Silicon sensors R&D for High energy Physics

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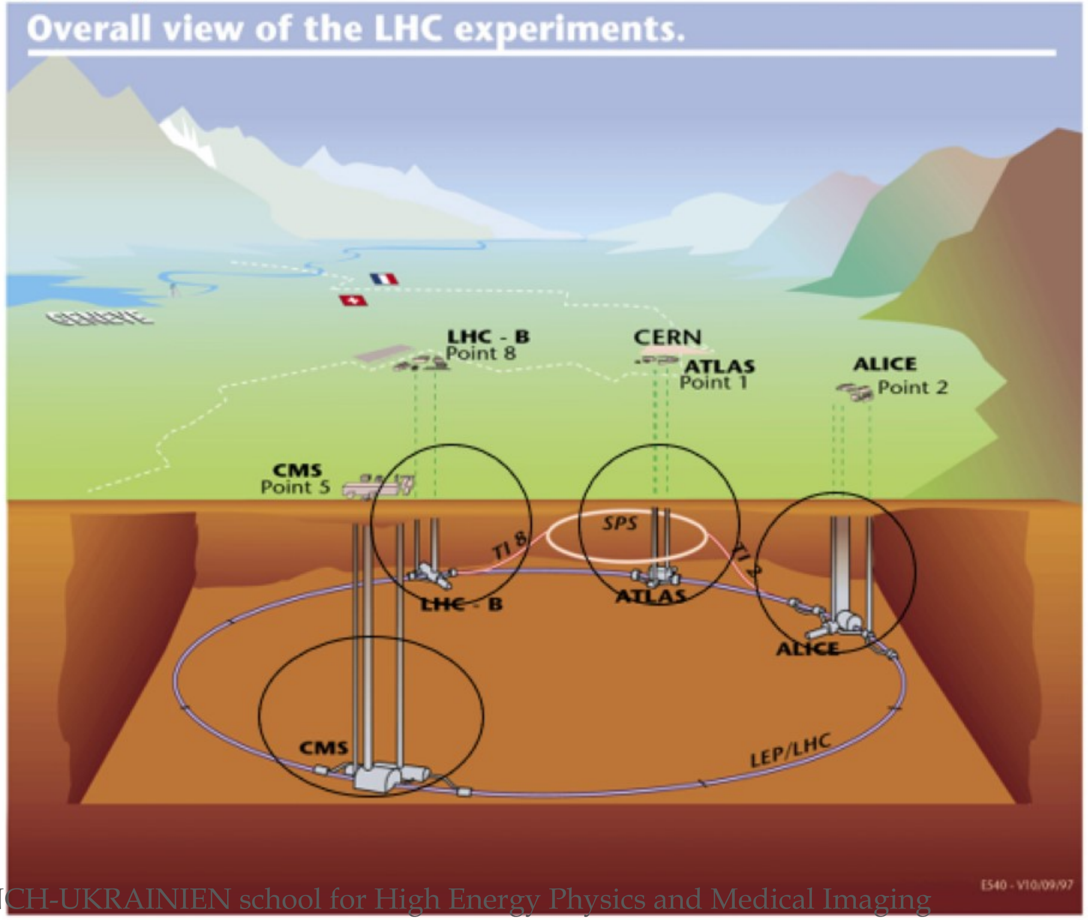
Plan

- Introduction
- What do we measure with silicon ?
- Basic considerations
- Key parameters
- Silicon pixels for ATLAS
  - Overview of R&D developments
- Conclusions

CERN's mission: to build particle accelerators

The Large Hadron Collider (LHC) will be the most powerful instrument ever built to investigate particles properties.

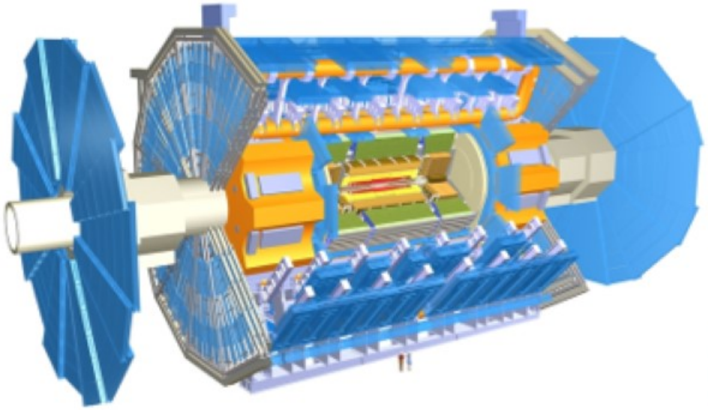


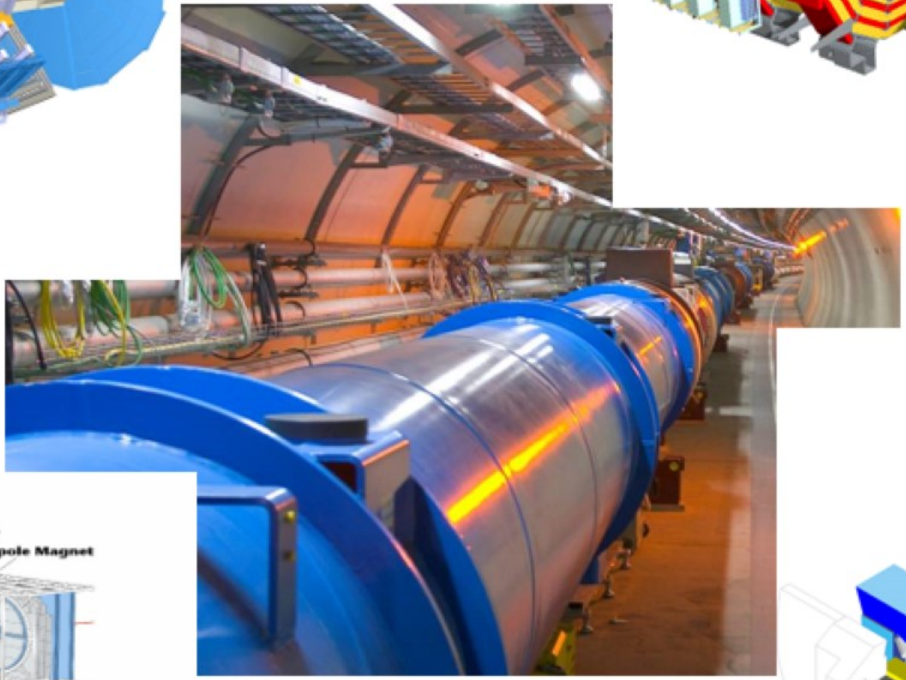
- Four gigantic underground caverns to host the huge detectors
- The highest energy of any accelerator in the world
- The most intense beams of colliding particles
- It will operate at a temperature colder than outer space

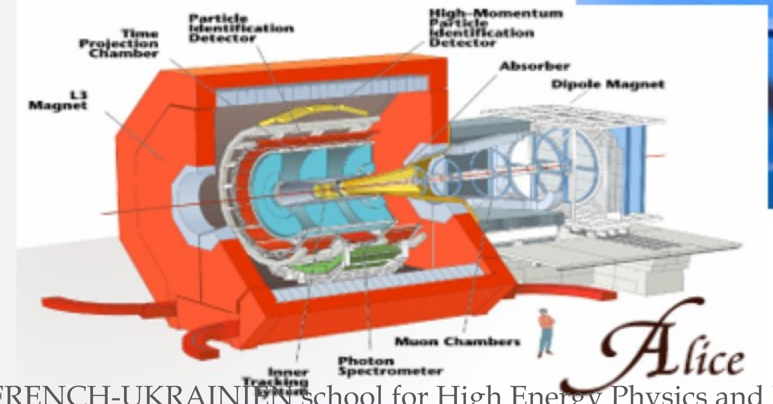
The ATLAS Collaboration

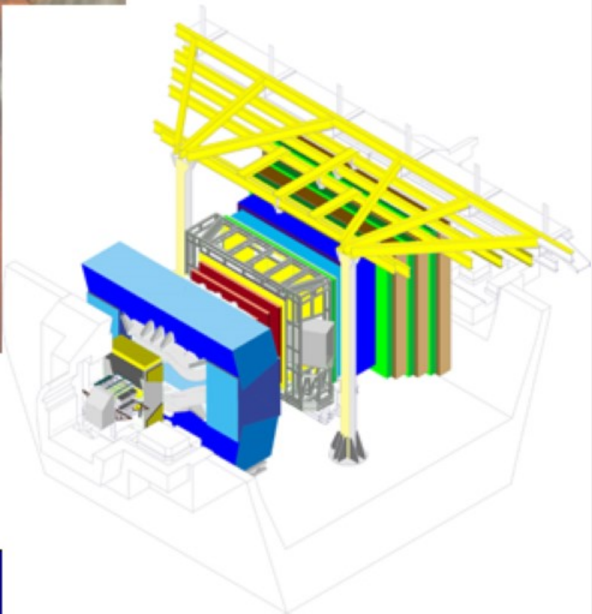
36 Countries
165 Institutions
2000 Scientific Authors

Accelerator and experiments, big objects



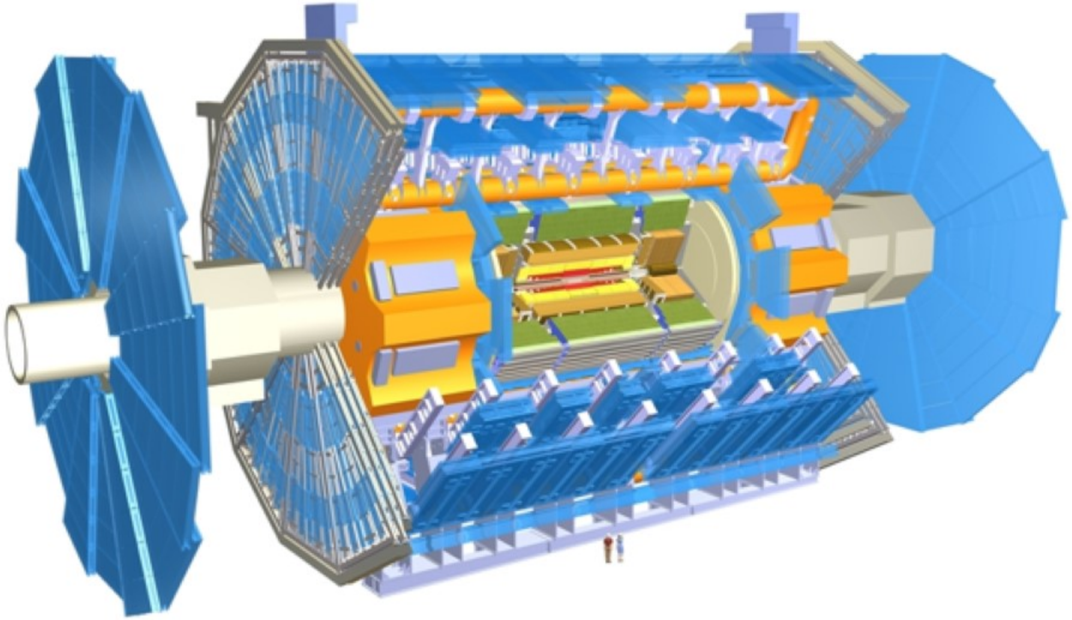




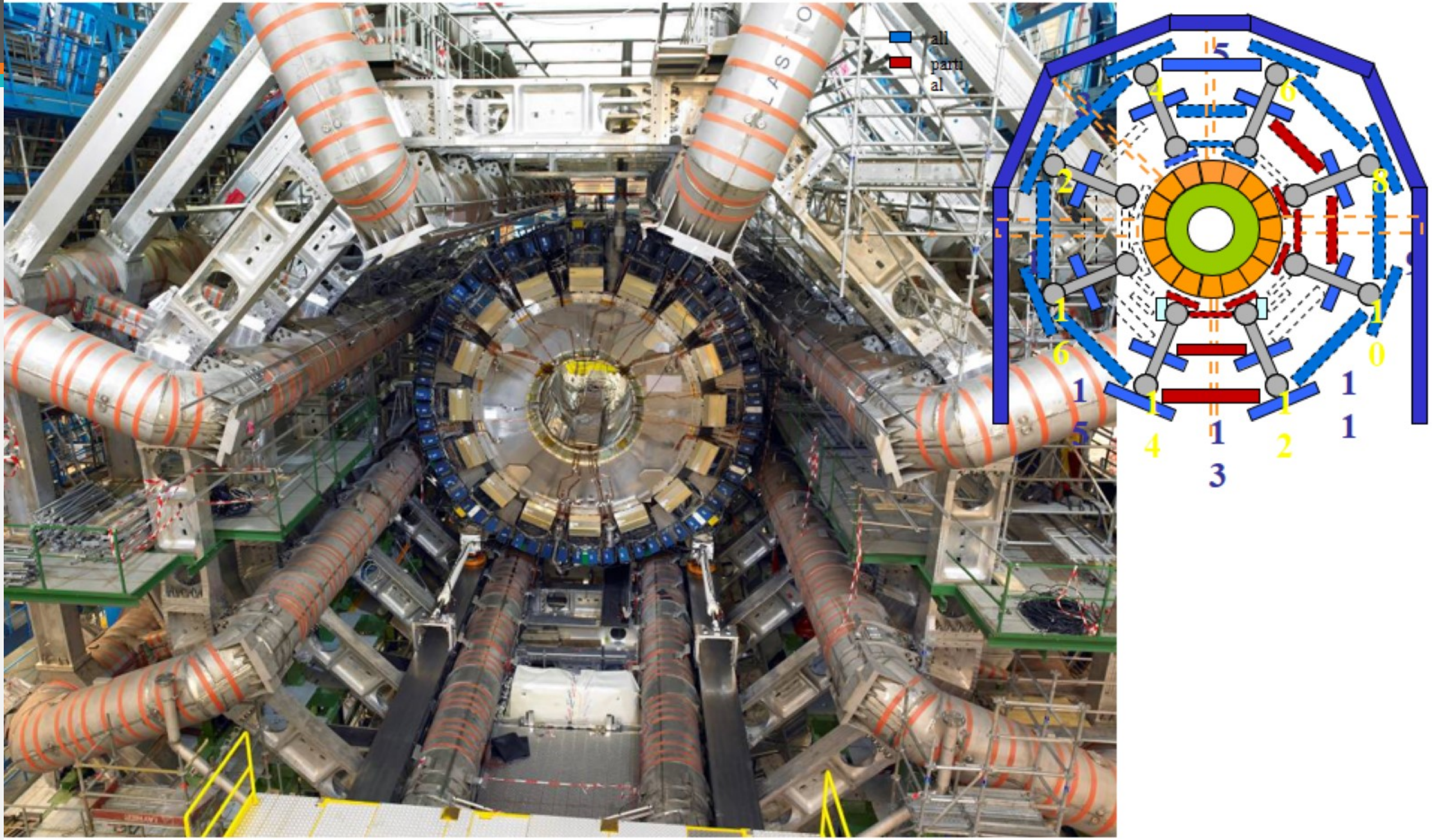


The ATLAS Detector

ATLAS superimposed to
the 5 floors of building 40



Diameter	*25 m*
Barrel toroid length	*26 m*
End-cap end-wall chamber span	*46 m*
Overall weight	*7000 Tons*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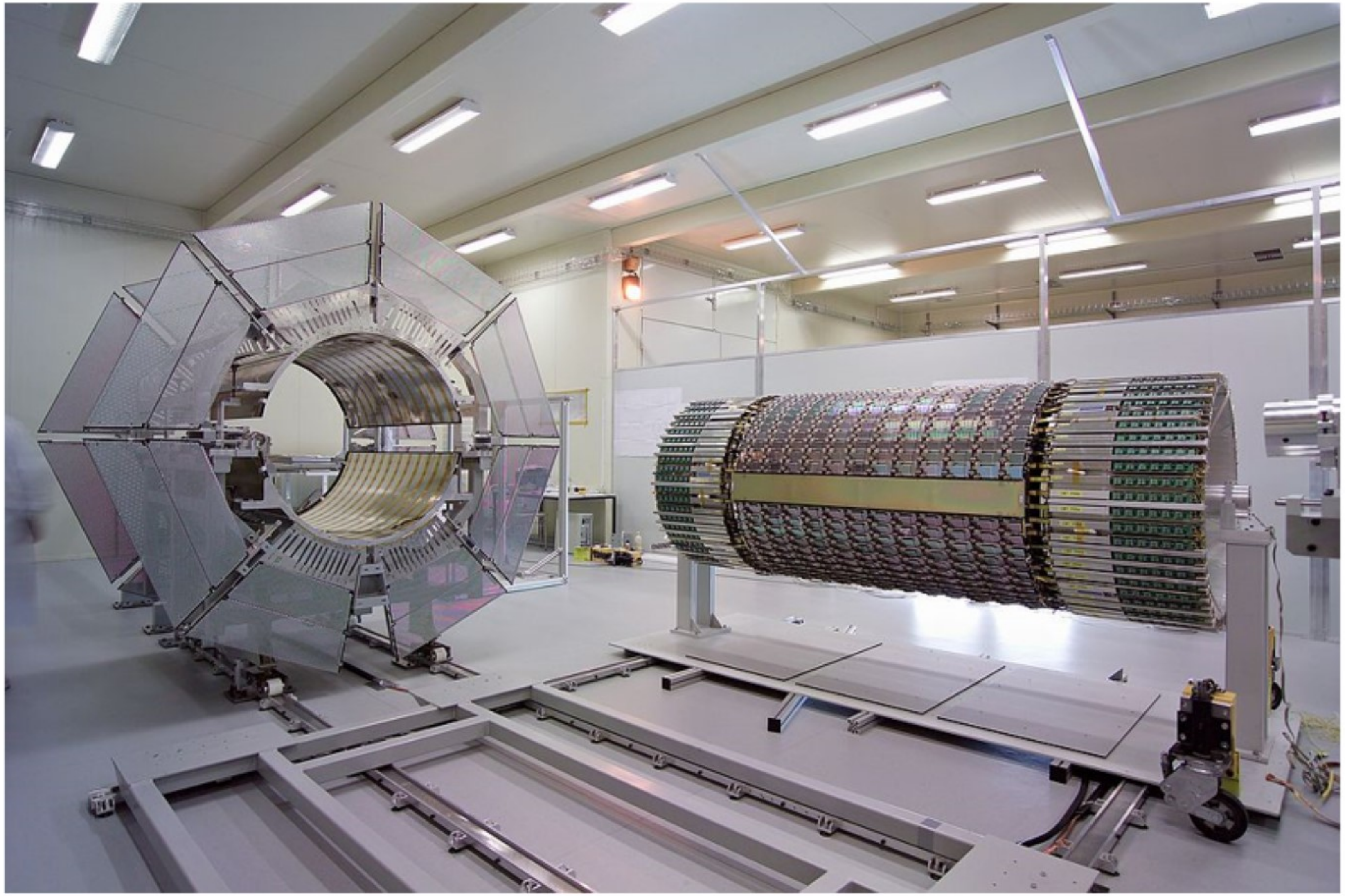
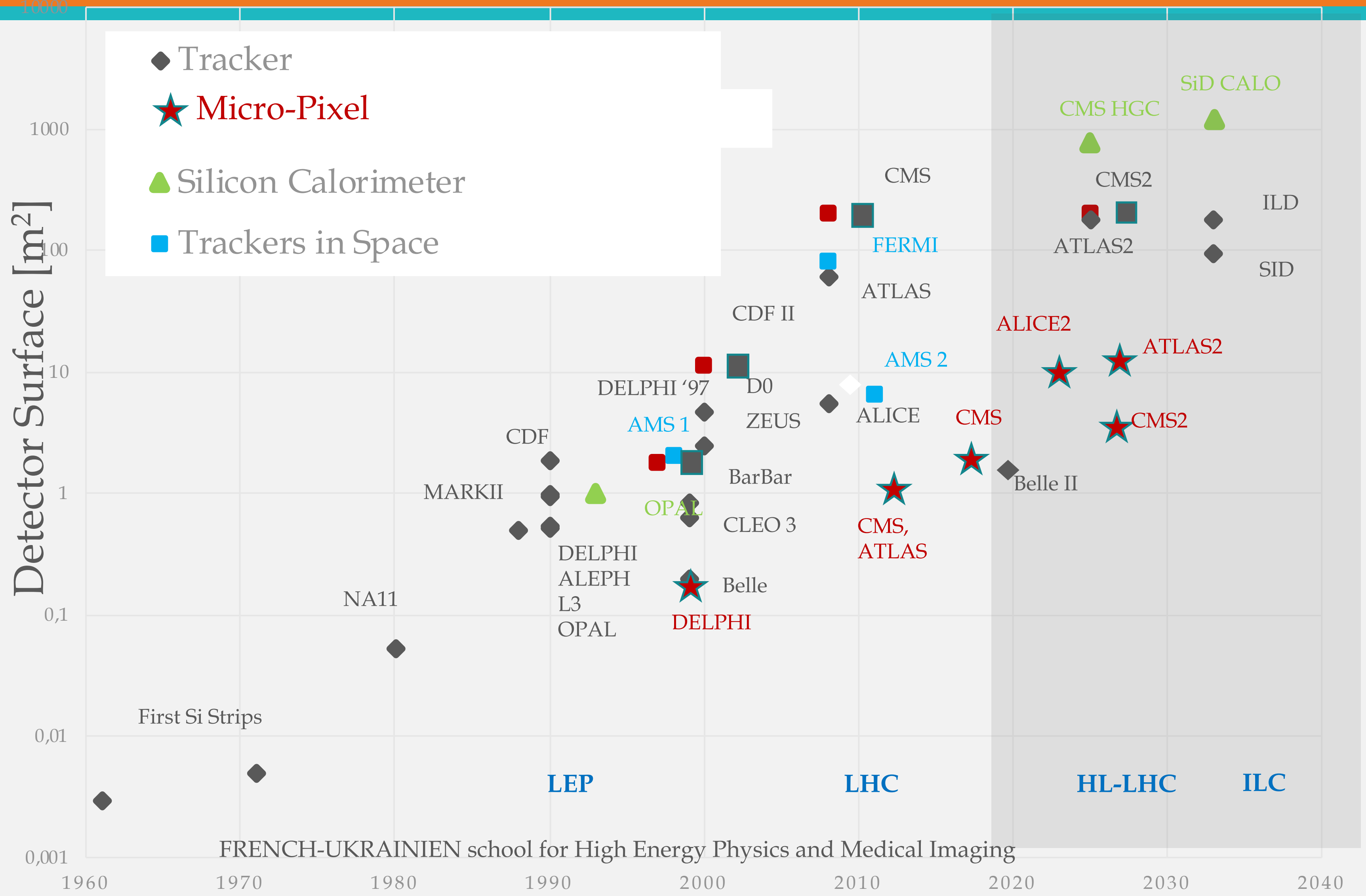
Inner silicon tracker



Silicon as material for Trackers!
Actual situation

Detector surface
- Globally stays constant
- Pixel area goes up significantly

Cell size **goes down significantly**



Detector	Strip length [cm]	Strip length [cm]
	pixel size [µm²]	pixel size [µm²]
ATLAS pixel	50x400	25x100 (50x50)
CMS pixel	150x100	50x50 (25x100)
VELO	1 to 7 cm	55x55
ALICE	50X425	**28x28**

Detector	Channels	Channels
CMS strips	9.8M	42M + **172M**
CMS Pixels	127M	2GP
ATLAS strips	6.3M	60M
ATLAS pixels	92M	**5GP**
VELO	171k	41M
ALICE	12.5M	**12.5G**

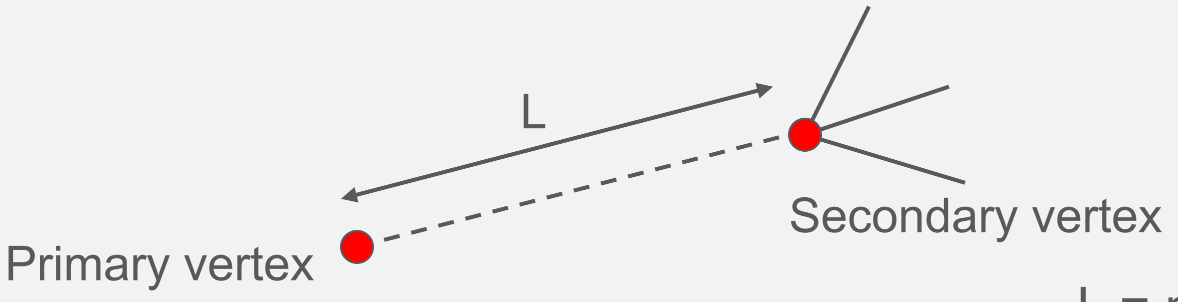
What is measured

- Measure space points
- Deduce
  - Vertex location
  - Decay lengths
  - Impact parameters

Signature of Heavy Flavours

Stable particles $\tau > 10^{-6}$ s		$c\tau$
n		2.66km
μ		658m
Very long lived particles $\tau > 10^{-10}$ s		
π, $K^{\pm}$, K_L^0	2.6×10^{-8}	7.8m
K_S^0, $E^{\pm}$, Δ^0	2.6×10^{-10}	7.9cm
Long lived particles $\tau > 10^{-13}$ s		
$\tau^{\pm}$	0.3×10^{-12}	91μm
B_d^0, B_s^0, Δ_b	1.2×10^{-12}	350μm
Short lived particles		
π^0, η^0	8.4×10^{-17}	0.025μm

Decay lengths

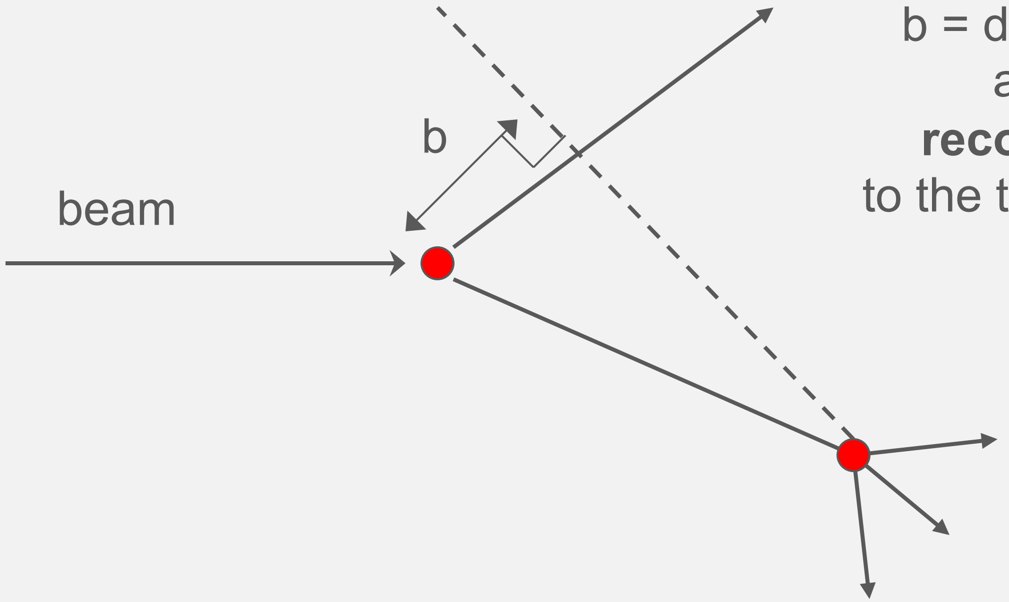


E.g. $B \rightarrow J/\Psi\ K_s^0$

$L = p/m\ c\ \tau$

- By measuring the decay length, L, and the momentum, p, the lifetime of the particle can be determined
- Need accuracy on both production and decay point

Impact parameter (b)



b = distance of closest approach of a **reconstructed** track to the true interaction point

Impact parameter

- Error in impact parameter for 2 precision measurements at R_1 and R_2 measured in two detector planes:

$$\sigma_b = a^2 + \left(\frac{b}{p} \right)^2 + c^2$$

- a=f(R_1 & R_2) function of intrinsic resolution of vertex detector
- b due to multiple scattering in detector
- c due to detector alignment and stability

Impact parameter

- σ_b = f(vertex layers, distance from main vertex, spatial resolution of each detector, material before precision measurement, alignment, stability)

- Requirements for best measurement
  - Close as possible to interaction point
  - Maximum lever arm $R_2 - R_1$
  - Maximum number of space points
  - High spatial resolution
  - Smallest amount of material between interaction point and 1^{st} layer
  - Good stability and alignment – continuously measured and correct for

  100% detection efficiency
  - Fast readout to reduce pile up in high flux environments

Basic considerations

Silicon Pixel detectors

Why Silicon?

