Pixel Vertex Detectors

N. Wermes
Bonn University

Outline

1. **Introduction**

   From gas-filled chambers to pixel vertex detectors

2. **Hybrid Pixel Detectors for the LHC**

   The Signal and the Noise in Pixel Detector

3. **Making a Pixel Detector**

   From sensor to module-ladder

4. **Pixel R&D for Future Colliders (addendum)**

   New developments for the ILC

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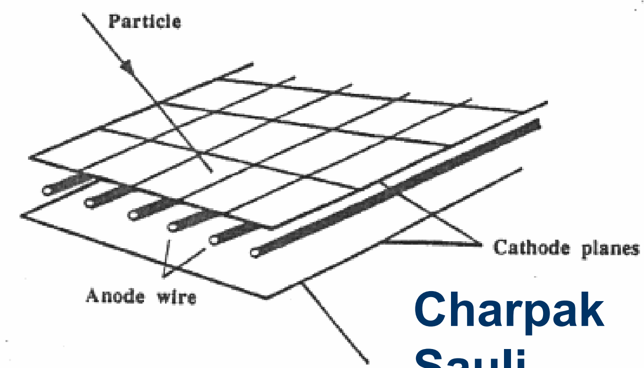
Introduction

important advances in tracking through …

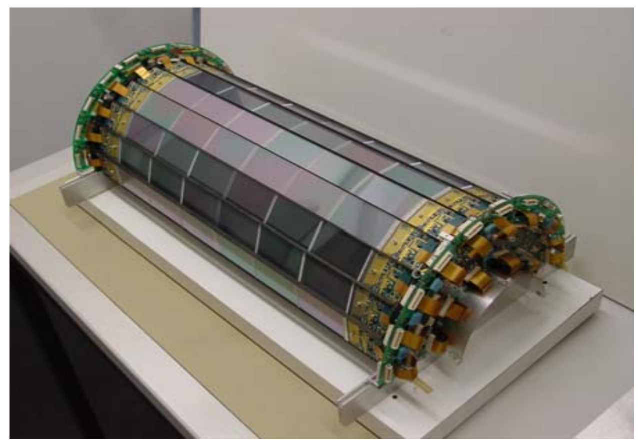
- multi-wire proportional chambers (1968) and drift chambers (>1972)
  - → electronic recording of tracks
  - → σ = mm - 100µm, 0.05 channels / cm^2
- vertex drift chambers (~1981)
  - → vertexing, life times of long lived particles
  - → σ ~ 50µm, 0.1 channels / cm^2
- silicon micro strip detectors (1983)
  - → precision vertexing
  - → σ < 10µm, 100 channels / cm^2



Charpak Sauli

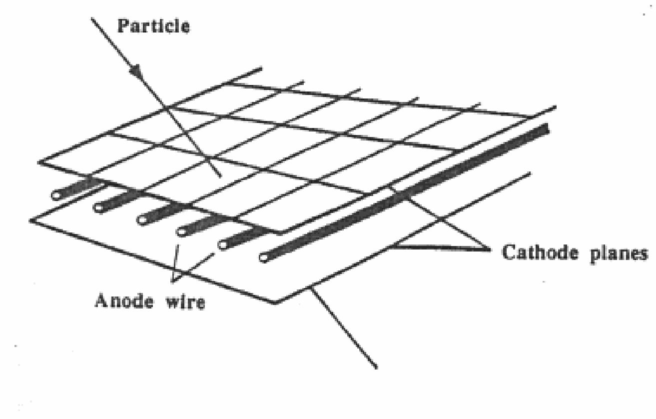
Jaros, Foster, …

Hyams, Weilhammer, Klanner, Lutz



Introduction

important advances in tracking through …



- multi-wire proportional chambers (1968) and drift chambers (~1975)
  - → electronic recording of tracks
  - → σ = mm - 100µm, 0.05 channels / cm^2
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  - → vertexing, life times of long lived particles
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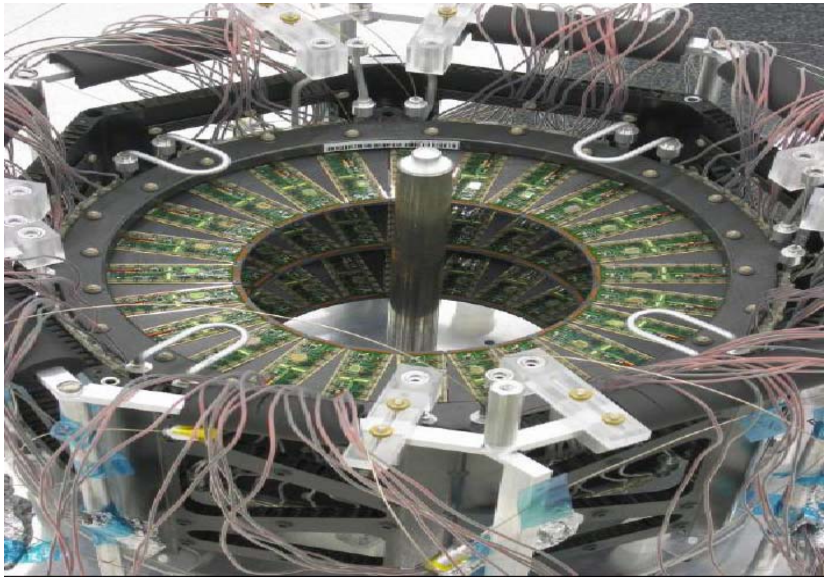
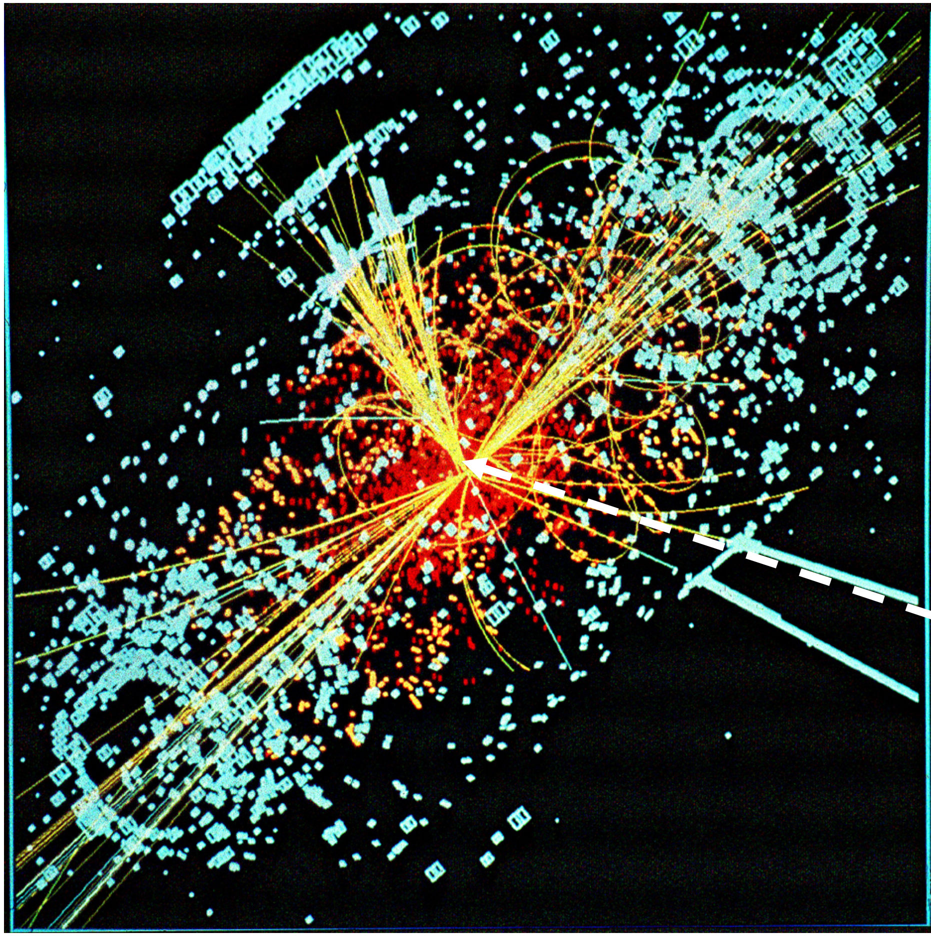
- silicon micro strip detectors (1983)
  - → precision vertexing
  - → σ < 10µm, 100 channels / cm^2
- **pixel detectors** (since ~1993)
  - → tracking and vertexing in LHC environment
  - → σ ~ 10µm, 5000 channels / cm^2



Tracking in pp collisions at 14 TeV (LHC)



~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 the ionisation of
mips in 250 µm bulk silicon

pixel detector
5000 ch/cm^2

LHC ≅ 10^6 x LEP in track rate !

Detection tasks of pixel detectors

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), ~70 µm (z)
- primary vertex resolution ~11µm (rφ), ~45µm (z)
- (life) time resolution ~70 fs
- (vertex counting → luminosity measurement)

3. Momentum measurement [1)]

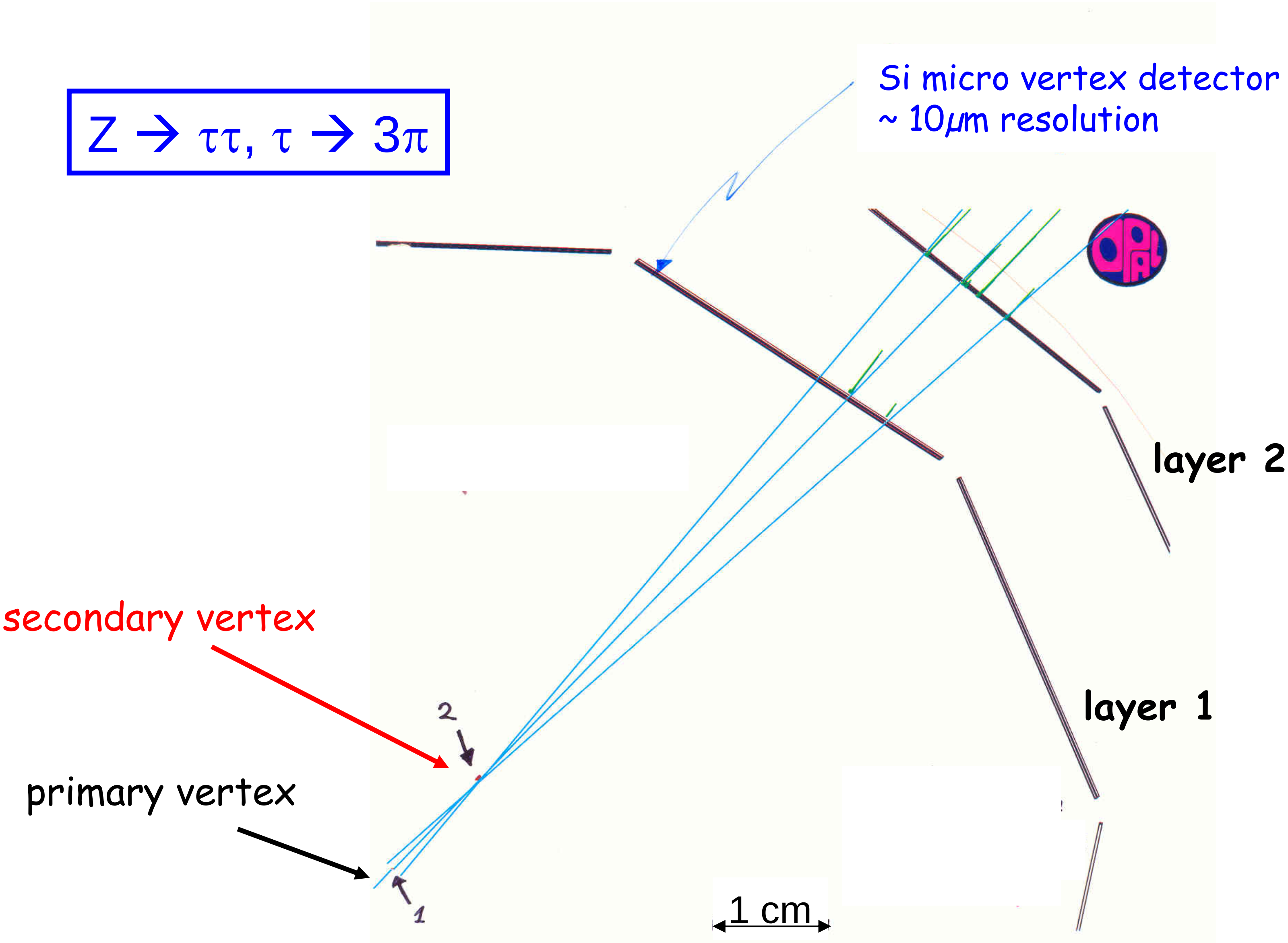
$$\frac{\sigma_{p_T}}{p_T} = 0.03\%\ p_T(\mathrm{GeV}) \oplus 1.2\%$$

(inner detector)

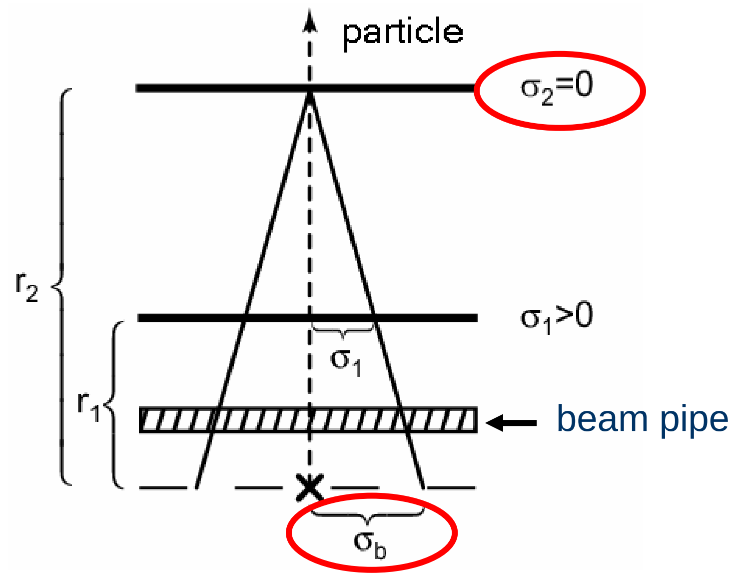
[1)] values for ATLAS

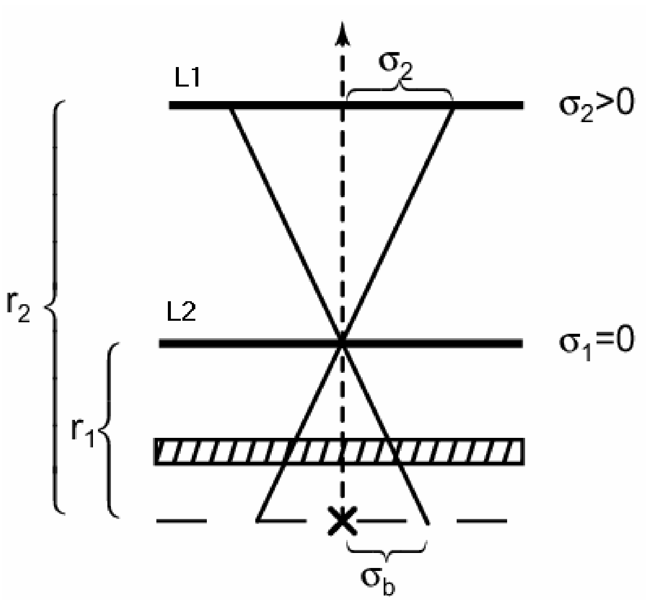
Vertexing at LEP …

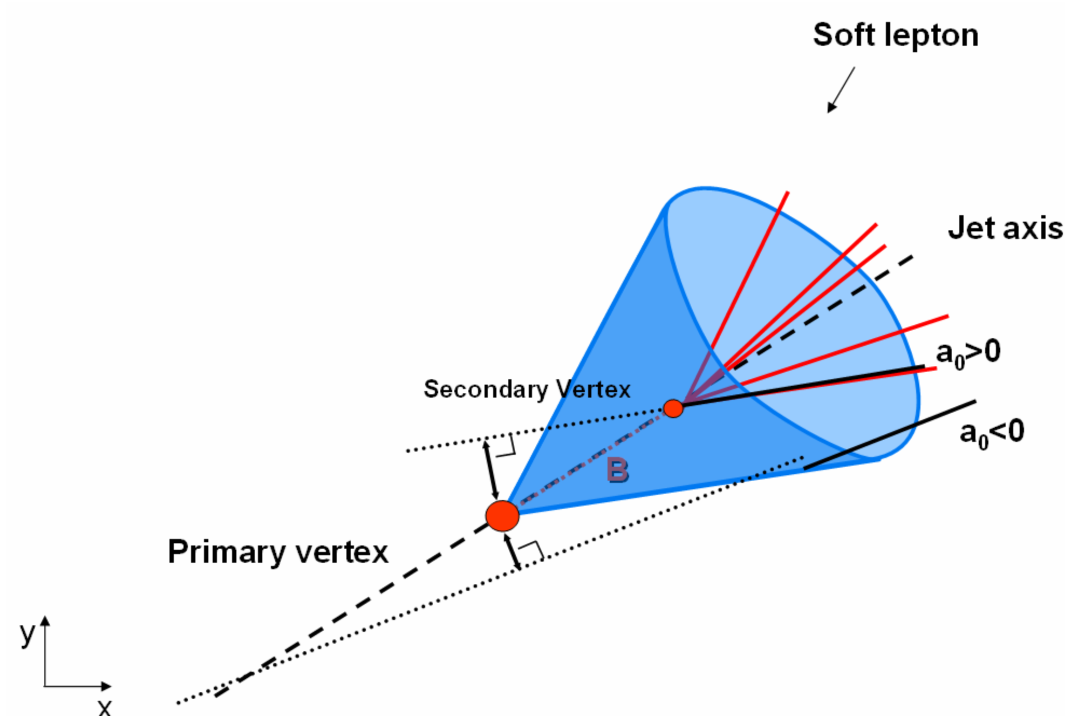
Z → ττ, τ → 3π



Impact parameter resolution (simplified)







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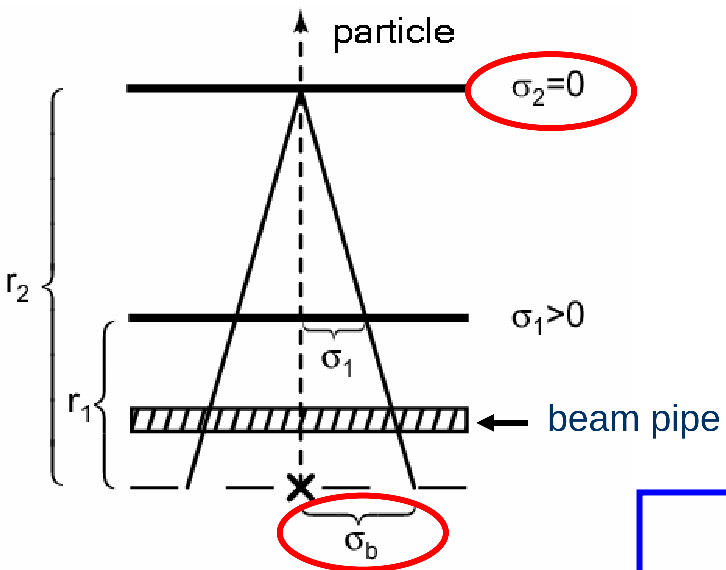
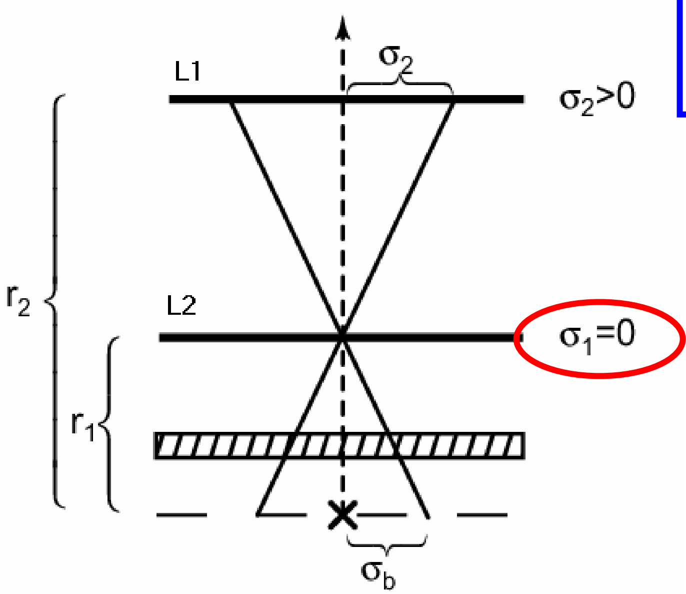


$$\frac{\sigma_b}{\sigma_1} = \frac{r_2}{r_2 - r_1}$$

small ! small !

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



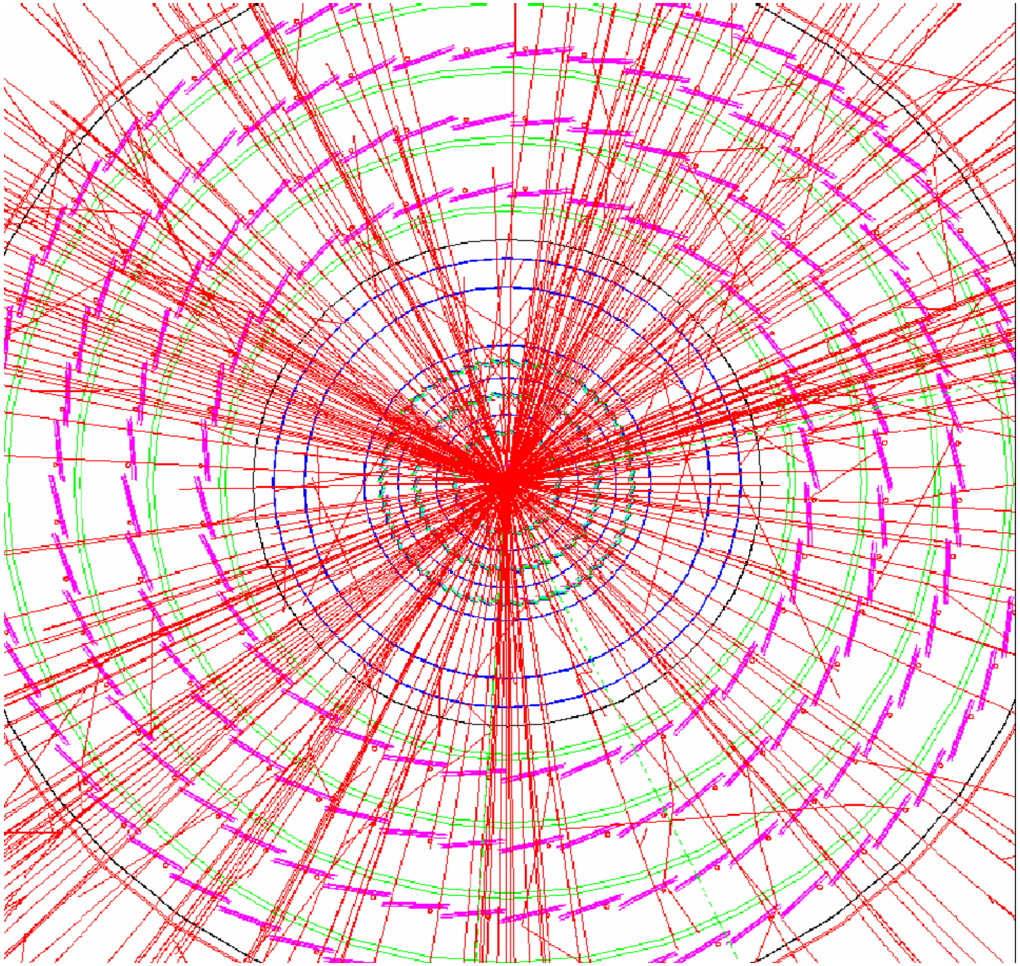
$$\frac{\sigma_b}{\sigma_2} = \frac{r_1}{r_2 - r_1}$$

small x/X_0

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

… compare … vertexing at LHC

pp → ttH (m=120 GeV)
H → bb
tt → W(lνl)b W(qq)b



~ 1200 tracks/BX

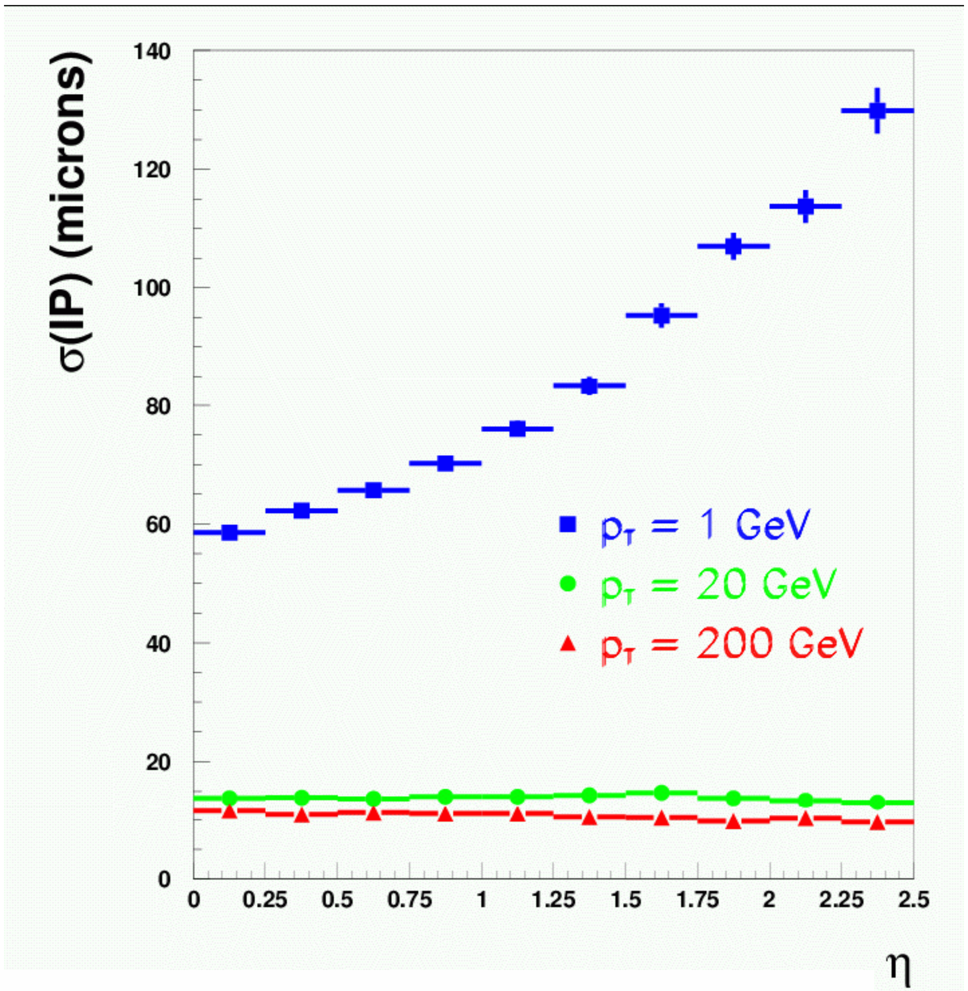
high track density
in particular in jets

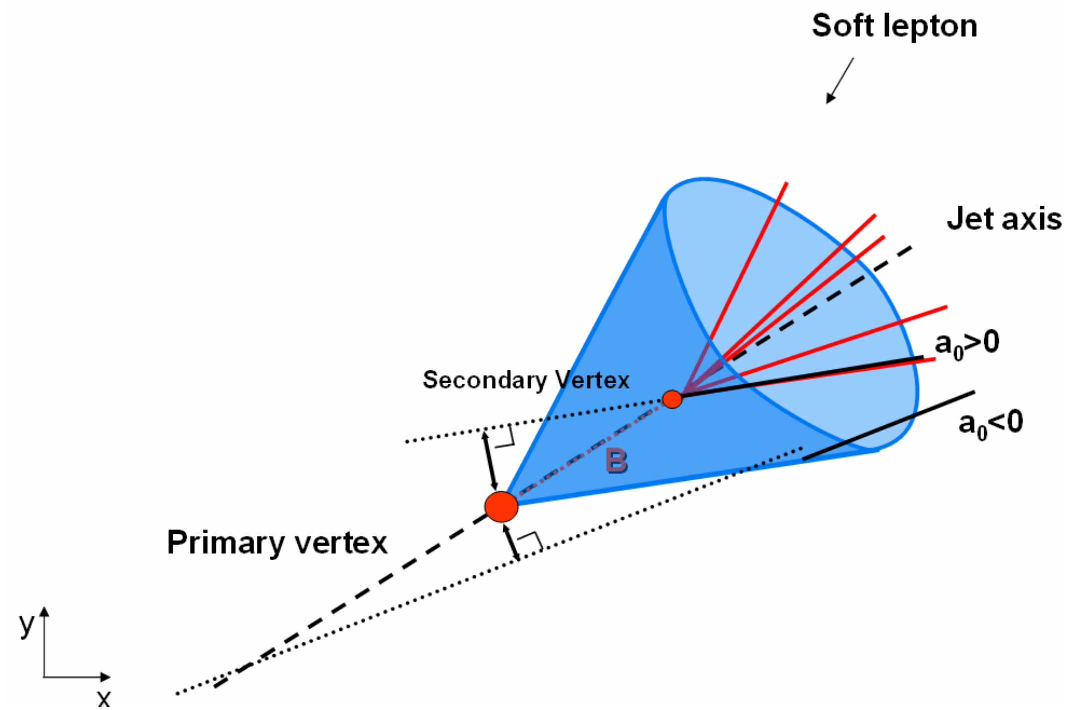
3D hit information
mandatory

⬇

pixels

Expected resolutions (ATLAS)

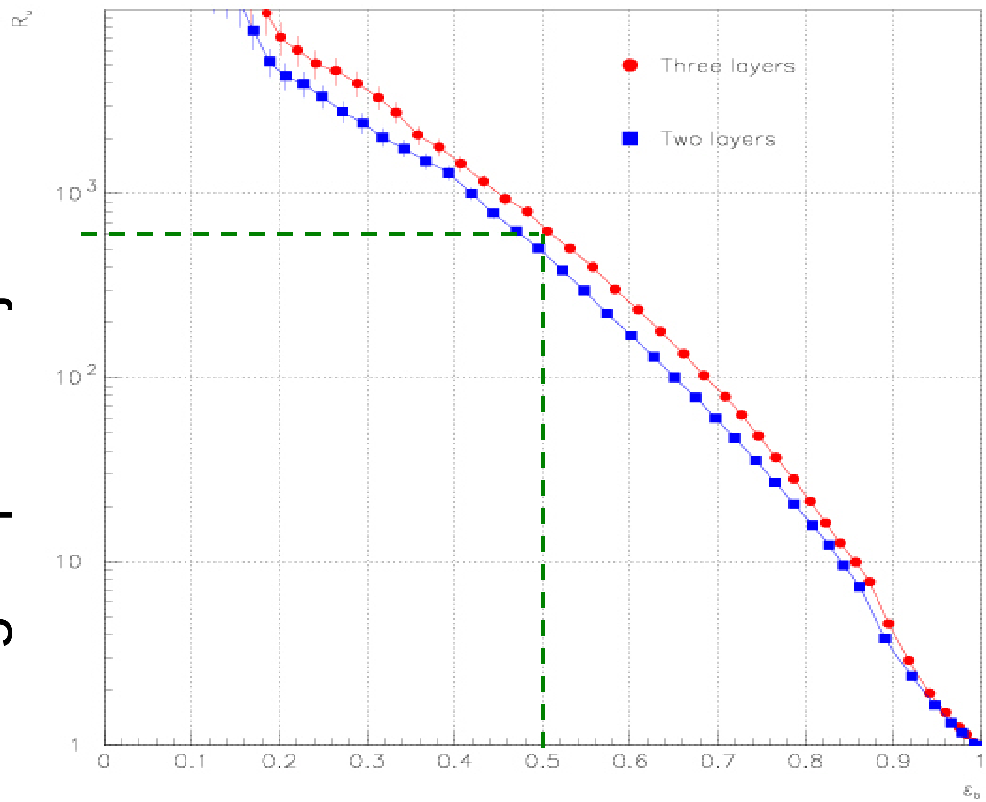




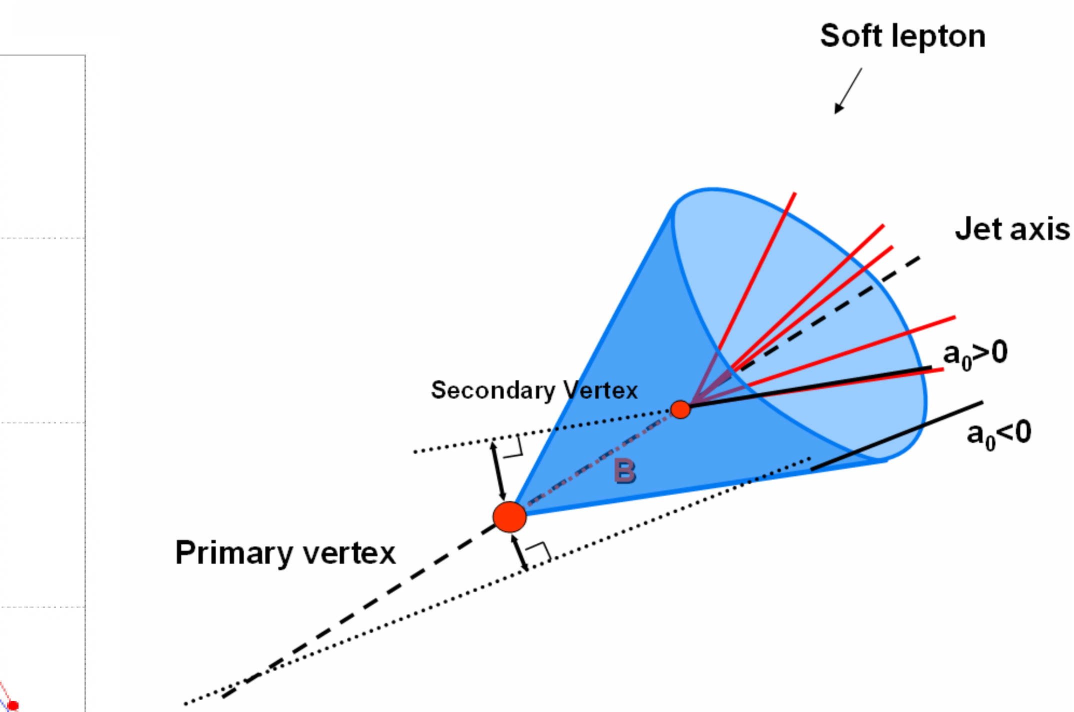
$$\sigma(d_0) \approx 10 \oplus \frac{98}{p_T\sqrt{\sin\theta}}\ \mu\mathrm{m}$$

Expected resolutions (ATLAS)

