry induced – radiation effects to deal with
- Requires long and tedious study program ...



RINCE = Radiation Induced Narrow Channel Effects
RISCE = Radiation Induced Short Channel Effects

see F. Faccio, TWEPP 2015, Proceedings

Radiation effects in 65 nm CMOS small channel devices

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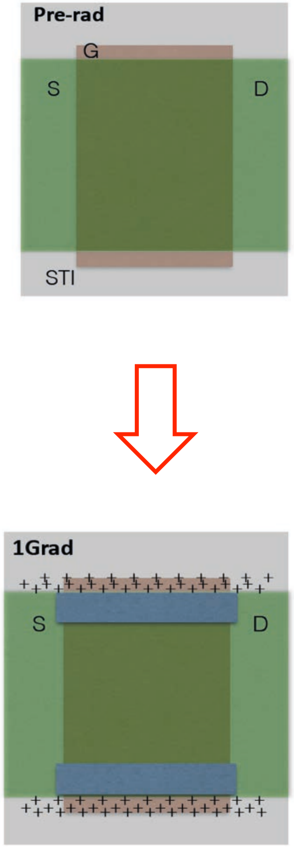
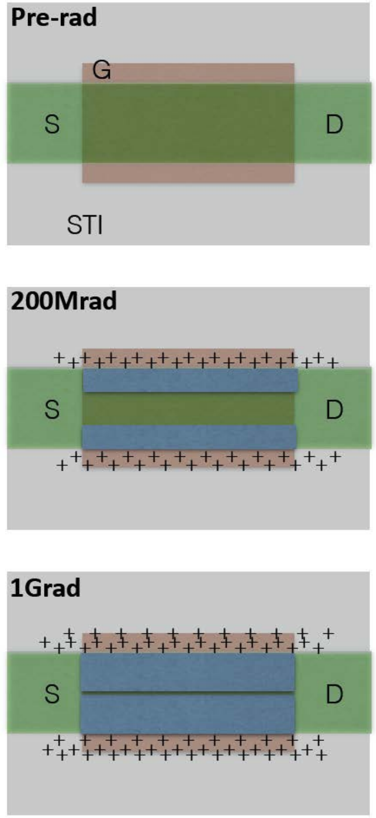
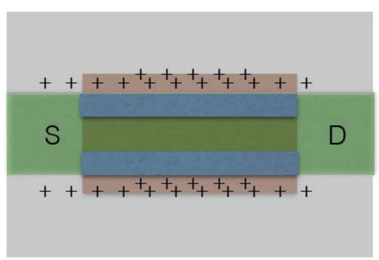
W = moderate size



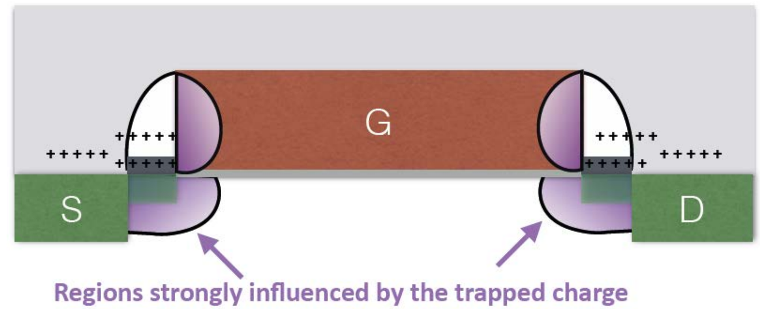
W = minimum size



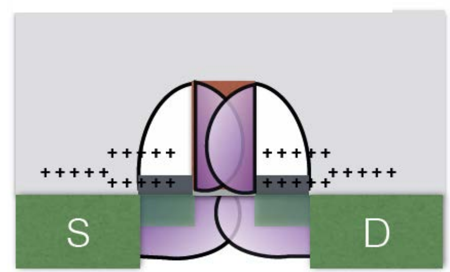
heating trap release



L = moderate size



L = minimum size



cartoons: F. Faccio, TWEPP2015

For very high fluences -> thin planar (pixel) sensors

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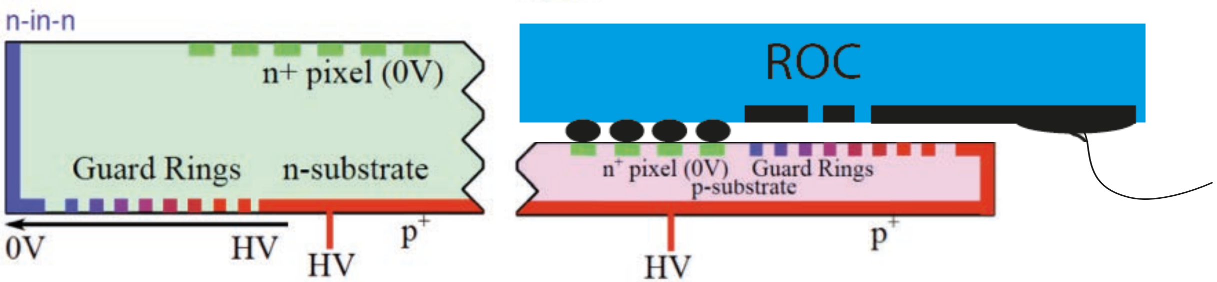
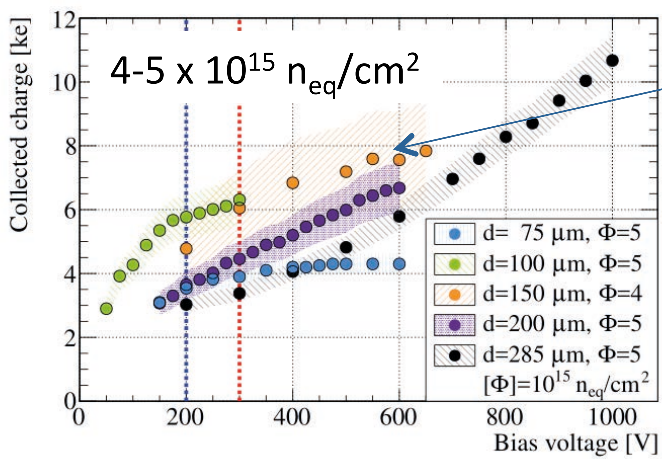
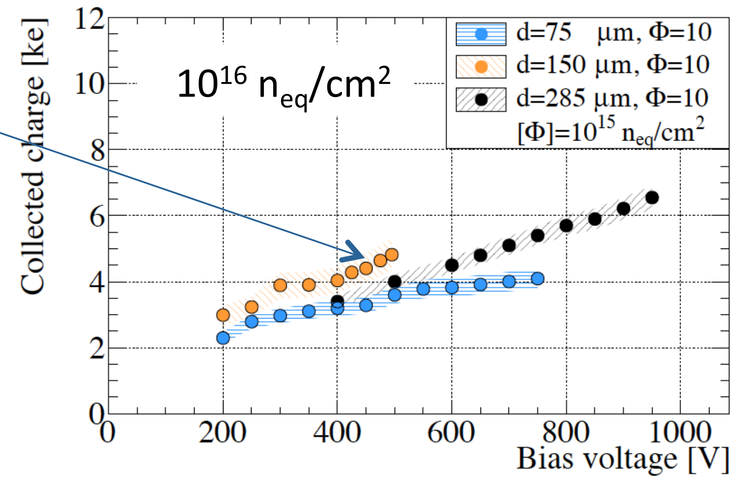


- thin n⁺ in p sensors after high fluences (neutrons)

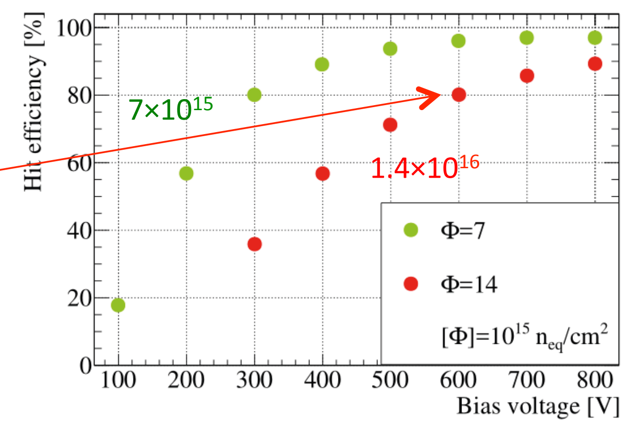
best (150 µm)





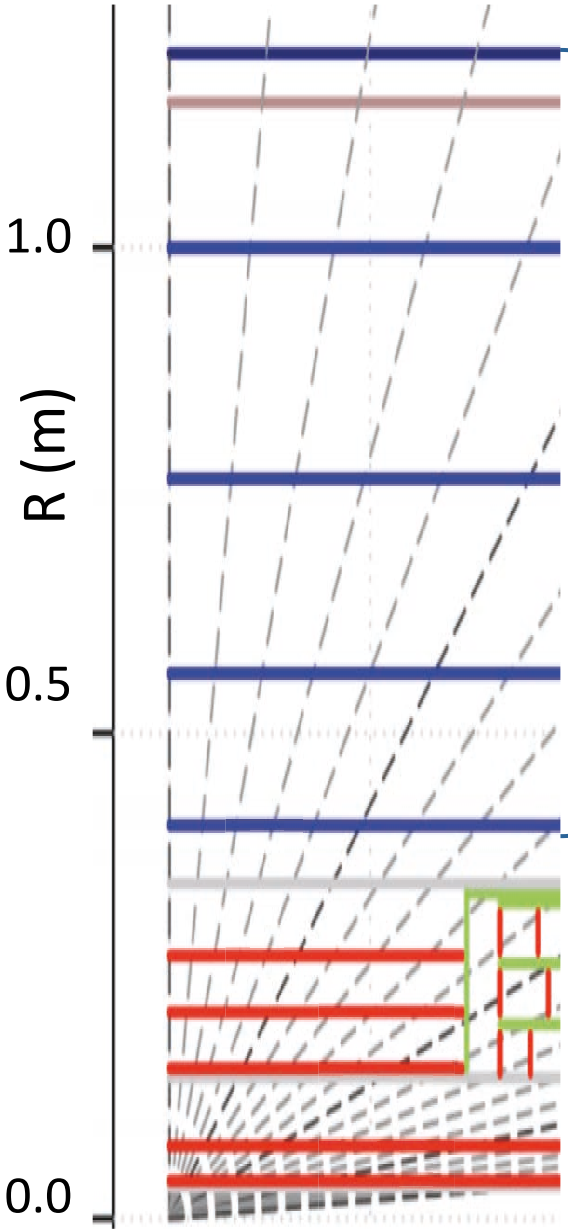
- **6000 – 7000 e-**
  for 100 - 200 µm sensors @ 300 V – 600 V bias

- hit efficiencies still reasonable at $\Phi > 10^{16}$



Terzo, Andricek, Macchiolo, Nisius et al, JINST 9 (2014) C05023

Typical favourite views ...

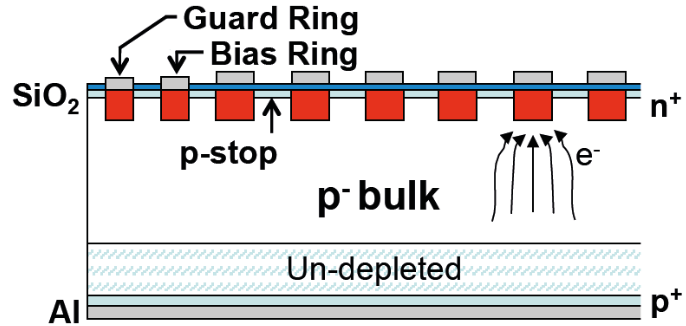


strips

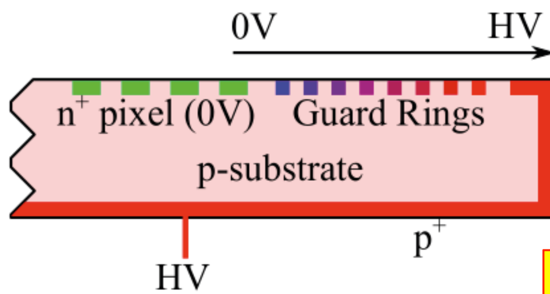
outer pixel

inner pixel

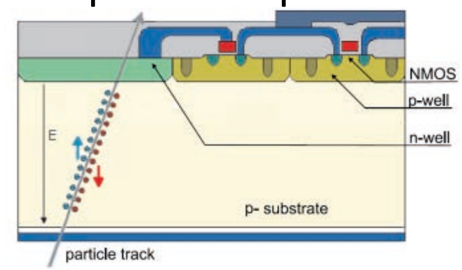
innermost pixel



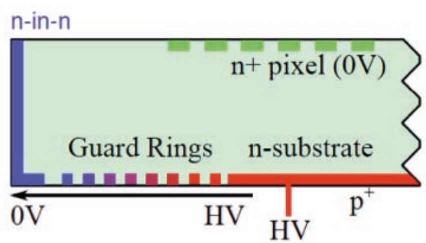
n in p
strip modules

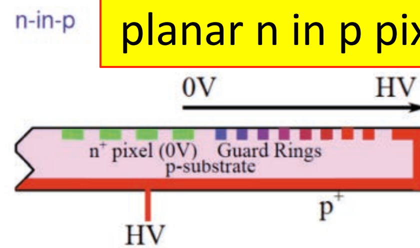


depl. CMOS pixels

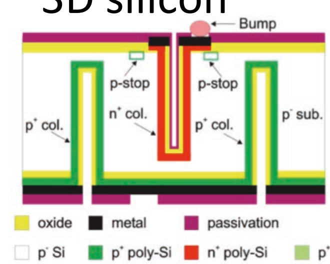


large modules
planar n in p pixels / CMOS?

