SIMDET 2016, 05-07 September 2016, LPNHE Paris

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

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Detector Technologies

Outline

- **I. Basics of Silicon Detectors for High Energy Physics Applications**
  - **The basic concept of Semiconductor Detectors: A reverse biased pn-junction**
  - **Silicon Detectors at the Large Hadron Collider (LHC) at CERN**
  - **Upgrade of the Large Hadron Collider**
    - Timeline, challenges & motivation to study and understand radiation damage
  - **Recent developments**
    - MAPS sensors and sensors with intrinsic gain for harsh radiation environments

- **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 Mathieu Benoit and Geetika Jain

- **Summary & Further reading**

I.Basic operation principle of a silicon sensor

Solid State Detectors – Why silicon?

- Some characteristics of silicon crystals
  - **Small band gap** E_g = 1.12 eV ⇒ E(e-h pair) = 3.6 eV (≈ 30 eV for gas detectors)
  - **High specific density** 2.33 g/cm^3 ; dE/dx (M.I.P.) ≈ 3.8 MeV/cm ≈ 10^6 e-h/µm (average)
  - **High carrier mobility** μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs ⇒ fast charge collection (<10 ns)
  - **Very pure** < 1ppm impurities and < 0.1ppb electrical active impurities
  - **Rigidity** of silicon allows thin self supporting structures
  - **Detector production by microelectronic techniques**

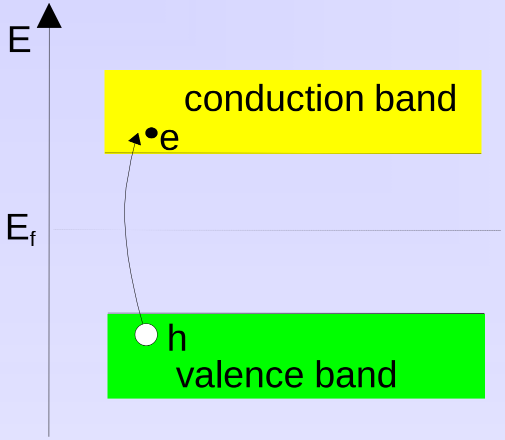
    ⇒ well known industrial technology, relatively low price, small structures easily possible

    ⇒ sophisticated commercial TCAD tools available for sensor simulation

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

	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
E(e-h pair) [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.515	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

How to obtain a signal?

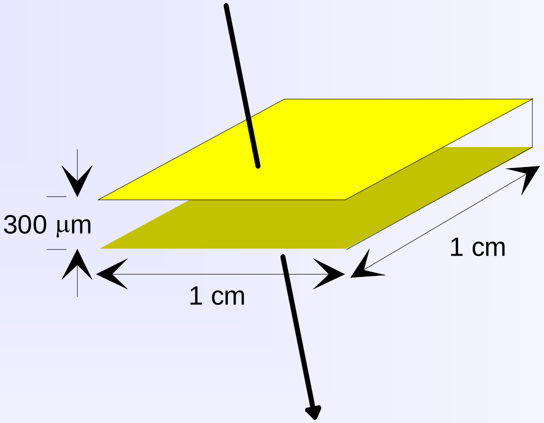


- **Intrinsic semiconductor**
  - In a pure intrinsic (undoped) semiconductor the electron density n and hole density p are equal.

$$n = p = n_i$$

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

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

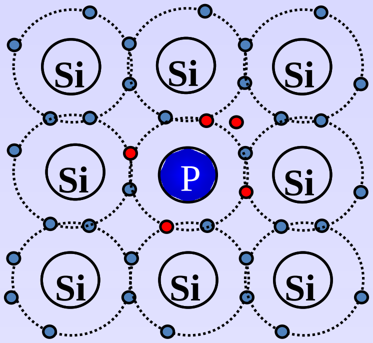


➢ **Need to reduce number of free carriers, i.e. deplete the detector**

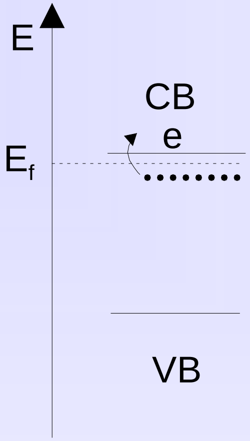
➢ **Solution: Make use of reverse biased p-n junction (reverse biased diode)**

Doping, Resitivity and p-n junction

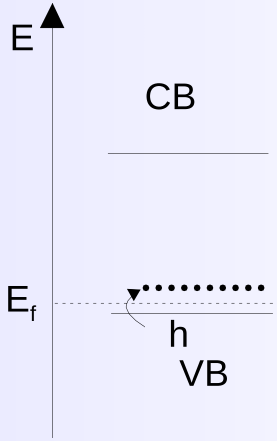
e.g. Phosphorus



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



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



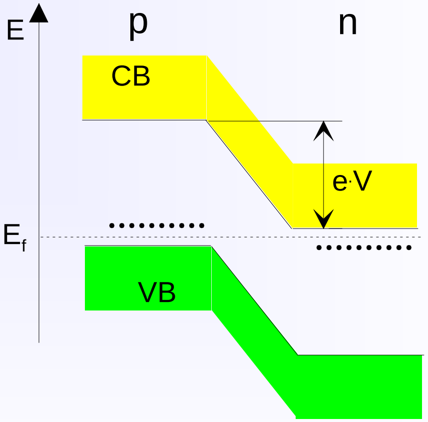
- **Resistivity**
  - carrier concentrations *n, p*
  - carrier mobility μ_n, μ_p

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

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

- **p-n junction**
  - There must be a single Fermi level !

⇒ band structure deformation
⇒ potential difference
⇒ depleted zone



Abrupt junction – Depletion depth

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

Poisson equation

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

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

$$\boxed{E(w) = 0}$$

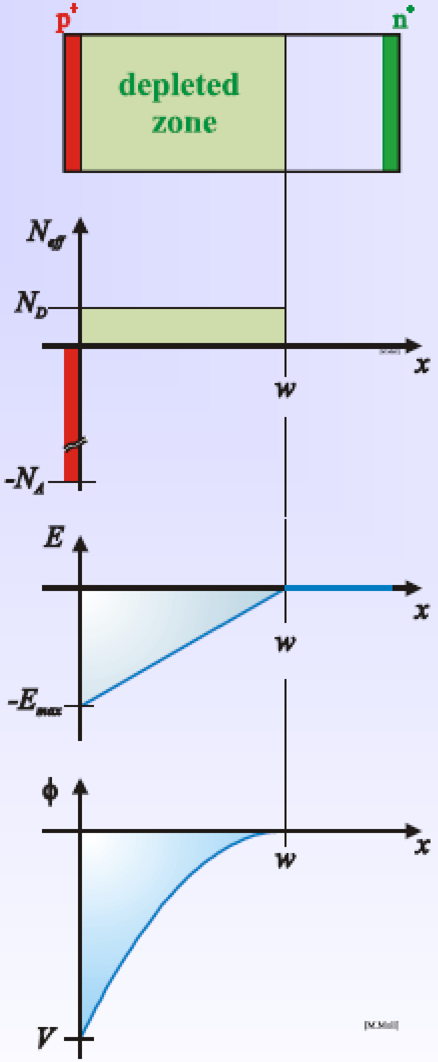
Electric field strength

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

$$\boxed{\phi(w) = 0}$$

Electrostatic potential

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



- electric field strength linear function of depth
- depleted zone growing in depth proportional to sqrt(V)

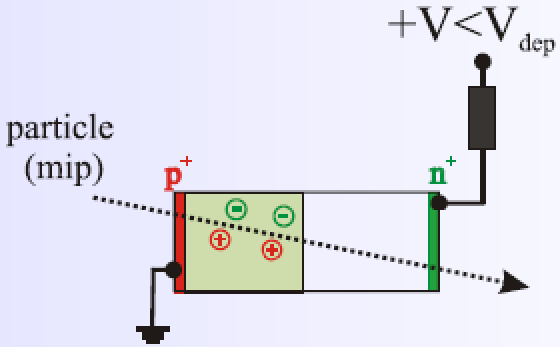
$$\boxed{E_{max} = -\frac{e \cdot N_{eff}}{\varepsilon} \cdot w}$$

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

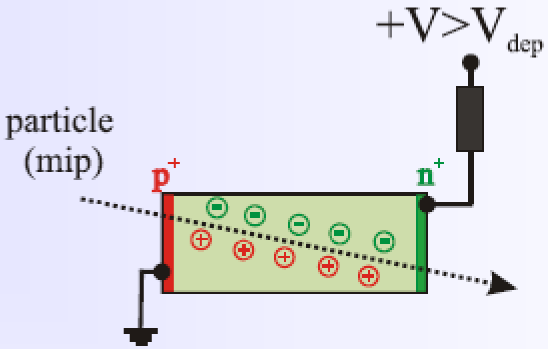
Depletion depth w

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:
    - $d = 300\ \mu m$
    - $N_{eff} = [P] = 1.5\times10^{12}\ cm^{-3}$ ($\rho \approx 3k\Omega cm$)
    - $V_{dep} \approx 100V$



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

depletion voltage V_{dep}

detector thickness d

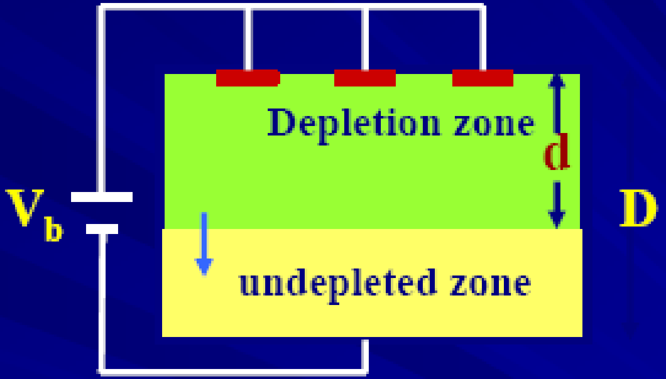
$$\boxed{V_{dep} = \frac{e}{2\cdot\varepsilon}\cdot\left|N_{eff}\right|\cdot d^2}$$