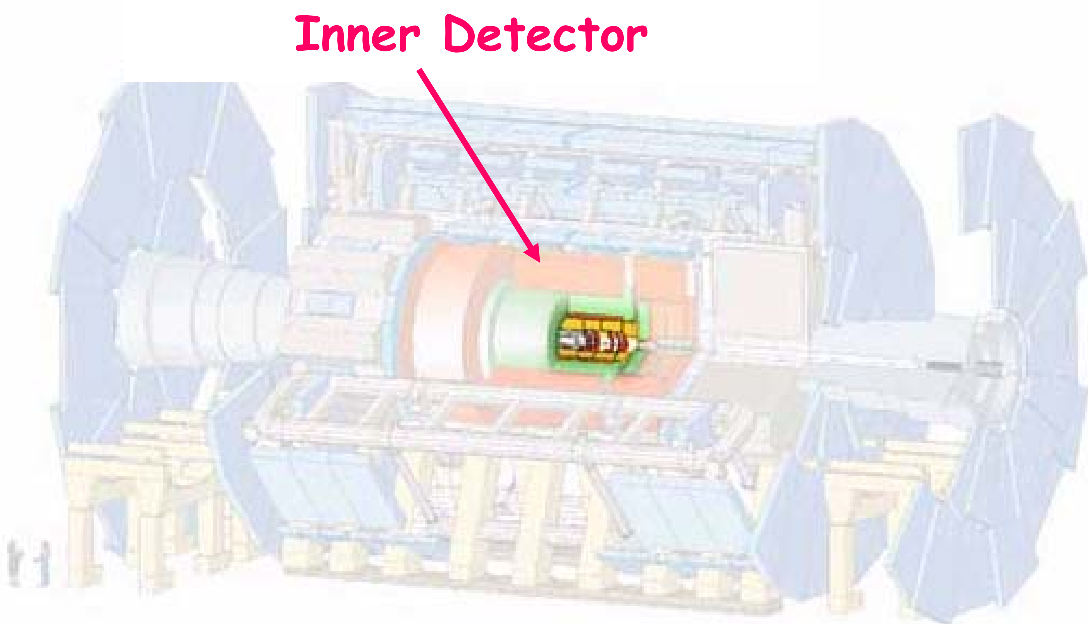
light quark rejection



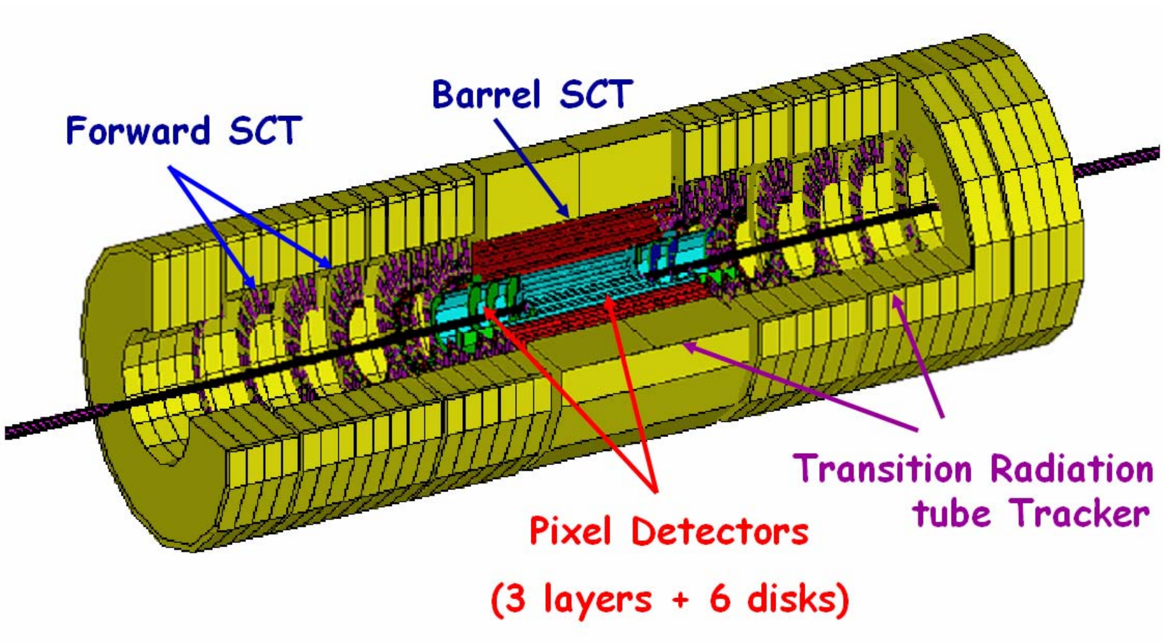
b-tagging efficiency



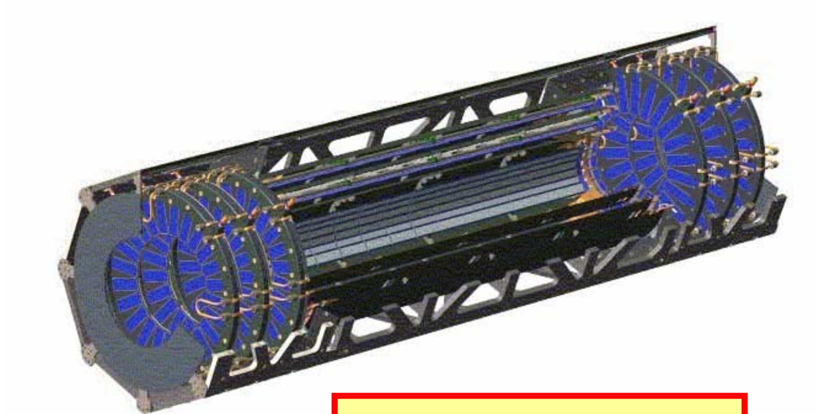
Tracking Detectors: ATLAS



Tracking Detectors: ATLAS



Pixel Detector
(3 layers, 3 disks)



$50 \times 400\ \mu m^2$ cells
80×10^6 pixels

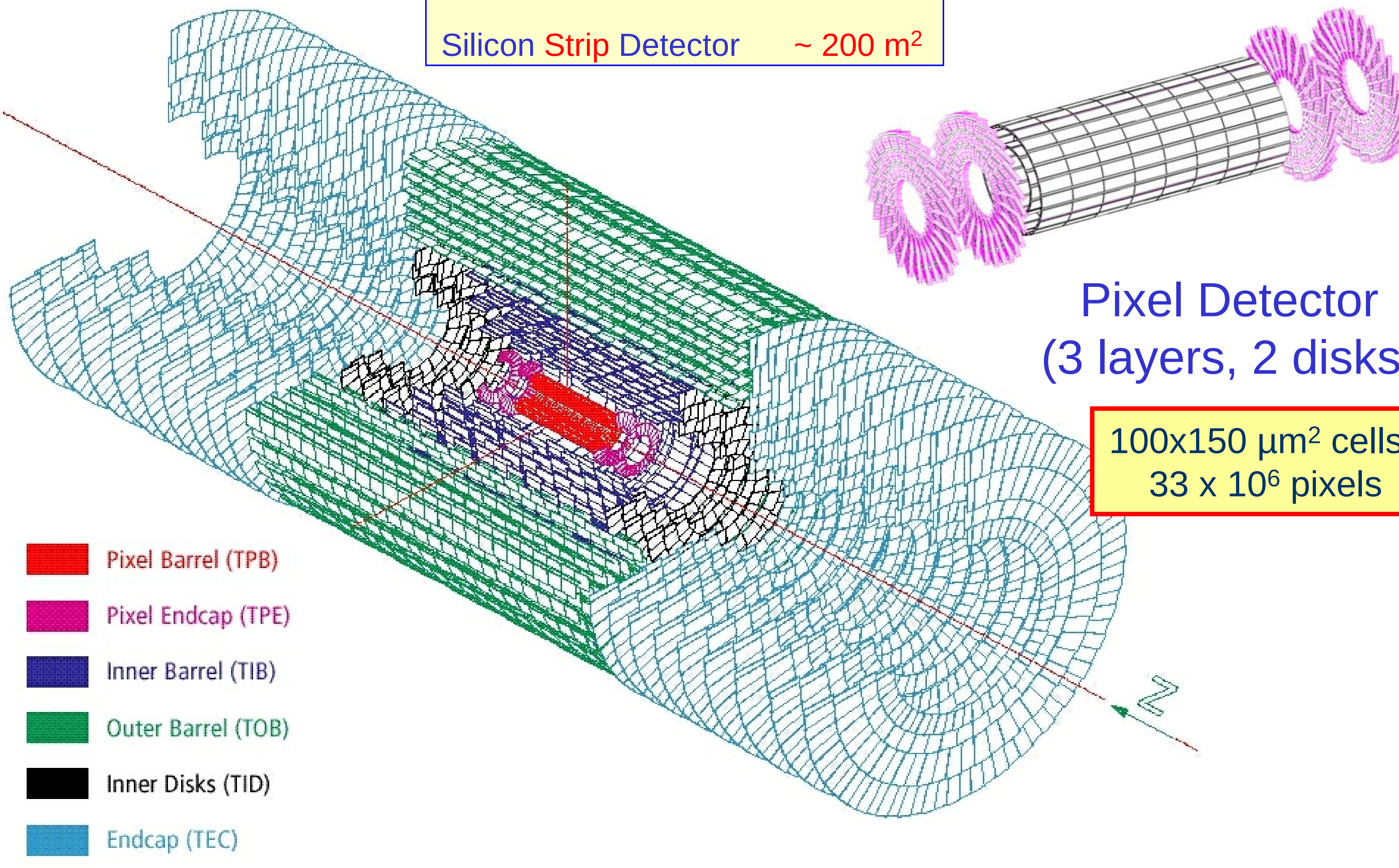
	points	σ (Rφ) (μm)	σ (Rz) (μm)
pixel	3	12	60
SCT	4	17	580
TRT	36	170	-

Silicon Pixel Detector	~ 1.8 m^2
Silicon Strip Detector	~ 60 m^2
Transition Radiation Tracker	~ 300 m^2_{eq}

Tracking Detectors: CMS

Silicon Pixel Detector ~ 1 m^2

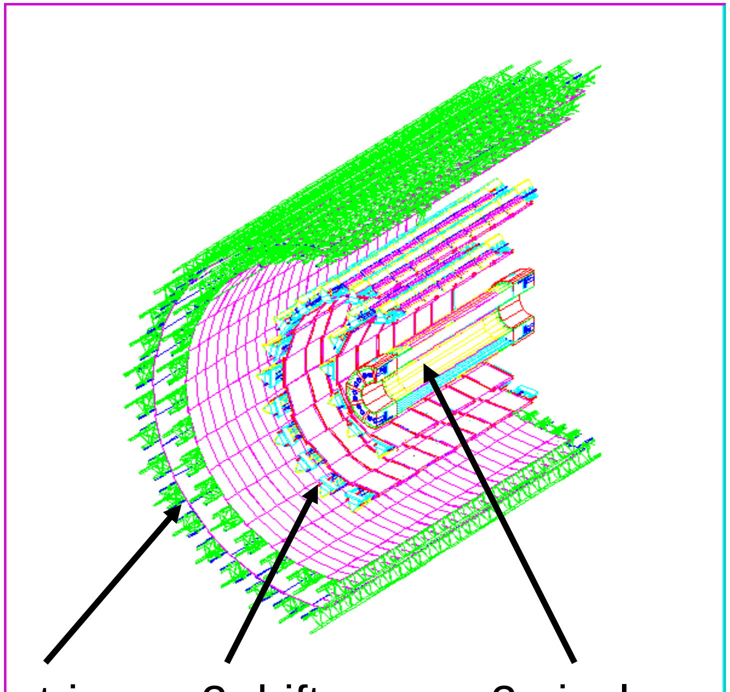
Silicon Strip Detector ~ 200 m^2

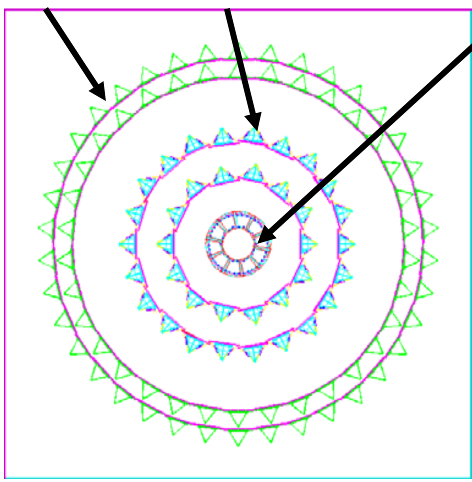


Pixel Detector
(3 layers, 2 disks)

100x150 μm^2 cells
33 x 10^6 pixels

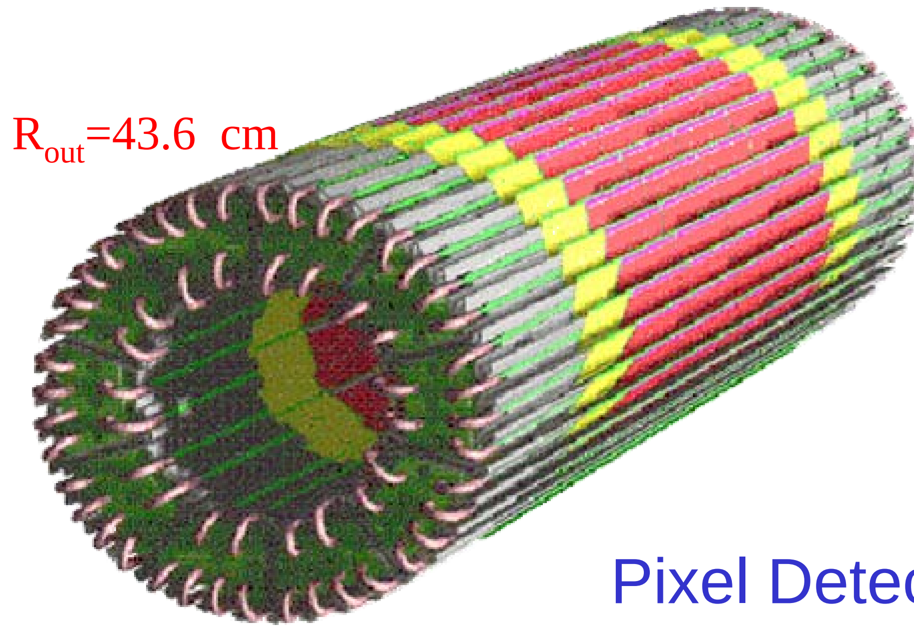
Inner Tracking Detectors: ALICE





+ TPC

Silicon Pixel Detector	~ 0.2 m^2
Silicon Drift Detector	~ 1.3 m^2
Silicon Strip Detector	~ 4.9 m^2



Pixel Detector
(2 layers, no disks)

50x450 μm^2 cells
10 x 10^6 pixels

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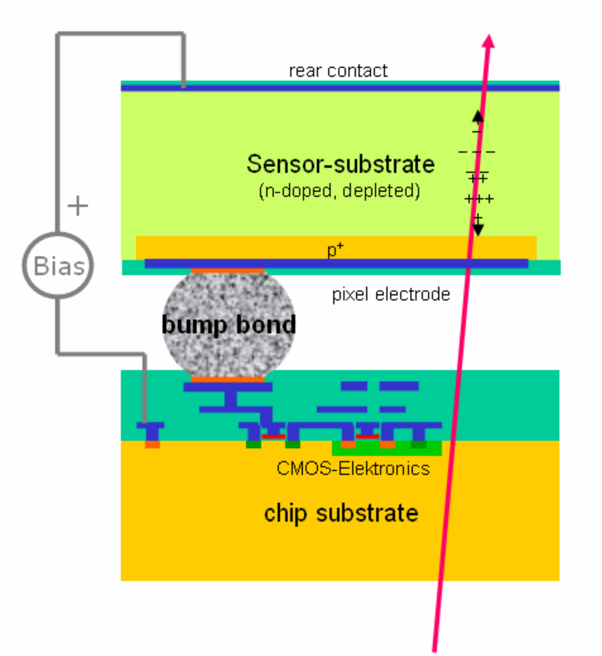
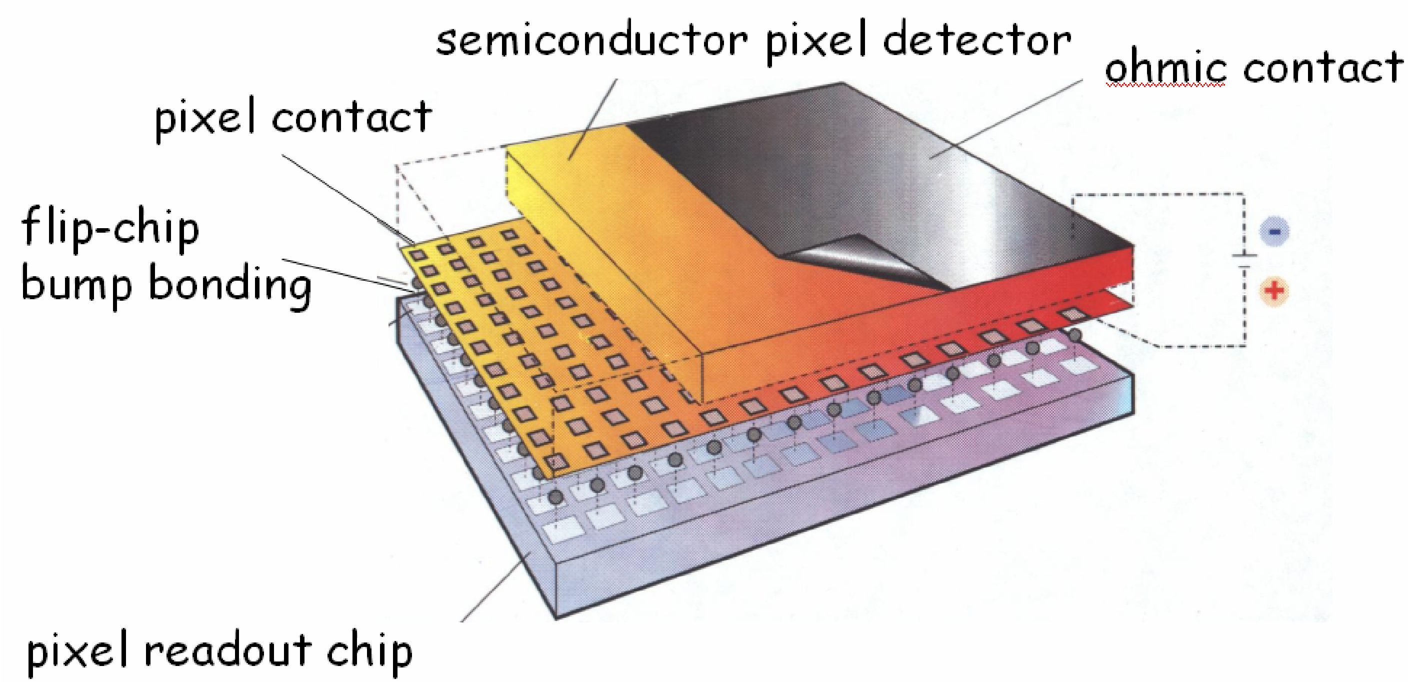
Hybrid Pixel Detectors for the LHC



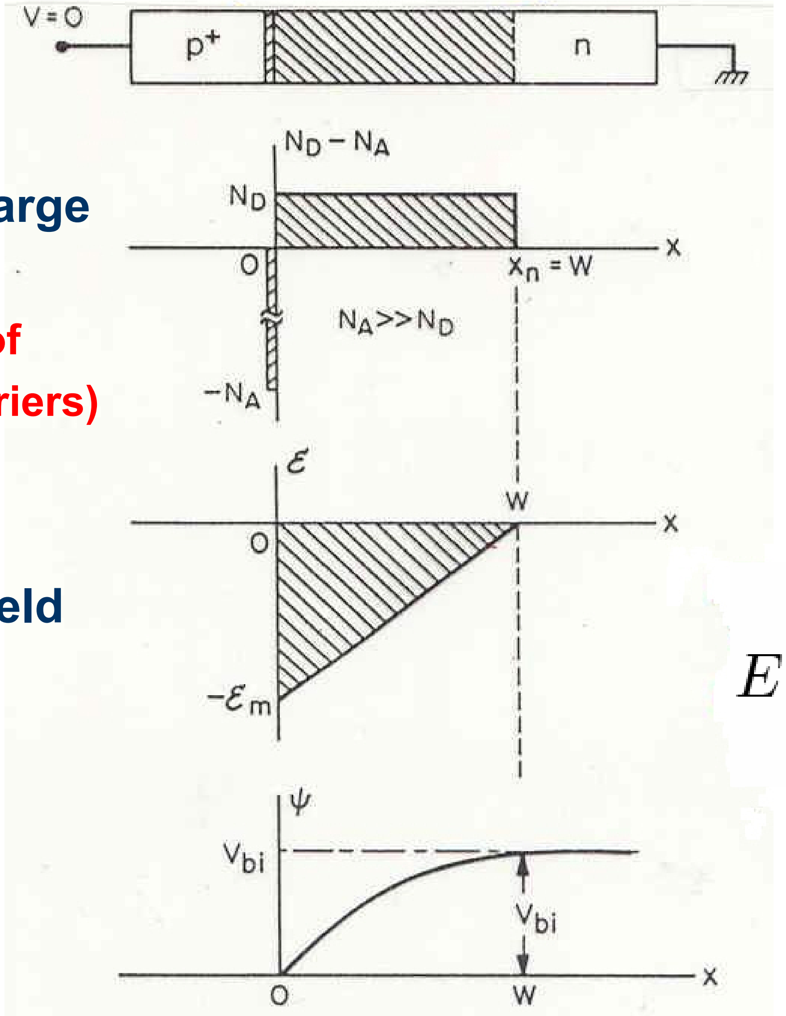
Hybrid Pixel Detector (state of the art)



- amplification by a dedicated R/O chip
- 1-1 cell correspondence

The pn junction as a semiconductor particle detector

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 carriers)

Electric field

Potential

reverse biased junction

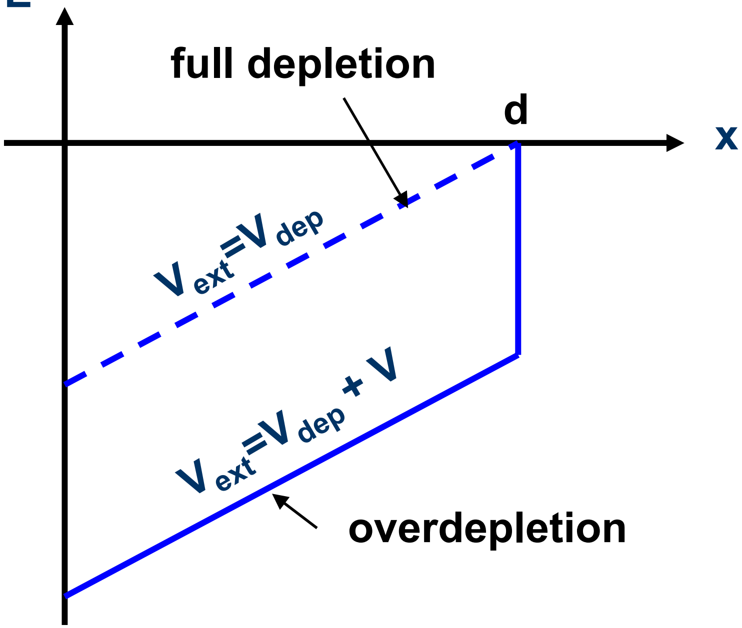
$$N_A x_p = N_D x_n$$ **neutrality condition**

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



$E_{max} = 2V_{ext}/d$

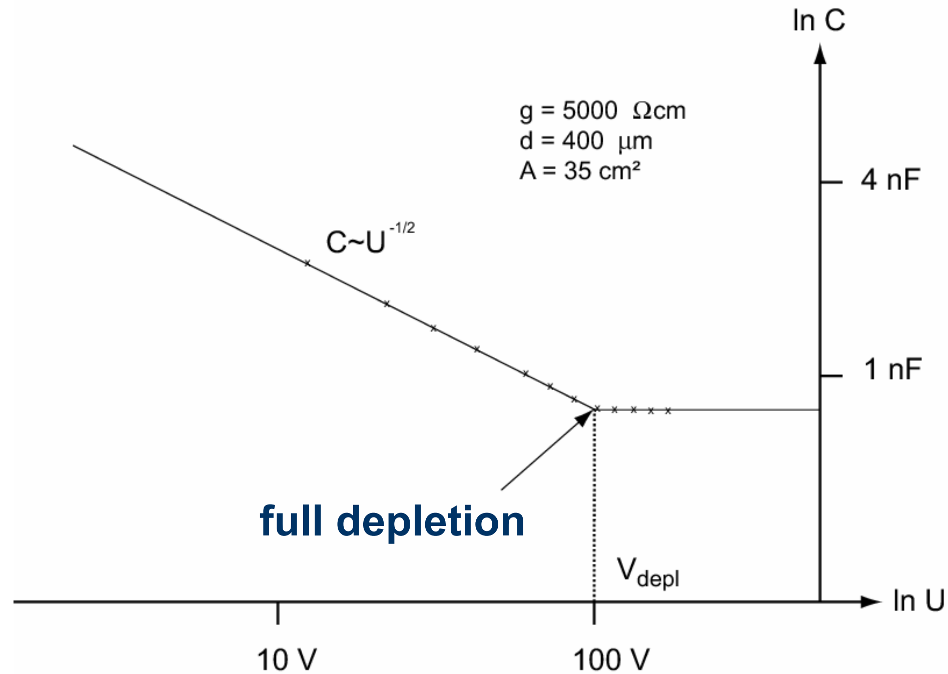
with applied external bias voltage

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

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

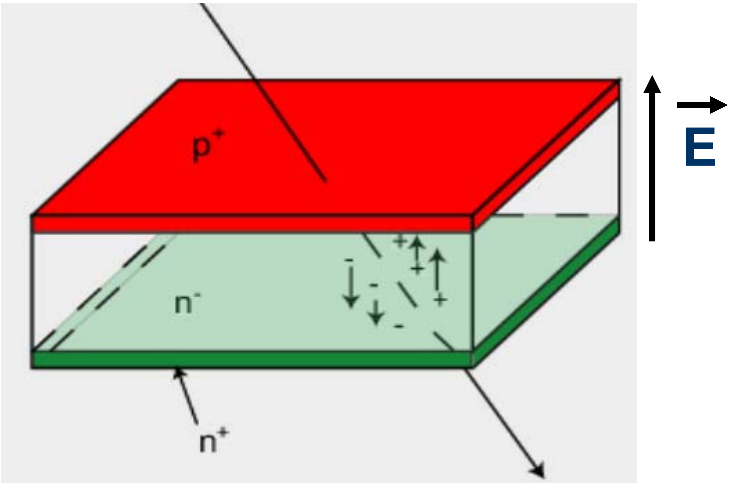
capacitance

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



depletion zone grows from the junction into the lower doped bulk

The Signal and the Noise in pixel detectors



in Si bulk fully depleted
- w_i = 3.61 eV per e/h
- a high energy particle
  → ~ 80 e/h per µm
- all charge is collected
- ~ 20 000 e/h per 250 µm
  = 3 fC

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

created charge carriers (e/h) move in depletion region by

drift $$v_{drift}(x) = \mu E(x)$$

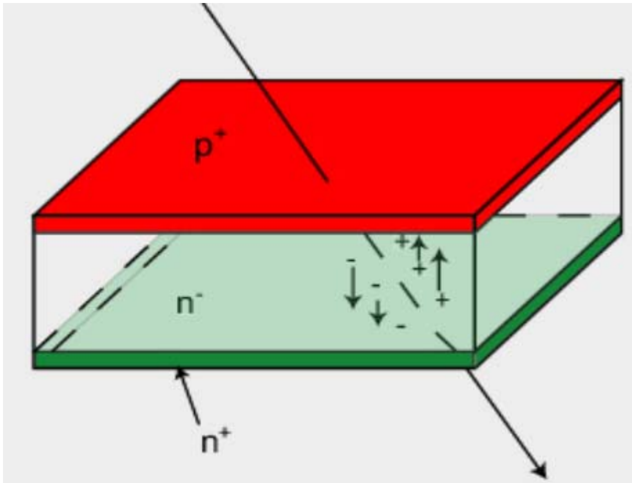
and

diffusion $$\sigma_{diff}(t) = \sqrt{2Dt}$$

typically 8-10 µm in 300 µm Si

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

The Signal and the Noise in pixel detectors



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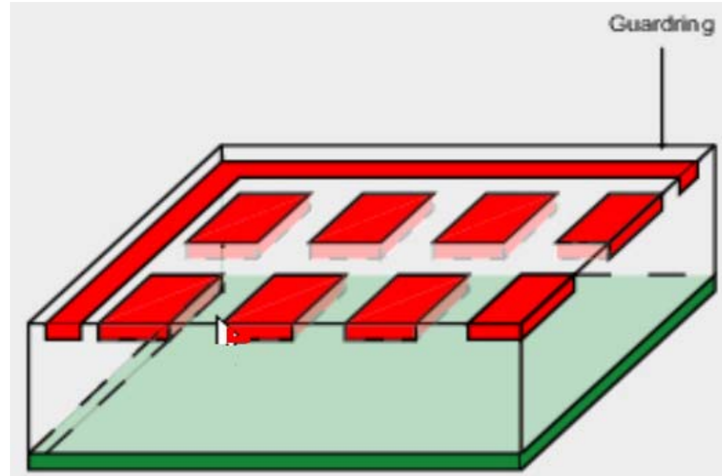
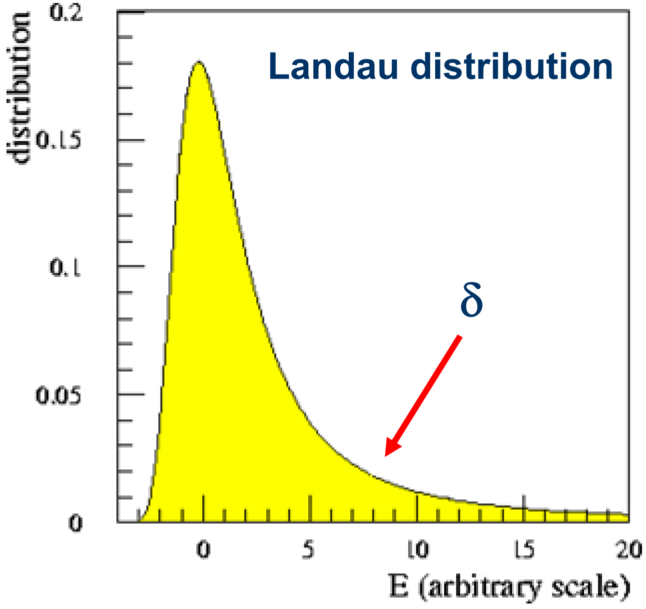


- pixel pattern
- typical cells: 100 x 150 μm^2
  50 x 400 μm^2
- charge diffusion σ ~ 8-10 µm
- → charge spread over 2-4 pixels

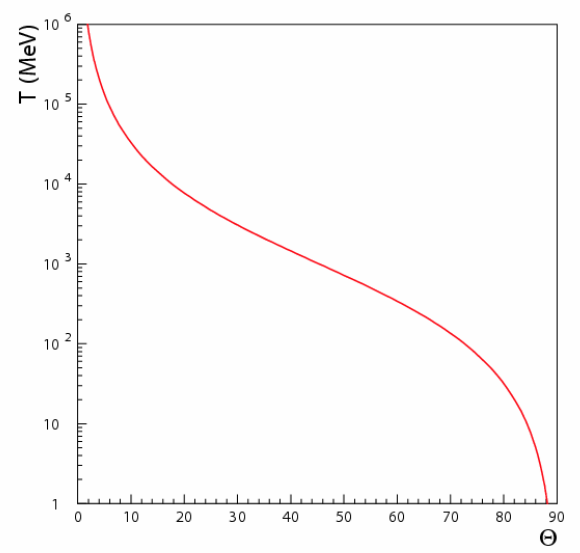
note: photo effect $\sim Z^{4\text{-}5}$
Si → CdTe, CZT, HgI_2, …

Delta electrons



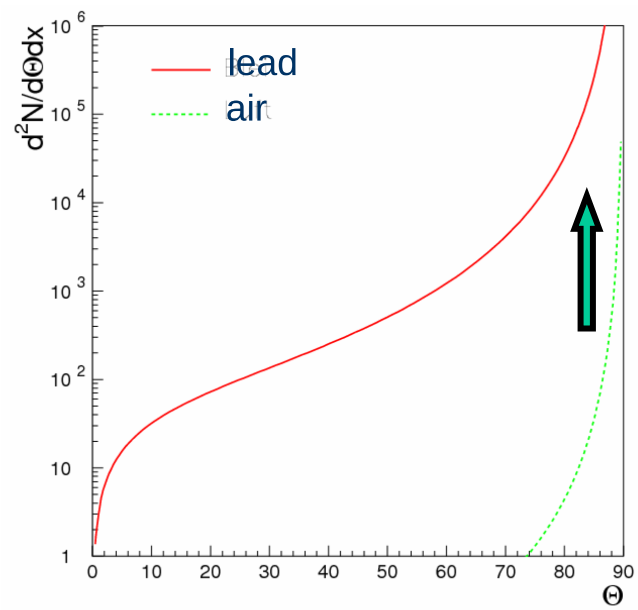
kinematics: 1-1 relation between emission angle and kin. energy

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



slow ones emitted at right angles
→ in 1/β² part of BBF
→ highly ionizing

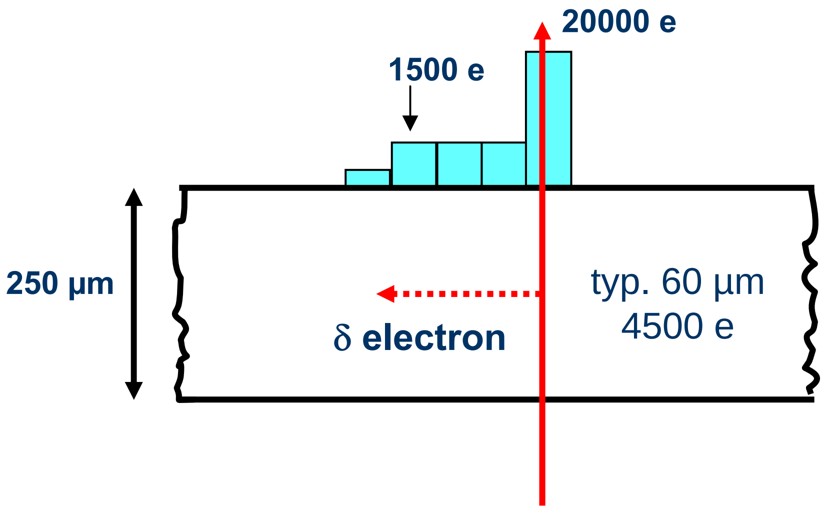
$$\frac{dN}{d\Theta} = \frac{1}{2} D z^2 \frac{Z}{A} \rho x \frac{\sin\Theta}{\cos^3\Theta}$$



<u>for experimentalists</u>

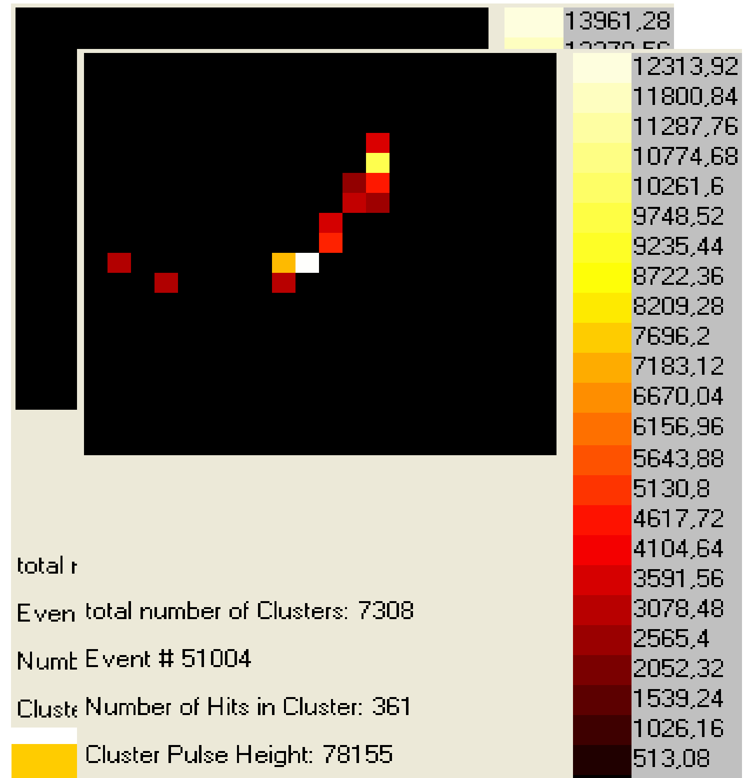
δ- electrons are "always" emitted at 90⁰ and are highly ionizing

Delta electrons



effect of δ -electrons

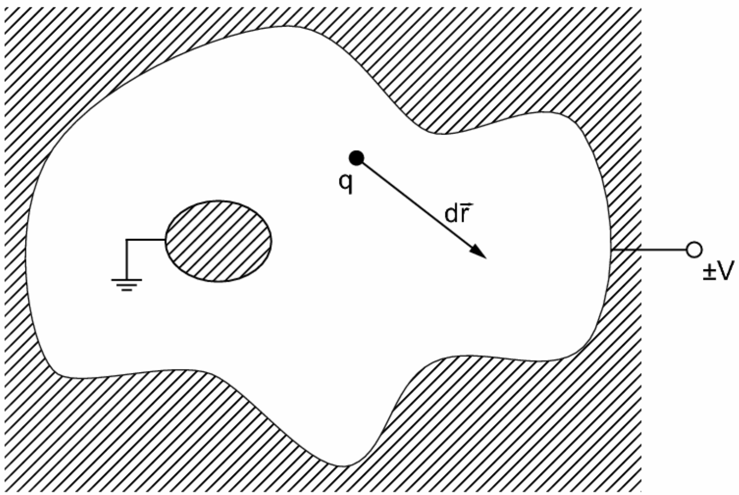
100 keV δ-electron occurs in 300 µm Si with 6% probability and has “range” of 60 µm



δ-electron with perpendicular emission

DEPFET pixels (25 µm x 25 µm)

Signal generation in an electrode configuration



how does a moving charge couple to an electrode ?