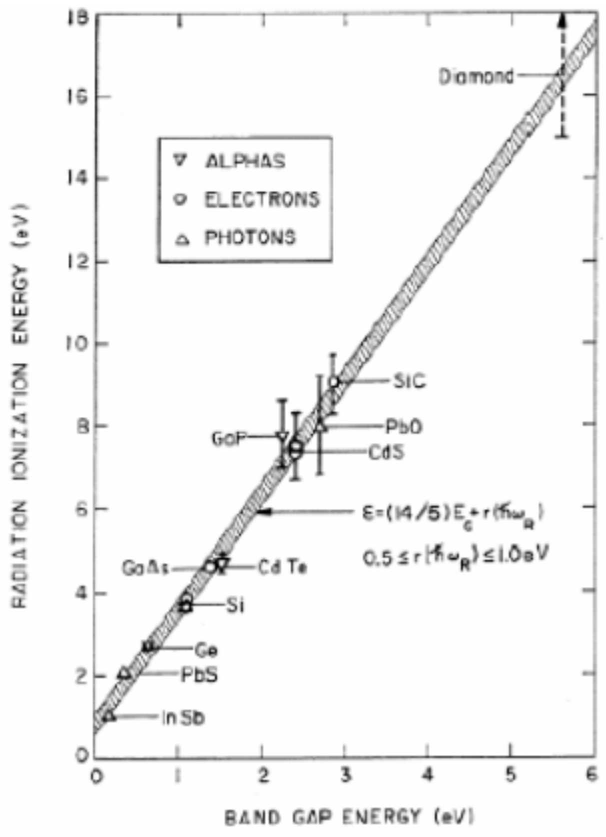
- Semiconductor with moderate bandgap (1.12 eV)
- Energy to create electron/hole pair (signal quanta) = 3.6 eV
  - (c.f. Argon gas = 15 eV)
  - high carrier yield
  - better energy resolution and high signal

- High density and atomic number
  - higher specific energy loss
    - → thinner detectors
    - → reduced range of secondary particles
    - → better spatial resolution

- High carrier mobility → Fast!
  - less than 30 ns to collect entire signal

- **Large experience in industry** with micro-chip technology

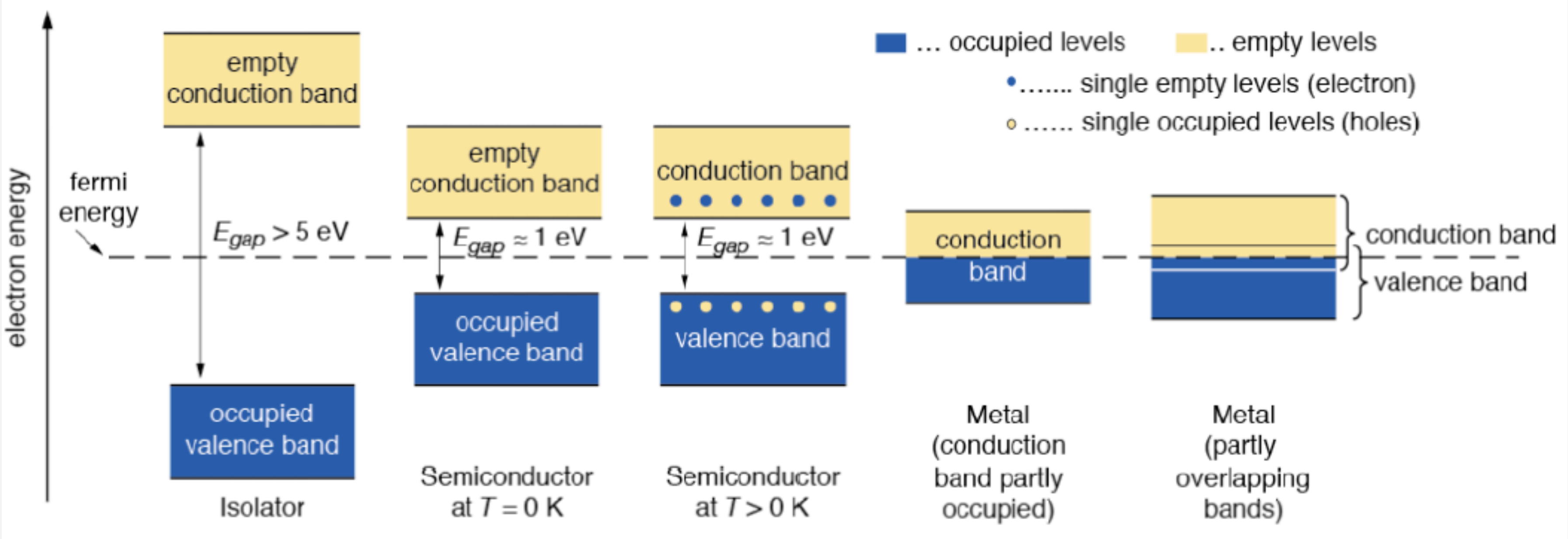
- High intrinsic radiation hardness



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

Energy bands: isolator – semiconductor - metal

In an isolated atom the electrons have only discrete energy levels. In solid state material the atomic levels merge to energy bands. In **metals** the conduction and the valence band **overlap**, whereas in isolators and semiconductors these levels are **separated** by an energy gap (**band gap**). In isolators this gap is large.



Comparison of different semiconductor materials

Material	Si	Ge	GaAs	GaP	CdTe	Diamond*
Atomic number Z	14	32	31+33	31+15	48+52	6
Mass Number A (amu)	28.086	72.61	69.72+74.92	69.72+30.97	112.4+127.6	12.011
Lattice constant a (Å)	5.431	5.646	5.653	5.451	6.482	3.567
Density ρ (g/cm^3)	2.328	5.326	5.32	4.13	5.86	3.52
E_g (eV) bei 300 K	1.11	0.66	1.42	2.26	1.44	5.47–5.6
E_g (eV) bei 0 K	1.17	0.74	1.52	2.34	1.56	≈ 6
rel. permittivity $\varepsilon_r = \varepsilon / \varepsilon_0$	11.9	16.0	12.8	11.1	10.9	5.7
Melting point (° C)	1415	938	1237	1477	1040	3527
eff. e$^-$-mass (m_n / m_e)	0.98, 0.19	1.64, 0.08	0.067	0.82	0.11	0.2
eff. hole mass$^+$ (m_h / m_e)	0.16	0.044	0.082	0.14	0.35	0.25

*usually considered an isolator

Source: http://www.ioffe.rssi.ru/SVA/NSM/Semicond/ ; S.M.Sze, *Physics of Semicon. Devices* , J. Wiley & Sons, 1981,
J. Singh, Electronic & Optoelectronic Properties of Semiconductor Structures, Cambridge University Press, 2003

Comparison of different semiconductor materials

Material	Si	Ge	GaAs	GaP	CdTe	Diamond*
eff. density of states in conduction band n_{CB} (cm^{-3})	$3 \cdot 10^{19}$	$1 \cdot 10^{19}$	$4.7 \cdot 10^{17}$	$2 \cdot 10^{19}$		$\approx 10^{20}$
eff. Density of states in valence band n_{VB} (cm^{-3})	$1 \cdot 10^{19}$	$6 \cdot 10^{18}$	$7 \cdot 10^{18}$	$2 \cdot 10^{19}$		$\approx 10^{19}$
Electron mobility μ_e bei 300 K (cm^2/Vs)	~1450	3900	8500	< 300	1050	1800
Hole mobility μ_h bei 300 K (cm^2/Vs)	~450	1900	400	< 150	100	1200
instrins. charge carrier density at 300 K (cm^{-3})	$1.45 \cdot 10^{10}$	$2.4 \cdot 10^{13}$	$2 \cdot 10^{6}$	2		$\approx 10^{-27}$
instrins. resistivity at 300 K (Ω cm)	$2.3 \cdot 10^{5}$	47	$\approx 10^{8}$		$\approx 10^{9}$	$\geq 10^{42}$
Breakdown field (V/cm)	$3 \cdot 10^{5}$	$\approx 10^{5}$	$4 \cdot 10^{5}$	$\approx 10^{6}$		$3 \cdot 10^{7}$
Mean E to create an e^-h^+ pair (eV), 300 K	3.62	2.9	4.2	≈ 7	4.43	13.25

*usually considered an isolator

Source: http://www.ioffe.rssi.ru/SVA/NSM/Semicond/ ; S.M.Sze, *Physics of Semicon. Devices* , J. Wiley & Sons, 1981, J. Singh, Electronic & Optoelectronic Properties of Semiconductor Structures, Cambridge University Press, 2003

Doping intrinsic silicon

A pn junction consists of n and p doped substrates:

- Doping is the **replacement of a small number of atoms** in the lattice by atoms of **neighboring columns** from the periodic table

- These doping atoms create **energy levels within the band gap** and therefore alter the conductivity.

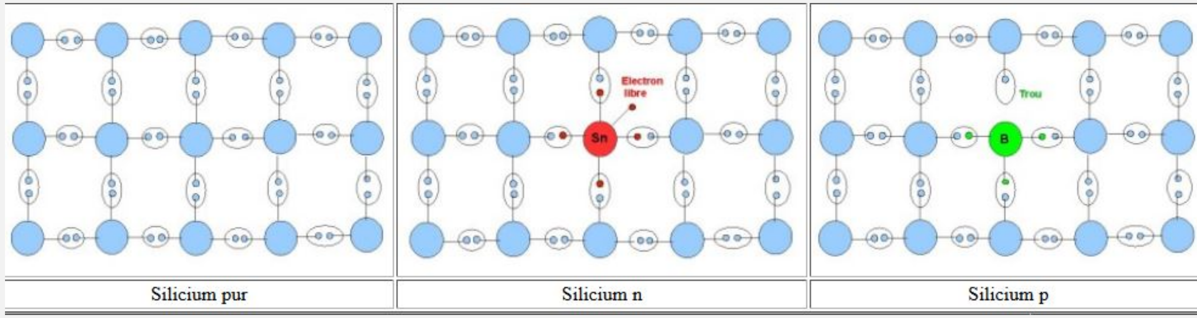
Definitions:

- An un-doped semiconductor is called an **intrinsic semiconductor**
  - For each conduction electron exists the corresponding hole.

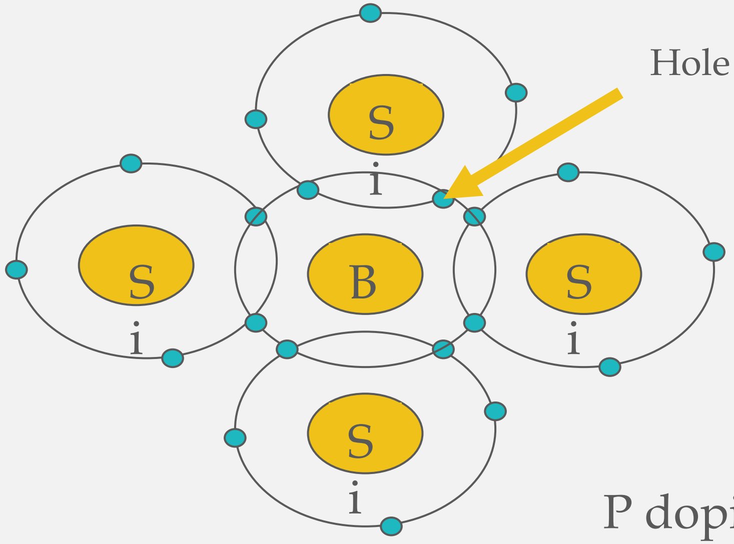
- A doped semiconductor is called an **extrinsic semiconductor**.
  - Extrinsic semiconductors have a abundance of electrons or holes.

doping

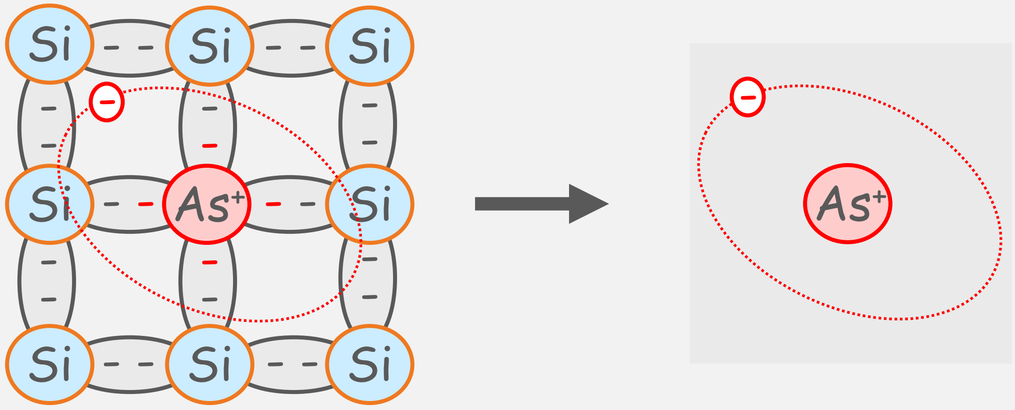
- In a semi-conductor the electric current is vehiculed by two types of carriers: electrons (negative carriers) and holes (positive carriers).
- N Doping: excess of electron carriers in the semiconductor.
- P doping : excess of holes (deficit of electrons) in the semiconductor.



Hole in the Boron atom



P doping
Boron doping



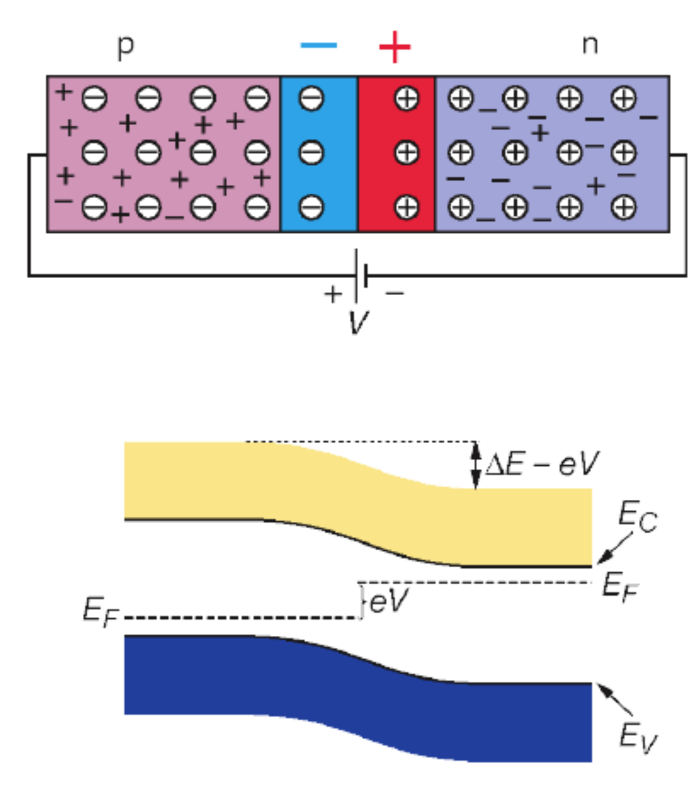
N doping

Operation of a pn-junction with forward bias

Applying an external voltage V with the anode to p and the cathode to n, e- and holes are refilled to the depletion zone. The **depletion zone becomes narrower** (forward biasing)

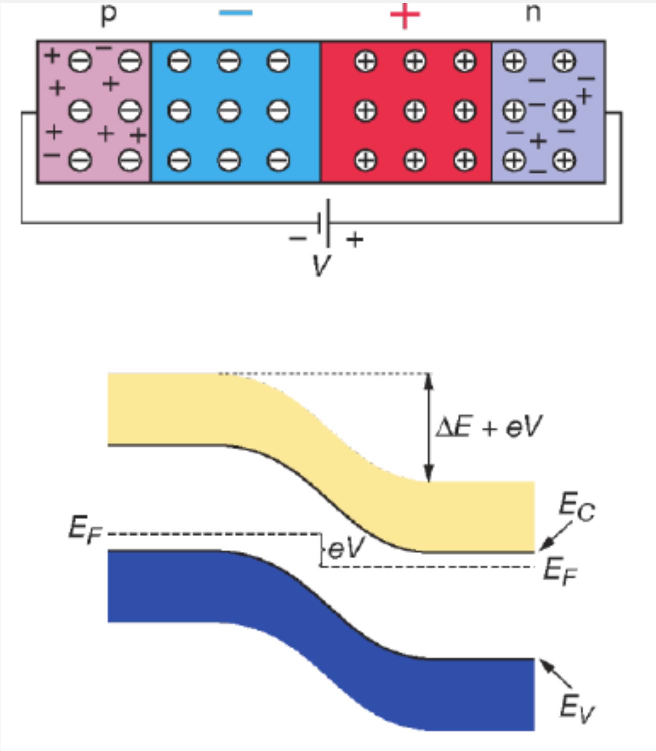
Consequences:

- The potential barrier becomes smaller by eV
- Diffusion across the junction becomes easier
- The current across the junction increases significantly.



Operation a pn-junction with reverse bias

Applying an external voltage V with the cathode to p and the anode to n e^- and holes are pulled out of the depletion zone. The **depletion zone becomes larger** (reverse biasing).



Consequences:

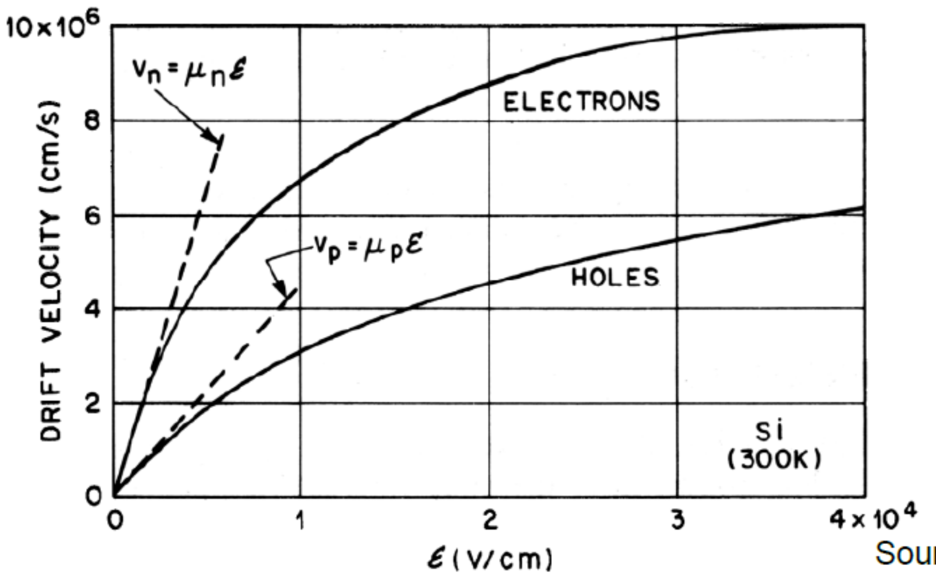
- The potential barrier becomes higher by eV
- Diffusion across the junction is suppressed.
- The current across the junction is very small (“leakage current”)

➢ This is the way we operate our semiconductor detector!

