ESIPAP School – 2023

Lab Training Session: Solid State Detectors

Introduction to Silicon Detectors for the LHC

and Radiation Damage to Silicon Detectors

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******Slides prepared by Michael Moll*

OUTLINE

- **The Large Hadron Collider (LHC) at CERN**
  - Where are the silicon detectors?

- **Silicon Detectors for High Energy Physics Applications**
  - The basic concept of Semiconductor Detectors: A reverse biased pn-junction
  - Strip and Pixel Detectors at the Large Hadron Collider (LHC) at CERN
  - *Some recent developments in Silicon Detectors*

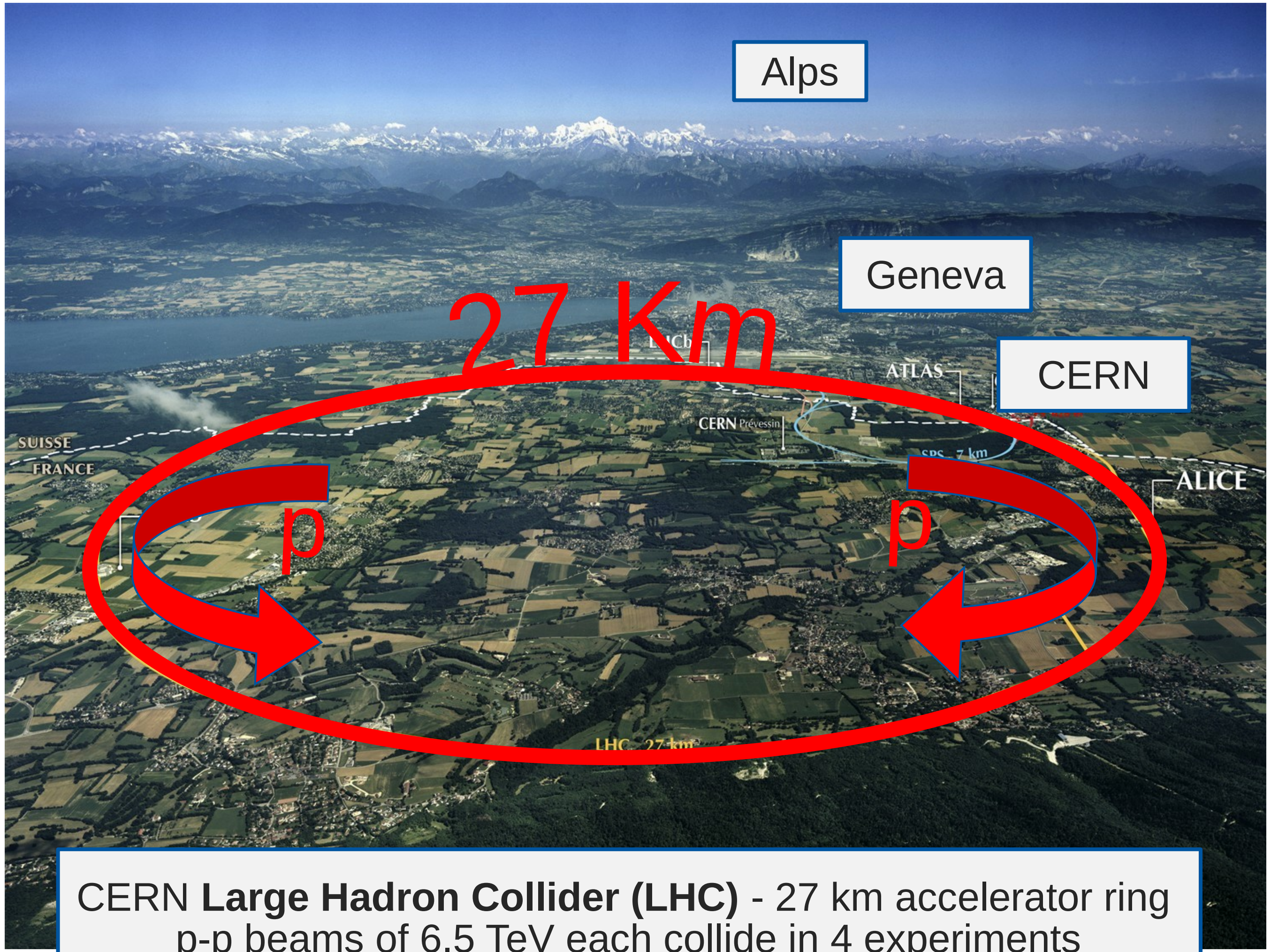
- **Radiation Damage to Silicon Detectors**
  - Upgrade of the Large Hadron Collider (HL-LHC)
  - Radiation damage mechanisms
  - *Mitigation techniques: What can we do against radiation damage?*

- **Characterization techniques for silicon sensors**
  - **Current-Voltage (IV) and Capacitance-Voltage (CV) measurements**
  - **Laser based measurements: Transient Current Technique (TCT)**

Lab Training Session

- **Summary & Further reading**

CERN & LHC - Large Hadron Collider

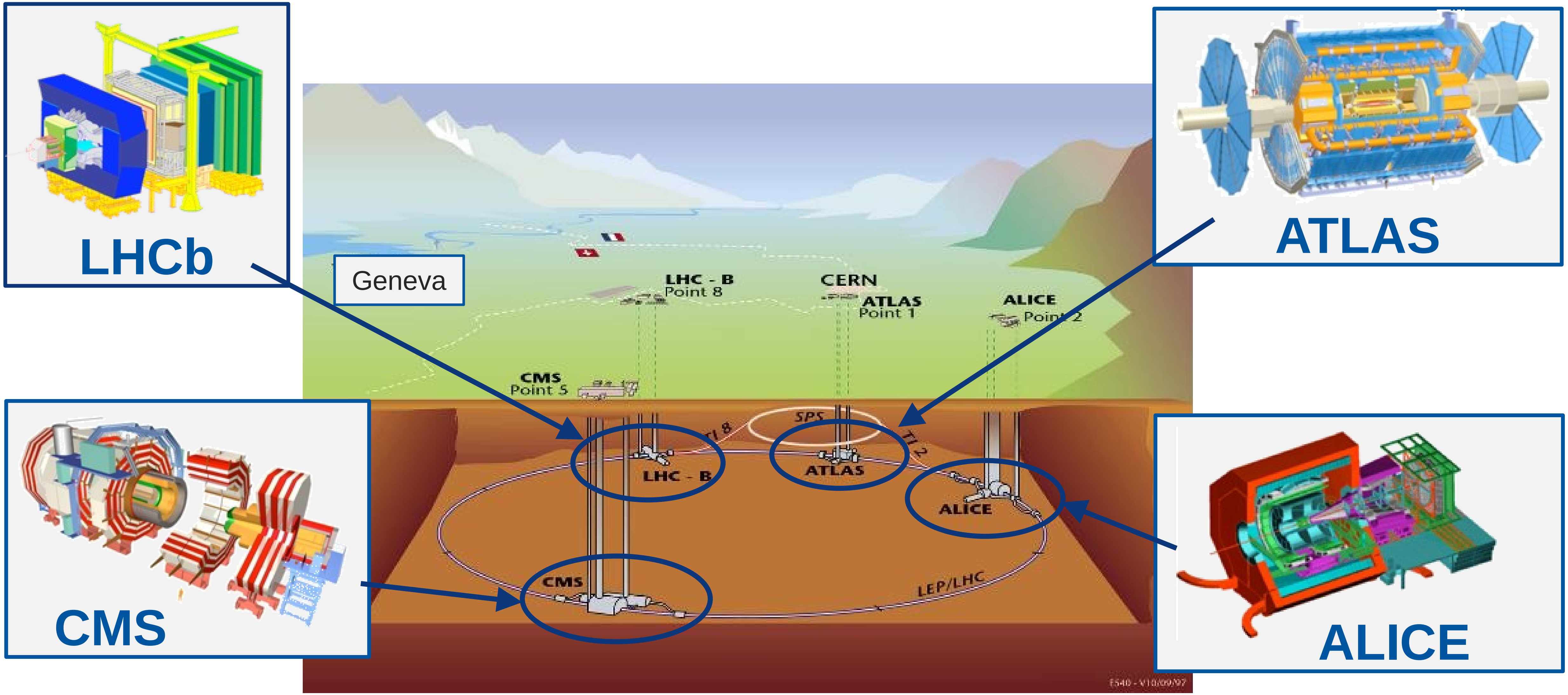


CERN **Large Hadron Collider (LHC)** - 27 km accelerator ring
p-p beams of 6.5 TeV each collide in 4 experiments

- **CERN:**
  - 23 member states
  - ~14000 scientists (Users)
  - ~ 2600 personnel
  - Budget ~1200 MCHF
- **LHC: 27 km tunnel**
  - 4000 MCHF (machine+experiments)
  - 1232 dipoles B=8.3T
  - Design: pp s = 14 TeV
    $L_{design} = 10^{34}$ cm^{-2} s^{-1}
    Heavy ions (e.g. Pb-Pb; 5TeV)
- **Circulating beams:**

2008: first beam
2012: Run 1 at 2 x 4 TeV (Higgs boson)
2015: Run 2 at 2 x 6.5 TeV
2016: Reaching 10^{34} cm^{-2} s^{-1}
2018: LS2; 2022: Run 3
2026: LS3; **2029: HL-LHC**

The LHC Experiments



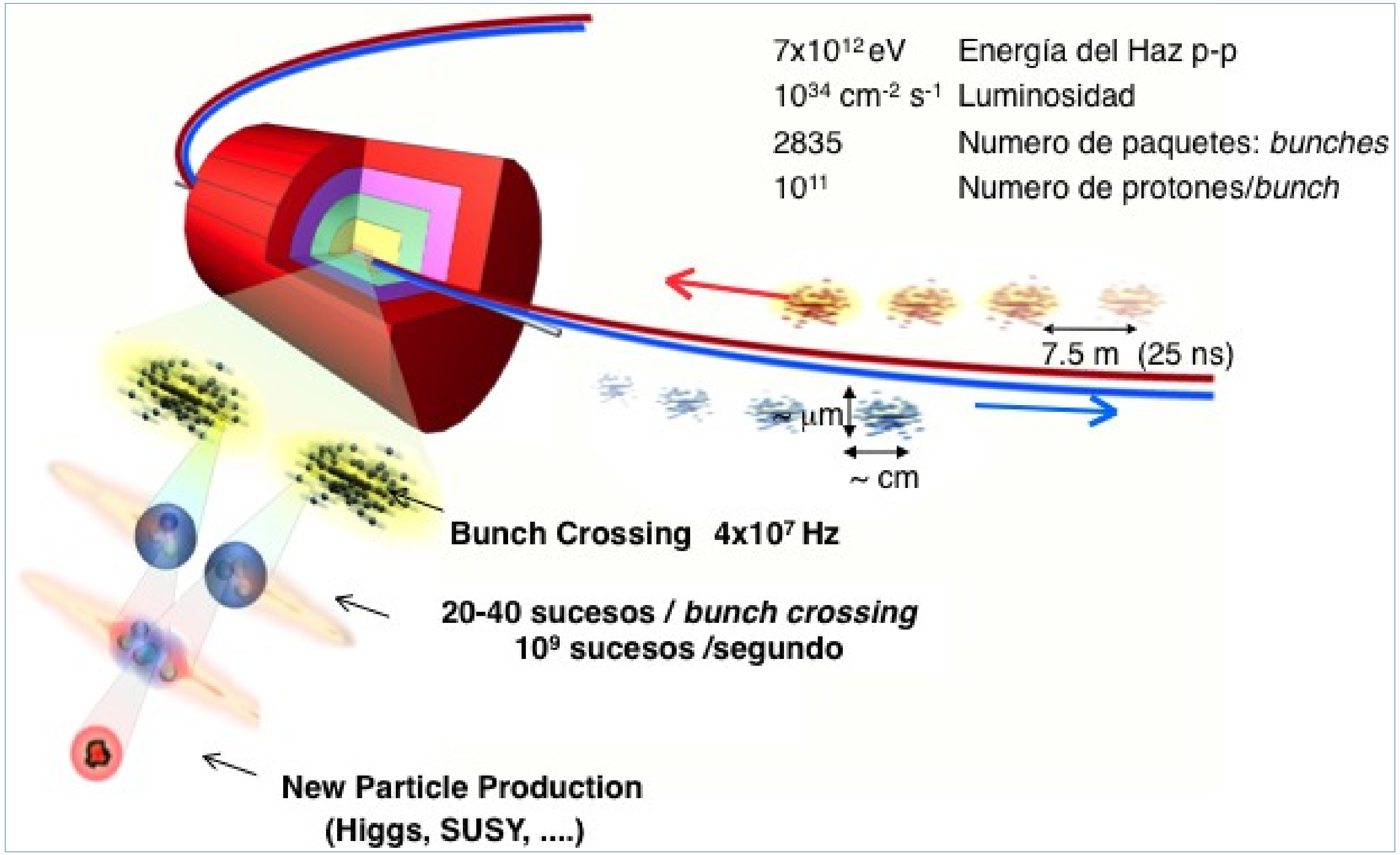
LHCb

ATLAS

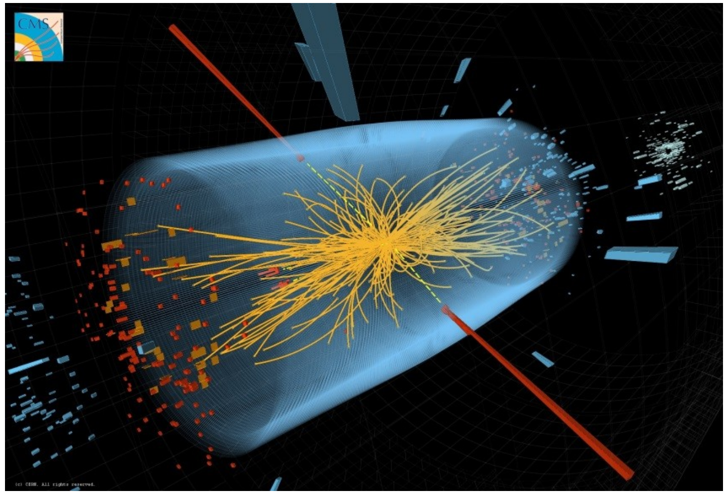
CMS

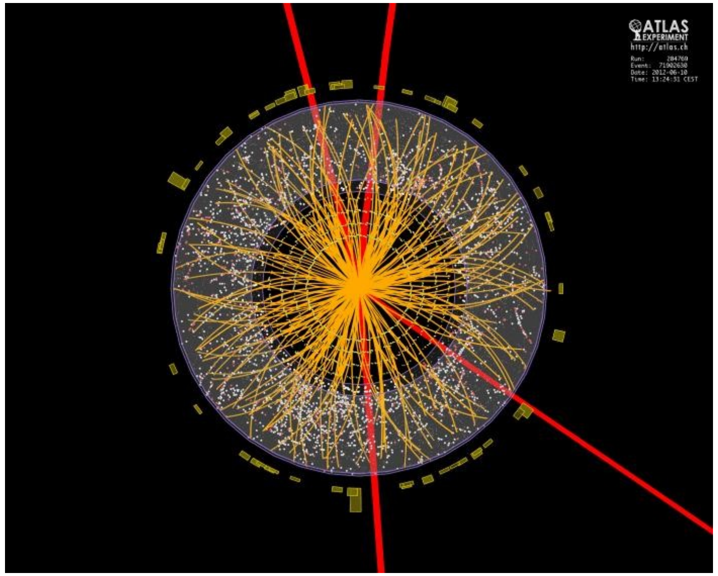
ALICE

Collisions in the LHC



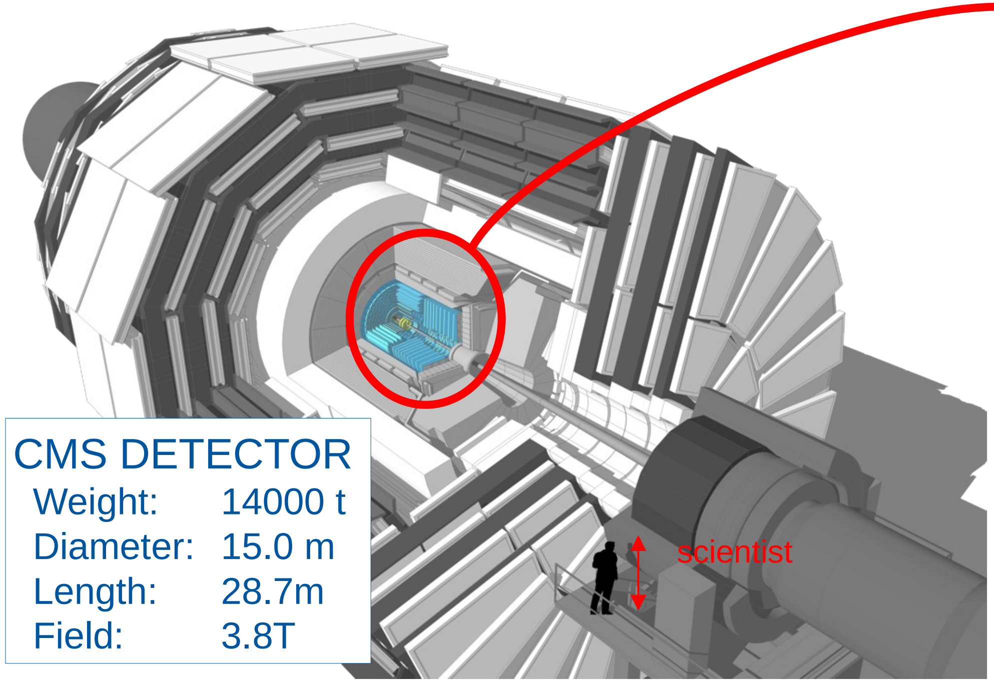
7×10^{12} eV	Energía del Haz p-p
10^{34} cm^{-2} s^{-1}	Luminosidad
2835	Numero de paquetes: *bunches*
10^{11}	Numero de protones/*bunch*