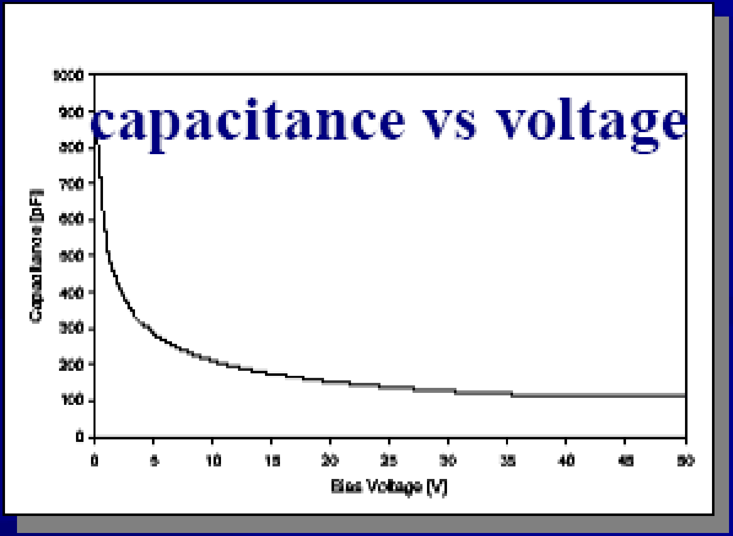
effective space charge density N_{eff}

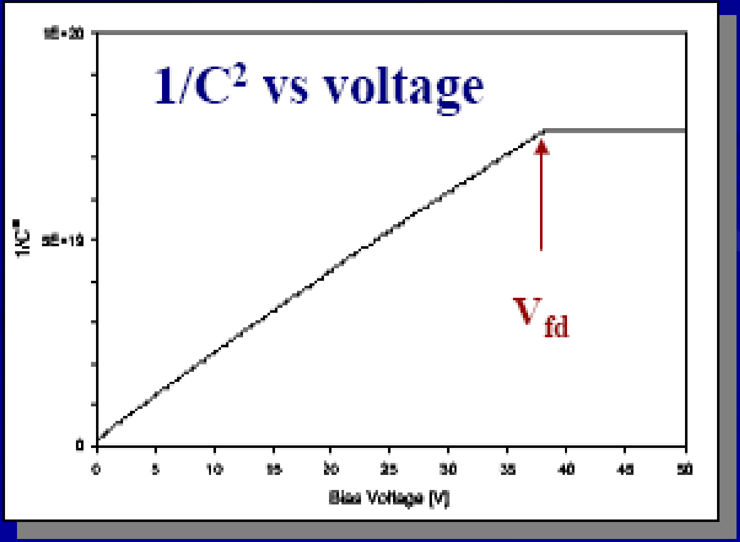
Depletion Zone: Properties

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

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

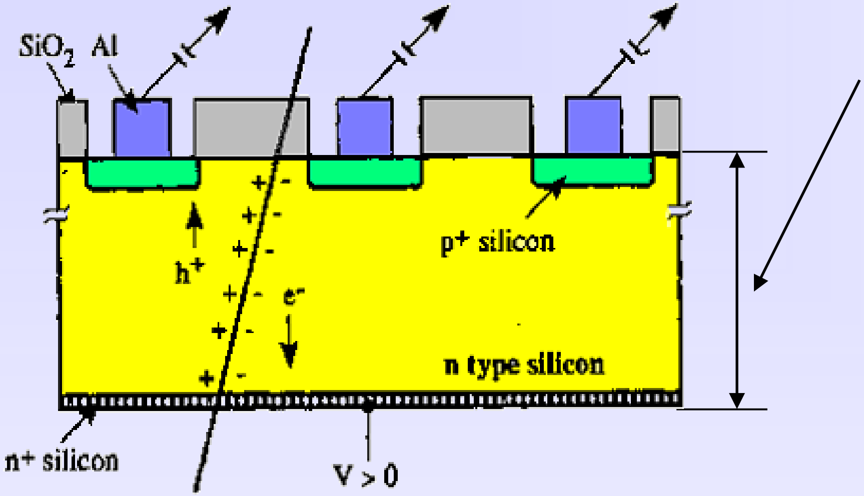






Single sided strip detector

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



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

- using n-type silicon with a resistivity of

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

results in a depletion voltage ~ 150 V

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

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

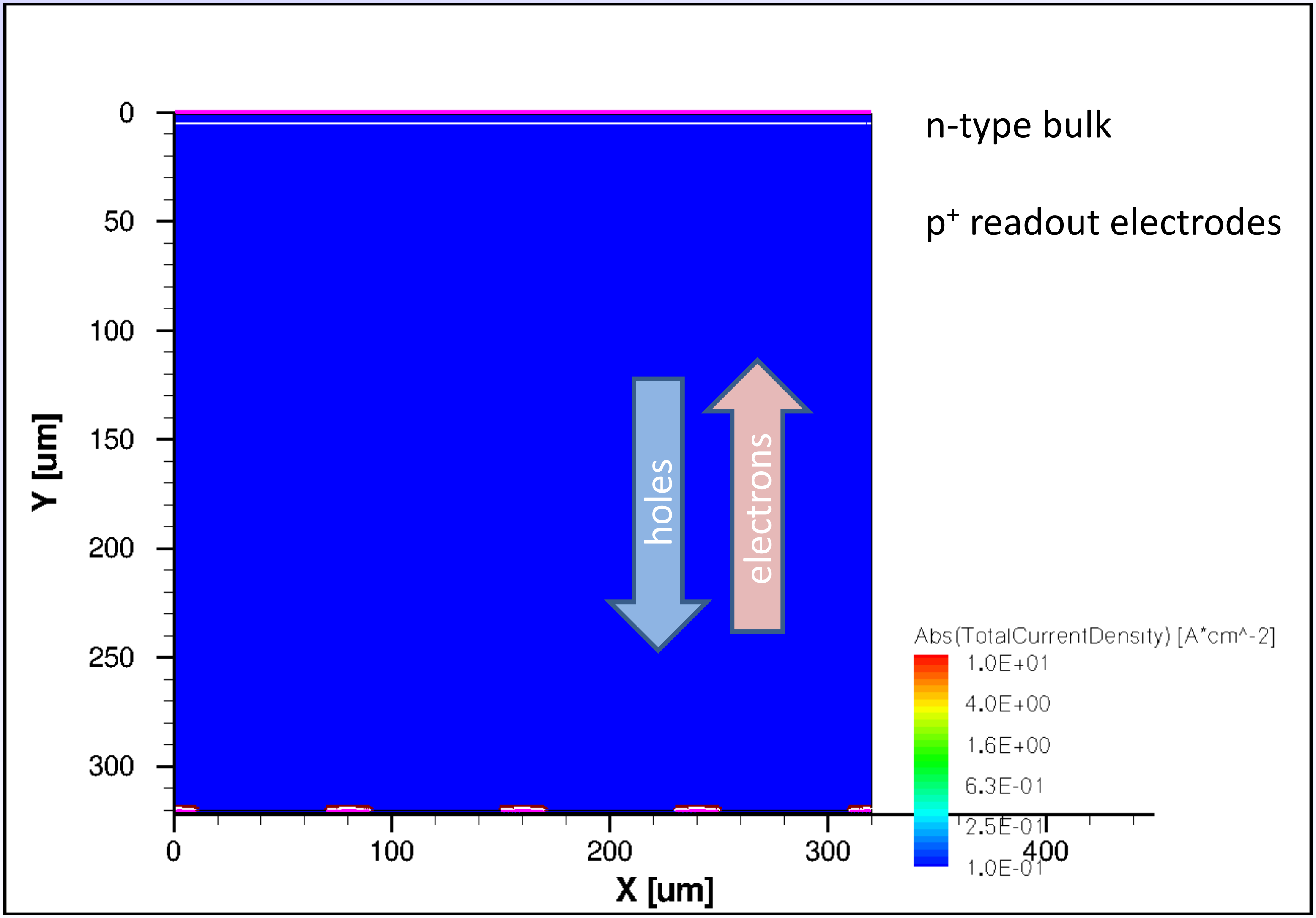
$$\sigma = \frac{p}{\sqrt{12}}$$

typical pitch values are 20 μm– 150 μm

⇒ 50 μm pitch results in 14.4 μm resolution

Signal formation in a strip sensor

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

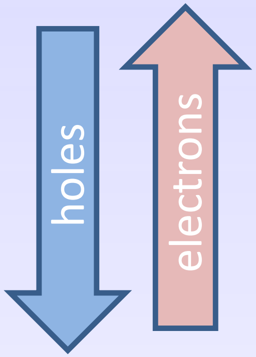


Simulation Thomas.Eichhorn@kit.edu

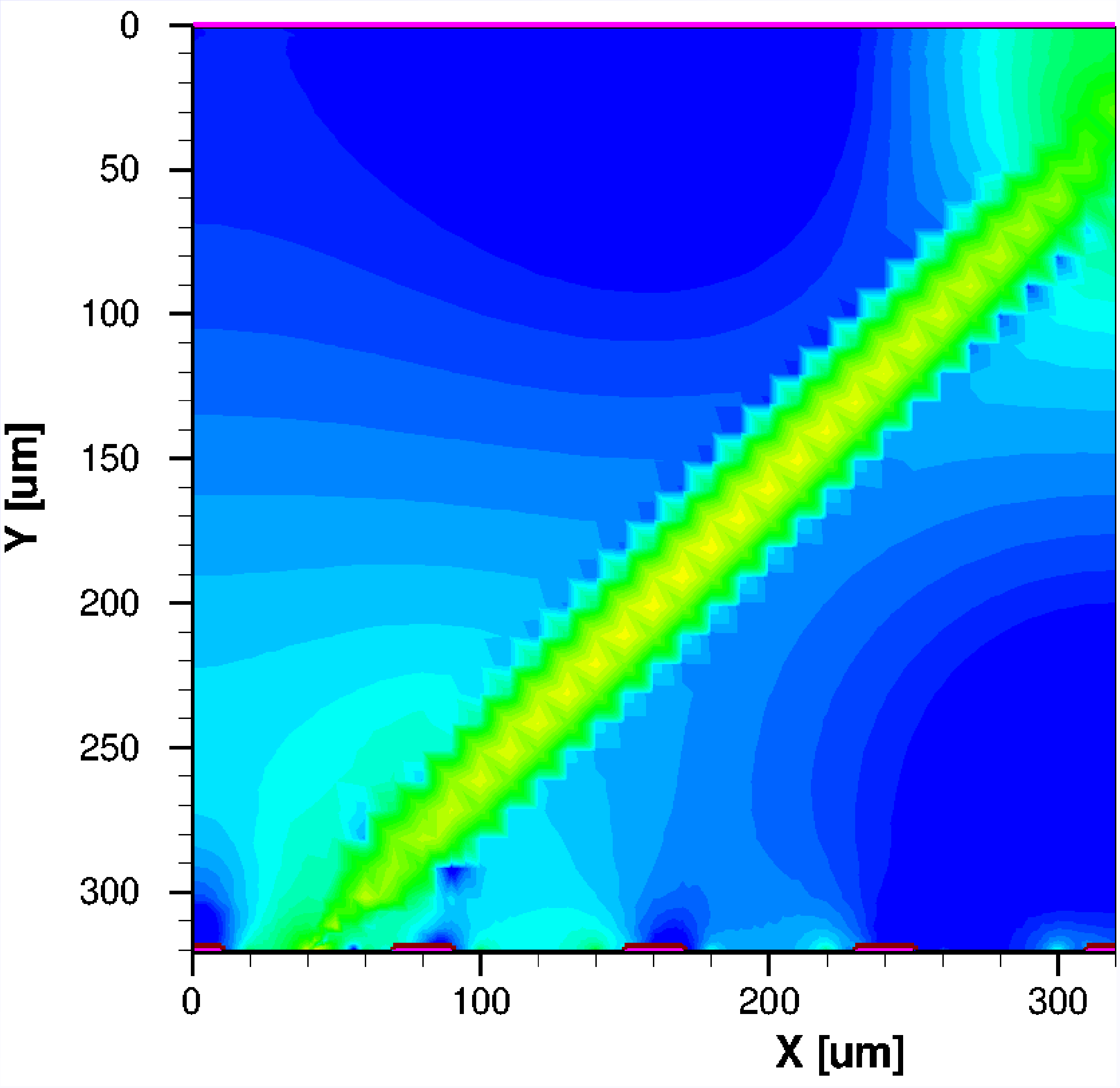
PhD thesis: Thomas Eichhorn 2015

Signal formation in a strip sensor

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



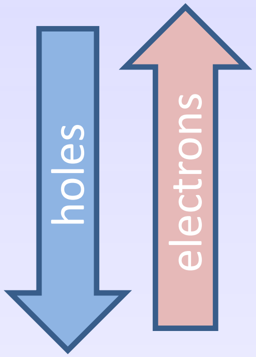
t = 1 ns



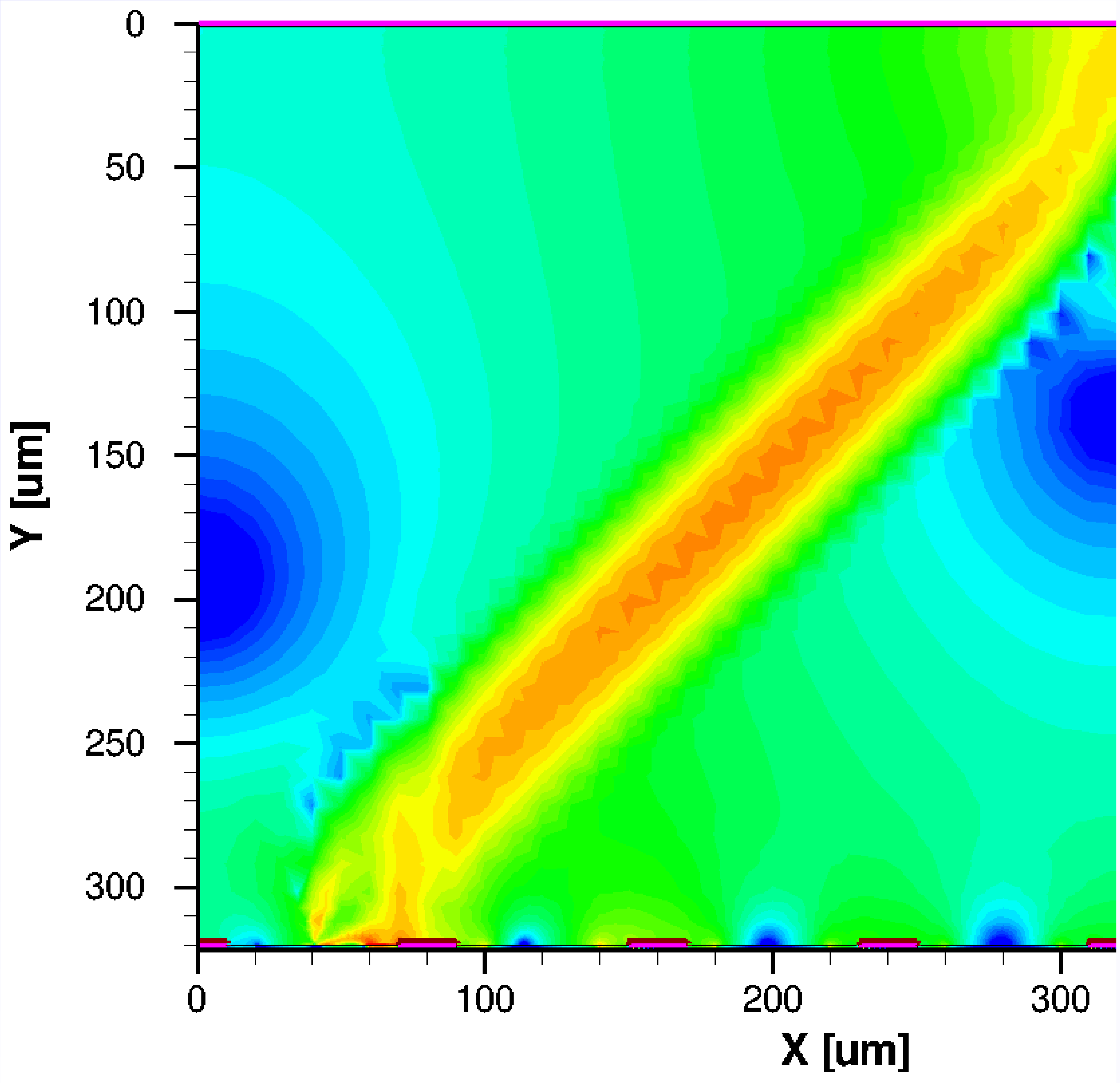
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



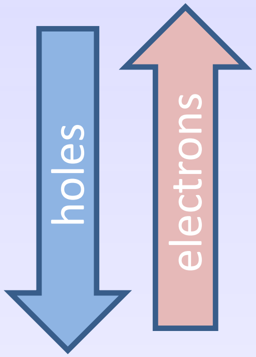
t = 1.2 ns



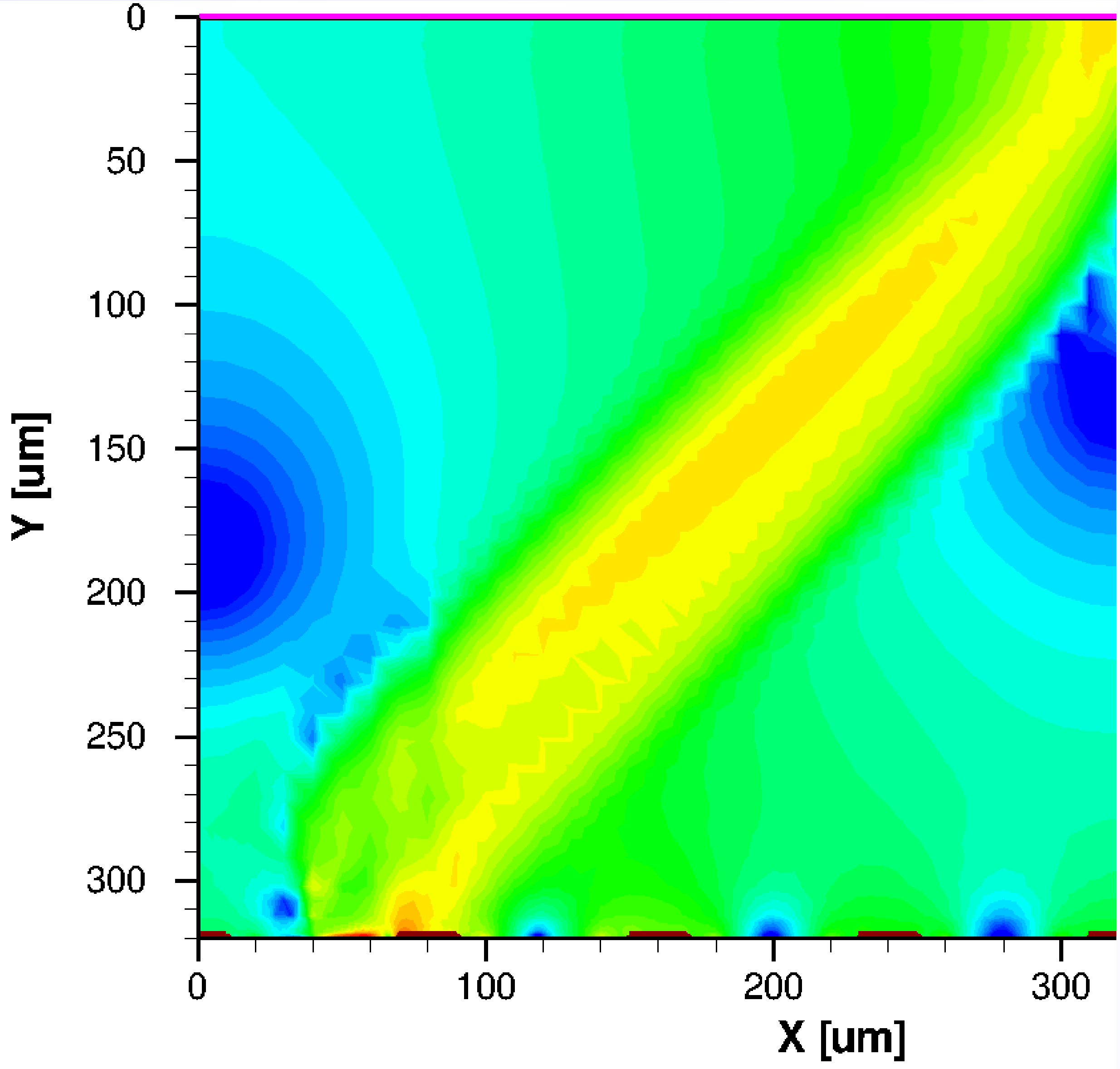
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



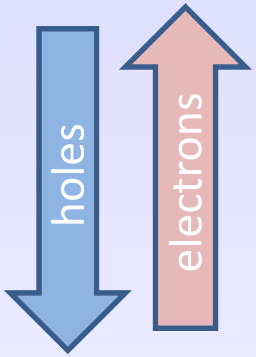
t = 1.4 ns



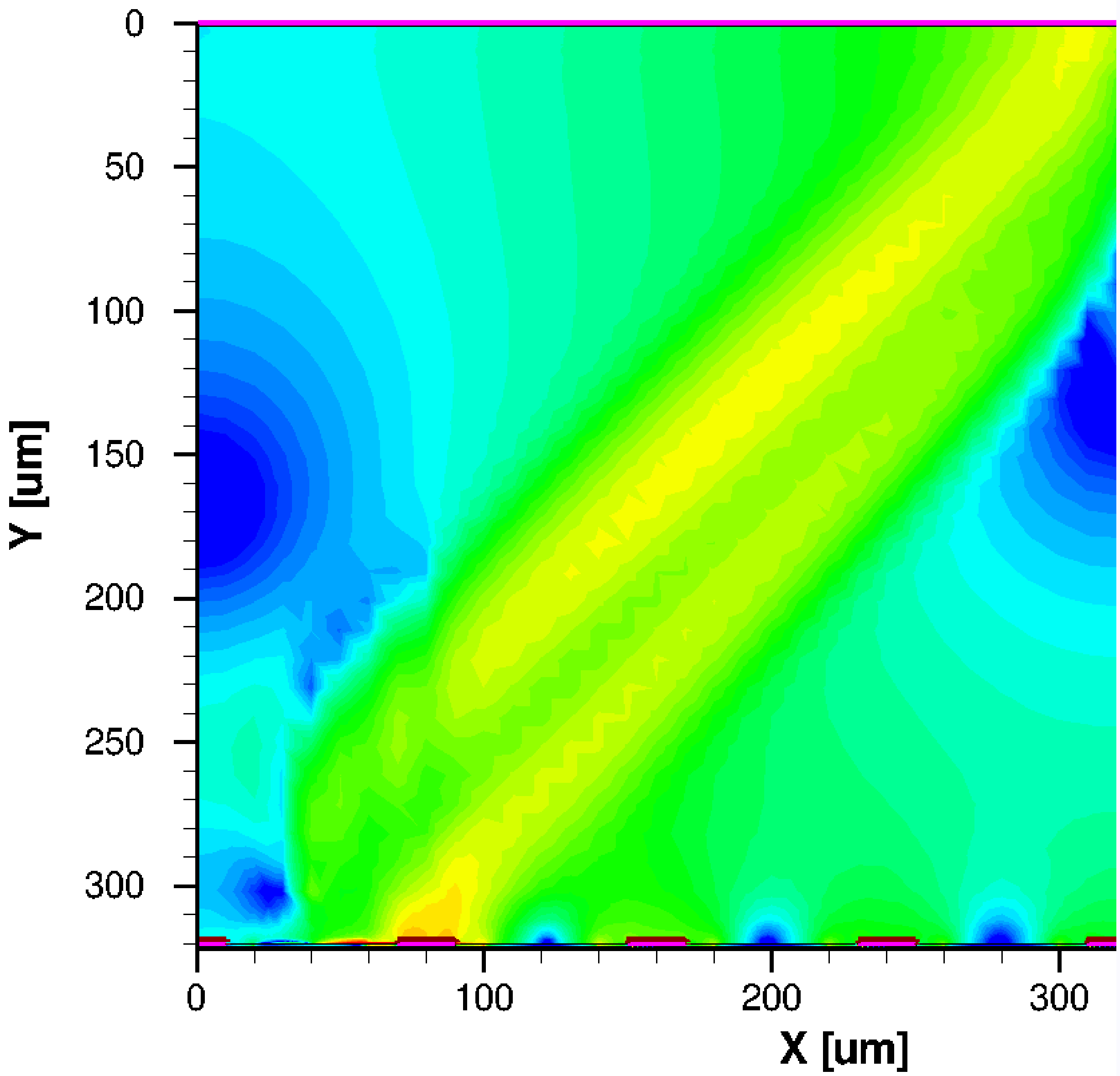
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



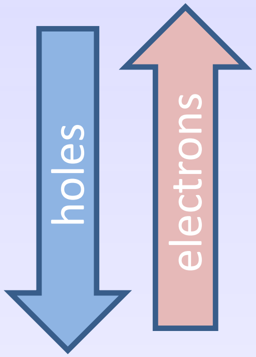
t = 1.6 ns



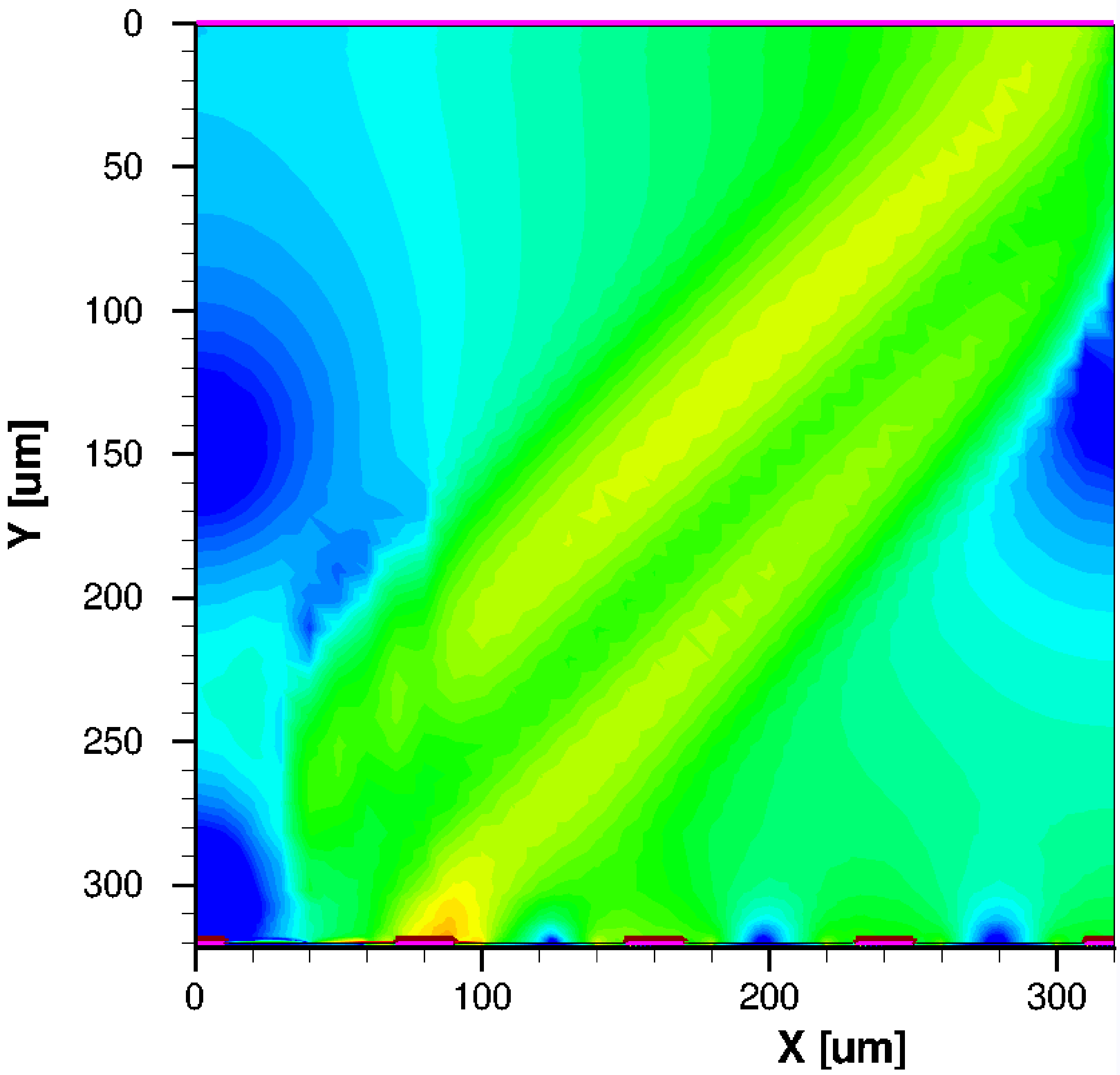
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



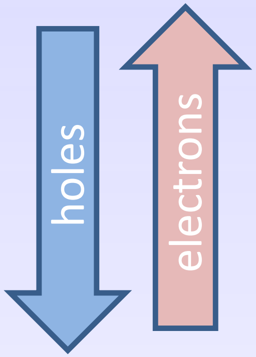
t = 1.8 ns



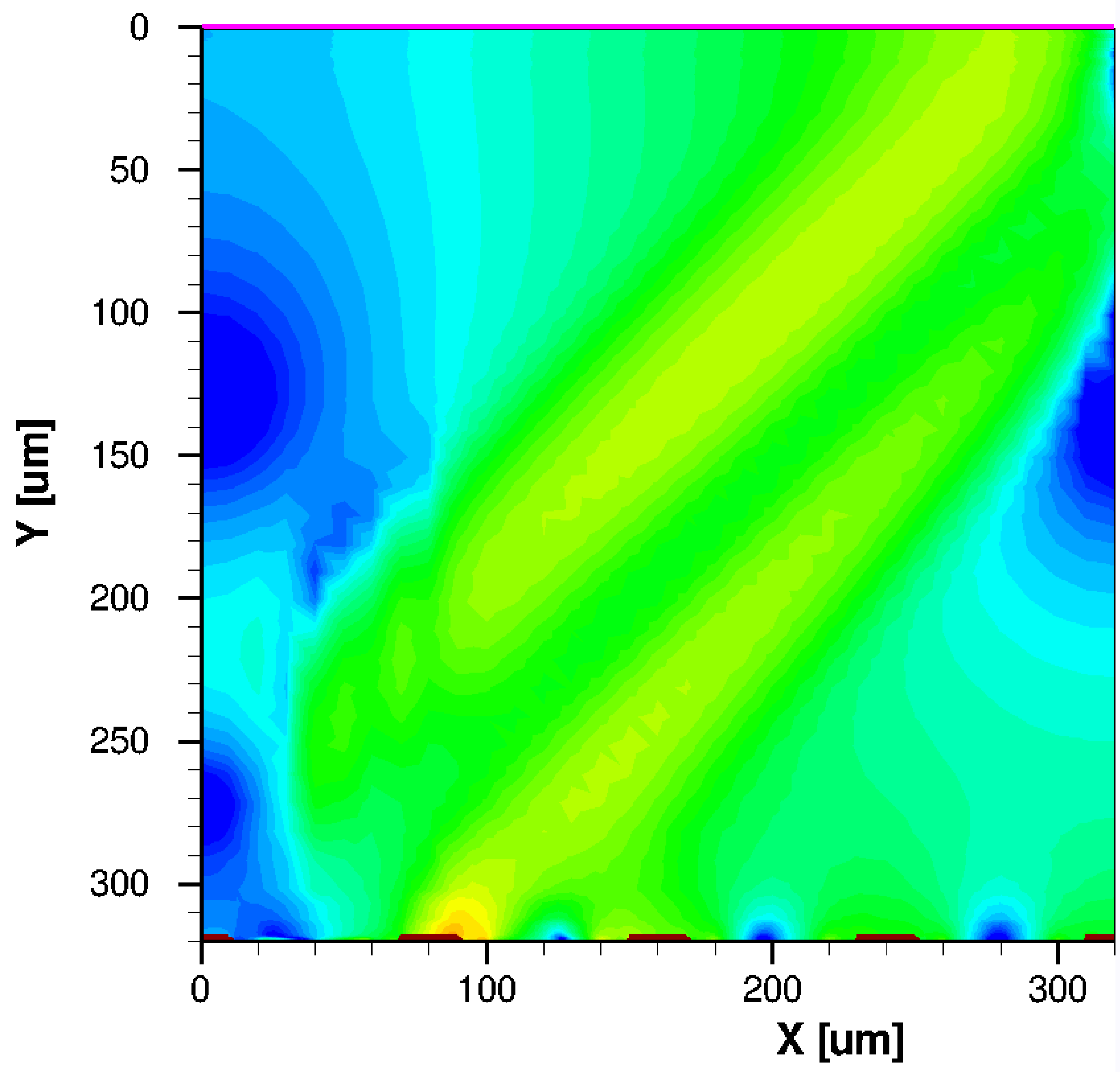
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



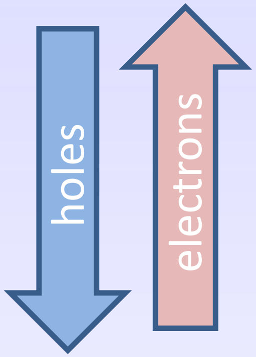
t = 2.0 ns



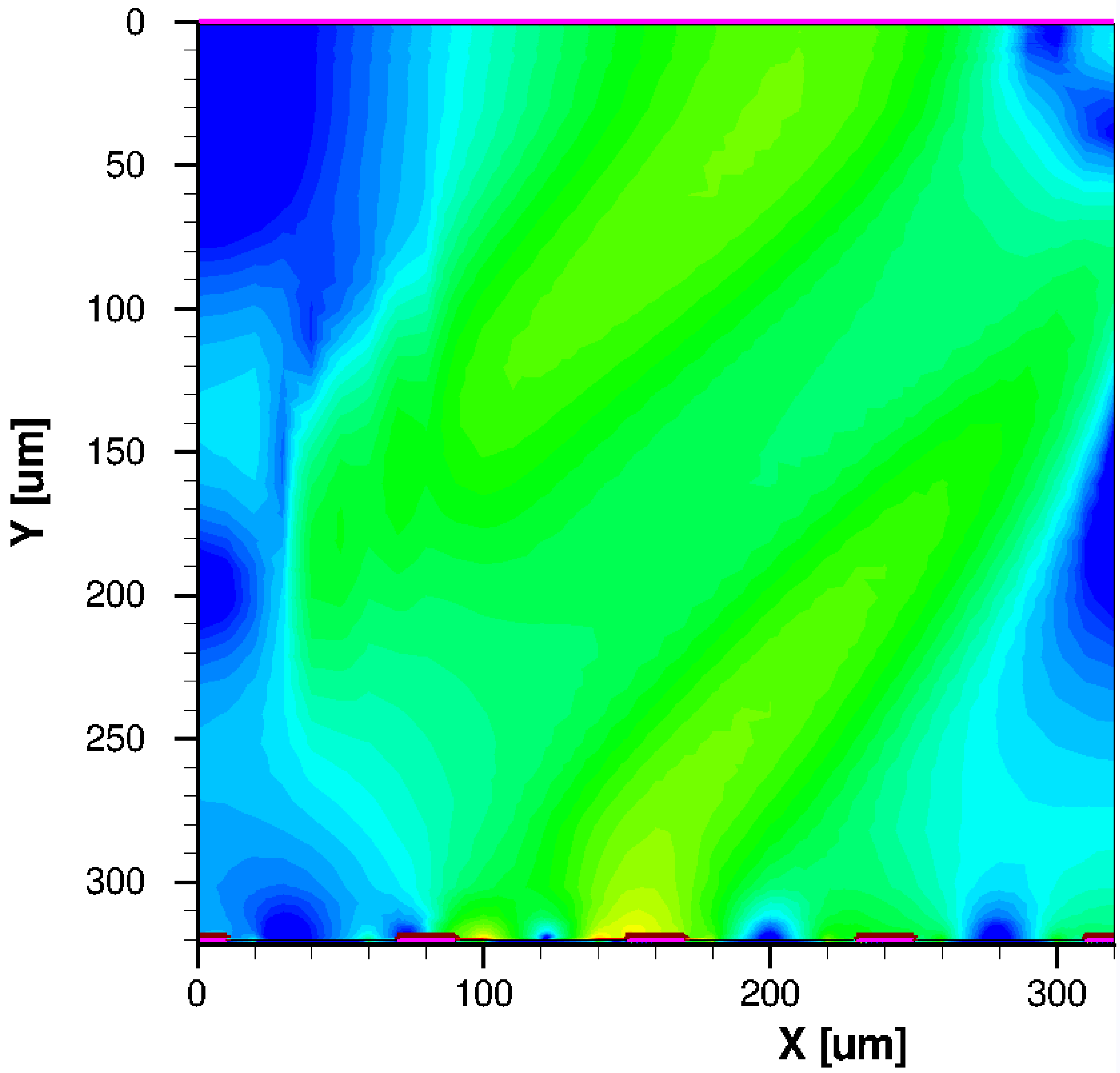
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



