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An introduction to Silicon Detectors

with focus on applications at Hadron Colliders

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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 (HL-LHC)**
    - Timeline, challenges & motivation to study and understand radiation damage
  - **Recent developments**
    - MAPS sensors and sensors with intrinsic gain for fast timing applications

- **II. Introduction to Radiation Damage in Silicon Detectors**
  - **What is Radiation Damage?**
  - **Mitigation techniques: What can we do against radiation damage?**
    - Examples: p-type strip sensors, 3D sensors

- **III. Why do we need TCAD simulations (introduction)?**
  - Example: Complex sensor structure: 3D sensor
  - Example: Simulation of irradiation effects

….see presentations of Joern Schwandt and Marco Bomben

- **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/cm³ ; dE/dx (M.I.P.) ≈ 3.8 MeV/cm ≈ 10^6 e-h/µm (average)
  - **High carrier mobility** μ_e =1450 cm²/Vs, μ_h = 450 cm²/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

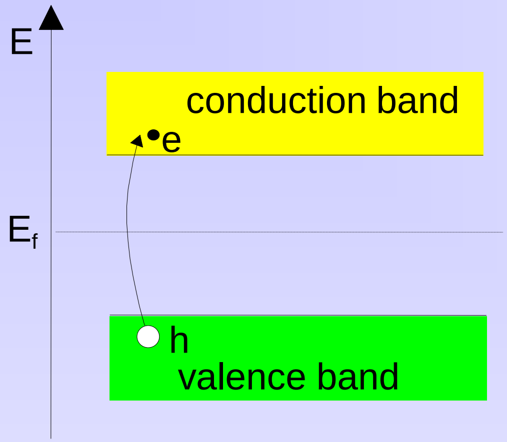
    ⇒ sophisticated commercial TCAD tools available for sensor simulation

- **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/cm³]	3.515	3.22	5.32	2.33	5.32
e-mobility μ_e [cm²/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm²/Vs]	1200	115	400	450	1900

Low field mobility!

How to obtain a signal?

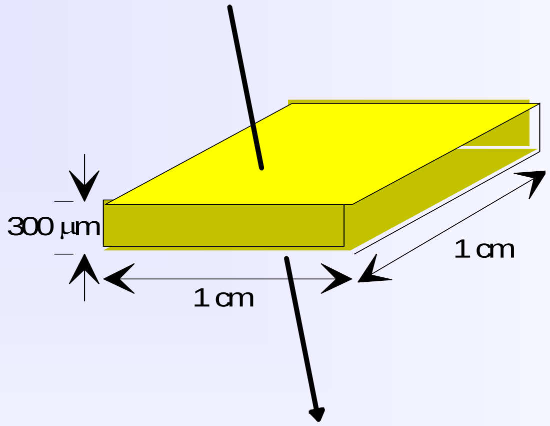


- **Intrinsic semiconductor**
  - In a pure intrinsic (undoped) semiconductor the electron density n and hole density p are equal.

$$n = p = n_i$$

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)*

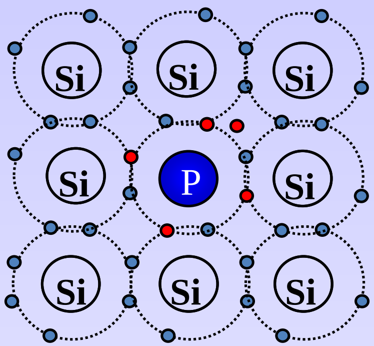


➢ **Need to reduce number of free carriers, i.e. deplete the detector**

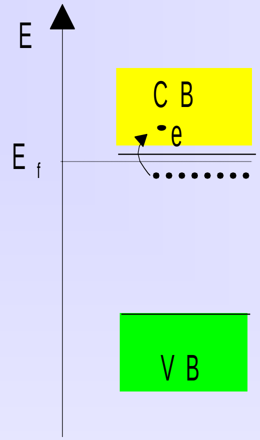
➢ **Solution: Make use of reverse biased p-n junction (reverse biased diode)**

Doping, Resitivity and p-n junction

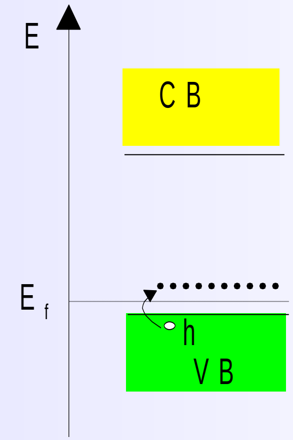
e.g. Phosphorus



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



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



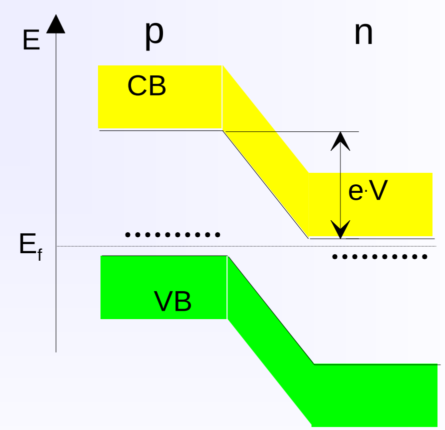
- **Resistivity**
  - carrier concentrations *n, p*
  - carrier mobility μ_n, μ_p

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

	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 !

  $\Rightarrow$ band structure deformation
  $\Rightarrow$ potential difference
  $\Rightarrow$ depleted zone



Abrupt junction – Depletion depth

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

Poisson equation

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

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

$$E(w) = 0$$

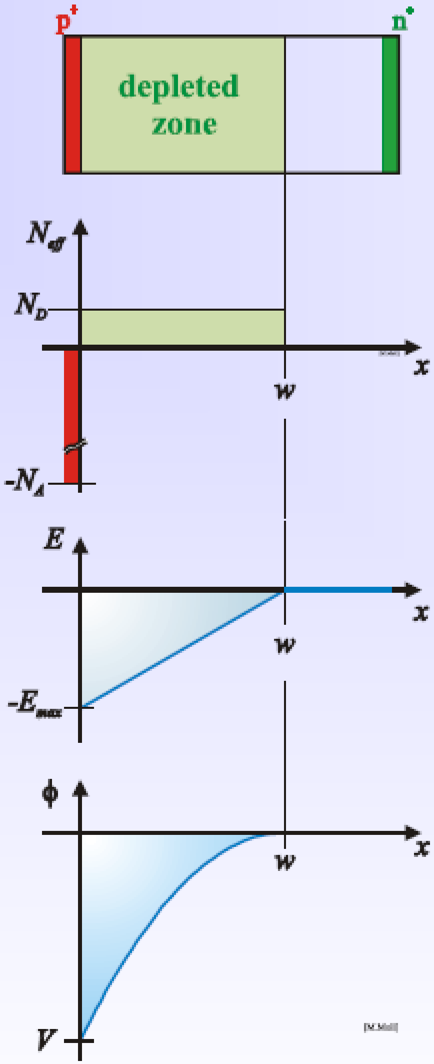
Electric field strength

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

$$\phi(w) = 0$$

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)

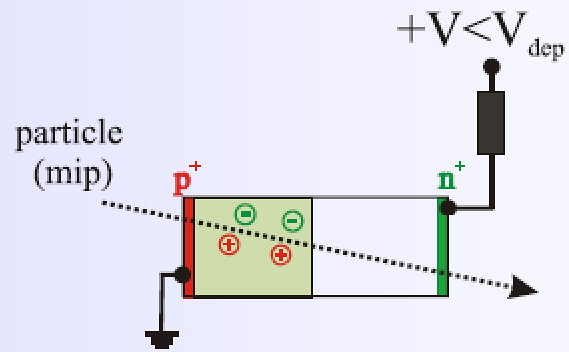
$$E_{\max} = -\frac{e \cdot N_{eff}}{\varepsilon} \cdot w$$

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

Depletion depth w

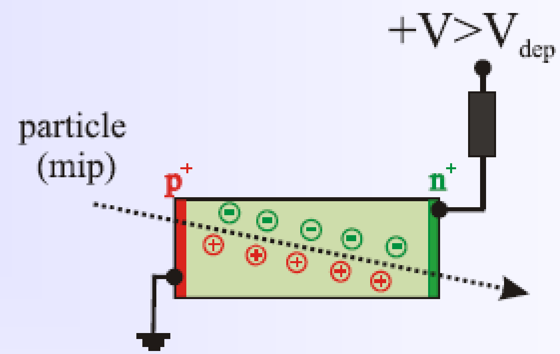
Depletion Voltage

- 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}
      ($\rho \approx$ 3kΩcm)
    - $V_{dep} \approx$ 100V



depletion voltage V_{dep}

detector thickness d

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

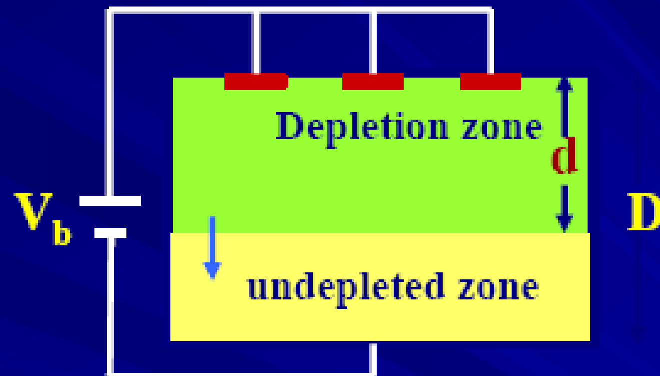
effective space charge density N_{eff}

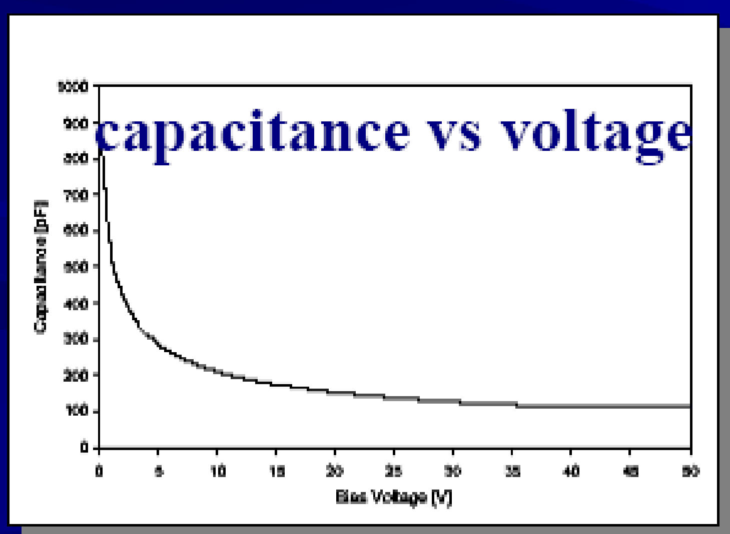
- Full charge collection only for ($V>V_{dep}$)

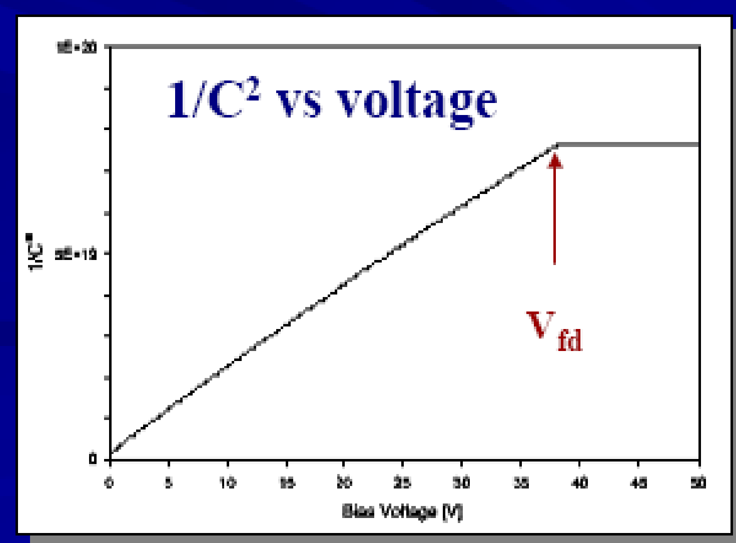
Depletion Zone: Properties

- 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.

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

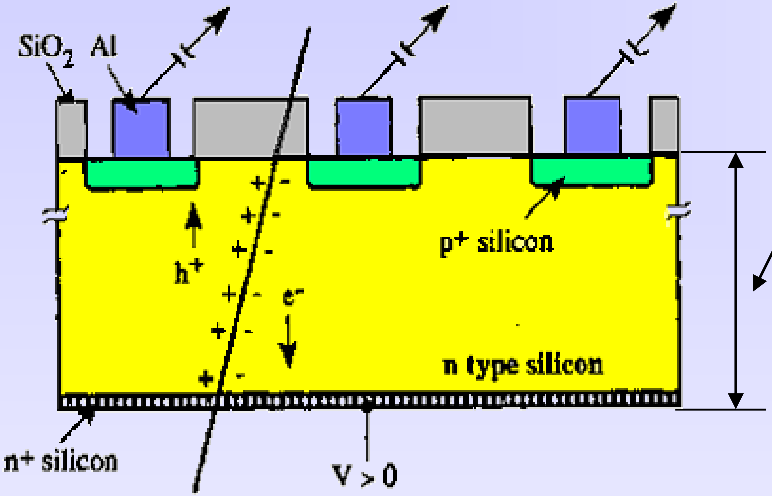






Single sided strip detector

- **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 ~$2.2\cdot10^{12}$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

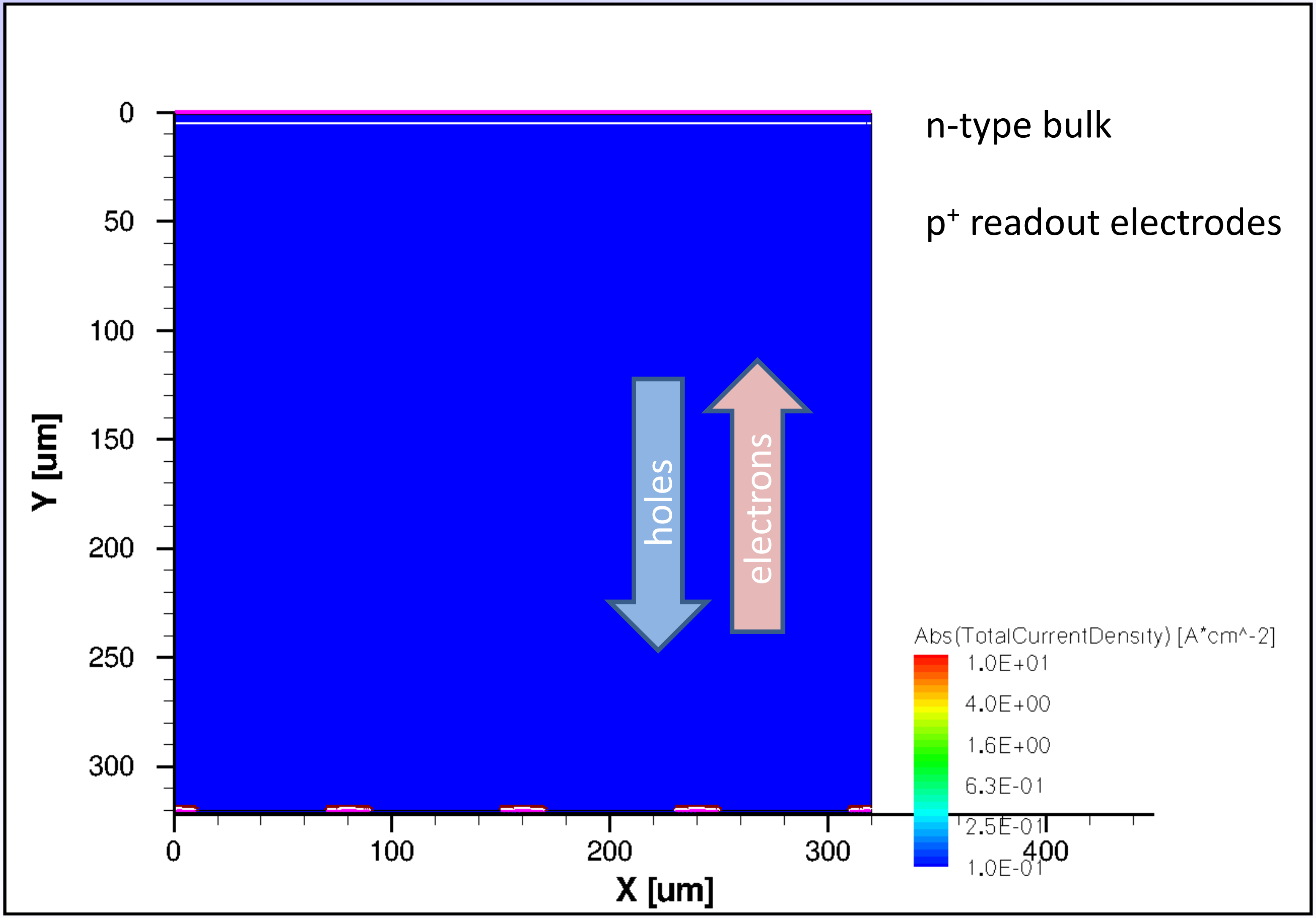
$$\sigma = \frac{p}{\sqrt{12}}$$

typical pitch values are 20 μm– 150 μm

⇒ 50 μm pitch results in 14.4 μm resolution

Signal formation in a strip sensor

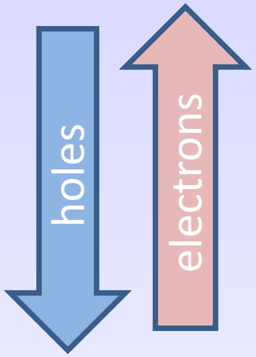
- **Simulation: Current density, minimum ionizing particle entering with 45° angle**



