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Introduction aux détecteurs semi-conducteurs

An introduction to Silicon Detectors with focus on High Energy Physics applications

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Outline

- **I. Basics of Silicon Detectors for High Energy Physics Applications**
  - **The basic concept of Semiconductor Detectors: A reverse biased pn-junction**
  - **Silicon Detectors at the Large Hadron Collider (LHC) at CERN**
  - **Upgrade of the Large Hadron Collider**
    - Timeline, challenges & motivation to study and understand radiation damage
- **II. Introduction to Radiation Damage in Silicon Detectors**
  - **What is Radiation Damage?**
  - **Mitigation techniques: What can we do against radiation damage?**
    - Examples: oxygenated silicon, p-type strip sensors, 3D sensors
- **III. Why do we need TCAD simulations?**
    - Example: Complex sensor structure: 3D sensor
    - Example: Irradiation effects: The double junction effect
- **Summary & Further reading**

I.Basic operation principle of a silicon sensor

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 ≈ 10^6 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**

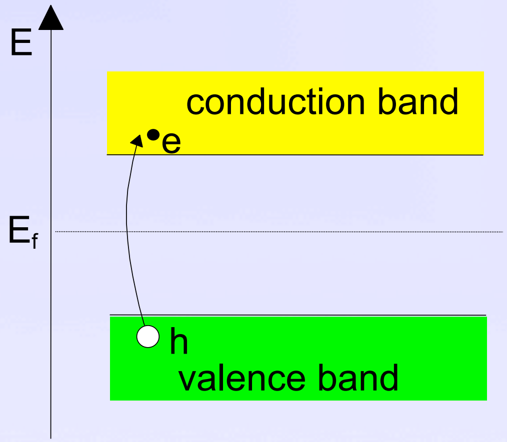
    ⇒ well known industrial technology, relatively low price, small structures easily possible

    ⇒ sophisticated commercial TCAD tools available for sensor simulation

- **Alternative Semiconductors**
  - Diamond
  - GaAs
  - Silicon Carbide
  - Germanium
  - GaN

	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]	3.515	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 a signal?

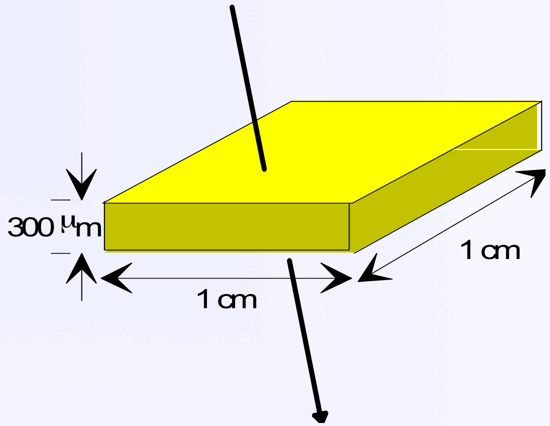


- **Intrinsic semiconductor**
  - In a pure intrinsic (undoped) semiconductor the electron density n and hole density p are equal.

$$n = p = n_i$$

For Silicon: $n_i \approx 1.45 \cdot 10^{10}$ cm^{-3}

- **Ionizing particle passing through Silicon**
  - $4.5 \cdot 10^8$ free charge carriers in this volume, but only $3.2 \cdot 10^4$ e-h pairs produced by a M.I.P. *(minimum ionizing particle)*

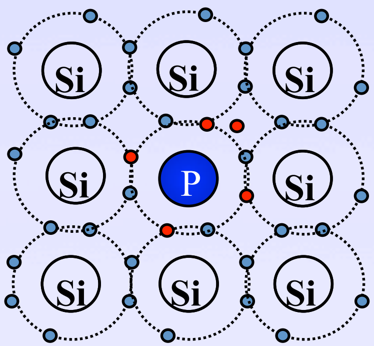


➢ **Need to reduce number of free carriers, i.e. <u>deplete</u> the detector**

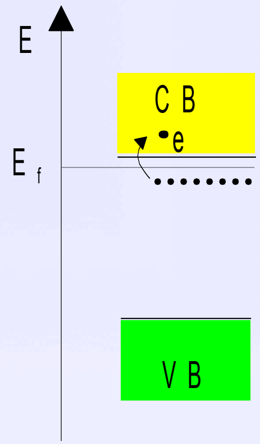
➢ **Solution: Make use of reverse biased p-n junction (reverse biased diode)**

Doping, Resitivity and p-n junction

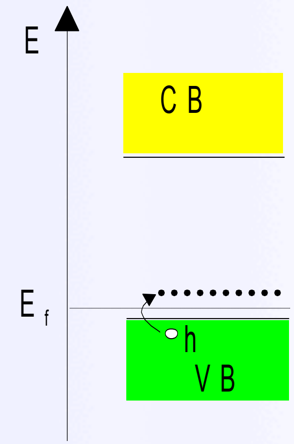
e.g. Phosphorus



- **Doping: n-type Silicon**
  - add elements from V^{th} group
    ⇒ donors (P, As,..)
  - electrons are majority carriers



- **Doping: p-type Silicon**
  - add elements from III^{rd} group
    ⇒ acceptors (B,..)
  - holes are majority carriers

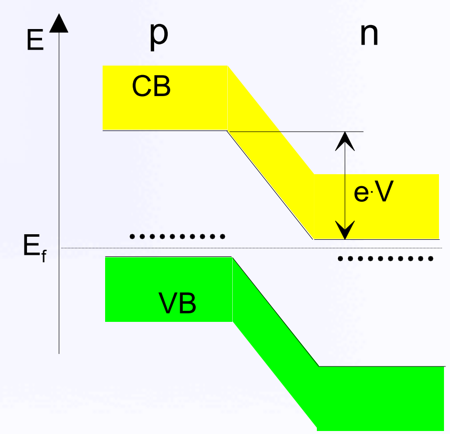


- **Resistivity**
  - carrier concentrations *n, p*
  - carrier mobility μ_n, μ_p

$$\rho = \frac{1}{q_0(\mu_n n + \mu_p p)}$$

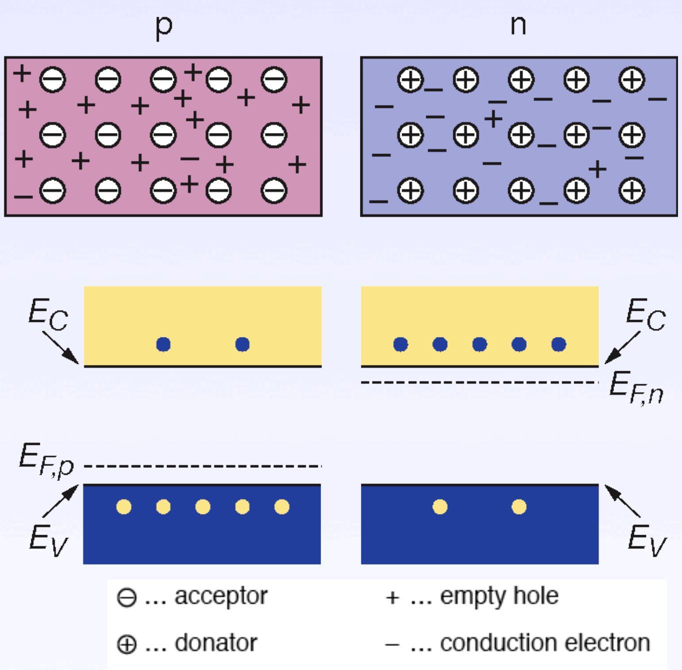
	detector grade	electronics grade
doping	≈ 10^{12} cm^{-3}	≈ 10^{17} cm^{-3}
resistivity ρ	≈ 5 kΩ·cm	≈1 Ω·cm

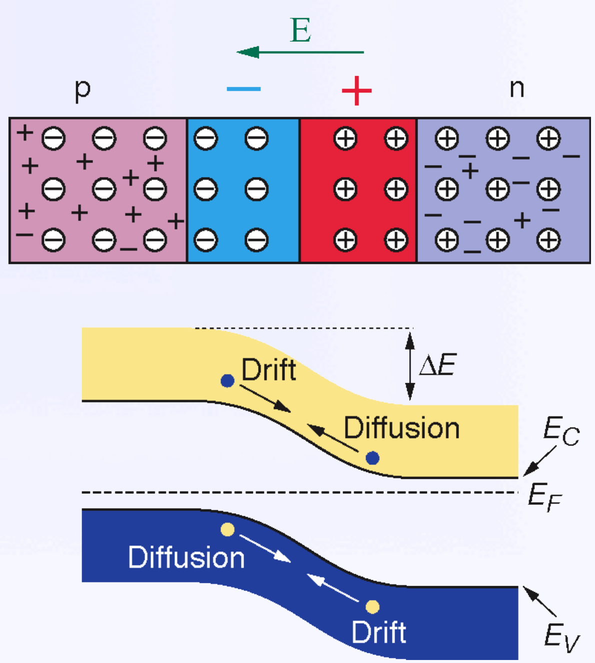
- **p-n junction**
  - There must be a single Fermi level !
  - ⇒ band structure deformation
  - ⇒ potential difference
  - ⇒ depleted zone



The p-n Junction

- **Creating a p-n junction**
  - **At the interface of an n-type and p-type semiconductor the difference in the fermi levels cause diffusion of surplus carries to the other material until thermal equilibrium is reached. At this point the fermi level is equal. The remaining ions create a space charge and an electric field stopping further diffusion.**
  - **The stable space charge region is free of charge carries and is called the depletion zone.**

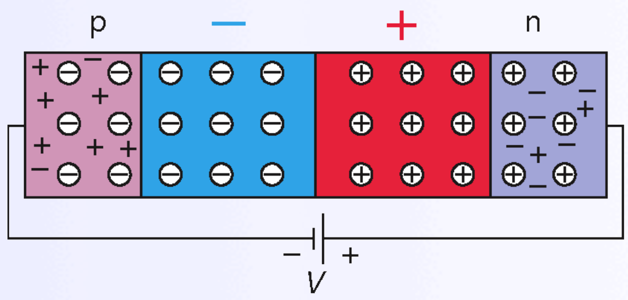


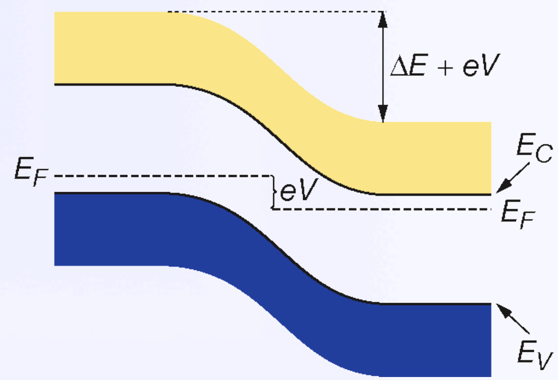


The p-n Junction

- **Operation with reverse bias**
  - **Applying an external voltage V with the cathode to p and the anode to n e- and holes are pulled out of the depletion zone. The depletion zone becomes larger.**
  - **The potential barrier becomes higher by eV and diffusion across the junction is suppressed. The current across the junction is very small "leakage current".**

p-n junction with reverse bias





That's the way we operate our semiconductor detectors!

Poisson equation – abrupt junction

- Poisson equation
  - relating charge density to electrostatic potential

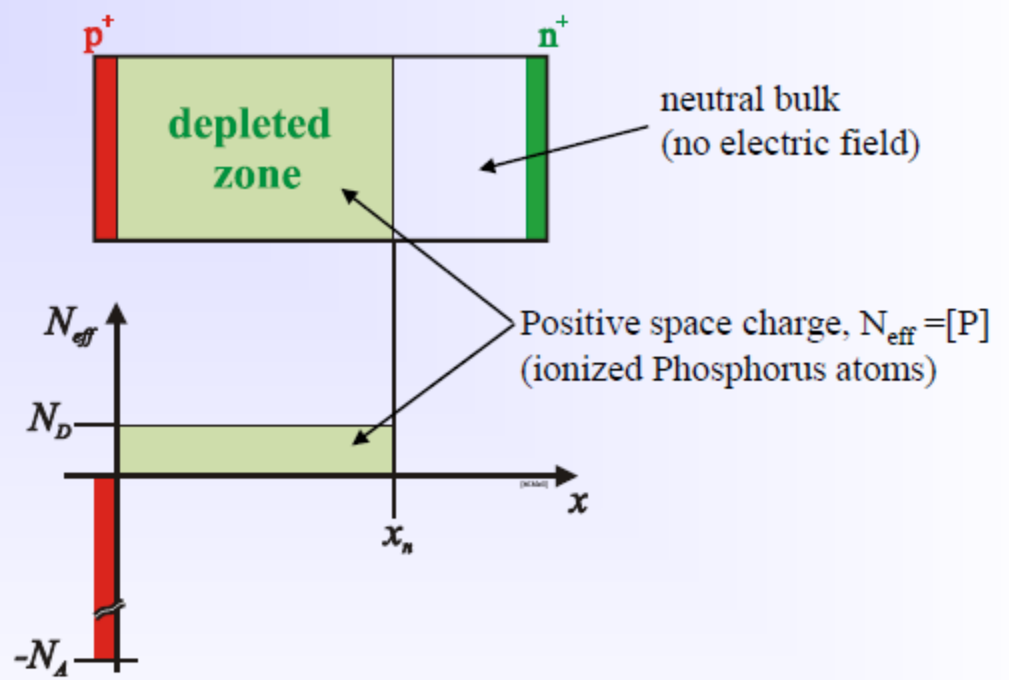
$$-\Delta\phi = -\nabla(\nabla\phi) = \nabla(\vec{E}) = \frac{\rho}{\varepsilon}$$

ϕ = electrostatic potential
ρ = charge density
ε = electric constant $(11.9\times\varepsilon_0)$
N_{eff} = effective space charge
e = elementary charge
E = electric field

  - in a one dimensional formulation for our simplified case under study

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

- Abrupt junction
  - **N_A (implant) >> N_D (bulk)**
    ⇒ electric field extending into the n-type bulk of the diode
  - **N_{eff} = N_D= [P]**
    positive space charge produced by n-type doping (Phosphorus)



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

Poisson equation

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

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

$$E(w) = 0$$

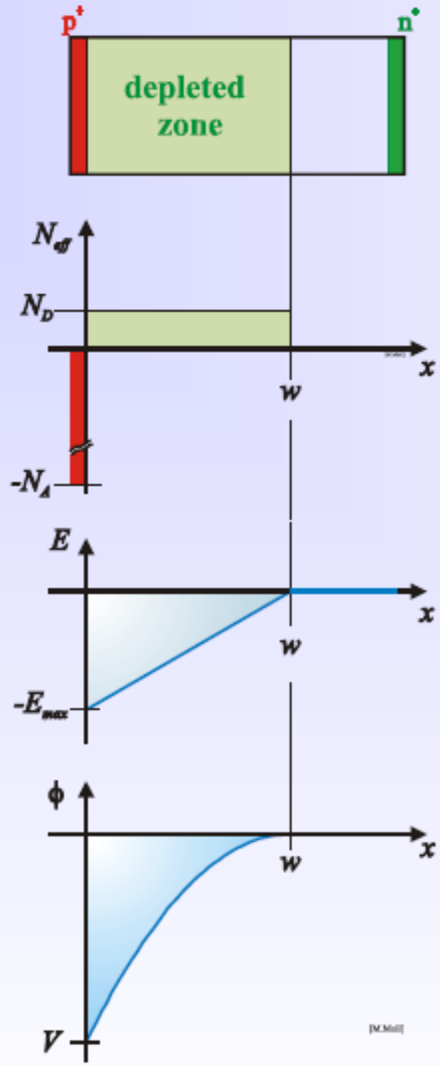
Electric field strength

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

$$\phi(w) = 0$$

Electrostatic potential

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



– electric field strength linear function of depth

– depleted zone growing in depth proportional to sqrt(V)

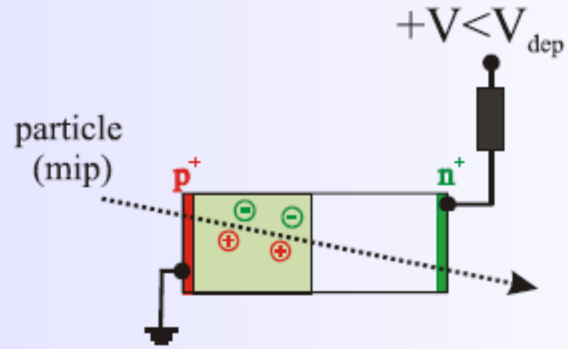
$$E_{max} = -\frac{e \cdot N_{eff}}{\varepsilon} \cdot w$$

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

Depletion depth w

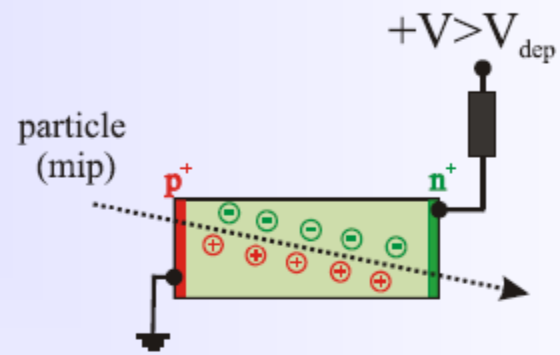
Depletion Voltage

- Below depletion ($V<V_{dep}$)
  - Depletion zone x_n growing with $w \propto \sqrt{V}$
  - Only charge generated inside depleted volume will be detected
  - Charge generated in 'neutral zone' (field free zone) will recombine



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

  - Example:
    - d = 300 μm
    - N_{eff} = [P] =1.5×10^{12} cm^{-3}
      (ρ ≈ 3kΩcm)
    - $V_{dep} \approx$ 100V



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

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

effective space charge density N_{eff}

- Full charge collection only for ($V>V_{dep}$)

Reverse biased abrupt p⁺-n junction

- some important formula

Poisson's equation

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

w = depletion depth
d = detector thickness
V = voltage
C = capacitance
N_{eff} = effective doping concentration

with $\frac{d}{dx}\phi(x=w) = 0$

$\phi(x=w) = 0$

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

$$\phi(x) = \frac{1}{2}\cdot\frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}\cdot(x-w)^2$$

$$C = \frac{dQ}{dU} = \frac{dQ\cdot dw}{dw\cdot dU}$$

$$dQ = q_0\cdot|N_{eff}|\cdot A\cdot dw$$

$$dw = \sqrt{\frac{\varepsilon\varepsilon_0}{q_0|N_{eff}|2U}}\cdot dU$$

$$w(V) = \sqrt{\frac{2\varepsilon\varepsilon_0}{q_0|N_{eff}|}\cdot V}$$

depletion voltage

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

effective space charge density

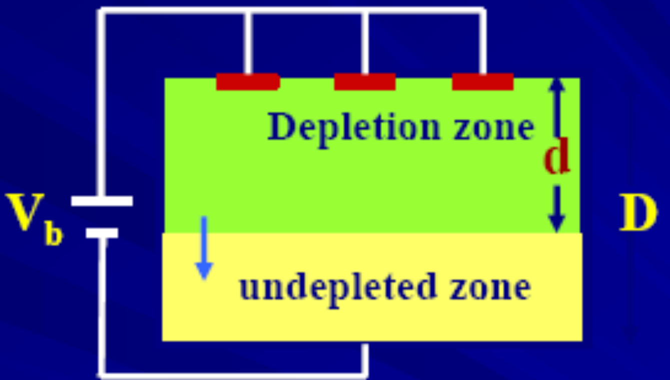
$$C(U) = A\cdot\sqrt{\frac{\varepsilon\varepsilon_0 q_0|N_{eff}|}{2U}}$$

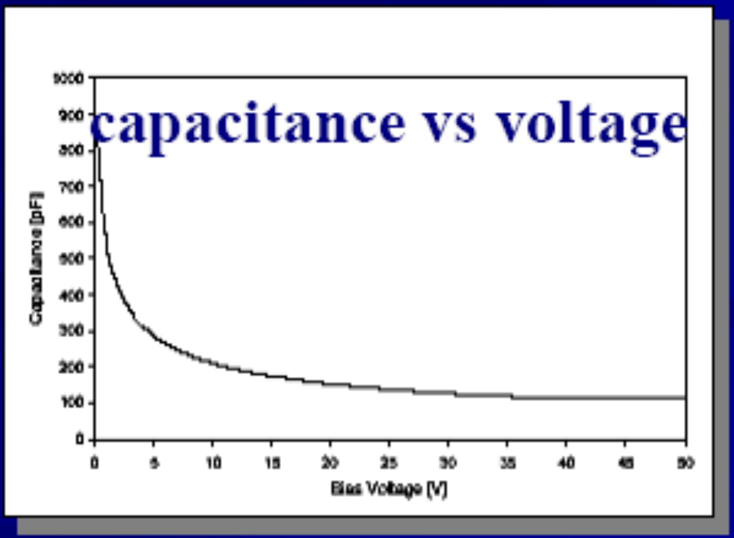
$$C(w) = \frac{\varepsilon\varepsilon_0 A}{w}$$