Drift velocity and mobility

Drift velocity for electrons: $\vec{v_n} = -\mu_n \vec{E}$ and for holes: $\vec{v_p} = -\mu_p \vec{E}$

Mobility for electrons: $\mu_n = \frac{e \cdot \tau_n}{m_n}$ and for holes: $\mu_p = \frac{e \cdot \tau_p}{m_p}$



e	…	electron charge
E	…	external electric field
m_n , m_p	…	effective mass of e⁻ and holes
τ_n , τ_p	…	mean free time between collisions for e⁻ and holes (carrier lifetime)

Source: S.M. Sze, *Semiconductor Devices* , J. Wiley & Sons, 1985

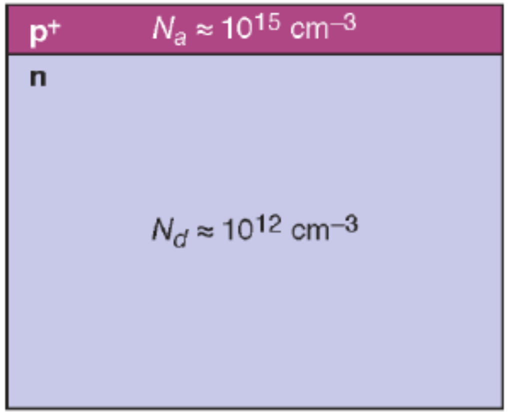
Width of the depletion zone

Effective doping concentration in typical silicon detector with p^+-n junction

- $N_a = 10^{15}$ cm^{-3} in p^+ region
- $N_d = 10^{12}$ cm^{-3} in n bulk

without external voltage:

$W_p = 0.02\ \mu m$
$W_n = 23\ \mu m$



p^+n junction

Applying a reverse bias voltage of 100 V:

$W_p = 0.4\ \mu m$
$W_n = 363\ \mu m$

Width of depletion zone in n bulk:

$$W \approx \sqrt{2\varepsilon_0 \varepsilon_r \mu \rho |V|} \quad \text{with} \quad \rho = \frac{1}{e\,\mu N_{eff}}$$

V … External voltage
ρ … specific resistivity
μ … mobility of majority charge carriers
N_{eff} … effective doping concentration

Resistivity

Specific resistivity is a measure of silicon purity

$$\rho = \frac{1}{e(\mu_n n_e + \mu_p n_h)}$$

n_e , n_h ... Charge carrier density for electrons and holes
μ_n , μ_p ... Mobility for electrons and holes
e ... elementary charge

Carrier mobilities: $\mu_p(\text{Si, 300K}) \approx 450\ \text{cm}^2/\text{Vs}$
$\mu_n(\text{Si, 300K}) \approx 1450\ \text{cm}^2/\text{Vs}$

The charge carrier concentration in pure silicon (i.e. intrinsic Si) for T = 300 K is:

$$n_e = n_h \approx 1.45\cdot 10^{10}\ \text{cm}^{-3}$$

This yields an intrinsic resistivity of:

$$\rho \approx 230\ \text{k}\Omega\text{cm}$$

Potential and field inside the junction

- Solving the Poisson equation for an abrupt p-n junction diode

Poisson equation

$$\rho(x) = e \cdot N_{eff} = const$$

$$-\frac{d^2}{dx^2}\phi(x) = \frac{e \cdot N_{eff}}{\varepsilon}$$

$$E(w) = 0$$

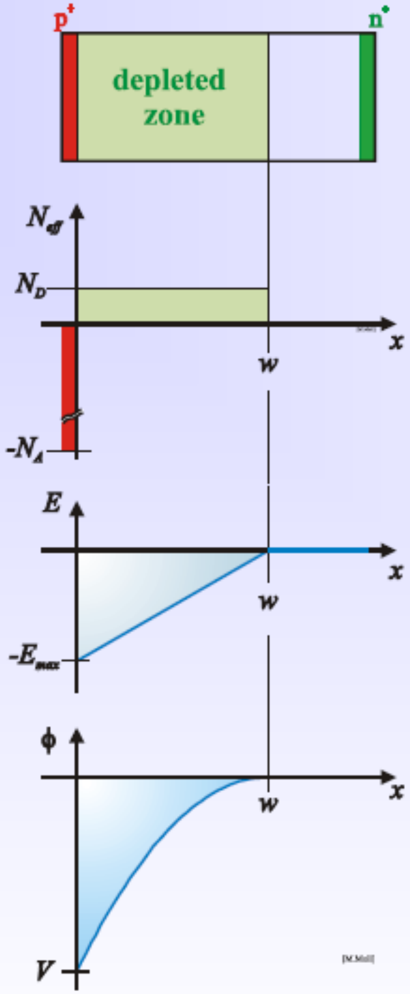
Electric field strength

$$E(x) = -\frac{e \cdot N_{eff}}{\varepsilon} \cdot (w - x)$$

$$\phi(w) = 0$$

Electrostatic potential

$$\phi(x) = -\frac{e \cdot N_{eff}}{\varepsilon} \cdot \frac{1}{2} \cdot (w - x)^2$$



- electric field strength linear function of depth
- depleted zone growing in depth proportional to sqrt(V)

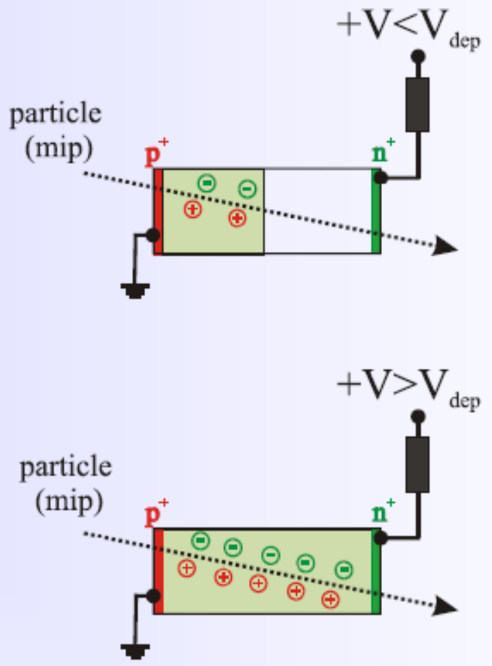
$$E_{max} = -\frac{e \cdot N_{eff}}{\varepsilon} \cdot w$$

$$w = \sqrt{(-V) \cdot \frac{2 \cdot \varepsilon}{e \cdot N_{eff}}}$$

Depletion depth w

Depletion voltage and sensitive volume

- Below depletion ($V<V_{dep}$)
  - Depletion zone x_n growing with $w \propto \sqrt{V}$
  - Only charge generated inside depleted volume will be detected
  - Charge generated in 'neutral zone' (field free zone) will recombine
- Depletion Voltage V_{dep}
  - Sensor depleted of free charge carriers
  - Electric field throughout complete device
  - Complete sensor volume sensitive (active)
  - Example:
    - d = 300 μm
    - N_{eff} = [P] =1.5×10^{12} cm^{-3} ($\rho \approx$ 3kΩcm)
    - $V_{dep} \approx 100V$
- Full charge collection only for ($V>V_{dep}$)



depletion voltage V_{dep} *detector thickness d*

$$V_{dep} = \frac{e}{2\cdot\varepsilon}\cdot|N_{eff}|\cdot d^2$$

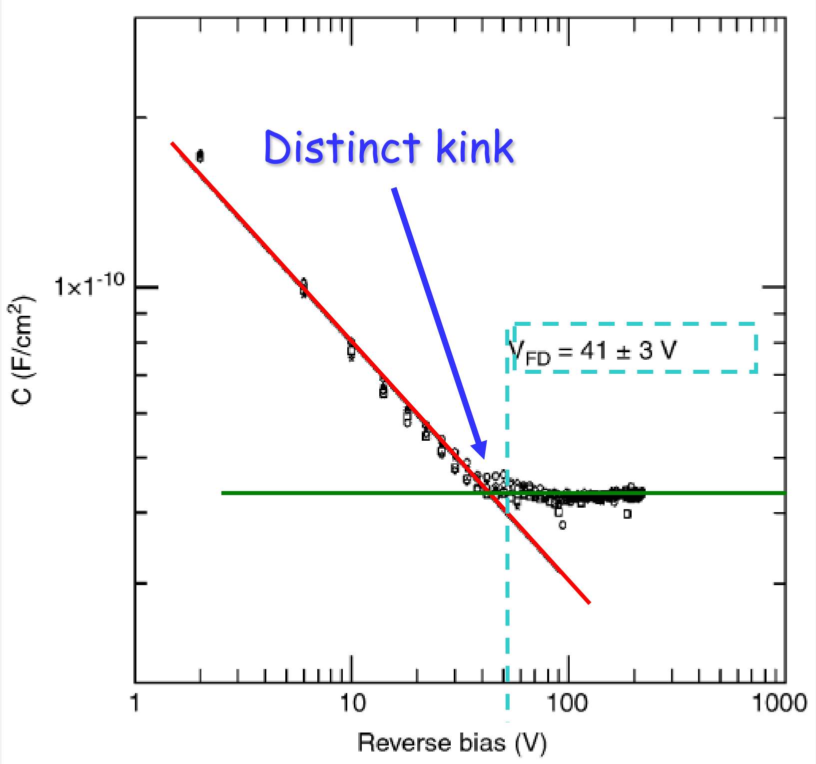
effective space charge density N_{eff}

Depletion voltage determination

❑ " Full Depletion Voltage V_{FD} "

- **Definition**
  - For a semiconductor detector to operate, it is necessary to create a carrier depletion layer in the pn-junction area.
  - The potential where this condition is reached is the " Full Depletion Voltage " (V_{FD}).
- **Determination of V_{FD} from CV curves**

The evaluation of V_{FD} can be performed by the double linear fit of the logarithm of the capacitance versus the logarithm of the voltage (CV method).

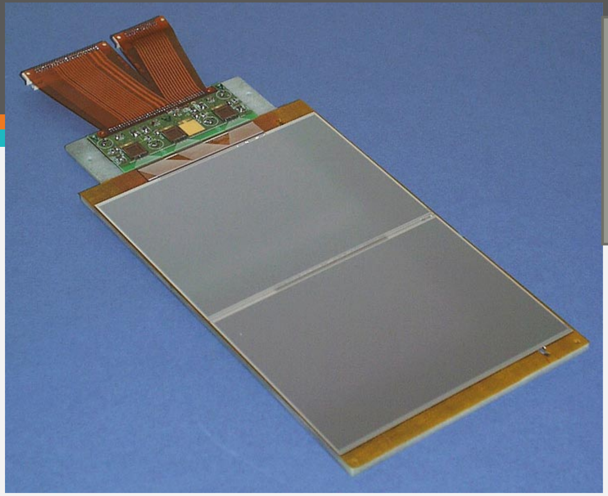


The frequency is generally taken around 1-10 kHz.

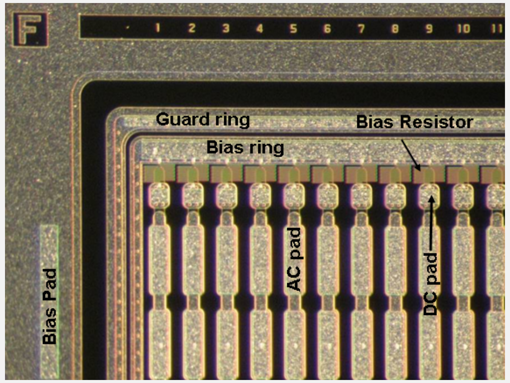
Design considerations

" The Key Parameters "

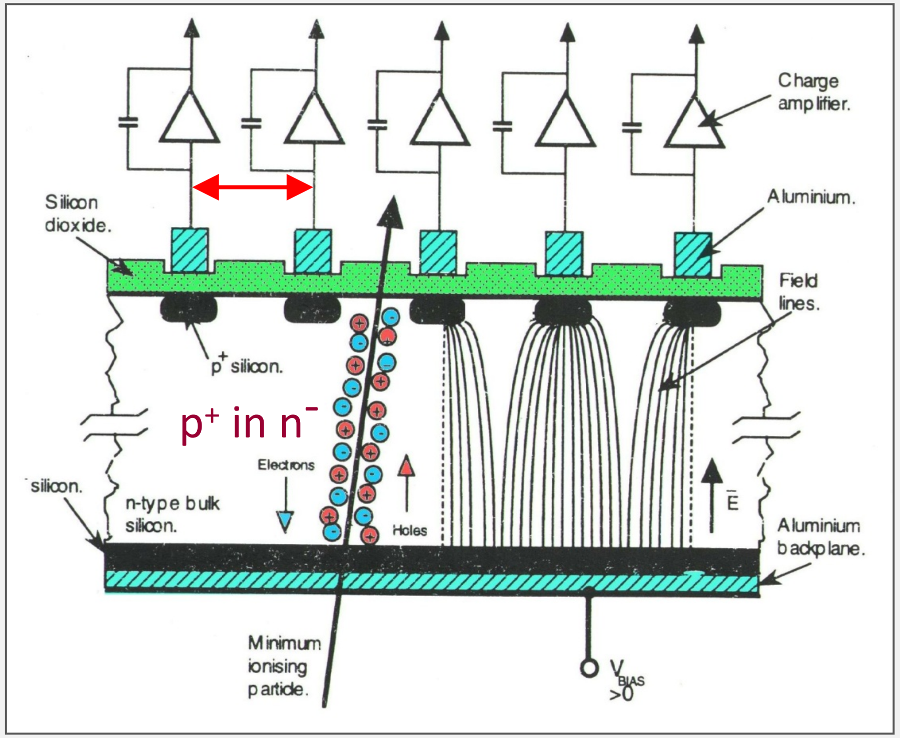
Micro-strip Silicon Detectors



Highly segmented silicon detectors have been used in Particle Physics experiments for nearly 30 years. They are favourite choice for Tracker and Vertex detectors
(high resolution, speed, low mass, relatively low cost)



Pitch ~ 50μm

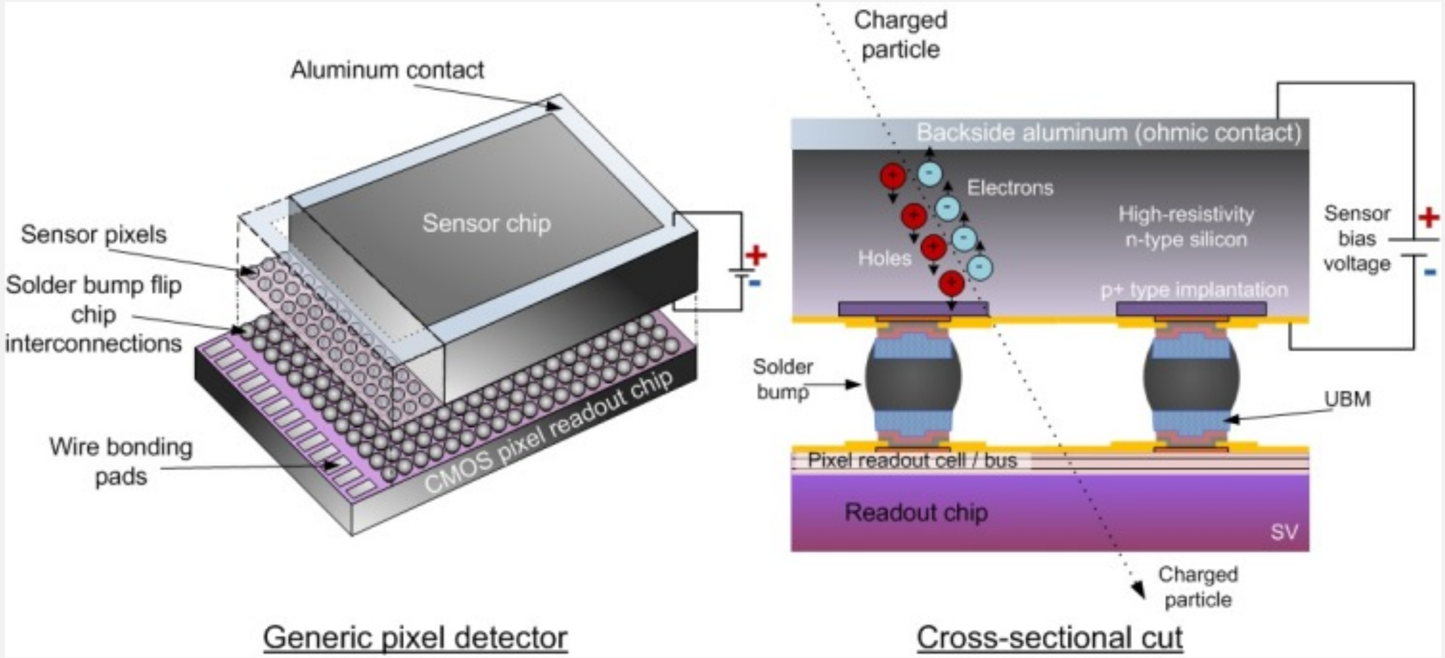


Resolution ~ 5μm

Main application: detect the passage of ionizing radiation with high spatial resolution and good efficiency.
Segmentation → position

Silicon pixel sensor principle

- Operation
  - Multi-PN diode in reverse bias
  - Depletion layer start from junction
  - Particle ionises Si, producing e/h pairs
  - e/h pairs drift in E-Field to electrodes
- Properties
  - Thickness from 50 to 300 um
  - ➔ signal 24000 e/h pairs (80 e/µm)
  - High segmentation required
  - Advantage of using silicon
    - Low ionisation energy
    - Fast signal collection



- Relevant parameters for performance
  - Leakage current
  - Depletion voltage (Vdep) Operational Voltage
  - Collected Charge
  - Heat load

Noise

- Depends upon detector capacitance and reverse current
- Depends upon electronics design
- Function of signal shaping time
- Lower capacitance ⇒ lower noise
- Faster electronics ⇒ noise contribution from reverse current less significant

Constructing a detector

Let's make a simple calculation for silicon:

- mean ionization energy $\mathbf{I_0 = 3.62\ eV}$.
- mean energy loss per flight path of a mip **dE/dx = 3.87 MeV/cm**

Assuming a detector with a thickness of d = 300 μm and an area of A = 1 cm^2

- **Signal of a mip in such a detector:**

$$\frac{dE/dx \cdot d}{I_0} = \frac{3.87 \cdot 10^6\ eV/cm \cdot 0.03cm}{3.62eV} \approx 3.2 \cdot 10^4 e^- h^+ - pairs$$

- **Intrinsic charge carrier in the same volume** (T = 300 K)

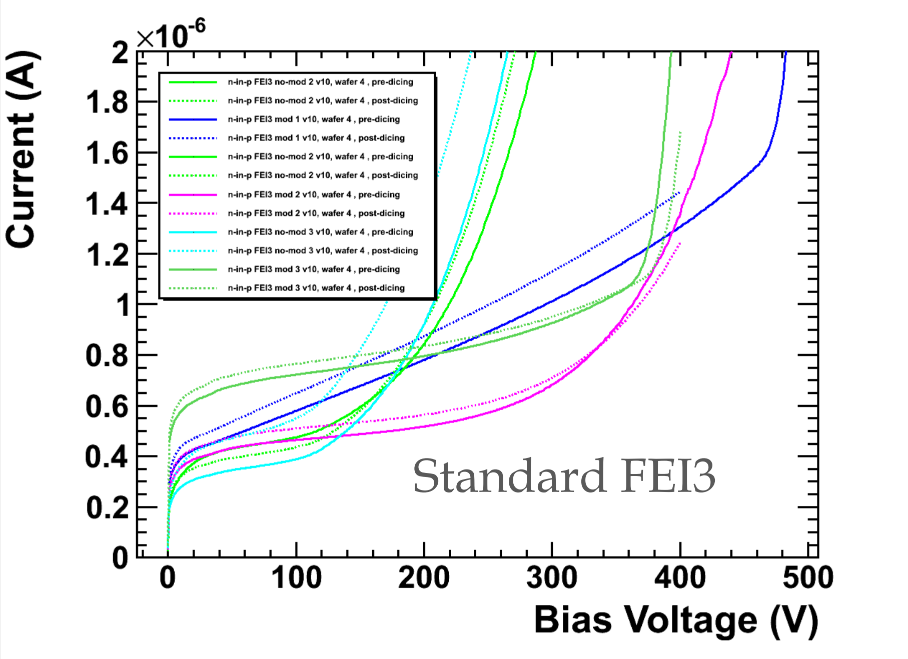
$$n_i \cdot d \cdot A = 1.45 \cdot 10^{10} cm^{-3} \cdot 0.03cm \cdot 1cm^2 \approx 4.35 \cdot 10^8 e^- h^+ - pairs$$

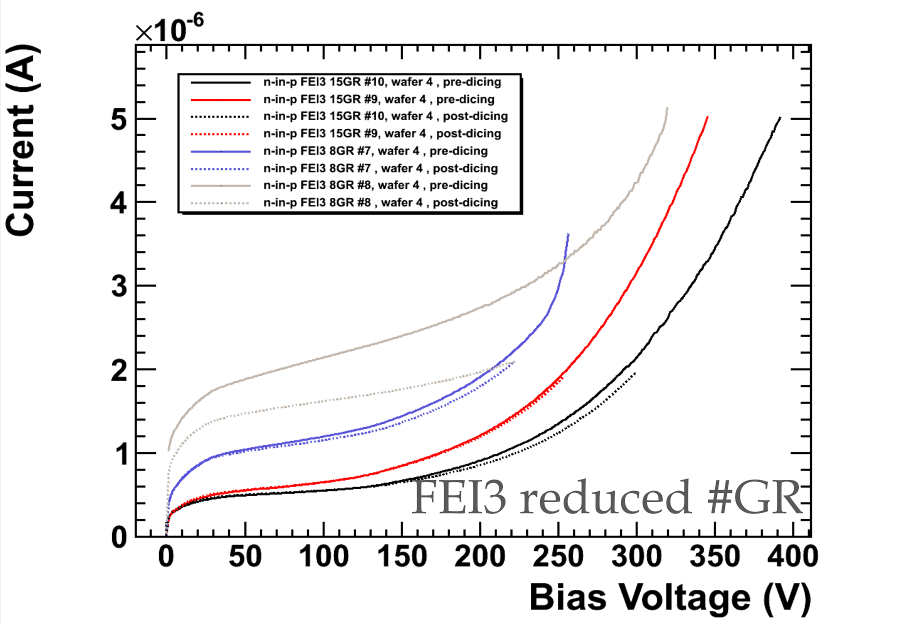
Result: the number of thermal created e-h+-pairs (noise is four orders of magnitude larger than the signal).

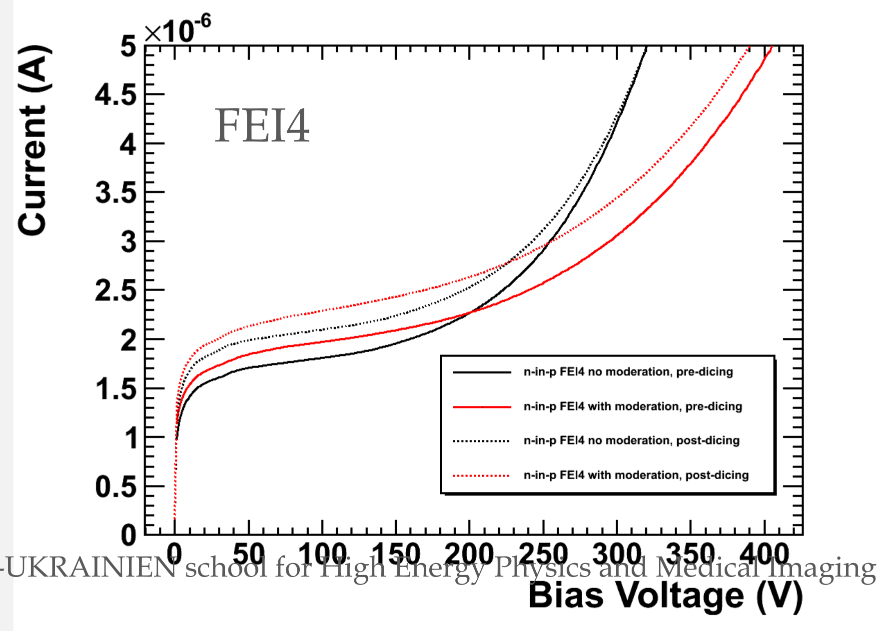
We have to remove the charge carriers

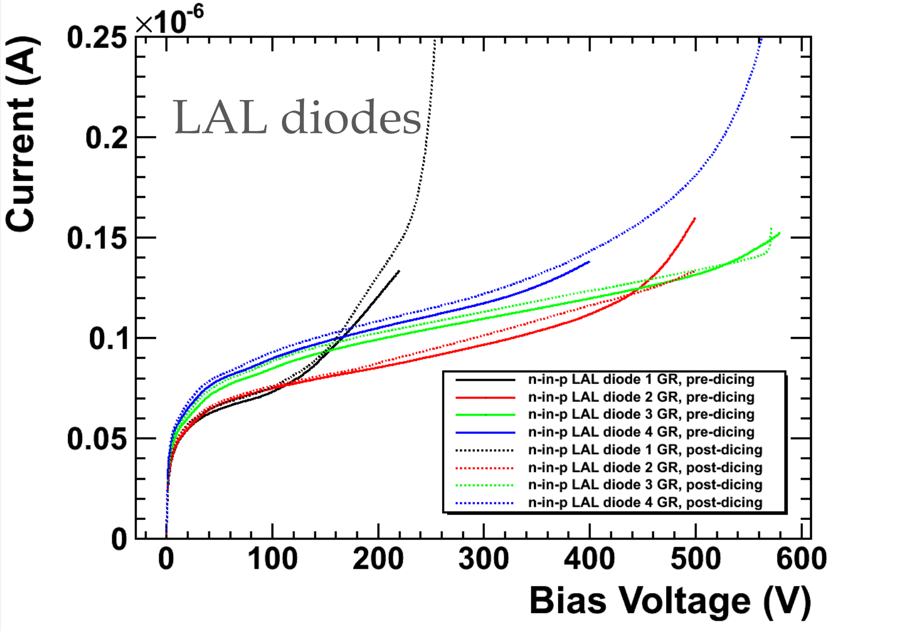
→ depletion zone in inverse biased **pn junctions**

Reverse current : characteristics on p-type wafer: a selection criteria









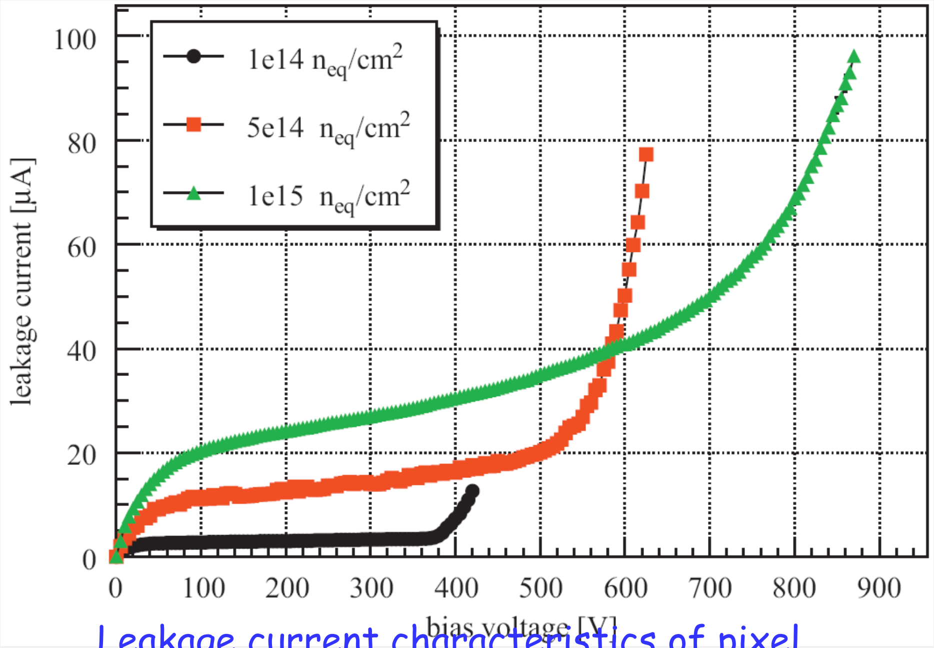
Leakage current and breakdown of irradiated devices

❑ " Break-Down Voltage V_{BD} "

- The breakdown voltage is defined as the highest measured voltage for a defined normalized leakage current.

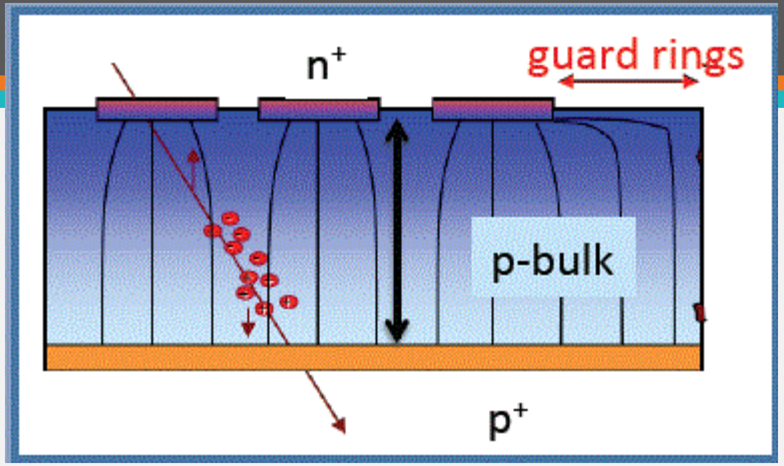
❑ " Leakage Current "

- The leakage current is a sensitive and effective signature for quality assurance and control. It originates from the introduction of generation/recombination centers.