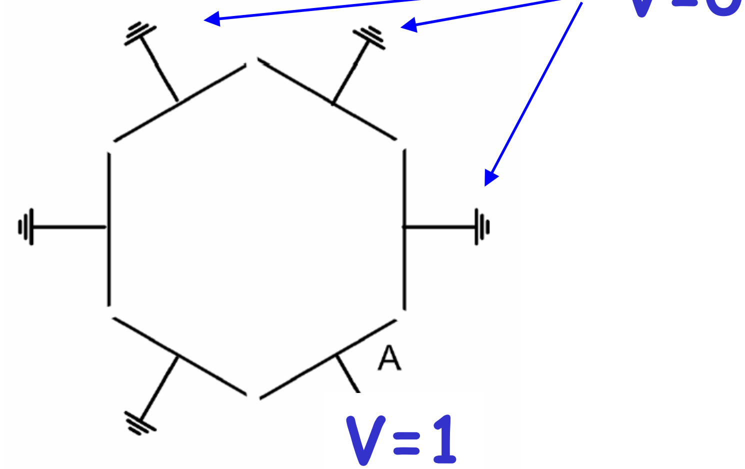
- respect Gauss' law and find

Ramo theorem

weighting field

$$i_{e/h} = \frac{dQ_{e/h}}{dt} = q\vec{E}_W \cdot \vec{v}$$

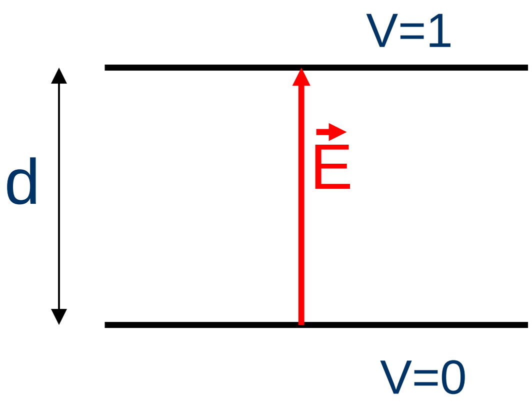
$$dQ = q\vec{\nabla}\Phi_W d\vec{r}$$

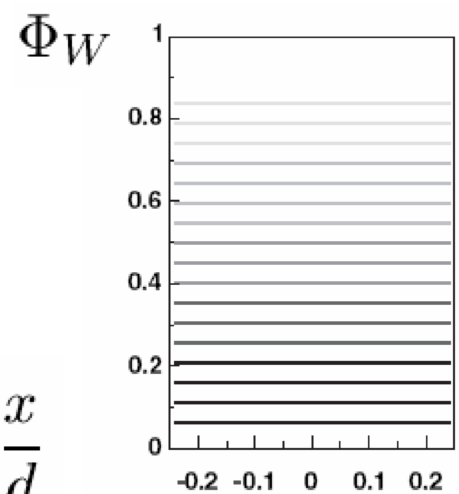


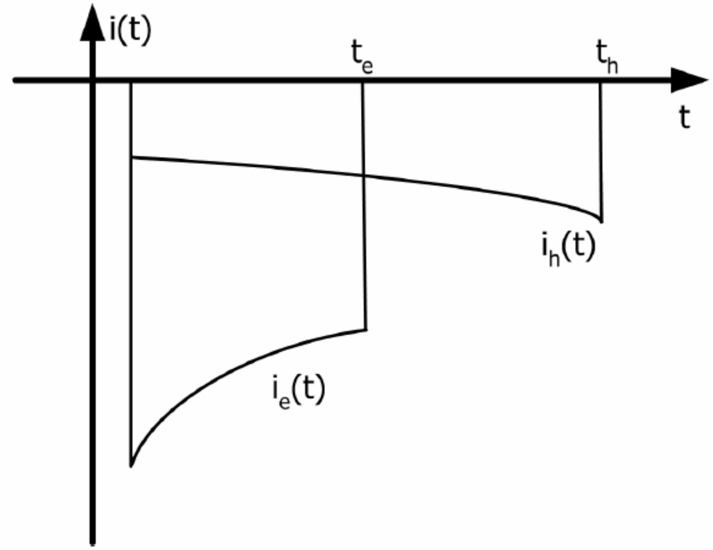
induction (weighting) potential

determines how charge movement couples to a specific electrode

Signal generation in a 2-electrode configuration







⇨ $$\vec{E}_W = \frac{1}{d}\hat{e} \Rightarrow \Phi_W(x) = \frac{x}{d}$$

⇨ $$i(t) = \frac{q}{d}\cdot v(t) = \frac{q}{d}\mu E(x(t))$$

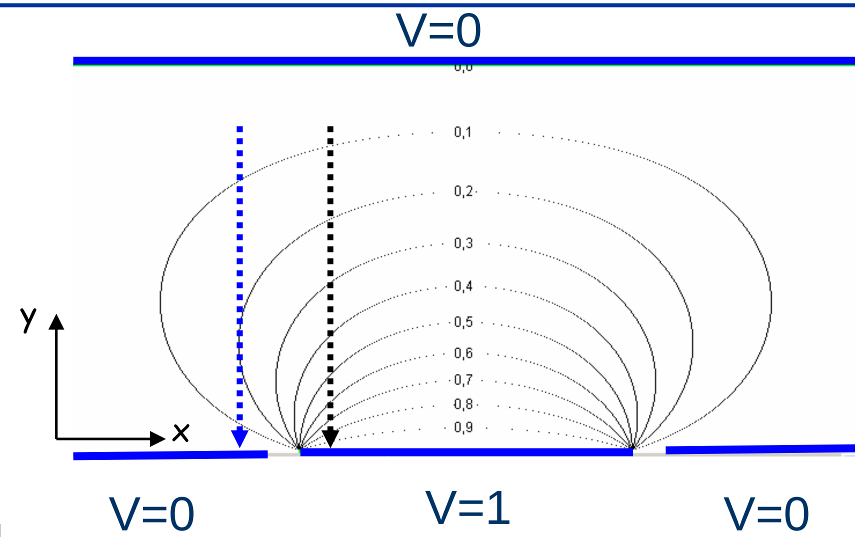
with $$E(x(t)) = -\frac{V+V_{dep}}{d} + \frac{2V_{dep}\,x(t)}{d^2}$$

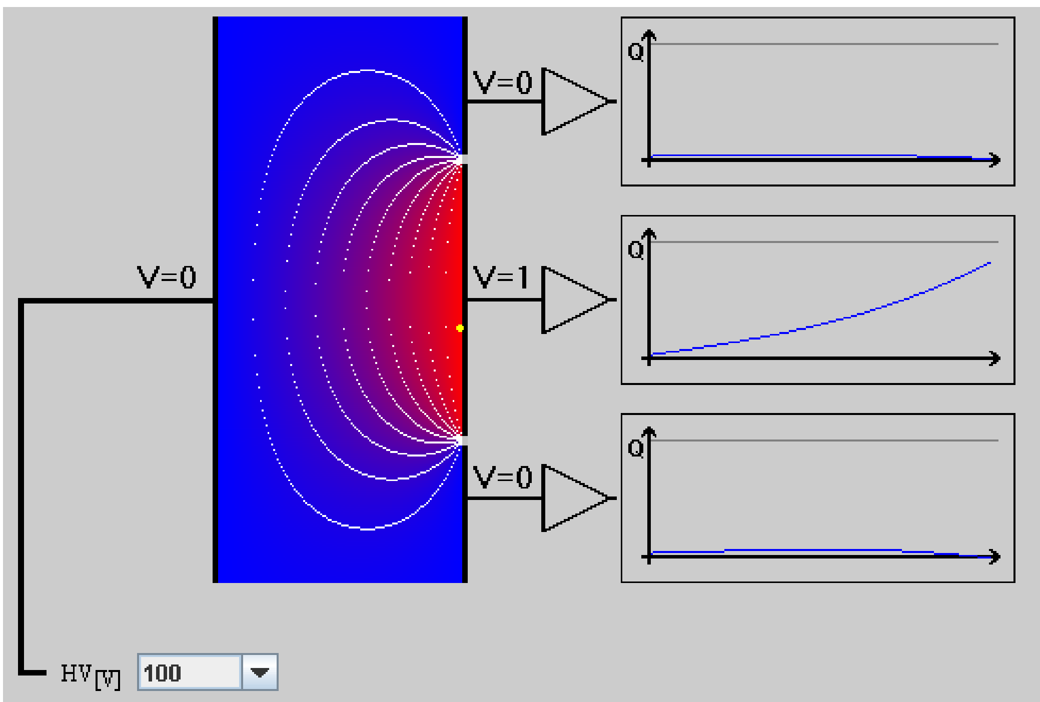
and $$v_e(t) = \frac{dx}{dt} = -\mu_e\left(\frac{V+V_{dep}}{d} + \frac{2V_{dep}\,x(t=0)}{d^2}\right)\cdot e^{-\frac{2\mu_e V_{dep}}{d^2}t}$$

Signal generation in a pixel detector (1-dim)

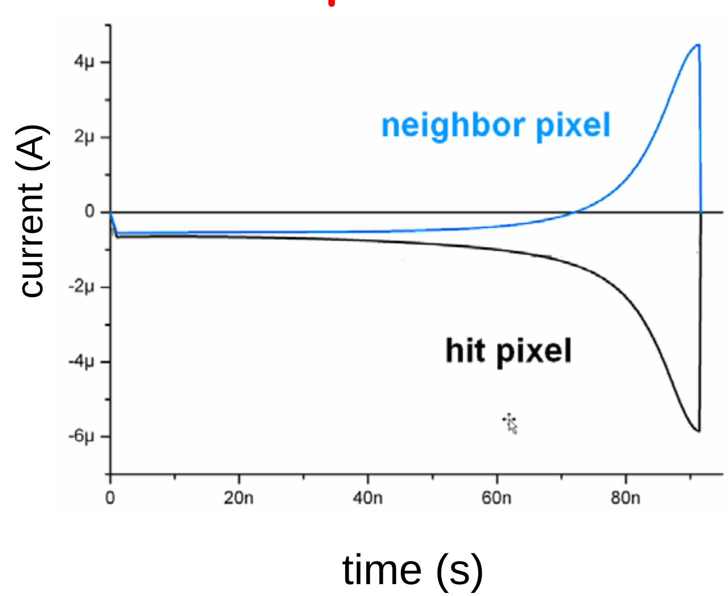
Φ_W for a strip/pixel geometry

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



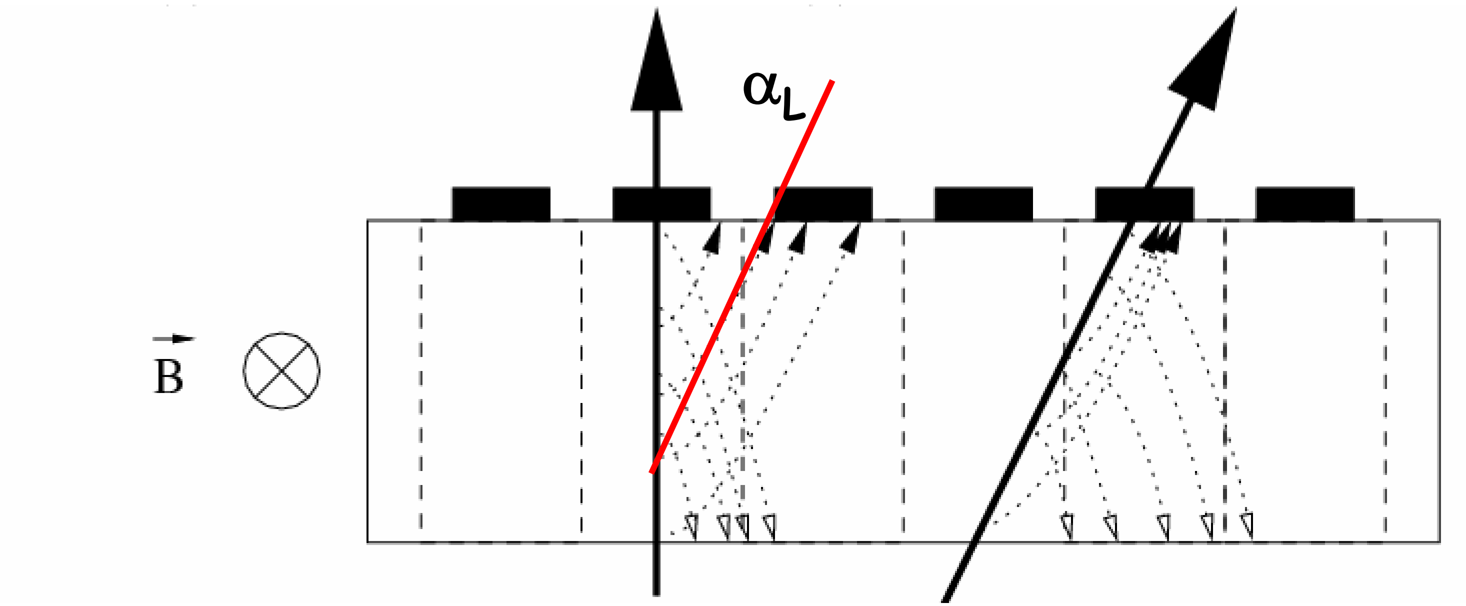


"small pixel effect" !



Charge collection in a magnetic field

Lorentz angle

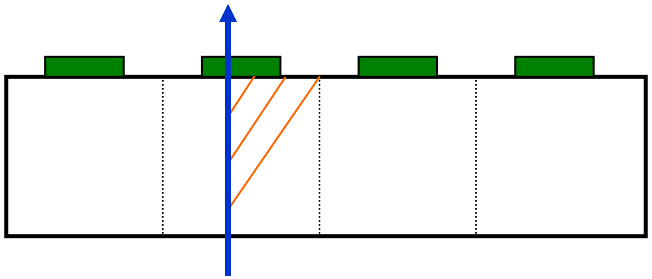


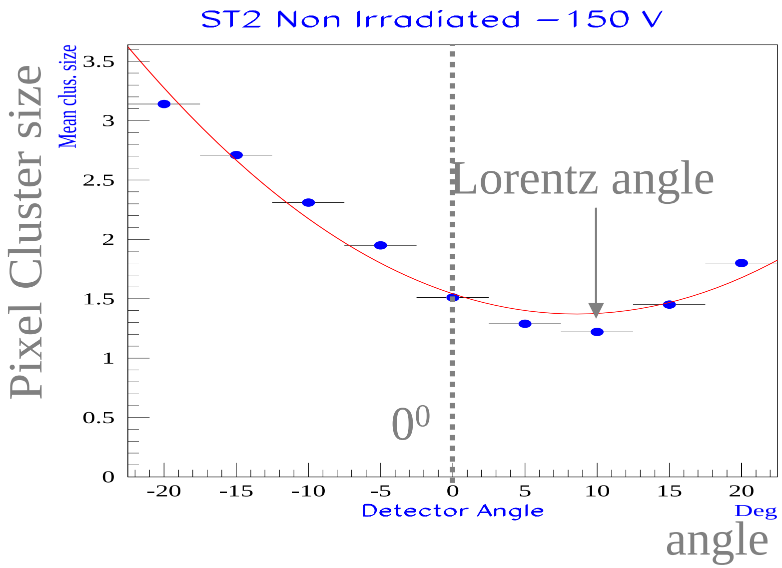
perpendicular track

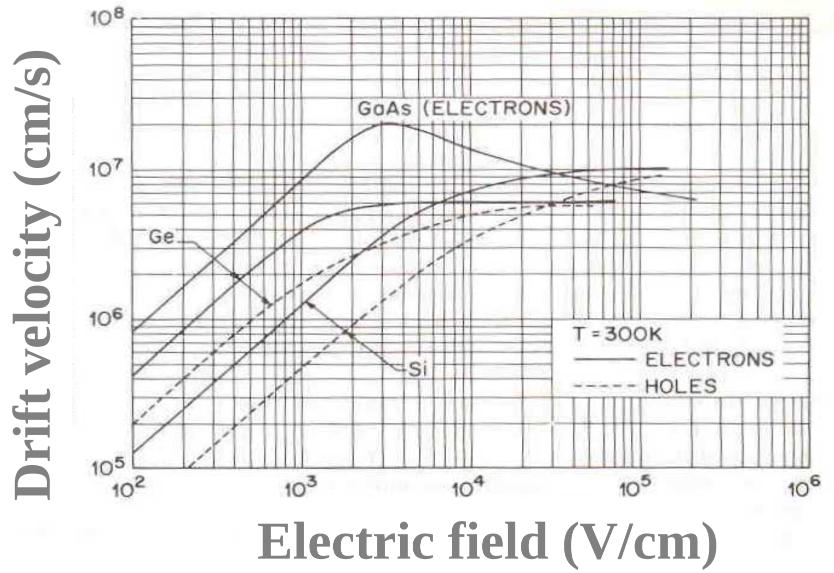
sensor angled w.r.t. track

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

Lorentz angle measurement (ATLAS)







$$\tan \alpha_L \propto \mu = \frac{v_s / E_c}{\left[1 + (E/E_c)^{\beta}\right]^{1/\beta}}$$

As bias voltage is increased to cope with irradiation, the Lorentz angle decreases:

Lorentz angle @2T, 150V = -10^0
Lorentz angle @2T, 600V = -5^0
Pixel modules tilt in ATLAS = $+20^0$

Measurement method: number of pixel hits is minimum when incidence angle is equal to the Lorentz angle

Effective incidence angle = tilt angle + Lorentz angle

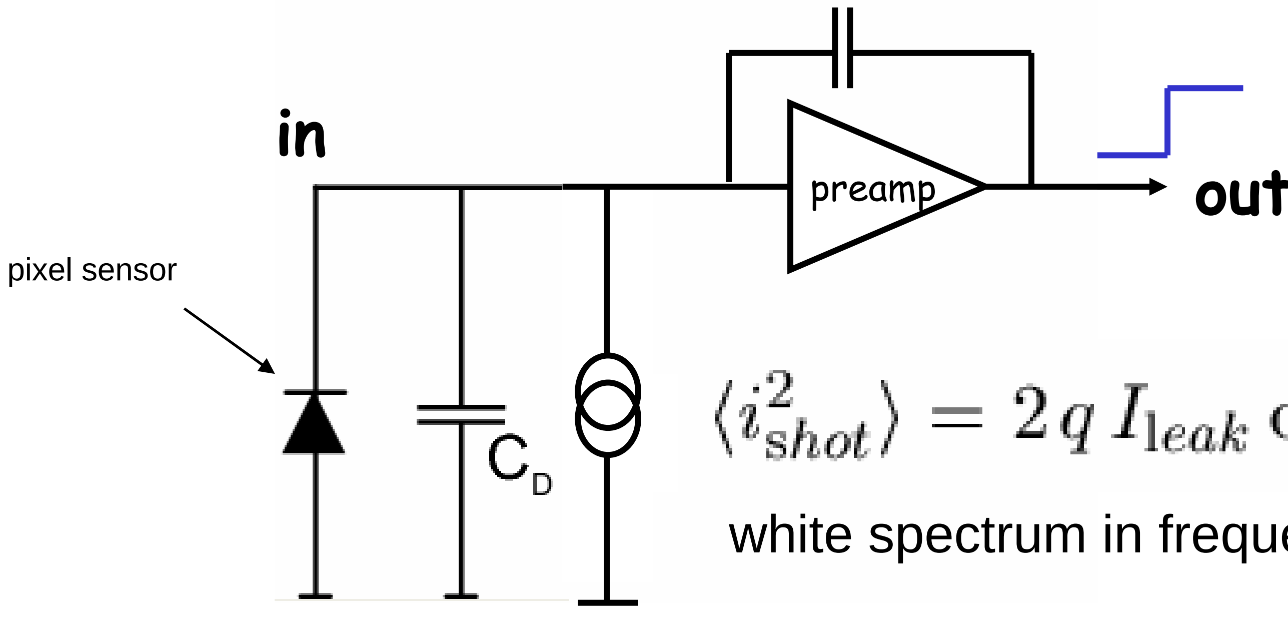
I. Gorelov et al. NIM A481:204-221,2002

Noise in a pixel detector

three physical noise sources:

number fluctuations of quanta → 1. shot noise and 2. 1/f noise
velocity fluctuations of quanta → 3. thermal noise

where do they appear in a typical pixel detector readout chain ?



$$\langle i_{shot}^2 \rangle = 2\, q\, I_{leak}\, \mathrm{d}f$$

white spectrum in frequency f

Noise in a pixel detector

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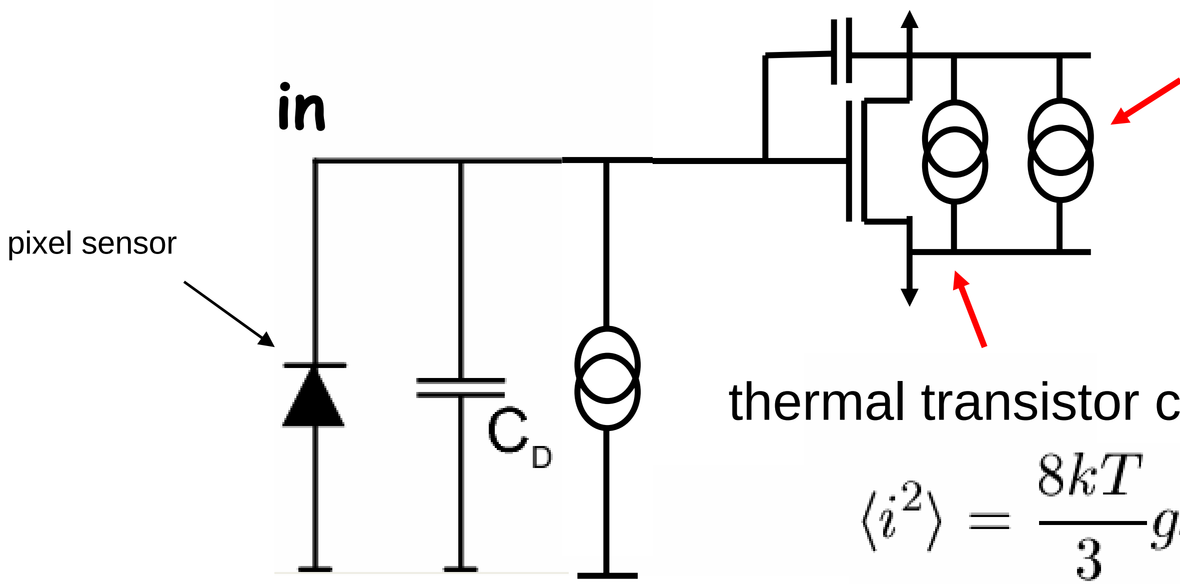

transistor 1/f noise

$$\langle i^2 \rangle = \frac{K_f}{C_{ox} W L} \frac{1}{f} \mathrm{d}f$$

thermal transistor channel (white) noise

$$\langle i^2 \rangle = \frac{8kT}{3} g_m \, \mathrm{d}f$$

Noise in a pixel detector

three physical noise sources:

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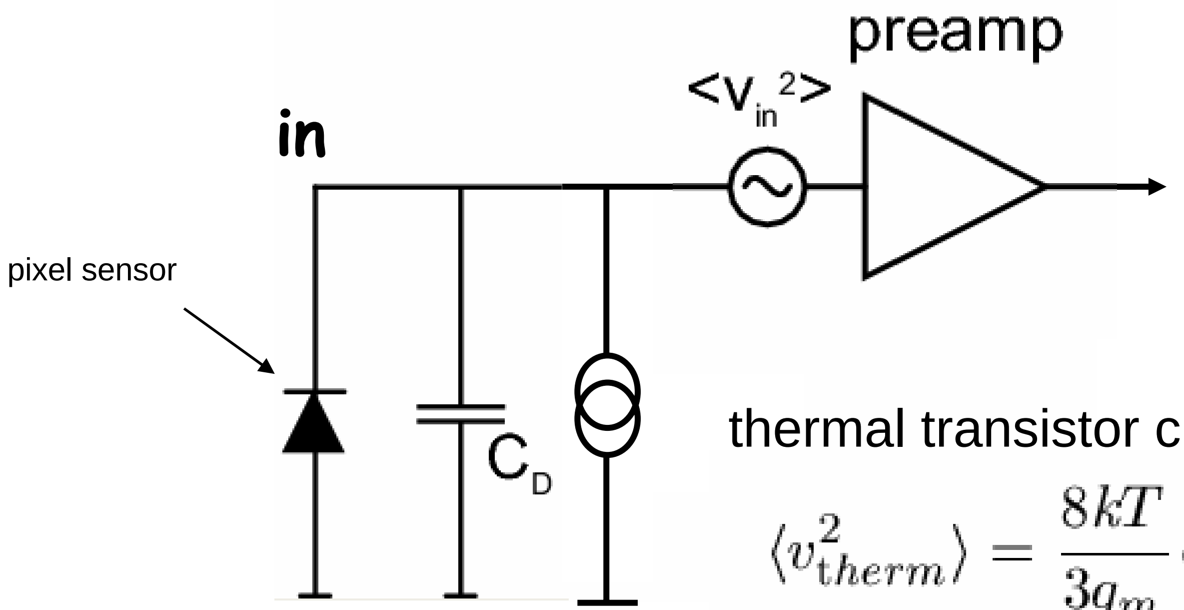
where do they appear in a typical pixel detector readout chain ?



transistor 1/f noise

$$\langle v_{1/f}^2 \rangle = \frac{K_f}{C_{ox} W L} \frac{1}{f} \mathrm{d}f$$

thermal transistor channel noise

$$\langle v_{therm}^2 \rangle = \frac{8kT}{3g_m} \mathrm{d}f$$

Noise in a pixel detector

equivalent noise charge $\mathrm{ENC} = \dfrac{\text{noise output voltage (rms)}}{\text{signal output voltage for the input charge of } 1e^-}$

$$ENC_{tot}^2 = ENC_{shot}^2 + ENC_{therm}^2 + ENC_{1/f}^2$$

charge sensitive preamplifier only

$$ENC_{\mathrm{shot}} = \sqrt{\frac{I_{leak}}{2q}\tau_f} = 56e^- \times \sqrt{\frac{I_{leak}}{\mathrm{n}A}\frac{\tau_f}{\mu s}}$$

$$ENC_{\mathrm{therm}} = \frac{C_f}{q}\sqrt{\langle v_{\mathrm{therm}}^2\rangle} = \sqrt{\frac{kT}{q}\frac{2C_D}{3q}\frac{C_f}{C_{load}}} = 104e^- \times \sqrt{\frac{C_D}{100\,\mathrm{fF}}\frac{C_f}{C_{load}}}$$

$$ENC_{1/\mathrm{f}} \approx \frac{C_D}{q}\sqrt{\frac{K_f}{C_{ox}WL}}\sqrt{\ln\left(\tau_f\frac{g_m}{C_{load}}\frac{C_f}{C_D}\right)} = 9e^- \times \frac{C_D}{100\,\mathrm{fF}}(\text{for NMOS trans.})$$

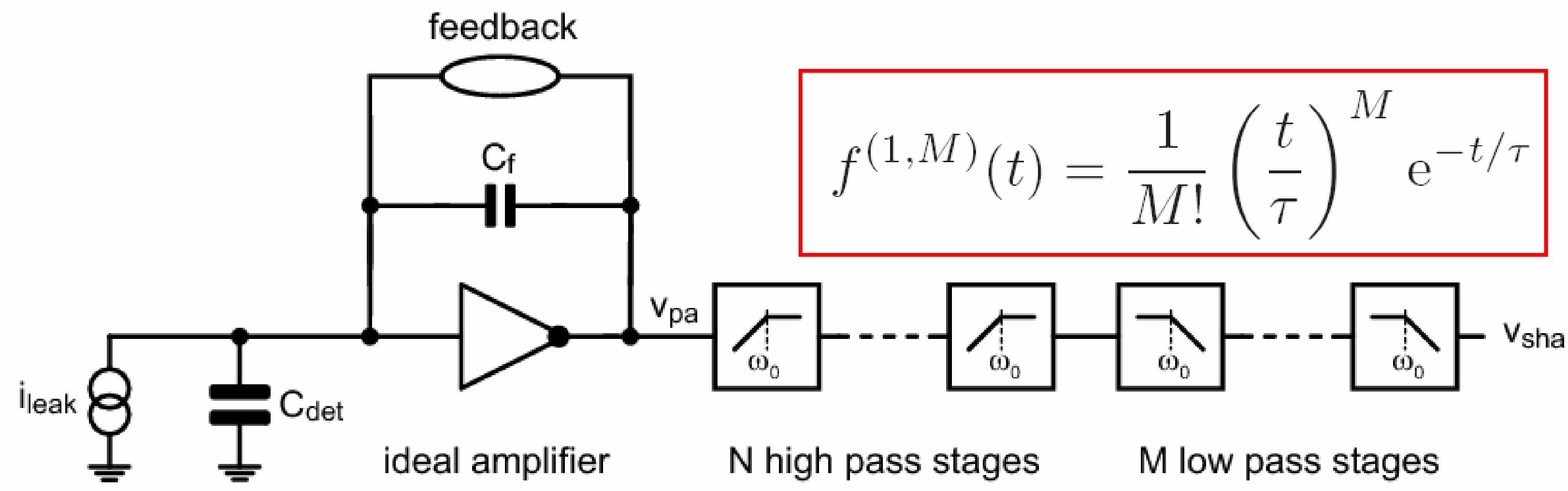
W, L = width and length of trans. gate
K_f = 1/f noise coefficient
C_{ox} = gate oxide capacitance

C_f = feedback capacitance
C_{load} = load capacitance
C_D = detector capacitance
τ_f = feedback time constant

reference
Rossi, Fischer, Rohe, Wermes
Pixel Detectors
Springer 2006

Noise in a pixel detector

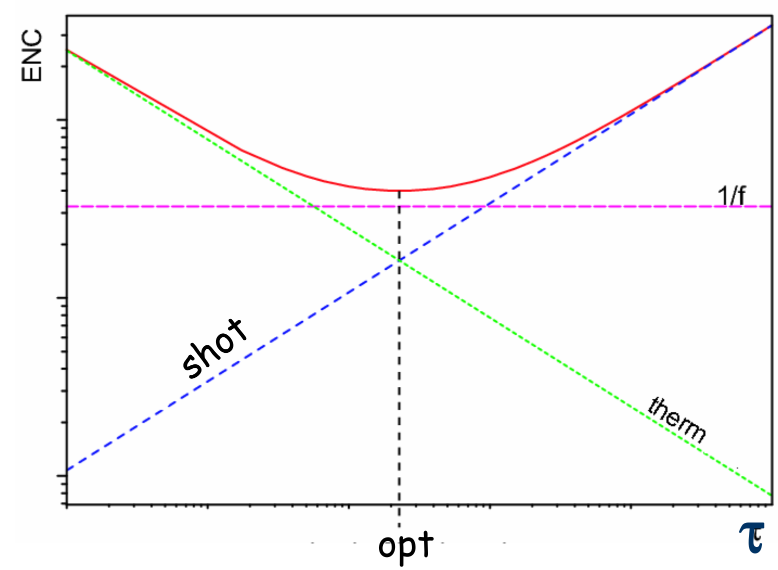
… with an additional filter amplifier (shaper) being the band width limiter



$$f^{(1,M)}(t) = \frac{1}{M!}\left(\frac{t}{\tau}\right)^{M} \mathrm{e}^{-t/\tau}$$

$$\left(\frac{\mathrm{ENC}}{\mathrm{e}^-}\right)^2 = 115 \cdot \frac{\tau}{10\,\mathrm{ns}} \cdot \frac{I_{\mathrm{leak}}}{1\,\mathrm{nA}} + 388 \cdot \frac{10\,\mathrm{ns}}{\tau} \cdot \frac{\mathrm{mS}}{g_m} \cdot \left(\frac{C_{\mathrm{in}}}{100\,\mathrm{fF}}\right)^2 + 74 \cdot \left(\frac{C_{\mathrm{in}}}{100\,\mathrm{fF}}\right)^2 .$$

~200 fF for pixels



Signal/Noise in a pixel detector

typical figures for an LHC pixel detector

Noise = 150 e^- initially
200 e^- after 10 years @ LHC

Signal = 20000 e^- total charge in 250 µm Si
13000 e^- including charge sharing
6000 – 8000 e^- after 10 yrs @ LHC

S/N > 30

Outline of the Lecture

1. Introduction

   From gas-filled chambers to pixel vertex detectors

2. Hybrid Pixel Detectors for the LHC

   The Signal and the Noise in Pixel Detector

3. **Making a Pixel Detector**

   From sensor to module-ladder

4. Pixel R&D for Future Colliders

   New developments for the ILC

Main issue for ATLAS and CMS: Irradiation

target: 10 years LHC $\cong 10^{15}\ n_{eq}/cm^2$ (600 kGy)

- **Si sensors:** depletion voltage and leakage currents rise
- **FE chips:** threshold shifts & parasitic transistors occur
- **glue:** becomes hard and brittle
- **mechanics:** material performance degrades
- **cooling:** larger capacity is needed to cool more power

➔ intensive irradiation and test beam program over years including dedicated high intensity beams with LHC like rates and timing structure

Note: Plans for Super – LHC (~2015): SLHC = LHC x 10

Hybrid Pixel Assembly

Sensors

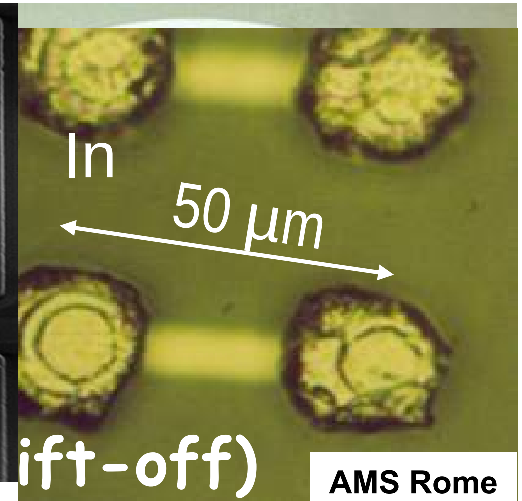
- n^+ in n (oxygenated Si)
- wafer size (Ø 10 cm)
- ~200-250 µm thick

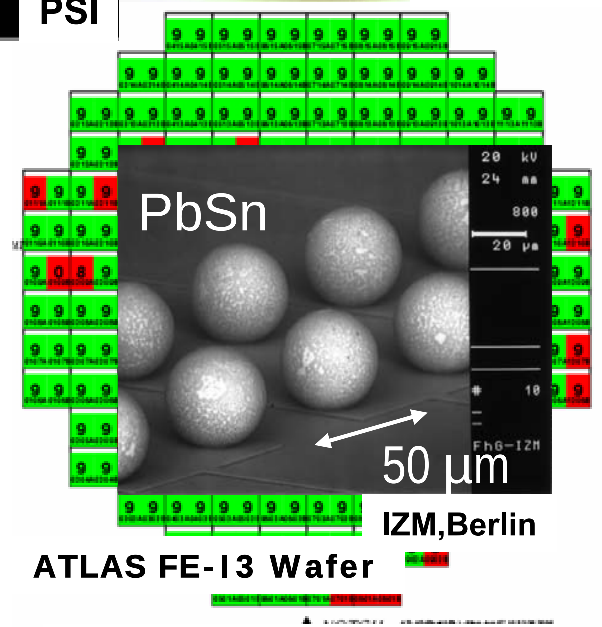
Electronics - Chip

- chip size limited by yield ~1-2.5 cm^2
- wafer size (Ø 20 cm)

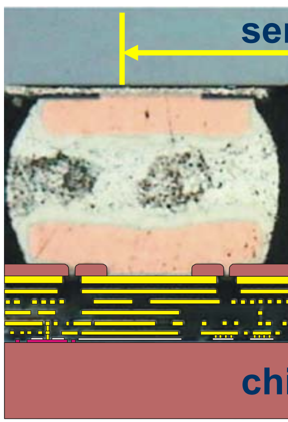
Hybridization

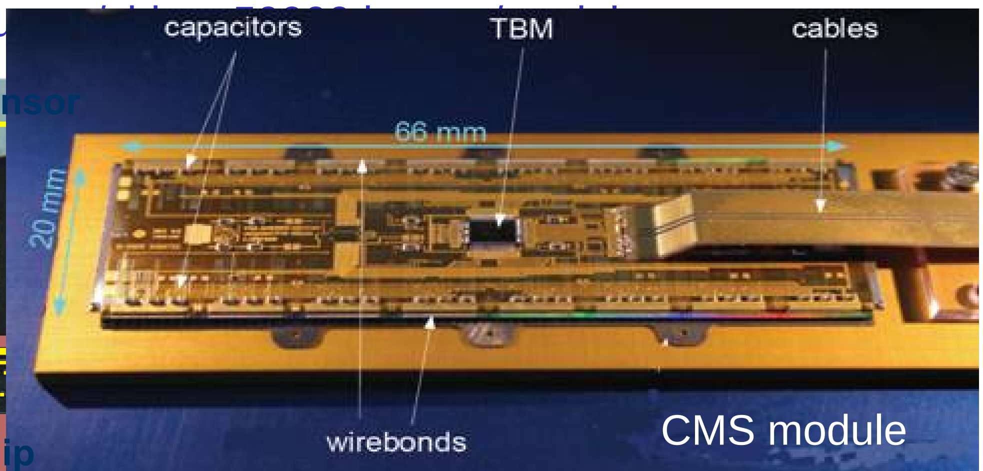
- PbSn or Indium bumps (wafer scale)
- IC wafers thinned after bumping to ~180 µm
- ‚flip-chip' to mate the parts
- ~3000 bu





