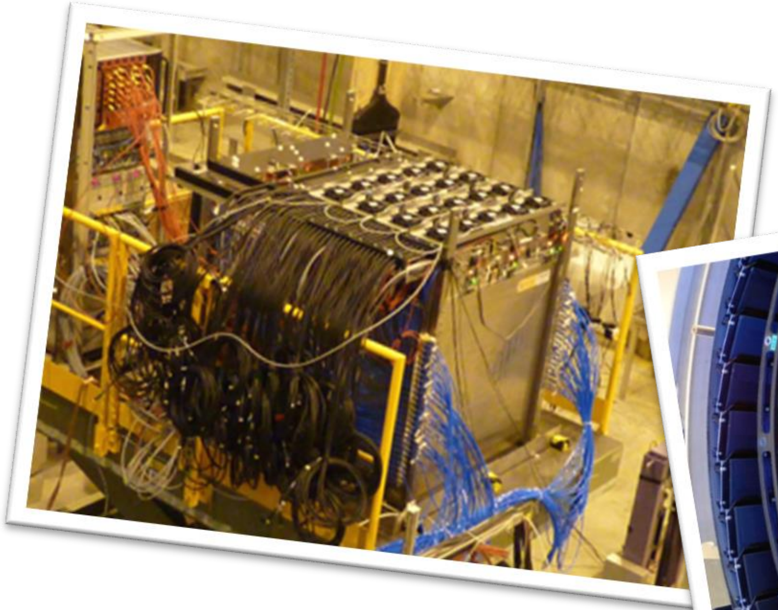
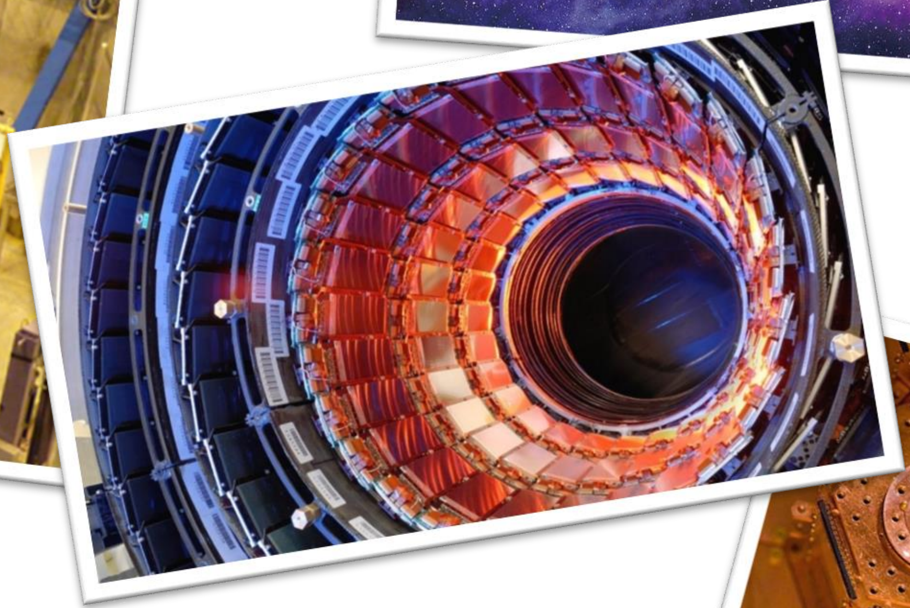
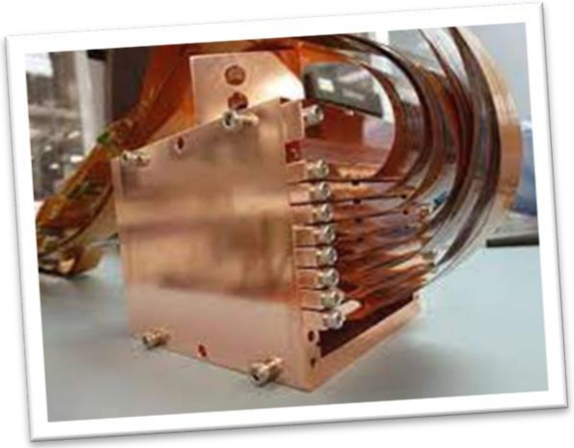
Detectors for frontier science

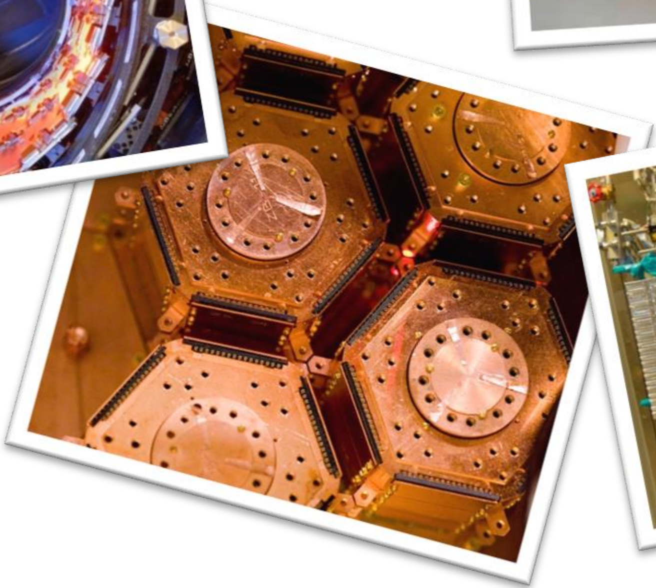
Taller de Altas Enegías

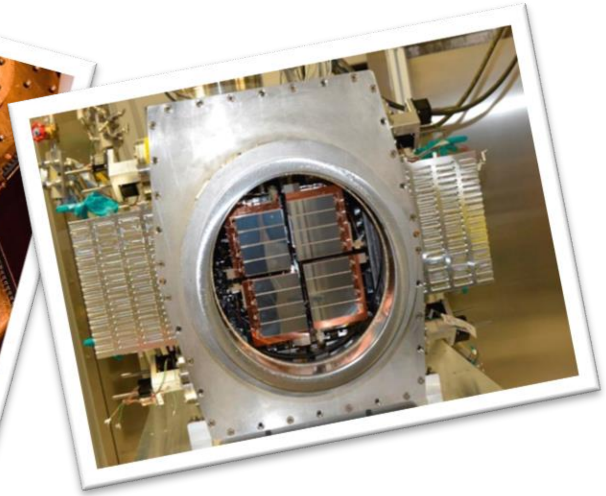
Benasque, September 14, 2023











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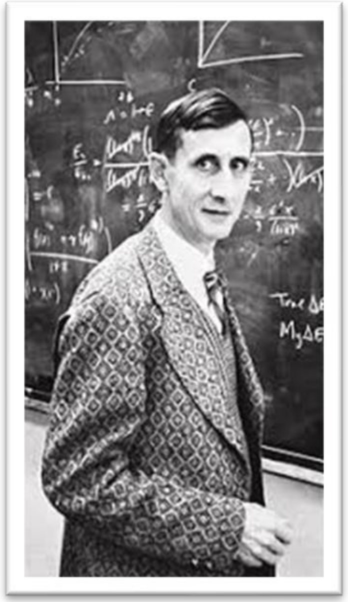
Outline

- Introduction: motivation & scope
- Part 1: Basics of semiconductor radiation sensors.
- Part 2: R&D challenges and Review of Key Technologies.

Motivation

Why should we talk about instrumentation?

(The) Motivation: Technology as Science Revolution enabler

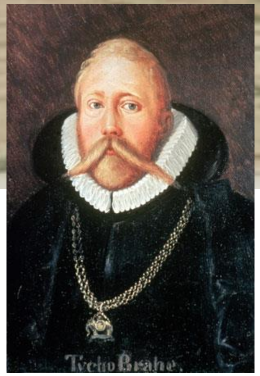


Freeman Dyson

"New directions in science are launched by ***new tools*** *much more often than by new concepts. The effect of a* ***concept-driven revolution*** *is to explain old things in new ways. The effect of a* ***tool-driven revolution*** *is to discover new things that have to be explained"*

Arguably, the first tool-driven revolution in “big science”…

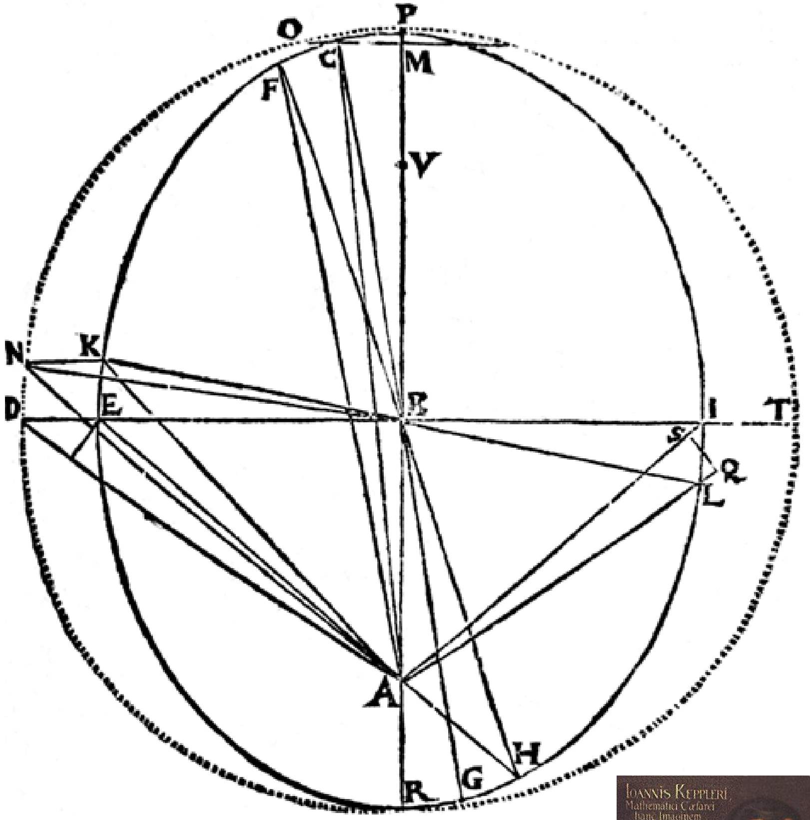
Uraniborg Observatory



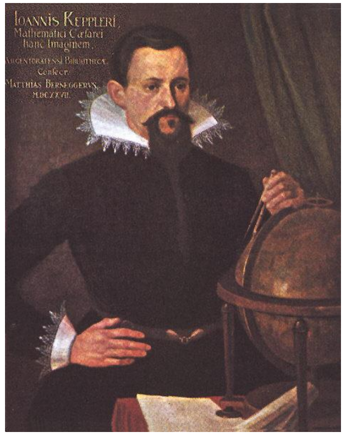
Tycho Brahe

- **Tycho Brahe** (1546-1601) a Danish nobleman embarked on a project to renew astronomy, starting with the improvement of observational methods and instruments.
- With the support of the Danish King Frederick II (%5 of his kingdom's budget), carried out the construction of an observatory for astronomy on the island of Hven in 1576
- Design and construction of the most accurate astronomical instruments ever built (since millennials) for naked-eye observation.
- Systematic measurement of more than 777 stars, the five planets, the sun and the moon for **more than 20 years.**
- Improved the accuracy of observations by a factor of 10

… that brought, arguably, the first concept-driven revolution

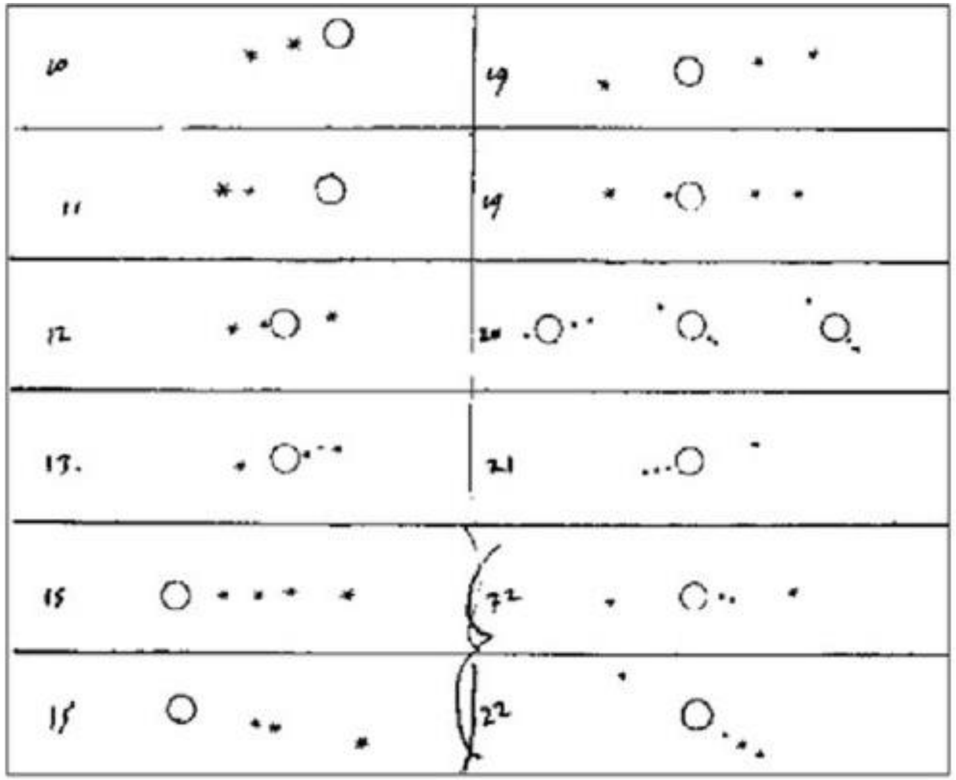


Kepler's drawings of the geometrical relationship between the Sun and Mars in various parts of the planet's orbit



- At the age of 27, Kepler became the assistant of Tycho Brahe, who asked him to describe the movement of Mars.
- For many years, Kepler struggled to describe the motions of Mars using the Aristotelian heaven sphere "model" (cycles and epicycles).
- Eventually, however, Kepler found that the planets move in an ellipse with the Sun at one focus point.
- Kepler while "inventing" the concept of orbit triggered, arguably, the first revolution in fundamental science abandoning the Aristotelian paradigm (Copernicus was just the last representative of the old school, nothing new in his proposal, as he even stated)

A second kind of tool-driven revolution: The enabling technology



Sketches that Galileo made of Jupiter and the changing positions of its four (Galilean) moons from night to night. Arguably, the simplest and most revolutionary sketch in physics.

- To achieve the best naked-eye observations in history, which paved the way for a new description of the world, Brahe conceived the Hven observatory, operated by hundreds of instrument builders, observers, collaborators and students: using **well-established technologies optimised to their maximum**.
- Complementary, to Brahe approach, Galileo optimized a **brand new technology,** introduced a few years before for civil (and military) purposes: the telescope.
- The telescope was an enabling technology that opened up a new world of phenomena **yet to be explained**.

Why should we (physicists) talk about instrumentation?

(The) Motivation: Technology in the tool belt of a physicists ?

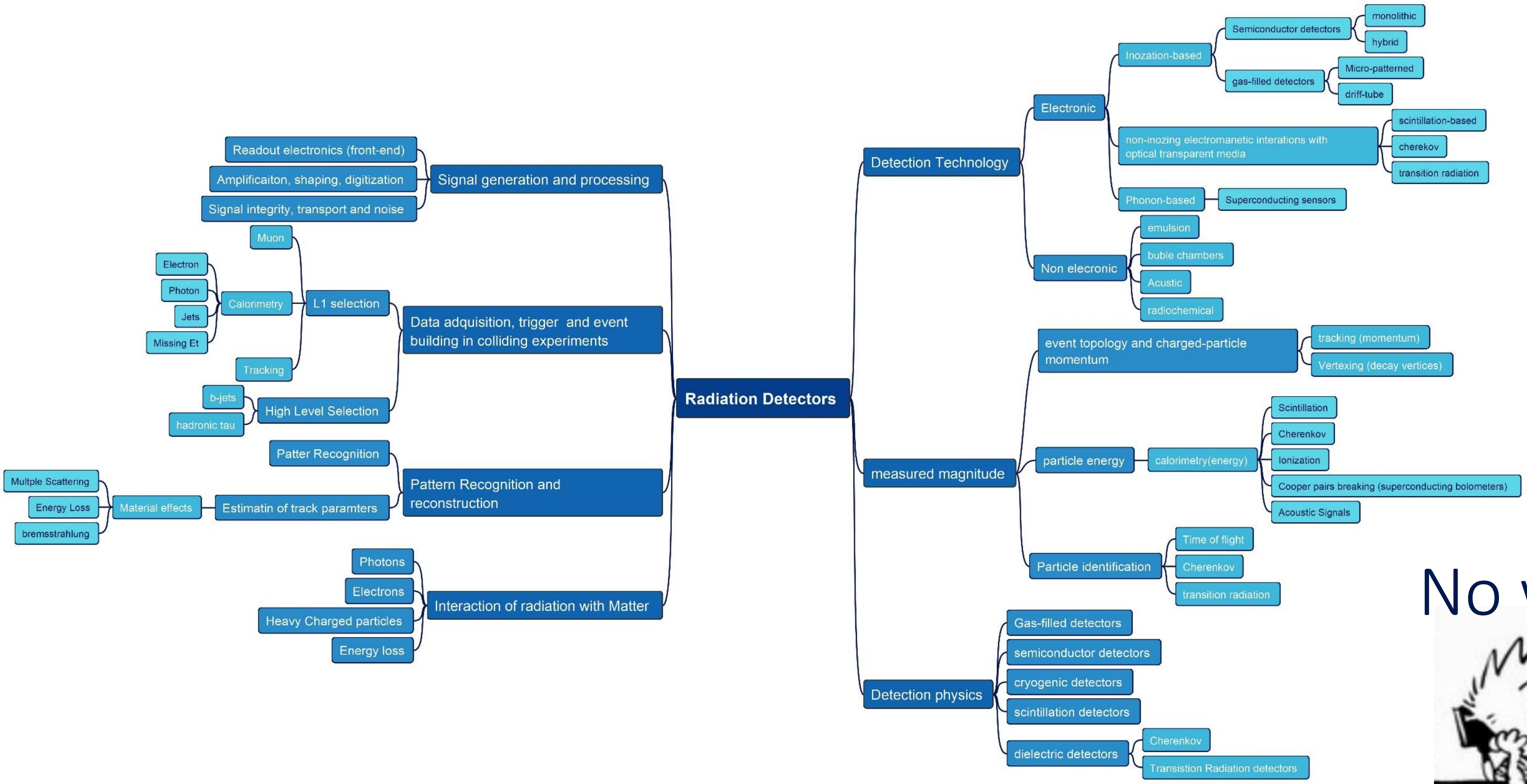
"No one does it better than physicists when it come to innovation for instrumentation, and thus the future of all scientific fields rests on our hands"

Michael S. Turner

… kind of excessive, other stablished technologies in other scientific fields can become breakthrough innovations in our field.

My advise: no need to reinvent the wheel but keep an open mind to find out other wheels that could accelerate your car.

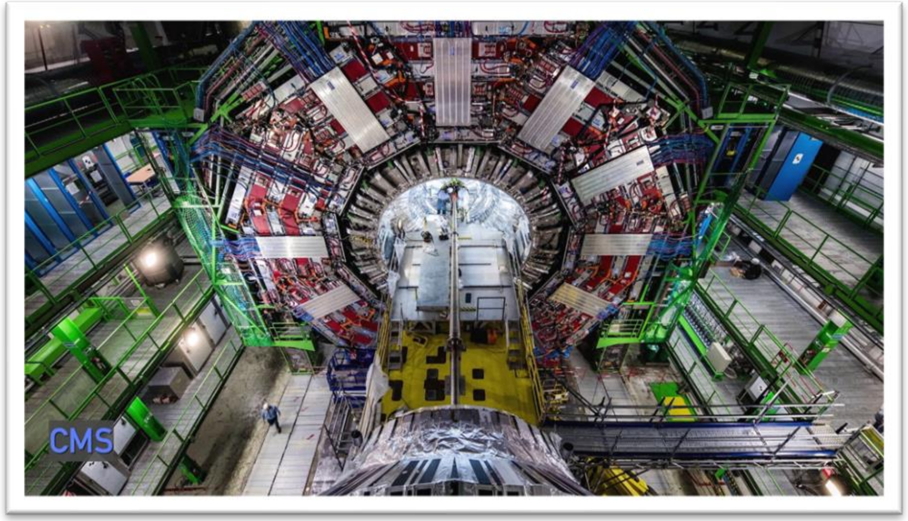
Scope: Captatio benevolentiae



No way !

Scope: The two detector development perspectives

Experiment building



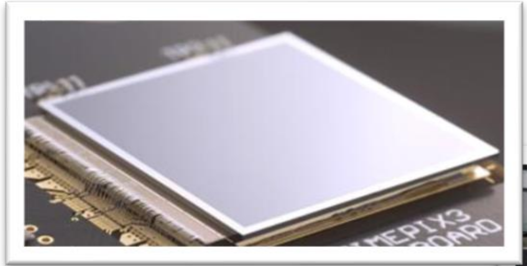
Established detector technologies

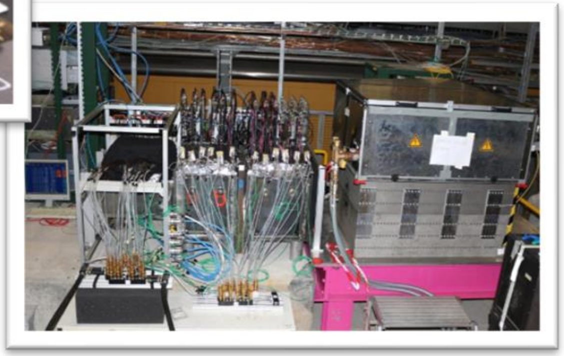
Targeting reliability, affordability and deadlines.

Challenge: system integration

Competitive collaborations (Atlas, CMS, LHCb, etc.)

Detector technology R&D





Proof-of-concept technologies

Targeting optimal performance

Challenge: exceed the state of the art

collaborative projects (CERN RDs, EU programs,...)

In same cases, there is no clear division between the two perspectives.

Scope: Captatio benevolentiae

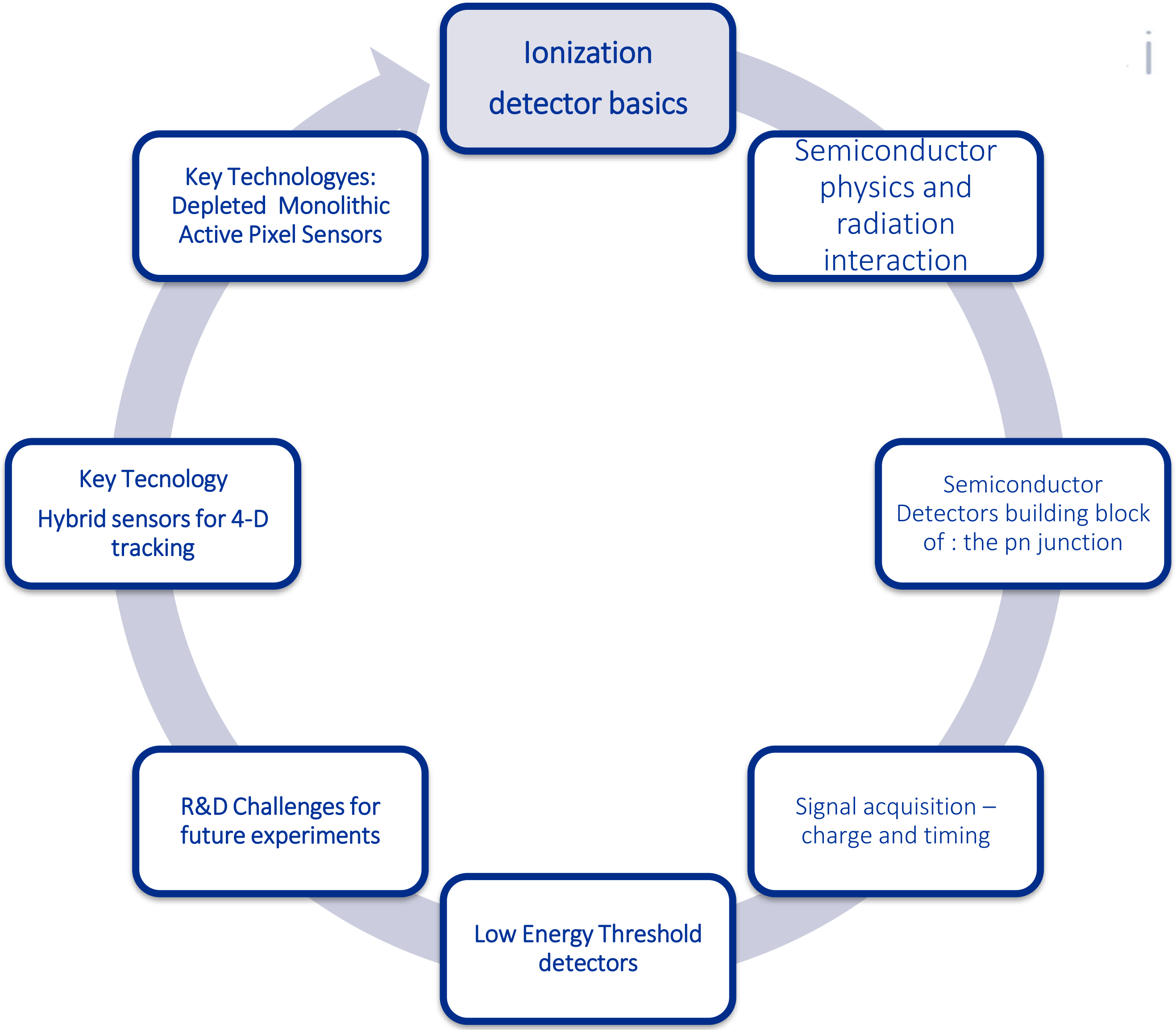
- Avoid a comprehensive review of the field, (too broad and too superficial to be useful)
- Focused on semiconductor sensor technologies aiming to a few key challenges:
  - High precision vertexing, tracking and imaging.
  - Radiation Tolerance.
  - 4D – tracking and 5D - calorimetry.
  - High sensitive, low energy threshold
- Many other innovative detection technologies impossible to be covered here.