Leakage current characteristics of pixel sensors for different proton fluences.

Design considerations



Readout chip connection to thin sensor

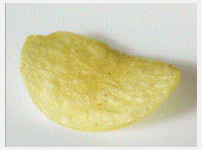
- Can lead to internal stress
- Can introduce disconnected bumps (open)
- Alignement inaccuracies

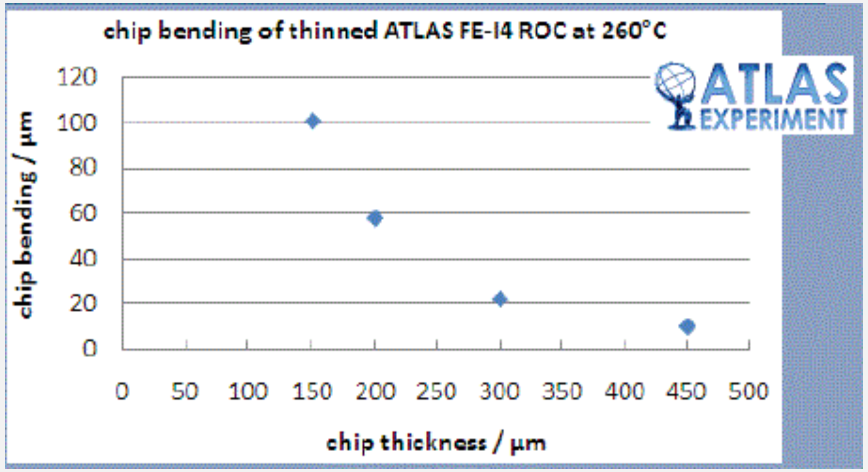
Thin planar process

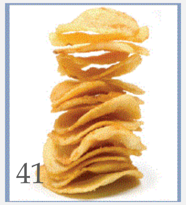
- ❖Low leakage current (before and after irradiation)
- ❖ Low operational voltage
- ❖ Less power consumption
- ❖ Short drift path ➔ less trapping
- ❖ Higher electric field at low Vbias (fast collection time)
- ❖ Less material (good for tracking)

Drawback

- ❖Smaller initial signal
- ❖Thinning cost extra money
- ❖Handle with care







How much charge can be collected : The Charge signal

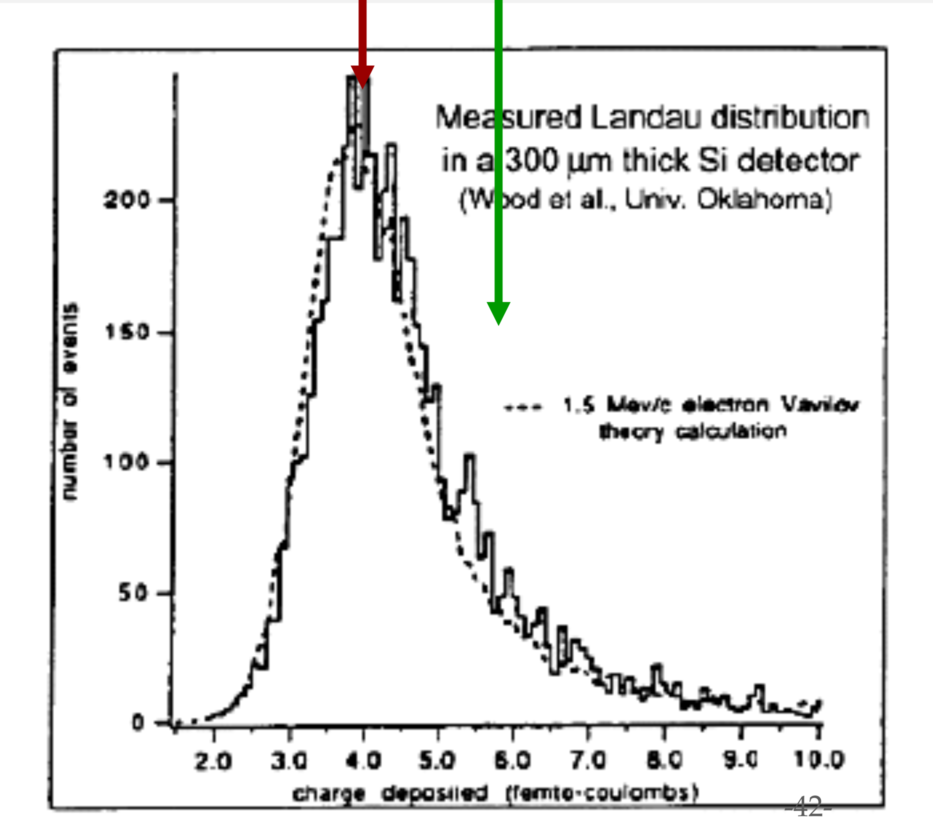
Collected Charge for a Minimum Ionizing Particle (MIP)

- Mean energy loss
  dE/dx (Si) = 3.88 MeV/cm
  ⇒ 116 keV for 300μm thickness
- Most probable energy loss
  ≈ 0.7 ×mean
  ⇒ 81 keV
- 3.6 eV to create an e-h pair
  ⇒ 108 e-h / μm (mean)
  ⇒ ~80 e-h / μm (most probable)
- Most probable charge **(300 μm)**

  ≈ 24000 e ≈ 3.6 fC

Most probable charge ≈ 0.7× mean

Mean charge



A few considerations on charge collection in case of trapping (Irradiation)

- Charge collection in pixel detectors:

The total charge collected by a detector , Q, can be written as : $Q=Q_0 \,.\, \theta .\, \eta$

θ is the geometrical factor and η the trapping factor

For a planar pad detector with no segmentation, the weigting field E_w is 1/d (ramo**) and the induced current by a moving charge $Q'_0(t)$ is :

$$i(t) = Q_0^{'}(t).E_w.v_{dr}(t) = Q_0^{'}(t).\frac{1}{d}.v_{dr}(t)$$

$v_{dr}(t)$ is the carrier drift velocity that depends on the detector internal field, and $Q'_0(t)$ is affected by trapping:

$$Q_0^{'}(t) = Q_0.e^{\frac{-t}{\tau_t}}$$

The total collected charge can be written :

$$Q\ (t) = \int_0^{tdr} Q_0.e^{\frac{-t}{\tau_t}}.\frac{1}{d}.v_{dr}(t).dt$$

τ_t is the trapping time constant that is inversely proportional to the trap concentration. t_{dr} is is the drift time or carrier transcient time

It could be rewritten as :

For constant electric field, we assume a constant drift velocity $v_{dr}(t) = V_{dr}$, we have :

$$Q = Q_{0.}.\frac{w}{d}.\frac{\tau_t}{t_{dr}}.(1-e^{-t_{dr}/\tau_t})$$

θ ($\frac{w}{d}$) η ($\frac{\tau_t}{t_{dr}}.(1-e^{-t_{dr}/\tau_t})$)

w is the full detector depletion depth and $w = V_{dr}.\ t_{dr}$ is used for planar detectors

Charge collection distance for large trapping

- If Q_0 is the charge deposited by a MIP particle in a detector of thickness d (**in microns**), then Q_0 can be expressed in terms of number of electrons: $Q_0(t) = 80.d$
- So, Q(t) in electrons could be written as :

$$Q(t) = 80.w.\frac{\tau_t}{t_{dr}}\left(1 - e^{\frac{-t_{dr}}{\tau_t}}\right)$$

- For situation with large trapping , such as HL-LHC, up to 10^{16} n_{eq}/cm^2 , we have : $\frac{\tau_t}{t_{dr}} \prec\prec 1$

Thus :

$$Q \cong 80.w.\frac{\tau_t}{t_{dr}} = 80.v_{dr}.\tau_t \equiv 80.d_{CCE}$$

- d_{CCE} is expressed in microns and is defined as a charge collection distance or trapping distance
- Note that d_{CCE} is equal to **20 microns** for 10^{16} neq/cm^2 if τ_t is 0.2 ns, $v_{dr}=10^7$ cm/s
- *Conclusion : it doesn't matter if a detector with thickness d>50 µm is fully depleted or not; the collected charge is about the same if* $d \geq 50\,\mu m$

It is in the order of **1600 electrons** for 10^{16} n_{eq}/cm^2 .

Low or moderate fluences

- For low or moderate fluences, where: $\frac{\tau_t}{t_{dr}} \succ\succ 1$

$$Q = 80w.\left(1 - \frac{1}{2}.\frac{t_{dr}}{\tau_t}\right)$$

- In this case, the detector depletion depth is still an important factor in the collected charge, which depends on the voltage :

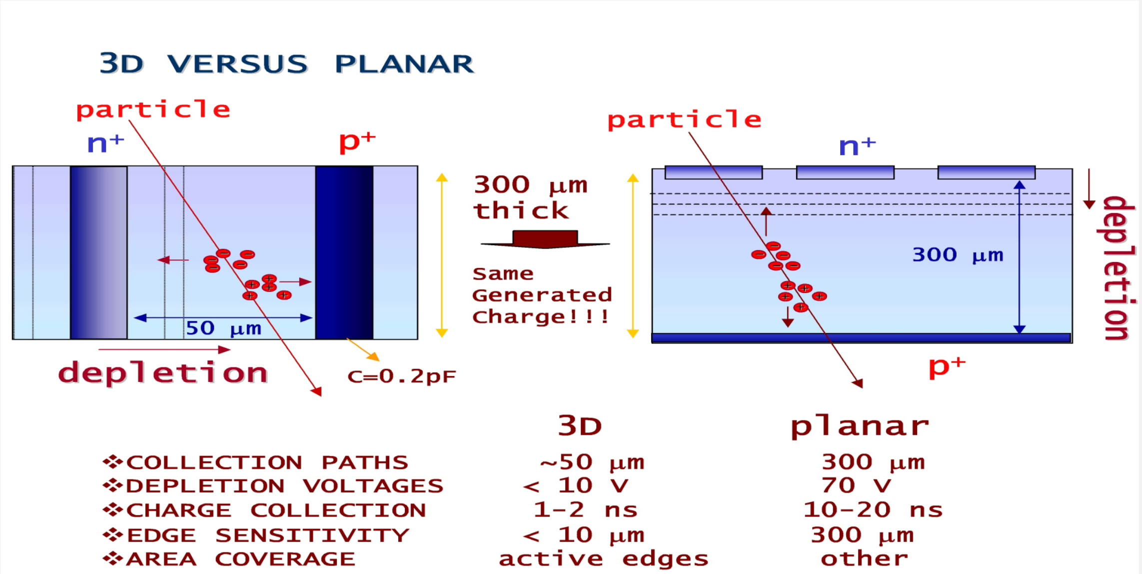
$$w = \sqrt{\frac{2\varepsilon.\varepsilon_0.V}{e.N_{eff}}}$$

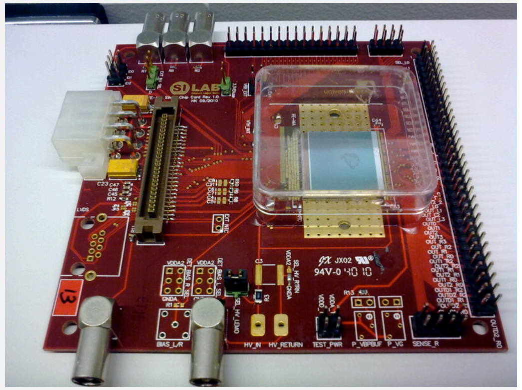
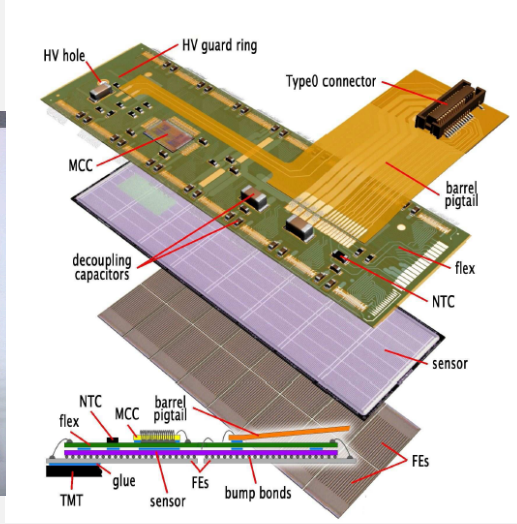
Good Idea

- The idea is to decouple the drift length and the detector thickness ==➔ Go toward 3D detectors where condition is satisfied (column separation 40 to 400 µm) and the total induced charge by mip is still 80 d ➔ 24000 electrons for 300 µm.

Improving charge collection efficiency

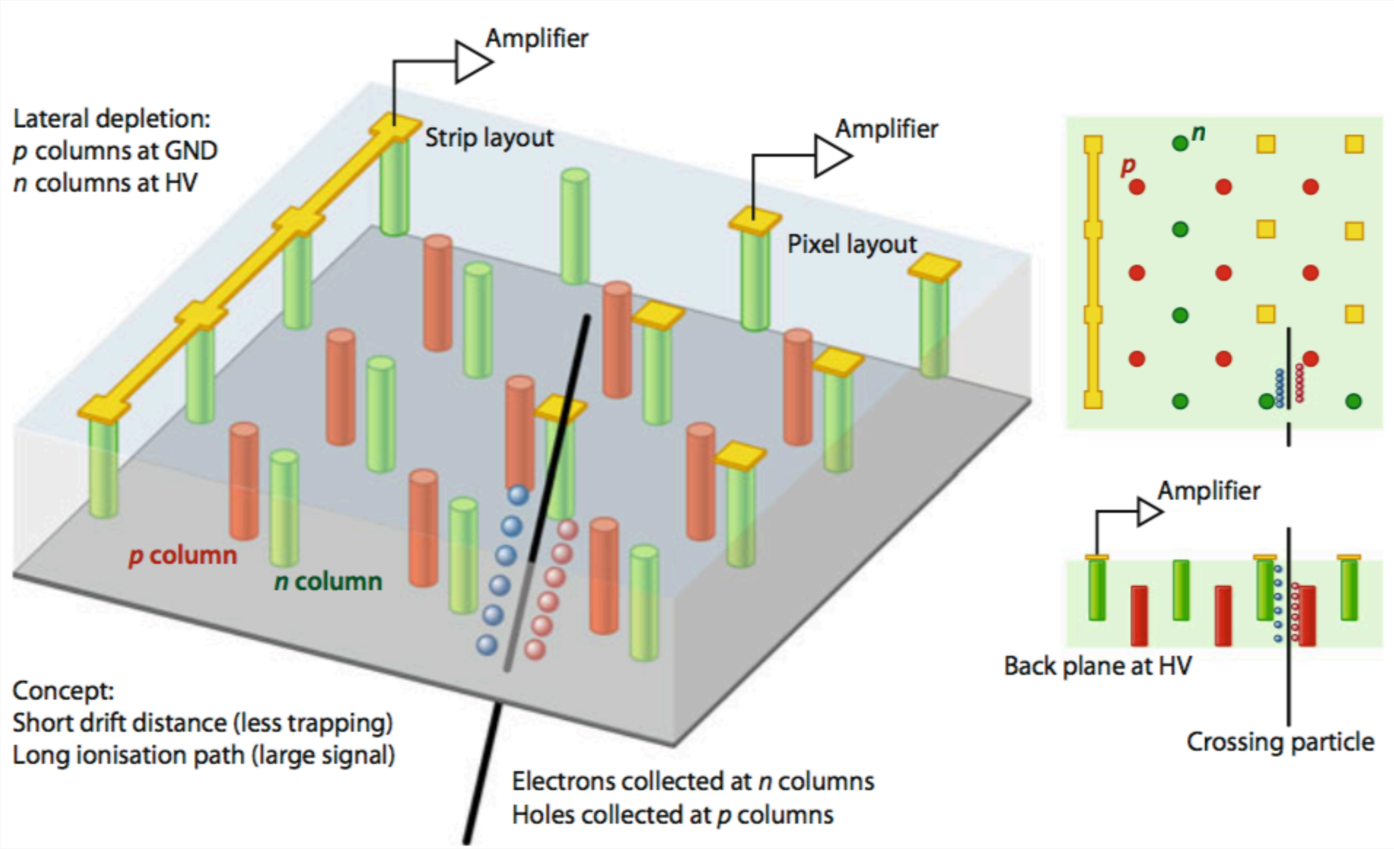
- The weigting field in 3D detector is given by : $Q_{3D} = 80.\frac{d}{\lambda_{cc}} d_{CCE}$ (very high fluences)
- λ_{cc} is the electrode spacing
- It is clear that the collected charge in a 3D detector is amplified by d/λc, as compared to planar sensors.
- *For a 300 µm thick sensor with 50 µm column spacing, the amplification is 6 !*



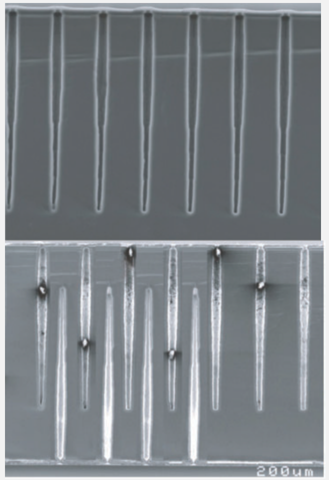



ATLAS FEI4 module

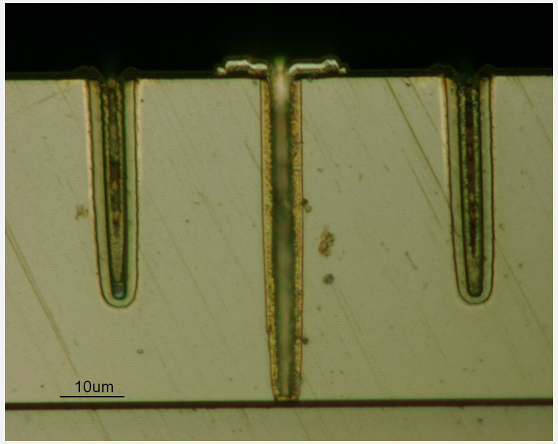
3D Principle



- Double or single type



- small pixel cells 25x100 μm²
  - We need narrow columns!
- High column depth/width is better…



Courtesy CNM

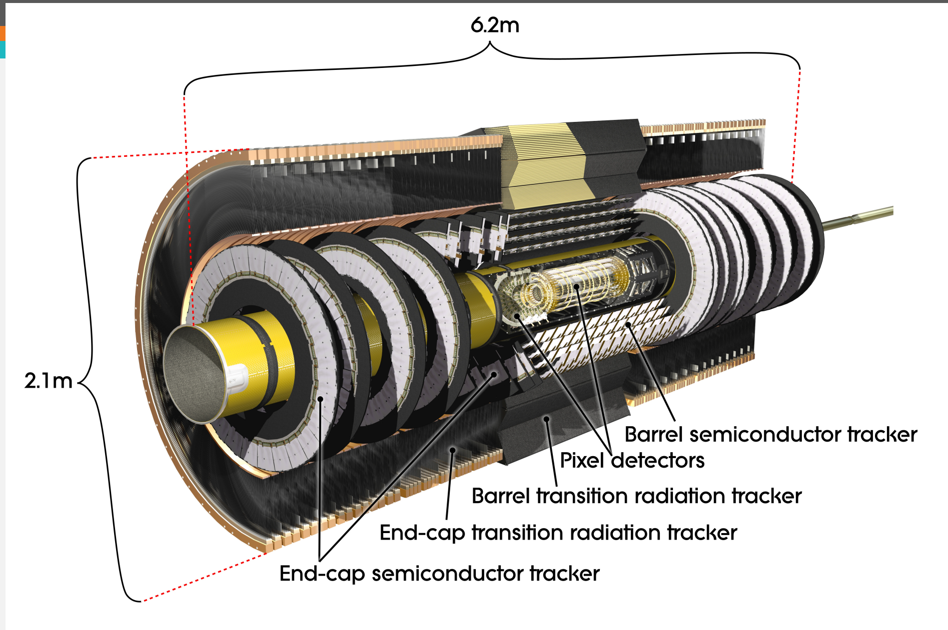
Silicon pixel detector for ATLAS

challenges and Constraints

Planar Technolgy

The **planar process** is a manufacturing process used in the semiconductor industry to build individual components of a transistor, and in turn, connect those transistors together.
It is the primary process by which modern integrated circuits are built. The process was developed by Jean Hoerni, while working at Fairchild Semiconductor, with a first patent issued 1959.
The key concept was to view a circuit in its two-dimensional projection (a plane), thus allowing the use of photographic processes concepts such as film negatives to mask the projection of light exposed chemicals. This allowed the use of a series of exposures on a substrate (Silicon) to create **silicon oxide (insulators) or doped regions (conductors)**. Together with the use of **metallization** (to join together the integrated circuits), and the concept of p-n junction isolation (from Kurt Lehovec), the researchers at Fairchild were able to create circuits on a single silicon crystal slice (a wafer) from a mono-crystalline silicon bar.
The process involves the basic procedures of (SiO_2) oxidation, SiO_2 etching and heat diffusion.
The final steps involves oxidizing the entire wafer silicon dioxyde with an SiO_2 layer, etching contact vias to the transistors, and depositing a covering metal layer over the oxide, thus connecting the transistors without manually wiring them together.

Challenges for a new inner tracker

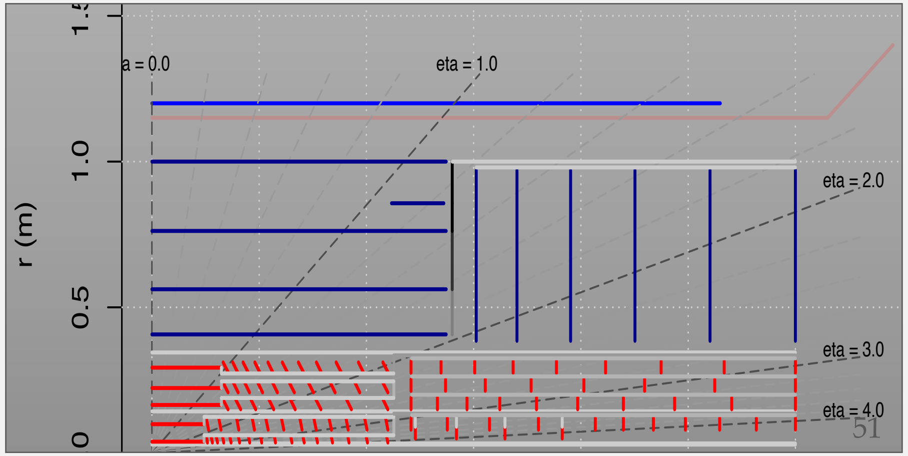


High Luminosity LHC conditions will affect Drastically the current design

- ➢ **Peak Luminosity will increase by a factor 5-7 : 5-7 10**34**
- ➢ **Average Pileup : a factor of 8 <μ> ~200**
- ➢ **Integrated luminosity : a factor 10 : 3000 fb^{-1}**
- ➢ **Radiation hardness : a factor 20 : $2x10^{16}$ n_{eq}/cm^2**

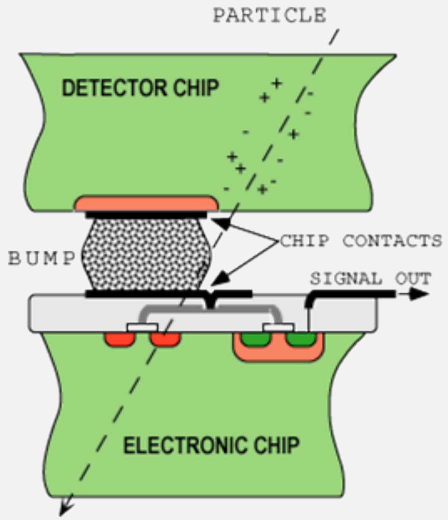
Upgrade of ATLAS phase 0

- Same or better performance required !
  - Use quite "transparent tracker" Low X0
  - Provide V. High granularity sensors
  - Go du deep submicron technologies -65 nm CMOS
  - Raise the transfer data band-with (5Gps)
  - Improve the layout and mechanics



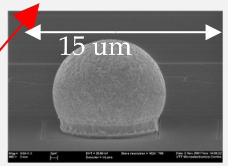
Hybrid Pixel Detectors used in ATLAS for 900 MChannels

- Hybrid Active Pixel Sensors
  - **segment silicon to diode matrix with high granularity (50x50 um2 or 50x125 um2)**
    (⇒ true 2D, no reconstruction ambiguity)
  - **readout electronic with same geometry**
    (every cell connected to its own processing electronics)
  - **connection by "bump bonding"**
  - **requires sophisticated readout architecture**
  - **Hybrid pixel detectors will be used in LHC experiments: ATLAS, ALICE, CMS and LHCb**

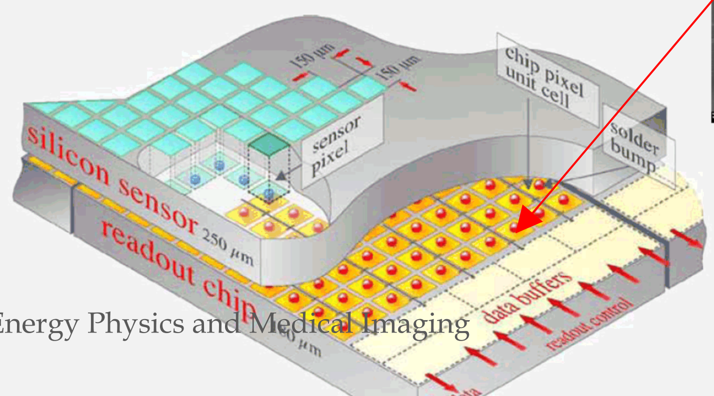


Flip-chip technique

(VTT/Finland)

