https://indico.in2p3.fr/e/simdet2023

SIMDET 2023, 22-24 November 2023, LPNHE Paris

Introduction to Semiconductor Detectors

with focus on applications at Hadron Colliders

Michael Moll, CERN EP-DT, Geneva, Switzerland

OUTLINE

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

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

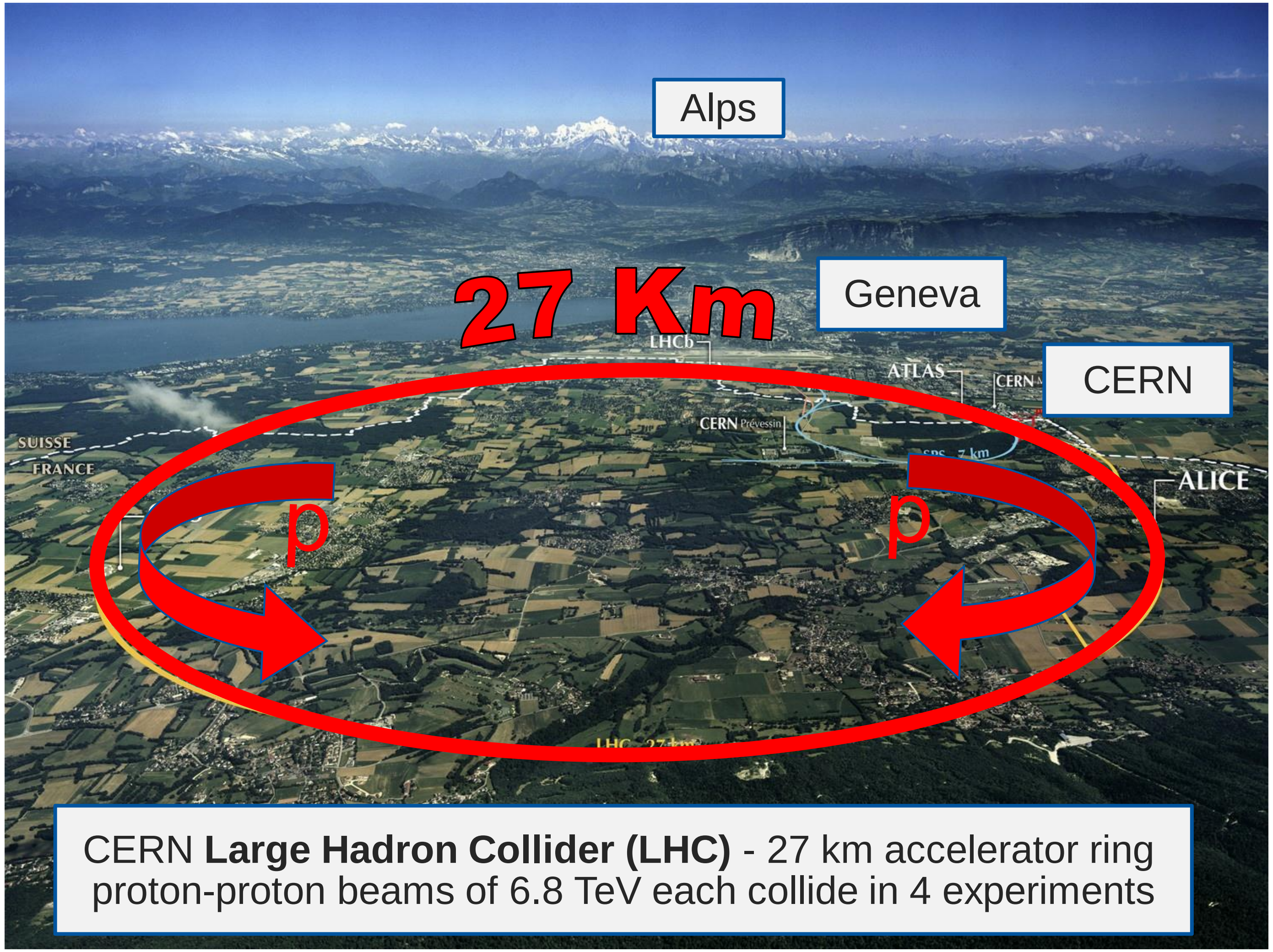
- **Radiation Damage to Silicon Detectors**
  - Upgrade of the Large Hadron Collider (HL-LHC)
  - Radiation damage mechanisms
    - Microscopic defects and macroscopic damage
  - Mitigation techniques: What can we do against radiation damage?
    - Examples of radhard devices for the HL-LHC: p-type strip sensors and 3D sensors

- **Why do we need (TCAD) device simulations (introduction)?**

- **Summary & Further reading**

Details in following presentations:
Marco Bomben; Arianna Morozzi;
Matteo C.Vignali; Jairo Antonio Villegas Dominquez; Li Long; Alexander Bähr

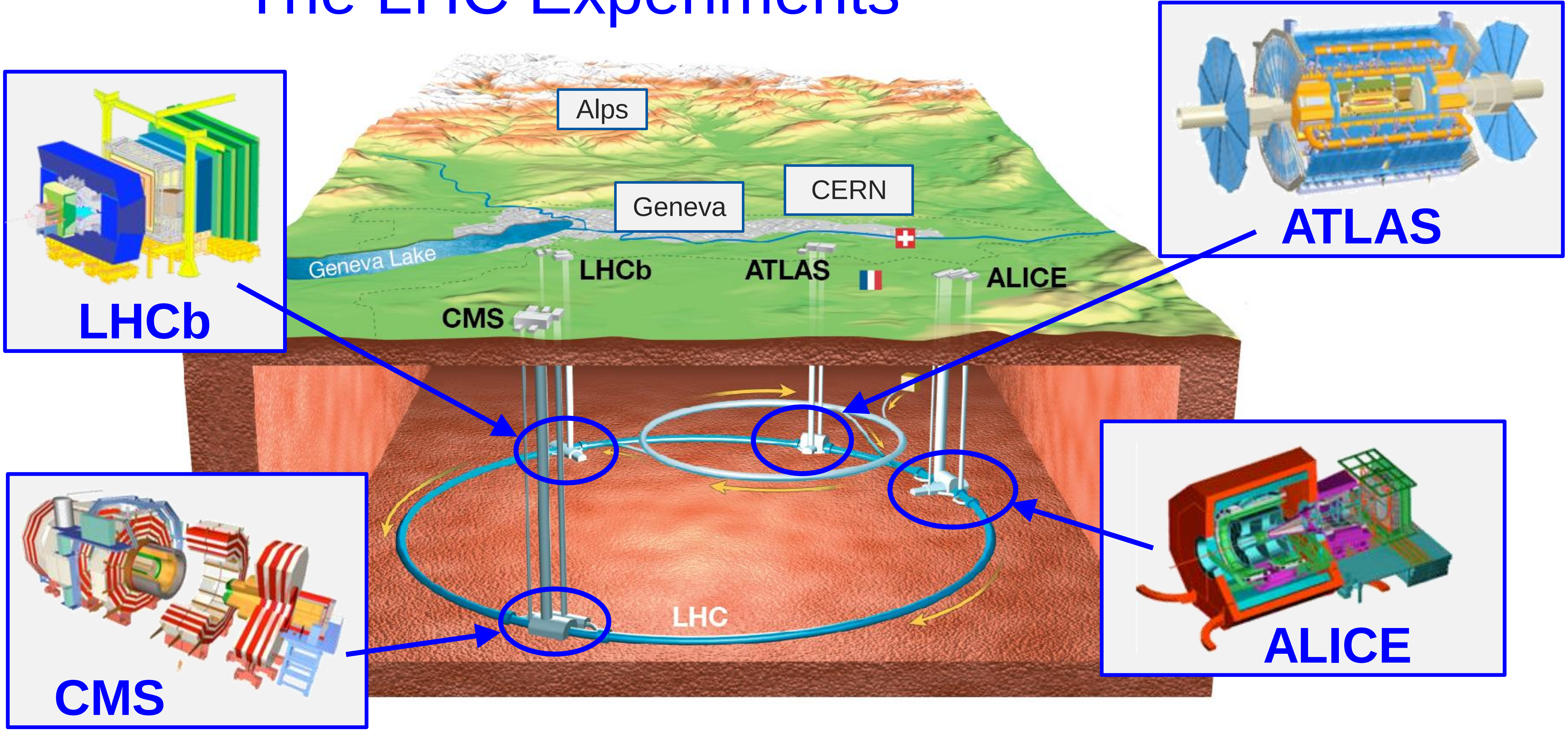
CERN & LHC - Large Hadron Collider



also a program with Pb beams at up to 5.36 TeV per nucleon

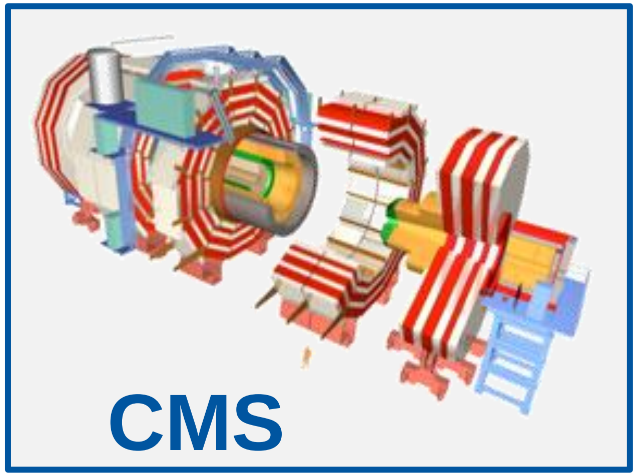
- **CERN (2023):**
  - 23 member states
  - ~13400 scientists (users)
  - ~ 2660 personnel (staff) + 900 Fellows
  - Budget ~1230 MCHF *(France: 13.2%)*
- **LHC: 27 km tunnel**
  - ≈ 4600 MCHF + 1200 MCHF (accelerator + experiments)
  - 1232 dipoles B=8.3T (959
  - Design: pp $\sqrt{s}$ = 14 TeV (L_{design} = 10^{34} cm^{-2} s^{-1})
    heavy ions (e.g. Pb-Pb; 5TeV)
- **Circulating beams:**
  - 2008: first beam
  - 2009-13: **Run 1** at 2 x 4 TeV
    - 2012: Higgs Boson "discovered"
  - 2015-18: **Run 2** at 2 x 6.5 TeV ($10^{34}cm^{-2}s^{-1}$ reached)
  - 2018-22: Long Shutdown 2 (LS2)
  - 2022-26: **Run 3** at 2 x 6.8 TeV ← today
  - 2026-28: Long Shutdown 3 (LS3)
  - **2028: HighLumi-LHC** (Run 4, ….)
    - collect 3000-4000 fb^{-1} until ~ 2042 (20 times more than today)

The LHC Experiments

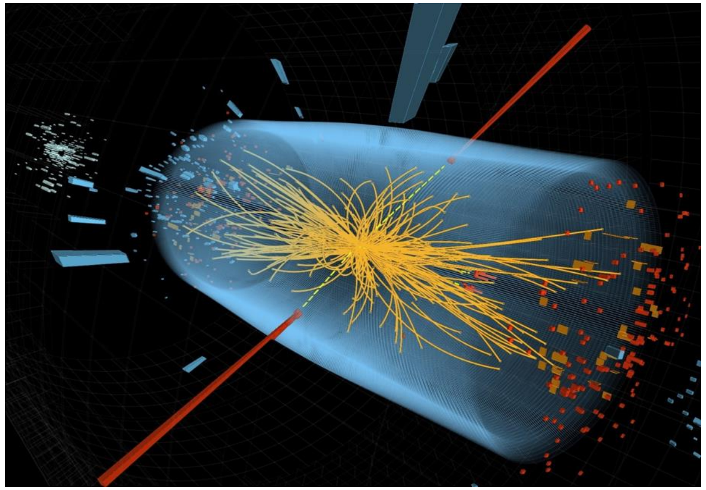


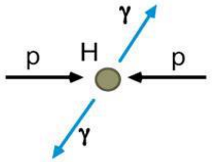
Collisions in the LHC

every 25ns (40 MHz)

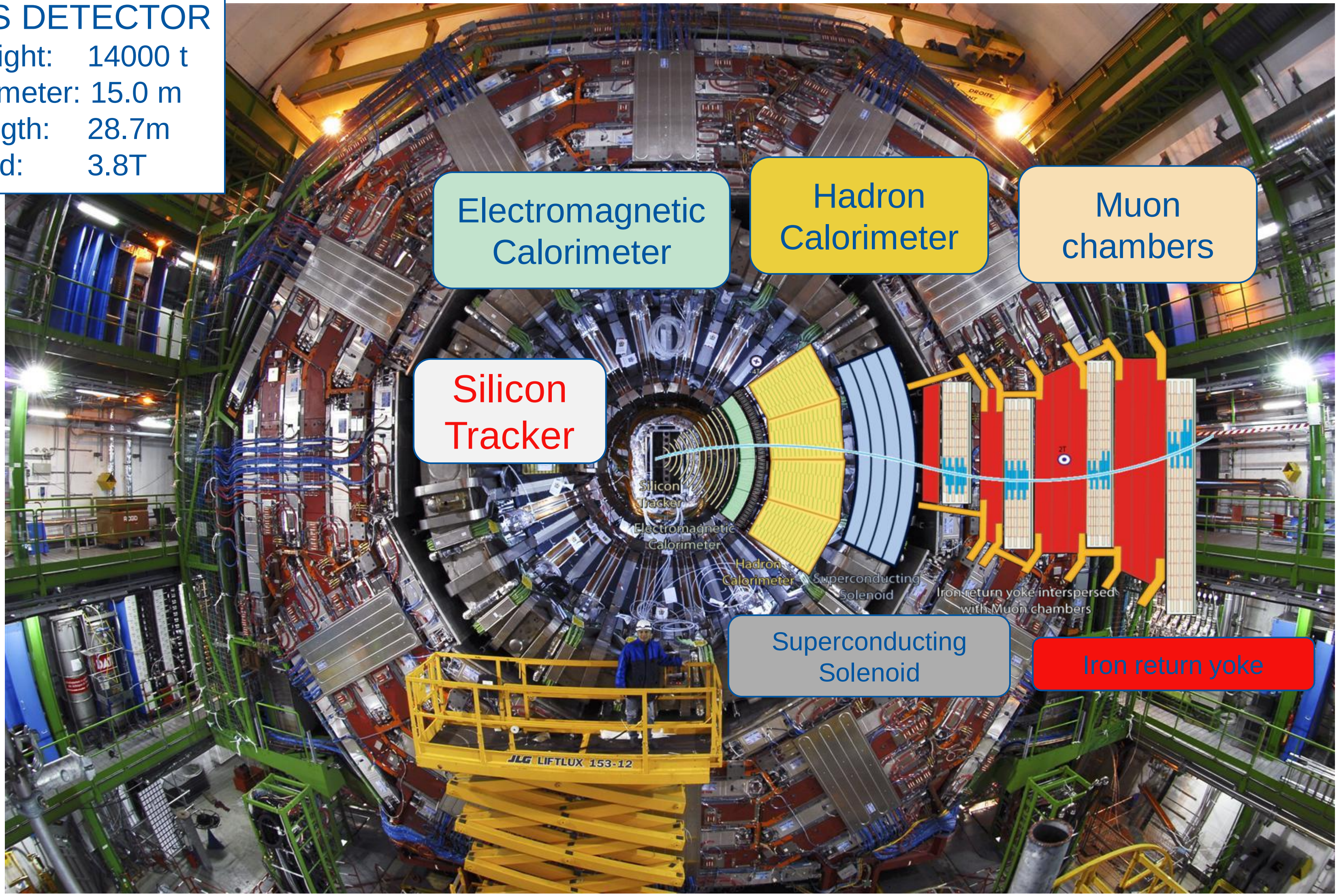


CMS DETECTOR
Weight: 14000 t
Diameter: 15.0 m
Length: 28.7m
Field: 3.8T



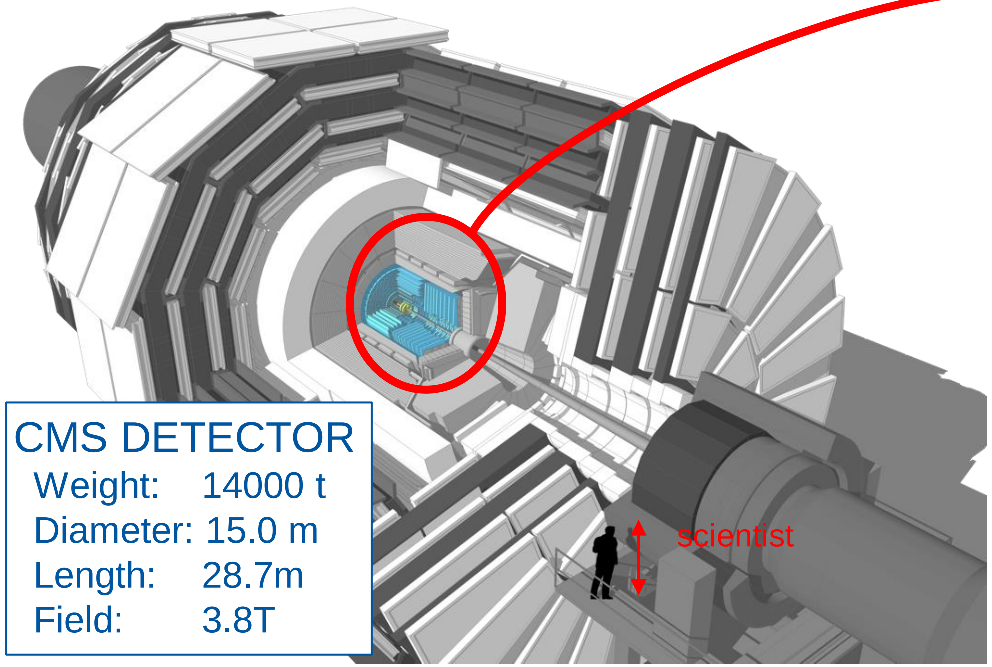


event seen in 2011
Higgs → 2 photons

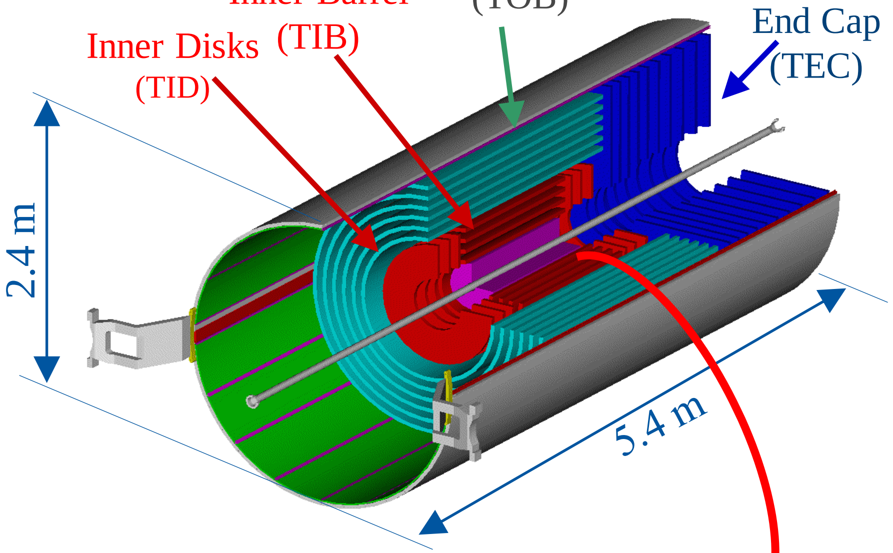


Silicon Tracking Detector

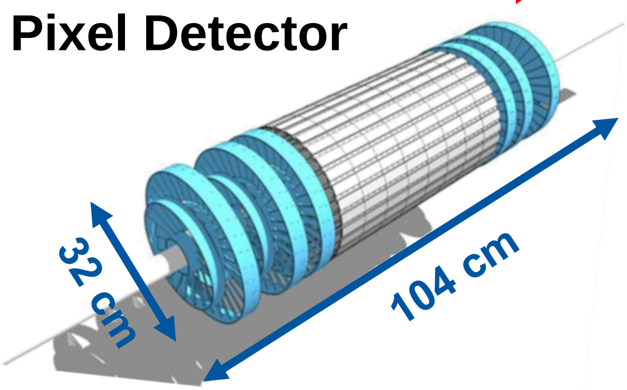
- **LHC example: The CMS DETECTOR**



- **Inner Tracker**

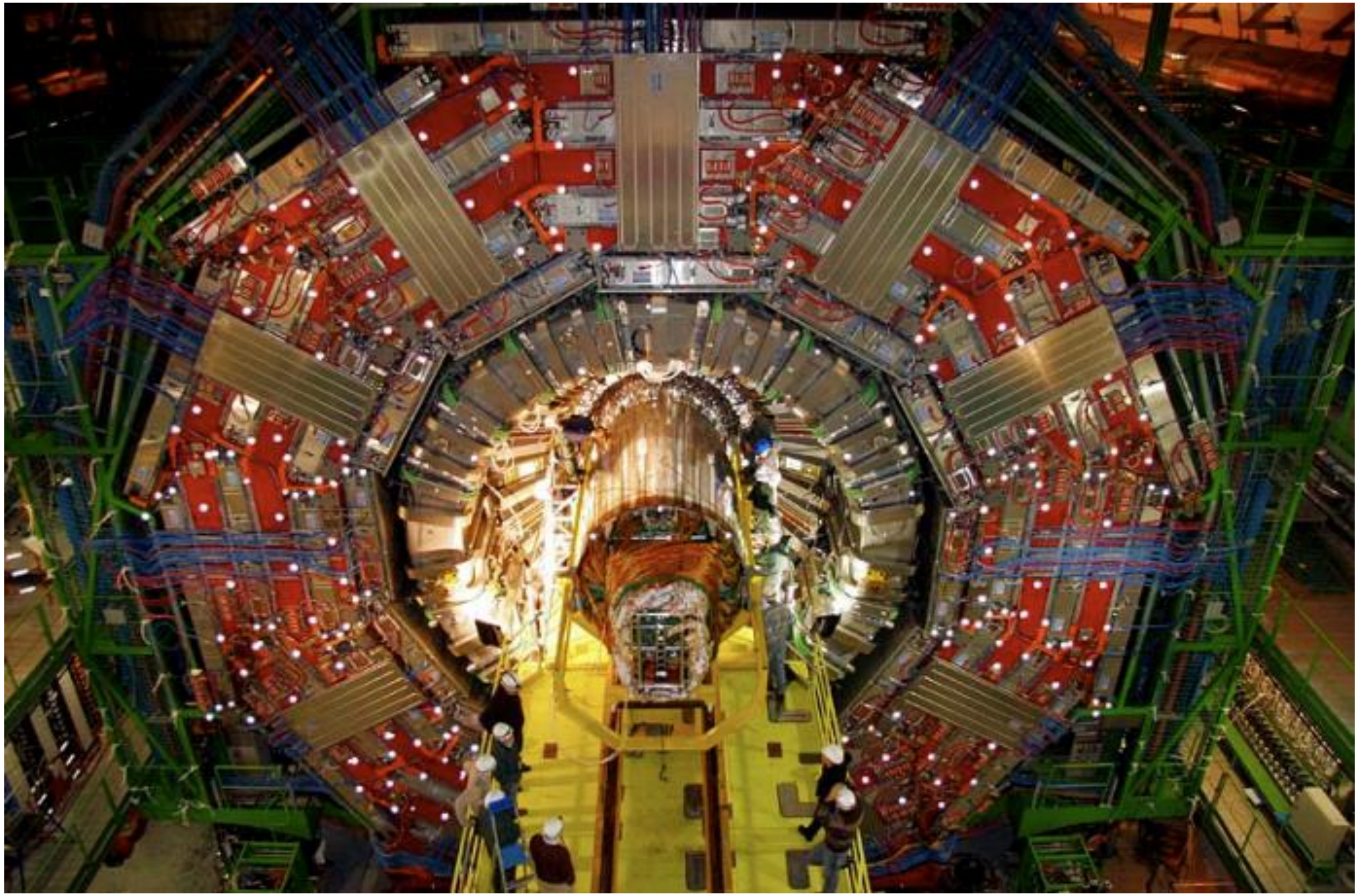


- **Pixel Detector**



- **CMS – Inner Tracker & Pixel Detector**
  - **Micro Strip:**
  - **~ 214 m^2 of silicon strip sensors, 11.4 million strips**
  - **Pixel:**
  - **4 layers & 2 x 3 disks: silicon pixels (~ 1m^2)**
  - **124 million pixels (100x150μm^2)**
  - **Resolution: $\sigma(r\varphi)$ ~ 10 μm, $\sigma(z)$ ~ 25μm**

Present LHC Tracking Sensors



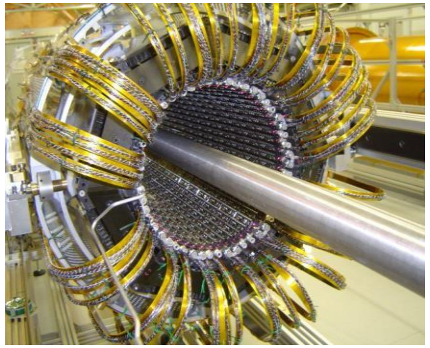
December 2007

CMS Tracker insertion

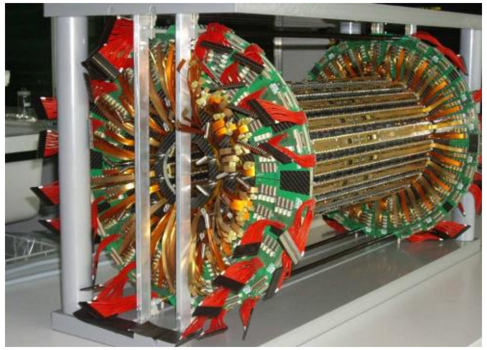
Silicon Tracking Detectors

Silicon tracking detectors are used in almost all HEP experiments:

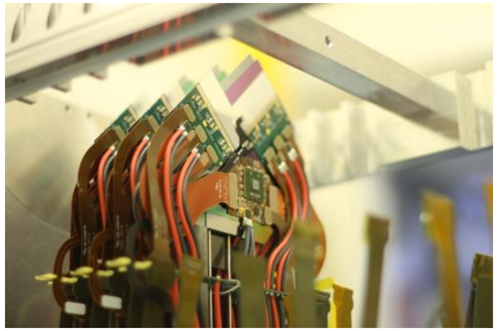
Different sensor technologies, designs, operating conditions,….



ATLAS Pixel Detector

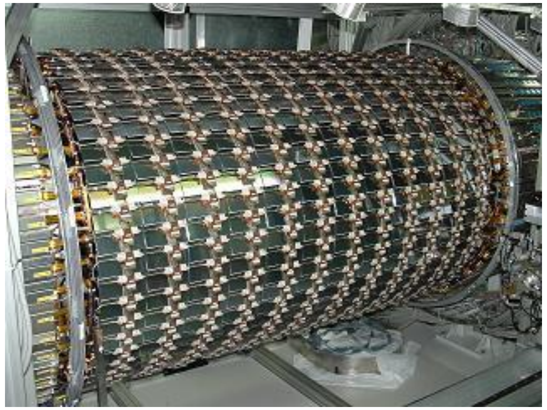


CMS Pixel Detector

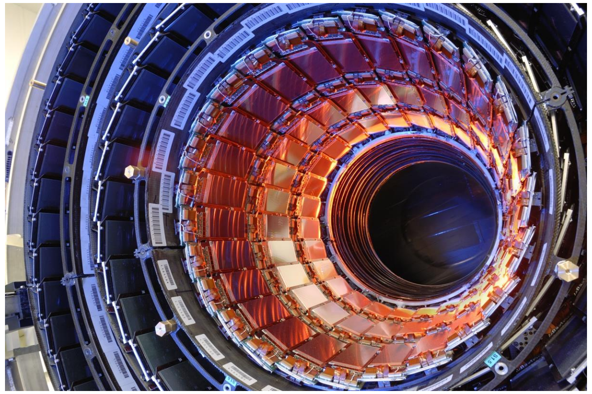


LHCb VELO (New VELO for Run3:2022)

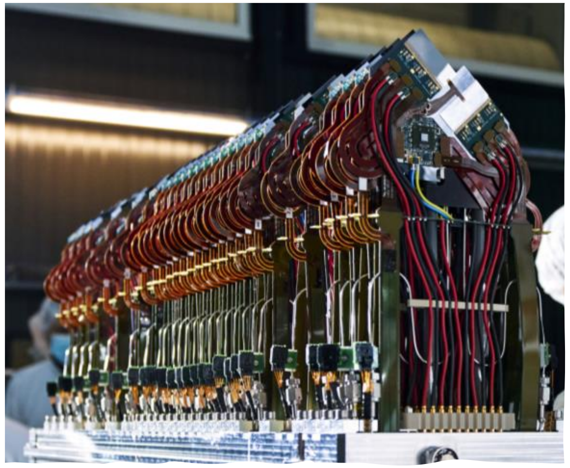
ALICE ITS Barrel
New ITS for Run3:2022



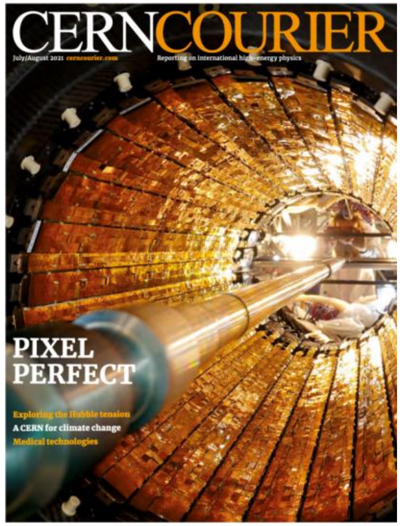
ATLAS SCT Barrel



CMS Strip Tracker IB



LHCb VELO (New VELO for Run3:2022)



ALICE ITS Outer Barrel
(Foto:Insertion Test 2021)

Silicon Sensors

Solid State Detectors – Why Silicon?