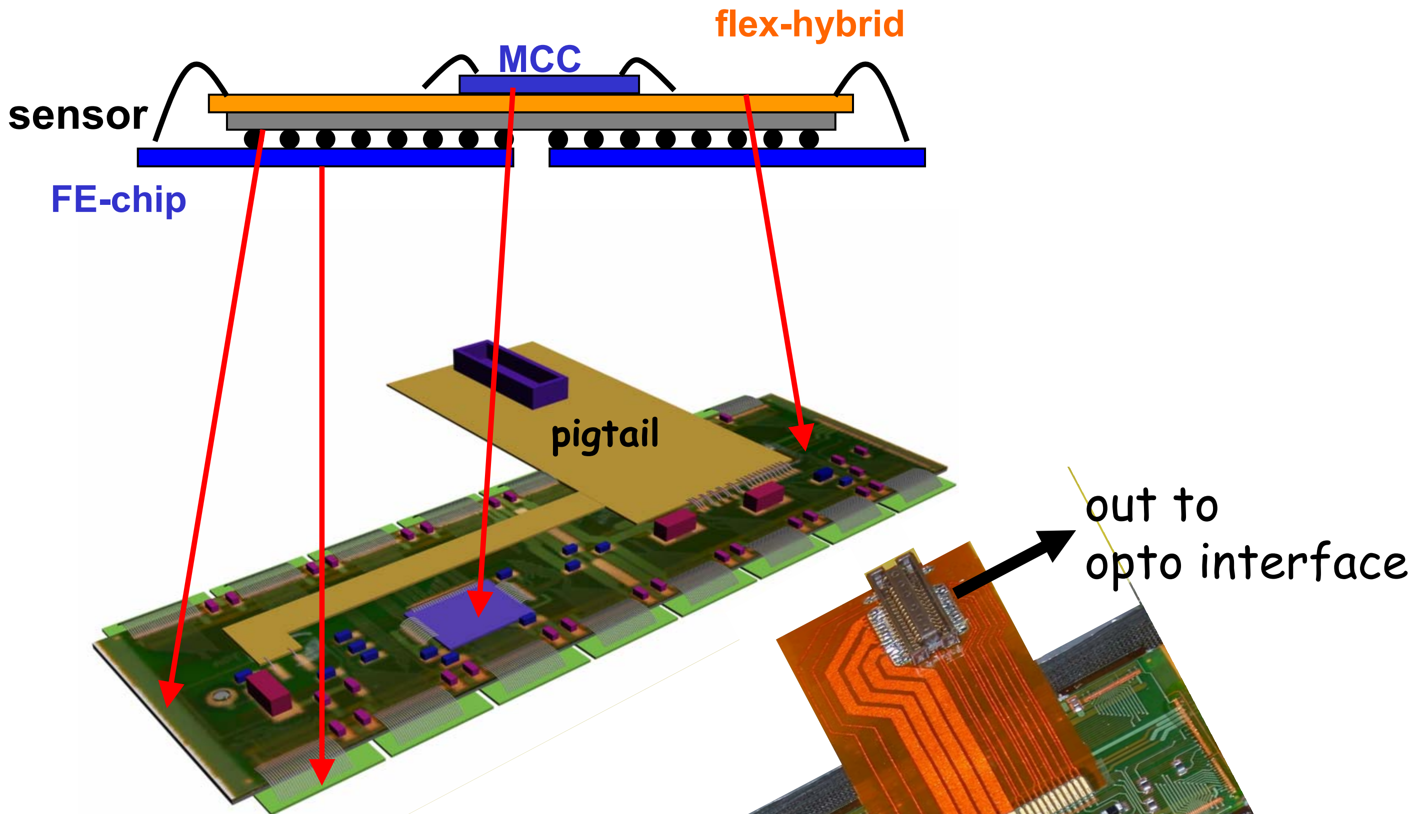
FE-I3 wafer map, 82% yield



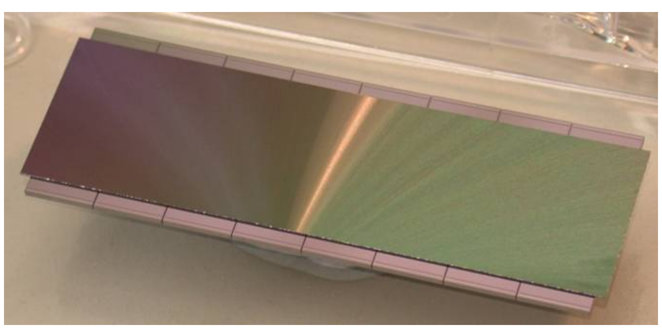


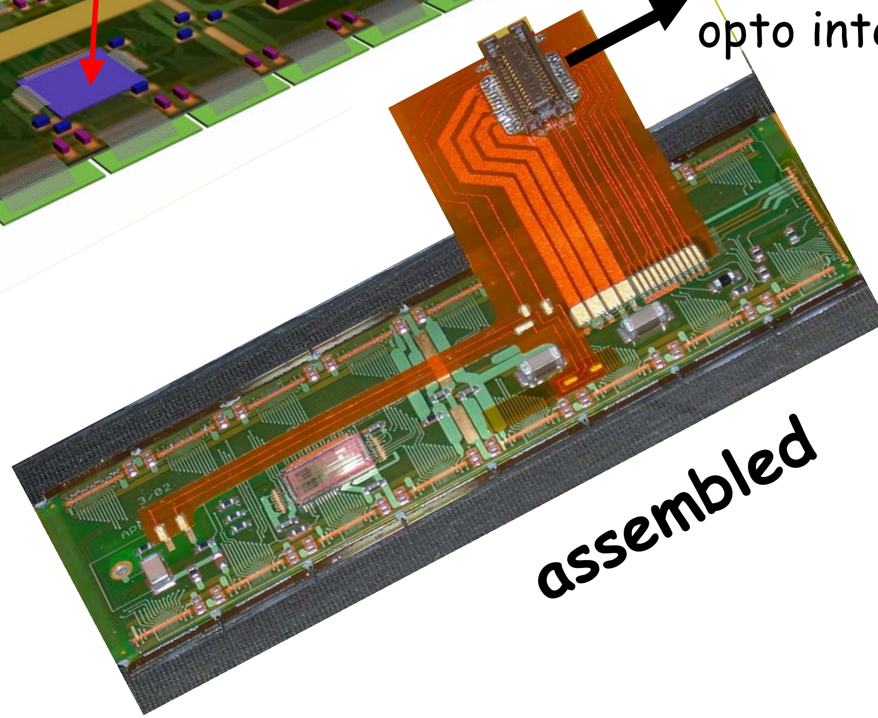
CMS Pixel Modul
(with Flex Hybrid and Controller Chip TBM)

Hybrid Pixel Assembly

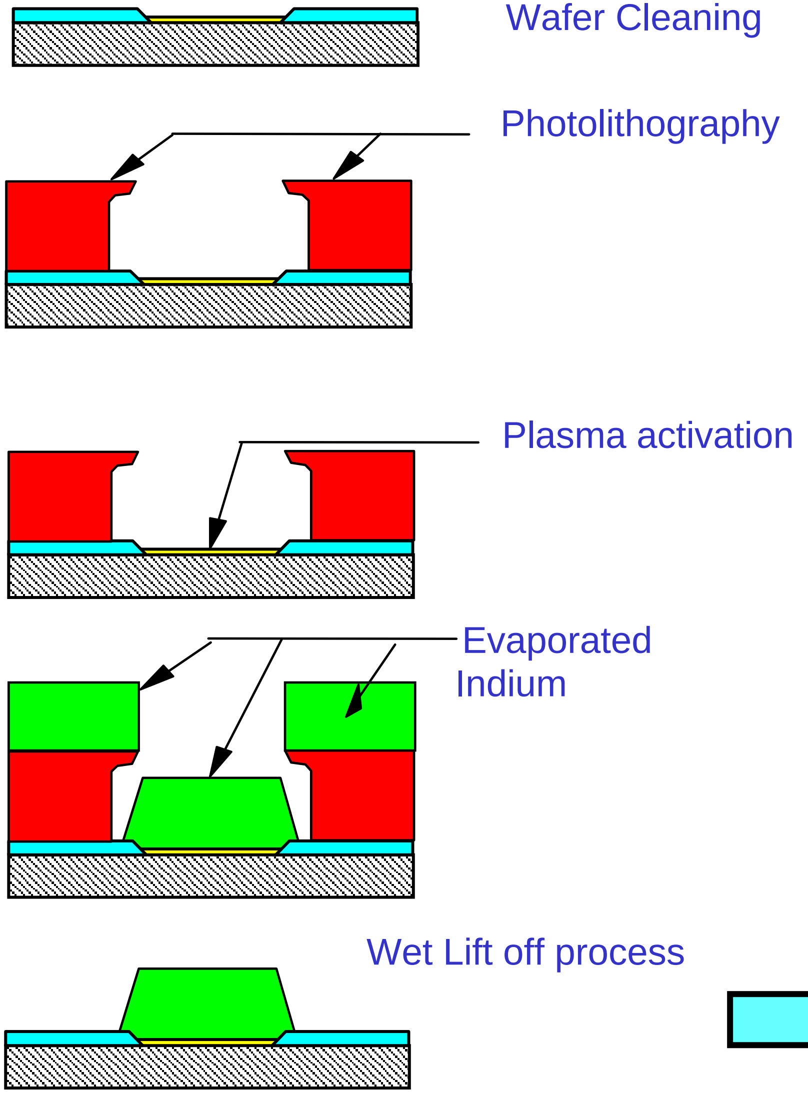


bare





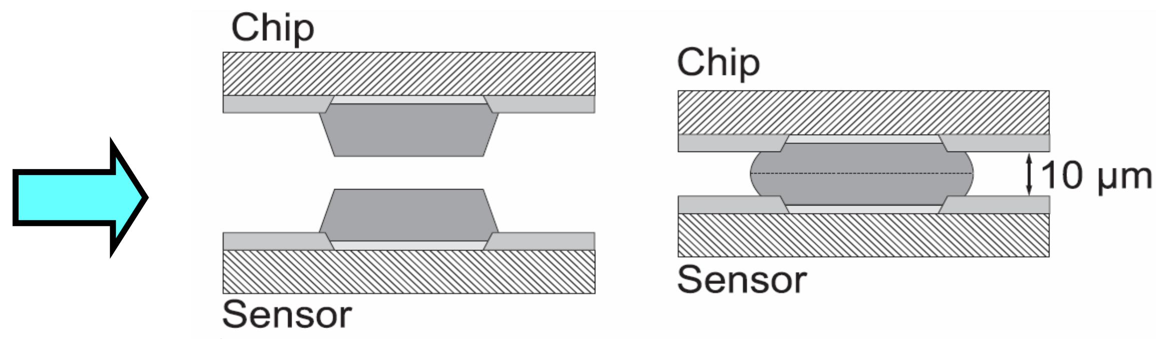
Indium bumping process



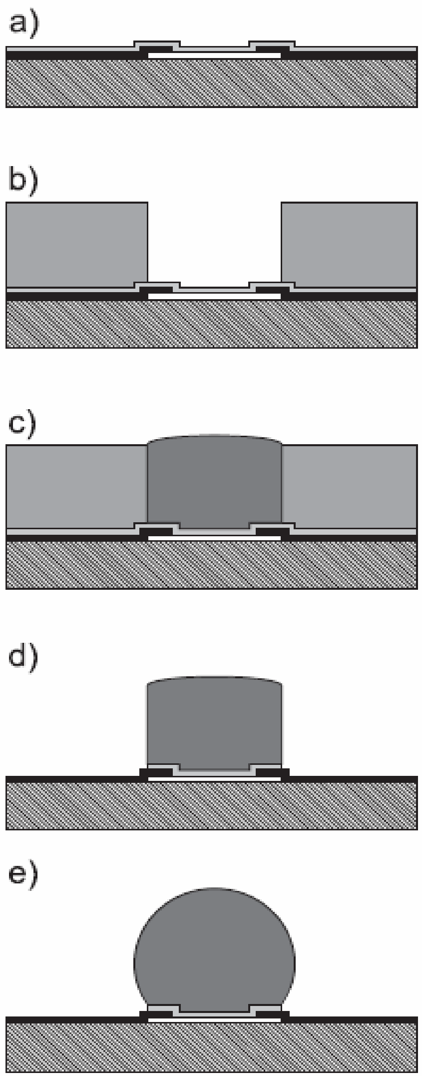
Process parameters:

- Resist Thickness: 15 μm
- Pre-bake: 30min @ 80 °C
- Deposition rate: 0.5 μm/min
- Dep. Pressure: 9 x 10 $^{-7}$ Torr
- Temp. during Dep. < 50 °C

Flip-Chip



Solder bumping process



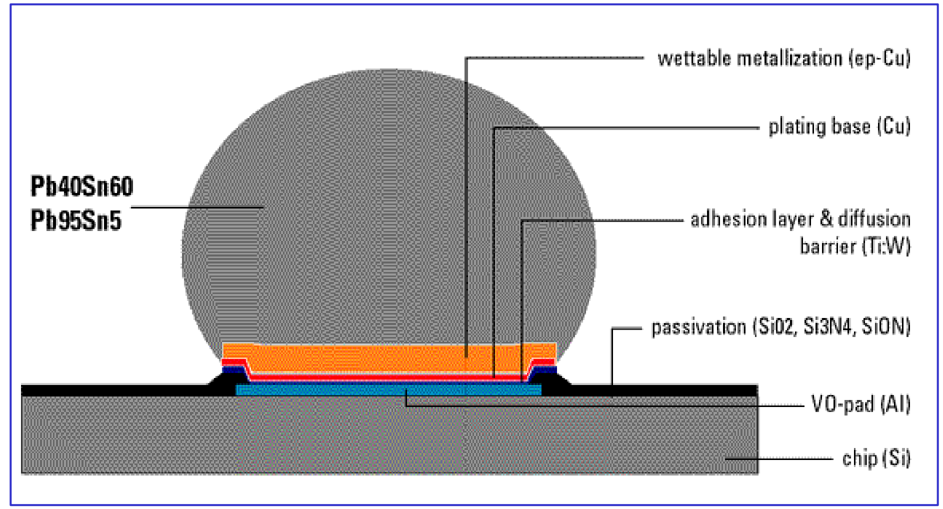
a) Sputter etching and sputtering of the plating base / UBM

b) Spin coating and printing of Photoresist

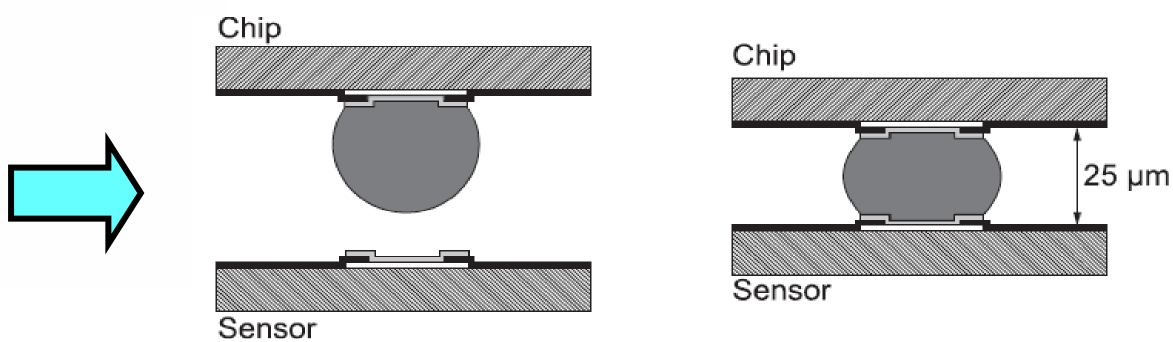
c) Electroplating of Cu and PbSn

d) Resist stripping and wet etching of the plating base

e) Reflow



Flip-Chip



Pixel Sensors in the LHC radiation environment

particle interactions with lattice nuclei

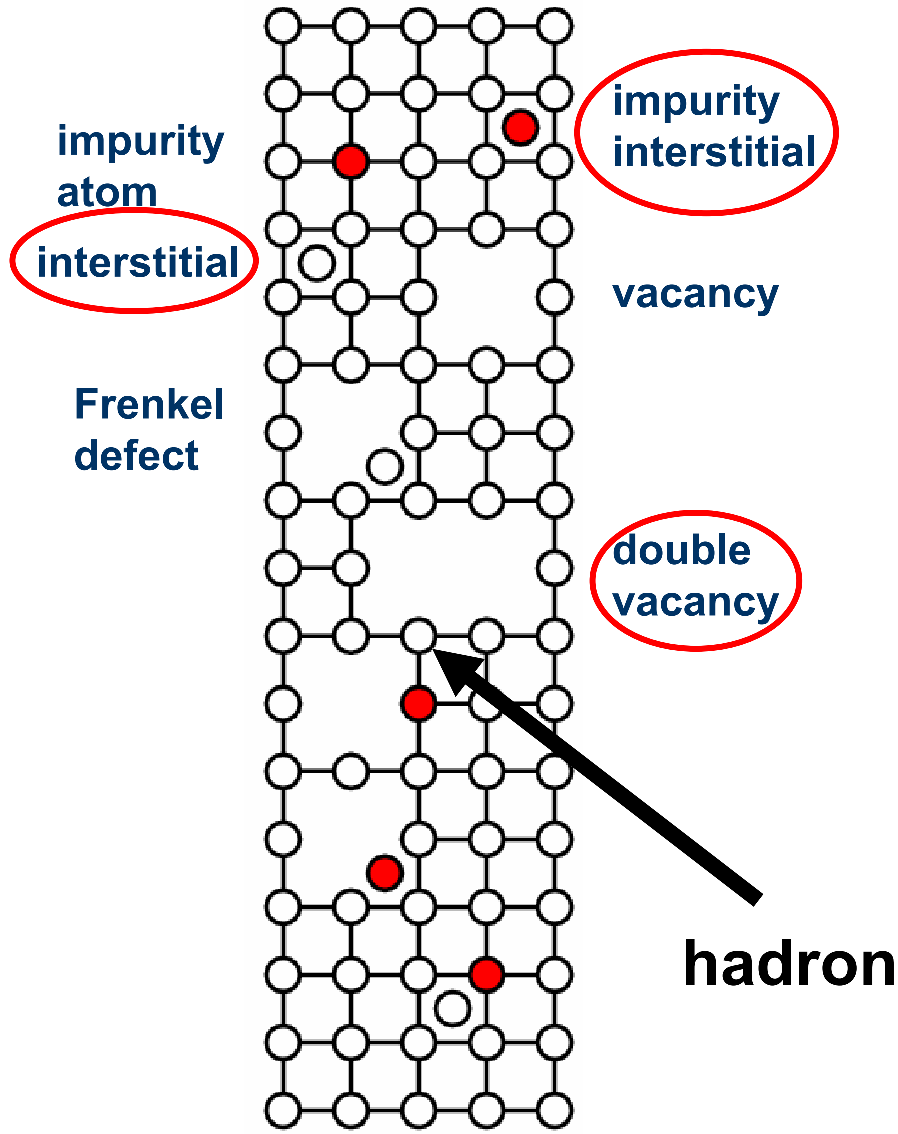
⇩

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**
3. trapping centers created
   → **trapping** of signal charge



Pixel Sensors in the LHC radiation environment

particle interactions with lattice nuclei

NIEL

non-ionizing
energy loss
(not reversible)
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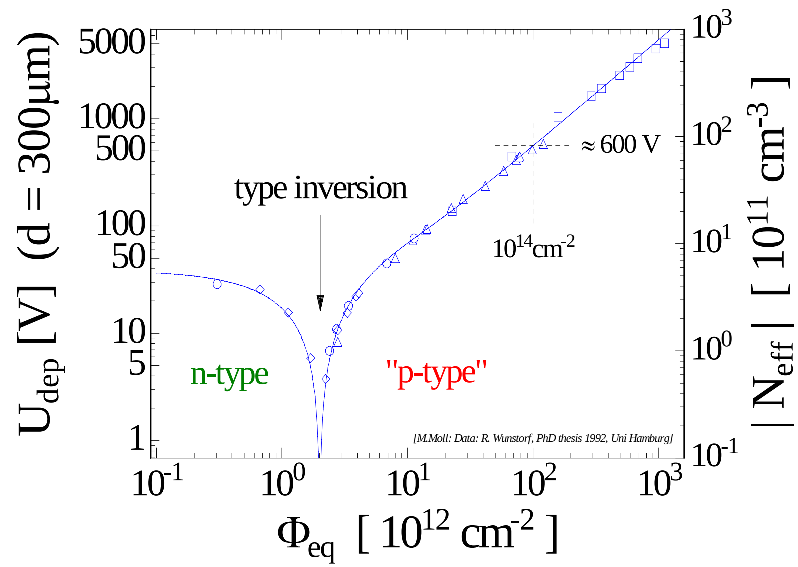
1 MeV neutron damage

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**
3. trapping centers created
   → **trapping** of signal charge

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

…. with particle fluence:



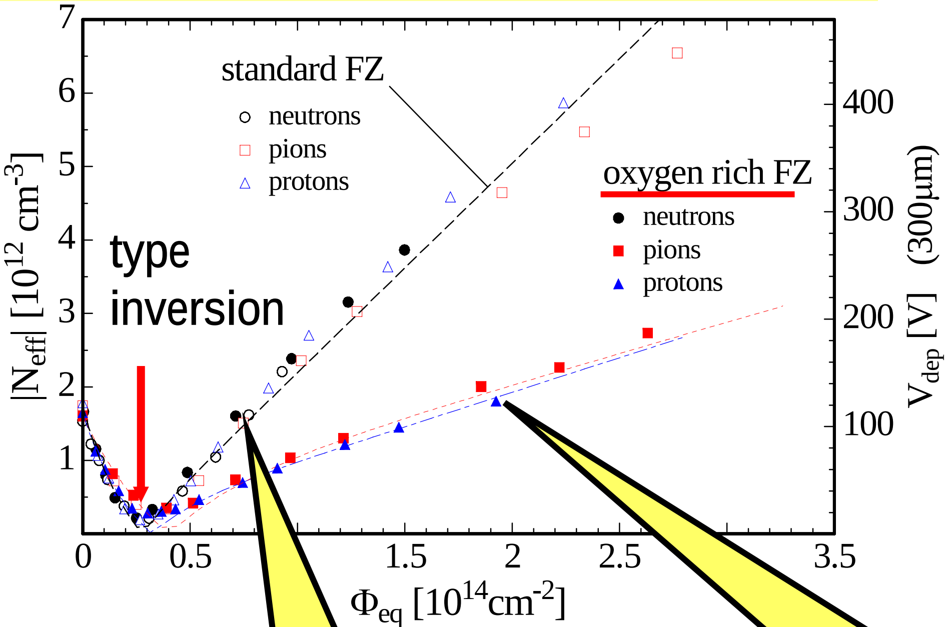
- "**Type inversion**": N_{eff} changes from positive to negative (Space Charge Sign Inversion)

fluence (NIEL) > 10^{15} n_{eq}/cm^2
total dose > 500 kGy

Pixel Sensors in the LHC radiation environment

solution: oxygenated FZ silicon

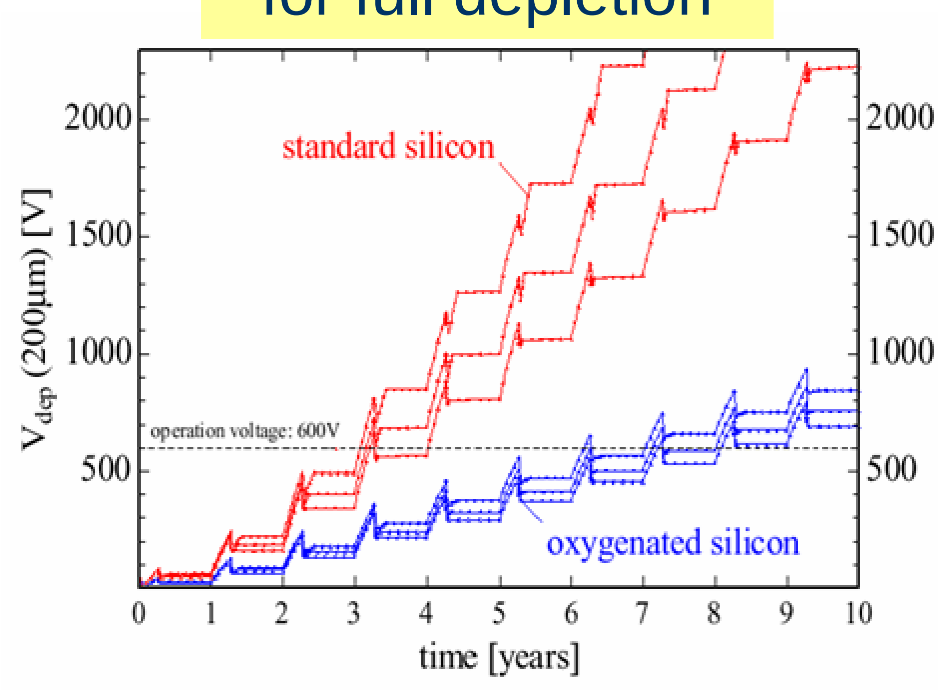
radiation tolerant to 10^{15} n_{eq} / cm^2 (600 kGy)



neutrons

protons
pions

necessary voltage for full depletion

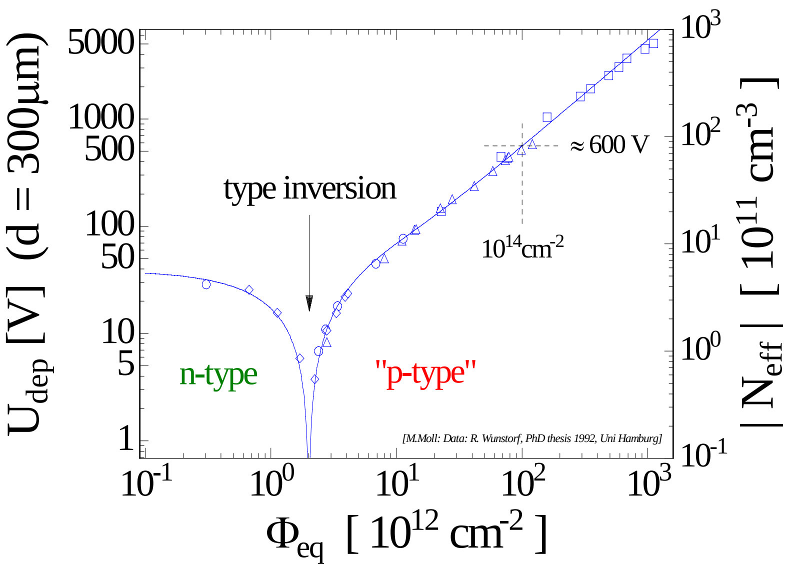


RD50, G. Lindström et al.
NIM-A 465 (2001) 60-69

Pixel Sensors in the LHC radiation environment

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

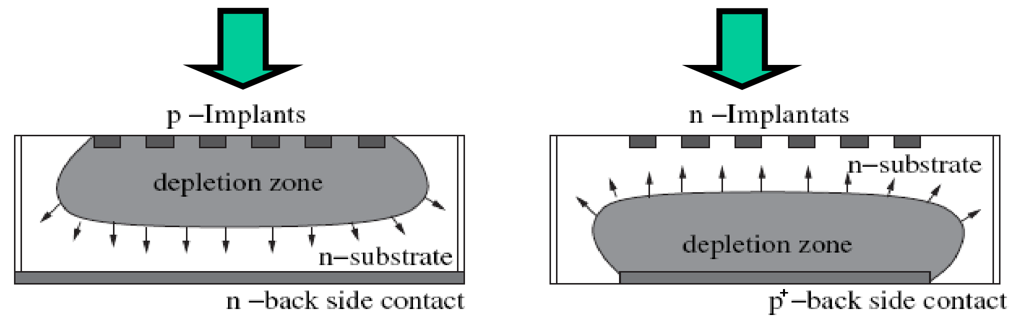
…. with particle fluence:



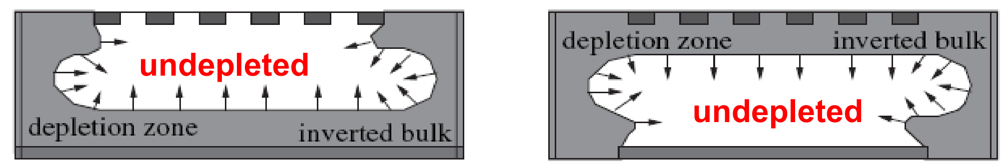
- "**Type inversion**": N_{eff} changes from positive to negative (Space Charge Sign Inversion)

fluence (NIEL) > 10^{15} n_{eq}/cm^2
total dose > 500 kGy

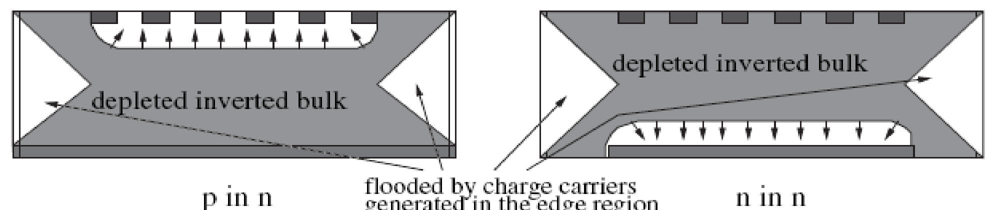
p^+ in n "normal" | **n^+ in n**



before type inversion



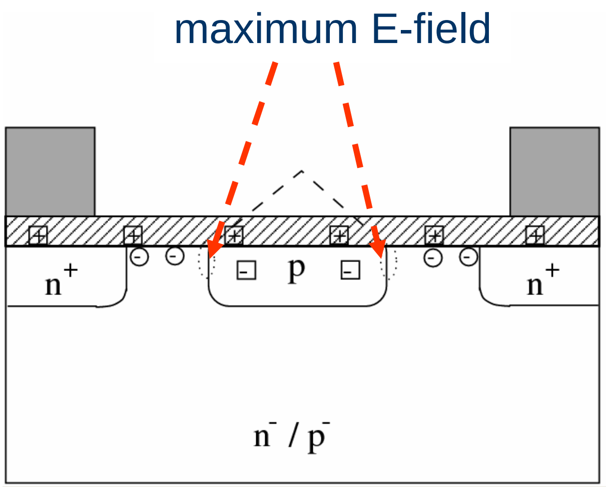
after type inversion



after heavy radiation damage

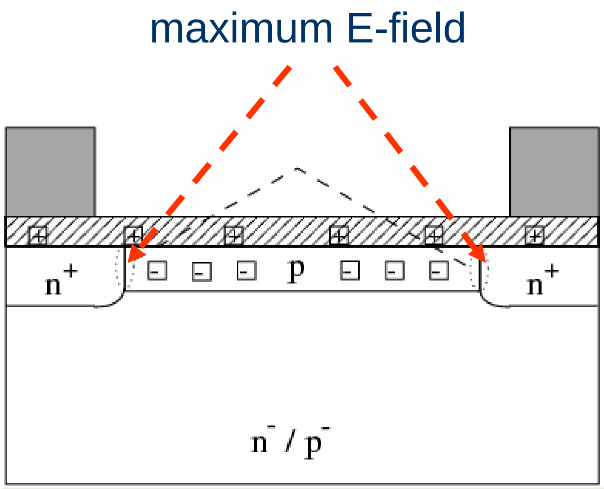
L. Andricek et al, NIM-A 409 (1998) 184-193

Pixel Sensors: isolation of pixel implants



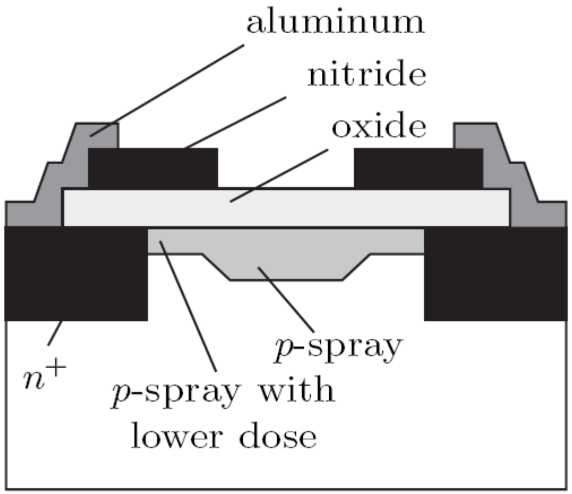
p-stop

highest E-fields after irradiation



p-spray

E-fields decrease with irradiation

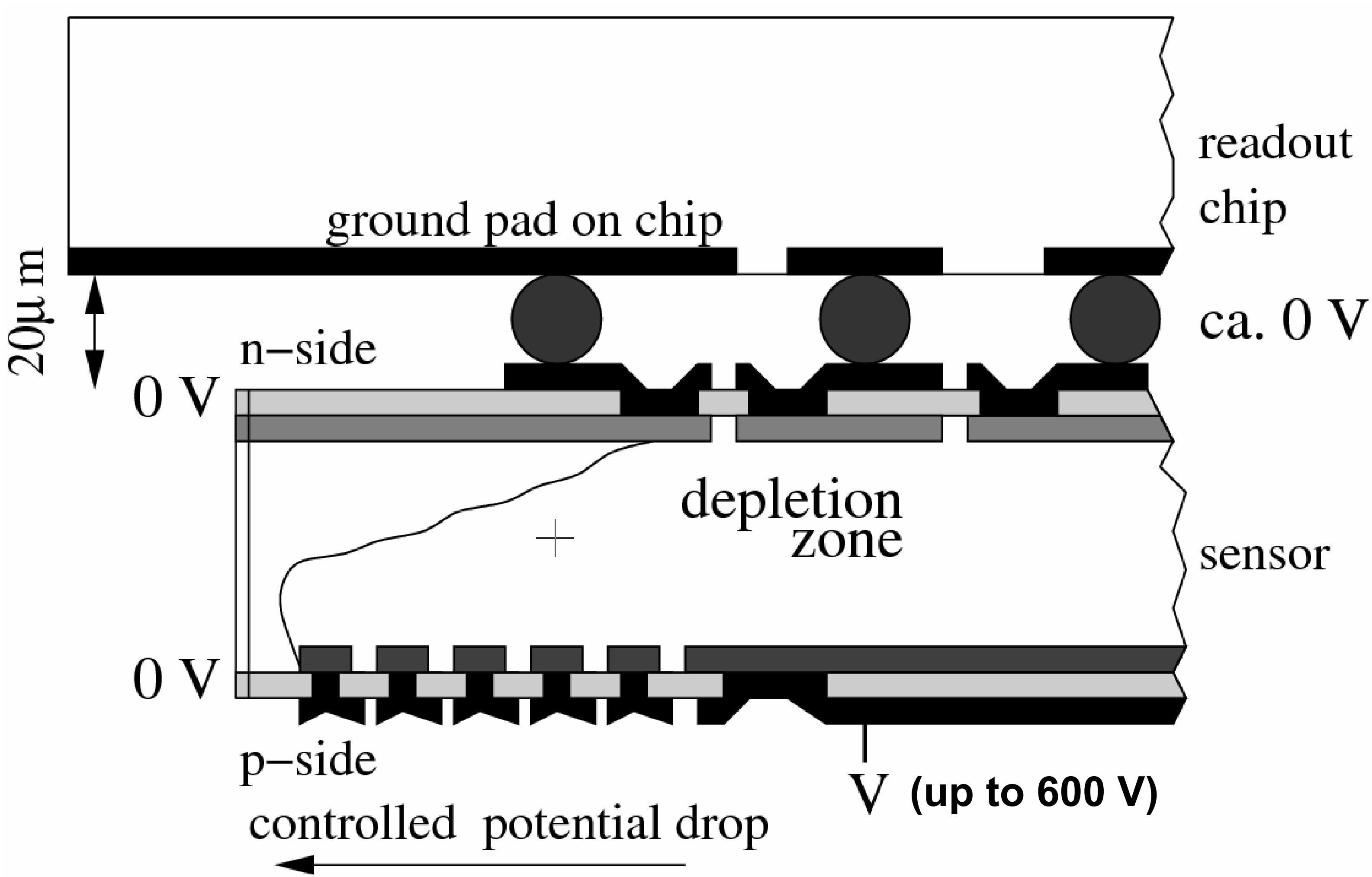


moderated p-spray

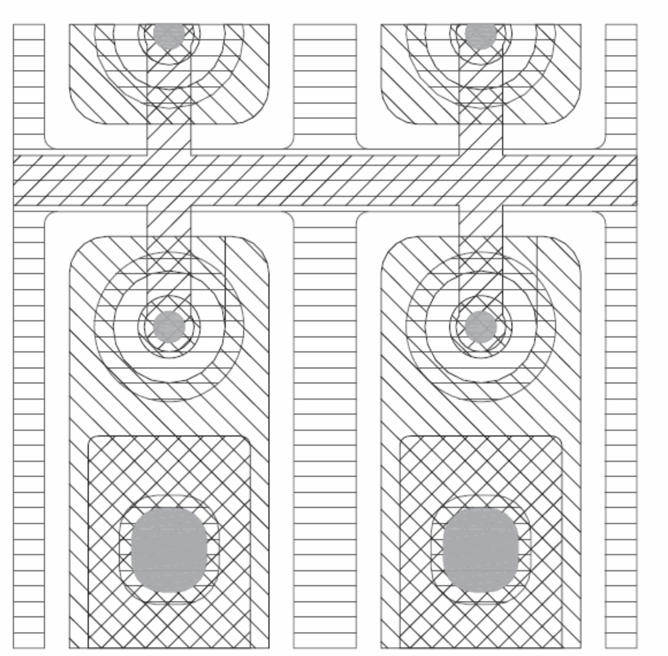
optimum configuration
for overall voltage stability