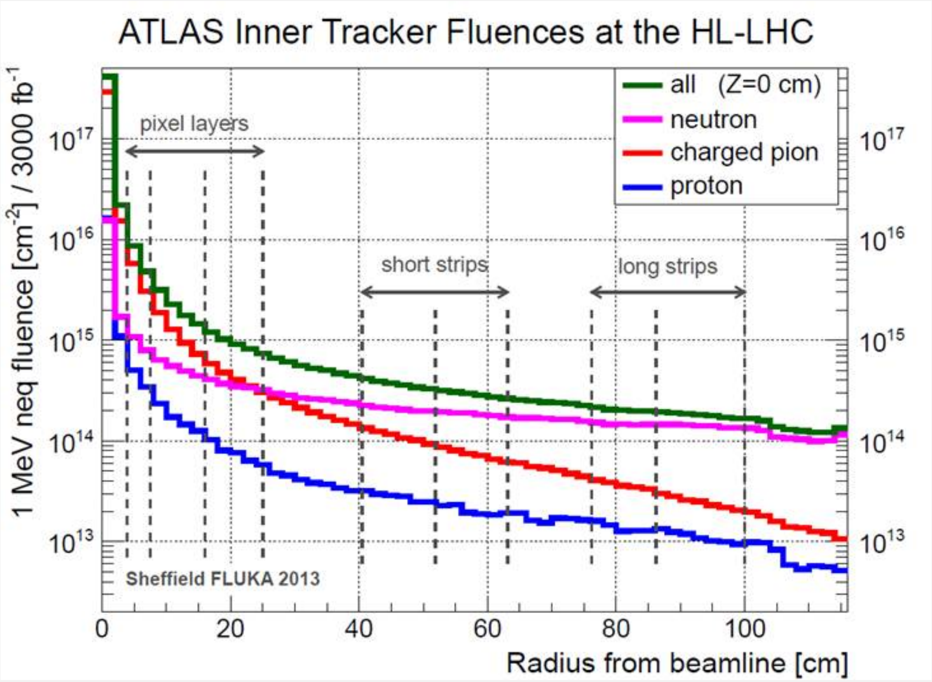


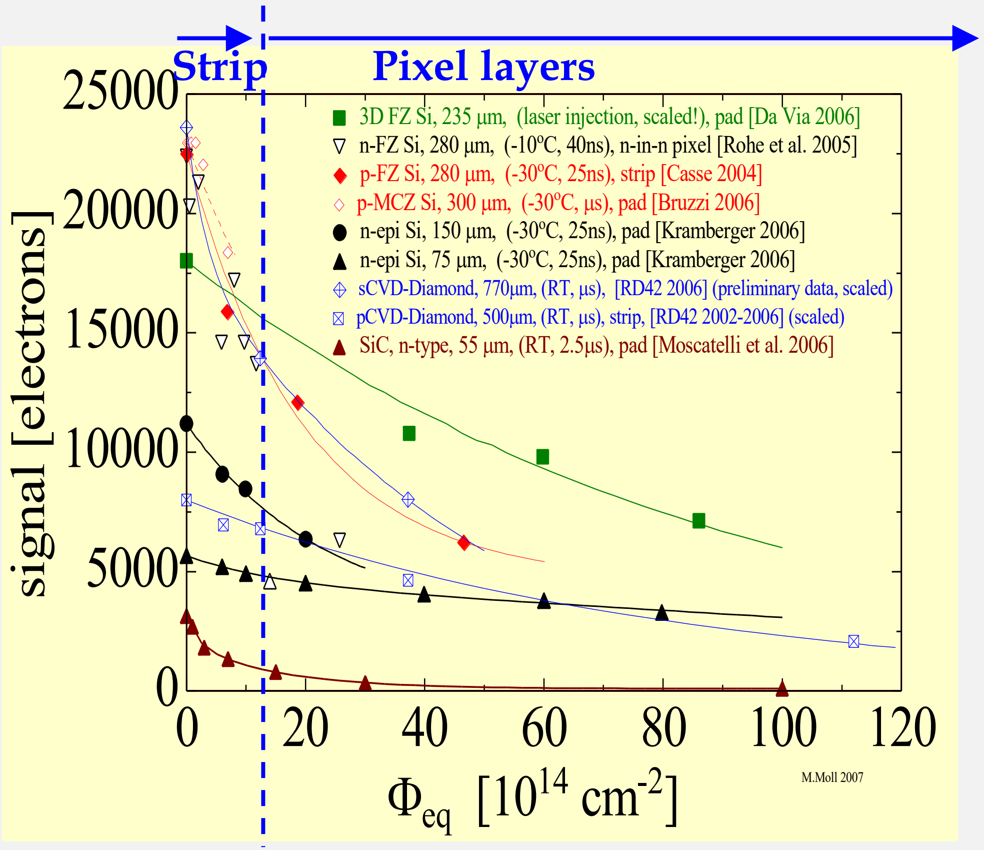
Solder Bump: Pb-Sn



Fluences and signal collection

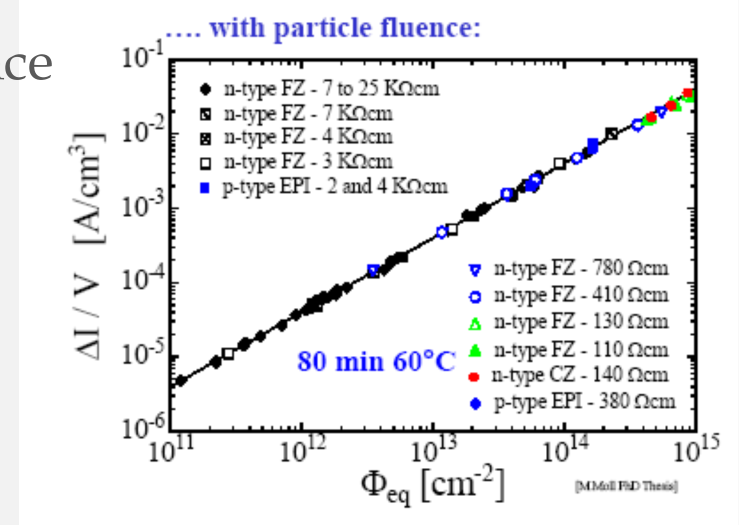
(HL-LHC conditions)





Effects of Radiation in pixel sensors

Current/fluence



1. **Radiation induced leakage current**

independent of impurities; every 7°C of temperature reduction halves current

⇔ cool sensors to ≈ -25°C

2. **“type inversion” from n to p-bulk**

⇔ **increased depletion voltage**

oxygenated silicon helps (for protons);

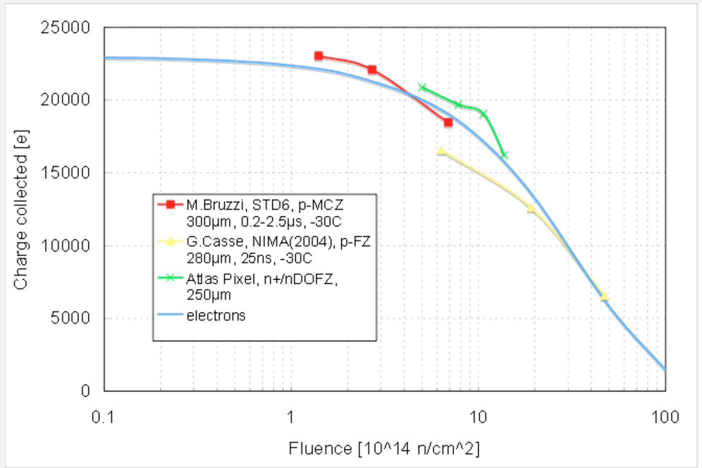
n+-in-n-bulk or n+-in-p-bulk helps

3. **Charge trapping**

the most dangerous effect at high fluences

⇔ collect electrons rather than holes

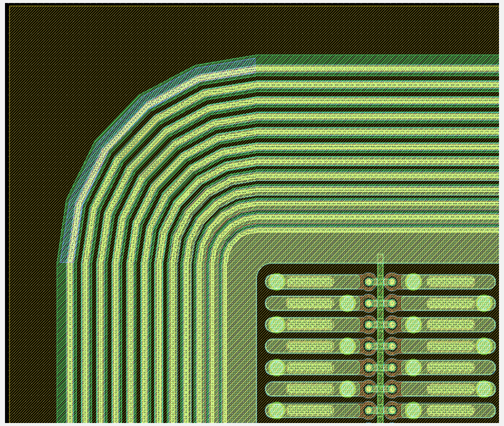
⇔ reduce drift distances



Overview of R&D activity

- How to improve the actual design ?
- Telescope Tool
- TCAD simulation Tool
- SIMS Tool

Summary of R&D contributions within ATLAS



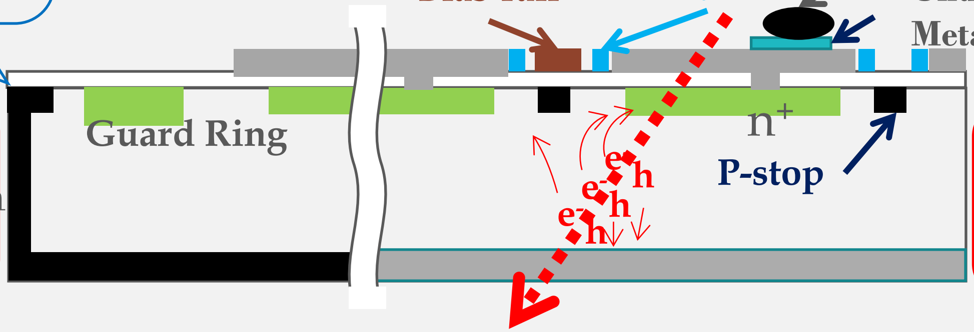
Goals

- Performance : evaluate & improve sensor design for radiation tolerance up to $3x10^{15} n_{eq}/cm^2$ fluence.
- Productions : work on various wafer productions (Cis, VTT Advacam & FBK)

Biasing Structure
- Optimize Biasing structure
- Higher Efficiency at Pixel boundary

Bumpbonding
- Better UBM material
- Higher Flip-Chip Yield

Active Edge
- Smaller Edge size
- Higher Efficiency at Edge region



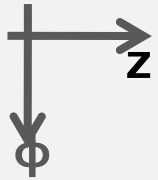
Simulation
- Doping concentration
- Charge collection

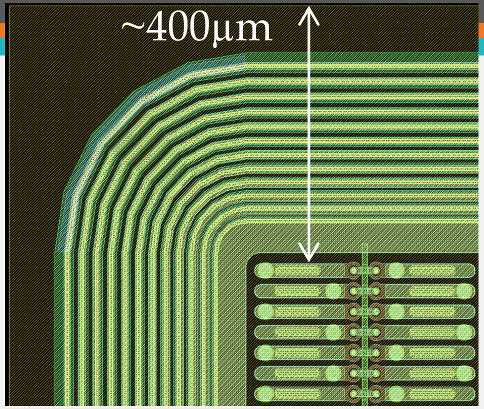
Radiation Tolerance
Assembly
Production…

Typical examples of VTT-LAL Edge design

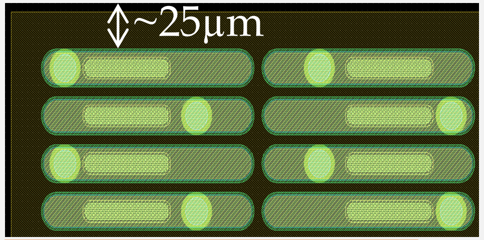
- VTT OMEGAPIX (SlimEdge & Edgeless) designs:
  1. 12 GR +BR
  2. 1GR + BR
  3. 0 GR + BR
  4. 0 GR & 0 BR
  5. 1GR & no BR

T. Rashid, PhD thesis 2019

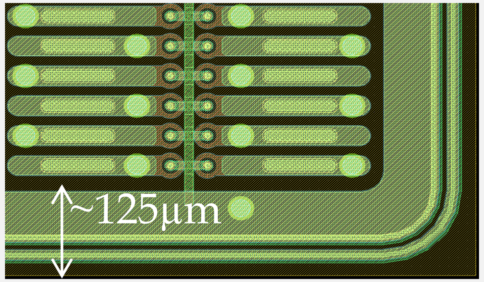




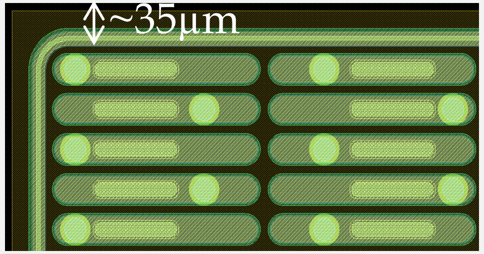
12GR+BR



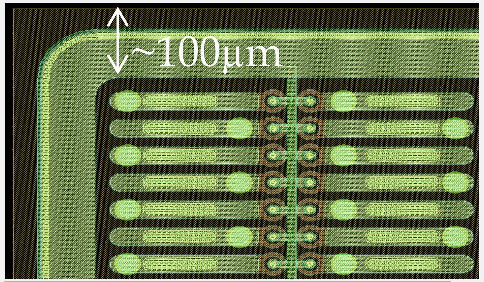
0GR + 0BiasRing



1GR +BiasRing



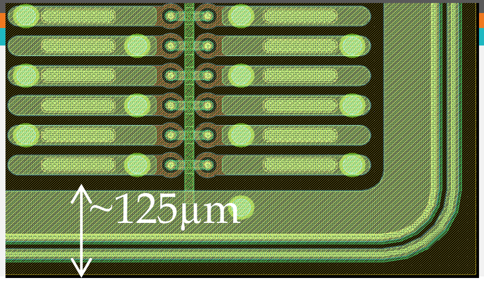
0BiasRing+1GR

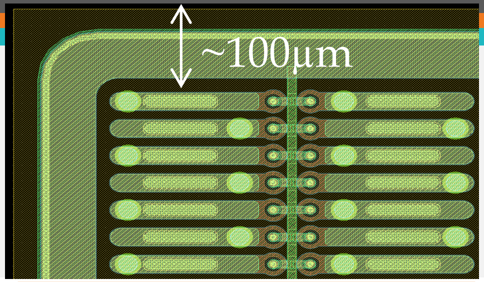


oGR+ BiasRing

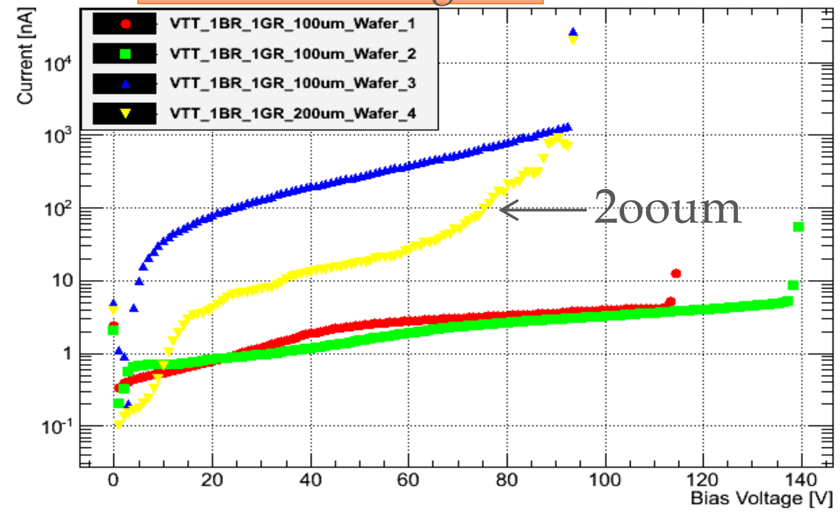
- All designs:
  - Active Area: 4800 x 3360 µm2
  - Array: 96 x 24 (ϕ,z)
  - Pixel Size : 35 x 200 µm2
  - Thickness: 50 to 200µm

VTT Slim Edge:

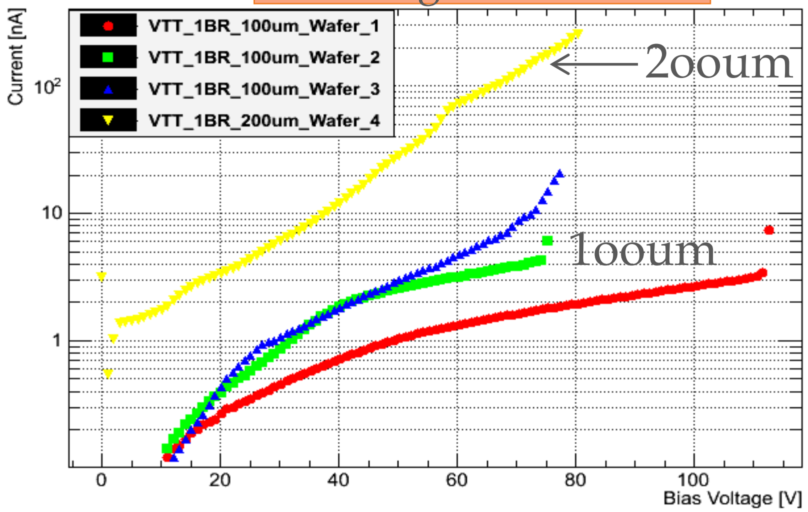




1GR + BiasRing



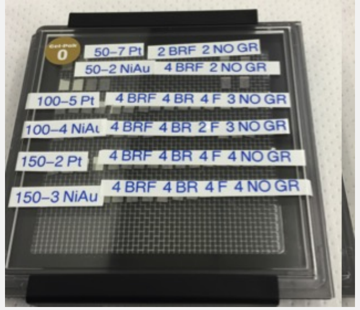
BiasRing + 0 GR



VTT: BiasRing + 1GR
100-200µm thickness
Vbd ~ 100V to 140V

VTT: BiasRing
100-200µm thickness
Vbd ~ 75V to 120V

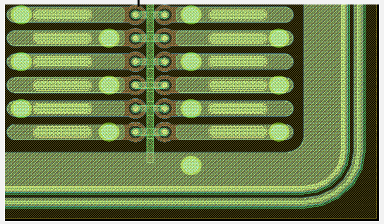
ADVACAM Active Edge Sensors

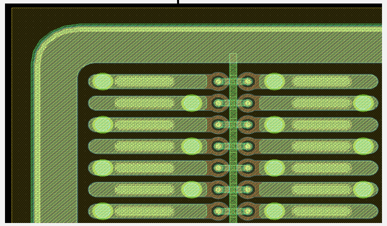


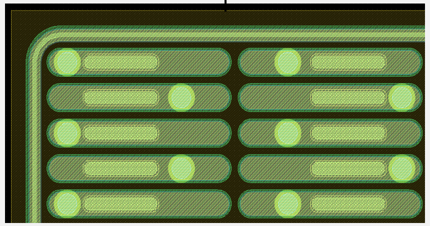
Thickness:
50µm, 100µm, 150µm.

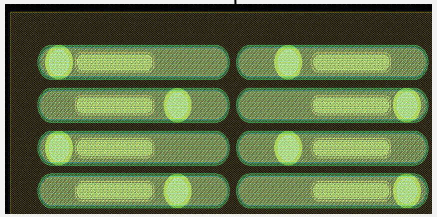
UBM:
Platinum (Pt) or Nickel-Gold (NiAu).

Edge Design:



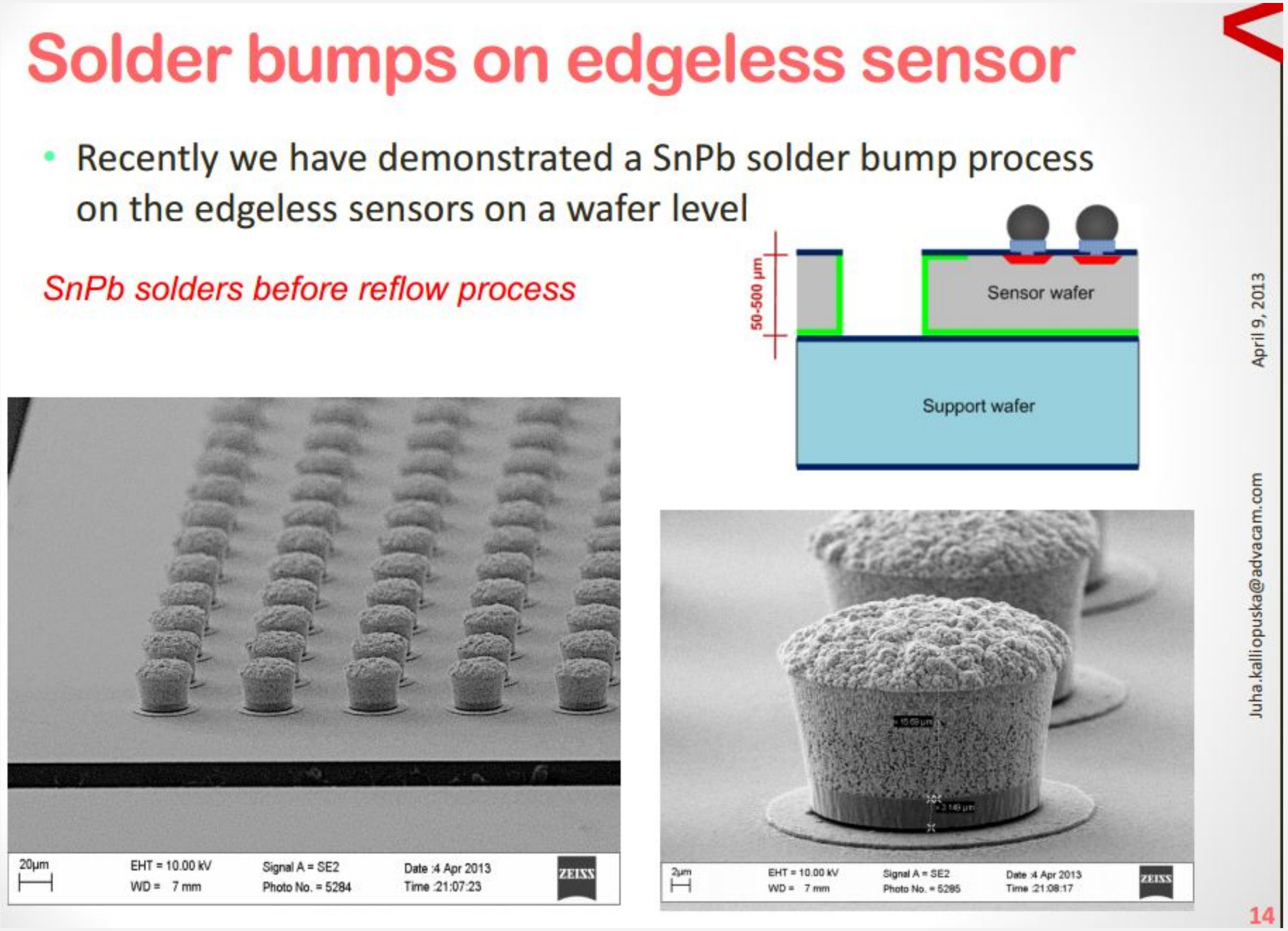






BR+GR	*BR+No GR*	*GR+No BR*	*No BR+No GR*
Inactive regions: 100µm	*78µm*	*47µm*	*47µm*

New challenges on interconnections for Edgless pixel sensor



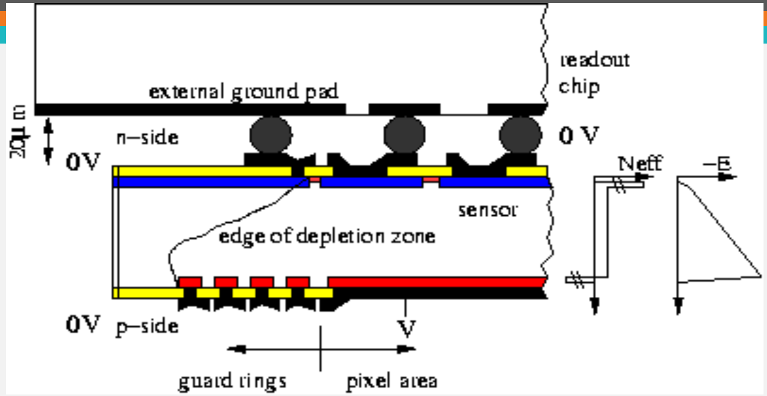
VTT finland

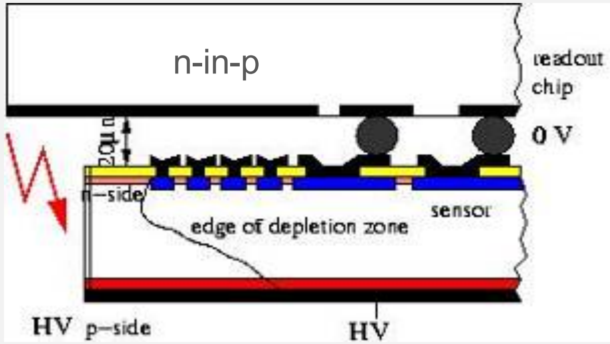
R&D :Towards (n-in-p) Edgless Sensors for the future HL-LHC