Silicon Tracking Detector

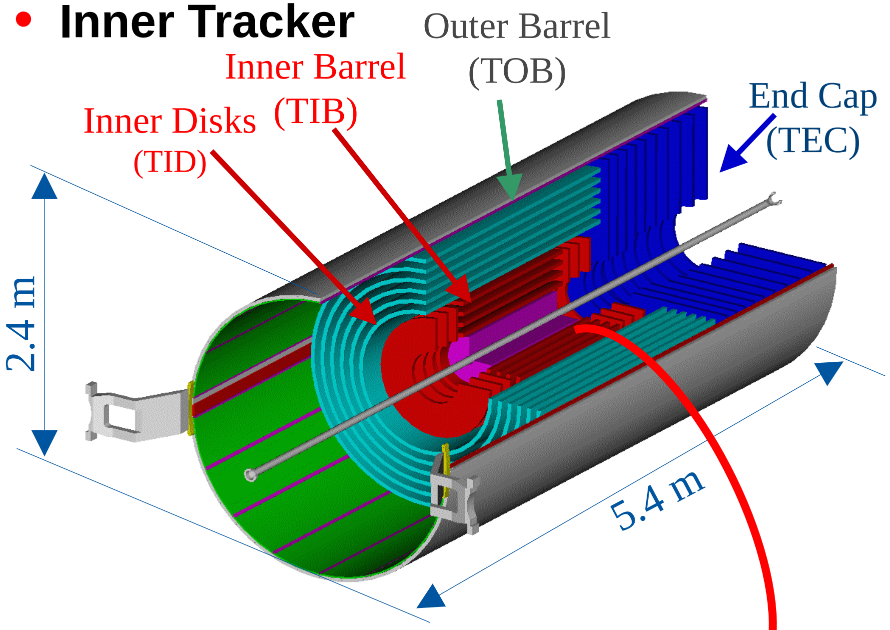
- **LHC example: The CMS DETECTOR**



CMS DETECTOR

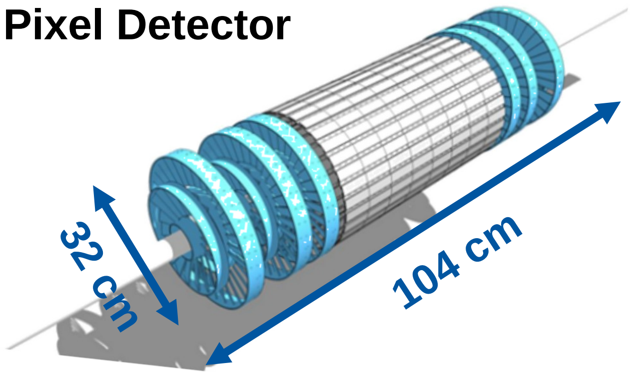
Weight:	14000 t
Diameter:	15.0 m
Length:	28.7m
Field:	3.8T

- **Inner Tracker**

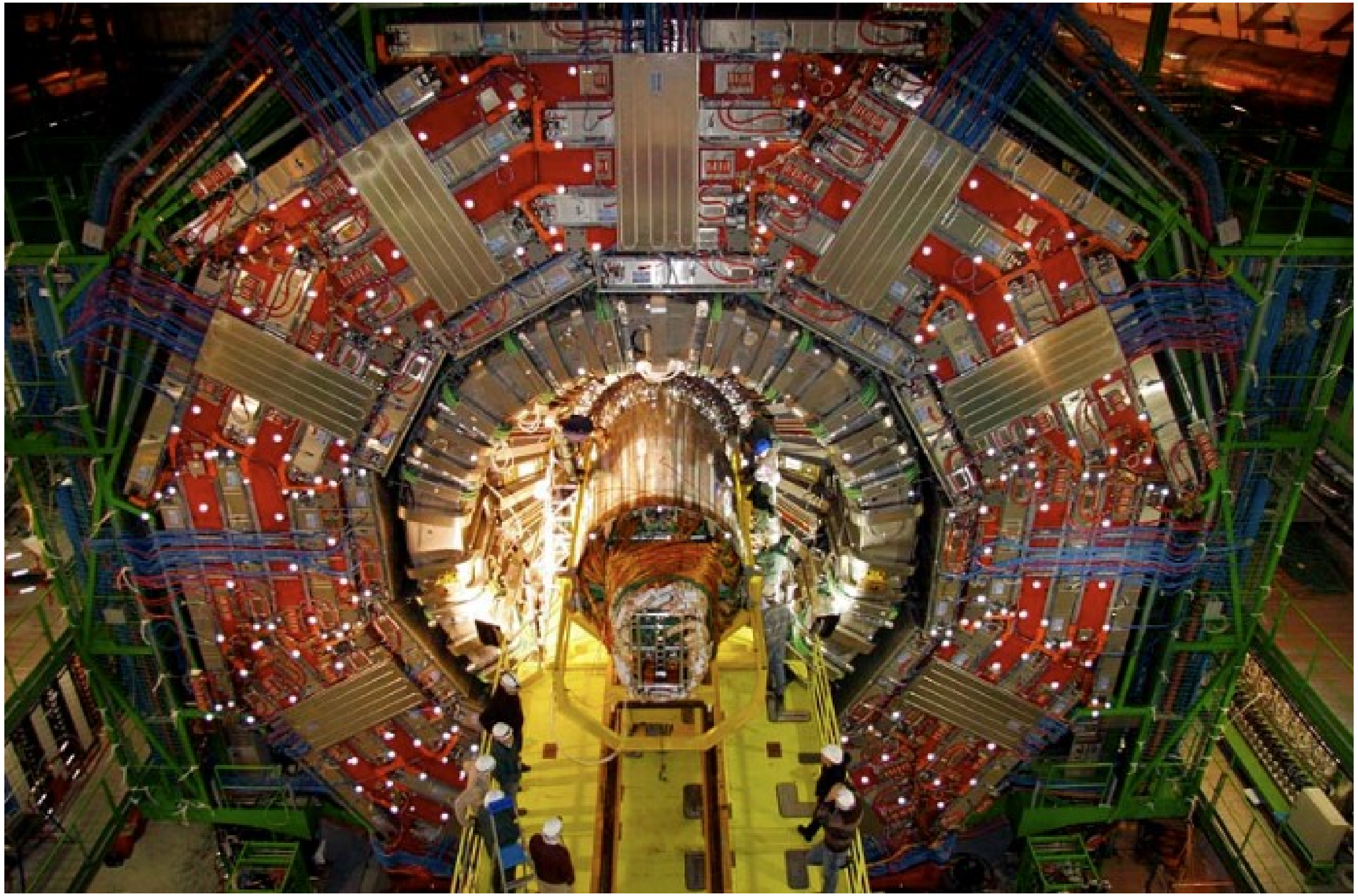


- **CMS – Inner Tracker & Pixel Detector**
  - **Micro Strip:**
  - **~ 214 m^2 of silicon strip sensors, 11.4 million strips**
  - **Pixel:**
  - **4 layers & 2 x 3 disks: silicon pixels (~ $1m^2$)**
  - **124 million pixels ($100x150\mu m^2$)**
  - **Resolution: $\sigma(r\varphi)$ ~ 10 µm, $\sigma(z)$ ~ 25µm**

- **Pixel Detector**



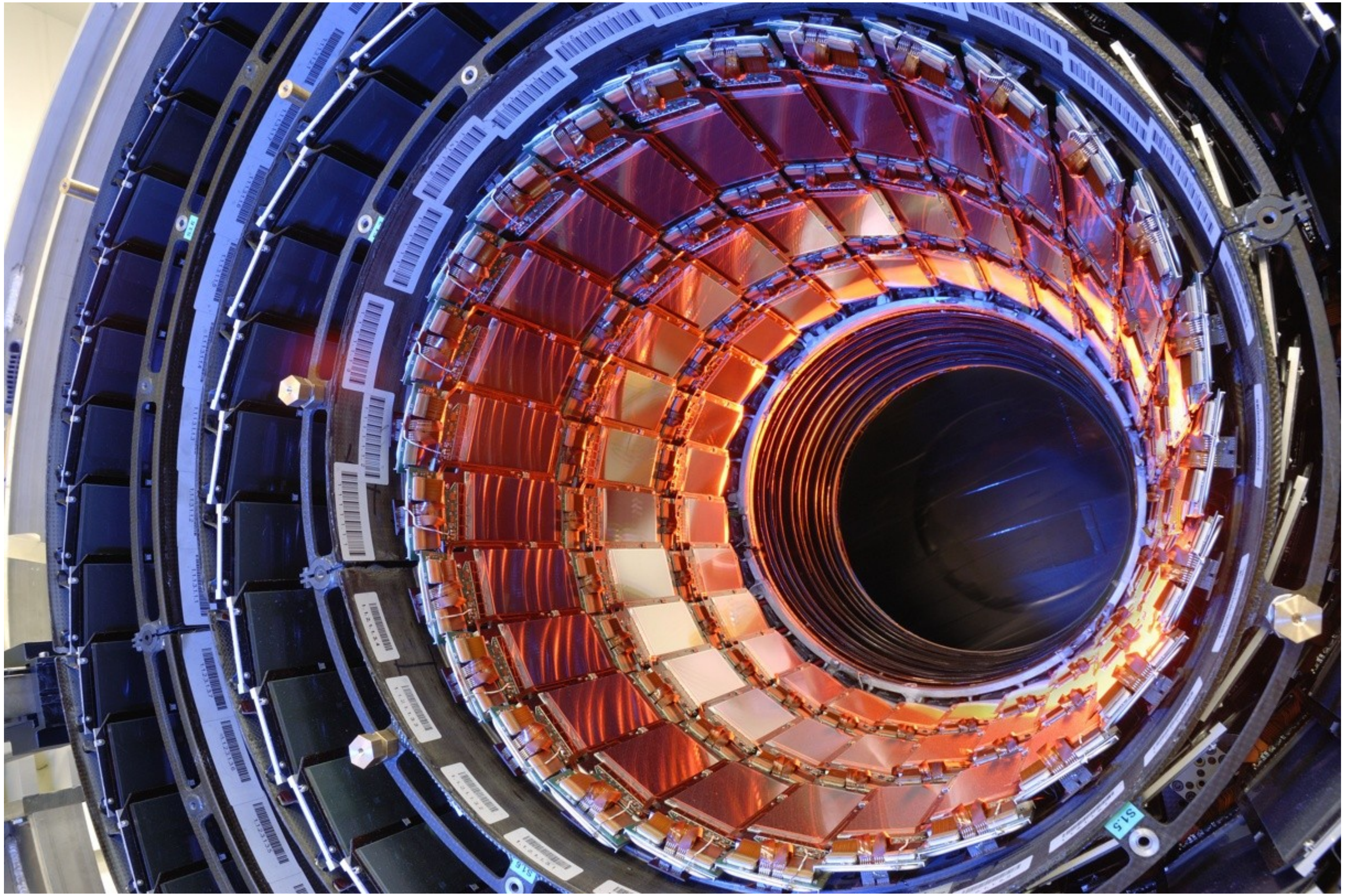
Present LHC Tracking Sensors



CMS Tracker insertion

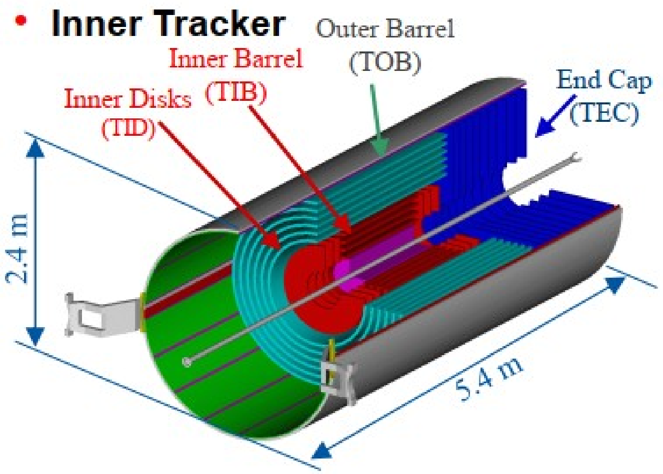
December 2007

Present LHC Tracking Sensors



M.Krammer, ICFA School, Bogota, 2013

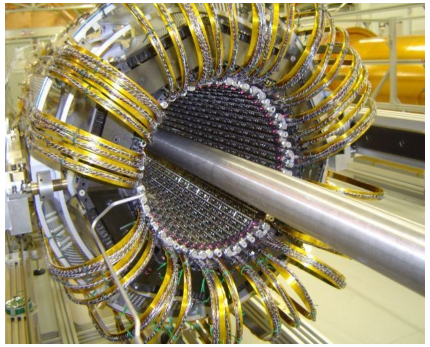
CMS Tracker



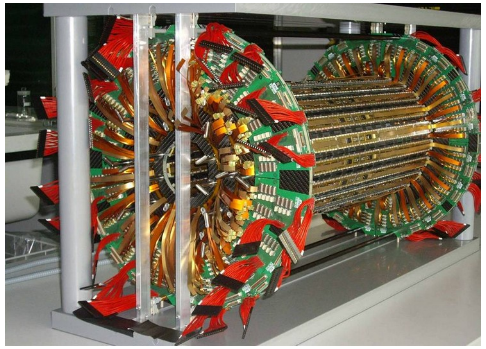
Silicon Tracking Detectors

Silicon tracking detectors are used in almost all HEP experiments:

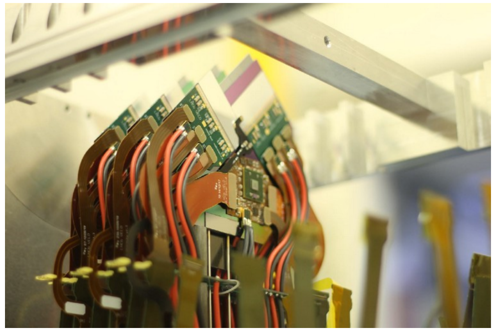
Different sensor technologies, designs, operating conditions,….



ATLAS Pixel Detector

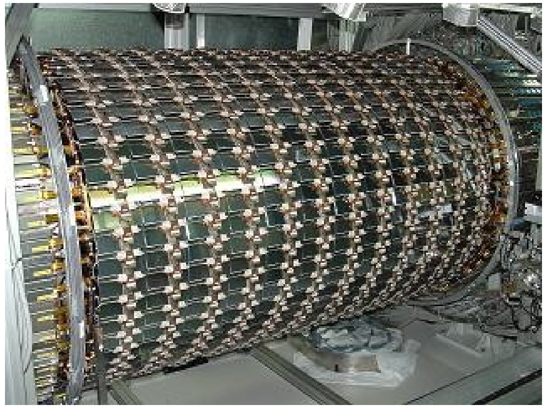


CMS Pixel Detector

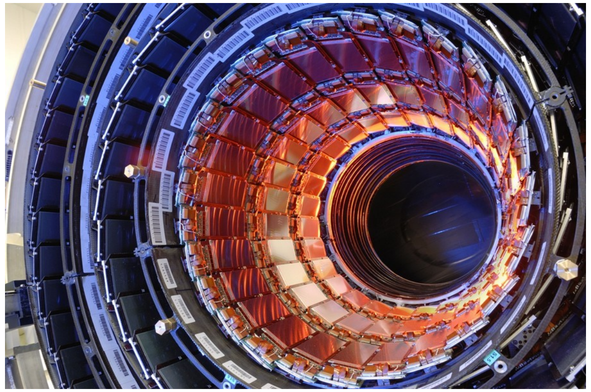


LHCb VELO (New Velo for Run3:2022)

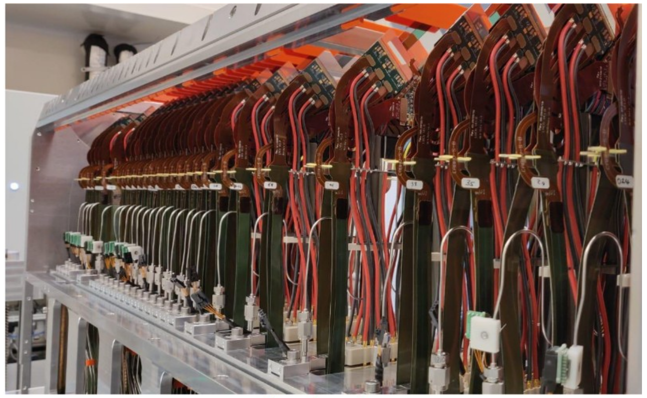
ALICE ITS Barrel
New ITS for Run3:2022)



ATLAS SCT Barrel



CMS Strip Tracker IB



LHCb VELO (New Velo for Run3:2022)

CERNCOURIER

July/August 2021 cerncourier.com

Reporting on international high-energy physics

PIXEL PERFECT

Exploring the Hubble tension

A CERN for climate change

Medical technologies

ALICE ITS Outer Barrel

(Insertion Test 2021)

Silicon Sensors

Solid State Detectors – Why Silicon?