- **Some characteristics of Silicon crystals**
  - Small band gap E_g = 1.12 eV $\Rightarrow$ E(e-h pair) = 3.6 eV ($\approx$ 30 eV for gas detectors)
  - High specific density 2.33 g/cm^3 ; dE/dx (M.I.P.) $\approx$ 3.8 MeV/cm $\approx$ 106 e-h/μm (average)
  - High carrier mobility μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs $\Rightarrow$ 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

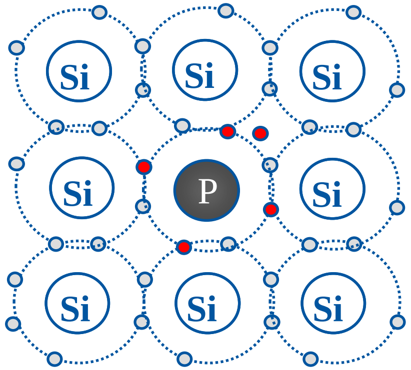
    $\Rightarrow$ well known industrial technology, relatively low price, small structures easily possible

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

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

Doping, resistivity and p-n junction

e.g. Phosphorus

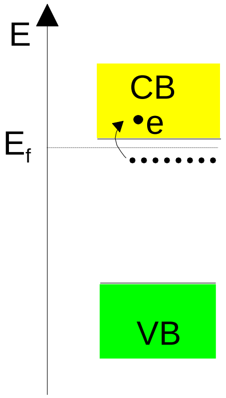


- **resistivity** ρ
  - carrier concentration n, p
  - carrier mobility μ_n, μ_p

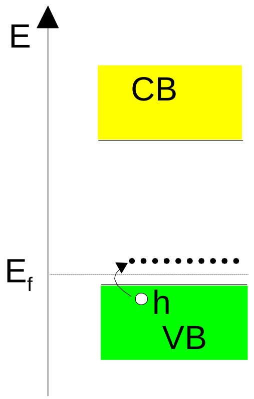
$$\rho = \frac{1}{q_0(\mu_n n + \mu_p p)}$$

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

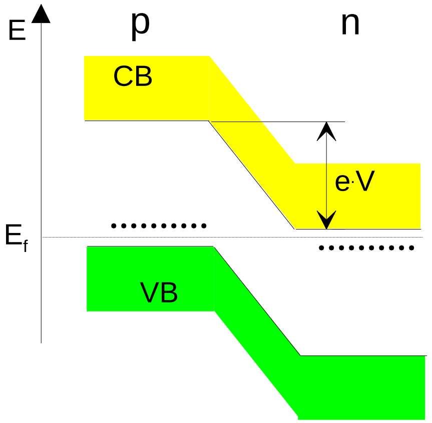
- **Doping**: n-type silicon
  - add elements from Vth group ⇒ **donors** (P, As,..)
  - electrons are majority carriers



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



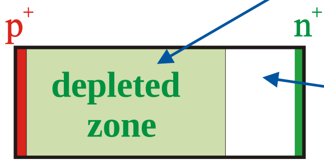
- p-n junction
  There must be a single Fermi level!
  ⇒ band structure deformation
  ⇒ potential difference
  ⇒ depleted zone



Reverse biased p-n junction

Poisson's equation

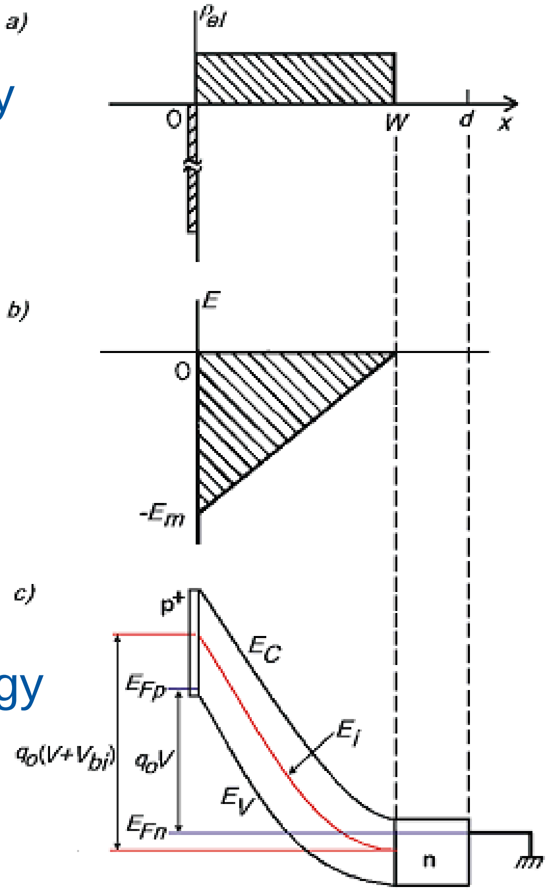
$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$



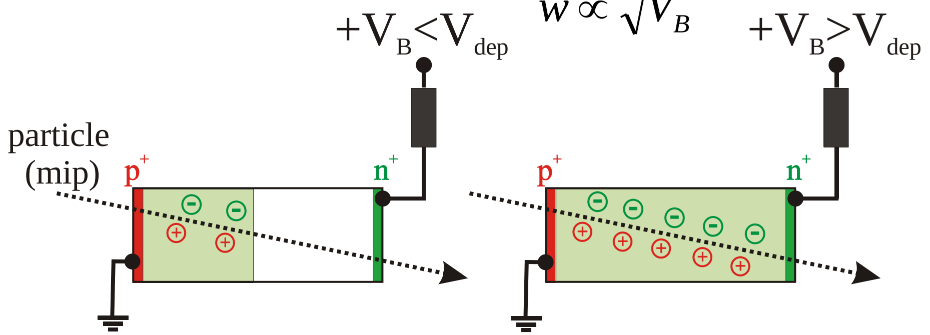
Electrical charge density

Electrical field strength

Electron potential energy



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



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

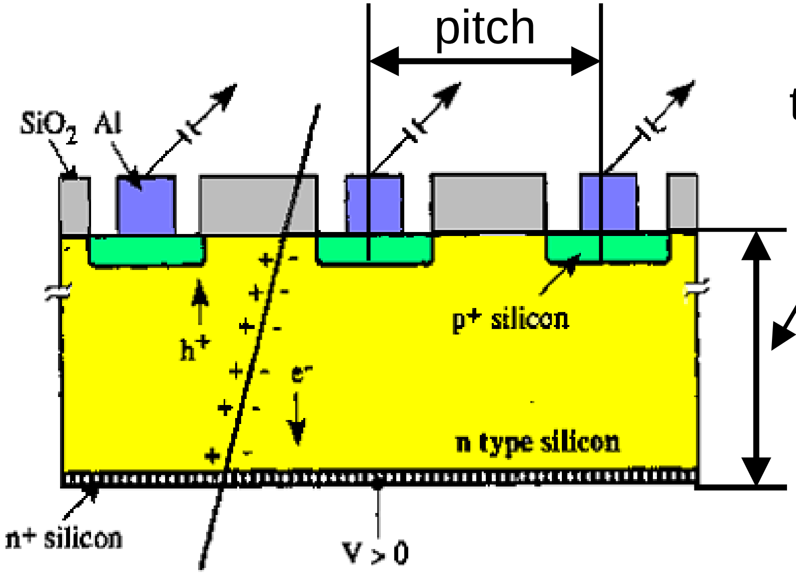
depletion voltage V_{dep} ***detector thickness d***

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

effective space charge density N_{eff}

Single Sided Strip Detector

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



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

- using n-type silicon with a resistivity of

  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)

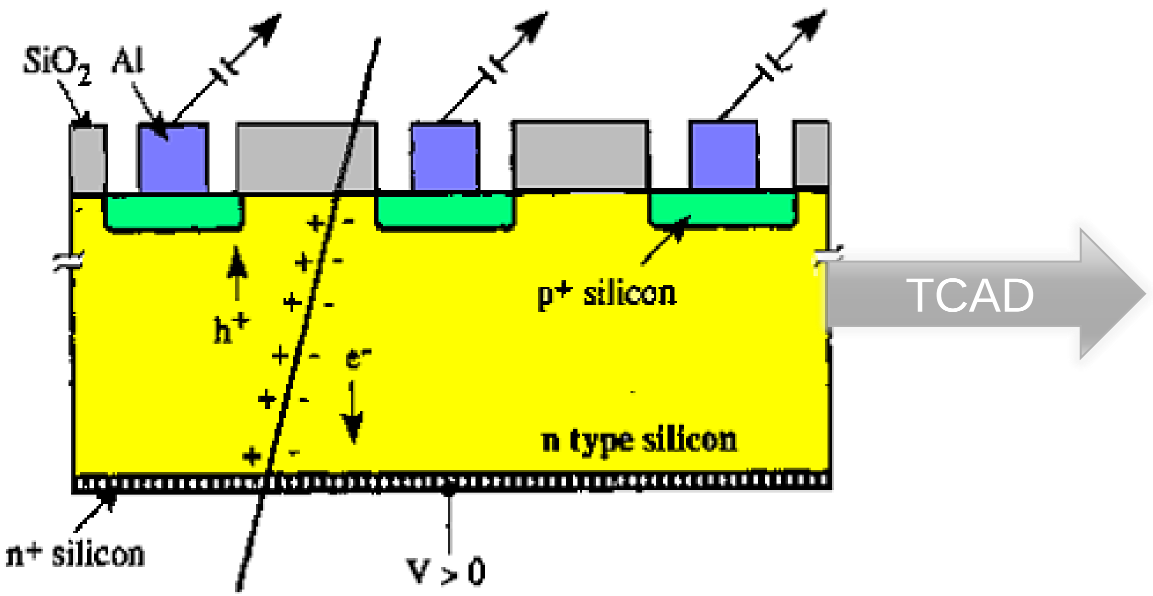
  - e.g. detection of charge in binary way (threshold discrimination) and using center of strip as measured coordinate results in

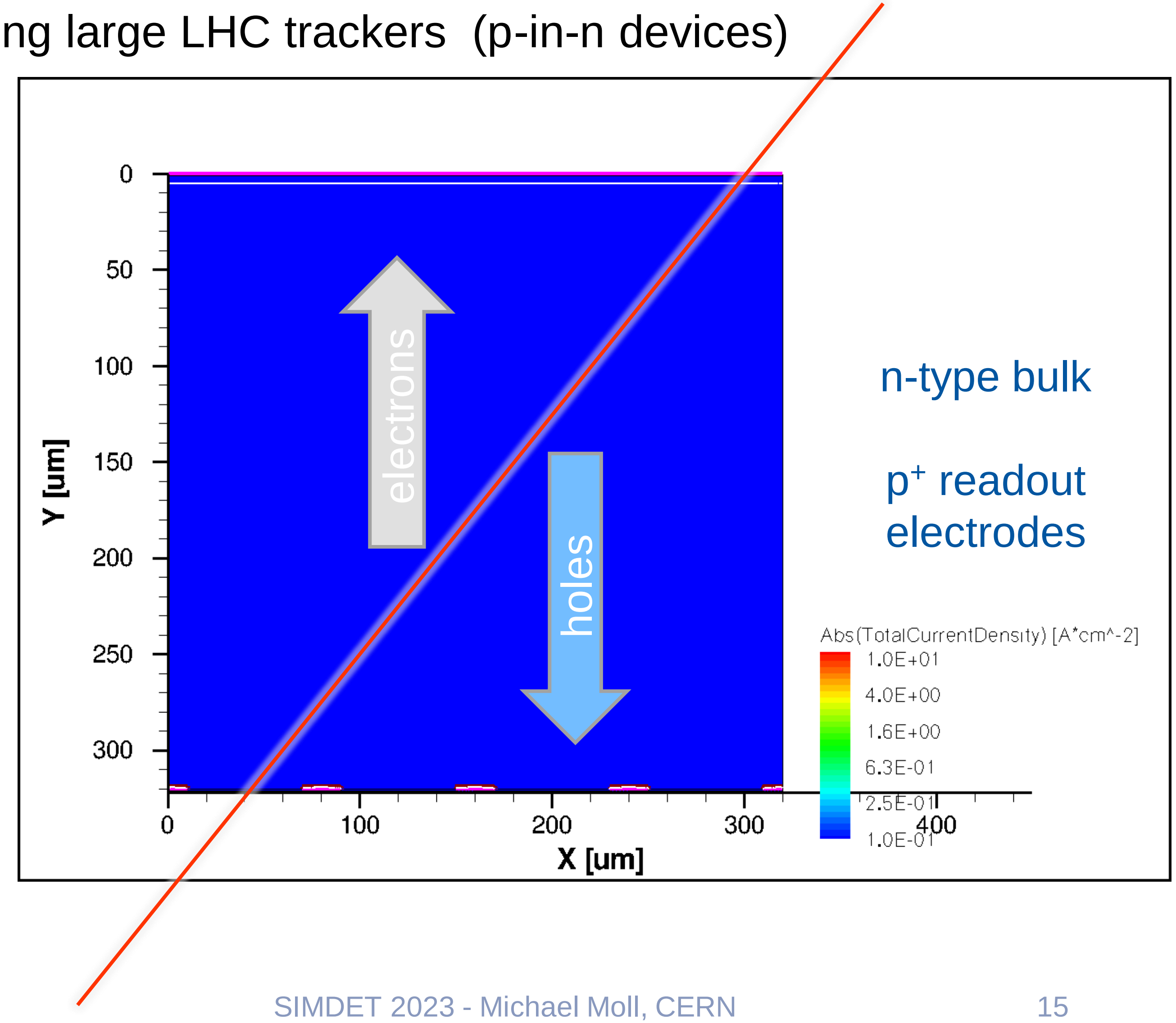
$$\sigma = \frac{p}{\sqrt{12}}$$

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

Signal Formation in a strip sensor

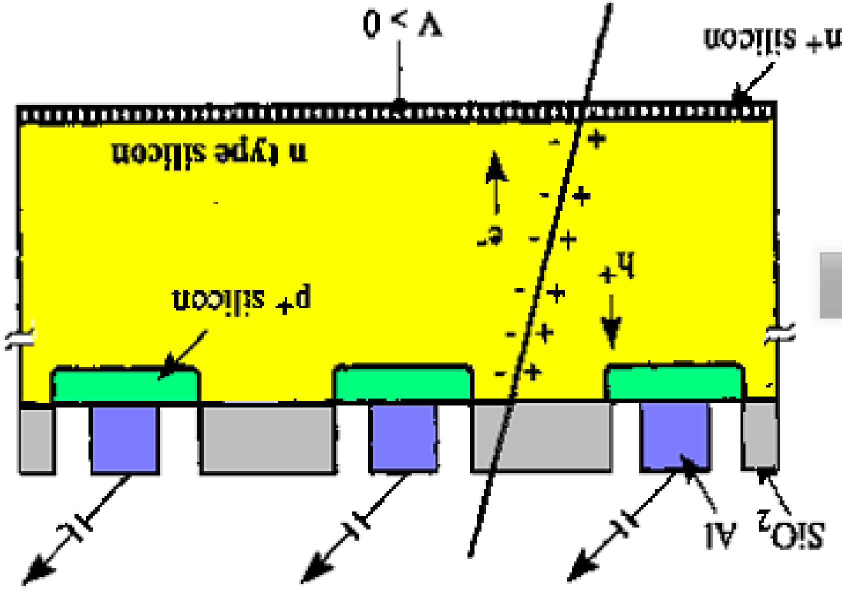
- TCAD simulation: minimum ionizing particle traversing the sensor
  - with typical dimensions for presently operating large LHC trackers (p-in-n devices)

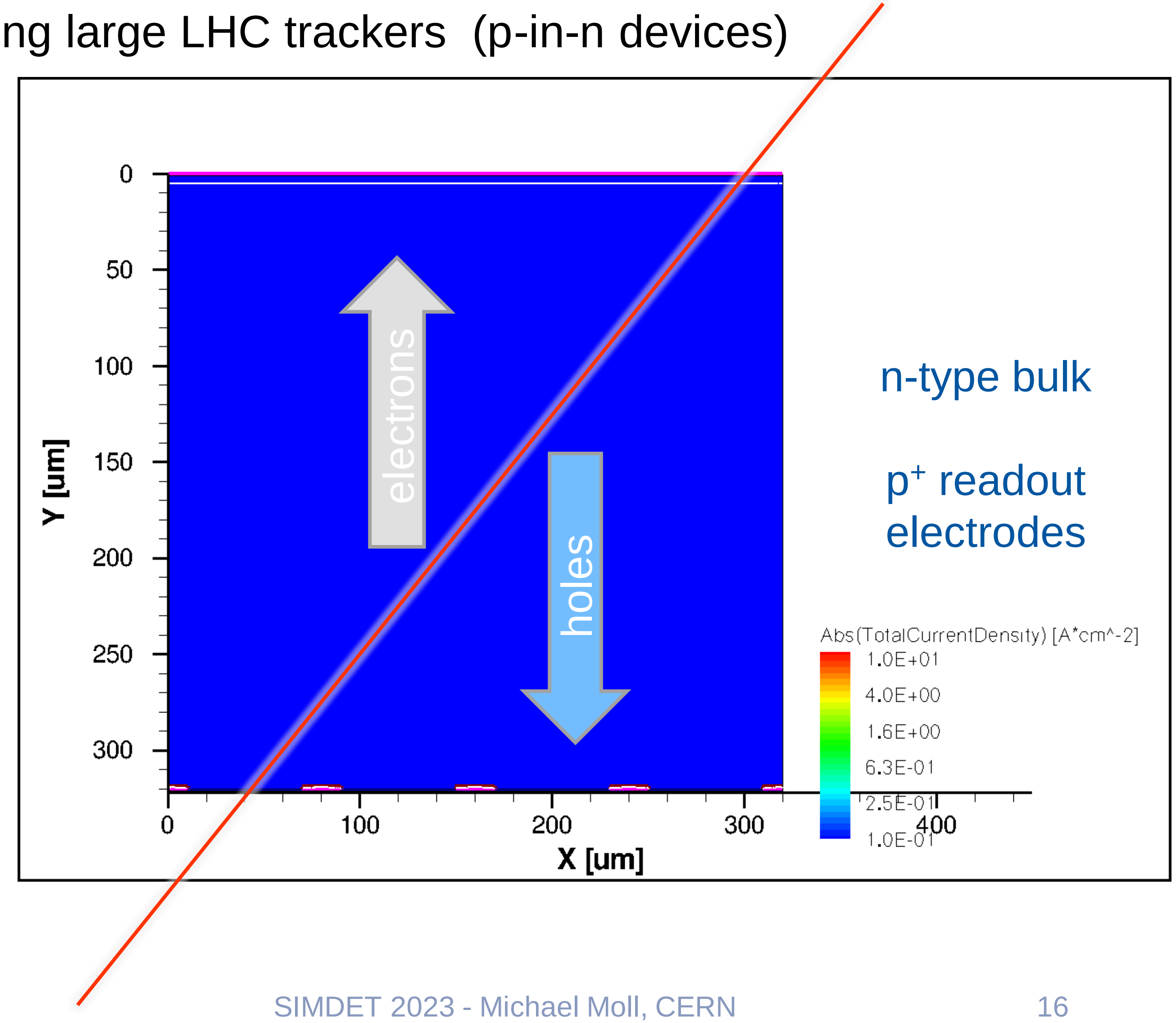




Signal Formation in a strip sensor

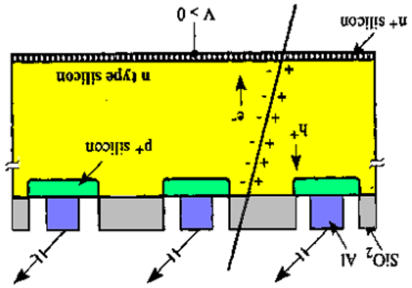
- TCAD simulation: minimum ionizing particle traversing the sensor
  - with typical dimensions for presently operating large LHC trackers (p-in-n devices)

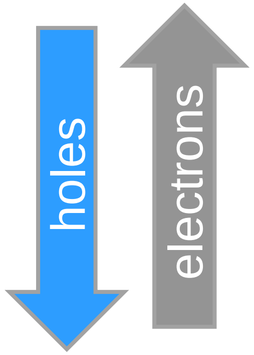




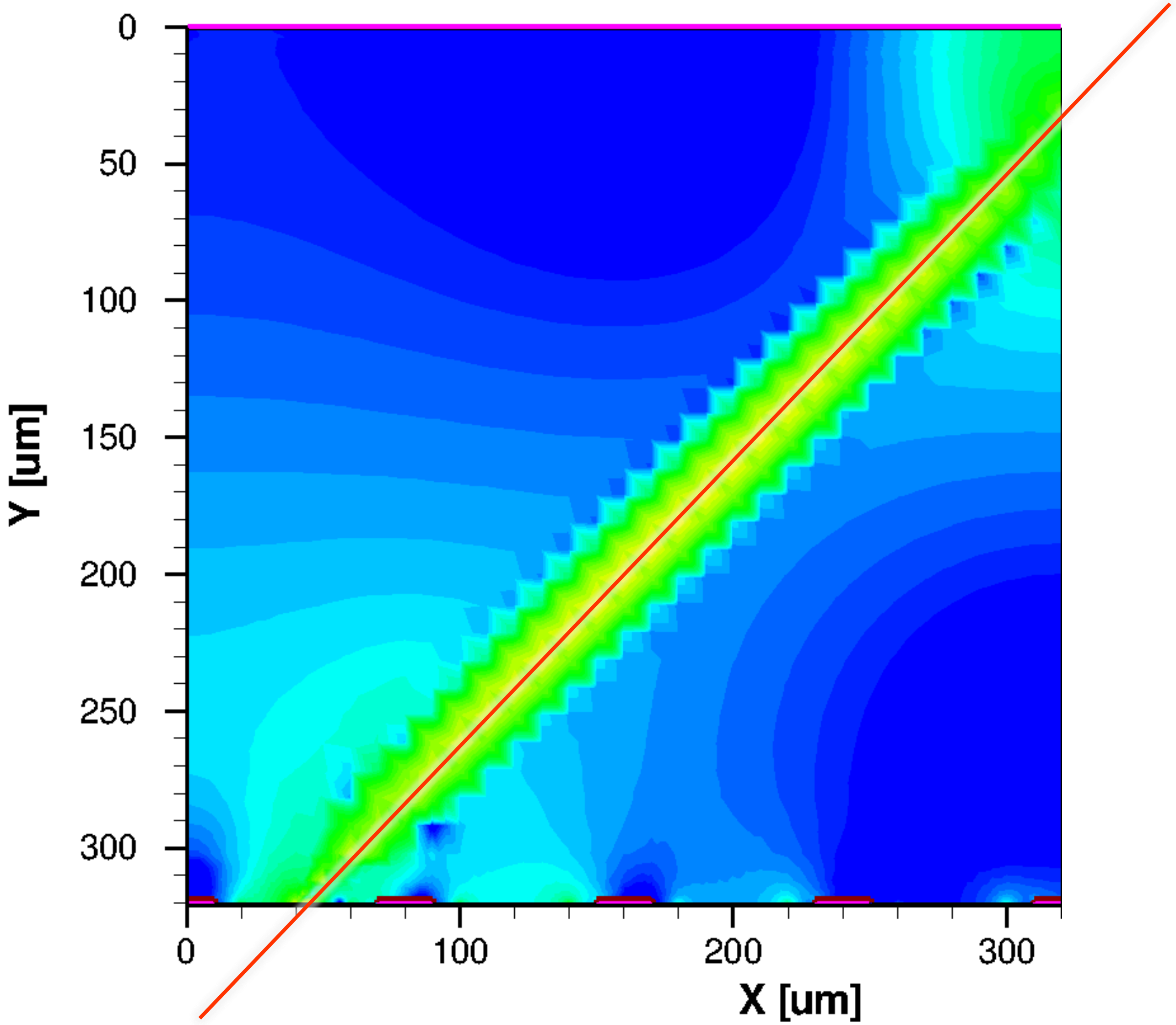
Signal formation in a strip sensor

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





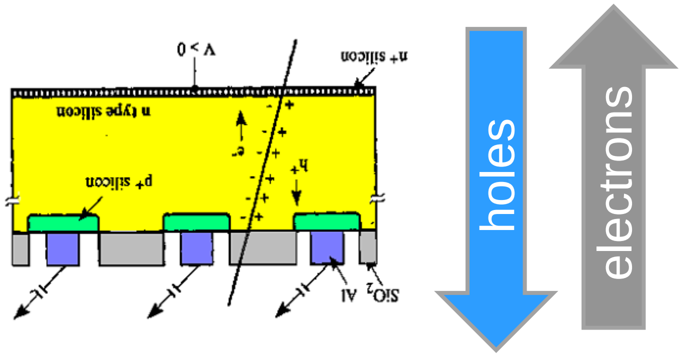
t = 1 ns

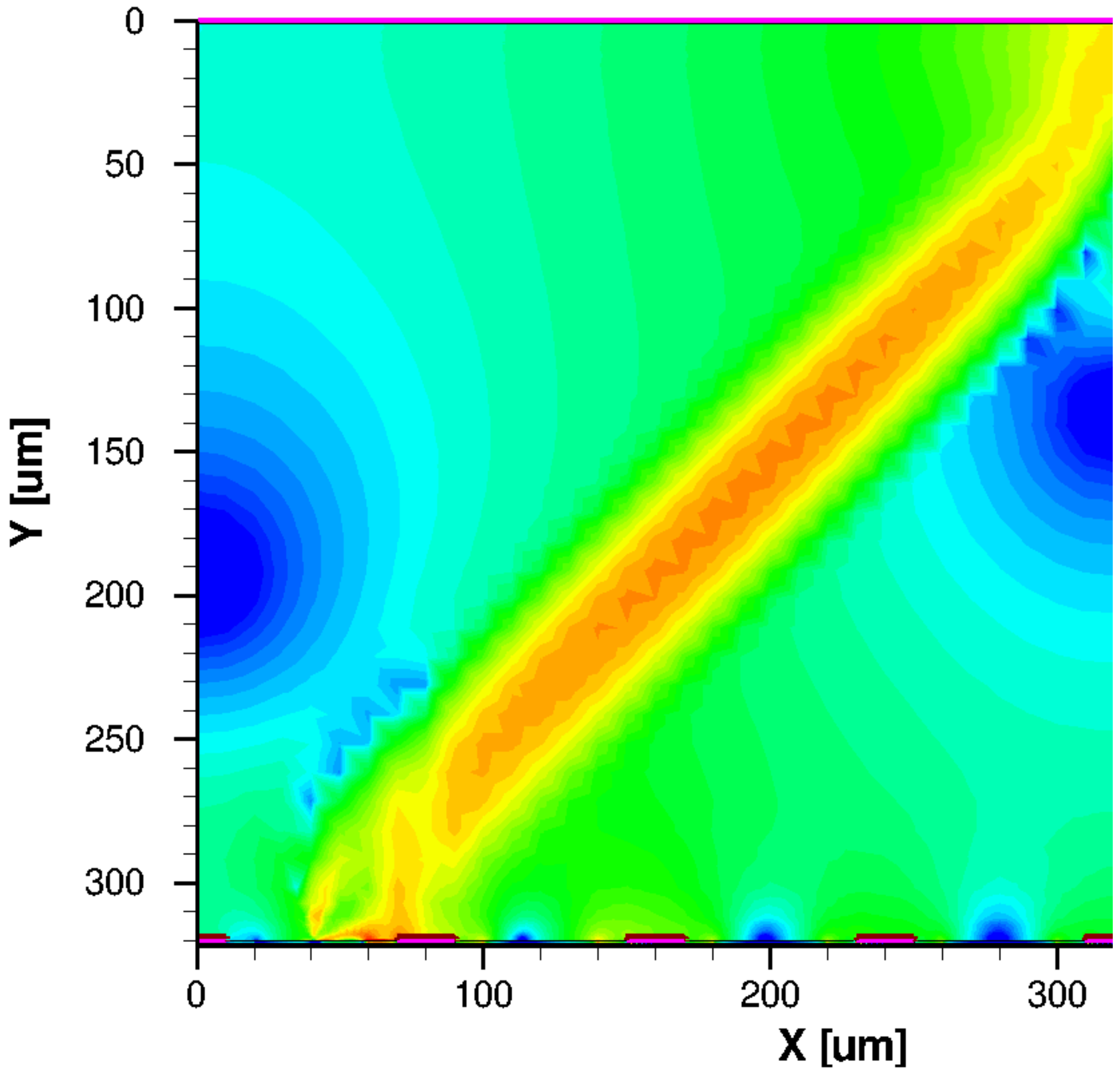


Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



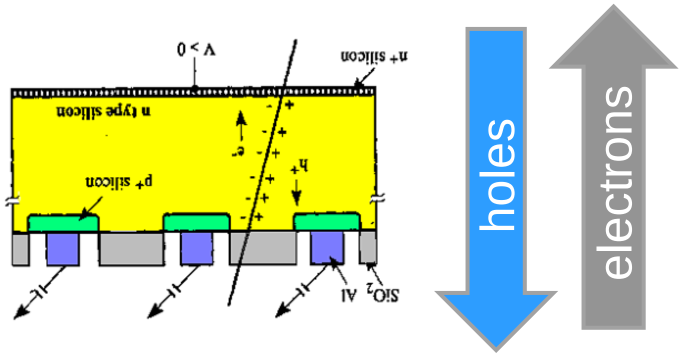


t = 1.2 ns

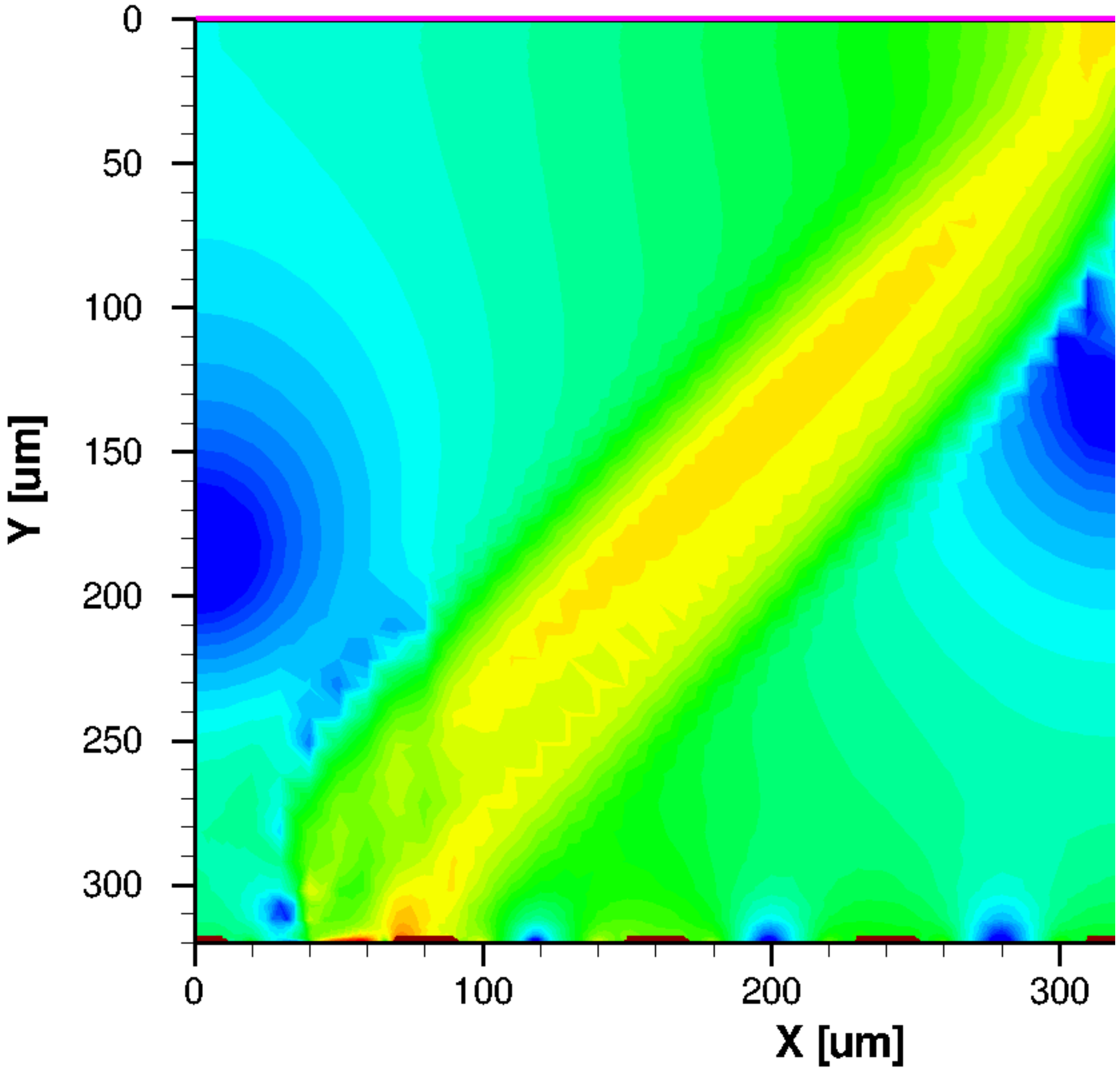
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