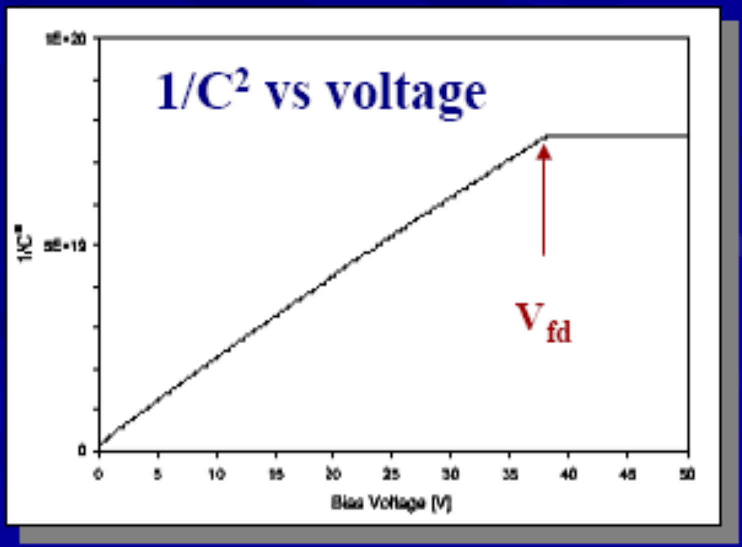
Depletion Zone: Properties

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

$$C = A\sqrt{\frac{\varepsilon}{2\rho\mu V_b}}$$

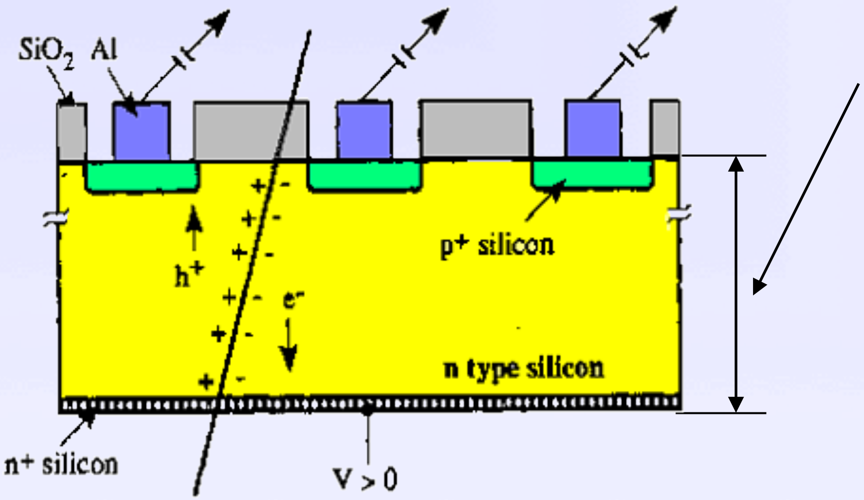






Single sided strip detector

- **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

ρ = 2 KΩcm (N_D ~$2.2 \cdot 10^{12}$ cm^{-3})

results in a depletion voltage ~ 150 V

- **Resolution σ 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

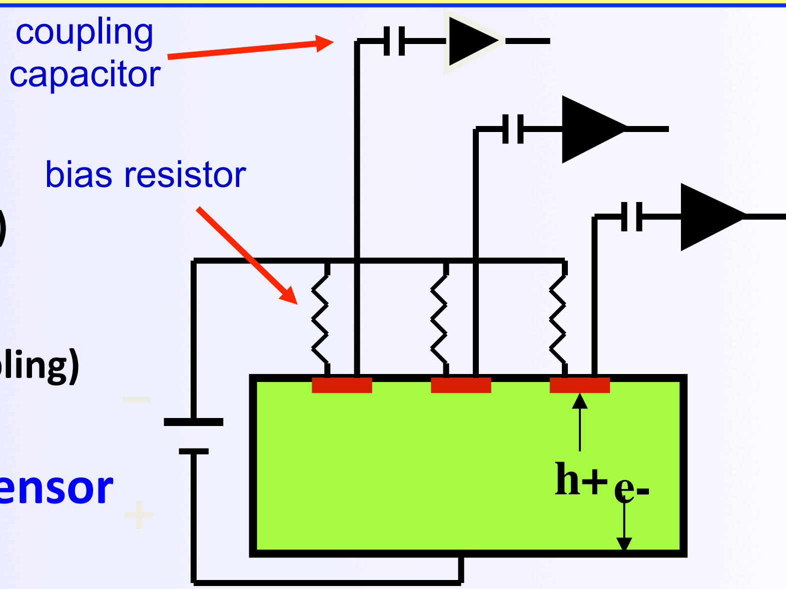
$$\sigma = \frac{p}{\sqrt{12}}$$

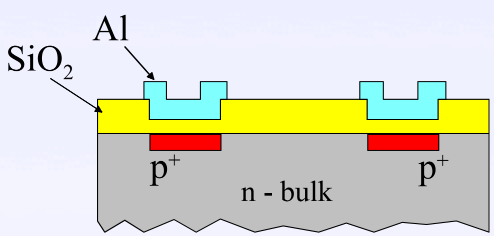
typical pitch values are 20 μm– 150 μm

⇒ 50 μm pitch results in 14.4 μm resolution

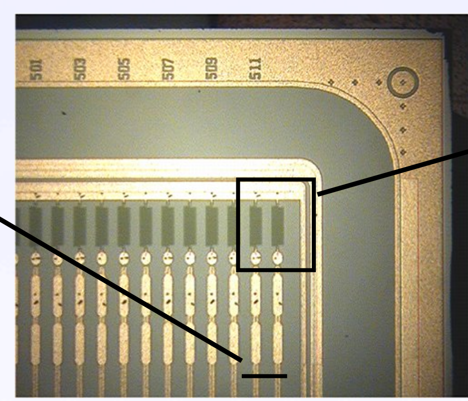
Bias resistor and AC Coupling

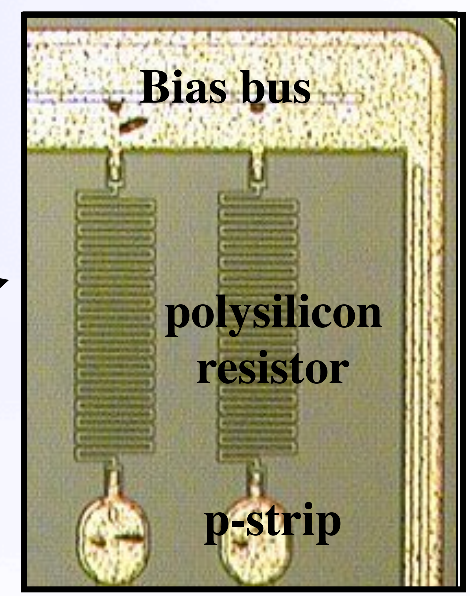
- **Bias resistor**
  - Need to isolate strips from each other to collect/measure charge on each strip
    ⇒ high impedance bias connection (≈ 1MΩ resistor)
- **Coupling capacitor**
  - Couple input amplifier through a capacitor (AC coupling) to avoid large DC input from leakage current
- **Integration of capacitors and resistors on sensor**
  - Bias resistors via deposition of doped polysilicon
  - Capacitors via metal readout lines over the implants but separated by an insulating dielectric layer (SiO_2,Si_3N_4).





⇒ nice integration
⇒ more masks, processing steps
⇒ pin holes





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

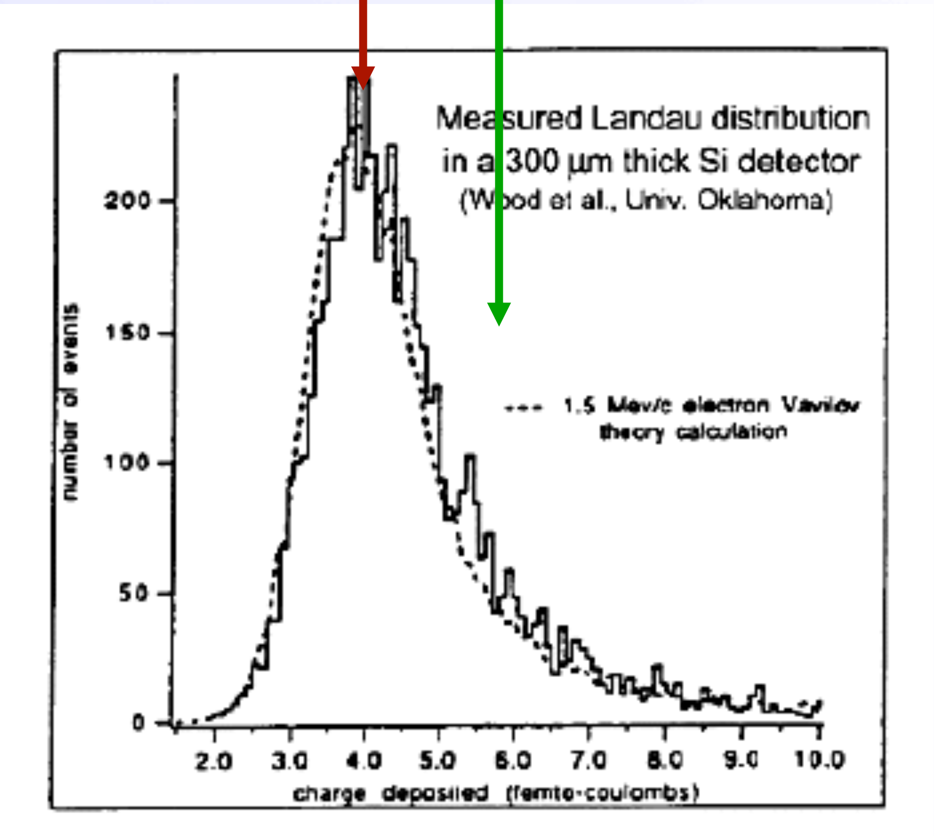
- 3.6 eV to create an e-h pair
  ⇒ 108 e-h / µm (mean)
  ⇒ 72 e-h / µm (most probable)

- Most probable charge **(300 µm)**

  ≈ 22500 e **≈ 3.6 fC**

Most probable charge ≈ 0.7× mean

Mean charge

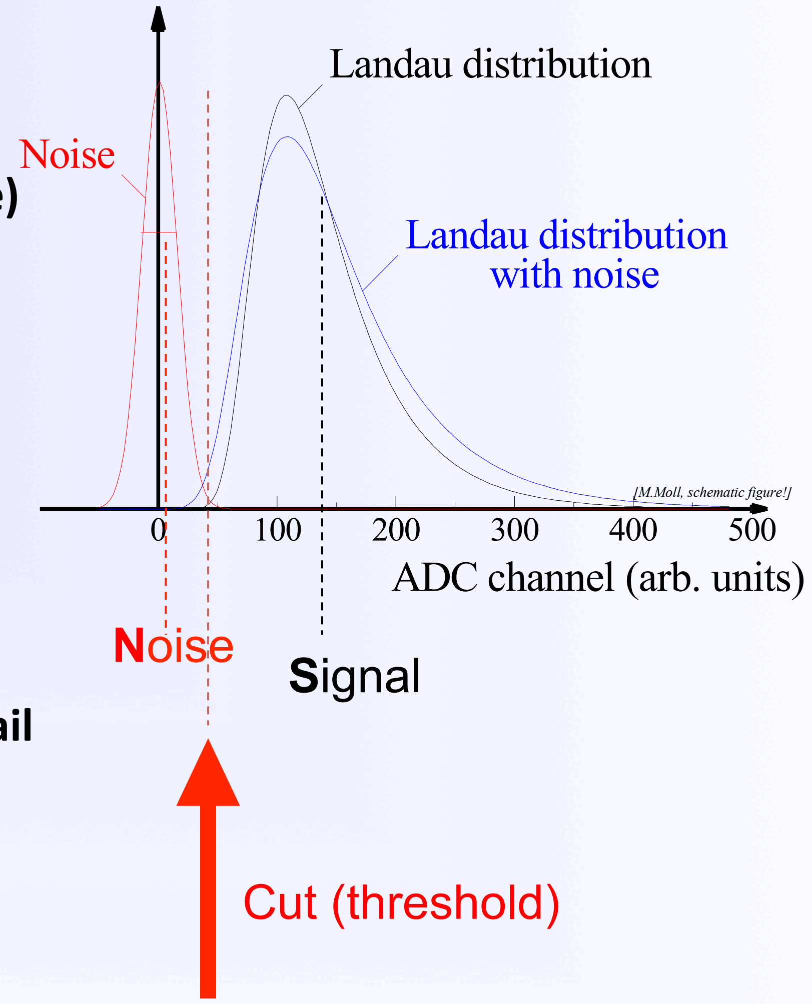


Signal to noise ratio (S/N)

- **Landau distribution has a low energy tail**
  - **becomes even lower by noise broadening**

Noise sources: (ENC = Equivalent Noise Charge)

- **Capacitance** $ENC \propto C_d$
- **Leakage Current** $ENC \propto \sqrt{I}$
- **Thermal Noise (bias resistor)** $ENC \propto \sqrt{k_B T / R}$



- **Good hits selected by requiring N_{ADC} > noise tail**
  If cut too high ⇒ efficiency loss
  If cut too low ⇒ noise occupancy
- **Figure of Merit: Signal-to-Noise Ratio S/N**
- **Typical values >10-15, people get nervous below 10.**
  Radiation damage severely degrades the S/N.

Silicon Detectors at the Large Hadron Collider at CERN

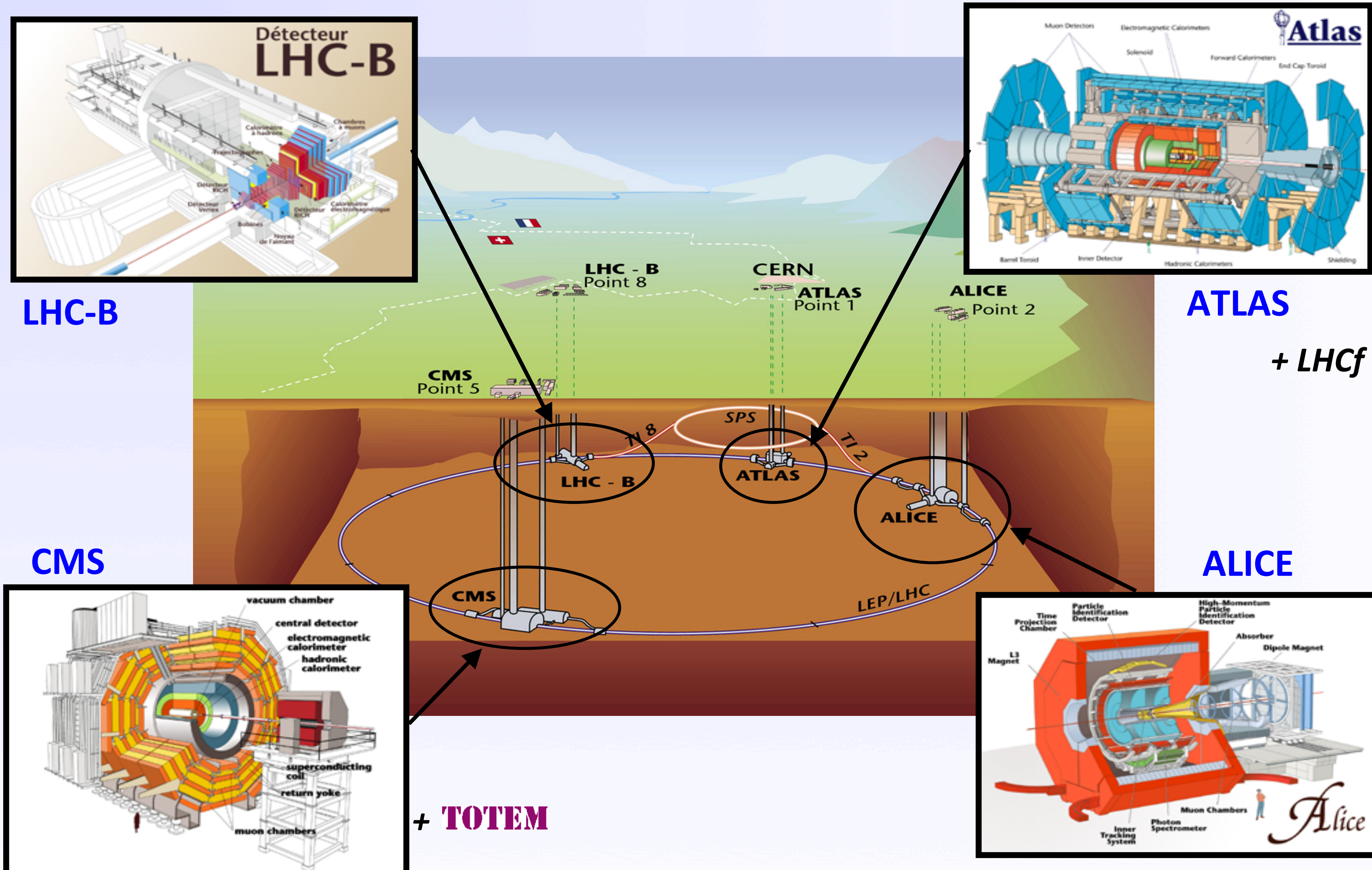
LHC - Large Hadron Collider

- LHC experiments located at 4 interaction points

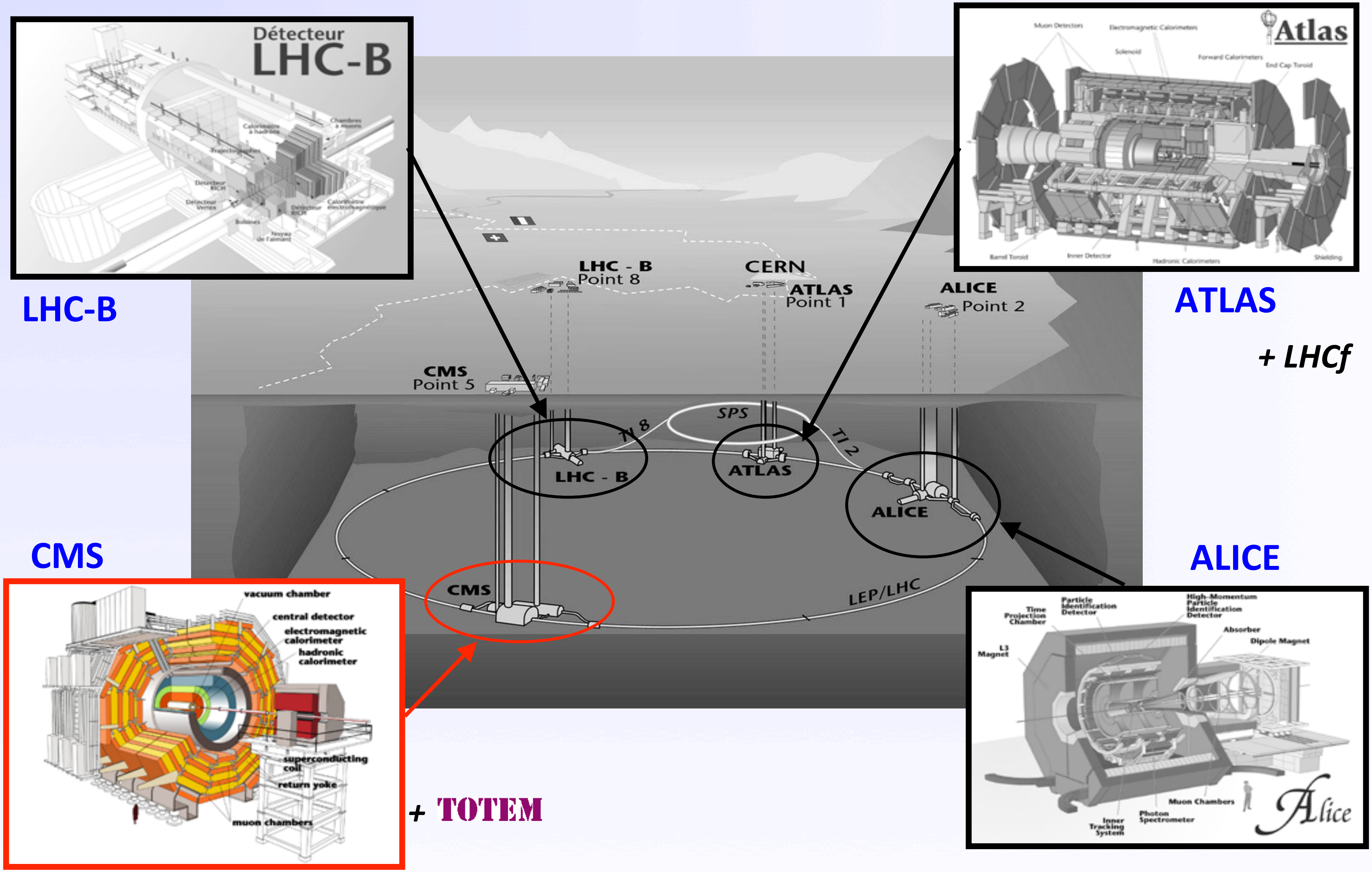
- Installation in existing LEP tunnel (27 Km)
- ≈ 4000 MCHF (machine+experiments)
- 1232 dipoles B=8.3T
- pp $\sqrt{s}$ = 14 TeV
  $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$
- Heavy ions (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)