PART 1

Semiconductor radiation detectors 101

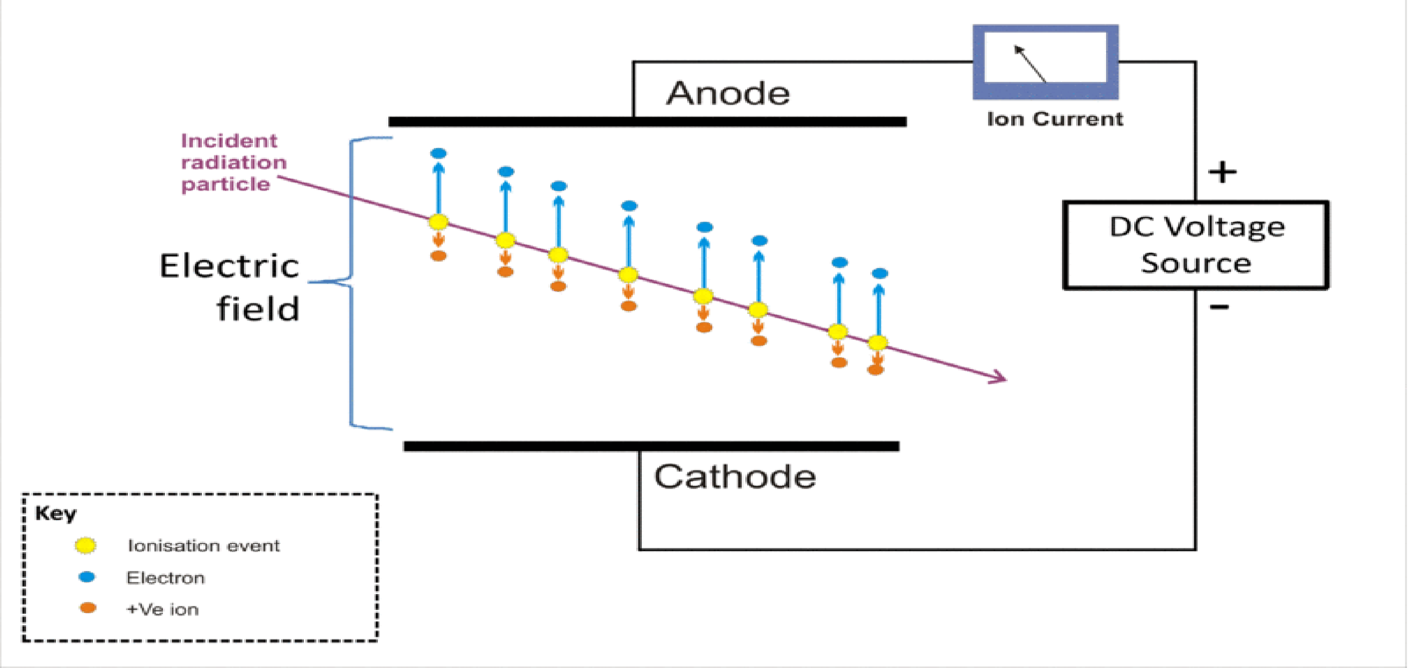
- Ionization detector basics
- Semiconductor physics and radiation interaction
- Semiconductor Detectors building block : the pn junction
- Signal acquisition – charge and timing
- Low Energy Threshold detectors
- R&D Challenges for future experiments
- Key Tecnology Hybrid sensors for 4-D tracking
- Key Technologyes: Depleted Monolithic Active Pixel Sensors

Semiconductor radiation detectors 101



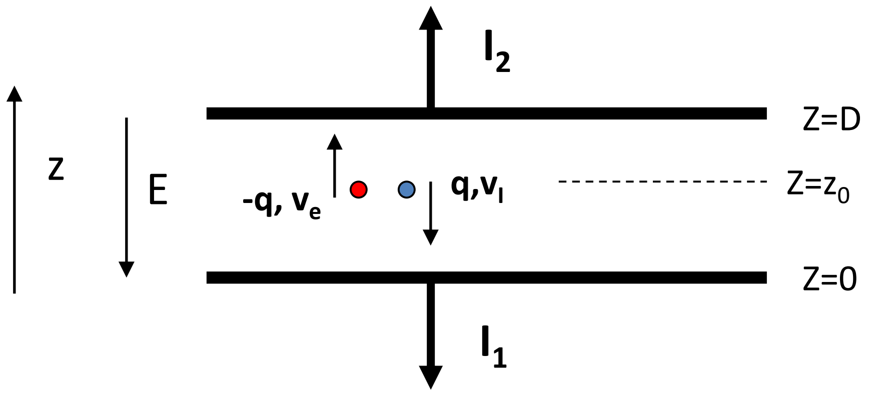
Ionization detector basics (1)

- Sensible to ionizing radiation:
  - Charged Particles & photons
- INGREDIENTS:
  - Medium to be Ionized
  - Drift field
  - Collecting electrodes.



Ionization detector basics (2): Toy detector model

Charge carriers created in a ionized media: Electron-ion pair in gas or Electron-hole pair in a solid (no pn junction)

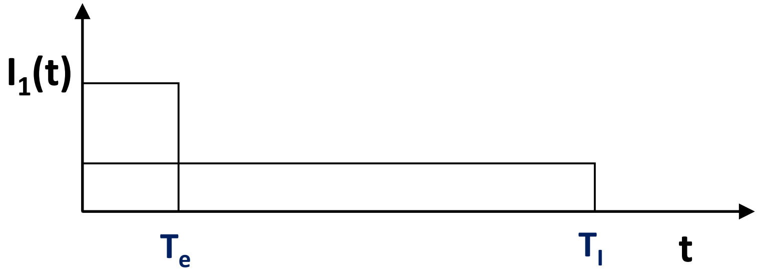


The positive and negative Charge carriers induce a opposite *image* charge in the collecting electrodes; the **movement of carriers** induces then a current (signal)

$$E=V_0/D \; ; \; v = \mu E$$

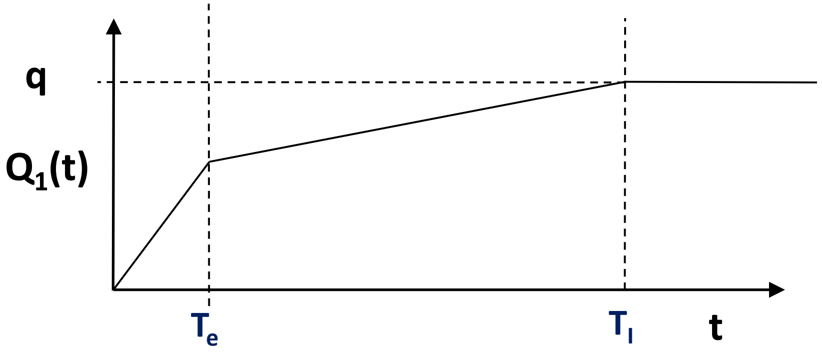
$$Q1 = q \cdot z_e/D - q \cdot z_I/D$$
$$Q2 = -Q1$$

$$I_1 = dQ1/dt = q/D \cdot v_e + q/D \cdot v_I$$
$$I_2 = -I_1$$



Integrating the current we determine the total charge collected

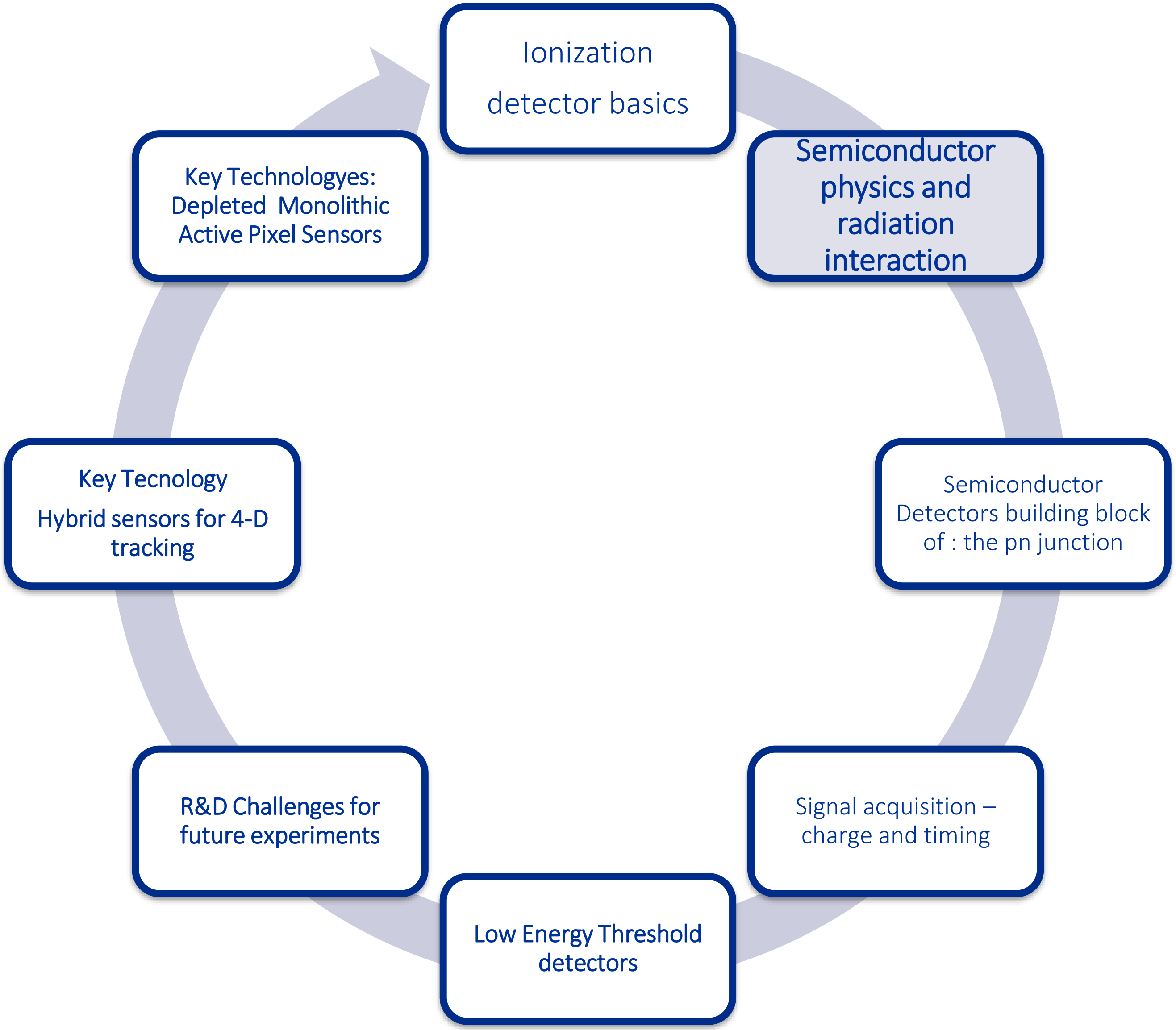
$$Q^{tot}_1 = \int I_1 dt = q/D \cdot v_e \, T_e + q/D \cdot v_I \cdot T_I$$
$$= q/D \cdot v_e \cdot (D-z_0)/v_e + q/D \cdot v_I \cdot z_0/v_I$$
$$= q(D-z_0)/D + qz_0/D = q$$



Ionization detector basics(3): take home messages

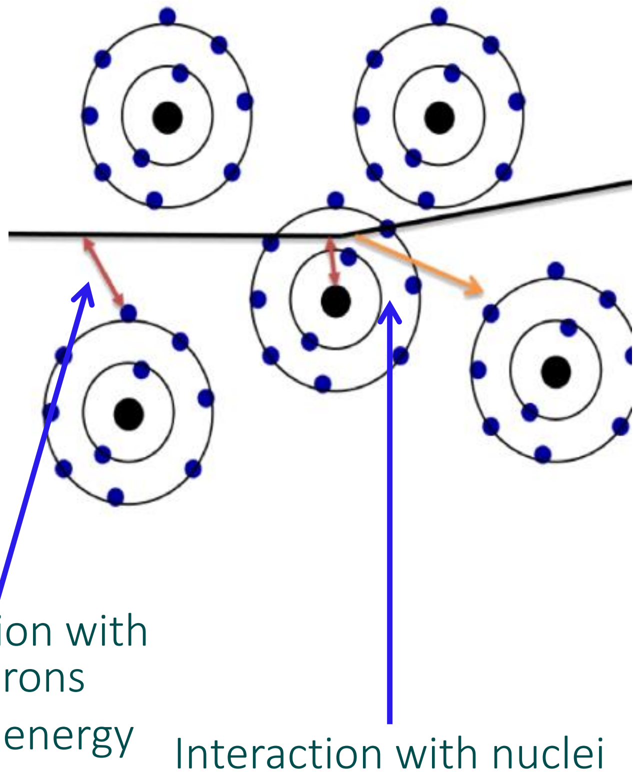
- The toy model illustrates the key features of signal generation and collection in ionization detectors with signal capacitive signal induction electrodes (the huge majority of current detectors).
- **The signal (current) is created by the moving charge carriers in the ionized media, it ends once the carriers reach the electrodes.**
- Both types of carriers (positive and negative contribute to the signal)
- The collected charge (if no trapping is present) equals the generated charge.
- If there is an electrode that does not collect charge, a current is also induced in it; although the collected charge (current integral) is zero, in other words, the induced current is bipolar.
- For lovers of formalism, the long explanation with a little more mathematics but same physics:
  - American Journal of Physics **44**, 1132 (1976); https://doi.org/10.1119/1.10207
  - S. Ramo, Proc. IRE 27 (1939) 584;
  - Signals in Particle Detectors, 5 hours course by Wener Riegler, https://indico.cern.ch/event/843083/

Semiconductor radiation detectors 101



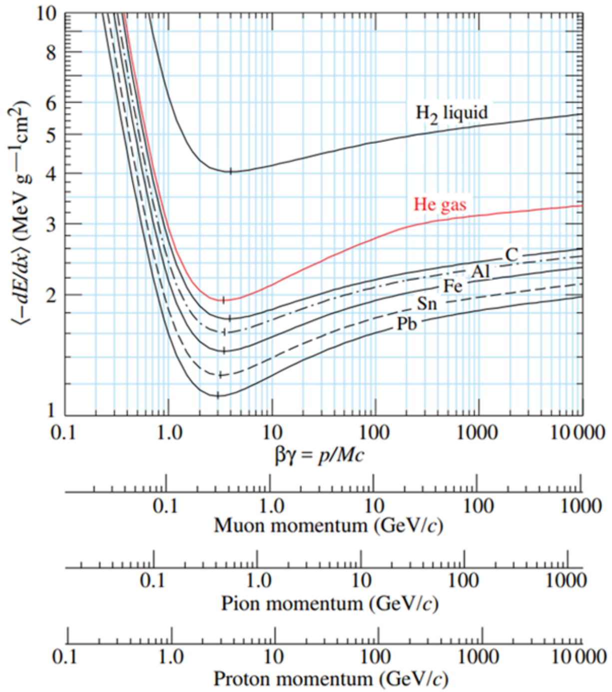
Radiation - semiconductor interaction: Ionization

- The dominant energy loss mechanism is ionization.
- define the average energy loss per unit of length as: –dE/dx



The average energy loss of a particle due to ionization is given by the **Bethe & Bloch Formula**

This formula is valid for particles with a mass much higher than the electrons $m_p >> m_e$



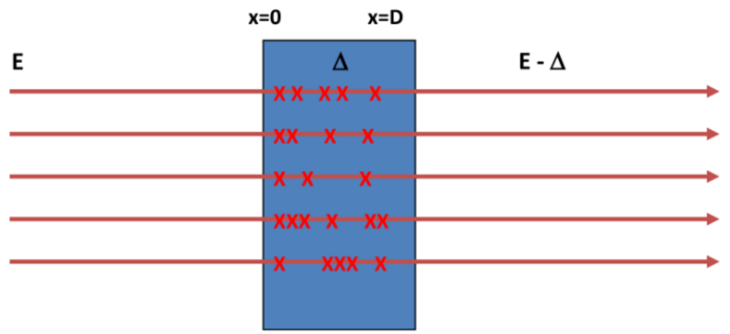
At low energy the term $1/\beta^2$ dominates (useful for PID detectors)

At high energy → logarithmic term

There is a minimum of ionization
MIP → Minimum Ionizing Particle (MIP)

Radiation - semiconductor interaction: Ionization

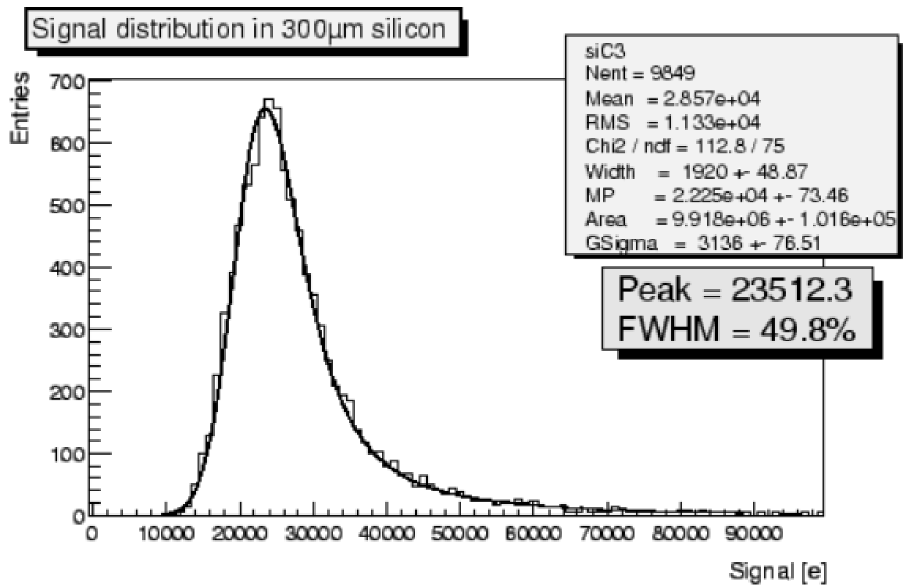
- The energy transfer between the particle and the semiconductor is of stochastic nature. For a given material thickness and we have obtain a distribution rather than a fixed energy loss.
- The energy loss distribution depends on the material thickness, in practice for a range from few tens of microns to few hundred of microns the energy loss distribution is a Landau.



The stochastic nature of

The ionization energy transfer is even present for processes where the particle is fully stopped in the material due to the **sharing of the particle´s initial kinetic energy between the ionization and vibrations (phonons)**

The Fano factor characterizes this effect



In Silicon

Mean energy loss
dE/dx (Si) = 3.88 MeV/cm $\Rightarrow$ 116 keV for 300μm

Most probable energy loss
$\approx$ 0.7 $\times$ mean $\Rightarrow$ 81 keV

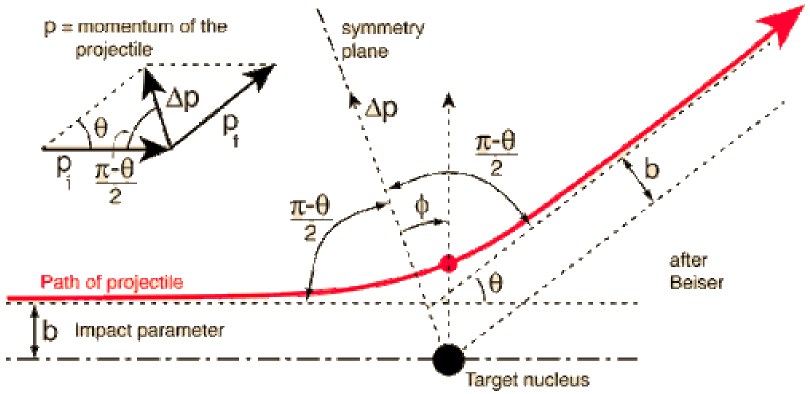
3.6 eV to create an e-h pair
$\Rightarrow$ 72 e-h / μm (most probable)
$\Rightarrow$ 108 e-h / μm (mean)

Most probable charge (300 μm) $\approx$ 22500 e 3.6 fC

Radiation - semiconductor interaction: Multiple (elastic) Scattering

- A charged particle traversing a medium is deflected many times mainly by small angles
- Each deflection is due mainly to the Coulombian interaction of the particle and a nucleus
- Energy transferred to the nucleus is small and neglected
- A single collision is described by Rutherford's formula (ignores spin and screening effects)

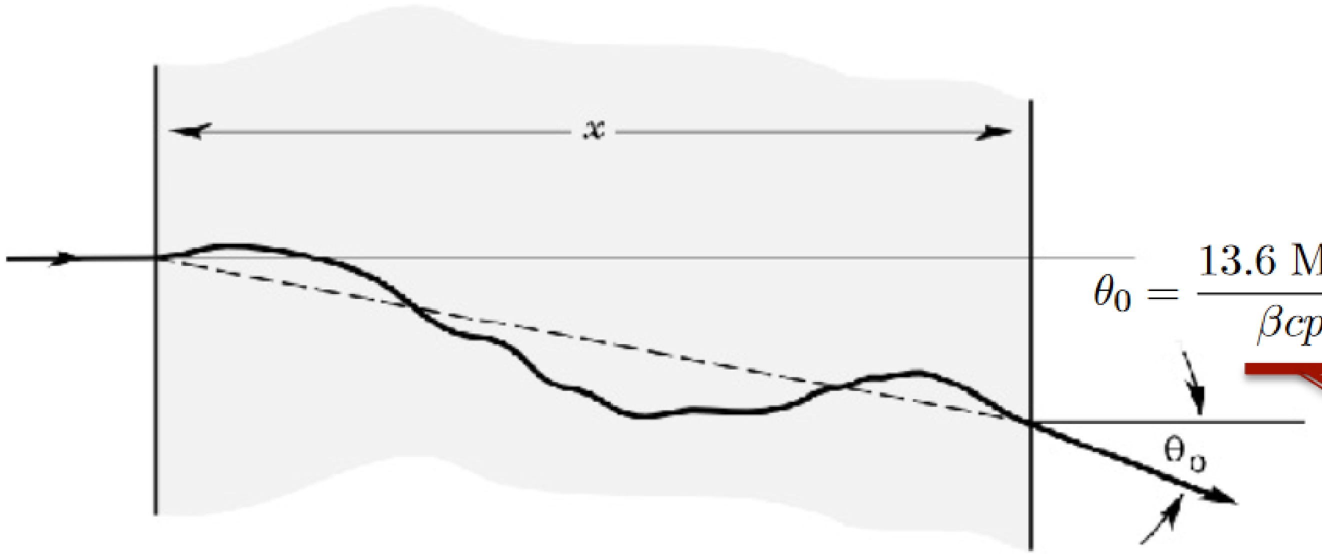
$$\frac{d\sigma}{d\Omega} = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4\theta/2}$$



- In multiple scattering typically many collisions take place during the trajectory
  - The particle follows a zig-zag trajectory of statistical nature
  - A global deflection angle given by Moliere's scattering

Radiation - semiconductor interaction: Multiple (elastic) Scattering

- The multiple scattering produces a global angular deflection and an orthogonal displacement
- For small deflection angles the distributions of deflections are approximately Gaussian

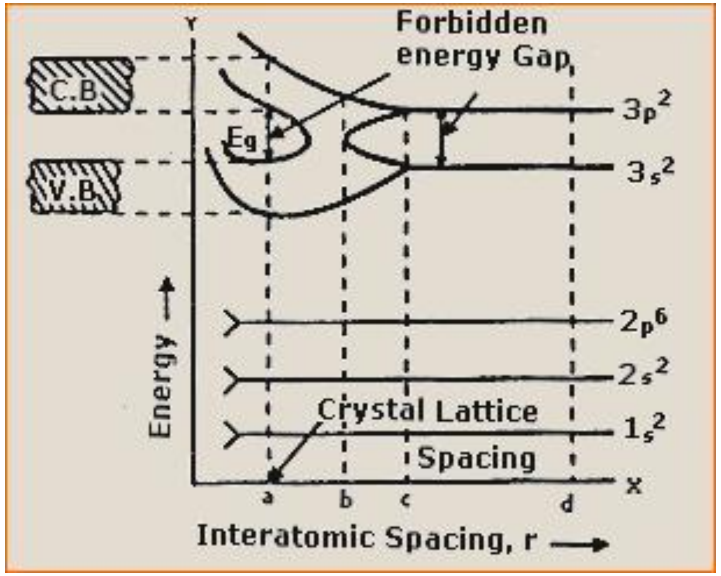


$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

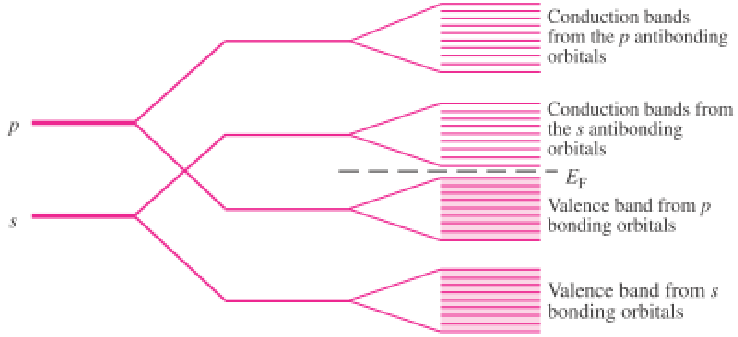
- The radiation length (X_0) is the characteristic length that describes the energy decay of a beam of electrons (defined as the length in which an electron has radiated 1/e of its energy)
- Radiation loss dE/dx is approx. independent of material when thickness expressed in terms of X_0

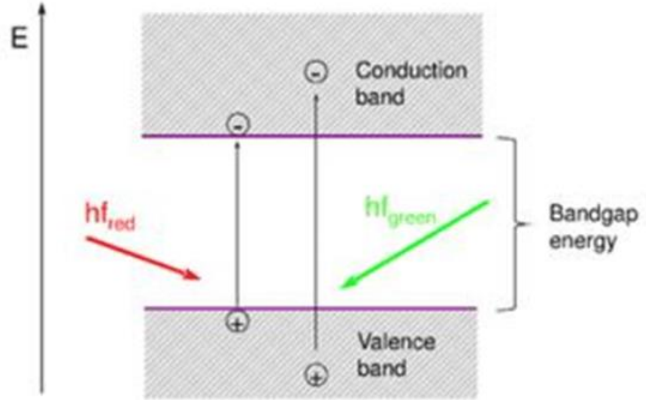
Semiconductor Physics: Semiconductors as ionizable material

1st ingredient of the ionization detector



- Silicon is the most convenient semiconductor material due to its high standardized processing and large availability of high purity substrates.
- Ionization energy transfer promotes a VB electro to the CB creating two charge carriers the electron and the hole (suitable to be detected as a current if E field is applied).
- Electrons an holes inside the bands behave as an electronic ideal quantum gas in a box (simple description).

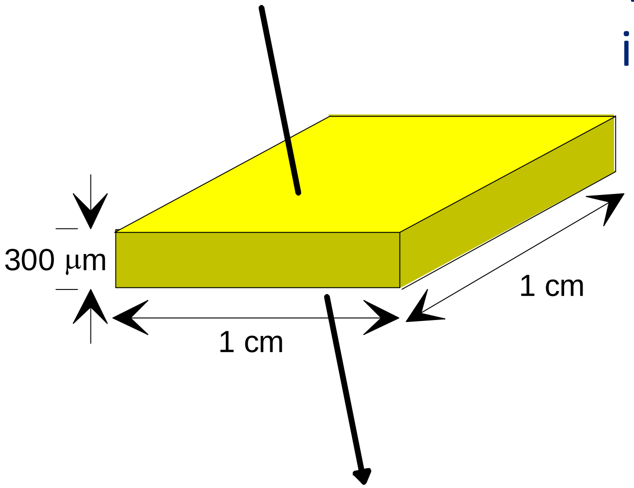




Semiconductor Physics: Semiconductors as ionizable material (2)

Physical state of the Ionizable material

	Gas	liquid	solid
Density	low	moderate	high
Z	low	moderate	moderate
Ionization energy ε_i	moderate	moderate	small
Signal velocity	moderate	moderate	fast



Two important problems for Silicon (the leading industrial semiconductor) as ionizable media

A - At room temperature the density of carriers (electrons and holes) in Silicon: $n_i \approx 1.45 \cdot 10^{10}$ cm^{-3} For a typical active volume of $4.5 \cdot 10^{8}$ cm^{-3} free charge carriers in this volume, but only $3.2 \cdot 10^{4}$ e-h pairs produced by a Minimum Ionizing particle. Expect **poor signal-to-noise ratio**.