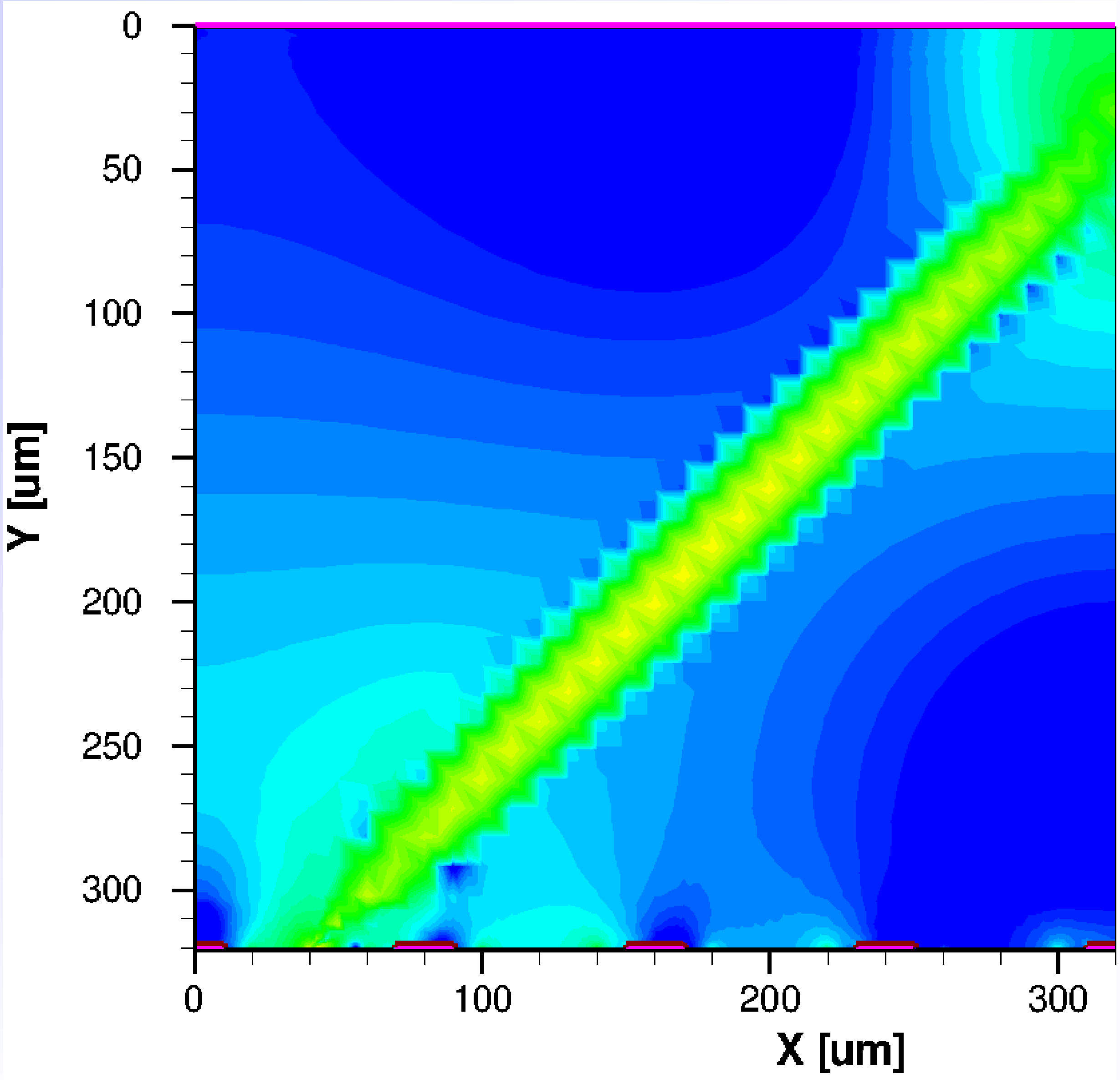
PhD thesis: Thomas Eichhorn 2015

Signal formation in a strip sensor

- **Simulation:**
  - **Current density**
  - **mip, 45° angle**

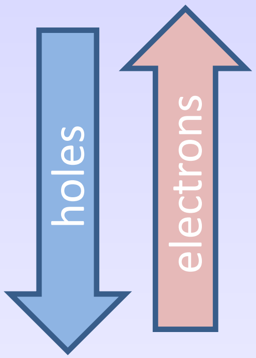


t = 1 ns

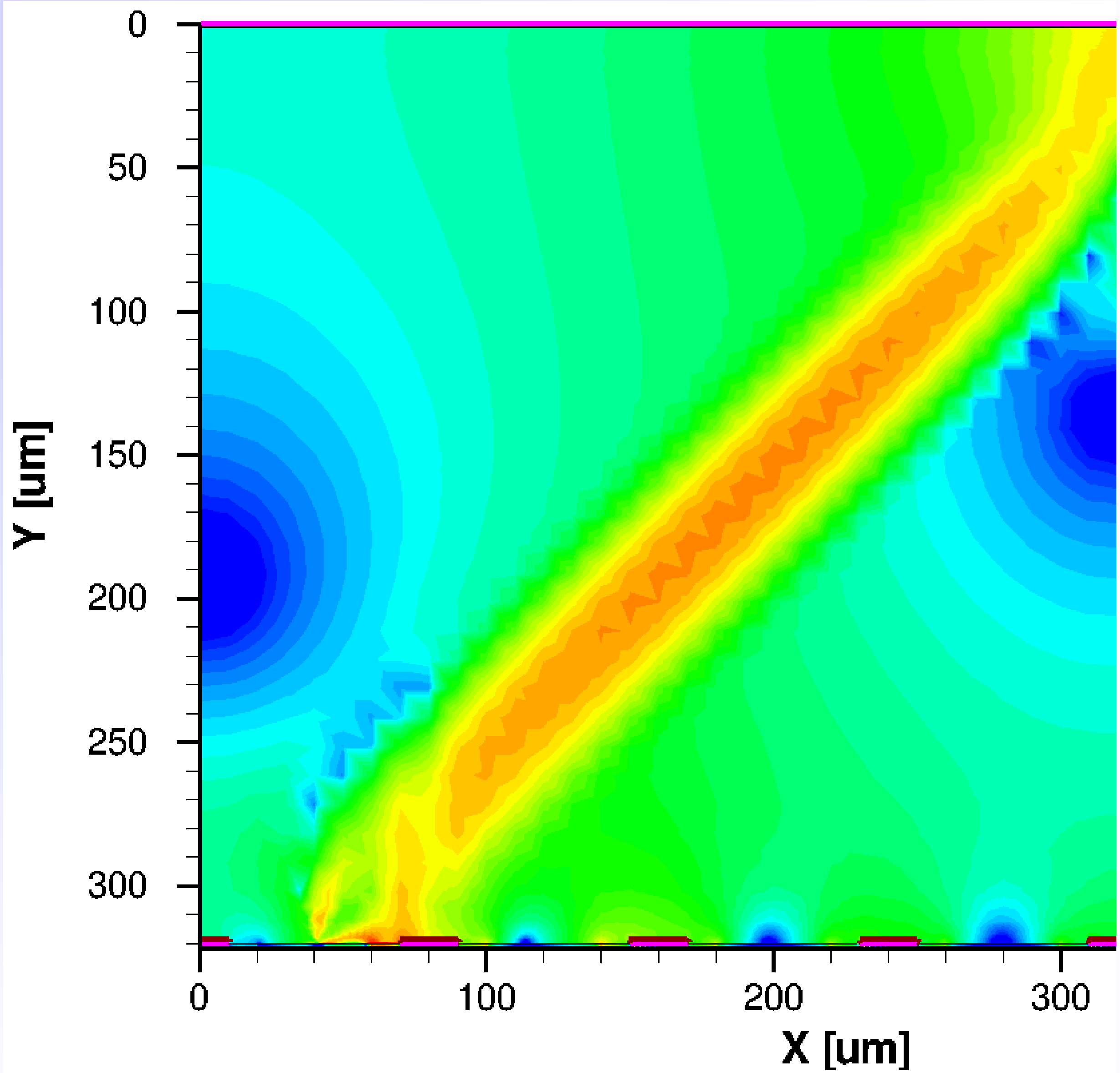


Signal formation in a strip sensor

- **Simulation:**
  - **Current density**
  - **mip, 45° angle**

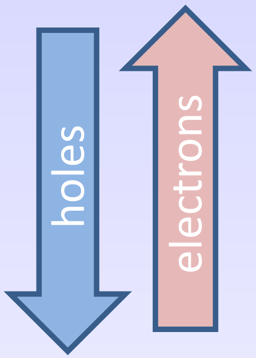


t = 1.2 ns

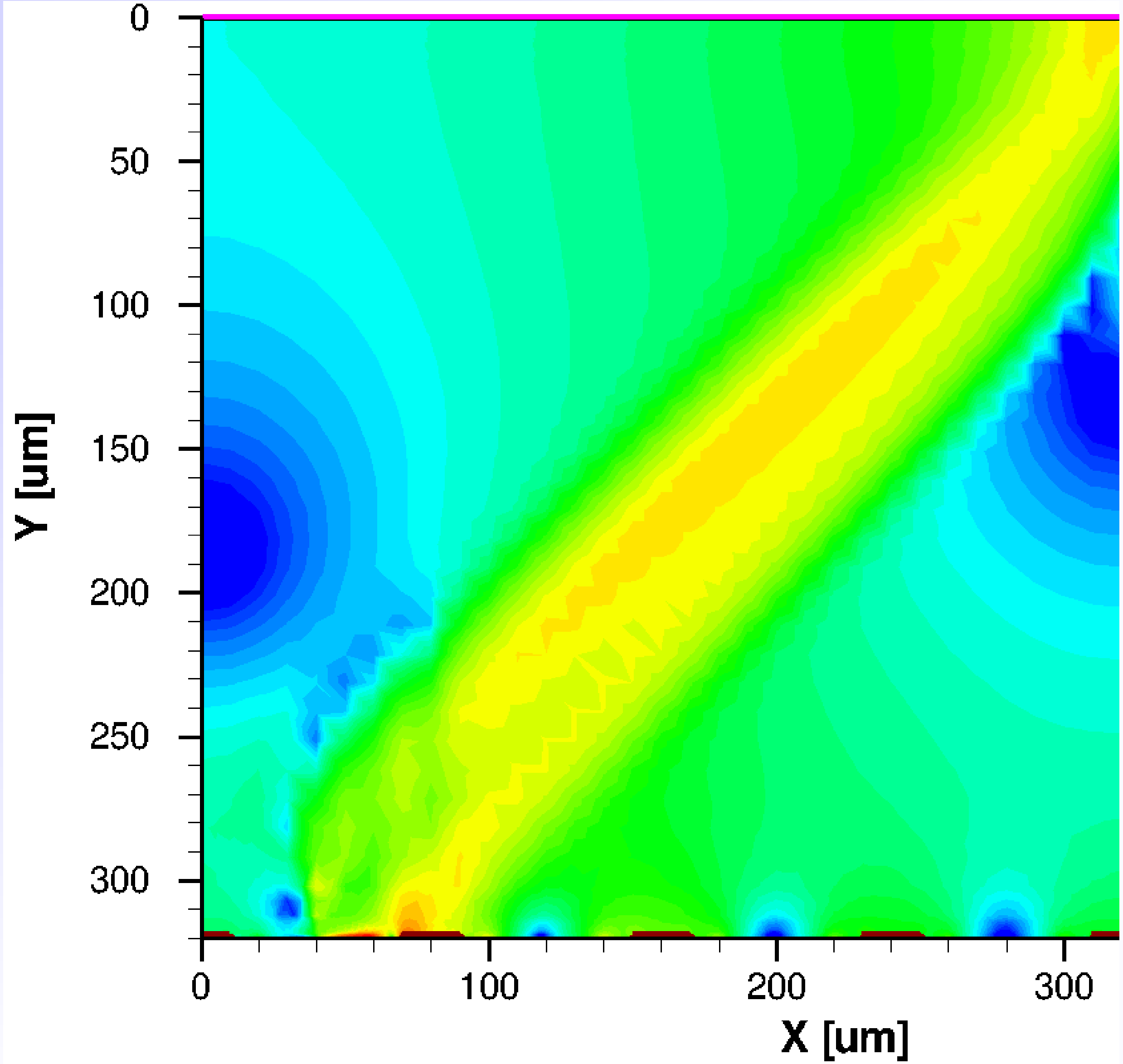


Signal formation in a strip sensor

- **Simulation:**
  - **Current density**
  - **mip, 45° angle**

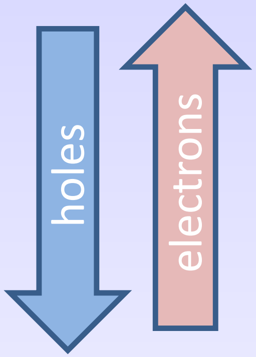


t = 1.4 ns

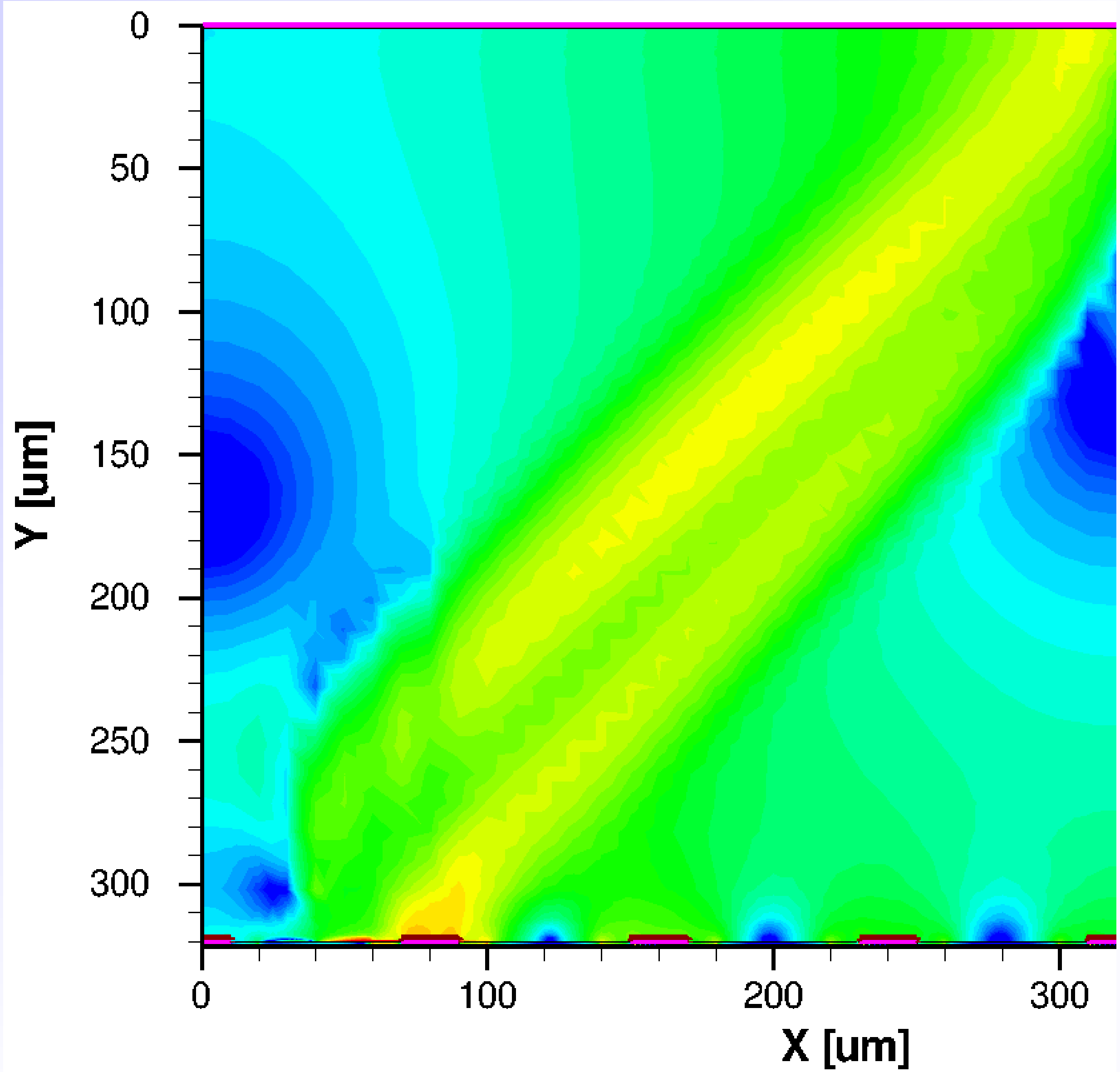


Signal formation in a strip sensor

- **Simulation:**
  - **Current density**
  - **mip, 45° angle**

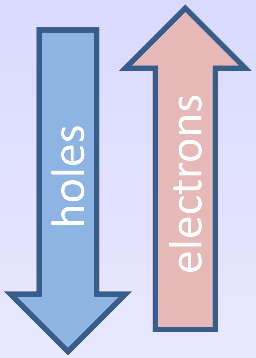


t = 1.6 ns

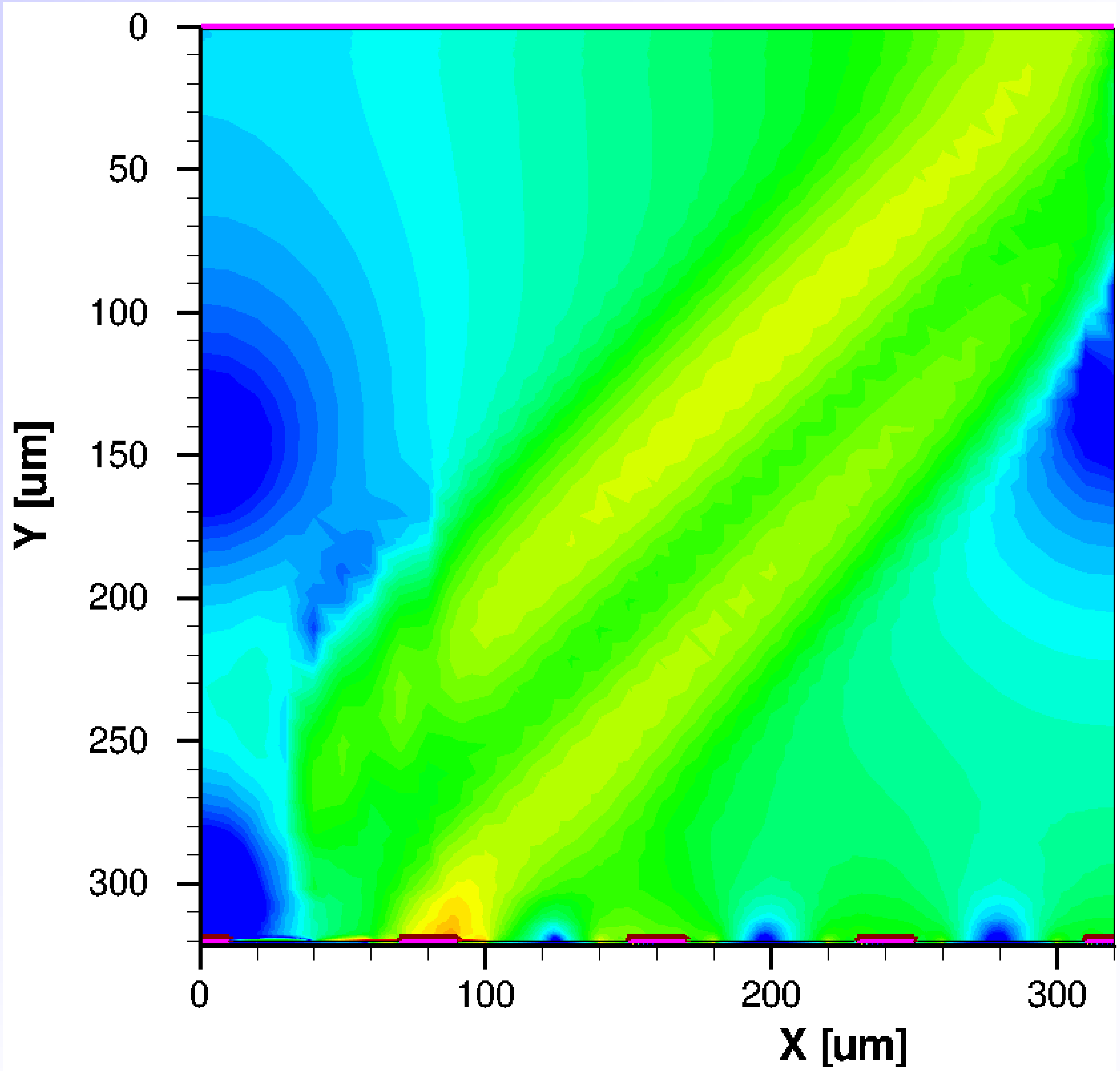


Signal formation in a strip sensor

- **Simulation:**
  - **Current density**
  - **mip, 45° angle**



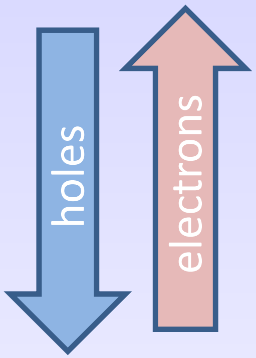
t = 1.8 ns



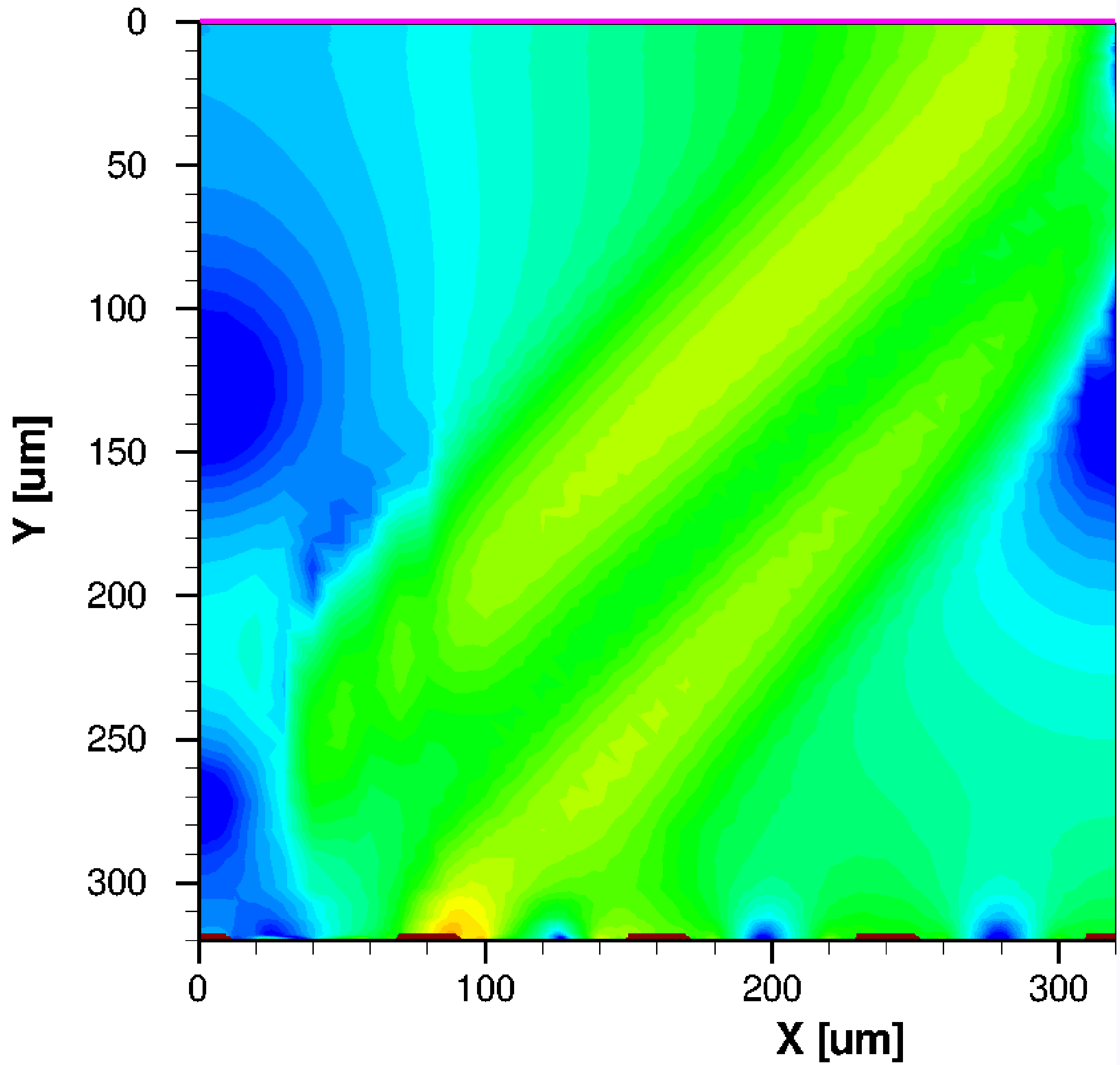
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