- **Circulating beams: 10.9.2008**
- **Incident: 18 Sept.2008**
- **Beams back: 19. Nov. 2009**
- **2012: reaching 2 x 4 TeV**
- **2015: Run 2 aim for ≥ 6.5 TeV**
- **….2018: LS2..2020: Run 3**
- **….2023: LS3…2025: Run 4**

LHC Experiments

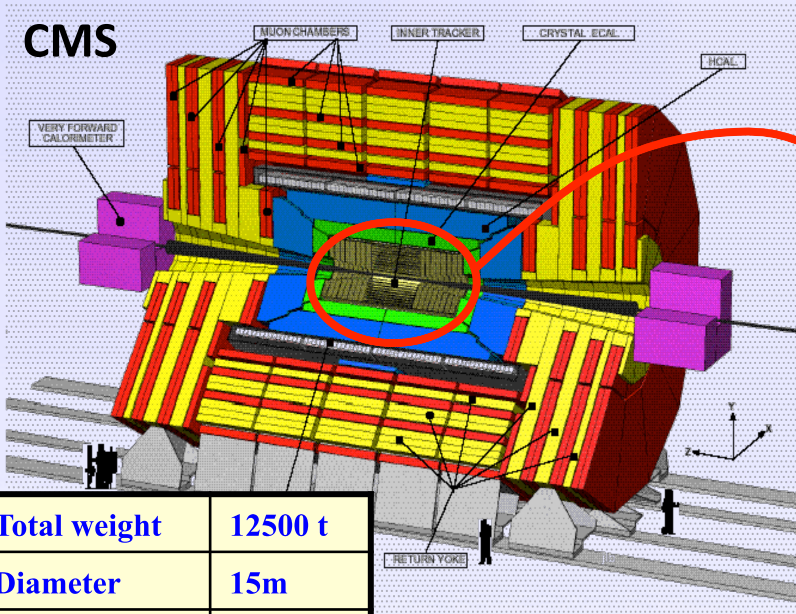


LHC Experiments



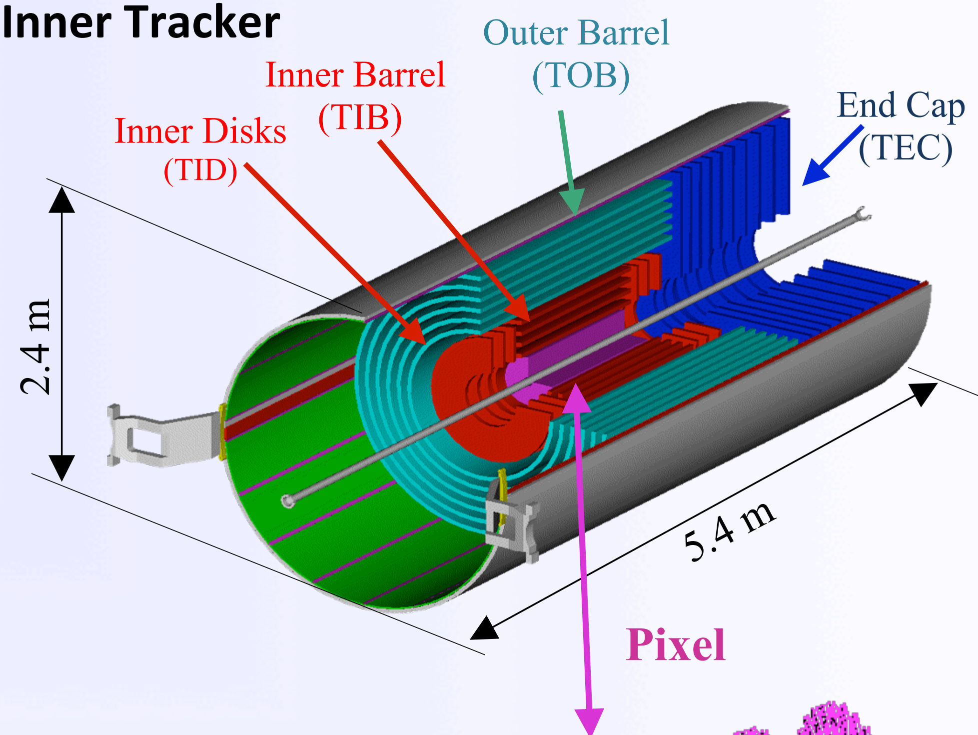
LHC example: CMS inner tracker

- **CMS**



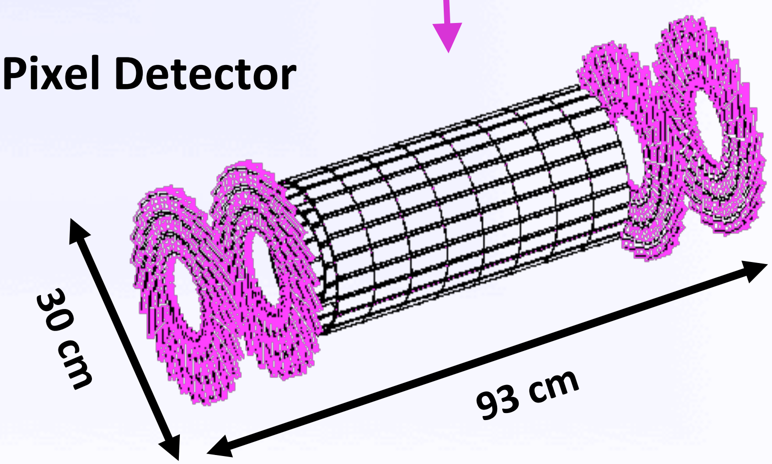
Total weight	12500 t
Diameter	15m
Length	21.6m
Magnetic field	4 T

- **Inner Tracker**

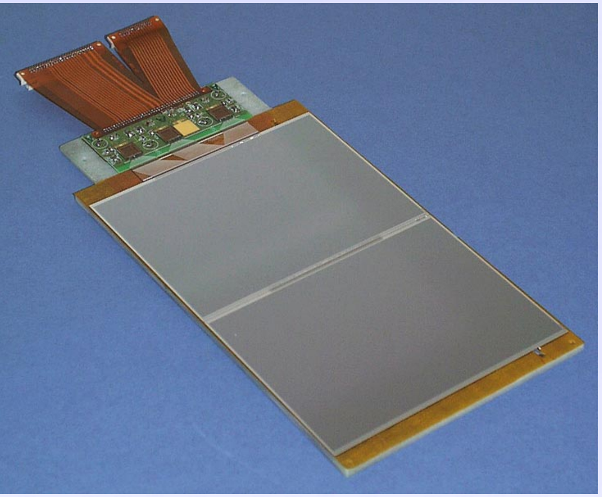


- **CMS – "Currently the Most Silicon"**
  - **Micro Strip:**
  - ~ 214 m^2 of silicon strip sensors, 11.4 million strips
  - **Pixel:**
  - Inner 3 layers: silicon pixels (~ 1m^2)
  - 66 million pixels (100x150μm)
  - Precision: $\sigma(r\phi) \sim \sigma(z) \sim 15\mu m$
  - Most challenging operating environments (LHC)

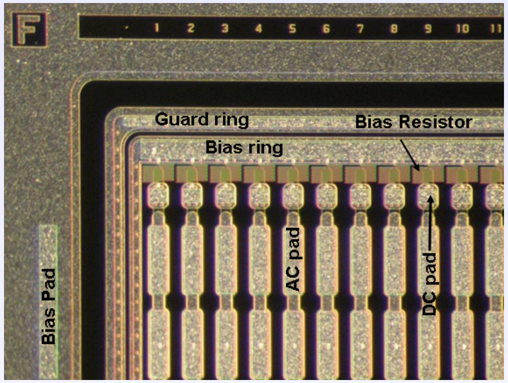
- **Pixel Detector**



Micro-strip Silicon Detectors

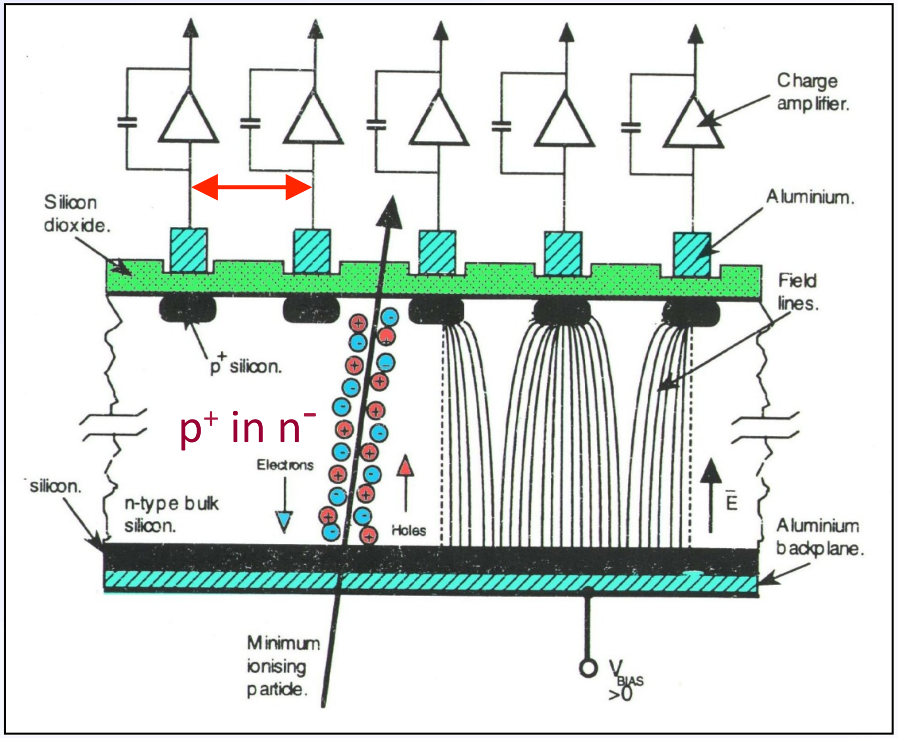


Highly segmented silicon detectors have been used in Particle Physics experiments for nearly 30 years. They are favourite choice for Tracker and Vertex detectors
(high resolution, speed, low mass, relatively low cost)



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

Pitch ~ 50μm



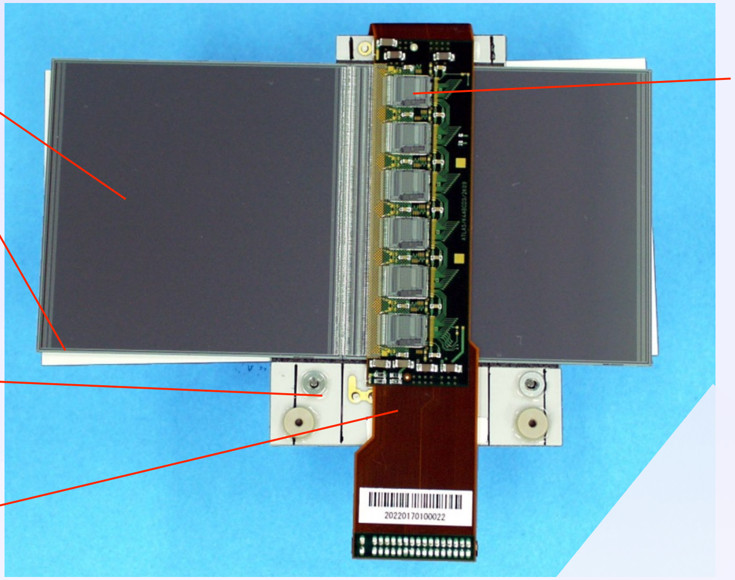
Resolution ~ 5μm

Detector Module

- **Detector Modules – "Basic building block of tracking detectors"**
  - **Silicon Sensors**
  - **Mechanical support (cooling)**
  - **Front end electronics and signal routing (connectivity)**
- **Example: ATLAS SCT Barrel Module**

SCT = SemiConductor Tracker
ASICS = Application Specific Integrated CircuitS
TPG = Thermal Pyrolytic Graphite

128 mm



- **Silicon sensors (x4)**
  - 64 x 64 mm^2
  - p-in-n, single sided
  - AC-coupled
  - 768 strips
  - 80μm pitch/12μm width
- **Mechanical support**
  - TPG baseboard
  - BeO facings
- **Hybrid (x1)**
  - flexible 4 layer copper/kapton hybrid
  - mounted directly over two of the four silicon sensors
  - carrying front end electronics, pitch adapter, signal routing, connector

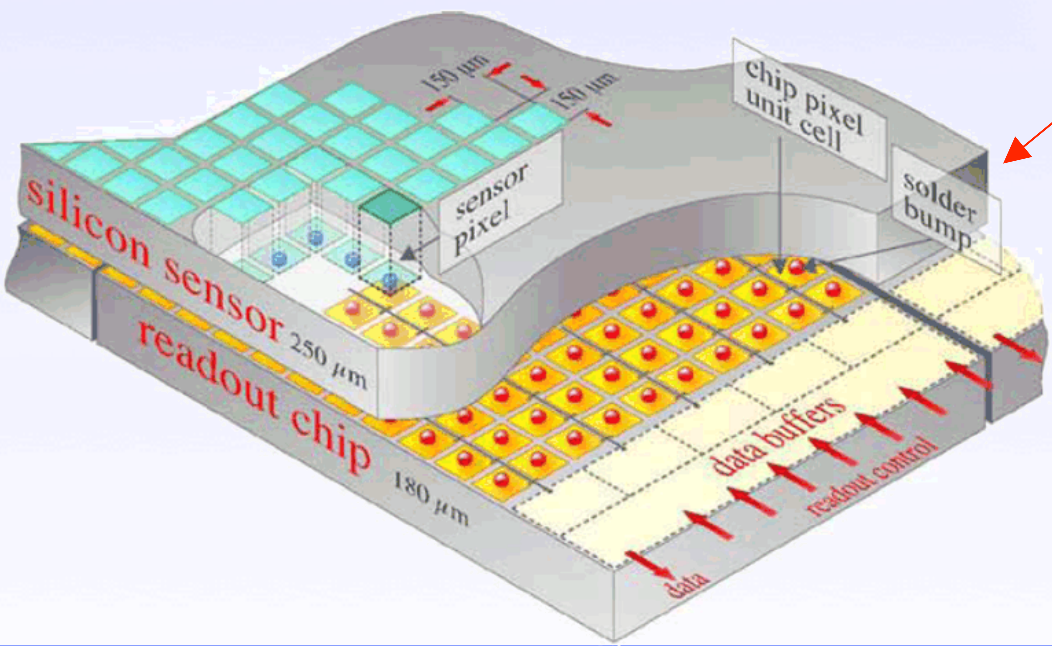
$\sigma(r\phi) \sim 16\ \mu m$, $\sigma(z) \sim 850\mu m$ [NIMA538 (2005) 384]

- **ASICS (x12)**
  - ABCD chip (binary readout)
  - DMILL technology
  - 128 channels
- **Wire bonds** (~3500)
  - 25 μm Al wires

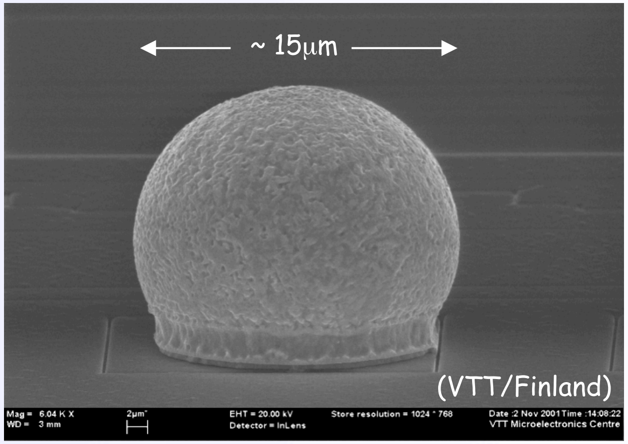
- **ATLAS SCT**
  - **15.552 microstrip sensors**
  - **2.112 barrel modules**
  - **1.976 forward modules**
  - **61 m^2 silicon**
  - **6.3.10^6 strips**

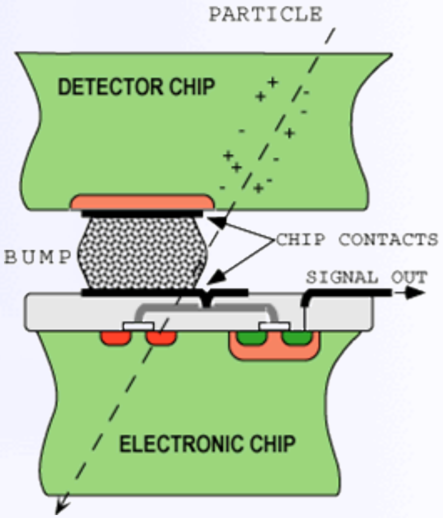
Hybrid Pixel Detectors

- **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 will be used in LHC experiments: ATLAS, ALICE, CMS and LHCb**



Solder Bump: Pb-Sn





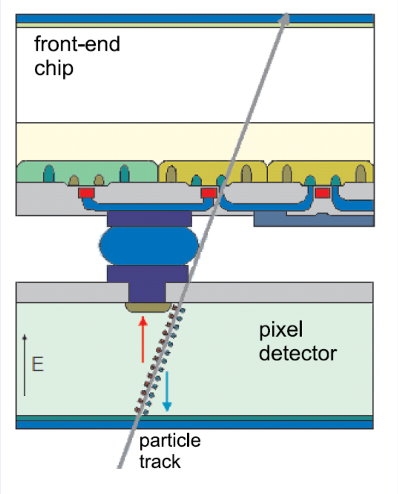
Flip-chip technique

Monolithic Pixel Detectors

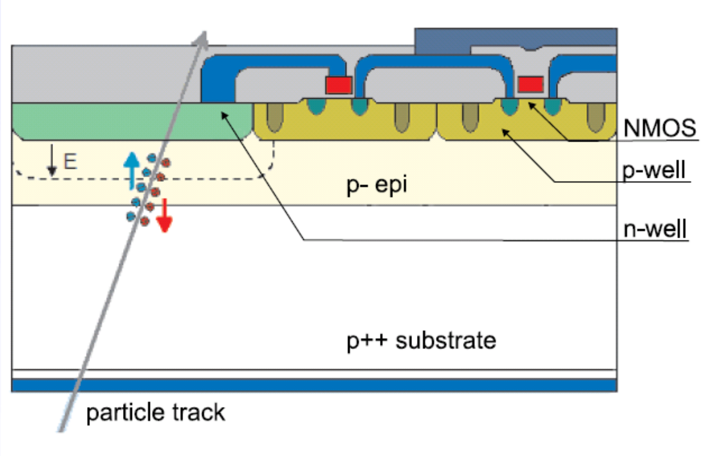
- **Combine sensors and all or part of the readout electronics in one chip**
  - **No interconnection between sensor and chip needed**
- **Many different variations with different levels of integration of sensor and readout part**
- **Standard CMOS processing**
  - **Wafer diameter (8")**
  - **Many foundries available**
  - **Lower cost per area**
  - **Small cell size – high granularity**
  - **Possibility of stitching (combining reticles to larger areas)**
- **Very low material budget**
- **CMOS sensors installed in STAR experiment**
- **Baseline for ALICE ITS upgrade**

More about MAPS see presentation from Andrei Dorokhov

Hybrid Pixel Detector



CMOS (Pixel) Detector

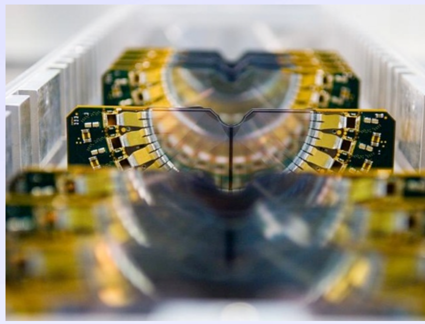


Present LHC Tracking Sensors

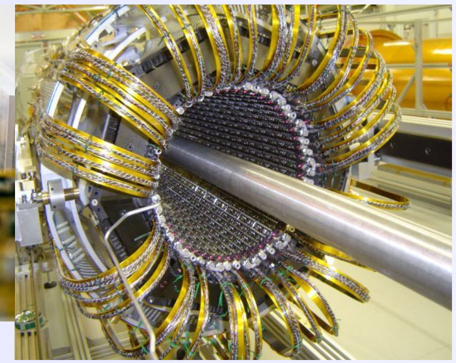
Silicon tracking detectors are used in all LHC experiments:

Different sensor technologies, designs, operating conditions,….