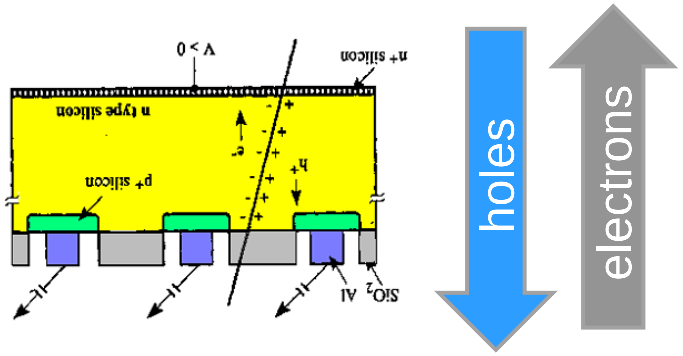
t = 1.4 ns

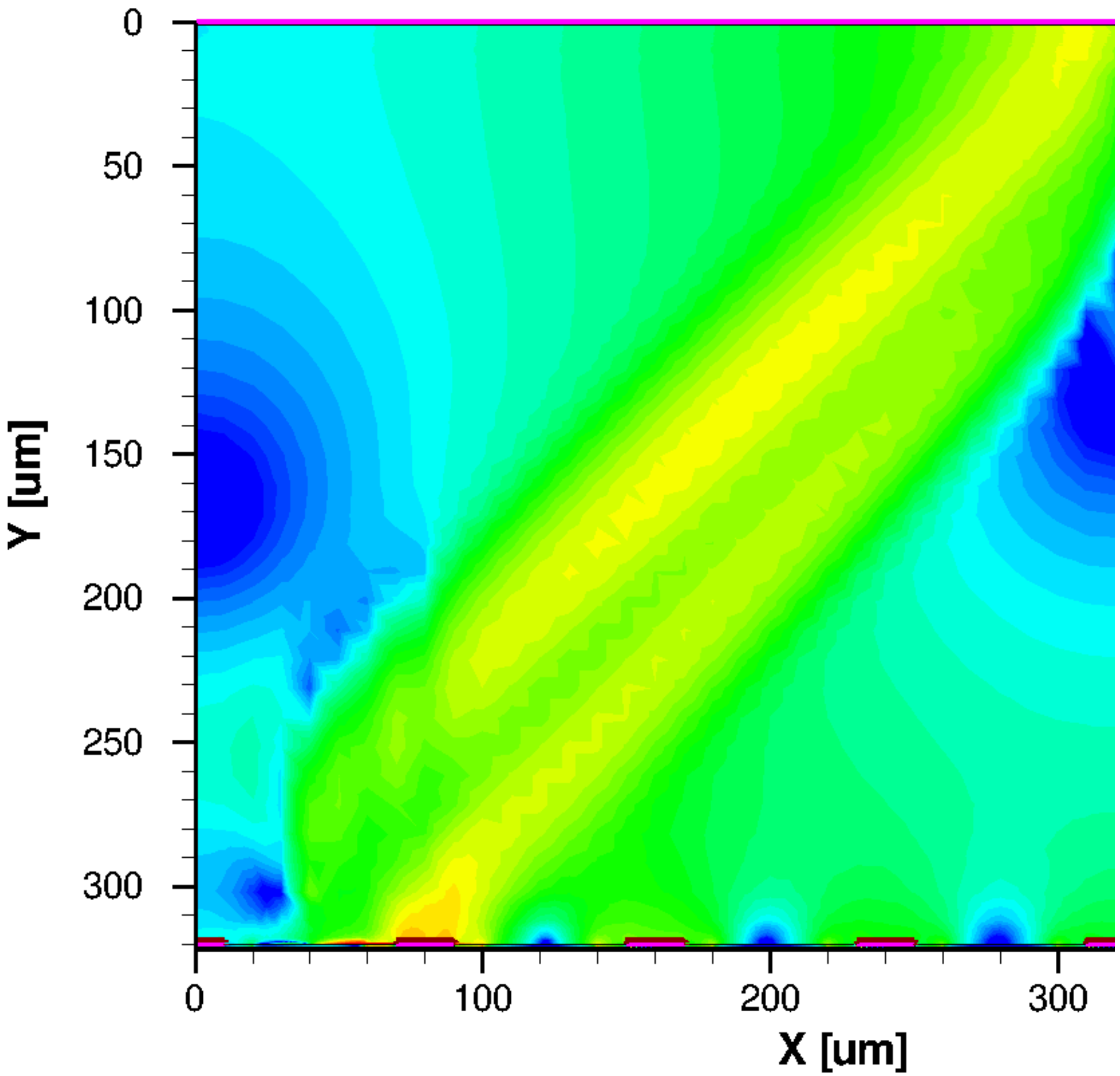


Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



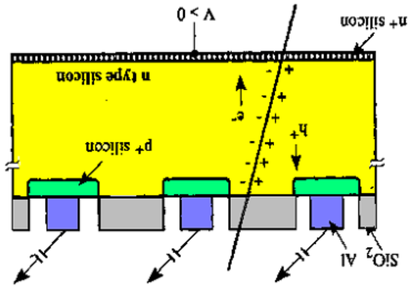


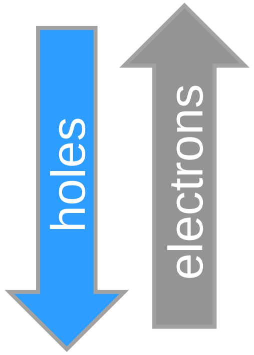
t = 1.6 ns

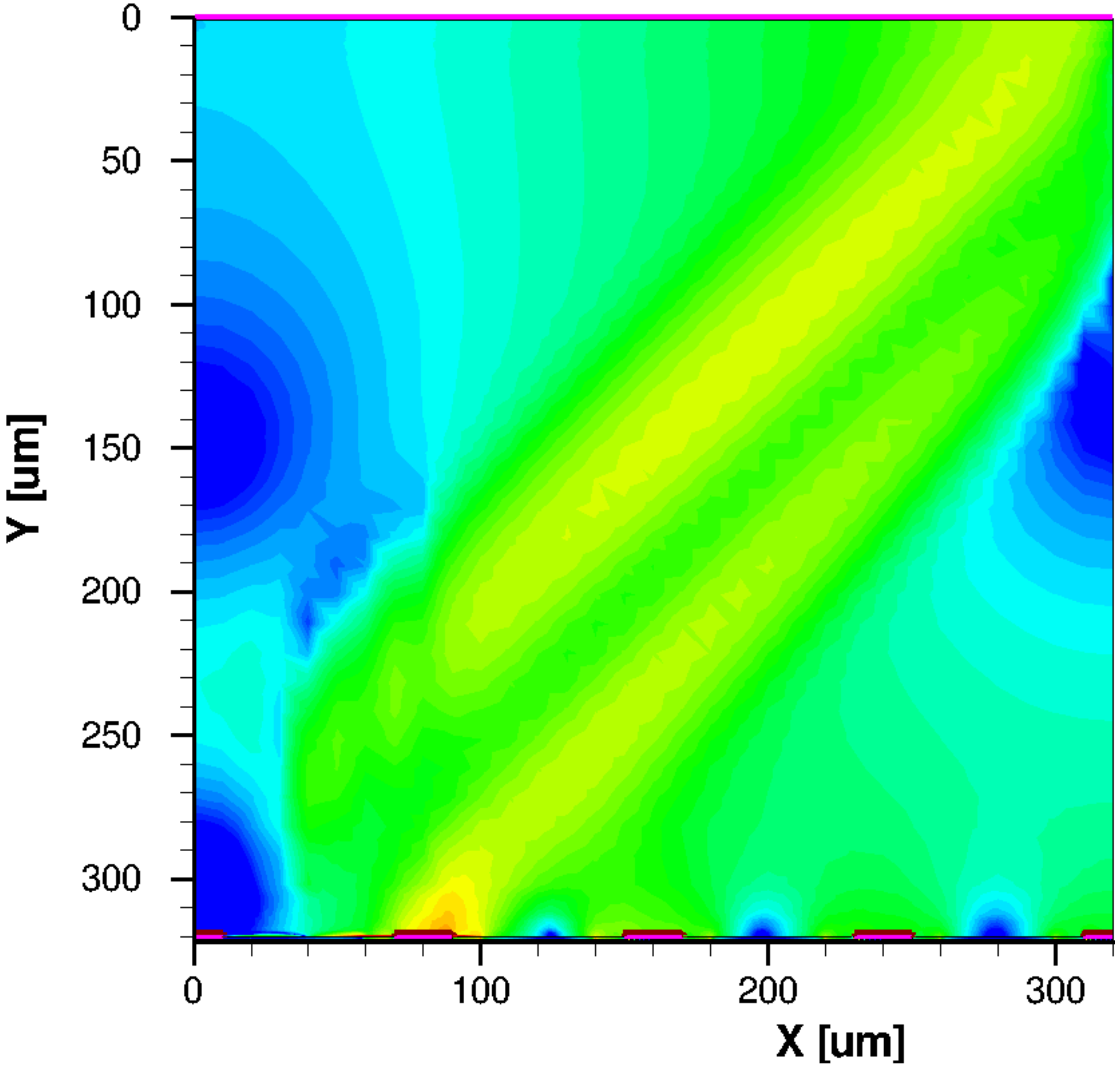
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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





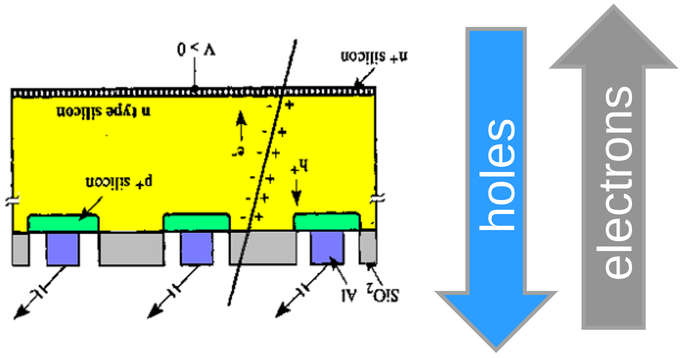


t = 1.8 ns

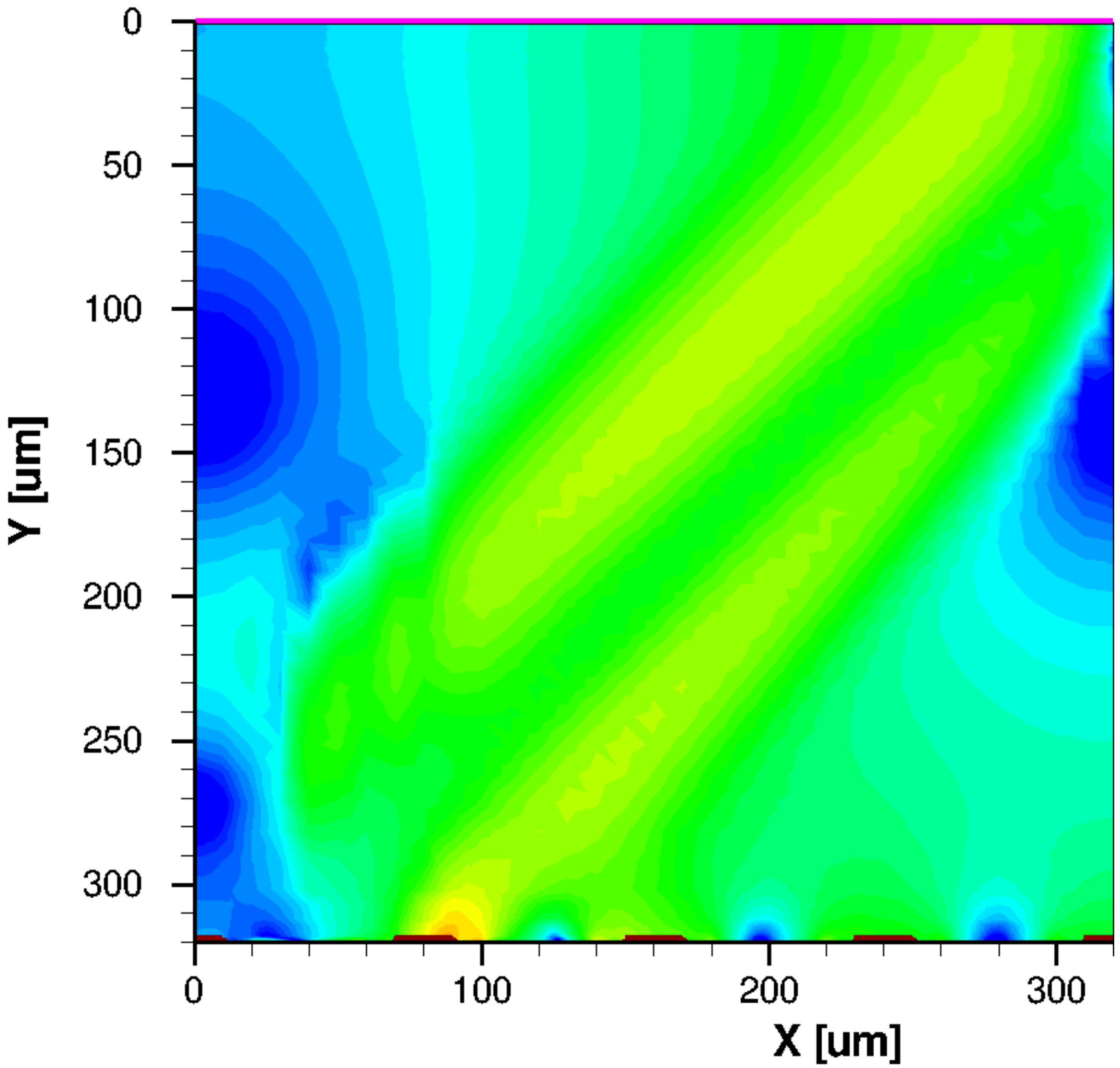
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



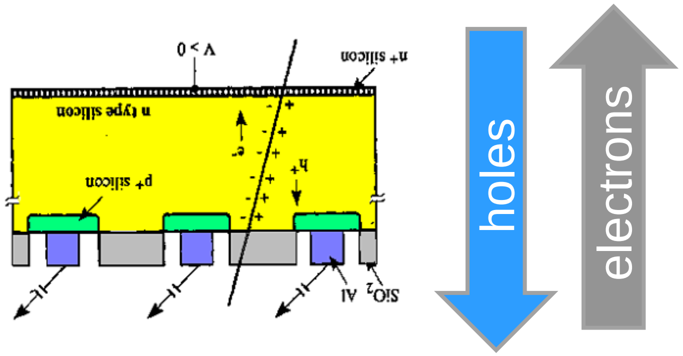
t = 2.0 ns



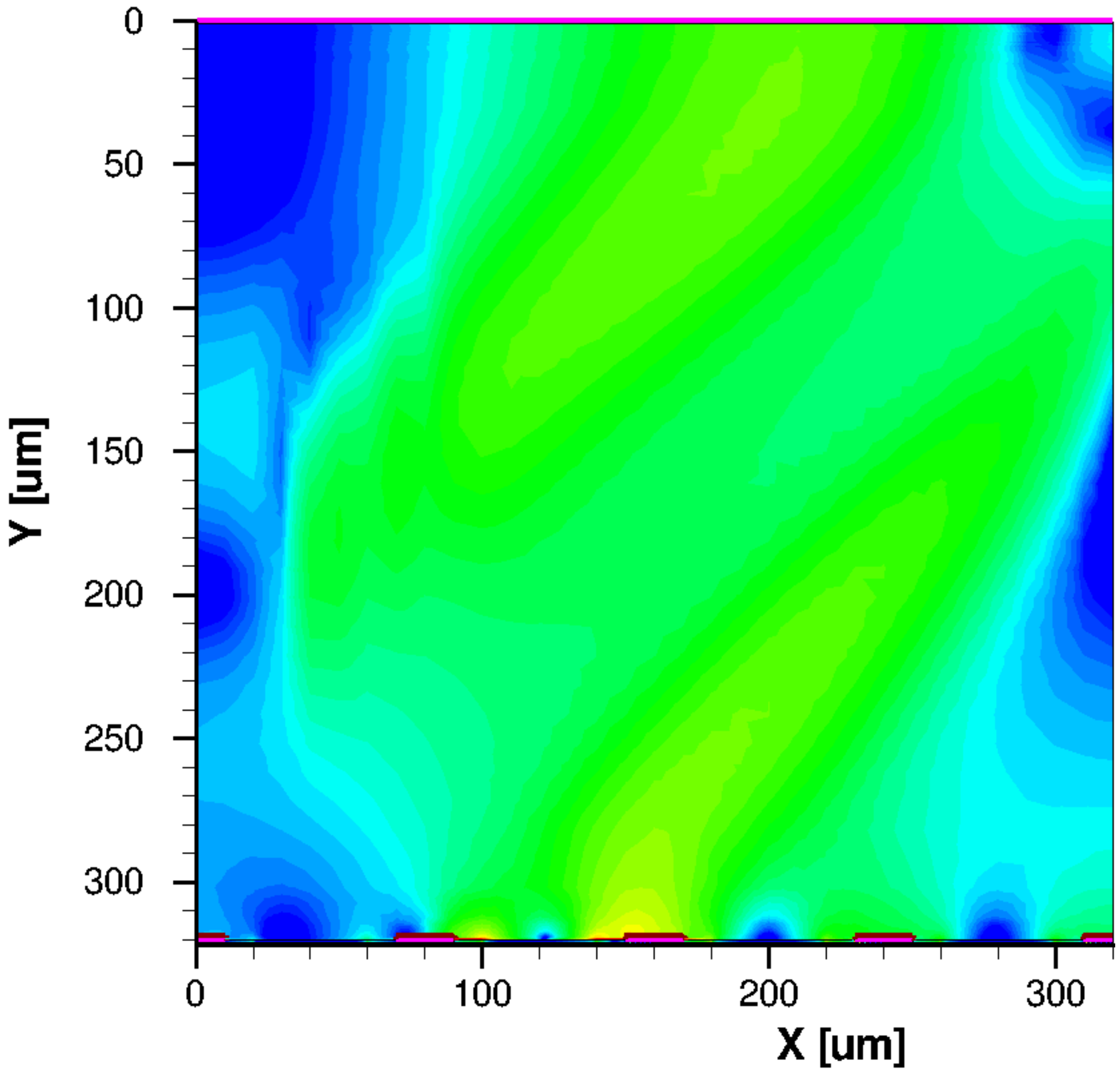
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



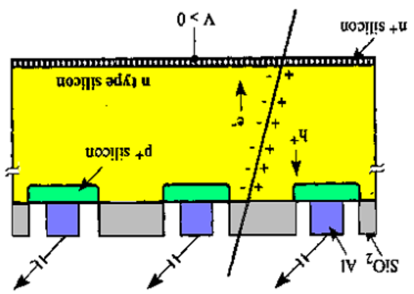
t = 3.0 ns

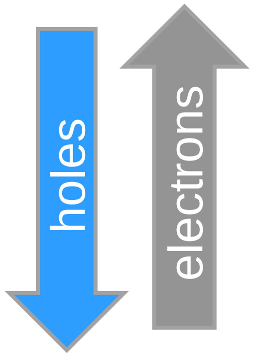


Simulation: Thomas.Eichhorn@kit.edu

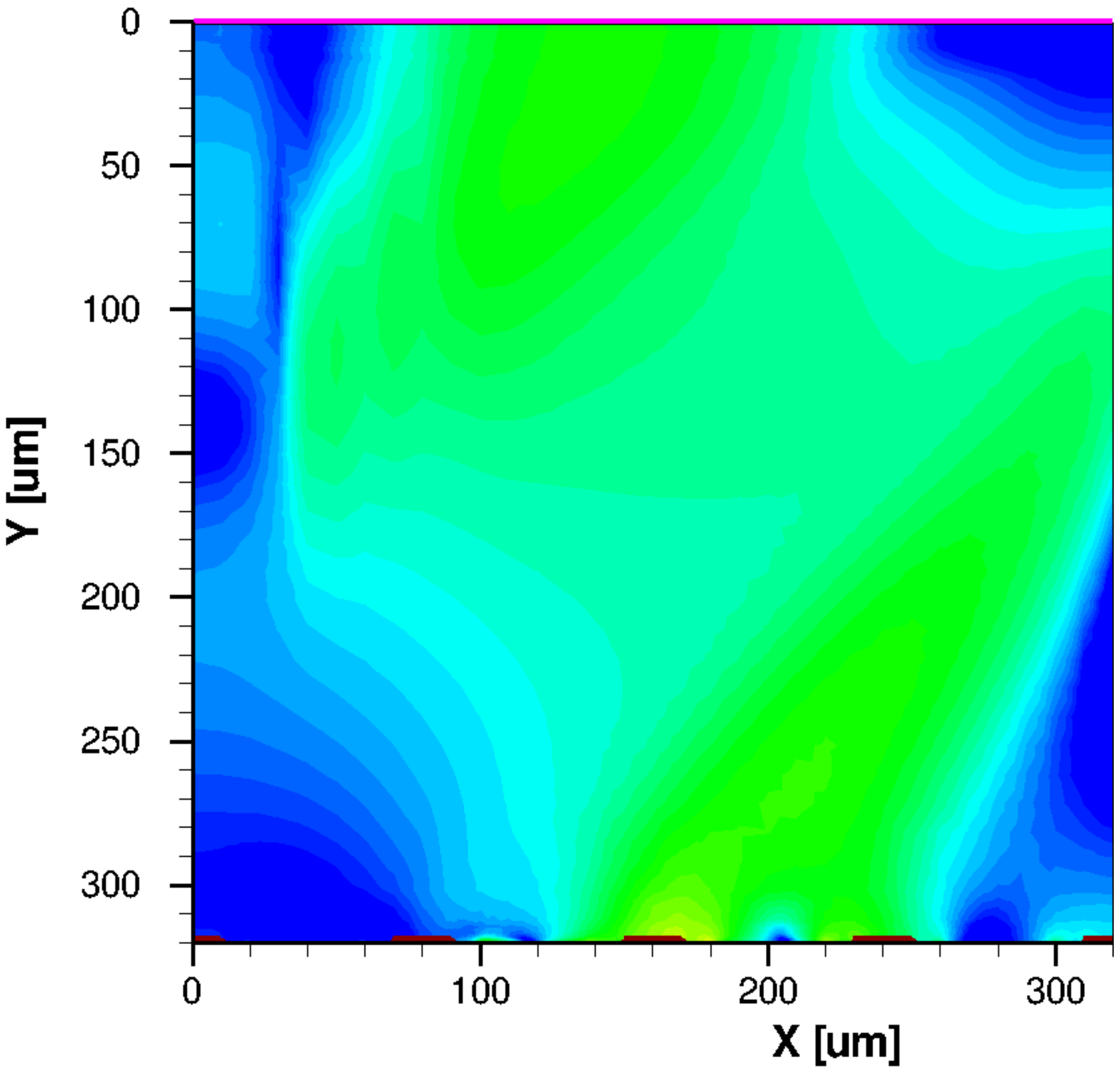
Signal formation in a strip sensor

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





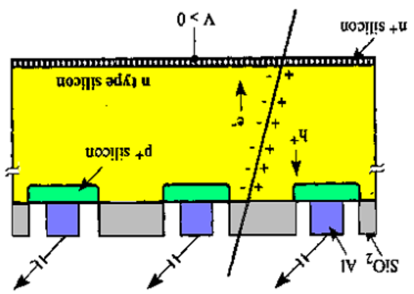
t = 4.0 ns

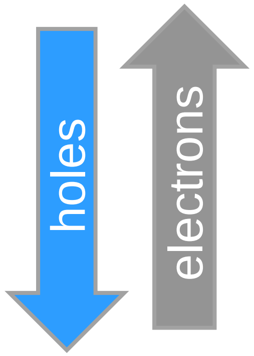


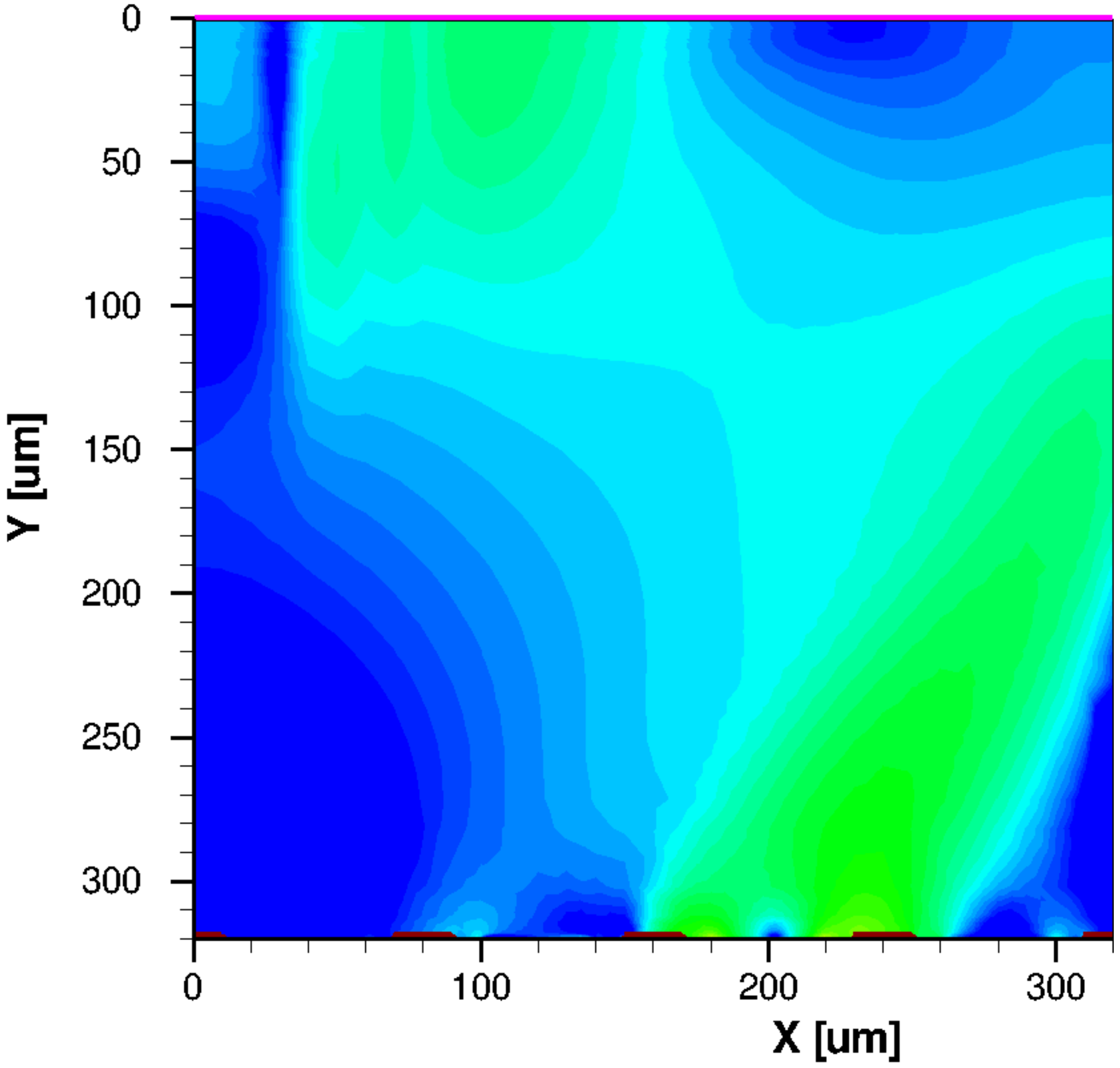
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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