- **Simulation:**
  - **Current density**
  - **mip, 45° angle**

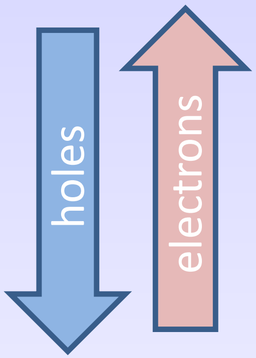


t = 2.0 ns

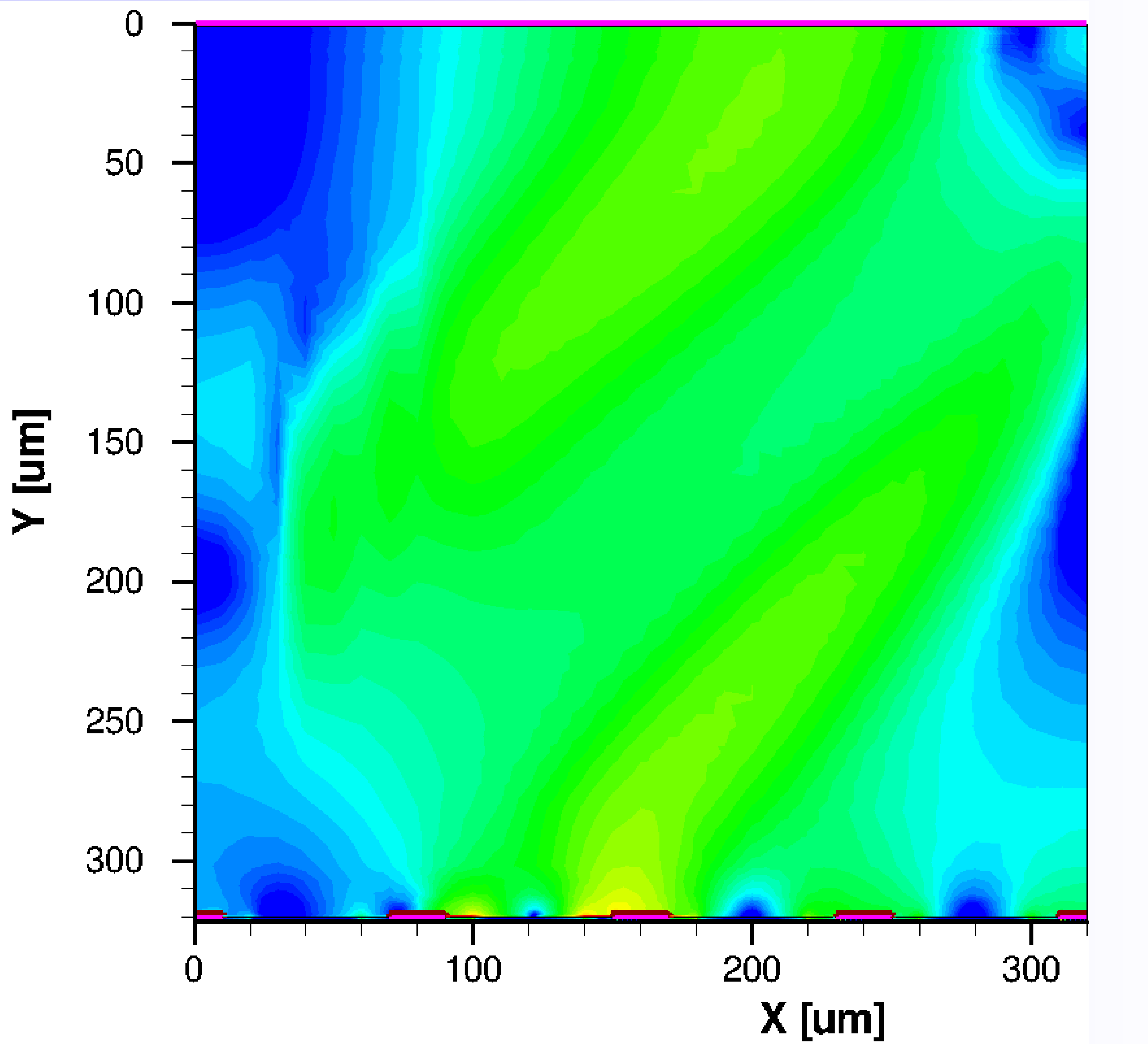


Signal formation in a strip sensor

- **Simulation:**
  - **Current density**
  - **mip, 45° angle**

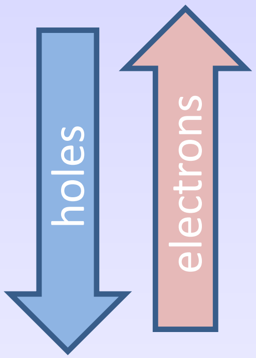


t = 3.0 ns

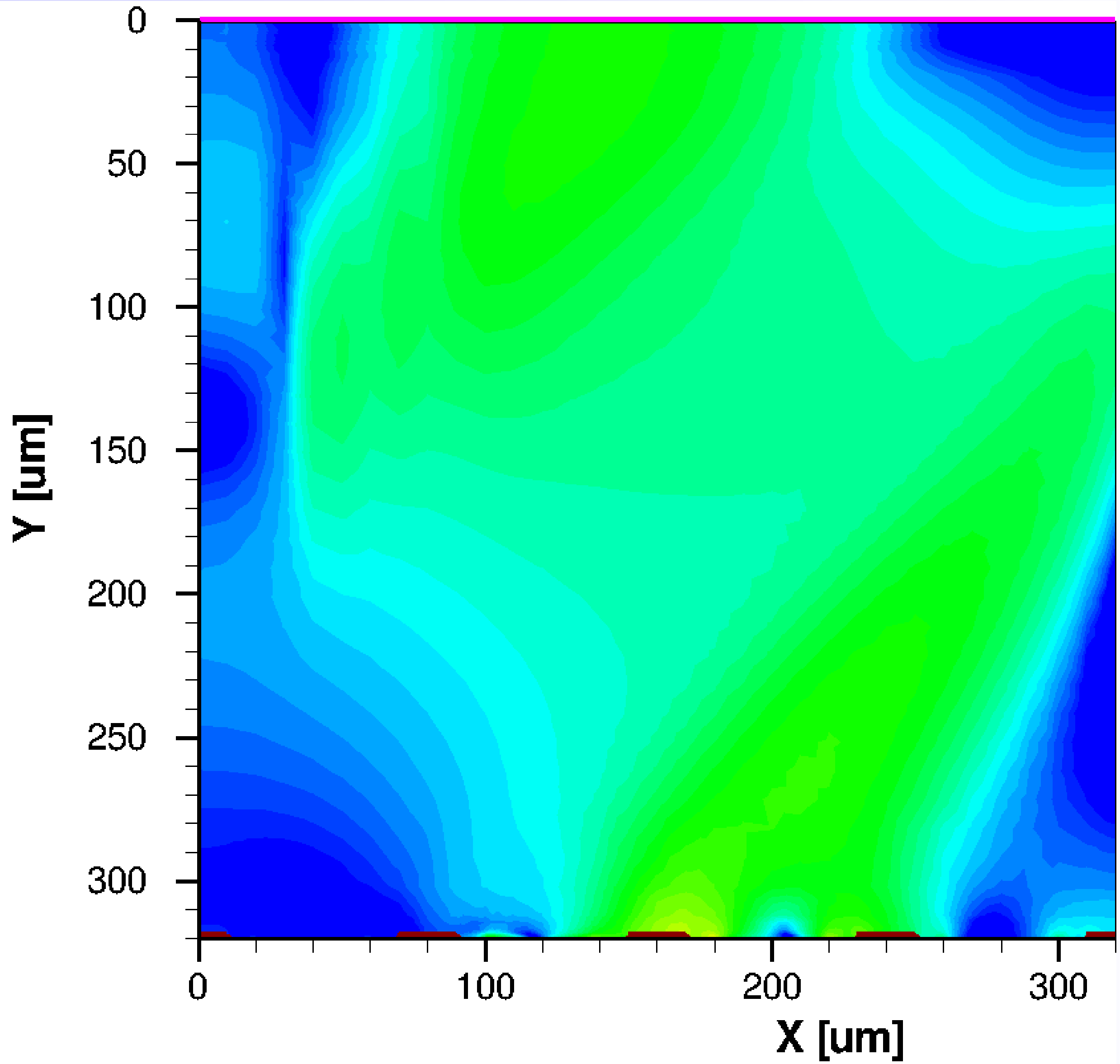


Signal formation in a strip sensor

- **Simulation:**
  - **Current density**
  - **mip, 45° angle**

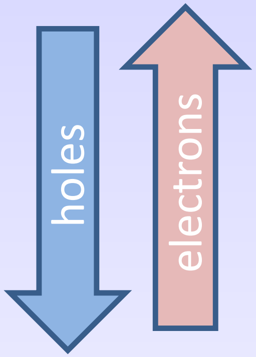


t = 4.0 ns

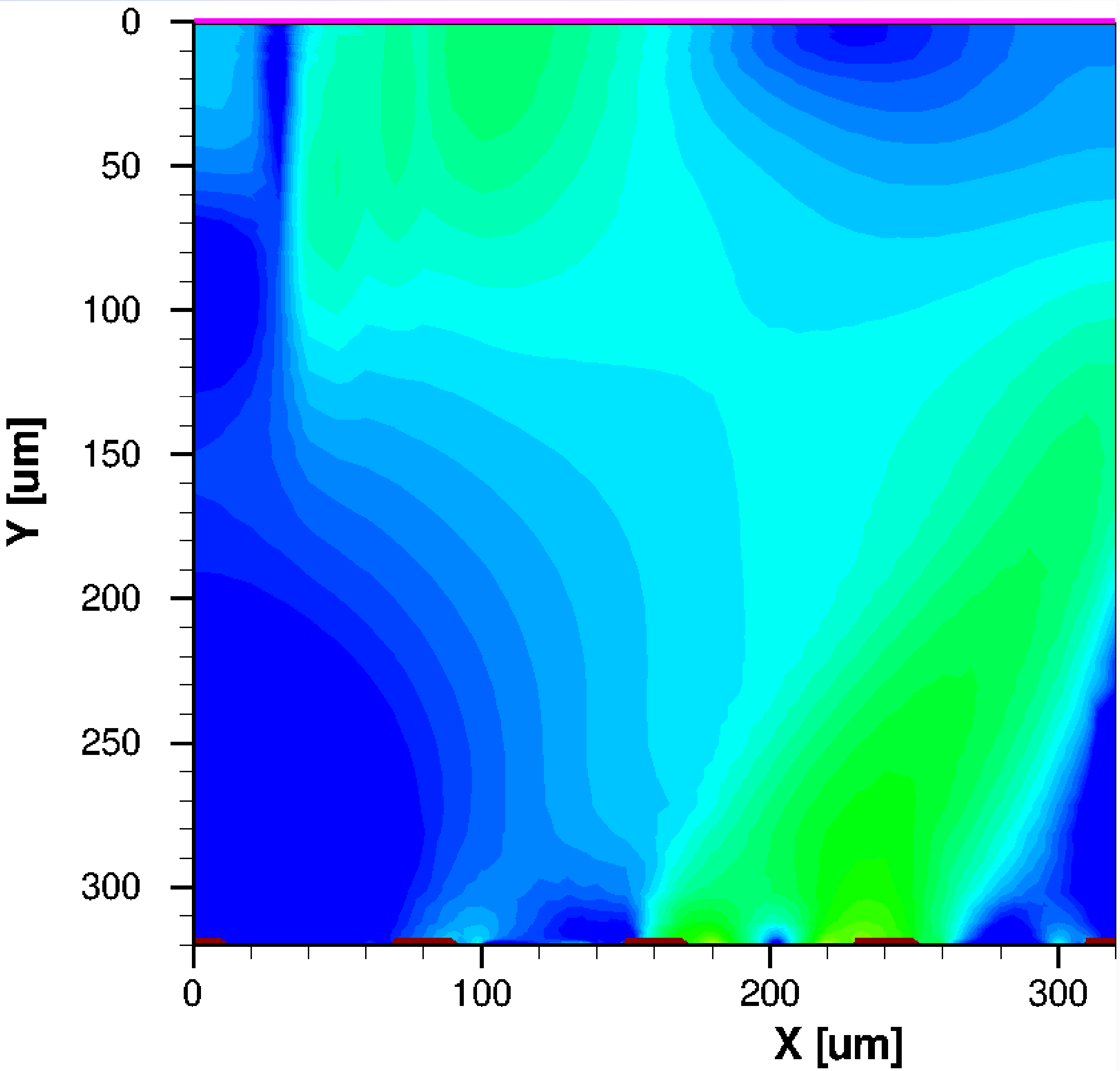


Signal formation in a strip sensor

- **Simulation:**
  - **Current density**
  - **mip, 45° angle**

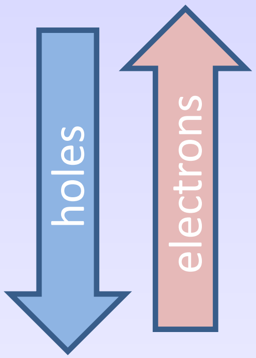


t = 5.0 ns

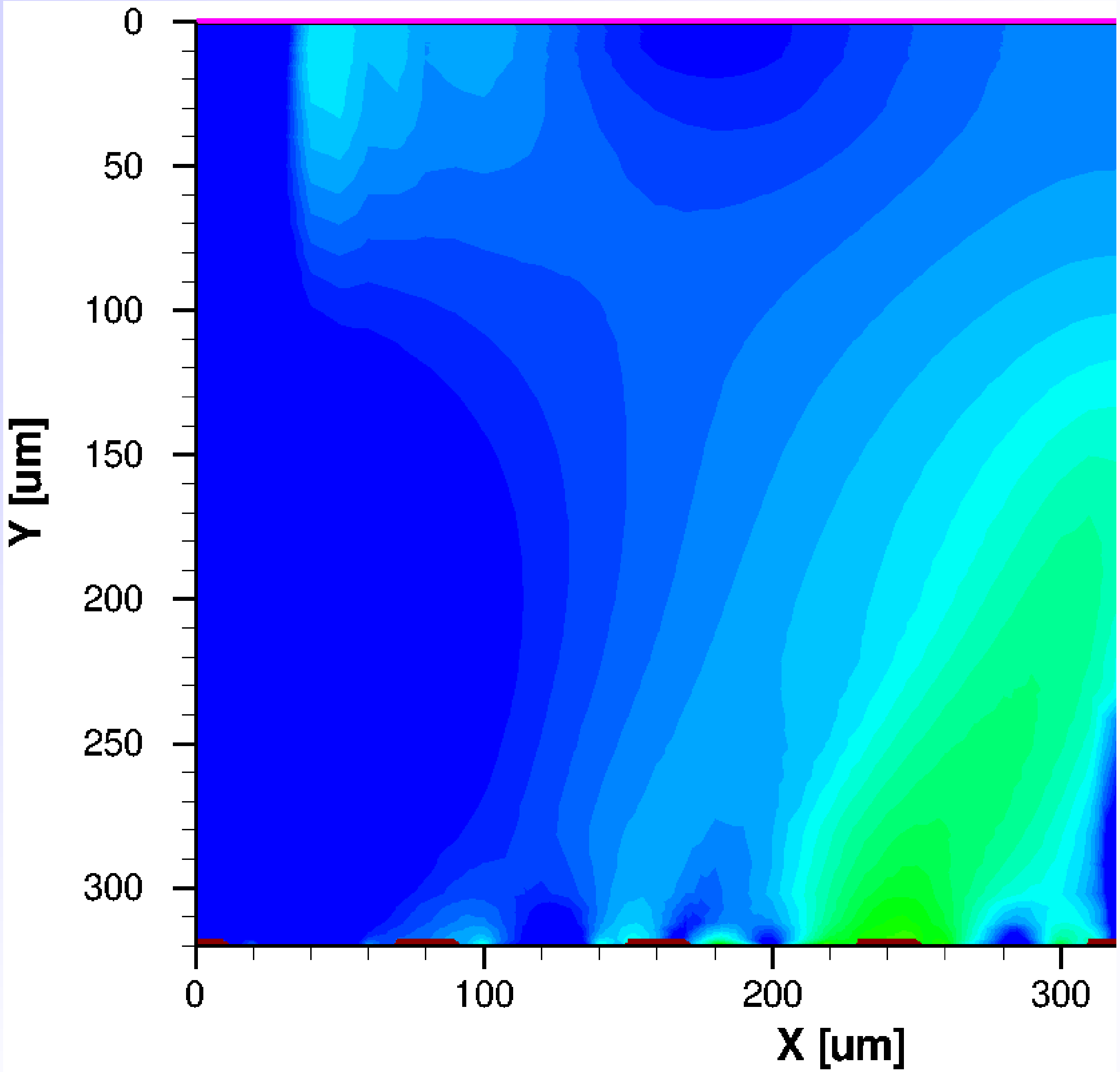


Signal formation in a strip sensor

- **Simulation:**
  - **Current density**
  - **mip, 45° angle**

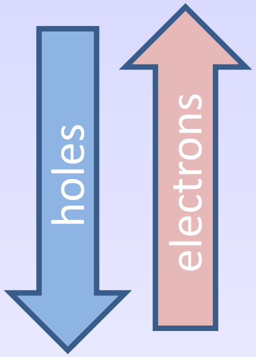


t = 6.0 ns

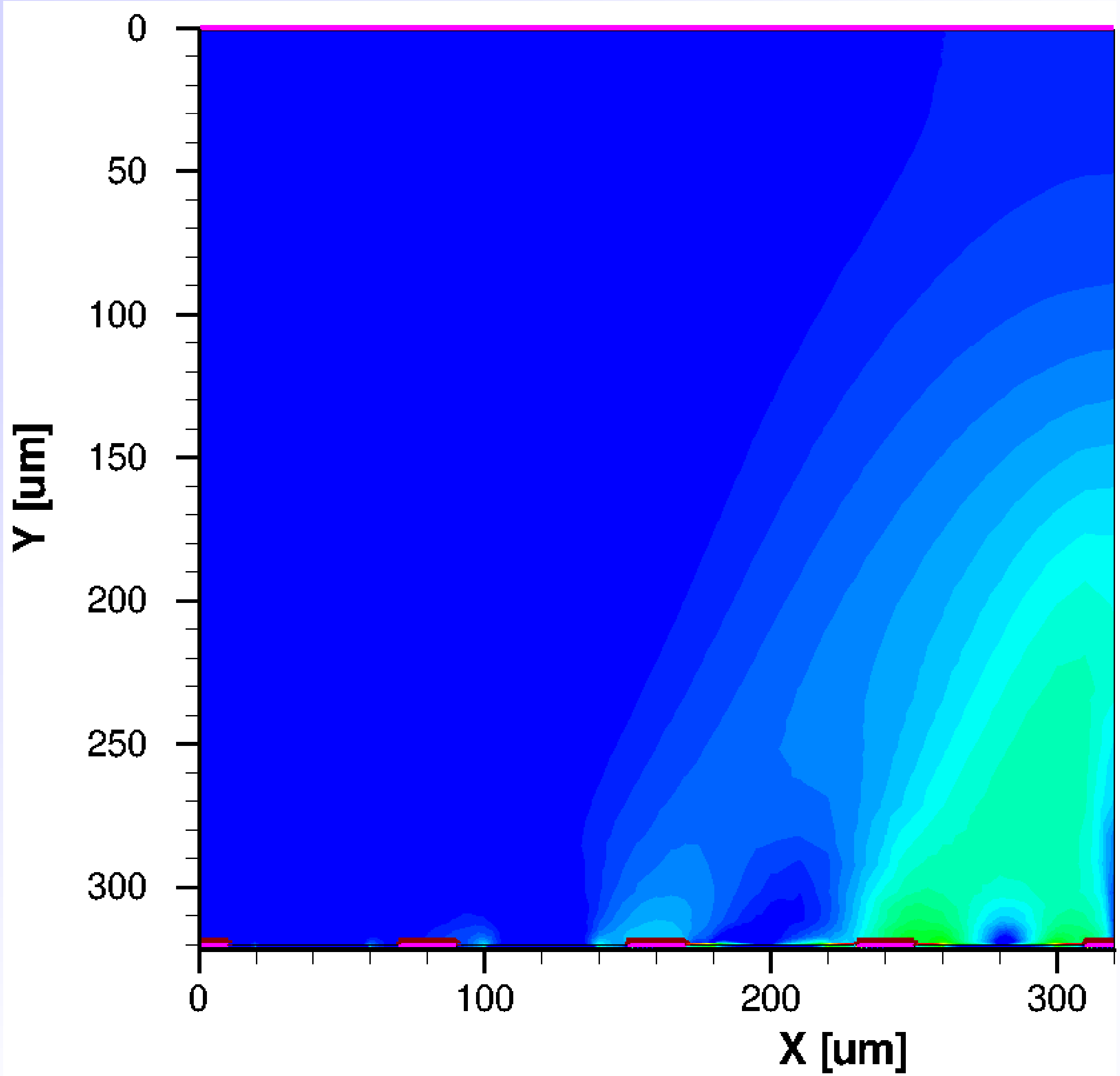


Signal formation in a strip sensor

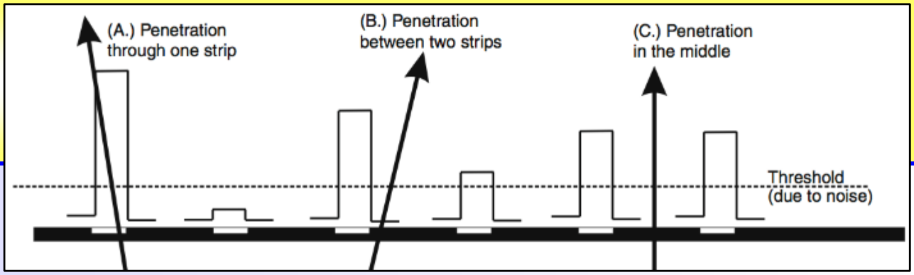
- **Simulation:**
  - Current density
  - mip, 45° angle



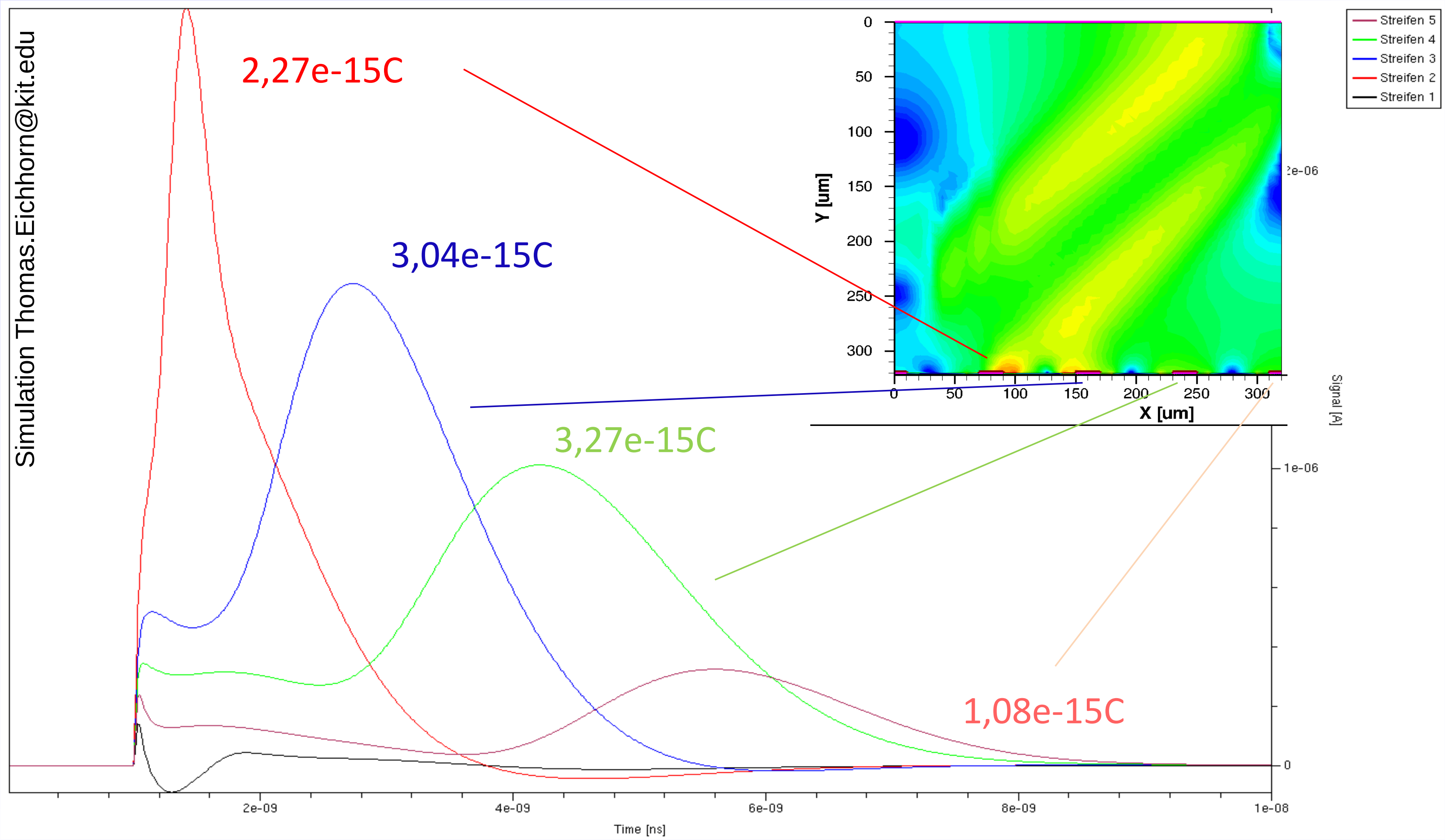
t = 7.0 ns



Signal strip sensor



- **Simulation: mip, 45° angle**
  - **Signals induced on electrodes (Integration gives collected charge)**



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

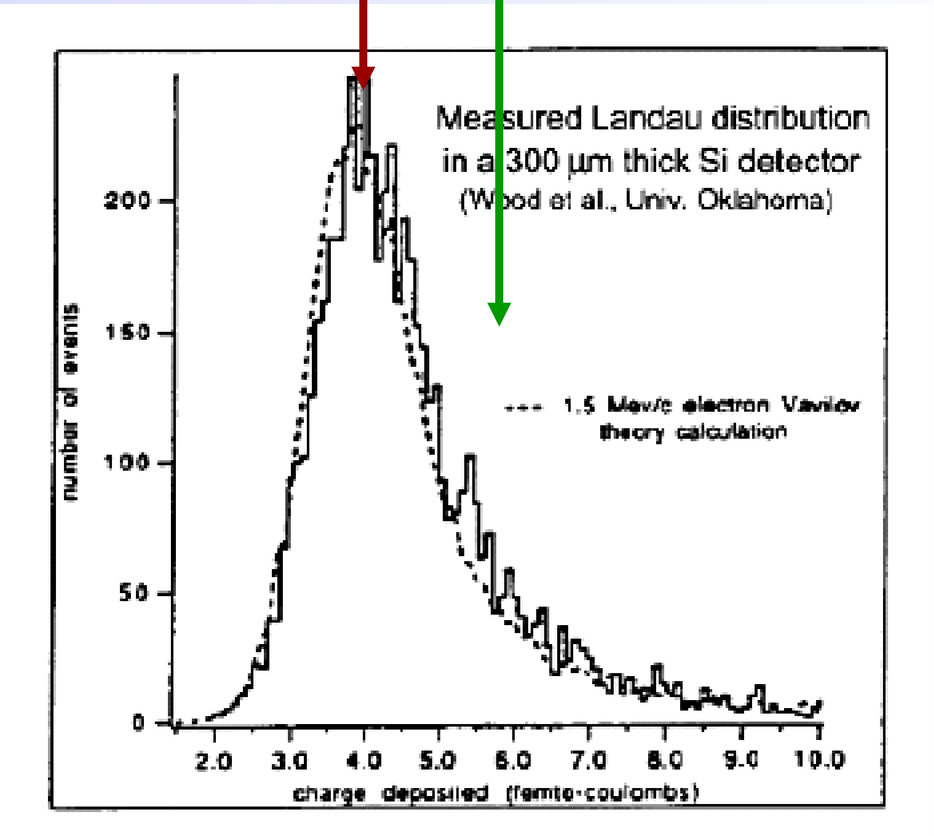
- 3.6 eV to create an e-h pair
  ⇒ 108 e-h / µm (mean)
  ⇒ 72 e-h / µm (most probable)

- Most probable charge **(300 µm)**

  ≈ 22500 e **≈ 3.6 fC**

Most probable charge ≈ 0.7× mean

Mean charge



Signal to noise ratio (S/N)

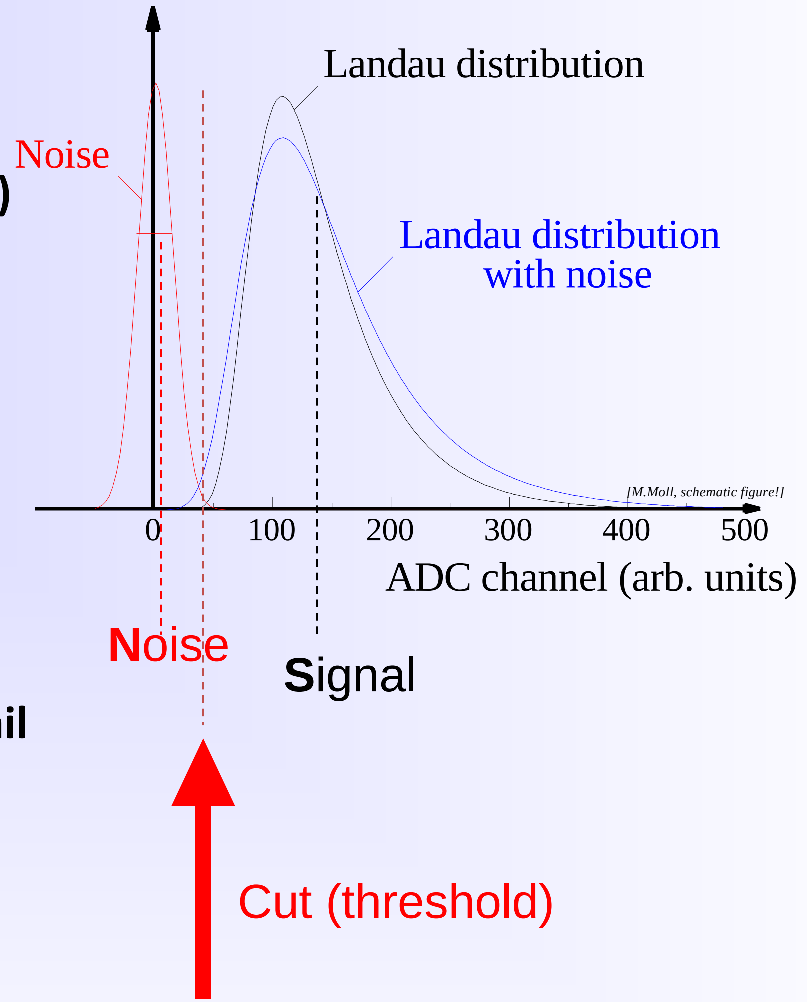
- **Landau distribution has a low energy tail**
  - **becomes even lower by noise broadening**

Noise sources: (ENC = Equivalent Noise Charge)

- Capacitance $ENC \propto C_d$

- Leakage Current $ENC \propto \sqrt{I}$

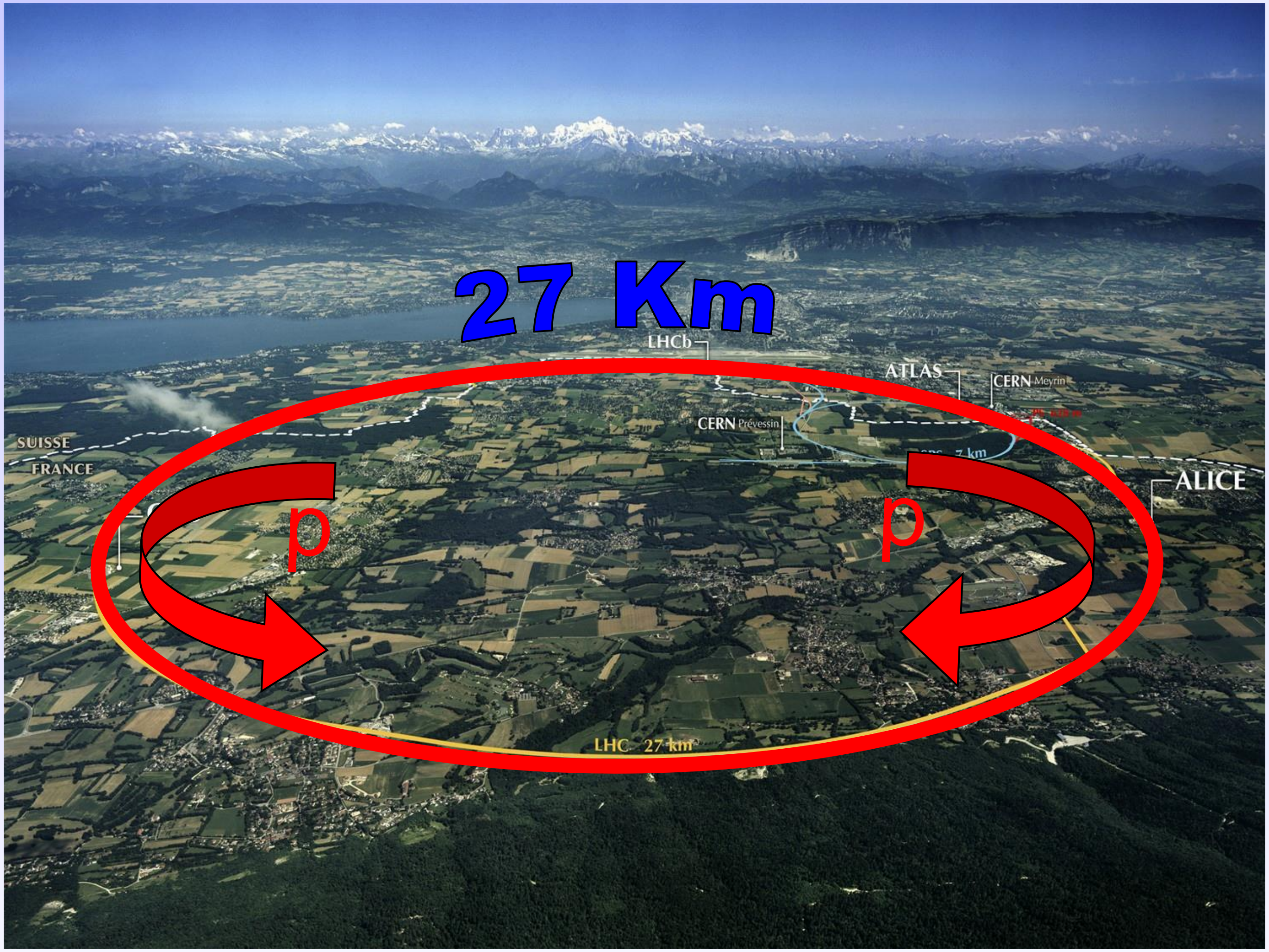
- Thermal Noise (bias resistor) $ENC \propto \sqrt{k_B T / R}$



- **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.

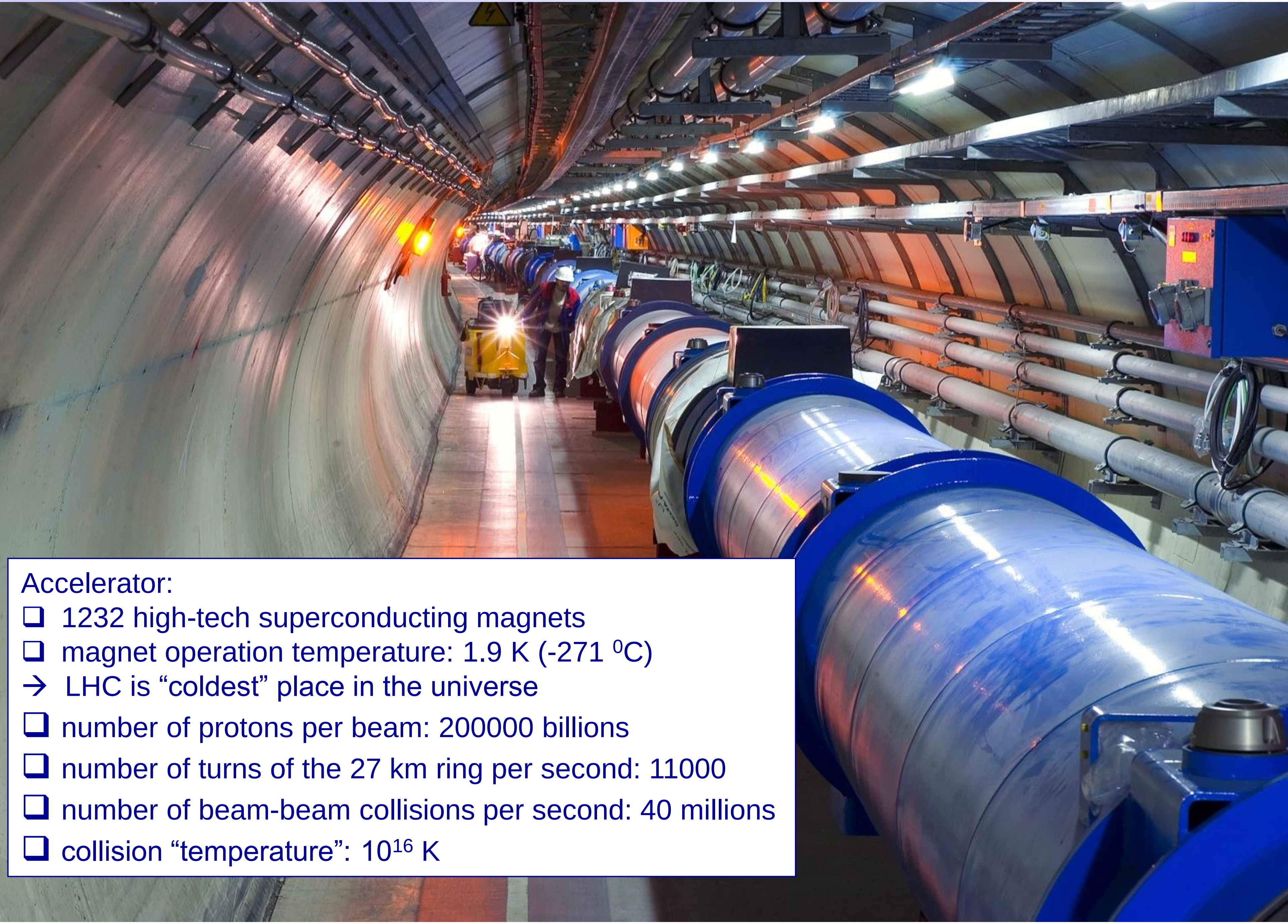
Silicon Detectors at the Large Hadron Collider at CERN