B- High-density material may introduce **unacceptable multiple scattering** for tracking applications

Semiconductor Physics: Semiconductors as ionizable material (3)

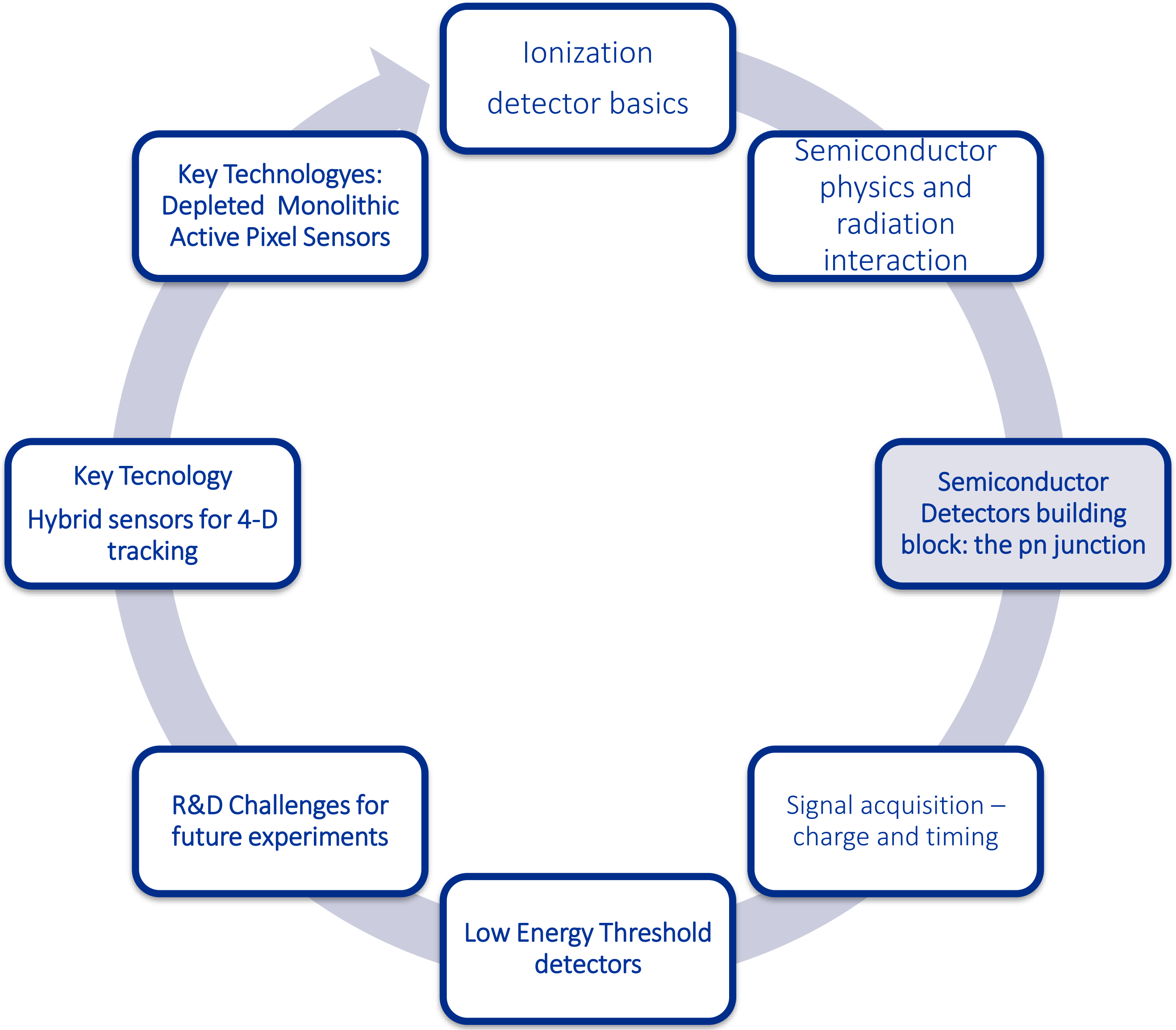
- **For solving the problem B (material Budget):** reduce the thickness while keeping sensible SNR either by increasing the signal (gain) or reducing the noise (reducing detector capacitance)
- **For solving the problem A (thermal noise):** reduce the thermal carrier density by reducing the temperature (as in the case High Purity Ge detectors for gamma spectrometry operated as LN temperature) or increase the band gap energy (as in the case wide band semiconductors as SiC or Diamond)
  - None of the two previous approaches for reducing the thermal noise are very popular, Ge and SiC are yet semiconductor materials that require very special (expensive) processing compared with mainstream Silicon semiconductor devices (though this is changing rapidly for the case of SiC)
  - The most preferred solution is the use of the **pn – junction** electric field to deplete the thermal carriers from the silicon bulk.

Property	Silicon	Germanium	Gallium arsenide	Silicon carbide (SiC)	Gallium nitride (GaN)	Diamond
Minimum band gap (E_g) [eV]	1.12	0.68	1.42	2.9	3.39	5.48
Electron drift mobility (μ) [$cm^2/V\text{-}s$]	1450	3900	8500	400	1000	1800
Mean ionization energy (ε) [eV]	3.63	2.96	4.13	6.88	8.9	12.4

Semiconductor as ionizable material & radiation-semiconductor interation (Take-home messages)

- The only relevant radiation-material (at high T) interaction processes in semiconductors are:
  - **Inelastic scattering by Ionization** (Bethe-Bloch) , energy loss, stopping power. The stopping power is approx. independent of the material and function of the speed with a common minimum for all the particle (MIP concept)
  - **Multiple elastic scattering** produces dispersion of the particle trajectory
  - Radiation (Bremsstrahlung) is only relevant for electrons or very fast particles (no consider here yet)
- In semiconductors the ionization is used to create electron-hole pairs suitable as charge carriers to generate a signal current:
  - Many advantages: high energy resolution, larger primary signals and very mature and mainstream industrial technology.
  - Two main draw backs: Relative high density materials (wrt to gases) induce **higher MS deviations;** and **thermal generation of noise carriers** can greatly exceed the excess carriers generated by radiation.

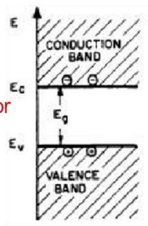
Semiconductor radiation detectors 101
The pn junction



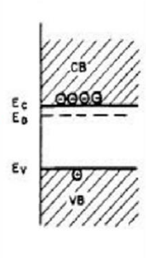
Semiconductor detector building block : pn junction

– Semiconductor rectifying junctions (diodes) provide the other two ingredients for a ionizing detector: the drift electric field and the collecting electrodes.
– The pn junction is the most used rectifying junction in semiconductor devices.
– Basic idea: at the transition region between a p-type bulk and n-type bulk of semiconductor a diffusion current is created.
– The ionized impurity atoms left behind by the free carriers produce a space charge region with an associated electric field that depletes the junction from carriers **suppressing the noise due from thermal generated carriers**

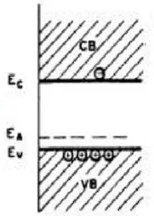
Intrinsic semiconductor

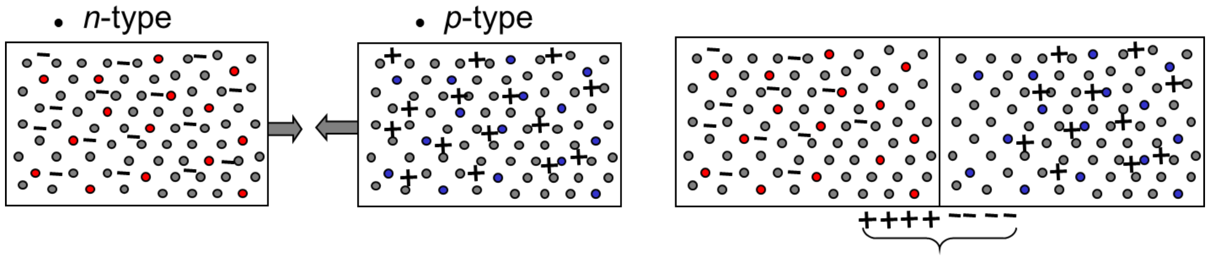


n-type doped semiconductor



n-type doped semiconductor



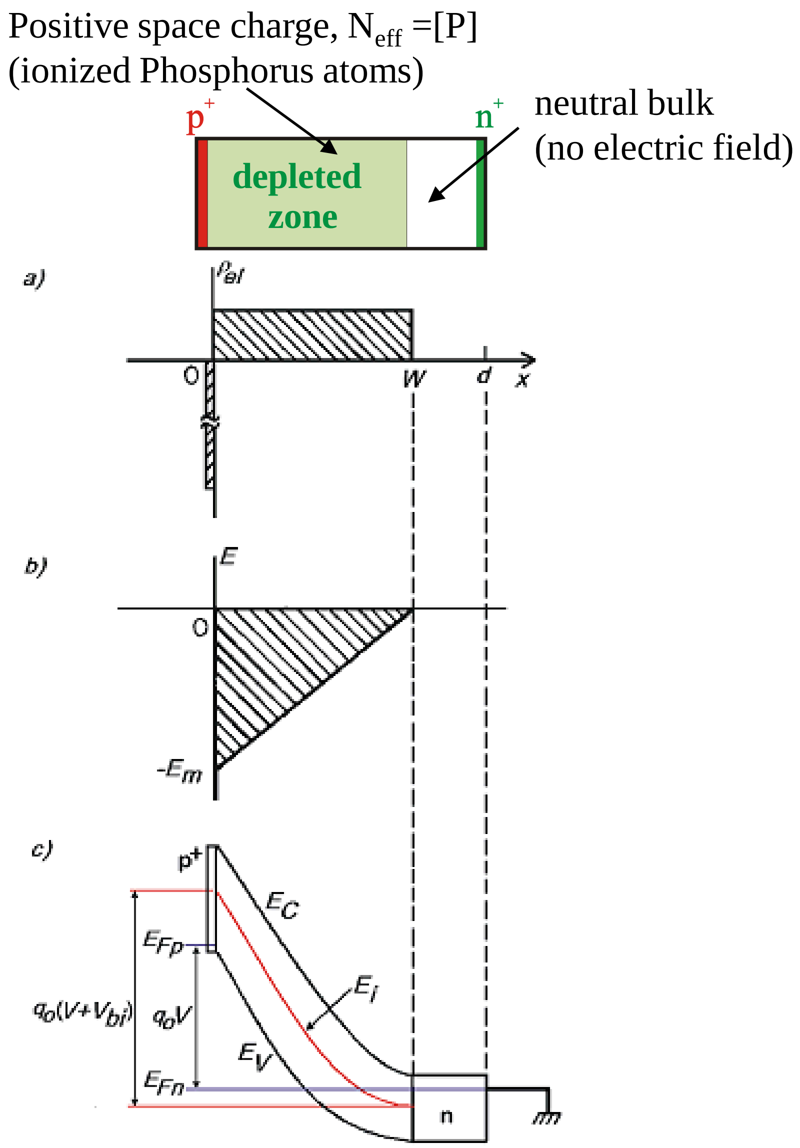


depleted juntion

Semiconductor detector building block : pn junction

Poisson's equation

$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$

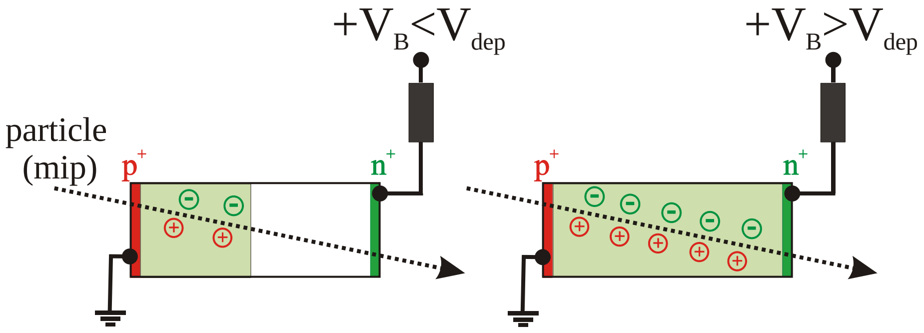


Electrical charge density

Electrical field strength

Electron potential energy

Depleted zone growth with increasing voltage ($w \propto \sqrt{V_B}$)



Full charge collection only for *fully depleted detector* ($V_B>V_{dep}$)

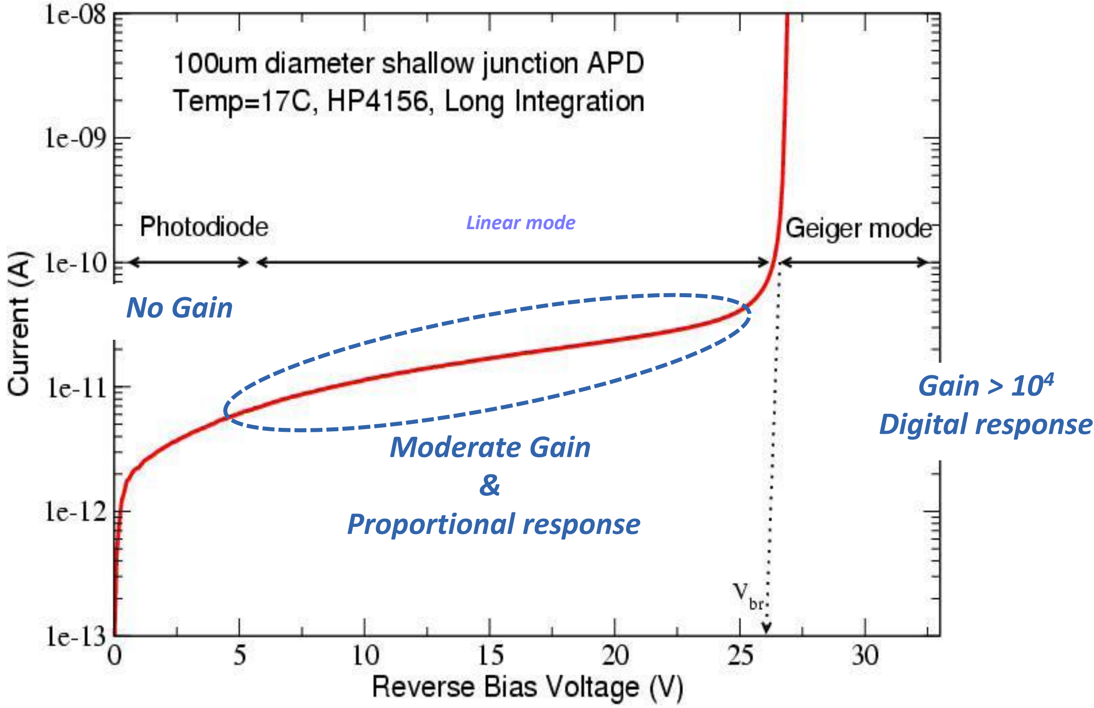
depletion voltage V_{dep} ***detector thickness d***

$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0}\cdot|N_{eff}|\cdot d^2$$

effective space charge density N_{eff}

Semiconductor detector building block : pn junction

- Silicon-based diodes provide both **fast rise time and relatively large signal/noise ratio**.
- Three operating modes depending on the biasing voltage:
  - 1st Generation -no signal gain (**PD aka PIN in HEP**),
  - 2nd Generation - Geiger mode (**SiPM**).
  - 3rd Generation - proportional (**APD aka LGAD in HEP**)



[1] A.G. Stewart et al. in Proc. of SPIE, Vol. 6119, 2006

Semiconductor detector building block : pn junction

- The use of semiconductor junctions as radiation detector started at the end of the 1950s for gamma ray spectroscopy (Nuclear physics).
- A breakthrough innovation with the use of planar semiconductor techniques for the fabrication of finely segmented pn junction based position-sensitive sensors, the key technology that opened up the high-precision heavy flavor sector for the collider experiments.

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FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

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Received 30 July 1979 and in revised form 22 October 1979

Dedicated to Prof Dr H -J Born on the occasion of his 70th birthday

By applying the well known techniques of the planar process oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than 1 nA cm^{-2}/100 μm at room temperature Best values for the energy resolution were 10 0 keV for the 5 486 MeV alphas of ^{241}Am at 22 °C using 5×5 mm^2 detector chips

- This is origin of the dominant vertexing and tracking technologies used in the LHC experiments. Plenty of non-HEP spin-offs.

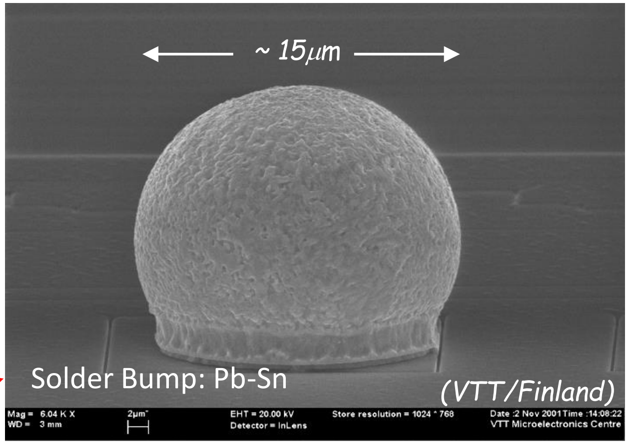
State-of-the-art: Vertex detectors at LHC and X-Ray Imaging at Synchrotron sources

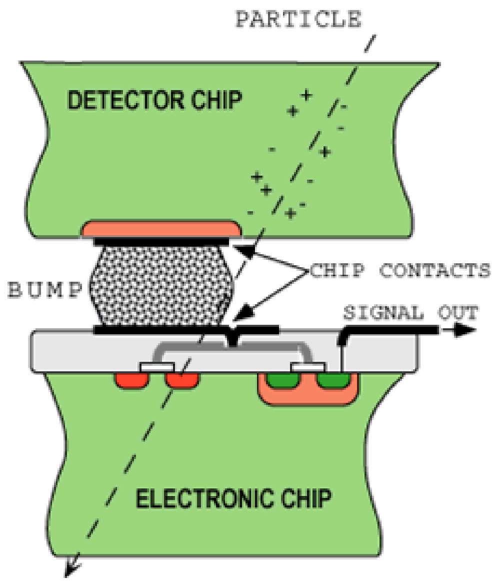
HPS – Hybrid Pixel Sensors

segment silicon to diode matrix with high granularity ⇒ true 2D, no reconstruction ambiguity

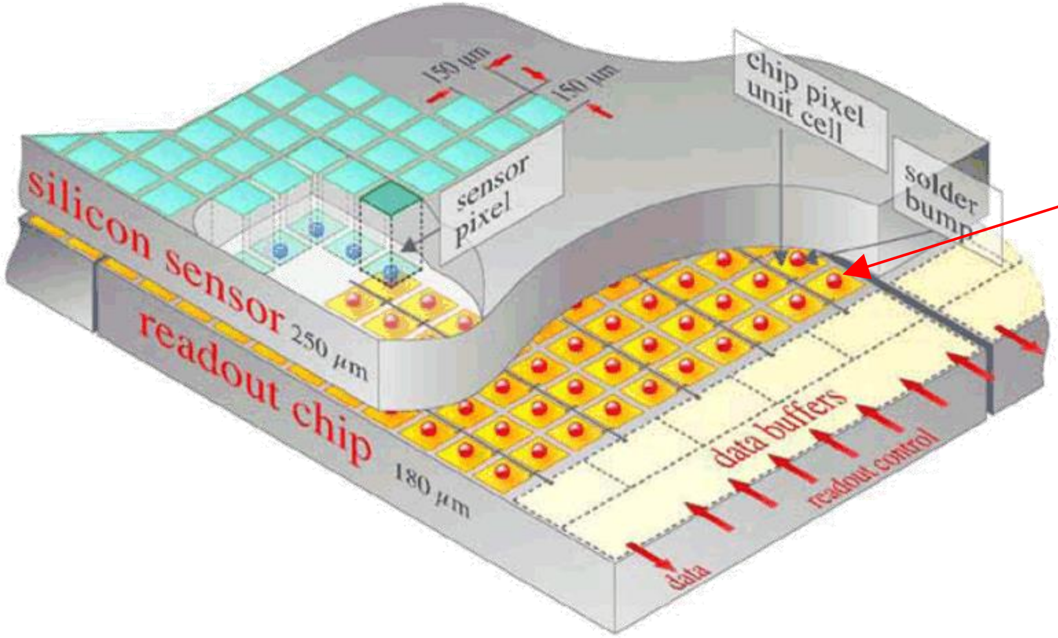
readout electronic with same geometry (every cell connected to its own processing electronics) connection by "bump bonding"

Hybrid pixel detectors used in LHC experiments and Synchrotron sources

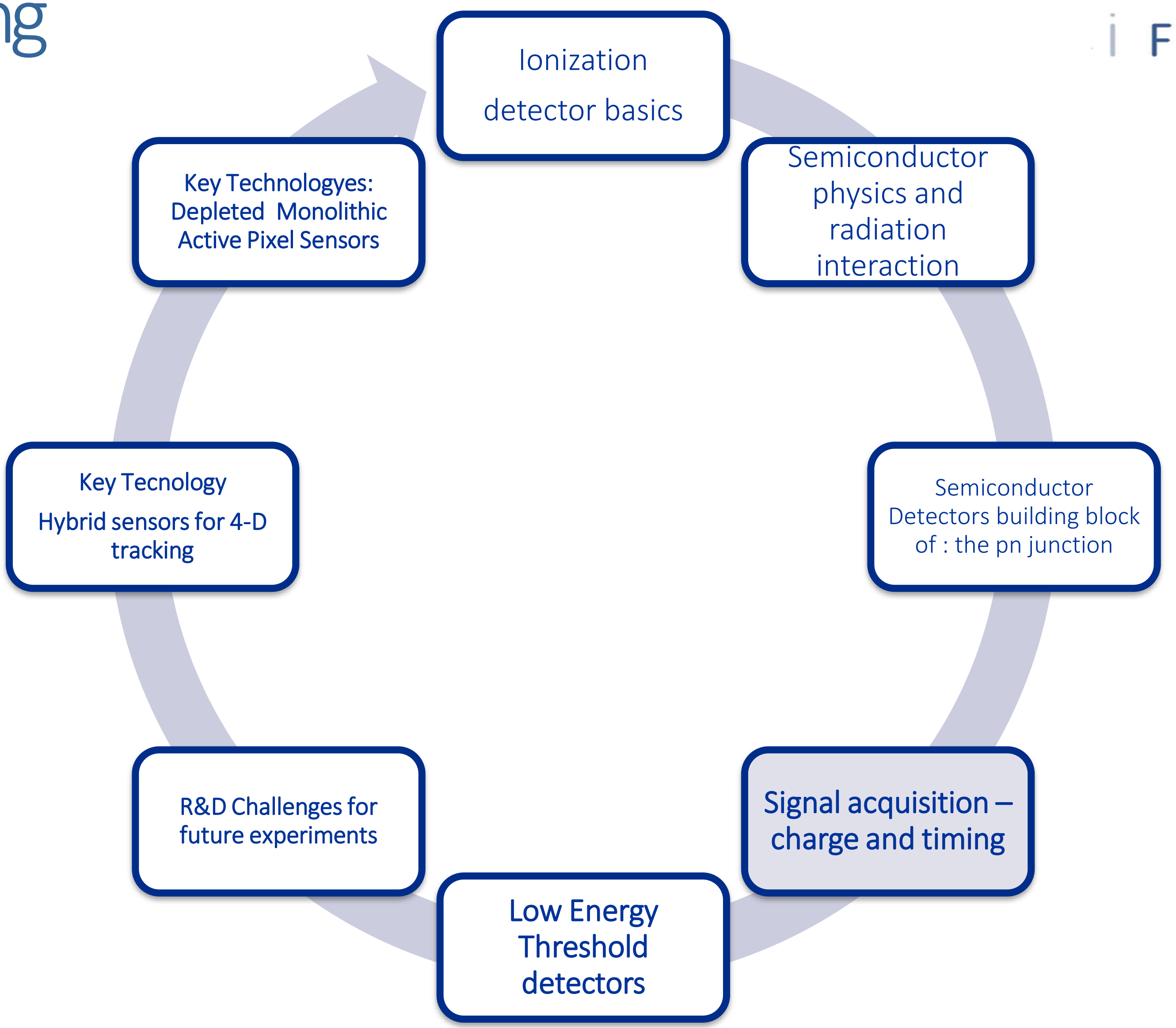




Flip-chip technique

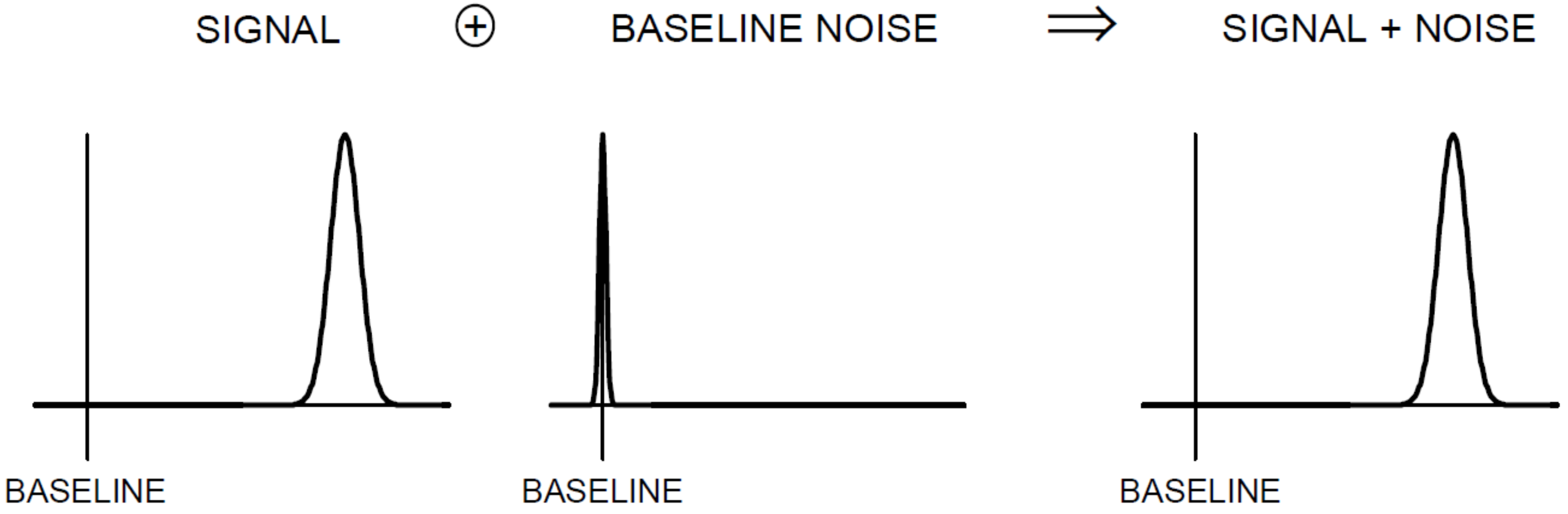


Semiconductor radiation detectors 101
Signal Acquisition Charge & Timing



Signal adquisition in semiconductors: noise

For a semiconductor typically the signal variance << baseline noise



- For a 50um think diode an perpendicular MIP would create and average of 5000 e-h pairs, the variance would be $\sigma_{ep} = \sqrt{F \cdot 5000}$ (with F=Fano Factor=0.1) then $\sigma_{ep} = 22\ e$ (typical noise levels in the range of 10 – 1000 electrons)
- The practical noise limit is the electronic noise

Signal adquisition in semiconductors: noise

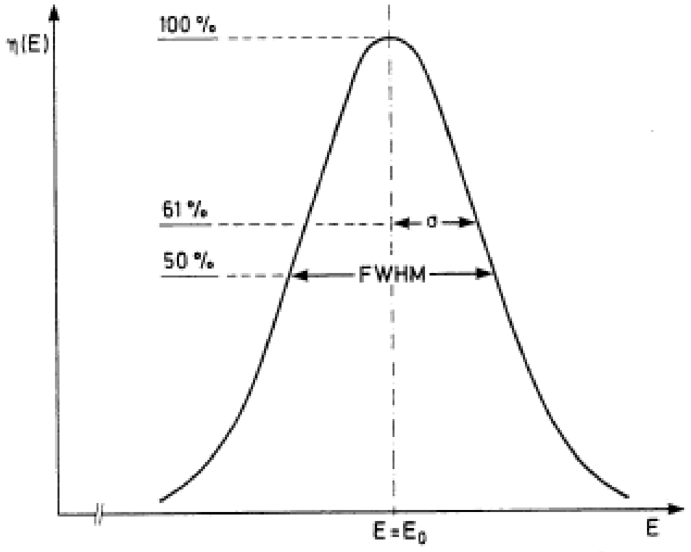
- Consider n carriers of charge e moving with a velocity v through a semiconductor of length l. The induced current i at the ends of the sample is:

$$i = \frac{n\,e\,v}{l}$$

- The fluctuation of this current is given by the total differential

$$\langle di \rangle^2 = \left(\frac{ne}{l} \langle dv \rangle \right)^2 + \left(\frac{ev}{l} \langle dn \rangle \right)^2$$

- Two mechanisms contribute to the total noise:
  - velocity fluctuations, e.g. thermal noise
  - number fluctuations, e.g. shot noise or '1/f ' noise
- Thermal noise and shot noise are both white- noise sources with gaussian distributed amplitude

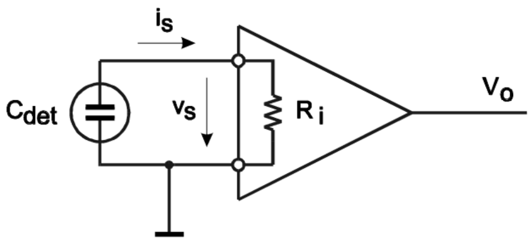


Signal adquision in semiconductors: signal (pre-)amplification

– Determine the ionization energy (charge) with improved SNR.