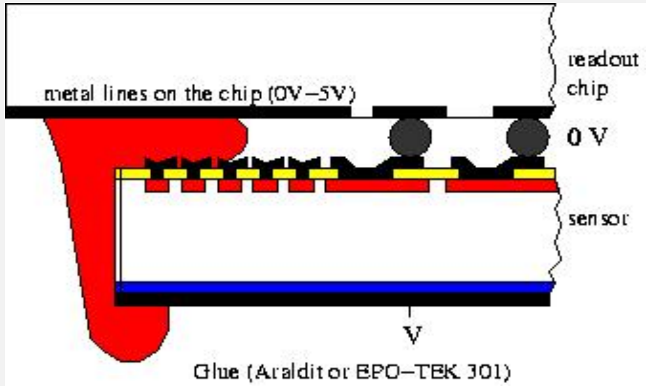
ATLAS pixel detector uses
n-in-n-sensors

- double sided processing (back side is structured)
- all sensor edges at ground
- most expensive part of the module

- *Exploring n-in-p sensors as alternative*
- Studies show radiation hardness
- single sided process ~ price benefit of factor 2-3
  - Develop Active Edge Technology
- Absence of guard rings on back side lead to risk of (destructive) sparking to the ROC

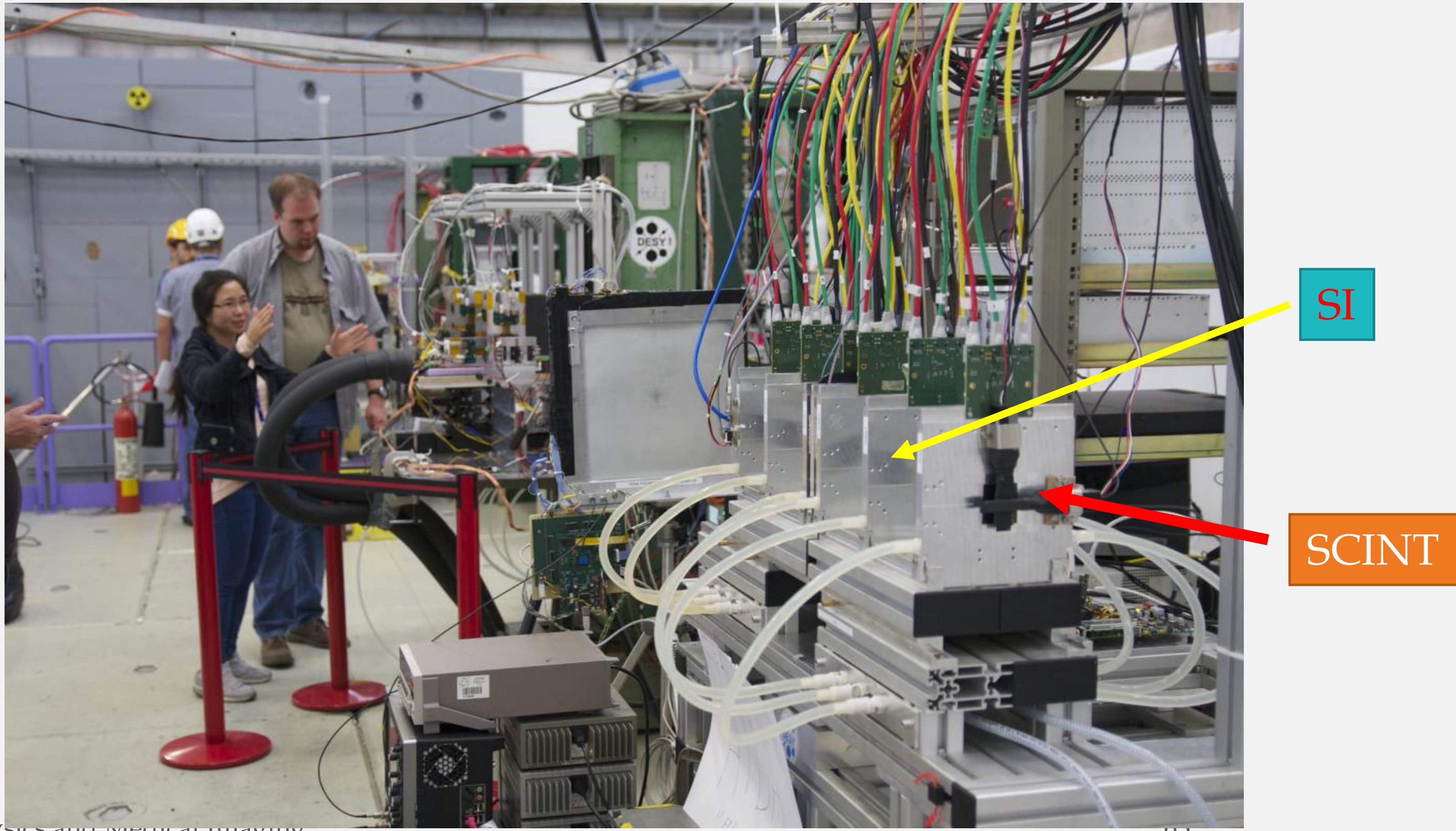






Beam Test Telescope Tool

- A tool to study performance of our devices with high energy particles



Test Beam setup conditions

Environment and purpose

Ref

3B (slim edge)

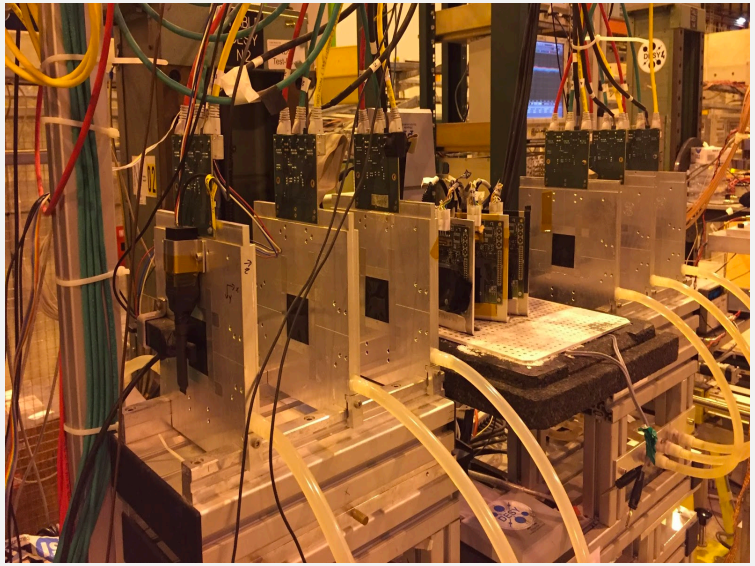
1A (active edge)

Ref

- Beam: CERN SPS 120 GeV pion
- Telescopes: ACONITE (H6A) and AIDA (H6B)
  - Telescope planes with Mimosa26 sensors (1152x576), pixel pitch 18.4µm

- **Normal** incidence (H6B #1)
  - Dry ice cooling (approx. -40 to -50 ˚C*)
  - Bias voltage points: 50 V, 80 V, 100 V, 120 V

- **Inclined** track (H6B #2)
  - DUT tilted at 27˚ (around y-axis)
  - Dry ice cooling (approx. -40 to -50 ˚C*)
  - Bias voltage points: 50 V, 80 V, 100 V, 120 V

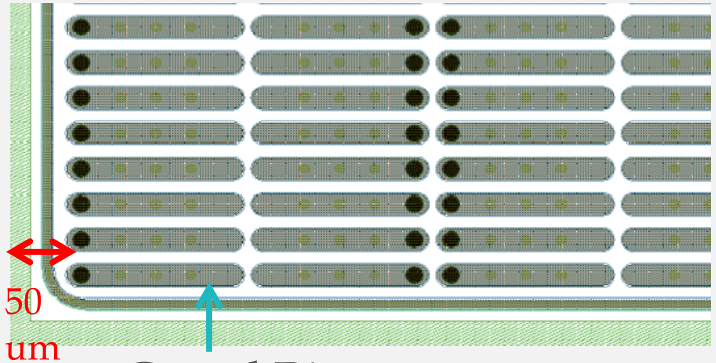


Active edge and slim edge designs

- ***Goal***:
  - Investigate the performance of the irradiated n-in-p planar pixel sensors with the active and slim edge design produced by **ADVACAM;**
  - Study the overall and edge efficiency with normal and inclined tracks

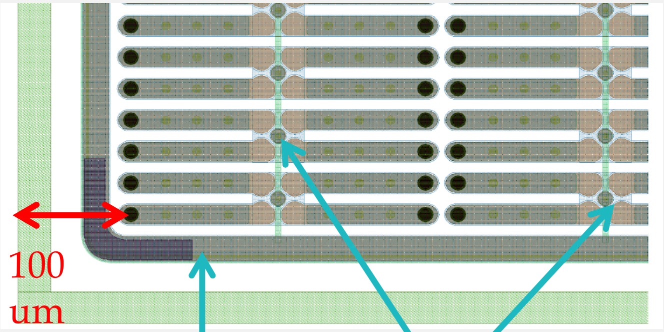
- **Samples: active and slim edge design, 50 μm thickness, low threshold tuning**
  - Irradiation: **Irr. = $1x10^{15}$ n_{eq}/cm^2**

Threshold : 520e-580e, 8ToT4ke



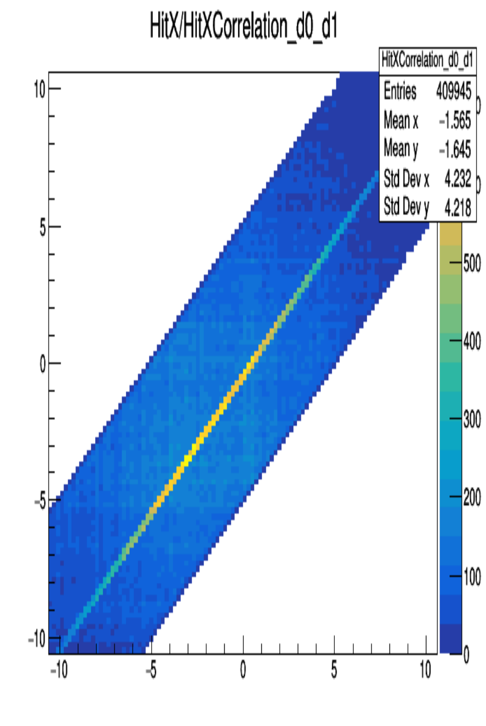
ADV-NP50-3-1A: **active edge**

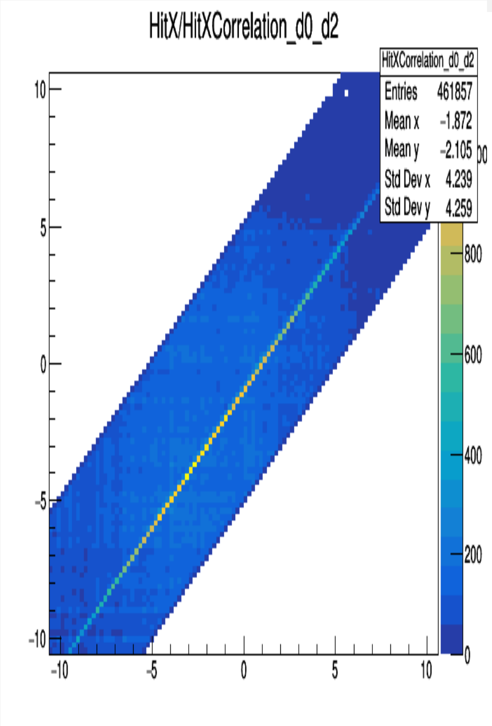
Threshold : 700e, 8ToT4ke

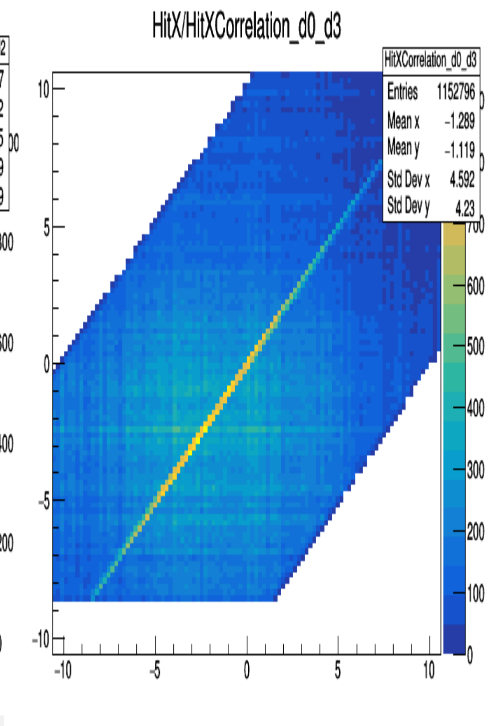


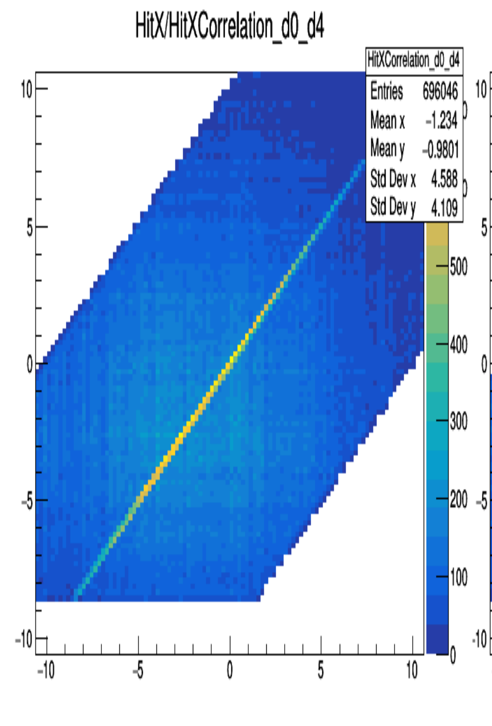
ADV-NP50-3-3B: **slim edge**

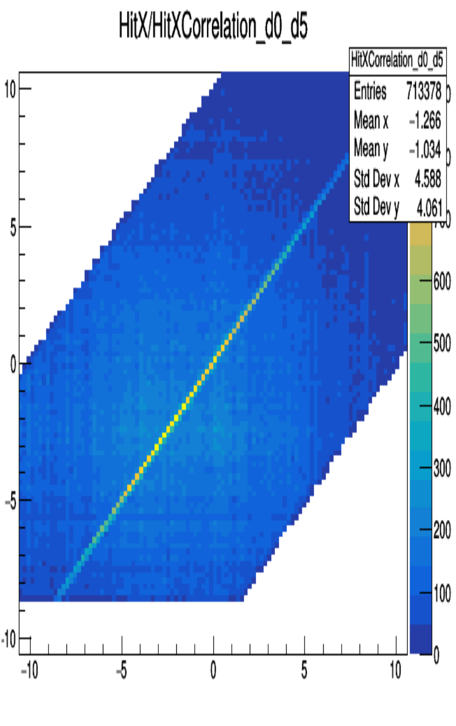
Correlations





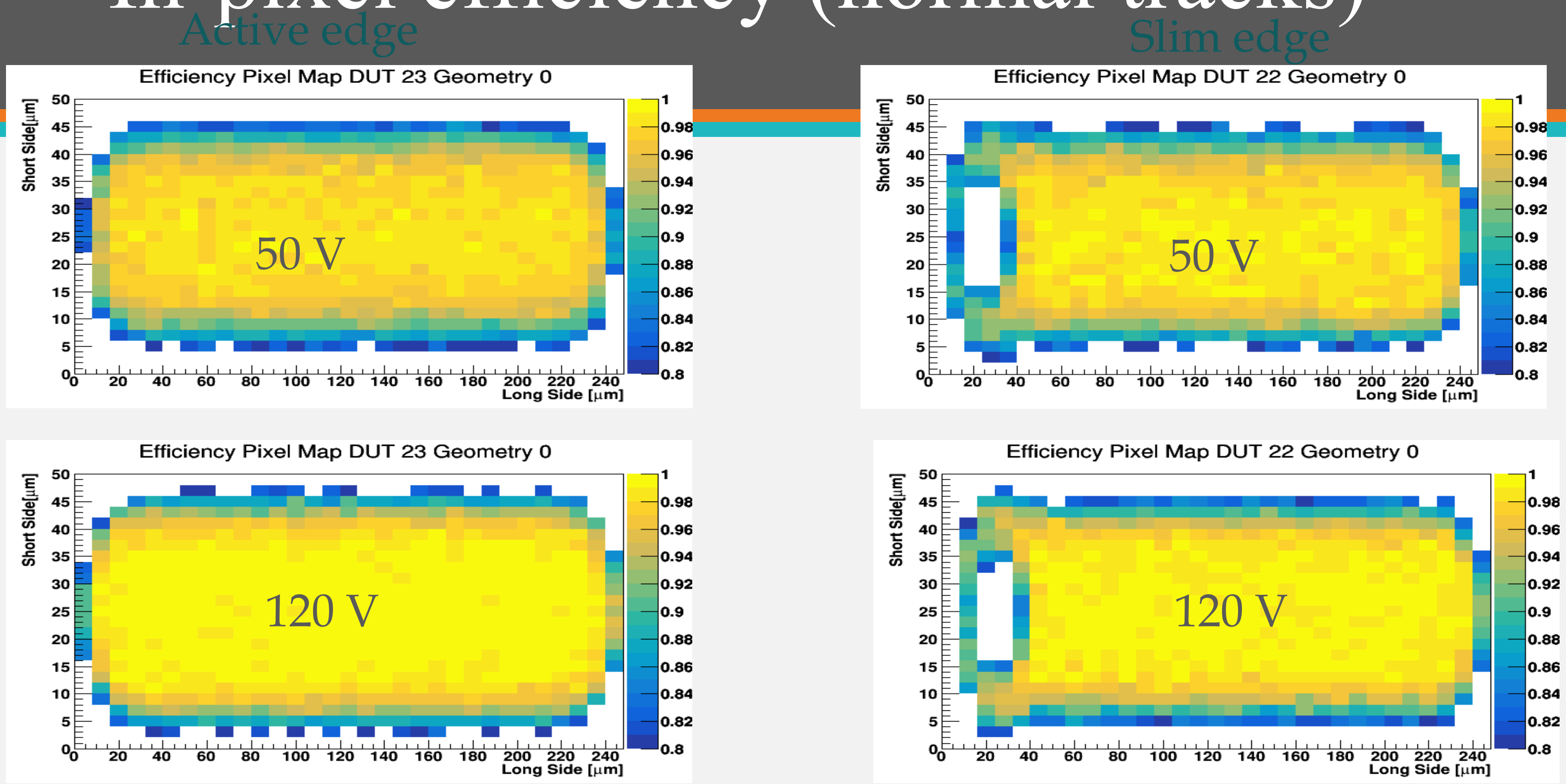






DUTs:
normal

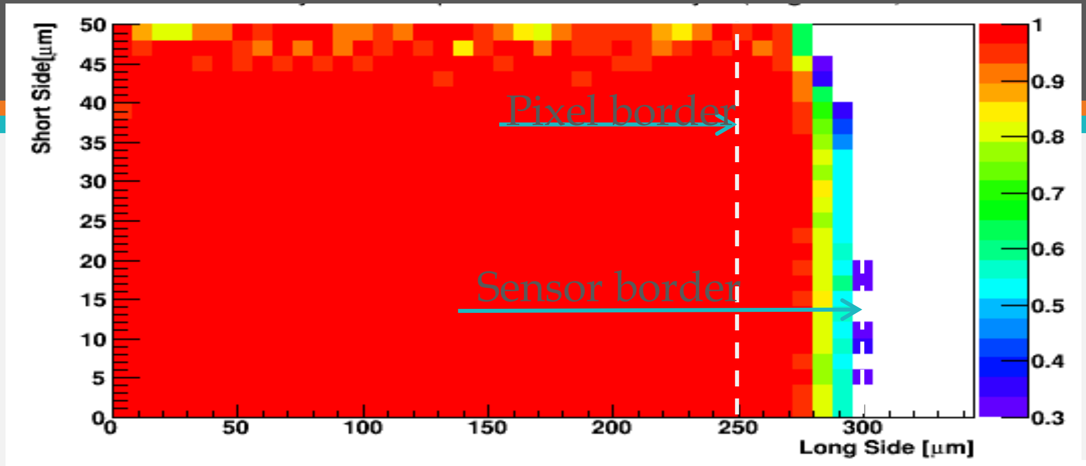
In-pixel efficiency (normal tracks)



- Depletion region recovered with higher voltage in **central** pixel region
- Inefficiency in pixel sides and corners due to large charge sharing between cells for thin sensors

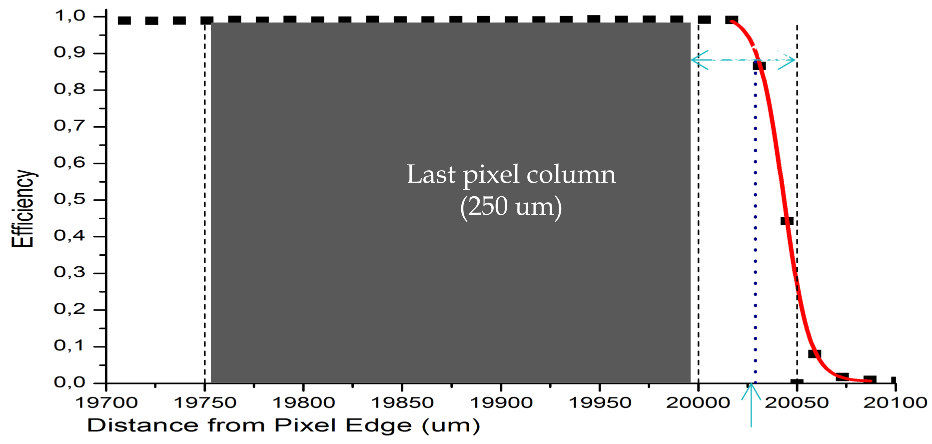
Testing the the performances at the borders to increase the overall surface efficiency

- Performances of pixels planaires under High energy Pions



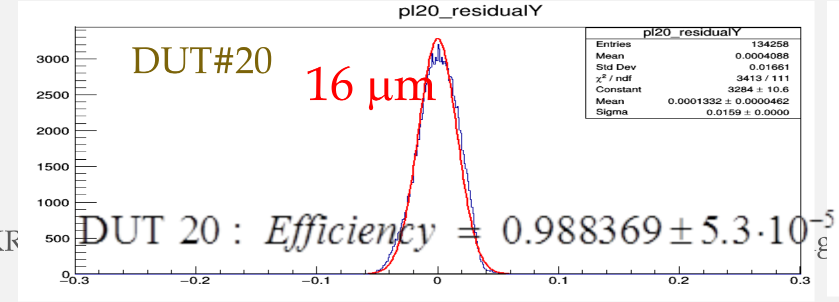
Active Edge 50 µm

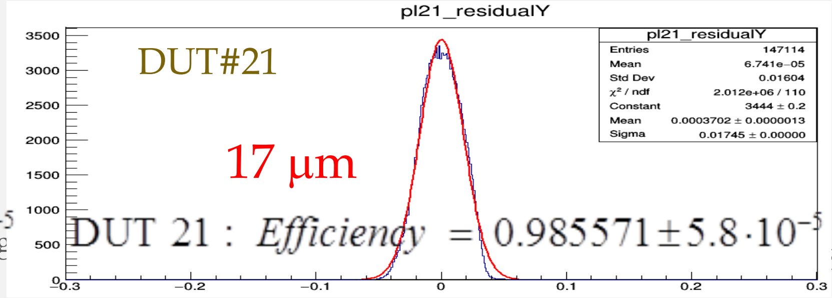
AIDA HIGH RESOLUTION PIXEL TELESCOPE



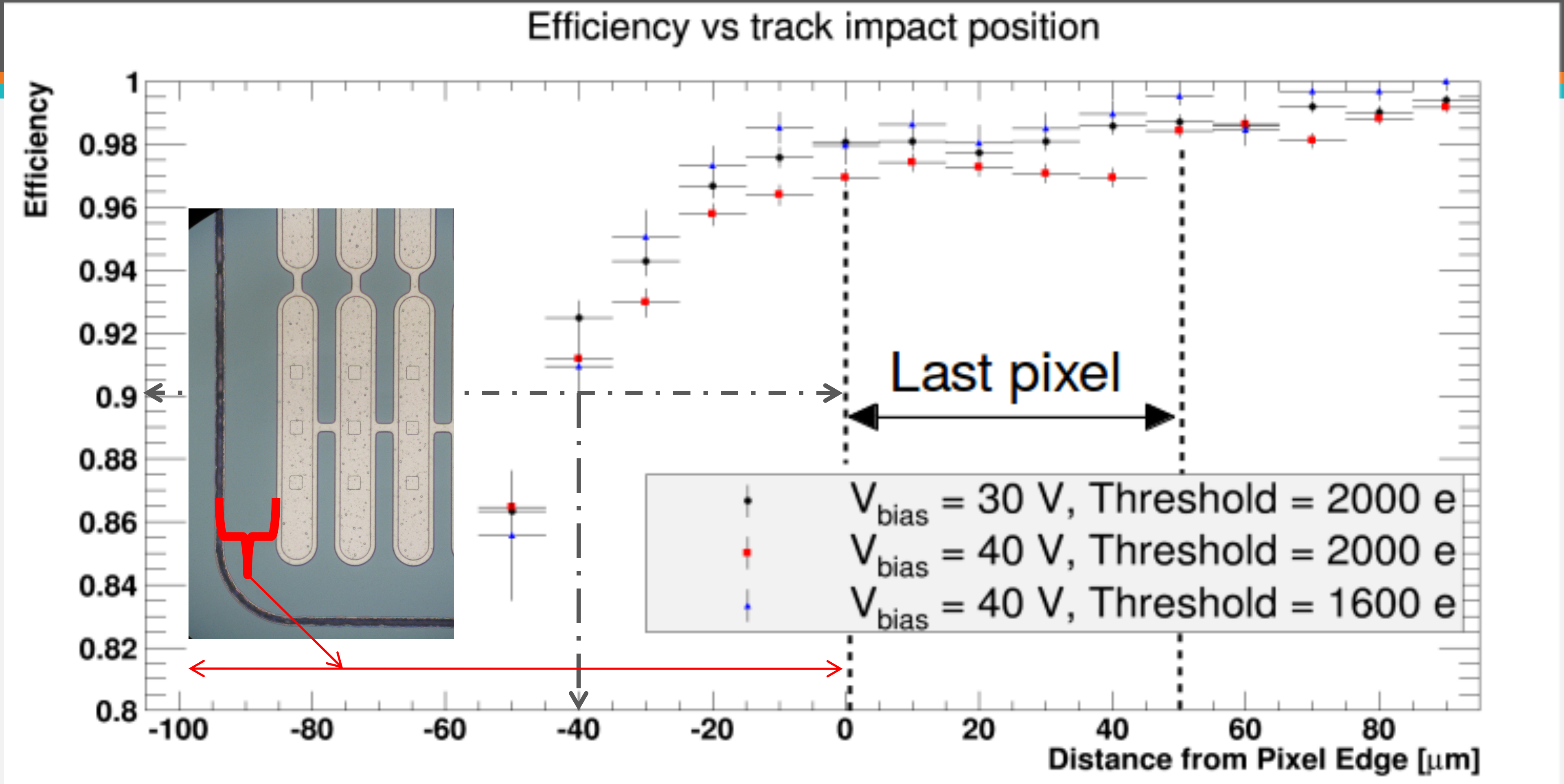
D. Hohov, Phd Thesis
University Paris Saclay 2019