CERN & LHC - Large Hadron Collider



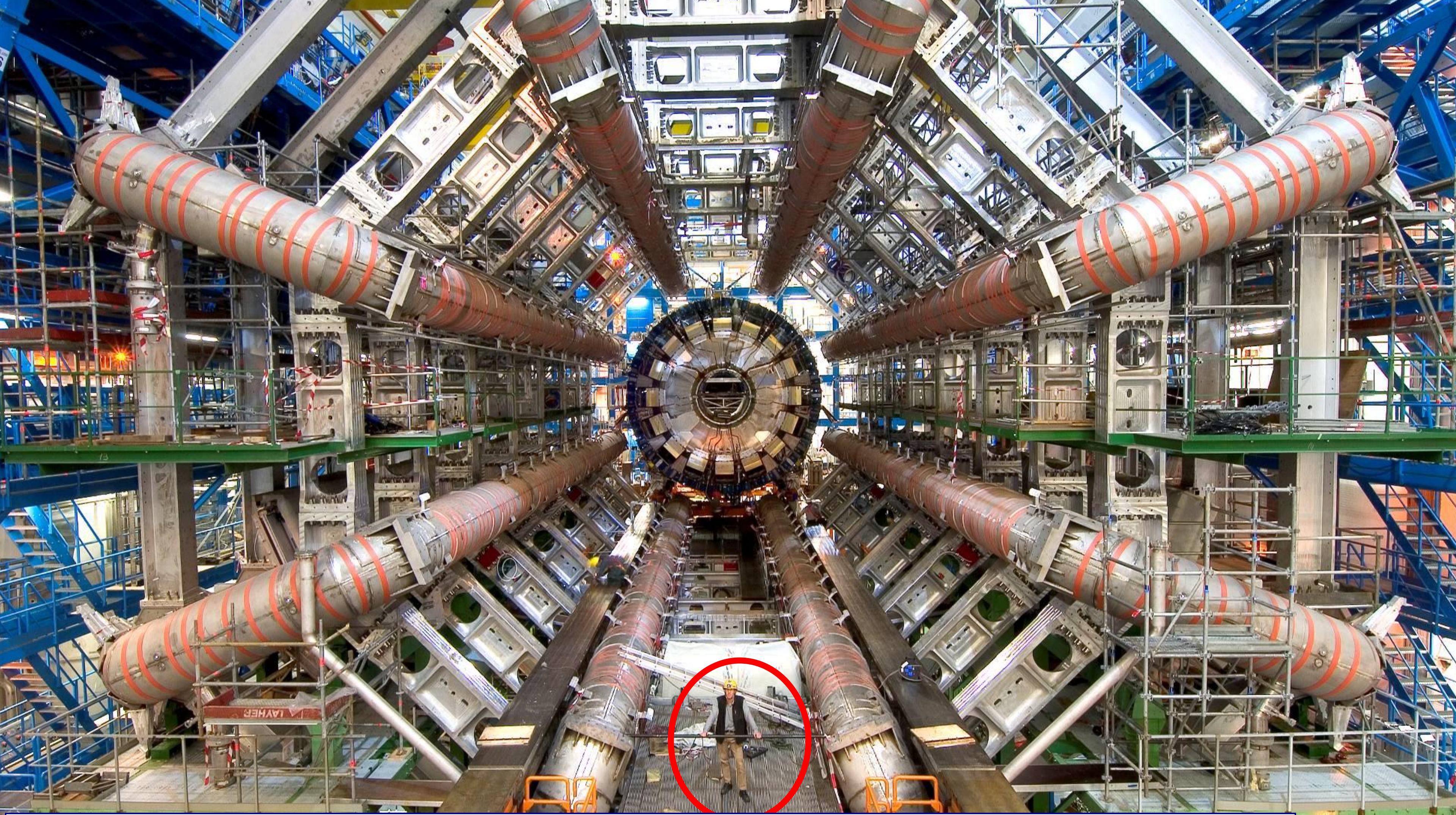
- **CERN:**
  - 22 member states
  - ~13000 scientists (Users)
  - 4300 staff or paid personnel
  - Budget(2017) ~1100MCHF
- **LHC installed in existing** LEP tunnel (27 Km)
  - $\approx$ 4000 MCHF (machine+experiments)
  - 1232 dipoles B=8.3T
  - pp $\sqrt{s}$ = 14 TeV
    $L_{design} = 10^{34}$ cm^{-2} s^{-1}
  - Heavy ions
    (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)
- **Circulating beams: 10.9.2008**
- **Incident: 18.9.2008**
- **Beams back: 19.11.2009**
- **2012: Run 1 up to 2 x 4 TeV**
- **2015: Run 2 at 2 x 6.5 TeV**
- **2018: up to 2.1 x 10^{34} cm^{-2} s^{-1}**
  ...excellent performance!
- **2019: LS2...2021: Run 3**
- **2024: LS3...2026: HL-LHC**

- **LHC experiments located at 4 interaction points**



Accelerator:

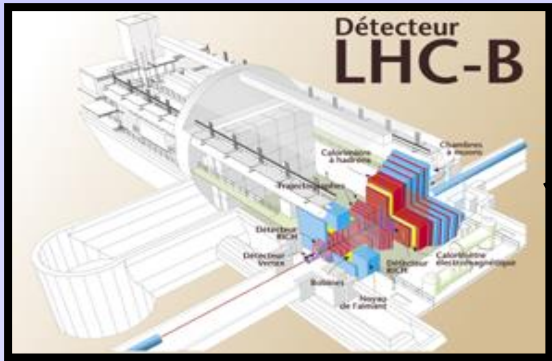
- ❑ 1232 high-tech superconducting magnets
- ❑ magnet operation temperature: 1.9 K (-271 ^{0}C)
- → LHC is “coldest” place in the universe
- ❑ number of protons per beam: 200000 billions
- ❑ number of turns of the 27 km ring per second: 11000
- ❑ number of beam-beam collisions per second: 40 millions
- ❑ collision “temperature”: 10^{16} K



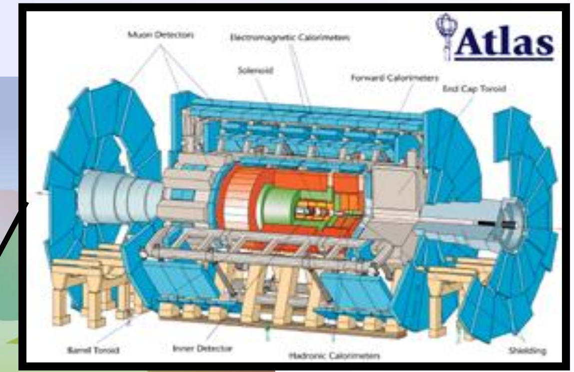
Detectors:

- size of ATLAS: ~ half Notre Dame cathedral
- weight of CMS experiment: 13000 tons (more than Eiffel Tour)
- number of detector sensitive elements: 100 millions
- cables needed to bring signals from detector to control room: 3000 km
- data in 1 year per experiment: ~10 PB (20 million DVD; more than YouTube, Twitter)

LHC Experiments

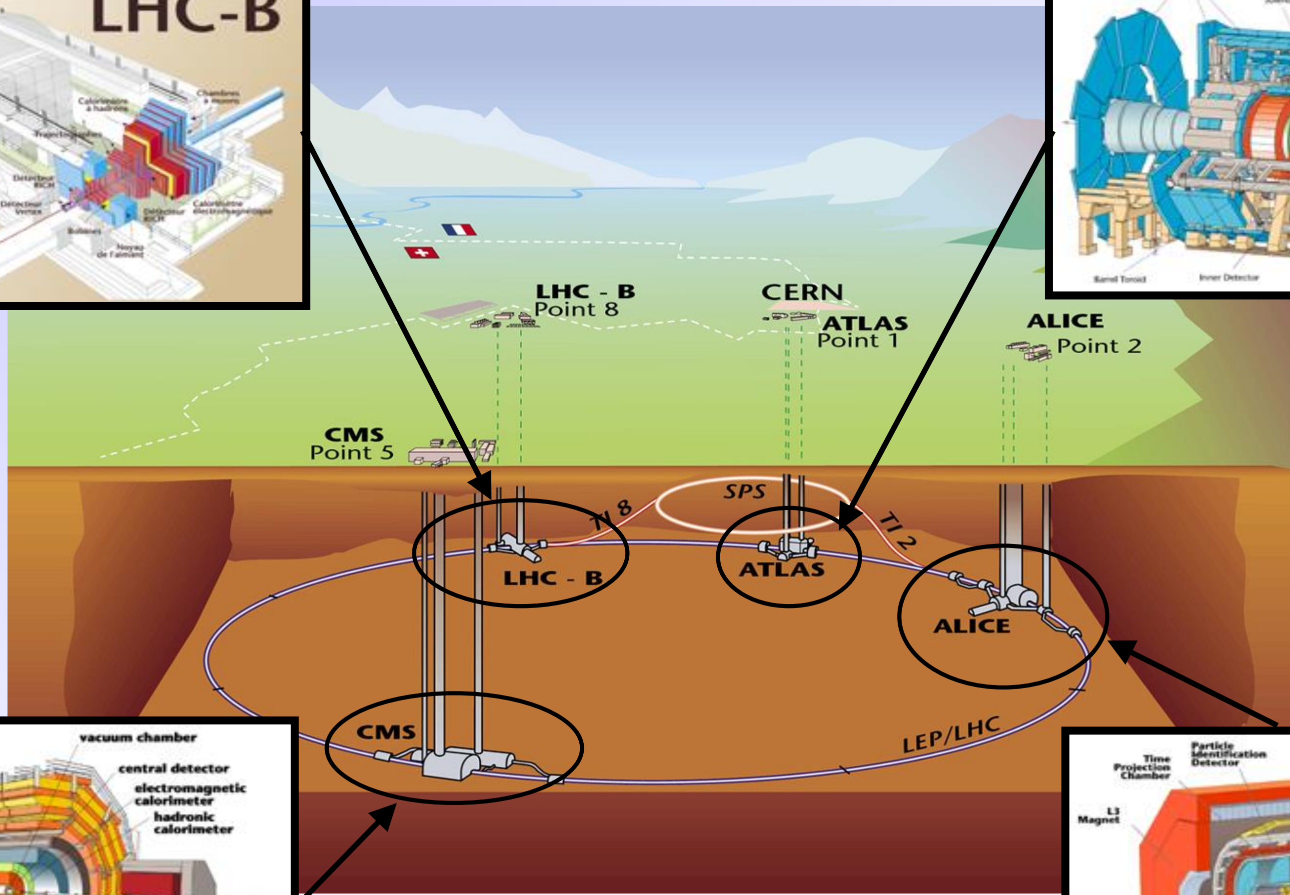


LHC-B

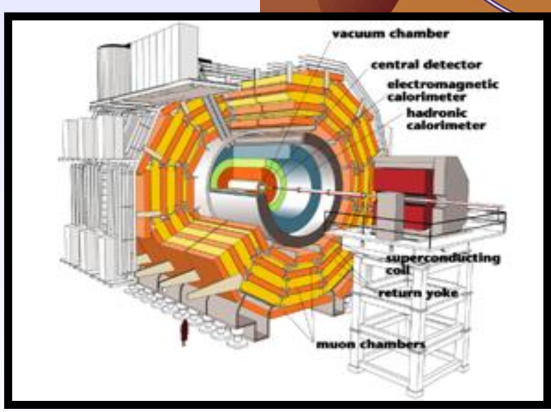


ATLAS

+ *LHCf*

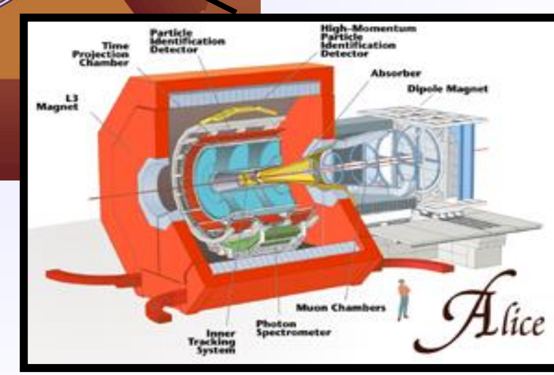


CMS

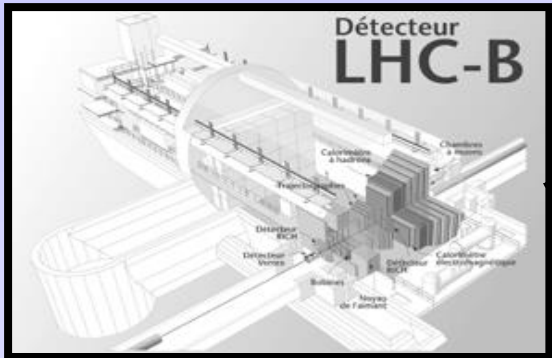


+ TOTEM

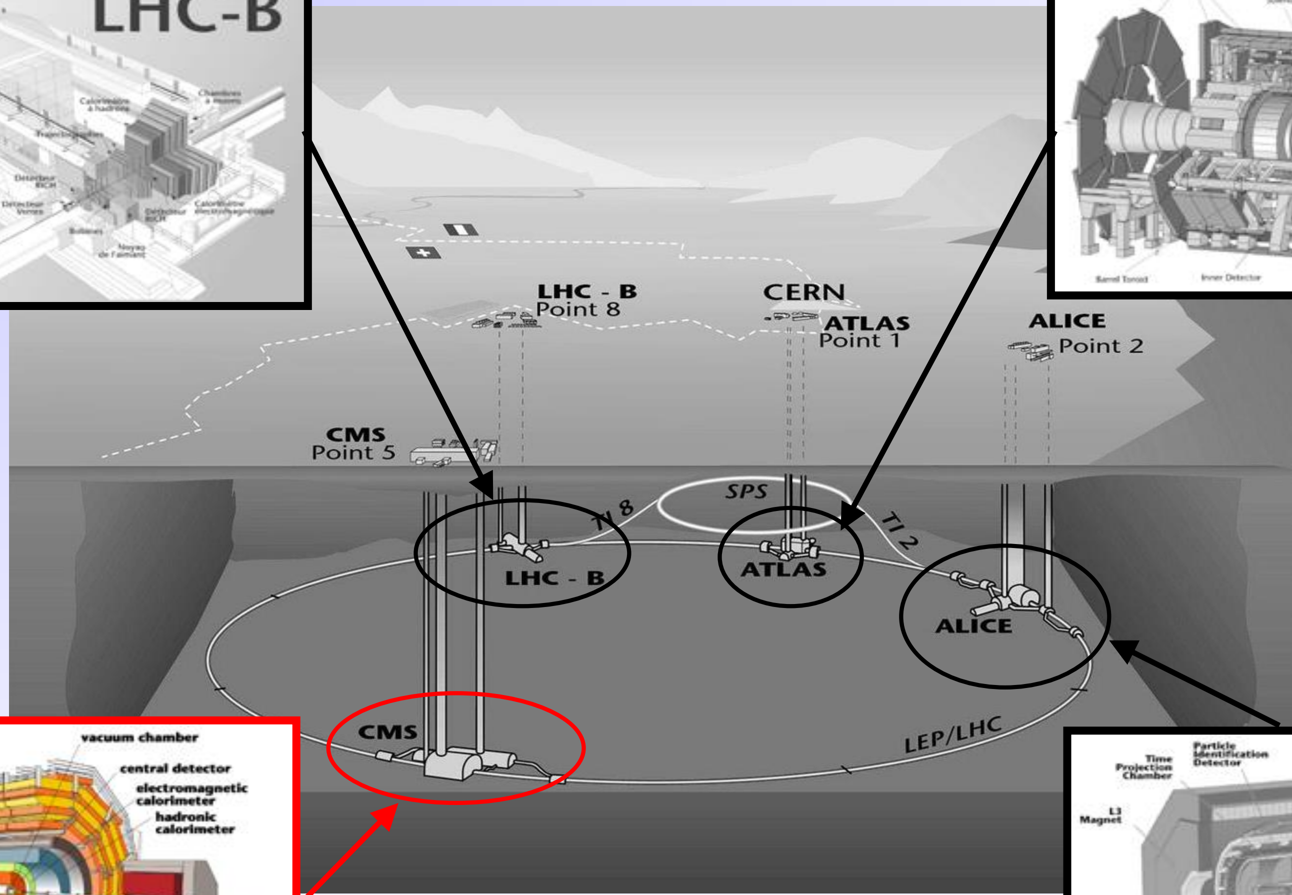
ALICE

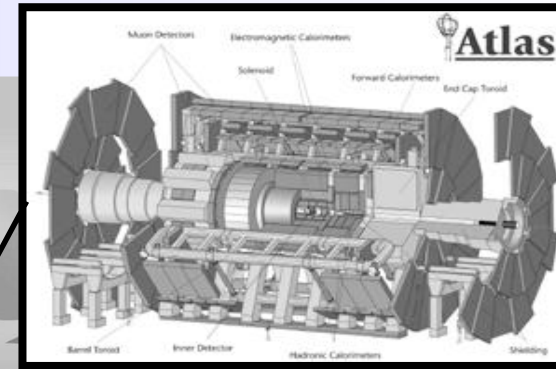


LHC Experiments



LHC-B

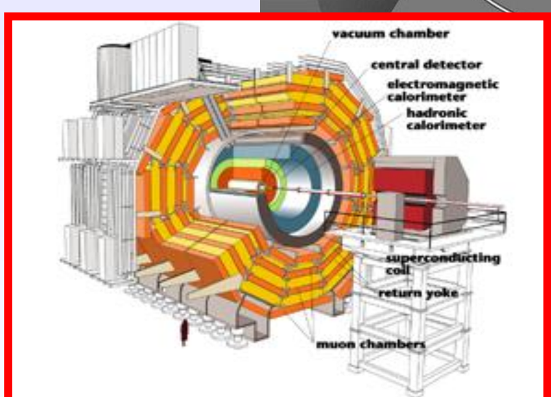




ATLAS

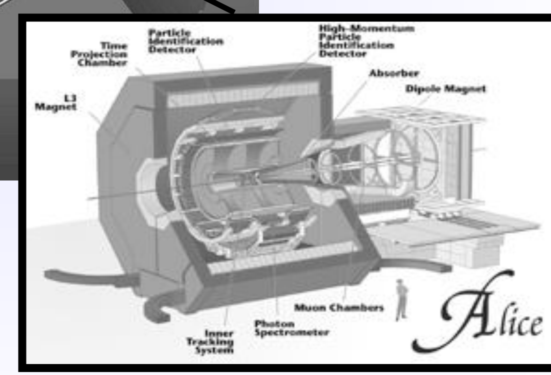
+ LHCf

CMS



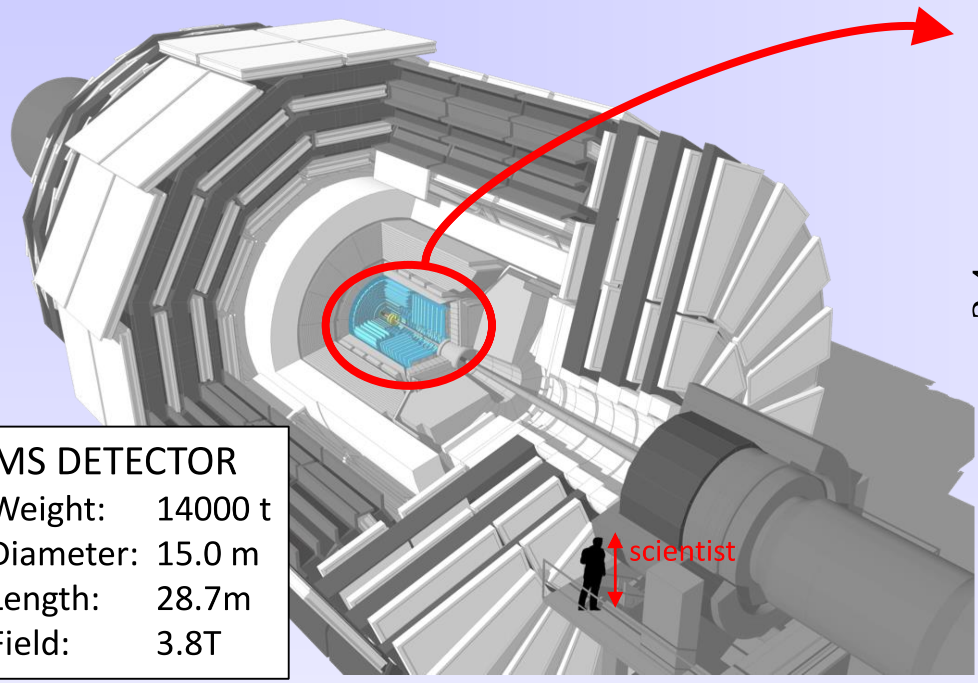
+ **TOTEM**

ALICE



Silicon Detectors in HEP

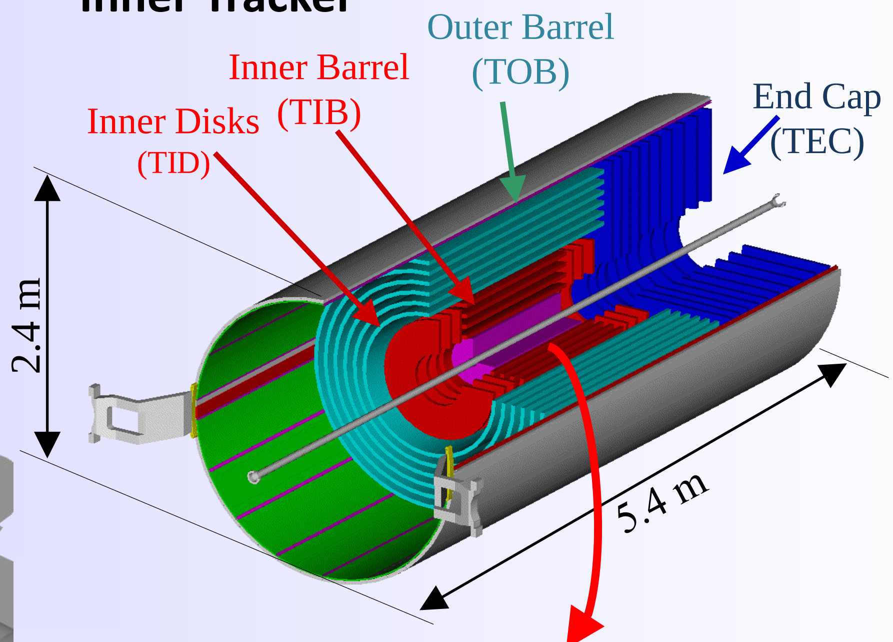
- **LHC example: The CMS DETECTOR**



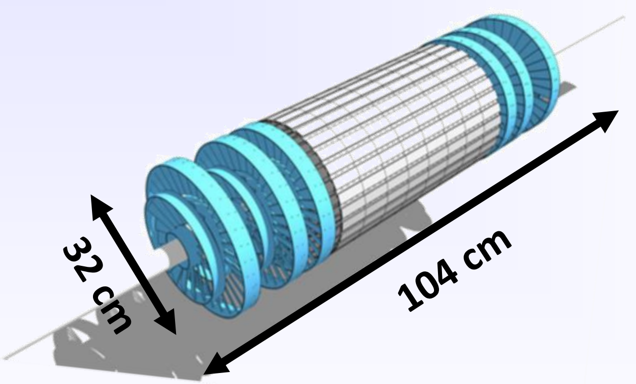
CMS DETECTOR

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

- **Inner Tracker**



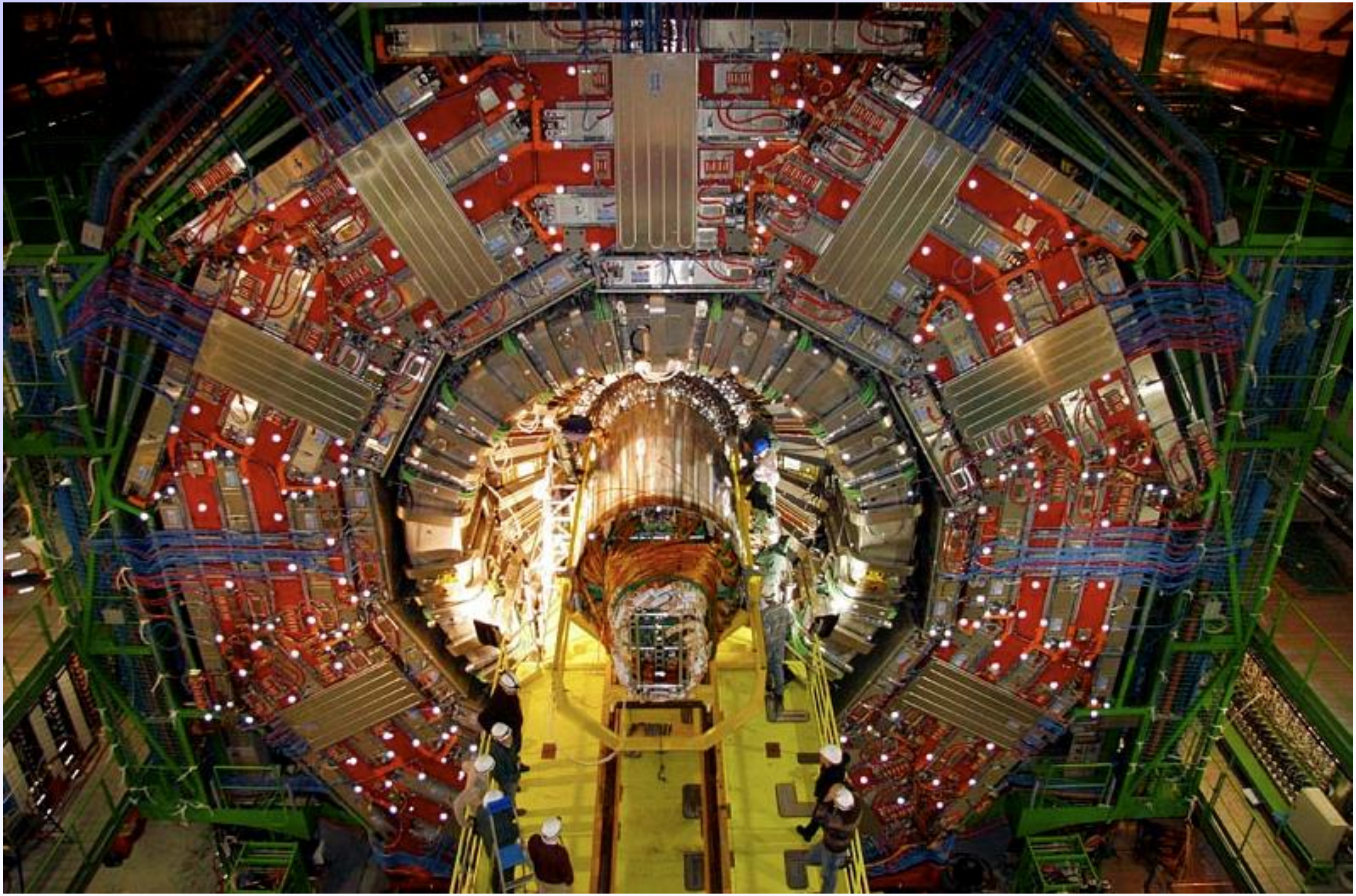
- **Pixel Detector** (upgraded in 2017)



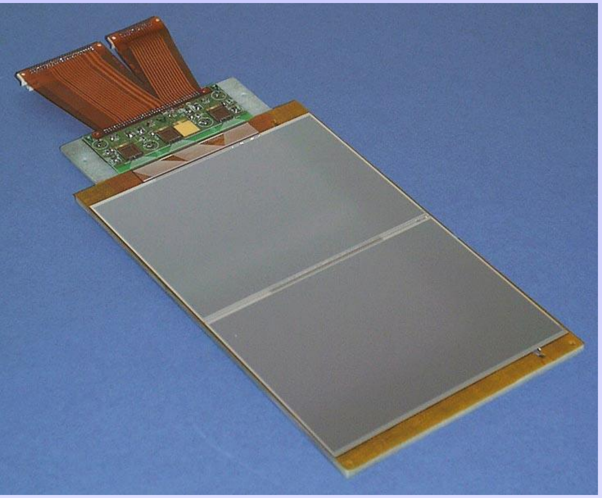
- **CMS – Inner Tracker & Pixel Detector**
  - **Micro Strip:**
  - **~ 214 m² of silicon strip sensors, 11.4 million strips**
  - **Pixel:**
  - **4 layers & 2 x 3 disks: silicon pixels (~ 1m²)**
  - **124 million pixels (100x150μm²)**
  - **Resolution: σ(rϕ) ~ 10 μm, σ(z) ~ 25μm**