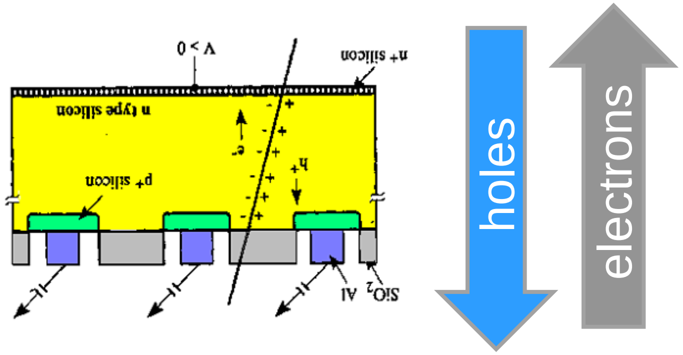


t = 5.0 ns

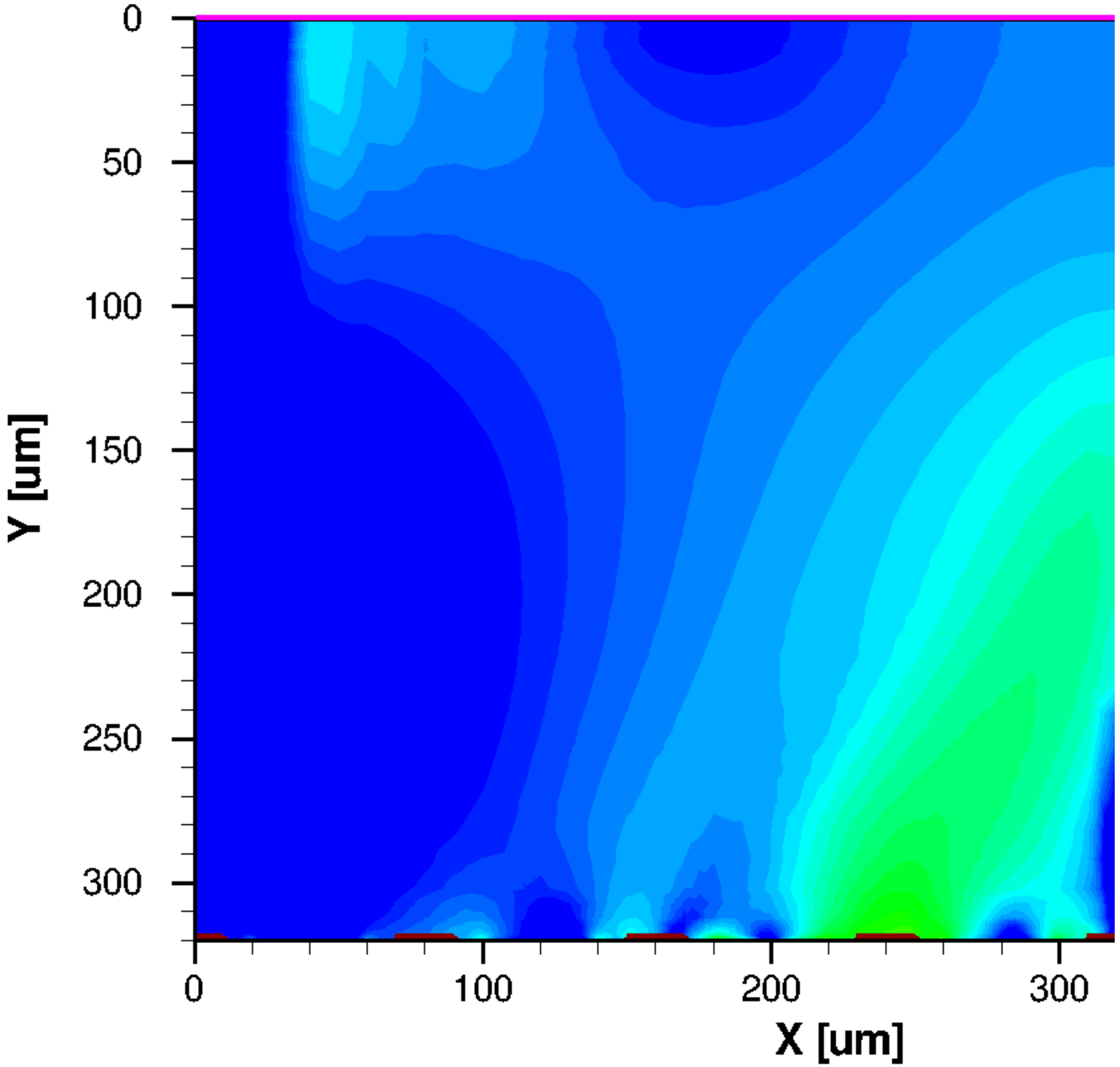
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



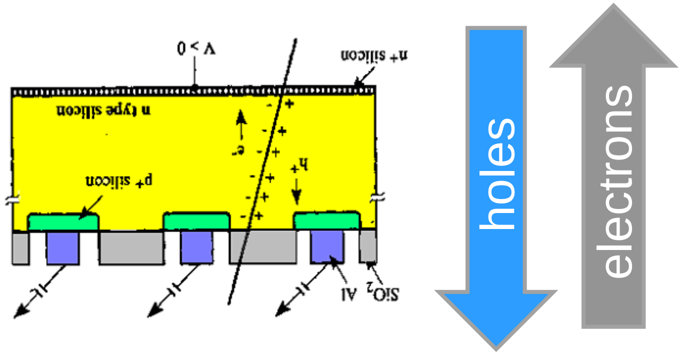
t = 6.0 ns

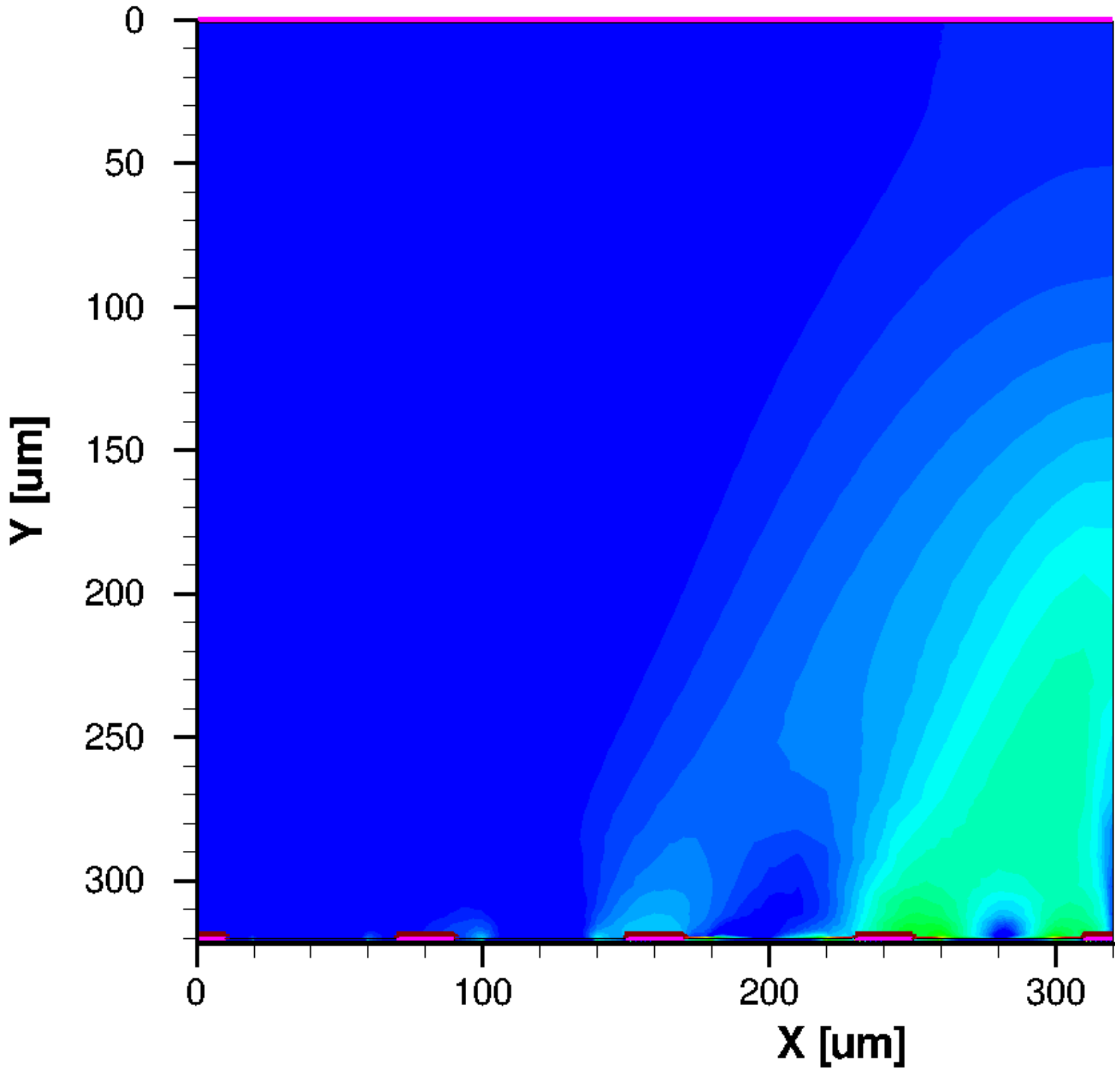


Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



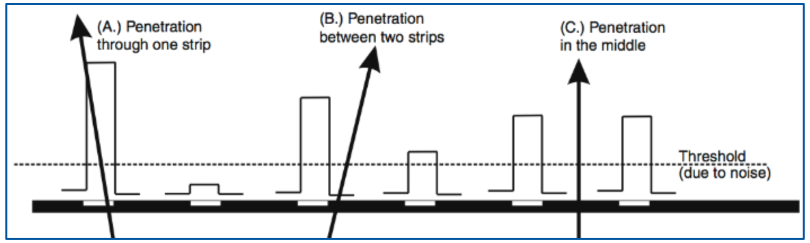


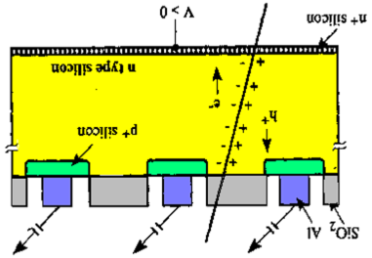
t = 7.0 ns

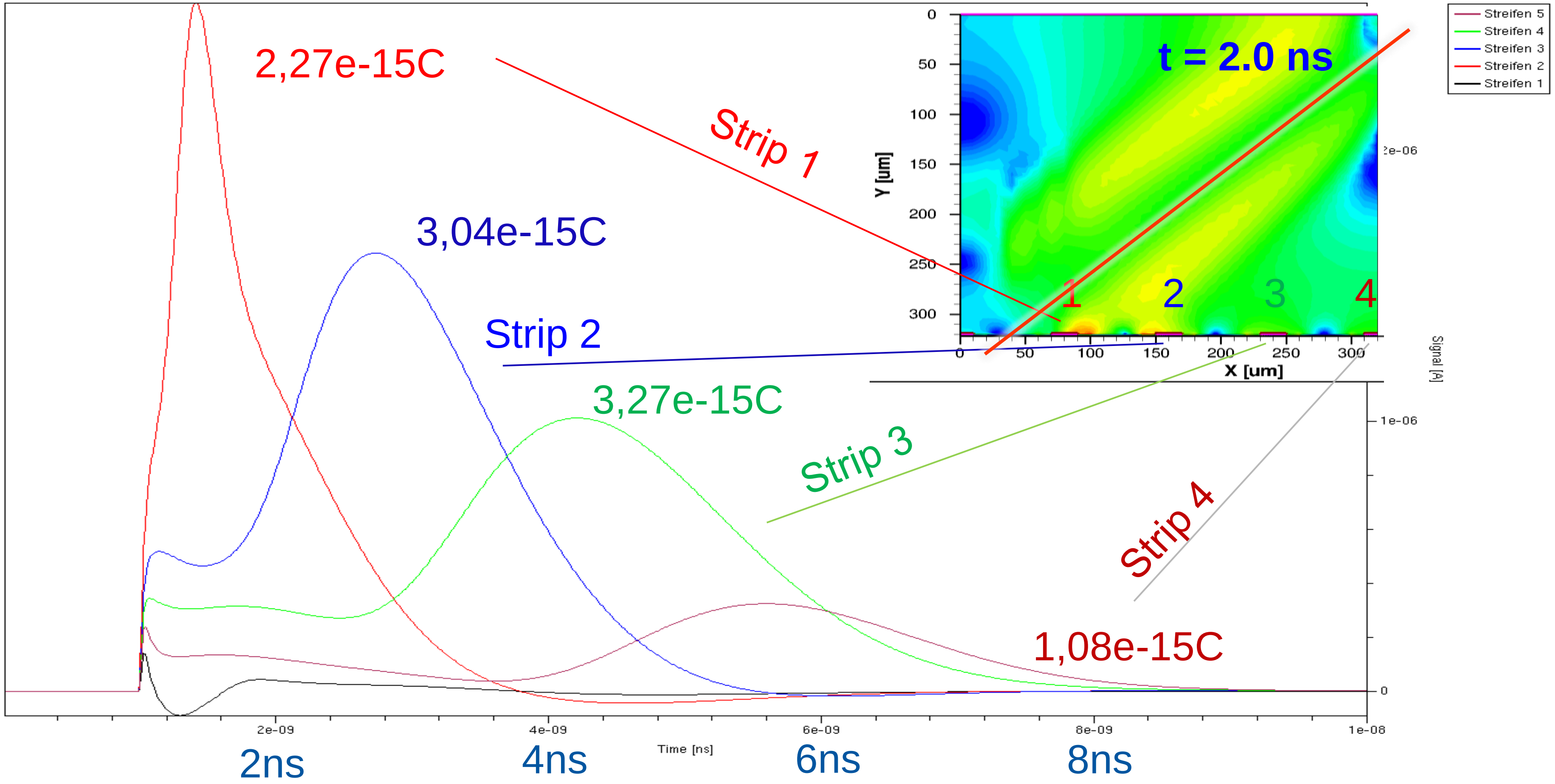
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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

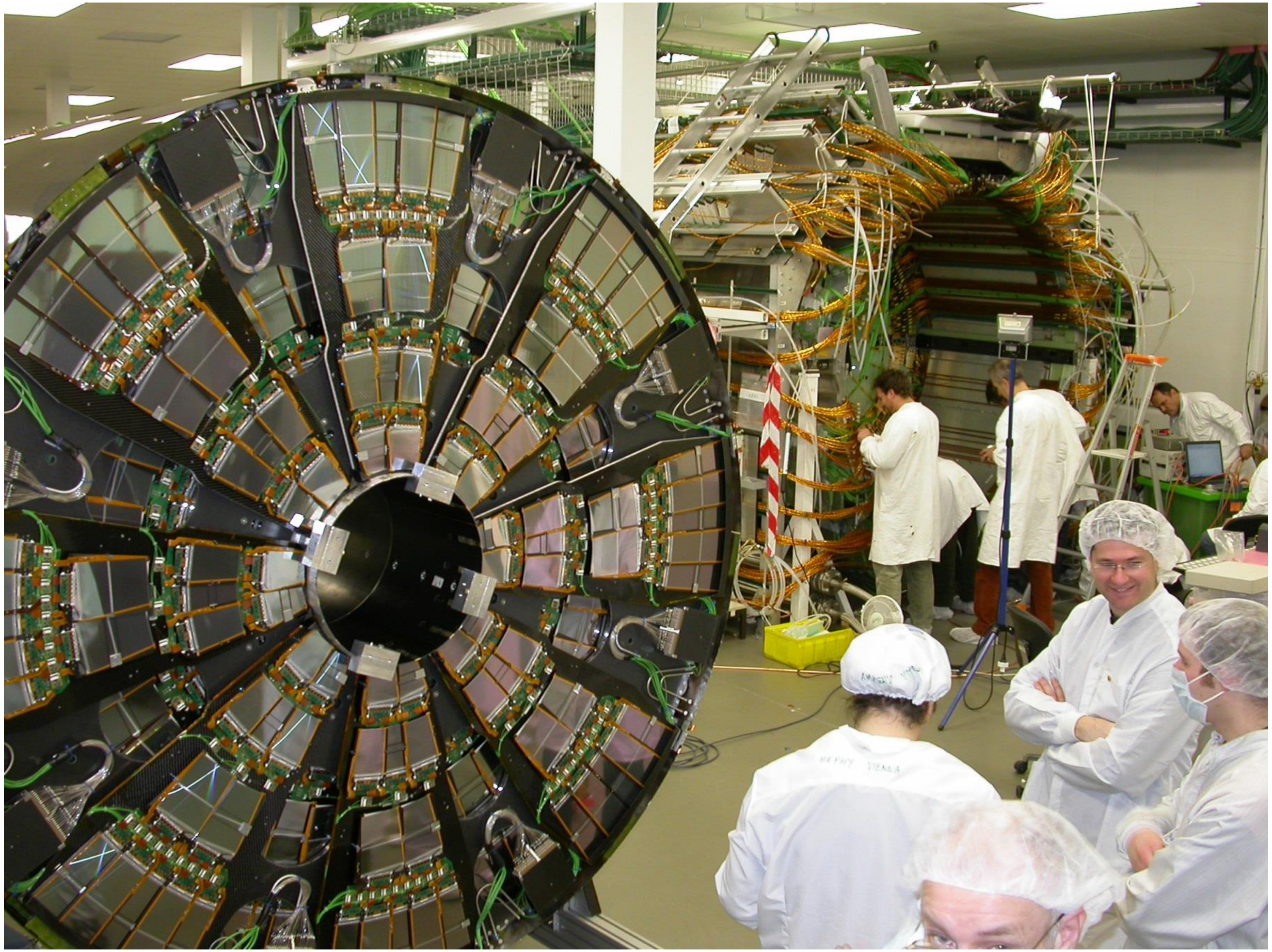






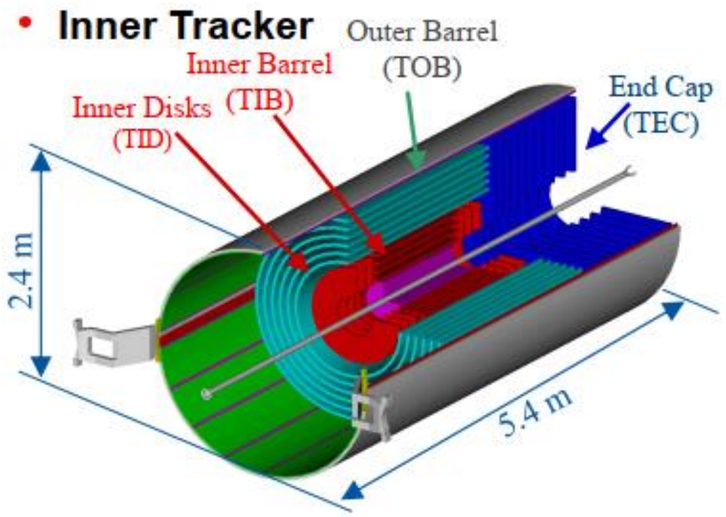
Simulation: Thomas.Eichhorn@kit.edu

Present LHC Tracking Sensors

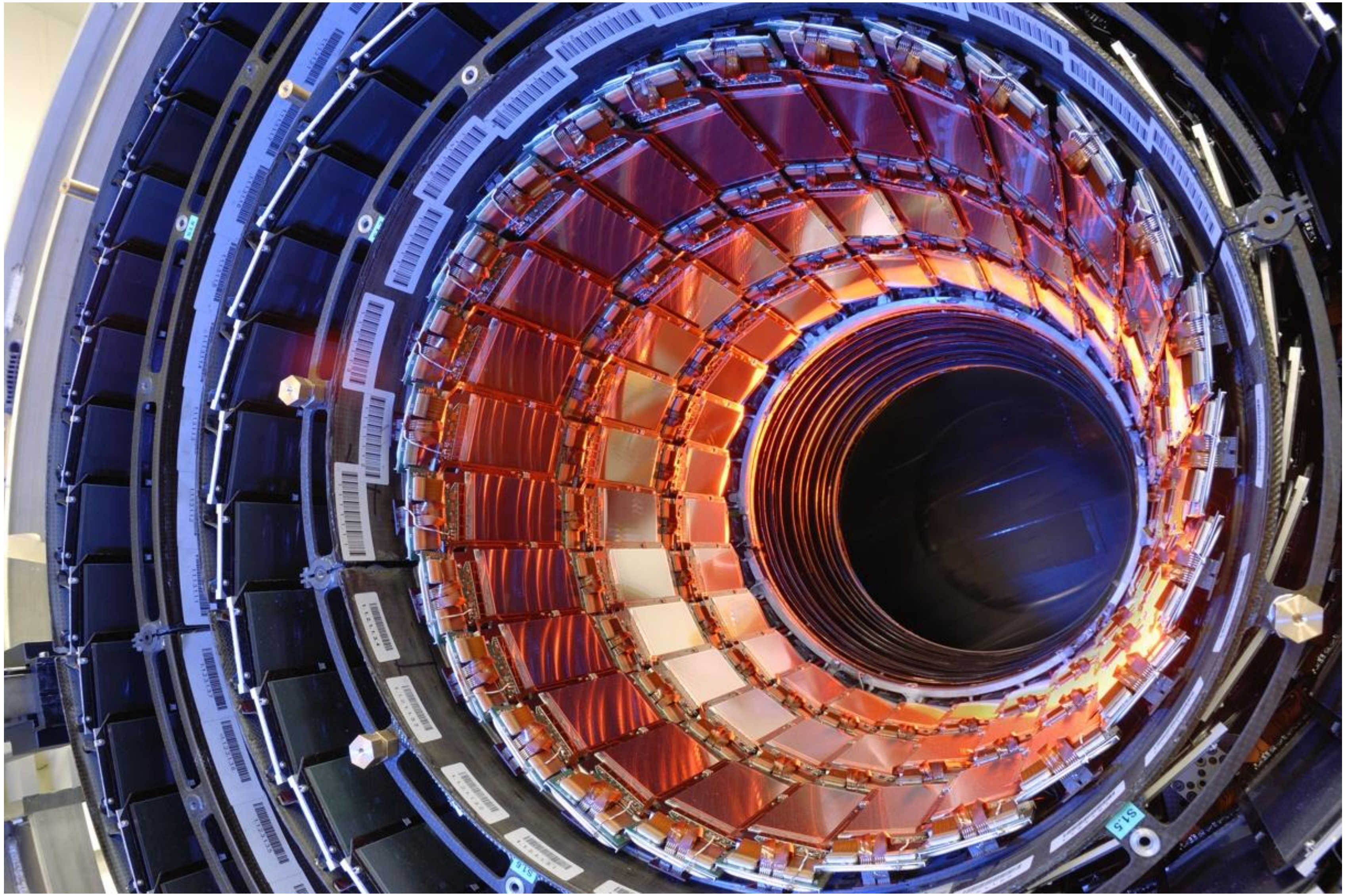


M.Krammer, ICFA School, Bogota, 2013

CMS Tracker



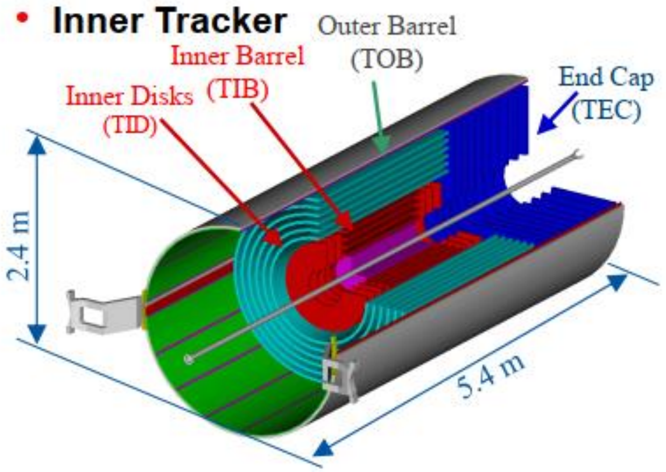
Present LHC Tracking Sensors



M.Krammer, ICFA School, Bogota, 2013

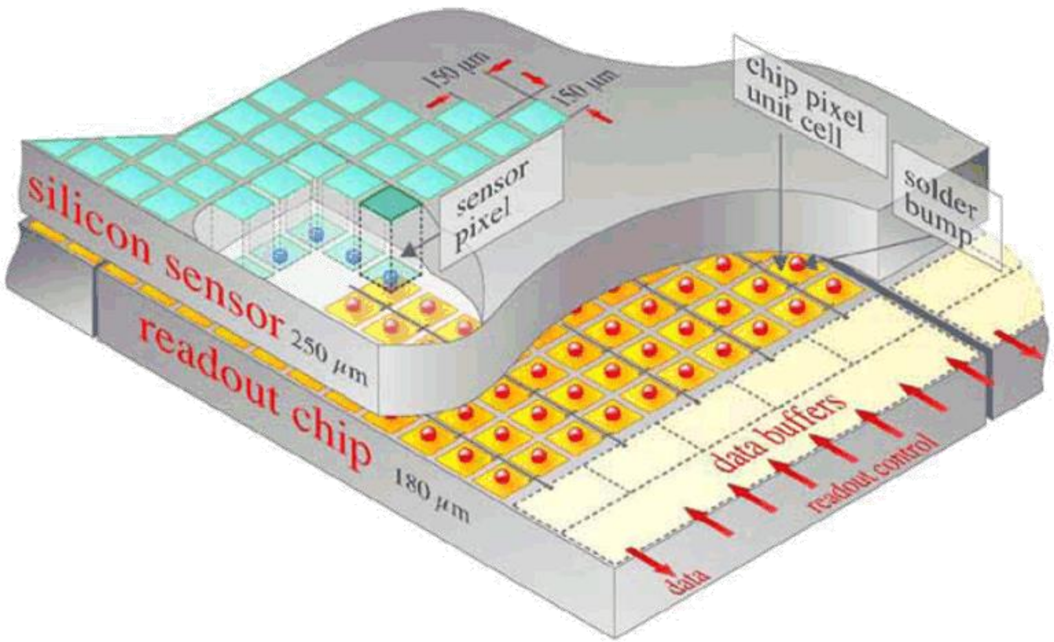
CMS Tracker

… 11.4 million strips

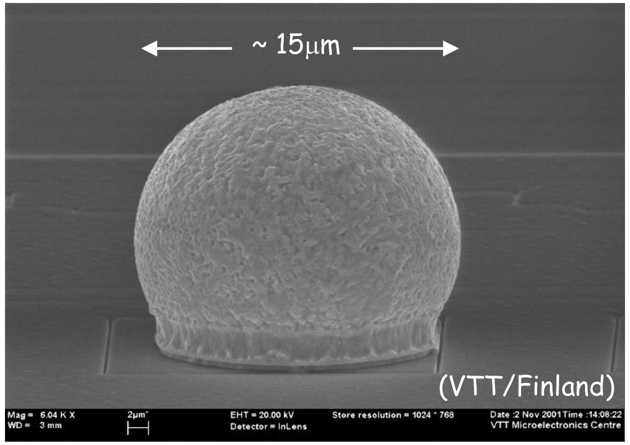


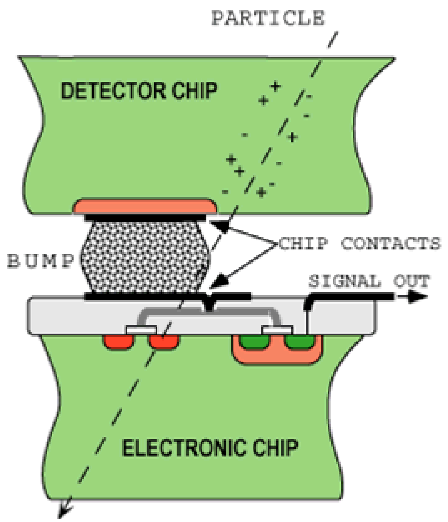
Hybrid Pixel Detectors

- HAPS – Hybrid Active Pixel Sensors
  - **segment silicon to diode matrix with high granularity**
    (⇒ true 2D, no reconstruction ambiguity)
  - **readout electronic with same geometry**
    (every cell connected to its own processing electronics)
  - **connection by “bump bonding”**
  - **requires sophisticated readout architecture**
  - **Hybrid pixel detectors are used in LHC experiments:**
    ATLAS, ALICE *(from Run3 monolithic)*, **CMS and LHCb** (from Run 3)



Solder Bump: Pb-Sn





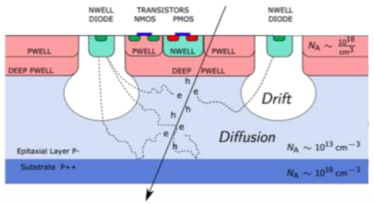
Flip-chip technique

Present LHC Tracking Sensors

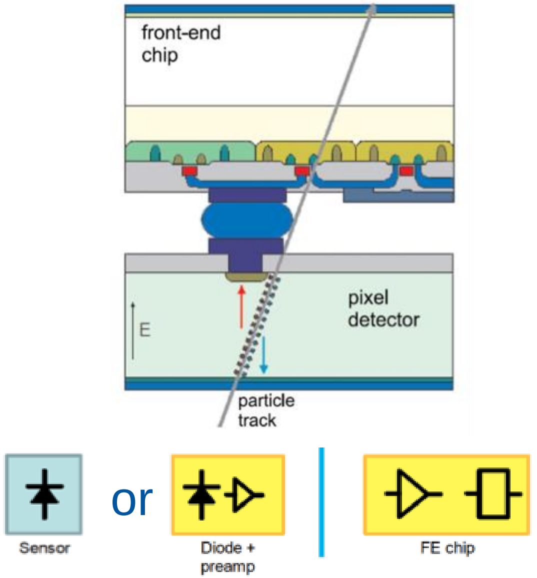
CMS Pixel (Half disk forward pixel)