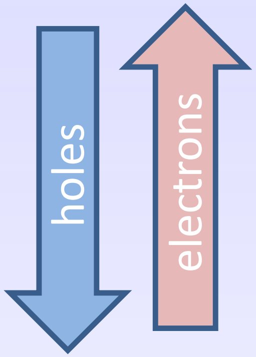
t = 3.0 ns



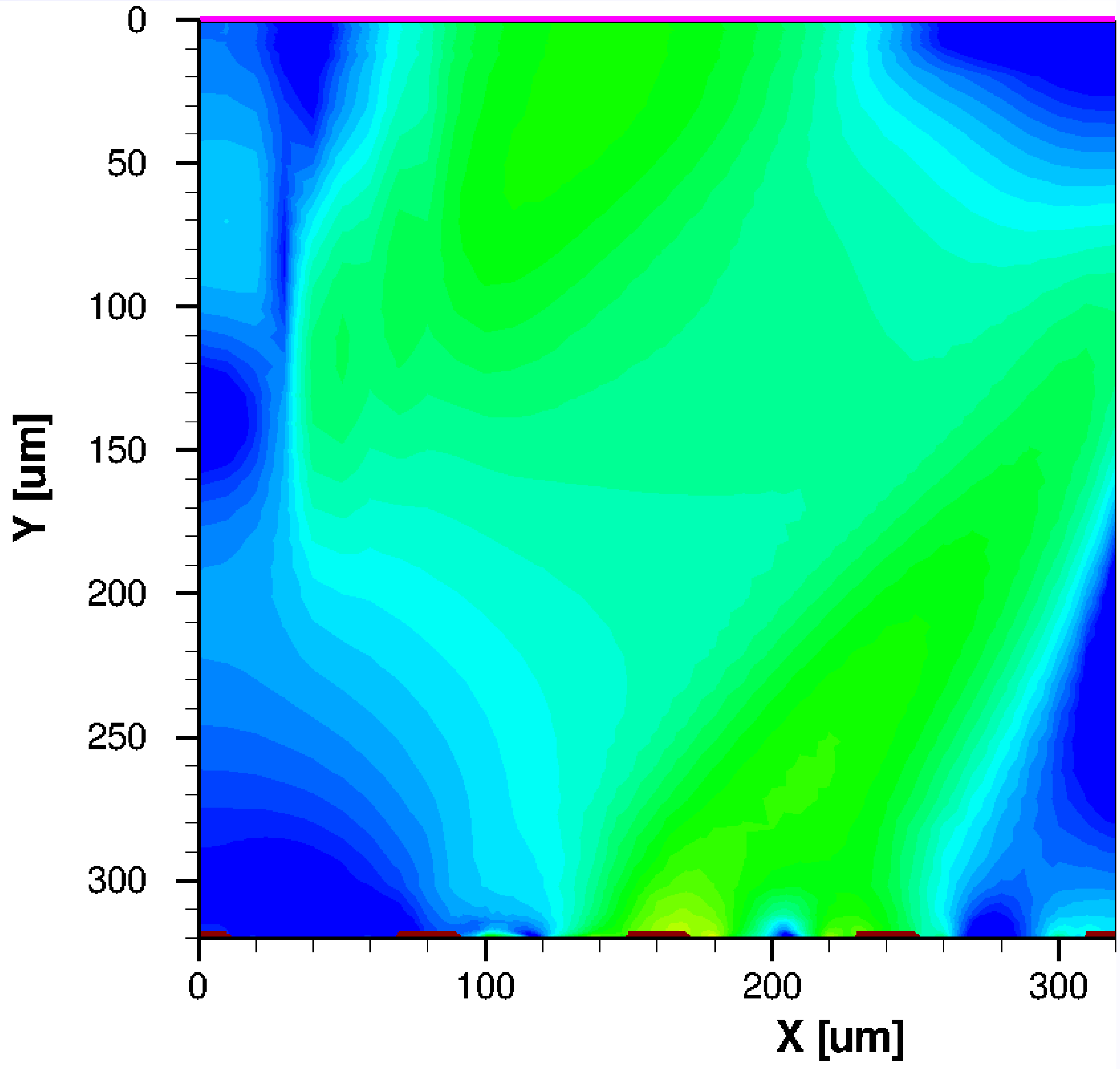
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



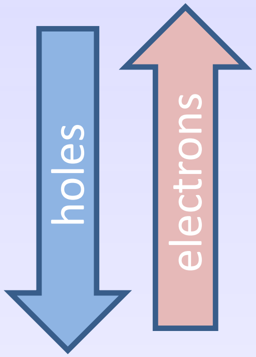
t = 4.0 ns



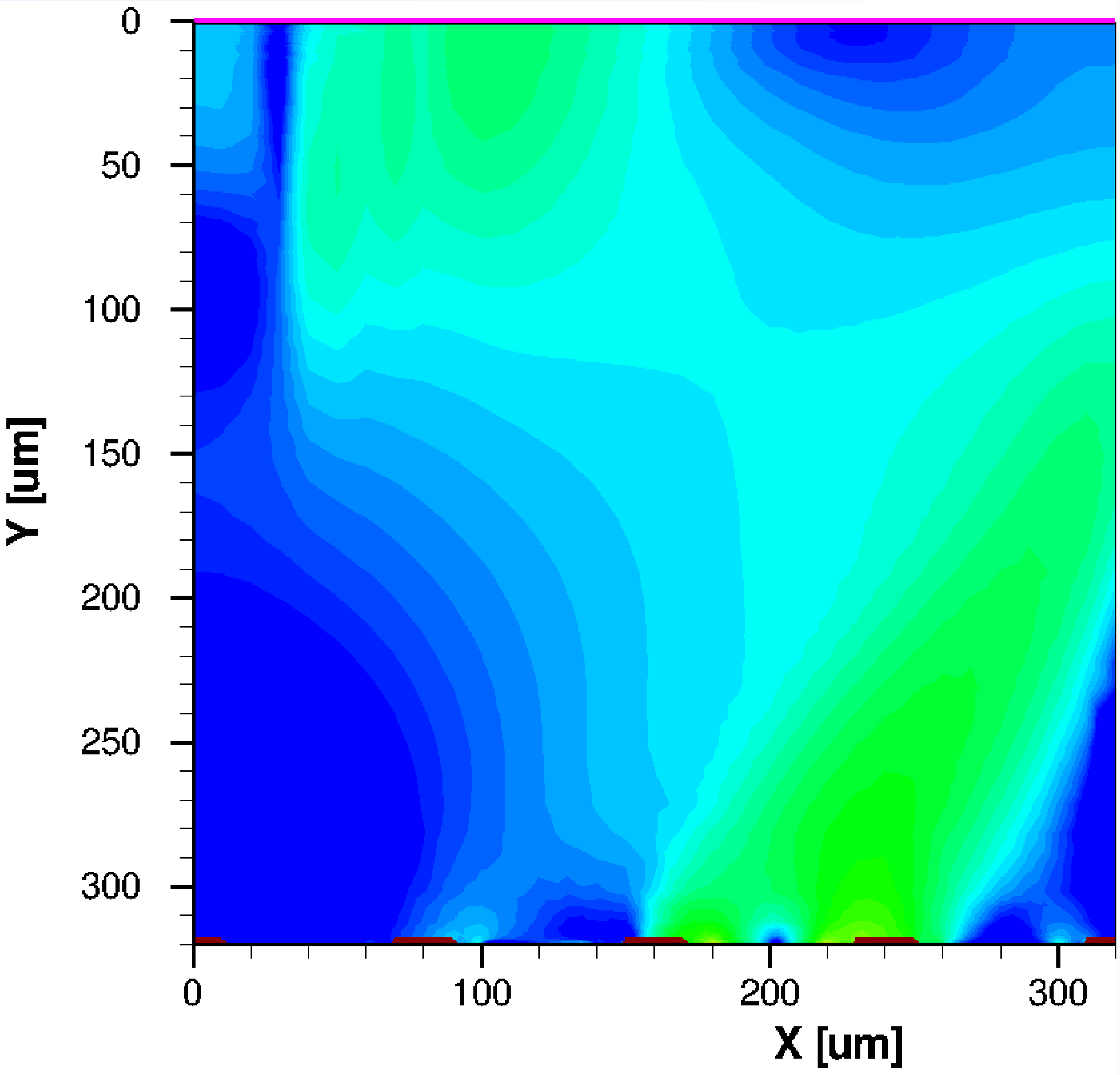
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



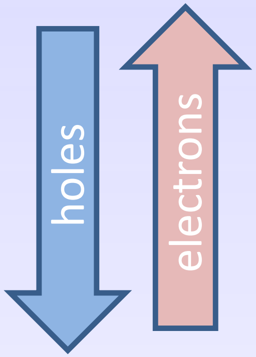
t = 5.0 ns



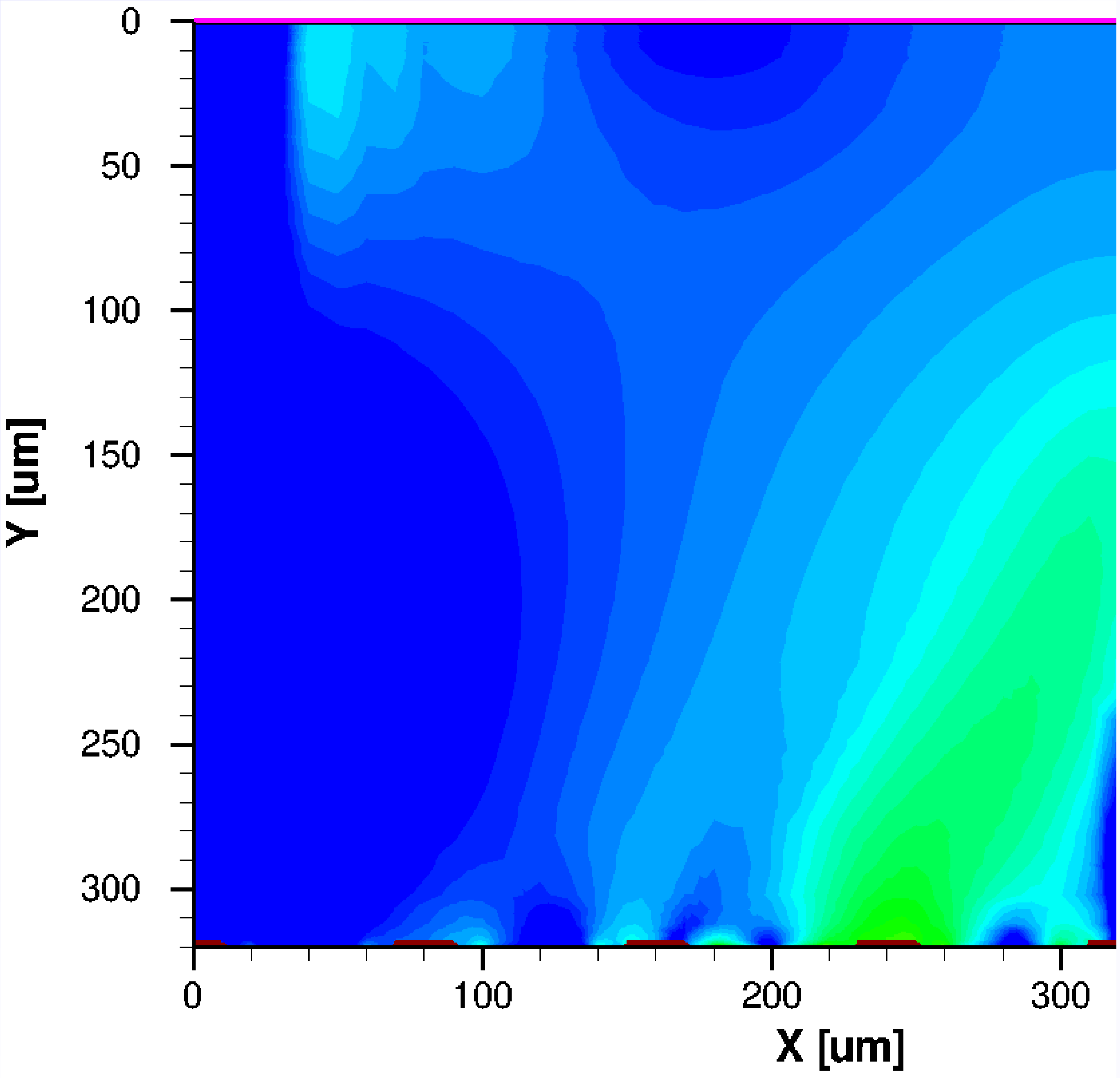
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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



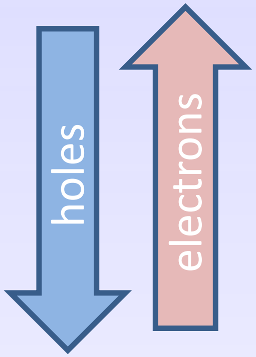
t = 6.0 ns



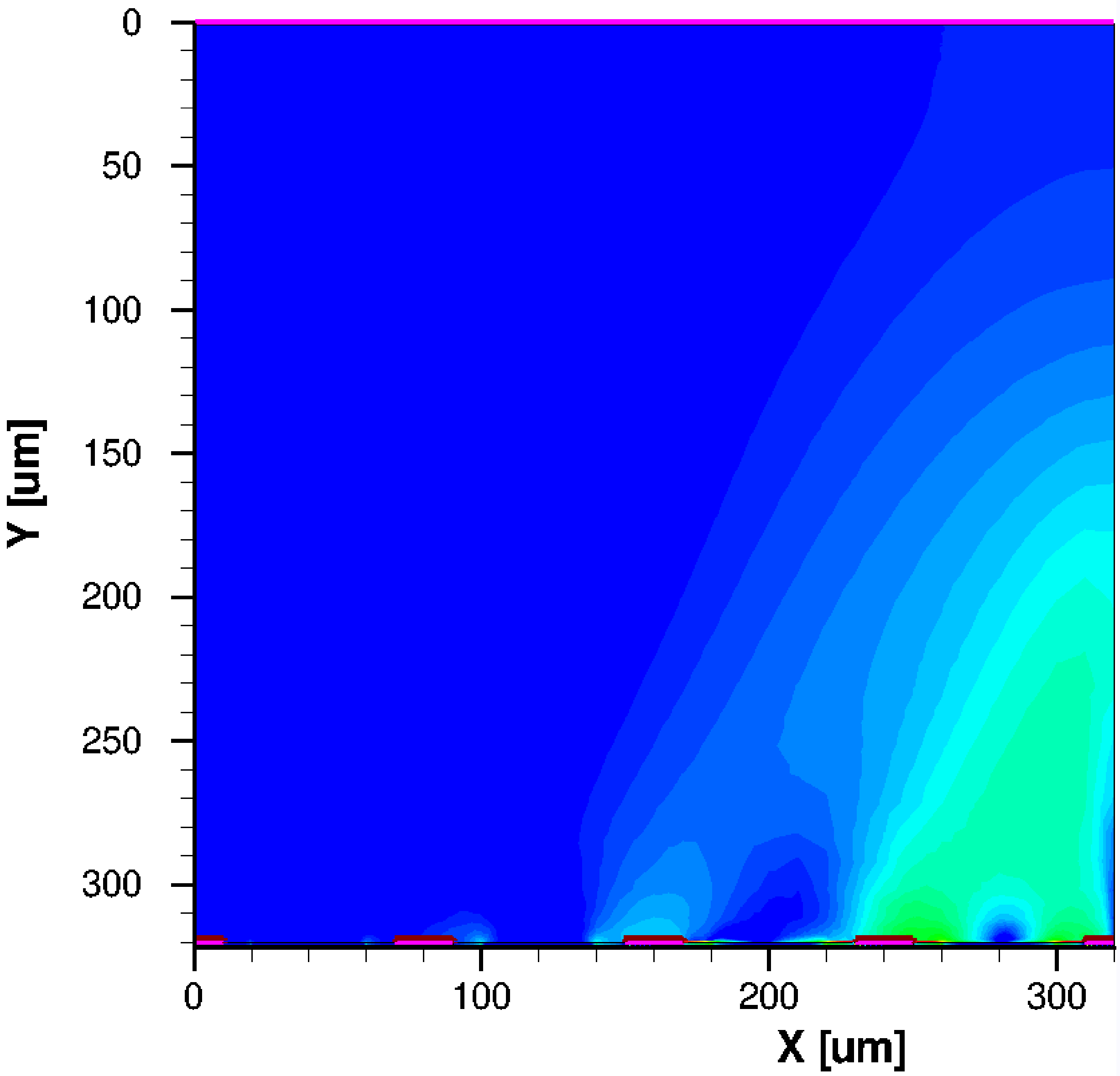
Simulation: Thomas.Eichhorn@kit.edu

Signal formation in a strip sensor

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

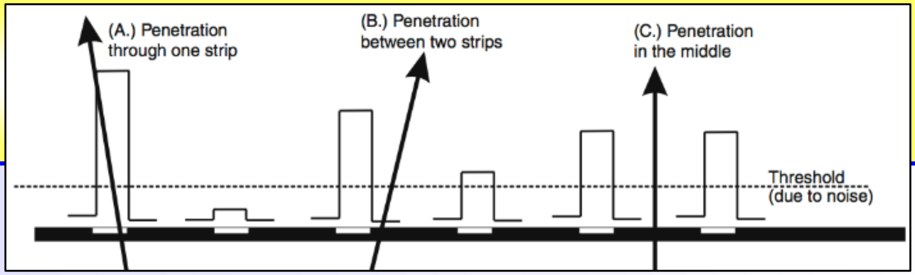


t = 7.0 ns

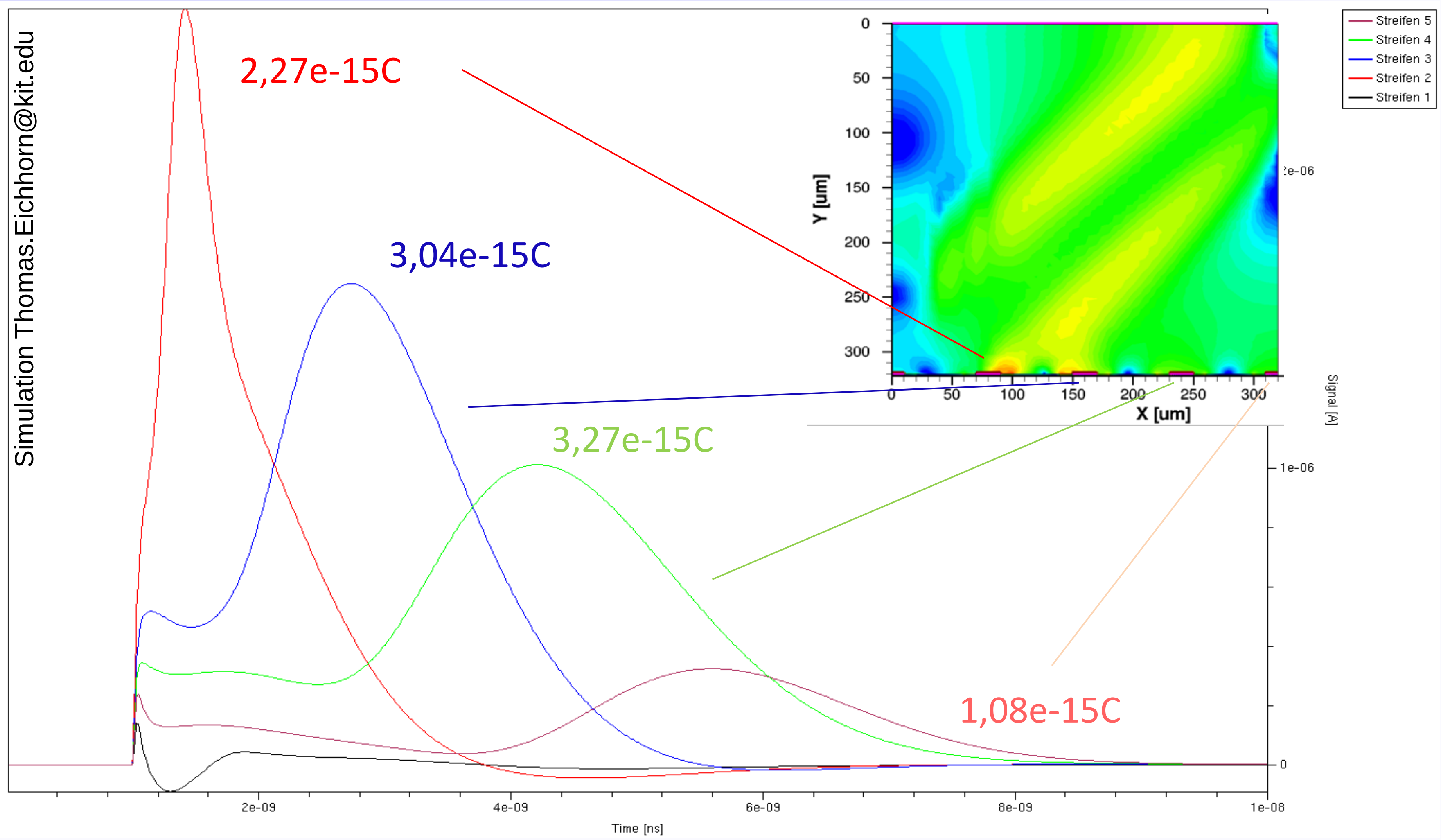


Simulation: Thomas.Eichhorn@kit.edu

Signal strip sensor



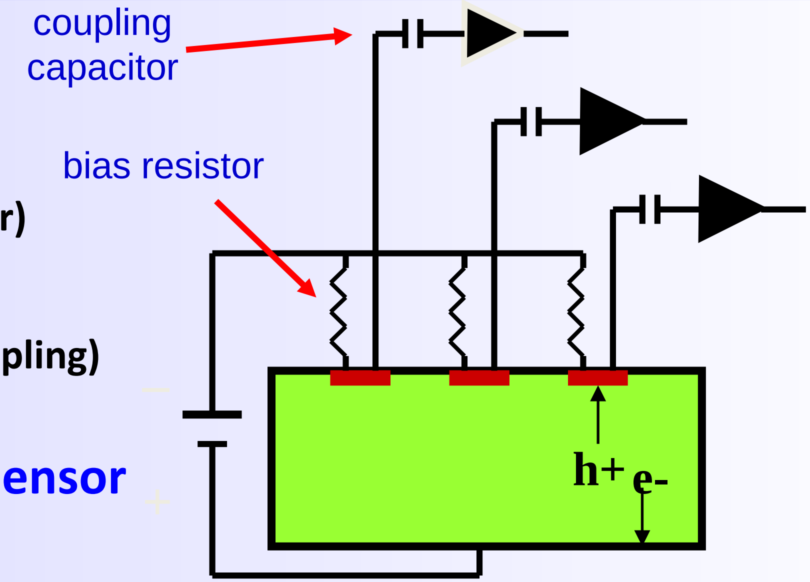
- **Simulation: mip, 45° angle**
  - **Signals induced on electrodes (Integration gives collected charge)**