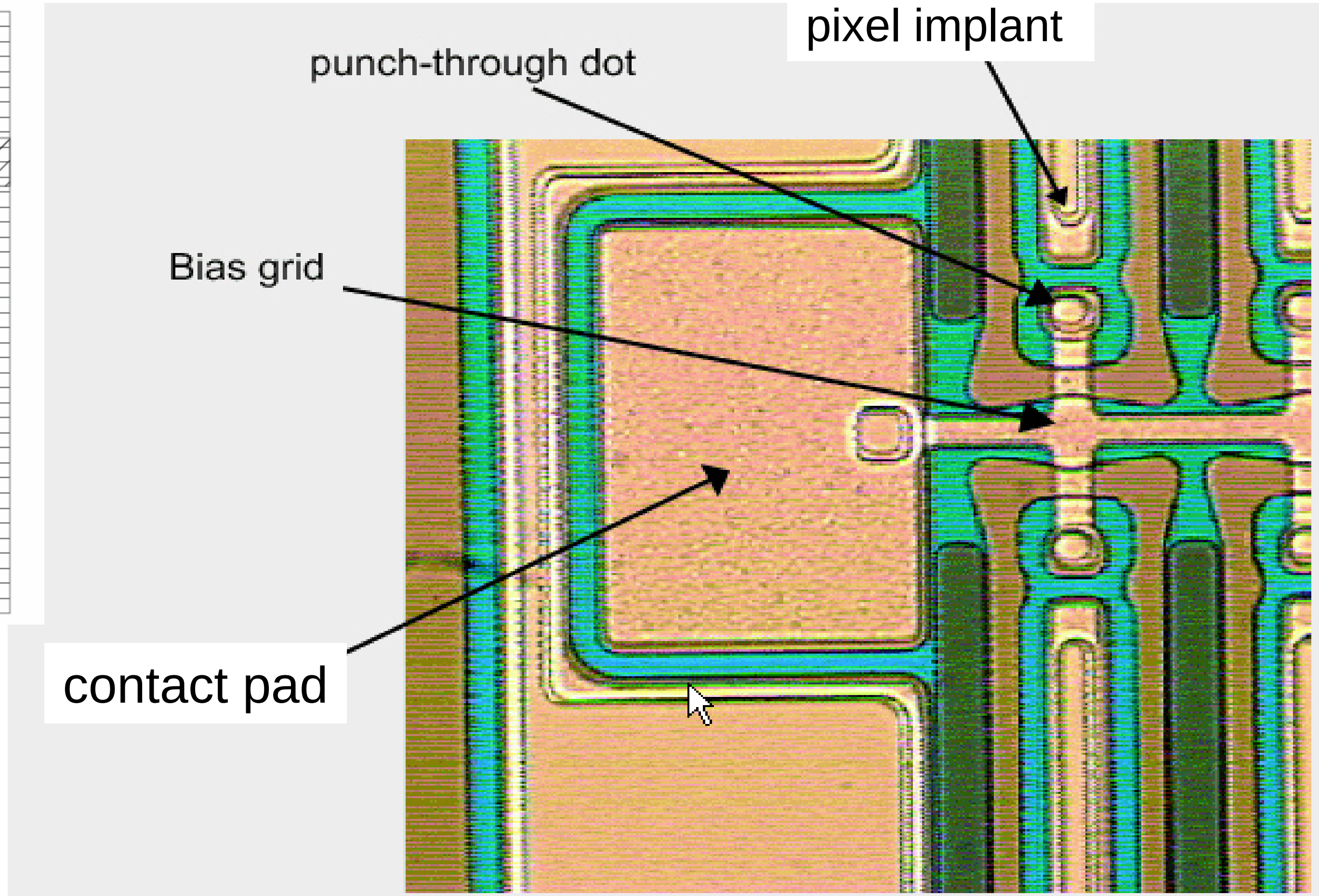
R. Richter et al, NIM-A 377 (1996) 412

Biasing of Pixel Sensors



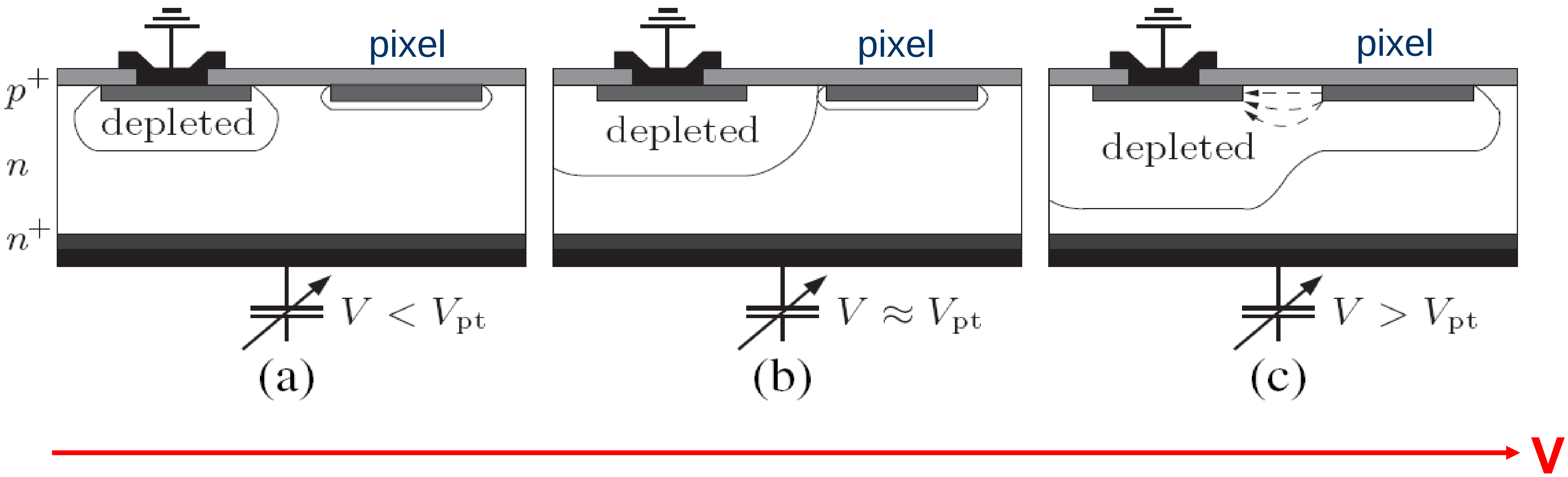
Biasing of Pixel Sensors





Biasing of Pixel Sensors

punch through biasing

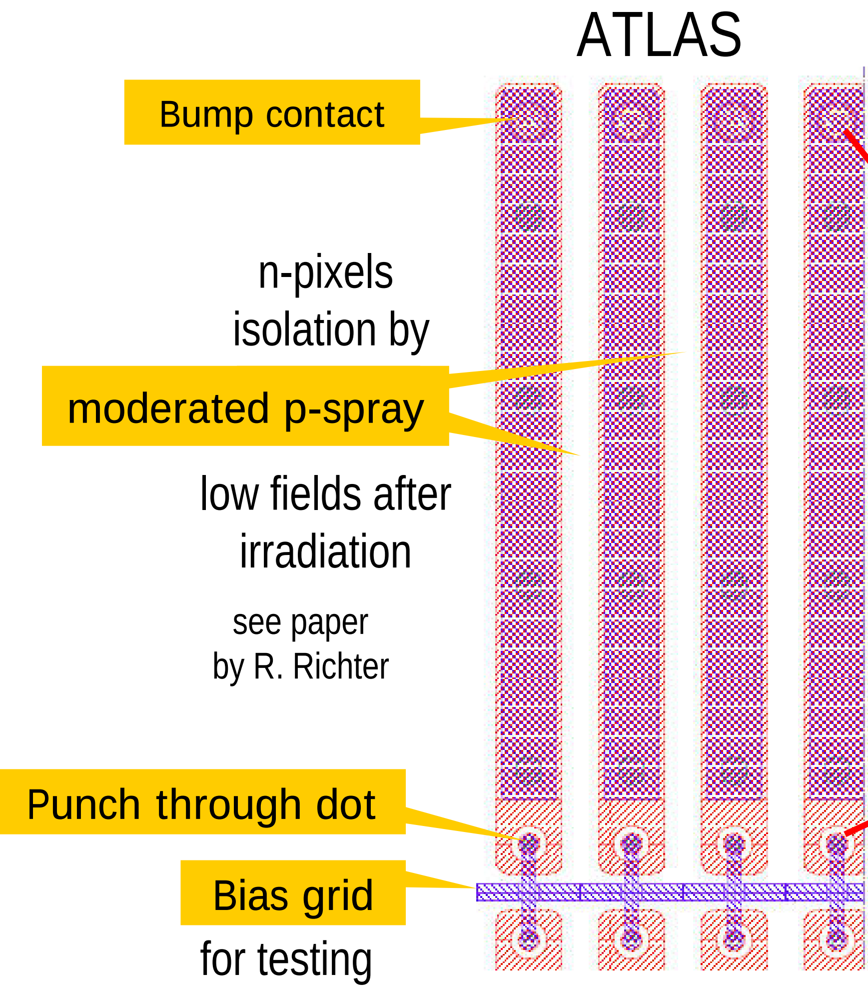


below $V_{\text{punch through}}$

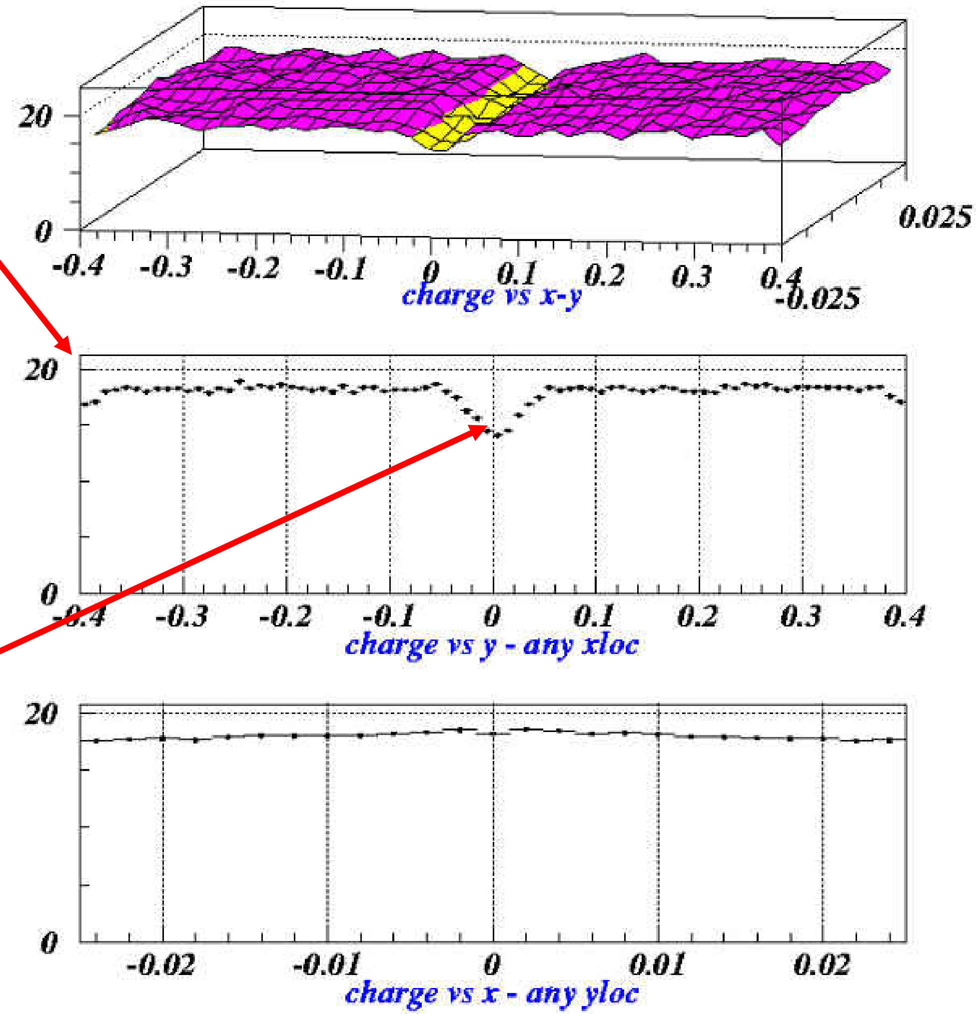
equal $V_{\text{punch through}}$

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

Biasing of Pixel Sensors

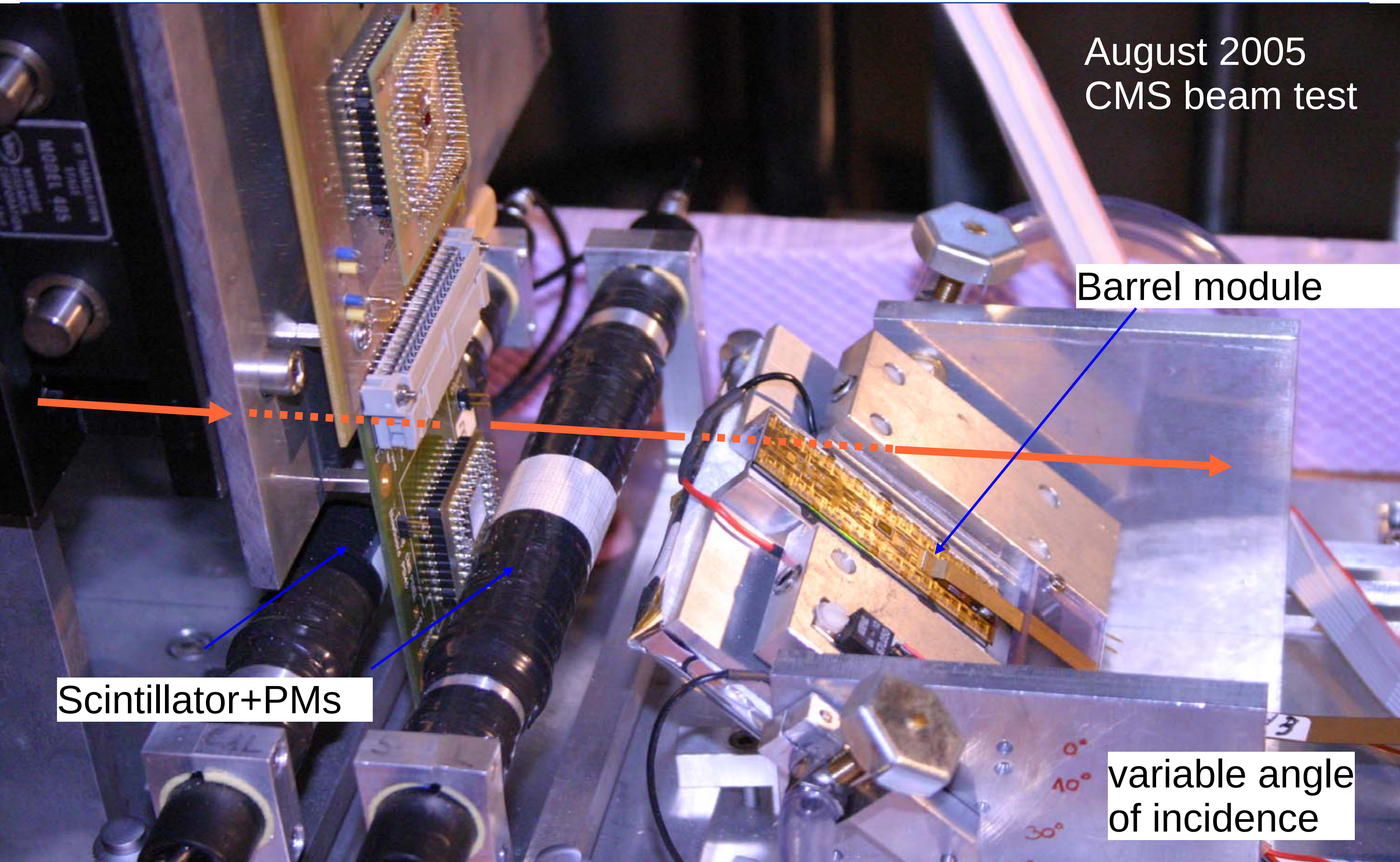


after irradiation to 10^{15} n_{eq}/cm^2



~ homogeneous charge collection after 10 years LHC

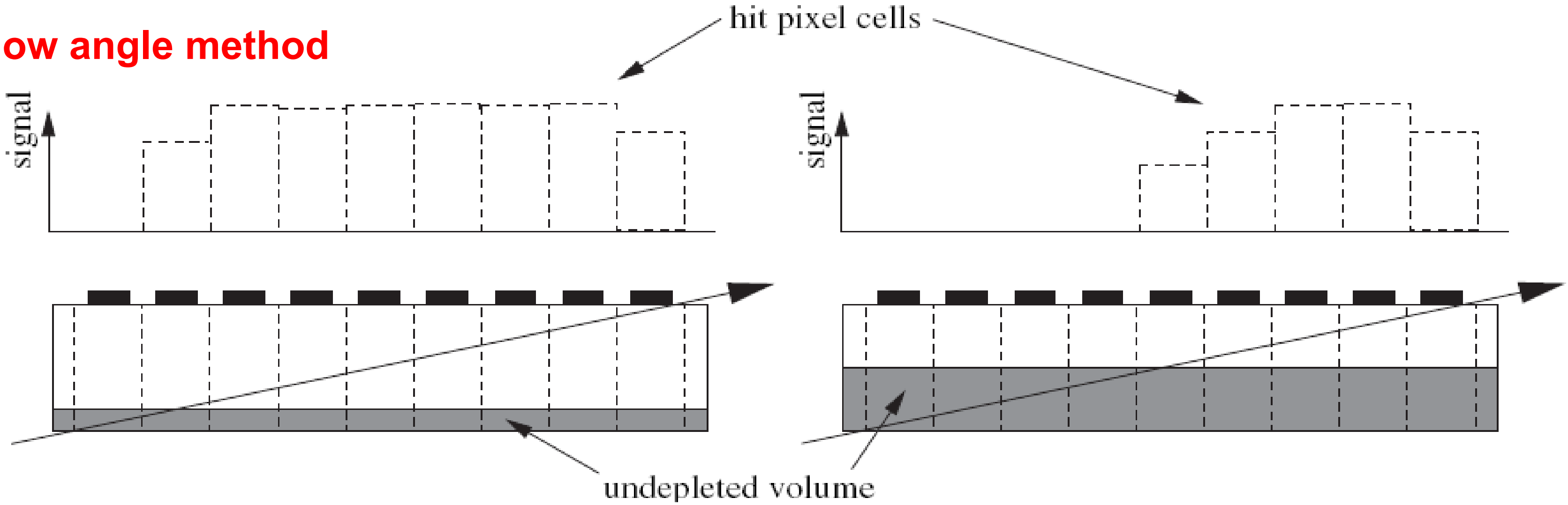
Measuring the effective depletion depth after irradiation

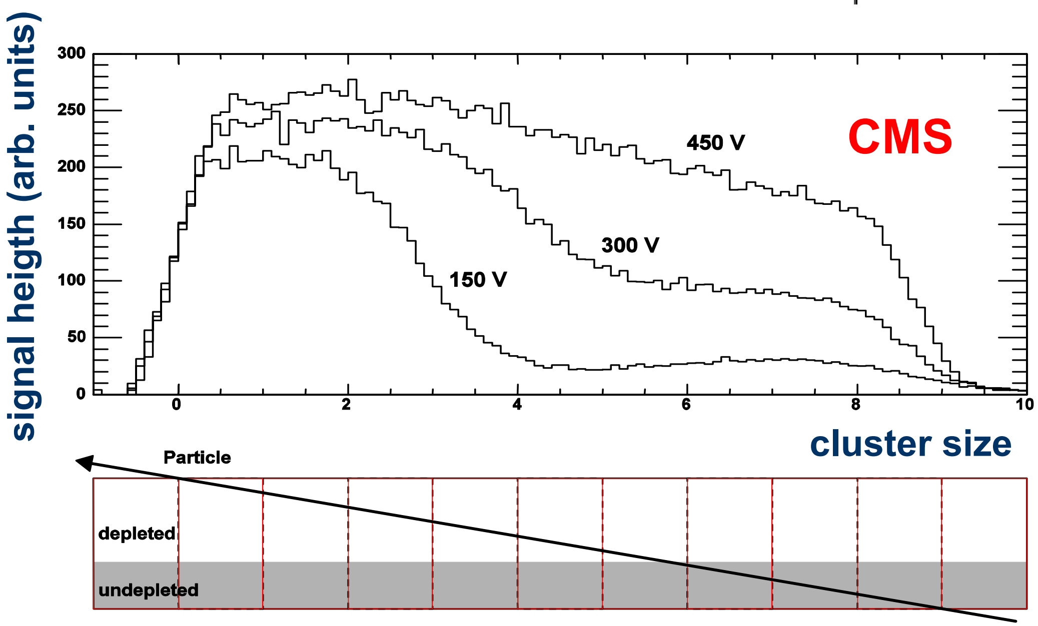


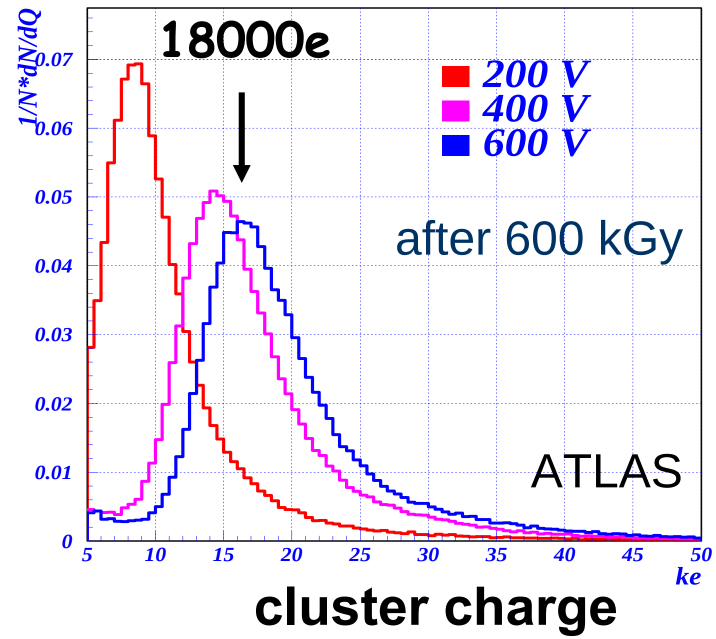
Measuring the effective depletion depth after irradiation

45min

- **Shallow angle method**

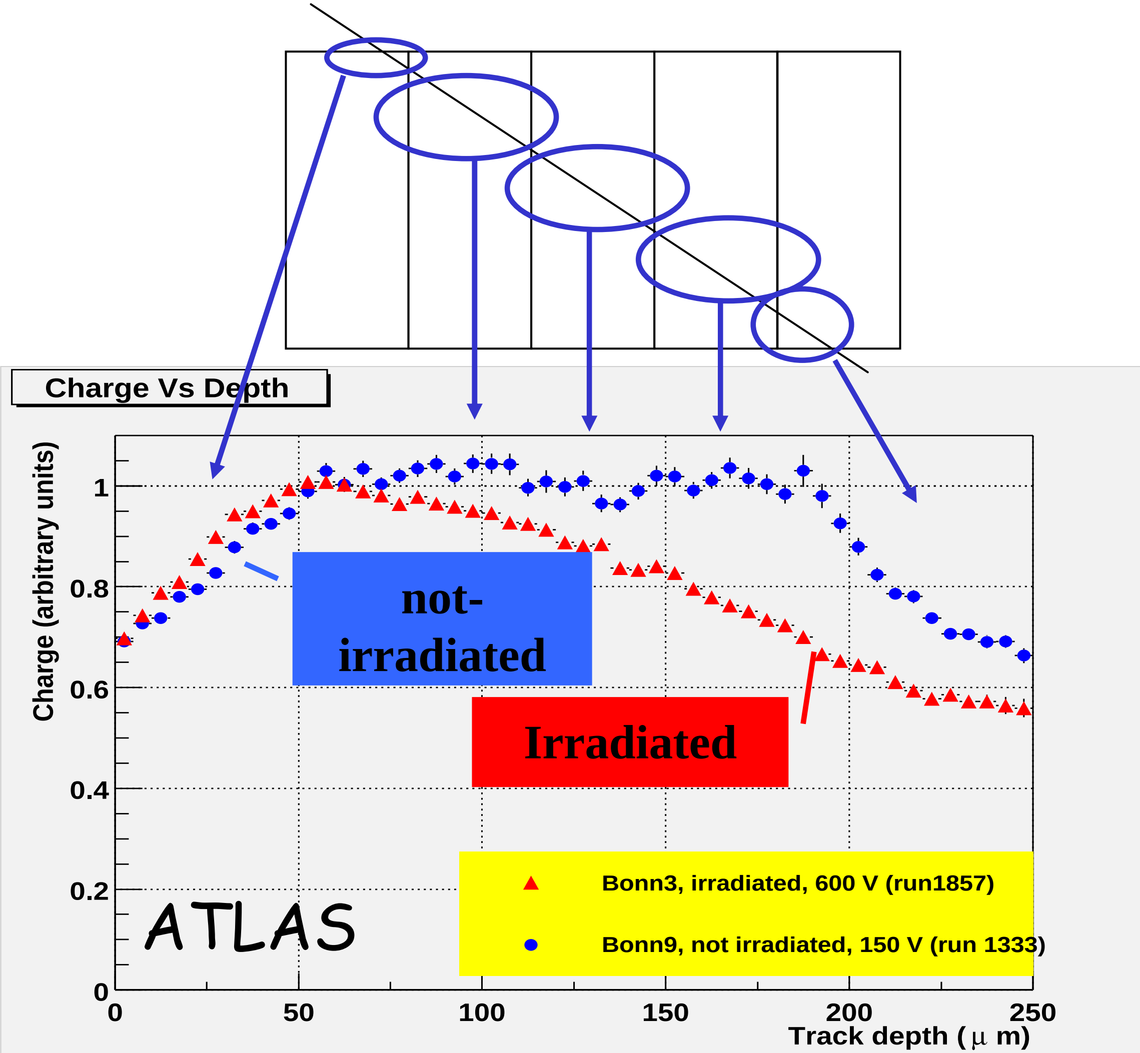






V.Chiochia, M. Swartz et al.
arxiv.org/abs/physics/0409049, IEEE NSS 04 in Rome

Trapping after 10 yrs @ LHC



Use tilted tracks again …

For non-irradiated sensors,the collected charge is uniform along the depth.

The charge yield yield as a function of the depth can be translated, via the drift velocity, in a carrier lifetime:

$$\tau_e = 4.1 \pm 0.3 \pm 0.5 \text{ ns}$$

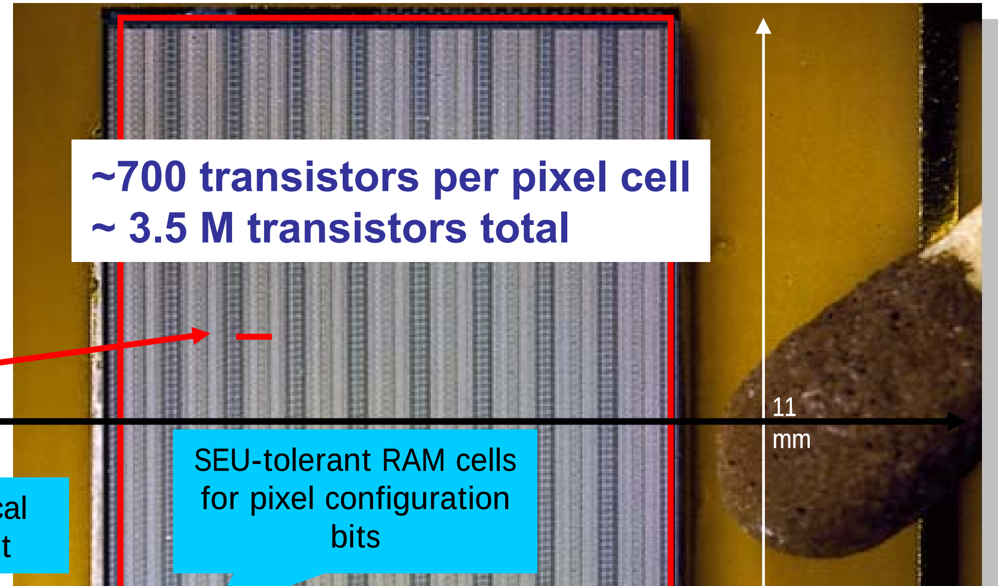
mean CCE after 10 yrs LHC ~ 80%
(with LHC type annealing scenario)

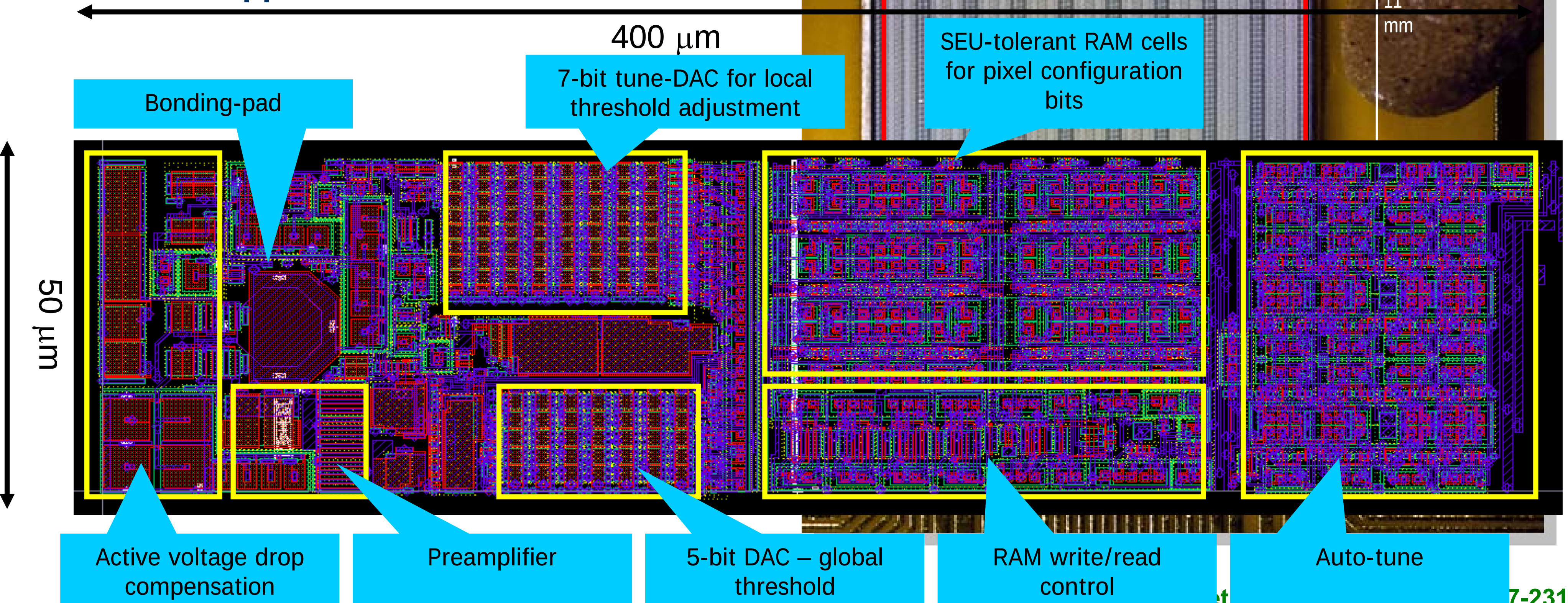
A. Andreazza et al

Pixel Frontend Chip

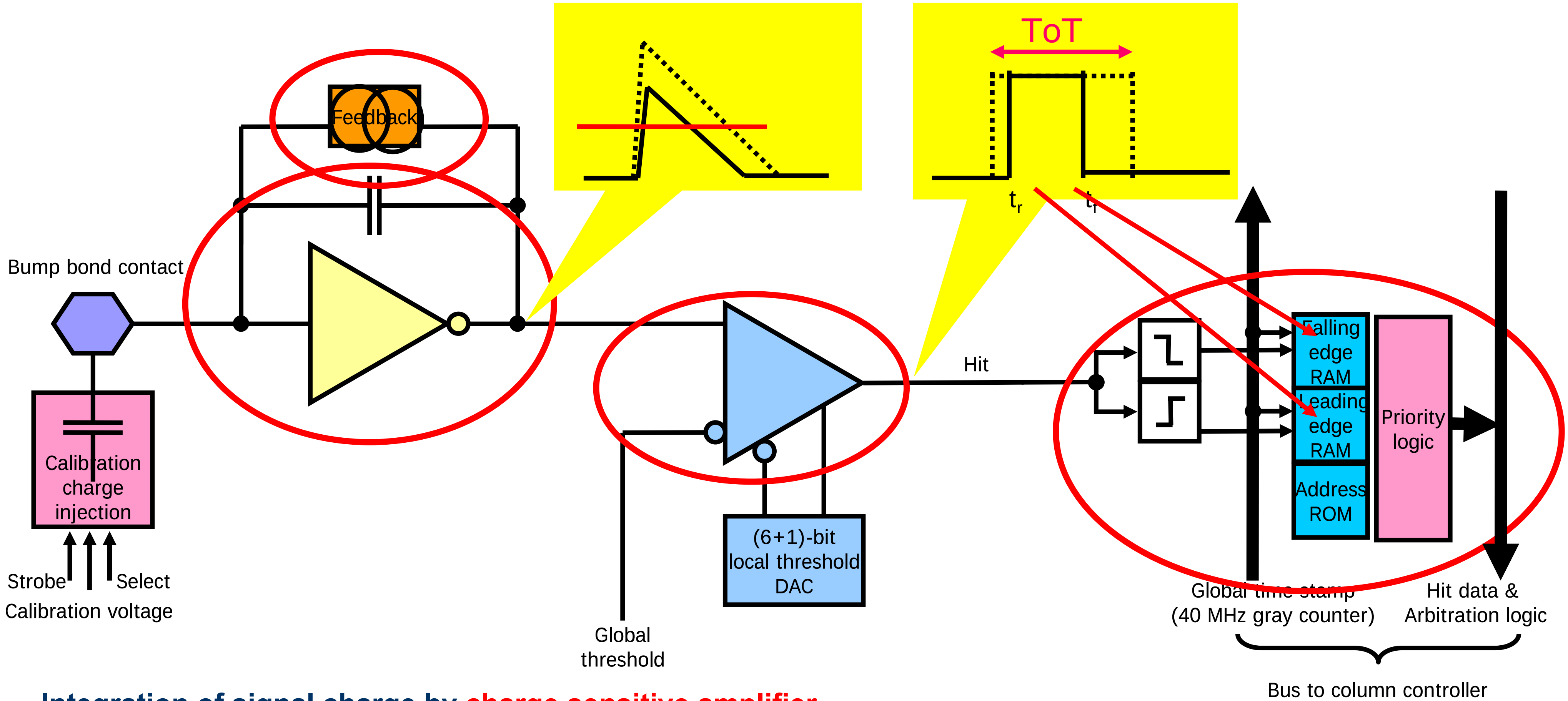
ATLAS FE-I3

- **0,25 µm CMOS technology**
- **pixel cell size: 50 x 400 µm²**
- **18 columns x 160 rows = 2880 cells**
- **parallel processing in all cells**
  - **- amplification**
  - **- zero suppression**





Functions in the cell (binary readout + „poor man‘s“ analog)

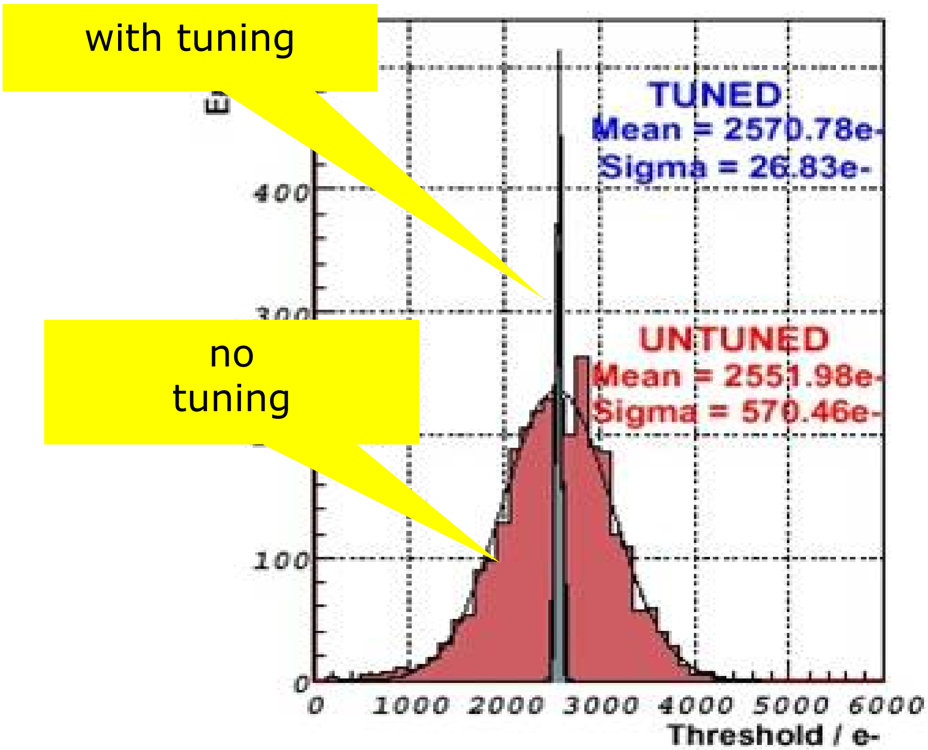


- **Integration of signal charge by charge sensitive amplifier**
- **Pulse shaping by feedback circuit with constant current feed back**
- **Hit detection by comparator**
- **~5 bit analog information via „time over threshold“**
- **storage of address and time stamps in RAM at the periphery**