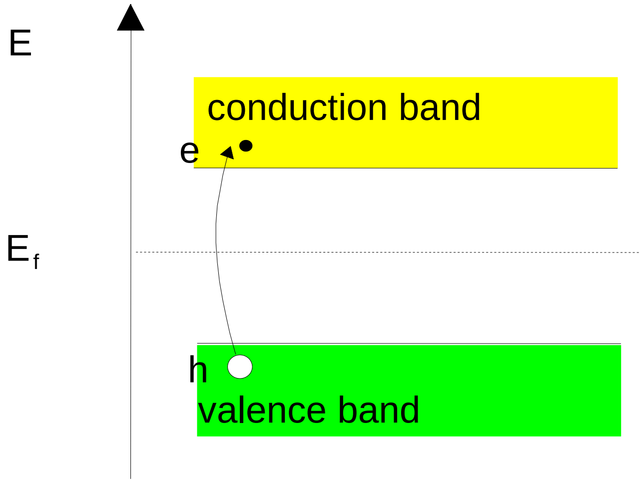
- **Some characteristics of Silicon crystals**
  - Small band gap E_g = 1.12 eV E(e-h pair) = 3.6 eV (30 eV for gas detectors)
  - High specific density 2.33 g/cm^3 ; dE/dx (M.I.P.) 3.8 MeV/cm 106 e-h/µm (average)
  - High carrier mobility μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs fast charge collection (<10 ns)
  - Very pure < 1ppm impurities and < 0.1ppb electrical active impurities
  - Rigidity of silicon allows thin self supporting structures
  - Detector production by microelectronic techniques

    well known industrial technology, relatively low price, small structures easily possible

- **Alternative semiconductors**
  - **Diamond**
  - Gallium arsenide (GaAs)
  - Gallium nitride (GaN)
  - **Silicon Carbide (SiC)**
  - Germanium (Ge)

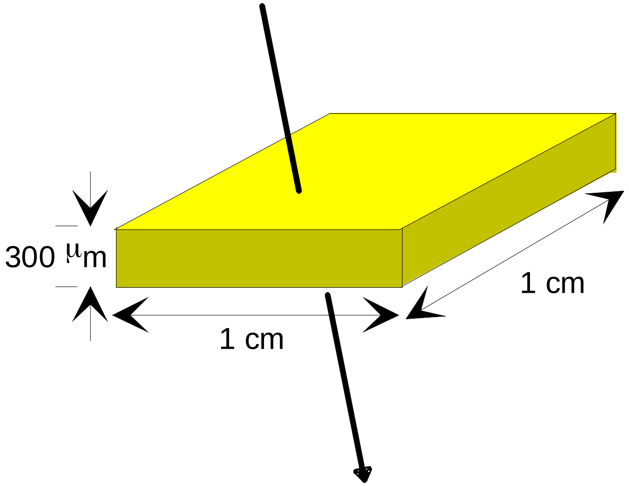
	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
E(e-h pair) [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.52	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

How to obtain the signal?



In a pure intrinsic (undoped) semiconductor the electron density *n* and hole density *p* are equal.

$n = p = n_i$ For Silicon: n_i $1.45\ 10^{10}$ cm^{-3}

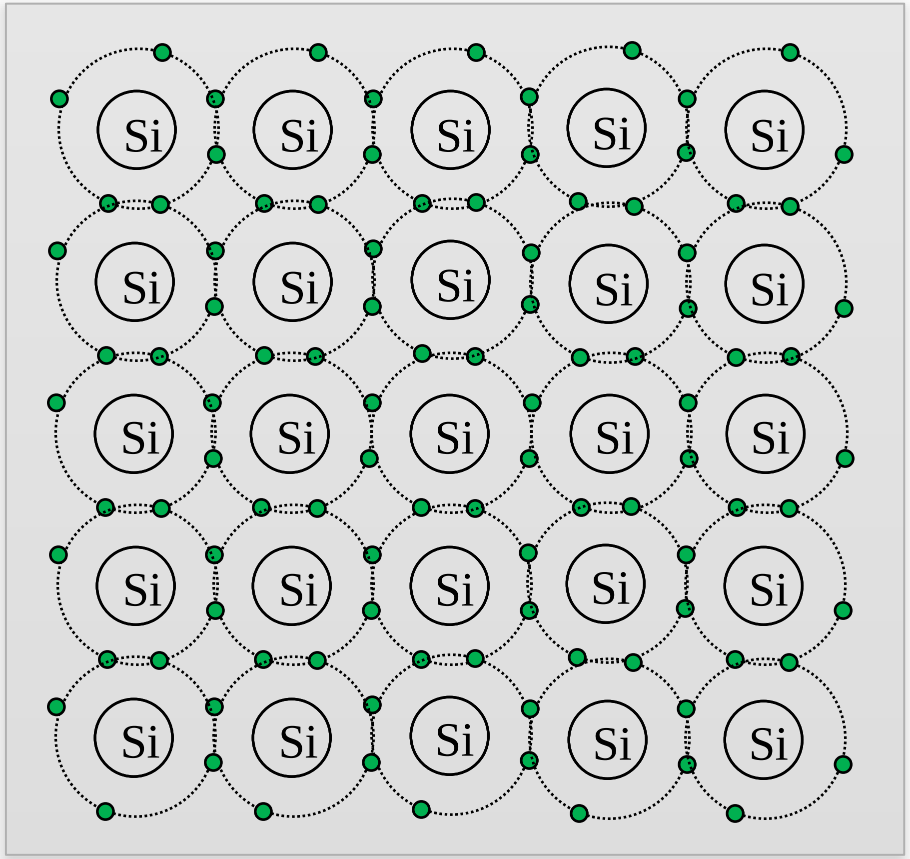


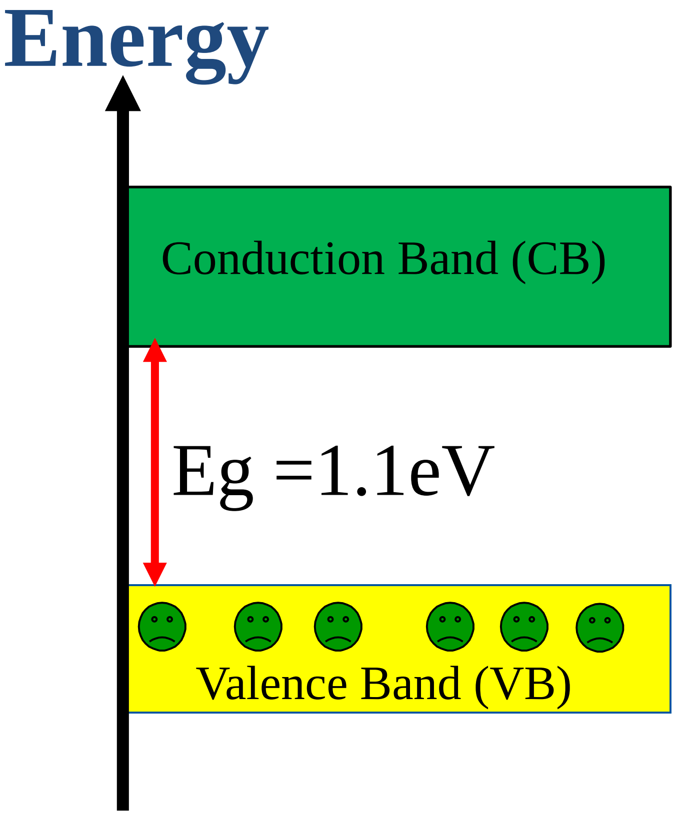
$4.5\ 10^8$ free charge carriers in this volume,
but only ~32000 e-h pairs produced by a M.I.P.

Reduce number of free charge carriers, i.e. deplete the detector

Most detectors make use of reverse biased p-n junctions

Covalent Bonding of Pure Silicon



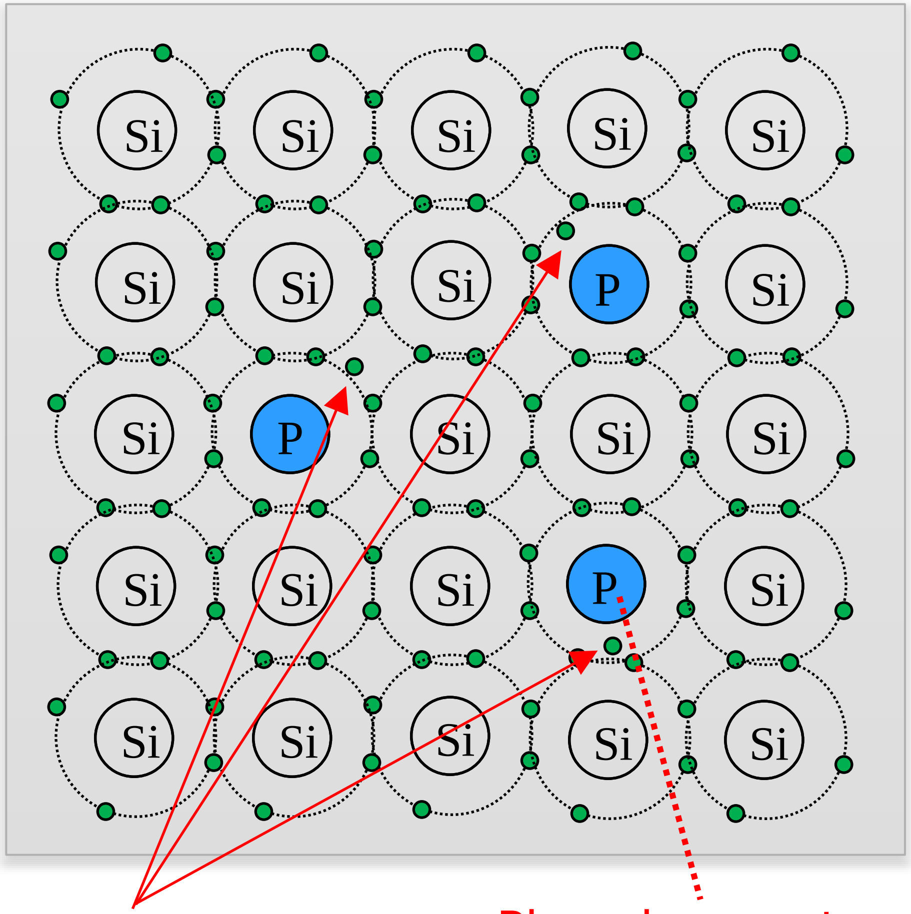


Silicon atoms share valence electrons to form insulator-like bonds.

Thermal energy at RT: 3/2 $k_B T$ ~40 meV

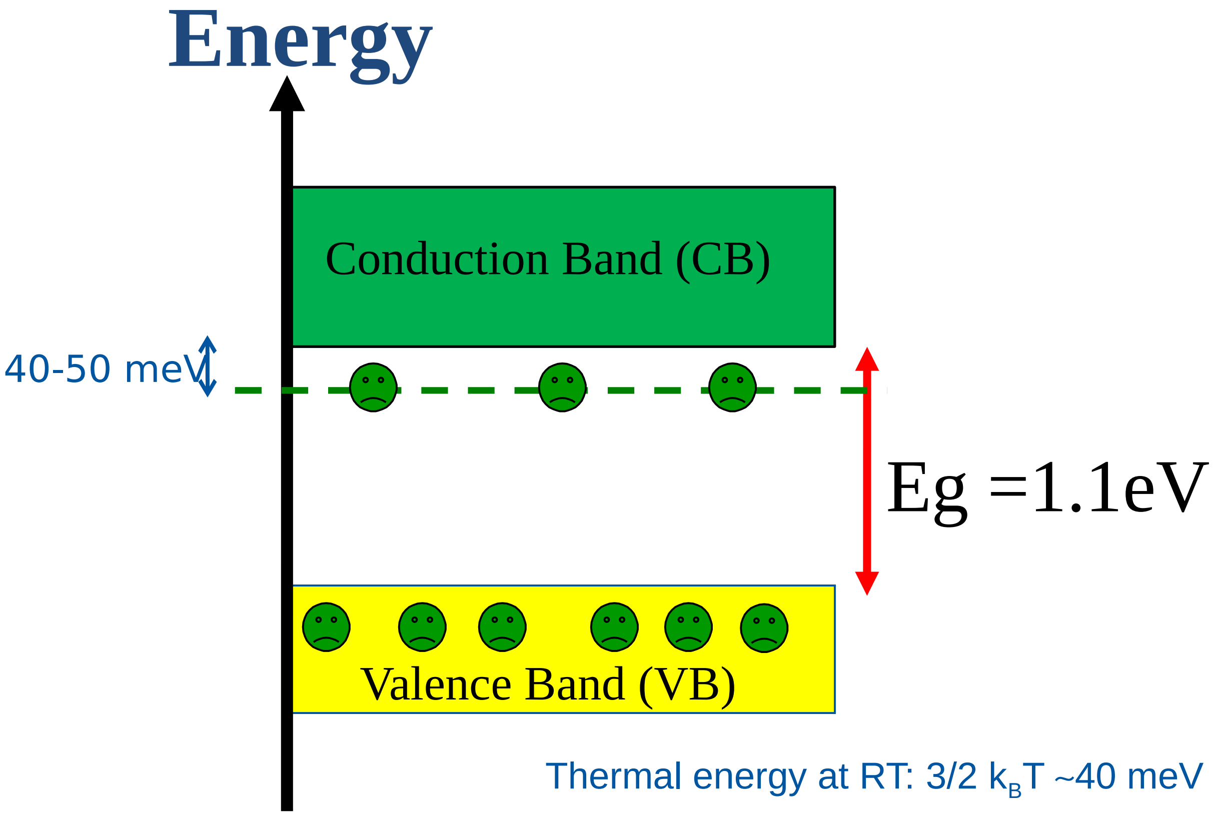
Electrons in n-type silicon with phosphorus dopant

Donor atoms provide excess electrons to form n-type silicon



Excess electron (-)