– Input: short current pulse (typicaly, pulse collection time t_{coll} < 10 ns)

Simple amplifiers (integrating charge in the detector capacitance)



Output voltage V_o = voltage gain $A_v \times$ input voltage v_s.

$R_i C_{det} << t_{coll}$ detector capacitance discharges rapidly

$\Rightarrow V_o \propto i_s(t)$

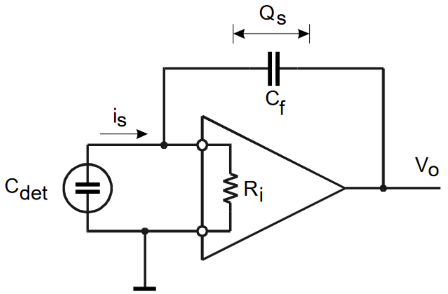
current sensitive amplifier

$R_i C_{det} >> t_{coll}$ detector capacitance discharges slowly

$\Rightarrow V_o \propto \int i_s(t) dt$

voltage sensitive amplifier

Feed-back amplifiers (integrating charge in feed-back capacitance)



$R_i C_{det} >> t_{coll}$

Signal current is on feedback capacitor Cf

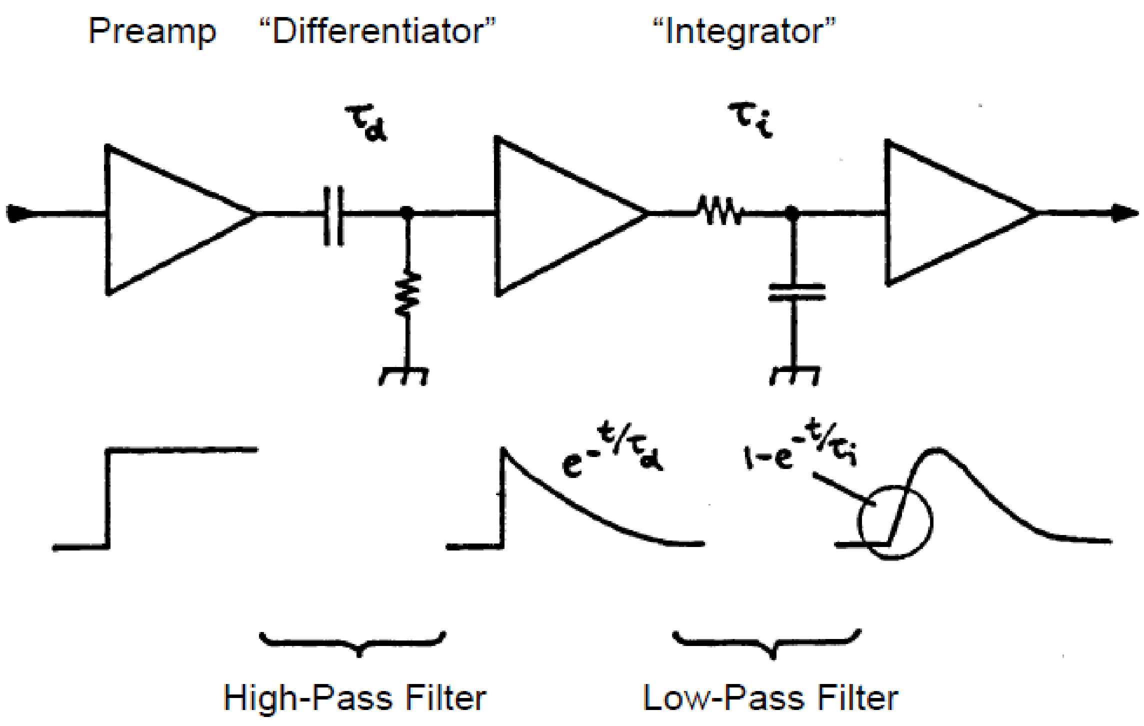
$$V_o \propto Q_s / C_f$$

Amplifier output directly determined by signal charge insensitive to detector capacitance (**Charge-sensitive amplifier)**

Signal adquision in semiconductors: signal shaping

– Improve the SNR and preserve the pulse leading-edge risetime, taylor the pulse duration to suppress signal pile up.

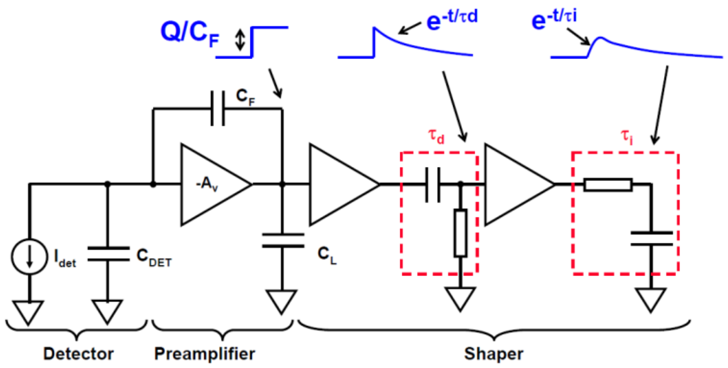
Simple CR-RC shaper



Equivalent Noise Charge (ENC)

– Inject known signal charge into preamp input (either via test input or known energy in detector).
– Determine signal-to-noise ratio at shaper output.
– Equivalent Noise Charge defined as Input charge for which *S/N*= 1

Timing 101: Timing resolution contributions - Jitter



Ideally, for a constant amplitude pulse, the time resolution is given by the jitter which depends on:

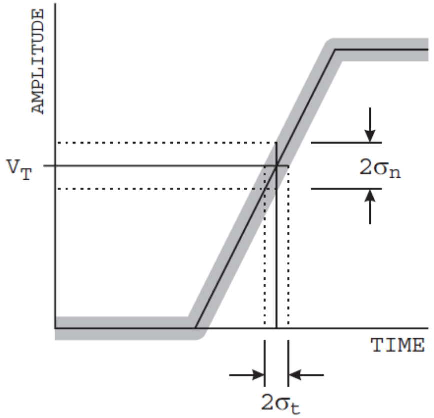
- **Noise** (dominated by the **amplifier** noise)

$$v_n \propto \sqrt{f_u} \propto \sqrt{\frac{1}{t_{ra}}}$$

- **Signal amplitude** (dominated by **sensor's** response)
- **Rise time** (dominated by **amplifier** risetime)

$$t_r = \sqrt{t_{rs}^2 + t_{ra}^2}$$

Leading Edge Timing



$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} \qquad \frac{dV}{dt} \approx \frac{V}{t_r} \rightarrow \sigma_t = \frac{t_r}{SNR}$$

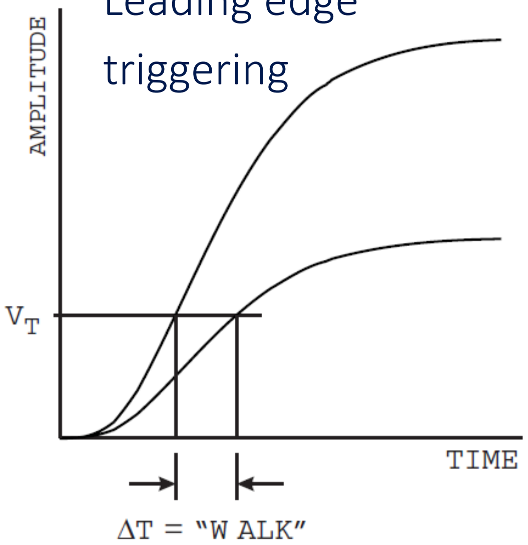
$$\sigma_t \propto \frac{1}{V_0} \frac{1}{\sqrt{t_{ra}}} \sqrt{t_{rs}^2 + t_{ra}^2}$$

Typical bandwidth of HL-LHC timing layer preamplifier of around 400 MHz → $t_r \sim t_{ra} \sim$ 1ns then a (modest) SNR of about 30 should provide a timing resolution of about 30 ps

Timing 101: Time resolution contributions – Time walk

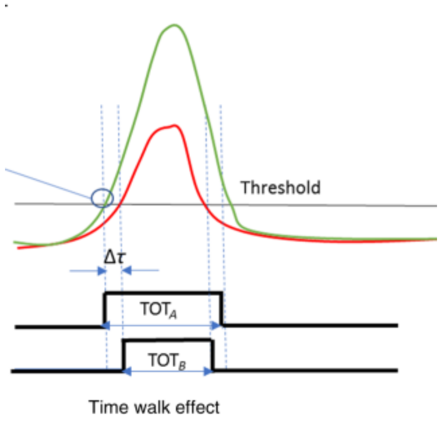
In real conditions, the pulse amplitude is not always constant.

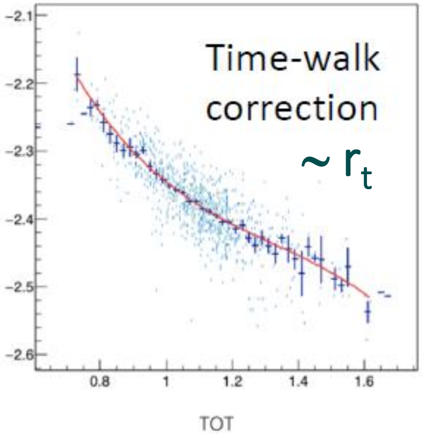
Leading edge triggering



Option 1

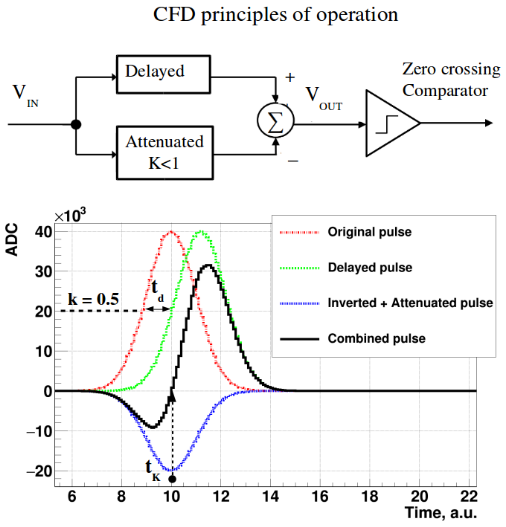
Correct the time shift using the pulse amplitude





Option 2

Constant Fraction Triggering



Both methods: Amplitude-corrected LET and CFT have a similar performance as long as THE SHAPE OF THE PULSE'S LEADING EDGE IS CONSTANT.

Caveat: ToT correction is (mostly) an off-line method while CDF is a real-time correction.

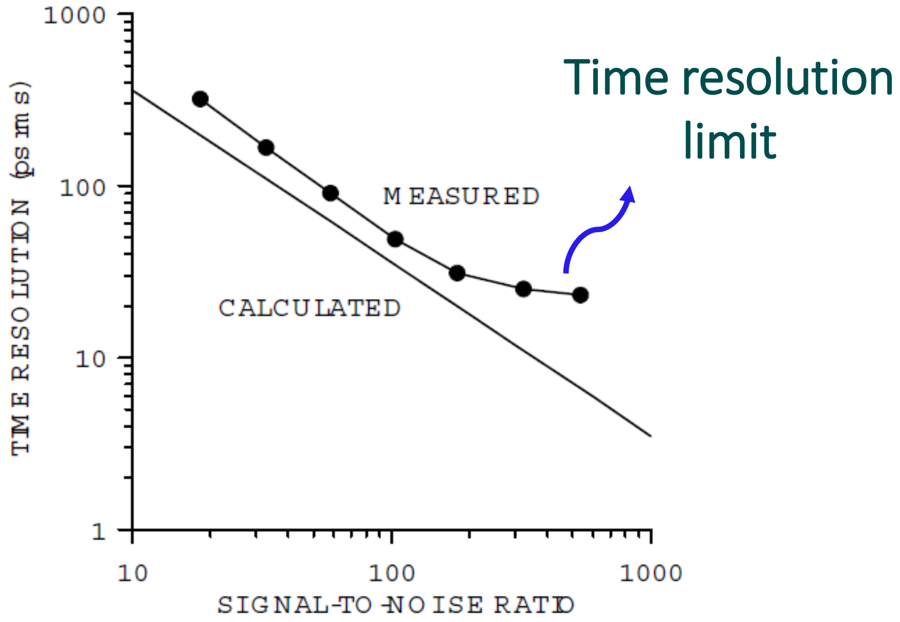
Timing 101: Time resolution contributions – limiting systematics

Jitter induced by pulse shape changes (non uniform ionization or weighting field)

- Changes on the leading edge shape (i.e., different rise times or its distortions) translate into additional jitter

System aspects:

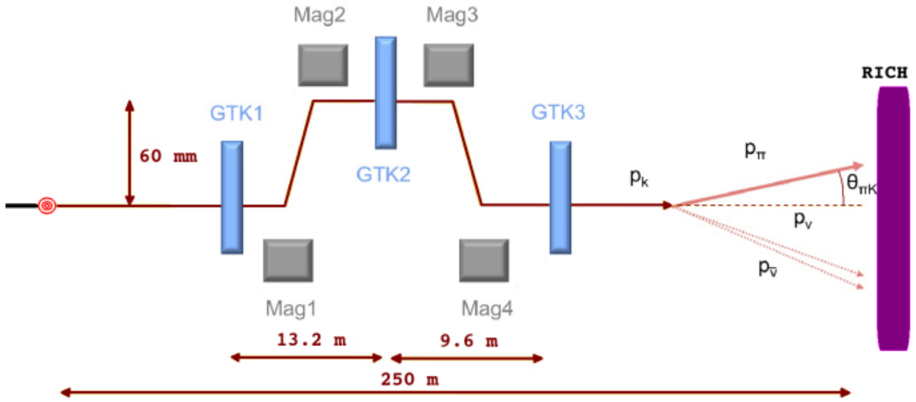
- TDC resolution.
- ADC (ToT) resolution limits time-walk correction.
- Clock distribution (jitter, slew and thermal drifts).

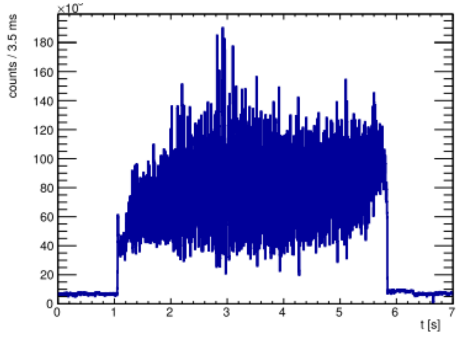


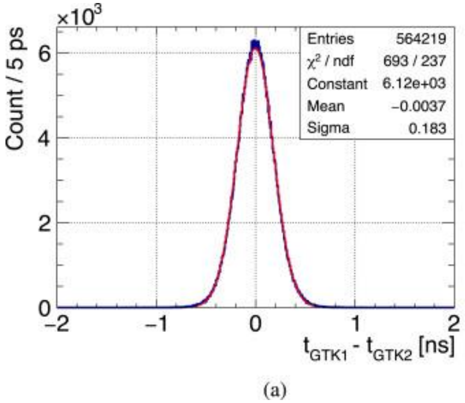
These are the limiting factors and off-line data-based corrections are needed.

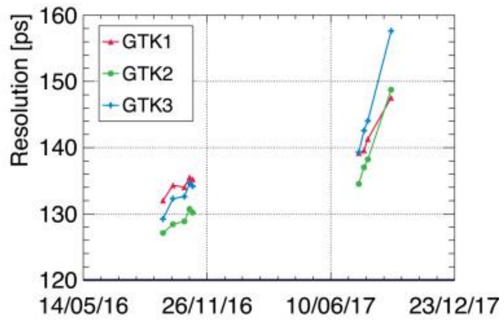
State-the-art: GigaTracker - A true 4th dimensional tracker

- Aim to measure Br(K+ → π +νν) SM branching fraction ~ 10^{-10}
- Unstructured particle beam with ~5 second burst every ~42 seconds (instantaneous rate 750 MHz)







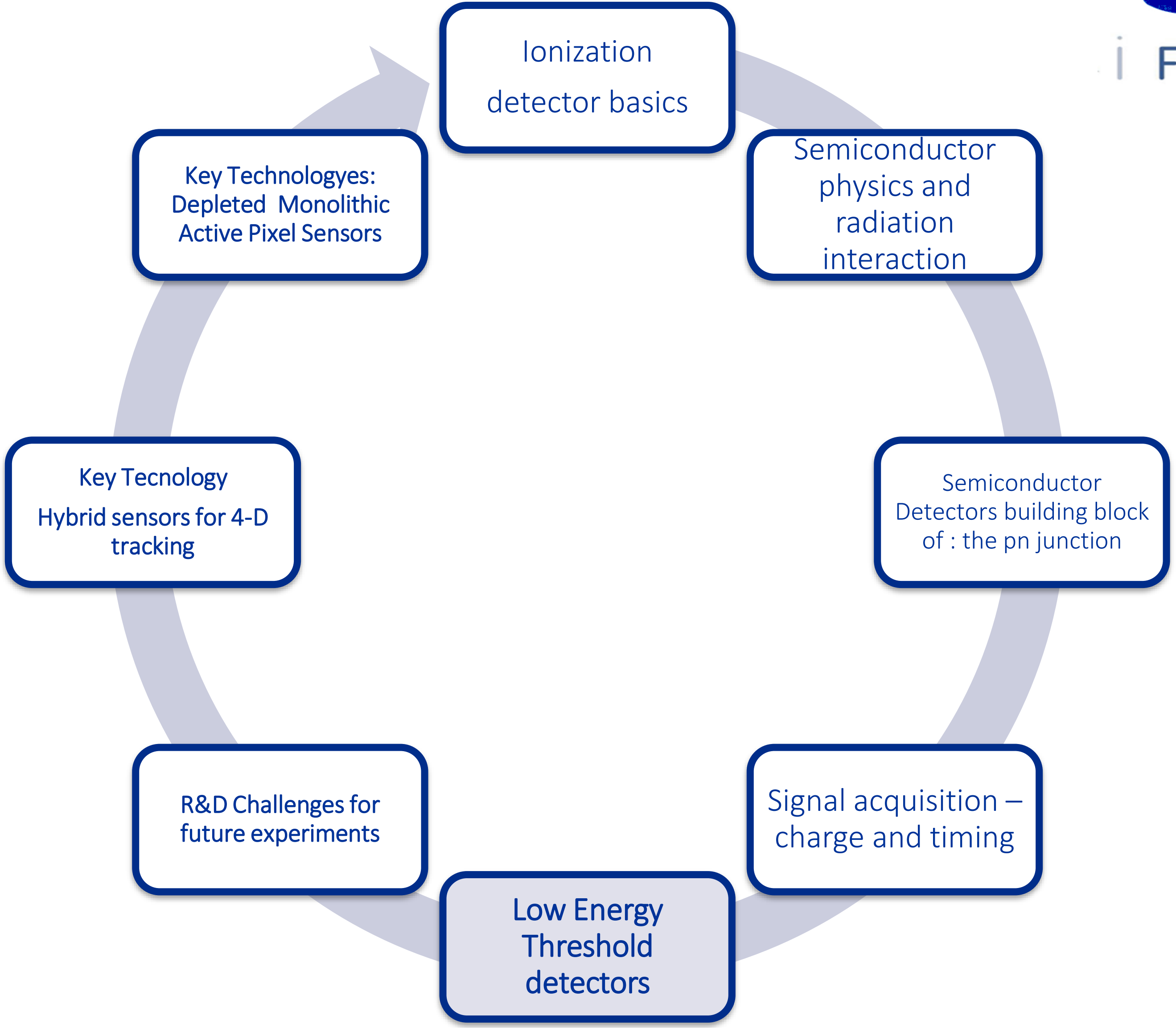


Hybrid pixel detector:

300 um × 300 um pixels

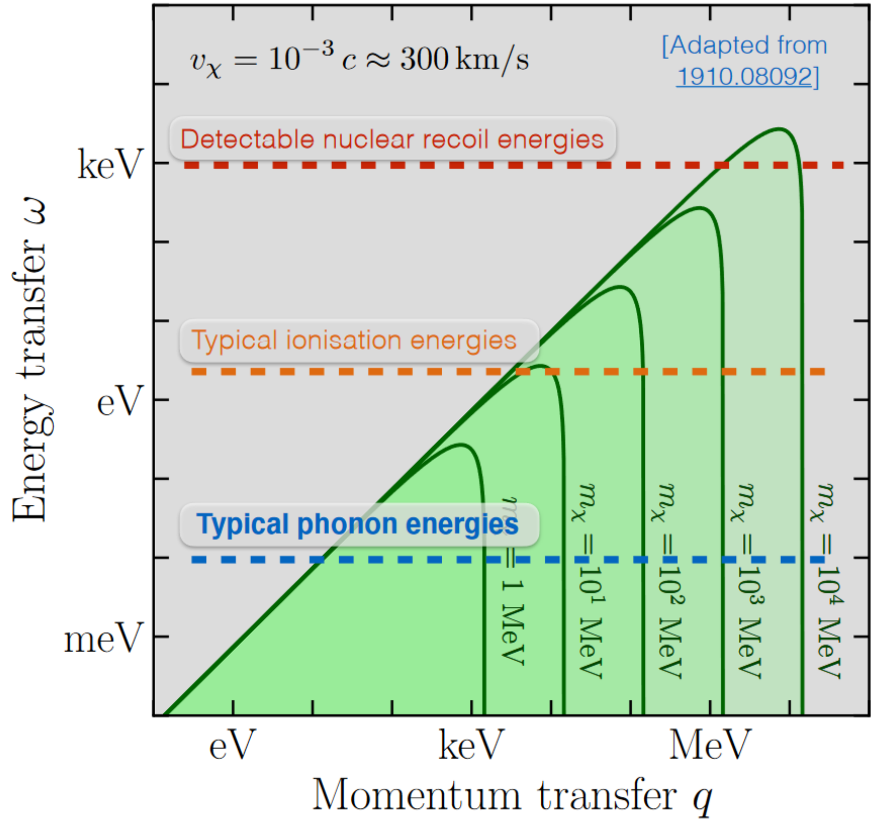
One sensor (~6×3 cm2) bump-bonded to 10 read-out chips (TDCpix)

Low Energy Threshold detectors



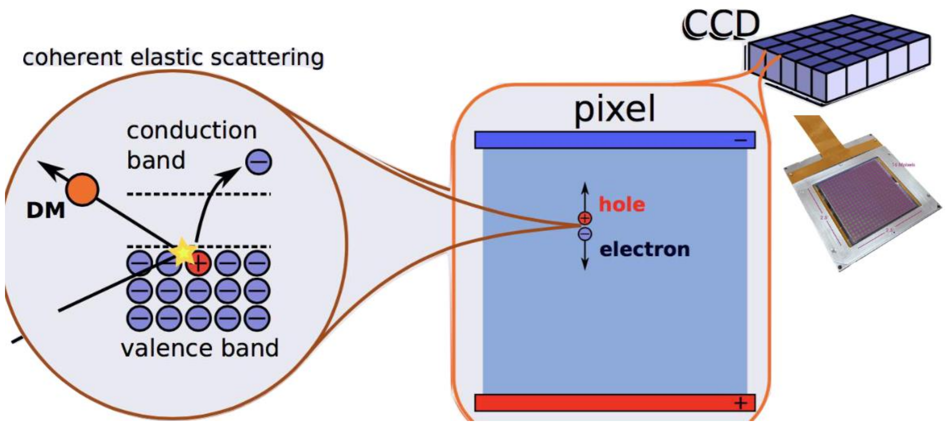
Low Energy Threshold detectors: Motivation

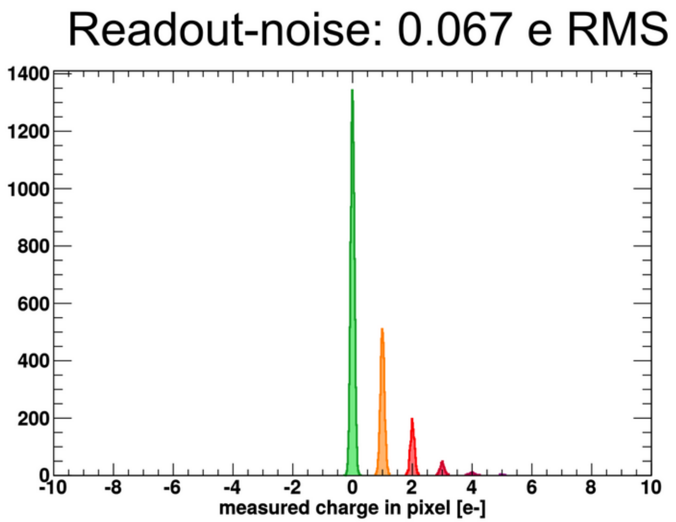
- During this decade, **increasing interest in light particle-like dark matter.**
- Ionization -> charge carriers:
  - ~ 10 eV (gas),
  - ~ 1 eV (semiconductor)
- Heat -> phonon ~ meV

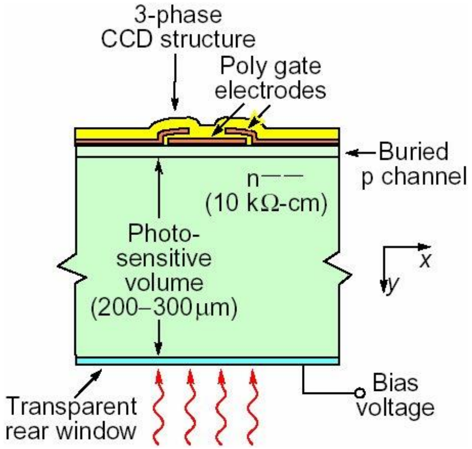


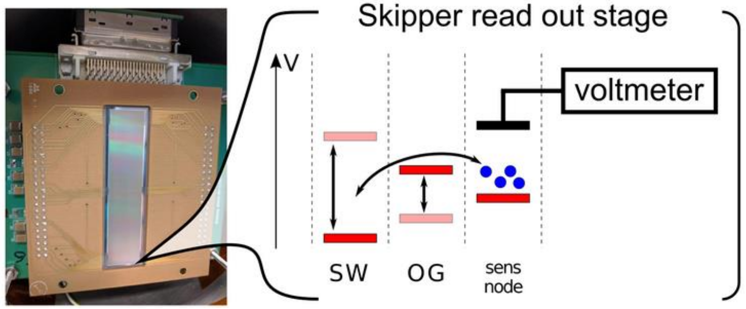
Low Energy Threshold detectors: Electron recoil

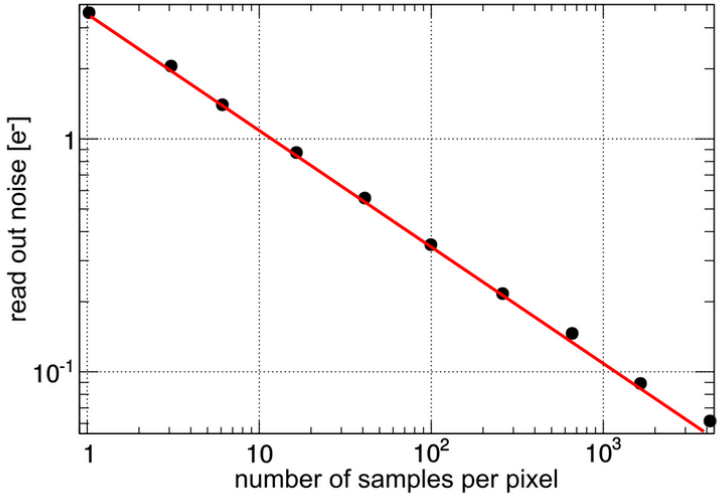
Skipper CCD - noise below the charge of the electron