L. Blanquart et al., NIM-A 456 (2001) 217-231

Requirements on the electronics performance

- **small noise hit rate → low noise and small threshold dispersion**
- **$\sigma_{noise} \oplus \sigma_{threshold}$ < ~ 600 e^- @ a threshold of 3000 e^-**
- **time stamp < 20 ns after BX for all signal heights**



Distribution of pixel cell thresholds

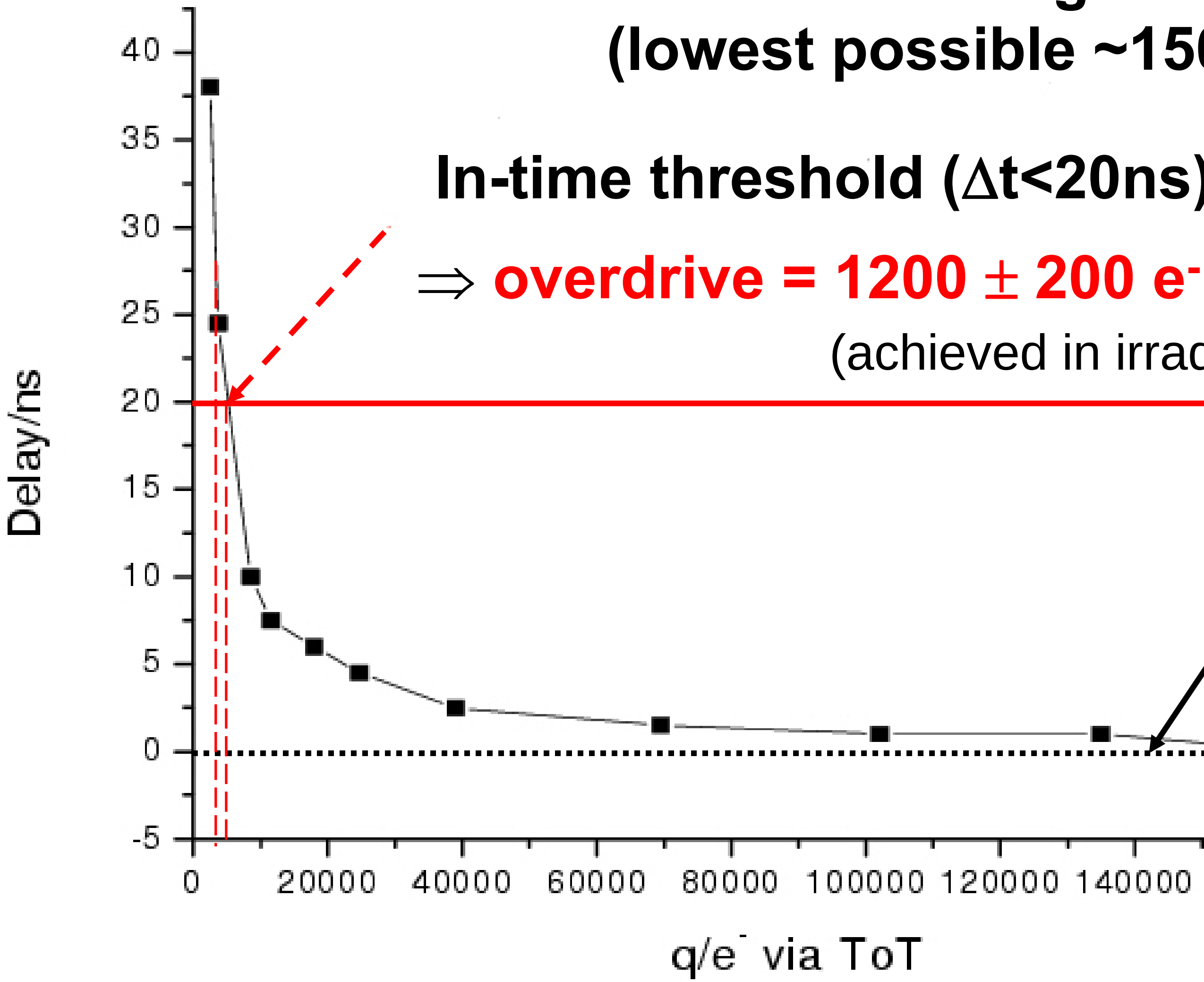
Important / in-time threshold & efficiency

set threshold e.g. to 4000 ± 200 e⁻
(lowest possible ~1500 e⁻)

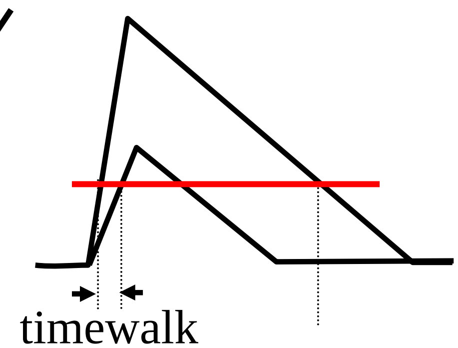
In-time threshold (Δt<20ns): 5200 ± 200 e⁻

⇒ overdrive = 1200 ± 200 e⁻

(achieved in irradiated assemblies)



zero time walk line for large signals



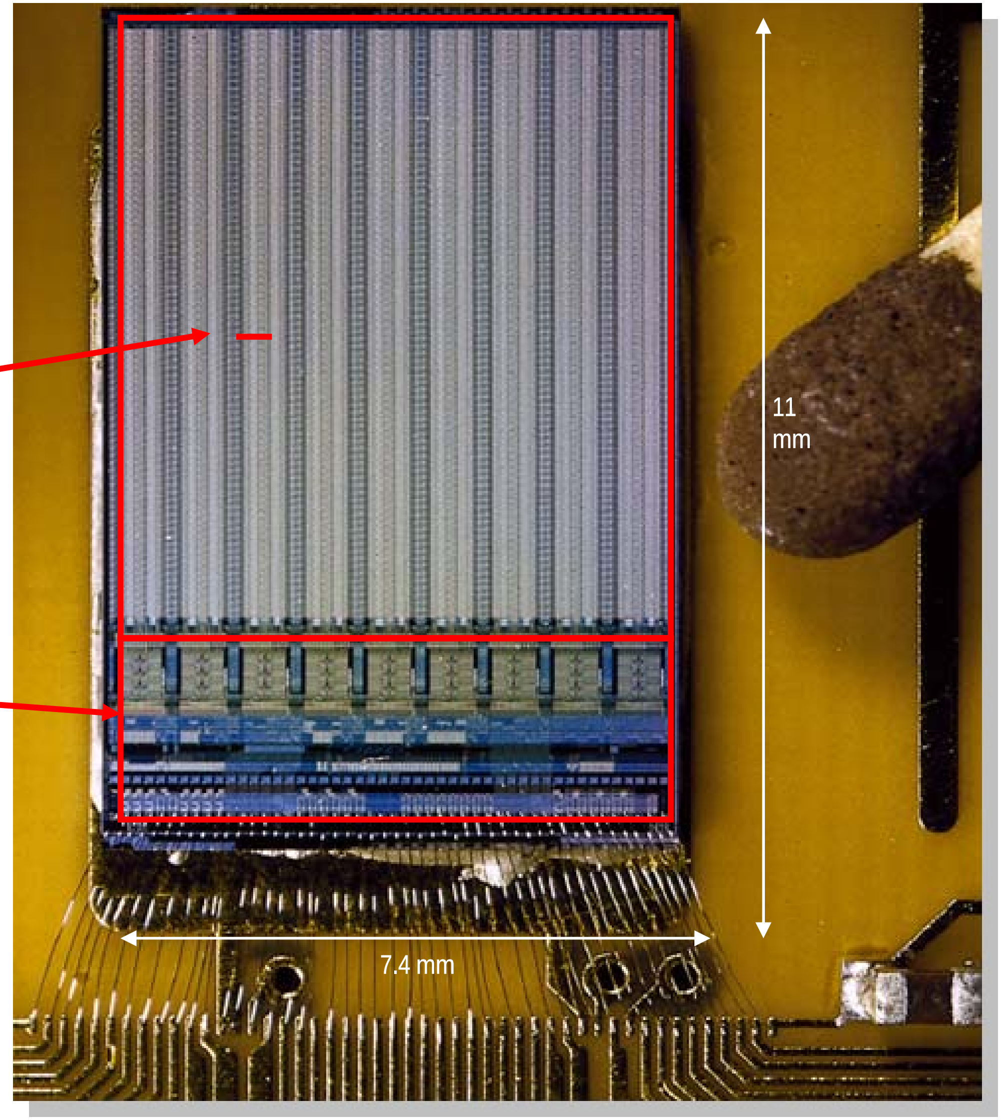
➔ in-time efficiency ~99% wanted and achieved !

Pixel Frontend Chip

ATLAS FE-Chip

- 0,25 µm CMOS technology
- pixel cell size: 50 x 400 µm^2
- 18 columns x 160 rows = 2880 cells
- parallel processing in all cells
  - amplification
  - zero suppression

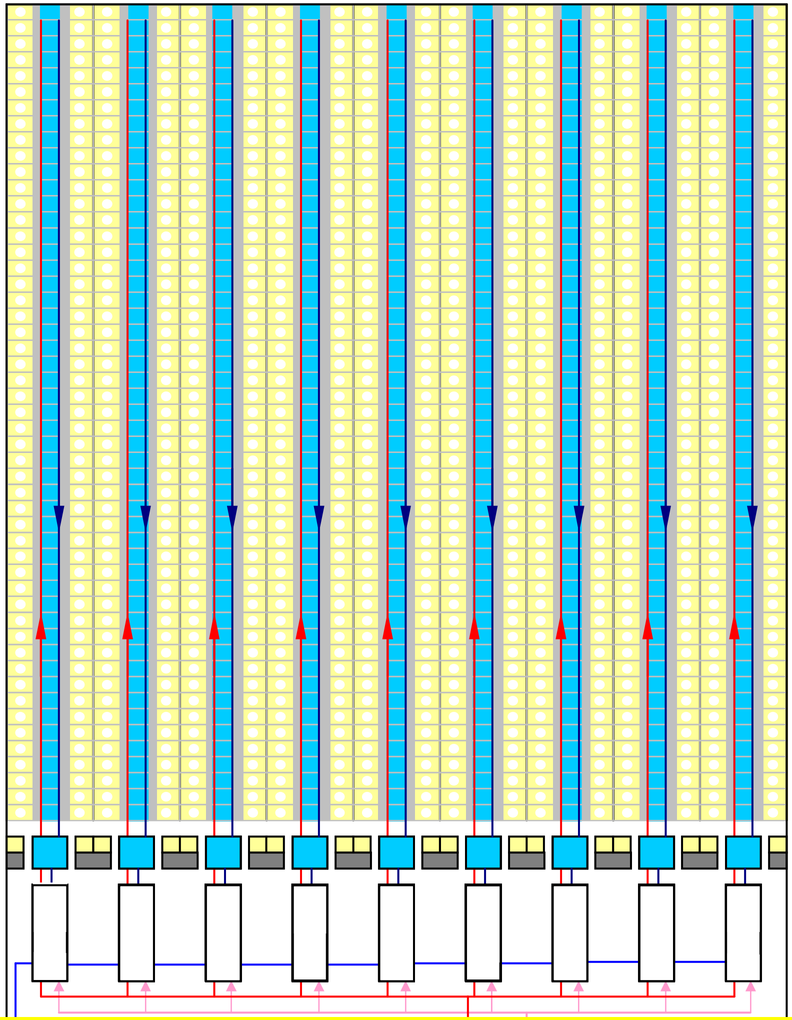
- **end of column logic**
  - storage of hit information during trigger latency (2.5 µs)
  - hit selection upon L1 trigger



L. Blanquart, P. Fischer et al., NIM-A 456 (2001) 217-231

ALTAS FE-chip readout architecture (animated)

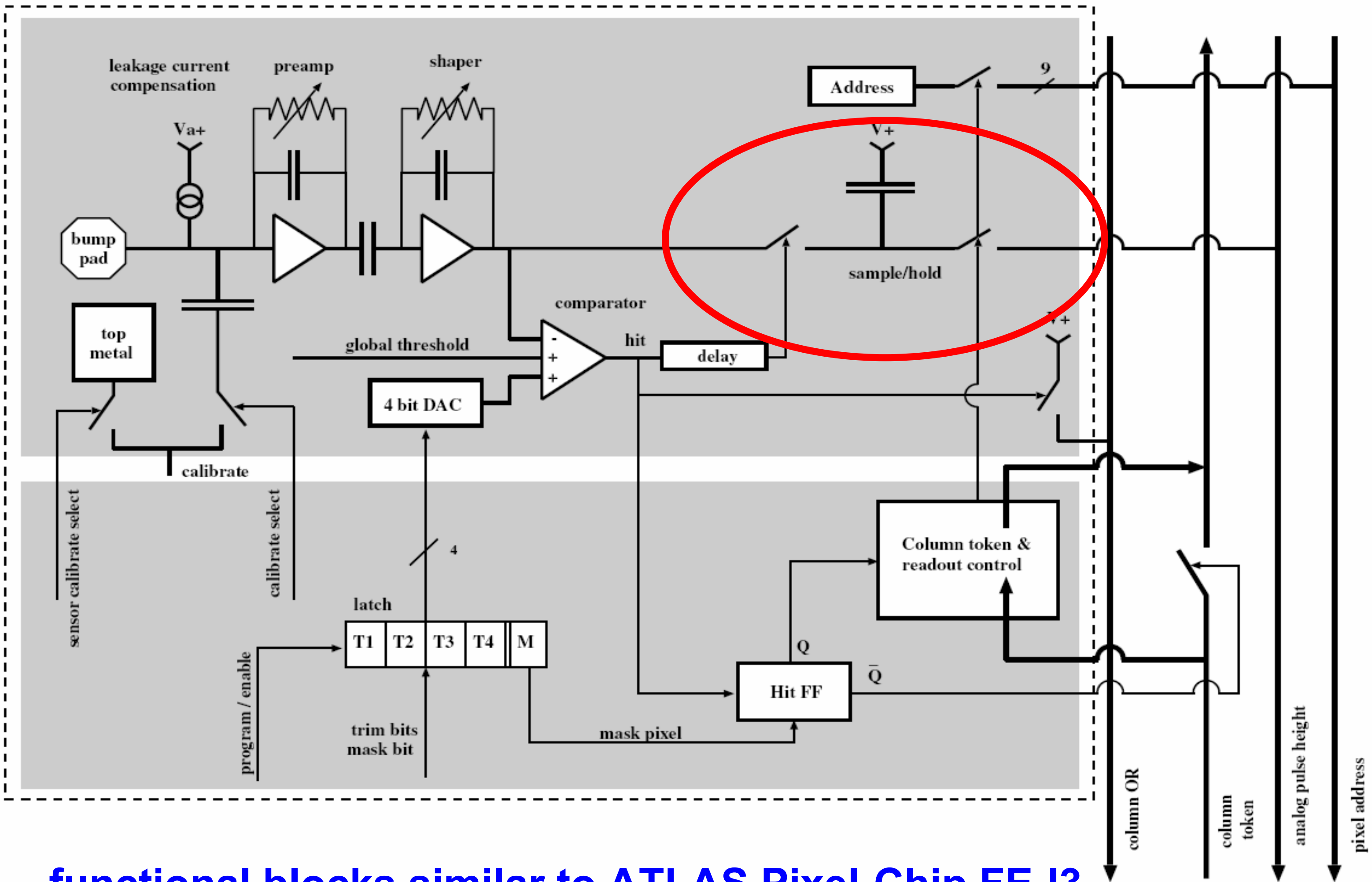
- 40 MHz Gray coded clock transmitted to all cells
- Pixel cells generate hit information (address and time stamp) which are stored at the end of column
- hits are removed if no trigger conicidence occurs
- Hit information agreeing with **L1 trigger time** are read out



- Analogue circuits
- Digital readout circuits
- Registers used to store configuration bits
- Time information
- Trigger

ATLAS Pixel Chip: binary hit information with additional information on signal hight via ToT measurement (~4-5 bit)

CMS pixel-chip (analog readout)



CMS Pixel-Chip PSI46V2

functional blocks similar to ATLAS Pixel-Chip FE-I3

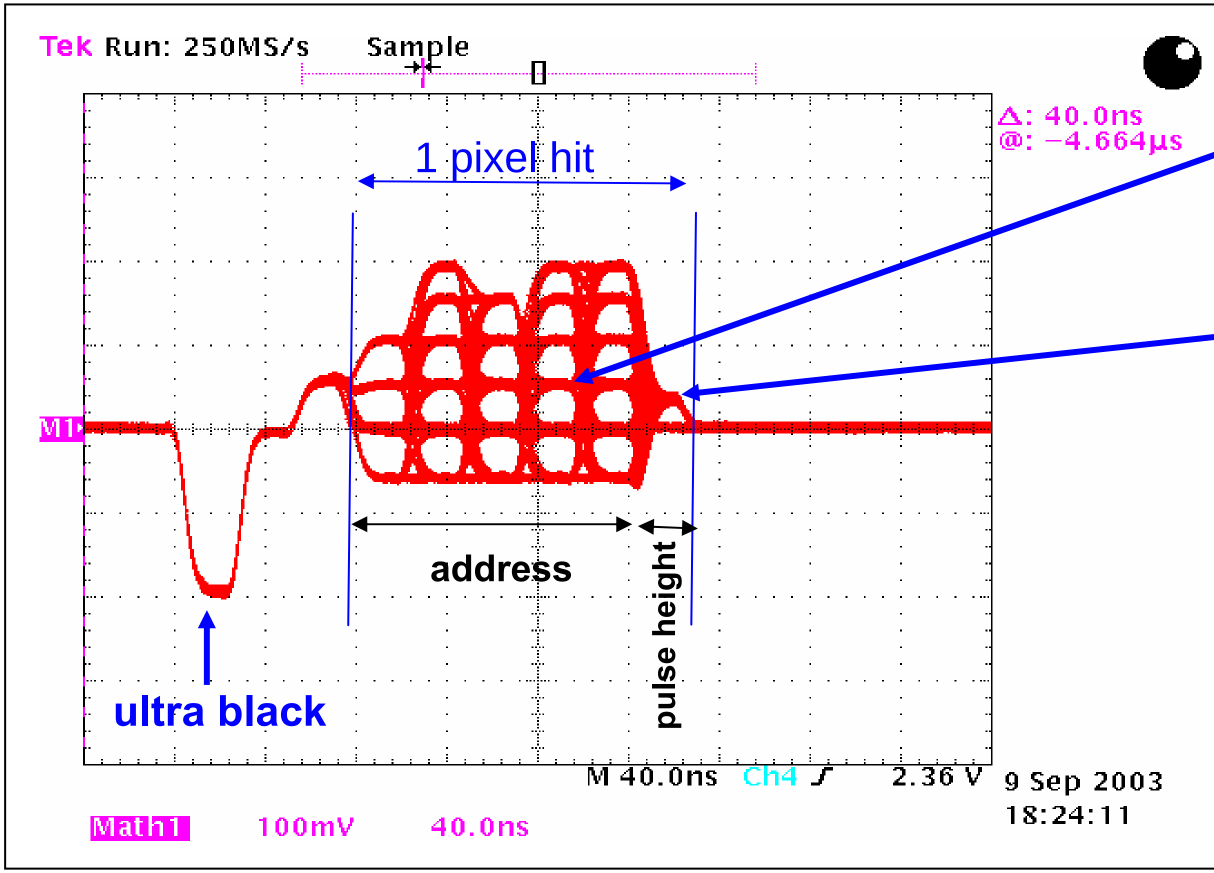
additional storage of analog pulse height (sample/hold)

analog output signal → amplitude + row/column address coded in analog levels

H.C. Kastli et al., e-print physics/0511166

CMS pixel-chip (analog readout)

• Overlay of 4160 pixel readouts (analog coded address levels)



5 clock cycles encode 13 bits of pixel address information.

analog pixel pulse height

pixel address decoded into binary numbers for DAQ

H.C. Kastli et al., e-print physics/0511166

Radiation damage to the FE-electronics … and cure

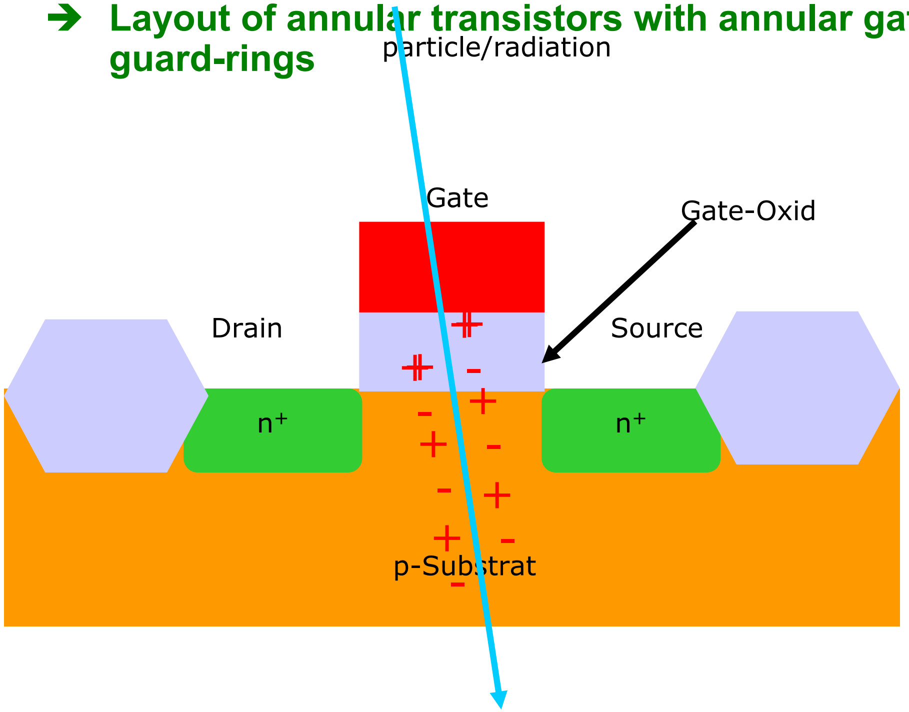
Effects: generation of positive charges in the SiO_2 and defects in Si - SiO_2 interface

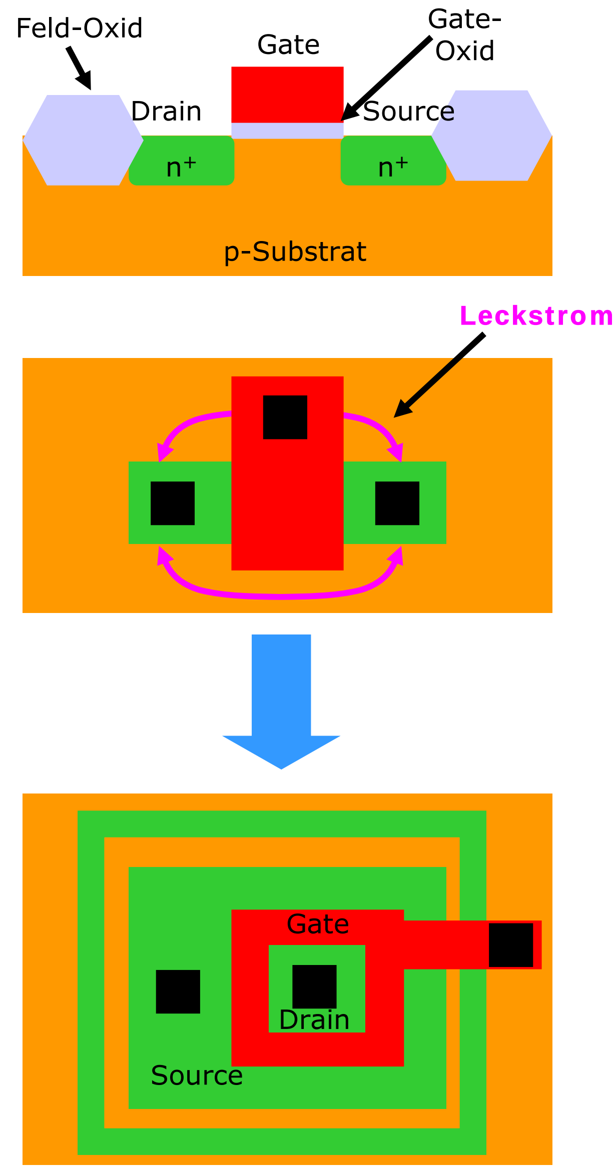
1. Theshold shifts of transistors

➔ **DSM CMOS technologies with small structure sizes (≤ 0,35 µm) and thin gate oxides (d_{ox} < 10 nm) → holes tunnel out**

2. Leakage currents under the field oxide

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



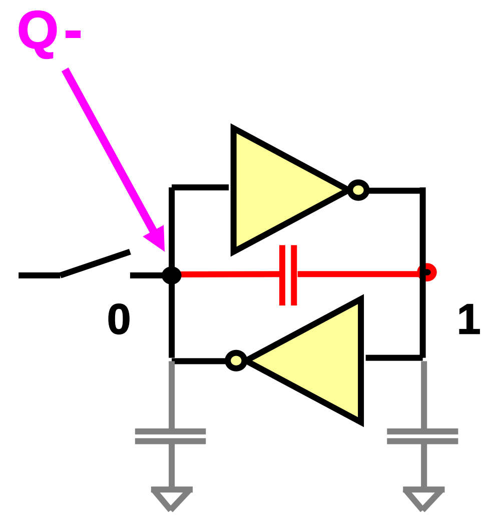


Radiation damage to the FE-electronics … and cure

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“

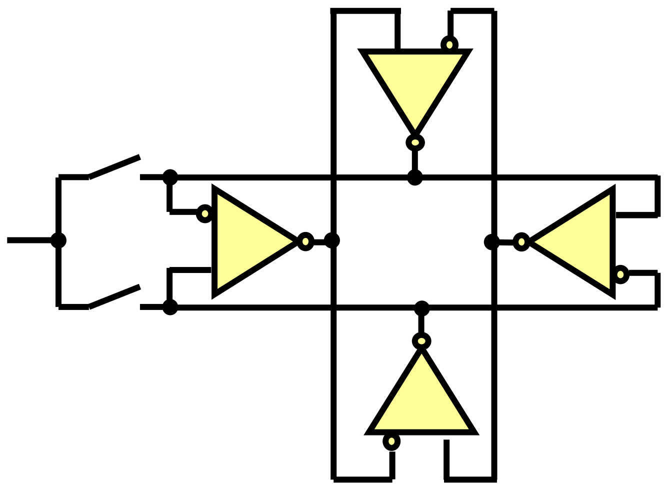


standard SRAM cell

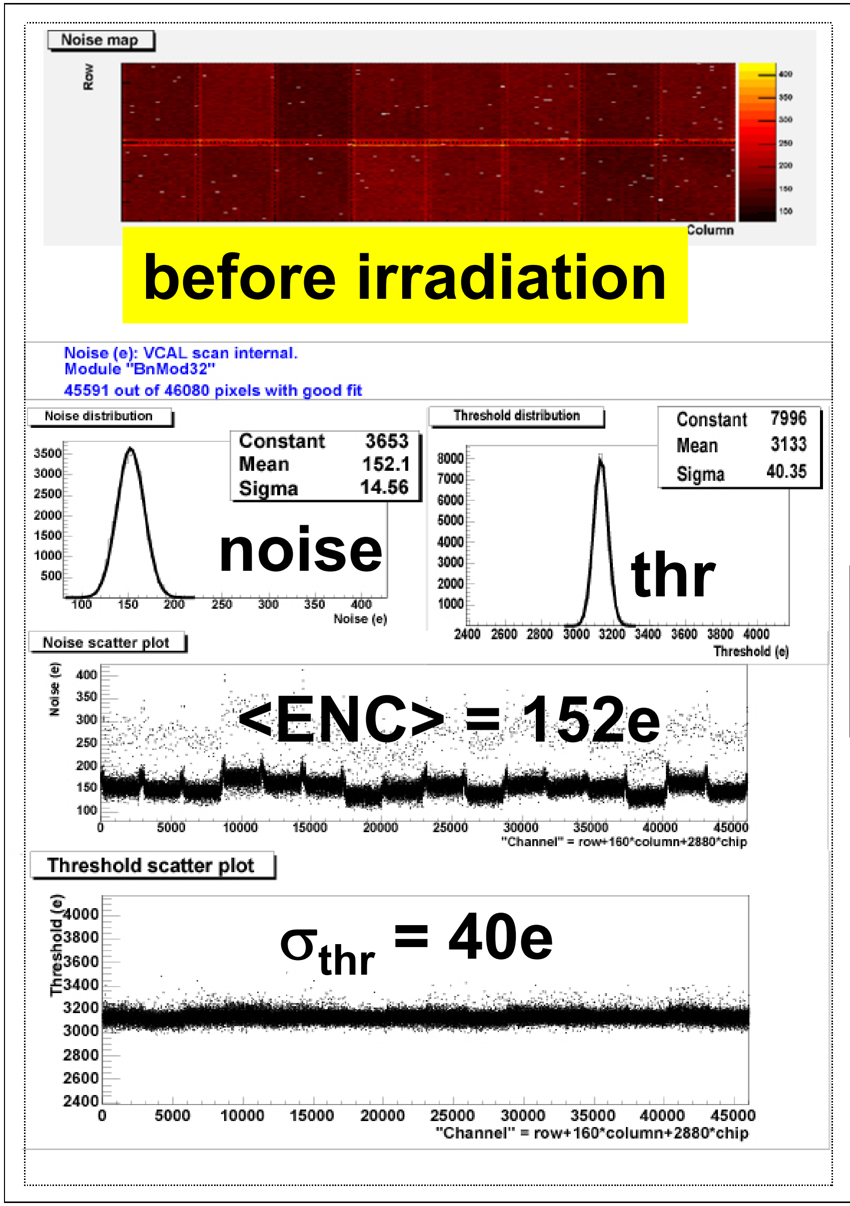
2 examples of error resistant logic cells

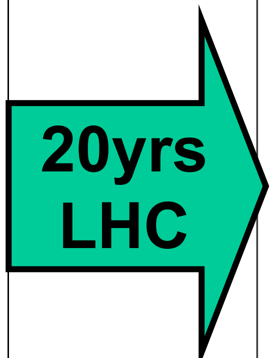
➔ enlarge storage capacitances in SRAM cells:
$Q_{crit} = V_{threshold} \cdot C$

➔ storage cells with redundancy (DICE SRAM cell)

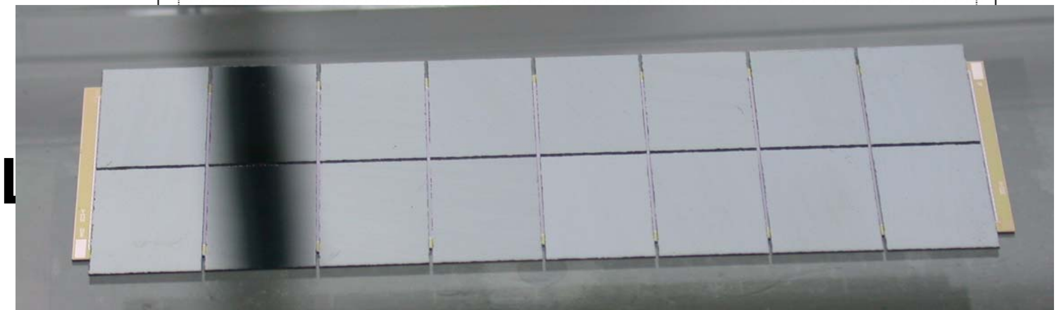

SEU tolerant DICE SRAM cell

Irradiated Modules after 1 MGy (20 years @ LHC)

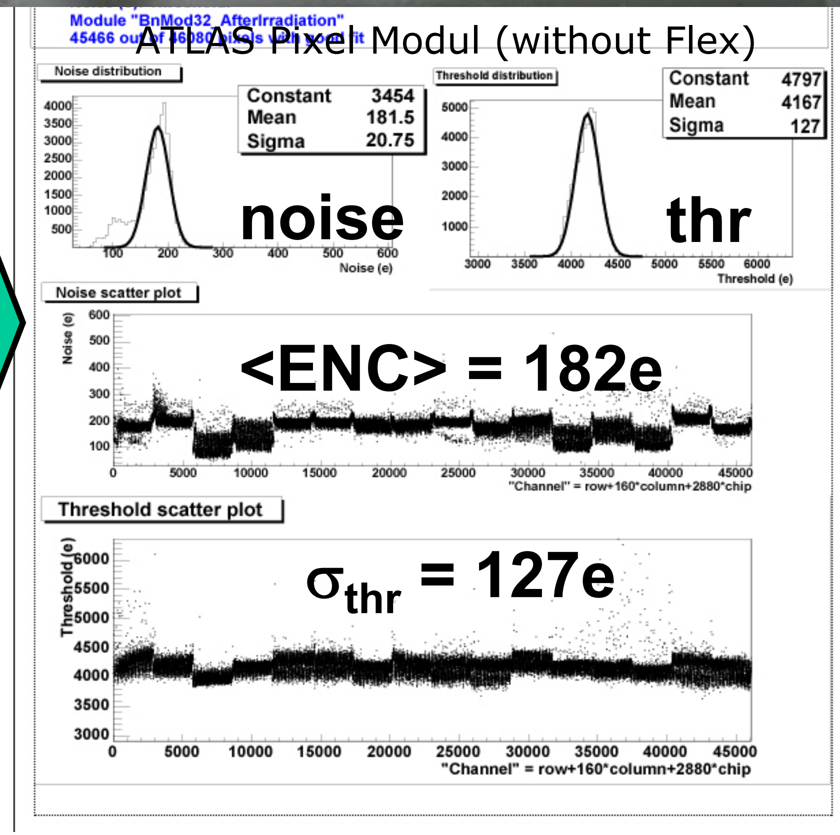




ATL

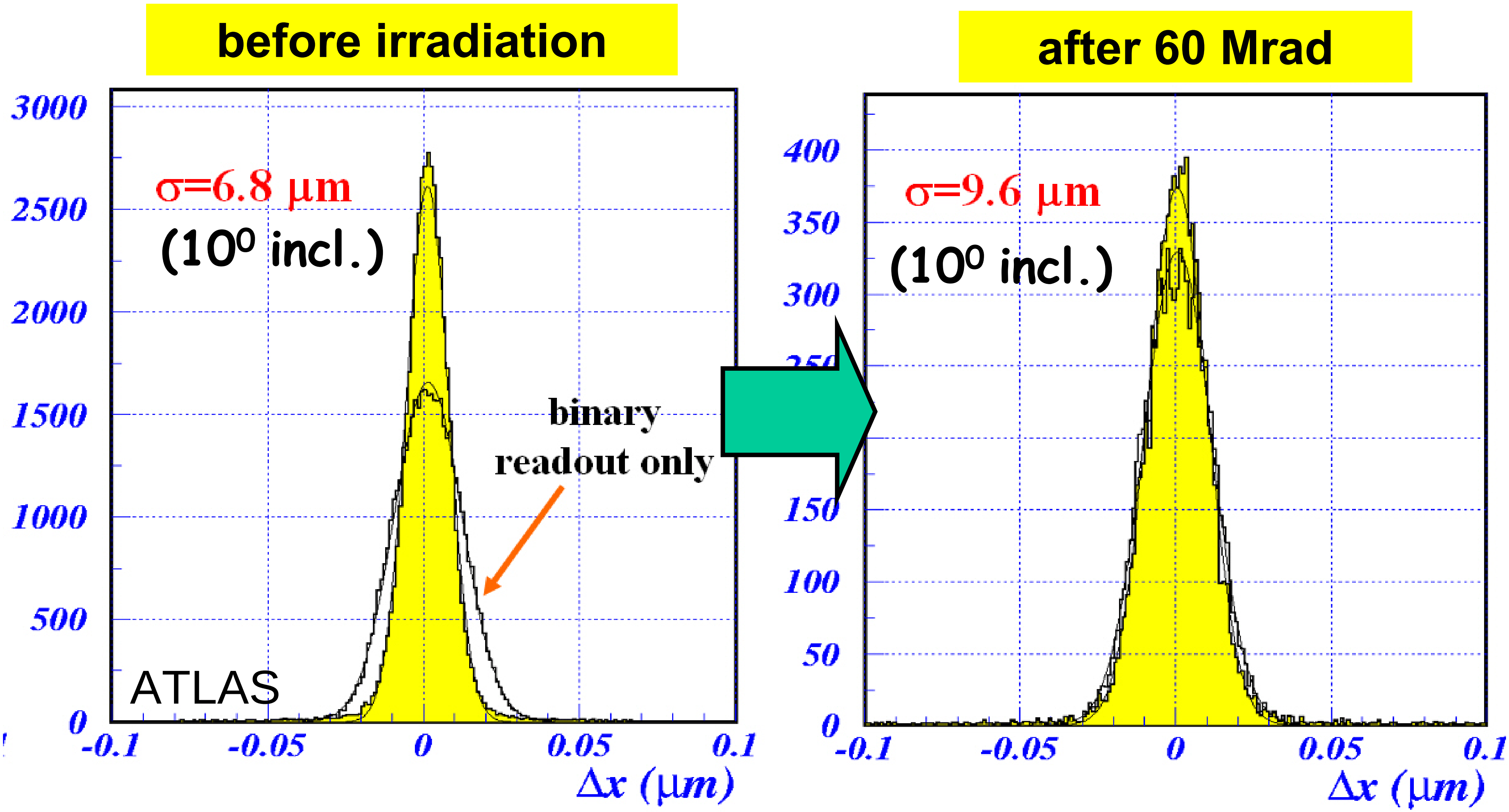


ATLAS Pixel Modul (without Flex)