Phosphorus atom serves as n-type dopant

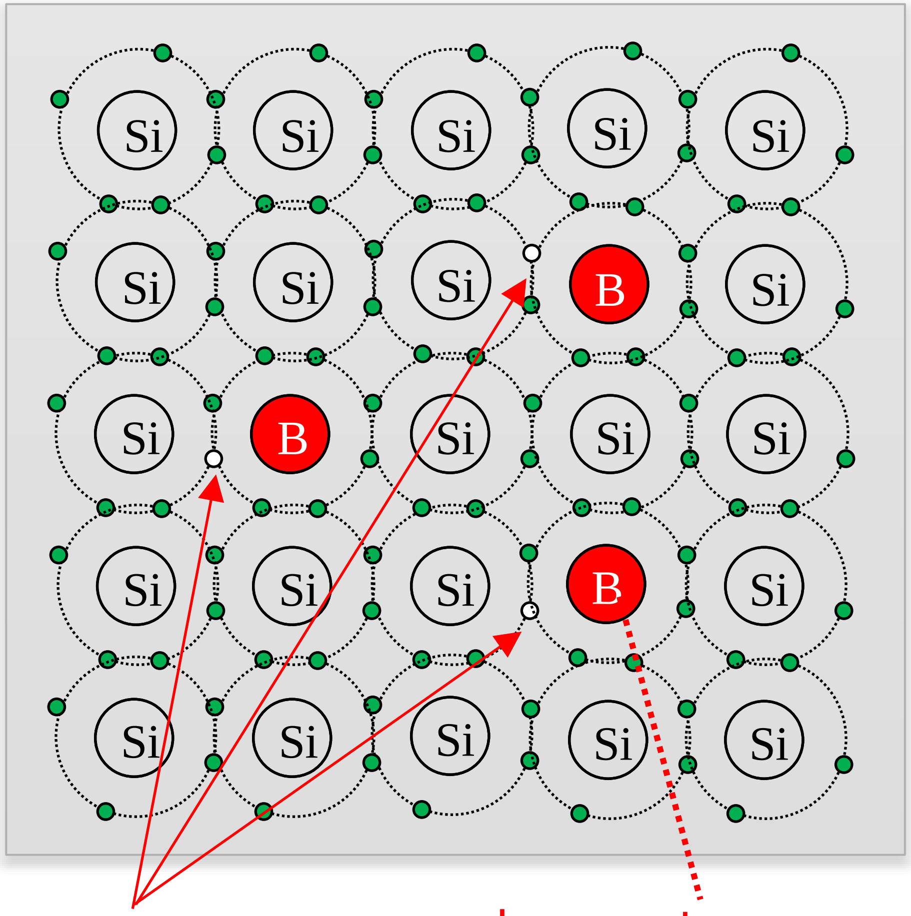


Thermal energy at RT: 3/2 k_BT ~40 meV

electrons are the majority carriers in n-type silicon

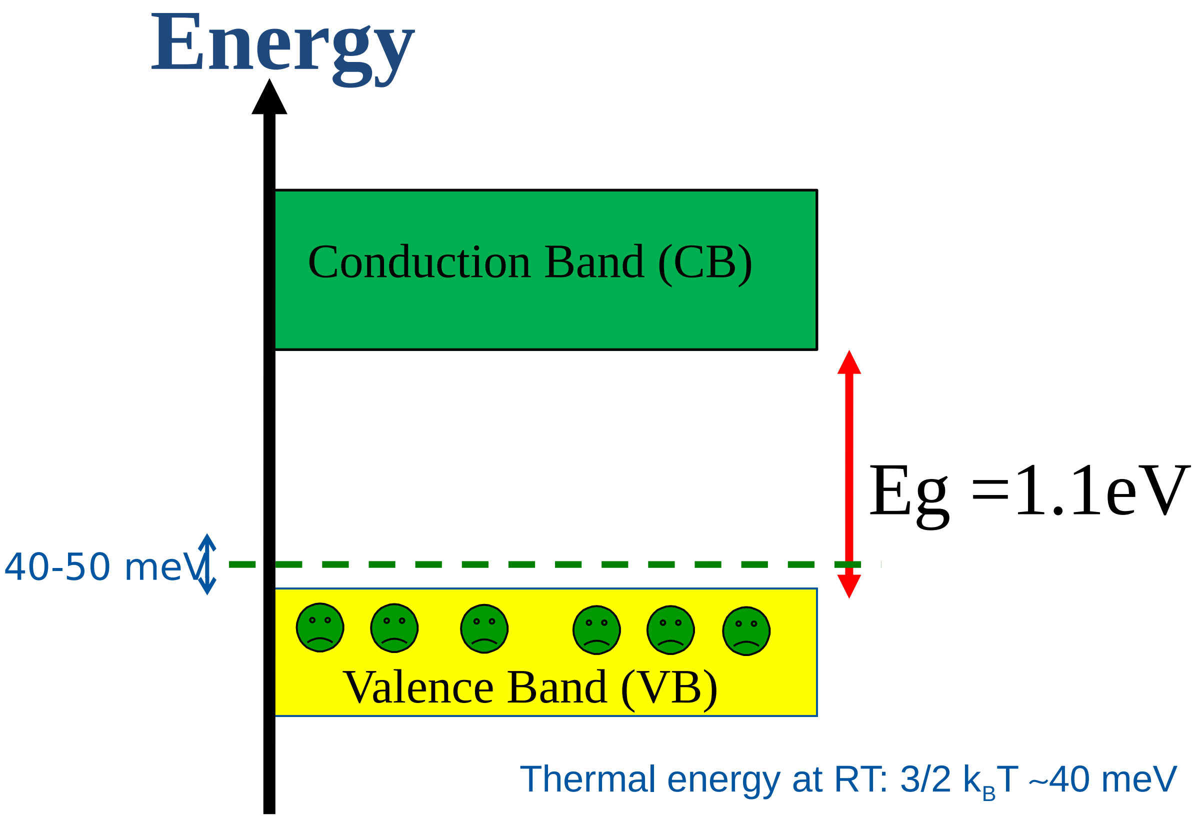
Holes in p-type silicon with boron dopant

Acceptor atoms provide holes
to form p-type silicon



holes(+)

boron atom serves as
p-type dopant

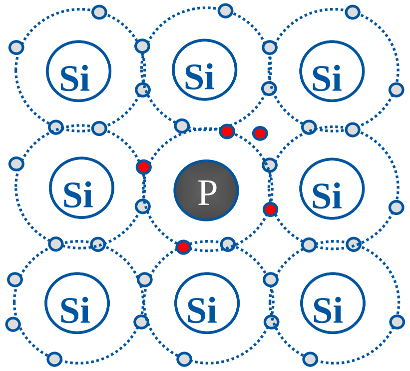


Thermal energy at RT: 3/2 k_BT ~40 meV

holes are the majority
carriers in p-type silicon

Doping, resistivity and p-n junction

e.g. Phosphorus

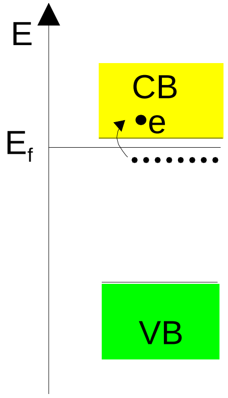


- **resistivity** ρ
  - – carrier concentration *n*, *p*
  - – carrier mobility μ_n, μ_p

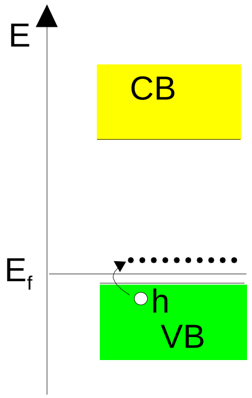
$$\rho = {}^{1}\!/_{q_0(\mu_n n + \mu_p p)}$$

	detector grade	**electronics grade**
doping	**10^{12} cm^{-3}**	**10^{17} cm^{-3}**
resistivity	**5 k ·cm**	**1 ·cm**

- **Doping**: n-type silicon
  - add elements from Vth group
    donors (P, As,..)
  - electrons are majority carriers



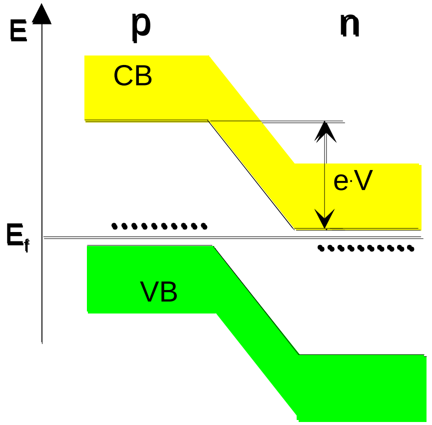
- **Doping: p-type silicon**
  - add elements from IIIrd group
    acceptors (B,..)
  - holes are majority carriers



p-n junction

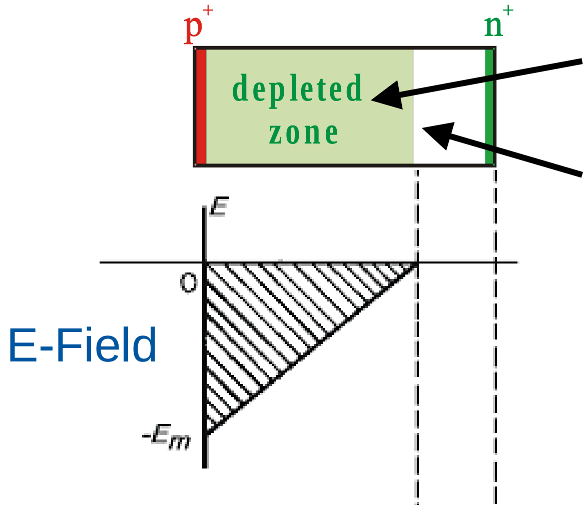
There must be a single Fermi level!

- – band structure deformation
- – potential difference
- – depleted zone



Depletion Voltage

- Below depletion



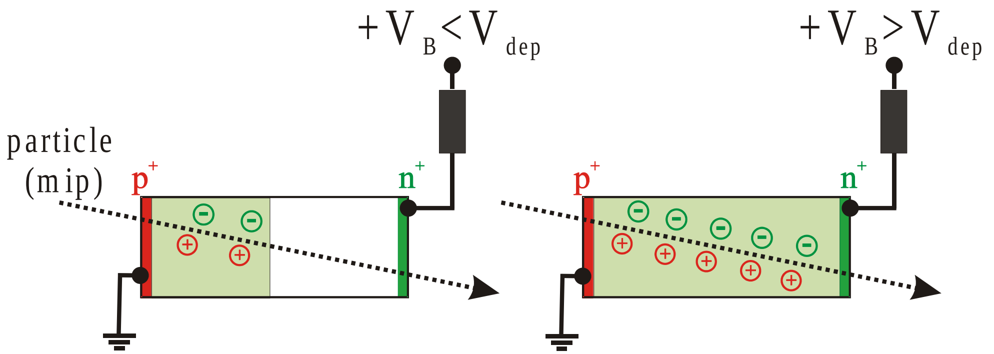
positive space charge, N_{eff} =[P] (ionized Phosphorus atoms)

neutral bulk (no electric field)

- Depletion Voltage V_{dep}
  - sensor depleted of free charge carriers
  - electric field throughout complete device
  - complete sensor volume sensitive (active)

  - Example:
    - d = 300 µm and N_{eff} = [P] =1.5 10^{12} cm^{-3} (ρ 3kΩcm)
    - Depletion Voltage: V_{dep} 100V

- 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}

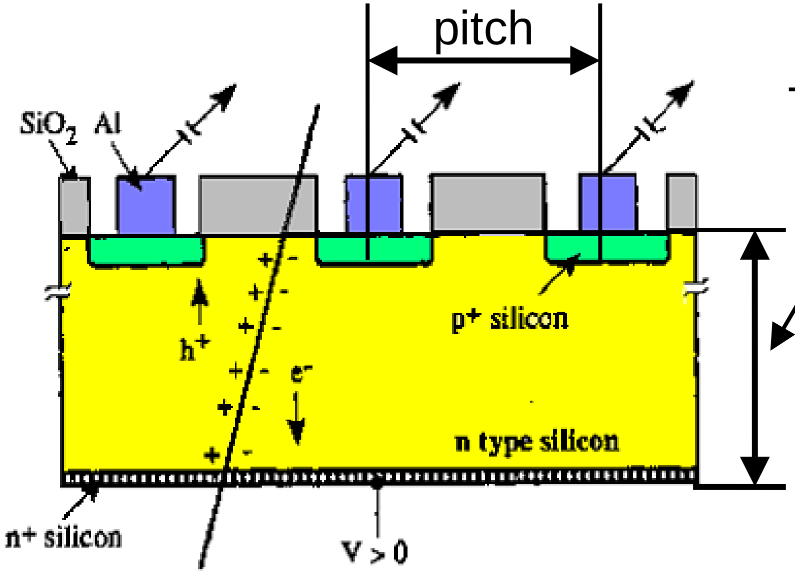
detector thickness d

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

effective space charge density N_{eff}

Single Sided Strip Detector

- Segmentation of the p^+ layer into strips (Diode Strip Detector) and connection of strips to individual read-out channels gives spatial information



Typical thickness: 300µm (150µm-500µm used)

- using n-type silicon with a resistivity of

  $= 2\ K\Omega cm\ (N_D \sim 2.2 \cdot 10^{12} cm^{-3})$

  results in a depletion voltage ~ 150 V

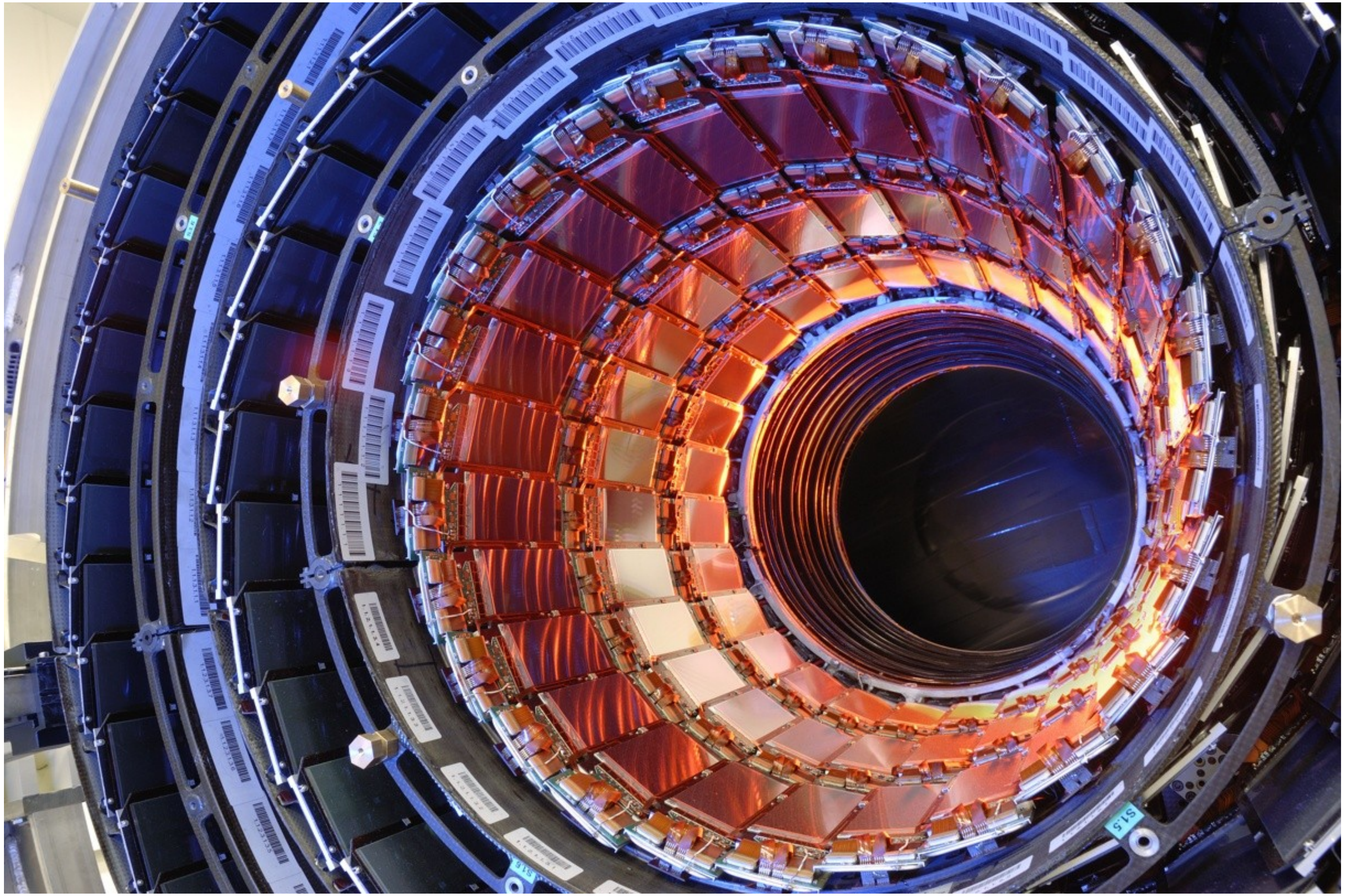
- Resolution depends on the pitch p (distance from strip to strip)