Distribution of residuals





Hit-efficiency at the edge with High energy particles



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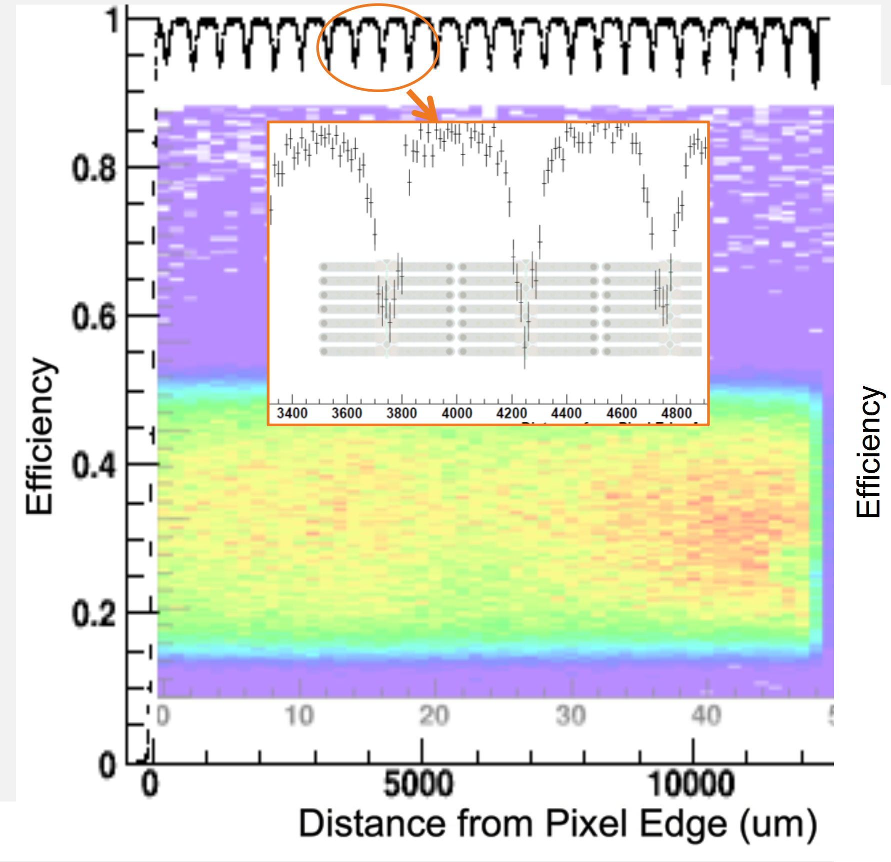
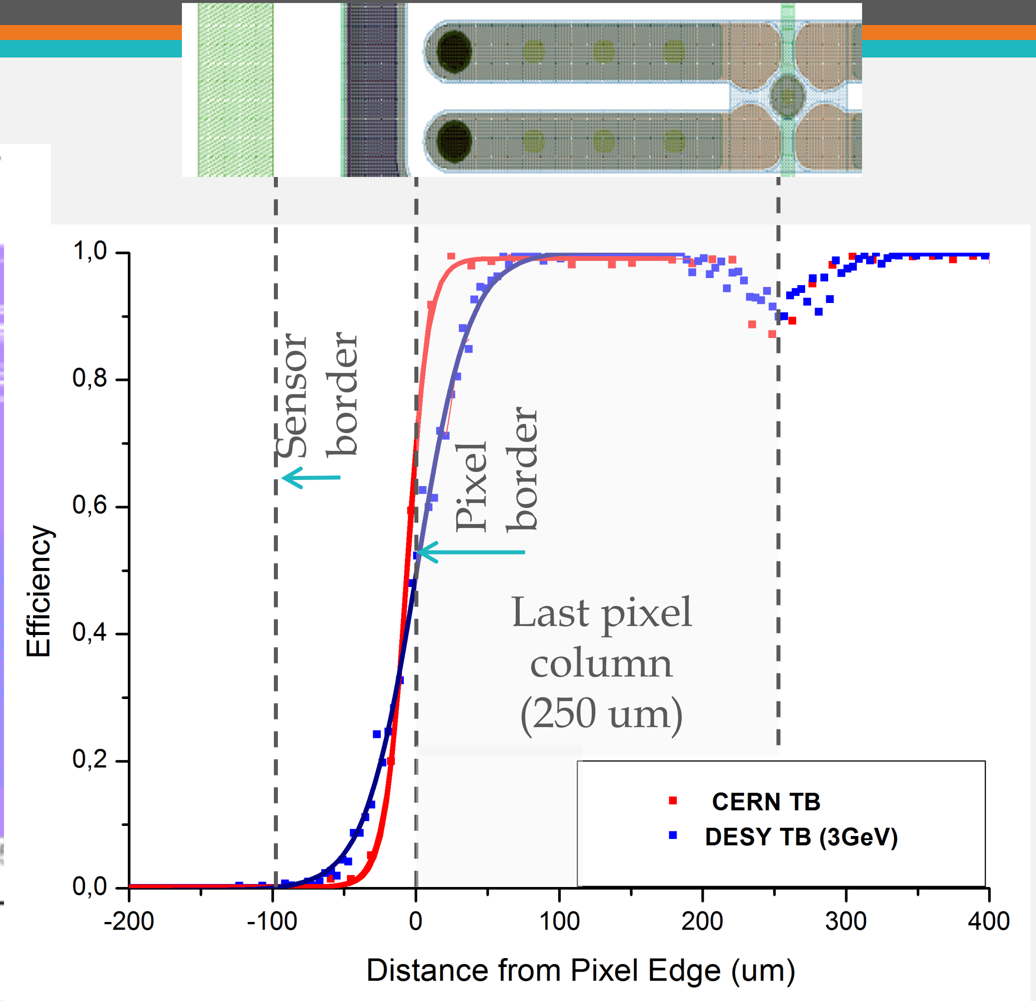
- Hit-efficiency above 90% up to 40 µm away from the last pixel

Efficiencies from beam tests

- *Efficiency vs track impact position DUT#22*

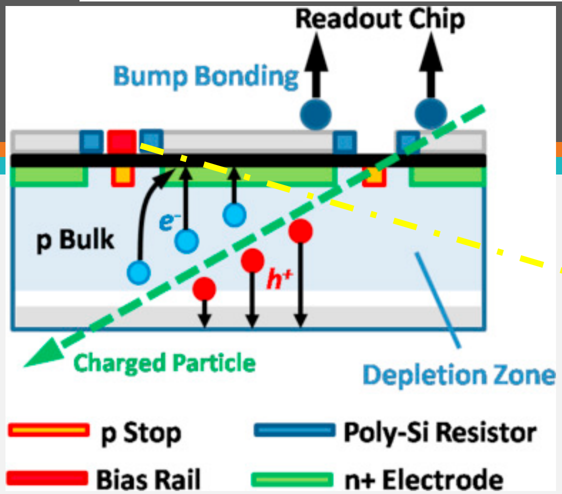


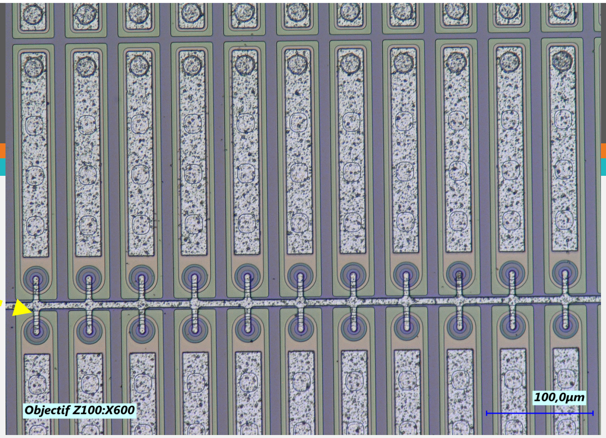


Analysis from Dmytro Hohov ATLAS@LAL

Irradiated pixel behavior at high fluence

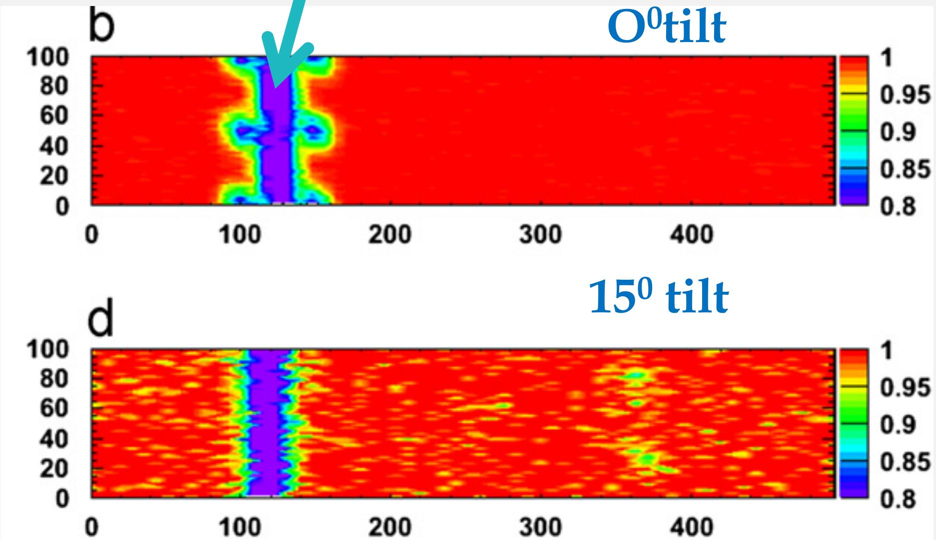
Beam-tests results





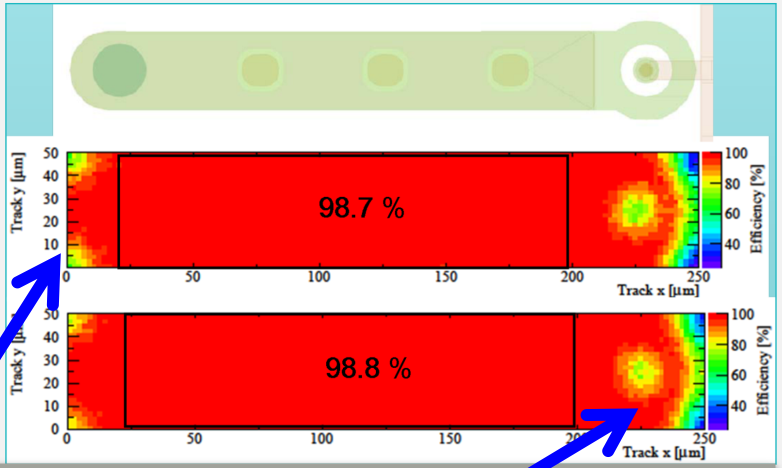
Bias Rail

Position of polarization rail



Pixel Matrix Hitmap at 5. 10^{15} neq/cm^2 and Temperature -15^{0}c.

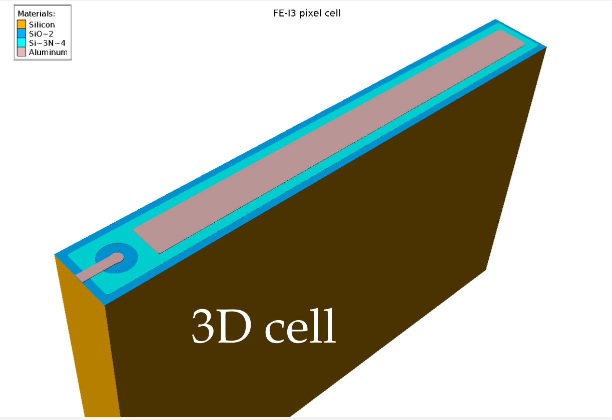
Eudet 120 GeV pions/ Φ=4x10^{15} n_{eq} cm^{-2}



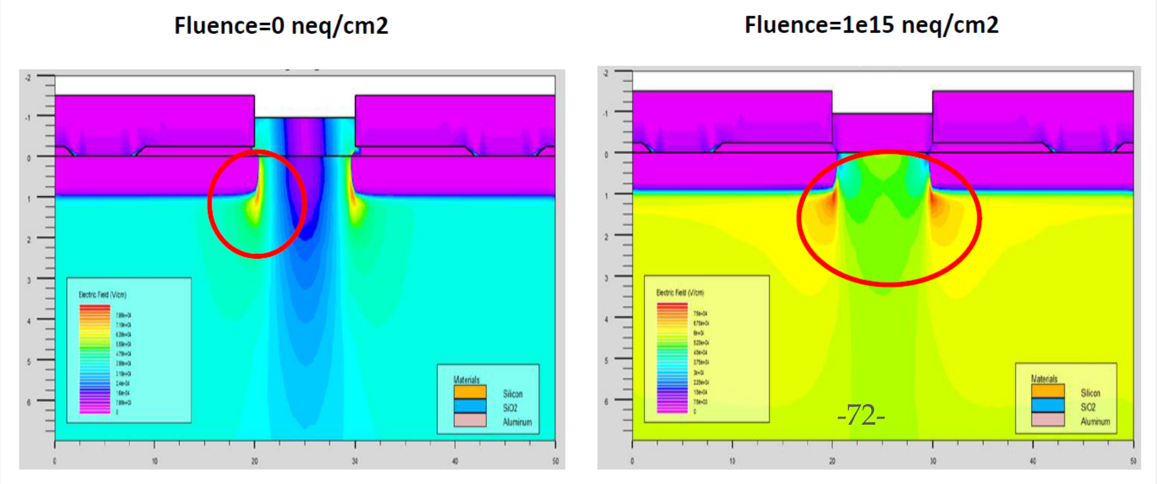
Loss of Effiicency around Bias rails and implants

An important TOOL for innovation :
Simulation TeChnology Aided Design (TCAD) (Finite element Method)

- Aim: Develop simulations (TCAD input parameters) allowing to simulate performance of irradiated silicon sensors and performance predictions under various conditions *(sensor design and material, irradiation fluence and particle type, annealing,…).*
  - Close collaboration with other ATLAS sensor simulation working groups (LAL member of RD50)
  - Challenge for irradiated sensors:
    - Correct implementation of bulk and surface damage by defect levels
    - Defect concentration is function of fluence, particle type, material, annealing, …. !
  - Validate the radiation damage model to be implemented in TCAD packages to be able to simulate of the performance of complex silicon devices after hadron irradiation. The simulation output is increasingly accurate in term of IV, CV, CCE inter-electrode resistance and capacitance, break-down voltage prediction etc.



Evaluating different pixel layout designs and production parameters (p-stop, p-spray)



Finite Element Simulation

- **Our Problem: Solution of Laplace Equation and Continuity equations in regions**

Physics models: Works by modelling electrostatic potential (Poisson's equation) and carrier continuity (drift-diffusion, dd, mainly)

Poisson $$\varepsilon_s \nabla . E = -\varepsilon_s \nabla^2 \psi = q(p - n + N)$$

Electron continuity $$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla . \underline{J}_n + (G - R)$$

Hole continuity $$\frac{\partial p}{\partial t} = \frac{-1}{q} \nabla . \underline{J}_p + (G - R)$$

$$\underline{J}_p = q \mu_n \underline{E} - q D_p \nabla p$$

$$\underline{J}_n = q \mu_n \underline{E} + q D_n \nabla n$$

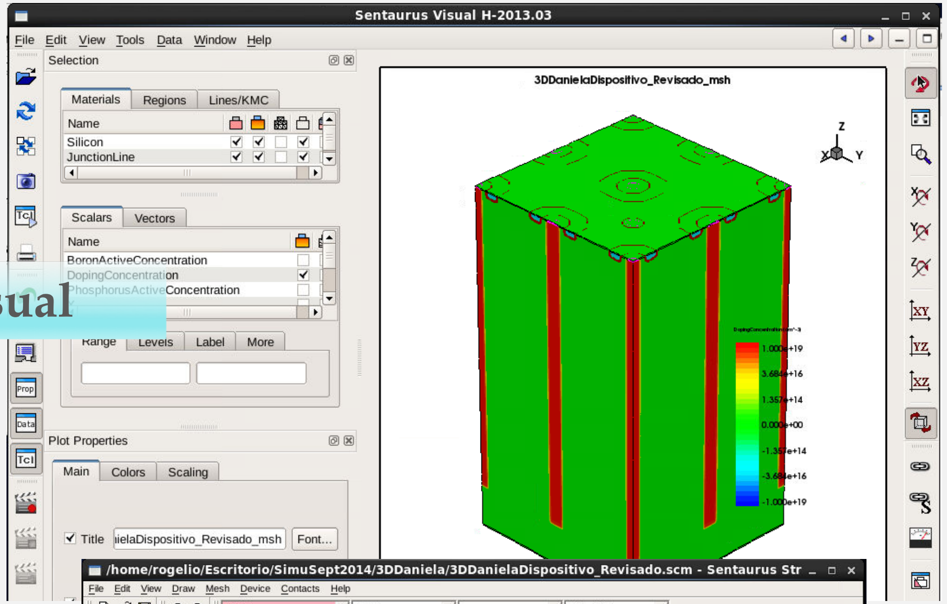
See Fichtner, Rose, Bank, "Semiconductor Device Simulation", IEEE Trans. Electron Devices 30 (9), pp1018, 1983

Different versions of physics models available

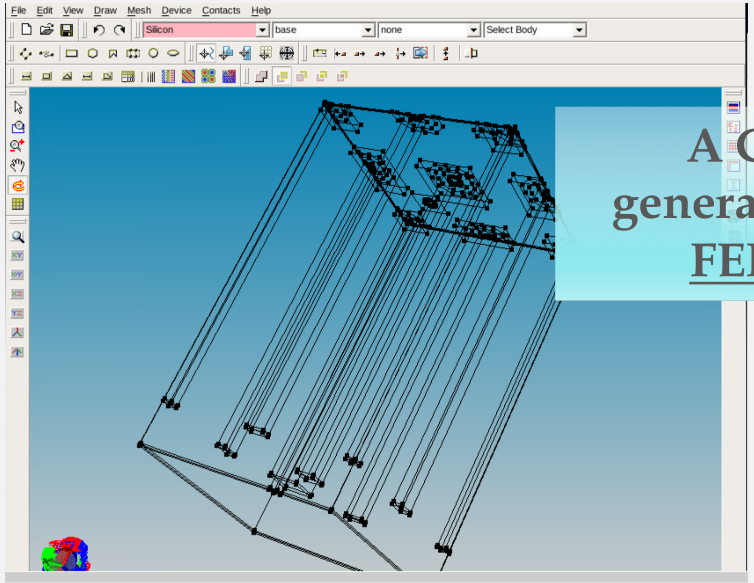
- Different models of mobility, bandgap…
- Generation and recombination rates may include avalanche effects, charge generation by high-energy particles…

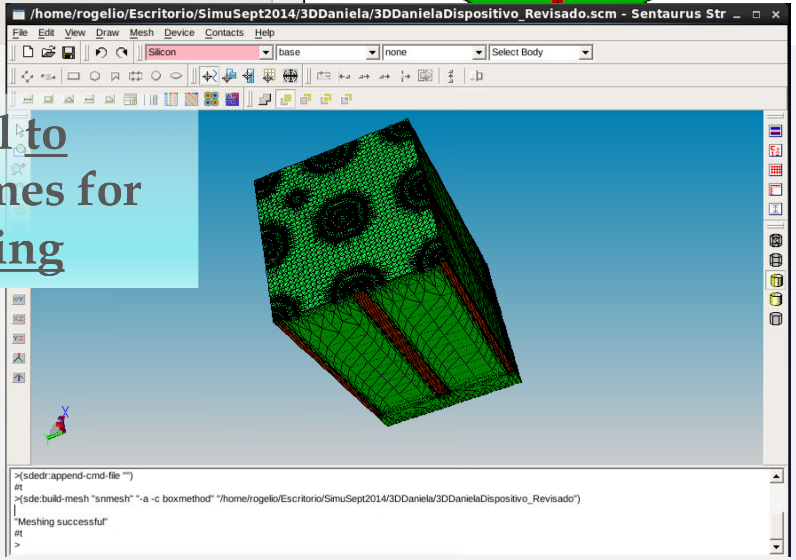
Finite Element Simulation

- Basic tools in a Finite Element simulator
  - Automatic Mesher Creator tool
    (Sentaurus Structure Editor, SSE)
  - Visualization tool
    (SVisual)
  - Solver tool
    Sentaurus Device



SVisual

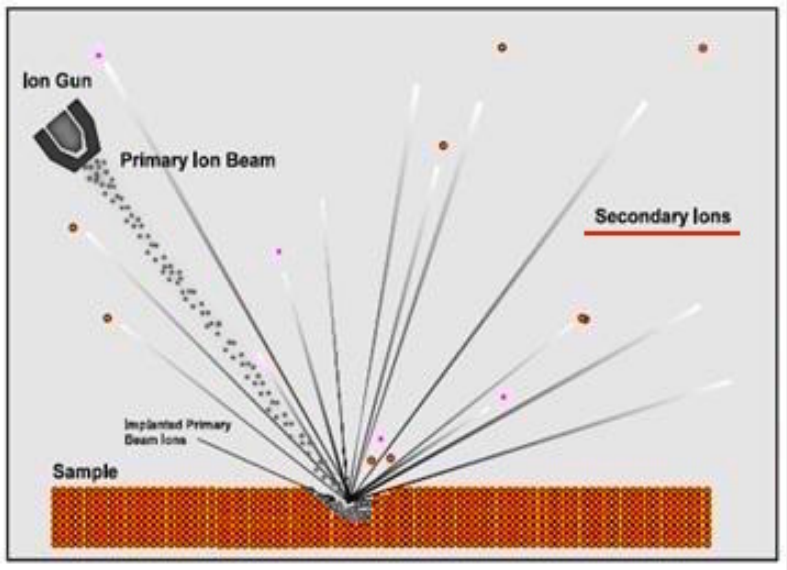




A CAD tool to generate volumes for FEM meshing

A Tool to help understanding Pixel devices :
Secondary Ion Mass Spectrometry (SIMS)

- SCANNING of intrinsic material : doping profile.
- secondary ions ejected from a sample surface when bombarded by a primary beam allows you to find out the atomic structure of your sample



Design improvements Tools: synopsis 3D & doping profile measurements

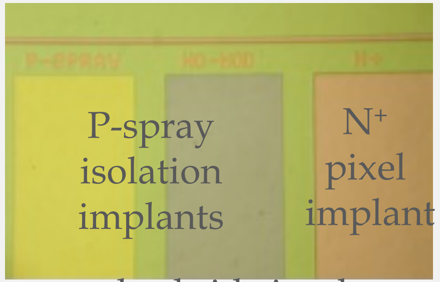
- To overcome the problem of non-accessibility of Technology parameters :
  - charge carrier distribution, doping profiles, density of defects and

Impurities etc…

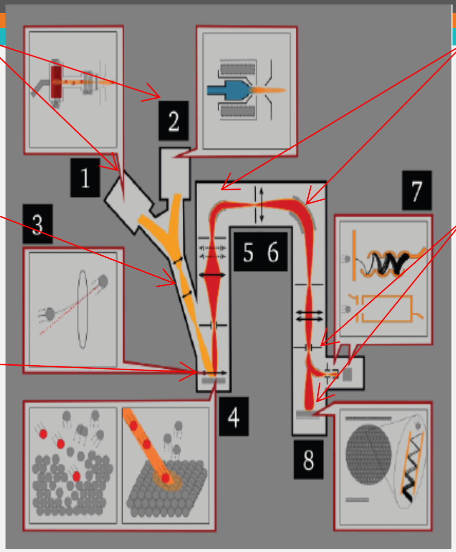
- TCAD simulation is absolutely needed
  - Tool for studying relationship: semiconductor physics - device characteristics
  - Process simulator: oxidation, ion implantation, diffusion, etching etc….
  - Device simulator: electrical parameters by solving eq.: Poisson,

current density , continuity etc..