M.Krammer, ICFA School, Bogota, 2013

Hybrid Pixels - Monolithic Pixels

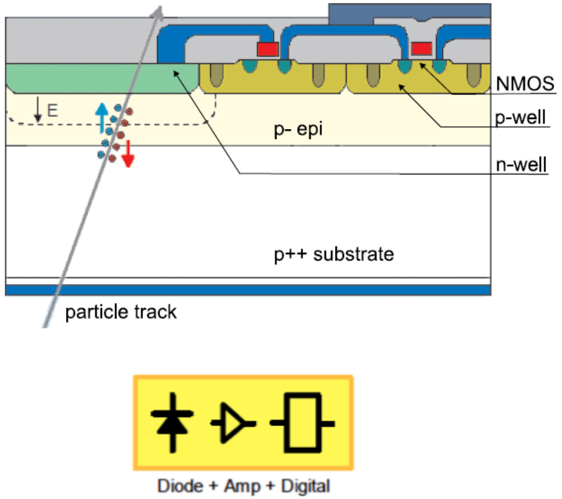


Hybrid Pixel



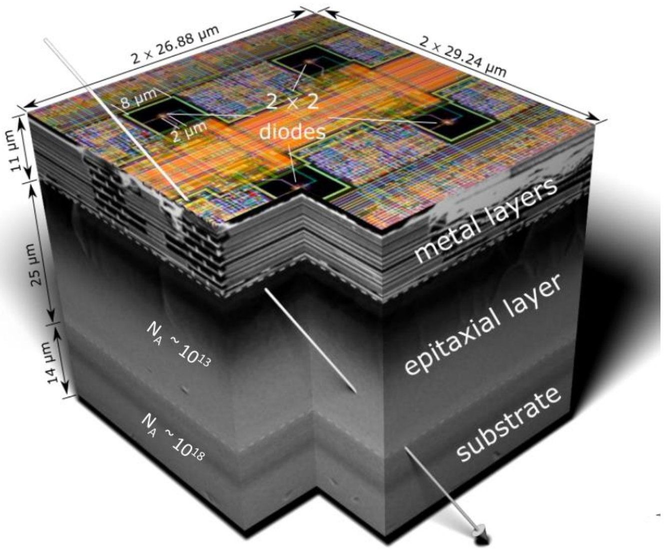
- Separately optimize sensor and FE-chip for very high radiation environment
- Fine pitch bump bonding to connect sensor and readout chip

Monolithic Pixel



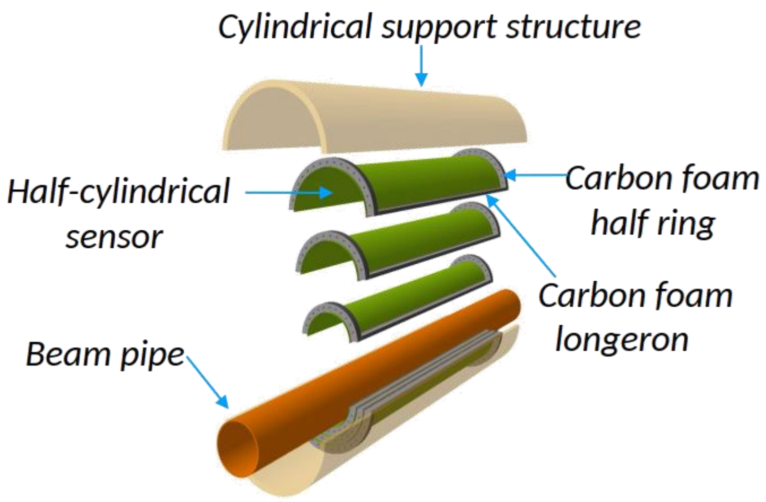
- Charge generation volume integrated into the ASIC, but many different variants!
- Thin monolithic CMOS sensor, on-chip digital readout architecture

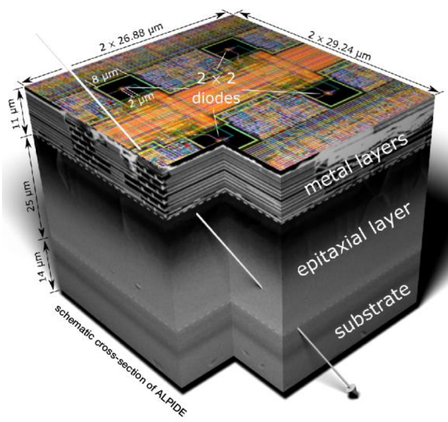
- Example: ALICE – Alpide Chip
  - **TowerJazz 0.18µm CMOS imaging process**
- N-well collection electrode in high resistivity epitaxial layer
- State-of-art: based on **quadruple well allows full CMOS**
- **High resistivity (> 1kΩ cm) epi-layer** (p-type, 20-40 µm thick) on p-substrate
- **Moderate reverse bias => increase depletion region** around N-well collection diode to collect more charges by drift

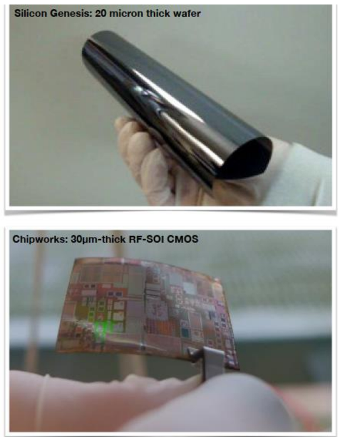


The future: Going full wafer monolithic!

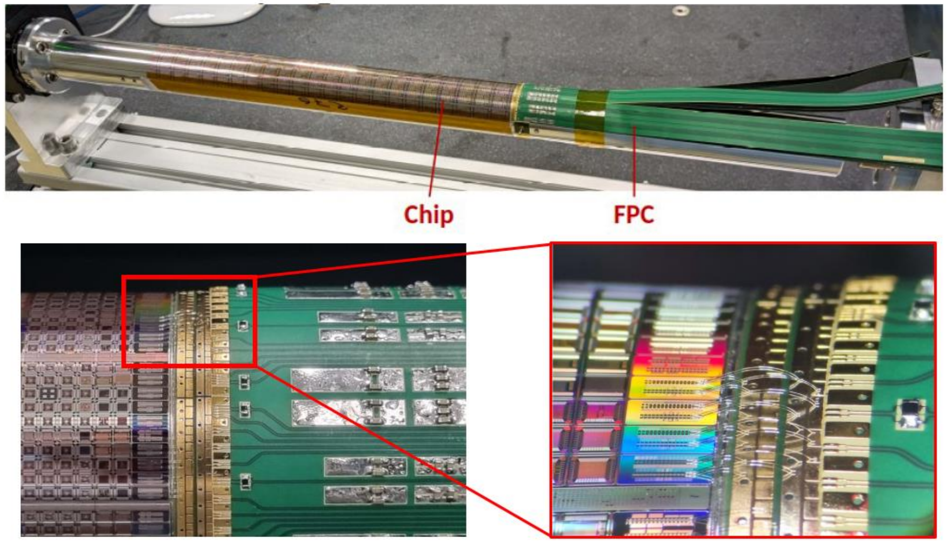
- ALICE ITS3 project (targeting installation in LS3 2026-2028)
  - Use of 300mm wafer-scale MAPS chips in 65 nm CMOS !
    - thinned down to ≤ 50 um making them flexible
    - sensor length 266 mm x width 55 / 74 / 93 mm
    - spatial resolution requirement 5 μm
  - ITS3 detector comprised of 6 chips only!
  - Mechanically held in place by carbon foam spacers







full scale chip
(50 μm thick)
bent to
19 mm radius



[Filip Krizek, VERTEX 2023]

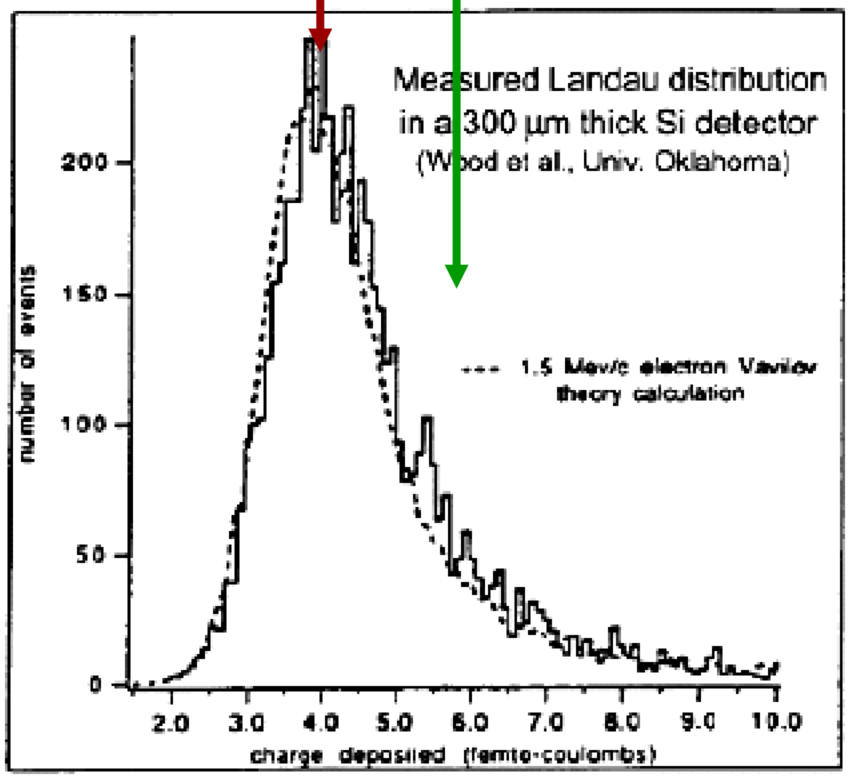
The Charge Signal

- Collected charge for a Minimum Ionizing Particle (MIP)
  - **Mean energy loss**
    dE/dx (Si) = 3.88 MeV/cm
    $\Rightarrow$ 116 keV for 300μm thickness
  - **Most probable energy loss**
    $\approx$ 0.7 $\times$mean
    $\Rightarrow$ 81 keV
  - **3.6 eV to create an e-h pair**
    $\Rightarrow$ 108 e-h / μm (mean)
    $\Rightarrow$ 72 e-h / μm (most probable)
  - Most probable charge (300 μm)

    $\approx$ 22500 e $\approx$ 3.6 fC

Most probable charge ≈ 0.7× mean

Mean charge



number of events

charge deposited [fC]

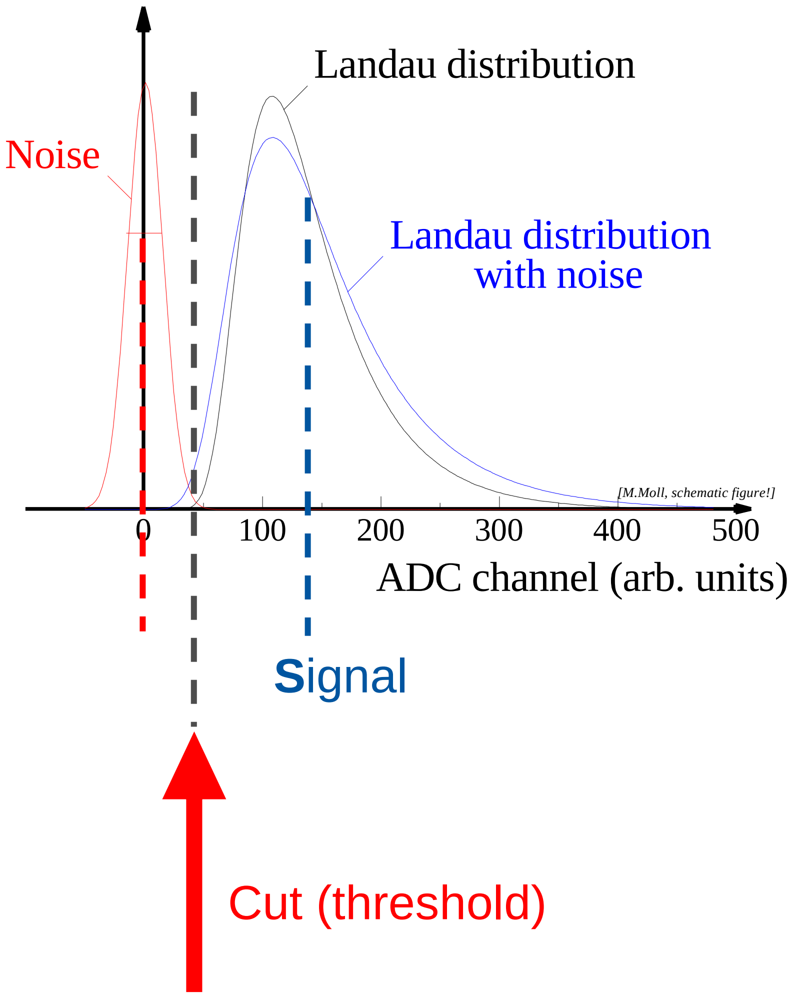
The Charge Signal

SIMDET 2023
5th school on silicon detectors simulation

- Collected Charge for a Minimum Ionizing Particle (MIP)
- Landau distribution has a low energy tail
  - becomes even lower by noise broadening

Noise sources: (ENC = Equivalent Noise Charge)

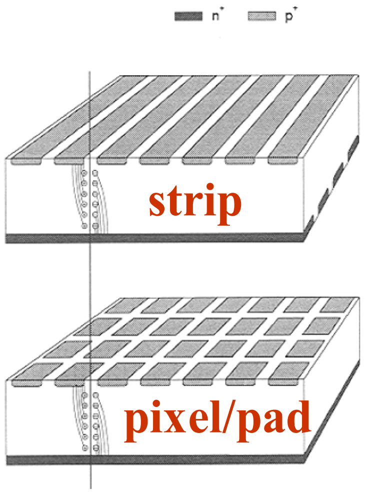
- Capacitance $ENC \propto C_d$
- Leakage Current $ENC \propto \sqrt{I}$
- Thermal Noise (bias resistor) $ENC \propto \sqrt{k_B T / R}$



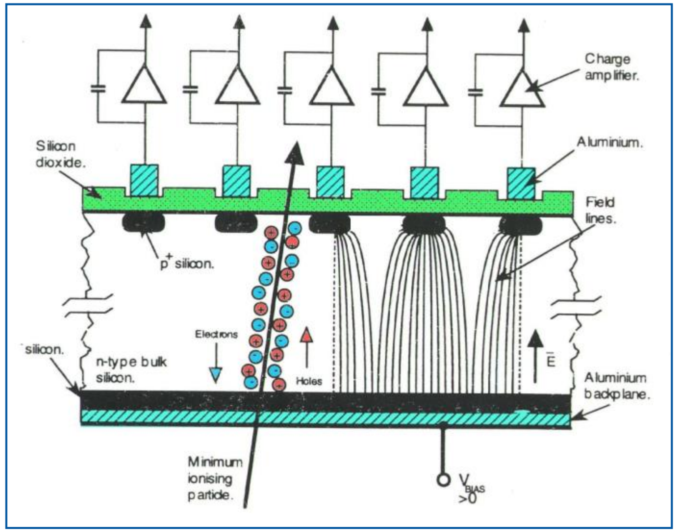
- Good hits selected by requiring N_{ADC} > noise tail
  If cut too high ⇒ efficiency loss
  If cut too low ⇒ noise occupancy
- Figure of Merit: Signal-to-Noise Ratio S/N
- Typical values >10-15, people get nervous below 10.
  Radiation damage severely degrades the S/N.

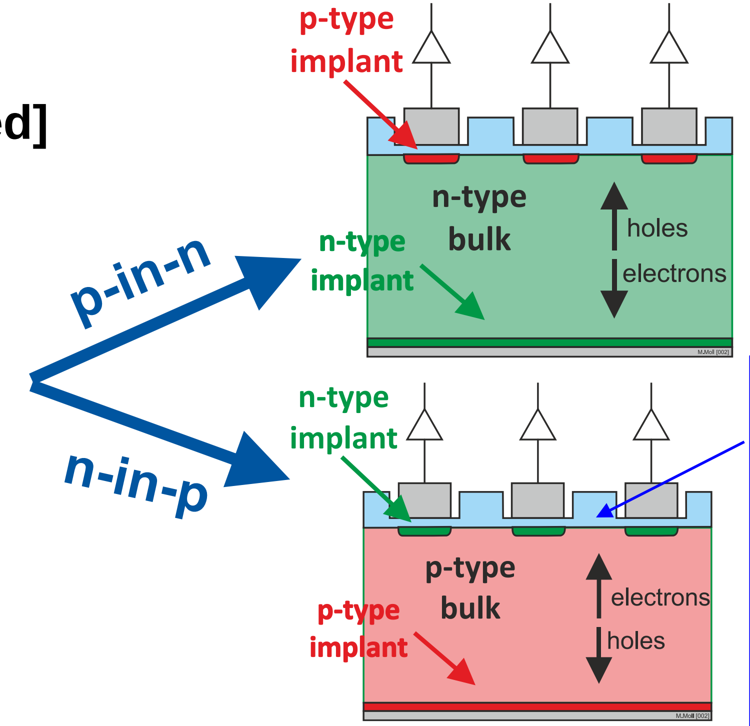
Summary: Silicon Sensors in HEP

Main sensor concepts:



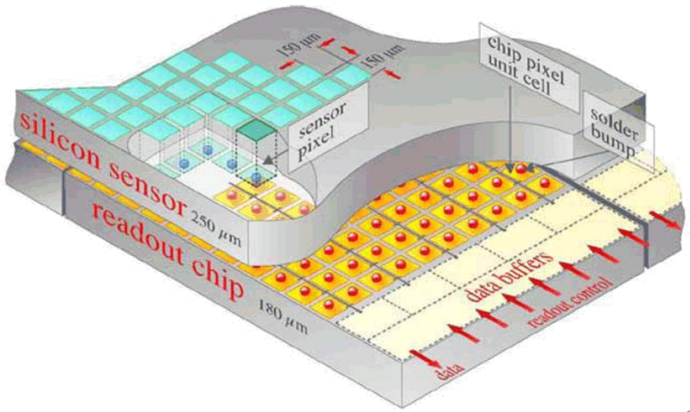
(Mini) Strip Detector [AC coupled]

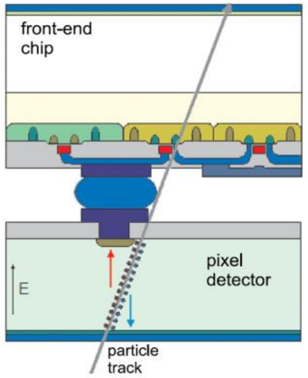




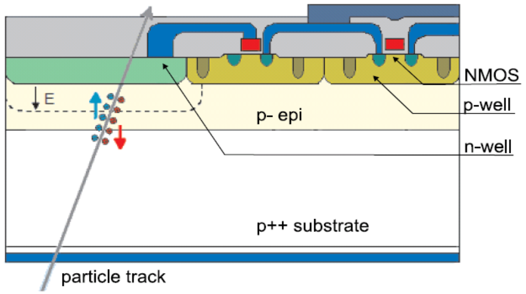
Need inter strip isolation!

Hybrid Pixel Detector



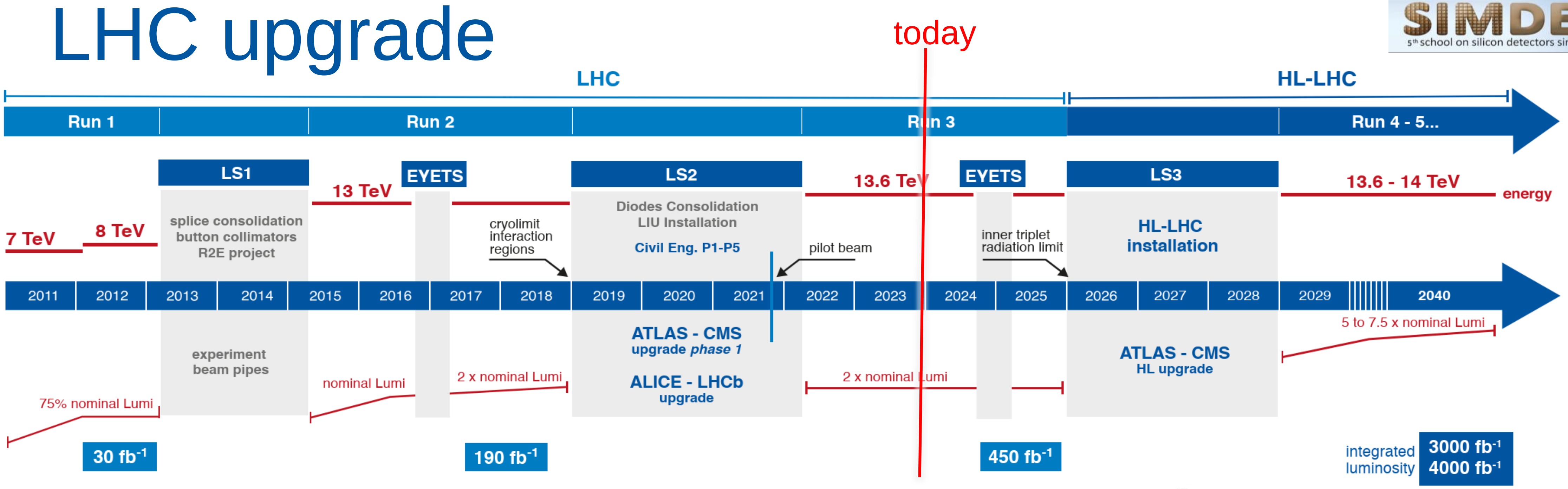


Monolithic CMOS Pixel Detector



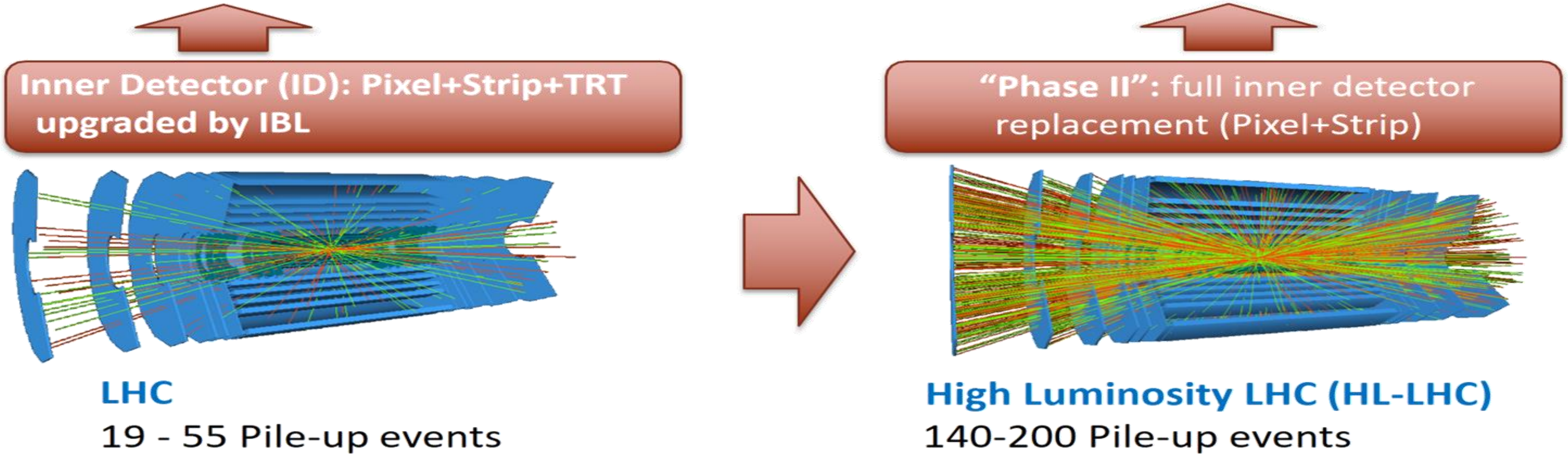
The LHC Upgrade

LHC upgrade



[HL-LHC schedule – Feb.2022]

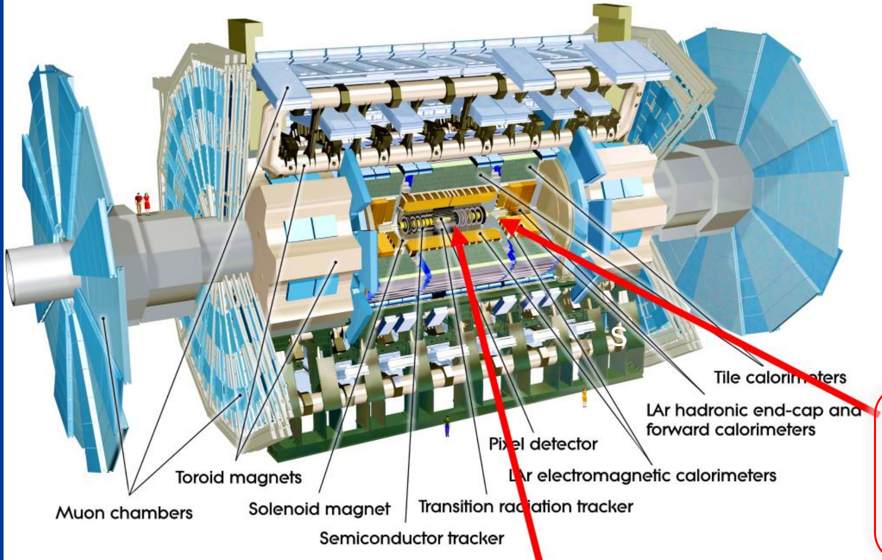
Example ATLAS:



[G.Calderini Vertex 2021]

Phase 2 upgrades – High Lumi LHC

ATLAS Phase-2 upgrade



Upgraded Trigger and Data Acquisition system
Level-0 Trigger at 1 MHz
Improved High-Level Trigger (150 kHz full-scan tracking)

Electronics Upgrades
On-detector and off-detector electronics upgrades of:
LAr Calorimeter
Tile Calorimeter
Muon Detectors

High Granularity Timing Detector (HGTD)
Forward region
Precision time recon. (30 ps) with Low-Gain Avalanche Detectors (LGAD)

New Muon Chambers
Inner barrel region with new Resistive Plate Chambers and new Monitored Drift Tubes (sMDT) detectors

New Inner Tracking Detector (ITk)
All silicon (9 layers), up to |η| = 4

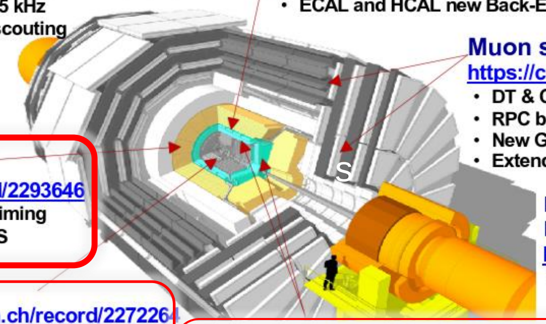
Additional small upgrades
Luminosity detectors (1% precision)
HL-ZDC (Heavy Ion physics)

CMS Phase-2 upgrade

L1-Trigger HLT/DAQ
https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2759072
- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3



Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity
http://cds.cern.ch/record/2759074
- Bunch-by-bunch luminosity measurement: 1% offline, 2% online

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8

MIP Timing Detector
https://cds.cern.ch/record/2667167
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

About 800 m² of silicon sensors for the phase 2 upgrades of ATLAS & CMS (RUN 4 ≥ 2029)

..and all based on p-type silicon and no longer n-type silicon. Why? … let's see

Radiation Damage

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

Radiation damage is just one of the many challenges in conceiving a High Energy Physics detector for hadron colliders.

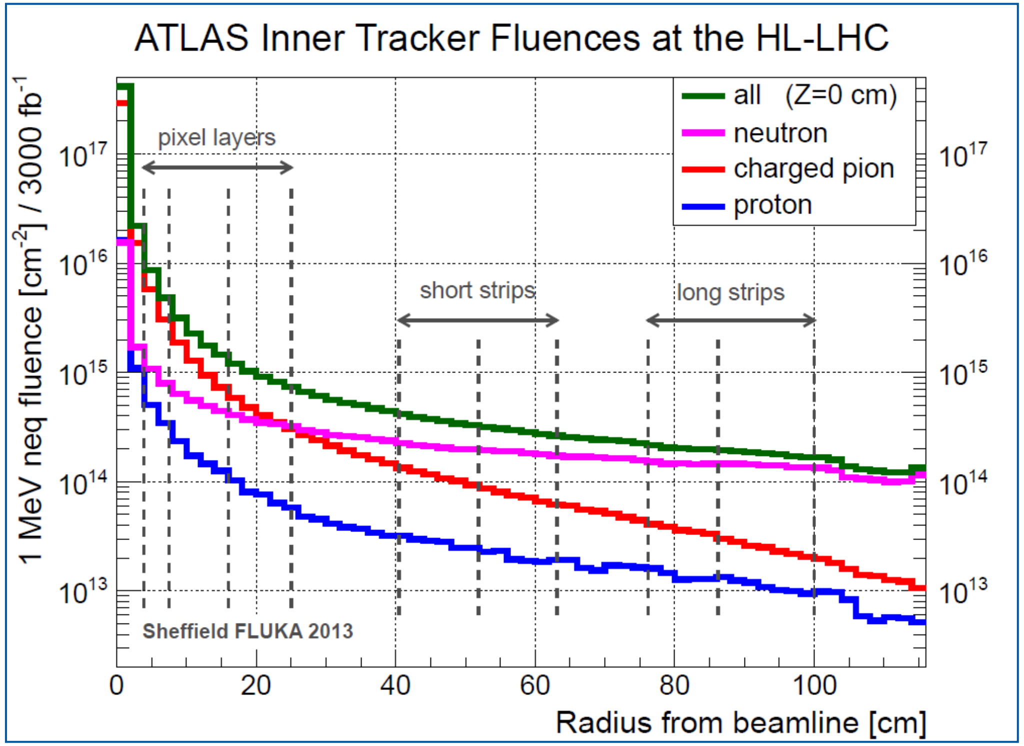
Constraints like needs for high granularity, low mass, efficient cooling and low power consumption, low cost, high rate capability, precision timing capability, …. are adding up to the challenge of building a detector.