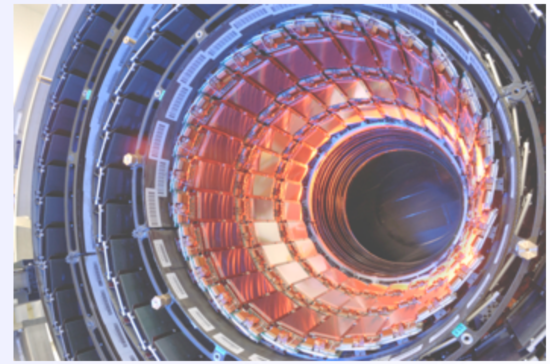
ALICE Pixel Detector



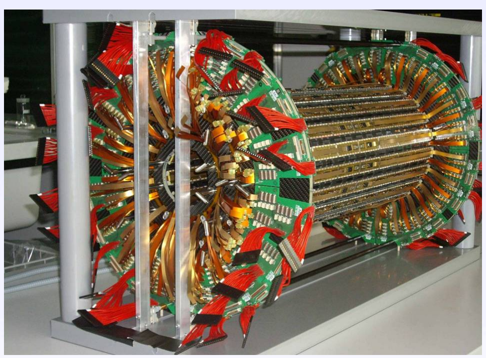
LHCb VELO



ATLAS Pixel Detector

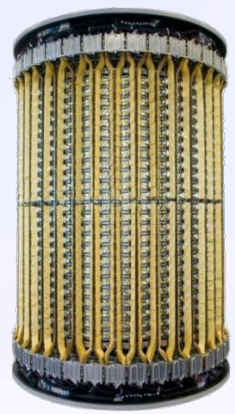


CMS Strip Tracker IB

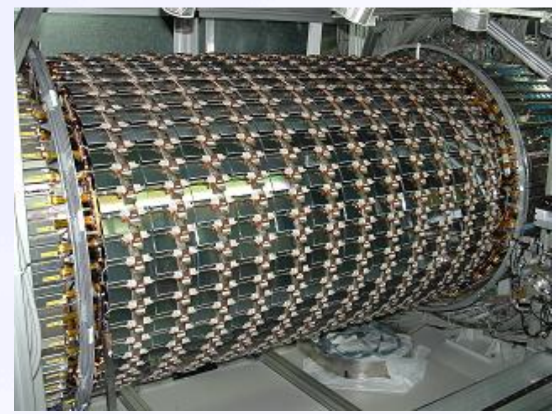


CMS Pixel Detector

ALICE Drift Detector



ALICE Strip Detector

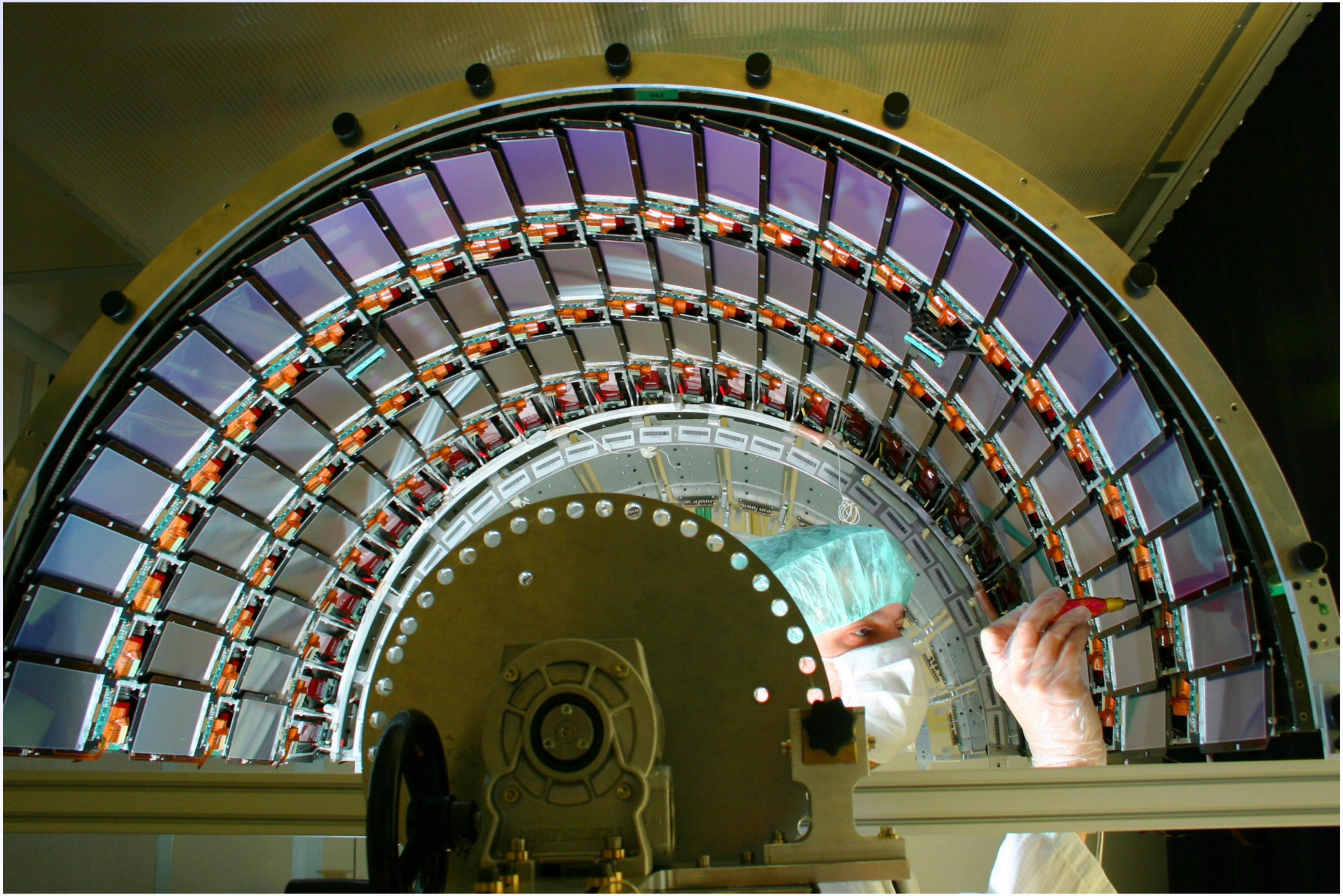


ATLAS SCT Barrel

P.Riedler, ECFA Workshop, Oct.2013

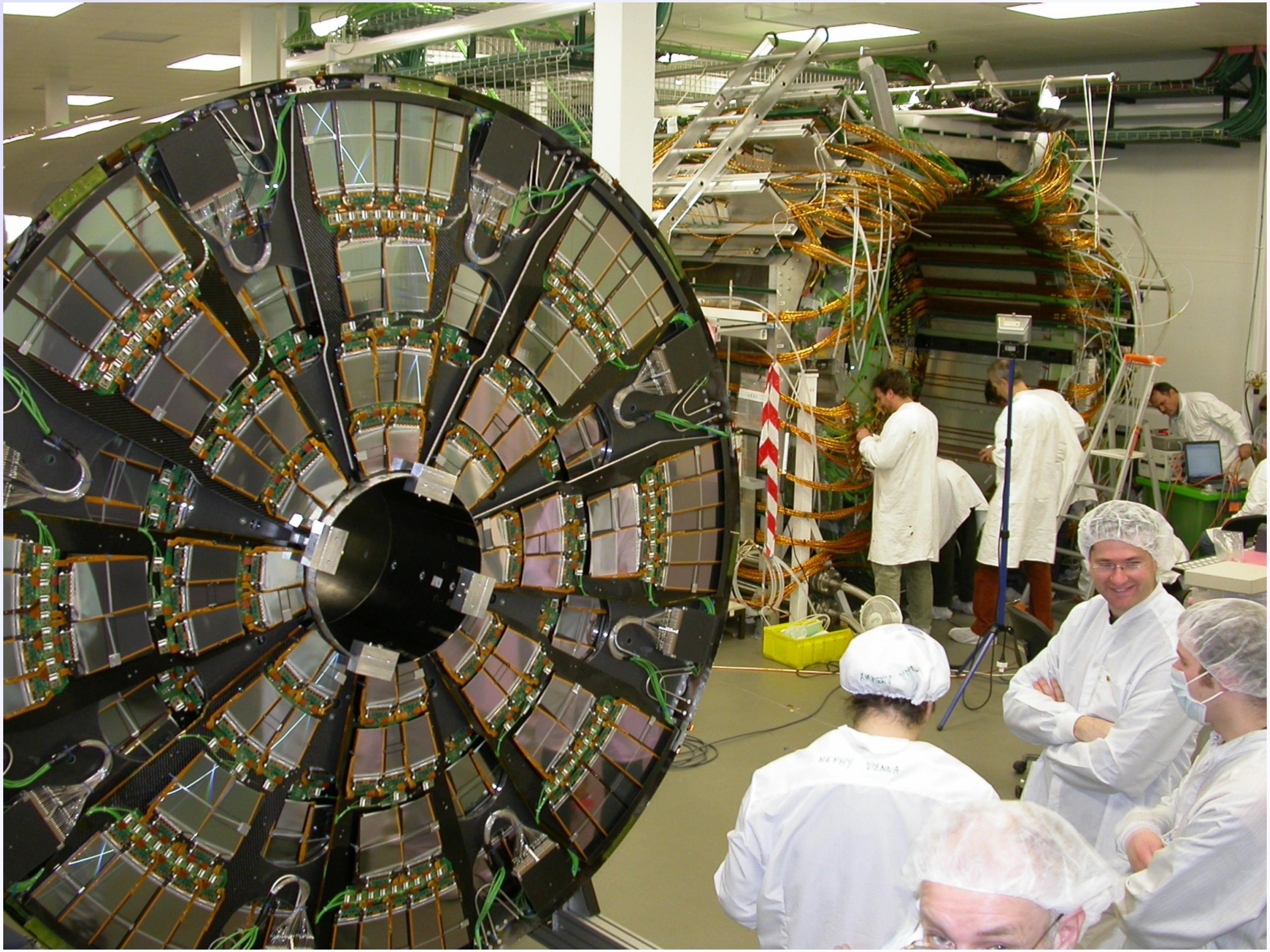
Present LHC Tracking Sensors

CMS Tracker



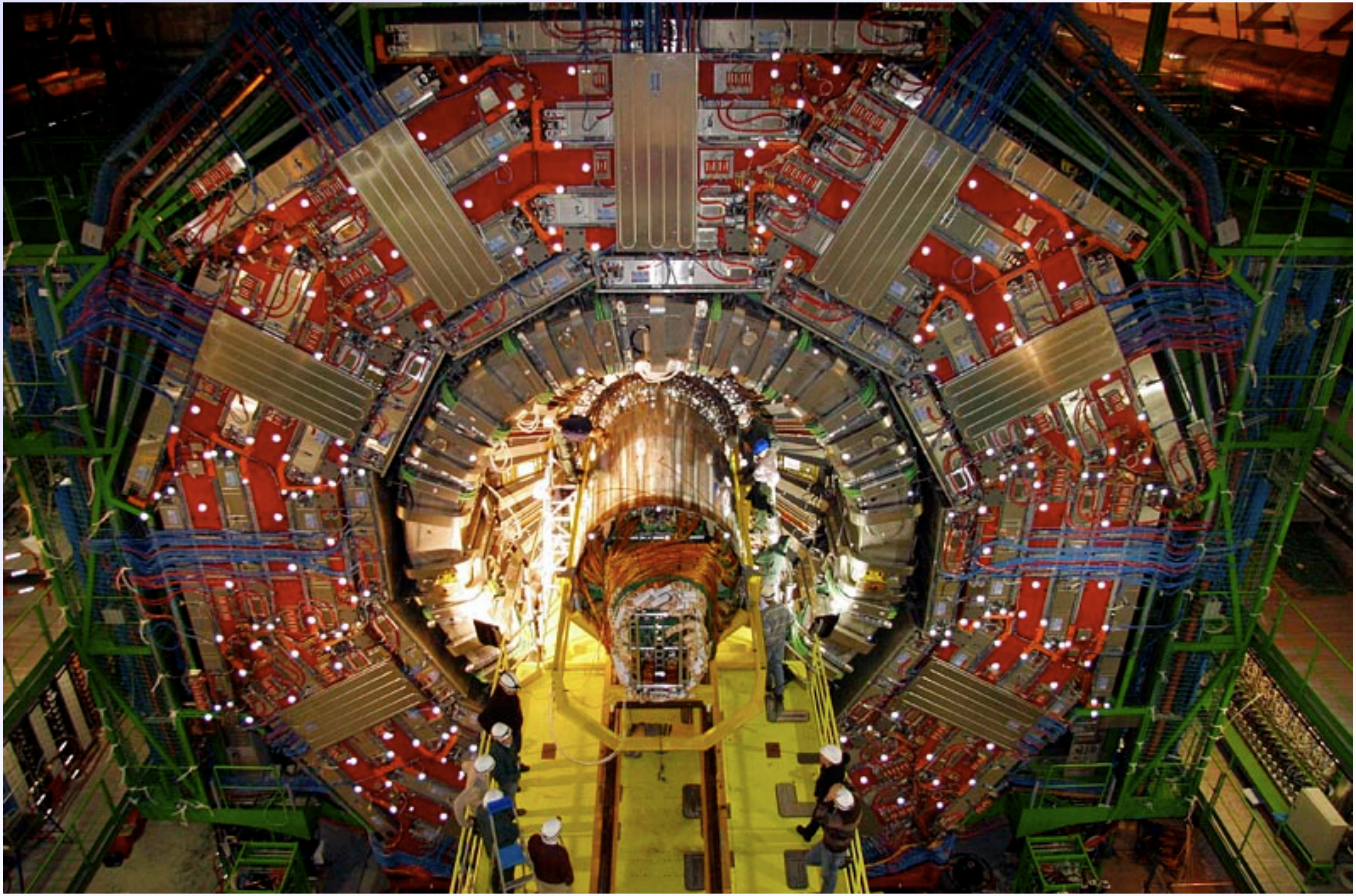
Present LHC Tracking Sensors

CMS Tracker



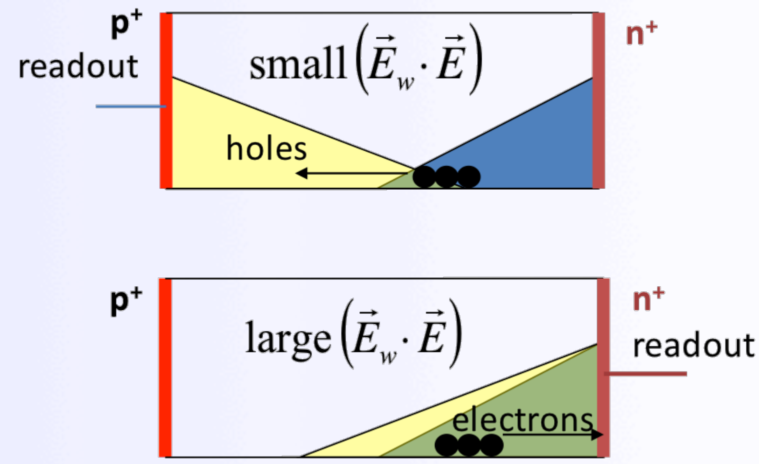
Present LHC Tracking Sensors

CMS Tracker insertion



Sensor Technology in Present Experiments

- **p-in-n, n-in-p (single sided process)**
- **n-in-n (double sided process)**
- **Choice of sensor technology mainly driven by the radiation environment**



G. Kramberger, Vertex 2012

	Fluence 1MeV n_{eq} [cm^{-2}]	**Sensor type**
ATLAS Pixel*	1×10^{15}	n-in-n
ATLAS Strips	2×10^{14}	p-in-n
CMS Pixels	3×10^{15}	n-in-n
CMS Strips	1.6×10^{14}	p-in-n
LHCb VELO	1.3×10^{14}**	n-in-n, n-in-p
ALICE Pixel	1×10^{13}	p-in-n
ALICE Drift	1.5×10^{12}	p-in-n
ALICE Strips	1.5×10^{12}	p-in-n

n-side readout (n-in-n, n-in-p):
- Depletion from segmented side (under-depleted operation possible)
- Electron collection
- Favorable combination of weighting field and
- Natural for p-type material