  - e.g. detection of charge in binary way (threshold discrimination) and using center of strip as measured coordinate results in

$$\sigma = \frac{p}{\sqrt{12}}$$

typical pitch values are 20 µm– 150 µm 50 µm pitch results in 14.4 µm resolution

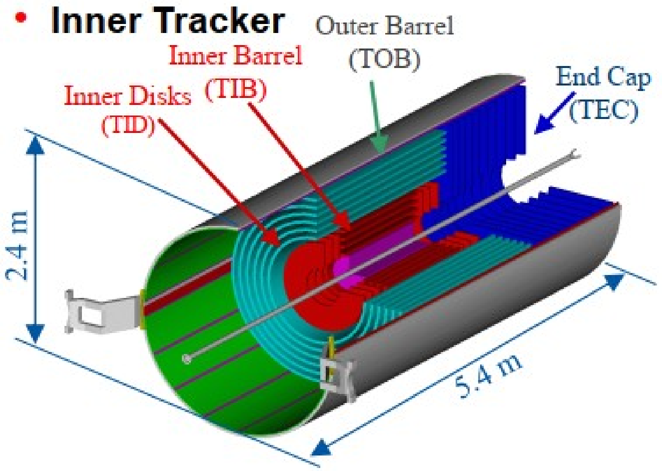
Present LHC Tracking Sensors



M.Krammer, ICFA School, Bogota, 2013

CMS Tracker

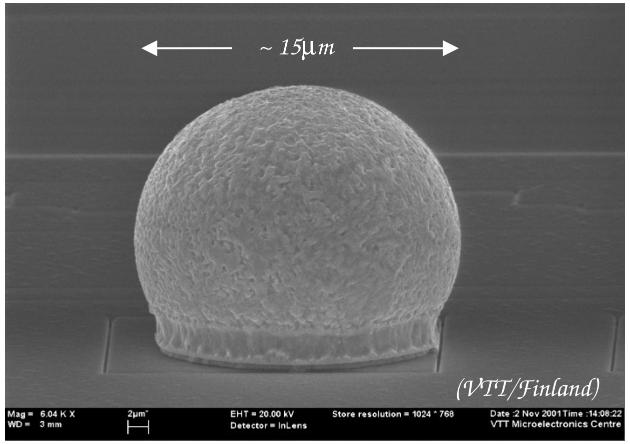
… 11.4 million strips

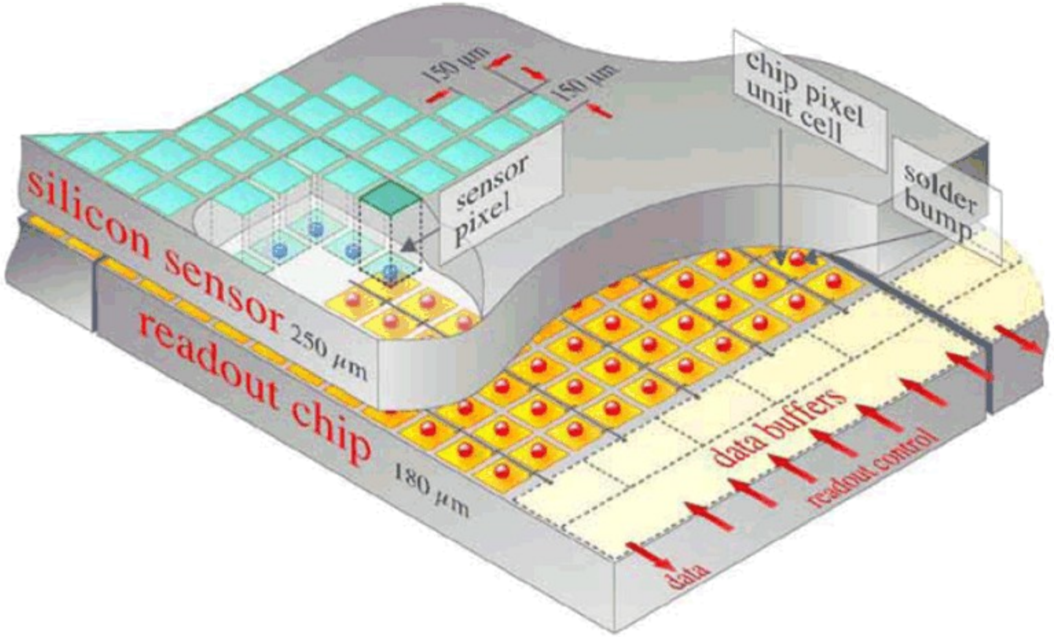


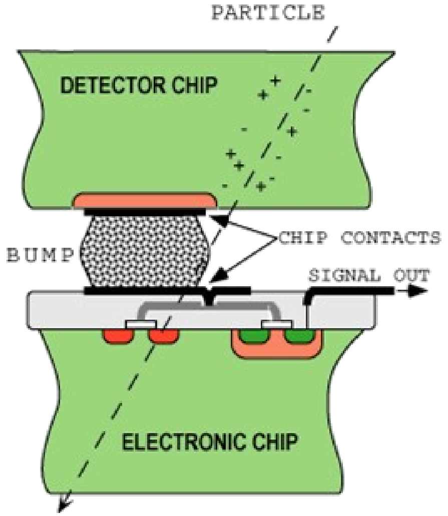
Hybrid Pixel Detectors

- HAPS – Hybrid Active 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"**
  - **requires sophisticated readout architecture**
  - **Hybrid pixel detectors are used in LHC experiments:**
    ATLAS, ALICE *(from Run3 monolithic)*, **CMS and LHCb**

Solder Bump: Pb-Sn

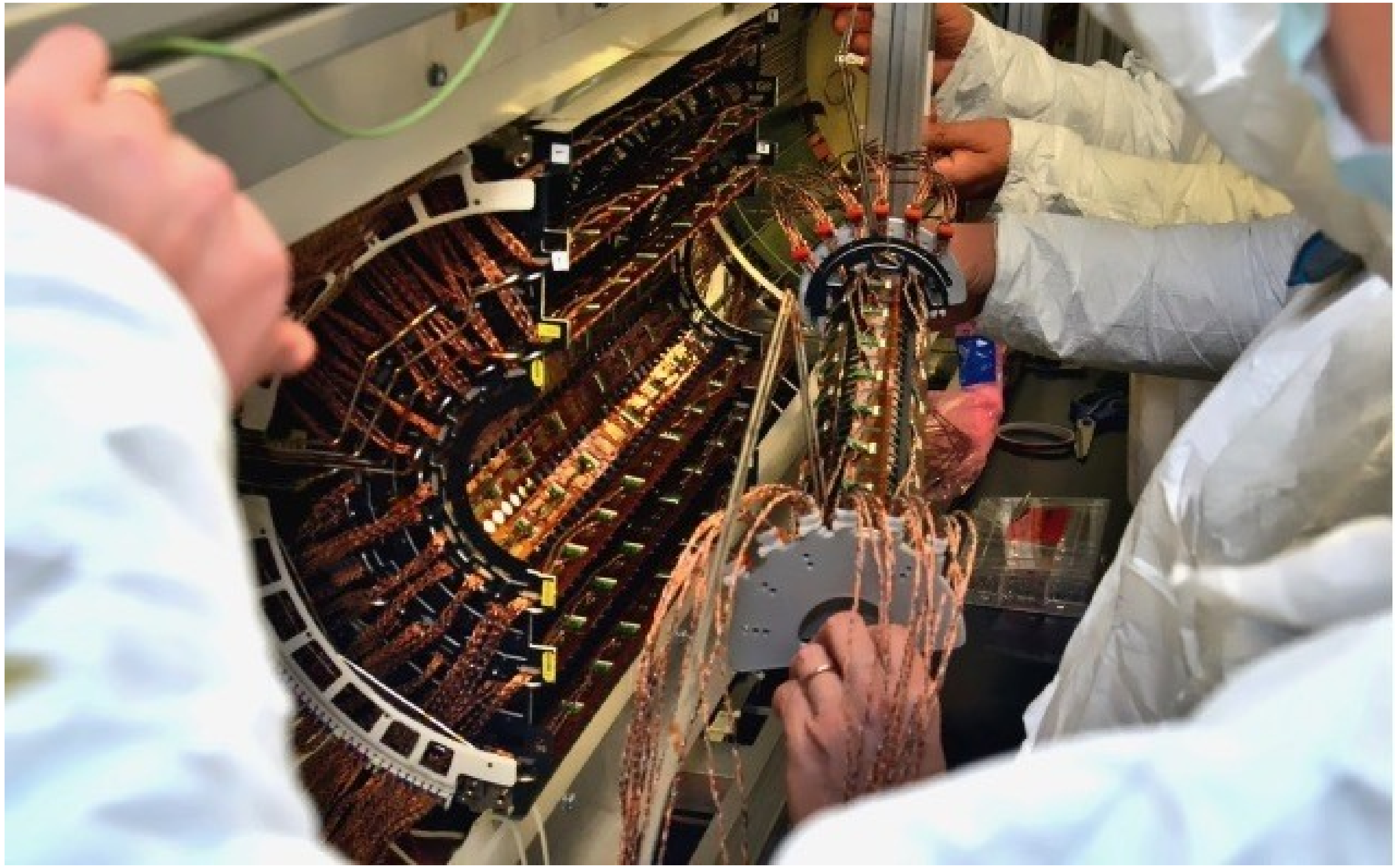




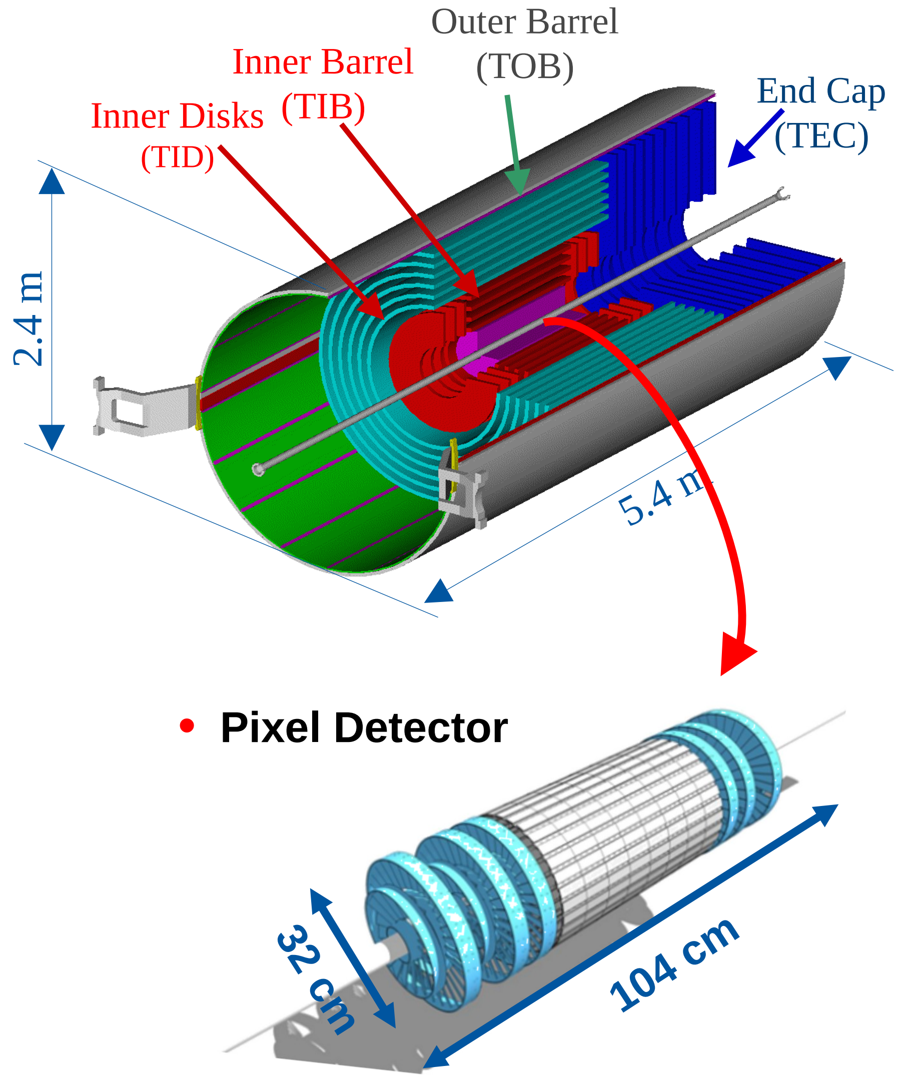


Flip-chip technique

Present LHC Tracking Sensors



CMS Pixel (Installation after maintenance in 2021)



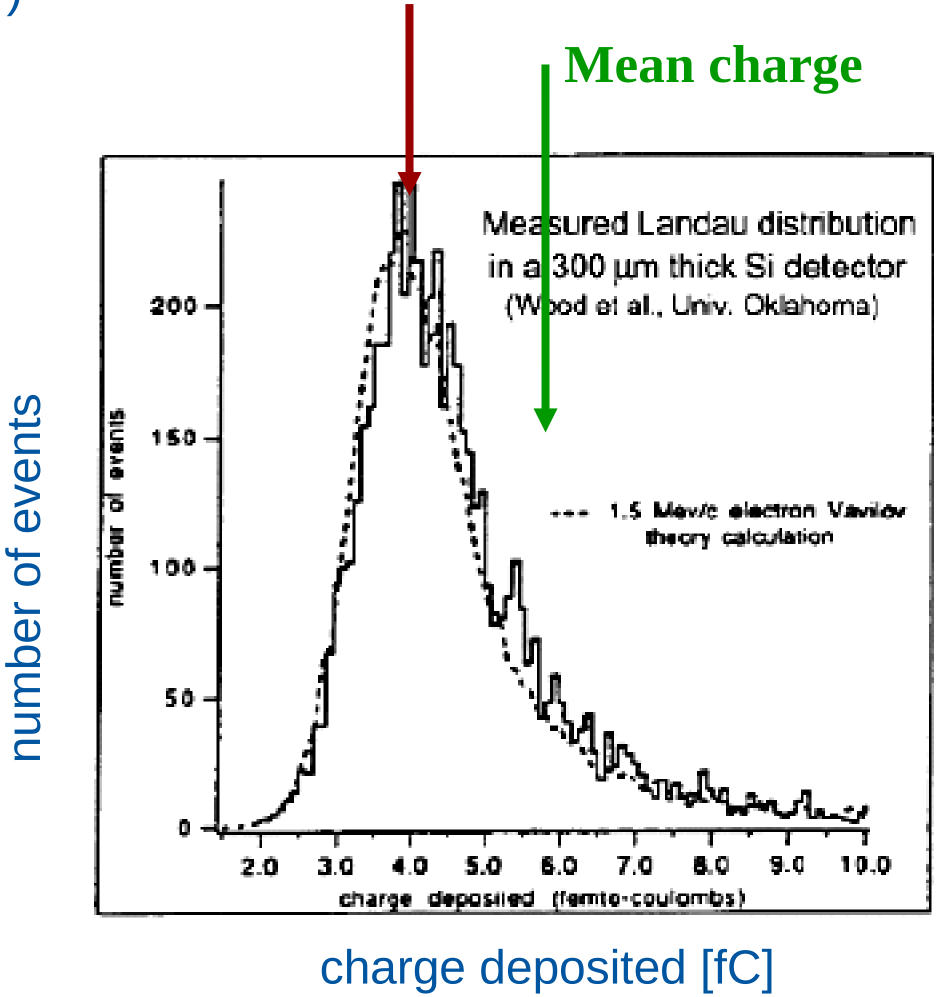
- **Pixel Detector**

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)
    72 e-h / µm (most probable)
  - Most probable charge (300 µm)

    ≈ 22500 e ≈ 3.6 fC

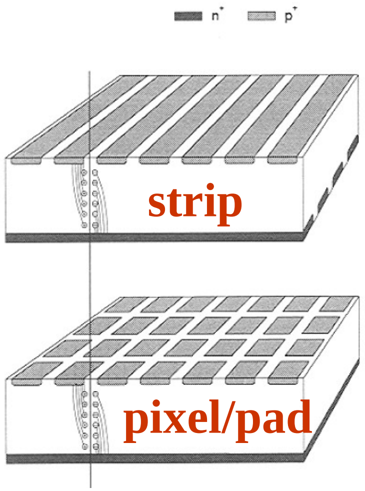
Most probable charge ≈ 0.7 mean



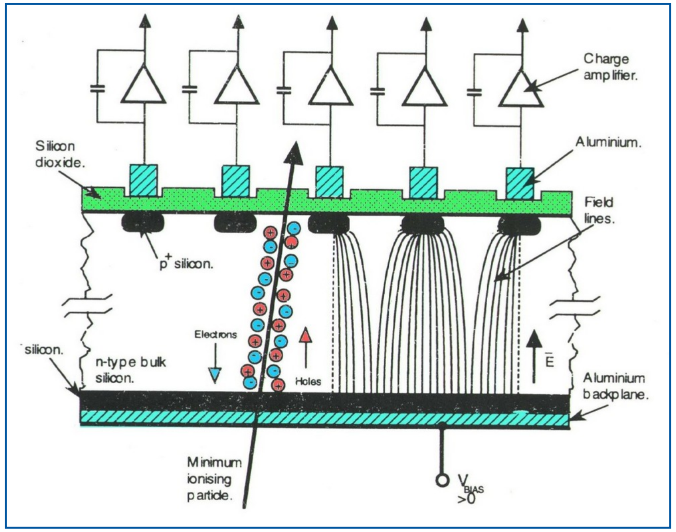
Mean charge

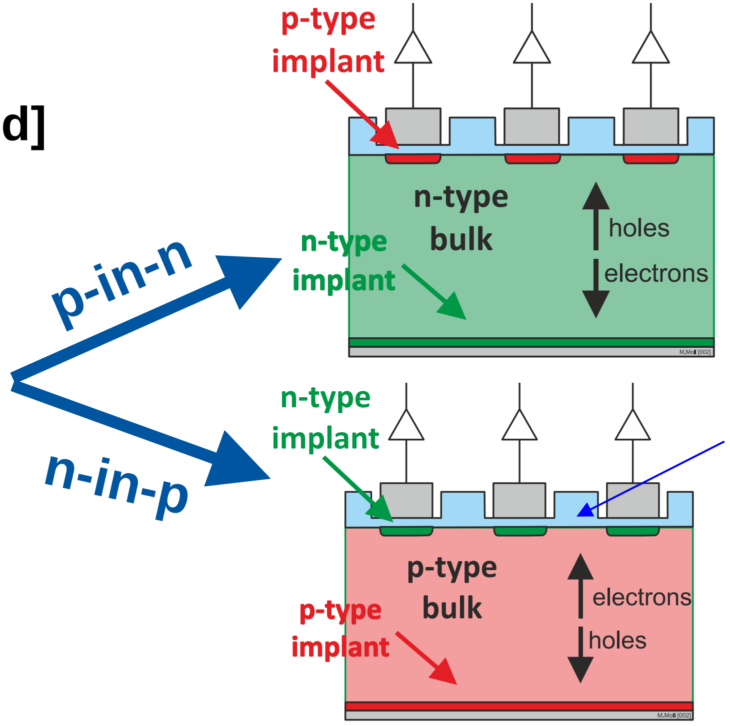
Summary: Silicon Sensors in HEP

Main sensor concepts:



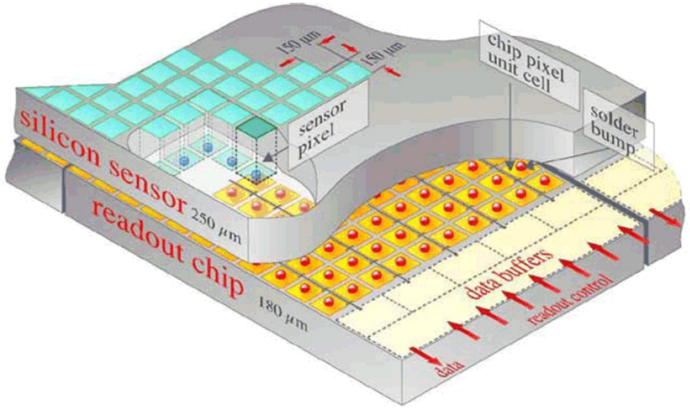
(Mini) Strip Detector [AC coupled]

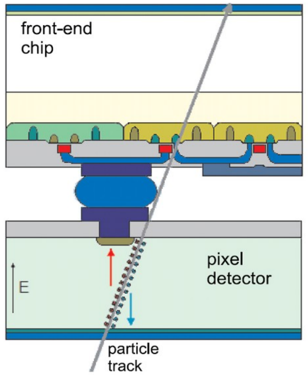




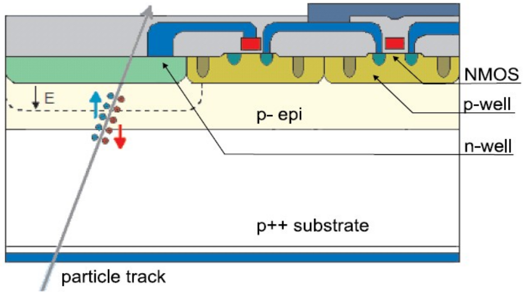
Need inter strip isolation!

Hybrid Pixel Detector





Monolithic CMOS Pixel Detector



Radiation Damage

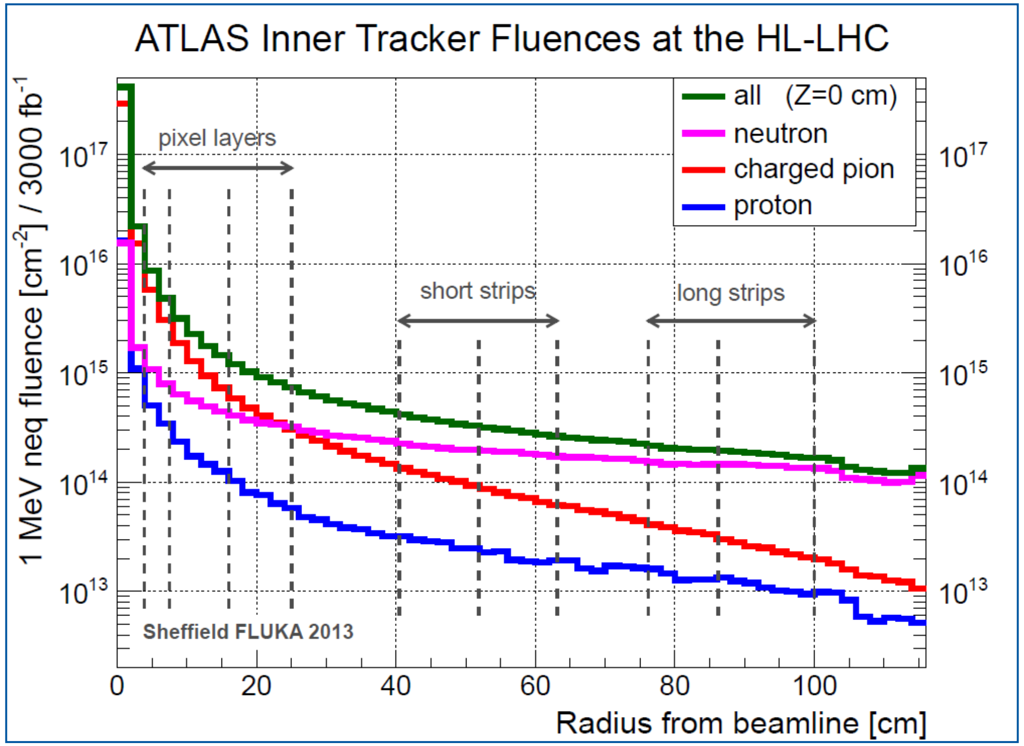
- Damage to dielectric layers and interfaces (not covered)
- Damage to the semiconductor bulk (introduction)

Motivation and Challenge

Silicon detectors upgrades and operation

- Radiation Hardness -

- **LHC operation**
- **HL-LHC (High Luminosity LHC)**
  - detector developments for HL-LHC
    - starting after LS3 (~2025-27);
    - expect 4000 fb^{-1} (nominal LHC was 300 fb^{-1})
- **HL-LHC operation & upgrades**
  - operation of HL-LHC
    - damage modelling, evaluation, mitigation
  - ATLAS Pixel replacement, LHCb upgrade, …
- **FCC – Future Circular Collider**
  - ..also FCC-ee



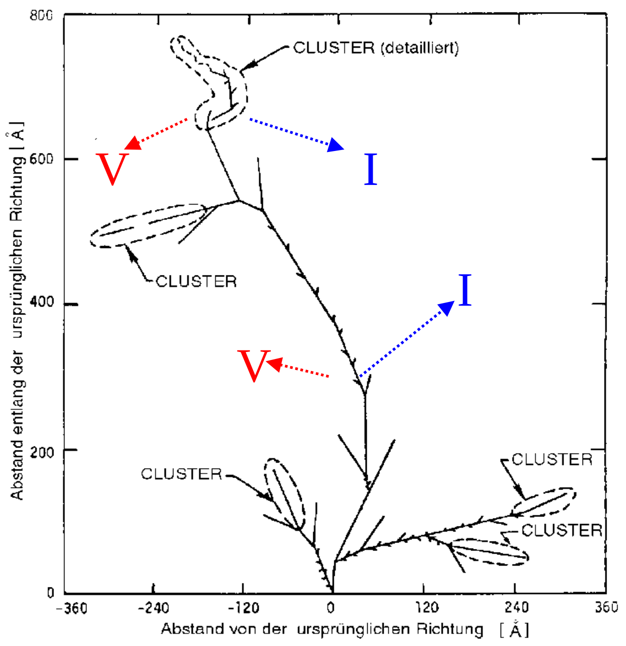
[I. Dawson, P. S. Miyagawa, Sheffield University, Atlas]

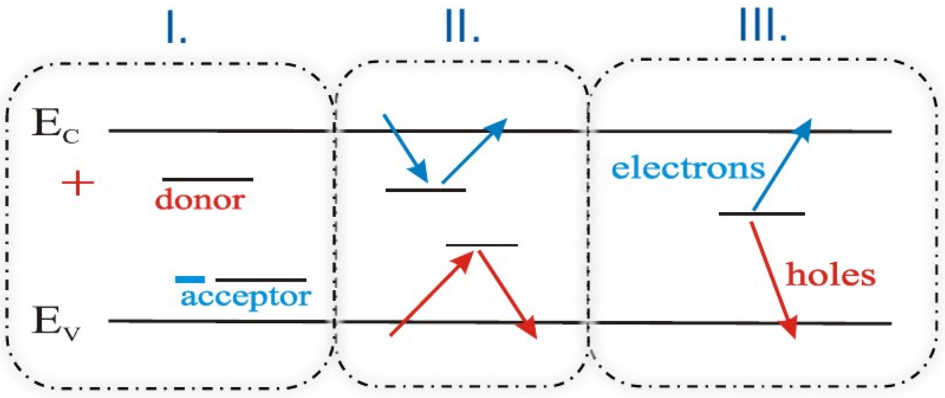
- **Increasing radiation levels**
  - Semiconductor detectors will face >10^{16} n_{eq}/cm^2 (**HL-LHC**) and >7×10^{17} n_{eq}/cm^2 (**FCC-hh**)
    - detectors used at LHC cannot be operated after such irradiation
- **New requirement and new detector technologies**
  - New requirements or opportunities lead to new technologies (e.g. HV-CMOS, LGAD,…) which need to be evaluated and optimized in terms of **radiation hardness and/or 4D tracking capabilities**

Problem: Radiation Damage

Main effects:

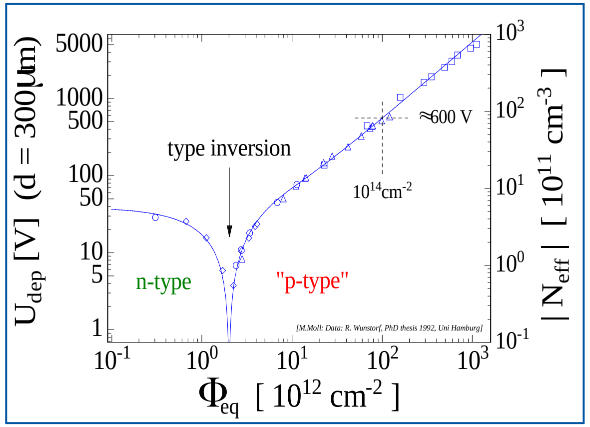
- **Ionizing Energy Loss (IEL)**
  - Surface effect: trapping charges in the oxide
  - Main effect for electronics (with SEUs)
- **Non Ionizing Energy Loss (NIEL)**
  - Bulk effect: Si atoms displaced from lattice position
  - Interstitials and Vacancies formed (Frenkel pairs) resulting in point and cluster defects
  - Creation of defect states in the band gap:
    - **I. Change of internal E-Field**
      charged defects change depletion,
      leading to under depletion, loss of signal
    - **II. Charge trapping**
      loss of signal charge
    - **III. Increase of leakage**
      increase of power consumption
      increase of noise



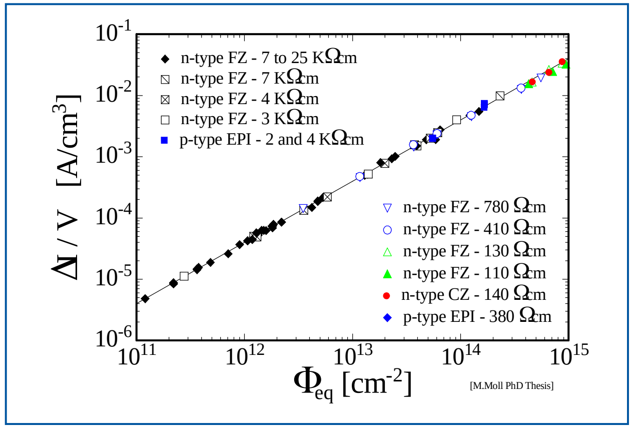


Radiation Damage Summary

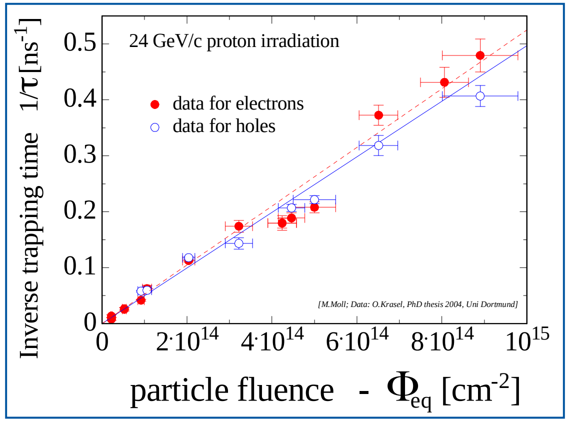
- Macroscopic bulk effects:



Depletion Voltage (N_{eff})

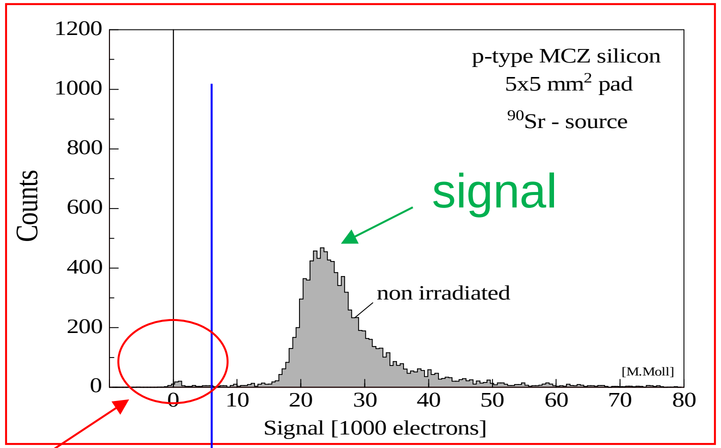


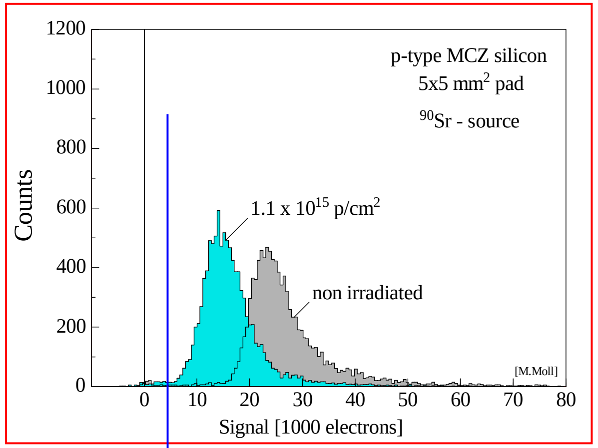
Leakage Current

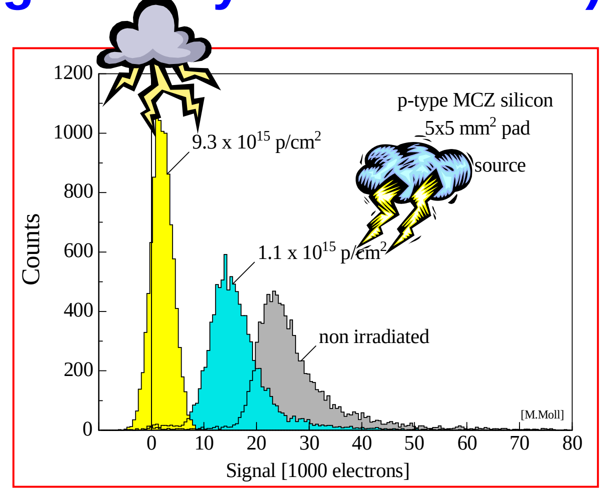


Charge Trapping

- **Signal to Noise ratio is quantity to watch (material + geometry + electronics)**







signal

noise

Cut (threshold)

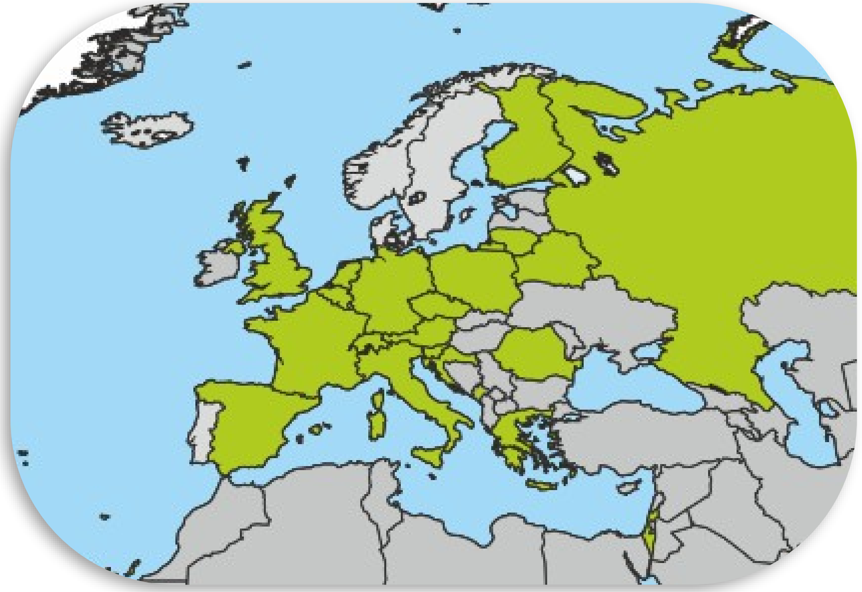
Radiation Hard Detectors

How to increase radiation hardness?