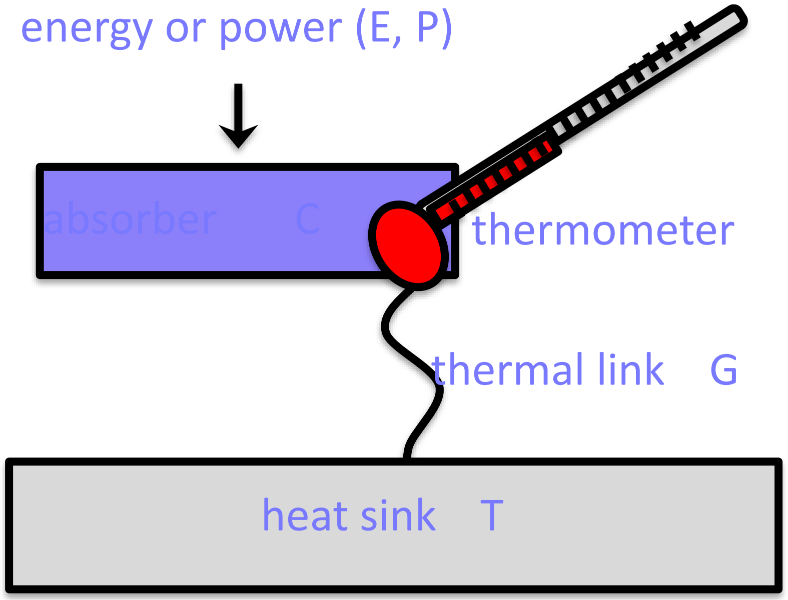


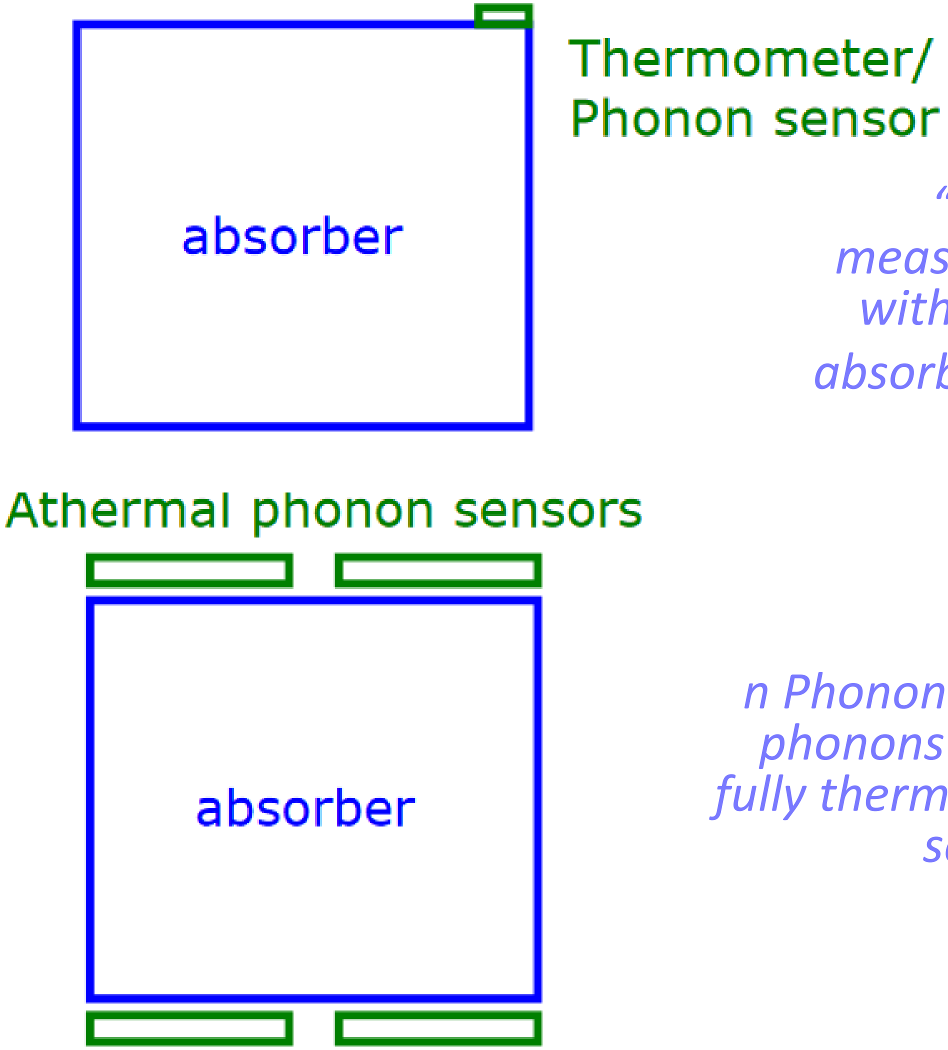






Low Energy Threshold Detectors: below the semiconductor bandgad



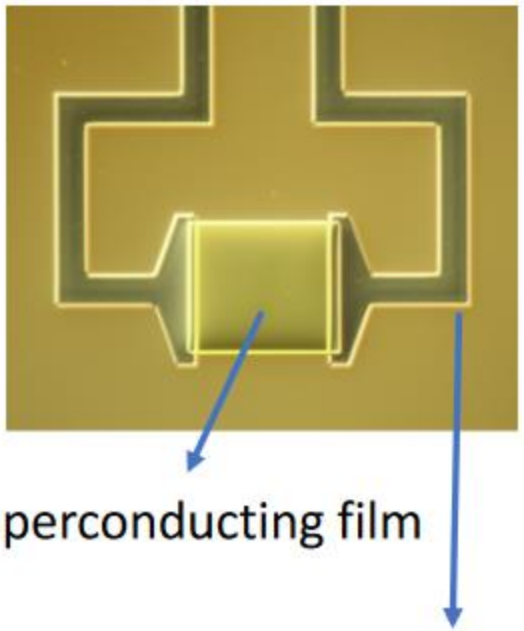


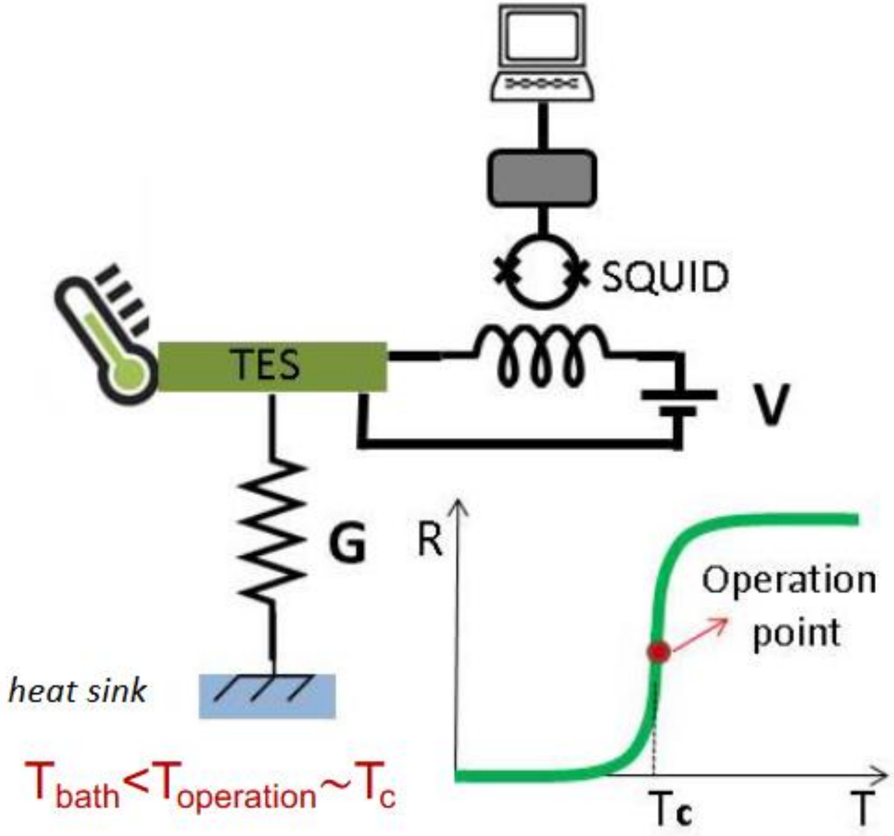
"True calorimetric measurement": $\Delta T = \Delta E/C$, with C = heat capacity of absorber. ΔT ~ Large number ~meV phonons.

n Phonon sensor: start to "count phonons" even before they are fully thermalized: faster + position-sensitive device

Low Energy Threshold detectors: Transition Edge Sensors (a canonical thermometer)

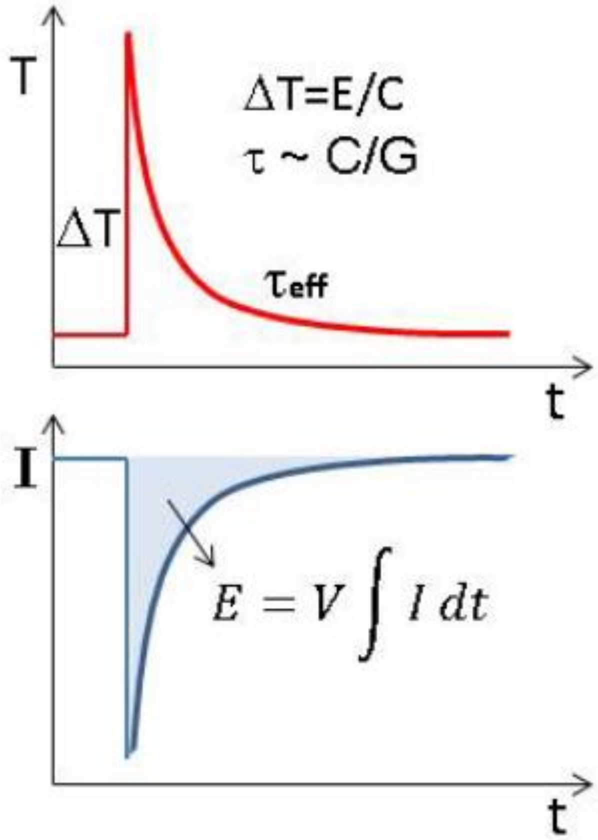
A TES is a superconducting thin film





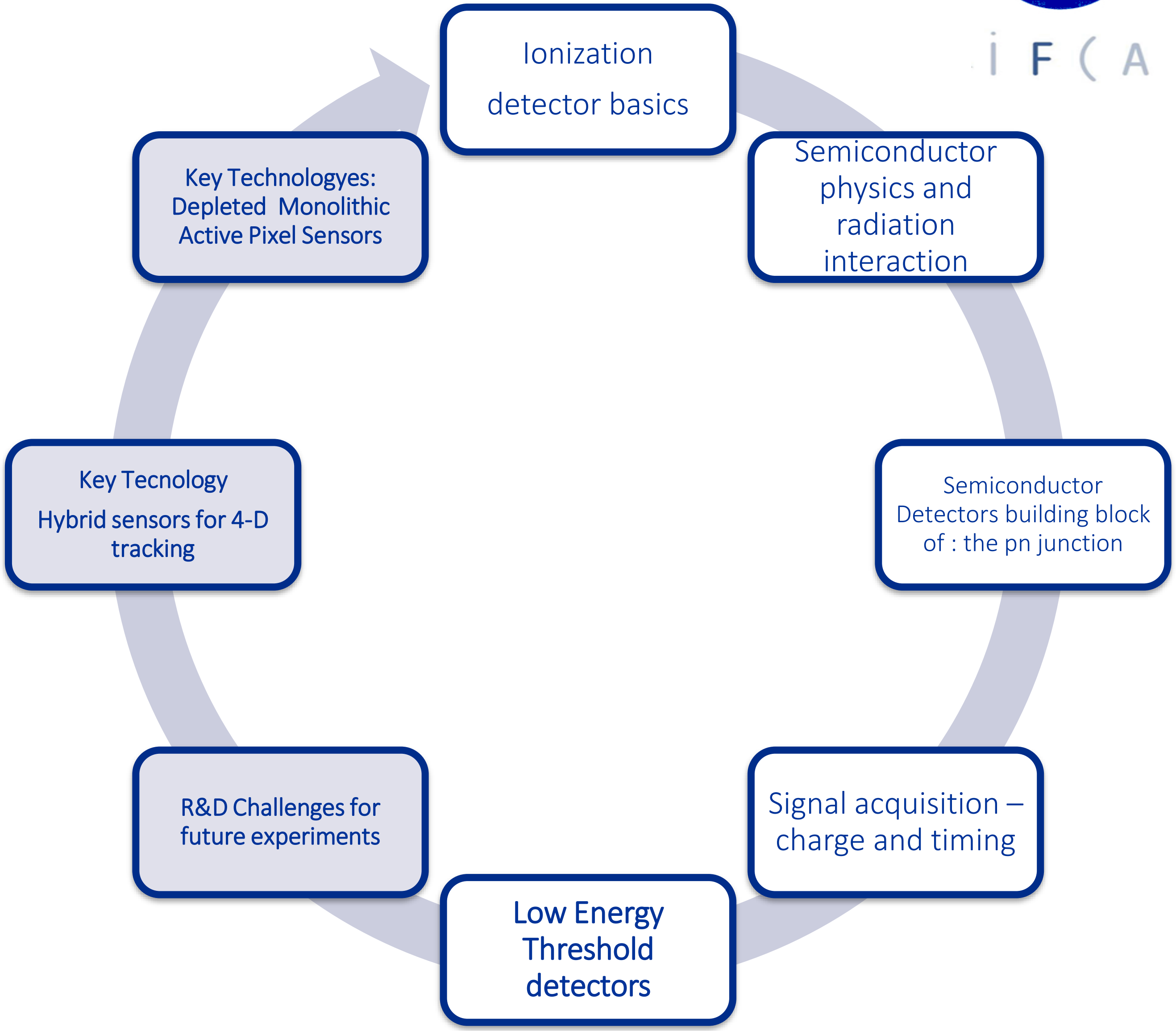
$T_{bath} < T_{operation} \sim T_c$

$T_{bath} \sim 0.5 T_c$

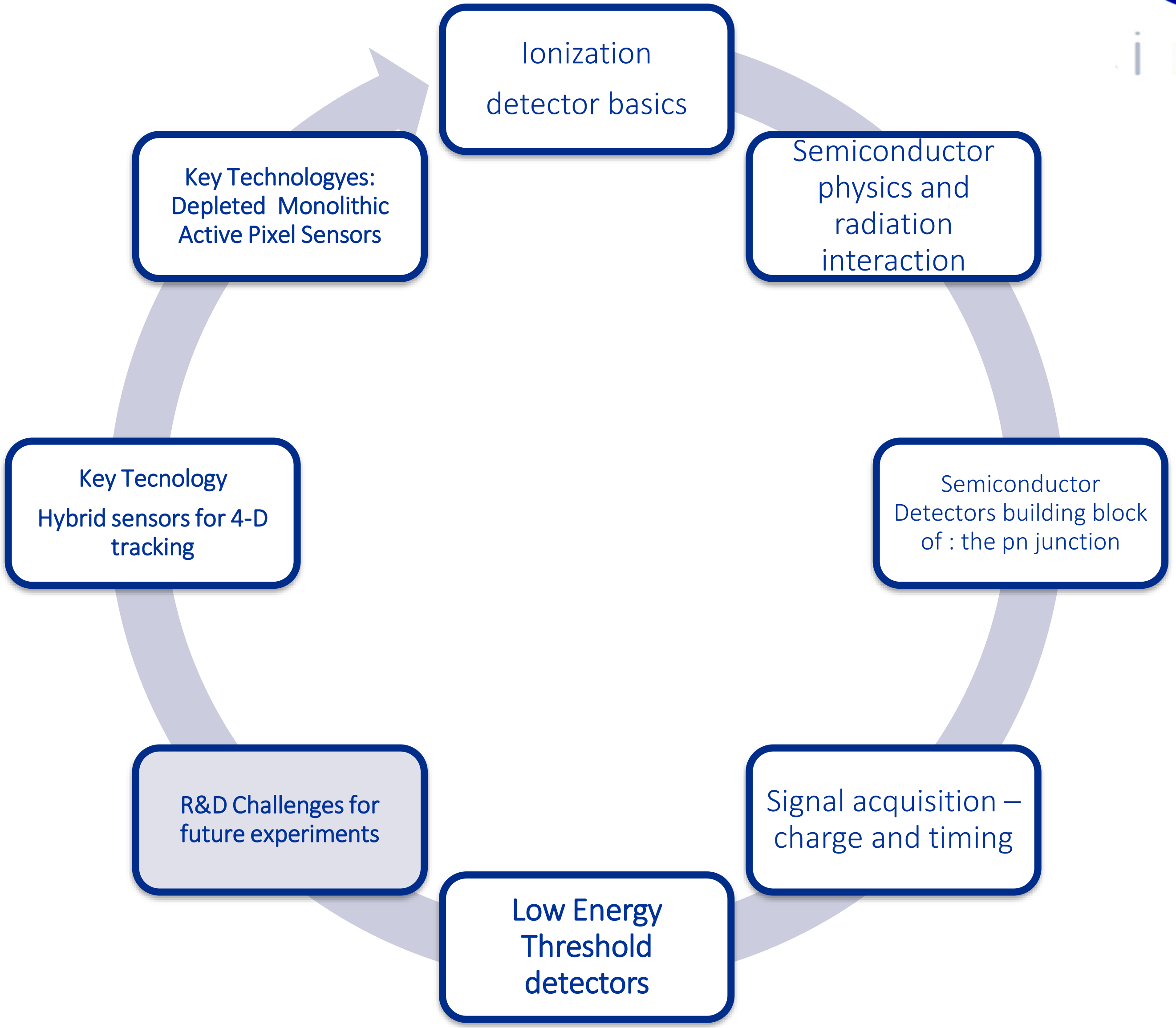


PART 2

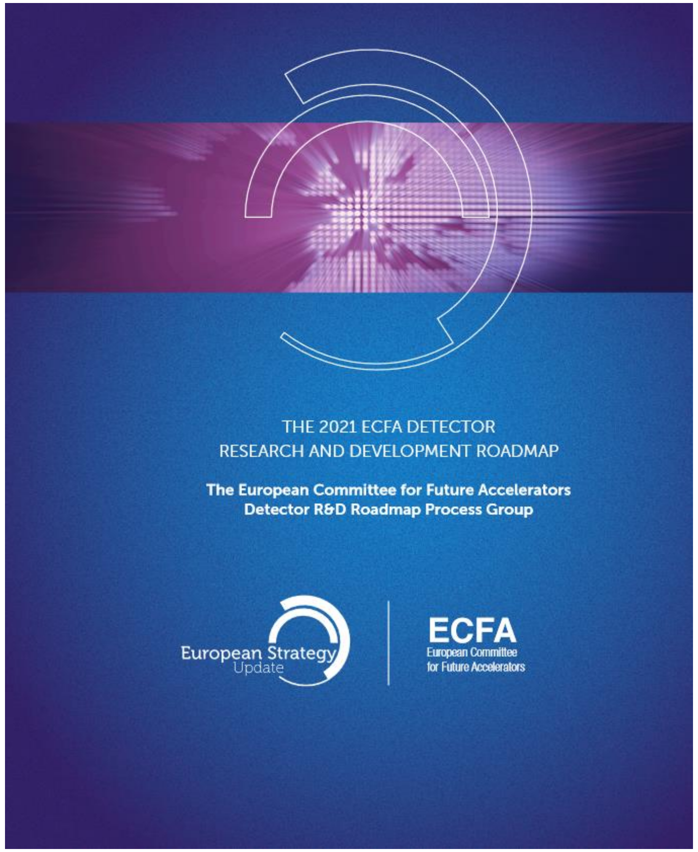
R&D challenges and Review of Key Technologies



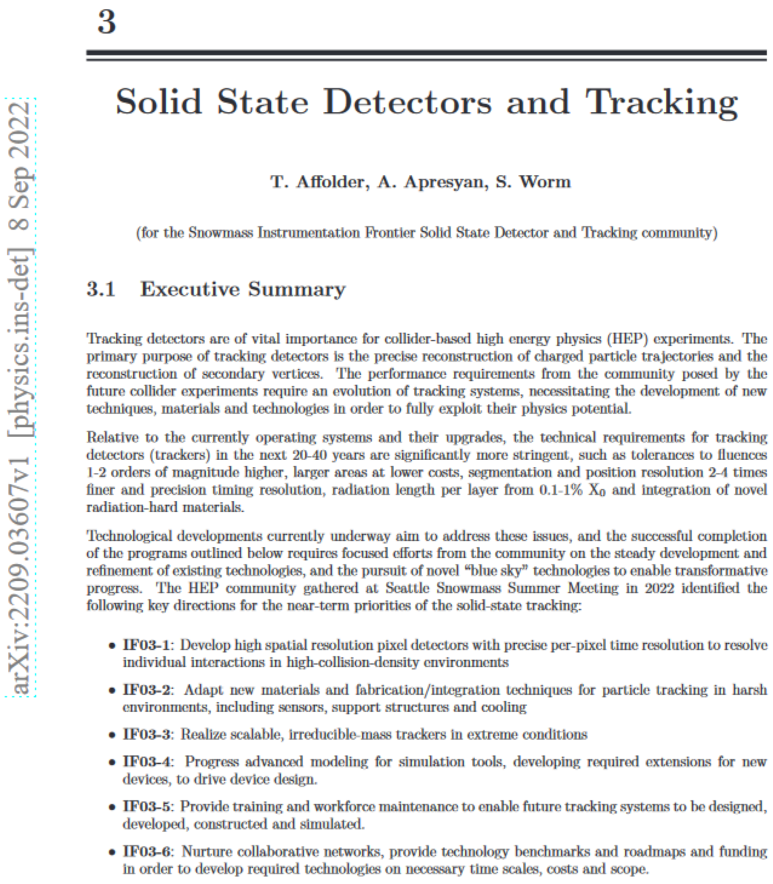
R&D Challenges



R&D Challenges: the R&D detectors roadmaps (EU Strategy and Snowmass 2021)



https://cds.cern.ch/record/2784893/files/ECFA%20Detector%20R&D%20Roadmap.pdf



arXiv:2209.03607v1 [physics.ins-det] 8 Sep 2022

3

Solid State Detectors and Tracking

T. Affolder, A. Apresyan, S. Worm

(for the Snowmass Instrumentation Frontier Solid State Detector and Tracking community)

3.1 Executive Summary

Tracking detectors are of vital importance for collider-based high energy physics (HEP) experiments. The primary purpose of tracking detectors is the precise reconstruction of charged particle trajectories and the reconstruction of secondary vertices. The performance requirements from the community posed by the future collider experiments require an evolution of tracking systems, necessitating the development of new techniques, materials and technologies in order to fully exploit their physics potential.

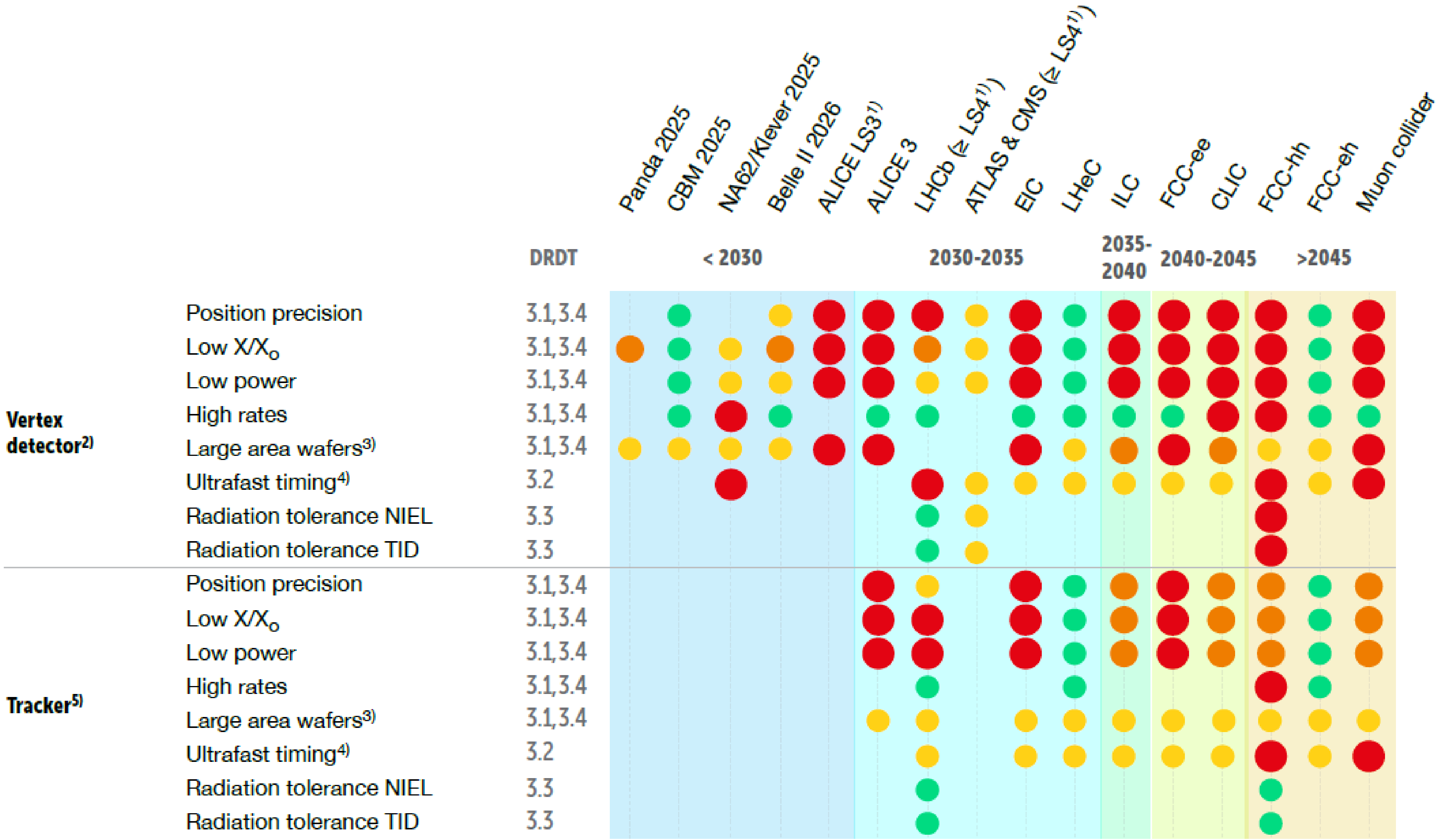
Relative to the currently operating systems and their upgrades, the technical requirements for tracking detectors (trackers) in the next 20-40 years are significantly more stringent, such as tolerances to fluences 1-2 orders of magnitude higher, larger areas at lower costs, segmentation and position resolution 2-4 times finer and precision timing resolution, radiation length per layer from 0.1-1% X_0 and integration of novel radiation-hard materials.