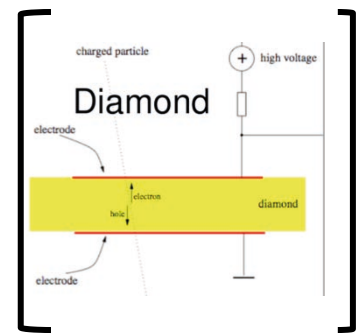




3D silicon



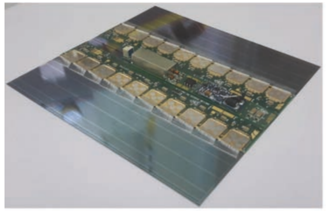
dedicated
rad.-hard
detectors



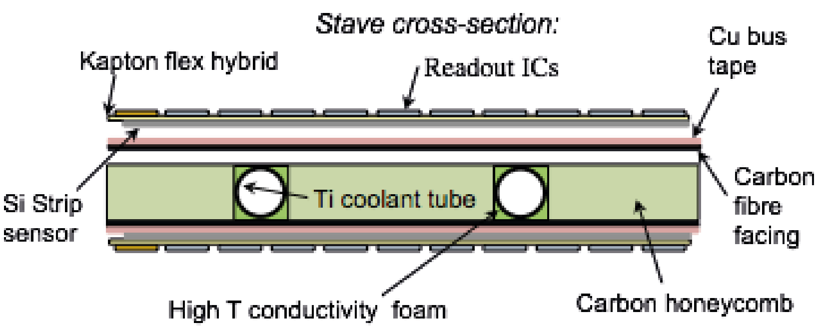
Large Area Strip Trackers of ATLAS and CMS upgrades

- “Large” meaning: 200 - 220 m² strips and 8 - 18 m² pixels

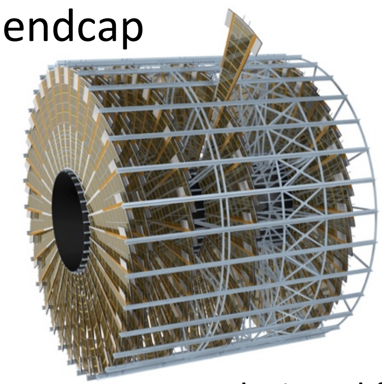
Main points
ATLAS
- affordable cost
- finer segmentation
- simplicity & robustness @ min. material

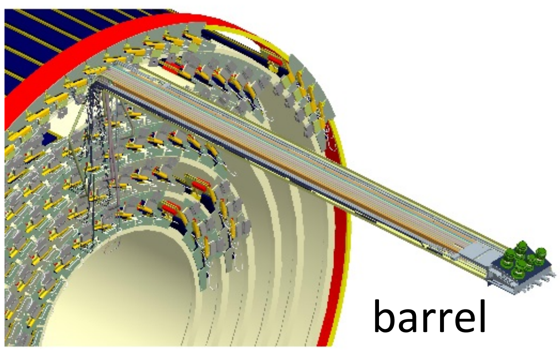


10x10 cm²
2.5 cm strips
limit of strip geom?



endcap

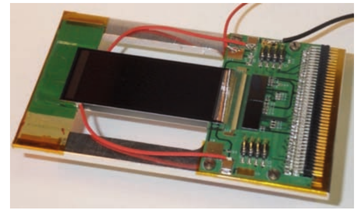




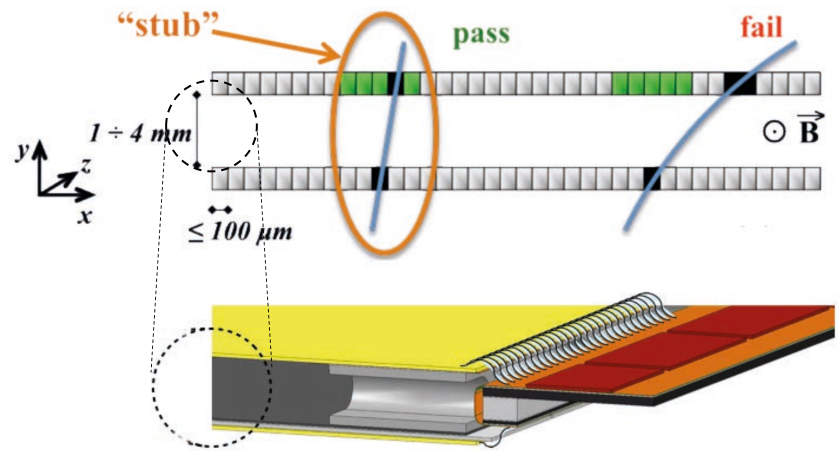
barrel

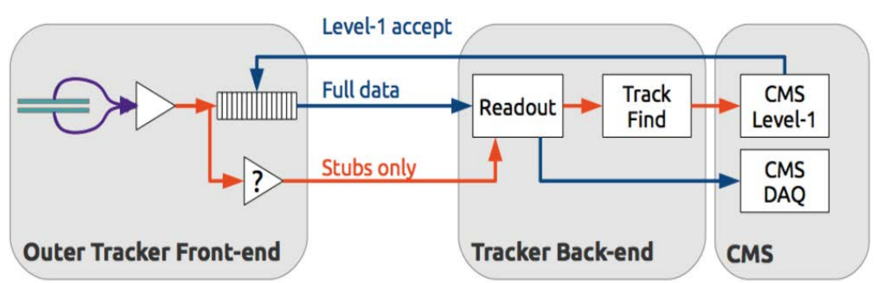
designed for end insertion

Main points
CMS



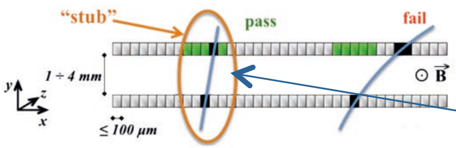
- same principle goals plus ...
- p_T module & tracks in trigger @ L1
- new industrial 8” (-> 12”) sensors

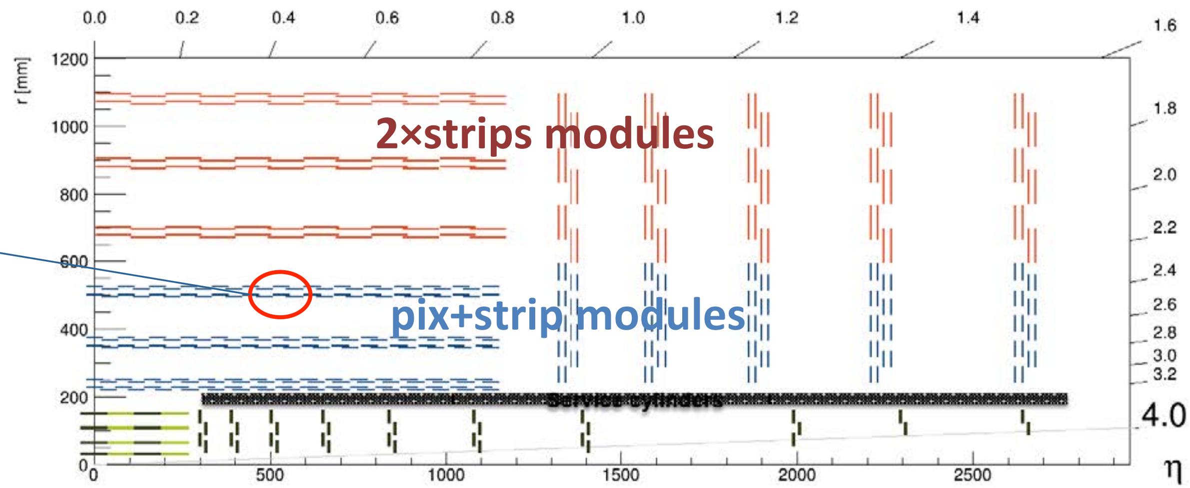




see e.g. T. Affolder, various talks
see e.g. D. Abbaneo, CERN PH seminar, F. Ravera 13th Pisa Meeting

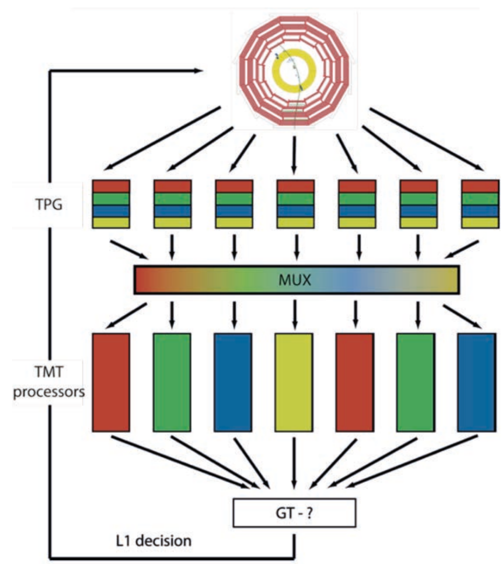
CMS Outer Tracker



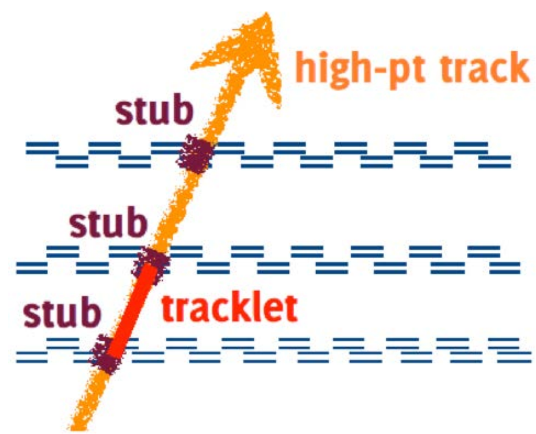


process stubs

use CAMs for fast pattern matching



use Time MUX Trigger to process <u>complete</u> event



get (high p_T) tracks seeded by stubs pairs

Rate and Radiation Levels

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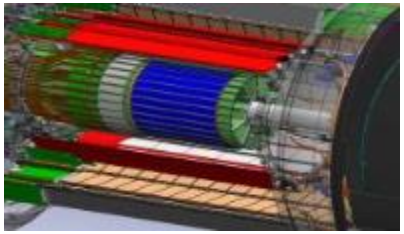
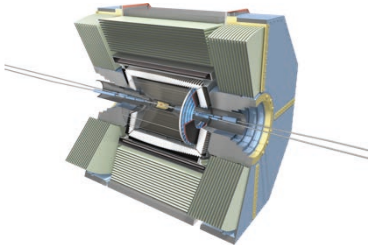
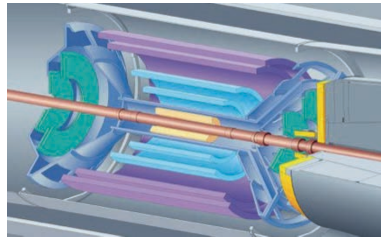
STAR



Belle II

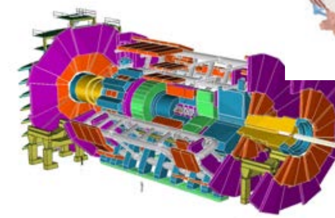


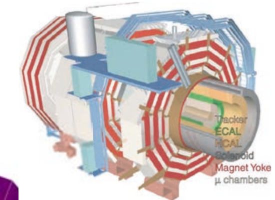
ALICE-(HL)-LHC



ILC

ATLAS





CMS

Numbers for innermost layers (r ≈ 5cm,) -> scale by 1/10 for typical strip layers (r > 25 cm)

	STAR	Belle II	ALICE-LHC heavy ion	ILC	LHC pp	HL-LHC-pp	
						Outer	Inner
BX-time (ns)	110	2	20 000	350	25	25	25
Particle Rate (kHz/mm^2)	4	400	10	250	1 000	1 000	10 000
Φ (n_{eq}/cm^2)	few 10^{12}	3×10^{12}	> 10^{13}	10^{12}	$2x10^{15}$	10^{15}	$2x10^{16}$
TID (Mrad)*	0.2	20	0.7	0.4	80	50	> 1000

Monolithic Pixels (STAR, Belle II, ALICE-LHC heavy ion, ILC)

Hybrid Pixels (HL-LHC-pp)

*per (assumed) liftetime
LHC, HL-LHC: 7 years
ILC: 10 years
others: 5 years

in need for
- much less material
- higher resolution
- thinner strips & monolithic pixels

state of the art
- large area strips
- hybrid pixels

- even larger area
- radhard sensors
- higher rates R/O
- CMOS pixel R&D

(Semi)-Monolithic Pixel Detectors

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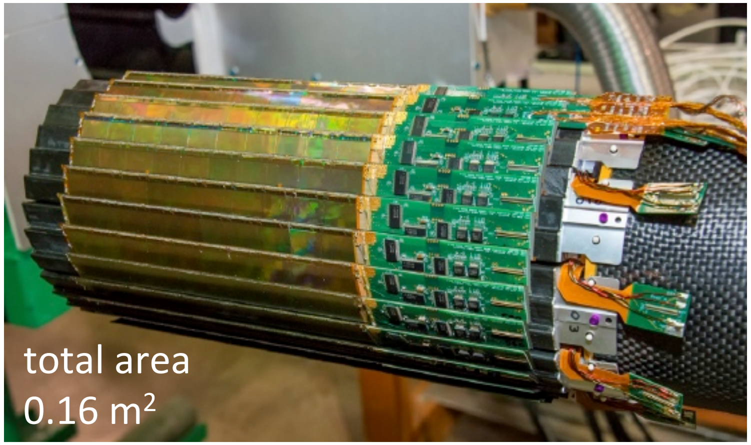
STAR / RHIC MAPS