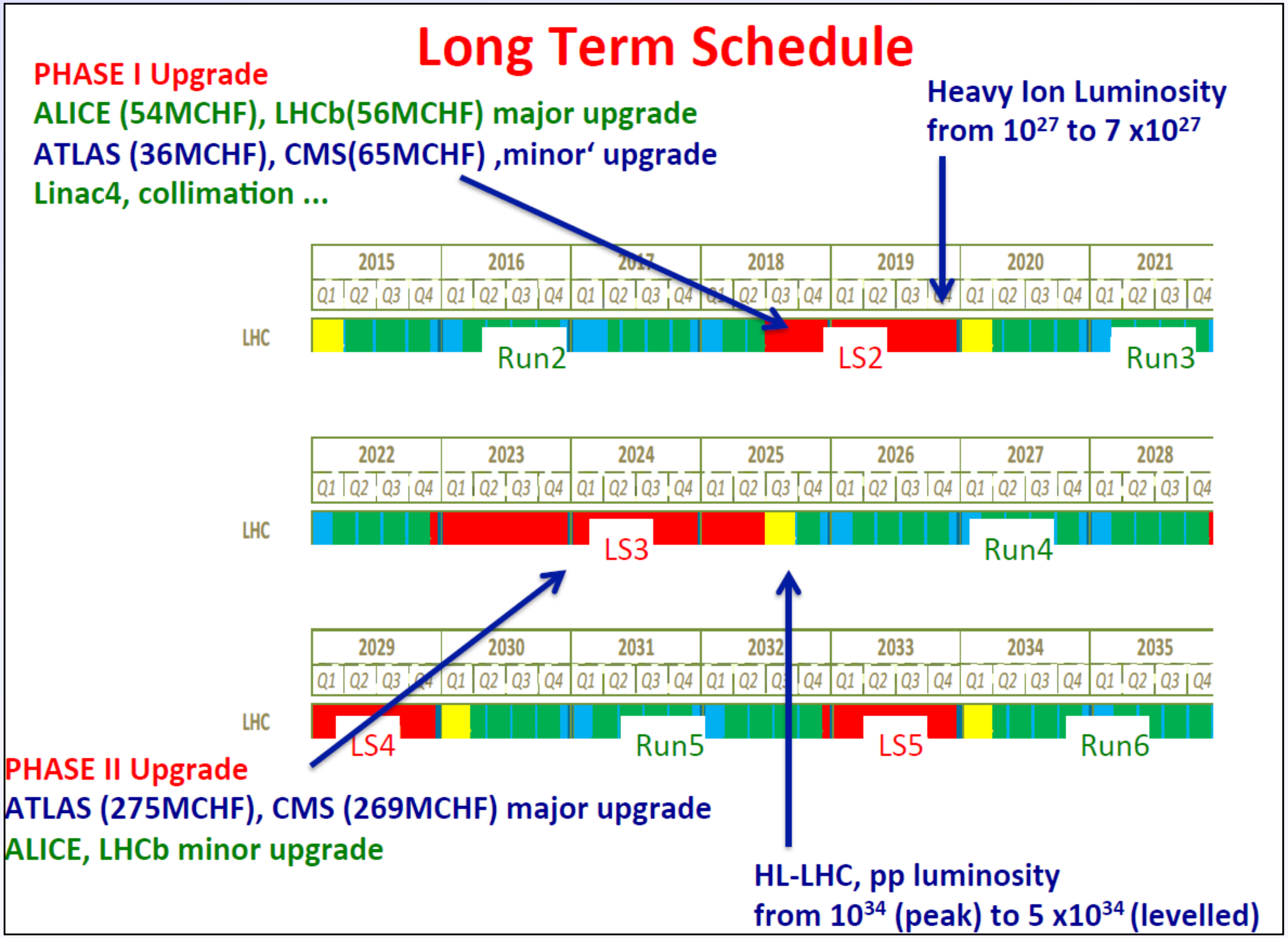
** per year

P.Riedler, ECFA Workshop, Oct.2013

Upgrade of the
Large Hadron Collider at CERN

The LHC Upgrade Program

- LHC luminosity upgrade (Phase II) ($L=5x10^{34}$ $cm^{-2}s^{-1}$) in 2025



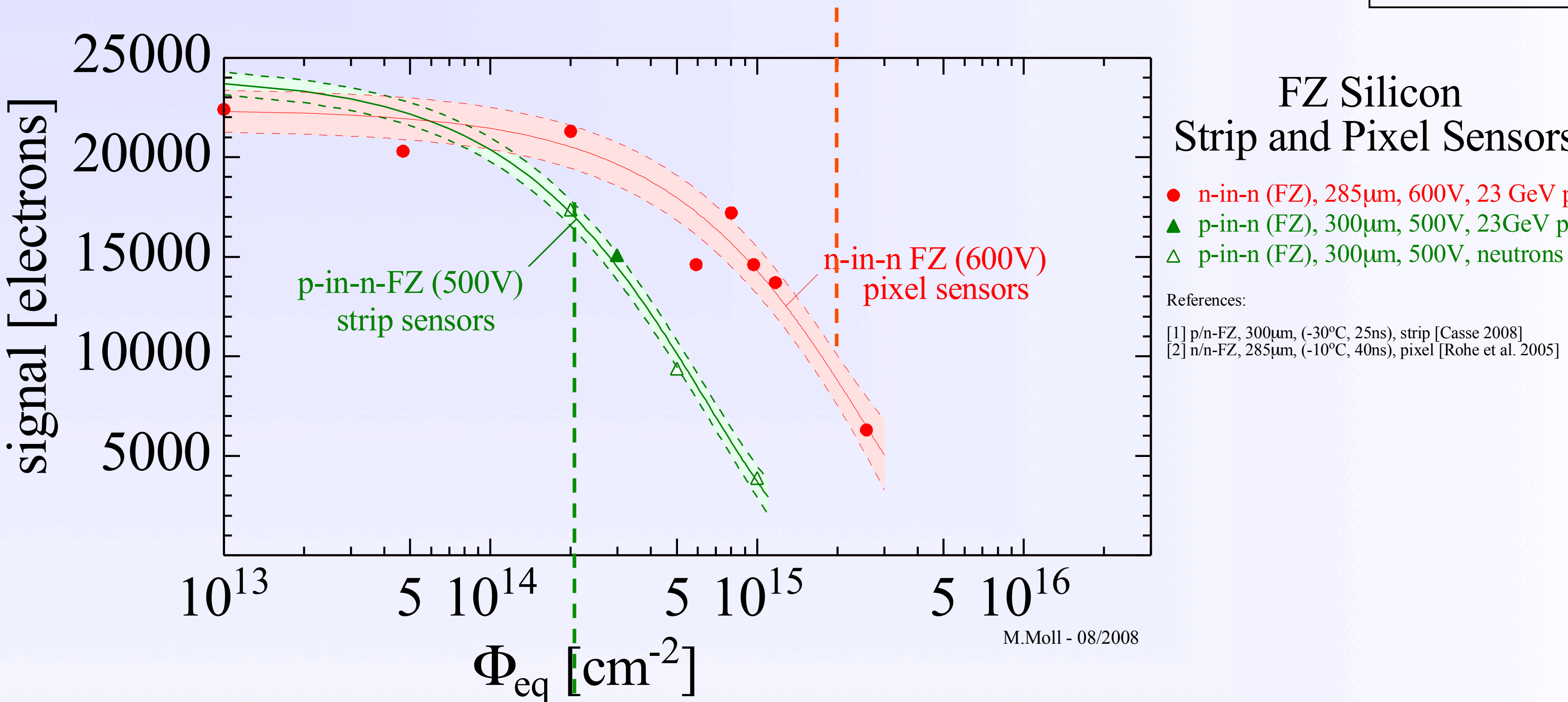
Challenge: Build detectors that operate after 3000 fb^{-1}

Signal degradation for LHC Silicon Sensors

Pixel sensors:

max. cumulated fluence for LHC

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!



Strip sensors:

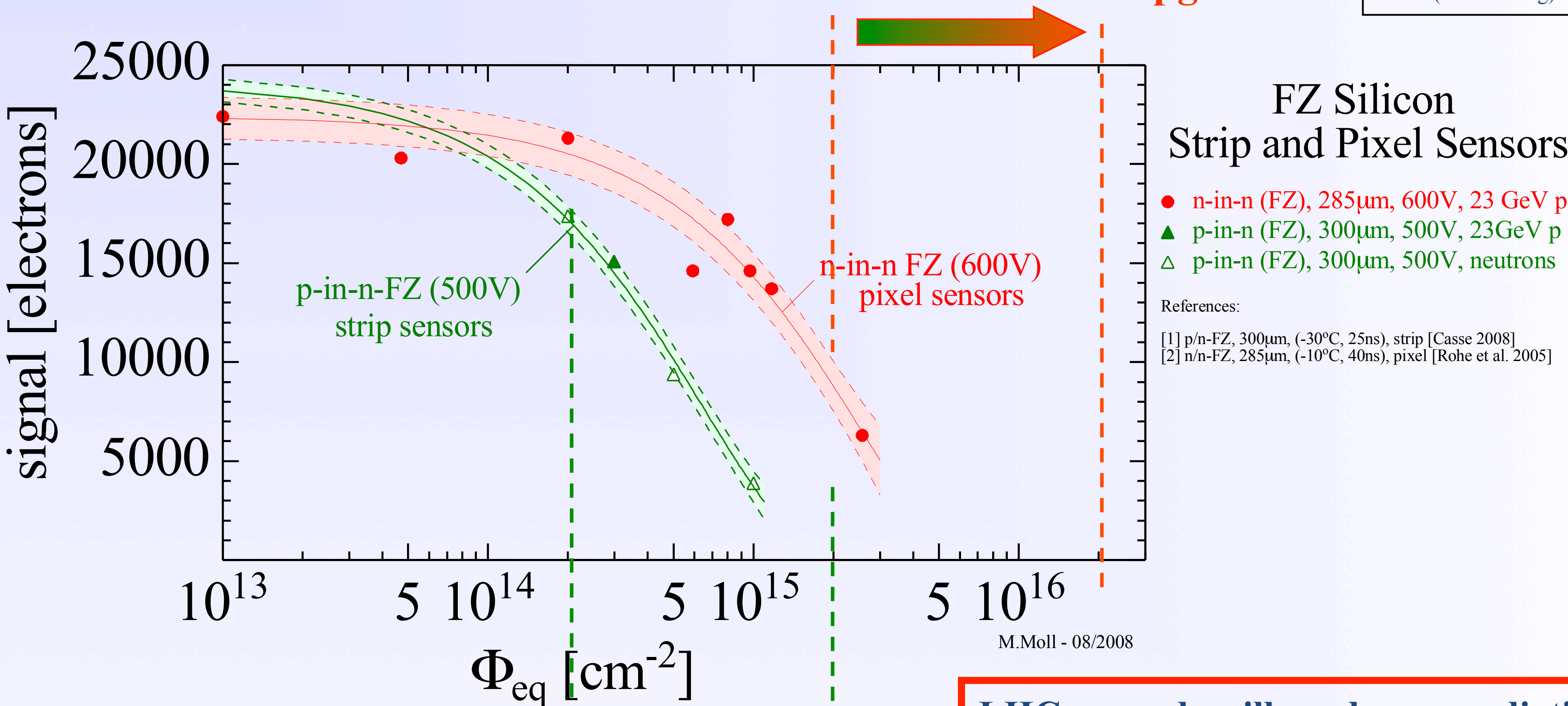
max. cumulated fluence for LHC

Situation in 2005

Signal degradation for LHC Silicon Sensors

Pixel sensors:
max. cumulated fluence for LHC and LHC upgrade

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!



Strip sensors:
max. cumulated fluence for LHC and LHC upgrade

LHC upgrade will need more radiation tolerant tracking detector concepts!

Boundary conditions & other challenges: Granularity, Powering, Cooling, Connectivity, Triggering, Low mass, Low cost!

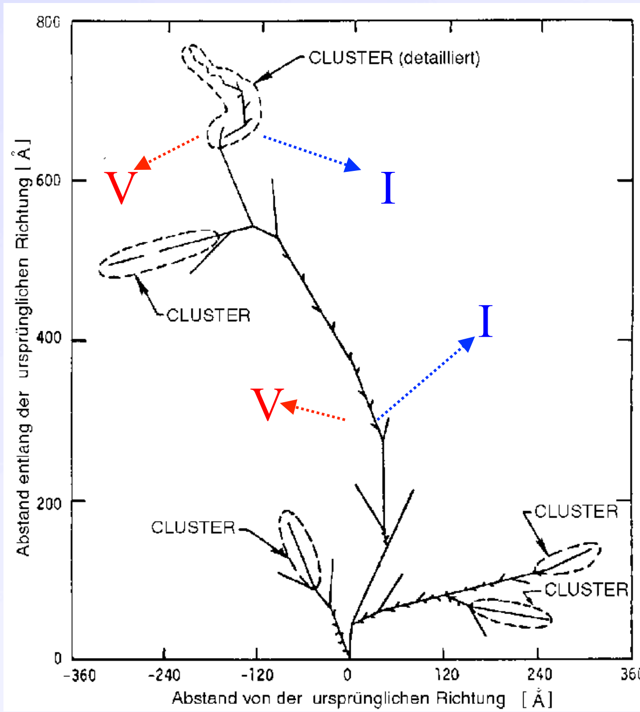
Radiation Damage

What is radiation damage?

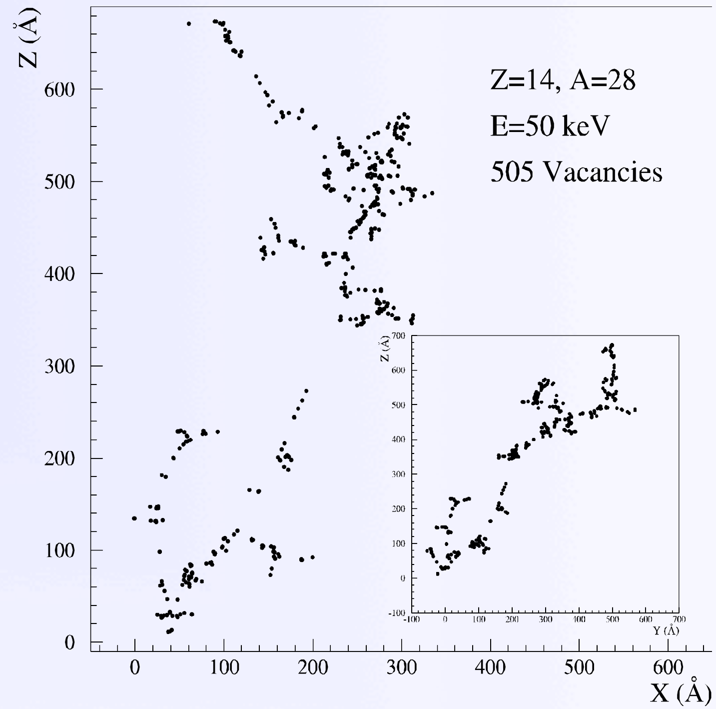
Radiation Damage – Microscopic Effects

- **Spatial distribution of vacancies created by a 50 keV Si-ion in silicon.**
  (typical recoil energy for 1 MeV neutrons)

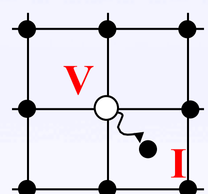
van Lint 1980



M.Huhtinen 2001



particle → Si_s → E_K>25 eV

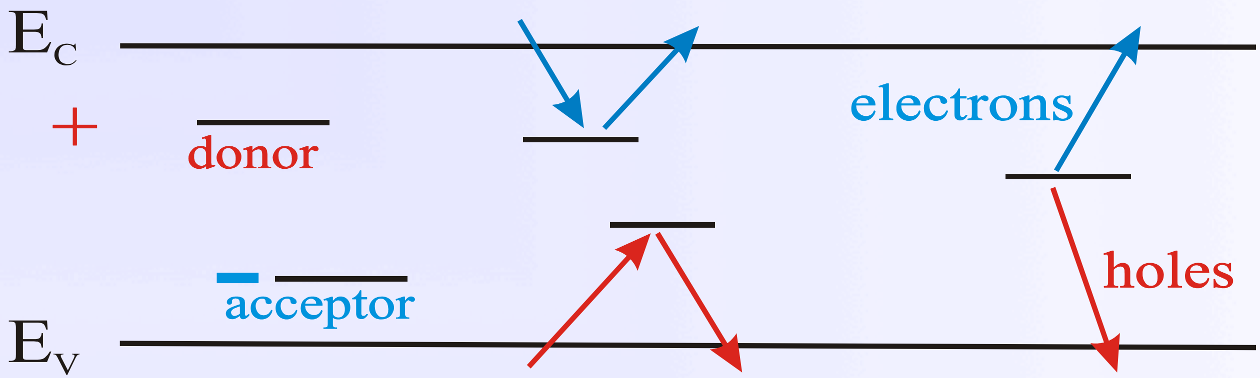


Vacancy + Interstitial → *point defects (V-O, C-O, ..)*

Si_s → E_K > 5 keV *point defects and clusters of defects*

Impact of Defects on Detector properties

Shockley-Read-Hall statistics
(standard theory)



charged defects
⇒ N_{eff} , V_{dep}
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)
⇒ CCE
shallow defects do not contribute at room temperature due to fast detrapping

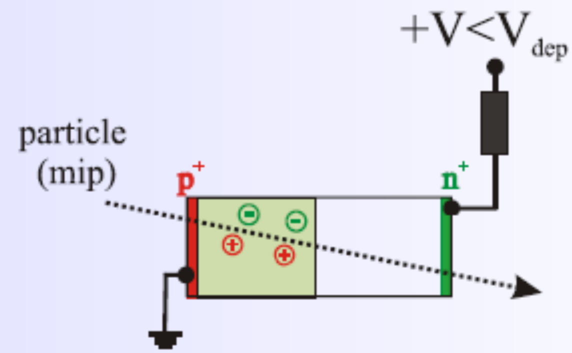
generation
⇒ leakage current
Levels close to midgap most effective

Impact on detector properties can be calculated if all defect parameters are known:

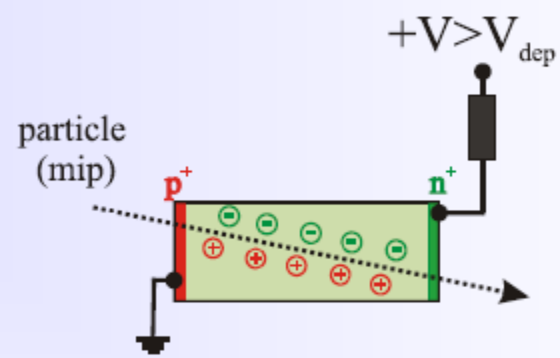
$\sigma_{n,p}$: cross sections **ΔE : ionization energy** **N_t : concentration**

Depletion Voltage

- Below depletion ($V<V_{dep}$)
  - Depletion zone x_n growing with $w \propto \sqrt{V}$
  - Only charge generated inside depleted volume will be detected
  - Charge generated in 'neutral zone' (field free zone) will recombine



- Depletion Voltage V_{dep}
  - Sensor depleted of free charge carriers
  - Electric field throughout complete device
  - Complete sensor volume sensitive (active)
  - Example:
    - d = 300 μm
    - N_{eff} = [P] =1.5×10^{12} cm^{-3} ($\rho \approx$ 3kΩcm)
    - $V_{dep} \approx$ 100V



depletion voltage V_{dep} *detector thickness d*

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

effective space charge density N_{eff}

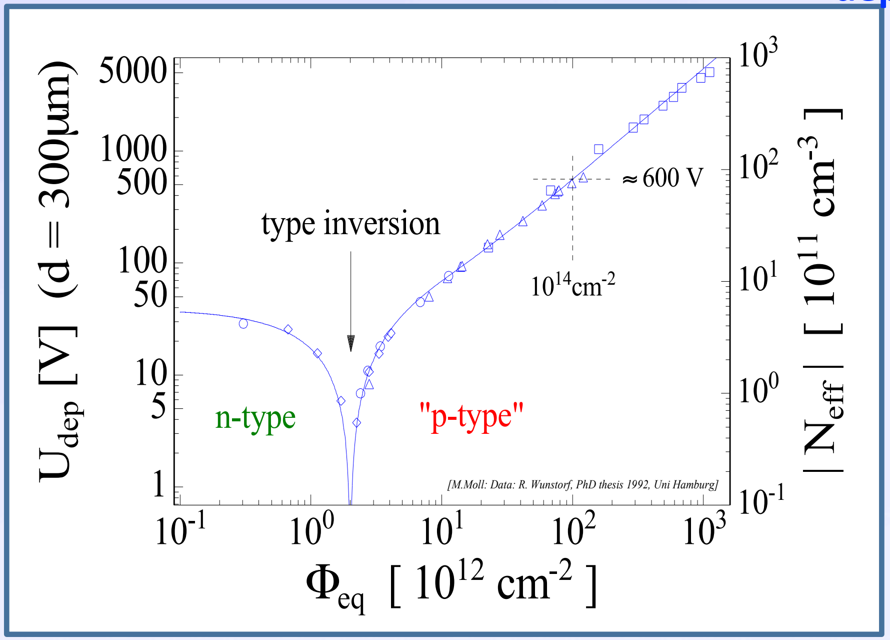
- Full charge collection only for ($V>V_{dep}$)

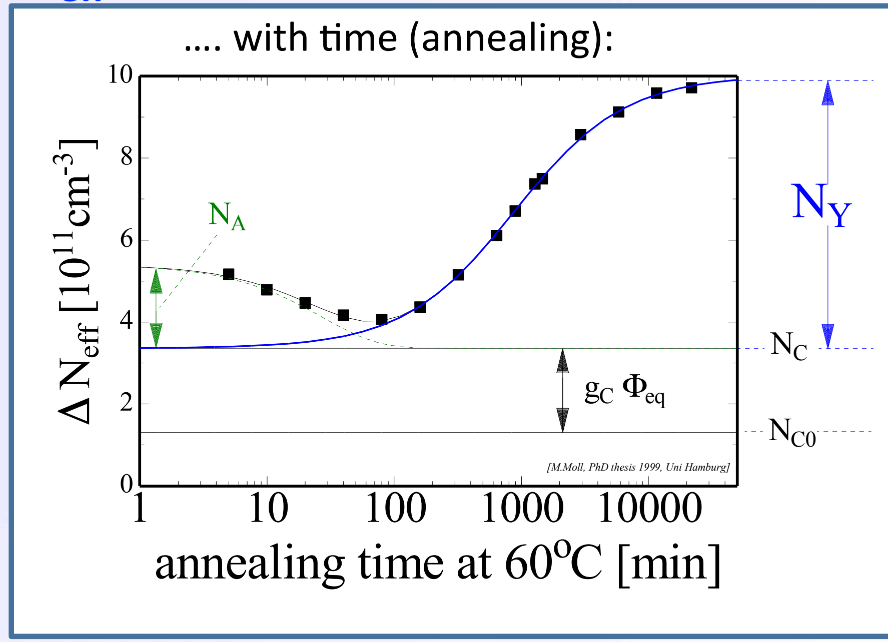
Radiation Damage: Depletion Voltage

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

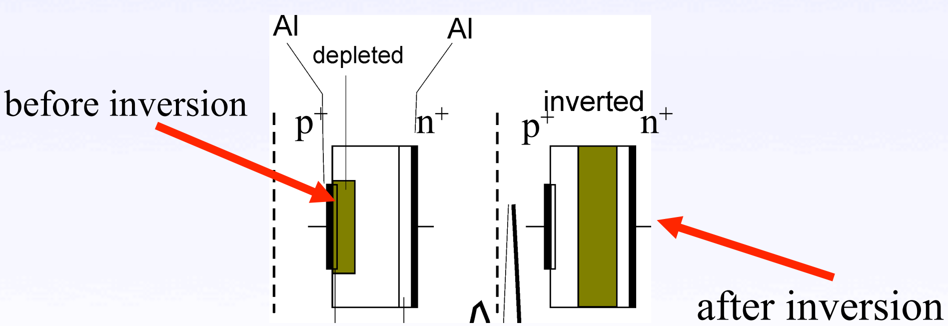
effective space charge density

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





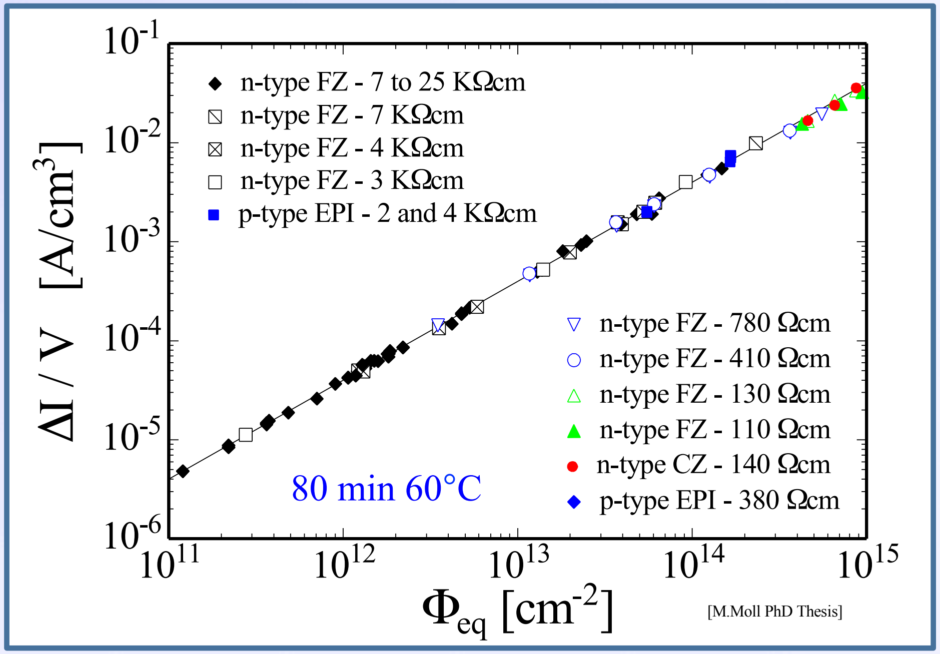
- "Type inversion": N_{eff} changes from positive to negative (Space Charge Sign Inversion)



- Short term: "Beneficial annealing"
- Long term: "Reverse annealing"
  - time constant depends on temperature:
    - ~ 500 years (-10°C)
    - ~ 500 days (20°C)
    - ~ 21 hours (60°C)
  - **Consequence: Detectors must be cooled even when the experiment is not running!**

Radiation Damage – II. Leakage Current

- **Change of Leakage Current (after hadron irradiation)**



- Damage parameter α (slope in figure)

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

Leakage current per unit volume and particle fluence

- α is constant over several orders of fluence and independent of impurity concentration in Si
  ⇨ can be used for fluence measurement

- Strong temperature dependence

$$I \propto \exp\left(-\frac{E_{g,eff}}{2k_B T}\right)$$

Consequence:

Cool detectors during operation!