Motivation and Challenge

Silicon detectors upgrades and operation

- Radiation Hardness -

- **LHC operation**
- **HL-LHC (High Luminosity LHC)**
  - detector developments for HL-LHC
    - starting after LS3 (~2026-28);
    - expect 4000 fb^{-1} (nominal LHC was 300 fb^{-1})
- **HL-LHC operation & upgrades**
  - operation of HL-LHC
    - damage modelling, evaluation, mitigation
  - ATLAS Pixel replacement, LHCb upgrade, …
- **FCC – Future Circular Collider**
  - ..also FCC-ee



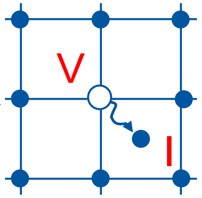
[I. Dawson, P. S. Miyagawa, Sheffield University, Atlas]

- **Increasing radiation levels**
  - Semiconductor detectors will face $>10^{16}$ n_{eq}/cm^2 (**HL-LHC**) and $>7\times10^{17}$ n_{eq}/cm^2 (**FCC-hh**)

    → detectors used at LHC cannot be operated after such irradiation
- **New requirement and new detector technologies**
  - New requirements or opportunities lead to new technologies (e.g. HV-CMOS, LGAD,…) which need to be evaluated and optimized in terms of **radiation hardness and/or 4D tracking capabilities**

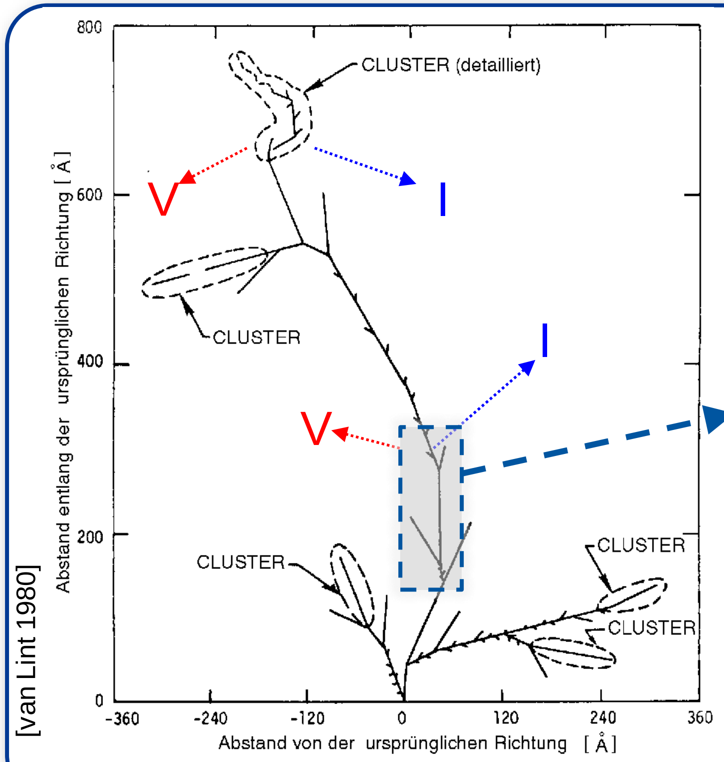
Displacement Damage

particle → *Si_S* → E_K>25 eV →



Vacancy + Interstitial → *….. a wide range of **point defects***

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

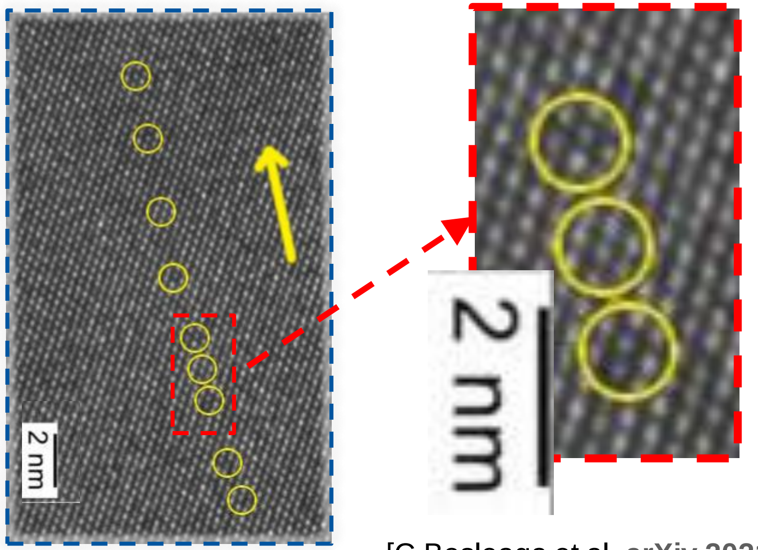


[van Lint 1980]

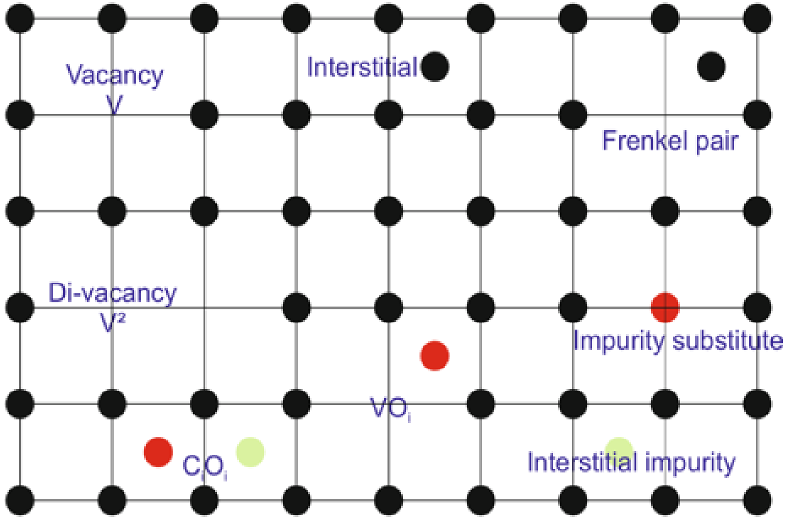
Can we see the defects?

HRTEM on Si: n-irradiated 10^{19} n_{eq}/cm^2

High Resolution Transmission Electron Microscopy



[C.Besleaga et al. arXiv 2021]



- example of point defect reactions:

V: *V+O → VO; V+P → VP* ← "dopant removal"

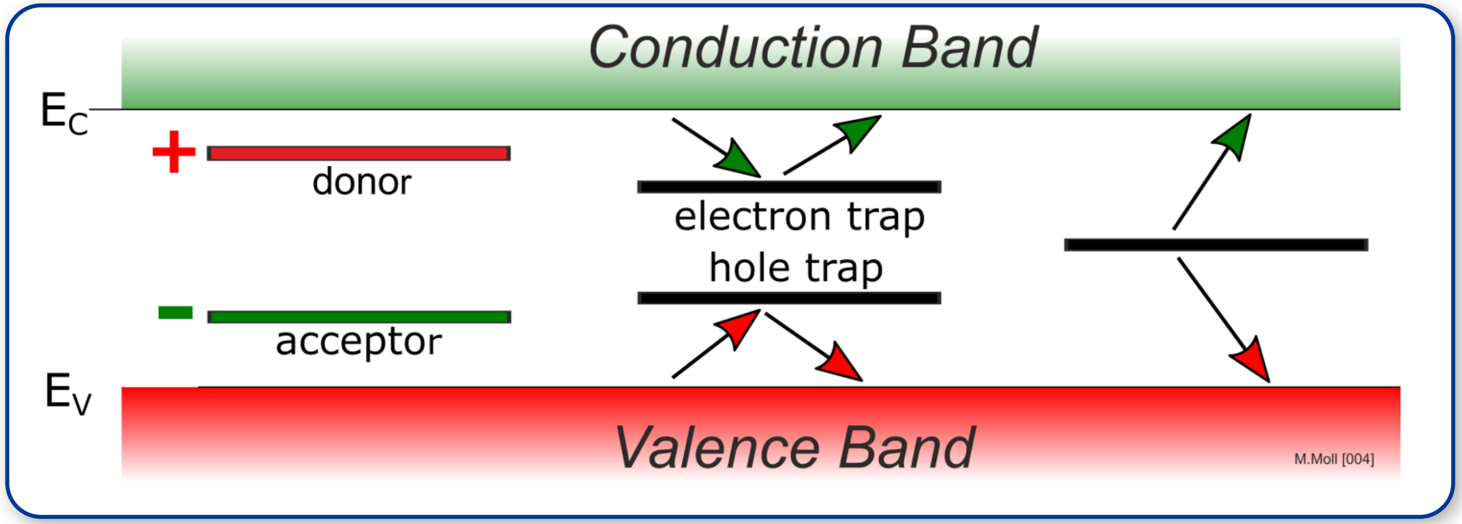
I: *$I+C_S$ → C_i → C_i + O → C_iO_i*

$I+B_S$ → B_i → B_i + O → B_iO_i

… many more reactions!

Impact of Defects on Detector Properties

- Shockley-Read-Hall statistics



charged defects
⇒ N_{eff} , V_{dep}

e.g. donors in upper half, acceptors in lower half of the band gap

trapping (e and h)
⇒ CCE

shallow defects do not contribute at RT due to fast de-trapping

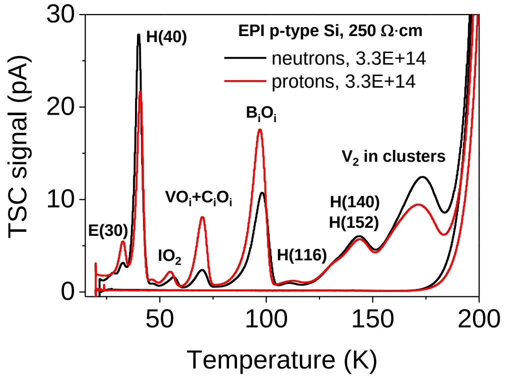
generation
⇒ leakage current

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

Defect spectroscopy

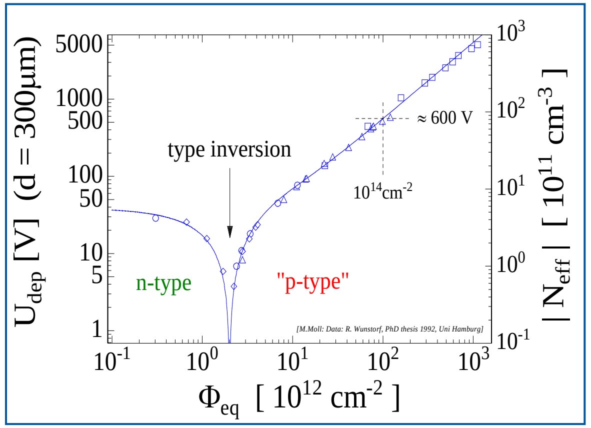


e.g. DLTS, TSC allows to measure the defect properties (see backup)

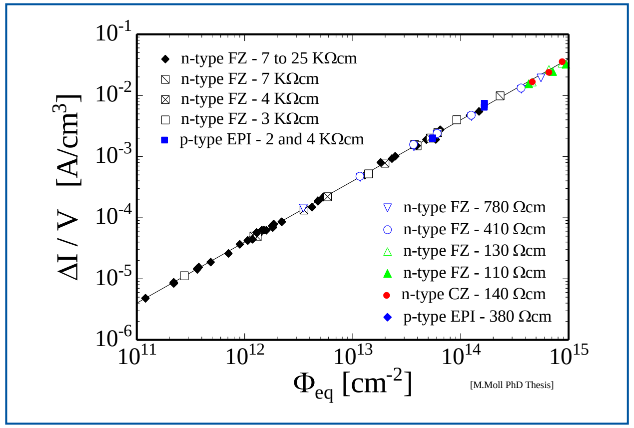
Extracted parameters serve as input to **TCAD** simulations (see backup)

Radiation Damage Summary

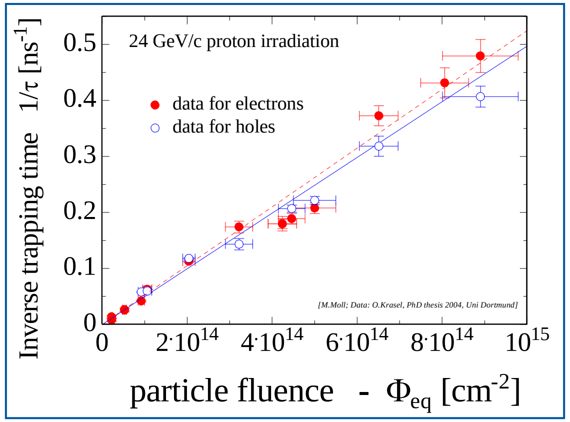
- Macroscopic bulk effects:



Depletion Voltage (N_{eff})

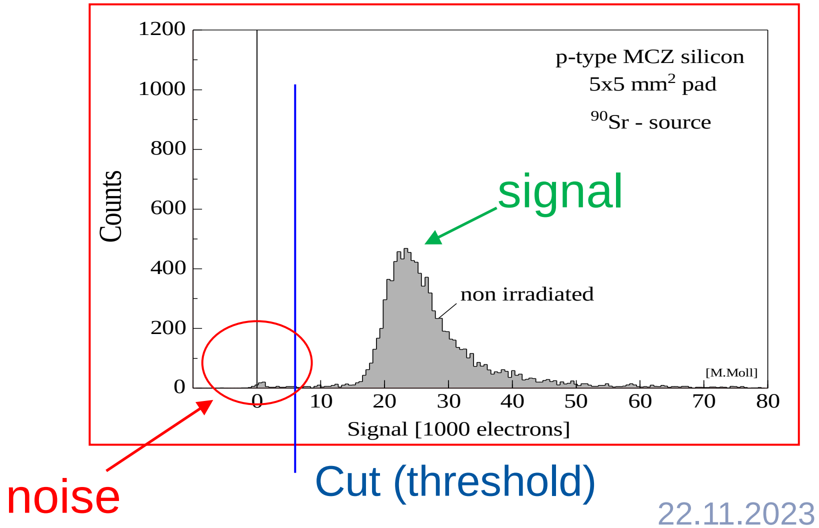


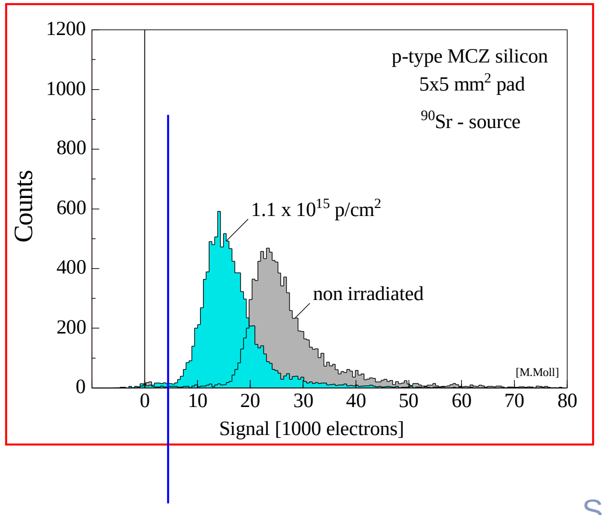
Leakage Current

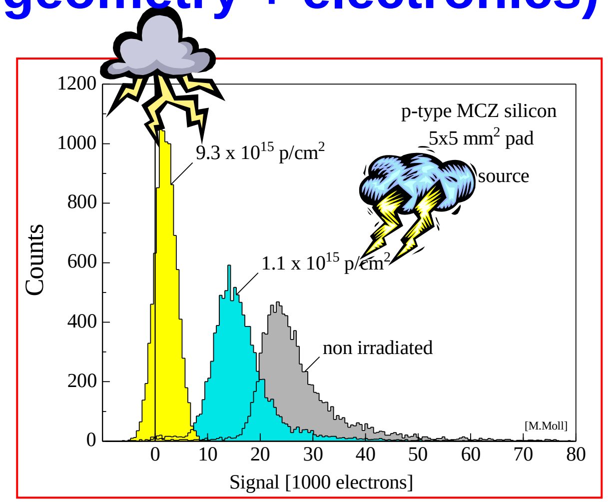


Charge Trapping

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







Radiation Hard Detectors

RD50 Collaboration (2002-2023)

Full member list: www.cern.ch/rd50

- RD50 (Nov.2023): 65 *institutes and 440 members*

Last RD50 Workshop: 28.11.-1.2.2023

..followed by a new collaboration called DRD3

51 European institutes

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

- **LPHNE, UPMC; Université Paris-Diderot; CNRS/IN2P3, Paris**
  Marco Bomben, Giovanni Calderini, J.Chauveau, F.Crescioli, Giovanni Marchiori
- **IJCLab - Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie**
  L.Iconomidou-Fayard, Abdenour Lounis, C.Nellist
- **CPPM Marseille;** Marlon Barbero, P.Barrillon, P.Breugnon, A.Habib, P.Pangaud, M.Zhao

8 North-American institutes

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

7 Asian institutes

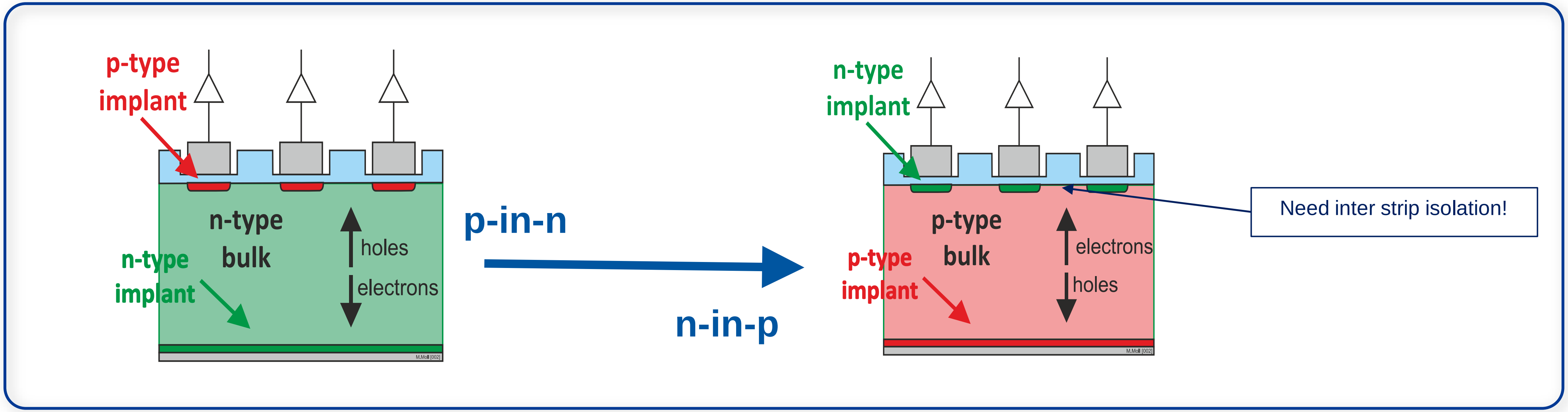
China (Beijing-IHEP, Dalian, Hefei, Jilin, Shanghai), **India** (Delhi), **Israel** (Tel Aviv)

Device engineering example: n-in-p sensors

- Why will we use p-type strip/pixel sensors (n-in-p) for the LHC upgrade in ATLAS and CMS instead of p-in-n sensors?

- Why are segmented sensors(*) build on p-type silicon sensors radiation harder than n-type sensors?

(*) 300 μm



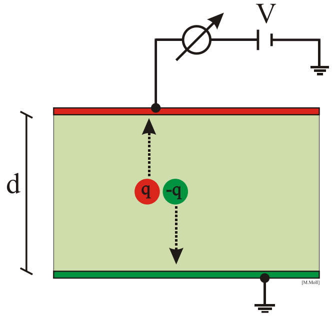
Sensor Signal: Pad vs. Strip/Pixel

- 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)

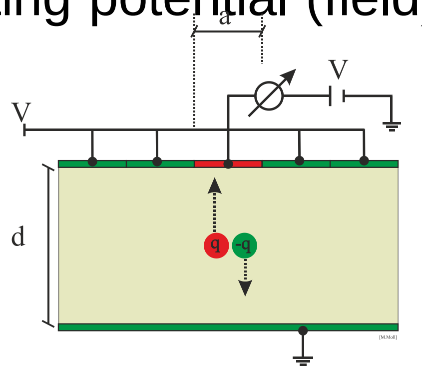
$$i = q \cdot \vec{v} \cdot \vec{E}_W(\vec{x})$$

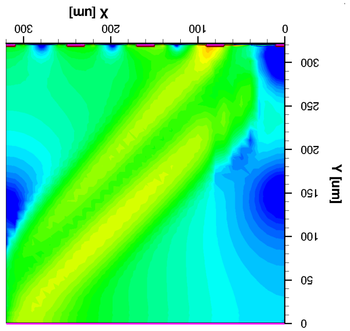
$$Q = -q \cdot \left(\phi_W(\vec{x}_2) - \phi_W(\vec{x}_1)\right)$$

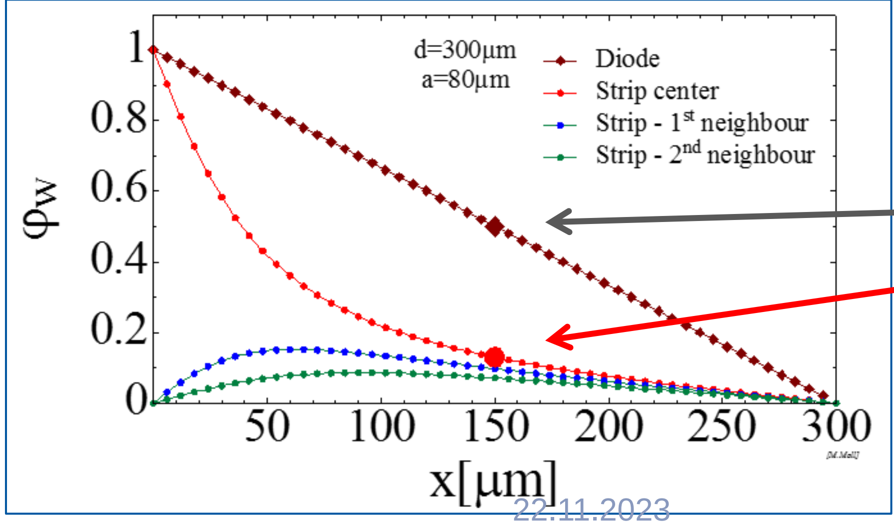
Pad



Strip







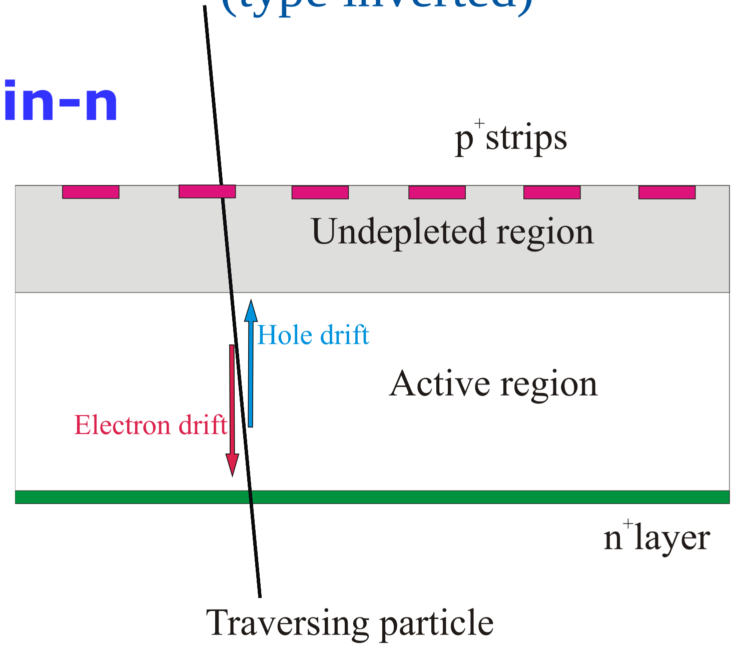
- Total collected charge in both cases 100% (Q = q) when charges have reached the electrodes, however
  - Diode: 50% from (+q); 50% from (-q)
  - Strip: 87% from (+q); 13% from (-q)
- In a p-in-n strip sensor the holes give a higher contribution to the (m.i.p.) signal than the electrons!

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

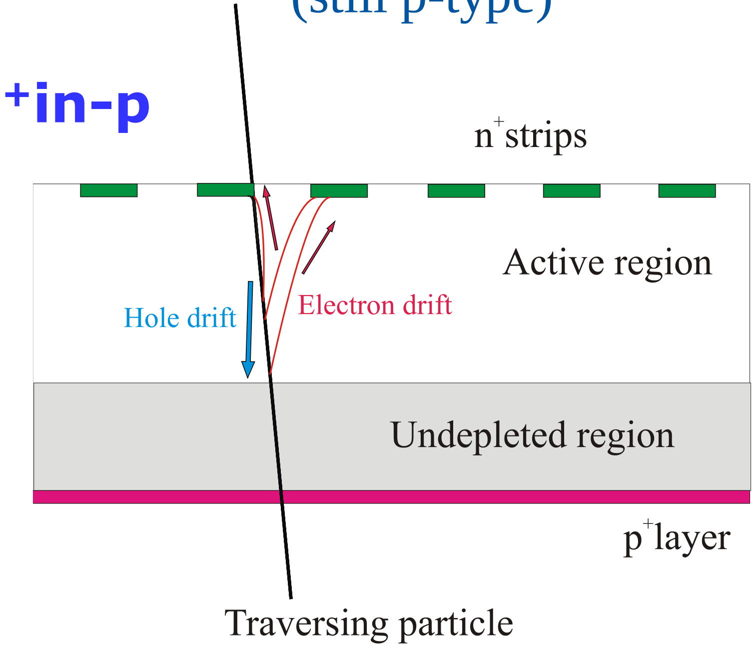
n-type silicon after high fluences:
(type inverted)

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**

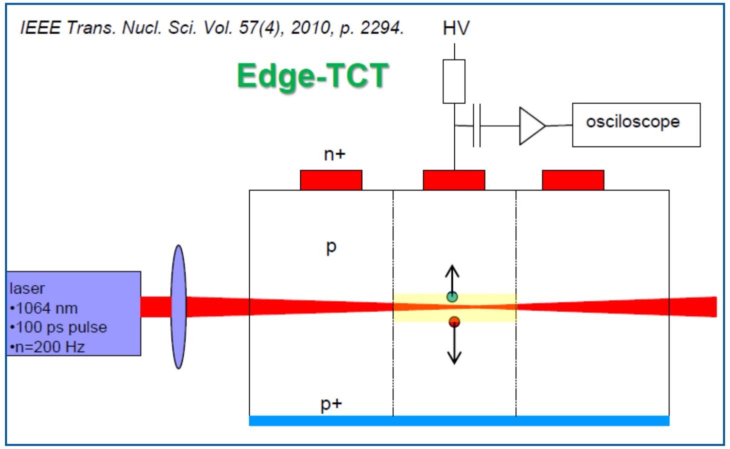
n-in-p silicon, under-depleted:

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

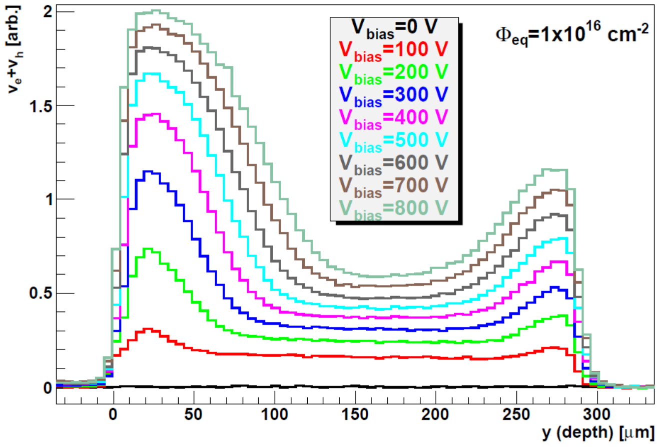
Comments:
- Instead of n-in-p also n-in-n devices could be used
- Reality is much more complex: Usually double junctions form leading to fields at front and back! (next slide)

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

- Investigation by measurement

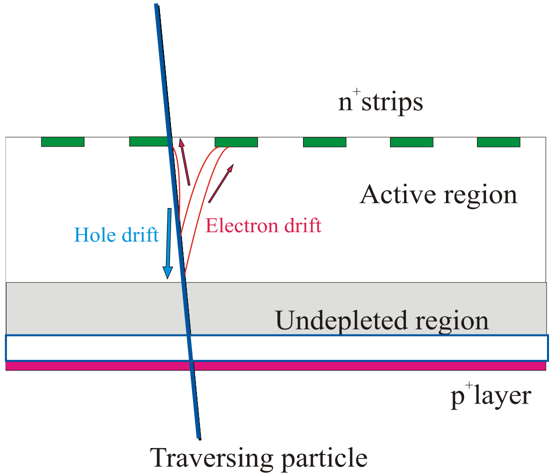


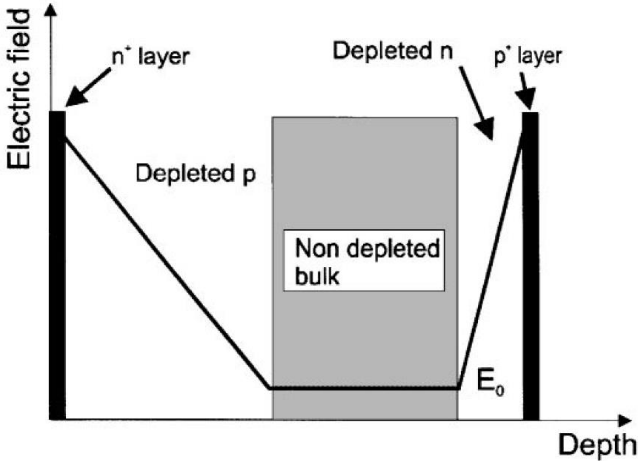
n-in-p sensor still "p-type" (i.e. highest field at front electrode) after high level of radiation