Technological developments currently underway aim to address these issues, and the successful completion of the programs outlined below requires focused efforts from the community on the steady development and refinement of existing technologies, and the pursuit of novel "blue sky" technologies to enable transformative progress. The HEP community gathered at Seattle Snowmass Summer Meeting in 2022 identified the following key directions for the near-term priorities of the solid-state tracking:

- **IF03-1**: Develop high spatial resolution pixel detectors with precise per-pixel time resolution to resolve individual interactions in high-collision-density environments
- **IF03-2**: Adapt new materials and fabrication/integration techniques for particle tracking in harsh environments, including sensors, support structures and cooling
- **IF03-3**: Realize scalable, irreducible-mass trackers in extreme conditions
- **IF03-4**: Progress advanced modeling for simulation tools, developing required extensions for new devices, to drive device design.
- **IF03-5**: Provide training and workforce maintenance to enable future tracking systems to be designed, developed, constructed and simulated.
- **IF03-6**: Nurture collaborative networks, provide technology benchmarks and roadmaps and funding in order to develop required technologies on necessary time scales, costs and scope.

http://dx.doi.org/10.48550/arXiv.2209.03607

A long list of R&D Tasks targeting future collider experiments



A long list of R&D Tasks targeting future collider experiments (2)

		DRDT	Panda 2025	CBM 2025	NA62/Klever 2025	Belle II 2026	ALICE LS3[1)]	ALICE 3	LHCb (≥ LS4[1)])	ATLAS & CMS (≥ LS4[1)])	EIC	LHeC	ILC	FCC-ee	CLIC	FCC-hh	FCC-eh	Muon collider
			< 2030					2030-2035					2035-2040	2040-2045		>2045		
Calorimeter[6)]	Position precision	3.1,3.4																
	Low X/X_o	3.1,3.4																
	Low power	3.1,3.4					yellow				yellow	orange	orange	orange	orange	orange	orange	orange
	High rates	3.1,3.4														red		
	Large area wafers[3)]	3.1,3.4					yellow				red	red	red	red	red	red	red	red
	Ultrafast timing[4)]	3.2										yellow	yellow	yellow	yellow	red	yellow	red
	Radiation tolerance NIEL	3.3														red		
	Radiation tolerance TID	3.3														red		
Time of flight[7)]	Position precision	3.1,3.4				yellow		yellow		yellow	yellow	yellow		yellow			yellow	
	Low X/X_o	3.1,3.4				yellow		yellow		yellow	yellow	yellow		yellow			yellow	
	Low power	3.1,3.4				yellow		yellow		yellow	yellow	yellow		yellow			yellow	
	High rates	3.1,3.4																
	Large area wafers[3)]	3.1,3.4				yellow		yellow		yellow	yellow			yellow				
	Ultrafast timing[4)]	3.2				red		red		yellow	red	red		orange			red	
	Radiation tolerance NIEL	3.3								yellow								
	Radiation tolerance TID	3.3								yellow								

red: Must happen or main physics goals cannot be met; orange: Important to meet several physics goals; yellow: Desirable to enhance physics reach; green: R&D needs being met

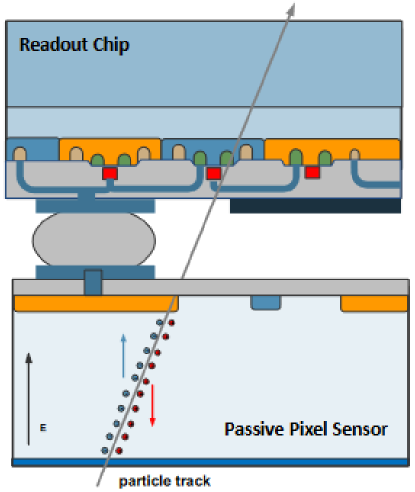
Detector R&D Themes (DRDTs) from ECFA Road Map

Solid state	**DRDT 3.1**	Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors
	DRDT 3.2	Develop solid state sensors with 4D-capabilities for tracking and calorimetry
	DRDT 3.3	Extend capabilities of solid state sensors to operate at extreme fluences
	DRDT 3.4	Develop full 3D-interconnection technologies for solid state devices in particle physics

– In the next slides I will briefly review the current R&D with emphasis in the first two Themes.

R&D Challenges: Path to Large detectors and high-precision tracking

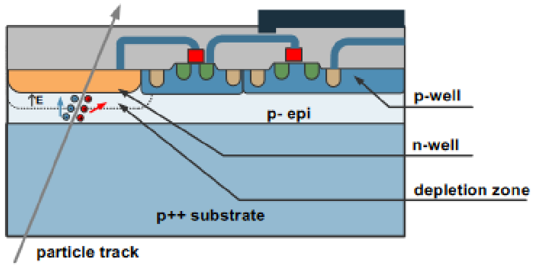
I. Hybrid detector



✓
- Optimized dedicated sensor ➞ high radiation tolerance

✗
- Labor and cost intensive bump-bonding

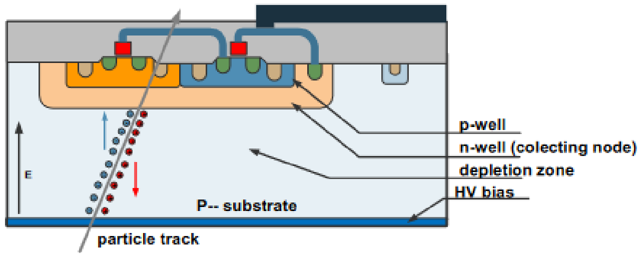
II. MAPS detector



✓
- Reduced material budget
- Lower module cost
- Larger wafers, throughput
- Fast turn-around time

✗
- The sensor volume is not fully depleted: Limited radiation tolerance

III. Depleted MAPS (DMAPS) detector

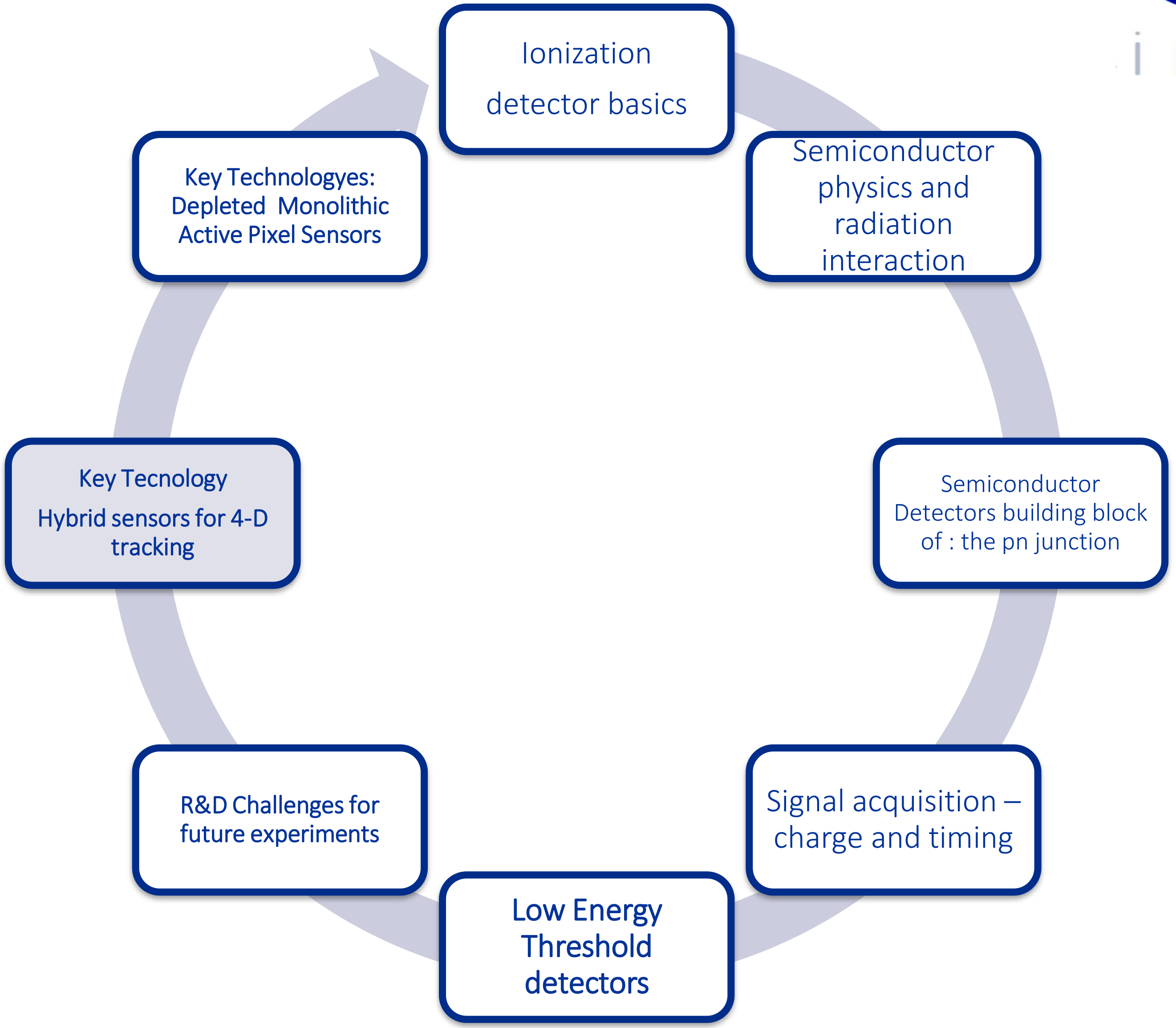


- CMOS processes offering high resistivity substrate (HR)
- High voltage biasing (HV)
- $d \sim \sqrt{\rho \cdot V}$

⇓

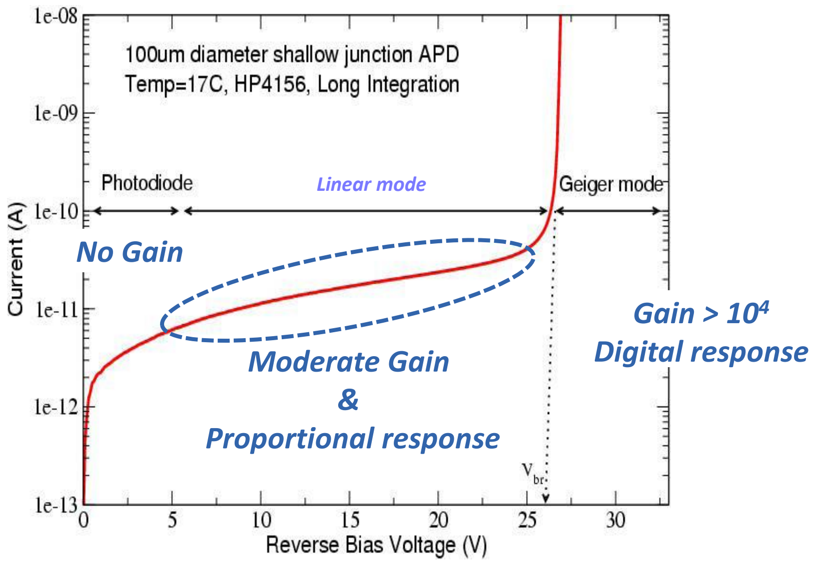
✓
- Strong drift field
- Enhanced charge collection & radiation tolerance
- Faster charge collection

Key Technologies:
Hybrid sensors for 4-D tracking

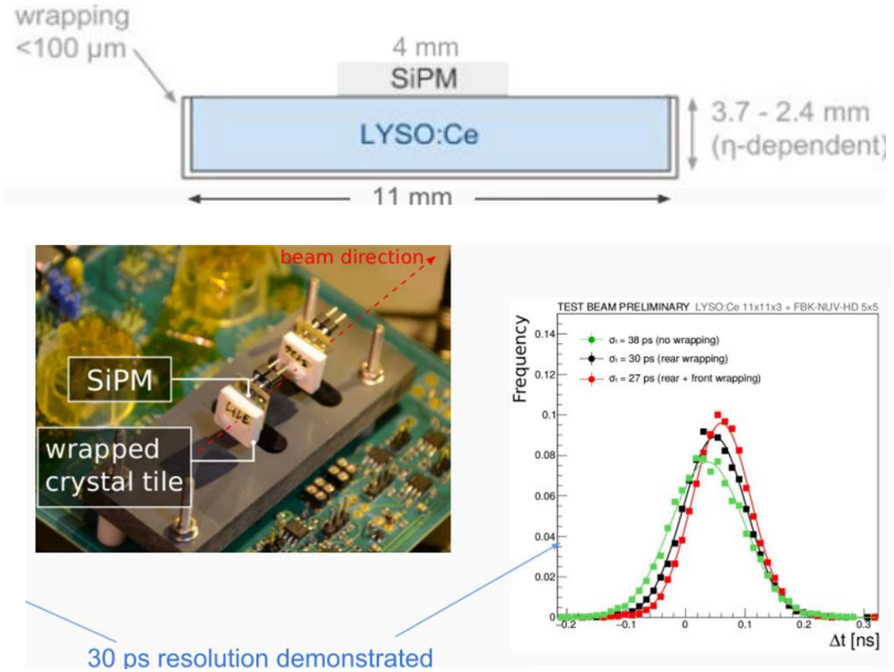


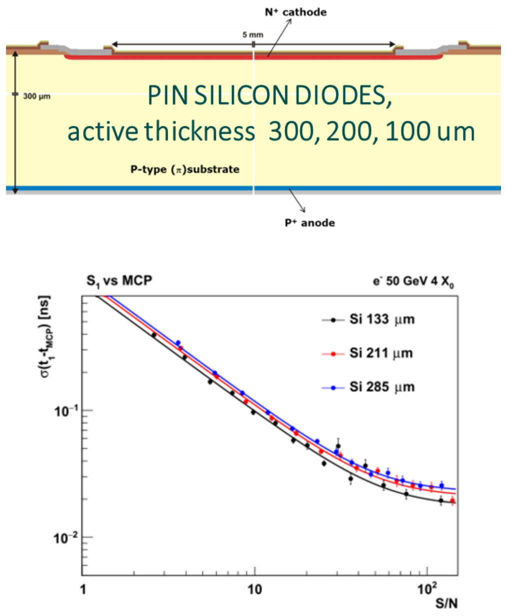
Silicon sensors as enabling sensing technology for 4D tracking ?

- Silicon-based diodes provide both **fast rise time and relatively large signal/noise ratio.**
- Well **stablished high-precision tracking technology** (electrode patterning)
- Three operating modes: no signal gain (**PIN**), proportional (**APD**) and Geiger mode (**SiPMT**).



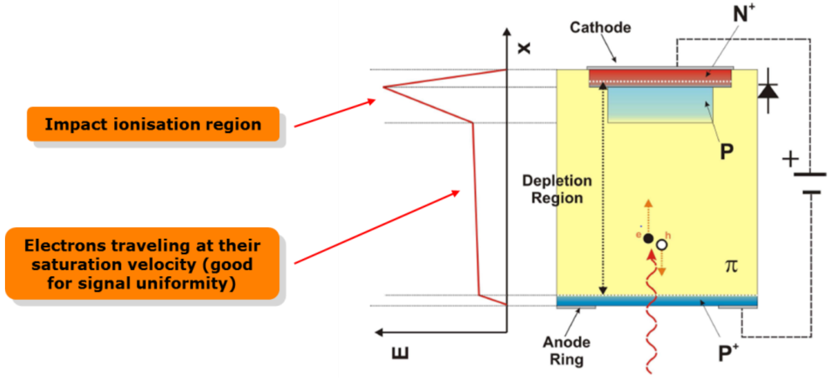
[1] A.G. Stewart et al. in Proc. of SPIE, Vol. 6119, 2006



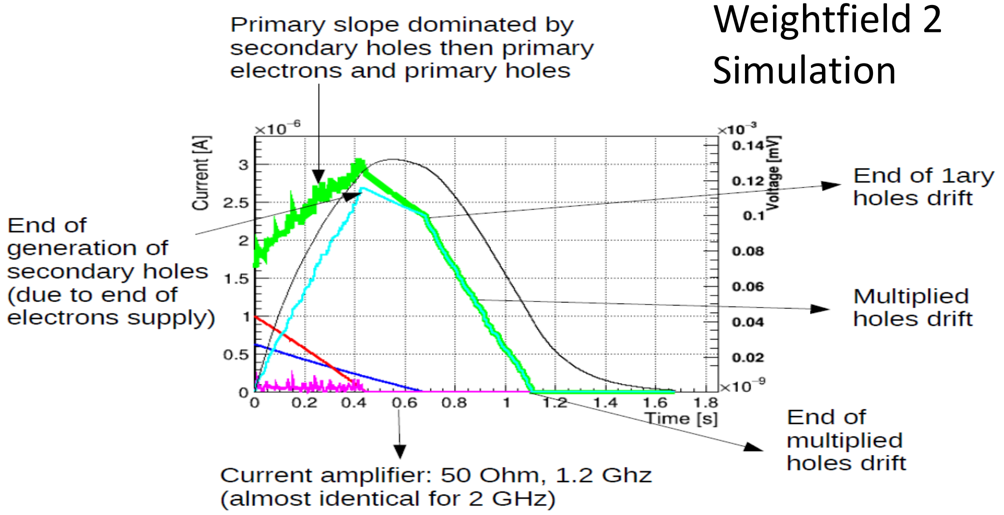


Avalanche mode diode (Low Gain Avalanche Detector LGAD) :

- Proportional multiplication mode (impact ionization of primary carriers)
- Main advantage: custom SNR for optimal for timing and tracking (introduced by IMB-CNM)



Weightfield 2 Simulation



LGAD have a larger rise-time (collecting time of primary electrons) than PIN (all carriers ballistic movement).

⇒ Go thinner to reduce the collecting time of the primary electrons and make $t_{rs} << t_{ra}$

LGAD **SNR** better than PIN due to gain

⇒ Taylor the gain for optimal jitter with respect to the intrinsic time resolution limit

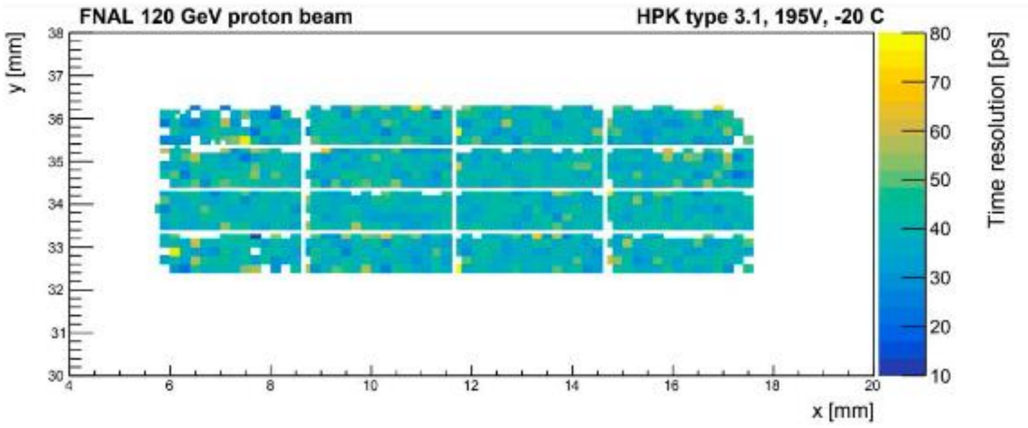
LGAD for HL-LHC timing layers (status report in nutshell)

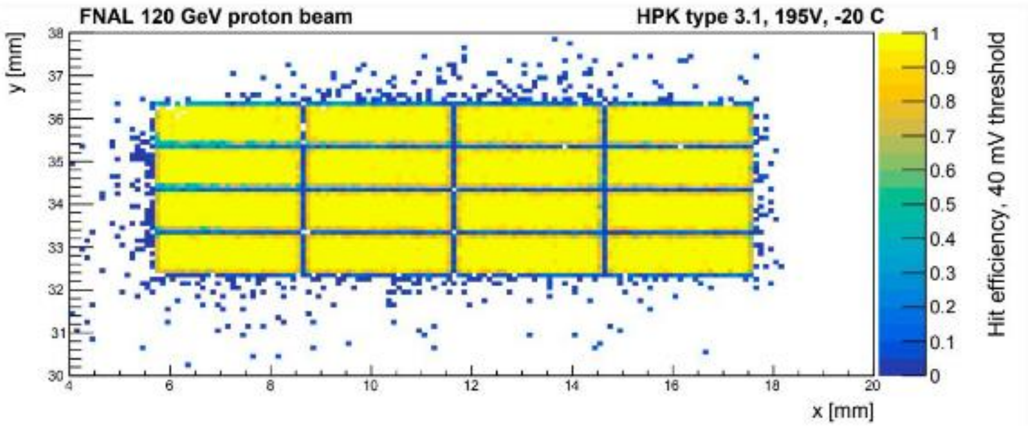
- Provide about 30ps MIP time stamping for disentangling between the different interaction vertices.
- LGAD is the baseline technology of the endcap MIP timing detector for the HL upgrade of Atlas and CMS experiments
- Main challenges (and solutions)
  - **Radiation tolerance to (mostly) neutrons and protons:**
    - **Damage Mechanisms:** primary carriers trapping, acceptor deactivation, mean-free-path reduced, electric field modification,
    - **Solutions:** Thin bulk (higher electric field), co-doping with Carbon (suppression of the acceptor removal mechanism), deep multiplication layer.
    - **Current status:** radiation tolerance up to 2.5 e15 n/cm2 achieved.
  - **Long-term reliability:**
    - **Damage mechanism: very rare highly ionizing events induce fatal diode breakdown (also in PINs @ very high HV)**
    - **Solution: limited average E field (< 11V/um).**
    - **Current status: fatal damage mechanism understood and implementation of maximum voltage bias.**
  - Large scale **manufacturing yield (99.8% of good pad achieved by HPK in recent manufacturing runs).**
  - Increase **fill-factor and increase the granularity** ← Next of the talk

The fill factor issue

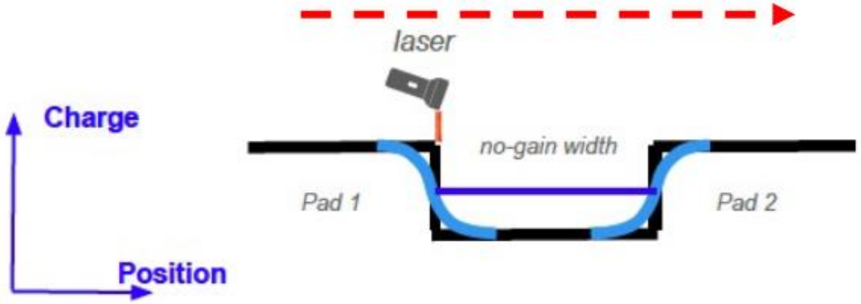
Time resolution uniformity,
$\sigma_t \sim$ **40 ps** all across the sensor active area

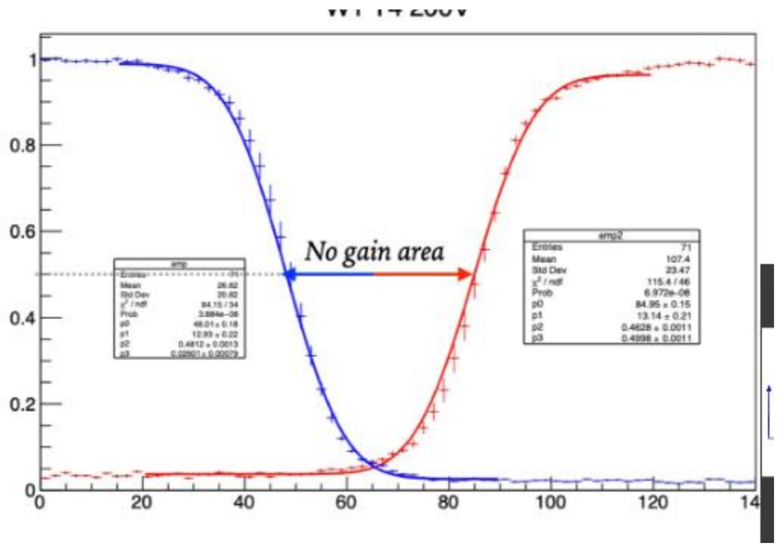
Hit efficiency uniformity ~ **100%**





1D scan along the optical window



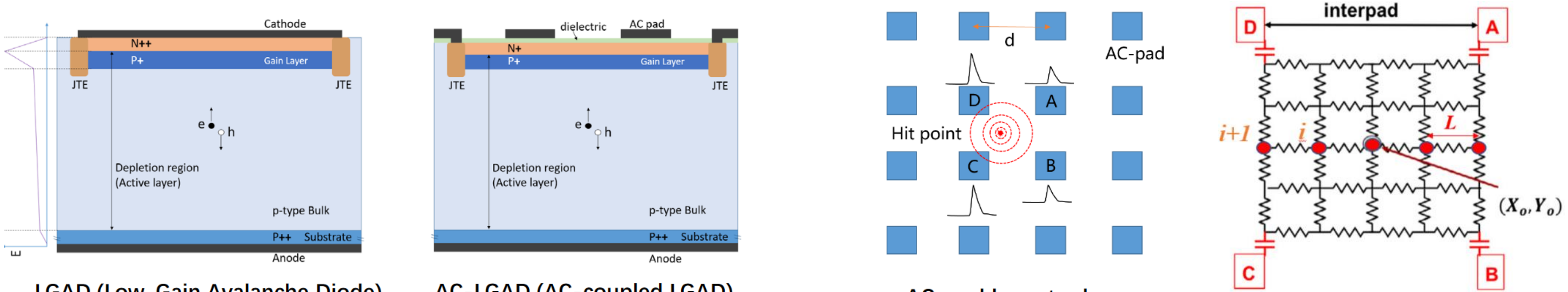


Towards a LGAD-based 4D tracking enabling sensor

– Several technologies for improving the spatial resolution and increased fill factor:
  - Resistive AC-Coupled LGADs (**AC- (RSD)-LGADs**)
    (First manufacturing run from FBK; new foundries joining IHEP, BNL, HPK, etc.)
  - Trench-isolated LGADs (**TI-LGAD**)
    (first manufacturing run from FBK)
  - Trenched Inverse Low Gain Avalanche detectors (Trenched-**iLGAD**)
    (Production in progress at IMB-CNM)
  - Deep Junction Low Gain Avalanche detectors (**DJ-LGAD**)
    (first manufacturing from BNL)

Resistive AC-Coupled Silicon Detectors

- 2D Resistive AC coupled readout in LGAD introduced by FBK (M. Mandurrino et al., IEEE Electron Device Lett. 40(11) (2019) pp.1780-1783.):
  - Non-segmented LGAD gain layer; segmented electrode on top of a dielectric layer.



LGAD (Low-Gain Avalanche Diode)   AC-LGAD (AC-coupled LGAD)   AC-pad layout scheme

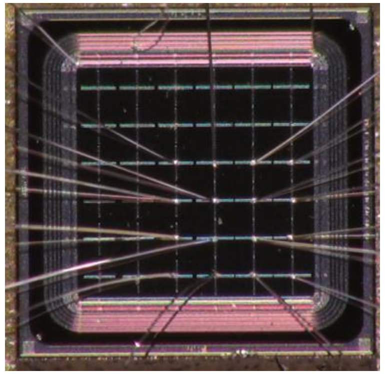
Mengzhao Li, 39th RD50 Workshop, Nov 2021

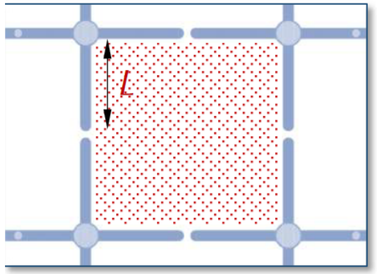
- Hit position reconstruction algorithm based on charge sharing among the electrodes (Smarter ML algorithms possible) achieve sub-pitch hit resolution figures.
- Timing resolution improved by multiple electron readout. Not as simple as sqrt of # of electrodes improvement due to correlations)
- Advantages:
  - 100% fill factor
  - high spatial resolution for large pitch devices.
- Limitations:
  - Hits on top of the electrode with do not have charge sharing (resolution degraded to the electrode size).
  - Maximum hit occupancy one hit / electrode pitch.
  - Bipolar front-end readout ballistic deficit, current reconstruction algorithm based on pulse amplitude.