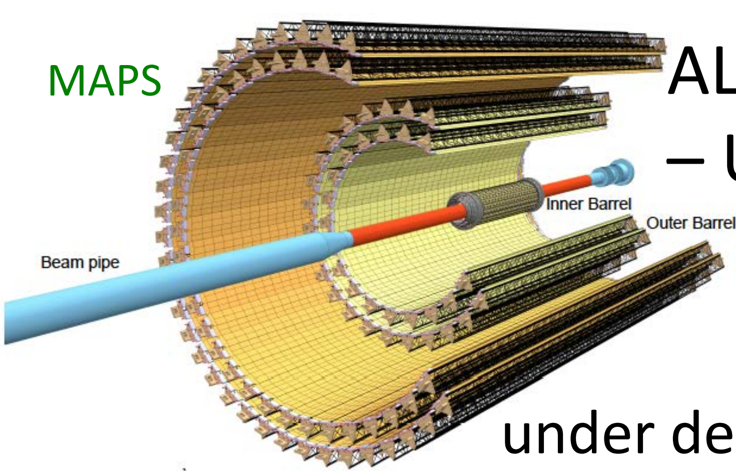


in operation since 2014

(Belle II) DEPFET

in production for 2017

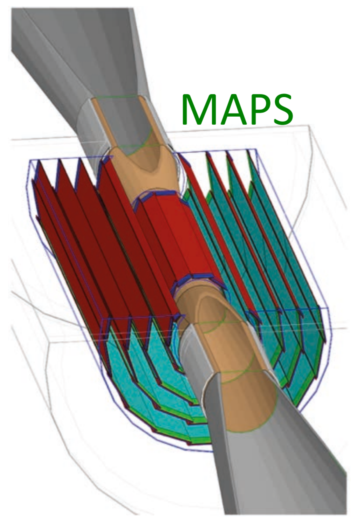
MAPS



ALICE – Upgrade

total area
~10 m^2

under development
target: 2018

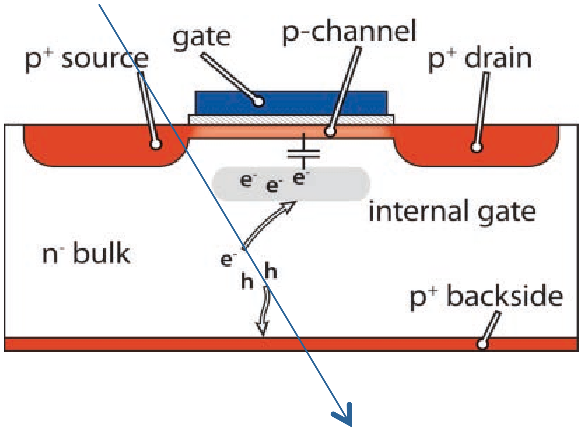


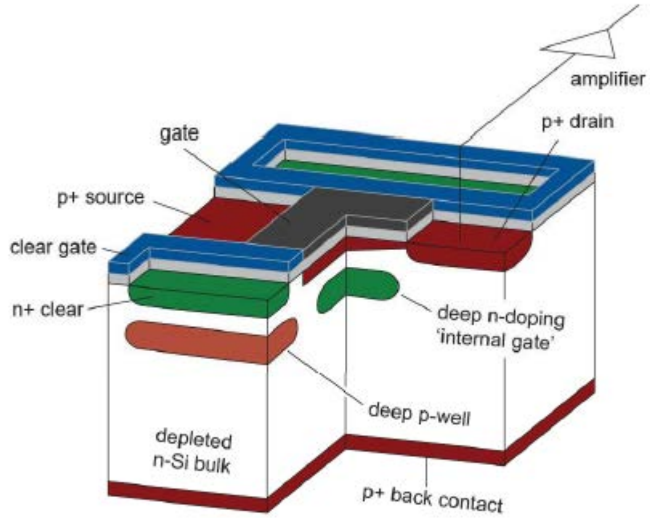
ILC

total area
? m^2

current baseline

DEPFET Pixels





How does a DEPFET work?

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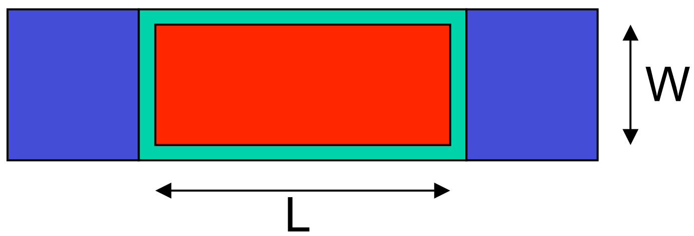
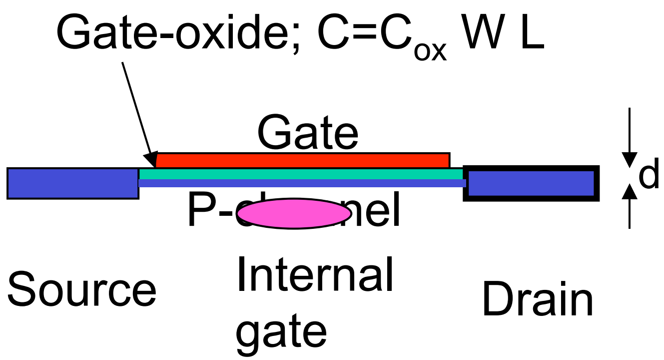




A charge q in the internal gate induces a mirror charge αq in the channel (α <1 due to stray capacitance). This mirror charge is compensated by a change of the gate voltage: ΔV = α q / C = α q / (C_{ox} W L) which in turn changes the transistor current I_d .

q

FET in saturation:

$$I_d = \frac{W}{2L}\mu C_{ox}\left(V_G + \frac{\alpha q_s}{C_{ox}WL} - V_{th}\right)^2$$

I_d: source-drain current
C_{ox}: sheet capacitance of gate oxide
W,L: Gate width and length
μ: mobility (p-channel: holes)
V_g: gate voltage
V_{th}: threshold voltage

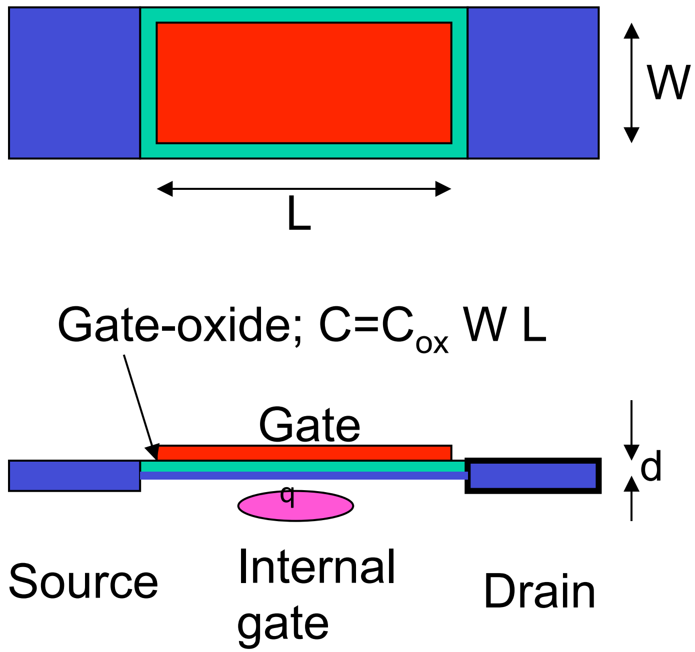
Conversion factor:

$$g_q = \frac{dI_d}{dq_s} = \frac{\alpha\mu}{L^2}\left(V_G + \frac{\alpha q_s}{C_{ox}WL} - V_{th}\right) = \alpha\sqrt{2\frac{I_d\mu}{L^3WC_{ox}}}$$

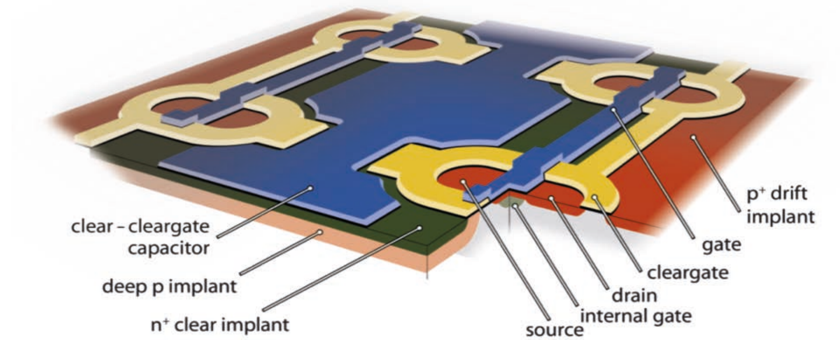
$$g_m : g_q = \alpha \frac{g_m}{WLC_{ox}} = \alpha \frac{g_m}{C}$$

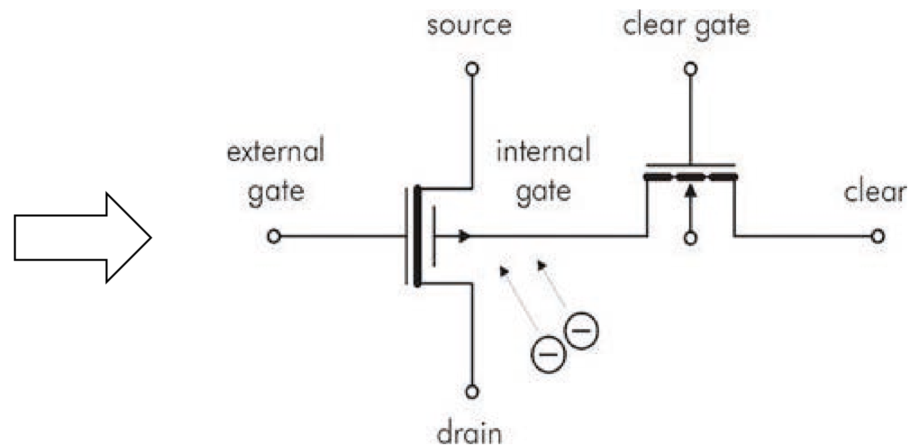
How does a DEPFET work?

universitätbonn



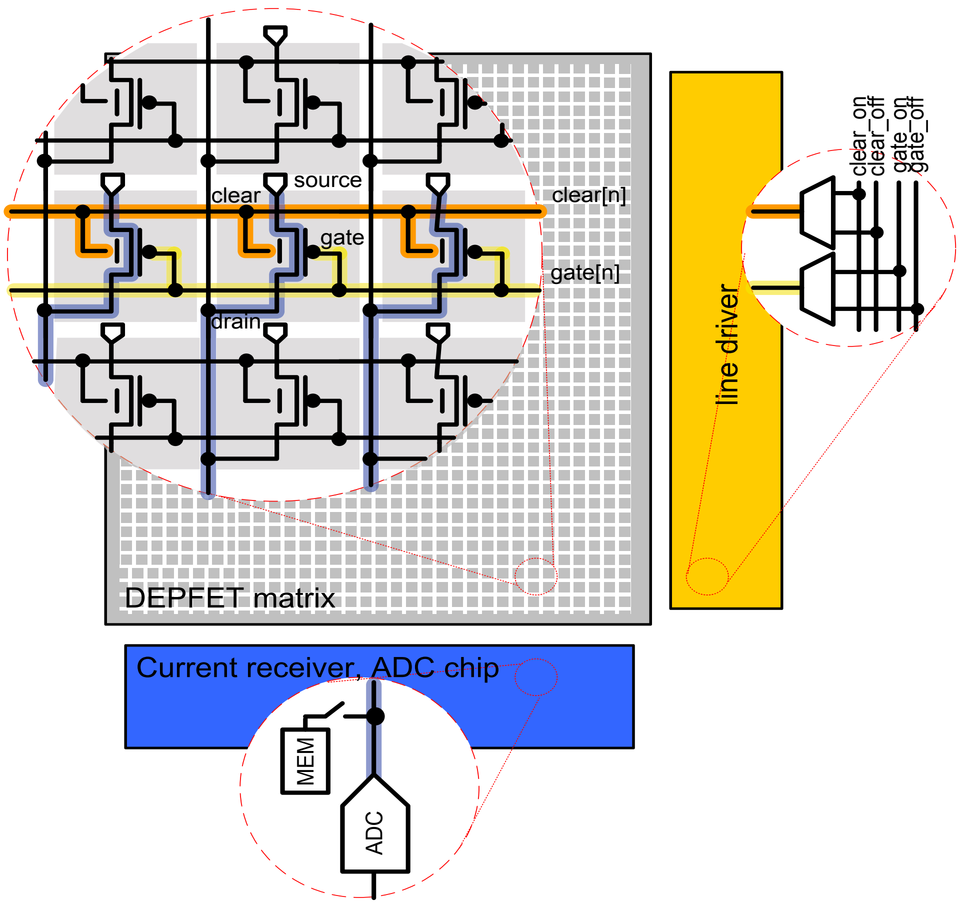
A charge q in the internal gate induces a mirror charge αq in the channel (α <1 due to stray capacitance). This mirror charge is compensated by a change of the gate voltage: $\Delta V = \alpha\, q / C = \alpha\, q / (C_{ox}\, W\, L)$ which in turn changes the transistor current I_d.