Present LHC Tracking Sensors

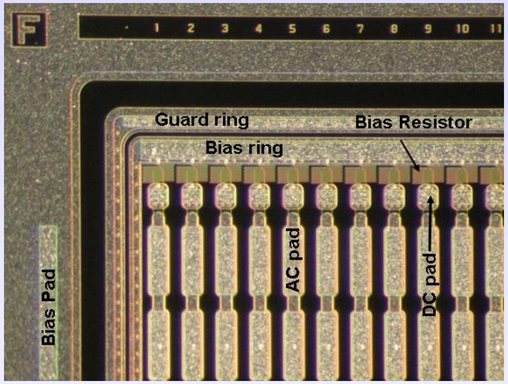
CMS Tracker insertion



Micro-strip Silicon Detectors

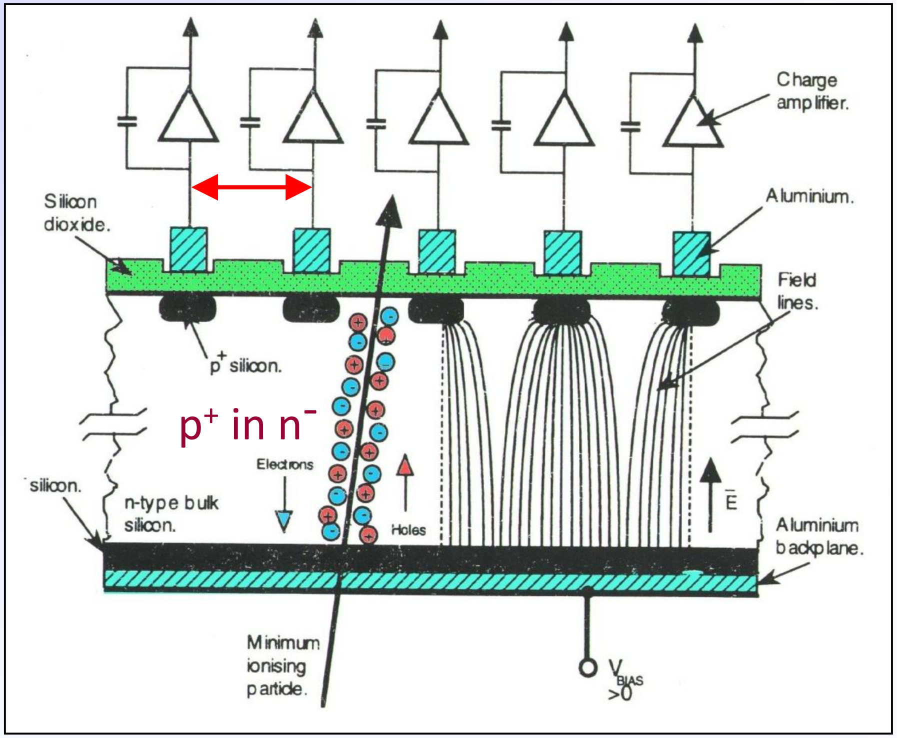


Highly segmented silicon detectors have been used in Particle Physics experiments for 30 years. They are favourite choice for Tracker and Vertex detectors
(high resolution, speed, low mass, relatively low cost)



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

Pitch ~ 50μm

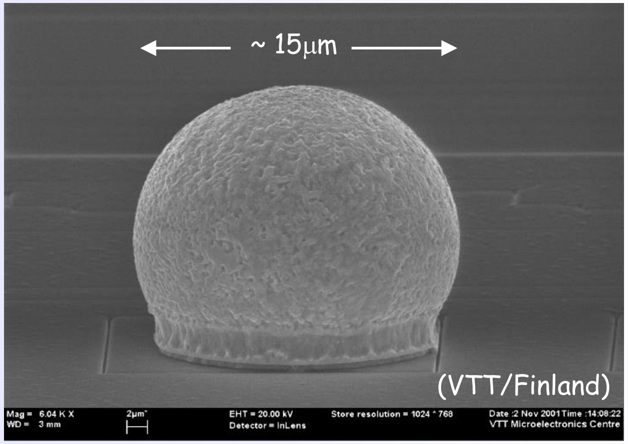


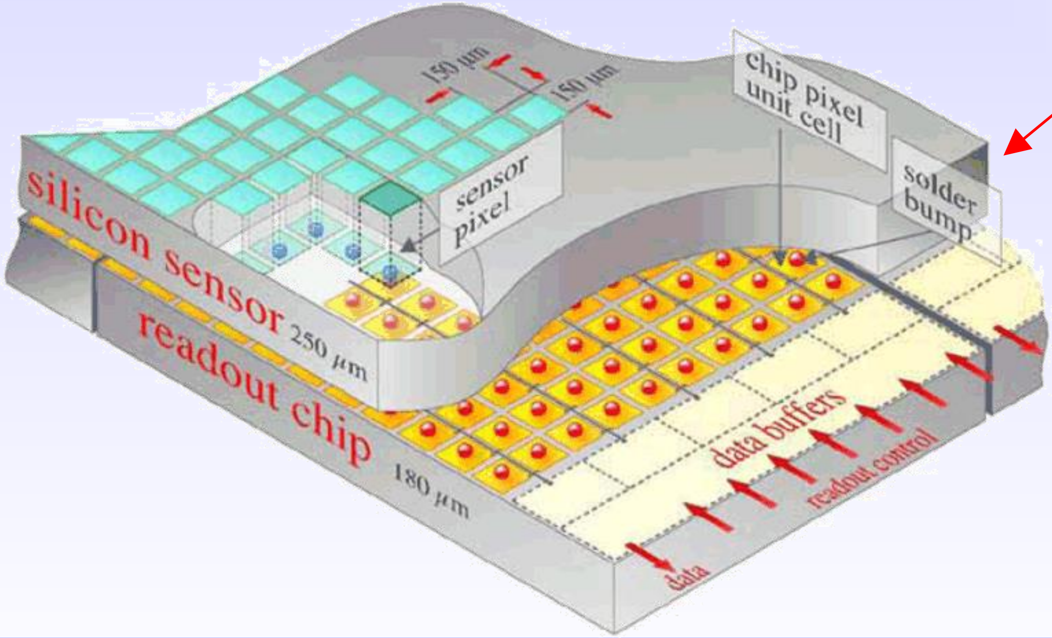
Resolution ~ 5μm

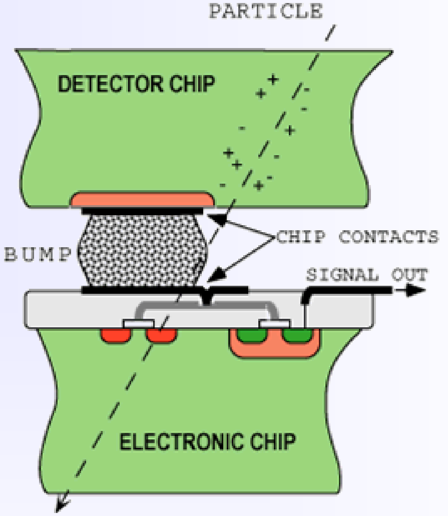
Hybrid Pixel Detectors

- **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 *(soon monolithic)*, CMS and LHCb**

Solder Bump: Pb-Sn







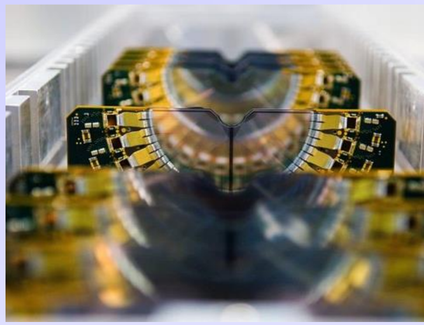
Flip-chip technique

LHC Silicon Tracking Detectors

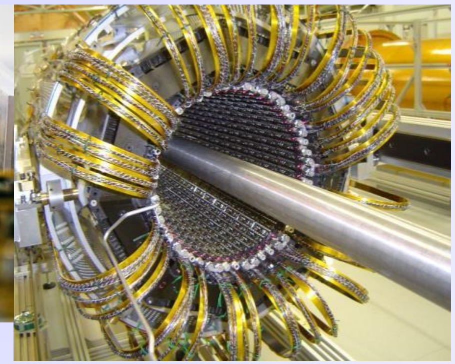
Silicon tracking detectors are used in all LHC experiments:

Different sensor technologies, designs, operating conditions,….

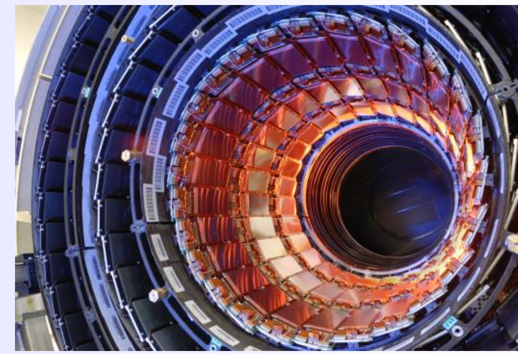
ALICE Pixel Detector



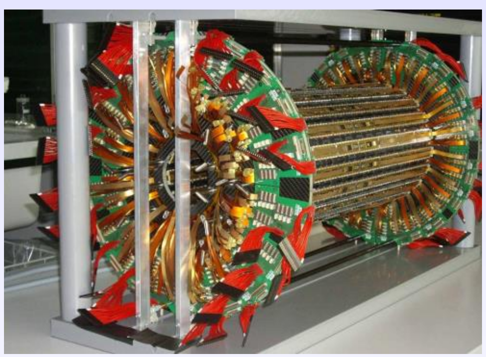
LHCb VELO



ATLAS Pixel Detector

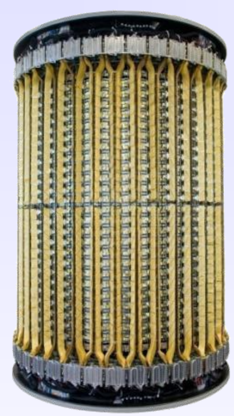


CMS Strip Tracker IB

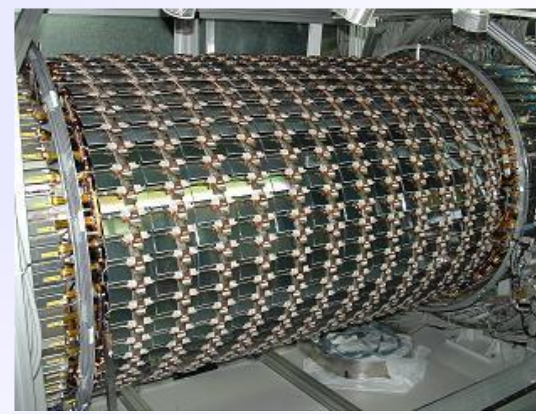


CMS Pixel Detector

ALICE Drift Detector



ALICE Strip Detector

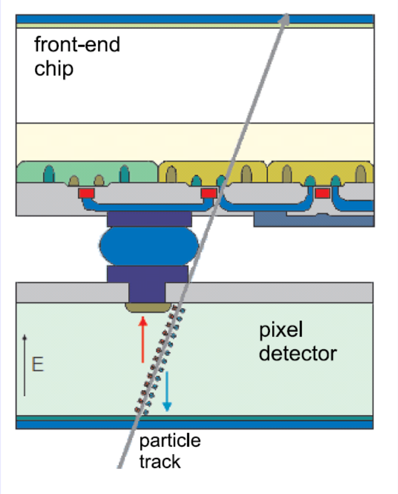


ATLAS SCT Barrel

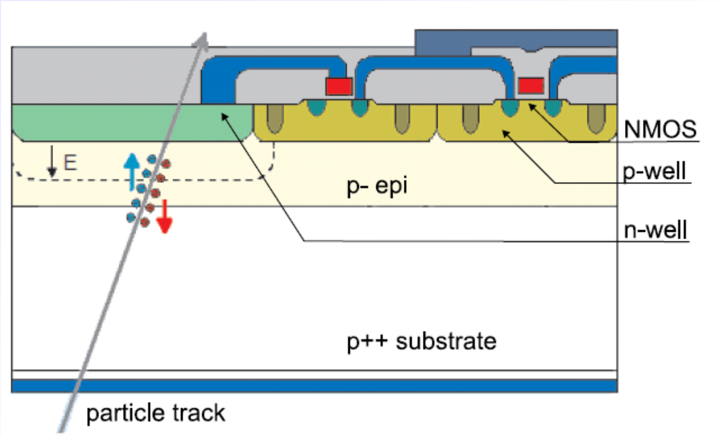
Monolithic Pixel Detectors

- 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
- Use of "standard" CMOS processing:
  - Wafer diameter (8")
  - Many foundries available, lower cost per area (mass production)
  - thin detectors possible (O(50 μm Si))
  - Small cell size – high granularity, reach O(20 μm x 20 μm)
  - Possibility of stitching (combining reticles to larger areas)
- Very low material budget
- CMOS sensors installed in STAR, BELLE2 experiments
- ALICE ITS upgrade 2019/20 based on MAPS sensors
- Option for ATLAS outermost HL-LHC pixel layer

Hybrid Pixel Detector

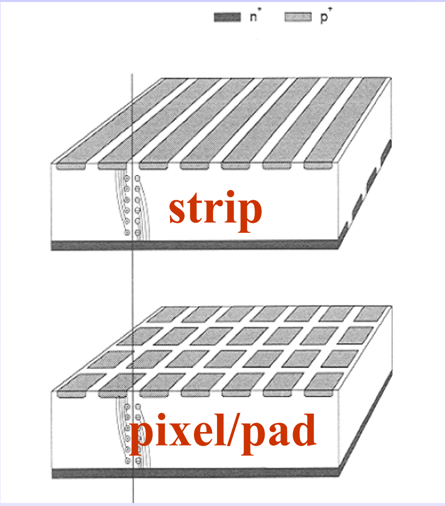


CMOS (Pixel) Detector

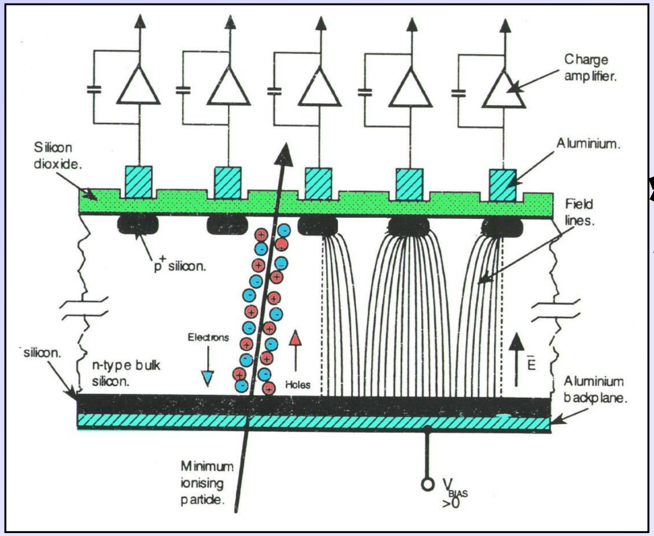


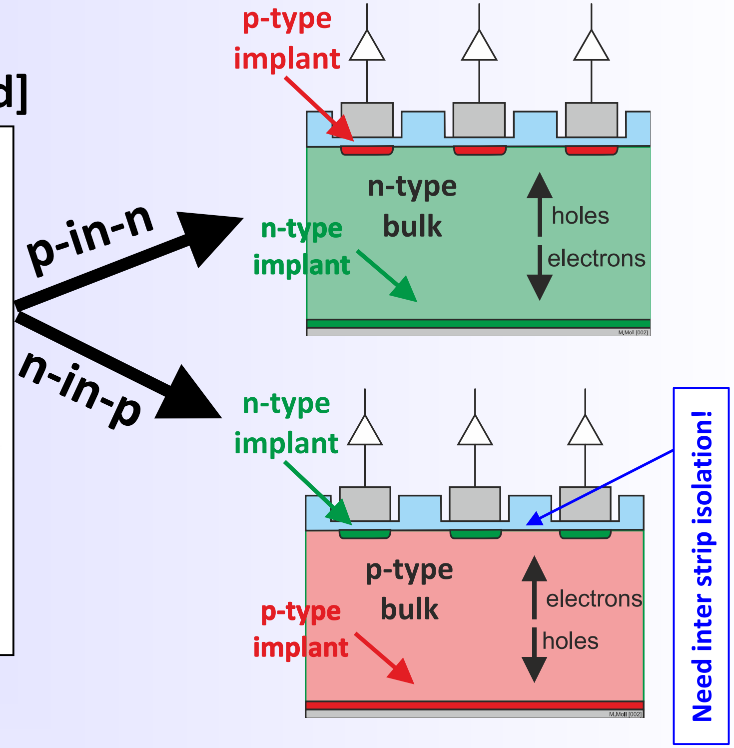
Summary: Silicon Sensors in HEP

- **Main sensor concepts**

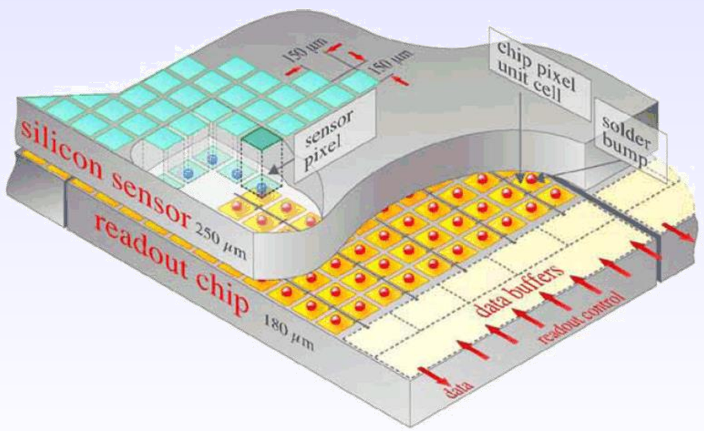


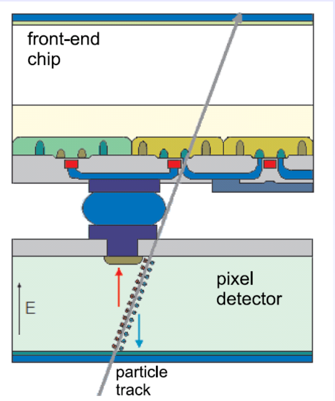
(Mini) Strip Detector [AC coupled]



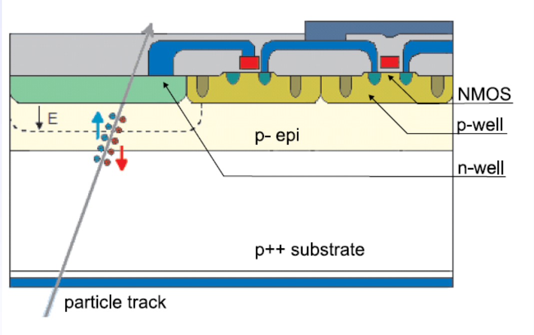


Hybrid Pixel Detector





Monolithic CMOS Pixel Detector

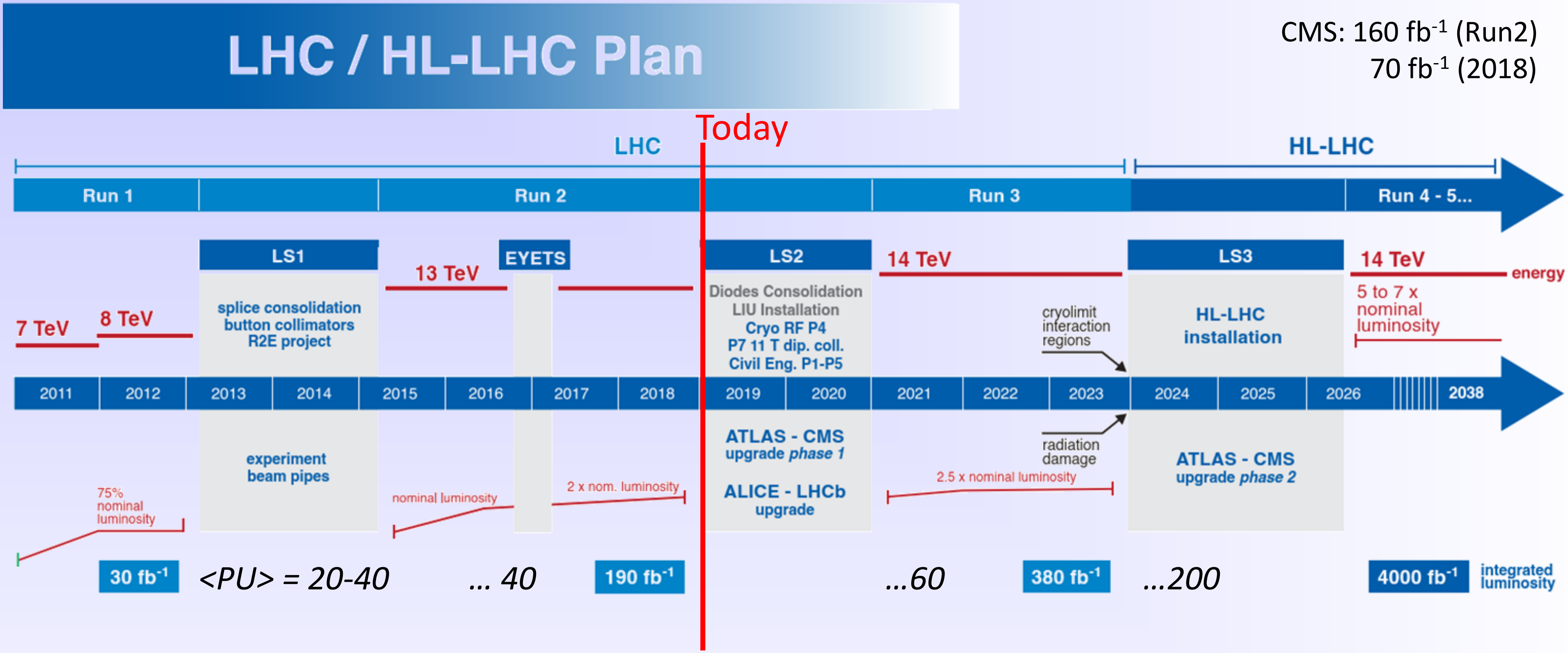


Upgrade of the Large Hadron Collider at CERN

The LHC Upgrade Program

- **HL-LHC luminosity upgrade (Phase II) (L_{peak} = 7.5 x10^{34} cm^{-2}s^{-1}) in ~2026**

CMS: 160 fb^{-1} (Run2)
70 fb^{-1} (2018)



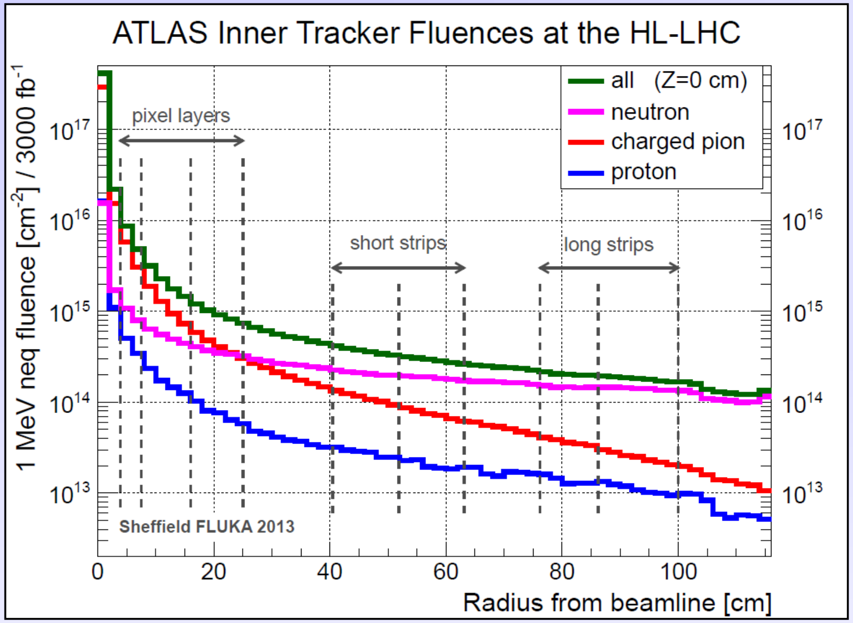
- **LS2 (now!): ALICE, LHCb major upgrades; ATLAS and CMS minor upgrades [Phase I]**
- **LS3: ATLAS and CMS: Major upgrades [Phase II]**

Challenges: Build detectors that operate after 4000 fb^{-1}; Pile up, Radiation, Rates

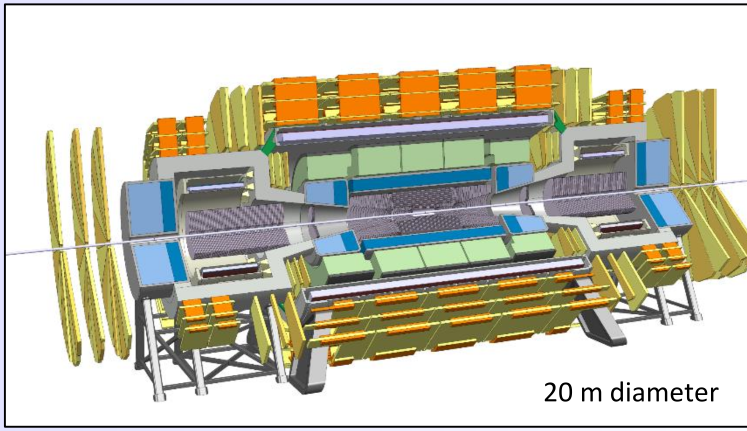
Motivation and Challenge

- **LHC Detectors: Detectors are suffering from radiation!**
- **LHC upgrade: New concepts developed, some open challenges**
  - **LHC upgrade towards High Luminosity LHC (HL-LHC)**
    *after LS3 (~2024-26); **expect 4000 fb^{-1}** (x7 nominal LHC)*

[I. Dawson, P. S. Miyagawa, Sheffield University, Atlas Upgrade radiation background simulations]



- ***FCC – Future Circular Collider***
  - **FCC-hh:2043** (FCC-ee:2039,HE-LHC: 2040)



[W.Riegler, FCC Week, 6/2017]

  - **Radiation levels innermost pixel layer** (30ab^{-1}, without safety factor): **~ 6x10^{17} n$_{eq}$/cm^2, ~400MGy**

Semiconductor detectors will be exposed to hadron fluences equivalent to more than 10^{16} n$_{eq}$/cm^2 (HL-LHC) and more than 6x10^{17} n$_{eq}$/cm^2 (FCC)
➔ detectors used today at LHC cannot operate after such irradiation!

Strong efforts ongoing (LHC Experiments, FCC study groups, RD50 collaboration) to understand physics of radiation damage and develop radiation harder devices.

RD50

RD50–Radiation Hard Semiconductor Devices for very high luminosity colliders (55 Institutes, 300 researcher)
www.cern.ch/rd50

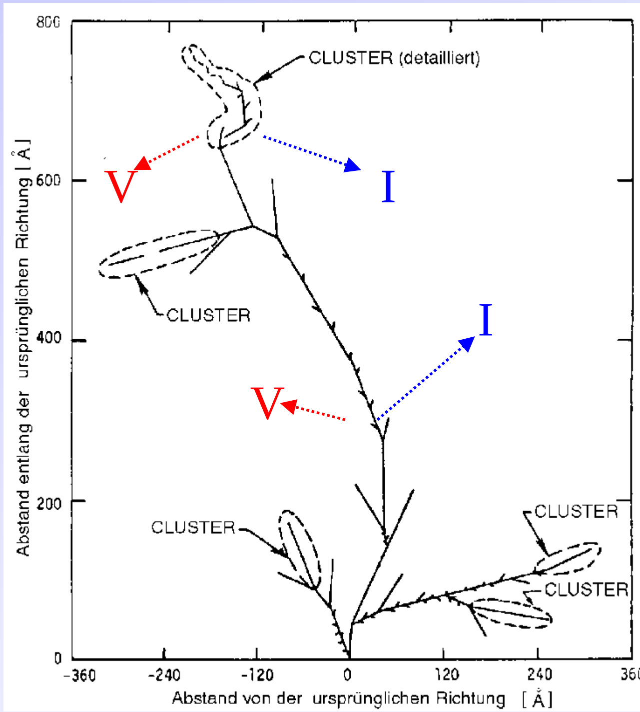
Radiation Damage

What is radiation damage?