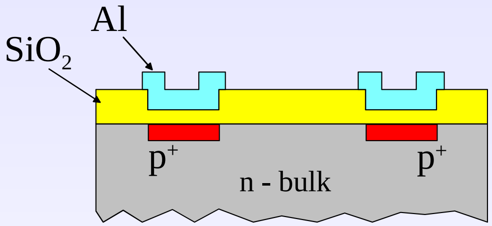


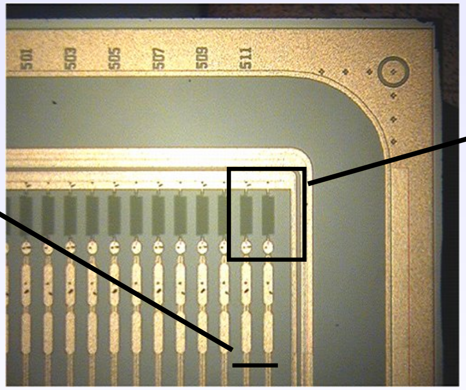
Simulation: Thomas.Eichhorn@kit.edu

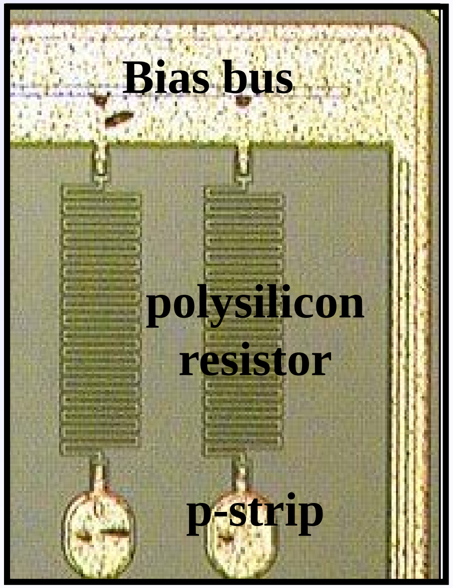
Bias resistor and AC Coupling

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









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

The Charge signal

Collected Charge for a Minimum Ionizing Particle (MIP)

- Mean energy loss

  dE/dx (Si) = 3.88 MeV/cm

  ⇒ 116 keV for 300µm thickness

- Most probable energy loss

  ≈ 0.7 ×mean

  ⇒ 81 keV

- 3.6 eV to create an e-h pair

  ⇒ 108 e-h / µm (mean)

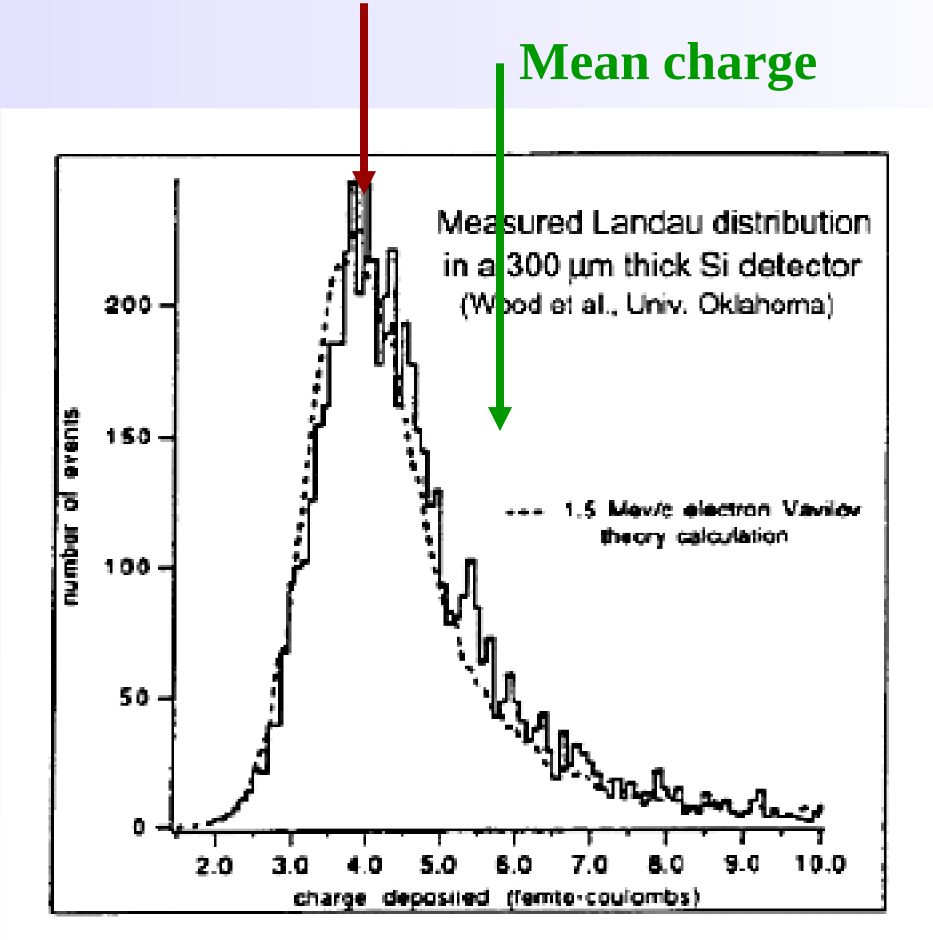
  ⇒ 72 e-h / µm (most probable)

- Most probable charge **(300 µm)**

  ≈ 22500 e **≈ 3.6 fC**

Most probable charge ≈ 0.7× mean

Mean charge



Signal to noise ratio (S/N)

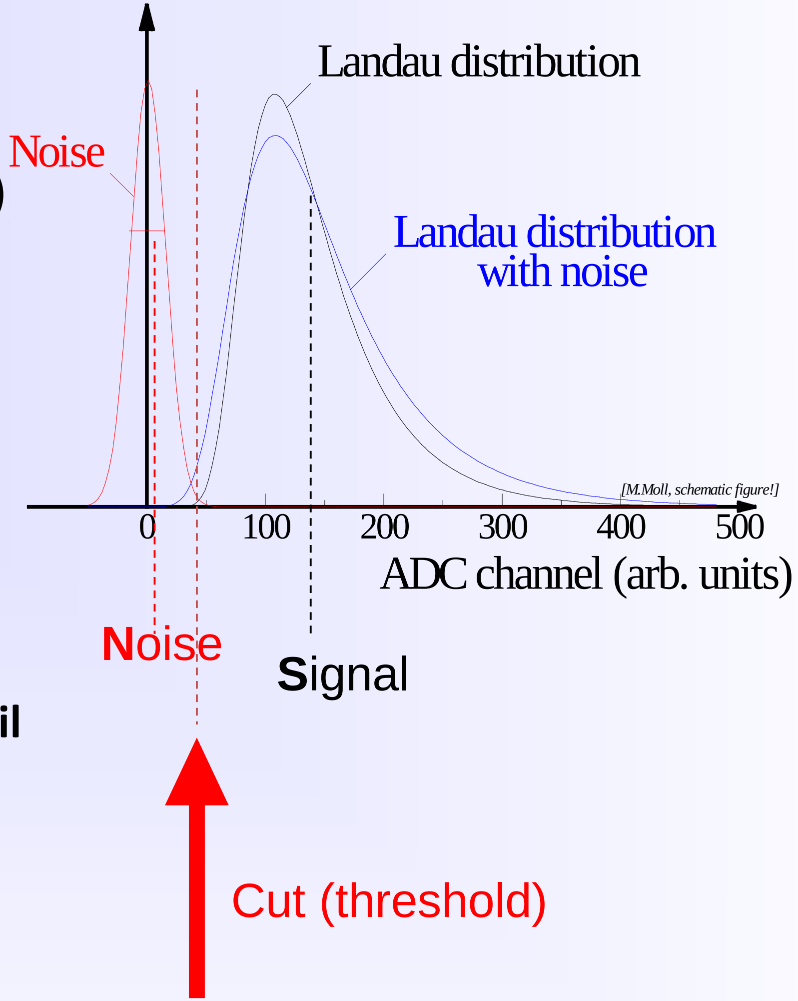
- **Landau distribution has a low energy tail**
  - **becomes even lower by noise broadening**

Noise sources: (ENC = Equivalent Noise Charge)

- Capacitance $ENC \propto C_d$

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

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



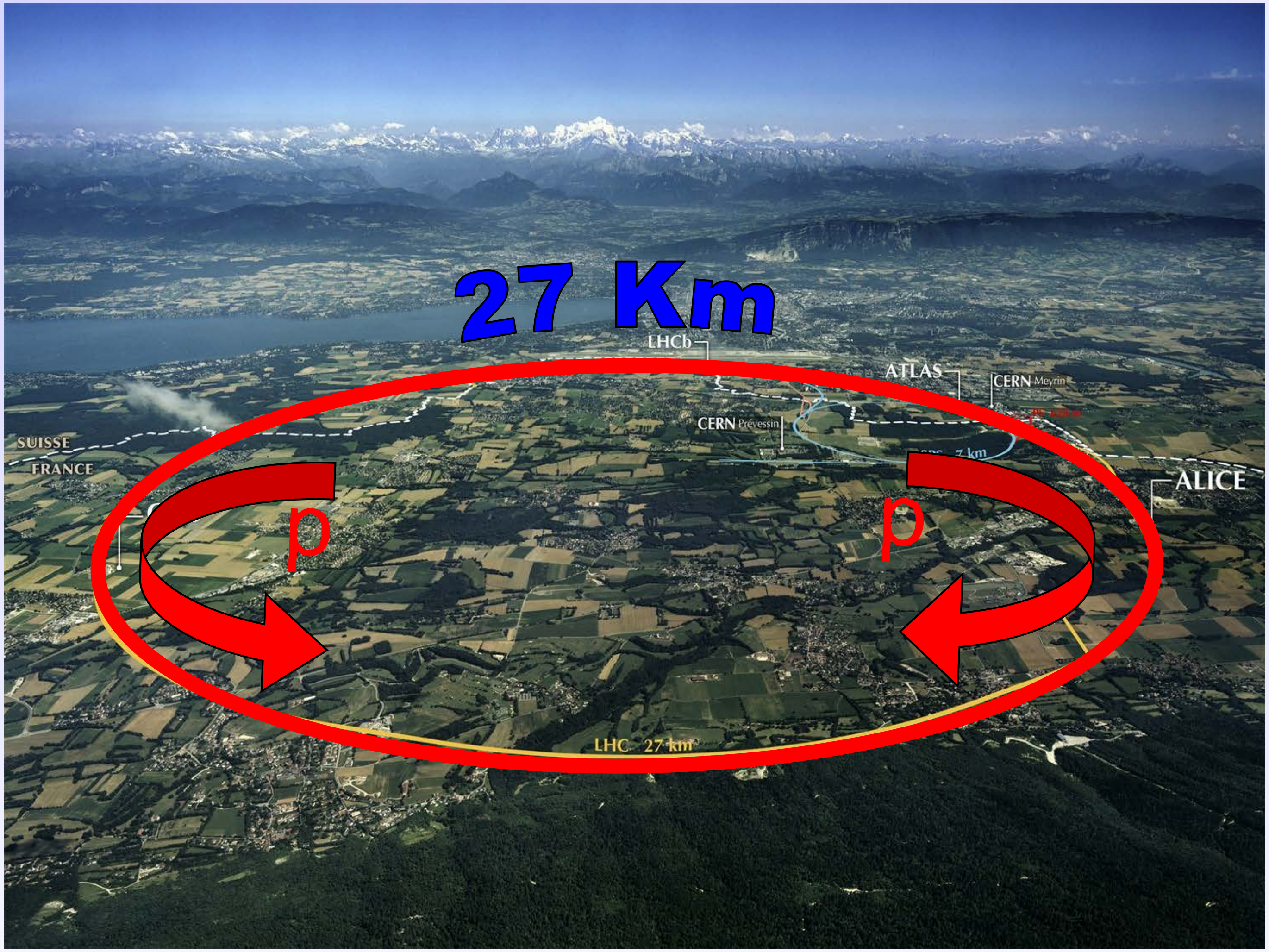
- **Good hits selected by requiring N_{ADC} > noise tail**
  If cut too high ⇒ efficiency loss
  If cut too low ⇒ noise occupancy

- **Figure of Merit: Signal-to-Noise Ratio S/N**

- **Typical values >10-15, people get nervous below 10.**
  Radiation damage severely degrades the S/N.

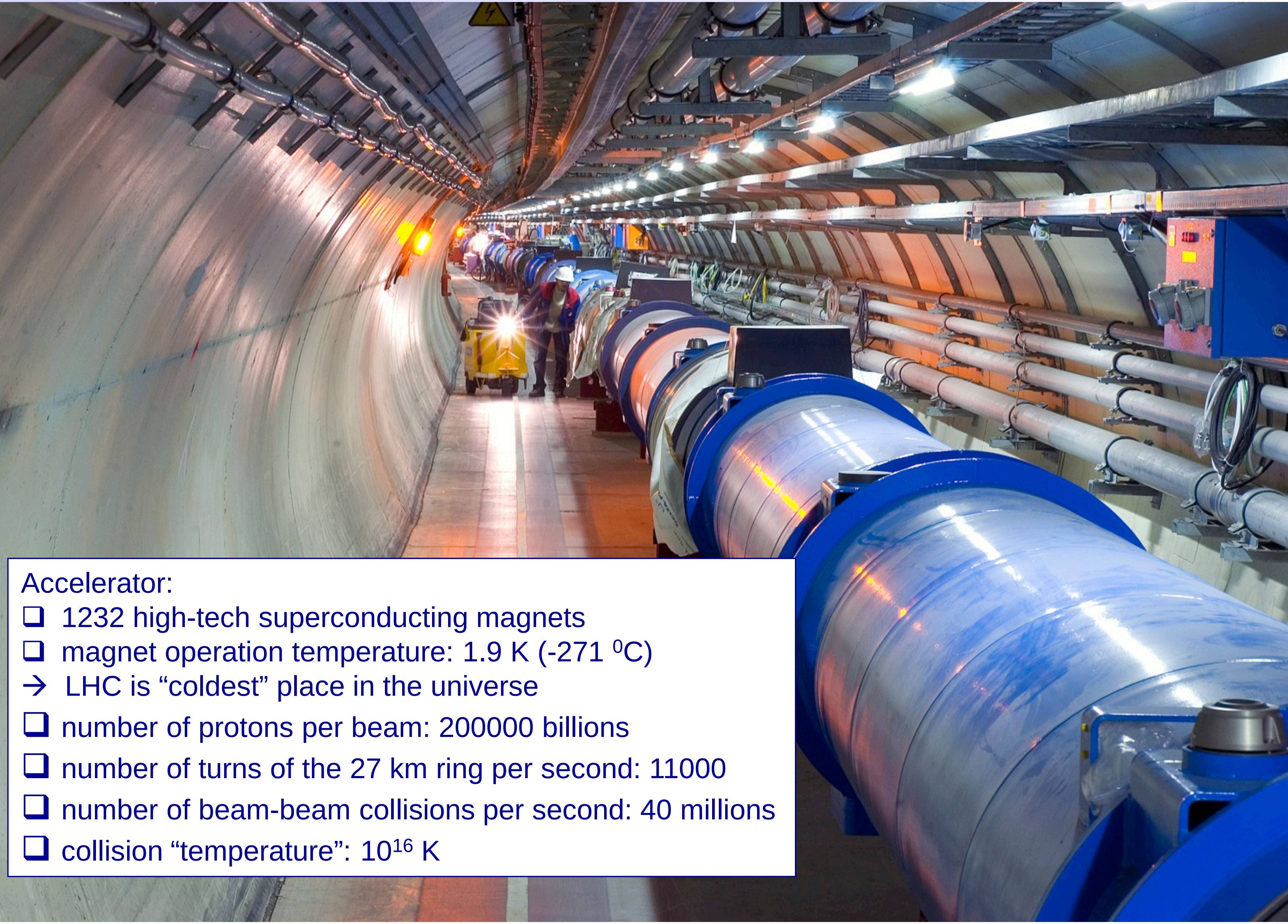
Silicon Detectors at the Large Hadron Collider at CERN

CERN & LHC - Large Hadron Collider



- LHC experiments located at 4 interaction points

- **CERN:**
  - 21 member states
  - ~12300 scientists (Users)
  - 3700 staff or paid personnel
  - Budget(2016) ~1000MCHF
- **LHC**: Installation in existing LEP tunnel (27 Km)
  - ≈ 4000 MCHF (machine+experiments)
  - 1232 dipoles B=8.3T
  - pp $\sqrt{s}$ = 14 TeV
    $L_{design} = 10^{34}$ cm^{-2} s^{-1}
  - Heavy ions
    (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)
- **Circulating beams: 10.9.2008**
- **Incident: 18.9.2008**
- **Beams back: 19.11.2009**
- **2012: reaching 2 x 4 TeV**
- **2015: Run 2 at 2 x 6.5 TeV**
- **2016: Reaching10^{34} cm^{-2} s^{-1}**
  …excellent performance!
- **….2018: LS2..2020: Run 3**
- **….2023: LS3…2026: HL-LHC**



Accelerator:

❑ 1232 high-tech superconducting magnets

❑ magnet operation temperature: 1.9 K (-271 ^{0}C)

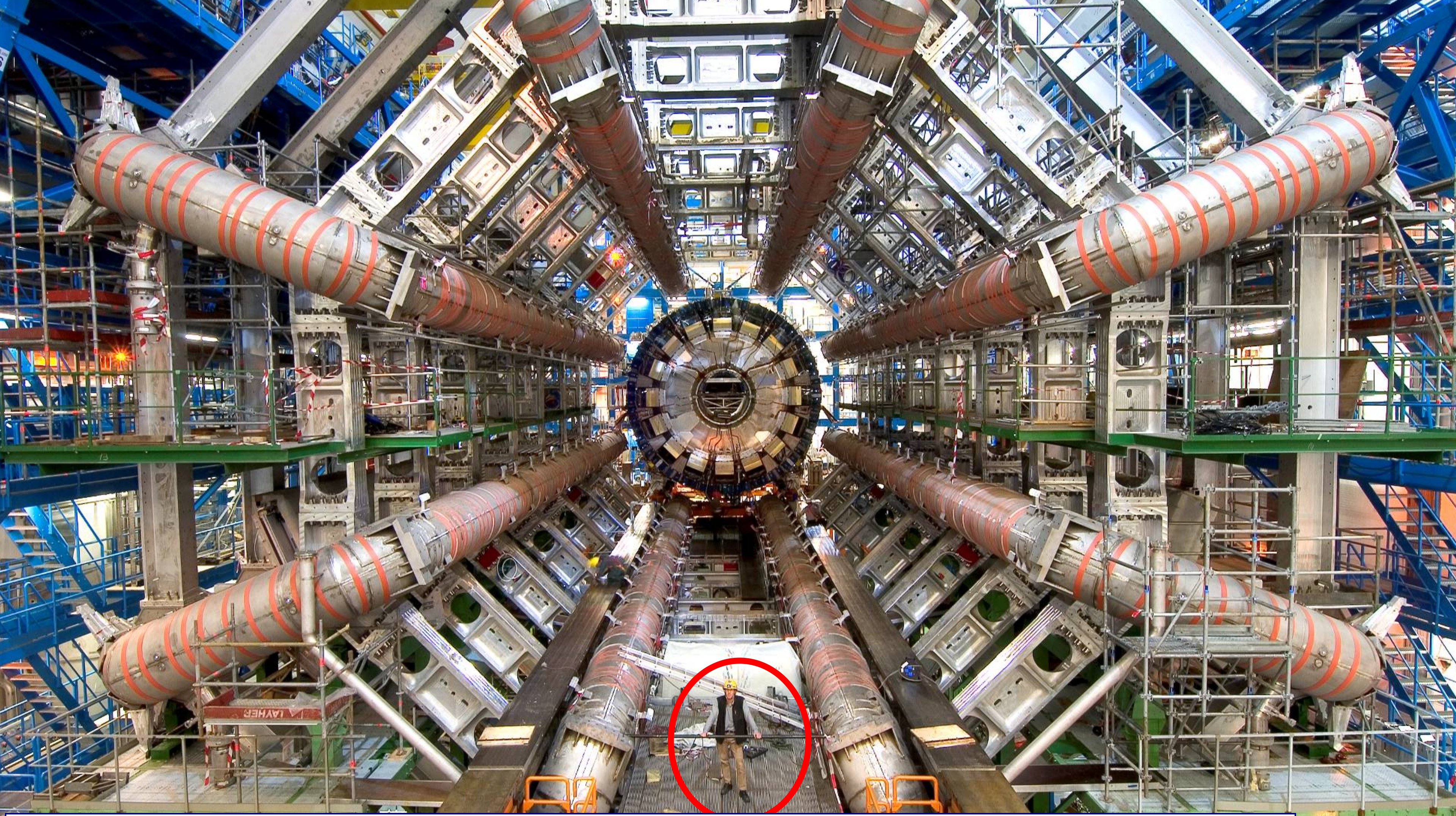
→ LHC is “coldest” place in the universe