- Internal amplification $g_q \sim 500$ pA/e$^-$
- Small intrinsic noise
- Sensitive off-state, no power consumption

DEPFET pixel array

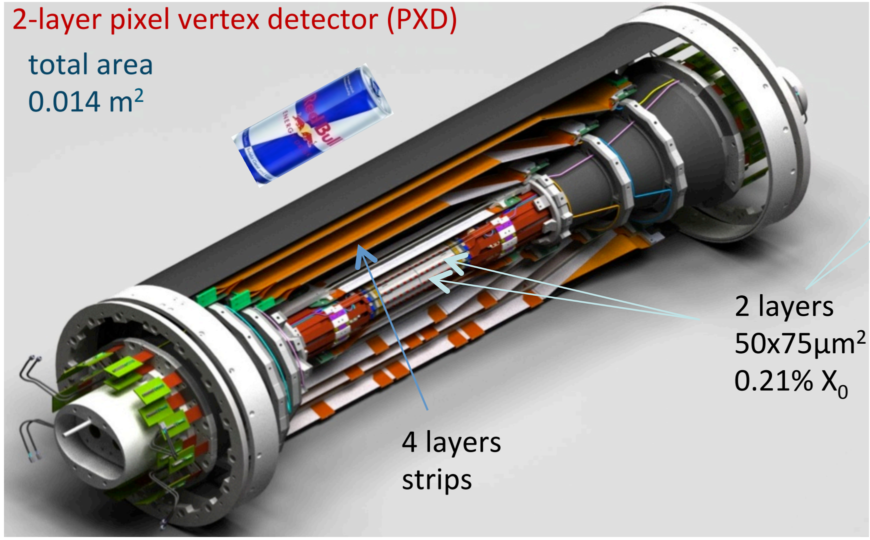


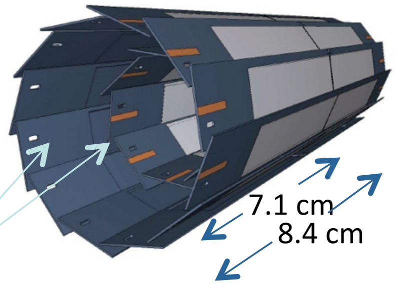
rolling shutter R/O mode

- DEPFET pixel transistors arranged in a matrix
- row wise select -> column wise readout of transistor (drain) currents
- Gate and clear lines need a steering chip
- Long drain readout lines to keep material out of the acceptance region
- 100 ns per row
  20 µs per frame

more in talk by Florian Lütticke (next)

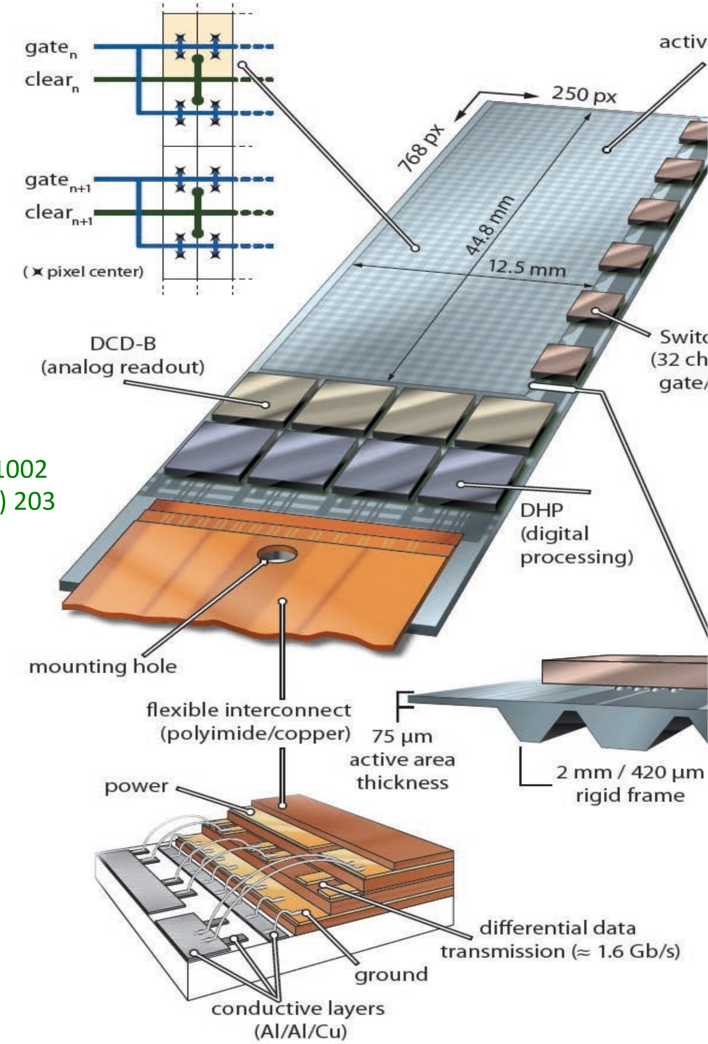
BELLE II Pixel Detector





2 layers
50x75µm^2 pixels
0.21% X_0

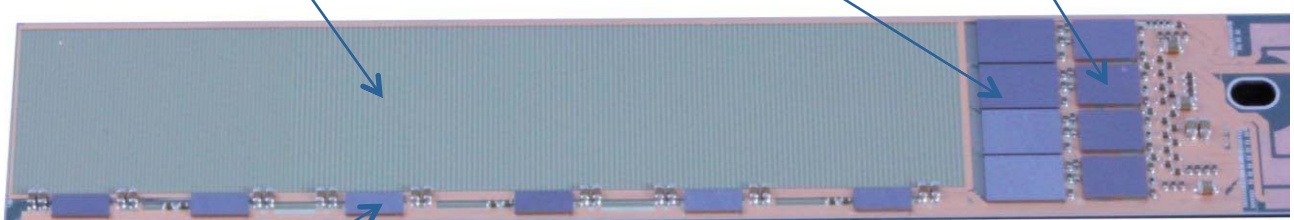
C. Marinas et al., JINST 10 (2015) 11, C11002
C. Kiesling et al., PoS EPS-HEP2011 (2011) 203



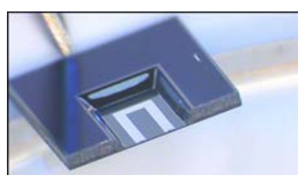
DEPFET sensor

current
digitizer chips

data processing
chips

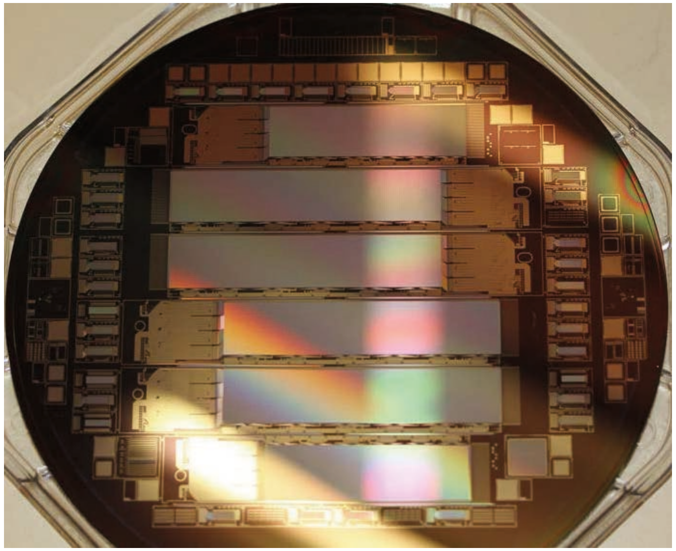


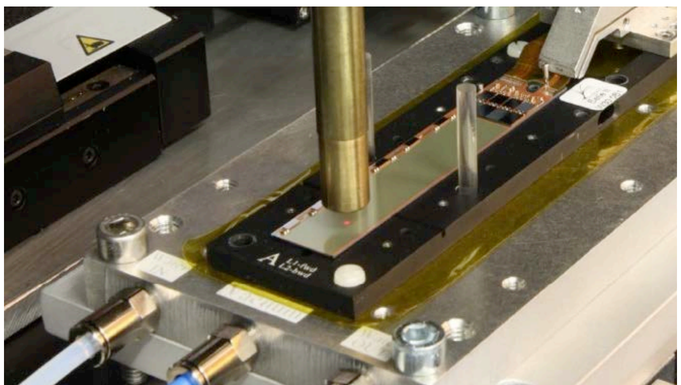
switcher chips

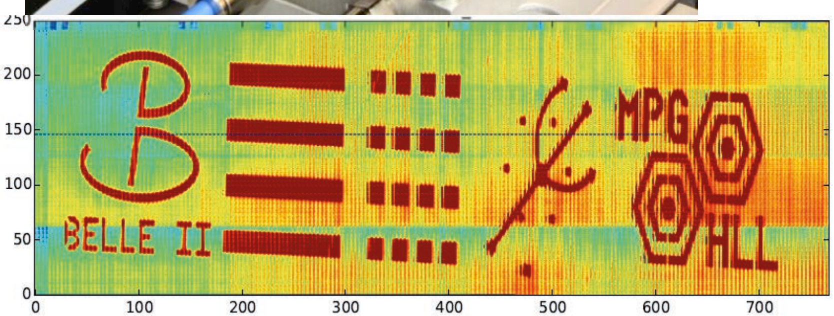


L. Andricek, IEEE Trans.Nucl.Sci. 51 (2004) 1117-1120

DEPFET PXD is closing in on production ...







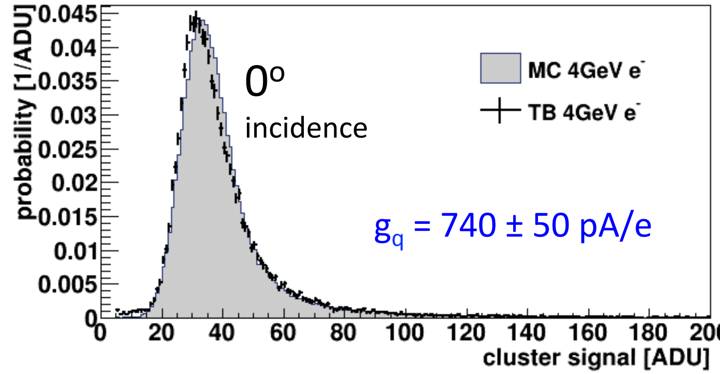
from . F. Müller (MPIM)

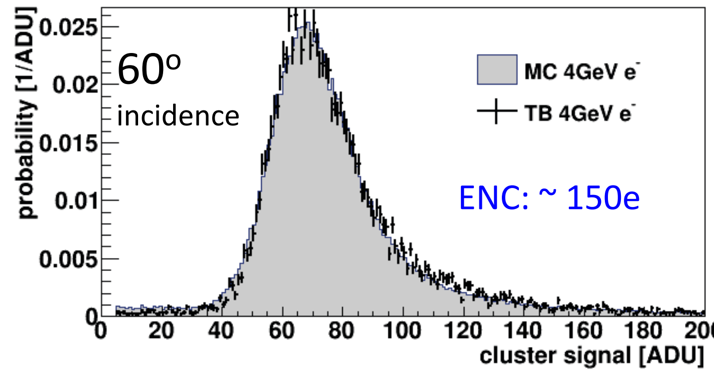
expected radiation

electrons and
synchr. radiation

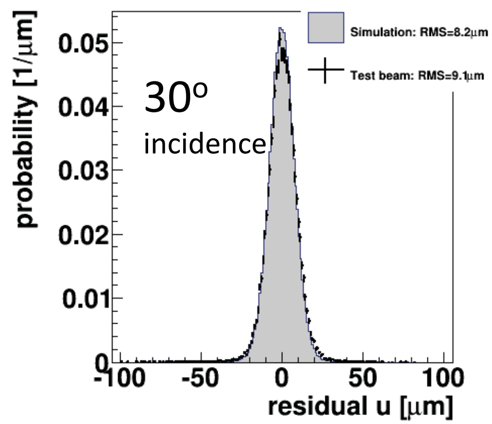
< 20 Mrad

testbeam results





from B. Schwenker (Göttingen)

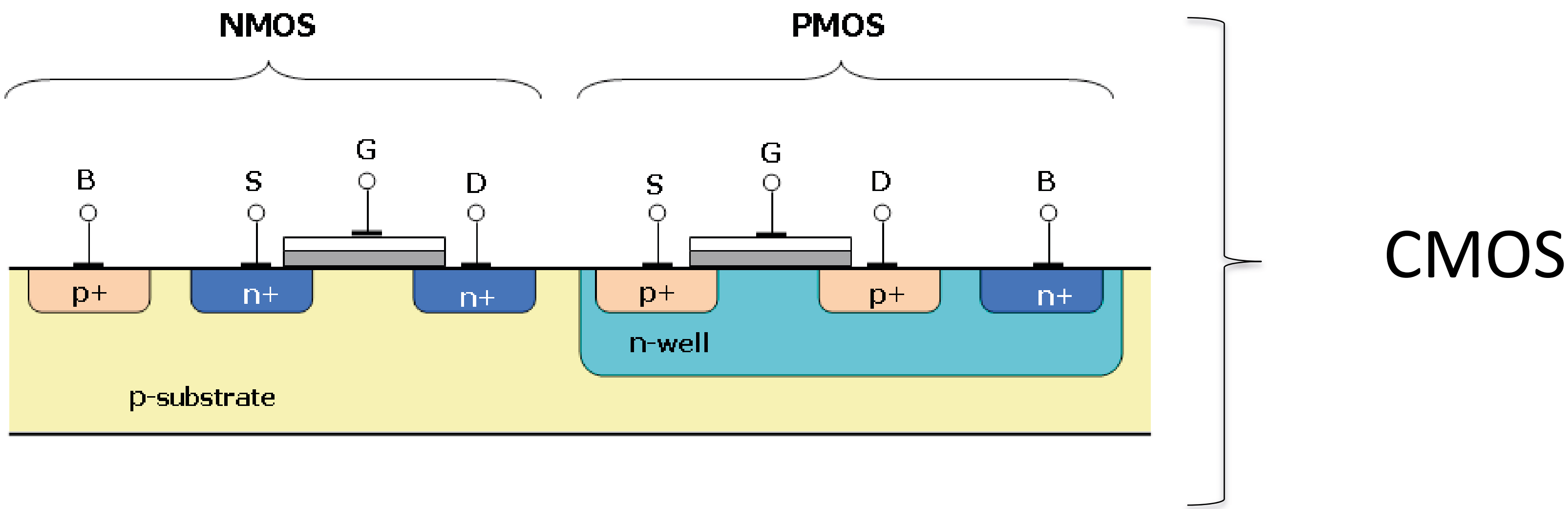


resolution

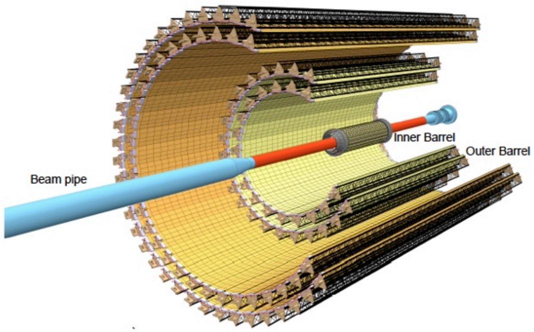
~ 8-11 μm (50 μm pitch)