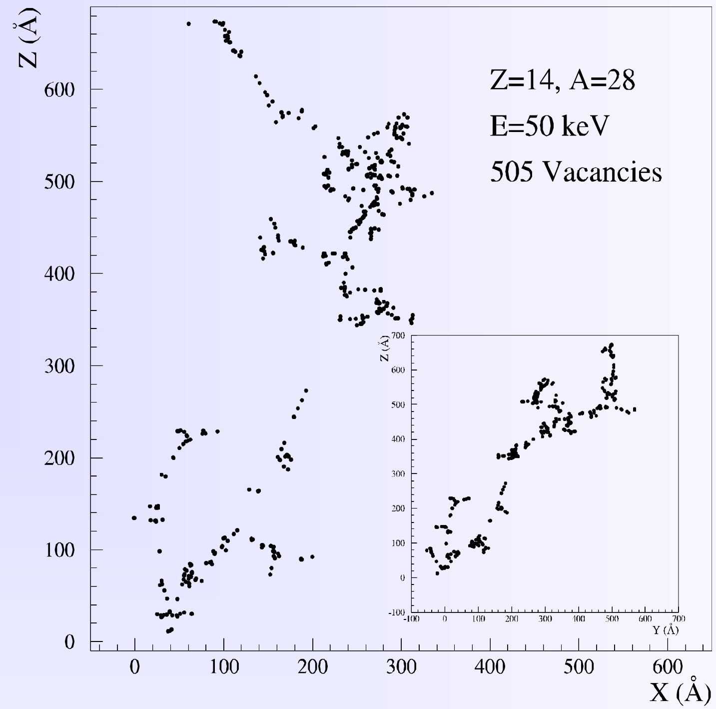
Radiation Damage – Microscopic Effects

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

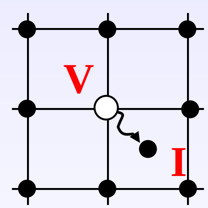
van Lint 1980



M.Huhtinen 2001



particle → Si_s → E_K>25 eV



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

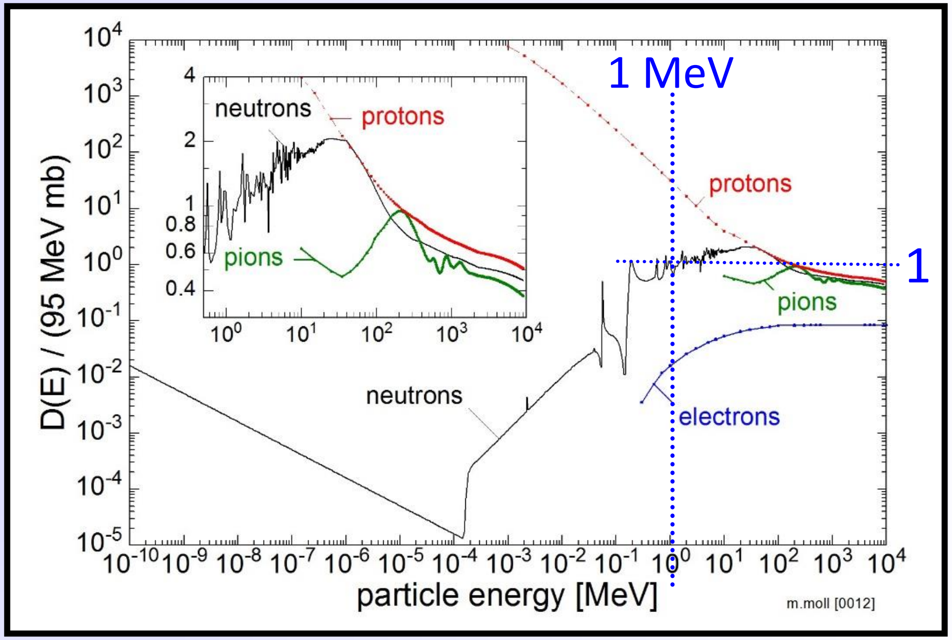
→ E_K > 5 keV *point defects and clusters of defects*

NIEL – Non Ionizing Energy Loss

- **Displacement Damage function**
  - **Normalization of radiation fields to 1 MeV neutron equivalent damage (n_{eq})**

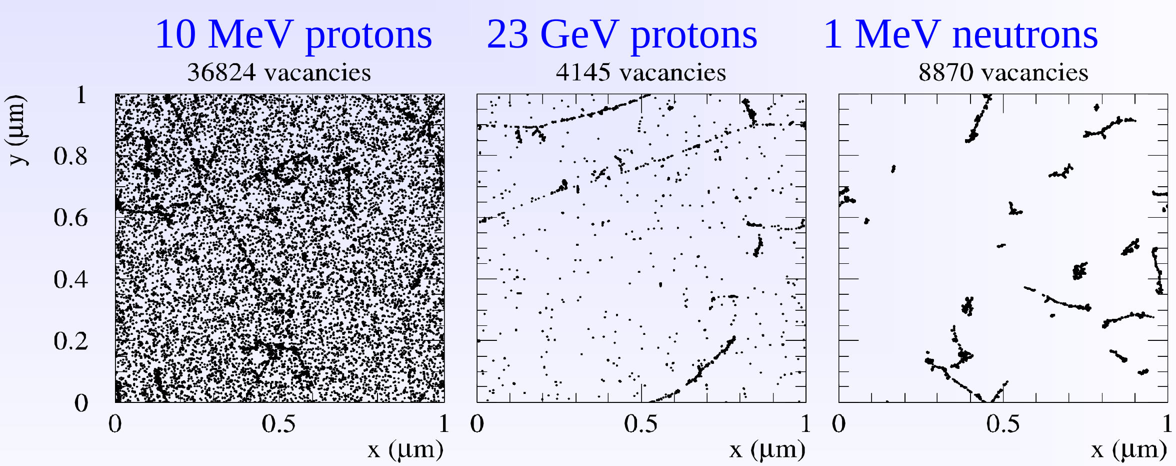
$$\Phi_{eq} = \kappa_x \Phi_x$$

κ_p = *0.57* (23 GeV protons)
κ_p = 1.85 (26 MeV protons)
κ_π = 1.14 (192 MeV pions)
κ_n = 0.92 (TRIGA reactor neutrons)



[Data: A.Vasilescu and G.Lindstroem]

- **NIEL Hypothesis:**
  - **Assumption: NIEL scaling of damage parameters**
  - **Applied to predict damage of radiation fields in HEP**
  - **"NIEL violation" observed:**
    - Material dependence
    - Proton vs. neutron damage
    - …

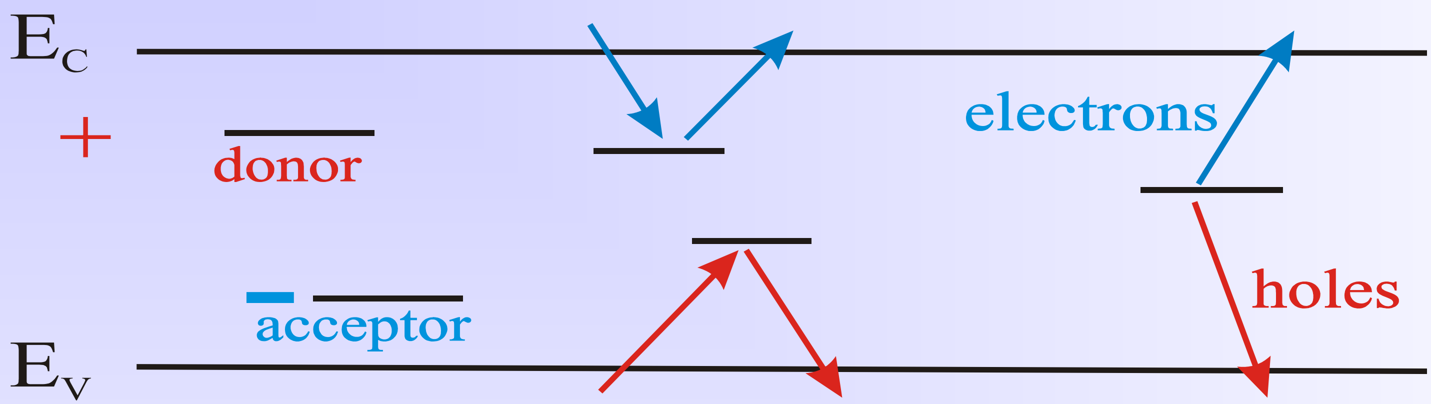


[M.Huhtinen, NIMA 491(2002), 194]

Simulation: Vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2

Impact of Defects on Detector Properties

- Shockley-Read-Hall statistics



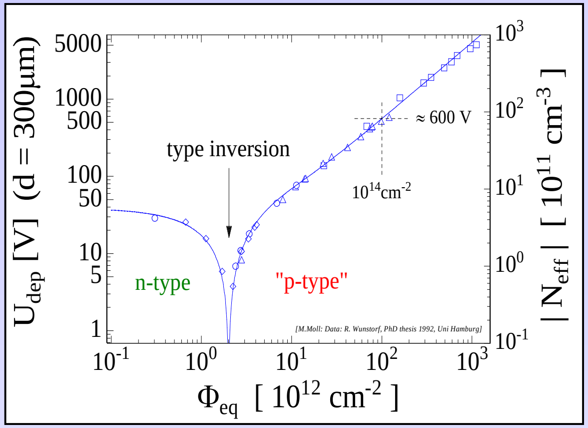
charged defects	trapping (e and h)	generation
$\Rightarrow N_{eff}, V_{dep}$	$\Rightarrow$ CCE	$\Rightarrow$ leakage current
e.g. donors in upper half, acceptors in lower half of band gap	shallow defects do not contribute at RT due to fast de-trapping	Levels close to midgap most effective

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

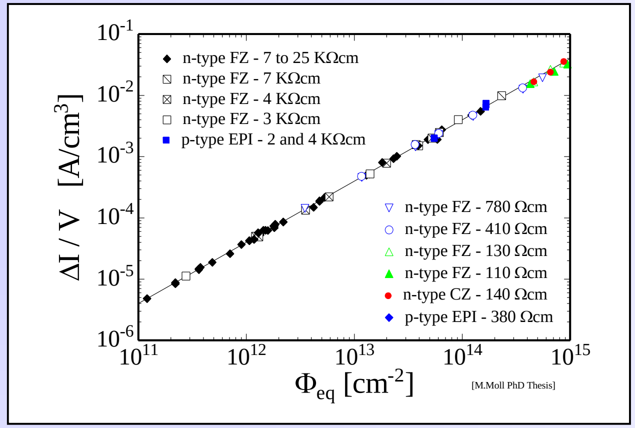
$\sigma_{n,p}$: cross sections ΔE : ionization energy N_t : concentration

Radiation Damage Summary

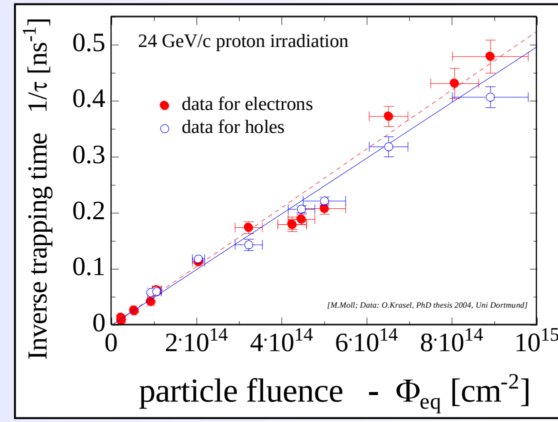
- **Macroscopic bulk effects:**



Depletion Voltage (N_{eff})

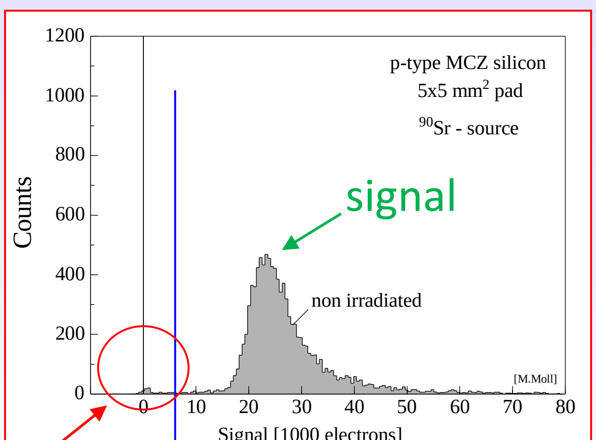


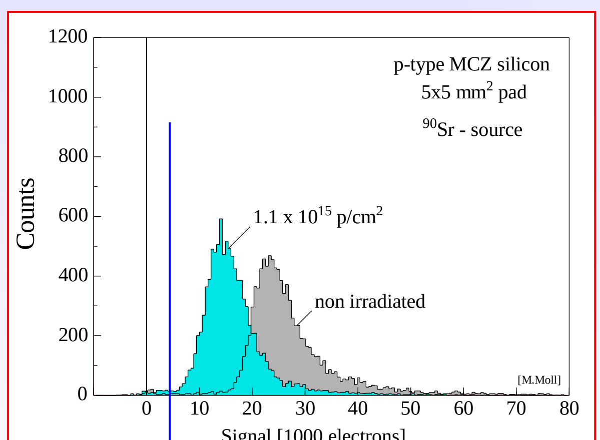
Leakage Current

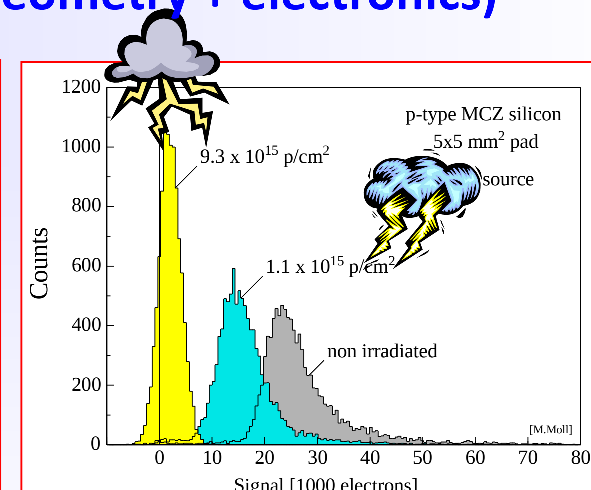


Charge Trapping

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







noise

Cut (threshold)

Summary: Basics of 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 –

    Influenced by impurities in Si – Defect Engineering is possible!

    I. Change of effective doping concentration & acceptor/donor removal (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)

    Same for all tested Silicon materials!

  - **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, …

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

  Can be optimized!

  Signal/noise ratio is the quantity to watch

  ⇒ Sensors can fail from radiation damage !

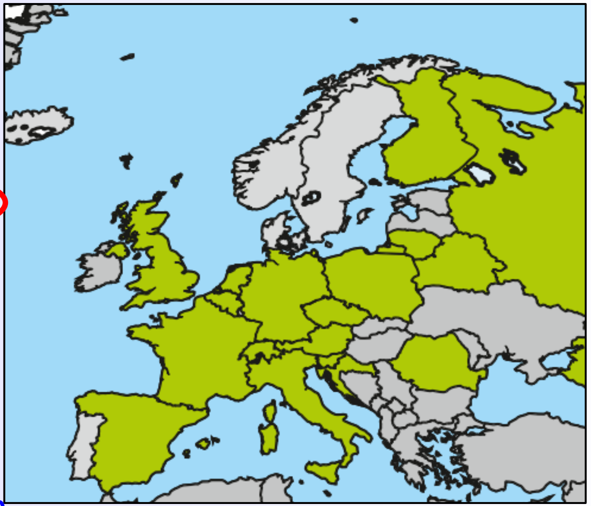
How to make silicon detectors radiation harder?

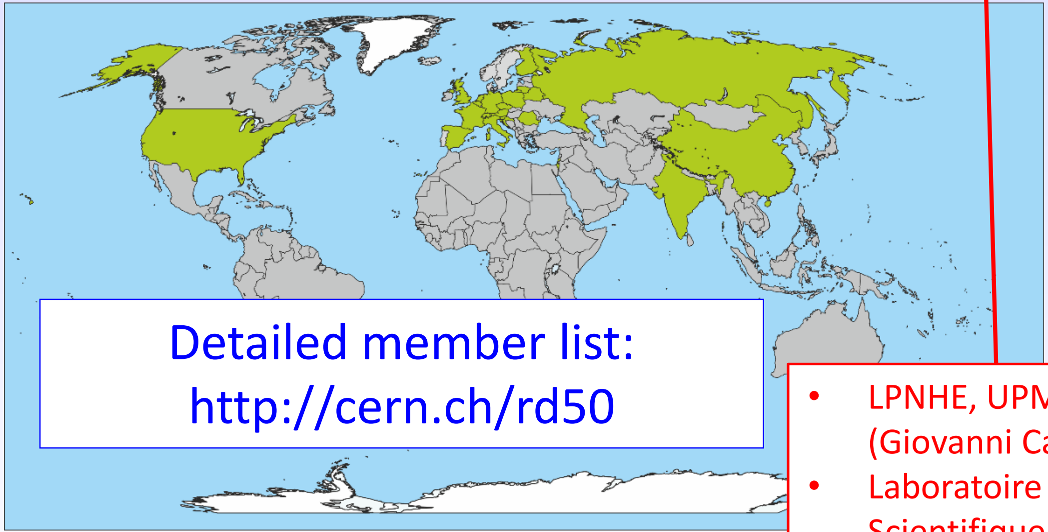
The RD50 Collaboration

- **RD50: 63 *institutes and 371 members***

53 European institutes

Austria (HEPHY), Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Paris, Orsay), Germany (Bonn, Dortmund, Erfurt, Freiburg, Goettingen, Hamburg (2x), Karlsruhe, Munich(2x)), Italy (Bari, Perugia, Pisa, Trento, Torino), Kroatia (Zagreb), Lithuania (Vilnius), Netherlands (NIKHEF), Poland (Krakow, Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona(3x), Santander, Sevilla (2x), Valencia), Switzerland (CERN, PSI, Zurich), United Kingdom (Birmingham, Glasgow, Lancaster, Liverpool, Manchester, Oxford, RAL)





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

7 North-American institutes

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

1 Middle East institute; Israel (Tel Aviv)

2 Asian institute; China(Beijing), India (Delhi)

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

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

Note: TCAD simulations are helpful/essential for all those approaches!

- **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
  - Cost effective detectors
  - Monolithic devices – HV-CMOS

Device Engineering Example

- Why will we use p-type strip/pixel sensors (n-in-p) for the LHC upgrade in ATLAS/CMS?
- Why are segmented sensors(*) build on p-type silicon radiation harder?

* 300 μm thick

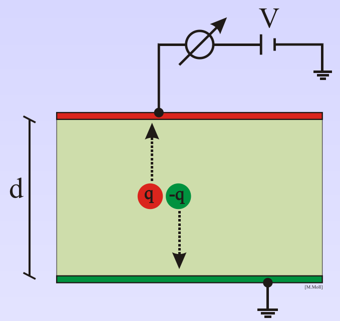
Sensor Signal: Pad vs. Strip/Pixel

- **Signal = Induced charge on read-out electrode**
  - **Described by Shockley-Ramo Theorem**
  - **Charged induced on electrode by moving charge can be calculated from the weighting potential (field)**

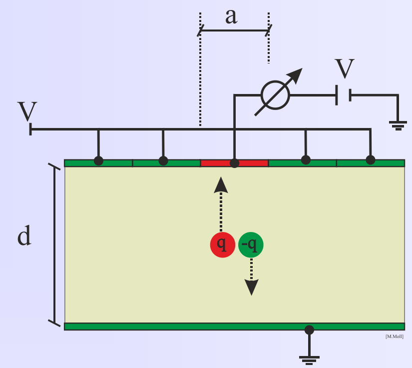
$$i = q \cdot \vec{v} \cdot \vec{E}_W(\vec{x})$$

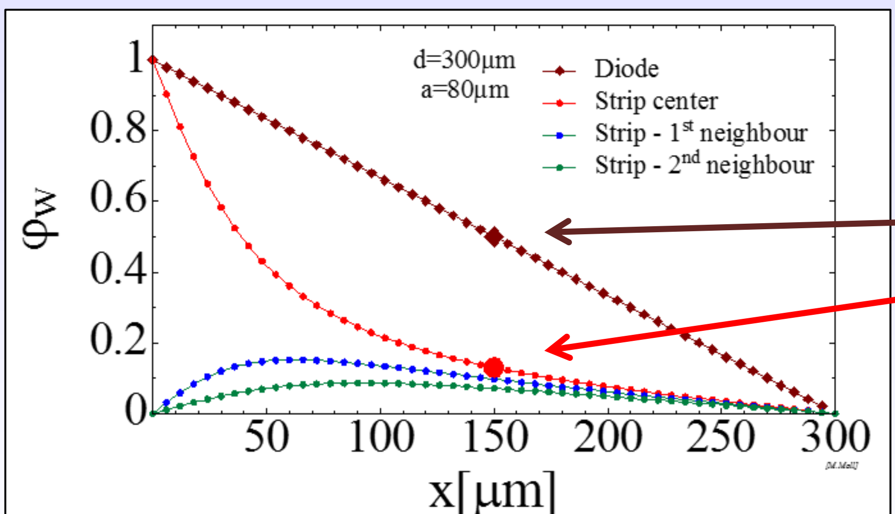
$$Q = -q \cdot \left(\phi_W(\vec{x}_2) - \phi_W(\vec{x}_1)\right)$$

Pad



Strip





– Total collected charge in both cases 100% (Q = q) when charges have reached the electrodes, however
  - Diode: 50% from (+q); 50% from (-q)
  - Strip: 87% from (+q); 13% from (-q)

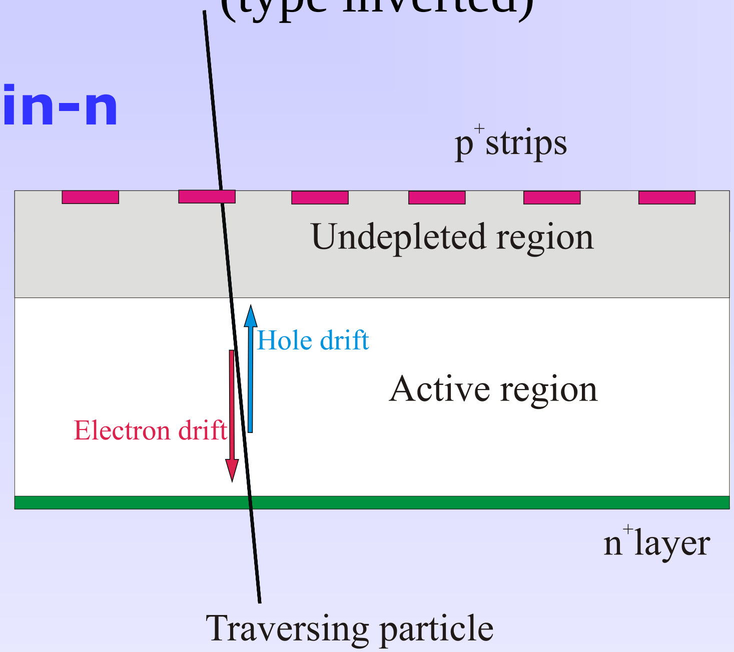
– In a p-in-n strip sensor the holes give a higher contribution to the (m.i.p.) signal than the electrons!

Device engineering: p-in-n vs. n-in-p (or n-in-n)

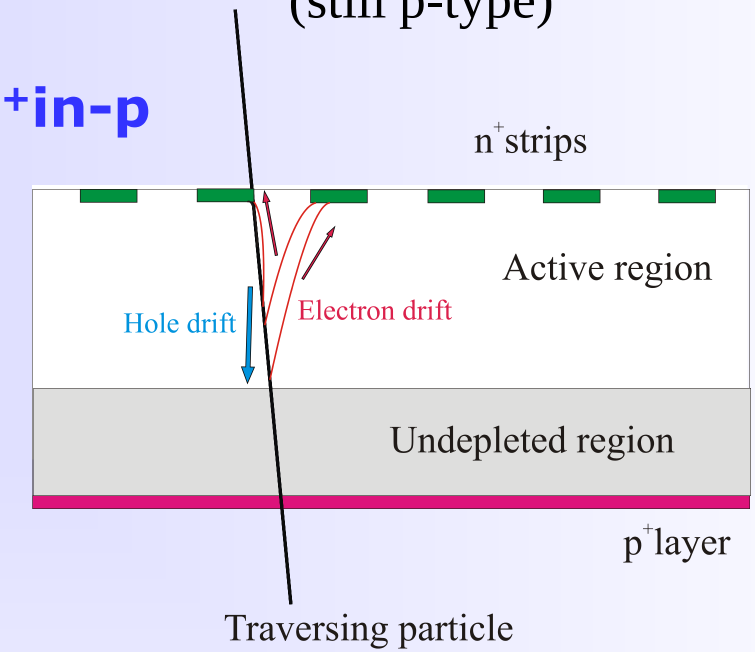
n-type silicon after high fluences: (type inverted)

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

p^{+}in-n



n^{+}in-p



p-in-n silicon, under-depleted:

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

n-in-p silicon, under-depleted:

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

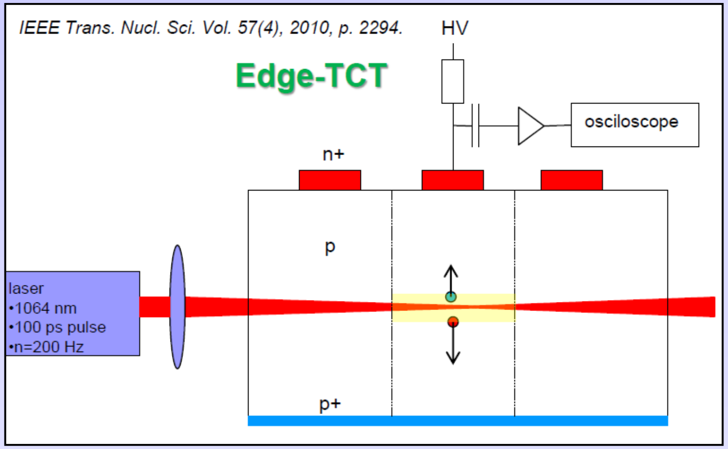
Comments:

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

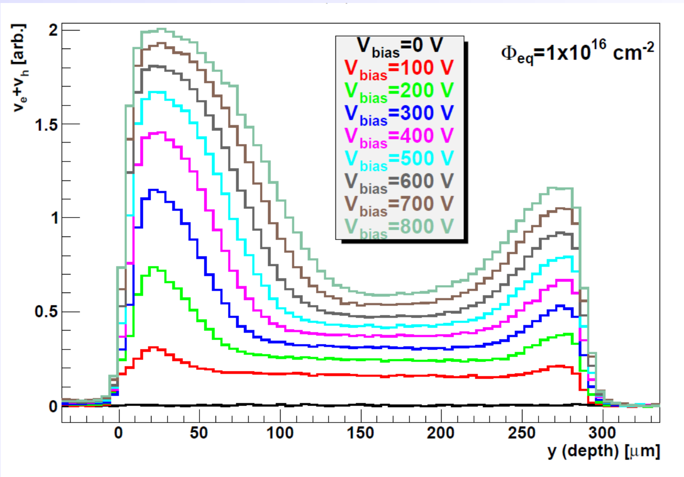
*- **Reality is much more complex: Usually double junctions form leading to fields at front and back!***

E-Field after irradiation: *"double junctions"*

- **Investigation by measurement**

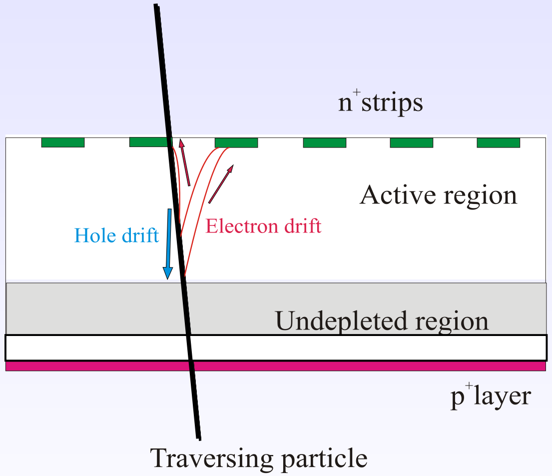


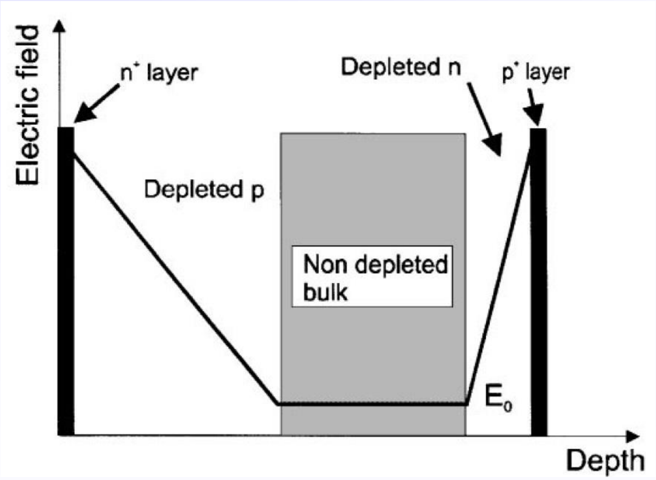
n-in-p sensor still "p-type" (i.e. highest field at front electrode) after high level of radiation