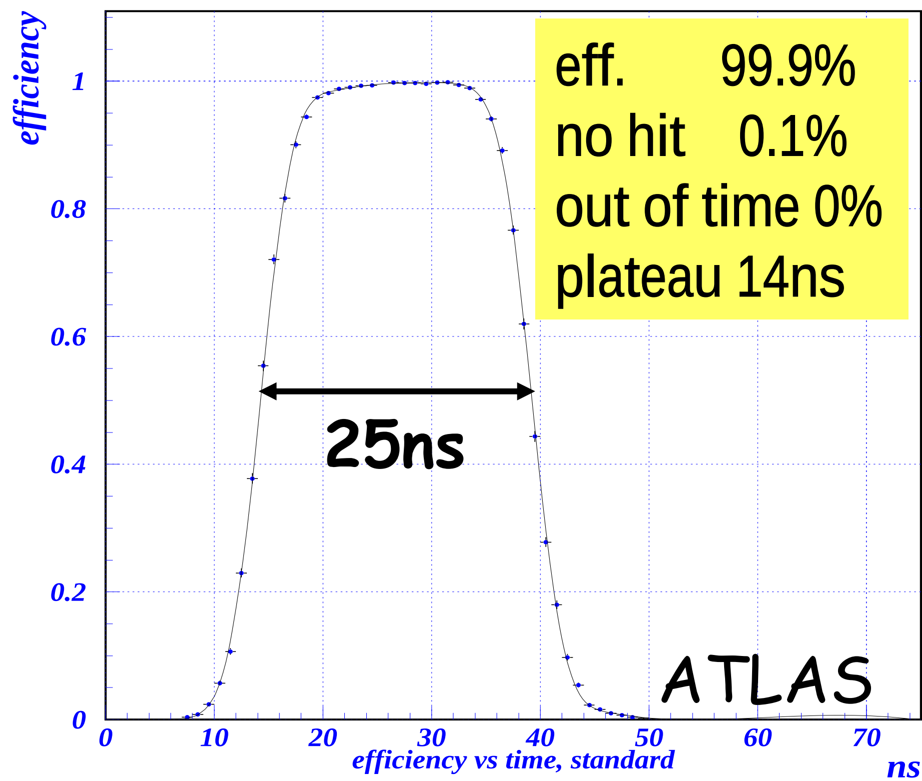
A. Andreazza NIM-A 513:103-106,2003

Spatial resolution in irradiated assemblies

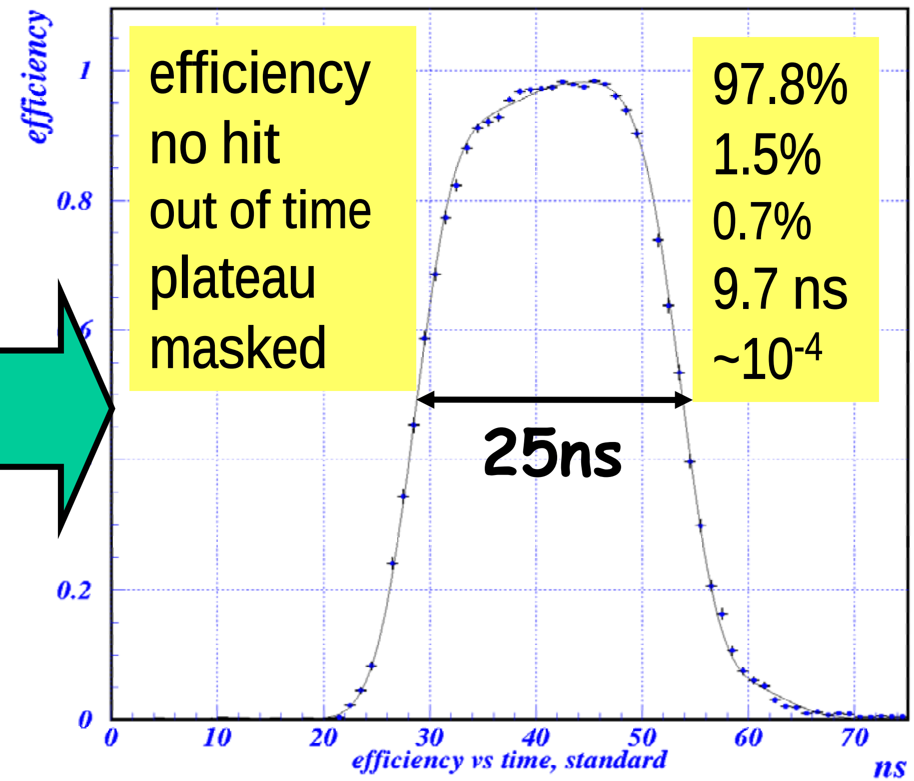


In-time track efficiency in irradiated assemblies

before irradiation



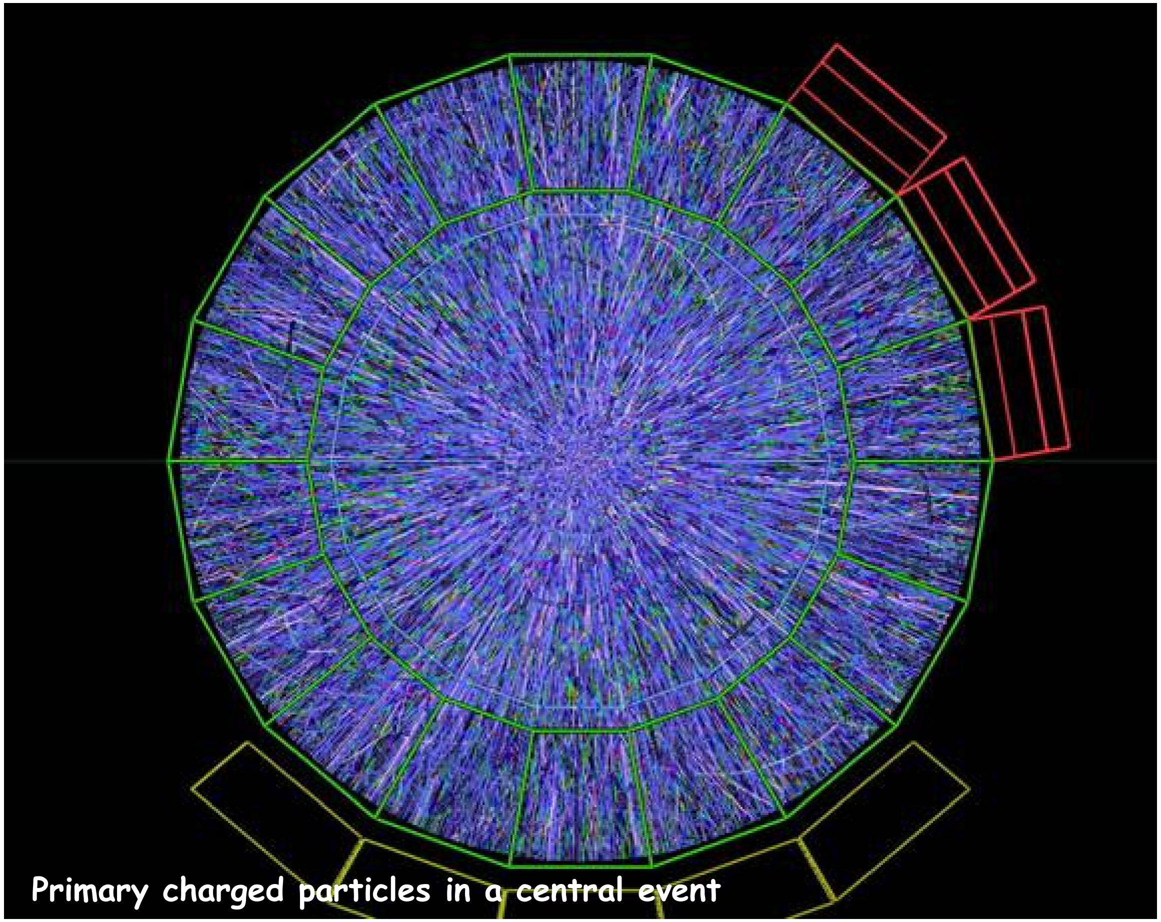
after 600 kGy



large in-time plateau for efficency margin

Main issue for ALICE: minimal material

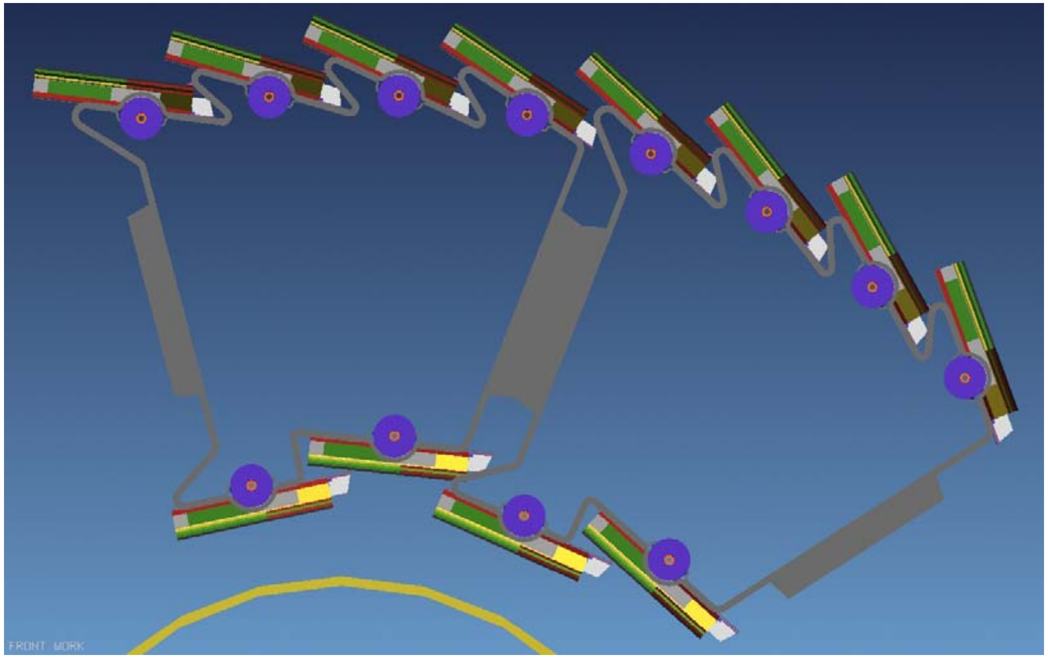
In central HI collisions up to 8000 charged particles/ |η| are expected.



~80 hits/cm²

radiation levels only ~ 5 kGy, $6x10^{12}$ n_{eq} / cm^2
→ operation at room temperature possible !

Main Issue for ALICE: minimal material



very light weight Carbon Fibre support structure (200µm,0.1 X_0)

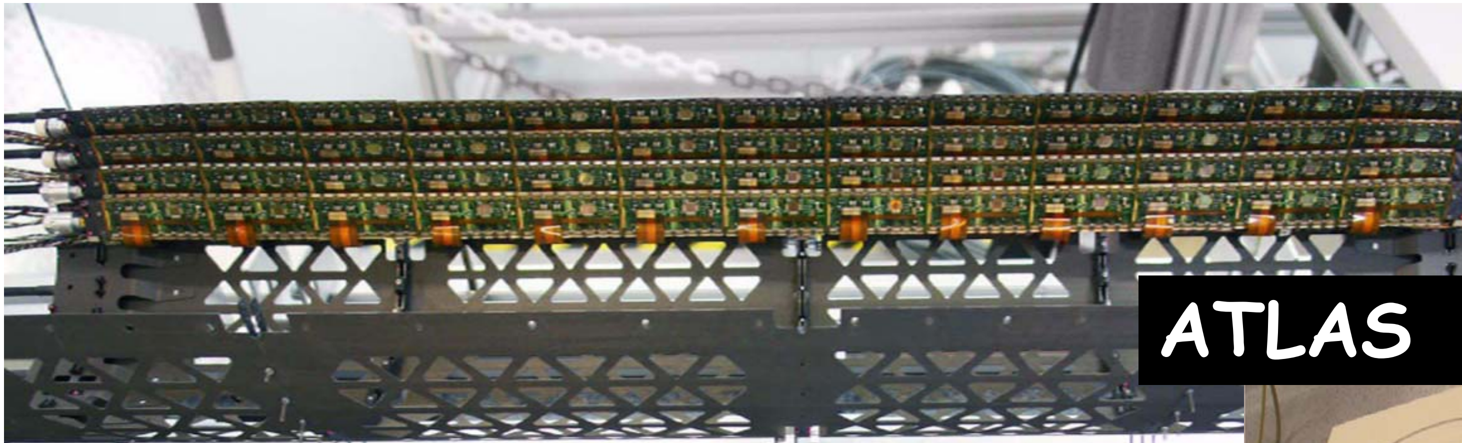
total X_0 per layer ~ 0.9%

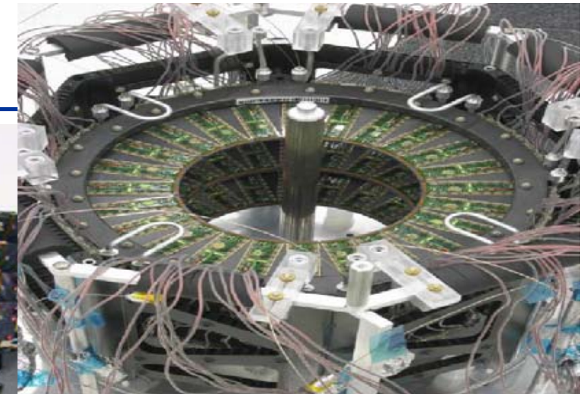
sensor	200µm
IC	150µm
cooling (C_4F_{10}) @ RT	0.3% X_0

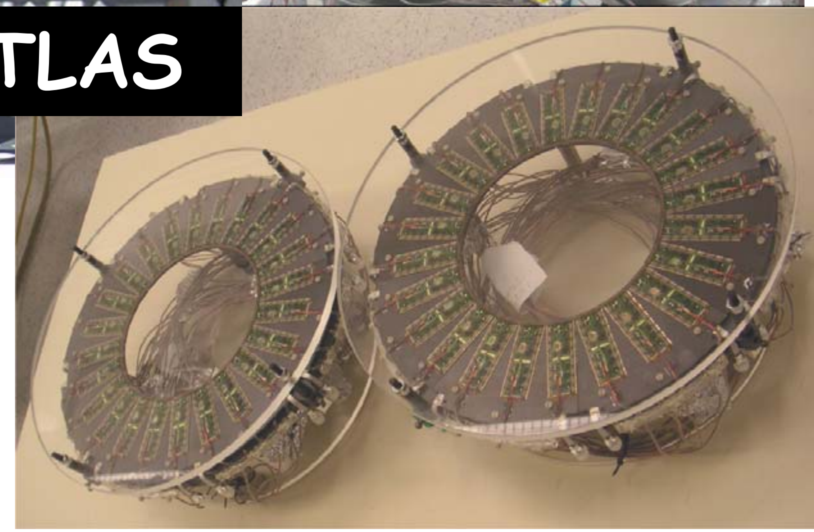
(PHYNOX tubes, wall 40µm)

(ATLAS, CMS > 2%)

Hybrid Pixels / Ladders and Disks







- minimal X_0 “C-C” structures
- cooling (pumped C_3F_8 : boil. point = -25^0)
- T < -6^0 C to limit damage from irradiation
- power dissipation: ~100W/stave
  (ATLAS) ~15kW/detector

Hybrid Pixel Detectors @ LHC

complex signal processing in cells

- **zero suppression**
- **temporary storage of hits during L1 latency**

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

spatial resolution ~ 10–15 µm

… but also

relatively large material budget: ~ 2% X_0 per layer (1% X_0 @ ALICE)

- **cooling, services**

complex and laborious module production

- **bump-bonding / Flip-Chip → expensive**
- **many production steps**

Conclusions

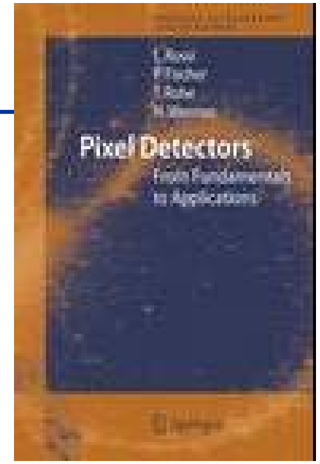
- hybrid pixel detectors are the "state of the art" of pixel vertex detectors

- spin-offs into imaging applications are abound
  - X-ray pixel detectors (MPEC, MEDIPIX, CiX)
  - X-ray astronomy (DEPFET, CdTe pixels)
  - time resolved autoradiography
  - … many more

- next challenges are around the corner
  - Super-LHC
    - radiation fluences up to 10^{16} n_{eq}/cm^2 → new sensor types
    - "light weight" → less power, new cooling, new mechanics
    - data band width → 40 MHz → >GHz
  - Monolithic pixel detectors for ILC
    - (semi)-monolithic pixel detectors: MAPS, DEPFET
    - new technologies: SOI pixels, a-Si:H pixels

- Join in ! There is enough to do !

Further Reading



- Rossi, Fischer, Rohe, Wermes, “Pixel Detectors: From Fundamentals to Applications”, Springer Berlin-Heidelberg-New York, 2006, (ISBN 3-540-283324)
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- N. Wermes, “Pixel Detectors for Tracking and theirs Spin-off in Imaging Applications” Nucl.Instrum.Meth.A541:150-165,2005, e-Print Archive: physics/0410282
  and “Pixel detectors”, in LECC2005 Heidelberg 2005, Electronics for LHC and future experiments
  e-print Archive: physics/0512037
- ATLAS Pixel Detector, Technical Design Report, CERN/LHCC/98-13 (1998)
  CMS Tracker Technical Design Report, CERN/LHCC/98-6 (1998)
  ALICE Inner Tracker System, Technical Design Report, CERN/LHCC/99-12 (1999)
- R. Horisberger, “Readout Architectures for Pixel Detectors”, NIM A465 (2001) 148-152
  L. Blanquart et al., “Pixel Readout Electronics for LHC and Biomedical Applications”, NIM A439 (2000) 403-412

Outline

1. **Introduction**

   From gas-filled chambers to pixel vertex detectors

2. **Hybrid Pixel Detectors for the LHC**

   The Signal and the Noise in Pixel Detector

3. **Making a Pixel Detector**

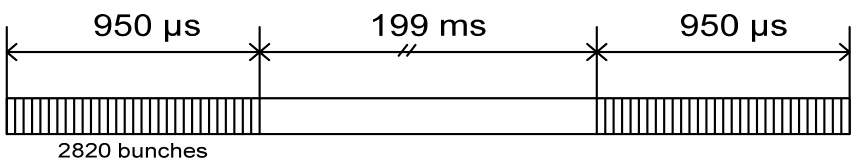
   From sensor to module-ladder

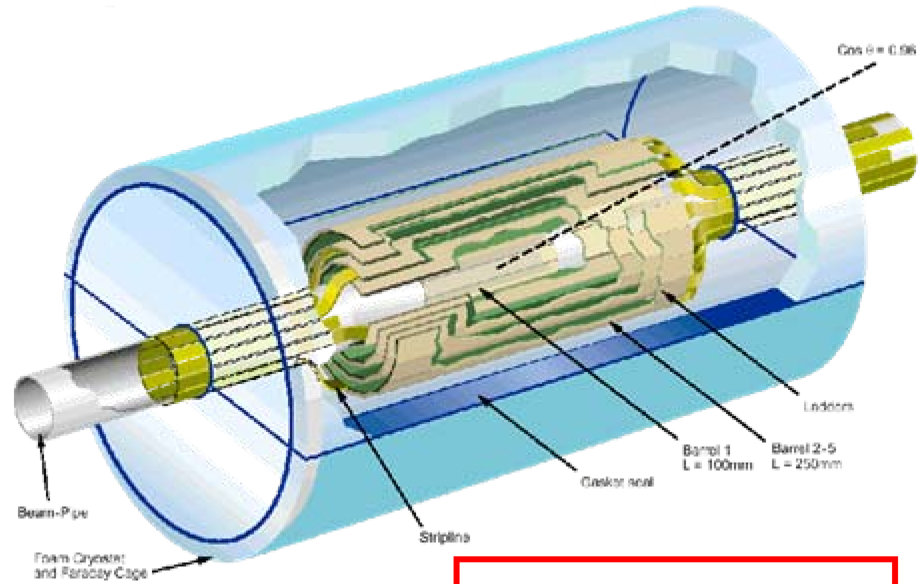
4. **Pixel R&D for Future Colliders (addendum)**

   New developments for the ILC

Pixel Detectors for a Linear Collider

Time structure and rates





- 80 hits / mm^2 / bunch train @ r=1.5 cm

→ b/c tagging

Requirements

- **Thin** (< 50 µm, 0.1% X_0) → **monolithic**
- > 500 Mpix with small cells (< 25x25 µm2)
- Fast (50 MHz/line, 25 kHz/frame ≈2Mpix)
- Low power (few Watts for full detector)
- Radiation tolerance < 4 kGy = 1/25 of LHC
- No trigger

R&D
CCD
MAPS
DEPFET
SOI …

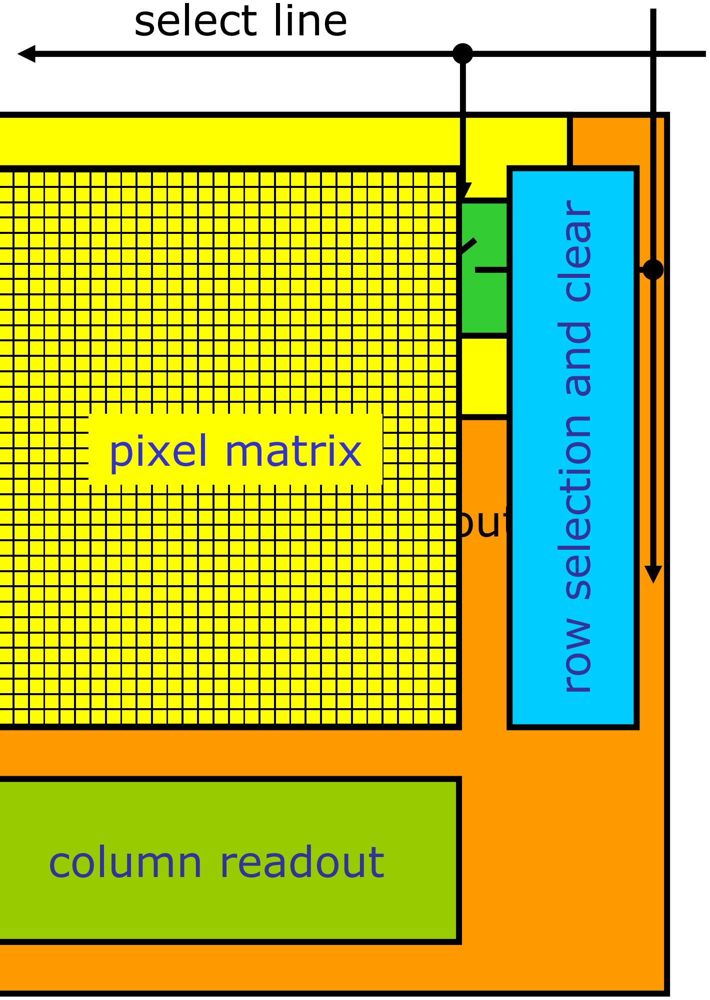
Principle of (semi-) monolithic pixel detectors

generation and integration of signal in same substrate

- pn-diode ➔ Q_{Signal}
- collection diode (transistor gate)

  ➔ $U_{Signal} = Q_{Signal} / C_g$

  or $I_{Signal} = g_m \cdot Q_{Signal} / C_g$
- row wise selection of pixels
- column wise readout
- switch in cell (select/reset)



MAPS (CMOS active pixels)

- same CMOS substrate (low resistivity) for steering/readout electronics and Q - collection

DEPFET

- amplifying transistor on fully depleted bulk (high resistivity), separate steering and R/O chips

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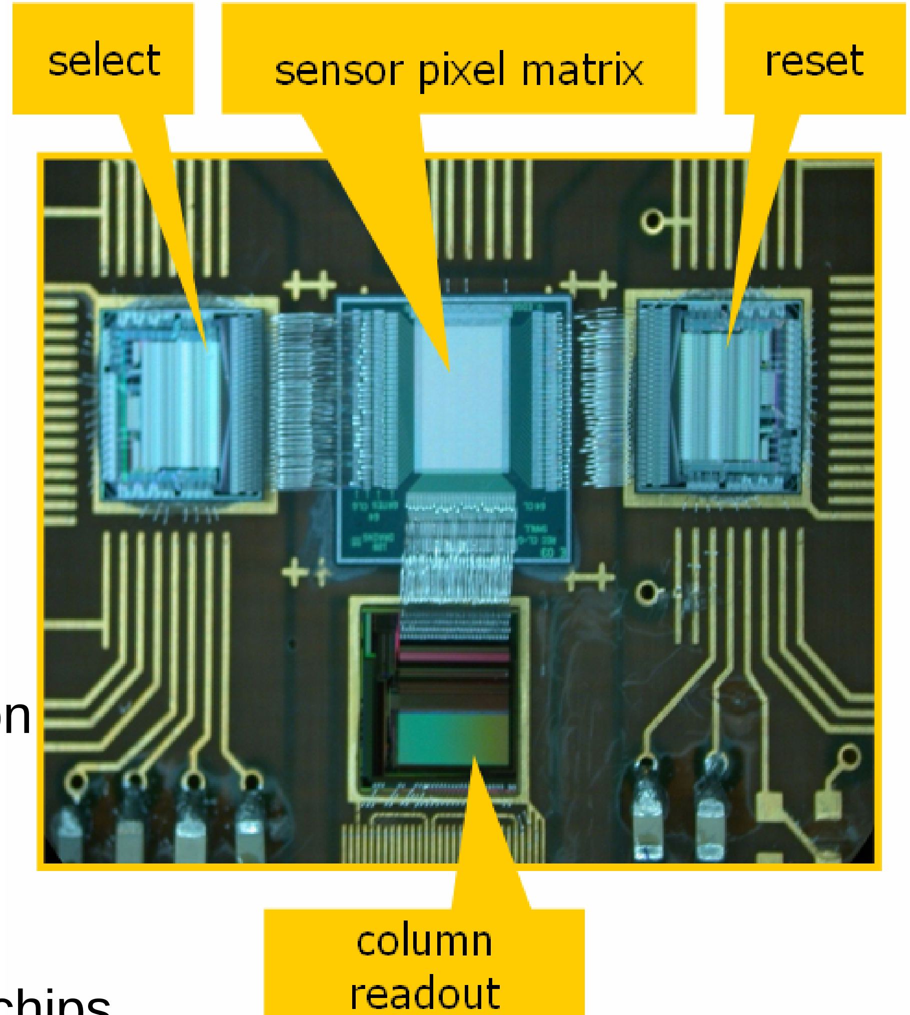

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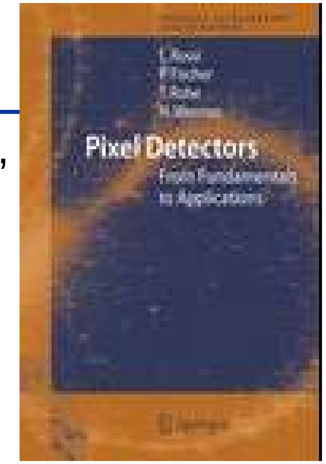

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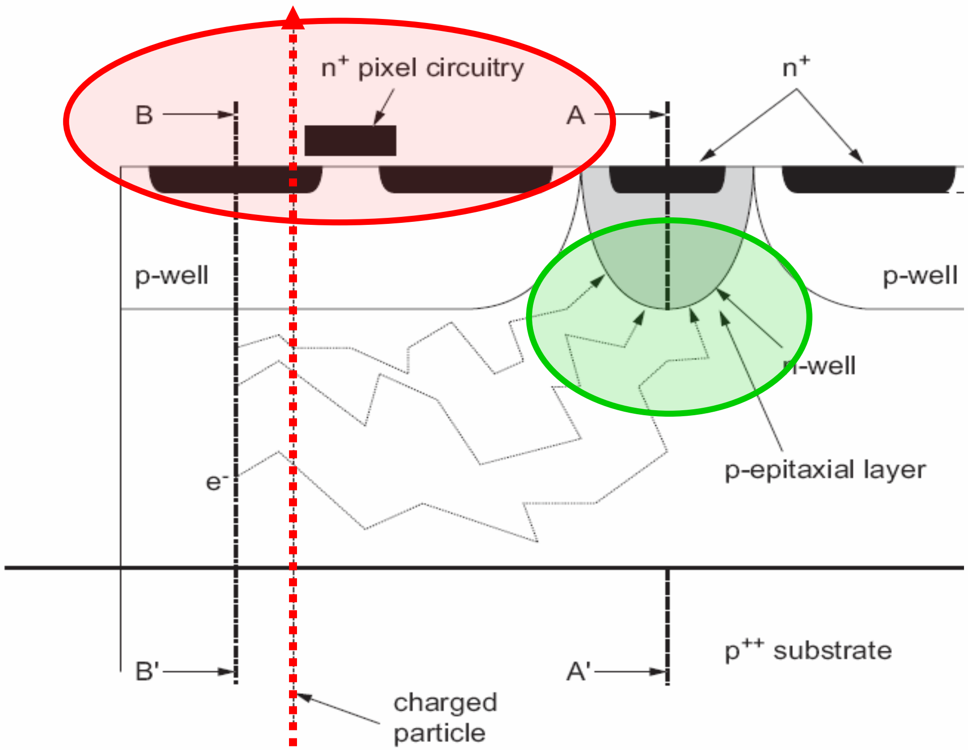
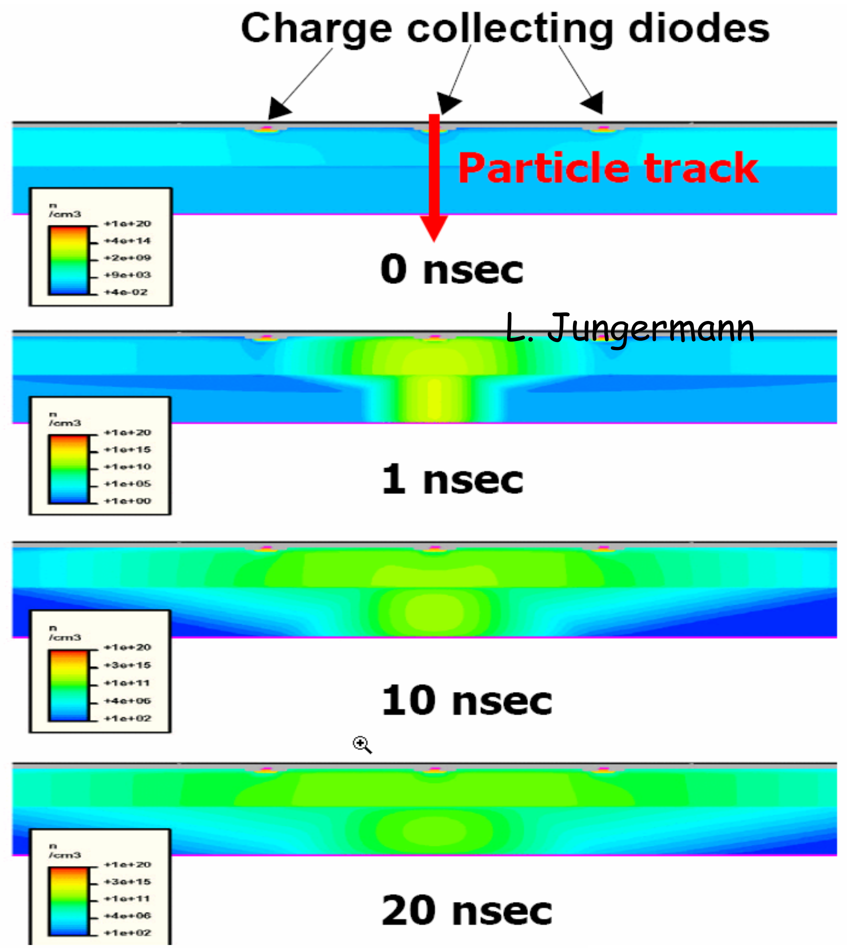
Addendum
Pixel Detectors
for ILC

CMOS Active Pixels

Meynants, Diericks, Scheffer, SPIE 3410:68-76 (1998)
R. Turchetta, NIM-A 458:677-689 (2001)

- charge coll. in several μm thin epi-layer by thermal diffusion to n-well/epi junction
- p-wells and substrate highly doped → charges kept between reflection boundaries
- signals processed by standard CMOS circuitry integrated on sensor
- only nMOS in active area (due to n-well/epi collection diode)
- Q-collection time ~100 ns (due to diffusion)
- incomplete Q-collection and small signals (< 1C
- small pixel sizes (< 20x20 μm²): a must and a

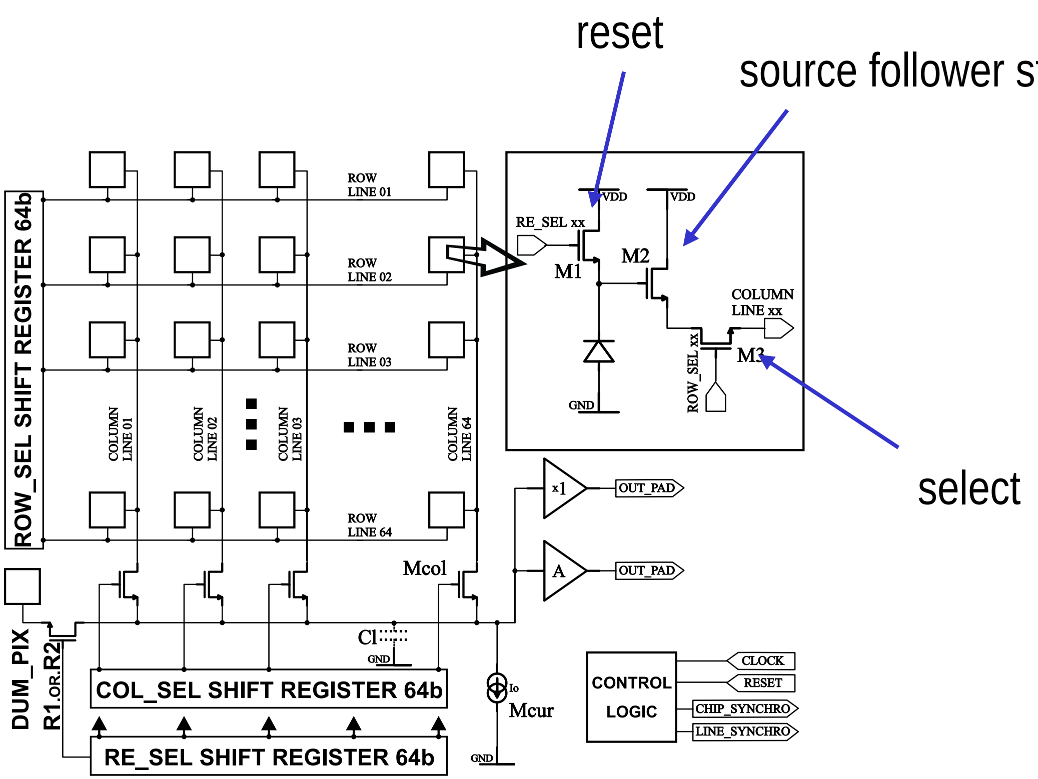




CMOS active pixels / R/O & performance

row selection → column R/0

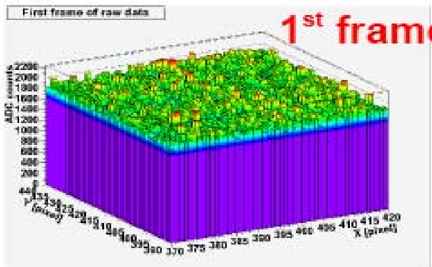
„standard“ 3 transistor R/O scheme
→ upgraded to include amplification, current memory (15 transitors, MIMOSA-7)



- small signal (< 1000e)
  => low noise needed
- detectors **sizes** up to 19.4 x 17.4 mm^2 (1Mpix)
- smallest **pitch**: 17 μm
- spatial resolution < 2μm

Detector image processing

1) Correlated Double Sampling (CDS): subtraction of two consecutive frames to eliminate base levels, 1/f and fixed pattern noise



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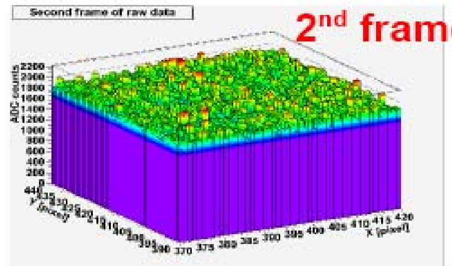