❑ 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

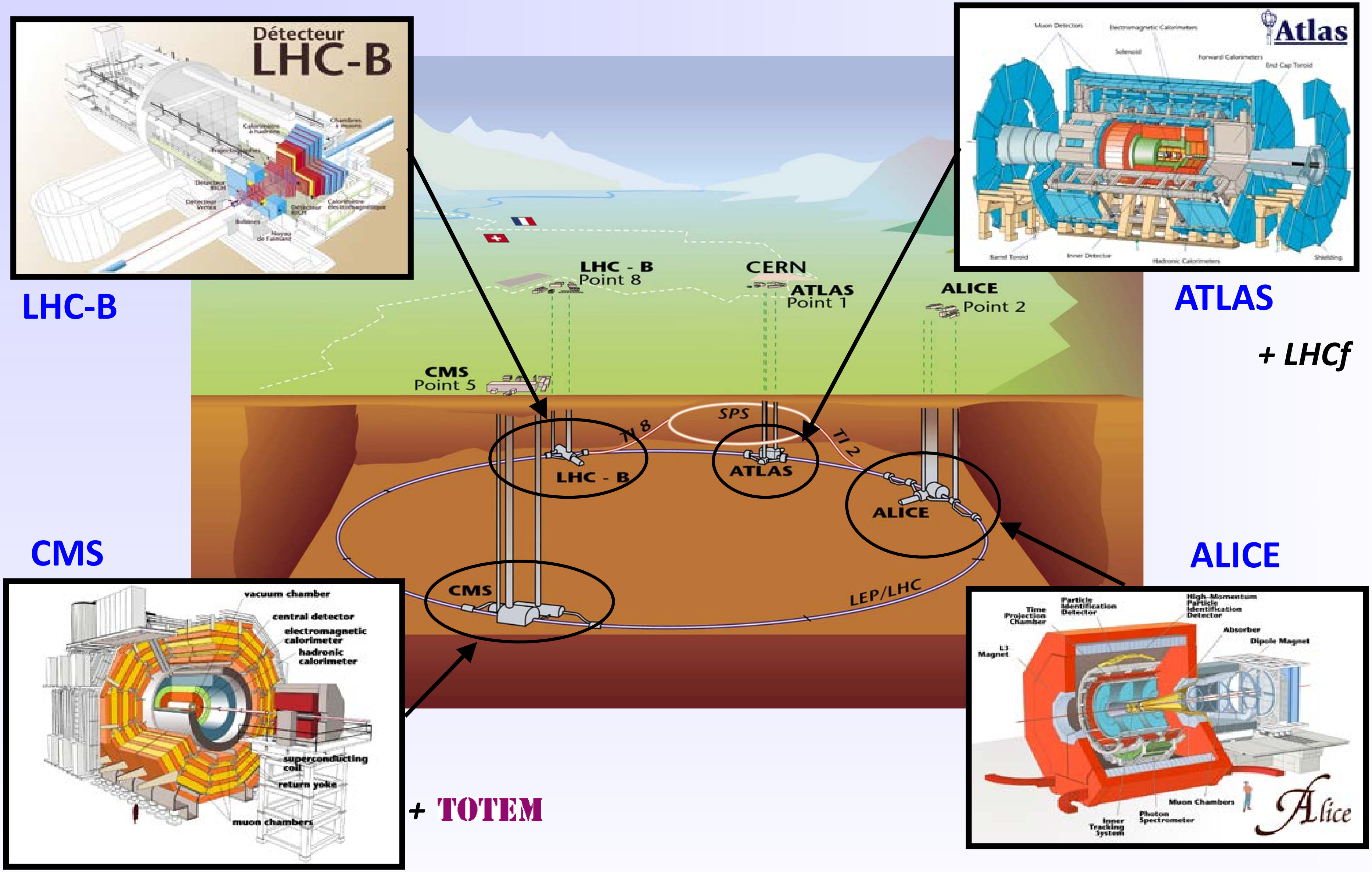
❑ collision “temperature”: 10^{16} K



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

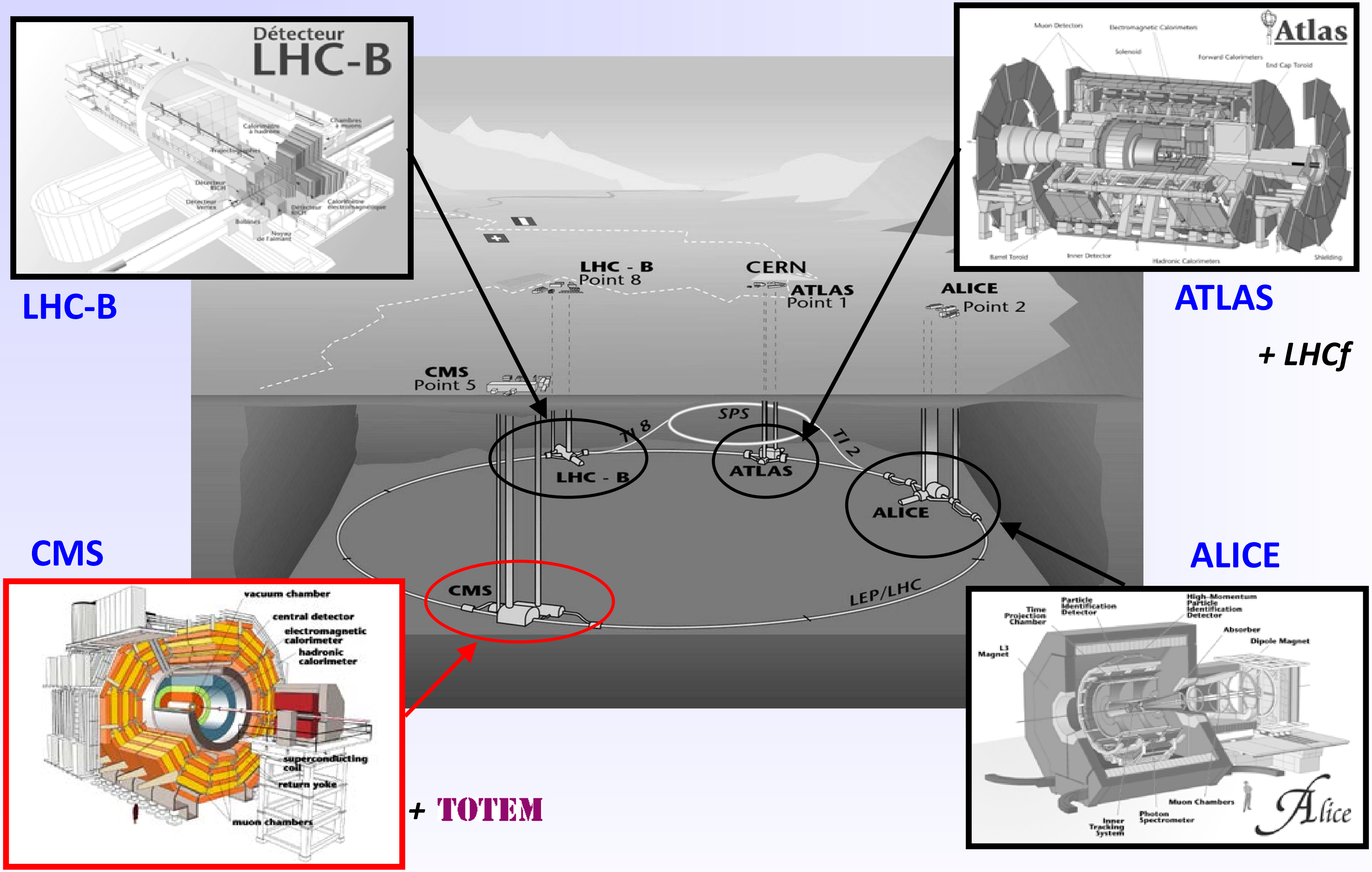
+ LHCf

CMS

ALICE

+ **TOTEM**

LHC Experiments



LHC-B

ATLAS

+ LHCf

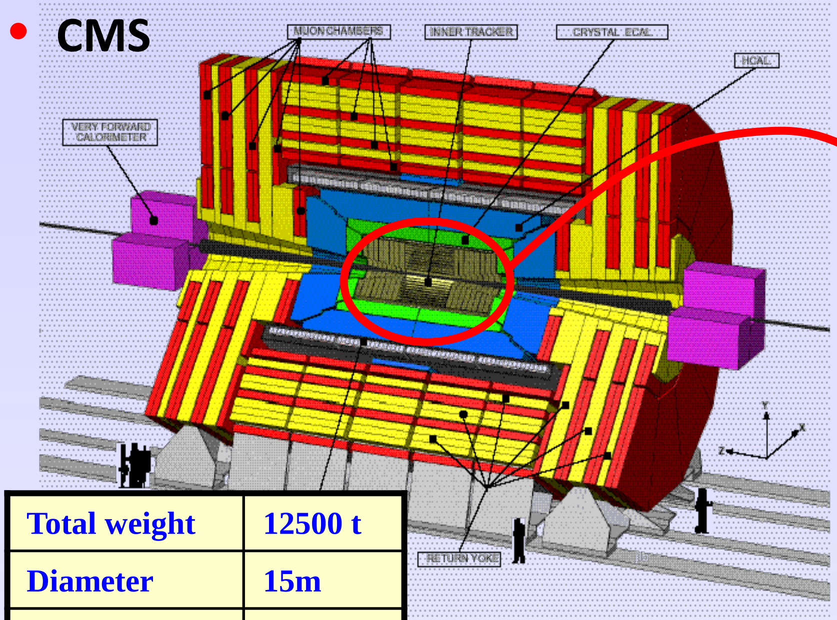
CMS

+ TOTEM

ALICE

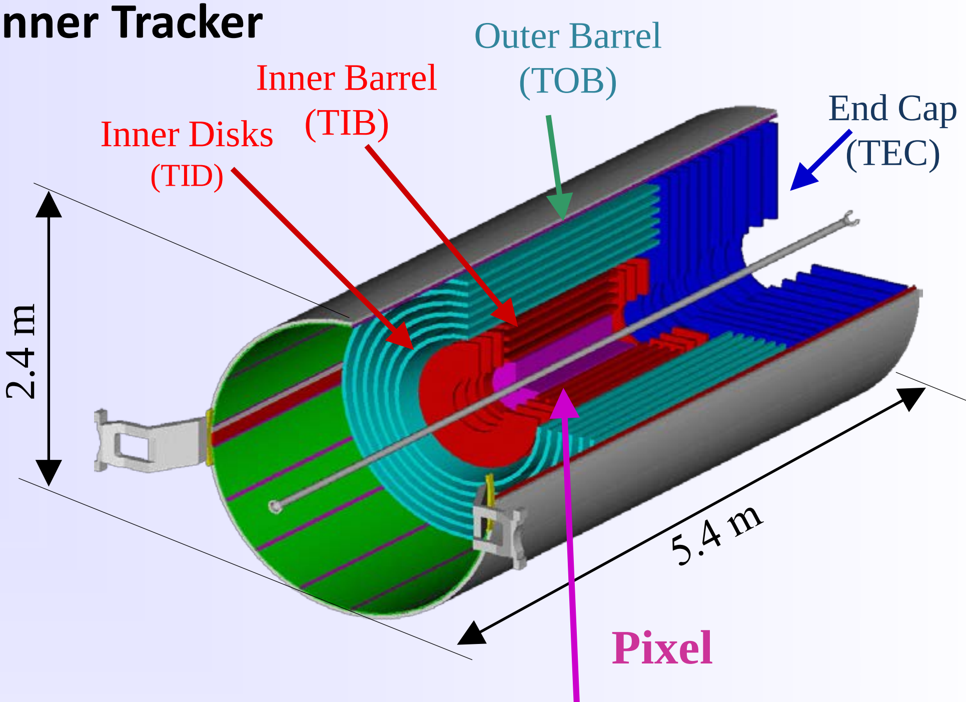
LHC example: CMS inner tracker

- **CMS**



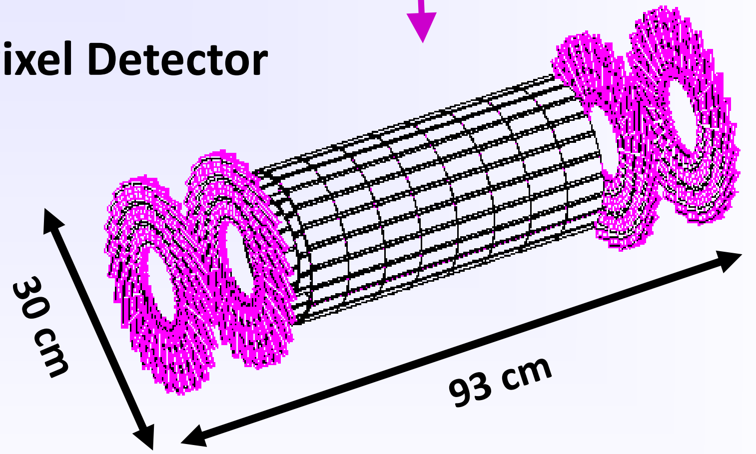
Total weight	12500 t
Diameter	15m
Length	21.6m
Magnetic field	4 T

- **Inner Tracker**



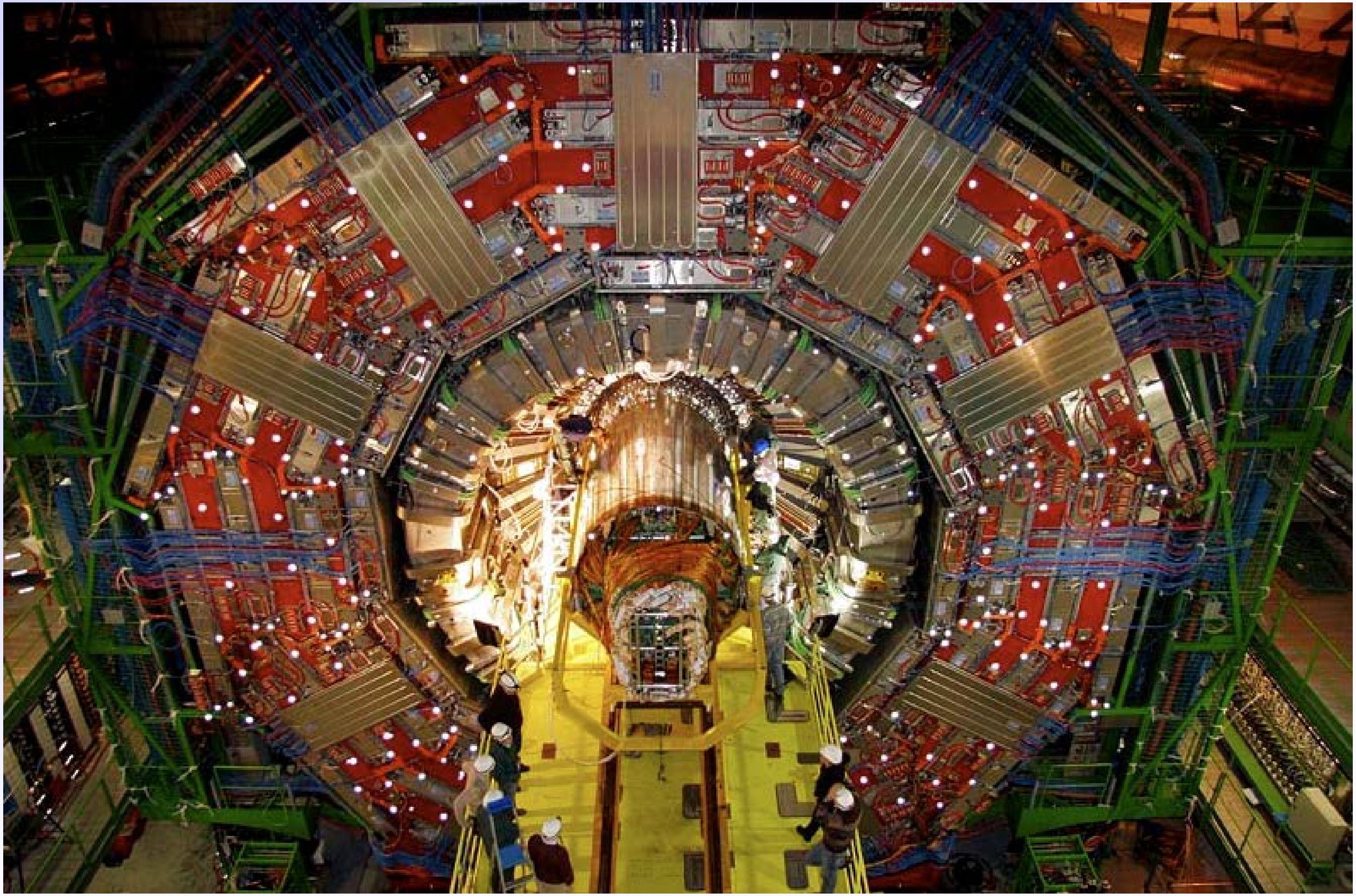
- **CMS – “Currently the Most Silicon”**
  - **Micro Strip:**
  - ~ 214 m^2 of silicon strip sensors, 11.4 million strips
  - **Pixel:**
  - Inner 3 layers: silicon pixels (~ 1m^2)
  - 66 million pixels (100x150µm)
  - Precision: σ(rϕ) ~ σ(z) ~ 15µm
  - Most challenging operating environments (LHC)

- **Pixel Detector**



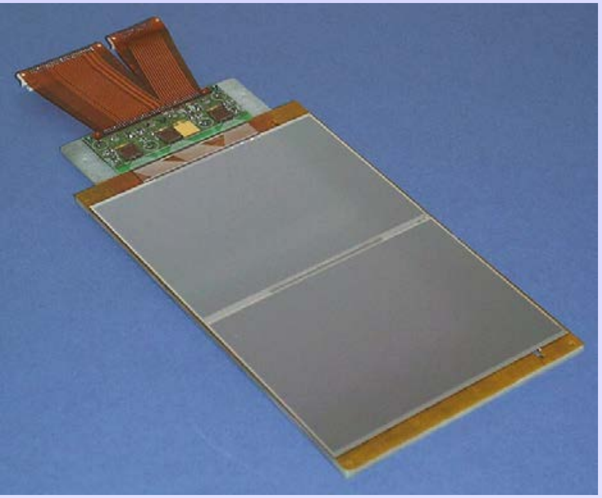
Present LHC Tracking Sensors

CMS Tracker insertion

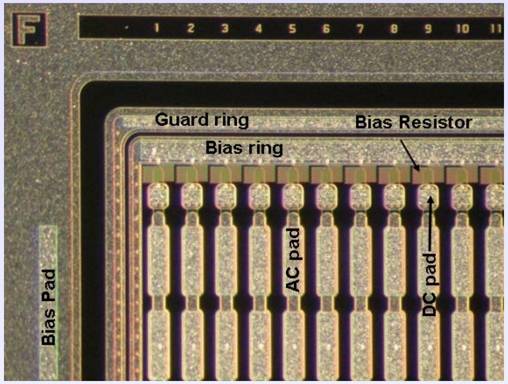


M.Krammer, ICFA School, Bogota, 2013

Micro-strip Silicon Detectors

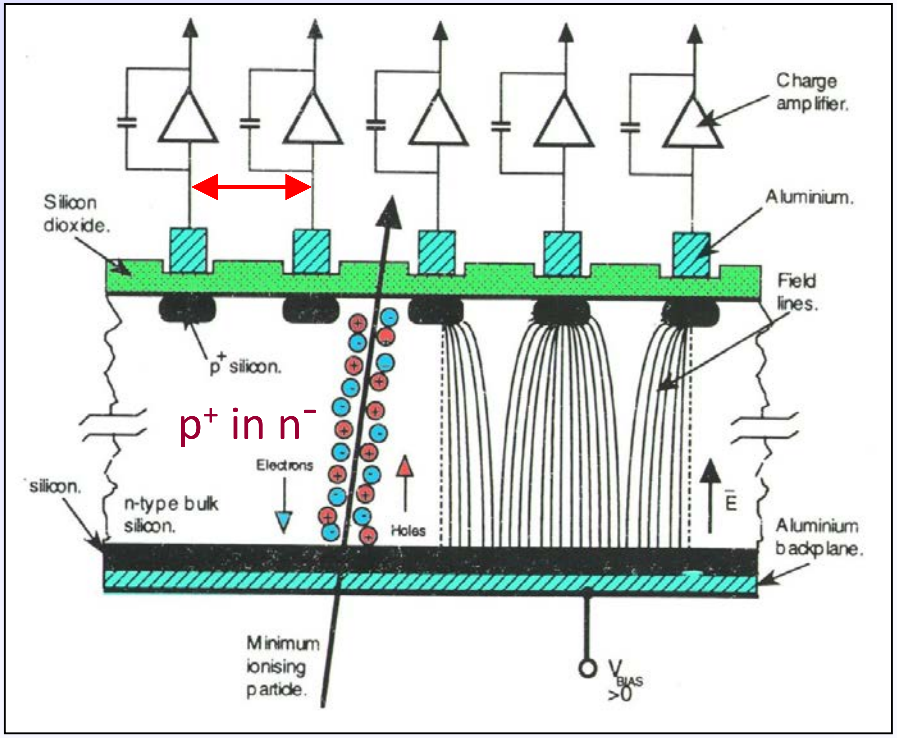


Highly segmented silicon detectors have been used in Particle Physics experiments for 30 years. They are favourite choice for Tracker and Vertex detectors
(high resolution, speed, low mass, relatively low cost)