The RD50 Collaboration

Full member list: www.cern.ch/rd50

- RD50: 66 *institutes and 420 members*



51 European institutes

Austria (HEPHY), **Belarus** (Minsk), **Czech Republic** (Prague (3x)), **Finland** (Helsinki, Lappeenranta), **France** (Marseille, Paris, Orsay), **Germany** (Bonn, Dortmund, Freiburg, Göttingen, Hamburg (Uni & DESY), Karlsruhe, Munich (MPI & MPG HLL)), **Greece** (Demokritos), **Italy** (Bari, Perugia, Pisa, Trento, Torino), **Croatia** (Zagreb), **Lithuania** (Vilnius), **Montenegro** (Montenegro), **Netherlands** (NIKHEF), **Poland** (Krakow), **Romania** (Bucharest), **Russia** (Moscow, St.Petersburg), **Slovenia** (Ljubljana), **Spain** (Barcelona(3x), Santander, Sevilla (2x), Valencia), **Switzerland** (CERN, PSI, Zurich), **United Kingdom** (Birmingham, Glasgow, Lancaster, Liverpool, Oxford, Manchester, RAL)

Full member list: www.cern.ch/rd50

8 North-American institutes

Canada (Ottawa), **USA** (BNL, Brown Uni, Fermilab, LBNL, New Mexico, Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

6 Asian institutes

China (Beijing-IHEP, Dalian, Hefei, Jilin, Shanghai), **India** (Delhi)

Approaches to develop radiation harder solid state detectors

Scientific strategies:

I. Material engineering

II. Device engineering

III. Change of detector operational conditions

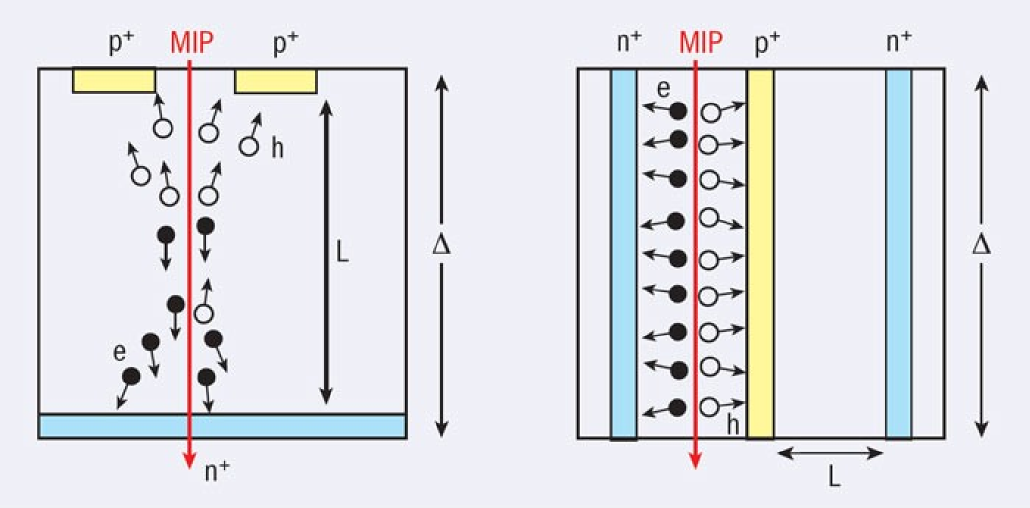
CERN-RD39 (closed, now part of RD50)
“Cryogenic Tracking Detectors”
operation at 100-200K to reduce charge loss

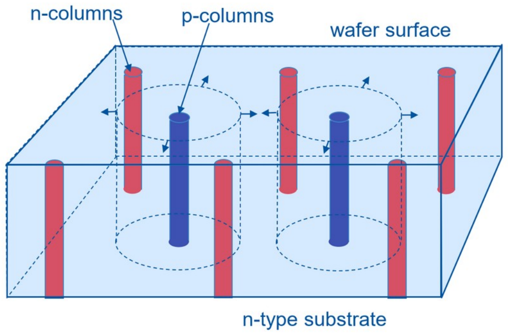
- Defect Engineering of Silicon

  Deliberate incorporation of impurities or defects into the silicon bulk to improve radiation tolerance of detectors

  - Needs: Profound understanding of radiation damage
    - microscopic defects, macroscopic parameters
    - dependence on particle type and energy
    - defect formation kinetics and annealing
  - Examples:
    - **Oxygen rich Silicon (DOFZ, Cz, MCZ, EPI)**
    - Oxygen dimer & hydrogen enriched Si
    - Pre-irradiated Si
    - Influence of processing technology
- New Materials
  - Silicon Carbide (SiC), Gallium Nitride (GaN)
  - Diamond (CERN RD42 Collaboration)
  - Amorphous silicon, Gallium Arsenide
- Device Engineering (New Detector Designs)
  - p-type silicon detectors (n-in-p)
  - thin detectors, epitaxial detectors
  - 3D detectors and LGAD - Low Gain Avalanche Detector
  - Cost effective detectors
  - Monolithic devices – HV-CMOS

Device engineering example:
3D Hybrid Pixel Detectors





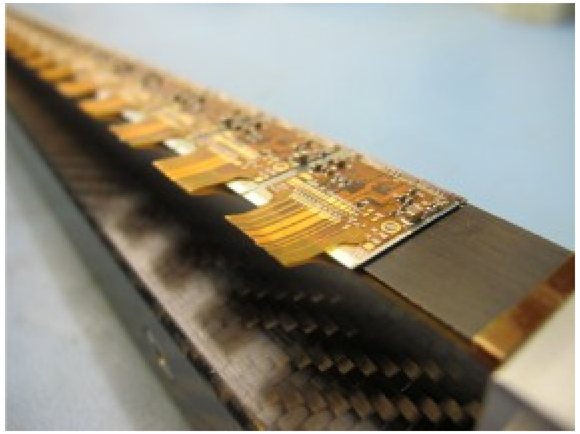
Array of narrow electrode columns (~ 5-10µm) passing <u>through</u> the silicon thickness (micromachining):

- Depletion voltage prop. spacing^2
- Collection time prop. spacing
- Reduced charge sharing

-- More suited to high radiation environment

Connected to standard pixel ASIC – hybrid pixel detector

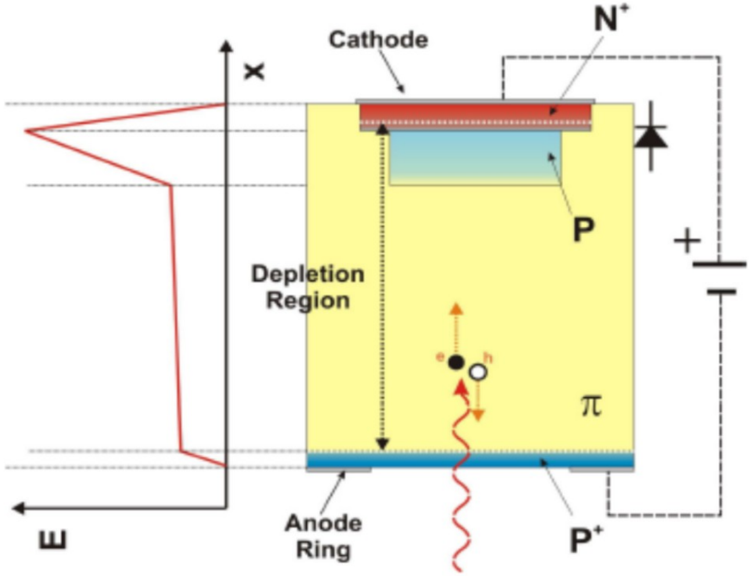
Installed 2014 in ATLAS IBL
(Inner b-layer)
&
Inner pixel layers
for LHC phase II (2028)



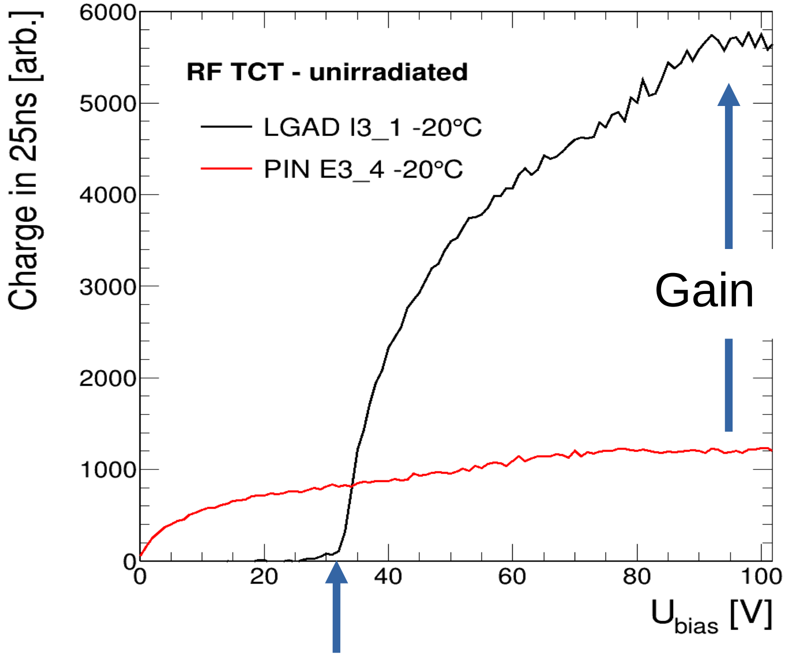
Device engineering example 2:
Low Gain Avalanche Detectors (LGAD)

Highly doped p-implant leads to charge multiplication through impact ionization
-- Larger signal and faster rise time.

LGADs are based on the APD concept but have a lower gain, optimized for 4D-tracking applications:
.. fast signal rise time
.. optimal S/N ratio
.. reduced cross-talk



M. Carulla,
Low Gain Avalanche Detectors



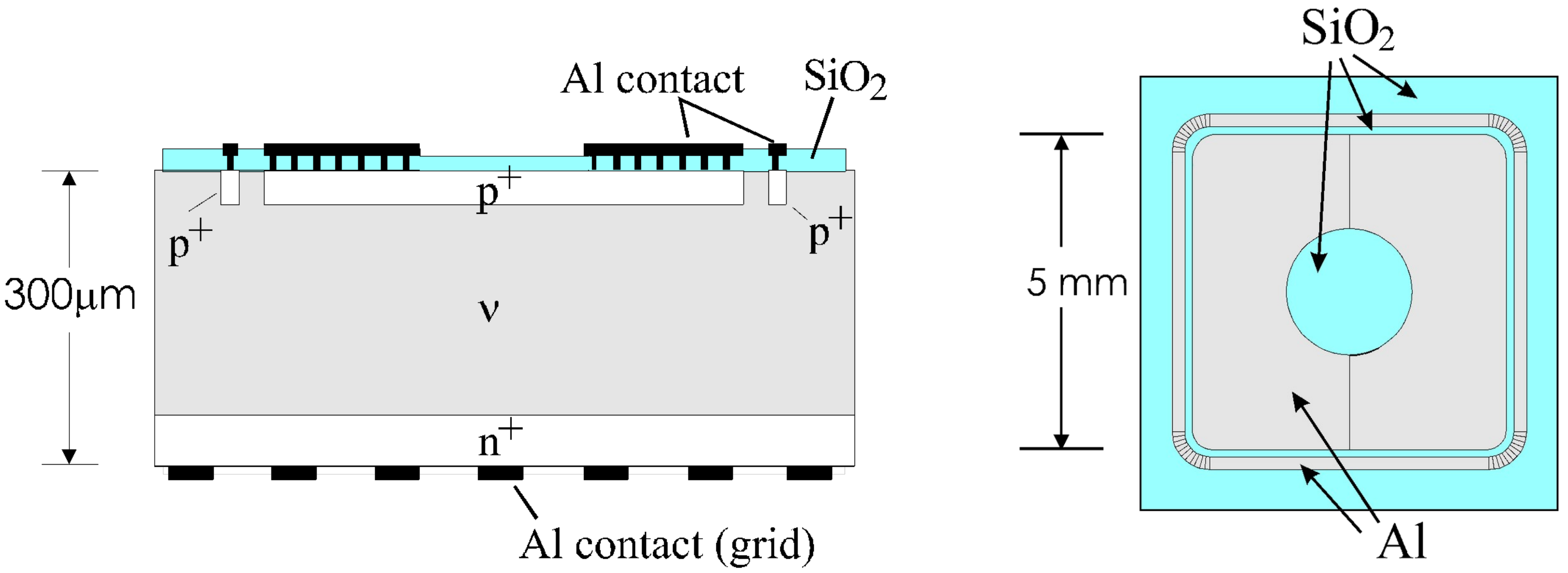
Gain

Amplification onset voltage

Characterization Techniques

What are we going to measure
in our “hands-on” workshop?

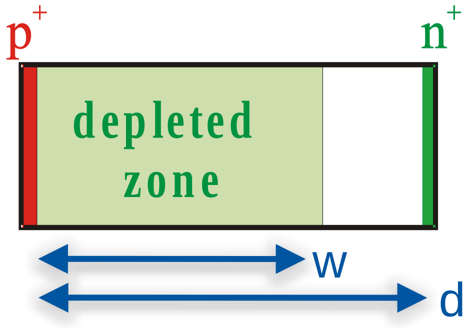
Testing Structures - Simple Diodes



- Very simple structures in order to concentrate on the bulk features
  - Typical thickness: 300µm
  - Typical active area: 0.5 × 0.5 cm^2
- Openings in front and back contact
  - optical experiments with lasers or LED

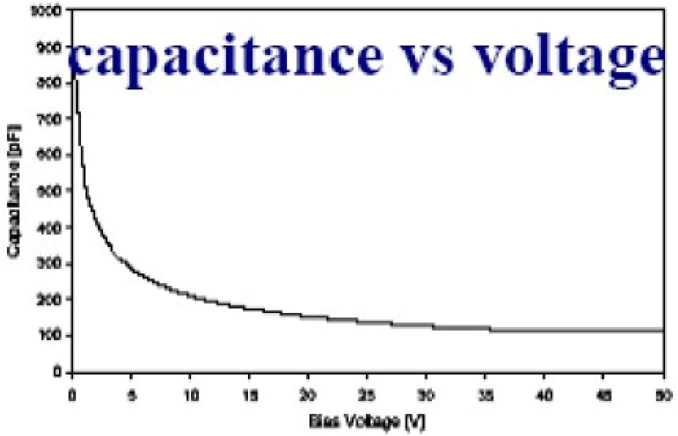
Depletion Zone: Properties

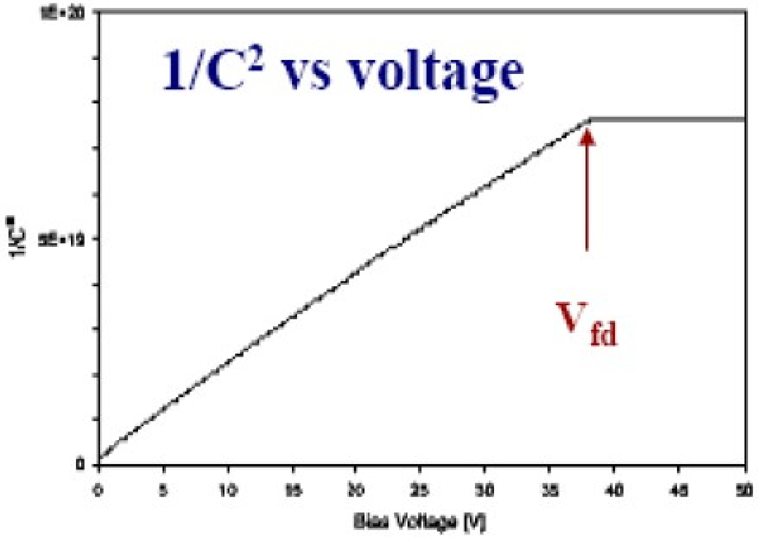
- The depletion voltage can be determined by measuring the capacitance versus the applied reverse bias voltage. The capacitance is simply the parallel plate capacity of the depletion zone.



$$C(V) = \frac{\epsilon\epsilon_0 A}{w} = A\cdot\sqrt{\frac{\epsilon\epsilon_0 q_0 |N_{eff}|}{2\cdot V}}$$