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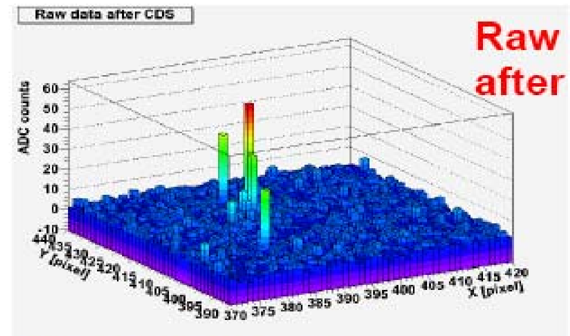
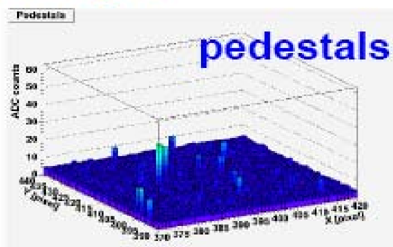
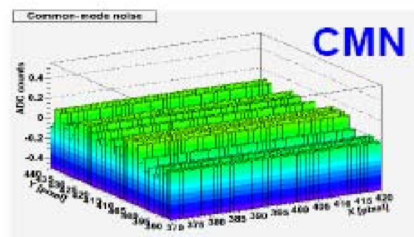
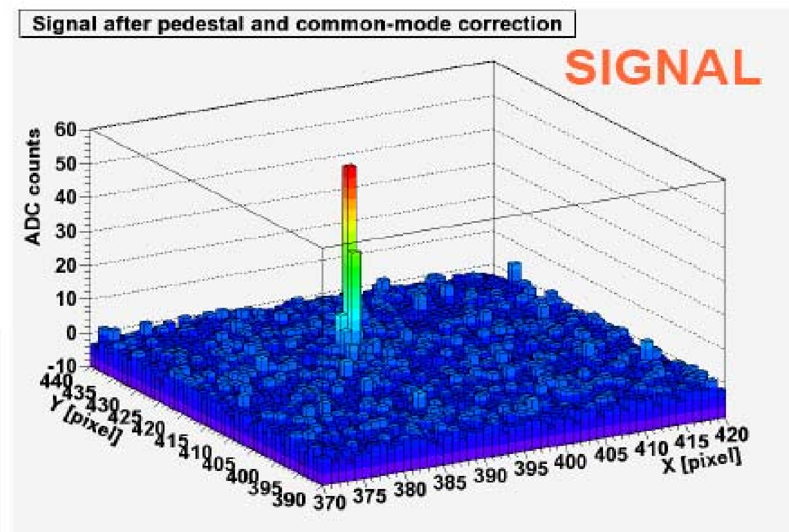


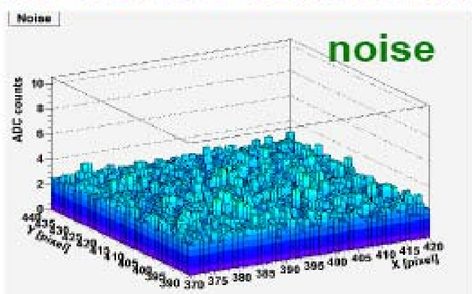
2) Correction for pedestal (~leakage current) and common mode noise: extraction of the physical signal

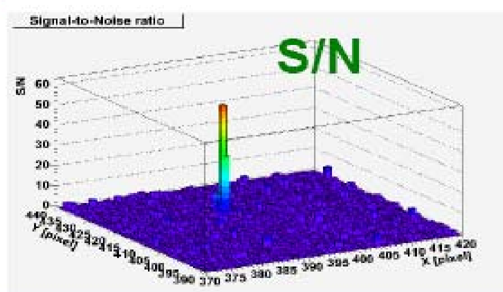






3) Noise and S/N determination

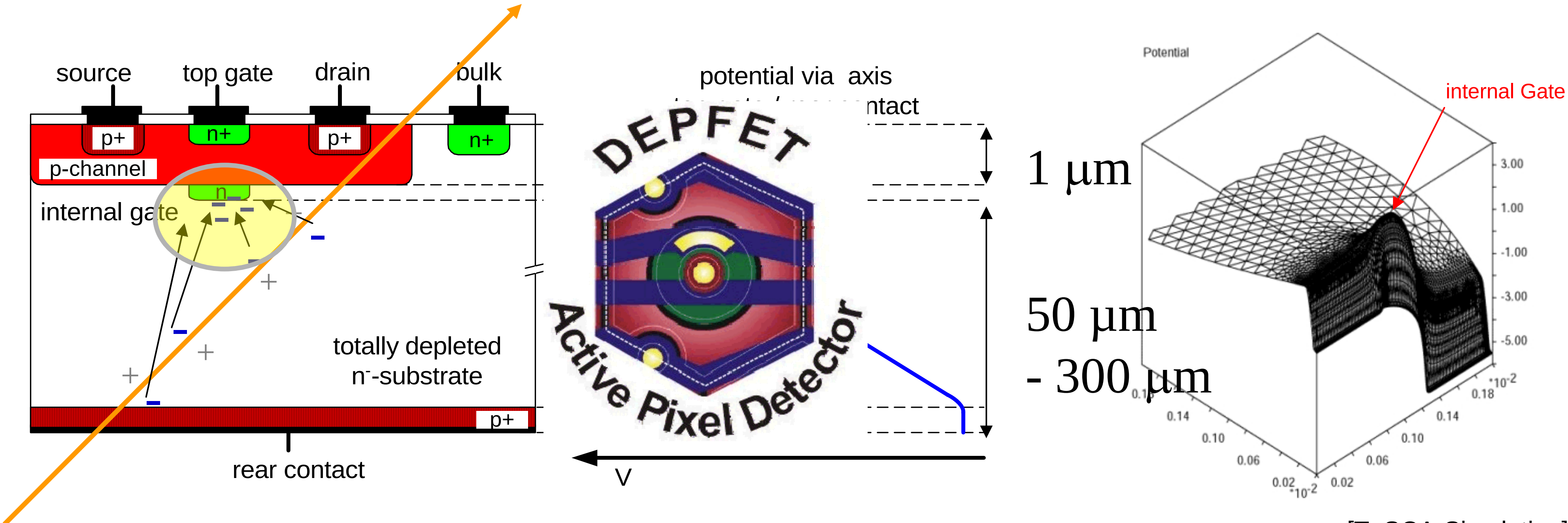




from D. Contarato

DEPFET pixels: high ohmic bulk

Potential distribution:



[TeSCA-Simulation]

(MOS)FET-Transistor integrated in every pixel (first amplification)

Local potential minimum (for e⁻) under transistor channel

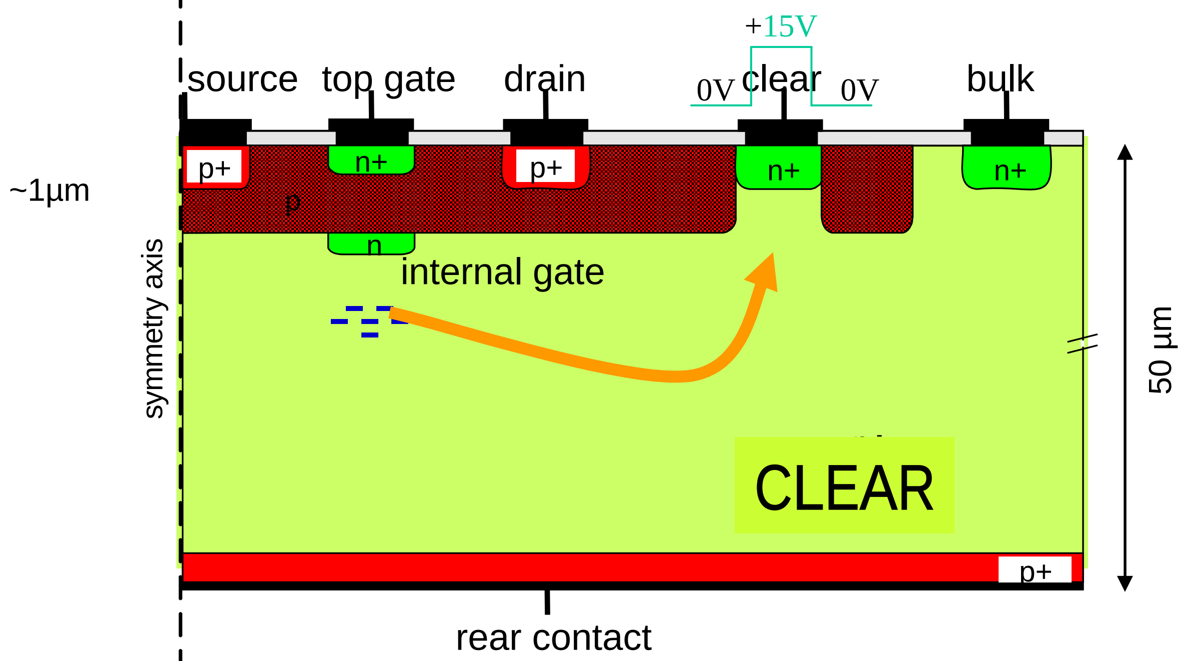
Electrons are collected in „internal gate“ and modulate the transistor-current

Signal charge removed via clear contact

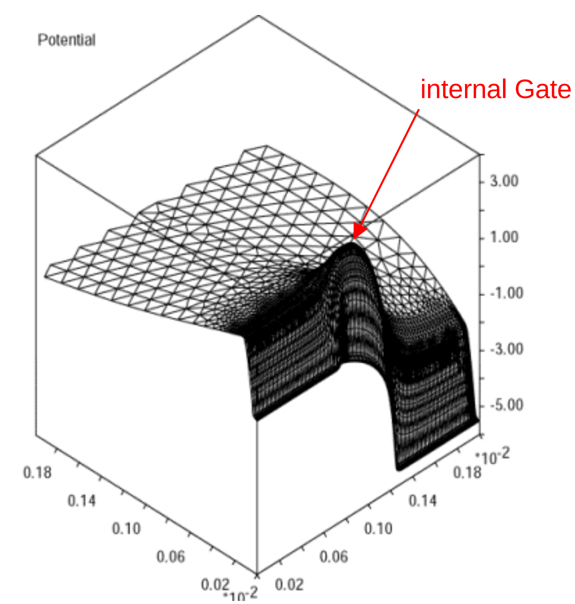
output is a current

J. Kemmer und G. Lutz;, NIM A253 (1987) 365

Monolithic Pixels / DEPFET pixels



Potential distribution:

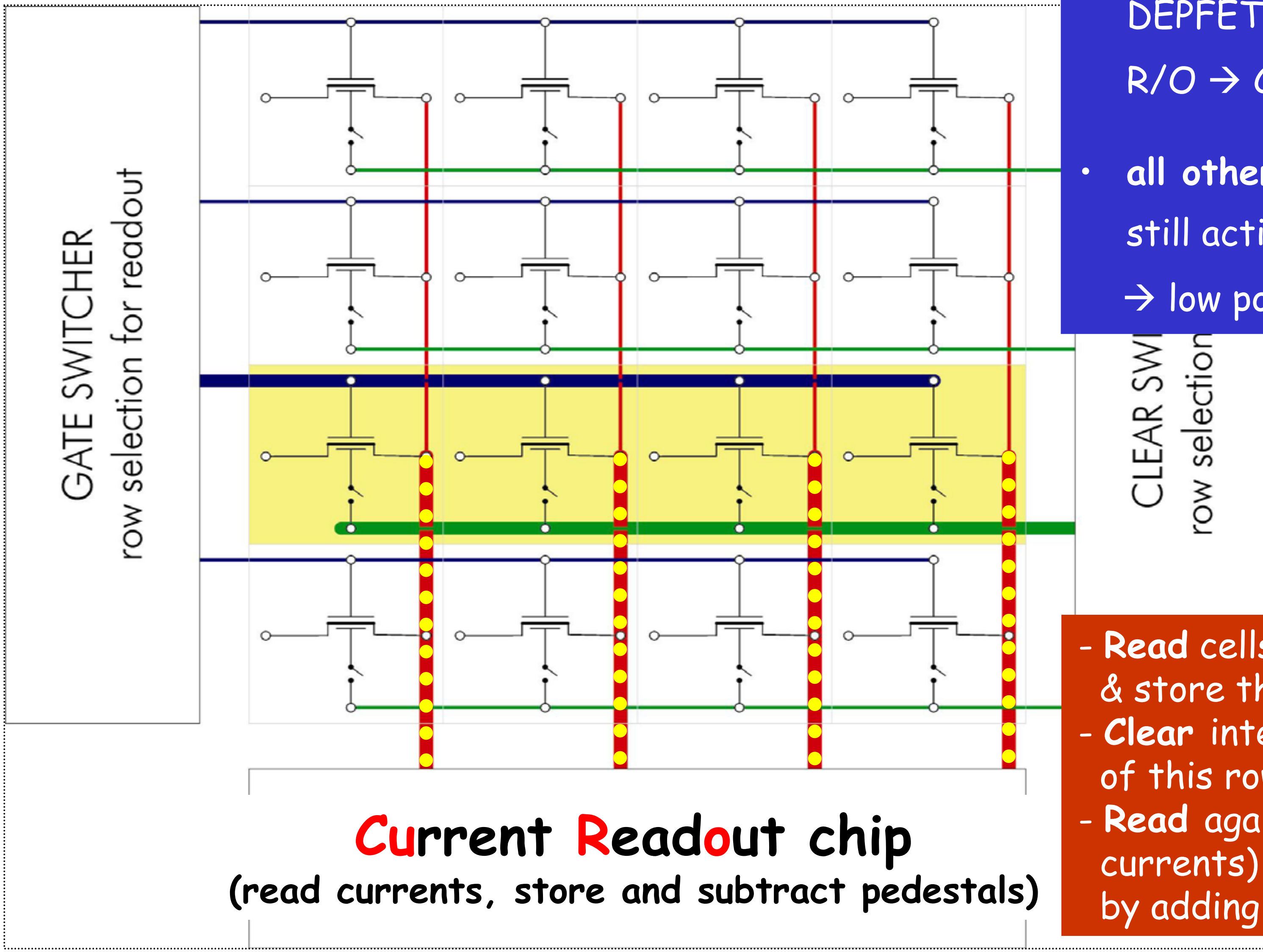


(MOS)FET-Transistor integrated in every pixel (first amplification

small C_D (fF) => very low noise (< 2e⁻ achieved in spectroscoopy devices, ~100e⁻ @ ILC)
large signal => thin detectors (50 µm) → S/N = 40-80 @ ILC
low power => ~ few watts for entire detector (5 layers) → save cooling (X_0)

detector sizes: 64 x 128 pixels, ~25x25 µm² cells

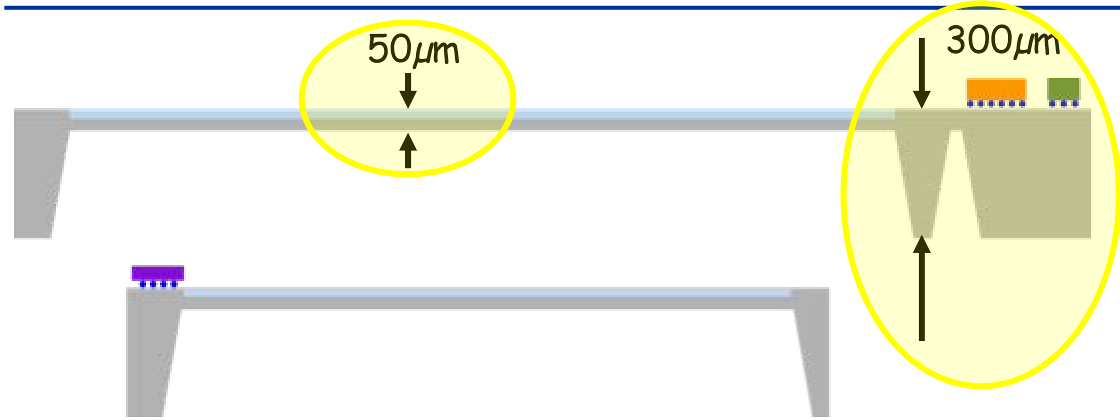
Operation of a DEPFET Matrix

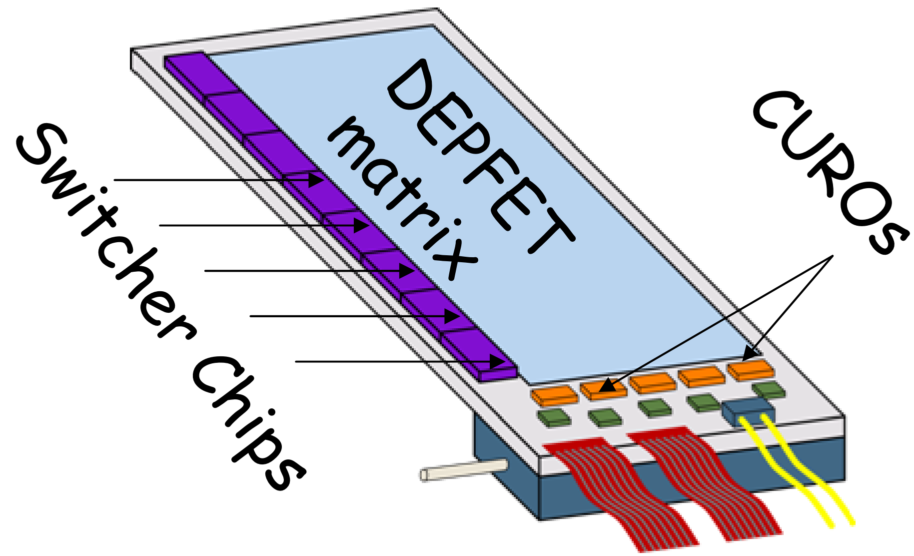


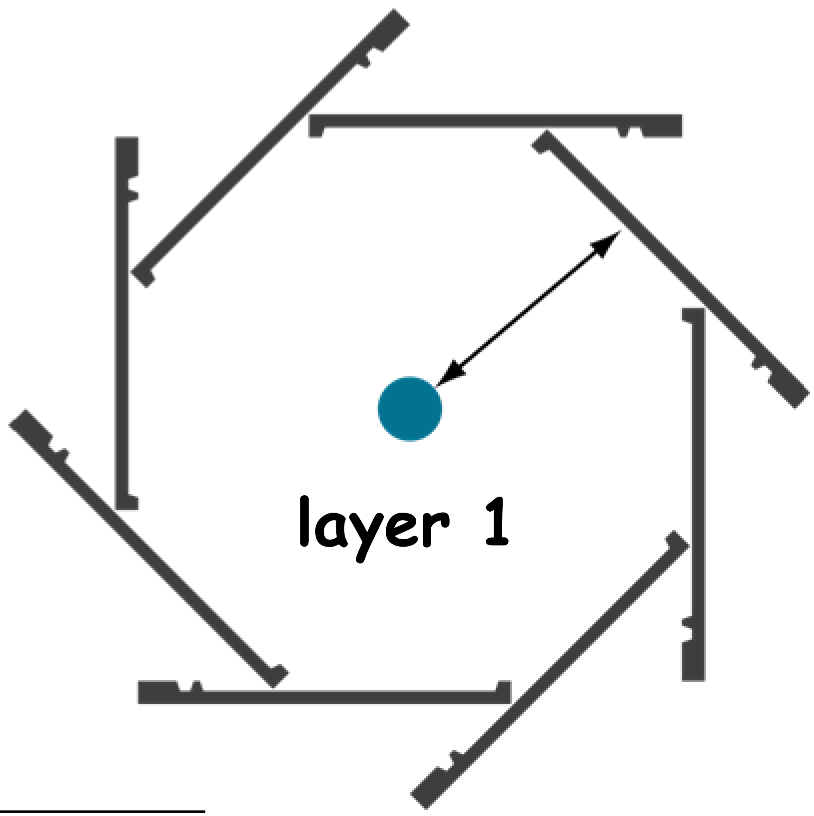
- **1 active row**
  DEPFETs are ON
  R/O → CLEAR → R/O
- **all other rows OFF**
  still active for signals
  → low power !

- **Read** cells of a row & store their currents
- **Clear** internal gates of this row completely
- **Read** again (pedestal currents) and subtract by adding currents

ILC Detector Concept





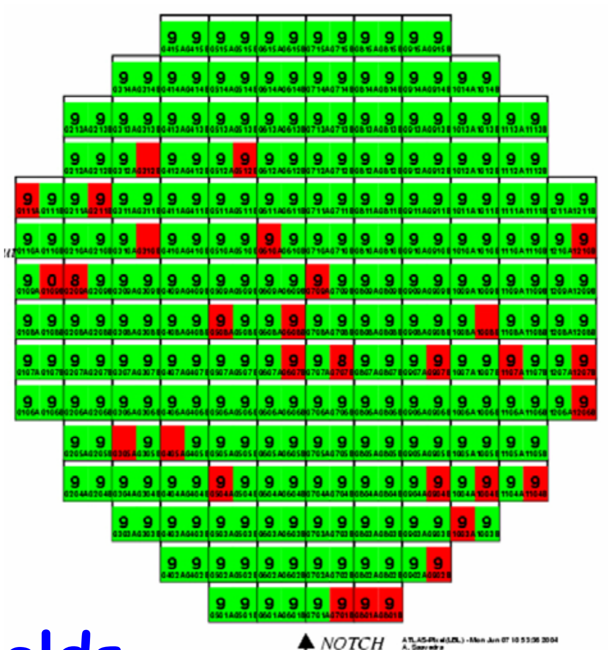
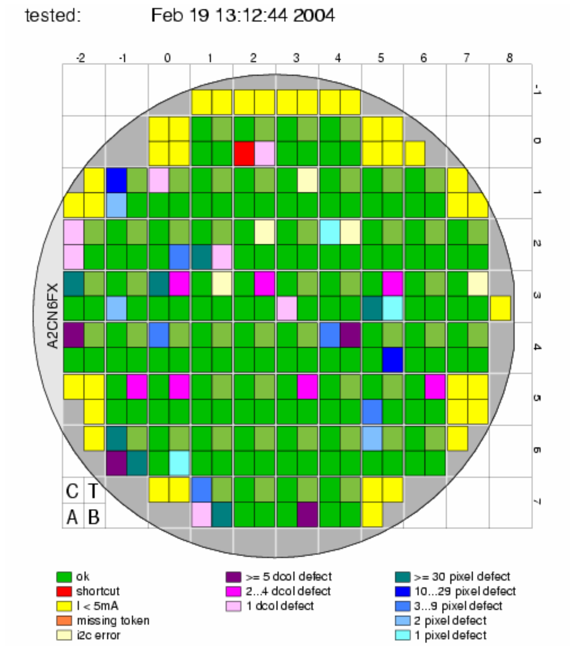
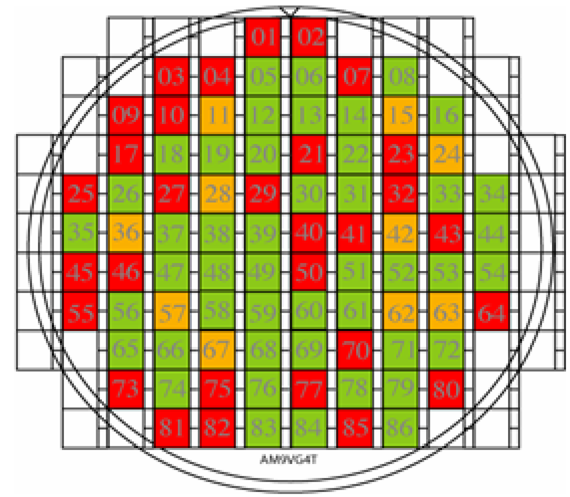


thinned sensor diode

minimal cooling (X_0) required
~ 5W for 5 layer VTX detector

Backup Slides

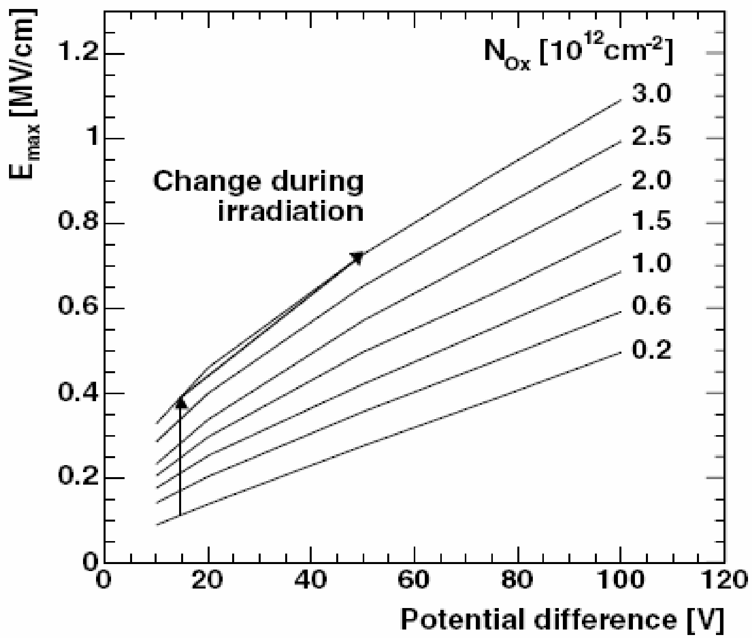
FE-chip wafer yields (0.25 µm CMOS)

ATLAS (FE-I3)	CMS (ROC)	ALICE (SPD-RO)
		

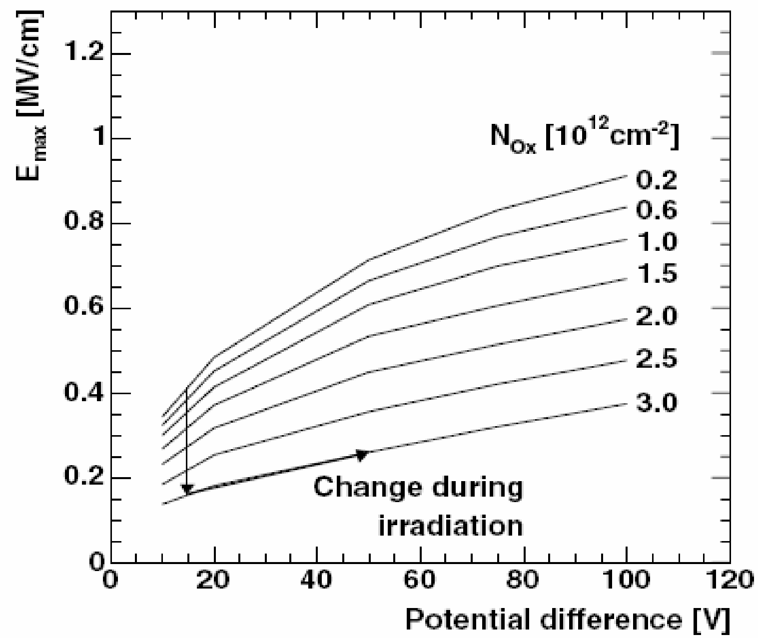
yields before thinning

ATLAS (FE-I3)	CMS (ROC)	ALICE (SPD-RO)
82%	> 80%	51%
11×7.4 mm^2	7.9×9.8 mm^2	13.5×15.8 mm^2
180µm thick	200µm thick	150µm thick

E-fields in “p-stop” and “p-spray” in comparison



(a) *p*-stop



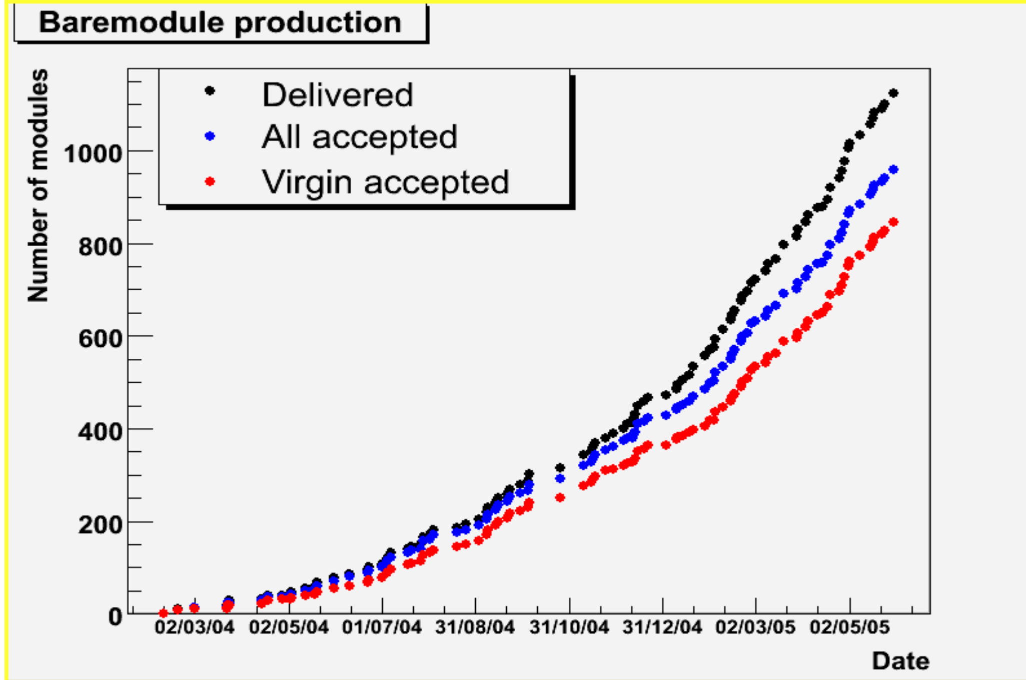
(b) *p*-spray

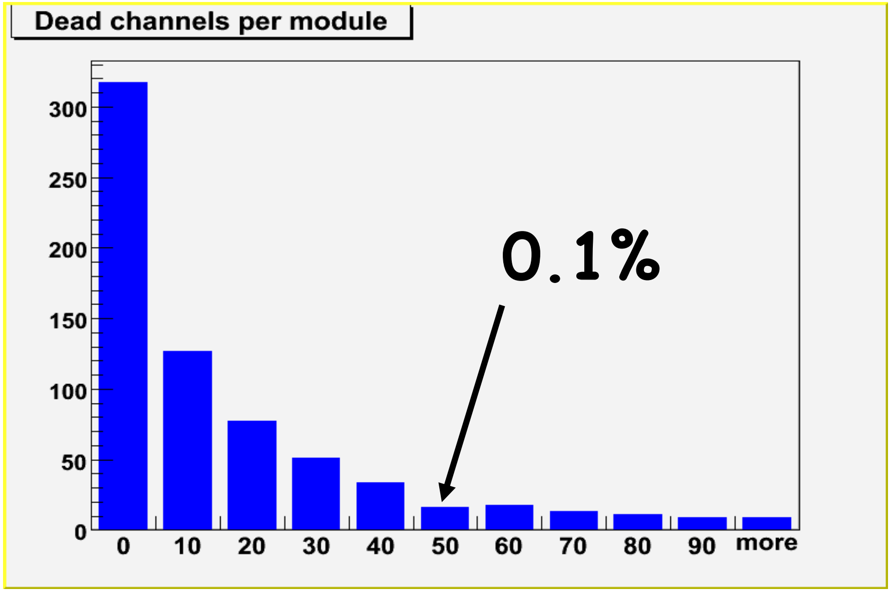
Fig. 2.40. The electric field maximum dependence on the potential difference between the isolating p-layer and the pixel n^+-implant for different values of the oxide charge N_{Ox}. The evolution of the electric field during the lifetime of a detector is indicated by *arrows* [123]

Hybrid Pixels / BARE module yield (ATLAS)

~90% produced @ IZM & AMS

- **~ 2x20 modules/week**
- **rework fraction : 10% - 15%**
- **rework efficiency:**
  solder ~100%, indium ~80%
- **module reject fraction:**
  solder ~ 1%, indium ~14%





total need (3 layers): 1744 + spares
total order @ bump vendors: ~2500
delivered (20.1.2006): ~2200
fully assembled (today): ~2000

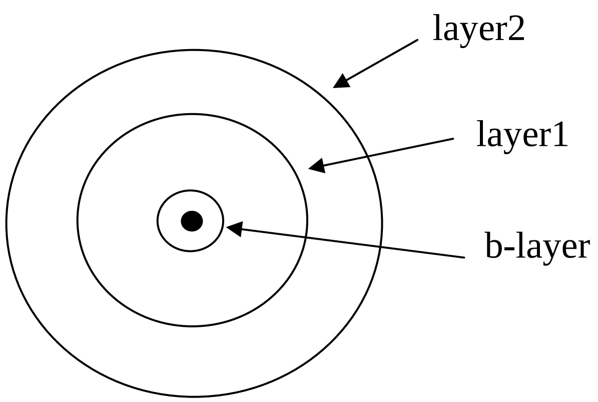
Hybrid Pixels / module quality yield

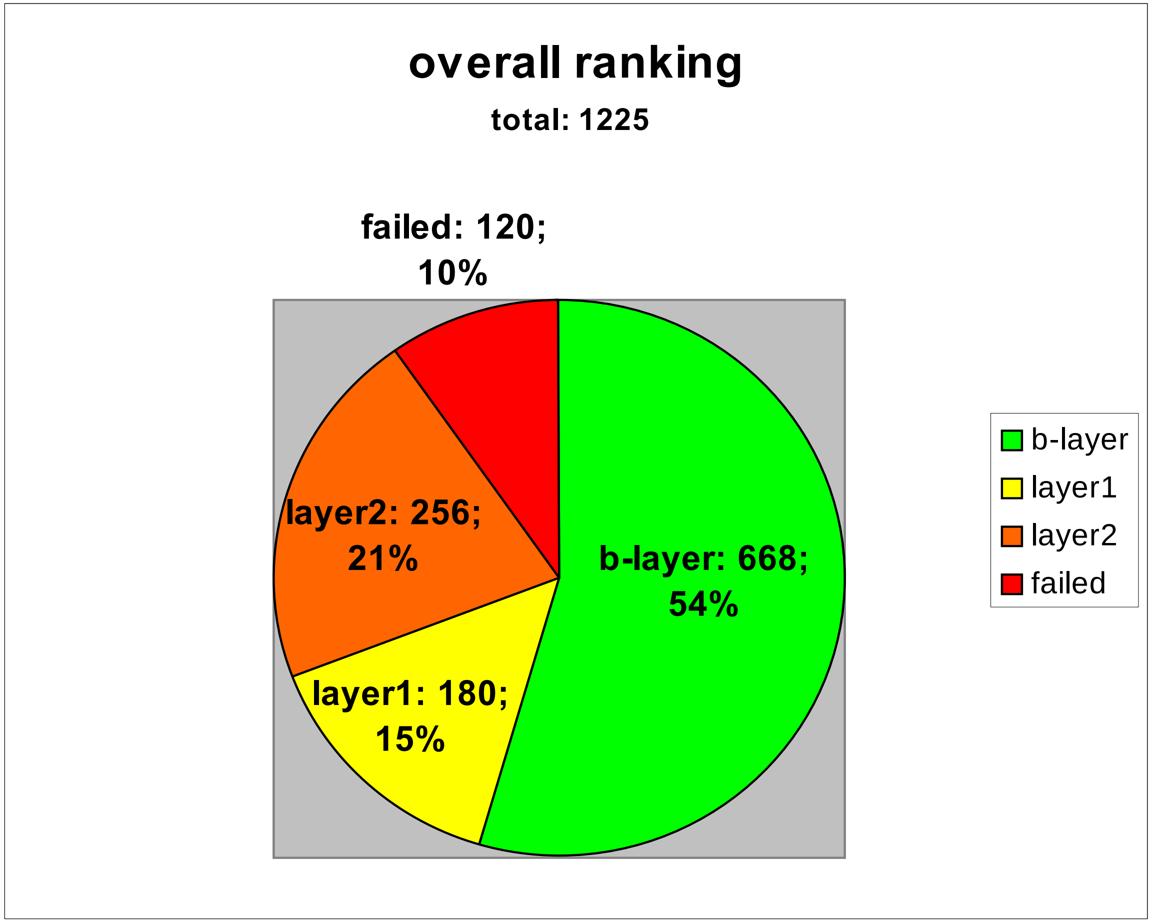
Ranking levels:

b-layer, layer 1, layer 2

ranking based on:

- inefficient pixel
- sensor quality
- noise performance
- threshold tuning
- rebonding
- BareModule rework





Making thin Sensors

- A novel technology to produce detectors with thin active area has been developed and prototyped (L. Andricek)

1. implant backside on sensor wafer
2. bond wafers with SiO_2 in between
3. thin sensor side to desired thick.
4. process DEPFETs on top side
5. etch backside up to oxide/implant

first ‘dummy’ samples:
50µm silicon with 350µm frame

thinned diode structures:
leakage current: <1nA /cm^2

Power consumption

Number of R/O channels @ TESLA:

L1 : 520x2x8 = 8320

L2-5: (880x2)x(8+12+16+20) = 98560

All: 106880 channels

- **R/O Chip:** 2mW / channel → 200 W (whole vtx-d)
- **Sensor:** P_{DEPFET} = 5V x 100 µA = 500µW → 50 W
- **Steering:** 0.94mW /channelDC, 3.13mW / channel @ 50MHz

L1 : 2x3.13 + (3998x0.94) mW= 34W

L2-5: [2*3.13 + (13538x0.94)] x (8+12+16+20) mW = 713W

→ All: 747 W

Total : 997W , 1/199 duty cycle : 5W