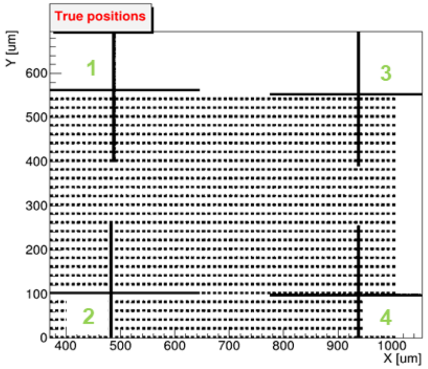
Resistive AC-Coupled Silicon Detectors (3)

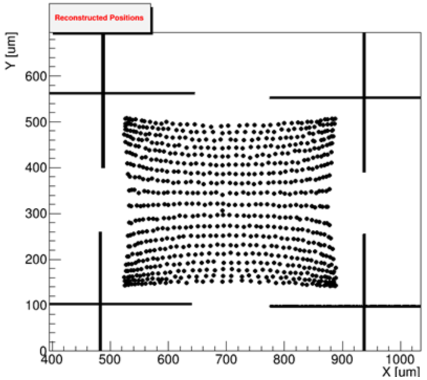
– Moving beyond the current technology limitations: trade off between signal detection efficiency and electrode area.

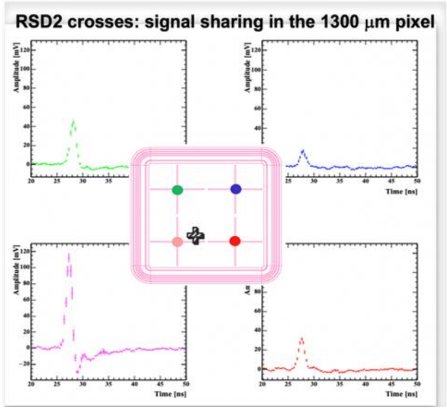
L Menzio
18th Trento Workshop on Advanced Silicon Radiation Detectors

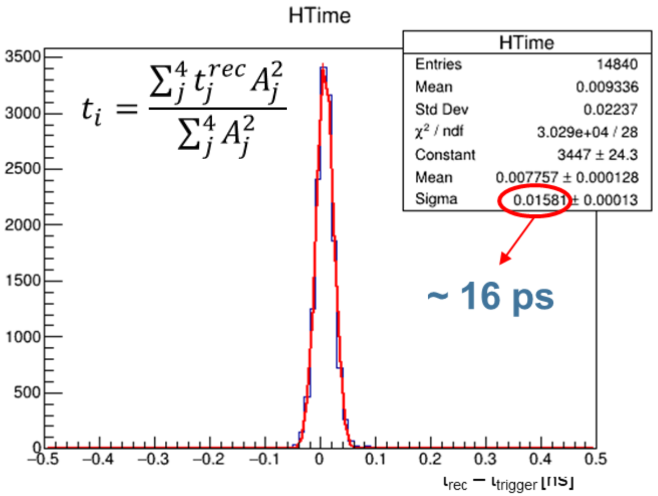






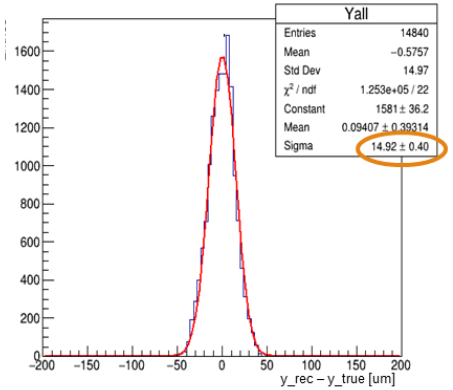






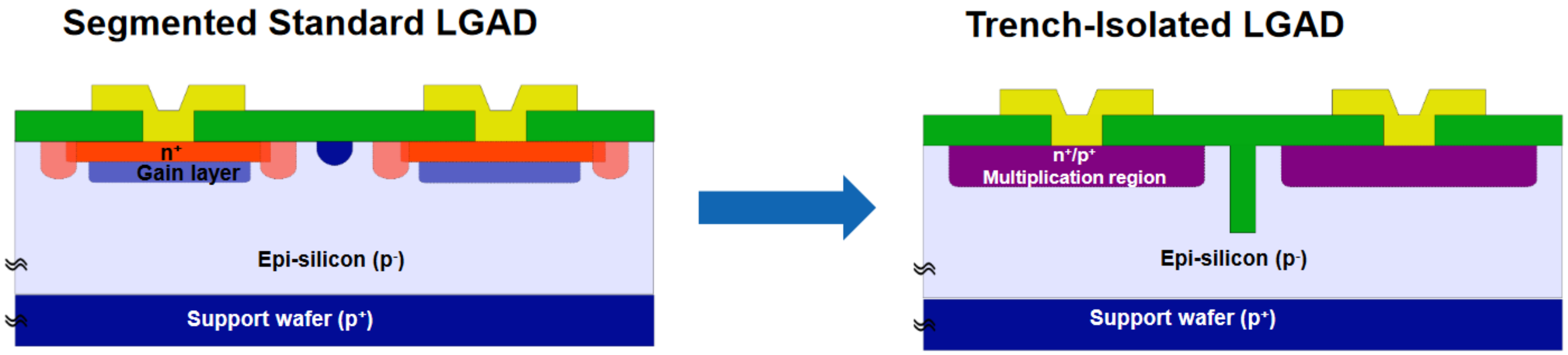
$$x_i = x_{center} + k_x \frac{pitch}{2} \frac{A_3 + A_4 - (A_1 + A_2)}{\sum A_j}$$

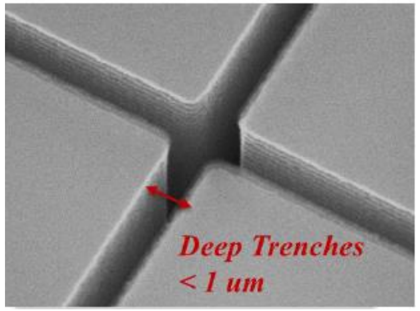
$$y_i = y_{center} + k_y \frac{pitch}{2} \frac{A_1 + A_3 - (A_2 + A_4)}{\sum A_j}$$



15 µm

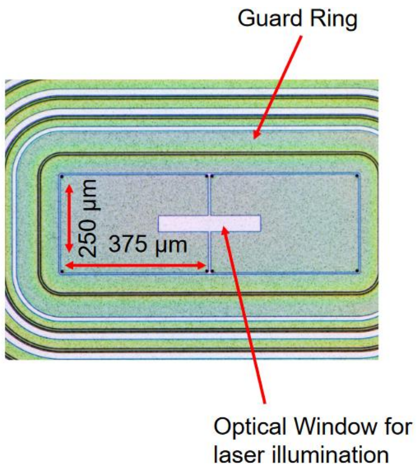
Trench-isolated Low Gain Avalanche detectors (**TI-LGAD**)

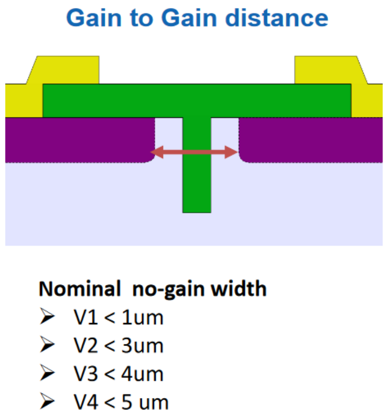


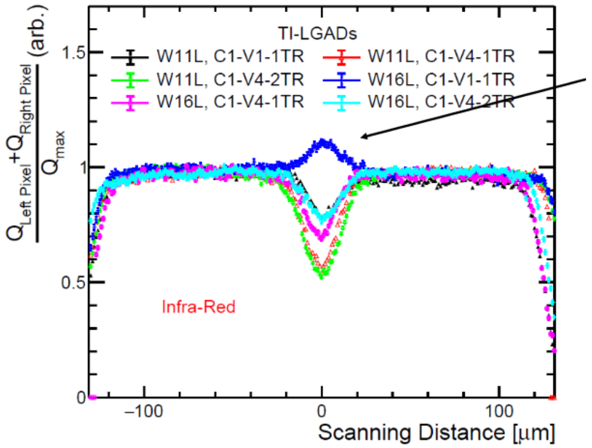


G. Paternoster, 39th RD50 Workshop, Nov 2021

– Pixel border region hosts structures to control E field (JTE, p-stop, etc..)
– Trench isolation could drastically reduce inter-pixel border region down to few μm
  - Typical trench width < 1 μm (max aspect ratio: 1:20)
  - Trench filling with: SiO2, Si3N4, Polysilicon





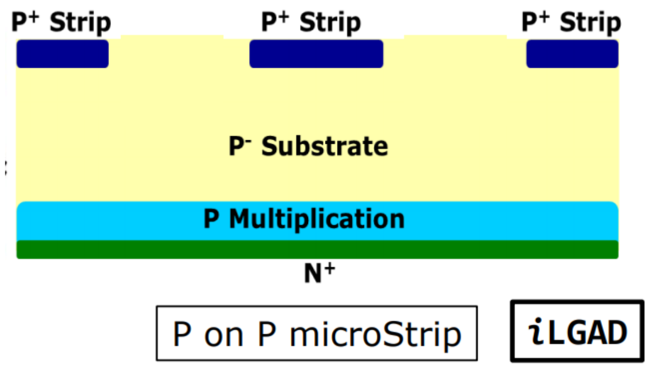


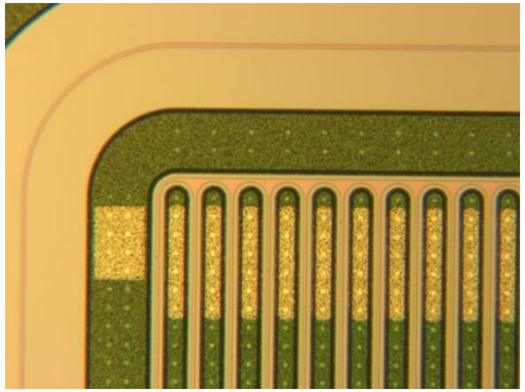
(Thin) Trenched-Inverse LGAD (T-iLGAD)

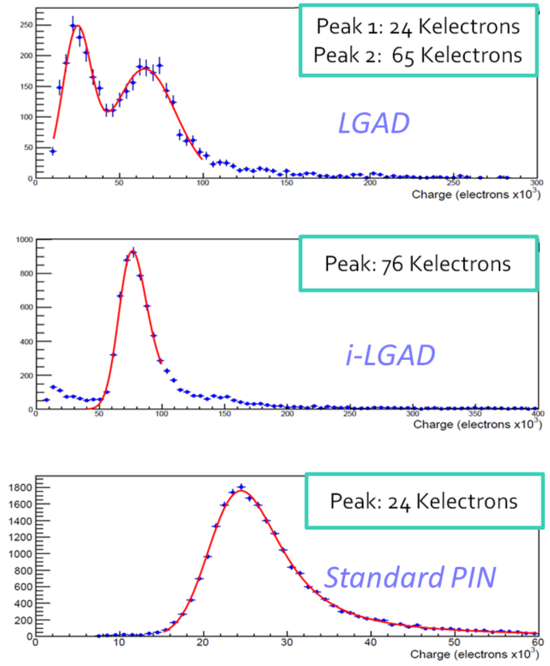
RD50

I. Vila, 13th Trento Workshop, February 2018

- Continuous multiplication layer, segmented hole readout.
- Proof-of-concept from IMB-CNM prototype demostrated at test beam (300um thick and no time readout.).

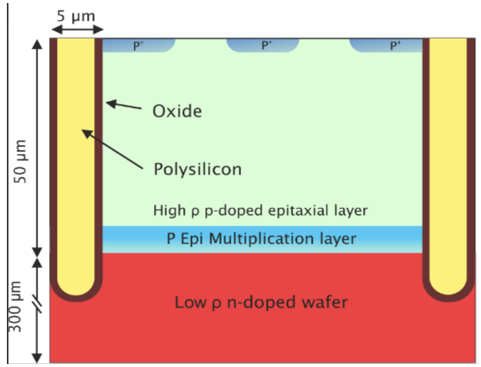


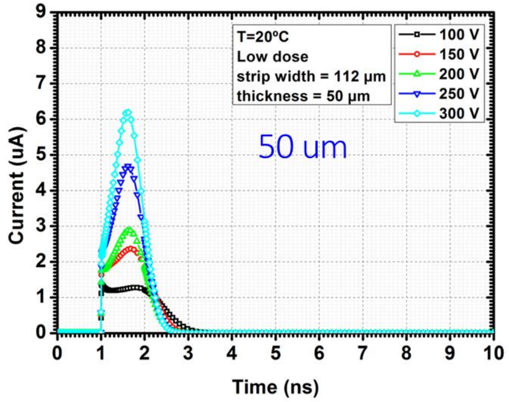




Gain Spatial Uniformity: Collected Charge

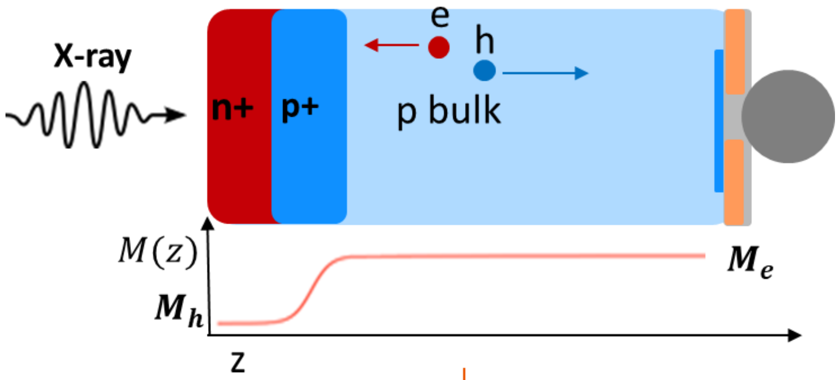
- Thin Single-sided design being manufactured at IMB-CNM





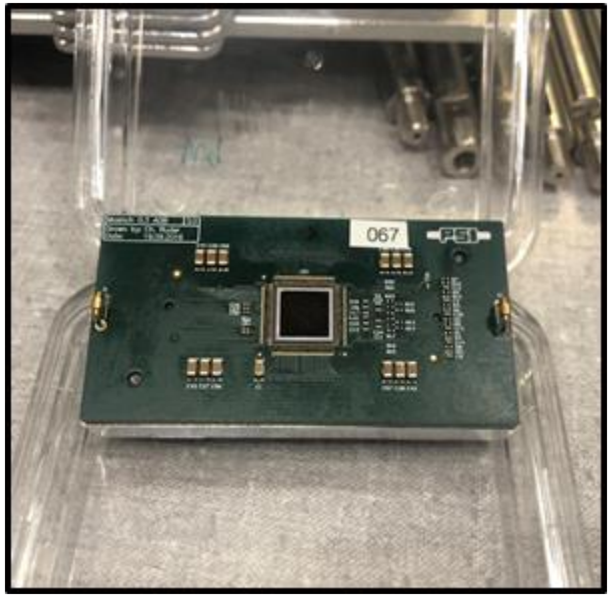
(Thin) Trenched-Inverse LGAD (T-iLGAD) (2)

- **8 iLGAD process splits from FBK**
- 275 μm thick with **different entrance window and gain layer (GL)** designs.
- Measurements at Synchrotron (**SLS**), $E_{ph} \in [200eV, 1keV]$.

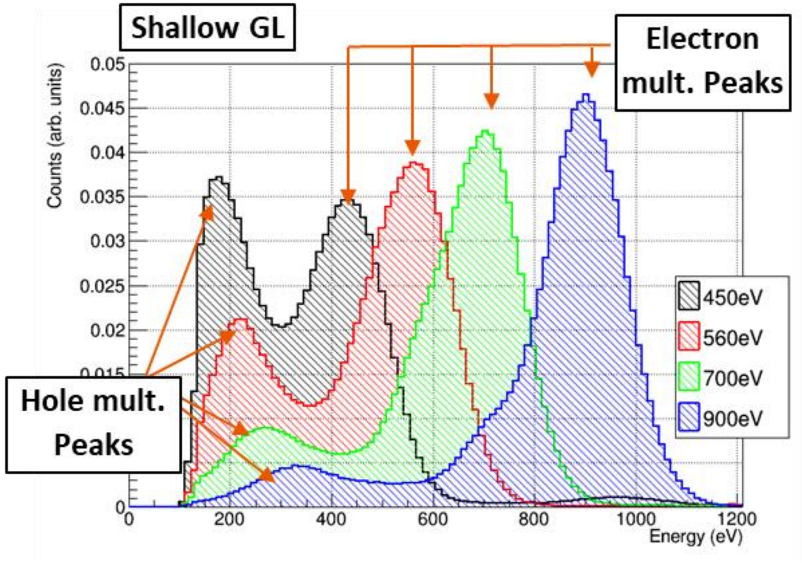


Multiplication factor $M(z)$ **increases from M_h to M_e** with absorption depth z

A Liguori, 18th Trento Workshop, February 2018

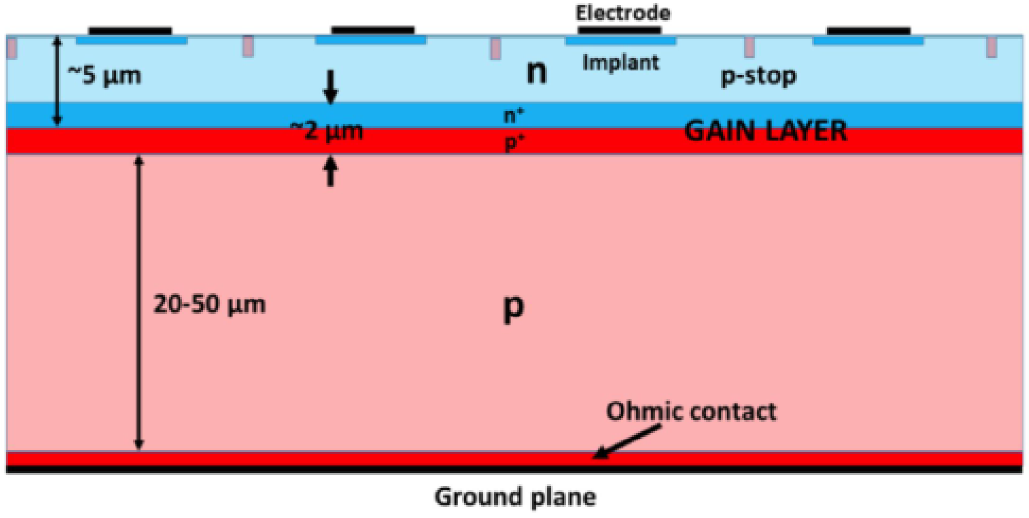


Pixelated iLGADs (25μm pitch) charge integrating Mönch readout

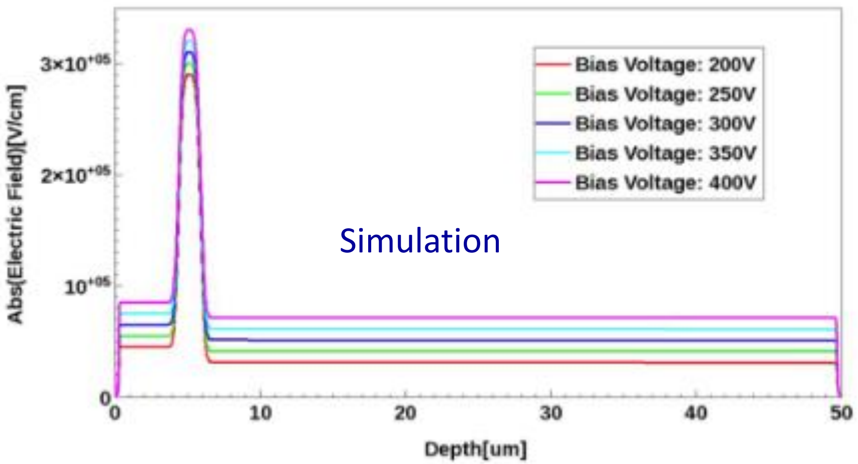


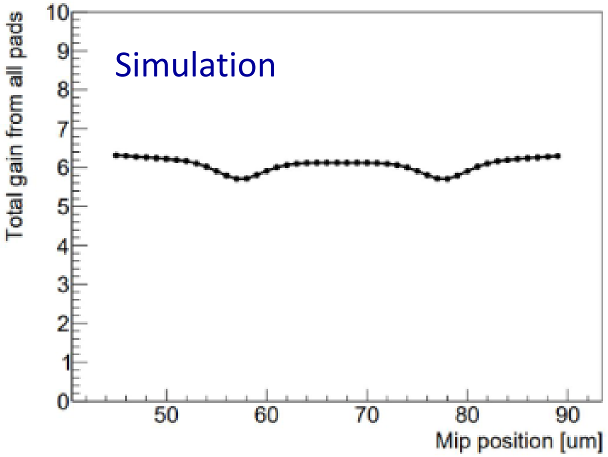
Deep Junction - LGAD

C. Gee, 39th RD50 Workshop, Nov 2021



- Advantageous to bury high p-n junction several um below the surface of the sensor so fields low at surface, allowing conventional granularization
- Electric field in p-n junction is high enough to maintain drift-velocity saturation
- Maintains fine granularity on order of tens of microns
- Preserves direct coupling of signal charge to readout electrodes
- Initial prototype manufacturing at BNL





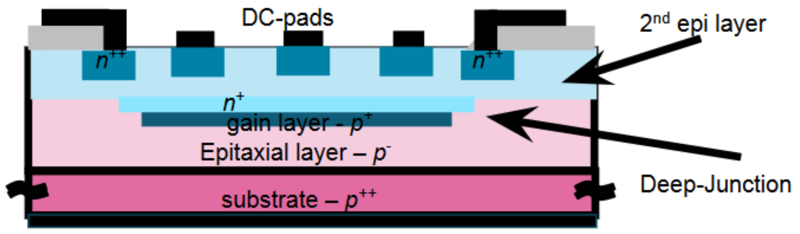
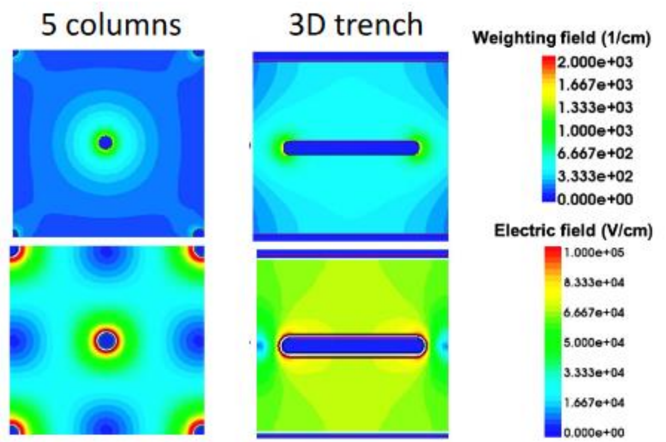


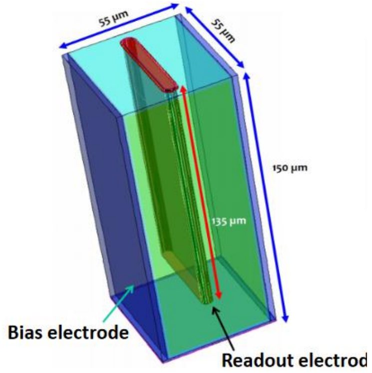
Diagram credit: BNL

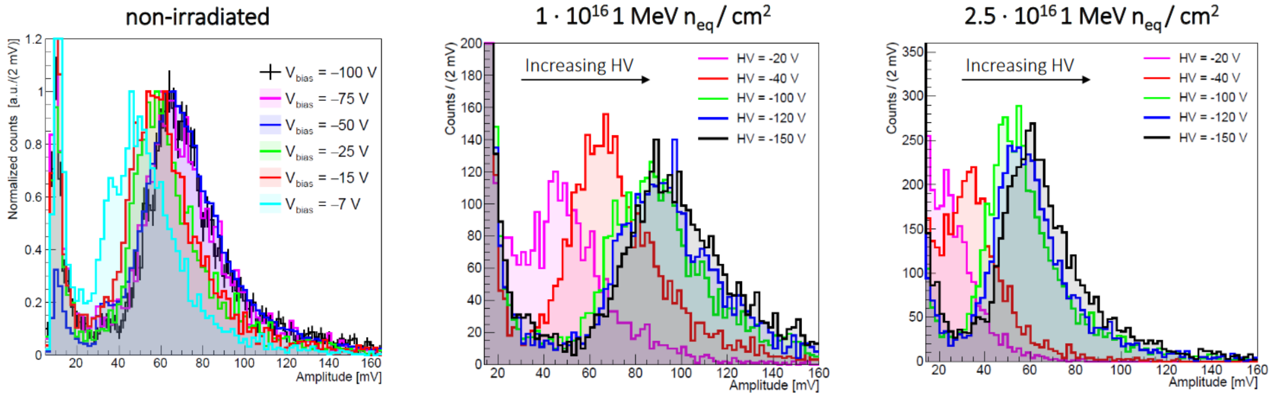
Take home messages

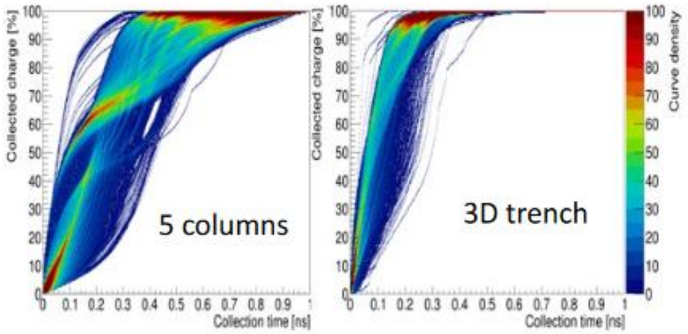
- LGAD (HEP jargon for an APD with moderate gain) is the solution towards:
  - larger SNR (decoupled from the material) for O(10ps) hit resolution
  - O(10um) spatial resolution with fine electrode segmentation and AC coupling
- Many 4D LGAD architectures are under intense R&D.
- The technology is maturing and attracting the interest of major manufacturing companies BUT still a long way to go:
  - Complete proof-of-concept studies.
  - Reliability (long term stability, noise and destructive breakdown)
  - Manufacturing yield?
  - Scalability (larger area sensors) ?
  - Radiation tolerance fine pitch devices?
  - **front-end readout electronics with a relatively high density of readout channels is still to be proven; the power consumption and the corresponding heat disipation could become the showstopper.**
- Other strategies for the implementation of a 4D tracking should be also considered: PIN diodes with special junction geometries (TimeSPOT project) or monolithic CMOS based.