[G.Kramberger et al, 2014 JINST 9 P10016]

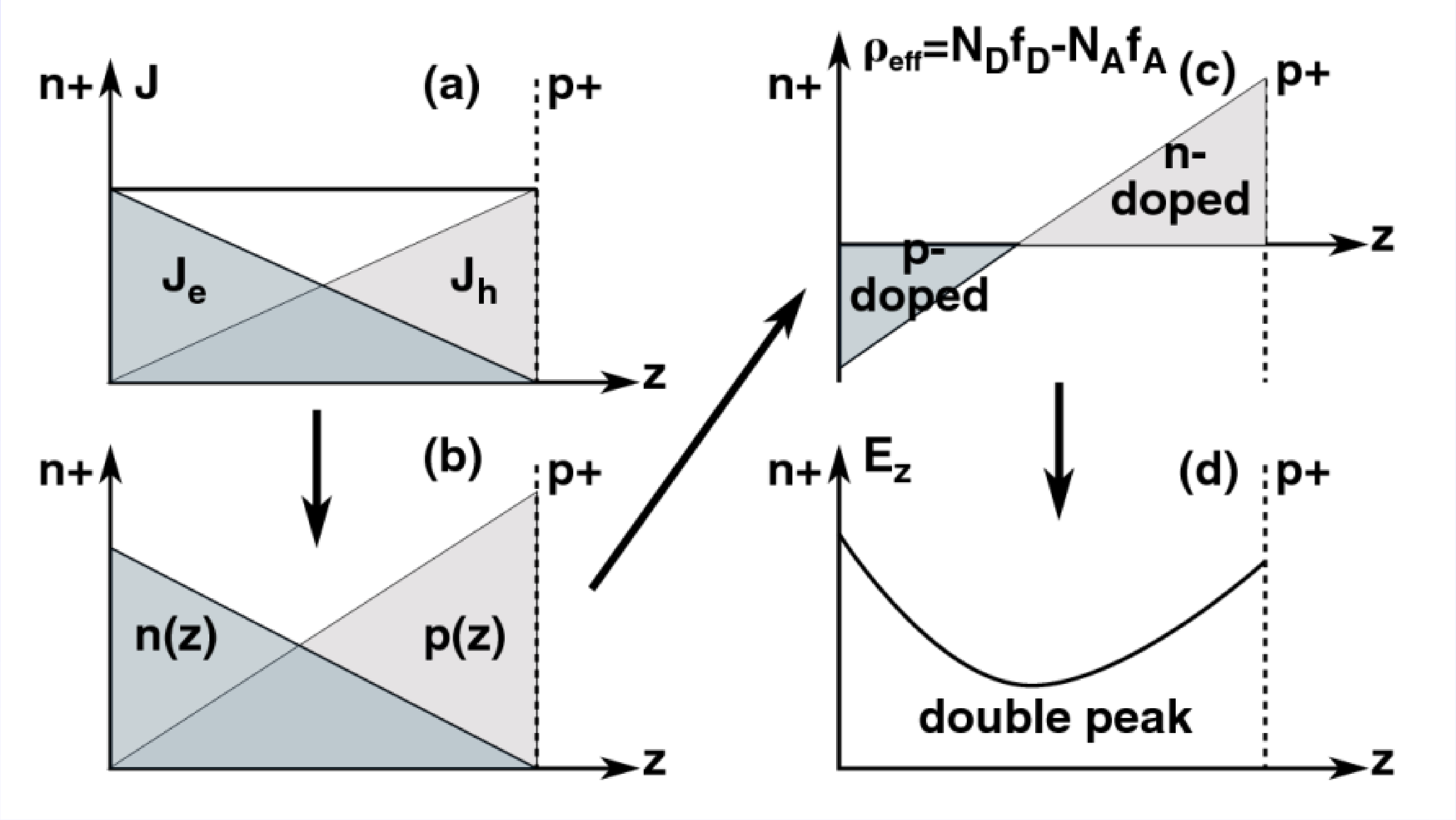
- Dominant junction close to n+ readout strip for FZ n-in-p





Double Junction

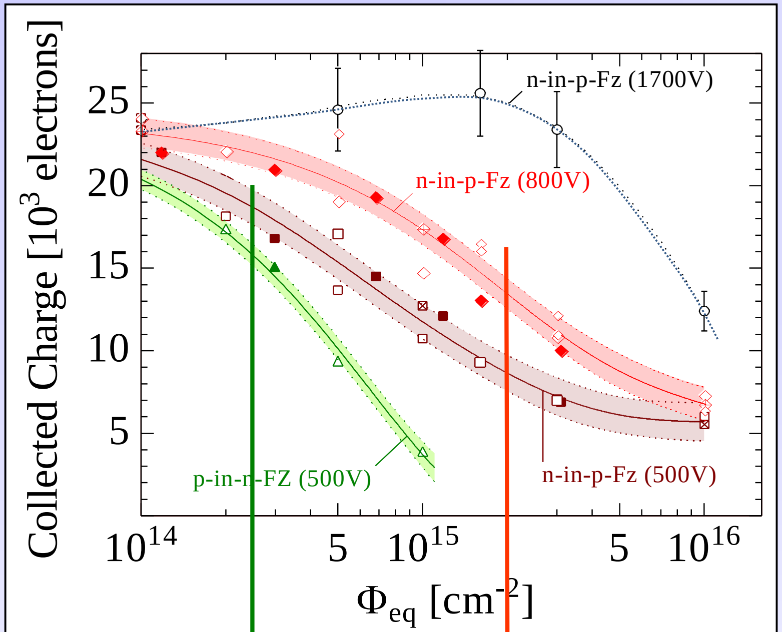
- **Double Junction = Polarization Effect**



Segmented sensors: n^+ vs. p^+ readout

- **p-type strip sensors with n^+ readout**
  - **Sensors for ATLAS and CMS Tracker upgrades!**

[M.Moll, World Scientific (ISBN: 978-981-4307-51-2/3), April 2010, pp 101-110.]



LHC **HL-LHC**

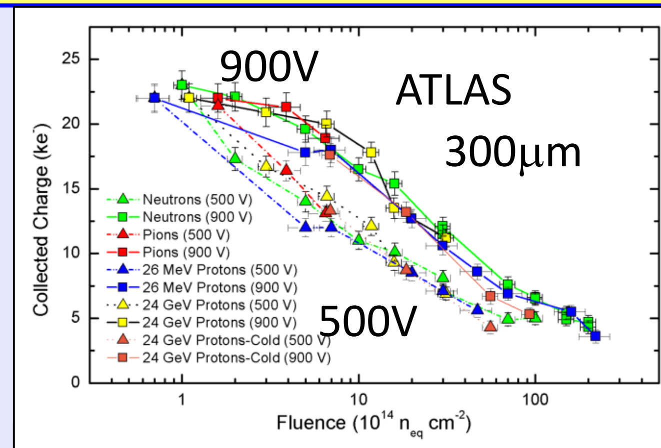
RD50

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

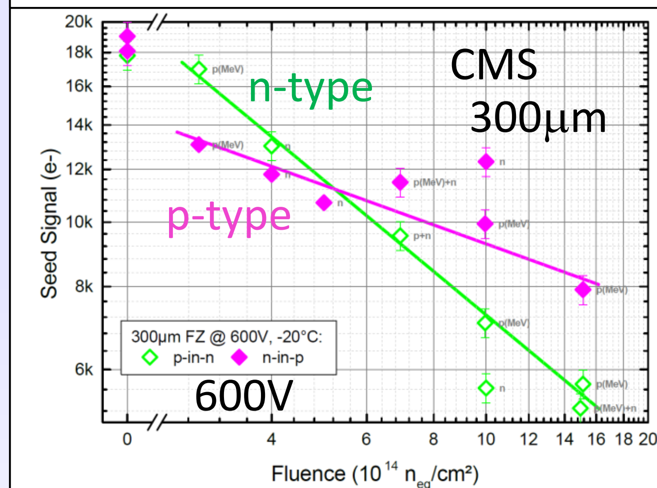
n-in-p technology needed at radii presently (LHC) occupied by strip sensors

Going from n- to p-type sensors: extensive radiation hardness test campaigns since ~2005

- particle type
- annealing
- sensor thickness
- sensor design
- surface damage
- edge design



[A.Affolder et al., NIMA 612 (2010) 470-473]



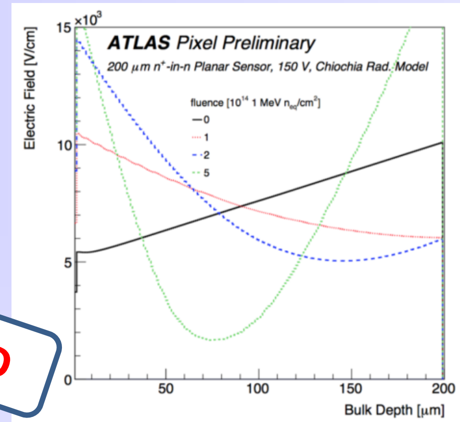
[CMS – Proposal for Phase II upgrade]

- **n^+-electrode readout** ("natural" in p-type silicon):
  - favourable combination of weighting and electric field in heavily irradiated detector (i.e. **field at electrode**)
  - **electron collection** is faster than hole collection, less trapping, multiplication at segmented electrode

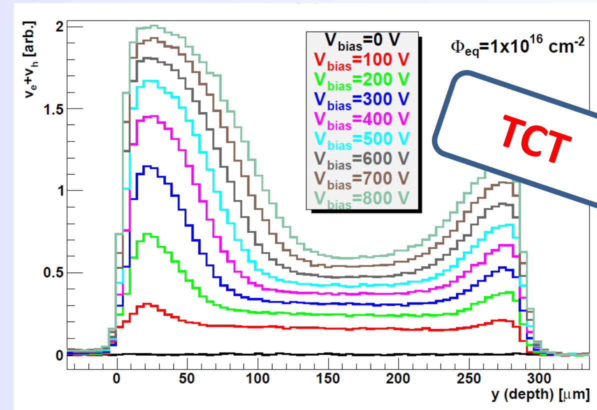
A comment on “depletion voltage” and “type inversion” in highly damaged detectors

- **Irradiation leads to a strong modification of the electric field within the sensor**
  - inhomogeneous space charge distribution
  - “double junction” effects
  - “type inversion” effects

TCAD



TCT



[Audrey Decourthial, PhD thesis, Paris 2018]
[G.Kramberger et al, 2014 JINST 9 P10016]

- **The meaning of “depletion voltage” (i.e. kink in CV, IV or CCE curve) is not clearly linked to Neff any more , i.e.**

detector thickness d

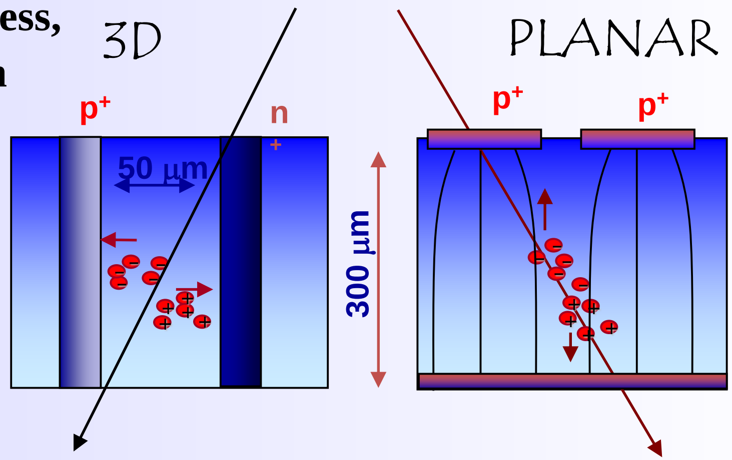
depletion voltage V_{dep} → $$\boxed{\cancel{V_{dep} = \frac{e}{2 \cdot \varepsilon} \cdot |N_{eff}| \cdot d^2}}$$ **is no longer valid.**

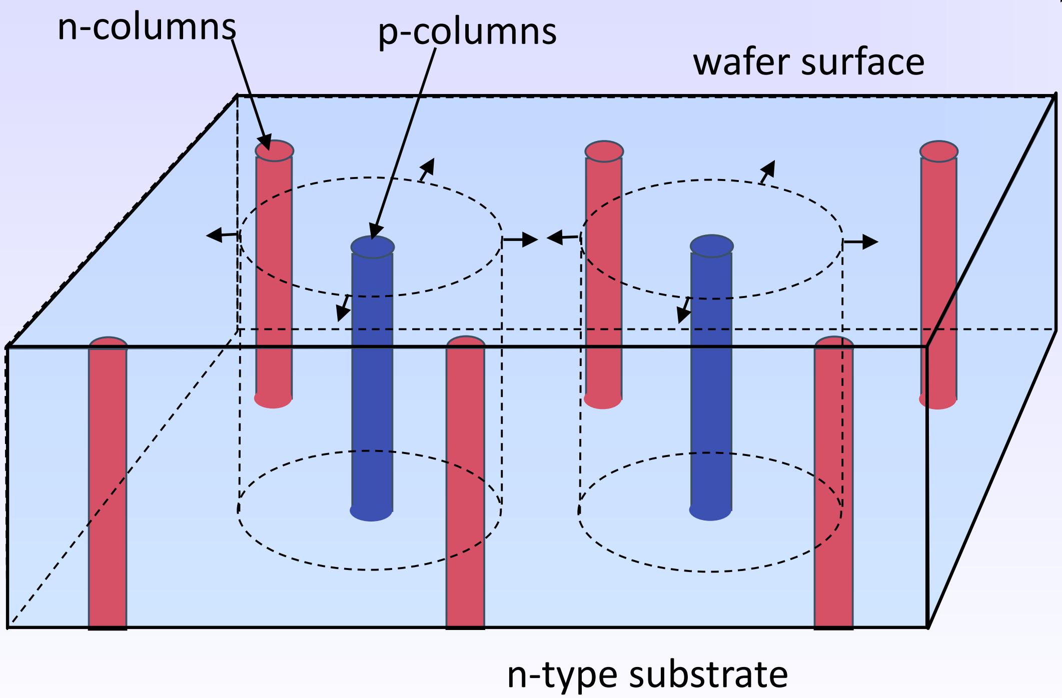
effective space charge density N_{eff}

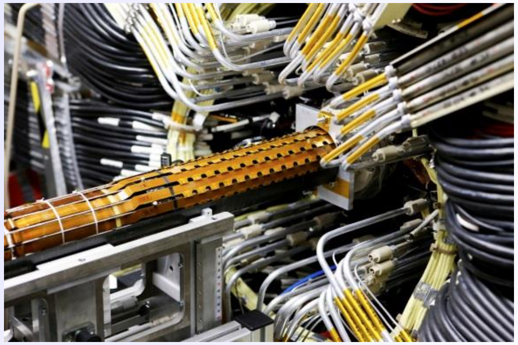
- **The term “type inversion” is not well defined**
  - space charge is position dependent (Neff(x)) and can even change sign over the detector depth (double junction)
  - we are looking at a detector under bias (a “depleted” detector) while the conduction type usually refers to the zero voltage steady state condition

Device Engineering: 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)
& ongoing developments
for LHC phase II (2024)

Radiation Damage & TCAD simulations

TCAD simulations

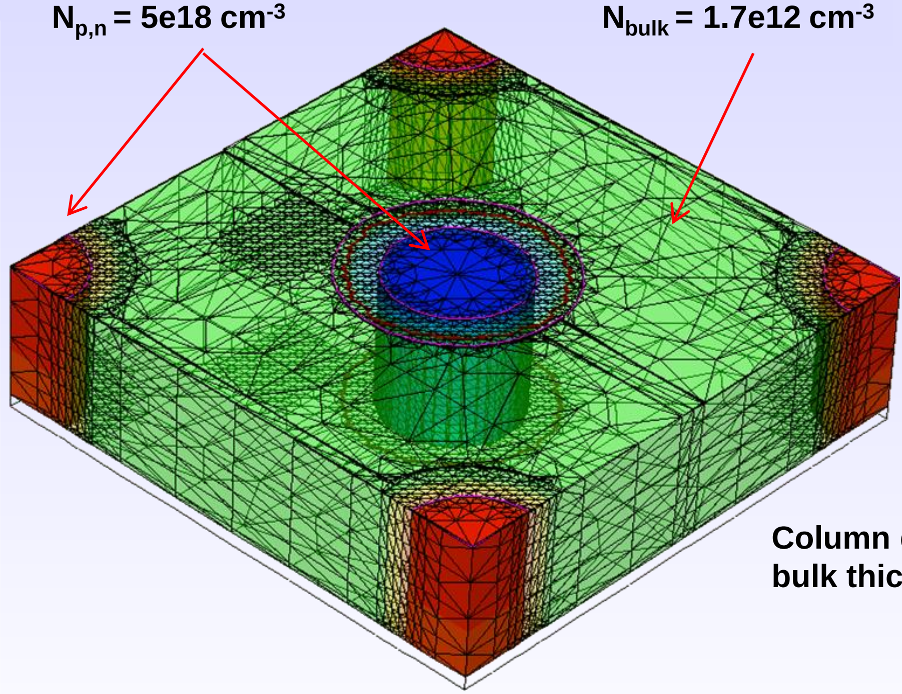
TCAD simulations

More about TCAD simulations in presentations from Matthieu, Joern, David & Marco

- **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***

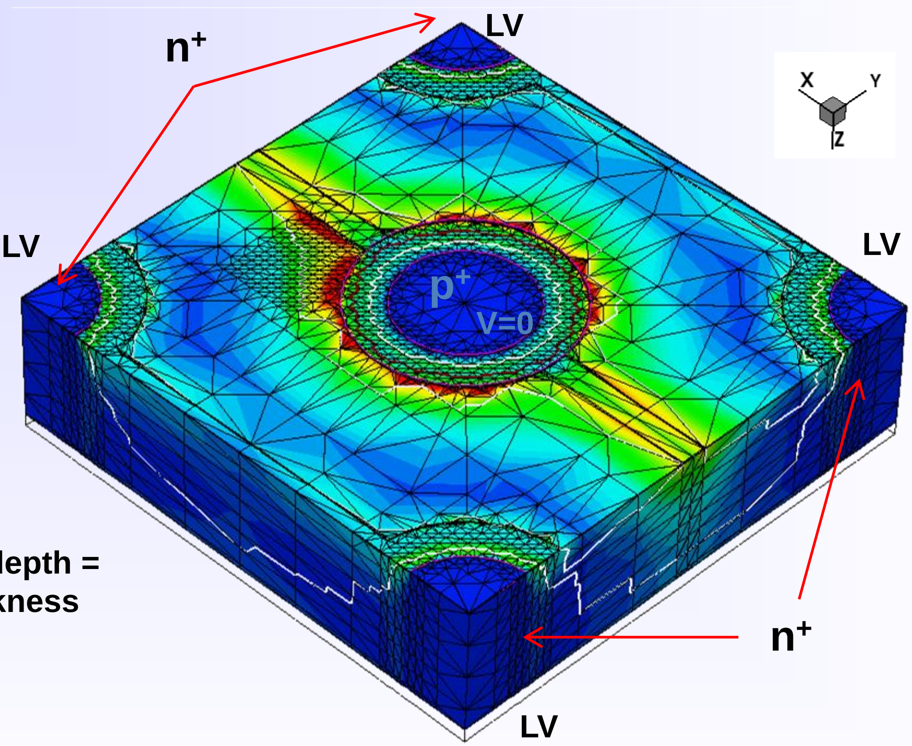
Doping profiles

$N_{p,n}$ = 5e18 cm^{-3} N_{bulk} = 1.7e12 cm^{-3}



Column depth = bulk thickness

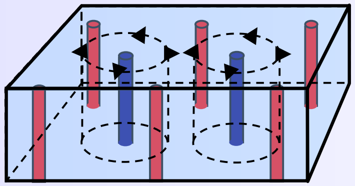
Electric field distribution in 3D detector (Al & oxide layer transparent for clarity)

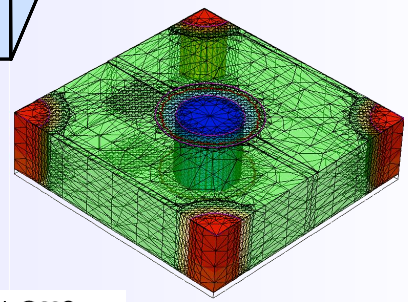


Example of 3D sensor: T.Peltola (HIP, Helsinki): CMS & RD50

Device simulation: TCAD & signal simulators

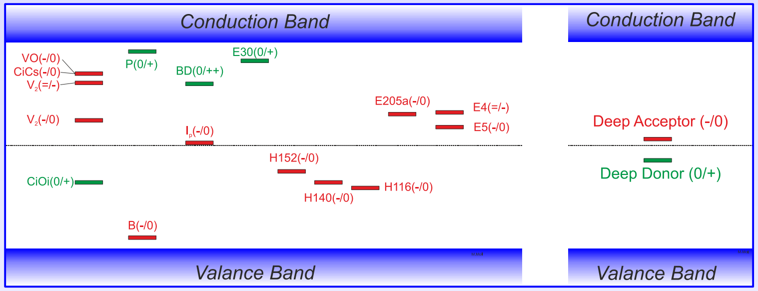
- **Status of TCAD simulations**
  - **Required by complexity of the problem:**
    - solve semiconductor equations with physics properties, complex geometry and radiation damage
    - mainly commercial tools used (Silvaco and Synopsis)
  - **Radiation damage TCAD: enormous progress over recent years**
    - getting predictive power but need further optimization!
      - "effective" defect levels (2 to 5 levels) are used

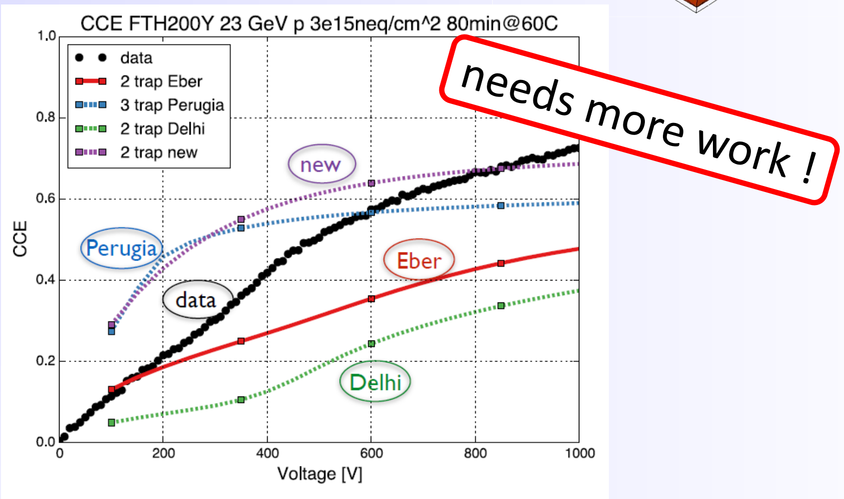




T.Peltola (HIP, Helsinki): CMS & RD50

Measured defects → TCAD input





      - > 10 models (for almost the "same problem")
      - Interface and oxide damage play a big role (partly included in models)
      - **Need**: include more defects and parameterization of input parameters, … work in progress!

[J.Schwandt, Hamburg, RD50 Workshop, 12/2015]

- Signal simulators
  - TCAD simulations are complex (time consuming, no fitting tool!)
  - Custom build signal simulators (open code) developed: sensor optimization, parameter fitting

Some TCAD models from literature

- **Several models available (non exhaustive list):**

TABLE II

COLLECTION (NONEXHAUSTIVE) OF RADIATION DAMAGE MODELS USED TO SIMULATE THE ELECTRIC FIELD WITHIN SILICON SENSORS AFTER HIGH FLUENCE HEAVY PARTICLE IRRADIATION (SEE TEXT). A: ACCEPTOR AND D: DONOR

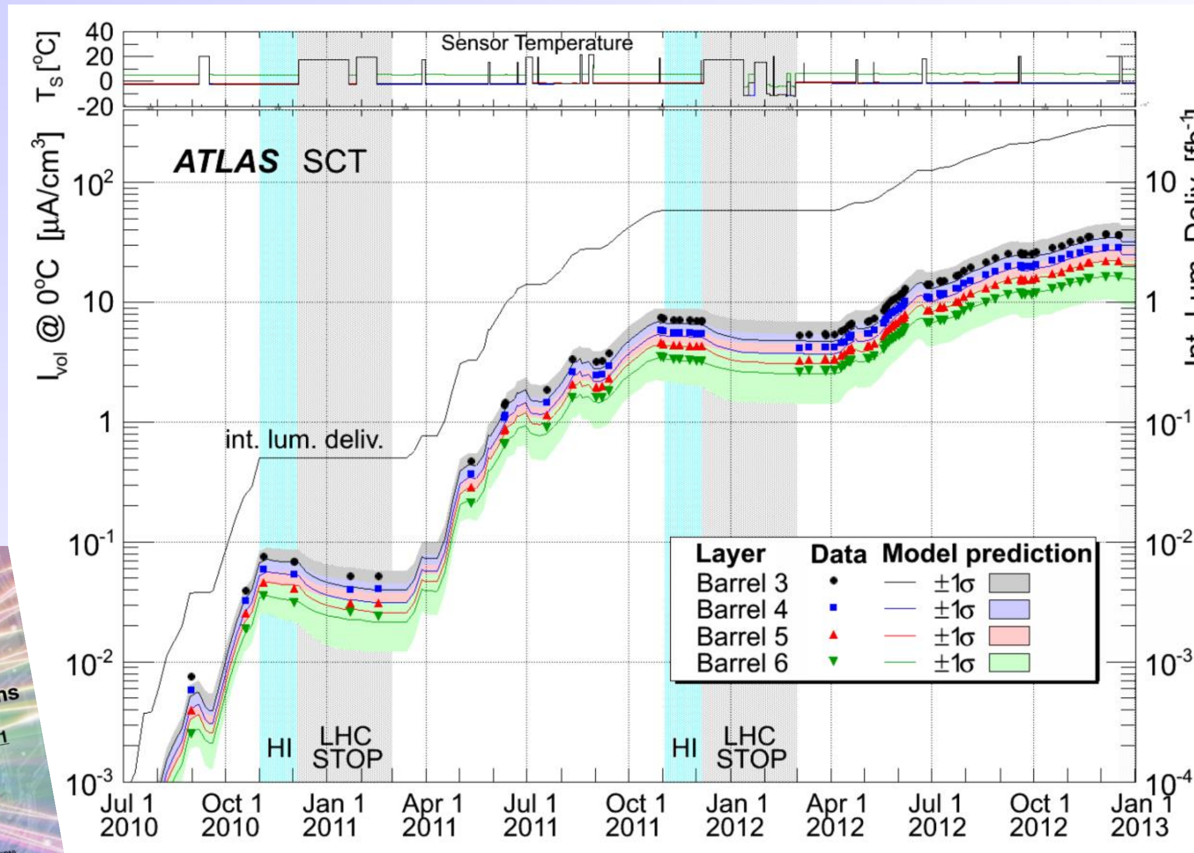
Model	Type	Level [eV]	$\sigma_{e,h}$ [cm^2]	η [cm^{-1}]	Comment
EVL 2002 [40]	A	$E_C - 0.525$	1×10^{-15}	–	Tool: Microsoft Excel [116]
	D	$E_V + 0.48$	1×10^{-15}	–	
	–	$E_C - 0.65^{(*)}$	1×10^{-13}	0.4	$^{(*)}$level for current generation, no space charge
Perugia 2006 [109]	A	$E_C - 0.42$	$2 \times 10^{-15}, 2 \times 10^{-14}$	1.613	Tool: Silvaco [117]
(p-type sensors)	A	$E_C - 0.46$	$5 \times 10^{-15}, 5 \times 10^{-14}$	0.9	
	D	$E_V + 0.36$	$2.5 \times 10^{-14}, 2.5 \times 10^{-15}$	0.9	
	A	$E_C - 0.42$	$2 \times 10^{-15}, 1.2 \times 10^{-14}$	13	
(n-type sensors)	A	$E_C - 0.50$	$5 \times 10^{-15}, 3.5 \times 10^{-14}$	0.08	
	D	$E_V + 0.36$	$2 \times 10^{-18}, 2.5 \times 10^{-15}$	1.1	
Glasgow 2008 [110]	A	$E_C - 0.42$	$9.5 \times 10^{-15}, 9.5 \times 10^{-14}$	1.613	Tool: Synopsys [118]
	A	$E_C - 0.46$	$5 \times 10^{-15}, 5 \times 10^{-14}$	0.9	model adapted from *Perugia 2006* [109]
	D	$E_V + 0.36$	$3.23 \times 10^{-13}, 3.23 \times 10^{-14}$	0.9	simulation of p-type 3D sensors
KIT 2013 [111]					Tool: Synopsys [118]
(protons)	A	$E_C - 0.525$	$1 \times 10^{-14}, 1 \times 10^{-14}$	–	$\eta_A = 1.189$ cm$^{-1} \times \phi - 6.454 \times 10^{13}$ cm^{-3}
	D	$E_V + 0.48$	$1 \times 10^{-14}, 1 \times 10^{-14}$	–	$\eta_D = 5.598$ cm$^{-1} \times \phi - 3.949 \times 10^{14}$ cm^{-3}
(neutrons)	A	$E_C - 0.525$	$1.2 \times 10^{-14}, 1.2 \times 10^{-14}$	1.55	
	D	$E_V + 0.48$	$1.2 \times 10^{-14}, 1.2 \times 10^{-14}$	1.395	
Delhi 2014 [112]	A	$E_C - 0.51$	$2 \times 10^{-14}, 2.6 \times 10^{-14}$	4	Tool: Silvaco [117]
	D	$E_V + 0.48$	2×10^{-14}	3	
Perugia 2016 [113]	A	$E_C - 0.42$	$1 \times 10^{-15}, 1 \times 10^{-14}$	1.613	improving *Perugia 2006* [109]
(p-type sensors)	A	$E_C - 0.46$	$7 \times 10^{-15}, 7 \times 10^{-14}$	0.9	$\phi_{eq} \leq 7 \times 10^{15}$ cm^{-2}
	–	–	$3 \times 10^{-15}, 3 \times 10^{-14}$	–	7×10^{15} cm$^{-2} \leq \phi_{eq} \leq 1.5 \times 10^{16}$ cm^{-2}
	–	–	$1.5 \times 10^{-15}, 1.5 \times 10^{-14}$	–	1.5×10^{16} cm$^{-2} \leq \phi_{eq} \leq 2.2 \times 10^{16}$ cm^{-2}
	D	$E_V + 0.36$	$3.23 \times 10^{-13}, 3.23 \times 10^{-14}$	0.9	

Table: *M.Moll, Displacement Damage in Silicon Detectors,* doi.org/10.1109/TNS.2018.2819506

In situ: LHC Experiments

- **LHC Experiments operating and "cumulating radiation damage"**
- **Example: The ATLAS SCT (Silicon Central Tracker)**

  - Leakage current in agreement with expectations
  - Annealing during the LHC shutdown and technical stop periods is visible



ATLAS, 2014 JINST 9 P08009

Next Radiation Effects at LHC Detectors Workshop, CERN 11-13 Feb. 2019.