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

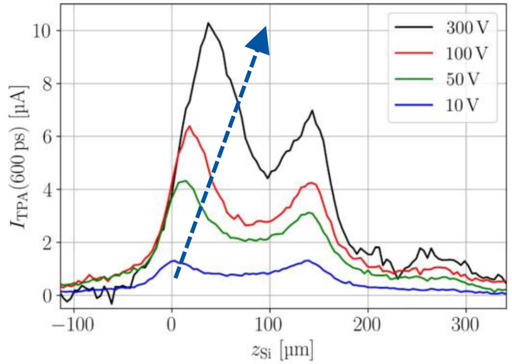
- Dominant junction close to n+ readout strip for FZ n-in-p



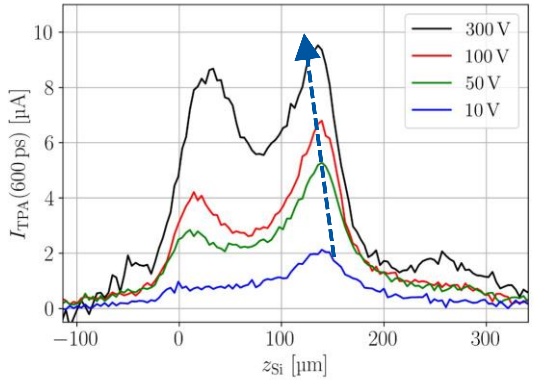


…to add more complexity

- different particle irradiation on identical sensors



neutron irradiated 7×10^{15} n_{eq}/cm^2

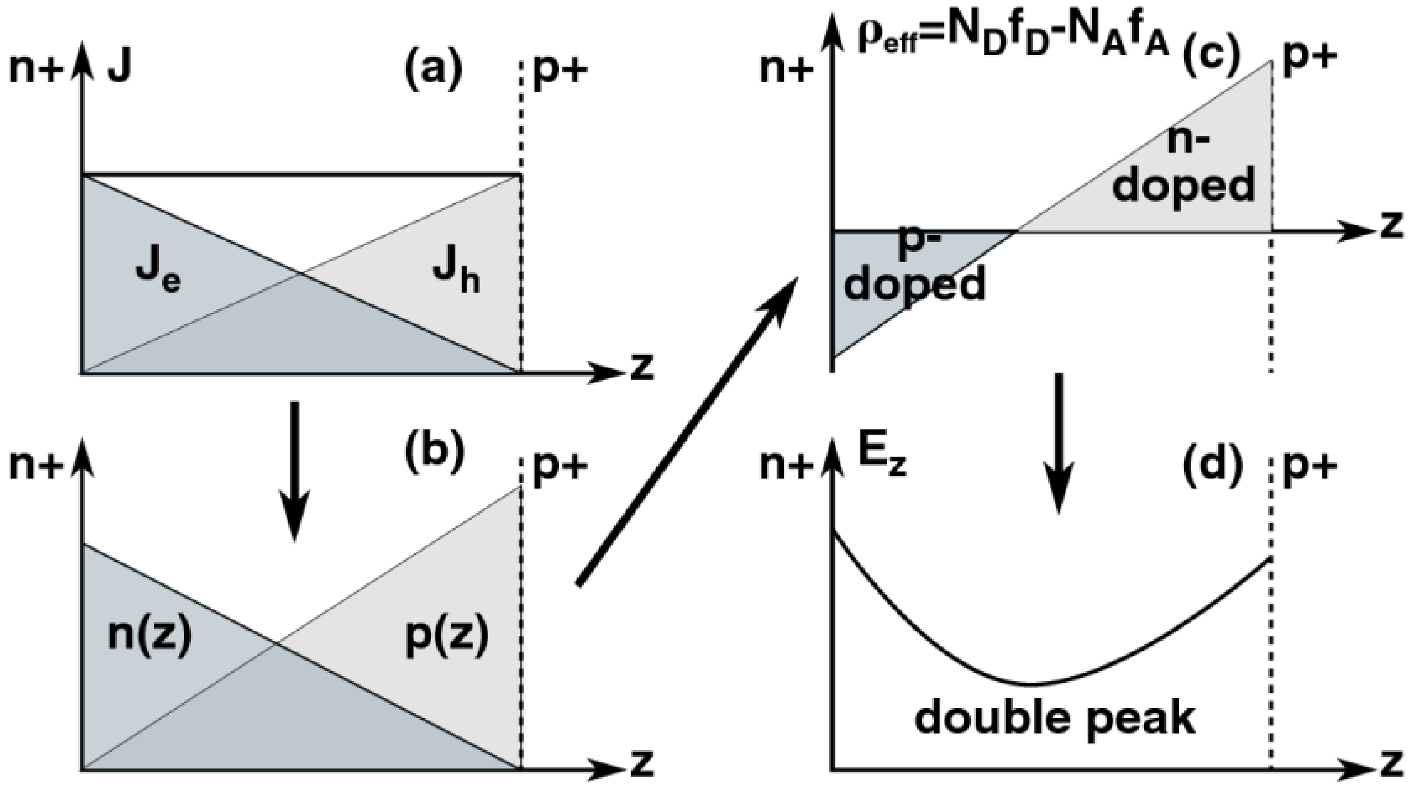


proton irradiated 7×10^{15} n_{eq}/cm^2

[S.Pape, 43rd RD50 Workshop, 29. November 2023]

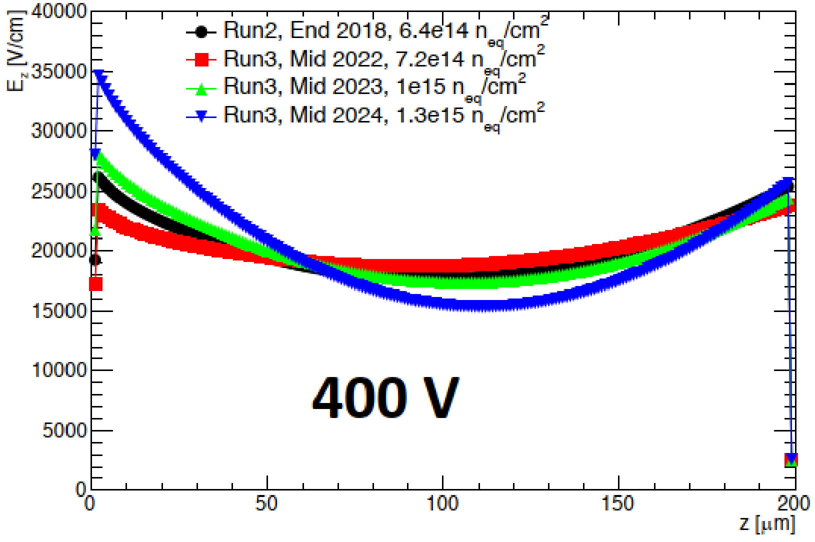
Double Junction

- Double Junction = Polarization Effect



[V.Eremin et al., NIMA 476 (2002) 556-564]

From fluence level the electric field is evaluated using TCAD tools

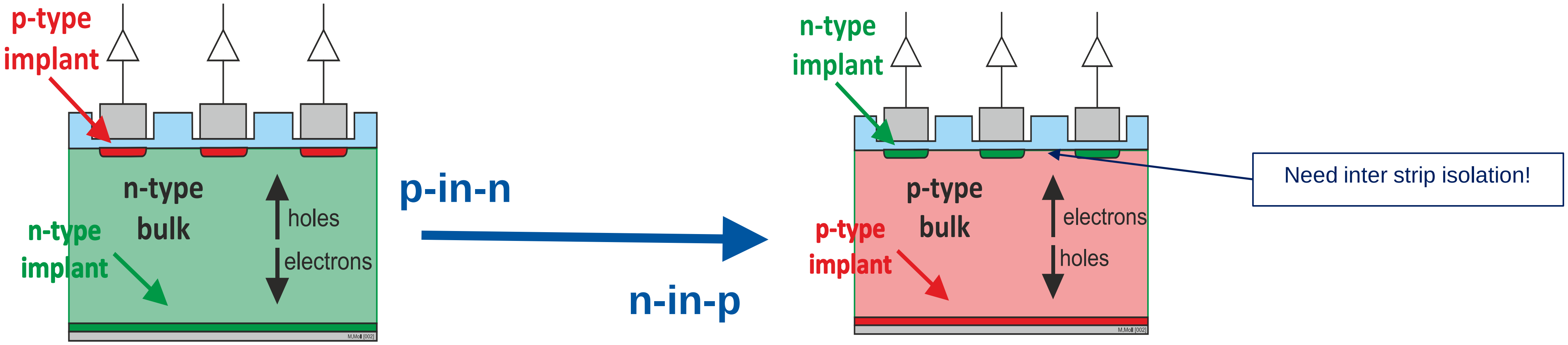


"Chiochia" model – NIM A 568 (2006)

Double junction in TCAD

(see e.g. M.Bomben, SIMDET 2020 in Nov. 2021)

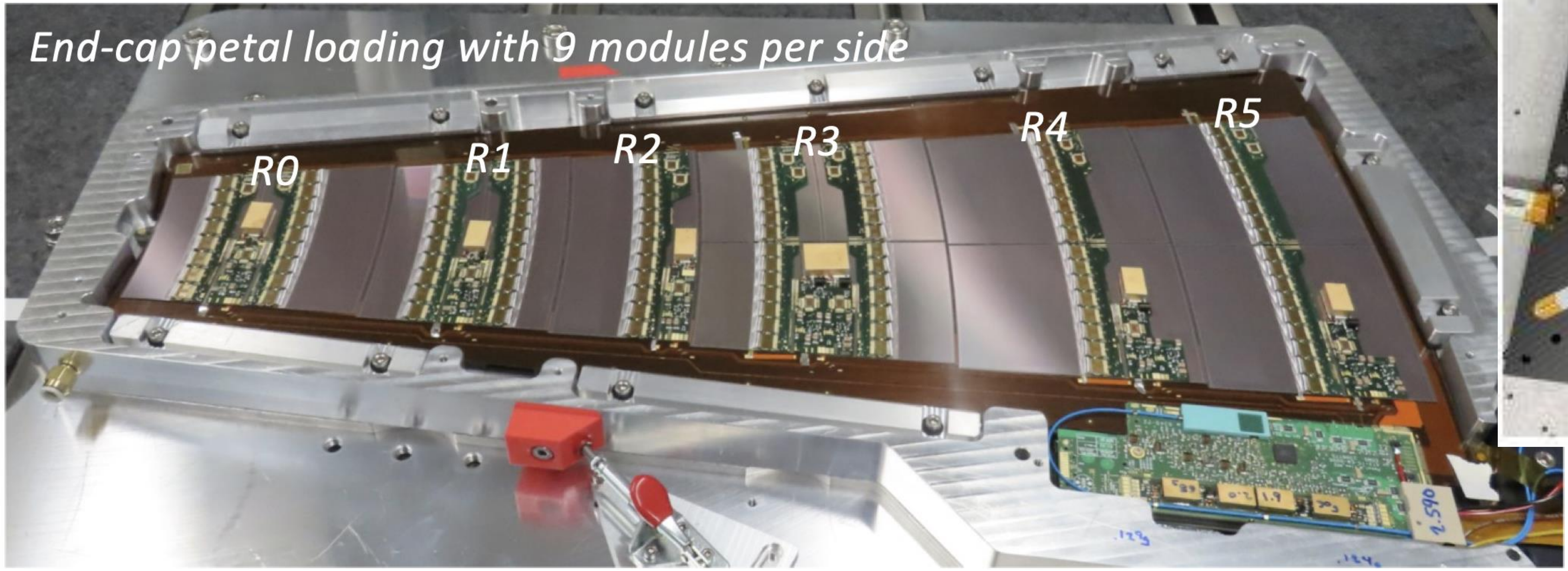
Device engineering example: n-in-p sensors

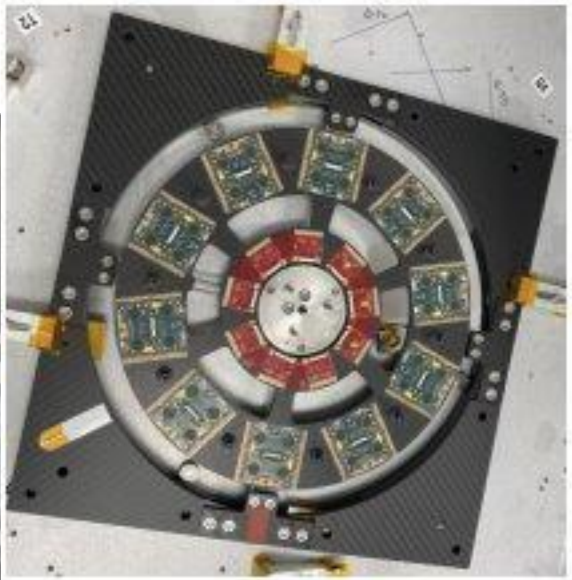


Sensors in LHC trackers today (ATLAS/CMS) → HL-LHC trackers tomorrow (2028)

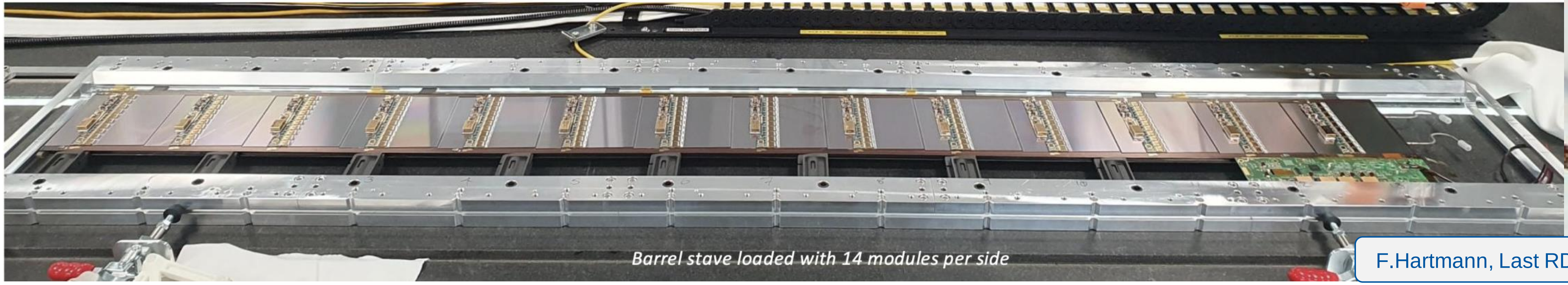
(… in production now)

ATLAS Phase II





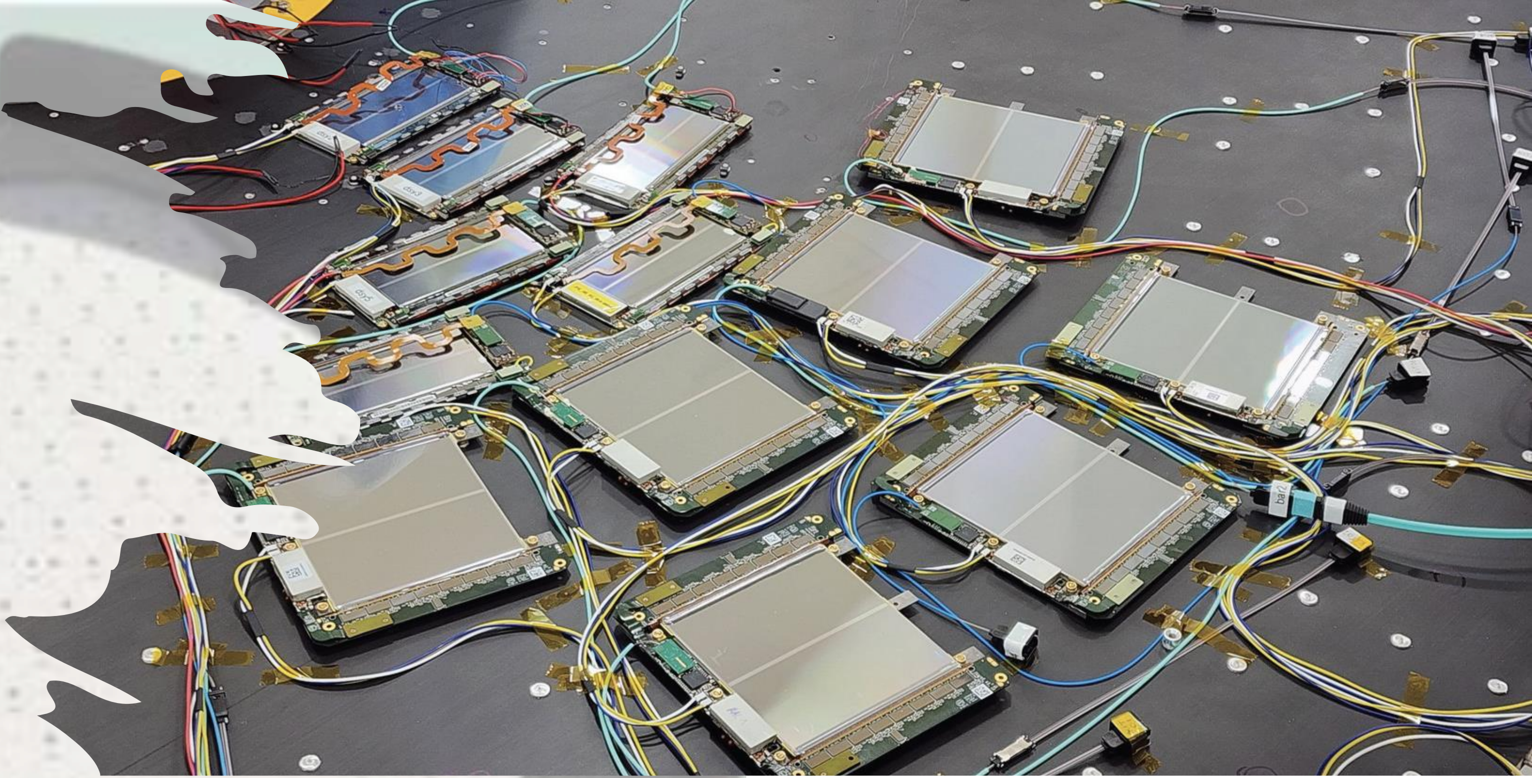
Strips & Pixel
all n-in-p

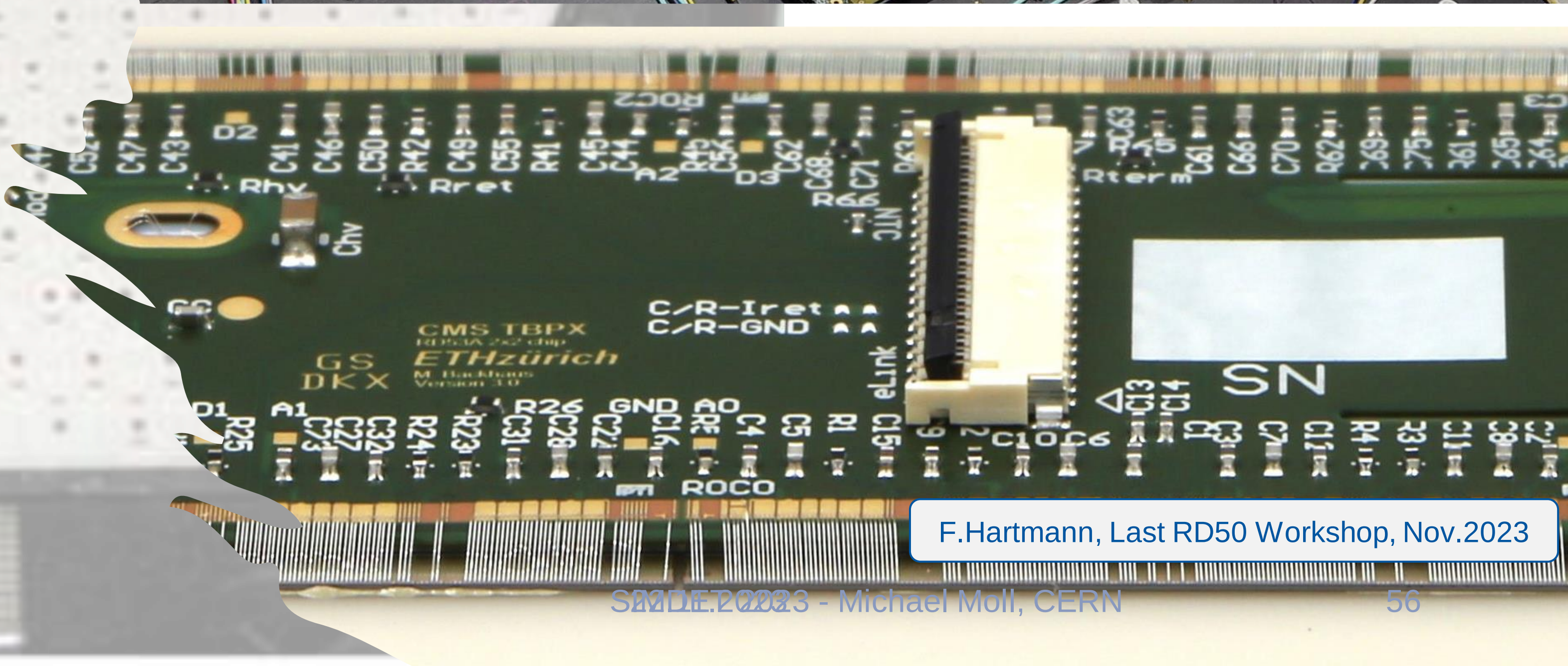


F.Hartmann, Last RD50 Workshop, Nov.2023

CMS Phase II

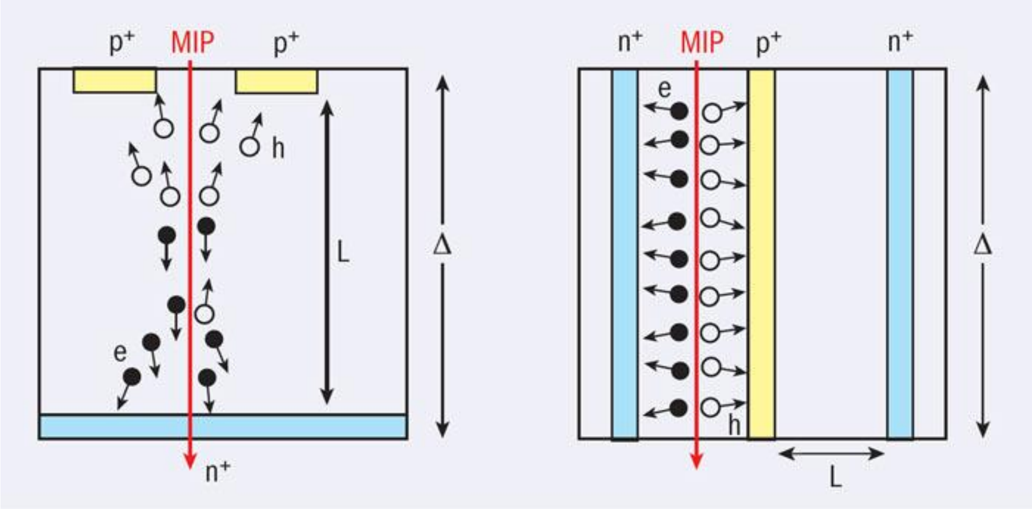
- Outer Tracker modules in final configuration
  - – n-in-p
- Pixel Tracker module
  - – n-in-p
- High Granularity Calorimeter
  - – n-in-p





F.Hartmann, Last RD50 Workshop, Nov.2023

Device engineering example: 3D Hybrid Pixel Detectors



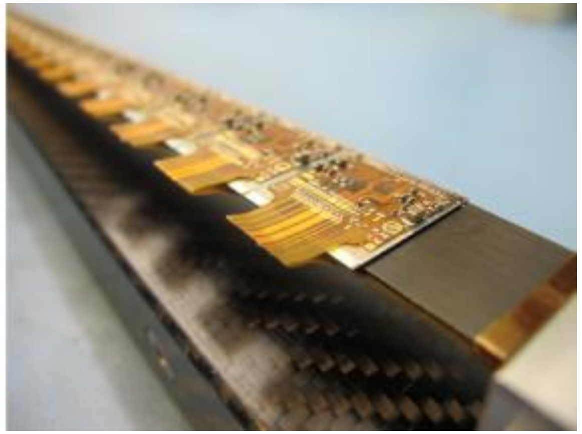
Array of narrow electrode columns (~ 5-10μm) passing through the silicon thickness (micromaching):

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

→ More suited to high radiation environment

Connected to standard pixel ASIC – hybrid pixel detector

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



TCAD simulations

TCAD simulations

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

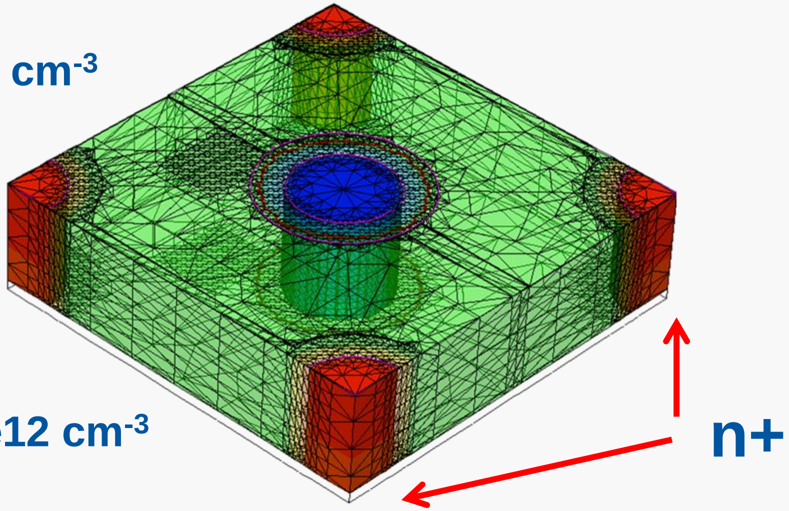
Details in the following presentations

3D detector

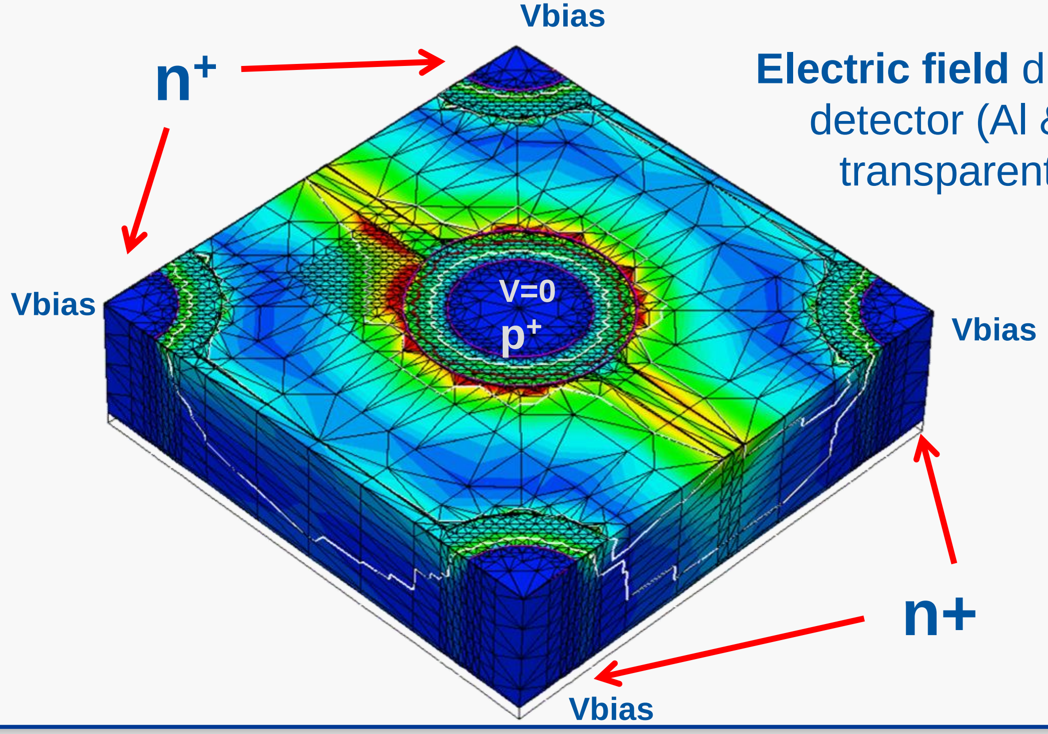
Doping profiles

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

N_{bulk} = 1.7e12 cm^{-3}



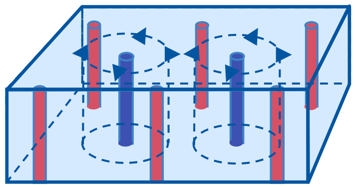
Electric field distribution in 3D detector (Al & oxide layer transparent for clarity**)**



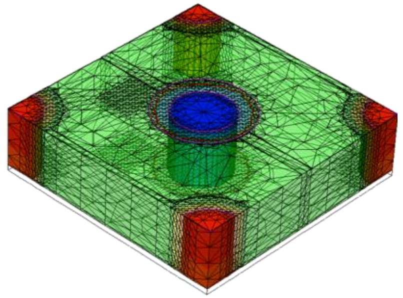
Column depth = bulk thickness

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

Device simulation: TCAD & signal simulators

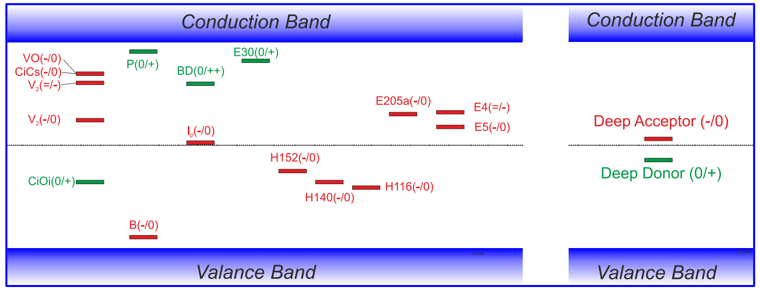


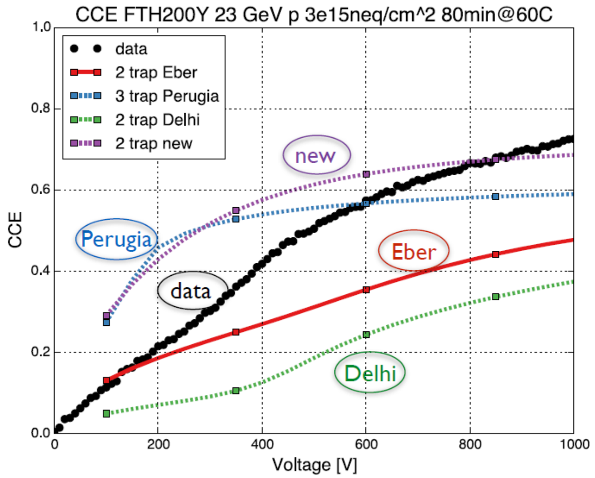
- Status of TCAD device simulations
  - Required by complexity of the problem:
    - solve semiconductor equations with physics properties, complex geometry and radiation damage
    - mainly commercial tools used (Silvaco and Synopsis)
  - Excellent tools for sensor optimization



- Radiation damage TCAD: enormous progress over recent years
  - getting predictive power but need further optimization!
  - “effective” defect levels (2 to 5 levels) are used

Measured defects → ***TCAD input***





needs more work !