~ 13 μm (75 μm pitch)

Depleted Monolithic Active Pixels DMAPS

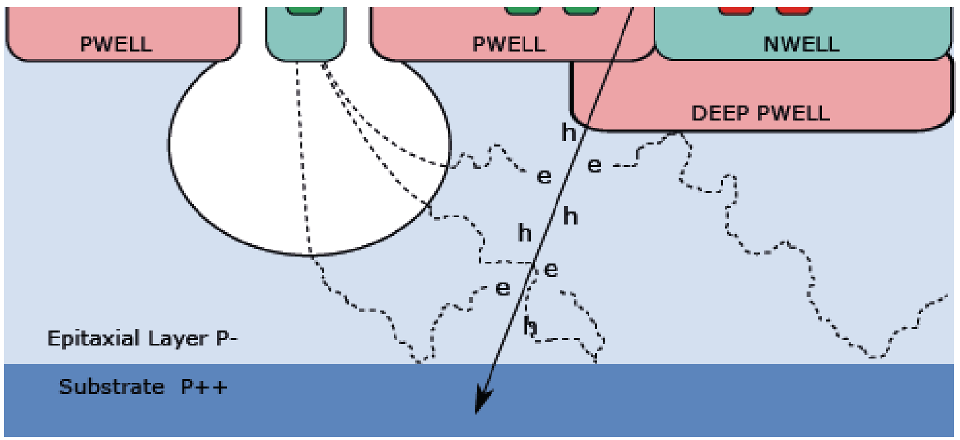


ALICE ITS: CMOS pixel: TowerJazz 0.18µm imaging process



- 3 inner (r < 2.1 cm) + 4 outer (r < 40 cm) layers
- ~ 10 m^2
- low material (0.3% X_0 inner barrel, 0.8% X_0 outer barrel)

from L. Musa 2015



Tower Jazz 0.18 µm CMOS

- feature size 180 nm
- metal layers 6

→ Suited for high-density, low-power

- Gate oxide 3nm

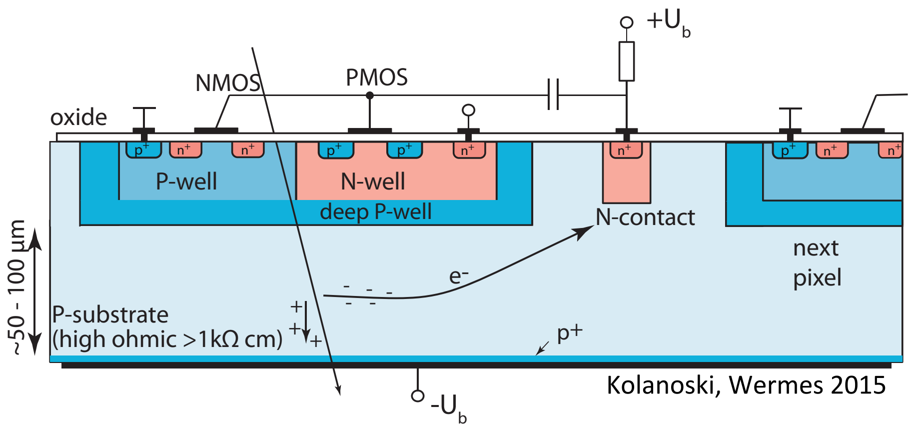
→ Circuit rad-tolerant

- high resistivity (> 1kΩ cm) **epi-**layer (p-type, 20-40 µm thick) on p-substrate
- very small n-well diodes => small C_{in}
- moderate reverse bias => increase depletion region around Nwell collection diode
- quadruple well process => shield Nwells by deep Pwells => full CMOS
- radiation tolerance to 700 krad / fluence $10^{13}/n_{eq}/cm^2$ (= 1/1500 of HL-LHC-pp)

Current DMAPS approaches

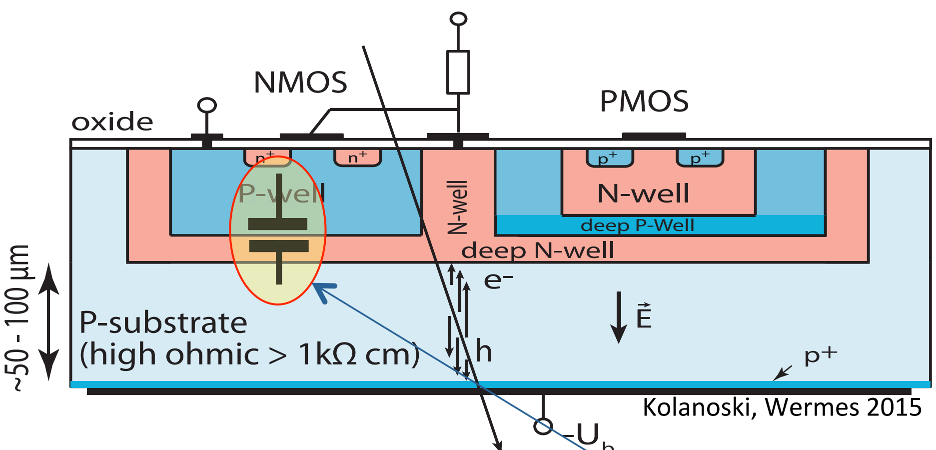
HR/HV - CMOS

I. Peric et al., NIM A582 (2007) 876-885 & NIM A765 (2014) 172-176
S. Mattiazzo, W. Snoeys et al., NIM A718 (2013) 288-291
M. Havranek, Hemperek, Krüger, NW et al. JINST 10 (2015) 02, P02013



- (D)MAPS like configuration but w/ depleted bulk
- small collection node
- long drift path

=> **smaller C, more trapping**



- deep n and deep p wells
- large collection node
- short drift path

=> **larger C, less trapping**

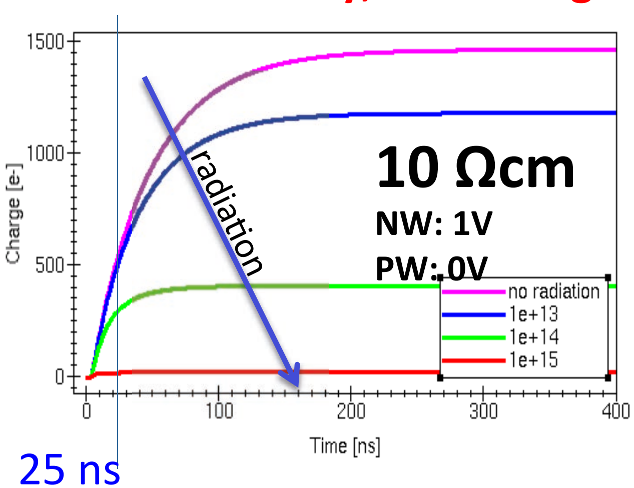
important: (number of) deep wells and detailed cell geometry

watch: capacitance between deep p- and n-wells

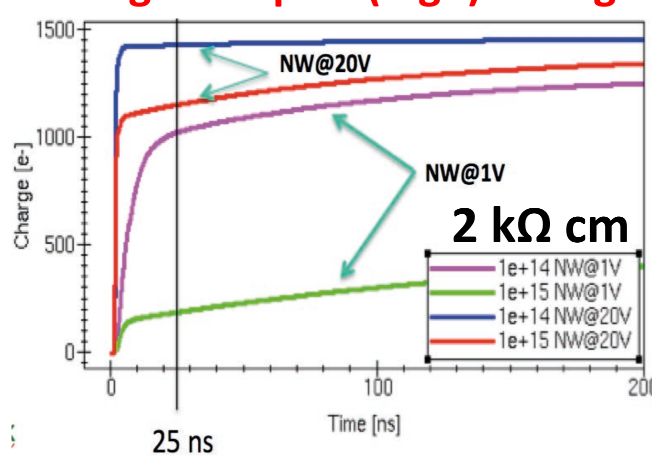
CMOS Pixels for HL-LHC -> DMAPS

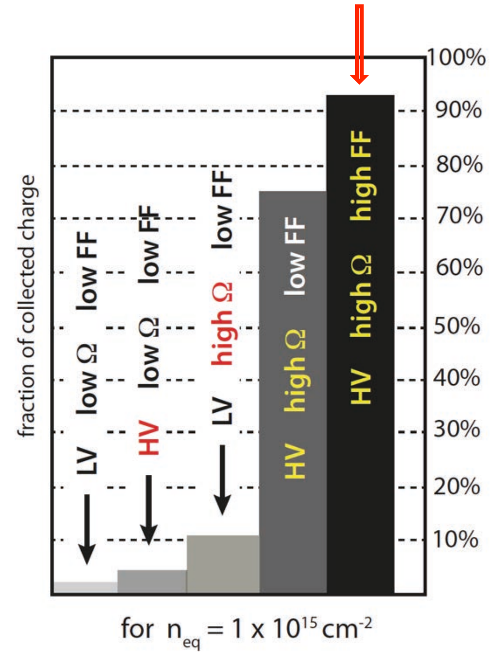
- ❑ driven by the need/hope for
  - low cost large area detectors … more pixel layers in trackers …. commercial
  - less material … ? less power … this is not at all clear
- ❑ but facing the rate/radiation challenges of the HL-LHC
- ❑ **goal:** some (40 – 80 µm) depletion depth for … ⇒ $d \sim \sqrt{\rho \cdot V}$
  - fast charge collection (< 25ns "in-time" efficient)
  - a reasonably large signal ~4000 e-
  - not too large a travel distance to avoid trapping (rad hardness)
- ❑ **need**

low resistivity, low voltage



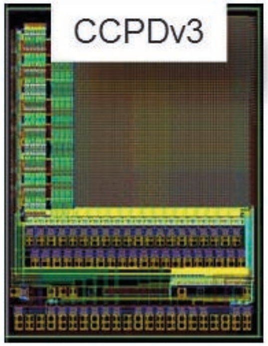
high res. plus (high) voltage

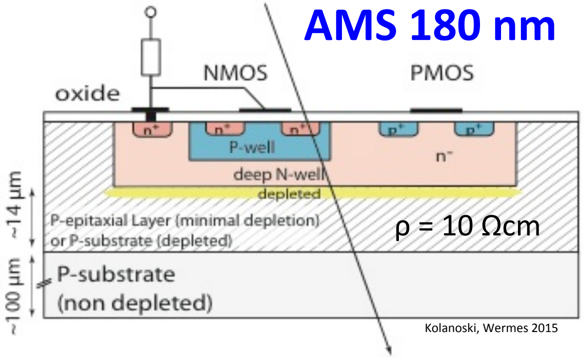




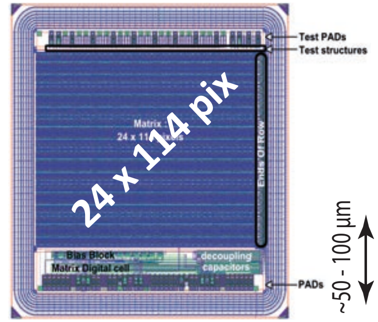
from Tomasz Hemperek

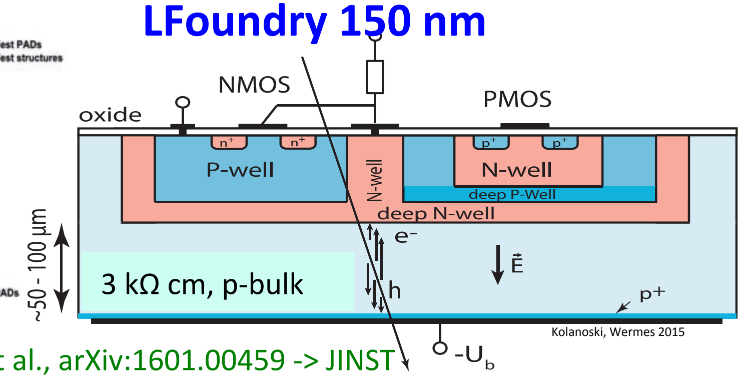
HV/HR CMOS Pixels





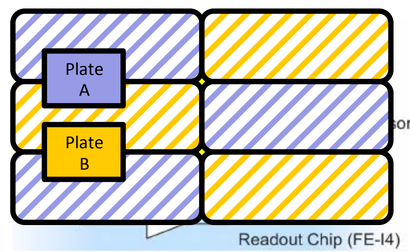
I. Peric et al., NIM A765 (2014) 172-176