Next RD50 Workshop, CERN 26-28 November 2018

Summary

- **Silicon Sensors: based on 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** (planar and 3D) and **strip sensors** implemented in LHC experiments
  - Radiation Hard Monolithic sensors for LHC under development (competing for HL-LHC ATLAS)

  New sensor developments: Need for TCAD simulations
- **Radiation Damage in Silicon Sensors**
  - Reason: **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
- **"Hot topics" in R&D on radiation hard silicon sensors**
  - Sensors for timing (i.e. with intrinsic gain, acceptor removal); Monolithic sensors; CMOS
  - **Reliability of TCAD simulations with defects**; characterization of damage beyond 10^{16} cm^{-2}

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***
  - ***M.Moll, Displacement Damage in Silicon Detectors for High Energy Physics 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 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***

https://indico.in2p3.fr/e/simdet2018

SIMDET 2018

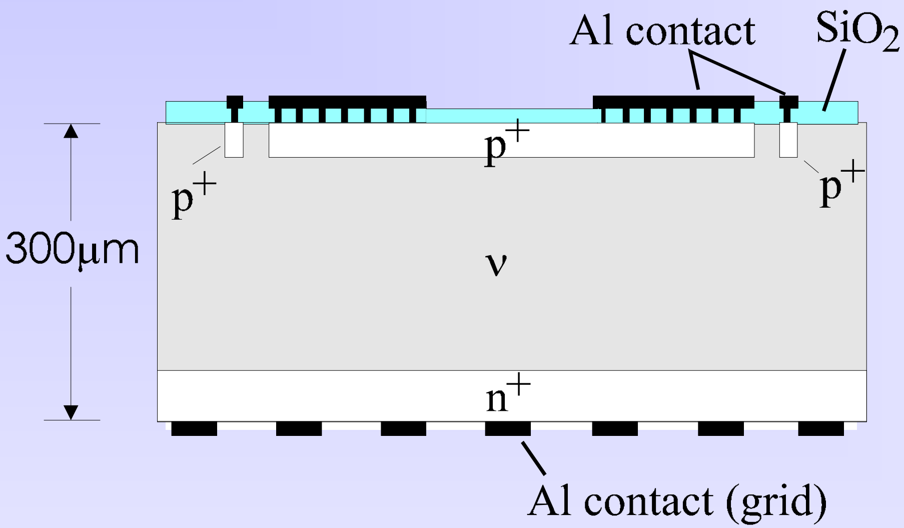
3rd school on silicon detectors simulation

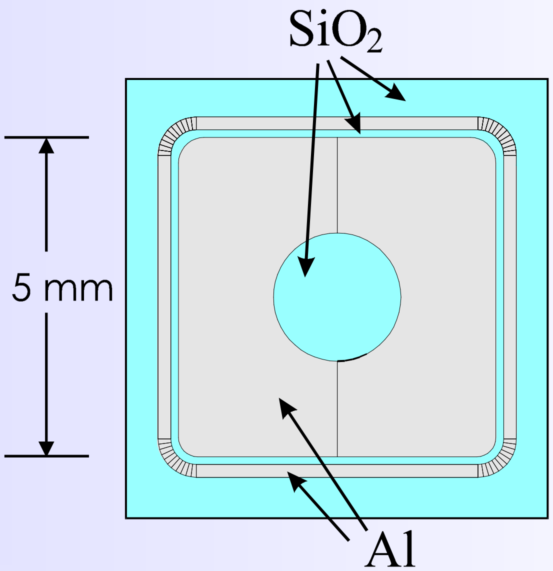
SPARE SLIDES

Michael Moll

CERN, Geneva, Switzerland

Test 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**

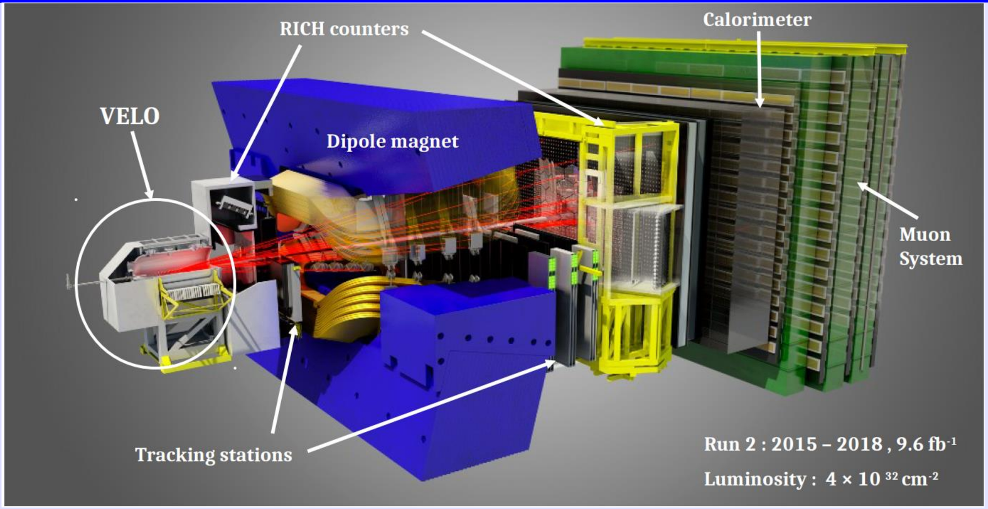
Summary on defects with strong impact on device performance after irradiation

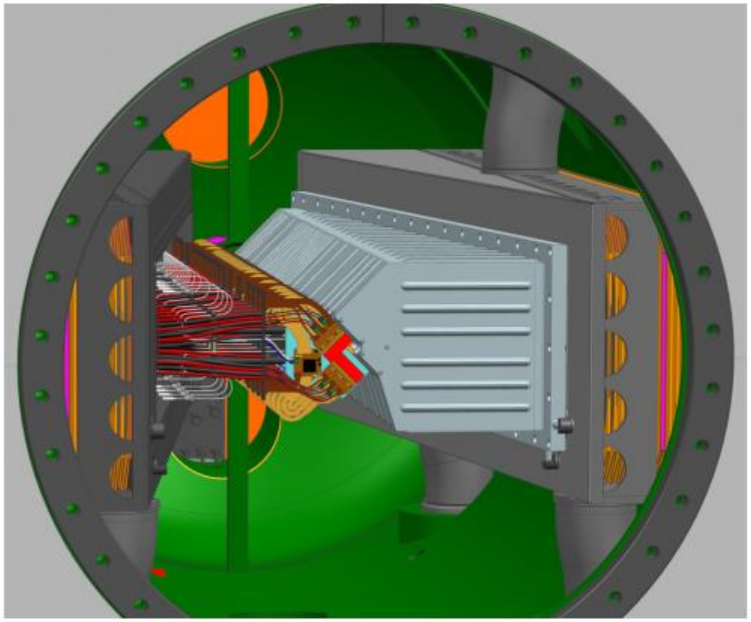
- **Most important defects** *[for details and references see JAP 117, 164503, 2015]*

Defect	Transition	Level(s) [eV]	$\sigma_{e,h}$ [cm^2]	Comment
E(30K)	(0/+)	$E_C - 0.1$	$\sigma_e = 2.3 \times 10^{-14}$	Not identified extended defect, donor level, contributes in full concentration with positive space charge to N_{eff}, strongly generated after charged particle irradiation with linear fluence dependence [32], [37], [89].
BD_A BD_B	(0/++) (+/++)	$E_C - 0.225$ $E_C - 0.15$	$\sigma_e = 2.3 \times 10^{-14}$ $\sigma_e = 2.7 \times 10^{-12}$	Point defect, TDD2, bistable donor existing in configuration A and B, strongly generated in O rich material, contributing in full concentration to positive space charge [36], [90], [91]
I_p	(+/0) (0/-)	$E_V + 0.23$ $E_C - 0.545$	$\sigma_h = (0.5 - 9) \times 10^{-15}$ $\sigma_e = 1.7 \times 10^{-15}$ $\sigma_h = 9 \times 10^{-14}$	Not identified point defect, tentatively V_2O or C related defect [37], generated via second order process (quadratic fluence dependence), strongly generated in O lean material, acceptor level contributing to current and N_{eff} [36], [37], [92], [93]
E_{75} E4 E5	(-/0) (=/-) (-/0)	$E_C - 0.075$ $E_C - 0.359$ $E_C - 0.458$	$\sigma_e = 3.7 \times 10^{-15}$ $\sigma_e = 2.15 \times 10^{-15}$ $\sigma_e = 2.4 \times 10^{-15}$ $\sigma_h = 2.15 \times 10^{-13}$	Tri-Vacancy (V_3), bistable defect existing in 2 configurations: FFC(E_{75}) and PHR(E4,E5), E5 is contributing to leakage current, linear fluence dependence [37], [94]–[98]
H(116K) H(140K) H(152K)	(0/-) (0/-) (0/-)	$E_V + 0.33$ $E_V + 036$ $E_V + 0.42$	$\sigma_h = 4 \times 10^{-14}$ $\sigma_h = 2.5 \times 10^{-15}$ $\sigma_h = 2.3 \times 10^{-14}$	3 non identified extended defects, linear fluence dependence, contributing in full cocentration negative space charge, responsible for *reverse annealing* [32], [37], [89], [99]
BiOi	(0/+)	$E_C - 0.23$		Dominant Boron related defect (electron trap) in oxygen rich Silicon, created during acceptor removal [100]–[103]

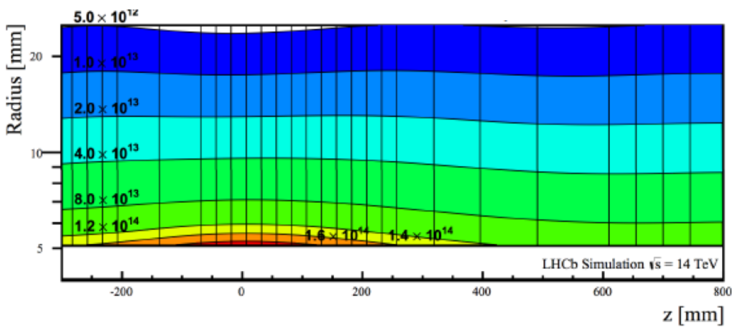
Table: *M.Moll, Displacement Damage in Silicon Detectors,* doi.org/10.1109/TNS.2018.2819506

LHCb – VELO UPGRADE





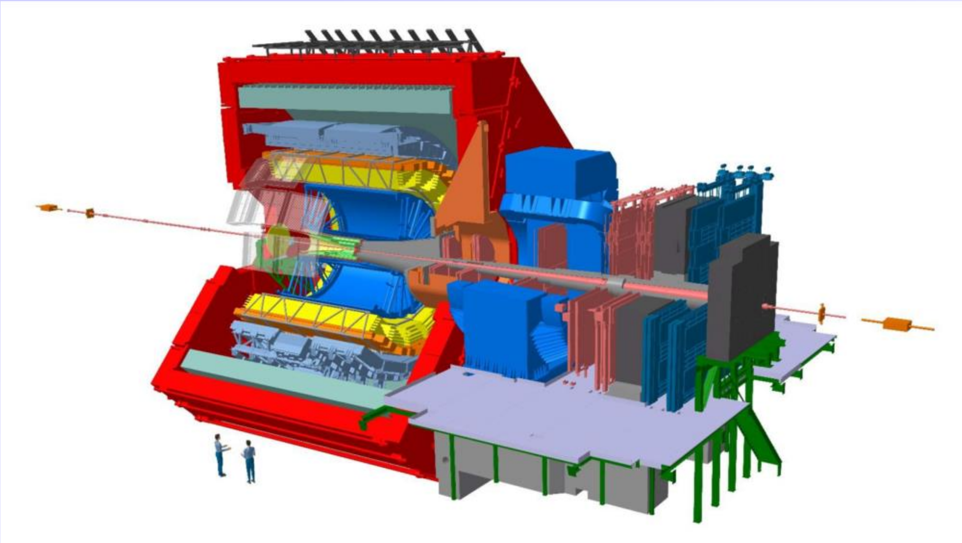
Feature	VELO	VELO Upgrade
Sensors	R and φ strips (n on n Si, 2 n on p) 300 μm thick, 0.22 m^2 173,032 strips (~0.2 M) Semicircular geometry	n on p Si Pixels 200 μm thick, 0.12 m^2 41 M pixels L shaped geometry
Distance From Beam	8.2 mm	5.1 mm
Maximum Fluence	5.2×10^{14} 1 MeV neq cm^{-2}	8×10^{15} 1 MeV neq cm^{-2}
HV Tolerance	500 V	1000 V
# of Modules	42 modules	52 modules
ASIC Readout Rate	1 MHz	40 MHz
Total Data Rate	~150 Gb/sec	2.8 Tb/sec
Power Consumption	~ 1.1 kW (~ 16.5 W/module)	1.6 kW (~ 28 W/module)
Operating Temperature	< -10 °C	< -20 °C
RF Foil thickness	300 μm	250 μm

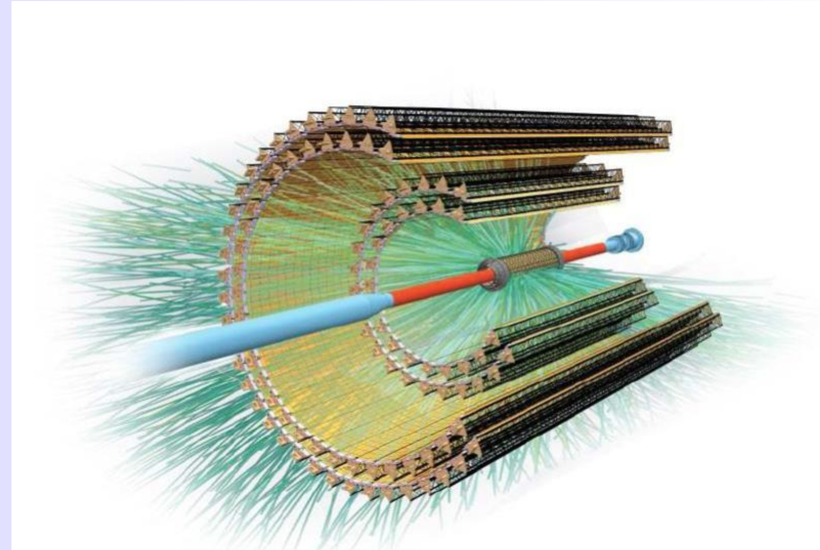


Integrated Radiation Dose per fb^{-1} (in 1 MeV neq cm^{-2})

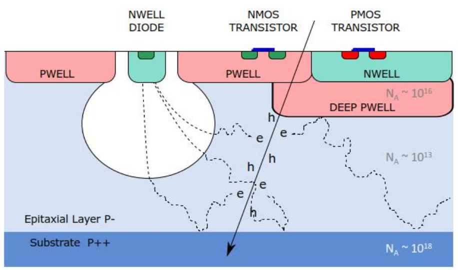
[Deepanwita Dutta, VERTEX 10/2018]

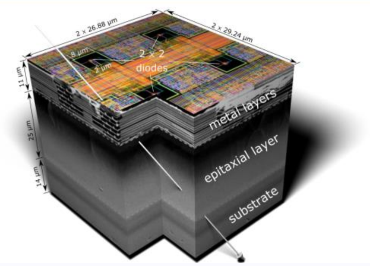
ALICE – ITS UPGRADE





ALPIDE – ALICE pixel detector





- TowerJazz 0.18 μm CIS process
- 2 μm low capacitance (~fF) NWELL diode
- Deep PWELL shields PMOS transistors
- 25 μm thick high resistivity (> 1kΩ·cm) epitaxial layer
- Reverse bias (down to -6V) to increase depletion

Summary

New ITS will feature

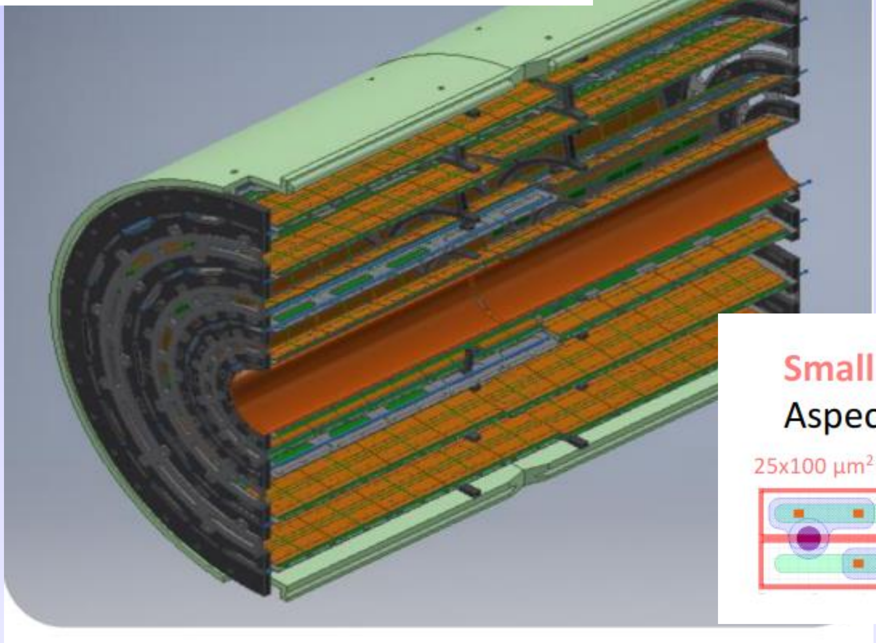
- 1000 times higher granularity
- 3 times lower material budget in the inner barrel

Production of all detector components has started and is advancing well

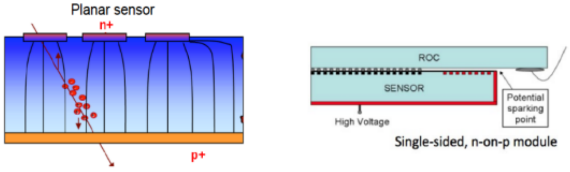
Detector installation in the cavern in May 2020.

CMS Pixel UPGRADE

Innermost layer: $2.3 \times 10^{16}\ n_{eq}/cm^2$
Outer & Service cylinder: $10^{15}\ n_{eq}/cm^2$



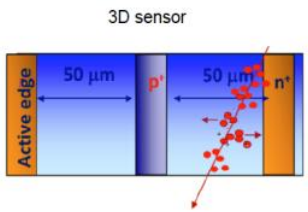
Thin Planar n-in-p sensors:
Optimal d~100 - 150 µm- lower signal unirradiated
Main challenges:
spark protection, limited space for structures, radiation



Small pitch pixel cells
Aspect ratio under study:

25x100 µm² (baseline) 50x50 µm²

3D sensor:
Option for TBPX L1/TFPX R1
Main challenge: complex fabrication



Objective:

Maintain or improve tracking capability with 200PU

Increase granularity	**Pixel Chip & Sensor 250 µm² : 2 billion pixels**
Reduce material	**Serial powering, CO_2 cooling, Light mechanics**
Increase coverage	**New layout extended to |η|=4**

ATLAS Pixel UPGRADE

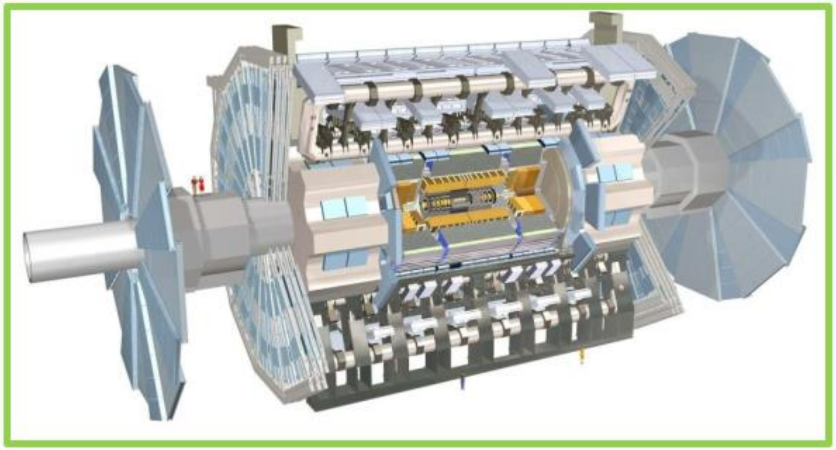
- 5 barrel layers:
  - flat section up to z = 500mm
  - inclined section up to z = 1200mm
  - endcap rings up to z = 3000mmm
- coverage of tracks with $|\eta| < 4$
- about 10.000 hybrid pixel modules
  - planar and 3D sensors
  - CMOS modules considered as a candidate for outermost barrel layer
- 50x50 μm^2 or 25x100 μm^2 pixels
- 2 innermost layers will be replaceable after collecting 2000 fb^{-1}

REQUIREMENTS

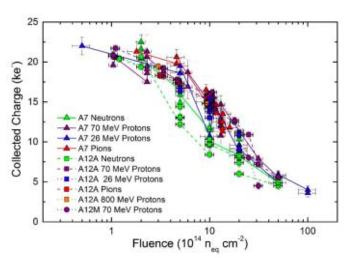
- radiation hardness: up to 10 MGy (TID) and 1.4×10^{16} n_{eq}/cm^2 in the innermost layer
- track reconstruction efficiency: > 99% for muons, > 85% for pions and electrons

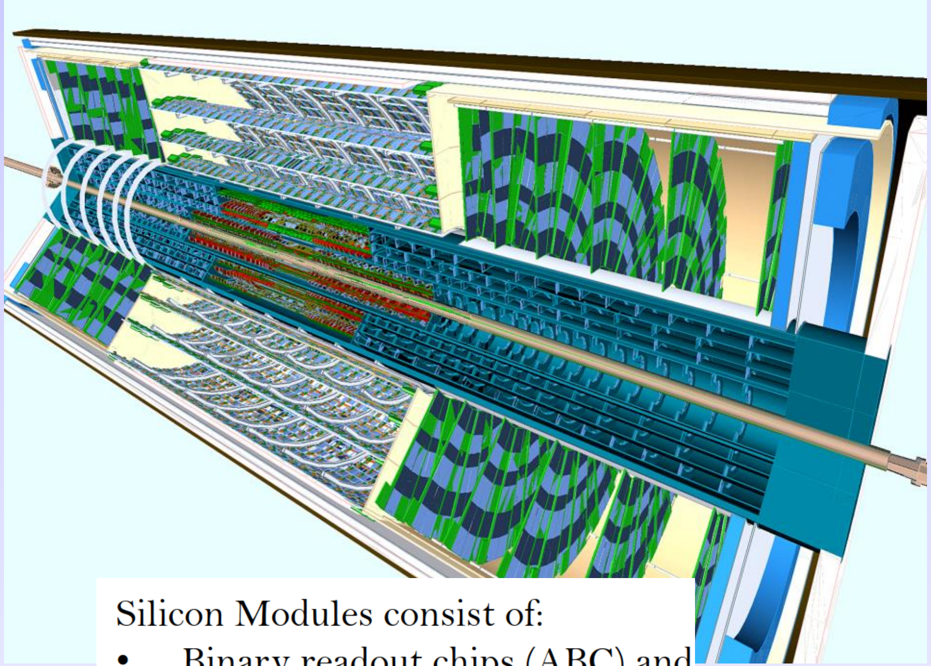
- fake rate < 10^{-5}
- robustness against loss of up to 15% of individual channels
- readout:
  - innermost layers: 1MHz
  - outermost layers: 4MHz (L1 track trigger)
  - output bandwidth: up to 5.12 Gb/s per front-end chip
- application of a serial powering scheme for multi-chip modules

- three different sensors to be used
  - 3D sensors for innermost layer
  - 100 μm thick planar sensors for L1
  - 150 μm thick planar sensors for L2-L4



ATLAS Tracker UPGRADE





- The new inner tracker (ITk) will be an all Si Tracker system
  - Will replace the current ID (Pixels, SCT + TRT)
  - 'All Silicon' -> no TRT
- 2T magnetic field, ~6m long, ~1m radius & up to $|\eta|=4$
- 5 Central and multiple Forward Pixel layers
- 4 Central and 6 Forward Strip layers

- Strips system consists of
  - **~18k Modules**
  - **59.87 million channels**
  - **165 m² of Silicon**

101 Institutes from 22 countries

Silicon Modules consist of:

- Binary readout chips (ABC) and hybrid controller chips (HCC)
  - Glued & wire bonded to a hybrid
  - Data transfer on hybrid at 320 Mbit/s
- Hybrids are glued to the surface of the Si sensor
  - Wire bonds connect Front End ABC channels to Si strips
  - ~5200 wire bonds /module
- DC-DC powering allows powering of all modules
  - Unlike SCT each module cannot have own Voltage Cables