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

Pitch ~ 50µm



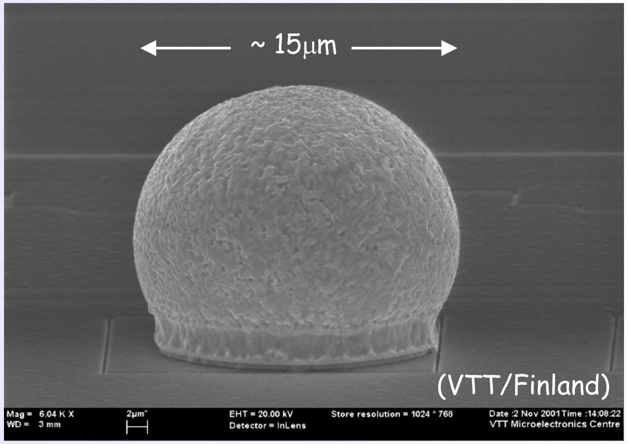
Resolution ~ 5µm

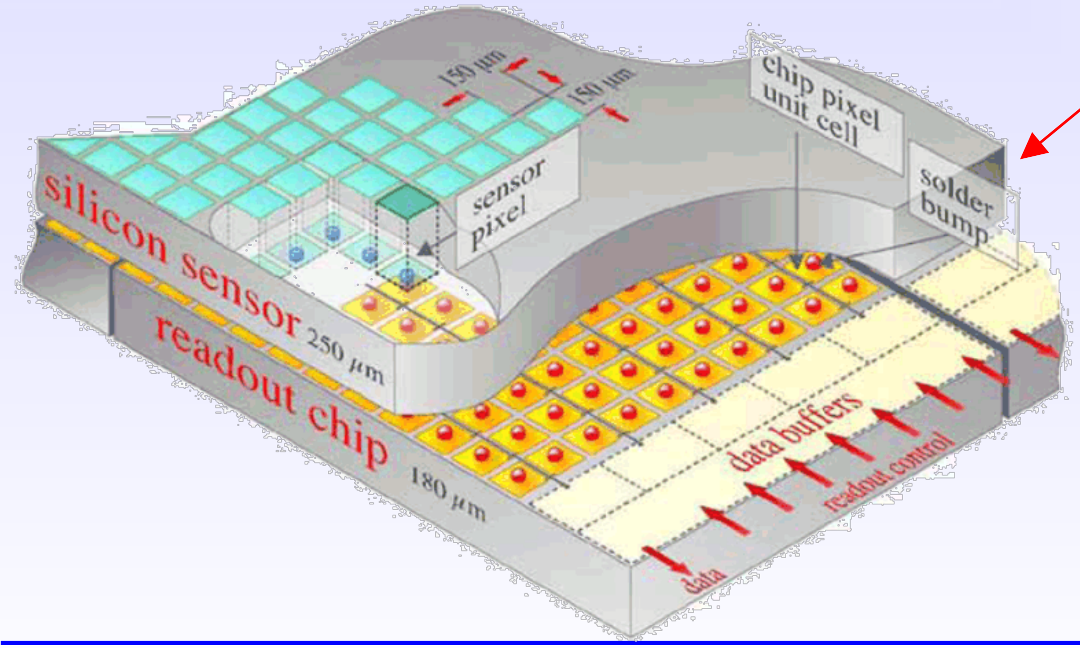
Reference: P.Allport, Sept.2010

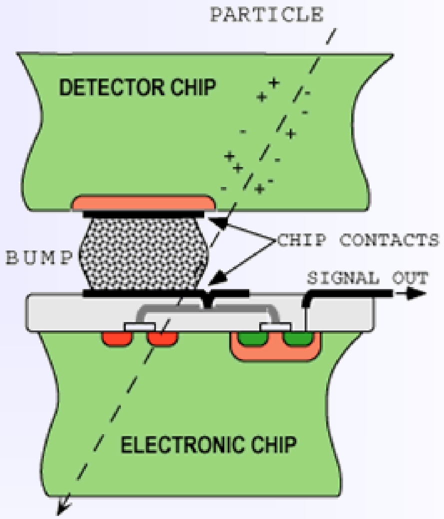
Hybrid Pixel Detectors

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

Solder Bump: Pb-Sn







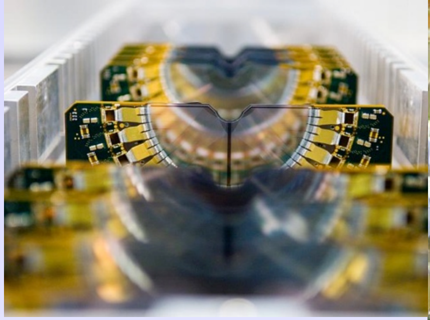
Flip-chip technique

Present LHC Tracking Sensors

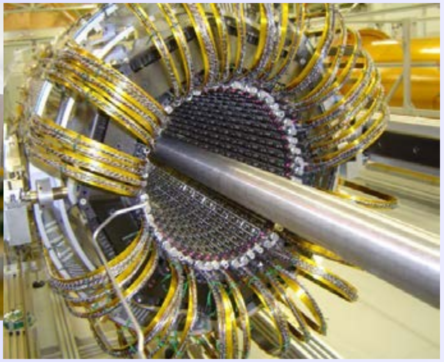
Silicon tracking detectors are used in all LHC experiments:

Different sensor technologies, designs, operating conditions,….

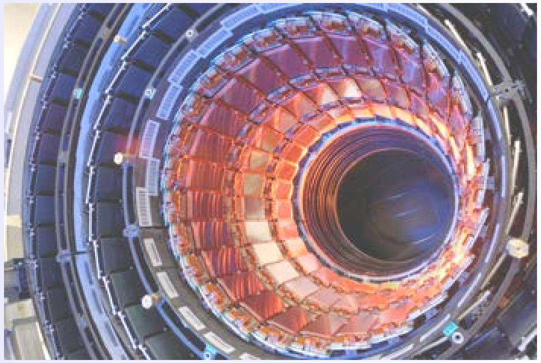
ALICE Pixel Detector



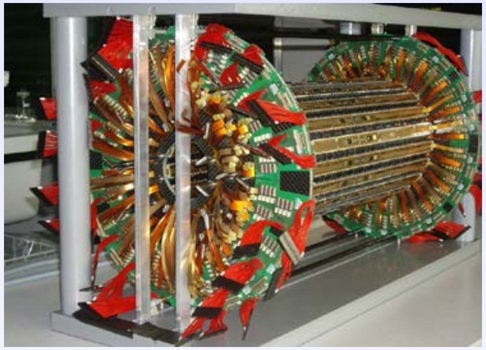
LHCb VELO



ATLAS Pixel Detector

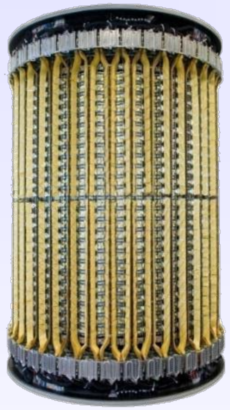


CMS Strip Tracker IB

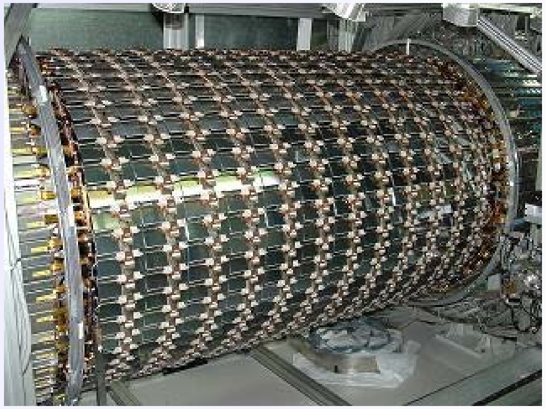


CMS Pixel Detector

ALICE Drift Detector



ALICE Strip Detector



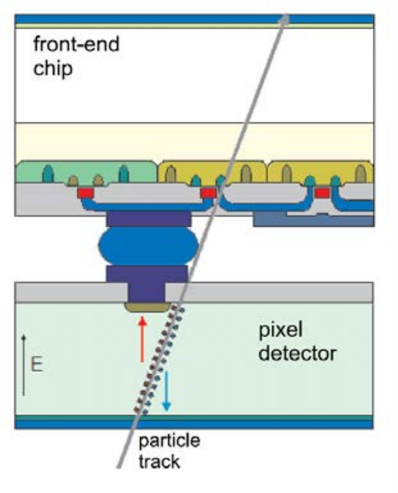
ATLAS SCT Barrel

P.Riedler, ECFA Workshop, Oct.2013

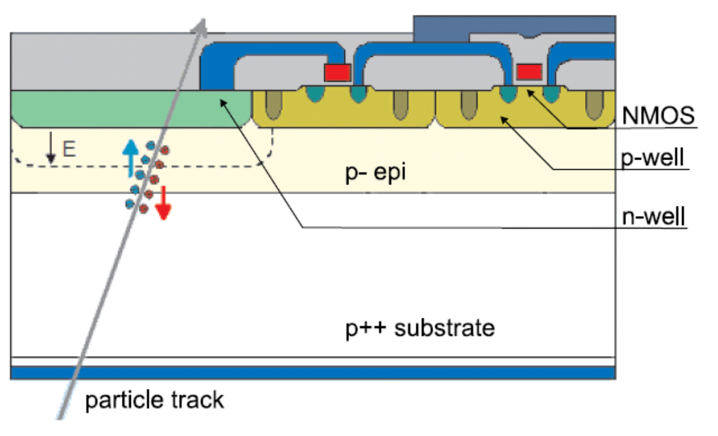
Monolithic Pixel Detectors

- **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 based on MAPS sensors**

Hybrid Pixel Detector

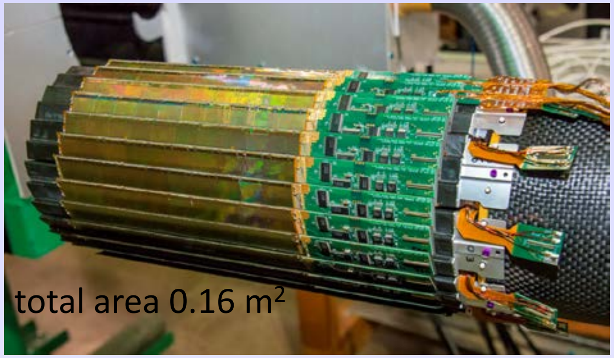


CMOS (Pixel) Detector

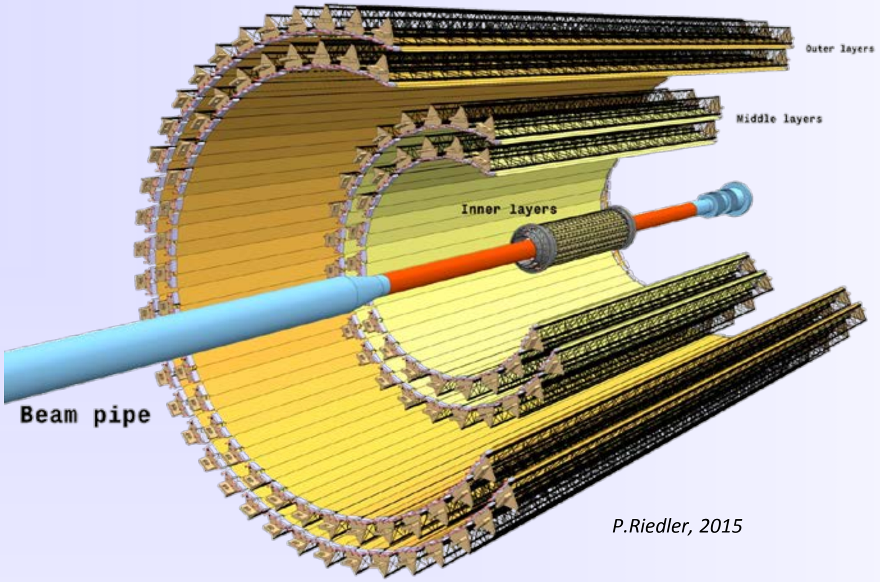


Monolithic Pixel Sensors

Monolithic Pixel sensors are used in HEP experiments (STAR, BELLE2), will be installed in ALICE and are an option under development for the LHC upgrade (ATLAS):



STAR Heavy Flavour Tracker (HFT) at RHIC
- Installed 2013 [L. Greiner, FEE 2014]



P.Riedler, 2015

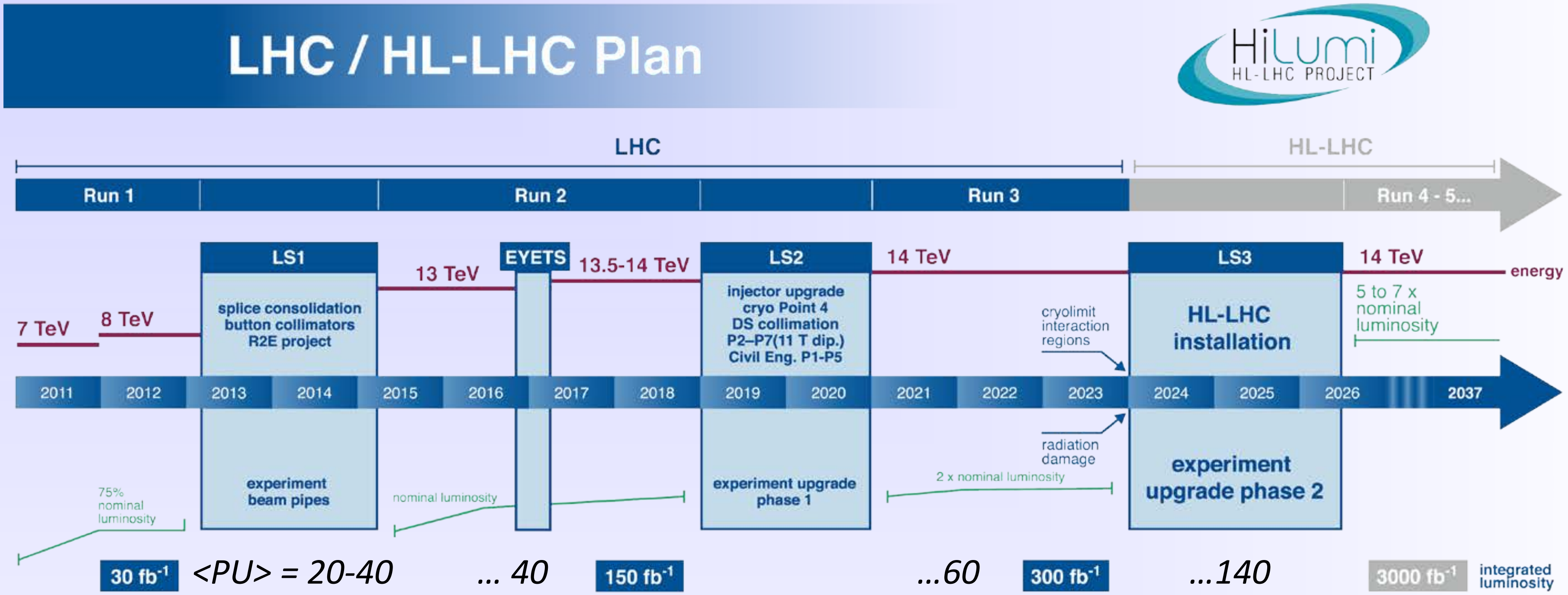
ALICE ITS – Inner Tracking System
- Based on high resistivity epi layer MAPS
- **3** Inner Barrel layers (IB) **0.3% X_0**/layer
- **4** Outer Barrel layers (OB) 0.8 % X_0/layer
- Radial coverage: 21-400 mm
- **~ 10 m²; 12.5 Giga-pixel tracker**
- **Installation during LS2 (2018)**

ILC, CLIC: MAPS sensors are current baseline

Upgrade of the Large Hadron Collider at CERN

The LHC Upgrade Program

- **HL-LHC luminosity upgrade (Phase II) (L = 5-7 x10^{34} cm^{-2}s^{-1}) in ~2026**



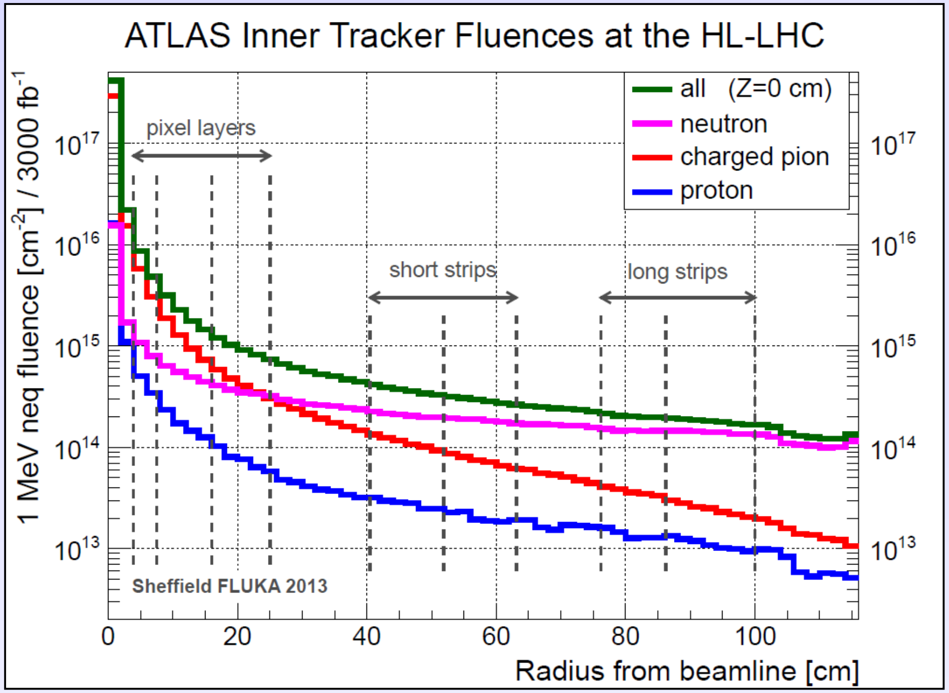
- **LS2: AlICE, LHCb major upgrades; ATLAS and CMS minor upgrades [Phase I]**
- **LS3: ATLAS and CMS: Major upgrades [Phase II]**

<u>Challenges</u>: Build detectors that operate after 3000 fb^{-1}; Pile up, Radiation, Rates

[http://hilumilhc.web.cern.ch/ , September 2016]

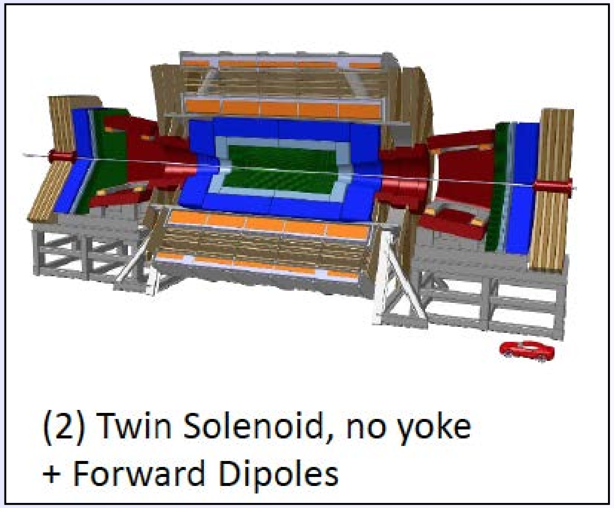
Motivation and Challenge

- **LHC upgrade**
  - **LHC upgrade towards High Luminosity LHC (HL-LHC)** *after LS3 (~2024-26); **expect*** **3000 fb^{-1}** *(x6 nominal LHC)*



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

- ***FCC – Future Circular Collider***
  - **….later than 2035**



(2) Twin Solenoid, no yoke
\+ Forward Dipoles

[W.Riegler, RD50 Workshop, 12/2015]

  - **Radiation levels innermost pixel layer** (30ab^{-1}, without safety factor): **7x10^{17} n$_{eq}$/cm^2, 200MGy**

Semiconductor detectors will be exposed to hadron fluences equivalent to more than 10^{16} n$_{eq}$/cm^2 (HL-LHC) and more than 7x10^{17} n$_{eq}$/cm^2 (FCC)

➔ detectors used now at LHC cannot operate after such irradiation

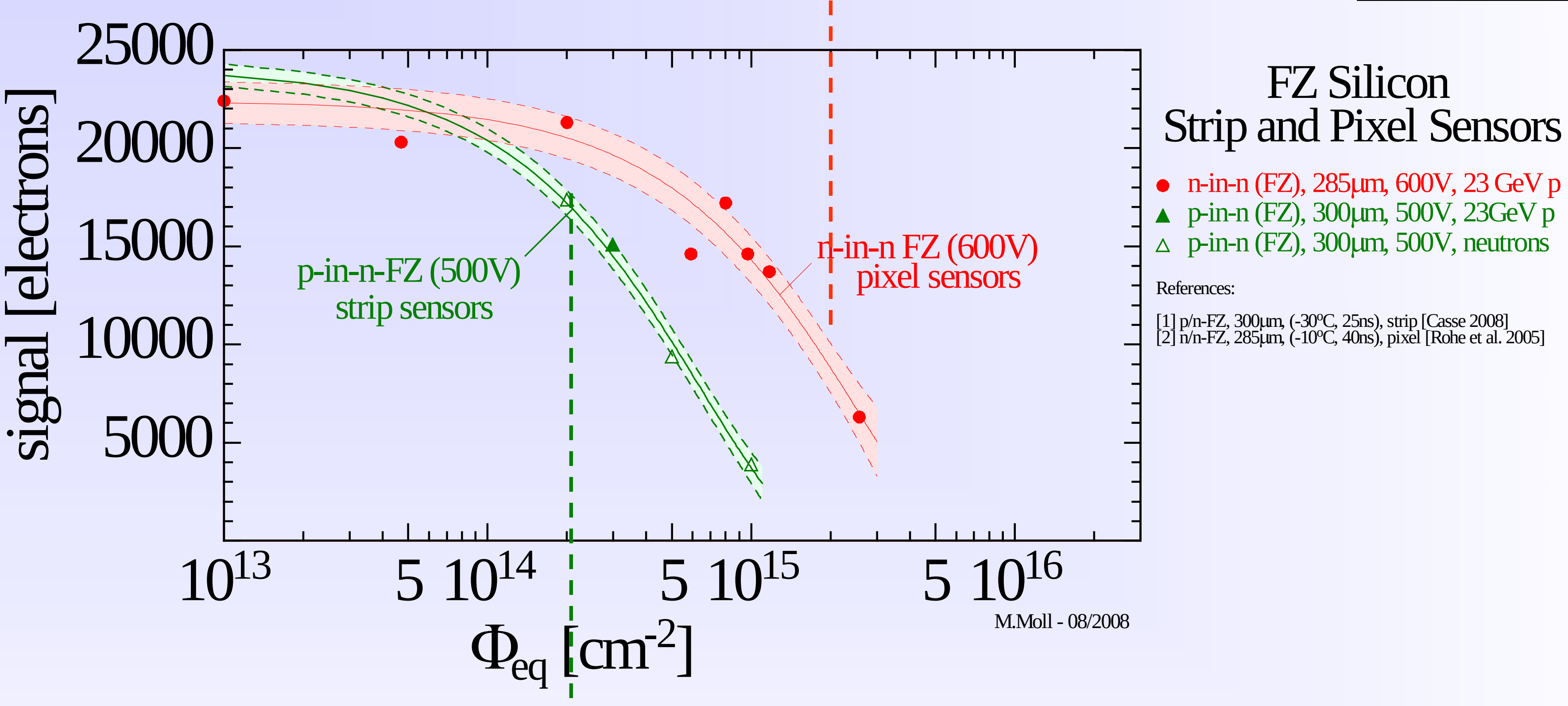
RD50 : mandate to develop and characterize semiconductor sensors for HL-LHC and beyond (FCC)