- ε, ε_0 dielectric constants
- A = area of sensor
- w = depletion width
- N_{eff}= effective doping concentration
- V = Voltage applied
- q_0 = elementary charge

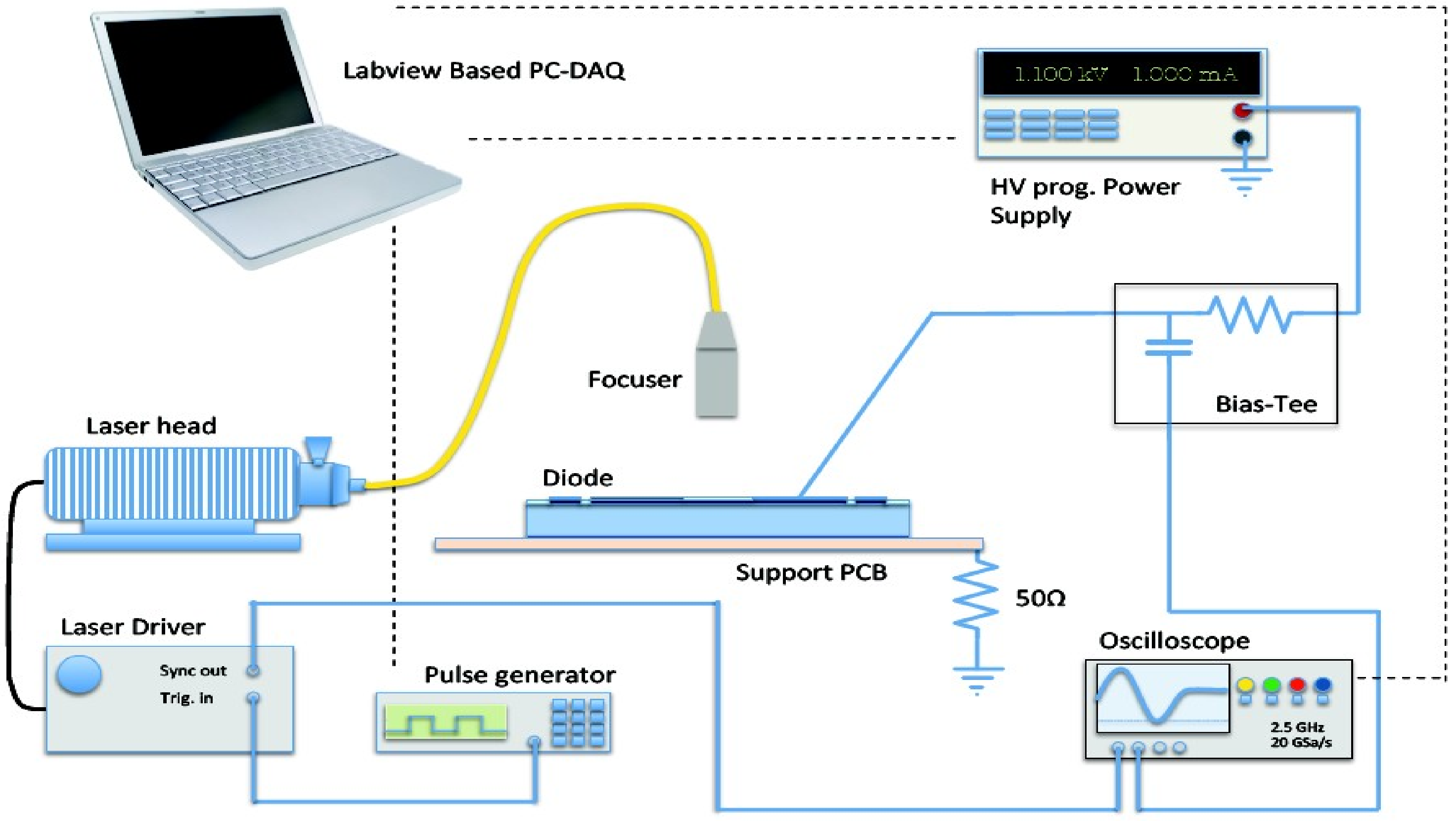




$$V_{dep} = \frac{q_0}{2\epsilon\epsilon_0}|N_{eff}|d^2$$

TCT – Transient Current Technique

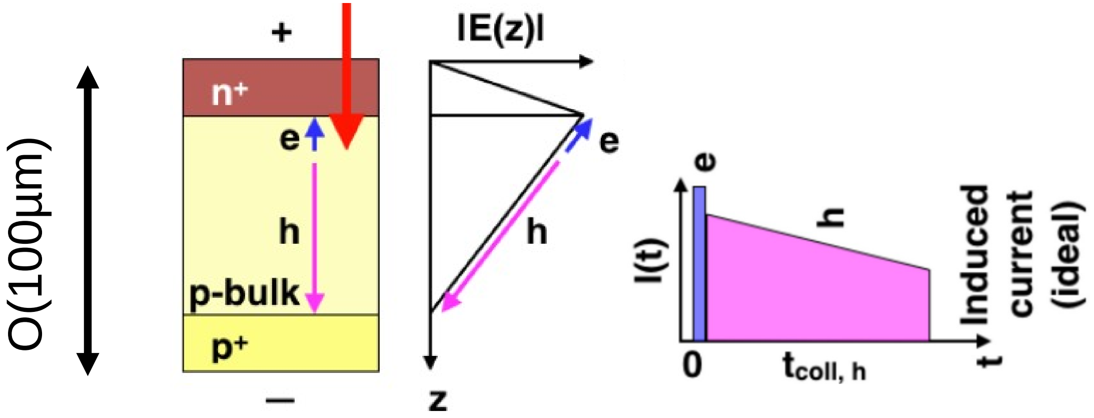
- Study of laser pulse induced current transients in silicon sensors
  - Schematic view of the TCT setup

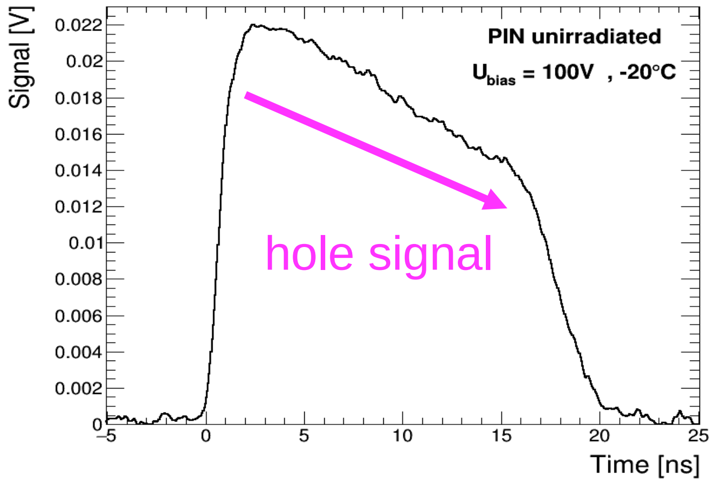


Nicola Pacifico, PhD thesis, CERN SSD & Bari University, 2012

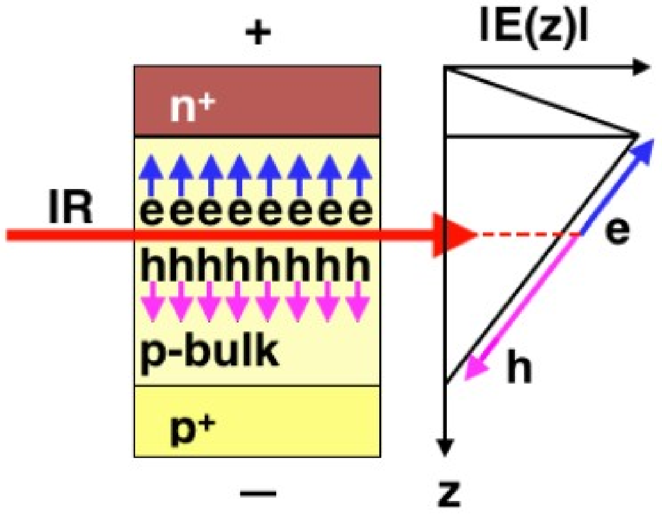
TCT explained

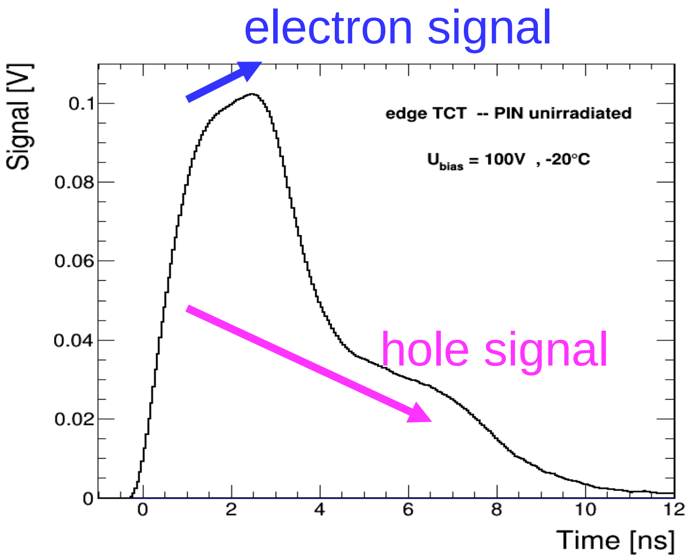
Red 660nm





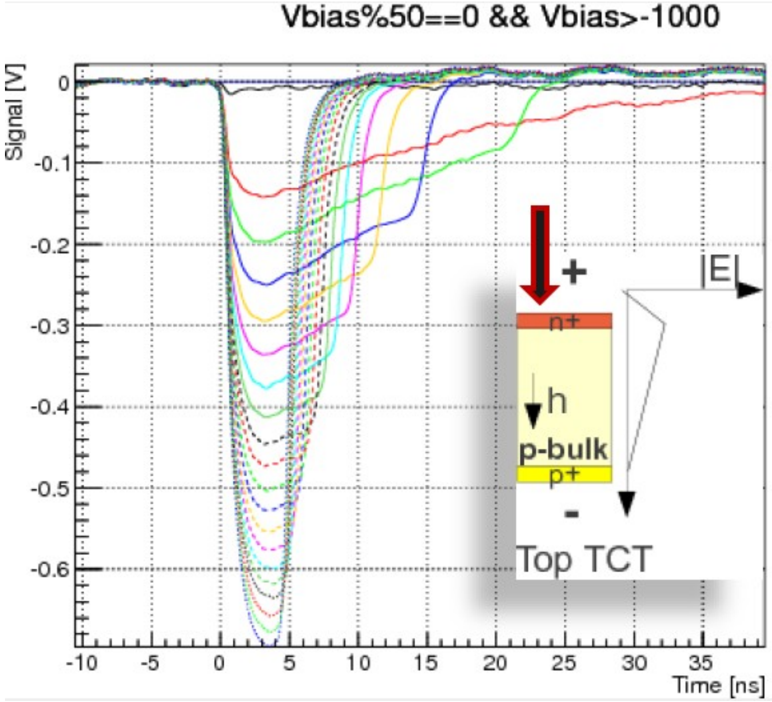
Near IR 1064nm
edge-TCT

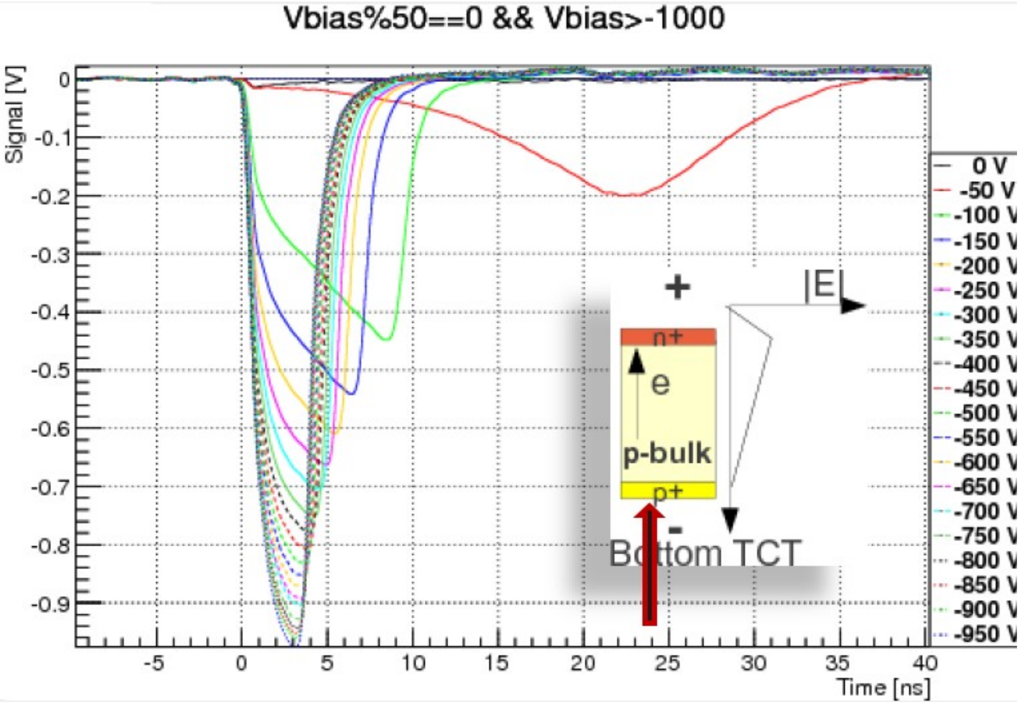




DT seminar: M. Fernández, The Transient Current Technique: laser characterization of silicon detectors https://indico.cern.ch/event/684193/
C. Gallrapp, The TCT+ setup - a system for TCT, eTCT and timing measurements, 1st TCT Workshop (2015)

TCT example: diode





- Top TCT, h-injection (p-bulk):
  - Induced current maximum at front junction
  - Longer collection time due to smaller drift velocity

- Bottom TCT, e-injection:
  - Drift velocity increase towards the front side
  - Shorter collection time, and higher amplitude of pulses, both due to higher drift velocity

Summary

- **Silicon Sensors are based on reverse biased pn-junctions** (silicon sensors are reverse biased diodes)

- **Silicon Detectors at the LHC and upgrade of LHC**
  - Inner tracking at LHC and HL-LHC done by silicon detectors
  - Hybrid-pixel (planar and 3D) and strip sensors implemented in LHC experiments (ALICE upgraded to monolithic sensors)
  - Radiation Hard Monolithic sensors under development (competing beyond LS3 for HL-LHC upgrades)

- **Radiation Damage in Silicon Sensors**
  - Damage: displacement damage that is evidenced as defect levels in the band gap of the semiconductor
    (+ some impact of surface damage in segmented sensors)
  - **Modification of internal electric field** (space charge distribution, depletion voltage, "type inversion", reverse annealing, loss of active volume, …), defect engineering possible!
  - **Increase of Leakage Current** and **Charge Trapping** (same for all silicon materials)
  - **Signal to Noise ratio** is quantity to watch (material + geometry + electronics)

- **Radiation tolerant silicon sensors**
  - Several examples of successful Material and Device Engineering (mitigation strategies)
    oxygenation, 3D sensors, p-type (n-readout) sensors

- **Hands-on:**
  - **Current-Voltage and Capacitance-Voltage measurements**
  - **Transient Current Technique (TCT) measurements**

Acknowledgements & References

- **Most references to particular works given on the slides**
  - RD50 workshop presentations: http://www.cern.ch/rd50/
  - Conferences: VERTEX, PIXEL, RESMDD, …
- **Instrumentation Schools**
  - ICFA, EDIT, ESI, CERN & DESY Summer Student Lectures
- **Books about silicon tracking detectors (and radiation damage)**
  - Helmuth Spieler, “Semiconductor Detector Systems”, Oxford University Press 2005
  - C.Leroy, P-G.Rancoita, “Silicon Solid State Devices and Radiation Detection”, World Scientific 2012
  - Frank Hartmann, “Evolution of silicon sensor technology in particle physics”, Springer 2009 & 2017
  - L.Rossi, P.Fischer, T.Rohe, N.Wermes “Pixel Detectors”, Springer, 2006
  - Gerhard Lutz, “Semiconductor radiation detectors”, Springer 1999
- **Review Articles**
  - 2018: Garcia-Sciveres and Wermes, A review of advances in pixel detectors for experiments with high rate and radiation, https://doi.org/10.1088/1361-6633/aab064
  - 2018: M.Moll, Displacement Damage in Silicon Detectors for High Energy Physics https://doi.org/10.1109/TNS.2018.2819506
- **Research collaborations and web sites**
  - CERN RD50 collaboration (http://www.cern.ch/rd50) - Radiation Tolerant Silicon Sensors
  - CERN RD42 collaboration – Diamond detectors
  - Inter-Experiment Working Group on Radiation Damage in Silicon Detectors (CERN)
  - ATLAS IBL, ATLAS and CMS upgrade groups