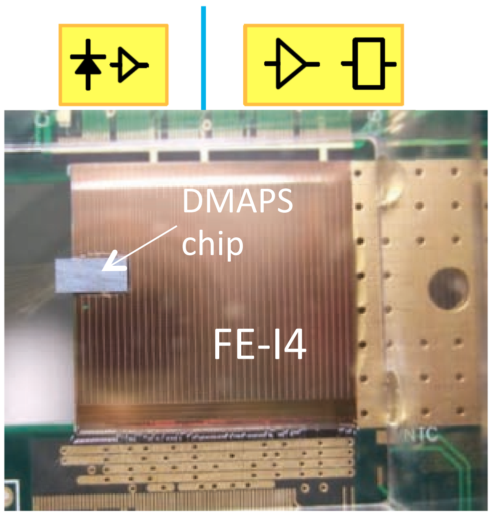
P. Rymaszewski et al., arXiv:1601.00459 -> JINST
T. Hirono et al., doi:10.1016/j.nima.2016.01.088

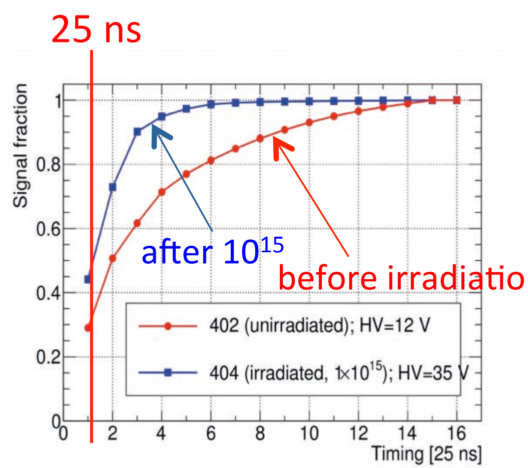
- triple well process
- 10 Ωcm – 1 kΩcm, 60 – 100 V
- depletion depth 10-20 µm -> 100 µm after irr.
- ~1000 e- by drift
- R/O via ATLAS pixel chip (AC coupling/glue)



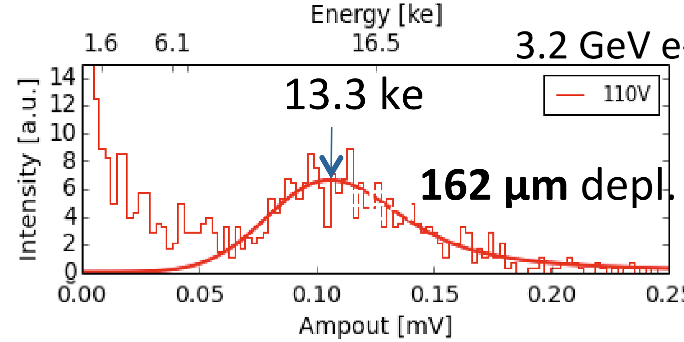
pixel area x 1/3

- quadruple well process
- 3 kΩ cm, 110 V bias
- large fill factor
- full CMOS (backside thinned)
- stand alone R/O and CCPD–R/O





acceptor removal effect



- ❑ encouraging results
- ❑ OK > 100 Mrad and > 5×10^{15} n_{eq}
- ❑ rate & in-time efficiency ...

❑ 4D with LGADs ?

Low Gain Avalanche Detectors

New: How to obtain fast timing with Si detectors?

- How would one go about getting into the 10 ps range with (structured) Si detectors?
- => exploit "in-silicon" charge amplification
  - in "Geiger Mode" fashion (like in gas **RPCs**)

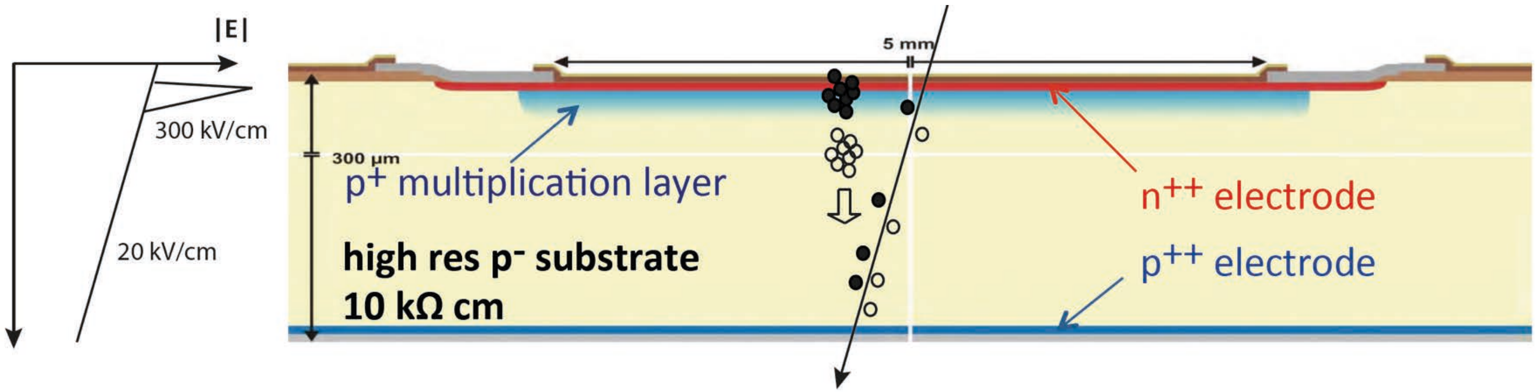
σ_t governed by avalanche fluctuations

$$\sigma_t \approx \frac{1.4}{(\alpha - \eta)\, v_D} \approx 50\text{ps}$$

Townsend coeff. (α), attachment coeff. (η)

see e.g. W. Riegler, C. Lippmann, R. Veenhof NIM A 500 (2003) 144

  - OR .... in "linear mode" fashion
    -> Low Gain Avalanche Detectors



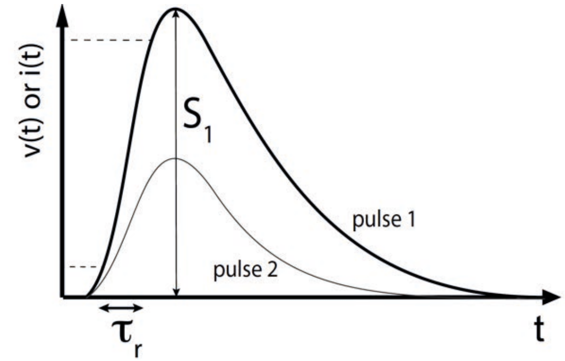
H. Sadrozinski et al., NIM A730 (2013) 226-231
N. Cartiglia et al., JINST 9 (2014) C02001
A. Seiden et al, Vertex2015, Proceedings

Towards 4D tracking ... Low-Gain Avalanche Detectors

- ❑ Separate the "collection" of charge from the signal gain
- ❑ Figure of merit for σ_t is the "slew rate" dV/dt ≈ Signal/τ_{rise}

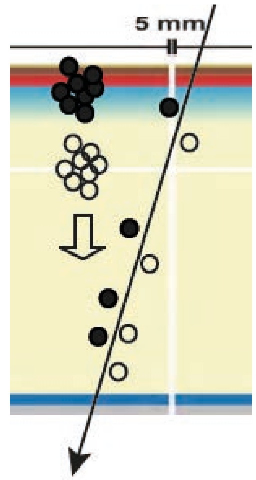
$$\sigma_t^2 = \underbrace{\left(\frac{V_{th}}{dV/dt}\bigg|_{rms}\right)^2}_{\text{signal time walk}} + \underbrace{\left(\frac{\text{Noise}}{dV/dt}\right)^2}_{\text{noise time jitter}} + \underbrace{\left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2}_{\text{TDC binning}}$$

TDC binning can be made negligible

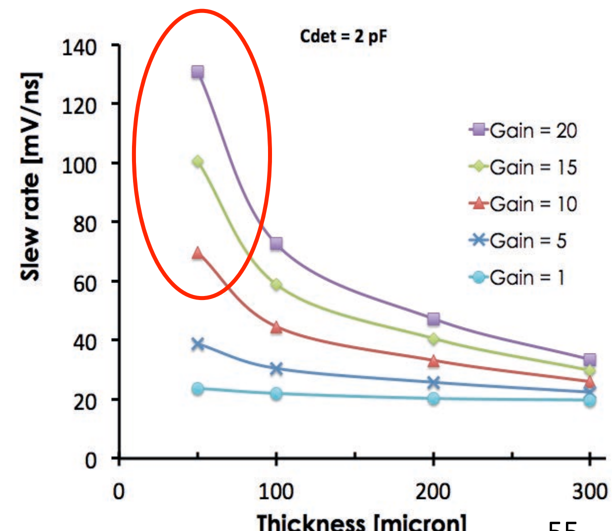


Need: fast drift - large signals – low noise

- e- drift in sat. (E = 20 kV/cm, $v_D \approx 10^7$ cm/s) => HV
- collect electrons fast => thin
- get large signals => from amplified holes (!)
- small C, small i_{leak}, low noise => small electrodes
- broad-band (non-CSA) amplifier & e.g. CF discr.



$$i_S = q\vec{E}_w \cdot \vec{v}$$

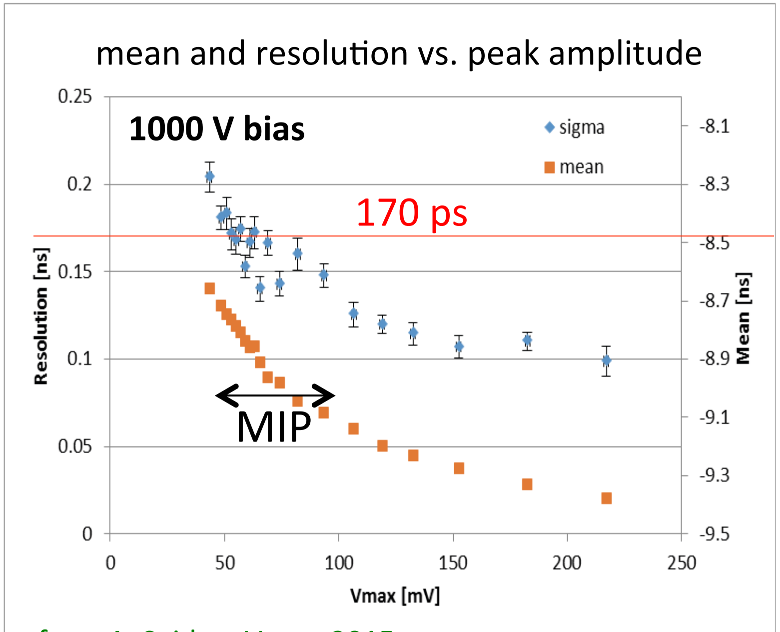


- ❑ Ultimate Goal: simultaneous space (~10µm) and time resolution (< 50 ps) -> pile-up killer
- ❑ Options for ATLAS (HighGranularityTimingDetector; Forward) and CMS-TOTEM (in Roman Pots)