Signal degradation for LHC Silicon Sensors

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

Pixel sensors:

max. cumulated fluence for LHC



Strip sensors:

max. cumulated fluence for LHC

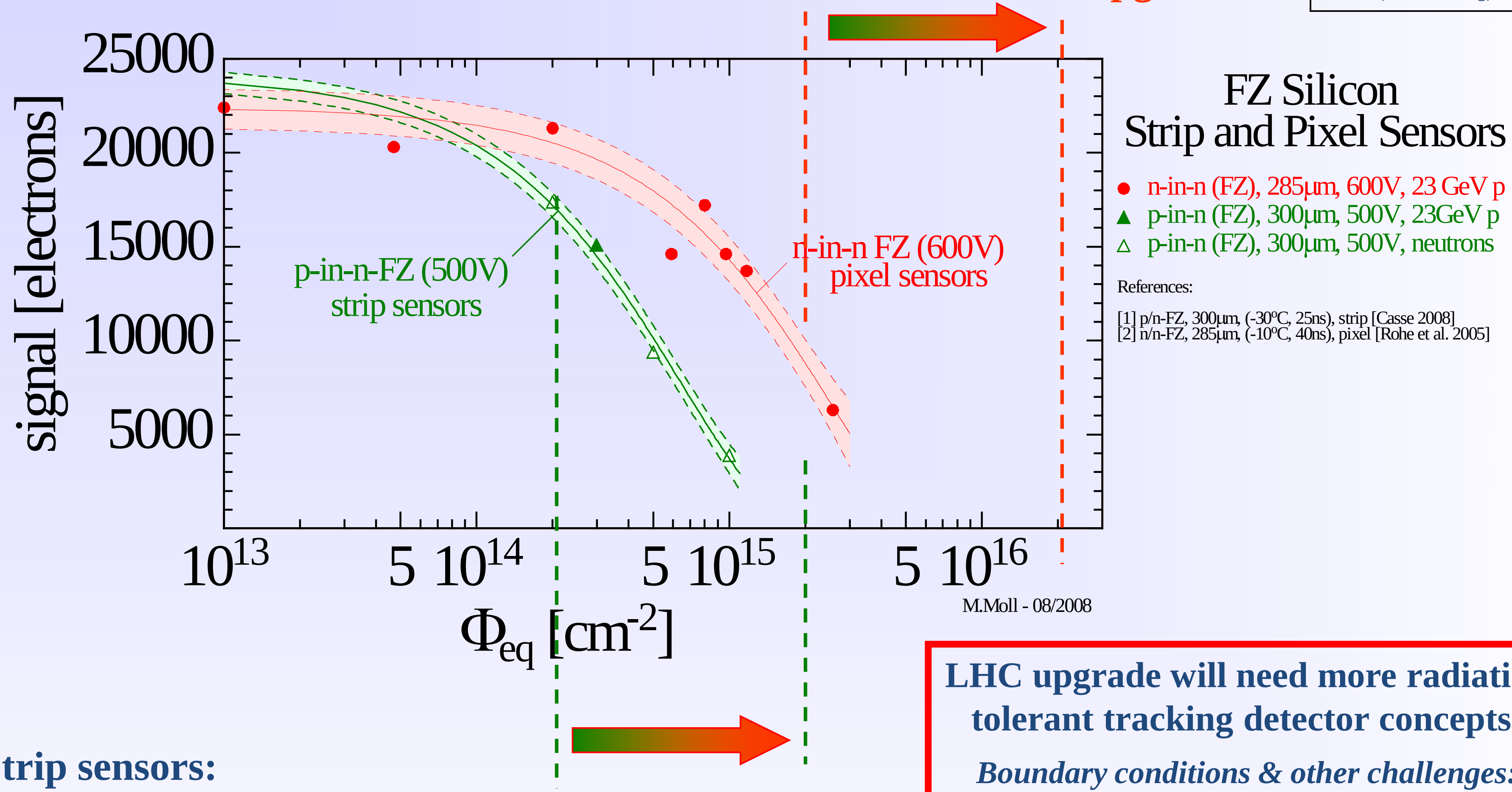
Situation in 2005

Signal degradation for LHC Silicon Sensors

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

Pixel sensors:

max. cumulated fluence for LHC and LHC upgrade



Strip sensors:

max. cumulated fluence for LHC and LHC upgrade

LHC upgrade will need more radiation tolerant tracking detector concepts!

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

Radiation Damage

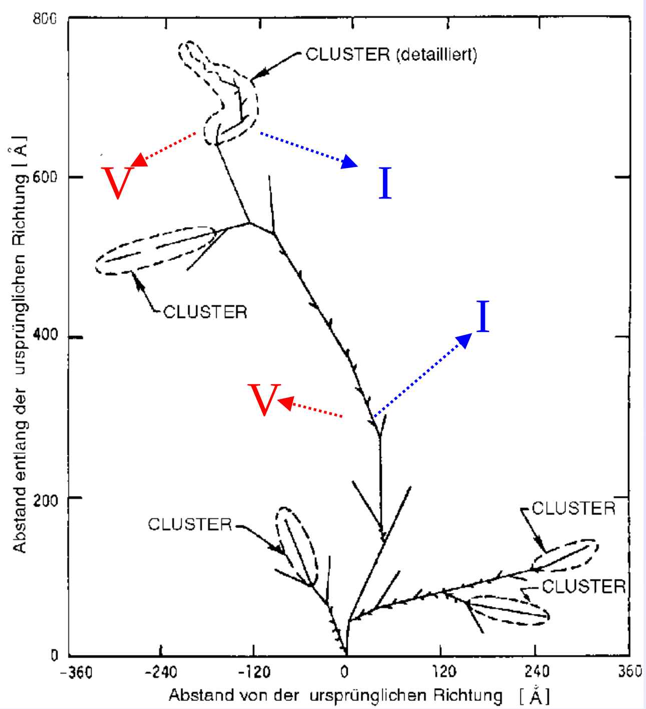
What is radiation damage?

Radiation Damage – Microscopic Effects

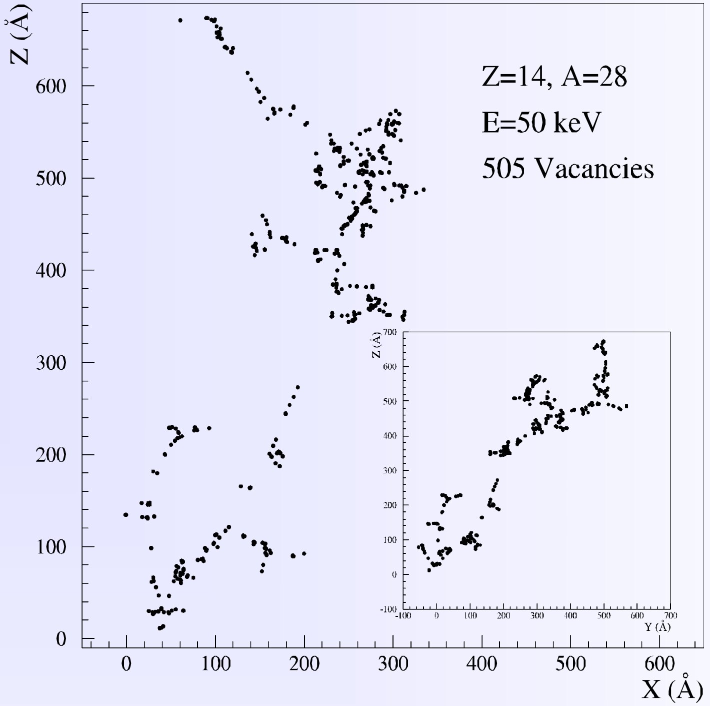
◆ **Spatial distribution of vacancies created by a 50 keV Si-ion in silicon.**

(typical recoil energy for 1 MeV neutrons)

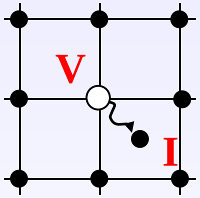
van Lint 1980



M.Huhtinen 2001



particle → *Si_S* → **E_K>25 eV**

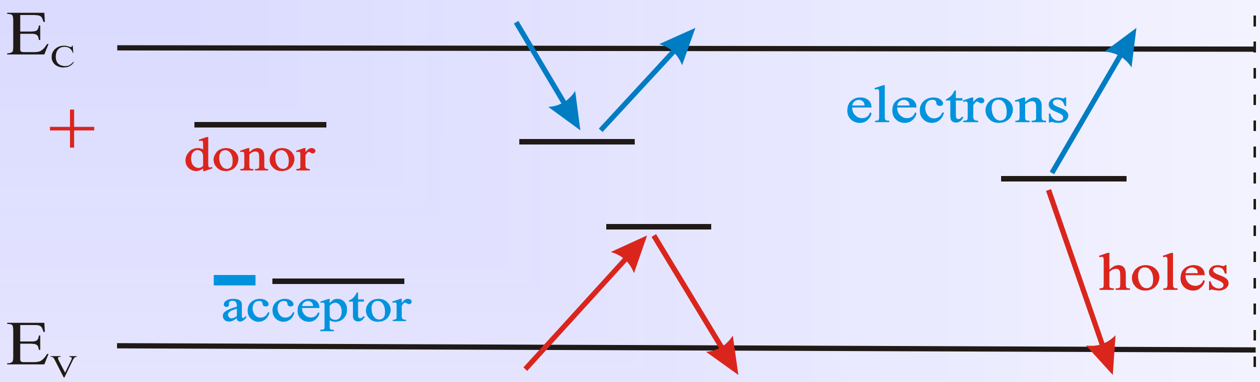


Vacancy
+
Interstitial → *point defects*
(V-O, C-O, ..)

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

Impact of Defects on Detector properties

Shockley-Read-Hall statistics
(standard theory)



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

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

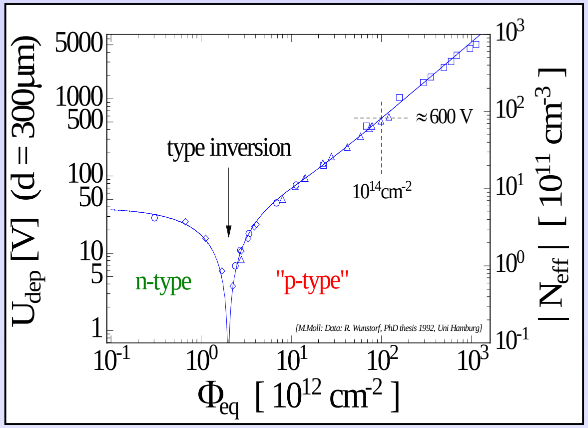
generation
⇒ leakage current
Levels close to midgap most effective

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

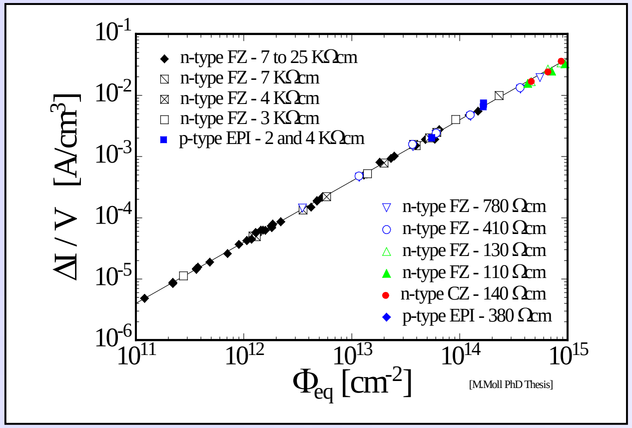
$\sigma_{n,p}$: cross sections **ΔE : ionization energy** **N_t : concentration**

Radiation Damage Summary

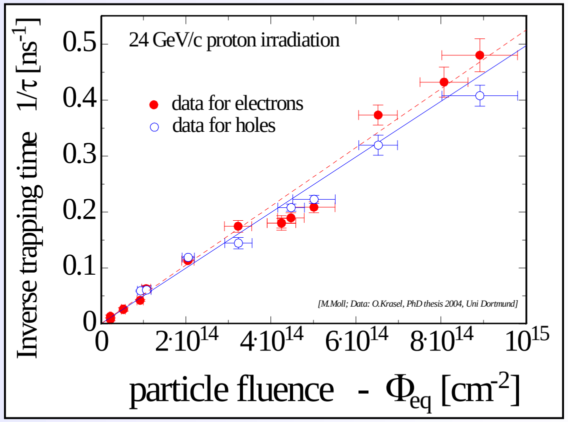
- **Macroscopic bulk effects:**



Depletion Voltage (N_{eff})

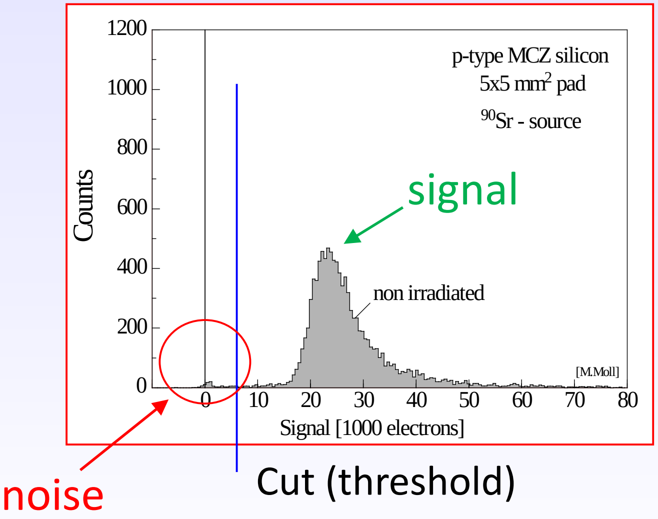


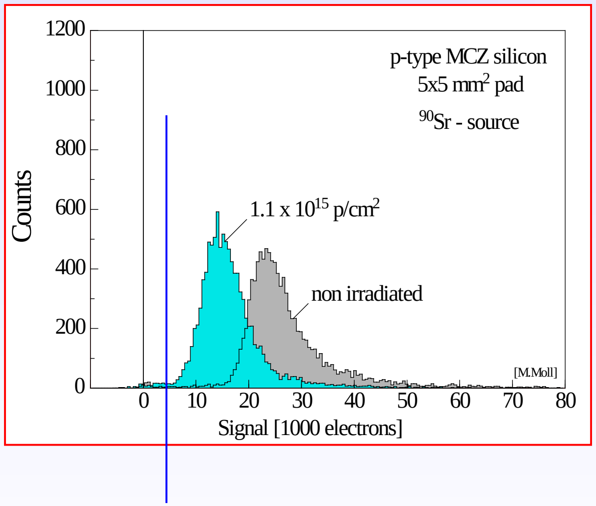
Leakage Current

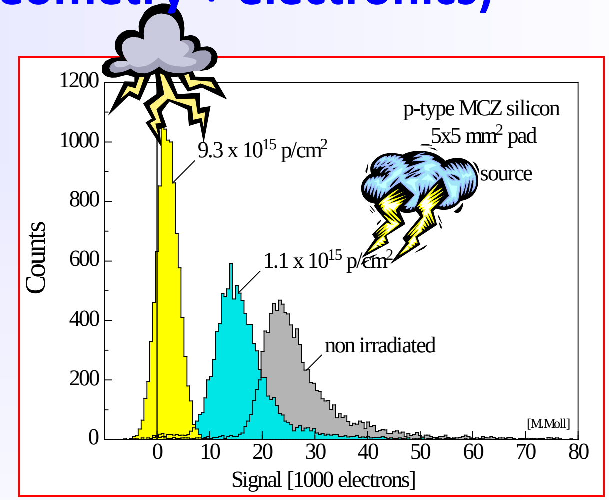


Charge Trapping

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







How to make silicon detectors radiation harder?

The RD50 Collaboration

- **RD50: *52 institutes and 282 members***

42 European and Asian institutes

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

6 North-American institutes

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

1 Middle East institute

Israel (Tel Aviv)

1 Asian institute

India (Delhi)

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

Approaches to develop radiation harder solid state tracking detectors

Scientific strategies:

I. **Material engineering**

II. **Device engineering**

III. **Change of detector operational conditions**

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

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

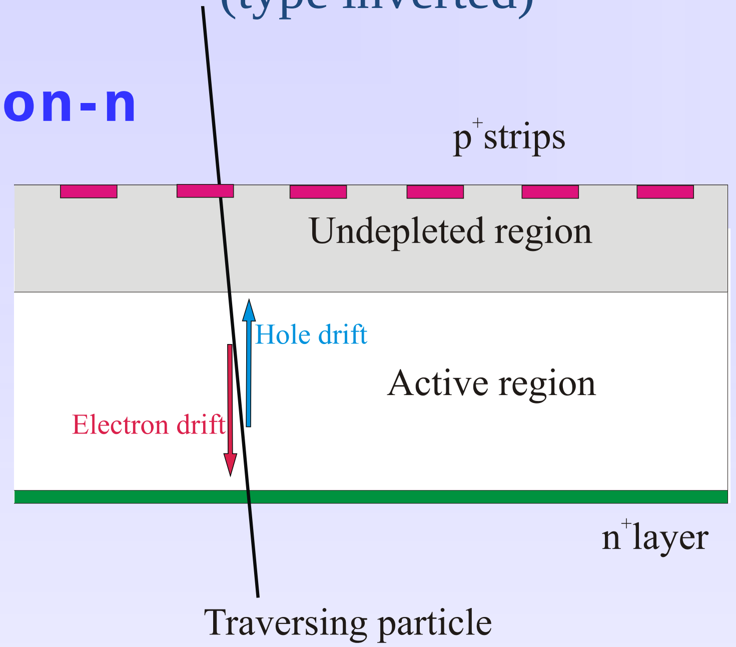
  - **Needs: Profound understanding of radiation damage**
    - microscopic defects, macroscopic parameters
    - dependence on particle type and energy
    - defect formation kinetics and annealing
  - **Examples:**
    - **Oxygen rich Silicon (DOFZ, Cz, MCZ, EPI)**
    - Oxygen dimer & hydrogen enriched 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 Semi 3D detectors, Stripixels
  - Cost effective detectors
  - Monolithic devices

Device engineering

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

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

p^+on-n

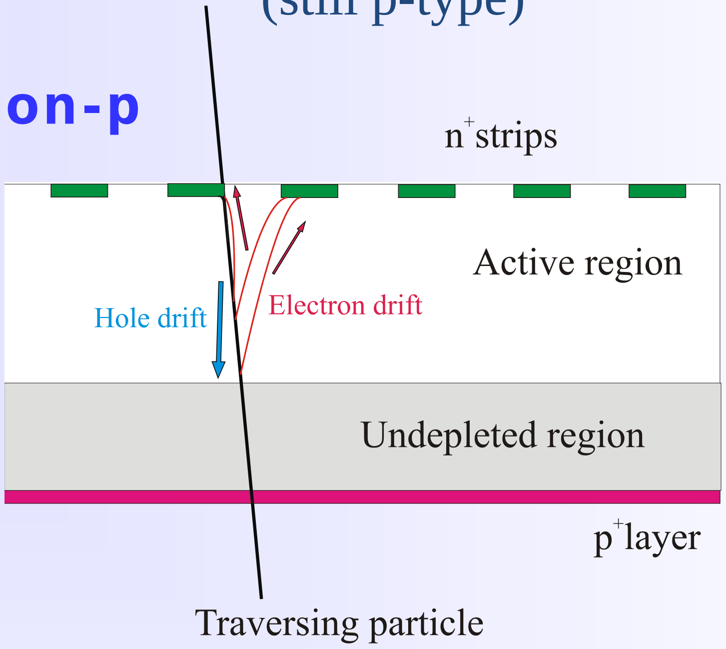


p-on-n silicon, under-depleted:

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

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

n^+on-p



n-on-p silicon, under-depleted:

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

Comments:

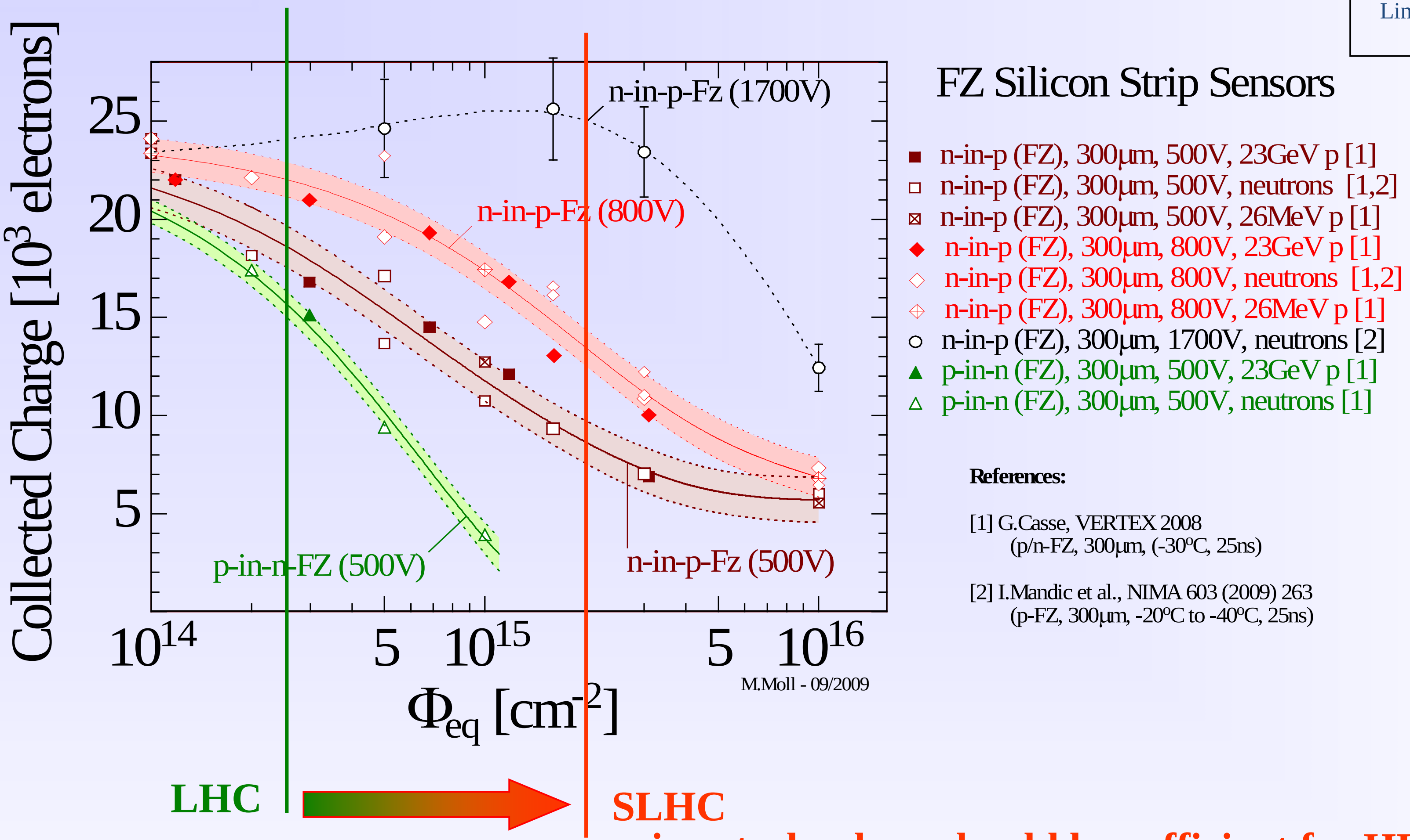
- Instead of n-on-p also n-on-n devices could be used