- Signal simulators
  - TCAD simulations for signal formation are complex (time consuming, TCAD is not a fitting tool!)
  - Custom build signal simulators (open code) developed: sensor optimization, parameter fitting
    - ..using E-Field and other parameters (e.g. charge trapping) from TCAD as input

PixelAV, KdetSim, Garfield++, Weightfield2, TRACS, (unpublished codes), ...

Summary

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

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

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

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

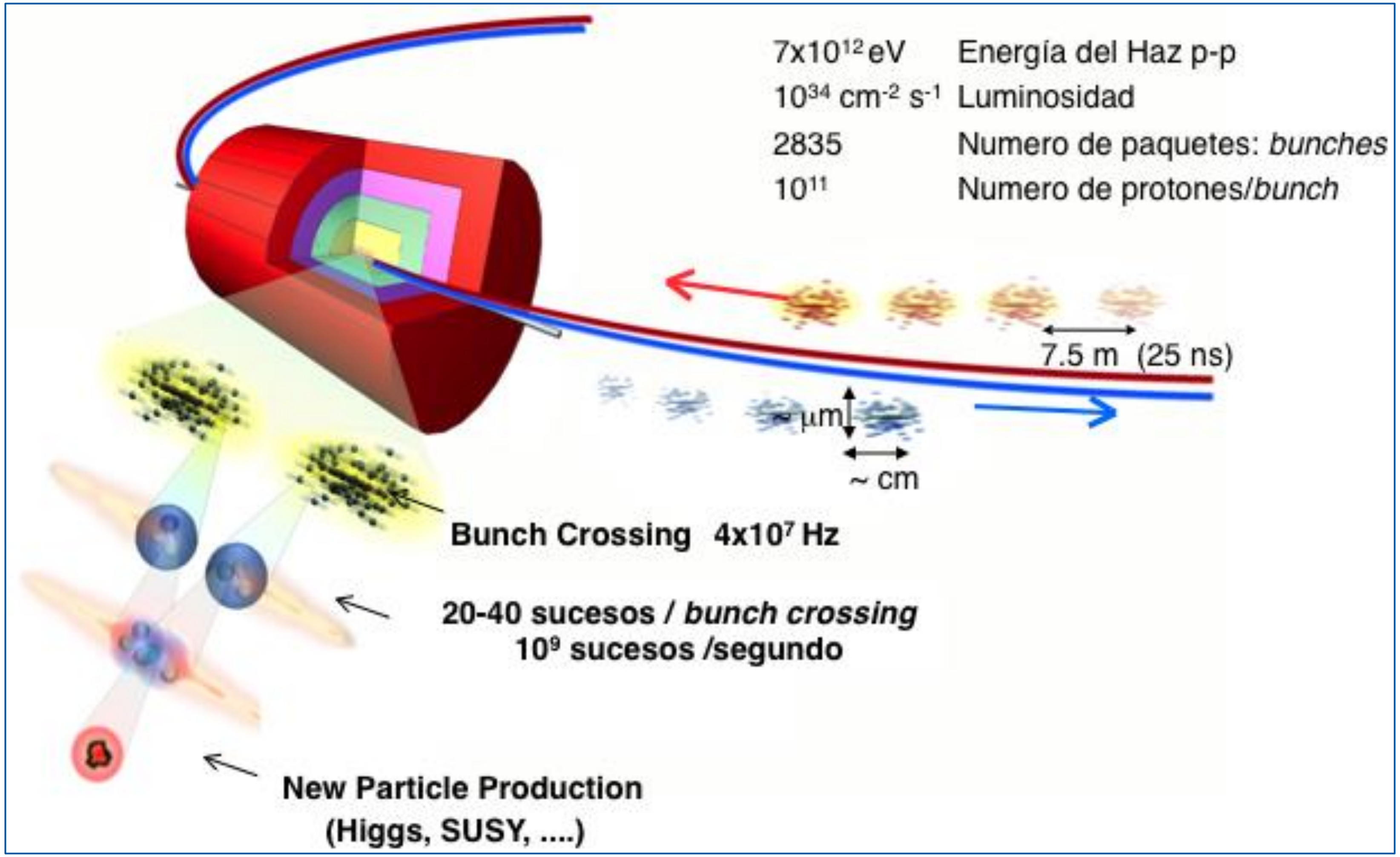
- **"Hot topics" in R&D on radiation hard silicon sensors**
  - Sensors for timing (i.e. LGAD with intrinsic gain, acceptor removal); monolithic sensors; CMOS; re-evaluation of SiC and Diamond sensors
  - **Reliability of TCAD simulations with defects**; characterization of damage beyond 10^{16} cm^{-2}

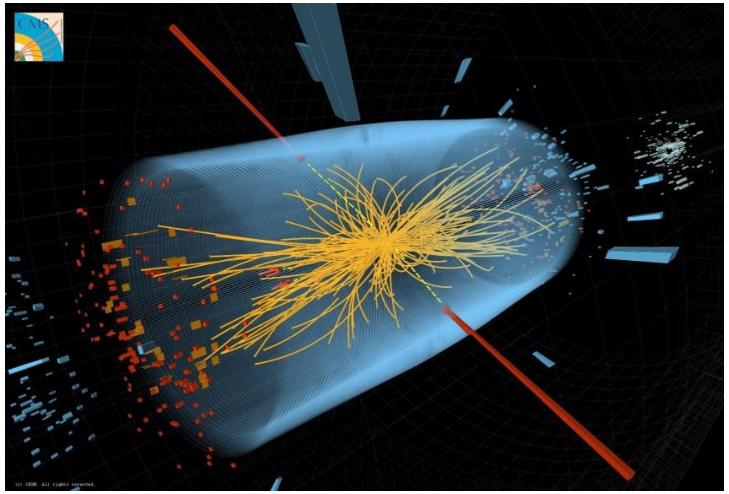
Acknowledgements & References

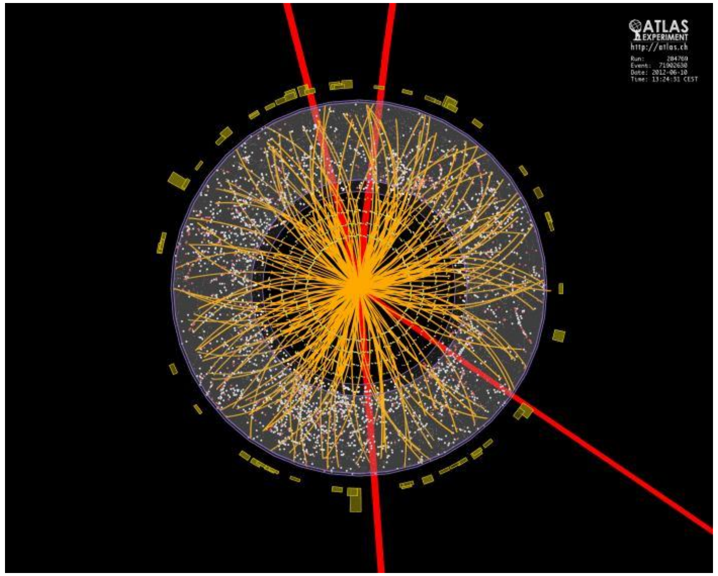
- **Most references to particular works given on the slides**
  - RD50 workshop presentations: http://www.cern.ch/rd50/
  - Conferences: VERTEX, PIXEL, RESMDD, …
- **Instrumentation Schools**
  - ICFA, EDIT, ESI, CERN & DESY Summer Student Lectures
- **Books about silicon tracking detectors (and radiation 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 *(2023: writing on new edition)*
  - L.Rossi, P.Fischer, T.Rohe, N.Wermes “Pixel Detectors”, Springer, 2006
  - Gerhard Lutz, “Semiconductor radiation detectors”, Springer 1999
  - Hermann Kolanoski and Norbert Wermes, “Particle Detectors – Fundamentals and Appilcations”, Oxford University Press 2020
- **Review Articles**
  - 2018: Garcia-Sciveres and Wermes, A review of advances in pixel detectors for experiments with high rate and radiation, https://doi.org/10.1088/1361-6633/aab064
  - 2018: M.Moll, Displacement Damage in Silicon Detectors for High Energy Physics https://doi.org/10.1109/TNS.2018.2819506
  - 2021: Radiation Effects in the LHC-Experiments, 154 pages, CERN Yellow Report https://cds.cern.ch/record/2764325
- **Research collaborations and web sites**
  - CERN RD50 collaboration (http://www.cern.ch/rd50) - Radiation Tolerant Silicon Sensors
  - CERN RD42 collaboration – Diamond detectors
  - Inter-Experiment Working Group on Radiation Damage in Silicon Detectors (CERN) – CERN Yellow Report
  - ATLAS IBL, ATLAS and CMS upgrade groups

Backup Slides

Collisions in the LHC







2012 – Discovery of the Higgs Boson

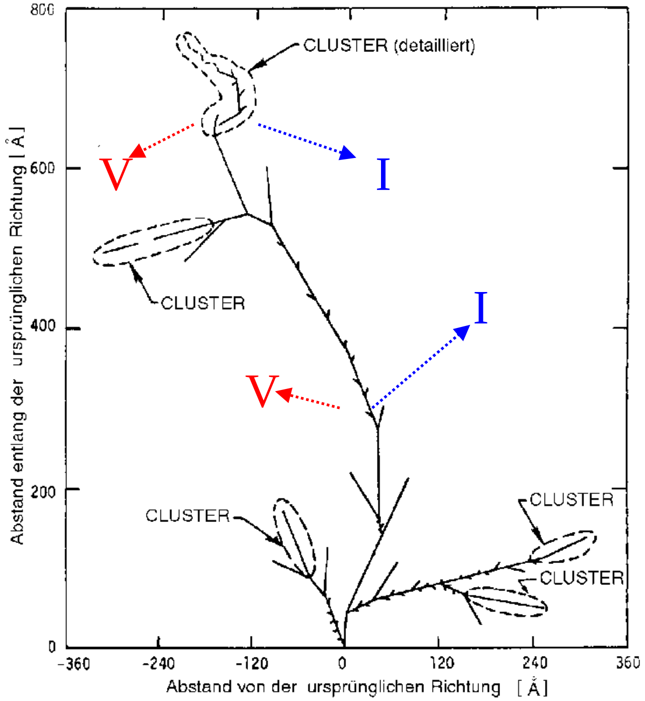
Microscopic Damage

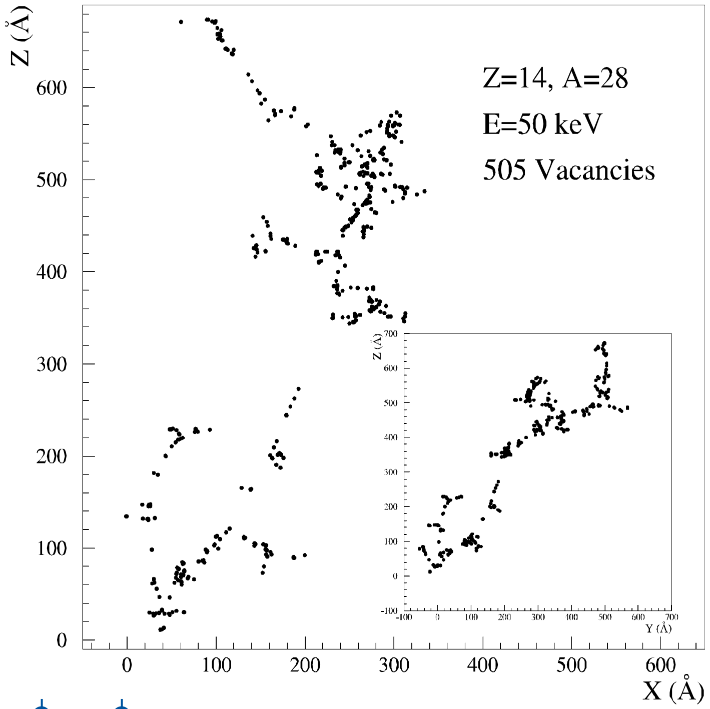
Formation of Defects and Impact on Detectors

Radiation Damage – Microscopic effects

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

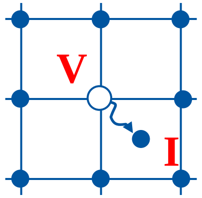
van Lint 1980





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*

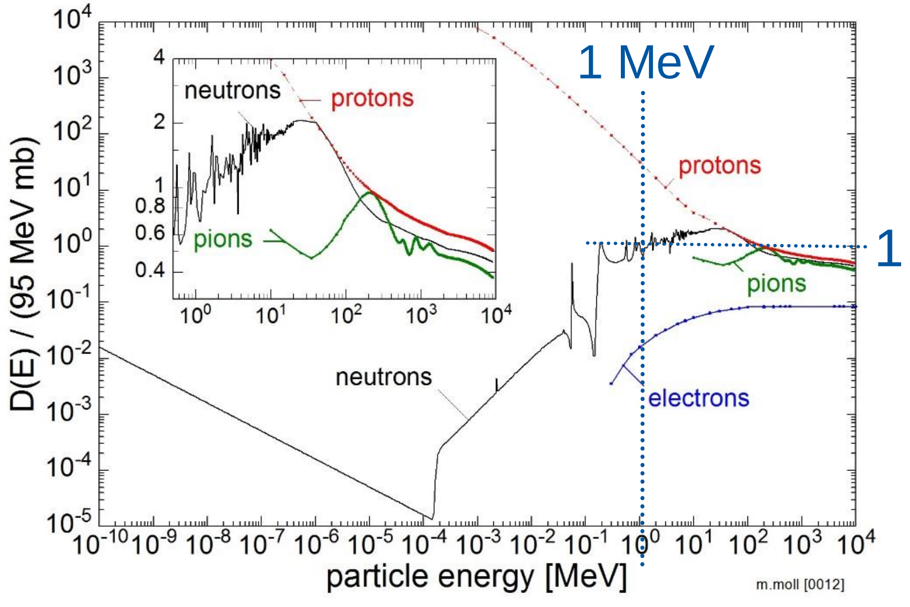
NIEL – Non Ionizing Energy Loss

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

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

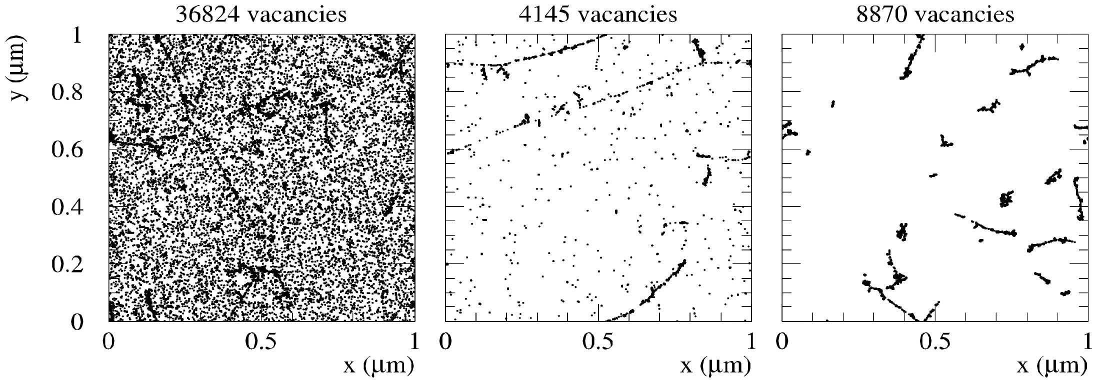
κ_p = 0.62 (23 GeV protons)
κ_p = 1.85 (26 MeV protons)
κ_p = 2.20 (23 MeV protons)
κ_π = 1.14 (192 MeV pions)
κ_n = 0.92 (TRIGA reactor neutrons)

- **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
    - …
    - Acceptor removal ?



[Data: A.Vasilescu and G.Lindstroem]

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

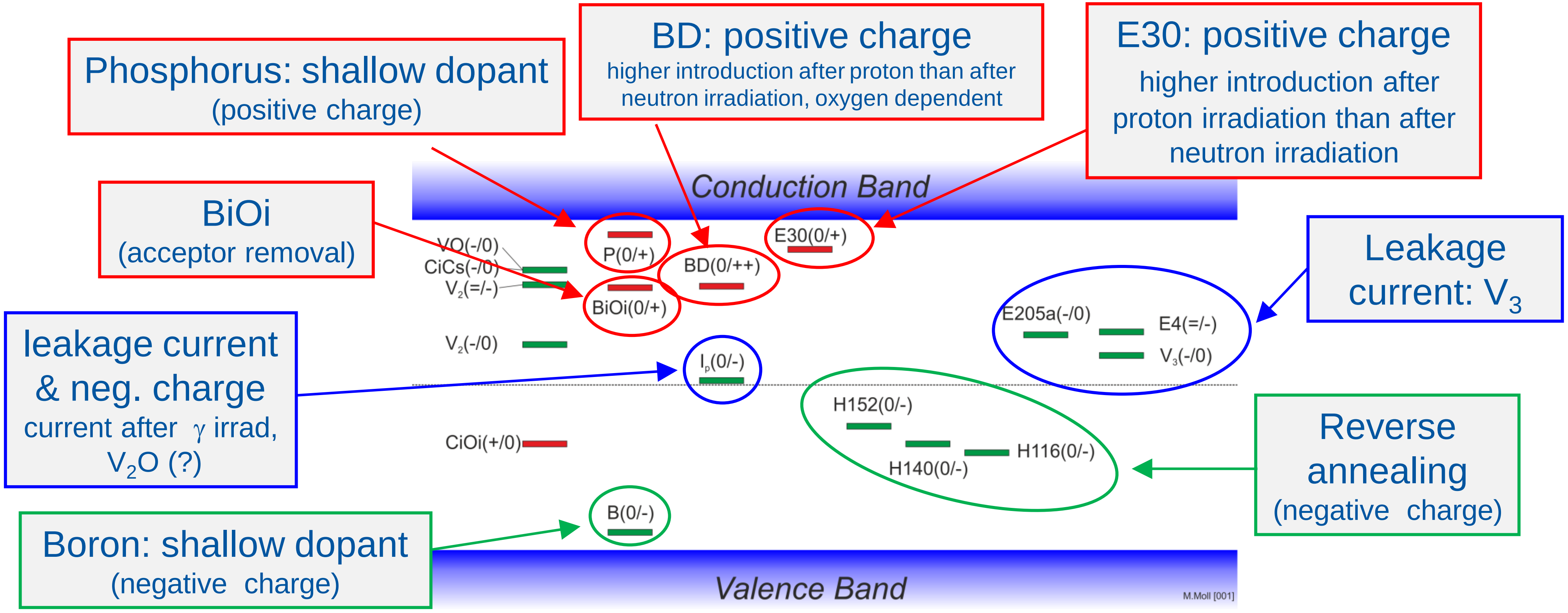


10 MeV protons | 23 GeV protons | 1 MeV neutrons

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

Radiation induced defects with impact on device performance

RD50 map of most relevant defects for device performance near room temperature:



- 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 energy, and some on material!

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

Macroscopic Damage

Degradation of Detector Performance

Summary: Basics of Radiation Damage in Silicon Sensors

SIMDET 2023 5th school on silicon detectors simulation

- **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 & 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)

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

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

  - **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! (geometry, readout electronics)

Signal/noise ratio is the quantity to watch

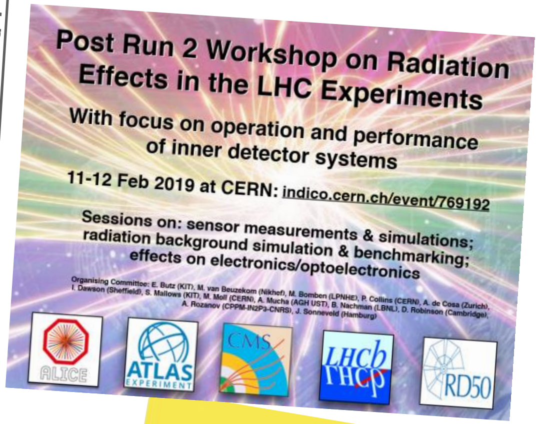
⇒ Sensors can fail from radiation damage !

Radiation Damage
in the LHC Experiments
(Silicon Detectors)

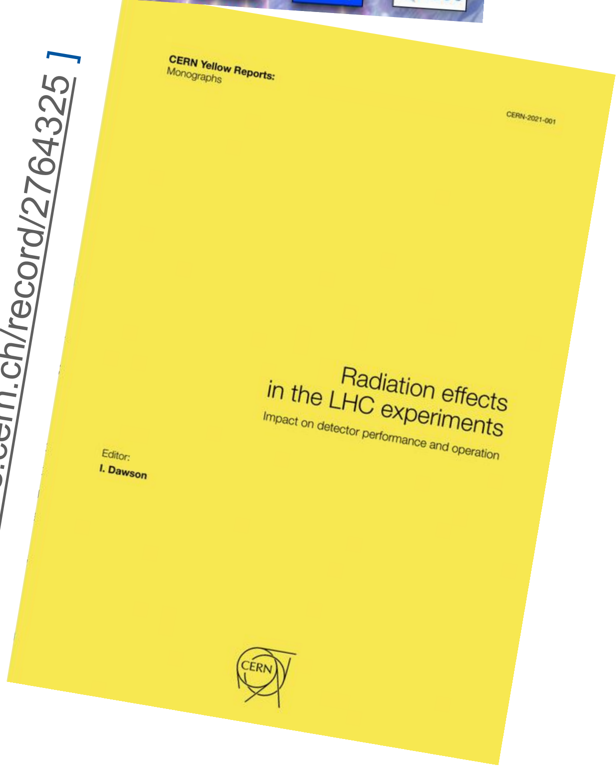
Radiation Effects in LHC Experiments

- 5 workshops on "Radiation Effects at LHC Experiments and Impact on Operation and Performance" organized (2011 - 2019)
  - Common Workshop: (ALICE), ATLAS, CMS, LHCb, RD50
    - Sensor Measurements
    - Electronics/Optoelectronics
    - Radiation Simulation and Monitoring
    - Sensor Simulation
- Outcome and follow-up:
  - Generally good agreement between RD50 damage prediction models (e.g."Hamburg model") and radiation damage observed by the LHC experiments.
  - More coherent approach in data analyses agreed and documented.
  - Modelling will have to be refined in some areas for run 3 !
- **CERN Yellow Report** written and edited by a team from RD50 & all LHC experiments has been published (154 pages, Radiation effects in the LHC experiments https://cds.cern.ch/record/2764325) summarizing observations, comparing results from different experiments against each other, listing open questions and outlining further work towards Run 3.

[https://indico.cern.ch/event/769192]

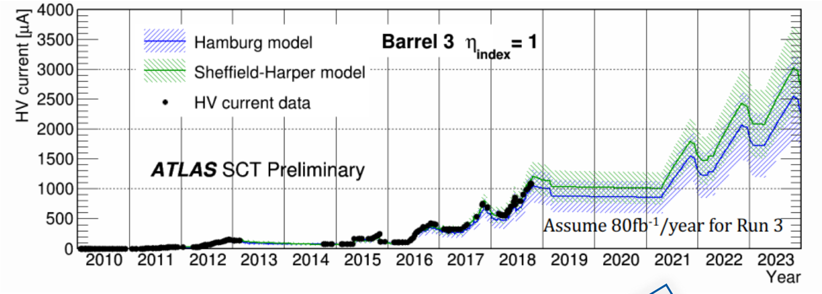


[https://cds.cern.ch/record/2764325]

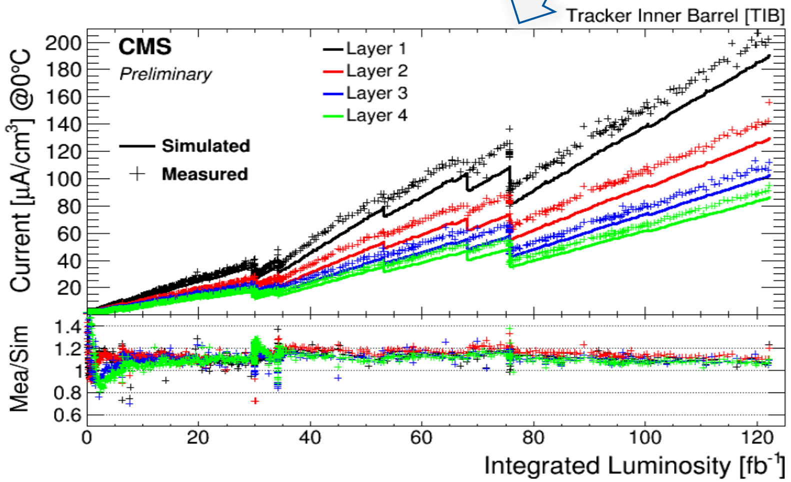


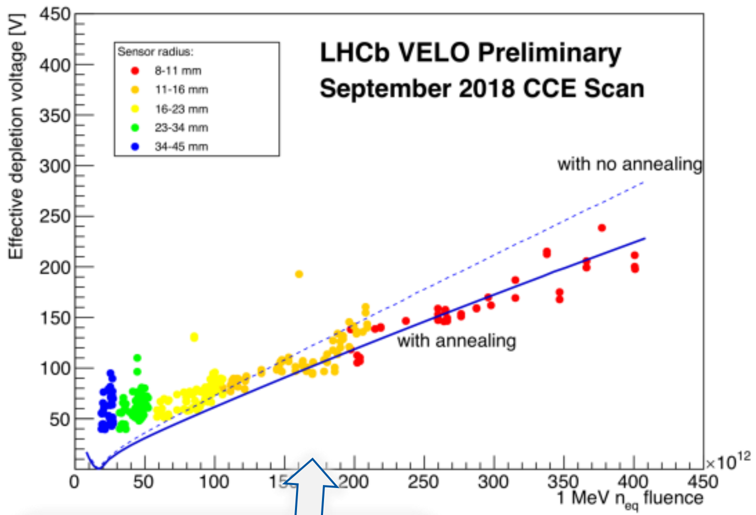
Radiation Effects in LHC Experiments

- Review of radiation effects in the LHC Experiments in several workshops [INDICO]
  - Common working group: RD50 & LHC experiments → Publication of a summary report in April 2021 [CERN Yellow Report link]

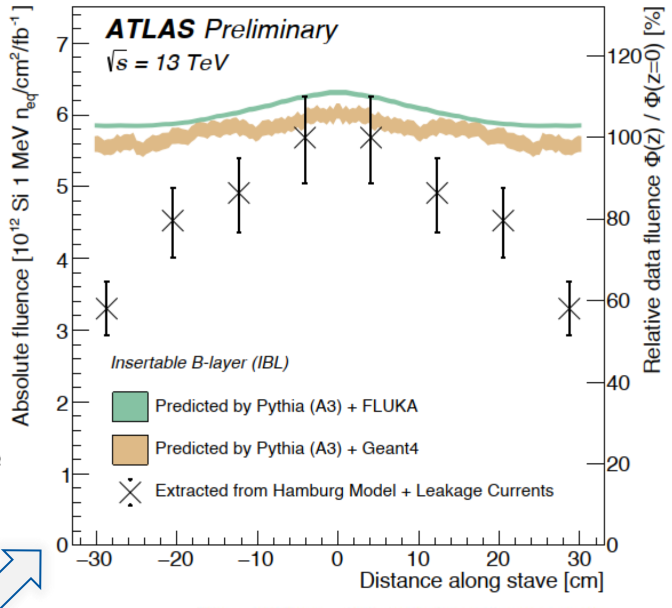


Leakage currents in **ATLAS SCT** and **CMS tracker** and model predictions

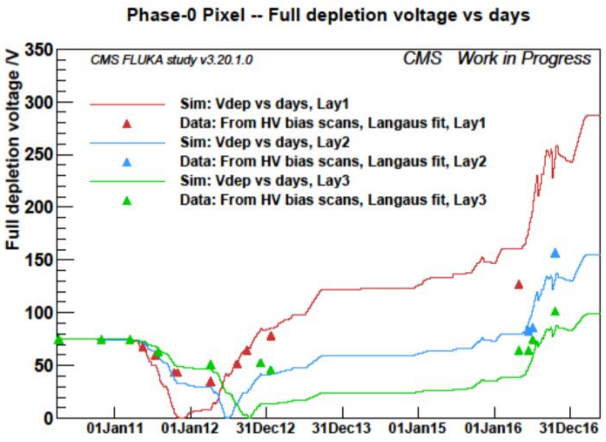




LHCb Velo depletion voltage reduced by annealing; according to model



ATLAS B-layer
data vs. MC&NIEL
strong z-dependence;
unexpected



CMS pixel layers;
deviation of V_{dep} from modelling at high fluences

Plots: Radiation Effects Workshop Feb.2019
K.Mochizuki(ATLAS SCT) J.L.Agram (CMS Tracker), Aiden Grummer (ATLAS Pixel) , G.Sarpis (LHCb Velo) , F.Feindt (ATLAS Pixel)

How to increase the radiation hardness?

Approaches to develop radiation harder solid state tracking detectors

SIMDET 2023 — 5th school on silicon detectors simulation

Scientific strategies:

I. Material engineering

II. Device engineering

III. Change of detector operational conditions

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

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