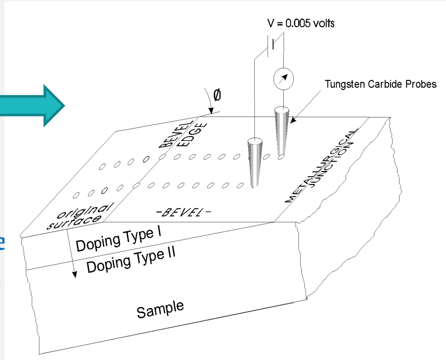
- Experimental methods used for TCAD calibration
  - Secondary Ion Mass Spectrometry (SIMS) – atomic doping profile
  - Spreading Resistance Profiling (SRP) – charge carriers doping profile



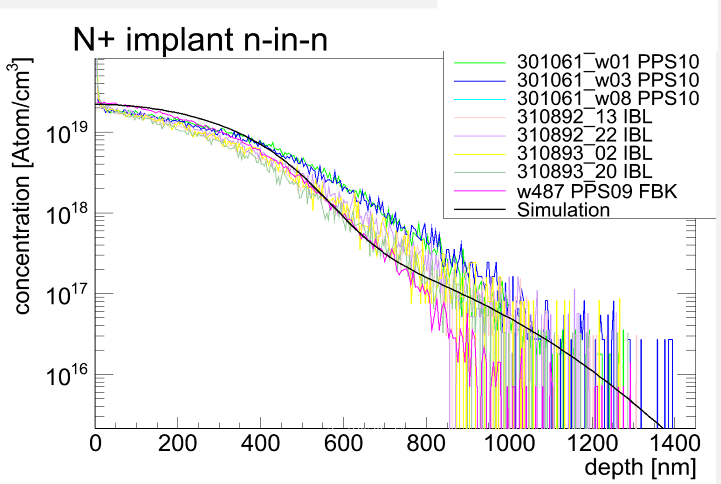
p+ backside implant



- Optimization of implantation & annealing parameters:
  - energy and dose, oxide thickness, annealing time and temperature



SRP : It relies on stepping a pair of small probes across the bevel surface of a sample and the measurement of a resistance when 5 mV are applied across the probes at each step



3D doping Profile Measurement : New Method

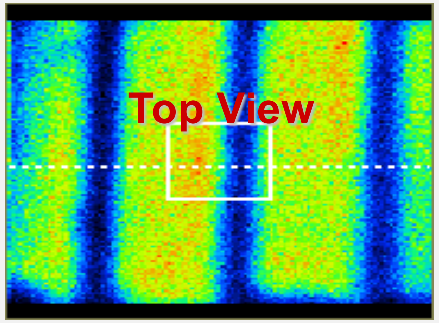
- Standard SIMS very helpful tool for: process control, in particular diffusion, identification of contaminants and failure in the fabrication.
- Results for 1D doping profiles of dopant are satisfactory.
- Now, we want to study the doping profile at the pixel level of an Advacam Active Edge Detectors.

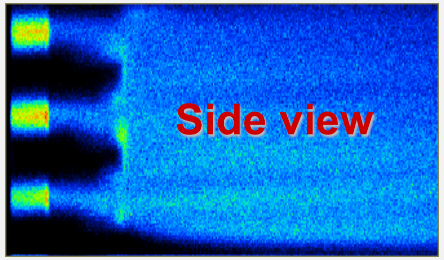
→ Analyzing small region of interest like the pixel region and the active edge region, need higher lateral resolution technique.

we need to move to another method called SIMS Imaging.

SIMS Imaging Method

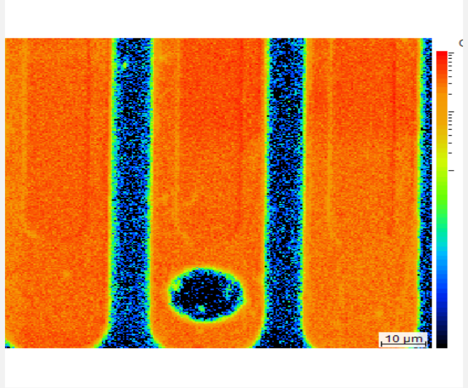
- What is SIMS imaging?
  - ➔ Allow a scan for the samples surface and depth.
  - ➔ Depth profiling and imaging can be combined to yield very powerful three-dimensional dopant maps





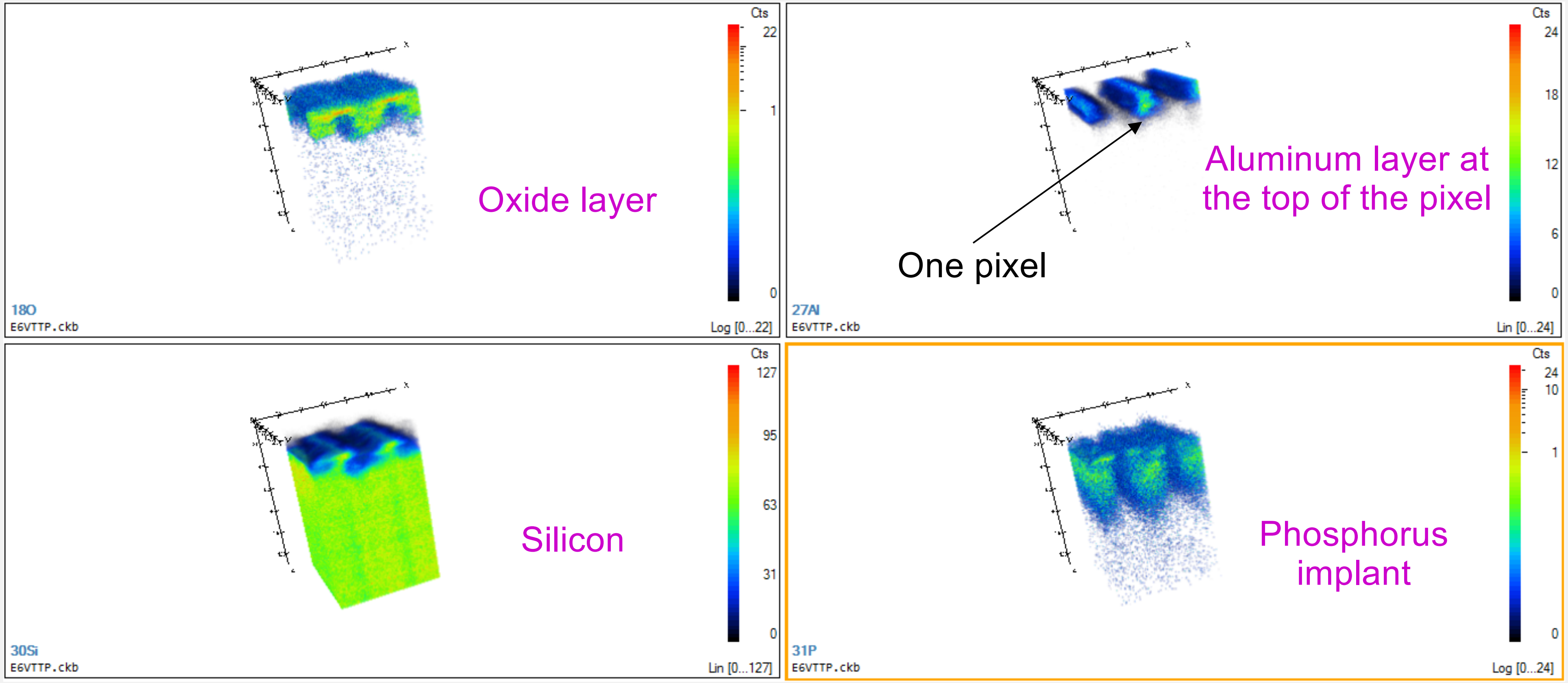
Why SIMS imaging?

- ✓ Can achieve lateral resolutions up to 5 µm .
- ✓ High surface sensitivity at ppb level can be reached.
- ✓ Sample preparation is rather simple.
- ✓ Equivalent measuring time with standard 1D SiMS.



Results: Phosphorus Implant 3D Doping Map

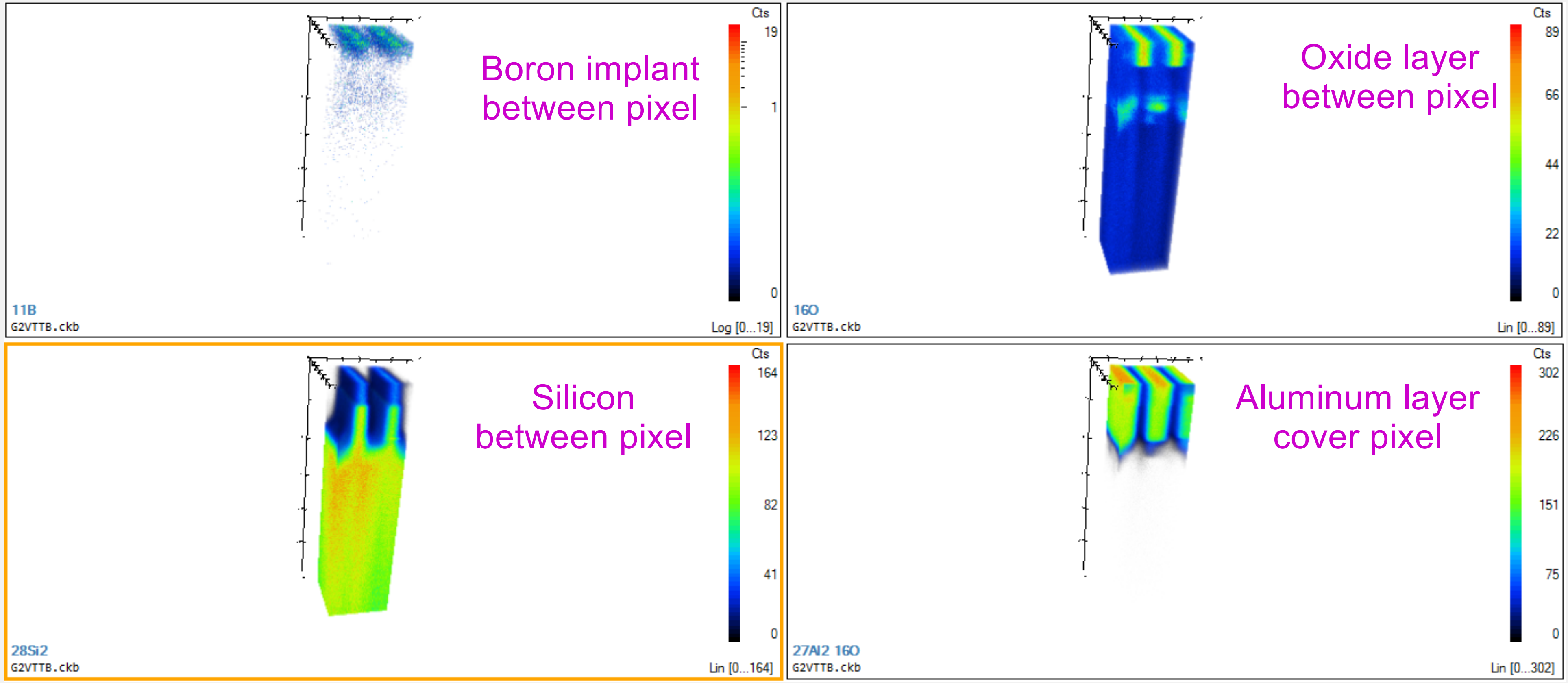
- Analyzed area: Center Pixel region.



Results: p-spray Boron Implant between the pixel

- Analyzed area: between pixel region.

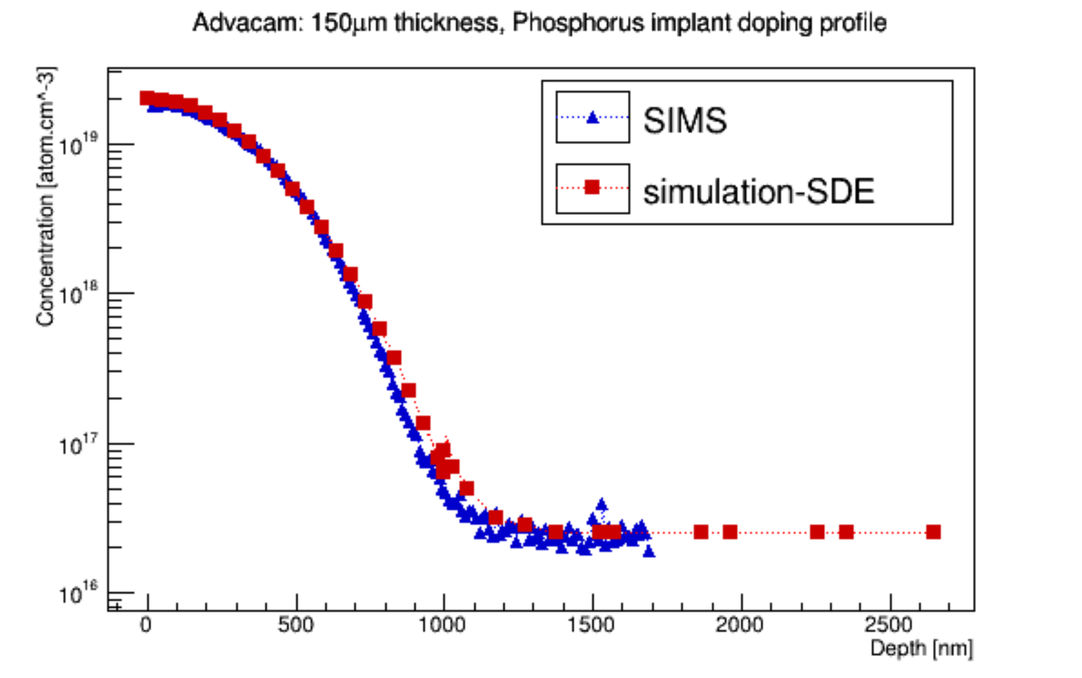
Preliminary results



Results: Phosphorus Implant Doping profile

- Analyzed area: Center Pixel region: SIMS-Simulation comparison.

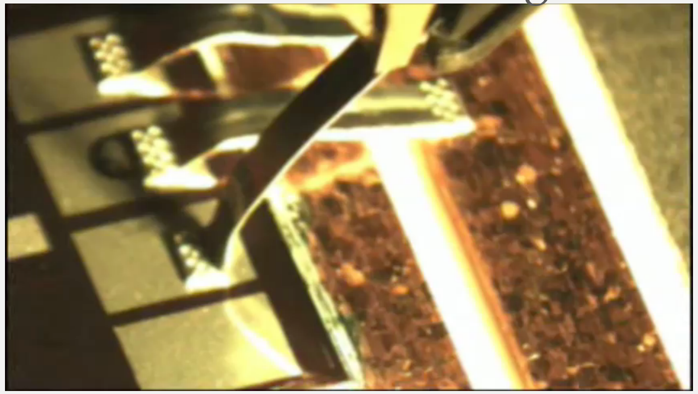
- Wafer 150-2: 150 μm, BR+GR design
- **SDE** Synopsys simulation.
- Simulation parameter:
  Analytical doping profile
  Peak Value concentration 2E19
  Depth of Implant 1.5 μm.
- The implant extends 2μm in the silicon substrate.
- Implant peak concentration 1E19 atom.cm^{-3}
- Oxide layer has not been simulated.



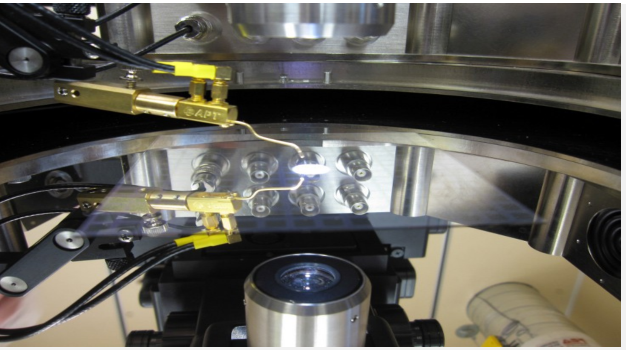
State of the art Infrastructure

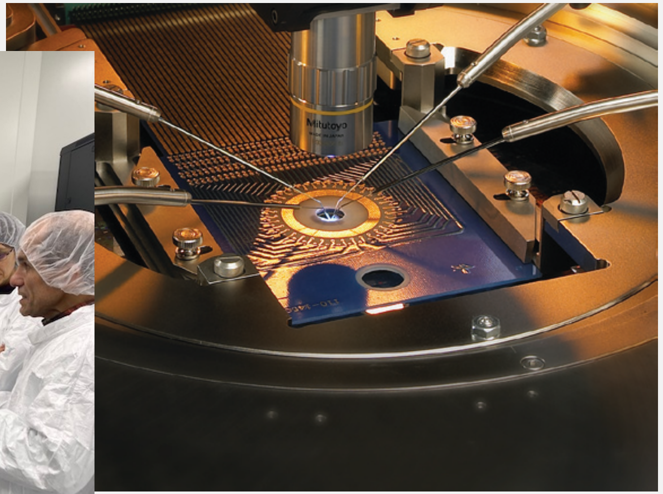
Probe

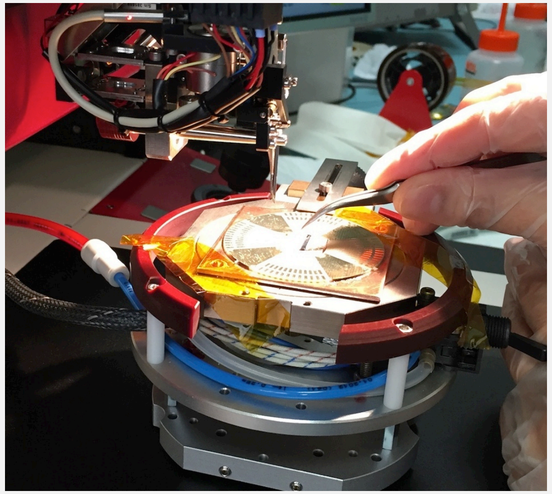
Wire Bonding machine



Clean room



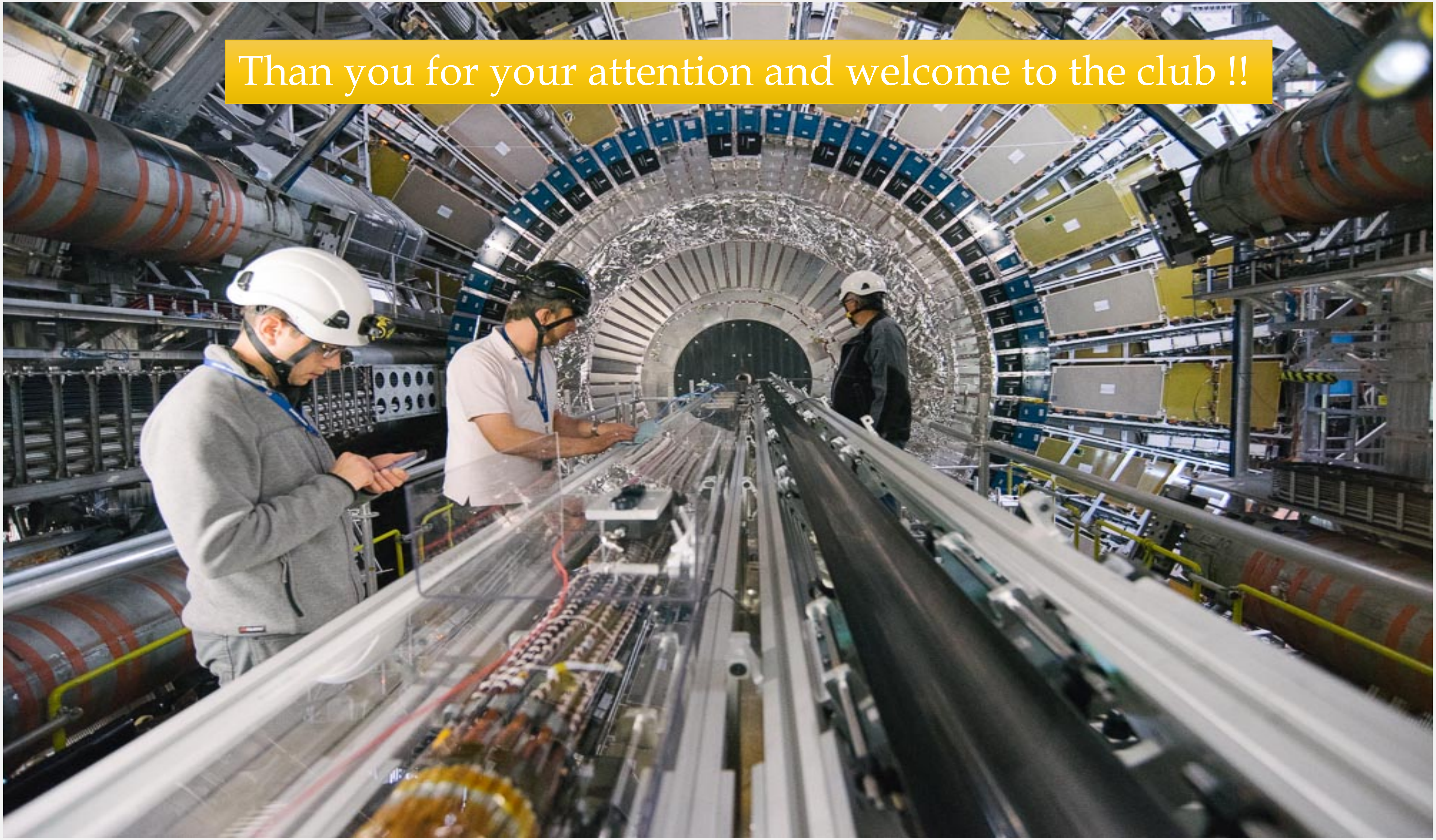




conclusions

- R&D on planar pixel sensors is driven by ATLAS High luminosity upgrade
- The goal is to optimize the design of the pixel sensors to cope
  - High radiation levels : radio-tolerant materials
  - High level of occupancy, favours high granular sensors
  - Develop innovative approach for device bulk type
  - Increase full sensor sensitivity , go to edgeless technology
  - Predict, improve new device concepts by TCAD simulations
  - Still room for improvement and innovations ….

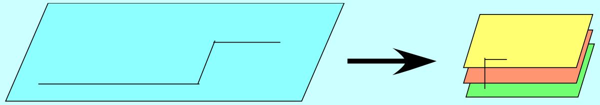
Than you for your attention and welcome to the club !!



The end

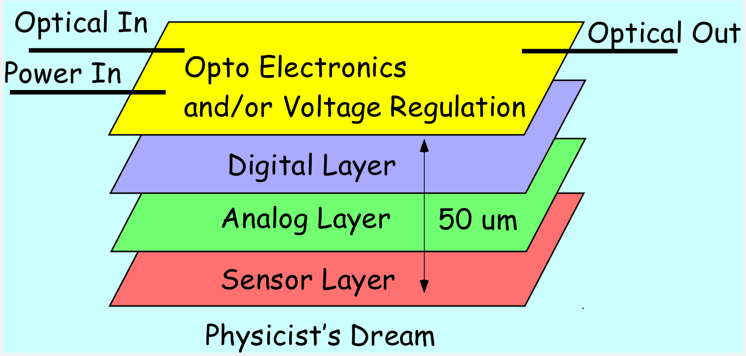
The ideal case : Physicist dream

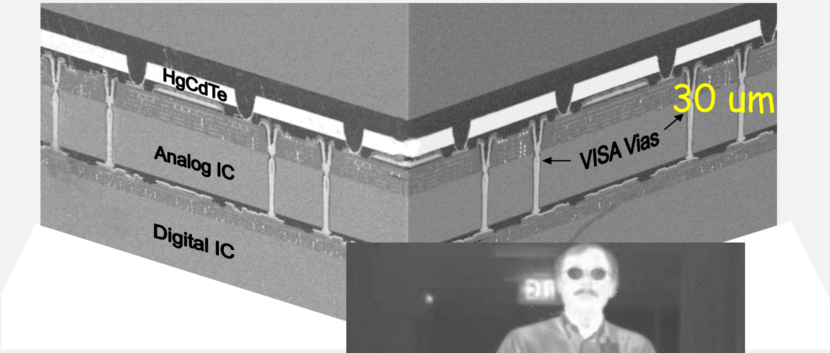
Vertical Scale Integration (3D)



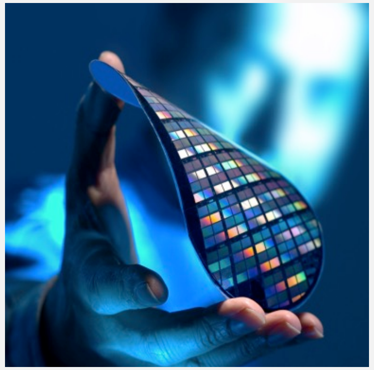
2D Routing (large chip) 3D Routing (small chip)

idea: implement thin layers of silicon, each with independant specific function.

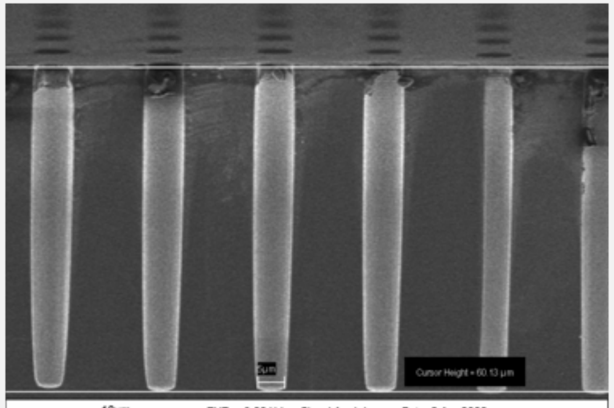




Future



Through silicon vias



Advantages: one object !! Monolithic!!

Reduction of R,L, C

Lower X_0 , better irradiation tolerance

low consumption, low capacity

Increase functionnalities (intelligence in chip)