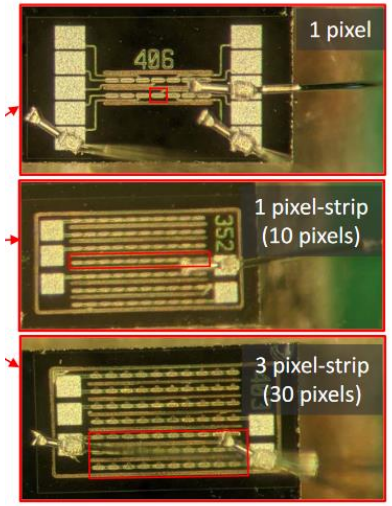
3D-trench sensors: The timespot project

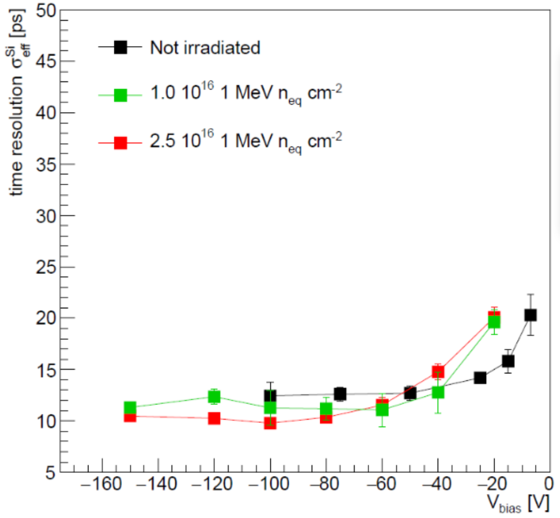




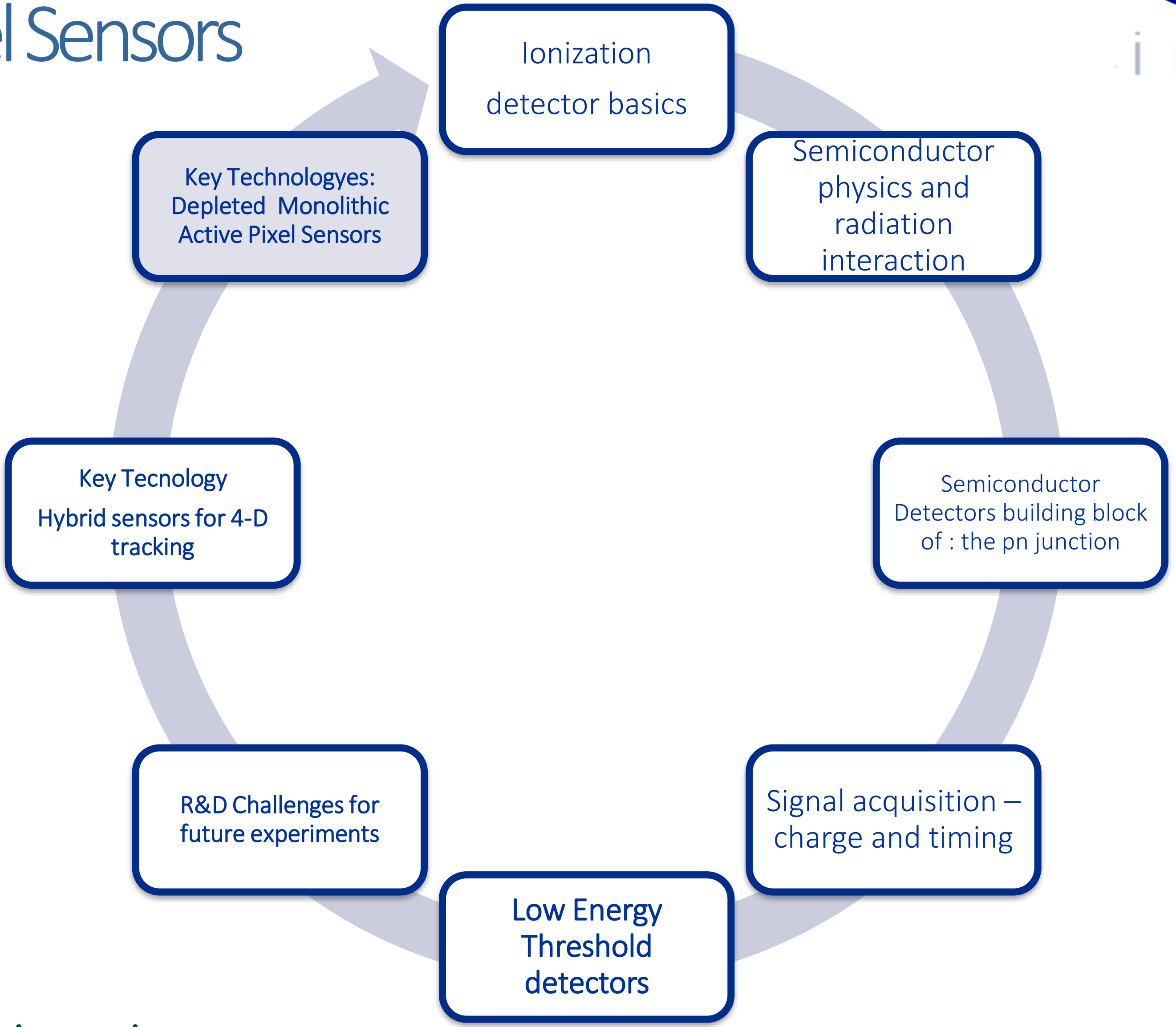








Key Technologies:
Depleted Monolithic Active Pixel Sensors
DMAPS



Thank you to C. Mariñas for his help preparing this section

State-of-the art: vertex detectors in STAR (MAPS) and ALICE (DMAPS)

- ***Monolitic Active Pixel Sensor (MAPS) from digital photography***
  - *Decoupled charge sensing and transfer (replacing CCDs in imaging applications)*
  - *CMOS standard process*
  - *Binary readout of hit pixels*

– High resistivity p-epi layer
  - Reduced charge collection time
  - Improved radiation hardness

– S/N ~ 30

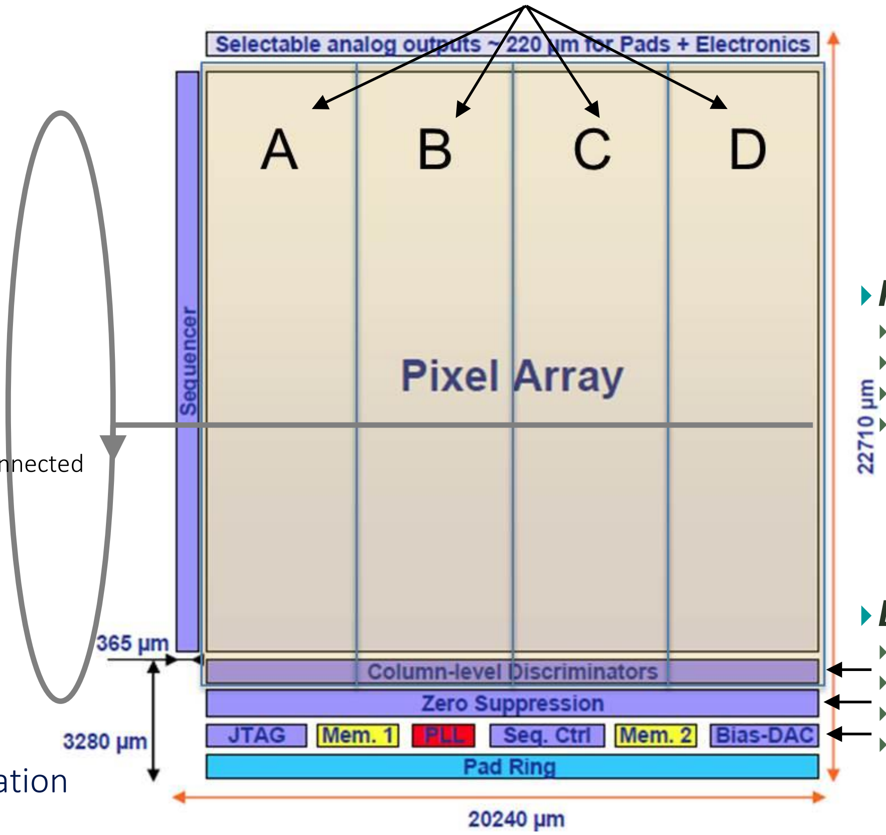
– MIP Signal ~ 1000 e-

– Rolling-shutter type readout
  - A row is selected
  - For each column, a pixel is connected to discriminator
  - Discriminator detects possible hit
  - Move to next row

– 185.6 μs integration time

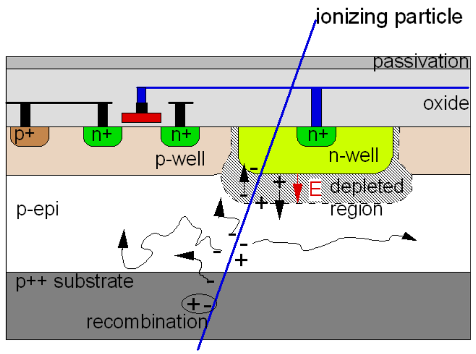
– ~170 mW/cm² power dissipation

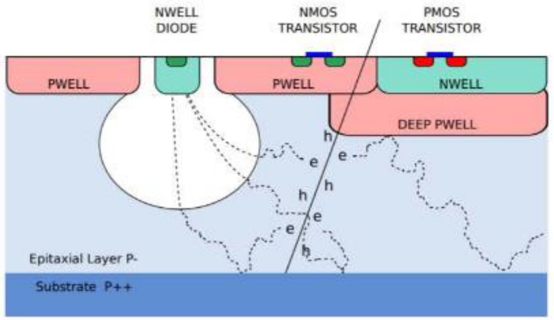
4 sub-arrays to help with process variation



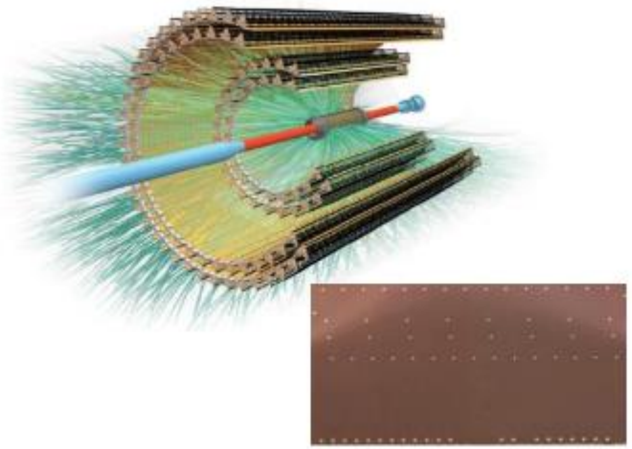
- ***Pixel matrix***
  - *20.7 μm x 20.7 μm pixels*
  - *928 rows x 960 columns = ~1M pixel*
  - *In-pixel amplifier*
  - *In- pixel Correlated Double Sampling (CDS)*

- ***Digital section***
  - *End-of-column discriminators*
  - *Integrated zero suppression (up to 9 hits/row)*
  - *Ping-pong memory for frame readout (~1500 w)*
  - *2 LVDS data outputs @ 160 MHz*





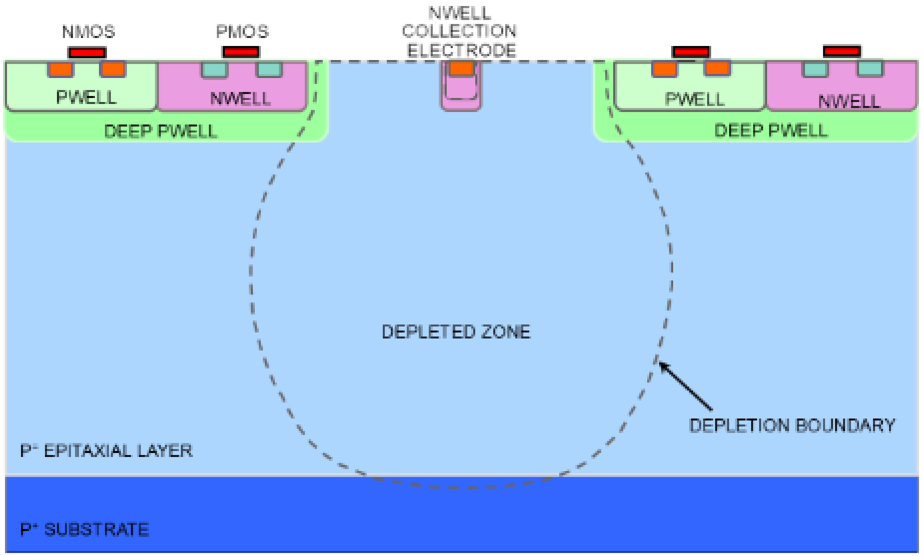
High Resistivity EPI Layer

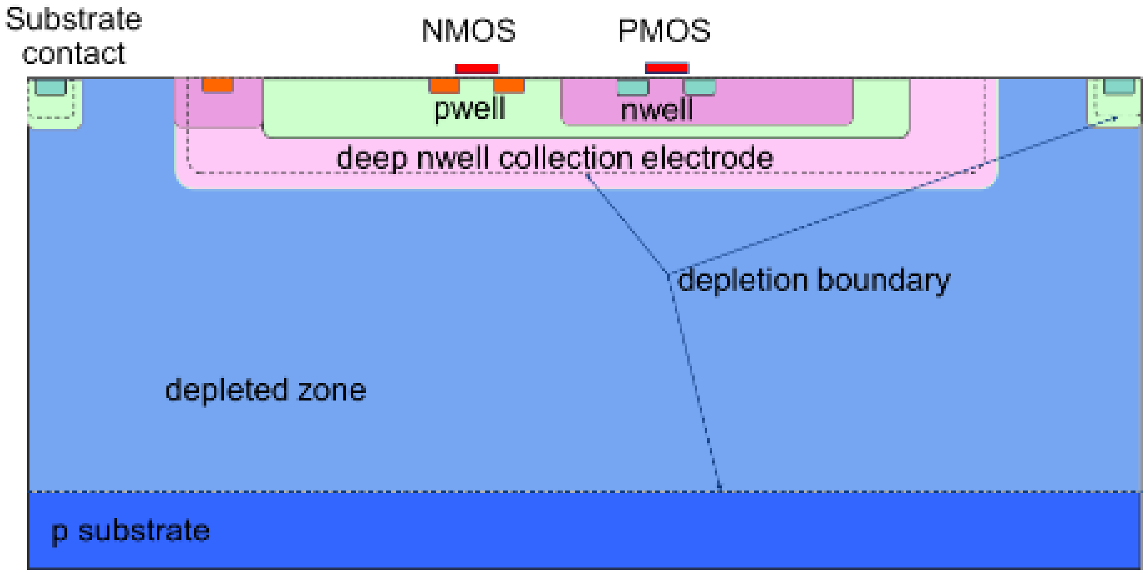


ALPIDE in **ALICE**

First MAPS with sparse readout similar to hybrid sensors

Depleted – MAPS: Large or small collecting electrodes?



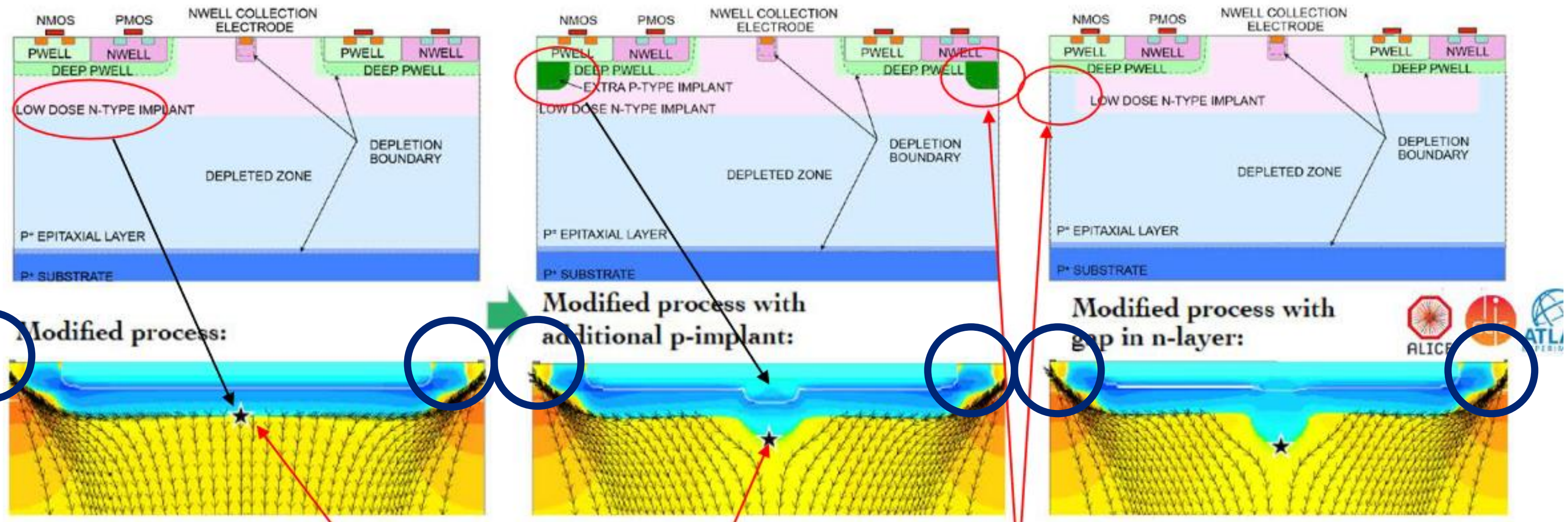


- *Long drift path*
- *Very low C - reduced noise (~10 e- & low power)*
- *Non-uniform weighting field – peaking close to electrode*

  Some adaptions help further (additional low doped deep n-well)
- *E.g. ALPIDE, MALTA, TJ-MONOPIX. CLICTD, FASTPIX*

- Short drift path (faster 'collection')
- High C - higher noise O(100 e-)
- Homogeneous weighting field
- High homogeneous electrical field
- E.g. MUPIX, RD50, MONOLITH, LF-MONOPIX, ATLASPIX

DMAPS: Improved charge collection



Position of the collecting electrodes

charge stacks here

charge pushed sideways

Extra pwell implant or break in blanket deep implant creates later push for carriers

Q: what is not enough?

A: charge drifting upwards get stack under wells with electronics; there is no lateral push to collection nwell

improvement of collection speed, CCE => radiation hardness

Further improvements accepted to TJ 180nm and good results were obtained but 180nm has density limitation => 10 μm pixels difficult

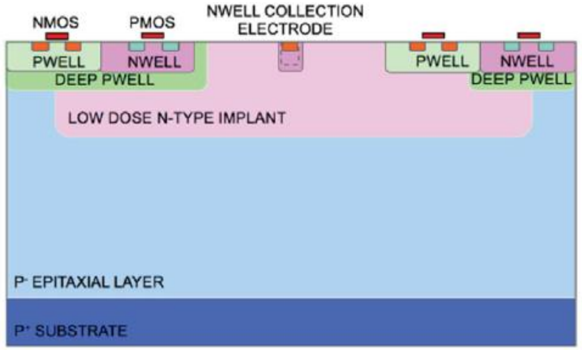
U.S. DEPARTMENT OF ENERGY

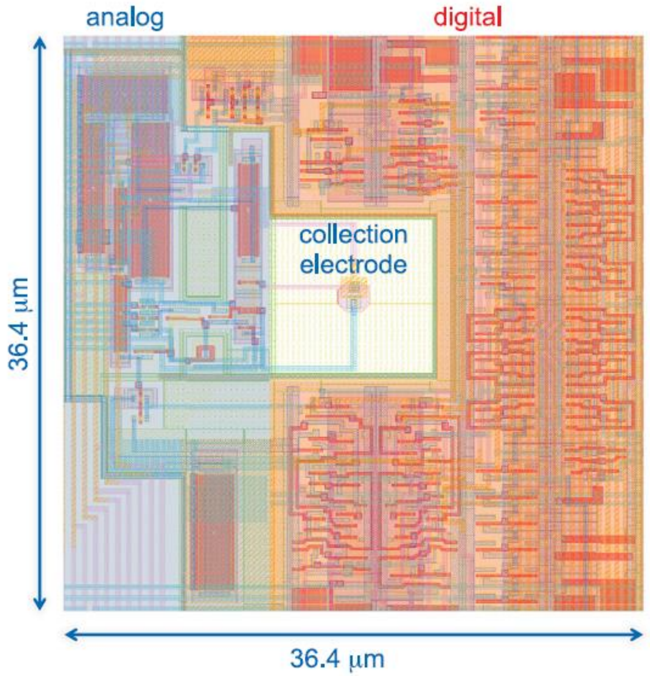
E. Schioppa, et al, VCI 2019
M.Munker, et al. PIXEL2018

BROOKHAVEN NATIONAL LABORATORY

DMAPS: Improved charge collection (2)

https://doi.org/10.1016/j.nima.2020.164381





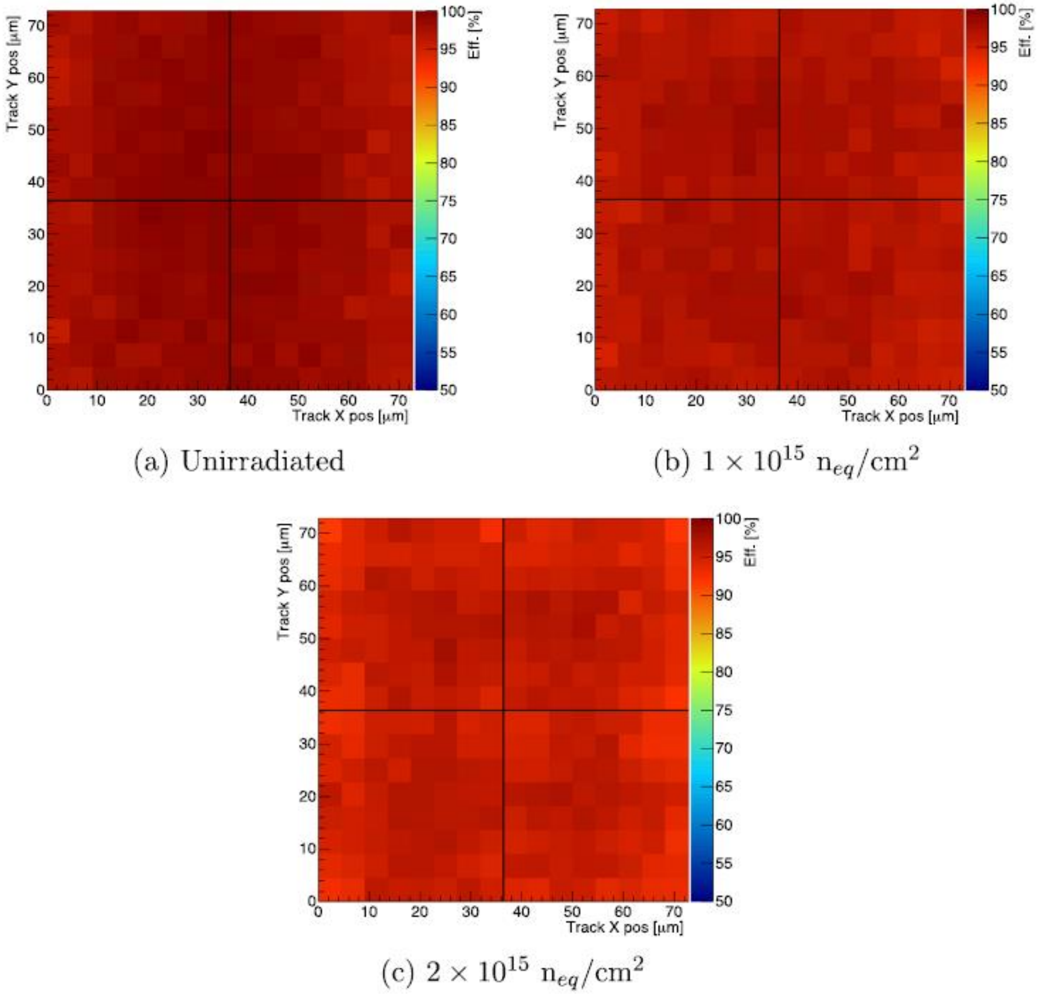
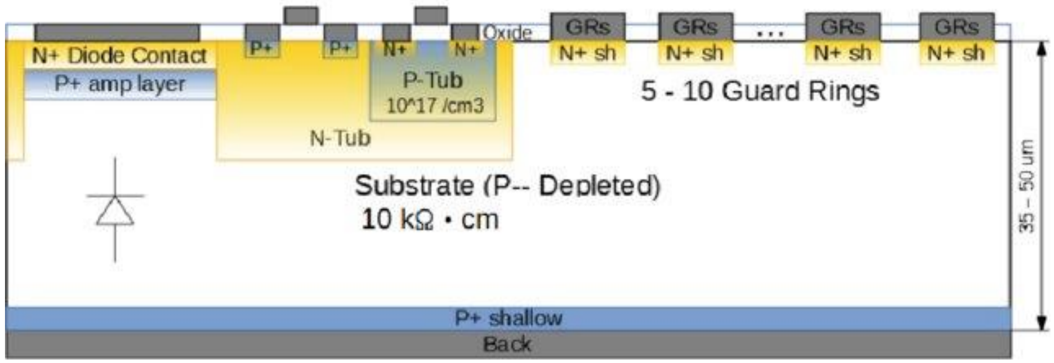
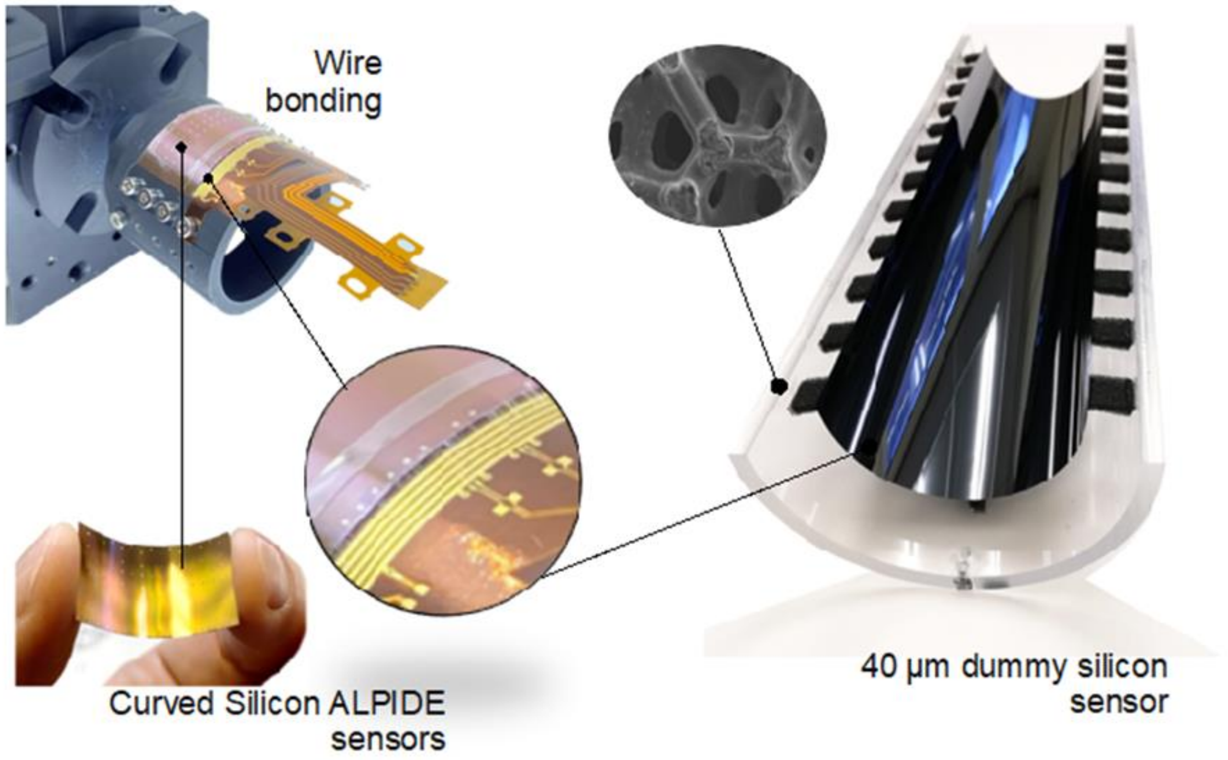


Fig. 6. 2-dimensional efficiency maps as function of hit position for an unirradiated MALTA-Cz sensor (continuous n^- layer) (a), and an irradiated MALTA-Cz (n-gap) at 10^{15} n_{eq}/cm^2 (b) and an irradiated MALTA-Cz (n-gap) at 2×10^{15} n_{eq}/cm^2 (c).

DMAPS: A fully monolithic future?



Monolithic LGAD DESIGN (TOPSIDE project)



A FINAL REMARK

- This brief overview only scratches the surface of the potential of the Semiconductor Radiation Detector, as there are numerous other fascinating advancements that have not been included.
- For over 70 years, there has been a continuous improvement in both the performance and affordability of semiconductor-based radiation sensors, leading to an expansion of their applications in the field of high-energy physics (vertexing, tracking, calorimetry, PID, DM, Neutrino)
- The future of this technology looks bright, with the emergence of various new technologies such as CMOS and LGAD, which are set to become dominant in radiation detection both within and outside the scientific community.
- There is still a lot of excitement to come.

THANK YOU FOR YOU ATTENTION!