Example: I(-10°C) ~1/16 I(20°C)

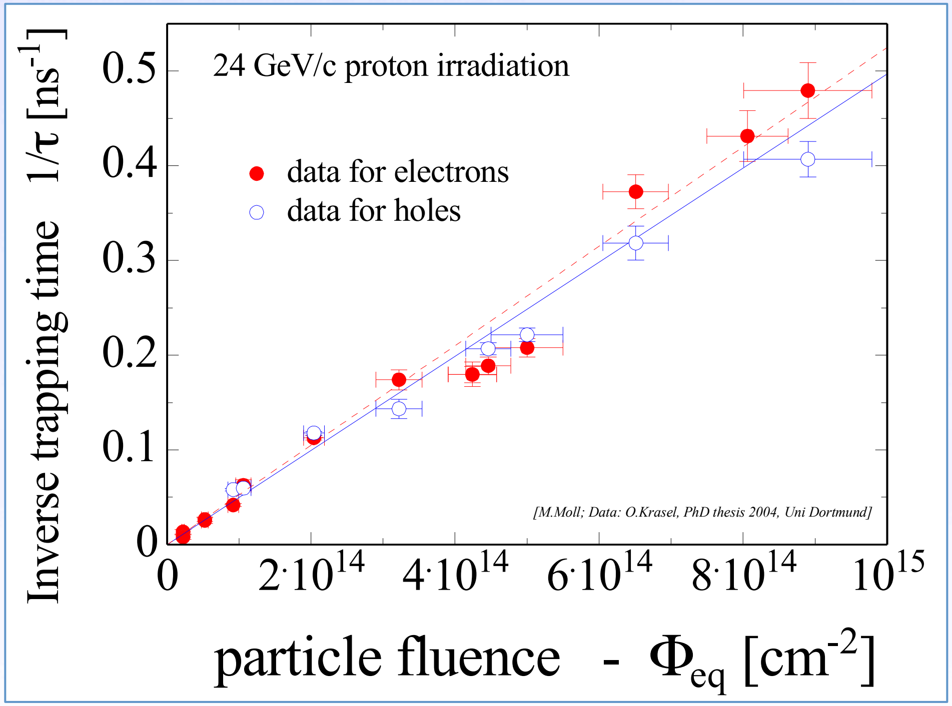
- Current decreases in time (annealing, not shown here)

Deterioration of Charge Collection Efficiency (CCE) by trapping

- **2 mechanisms:** **- Trapping of electrons and holes**
  - Underdepletion (loss of active detector volume due to increase of V_{dep})

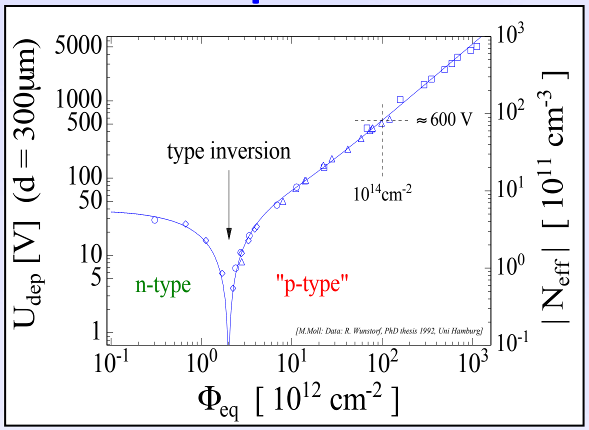
Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right) \quad \text{where} \quad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$

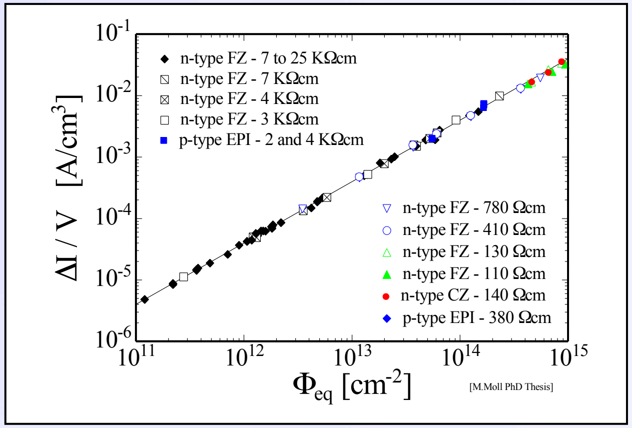


Radiation Damage Summary

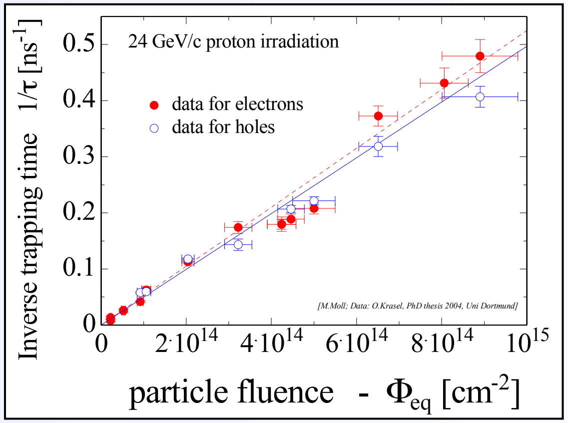
- **Macroscopic bulk effects:**



Depletion Voltage (N_{eff})

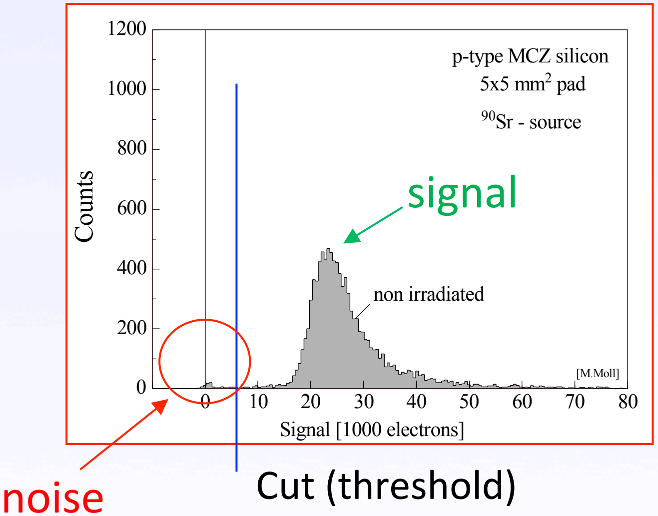


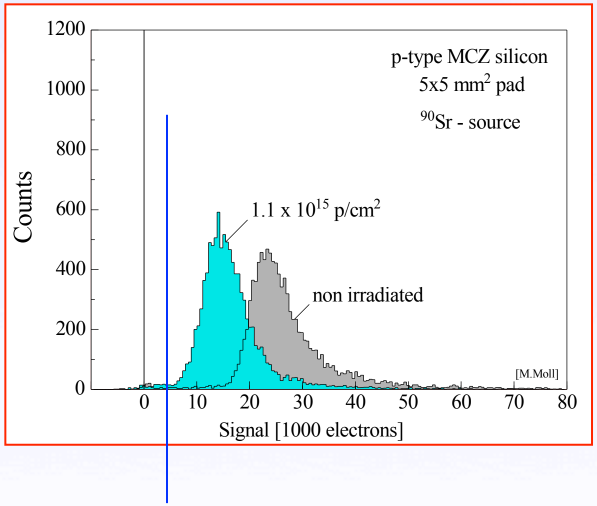
Leakage Current

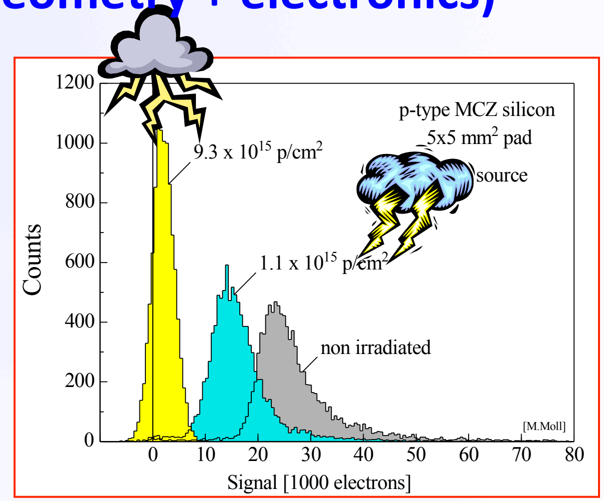


Charge Trapping

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







Summary: Radiation Damage in Silicon Sensors

- **Two general types of radiation damage to the detector materials:**

  - **Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)**
    - displacement damage, built up of crystal defects –

    I. Change of effective doping concentration (higher depletion voltage, under- depletion)

    II. Increase of leakage current (increase of shot noise, thermal runaway)

    III. Increase of charge carrier trapping (loss of charge)

  - **Surface damage due to Ionizing Energy Loss (IEL)**
    - accumulation of positive in the oxide (SiO_2) and the Si/SiO_2 interface –
    affects: interstrip capacitance (noise factor), breakdown behavior, …

Influenced by impurities in Si – Defect Engineering is possible! (I.)

Same for all tested Silicon materials! (II., III.)

- **Impact on detector performance and Charge Collection Efficiency**
  (depending on detector type and geometry and readout electronics!)

Can be optimized! (geometry, readout electronics)

Signal/noise ratio is the quantity to watch

⇒ Sensors can fail from radiation damage !

How to make silicon detectors radiation harder?

The RD50 Collaboration

- **RD50: 50 *institutes and 275 members***

42 European and Asian institutes

Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Paris, Orsay), Greece (Demokritos), Germany (Dortmund, Erfurt, Freiburg, Hamburg (2x), Karlsruhe, Munich(2x)), Italy (Bari, Florence, Perugia, Pisa, Torino), Lithuania (Vilnius), Netherlands (NIKHEF), Poland (Krakow, Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona(2x), Santander, Valencia), Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Glasgow, Liverpool)

6 North-American institutes

Canada (Montreal), USA (BNL, Fermilab, New Mexico, Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

1 Asian institute

India (Delhi)

- LPNHE, UPMC, Université Paris-Diderot, CNRS/IN2P3, (Giovanni Calderini)
- Laboratoire de l'Accélérateur Linéaire Centre Scientifique d'Orsay (Abdenour Lounis)

Detailed member list: http://cern.ch/rd50

RD50 Organizational Structure

Co-Spokespersons

Gianluigi Casse **and** ***Michael Moll***

(Liverpool University) (CERN PH-DT)

Defect / Material Characterization

Mara Bruzzi

(INFN & Uni Florence)

- Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation
- DLTS, TSC, ….
- SIMS, SR, …
- NIEL (calculations)
- WODEAN: Workshop on Defect Analysis in Silicon Detectors (G.Lindstroem & M.Bruzzi)

Detector Characterization

Eckhart Fretwurst

(Hamburg University)

- Characterization of test structures (IV, CV, CCE, TCT,.)
- Development and testing of defect engineered silicon devices
- EPI, MCZ and other materials
- NIEL (experimental)
- Device modeling
- Operational conditions
- Common irradiations
- Wafer procurement (M.Moll)
- Device Simulations (V.Eremin)

New Structures

Giulio Pellegrini

(CNM Barcelona)

- 3D detectors
- Thin detectors
- Cost effective solutions
- Other new structures
- Detectors with internal gain (avalanche detectors)
- LGAD – Low Gain Avalance Det.
- Slim Edges

- 3D (R.Bates)
- LGAD (V.Greco)
- Slim Edges (V.Fadeyev)

Full Detector Systems

Gregor Kramberger

(Ljubljana University)

- LHC-like tests
- Links to HEP
- Links electronics R&D
- Low rho strips
- Sensor readout (Alibava)
- Comparison:
  - pad-mini-full detectors
  - different producers
- Radiation Damage in HEP detectors

- Test beams (M.Bomben & G.Casse)

Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (PH-DT), Secretary: V.Wedlake (PH-DT), Budget holder & GLIMOS: M.Glaser (PH-DT)

Approaches to develop radiation harder solid state tracking detectors

Scientific strategies:

I. Material engineering

II. Device engineering

III. Change of detector operational conditions

CERN-RD39
"Cryogenic Tracking Detectors"
operation at 100-200K
to reduce charge loss

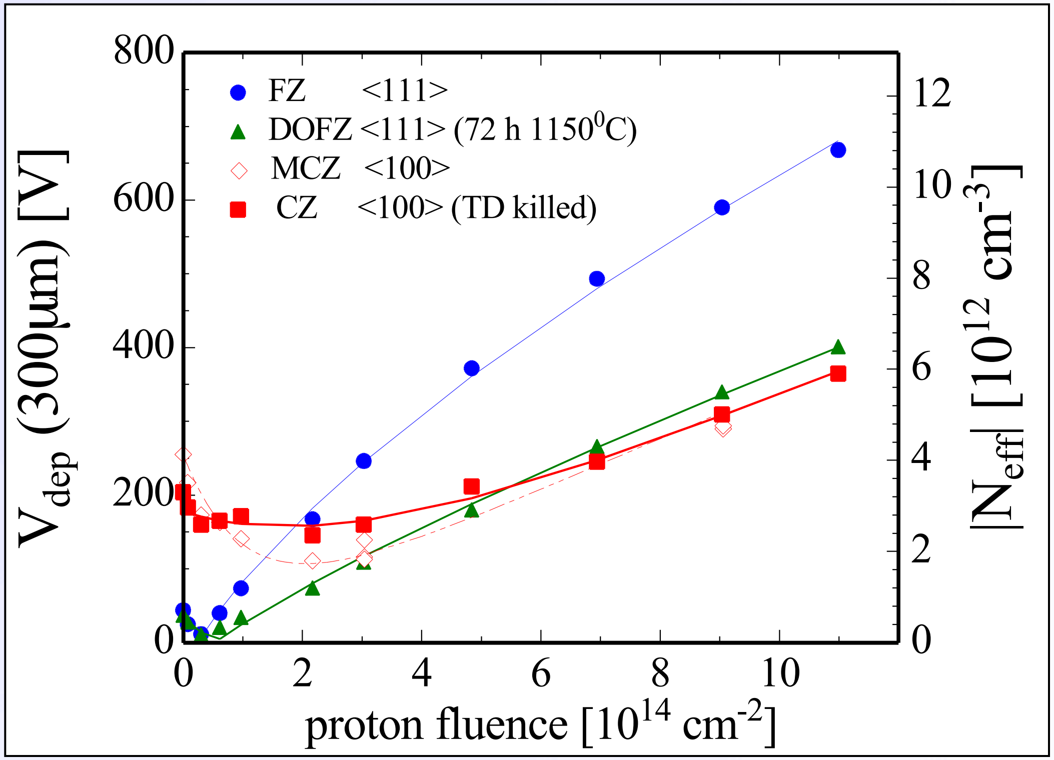
- **Defect Engineering of Silicon**

  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 Semi 3D detectors, Stripixels
  - Cost effective detectors
  - Monolithic devices

Standard FZ, DOFZ, MCz and Cz Silicon

24 GeV/c proton irradiation



- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - reduced N_{eff} increase at high fluence
- **CZ silicon and MCZ silicon**
  - "no type inversion" in the overall fluence range

(for experts: there is no "real" type inversion, a more clear understanding of the observed effects is obtained by investigating directly the internal electric field; look for: TCT, MCZ, double junction)

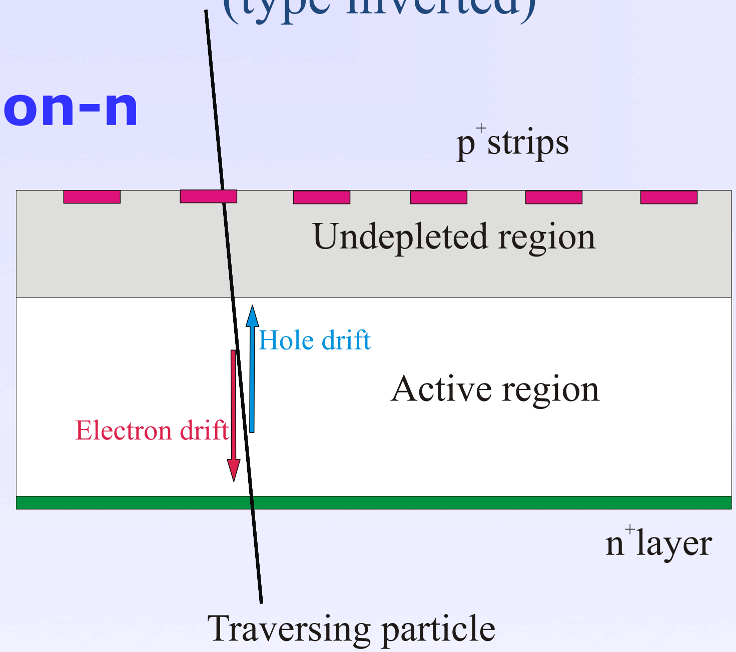
- **Common to all materials** *(after hadron irradiation, not after γ irradiation)***:**
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

Device engineering

p-in-n versus n-in-p detectors

n-type silicon after high fluences: (type inverted)

p$^+$on-n

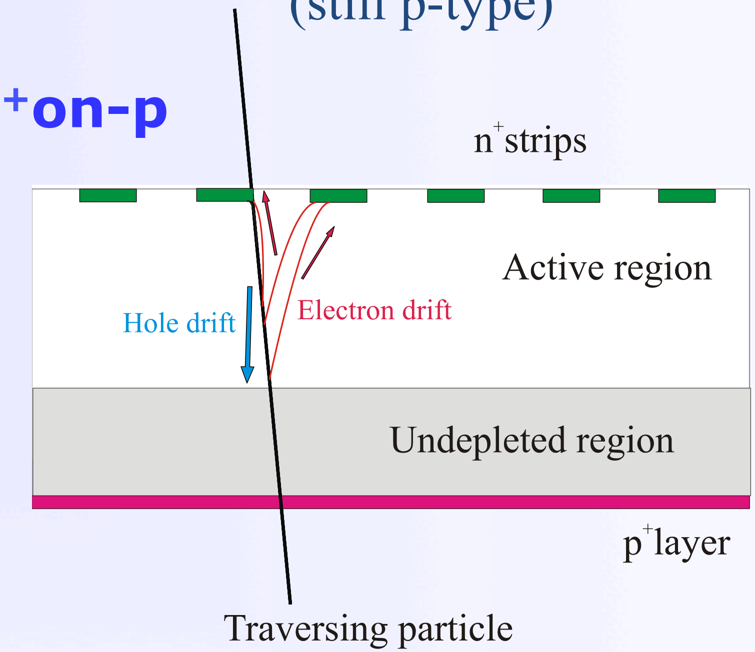


p-on-n silicon, under-depleted:

- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

p-type silicon after high fluences: (still p-type)

n$^+$on-p



n-on-p silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (3 x faster than holes)**

Comments:

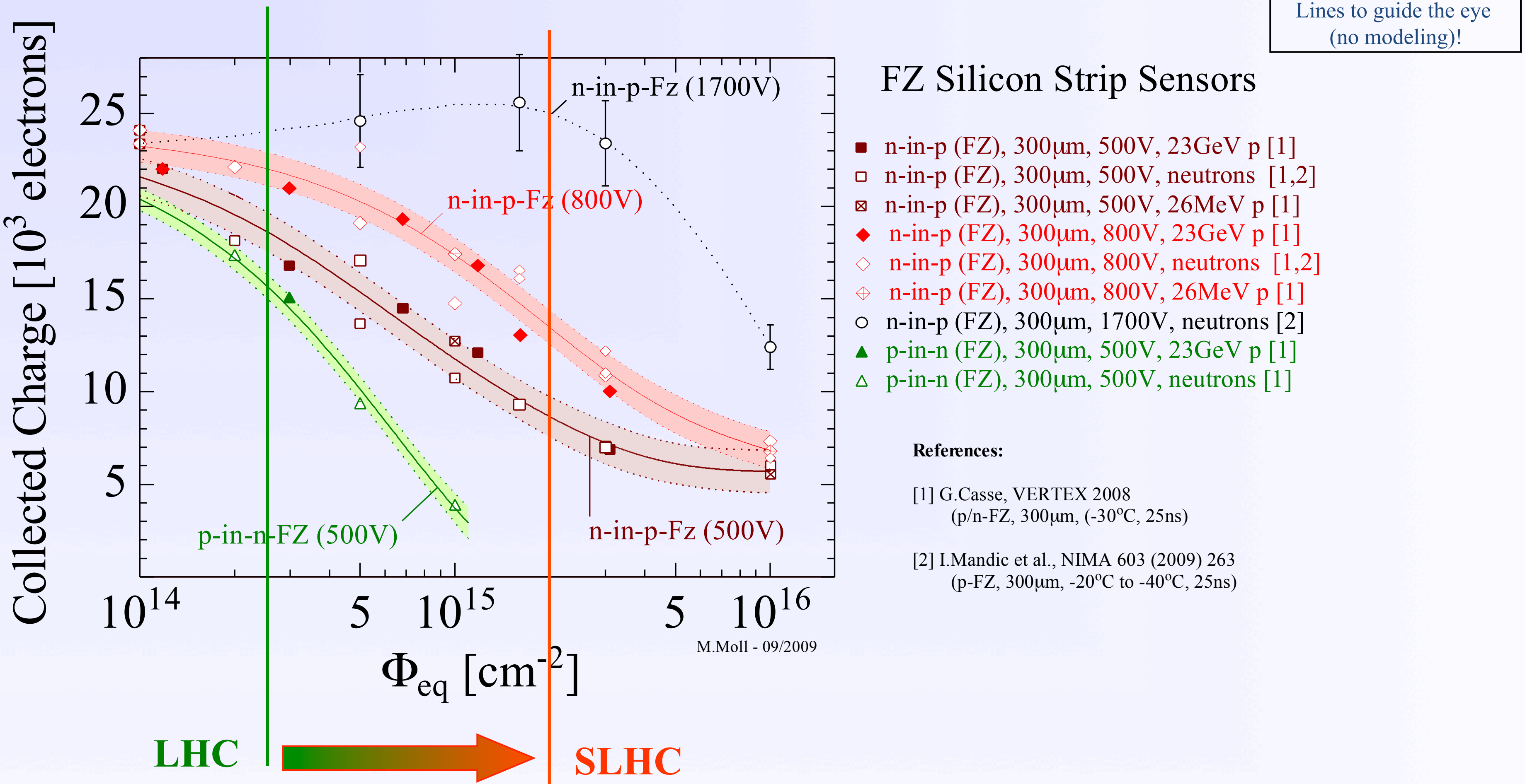
- Instead of n-on-p also n-on-n devices could be used

- Reality is much more complex: Usually double junctions form leading to fields at front and back!

Silicon materials for Tracking Sensors

- Signal comparison for p-type silicon sensors

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!



highest fluence for strip detectors in LHC: The used p-in-n technology is sufficient

n-in-p technology should be sufficient for HL-LHC at radii presently (LHC) occupied by strip sensors

Use of other semiconductor materials?

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.3**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4 \cdot 10^6$	$2.2 \cdot 10^6$	$3 \cdot 10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2 \cdot 10^7$	-	$2 \cdot 10^7$	$0.8 \cdot 10^7$
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
e-h pairs/X_0	4.4	~2-3	4.5	10.1

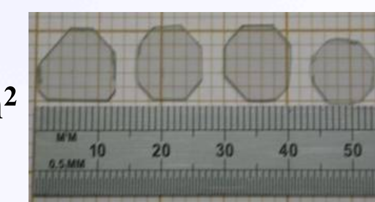
- **Diamond: wider bandgap**
  - ⇒ **lower leakage current**
  - ⇒ **less cooling needed**
  - ⇒ **less noise**
- **Signal produced by m.i.p:**
  - **Diamond 36 e/µm**
  - **Si 89 e/µm**
  - ⇒ **Si gives more charge than diamond**

- **GaAs, SiC and GaN** ⇒ **strong radiation damage observed**
  ⇒ **no potential material for LHC upgrade detectors**
  (judging on the investigated material)

- **Diamond (RD42)** ⇒ **good radiation tolerance** ***(CCE degradation similar to silicon)***
  ⇒ **already used in LHC beam condition monitoring systems**
  ⇒ **considered as potential detector material for sLHC pixel sensors**

poly-CVD Diamond –16 chip ATLAS pixel module

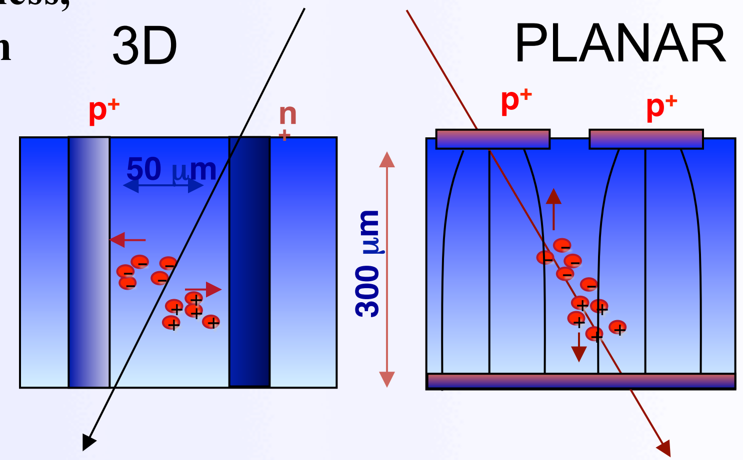
single crystal CVD Diamond of few cm²

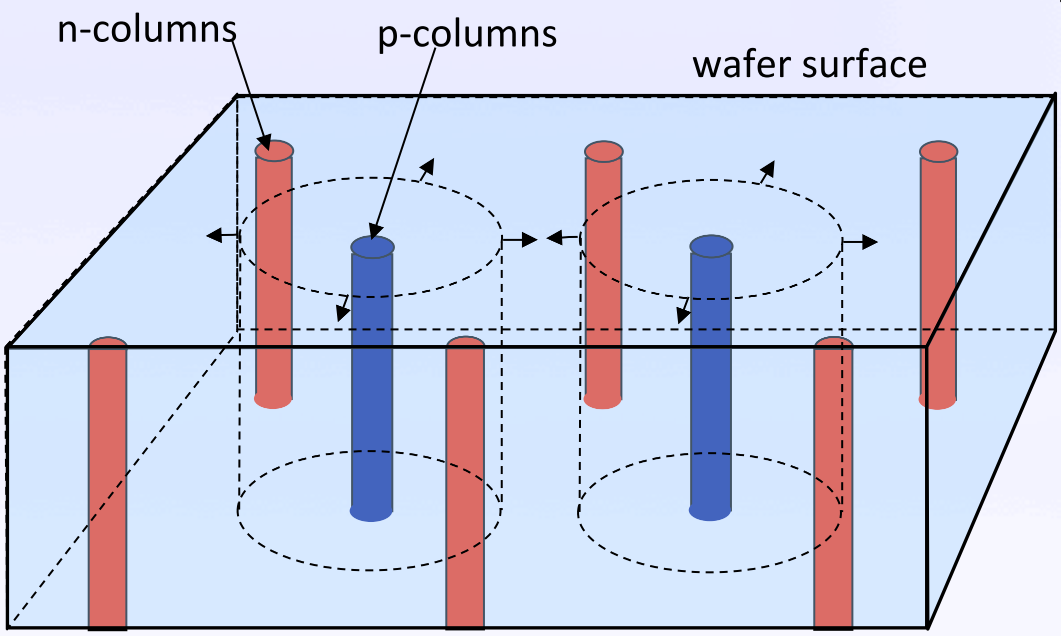


Diamond sensors are heavily used in LHC Experiments for Beam Monitoring!

3D detector concept

- **"3D" electrodes:** - narrow columns along detector thickness,
  - diameter: 10µm, distance: 50 - 100µm
- **Lateral depletion:** - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
  - radiation hard





Installed in ATLAS IBL
(Inner b-layer)

Radiation Damage

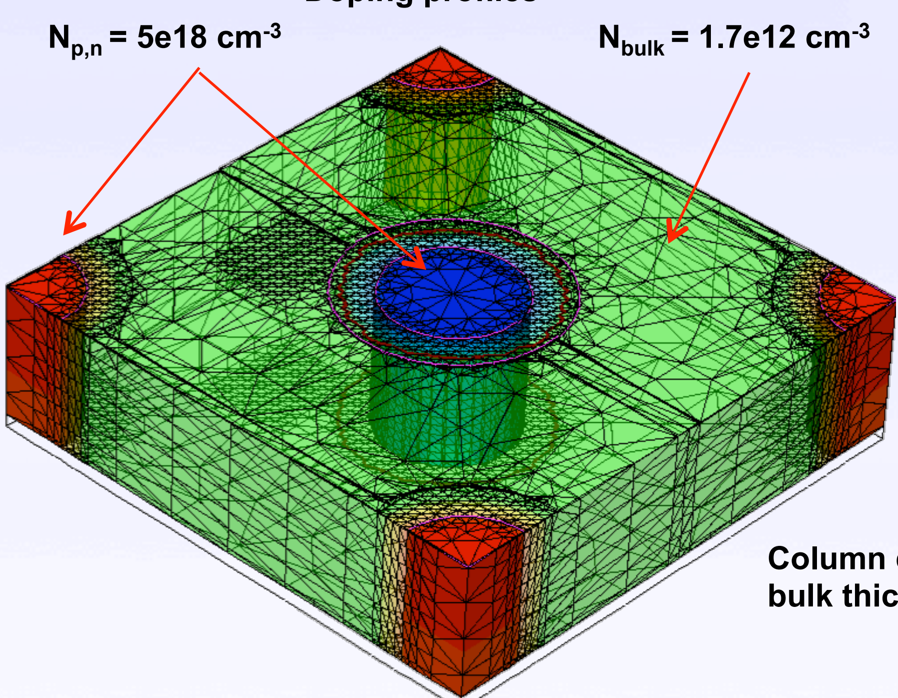
TCAD simulations

TCAD simulations

More about TCAD simulations in presentations from Andrei Dorokhov & Marco Bomben

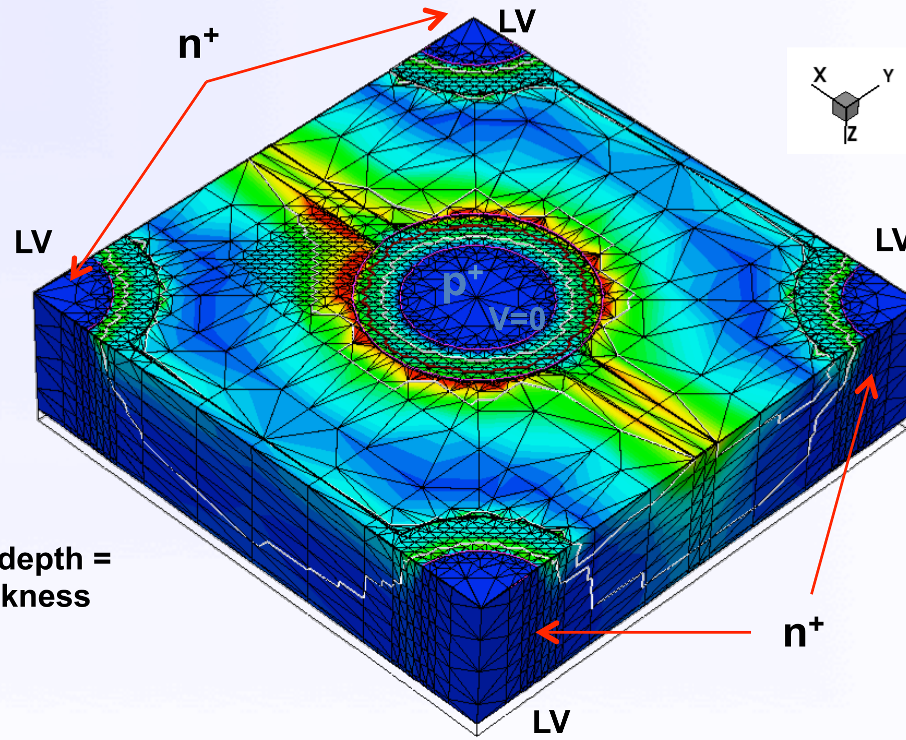
- **Why do we need TCAD simulations for irradiated sensors ?**
  - **Complexity of the problem**
    - Coupled differential equations (semiconductor equations)
    - Impact of defects depending on local charge densities, field-strength, … ("feedback loop")
    - Complex device geometry and complex signal formation in segmented devices ….
    - Interplay of surface and bulk damage
  - ***Example:* *3D sensors***

Doping profiles



Column depth = bulk thickness

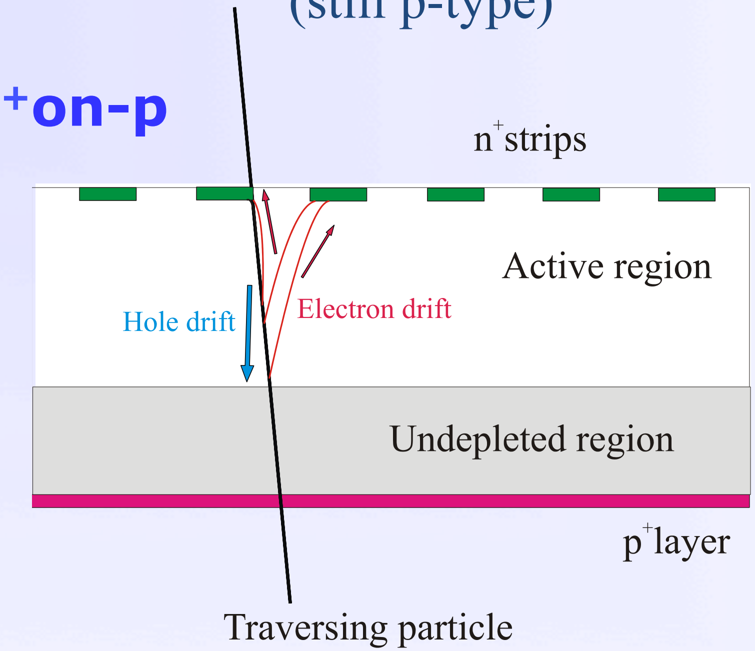
Electric field distribution in 3D detector (Al & oxide layer transparent for clarity)



Example of 3D sensor: T.Peltola (HIP, Helsinki): CMS & RD50

p-type silicon after high fluences:
(still p-type)

n⁺on-p



n-on-p silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (3 x faster than holes)**

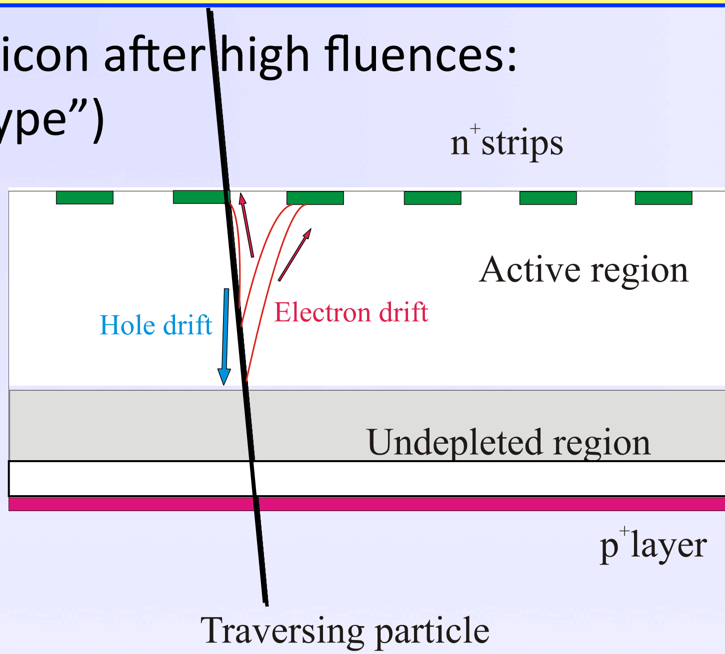
Comments:

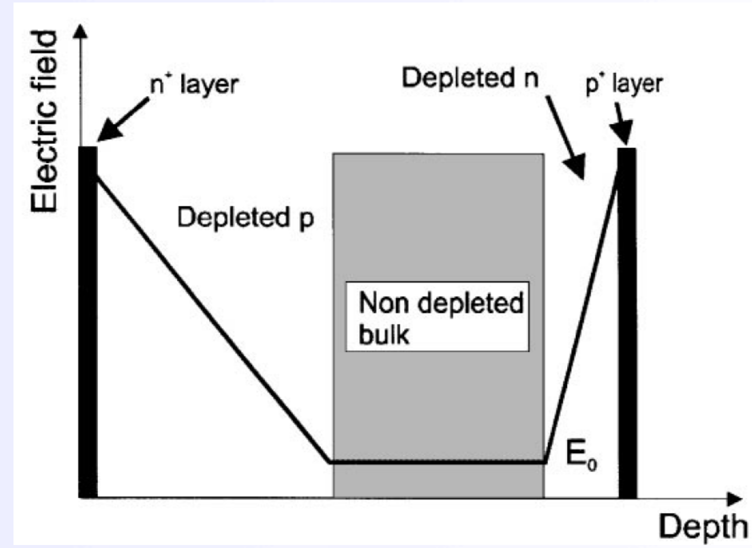
- Instead of n-on-p also n-on-n devices could be used

- Reality is much more complex: Usually double junctions form leading to fields at front and back!