LGAD – development starting with PAD detectors

universitätbonn

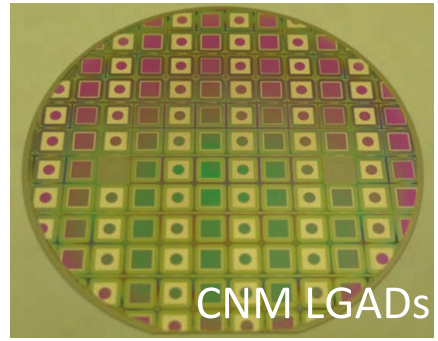
- LGAD pad detectors



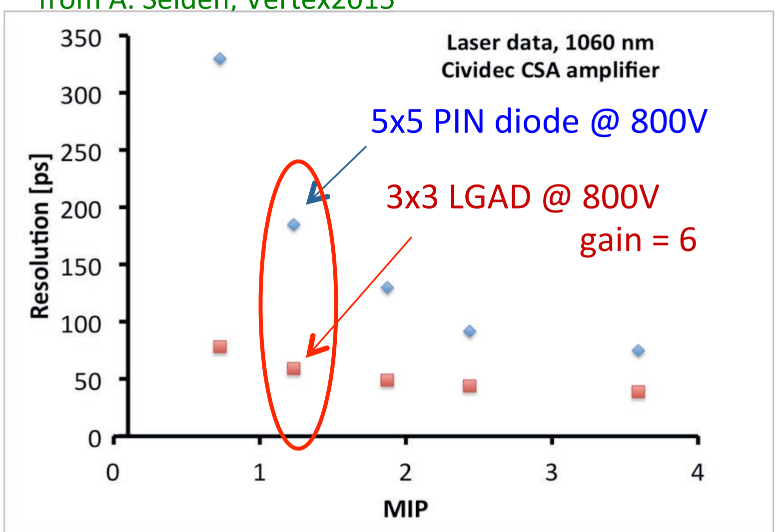
from A. Seiden, Vertex2015

<= CNM 8x8 mm^2
300 μm thick, 11 pF

in 120 GeV pion beam

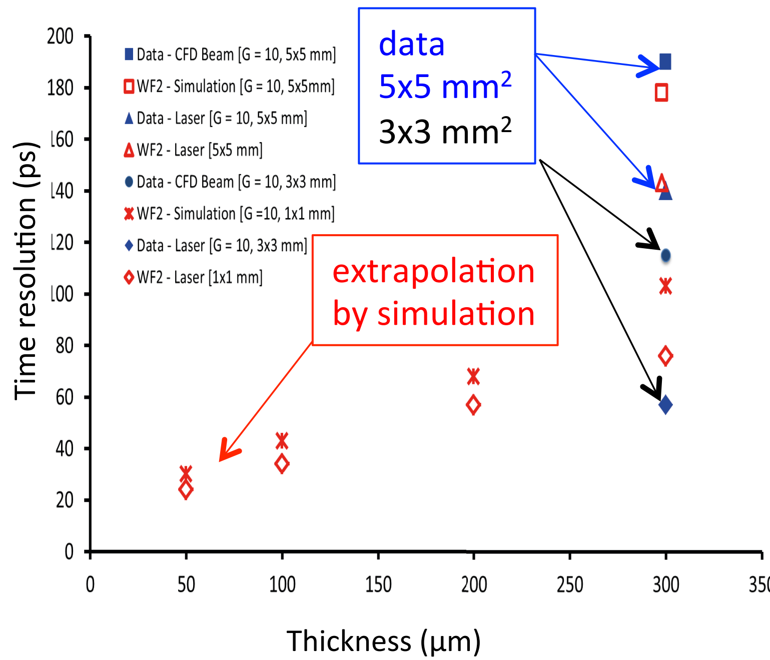


G. Pellegrini et. al, NIM A 765 (2014) 12–16.
G. Pellegrini et al., HSTD 2015, arXiv:1511.07175



<= CNM 3x3 mm^2
300 μm thick, 3 pF

in Laser Setup



End of Lecture 2

Further Reading

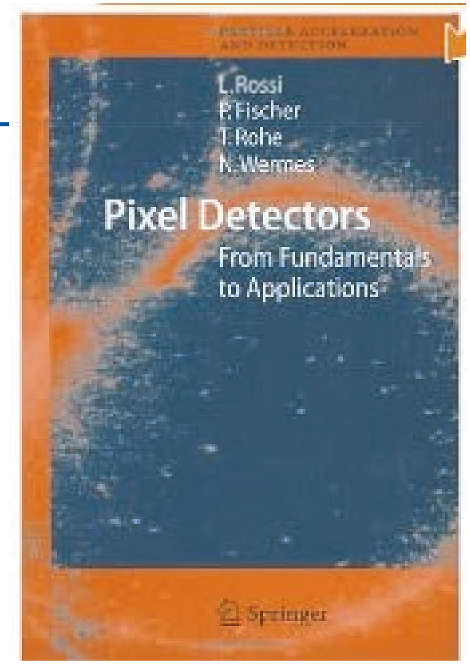
- ATLAS Experiment at LHC, JINST 3 (2008), S08003.
  ATLAS Pixel Detector, JINST 3 (2008), P07007
  CMS Experiment at LHC, JINST 3 (2008), S08004
  CMS Tracker Technical Design Report, CERN/LHCC/98-6 (1998)
  ALICE Inner Tracker System, Technical Design Report, CERN/LHCC/99-12 (1999)

- G. Lutz, "Semiconductor Radiation Detectors",
  Springer Berlin-Heidelberg-New York, 1999.

- Rossi, Fischer, Rohe, Wermes,
  "Pixel Detectors: From Fundamentals to Applications",
  Springer Berlin-Heidelberg-New York, 2006, (ISBN 3-540-283324)

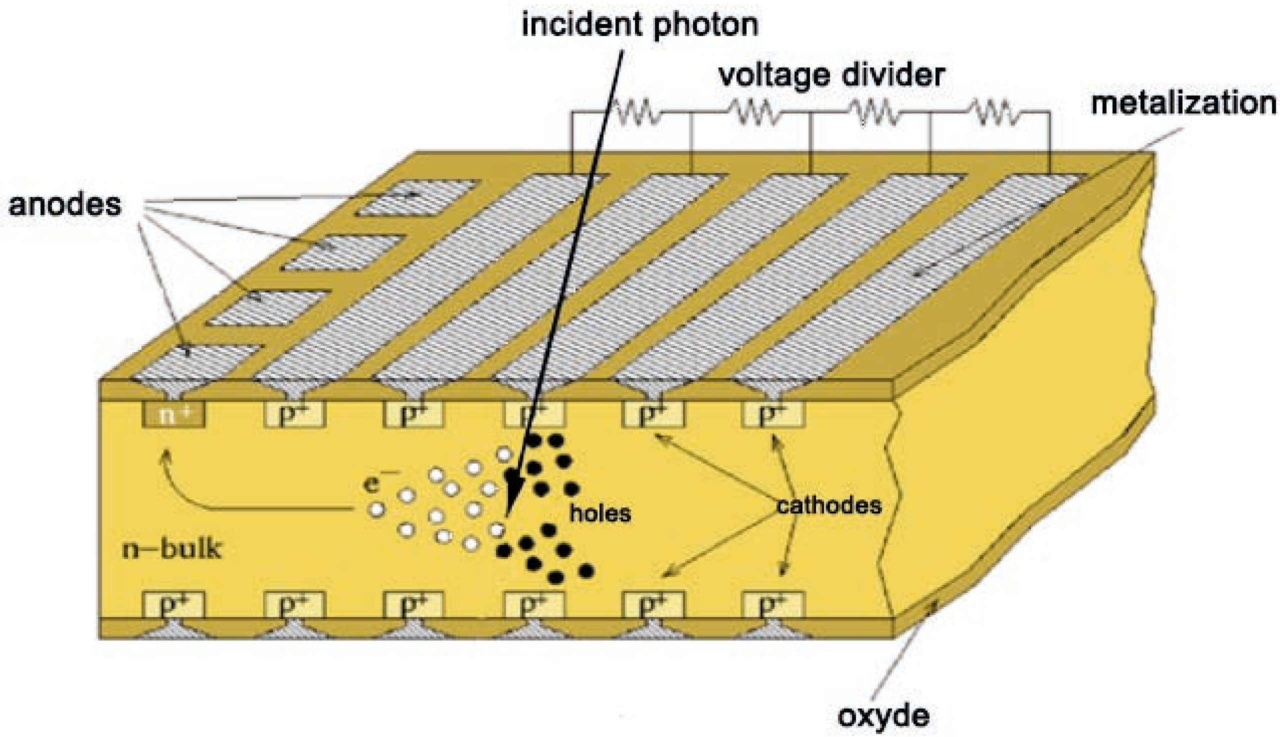
- Leroy, C.; Rancoita, P.-G.: Silicon Solid State Devices and Radiation Detection.
  Singapore: World Scientific, 2012

- H. Kolanoski , N. Wermes
  Teilchendetektoren – Grundlagen und Anwendungen, Springer, (2016)
  Particle Detectors – Fundamentals and Applications, English Edition 2017



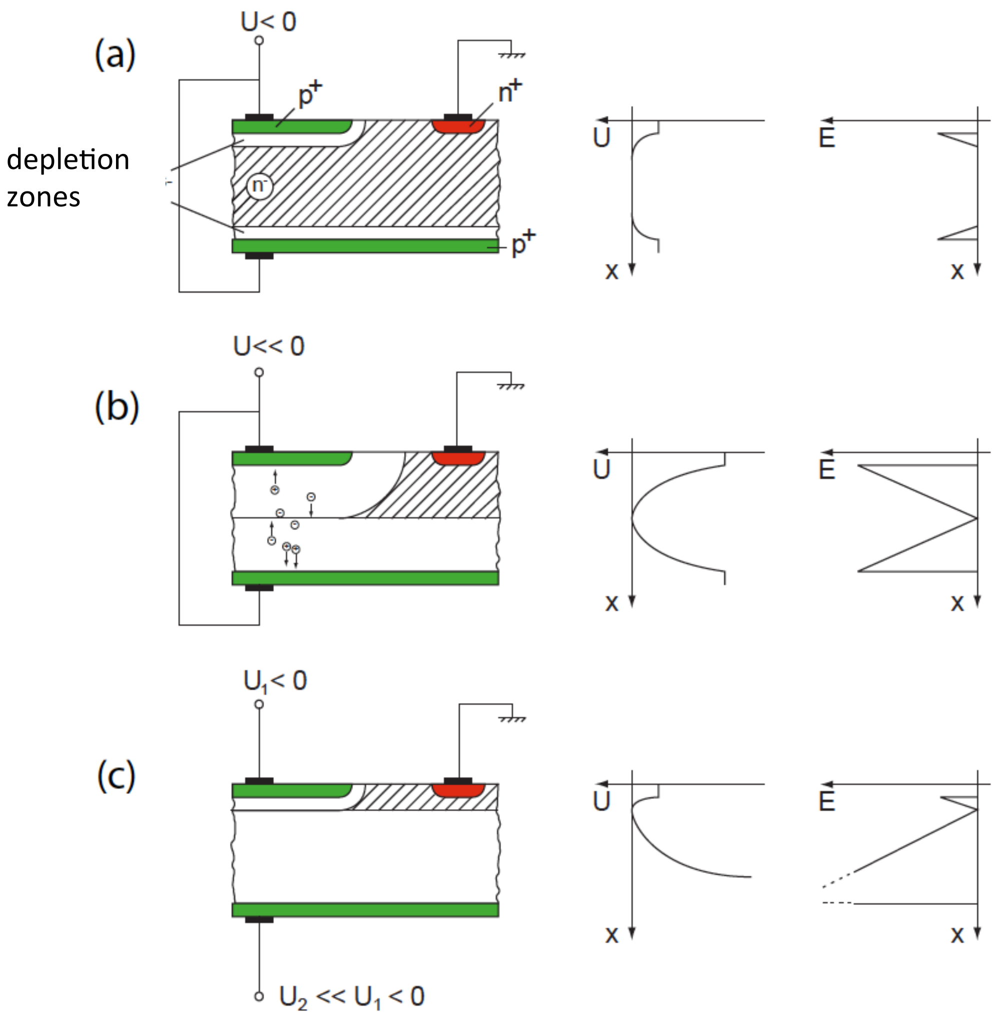
Backup

The silicon drift chamber



The principle of sidewards depletion

Gatti, Rehak (1984)



$$\frac{\partial^2 \phi}{\partial x^2} = -\frac{\rho}{\epsilon_0 \epsilon_r}$$

1-dim.
Poisson Equation

with boundary condition

$$\phi(x = -\tfrac{d}{2}) = \phi(x = \tfrac{d}{2}) = U_0(z)$$

$$\phi(x,z) = U_0(z) - \frac{\rho}{2\epsilon_0\epsilon_r}\left(x^2 - \frac{d^2}{4}\right)$$

quadratic potential for electrons

The silicon drift chamber principle

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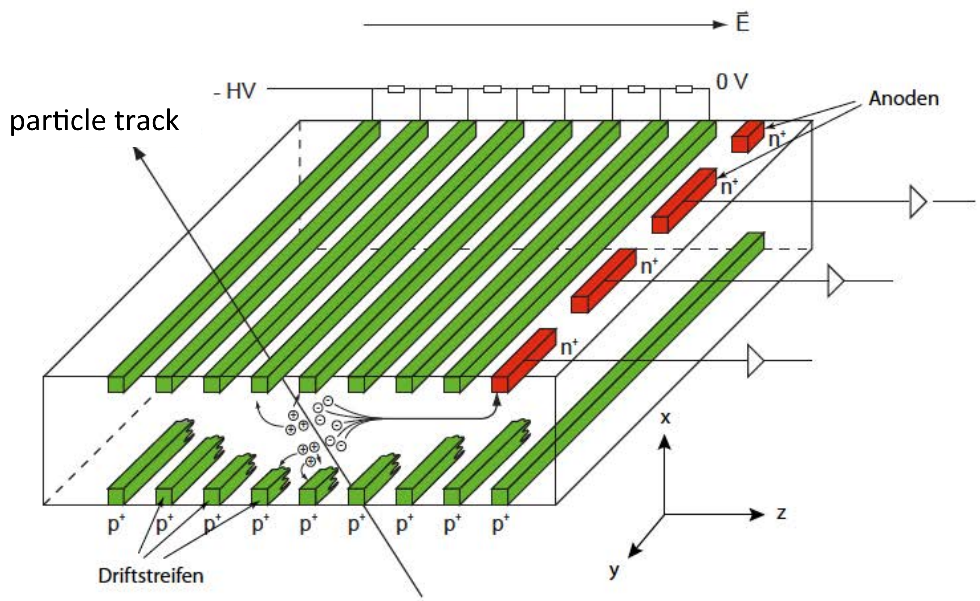
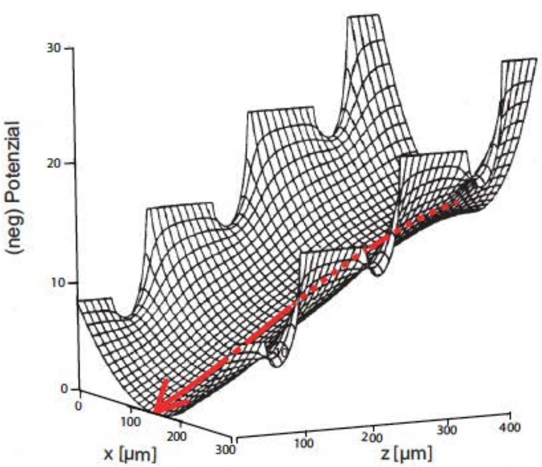
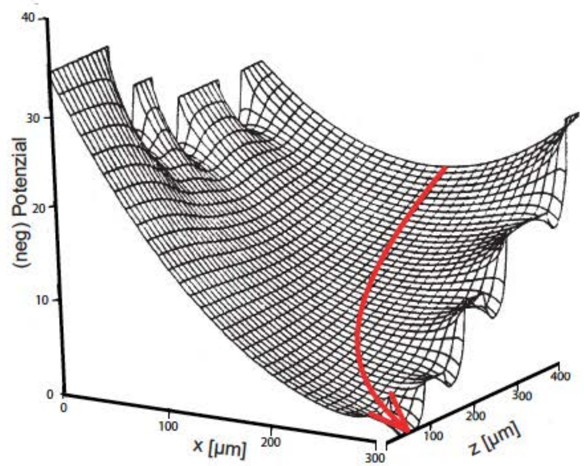