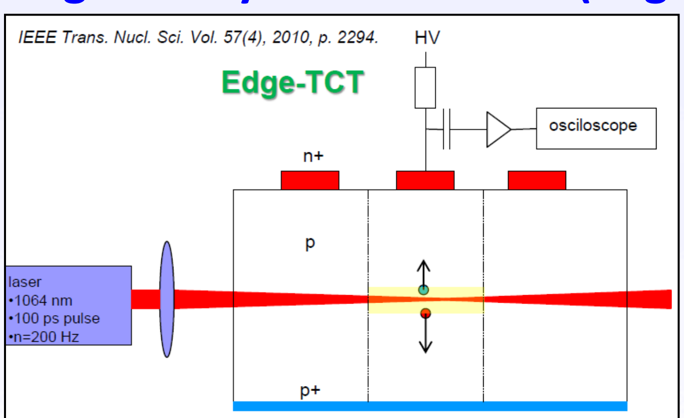
E-Field after irradiation: *Complex double junctions*

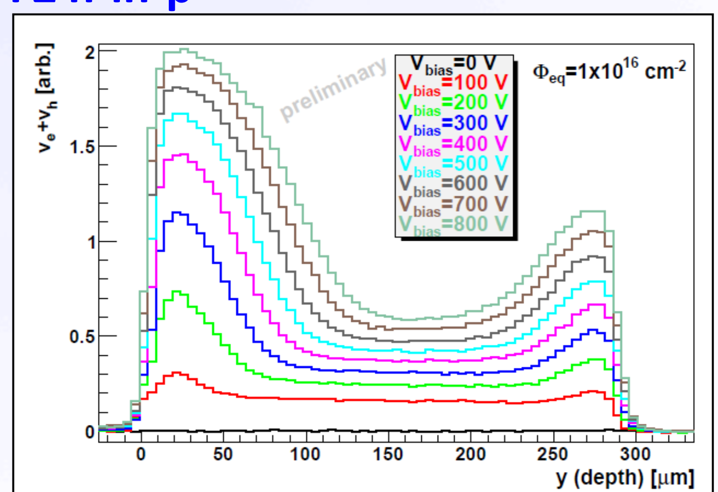
p-type silicon after high fluences:
(still "p-type")





- **Dominant junction close to n+ readout strip for FZ n-in-p**
- **Investigation by measurement (edge-TCT)**



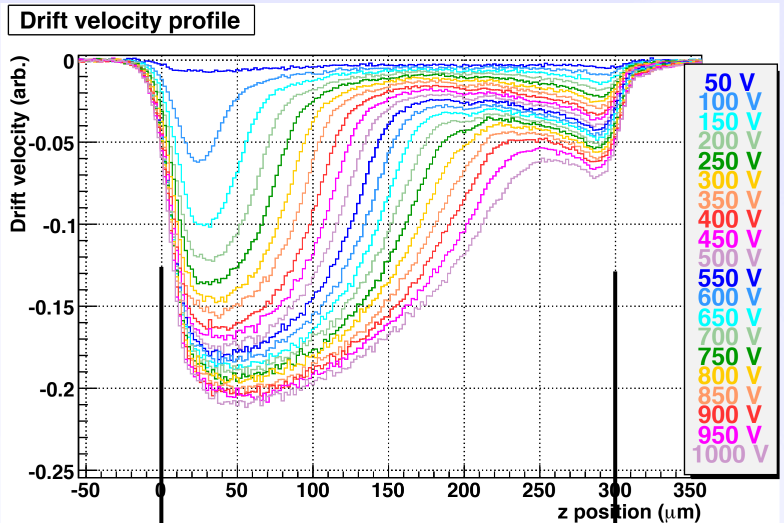


Edge-TCT – Example – Drift velocity

[N.Pacifico, 20th RD50 Workshop, Bari, 2012]

- **Sensors: MCZ and FZ p-type ministrip sensors** (pitch: 80μm, width 20μm)
- **Irradiation: 10^{16} p/cm^2 with 24 GeV/c protons** (6.1×10^{15} n_{eq}/cm^2)
- **Annealing: Isothermal at 60°C** (results after 560 min shown below)

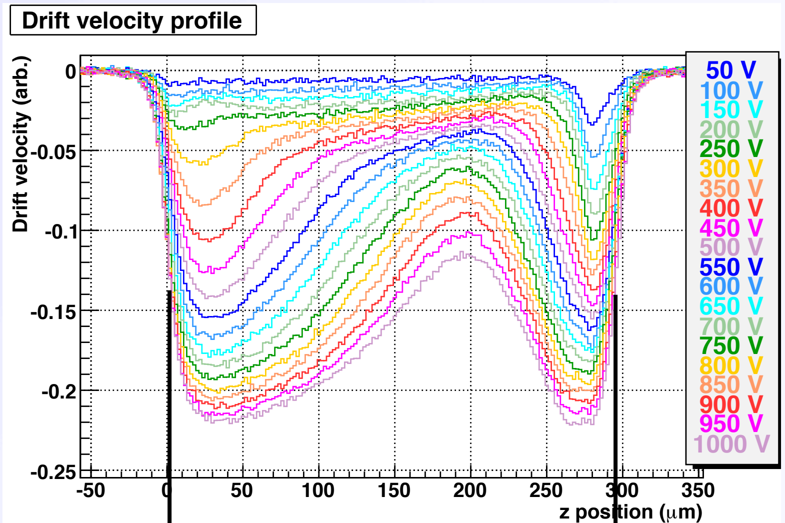
FZ



Front electrode (n-p junction)

Back electrode (p^+ contact)

MCZ



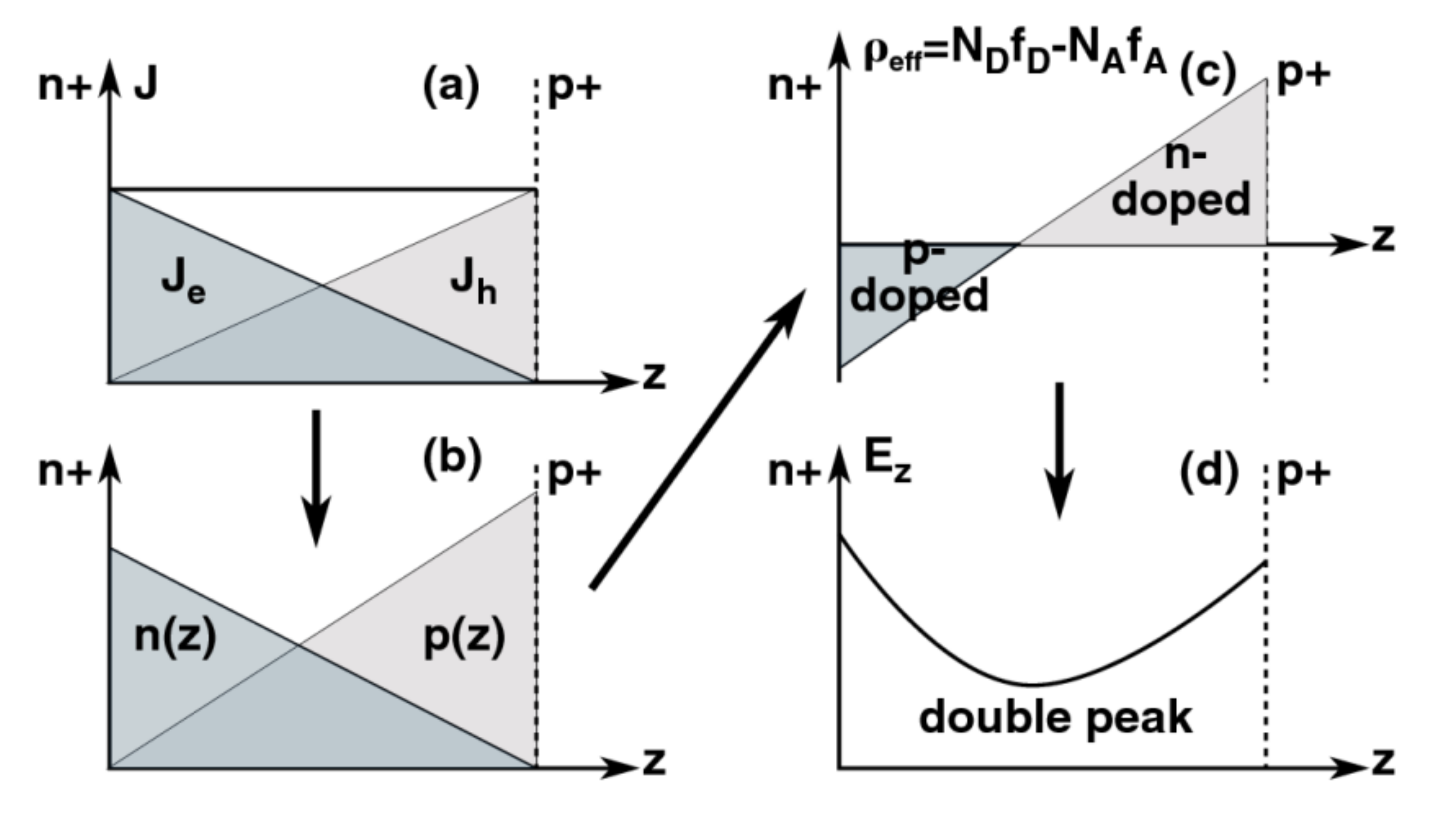
Front electrode (n-p junction)

Back electrode (p^+ contact)

- **Presence of electric field throughout sensor** (although depletion voltage expected to be > 6000 V)
- **MCZ: High electric field at back electrode** (but not 'useful' for this p-type sensor)
  - At this annealing stage both sensors give the same signal (as measured with beta particles on Alibava CCE system)
  - ~7400 electrons (most probable) at 1000 V

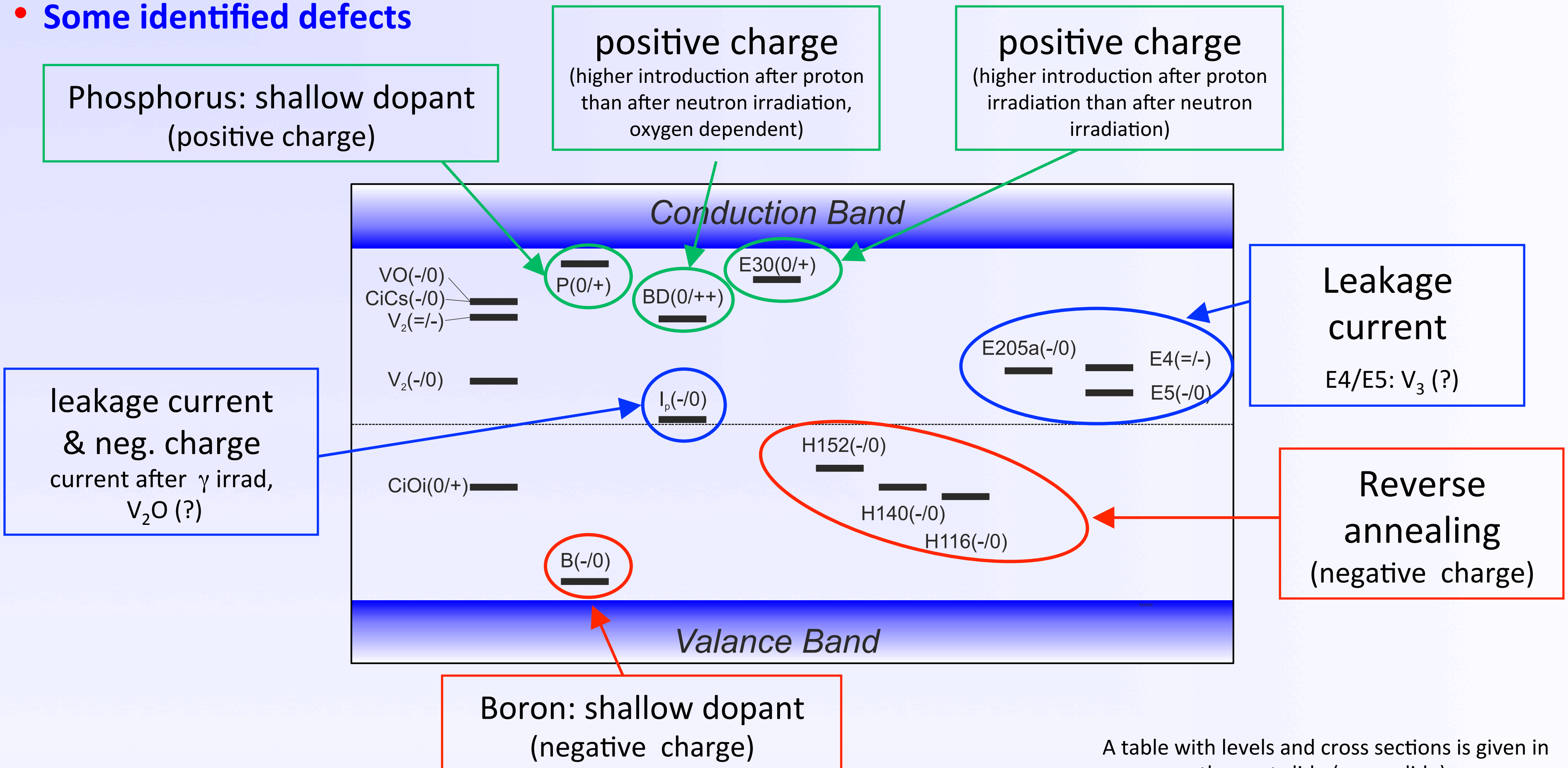
Double Junction

- **Double Junction = Polarization Effect**



Summary on defects with strong impact on device performance after irradiation

- **Some identified defects**



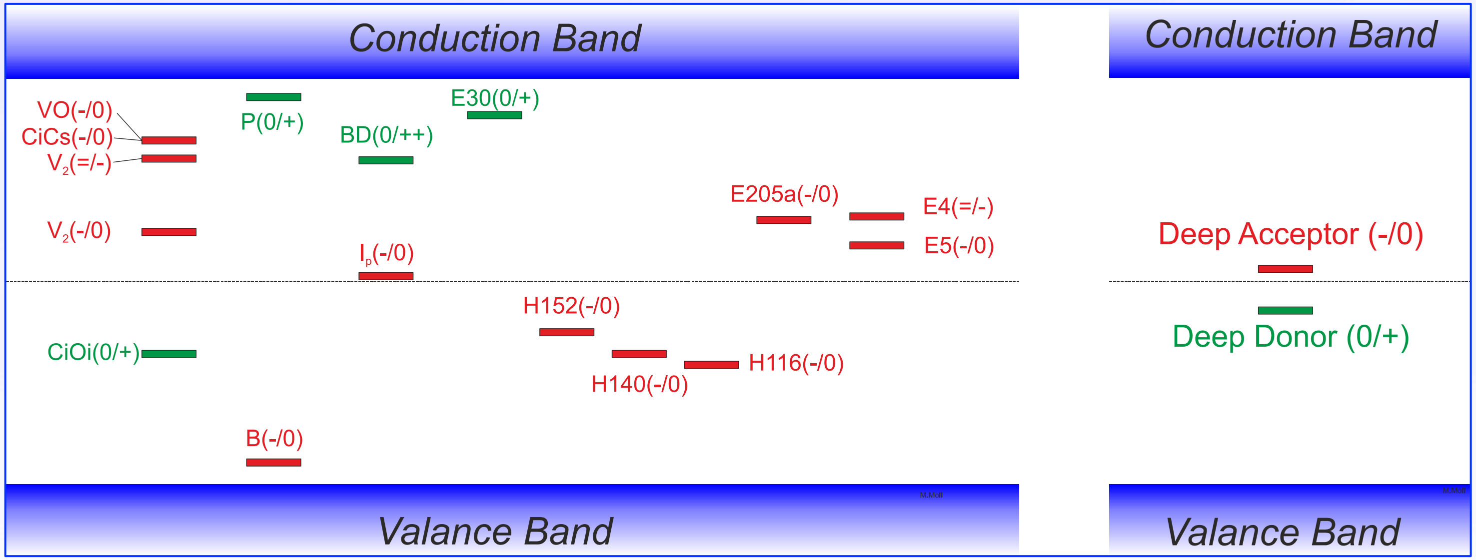
A table with levels and cross sections is given in the next slide (spare slide).

- **Trapping: Indications that E205a and H152K are important** (further work needed)
- Converging on consistent set of defects observed after p, π, n, γ and e irradiation.
- Defect introduction rates are depending on particle type and particle energy and (for some) on material!

TCAD - Simulations

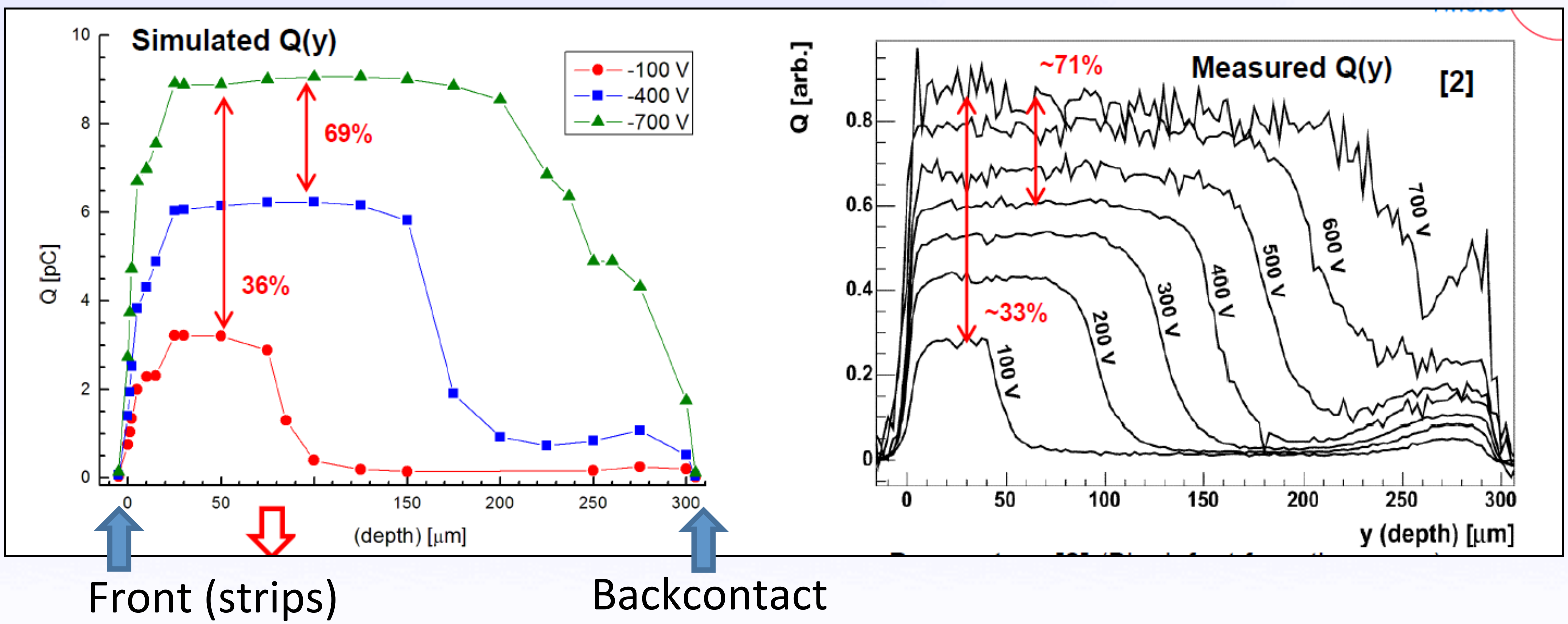
- **Device simulation of irradiated sensors**
  - **Using: Custom made simulation software and Silvaco & Synopsis TCAD tools**
    - Good progress in reproducing results on leakage current, space charge, E-Field, trapping …..
    - Enormous parameter space ranging from semiconductor physics parameters and models over device parameters towards defect parameters ➔ **Tools ready but need for proper input parameters!**
    - **…simulations are getting predictive power.**
- **Working with "effective levels" for simulation of irradiated devices**
    - Most often 2, 3 or 4 "effective levels" used to simulate detector behavior
    - Introduction rates and cross sections of defects tuned to match experimental data

Measured defects ➔ ***TCAD input***



RD50 Simulation working group

- **Device simulation working group formed in 2012**
  - **Aim:** Produce TCAD input parameters that allow to simulate the performance of irradiated silicon sensors and eventually allow for performance predictions under various conditions (sensor material, irradiation fluence and particle, annealing).
  - **Ongoing activity:** Inter-calibration of the used tools using a predefined set of defect levels and physics parameters & definition of defect levels & study surface effects
  - **Example of results (simulation vs. measurement):**
    - edge-TCT on a neutron irradiated p-type strip sensor (5e14n/cm^2); -20°C; simulation: 3 level model
    - Loss of efficiency at low voltages in region close to strips explained by simulations



[T.Peltola, RD50 Workshop – Nov. 2013]

Summary

- **Silicon Detectors**
  - Based on the concept of a reverse biased pn-junction (reverse biased diode)
- **Silicon Detectors at the LHC and upgrade of LHC**
  - **Inner tracking at LHC done by silicon detectors**
  - **Hybrid-pixel** and **strip sensors** implemented in LHC experiments (some drift sensors)
  - Monolithic sensors for LHC and LC under development
- **Radiation Damage in Silicon Detectors**
  - Reason: crystal damage (displacement damage) that is evidenced as defect levels in the band gap of the semiconductor
  - Change of **Depletion Voltage** (internal electric field modification, "type inversion", reverse annealing, loss of active volume, …)
  - 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**
  - Material and Device Engineering: oxygenation, 3D sensors, p-type (n-readout) sensors
- **TCAD simulations (of irradiated sensors)**
  - Essential to understand and optimize sensors (for high radiation environments)

Acknowledgements & References

- **Most references to particular works given on the slides**
  - ***RD50 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***
  - ***L.Rossi, P.Fischer, T.Rohe, N.Wermes "Pixel Detectors", Springer, 2006***
  - ***Gerhard Lutz, "Semiconductor radiation detectors", Springer 1999***

- **Research collaborations and web sites**
  - ***CERN RD50 collaboration (http://www.cern.ch/rd50) - Radiation Tolerant Silicon Sensors***
  - ***CERN RD39 collaboration – Cryogenic operation of 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***