Si Drift Chamber Principle

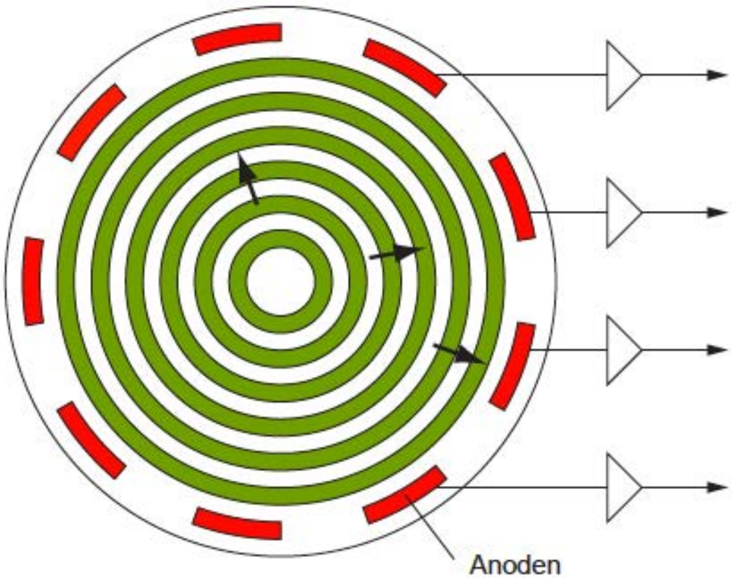


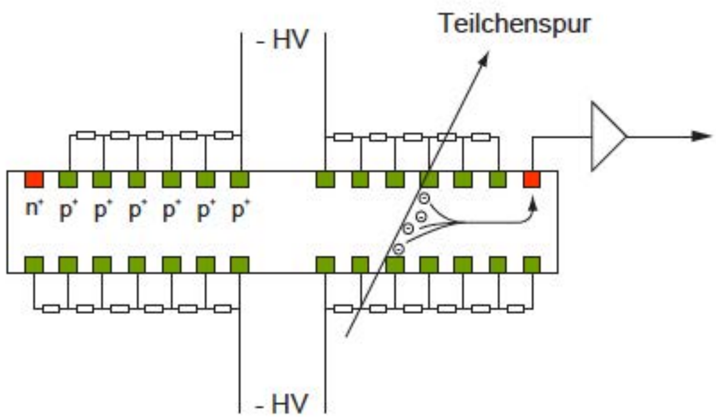


- ❑ add a linear potential gradient on top of the parabolic potential
- ❑ in anode region "push" electrons to anode electrodes
- ❑ PROS
  - 2-dim high resolution (typ. <50µm) readout w/ only few R/O electrodes
  - very good 2-particle separation
- ❑ CON
  - drift times typ. ~µs => not useful for high rate exp.
- ❑ application: Heavy Ion Experiments

Heavy Ion Experiment CERES/NA45

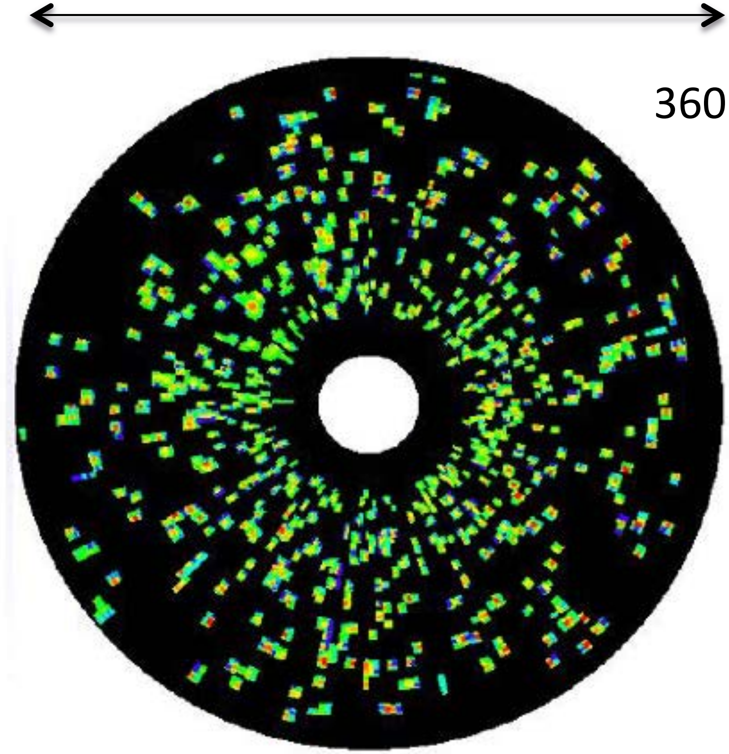
schematic only

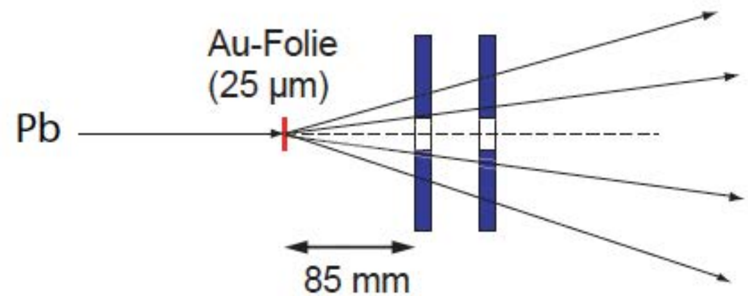




6.4 cm

360 anodes





only 360 R/O anodes (every 1°)

Silicon Drift Chamber for Imaging = SD-Diodes

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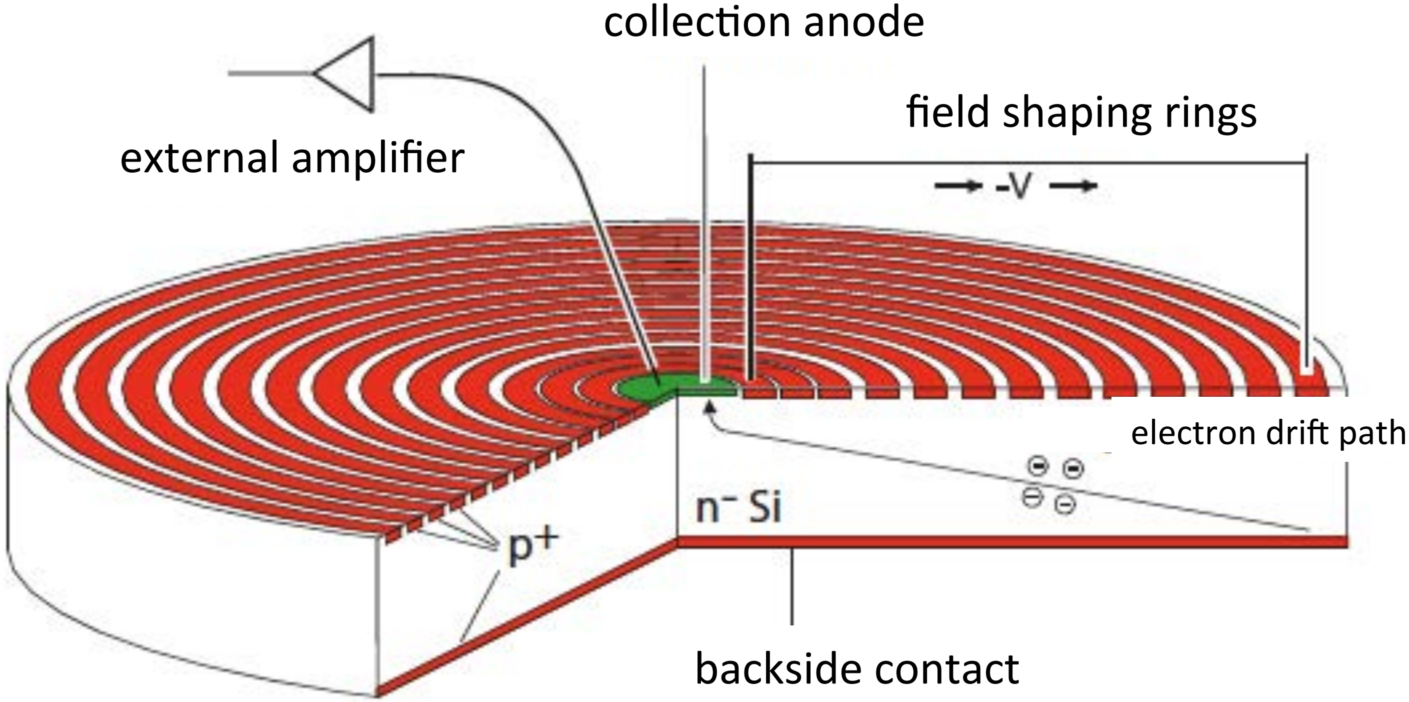
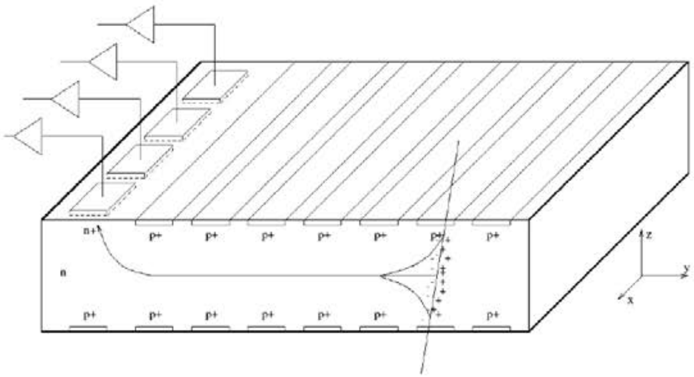
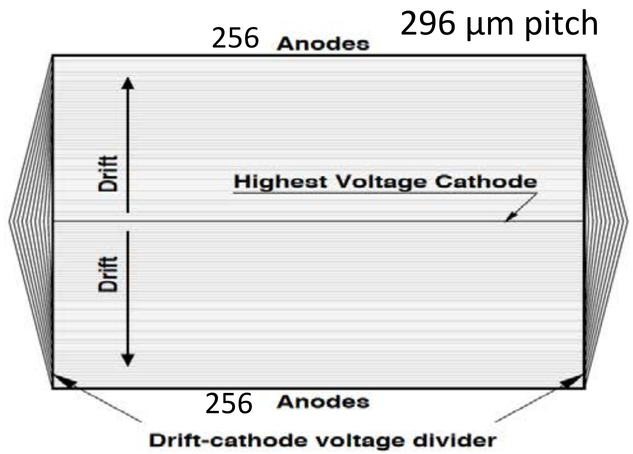
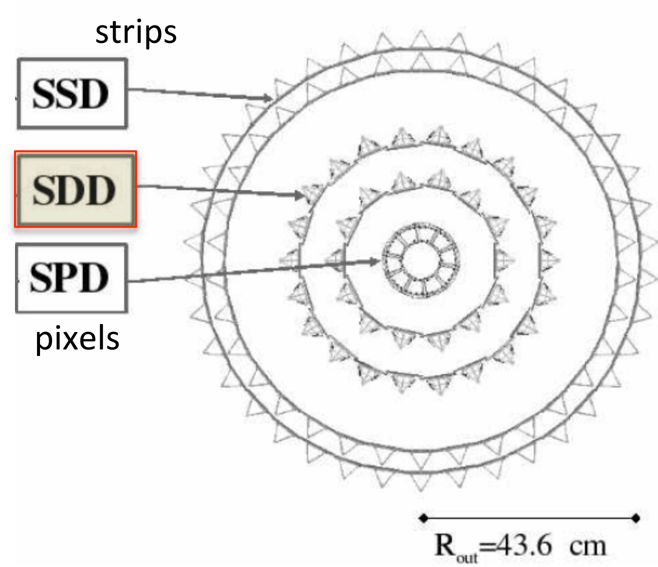
- only **one** anode in center
- small capacitance (10fF) => very low noise (~few e-)
- large sensing area



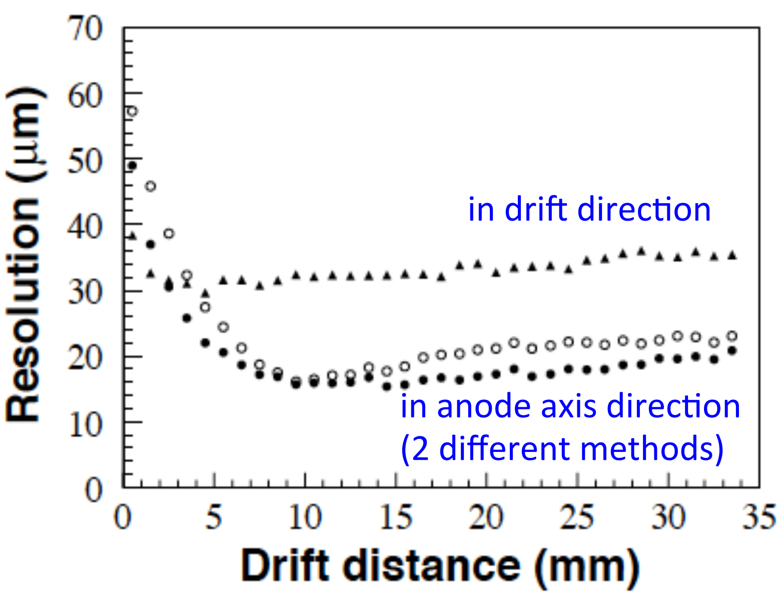
SDCs in ALICE ITS







from B. Alessandro et al., 2010_JINST_5_P02008



D. Nouais et al., NIM A501 (2003) 119–125