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

Silicon materials for Tracking Sensors

- **Signal comparison for p-type silicon sensors**

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



References:

[1] G.Casse, VERTEX 2008 (p/n-FZ, 300µm, (-30°C, 25ns)

[2] I.Mandic et al., NIMA 603 (2009) 263 (p-FZ, 300µm, -20°C to -40°C, 25ns)

LHC

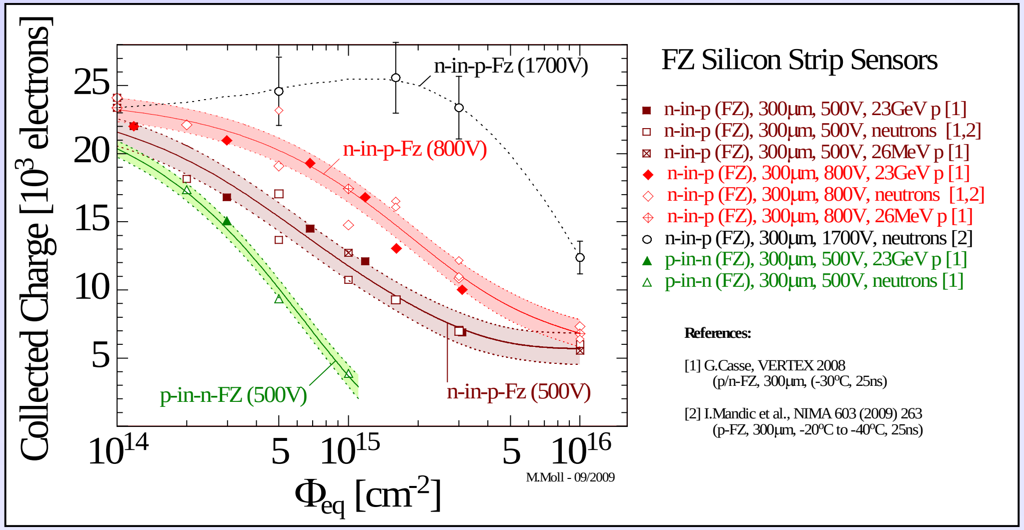
SLHC

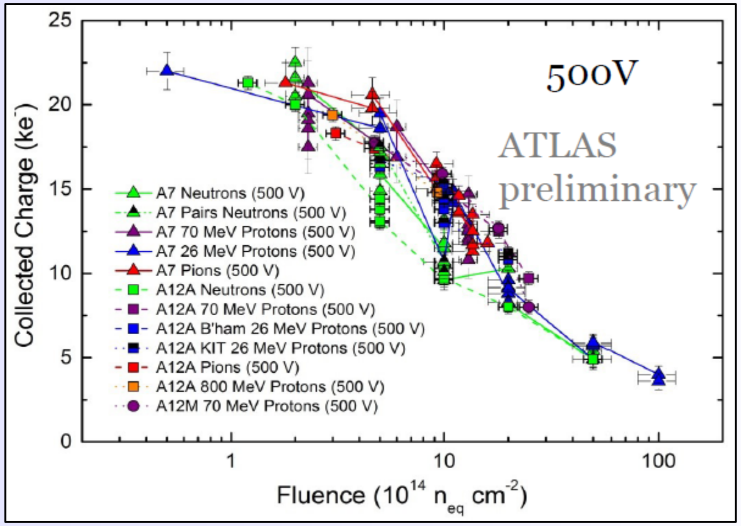
highest fluence for strip detectors in LHC: The used p-in-n technology is sufficient

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

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

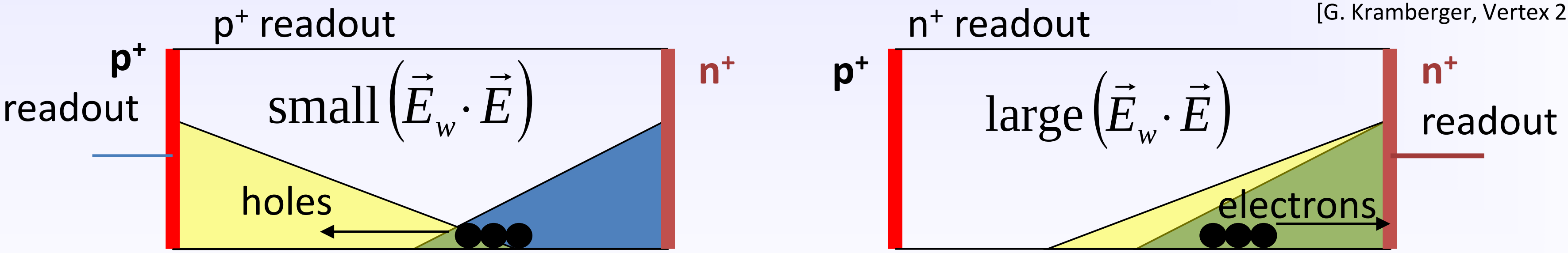
- **p-type strip sensors with n$^+$ readout** *(brought forward by RD50)*
  - **are now the sensor choice for ATLAS and CMS Tracker upgrades**





S. Wonsak, 25th RD50 Workshop Nov. 2014

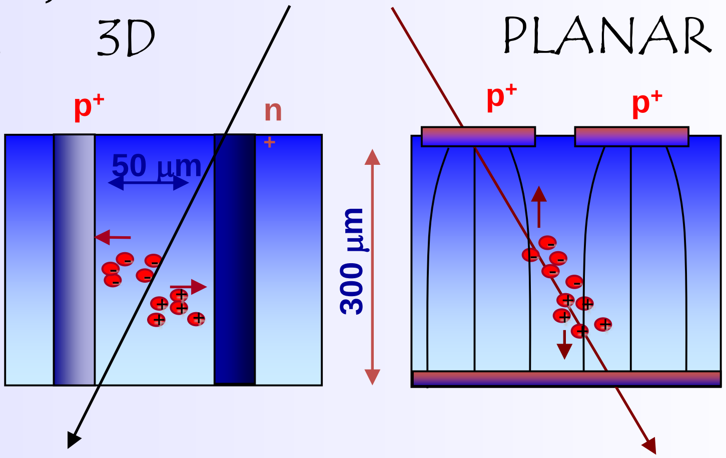
- **n$^+$-electrode readout (“natural in p-type silicon”):**
  - favorable combination of weighting and electric field in heavily irradiated detector
  - electron collection, multiplication at segmented electrode
- **Situation after high level of irradiation:**

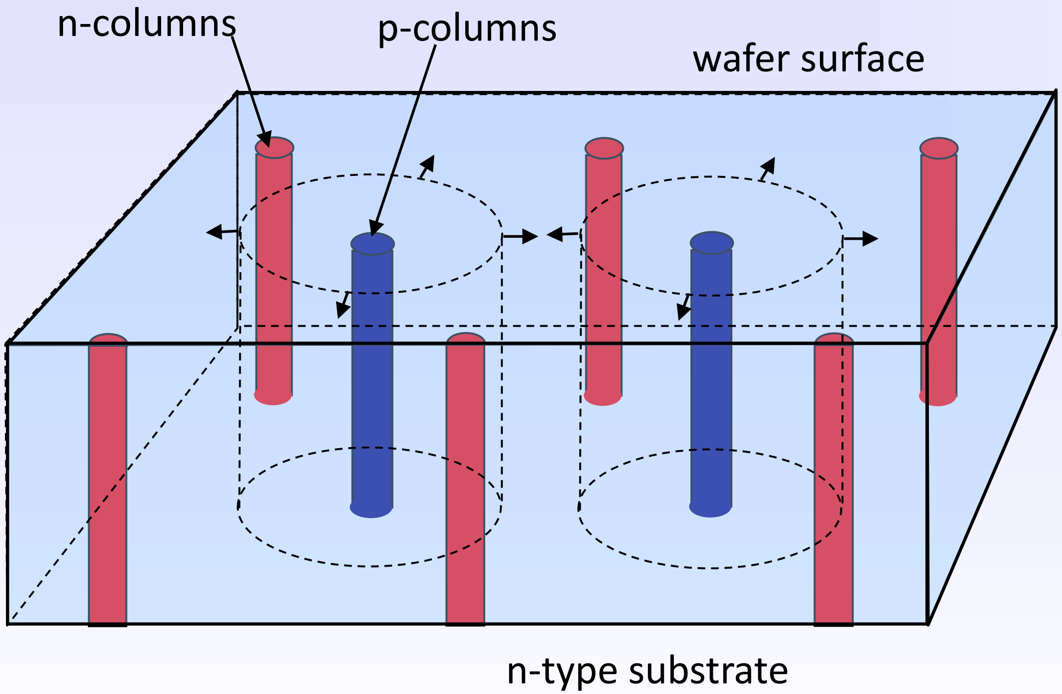


[G. Kramberger, Vertex 2012]

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

Radiation Damage & TCAD simulations

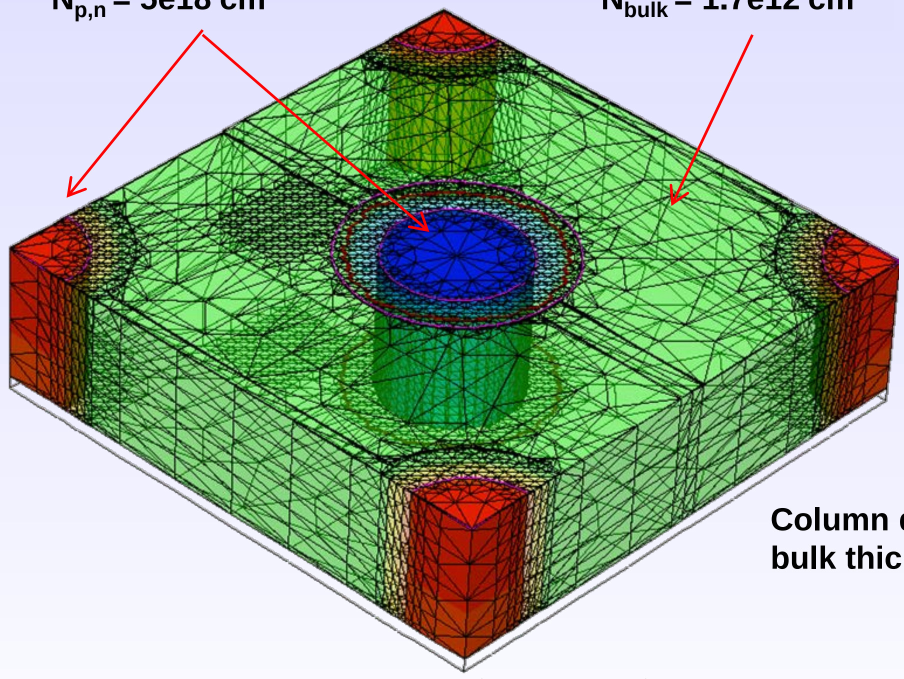
TCAD simulations

TCAD simulations

More about TCAD simulations in presentations from Geetika Jain & Marco Bomben

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

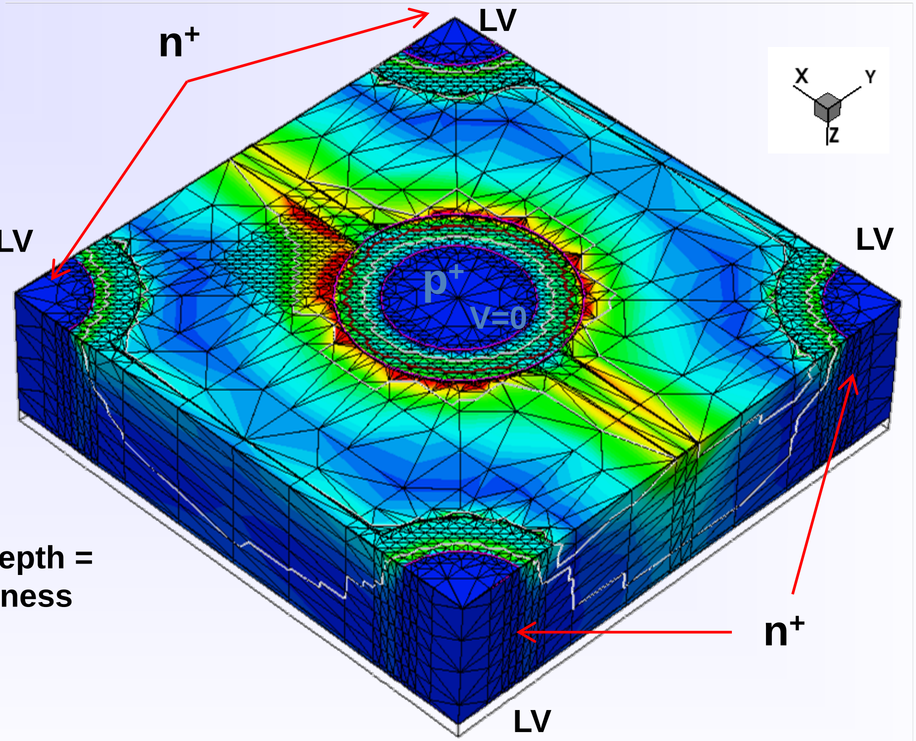
Doping profiles



Column depth = bulk thickness

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

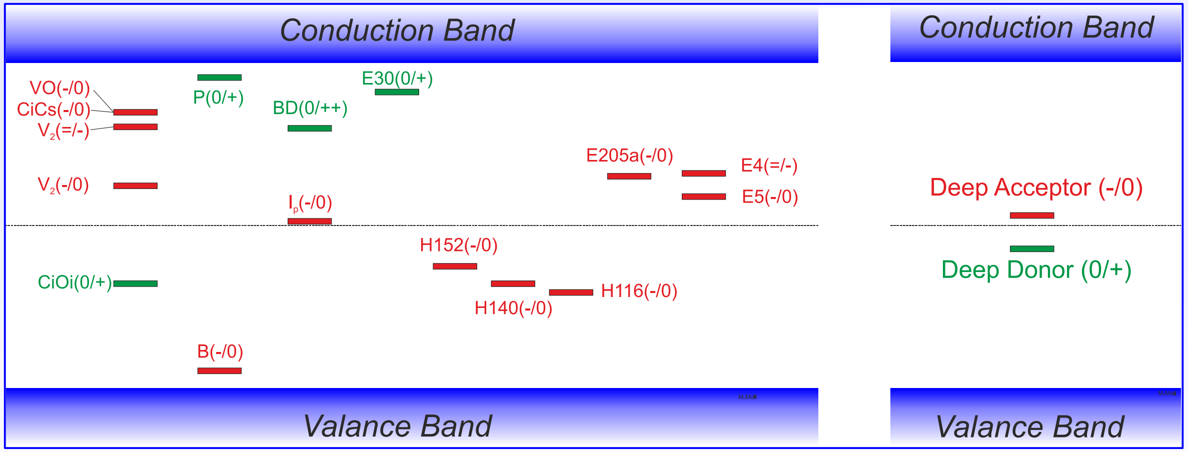
Electric field distribution in 3D detector (Al & oxide layer transparent for clarity)



TCAD - Simulations

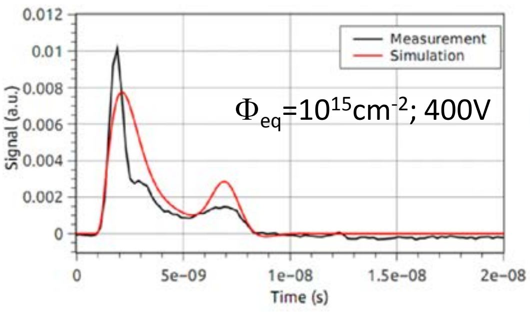
- **Device simulation of irradiated sensors**
  - **Using: Custom made simulation software and Silvaco & Synopsis TCAD tools**
  - **RD50 simulation working group**
    - Good progress in reproducing experimental data (leakage current, space charge, E-Field, trapping …)
    - However, …. still significant work on going to “inter-calibrate” the tools
    - Enormous parameter space ranging from semiconductor physics parameters and models over device parameters towards defect parameters ➔ **Tools ready but need for proper input parameters!**
- **Working with “effective levels” for simulation of irradiated devices**
  - Most often 2, 3 or 4 “effective levels” used to simulate detector behavior
  - Introduction rates and cross sections of defects tuned to match experimental data

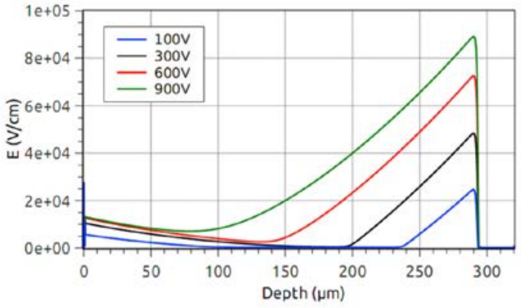
Measured defects ➔ ***TCAD input***



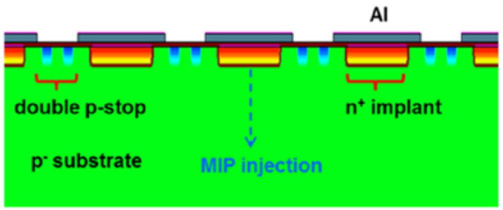
TCAD Simulations: Status

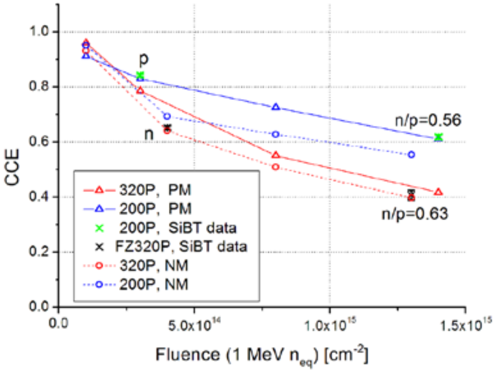
- **Bulk damage studies**
  - **Optimization of TCAD parameters**
  - TCT – Transient Current Technique and other methods used to produce data sets



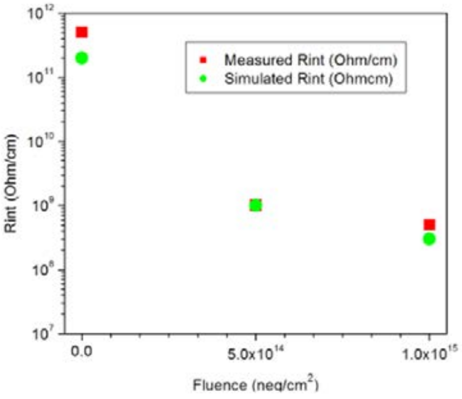


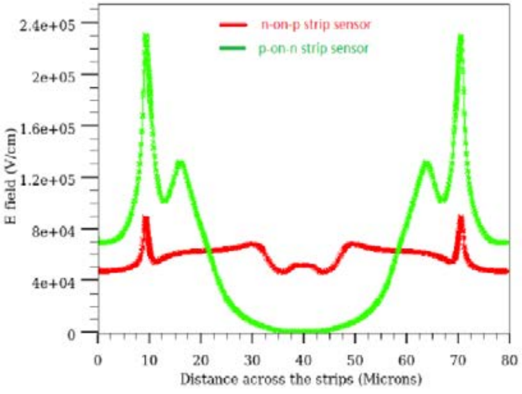
- **CCE in strip or pixel sensors**
  - **Complex geometries evaluated against test beam data**
  - **Good agreement between data and measurement**
  - **Simulations get predictive power** (taking into account validity range of model!)





- **Surface damage**
  - **SiO_2 charge-up and Si-SiO_2 interface states**
  - **Important role in detector performance:** some properties can only be understood if implementing surface damage in simulation
  - Surface damage properties (e.g. R_{int}) can also only be understood if bulk damage is included!
  - **Figure:** Left: Simulated and measured inter-strip resistance vs. fluence for n-on-p strip sensors with double p-stop isolation at V = 600V. 2 interface traps used and bulk defects. Right: Comparison n-in-p vs. p-in-n
  - **Example:**
    Random Noise Hits in n-type strip sensors explained by E-Field at surface:
    One of the arguments for CMS to decide for p-type sensors.





- TCAD is used for design optimization

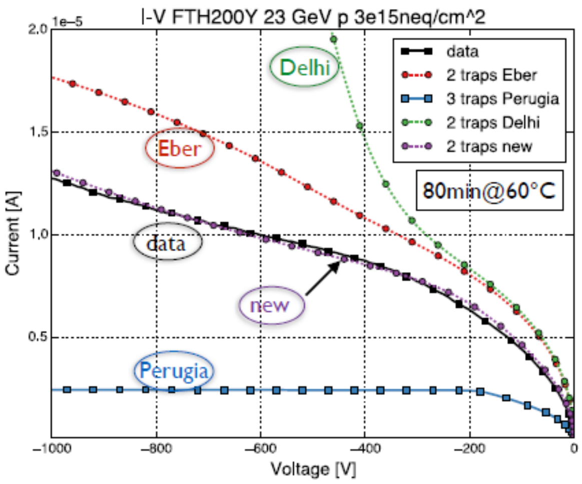
[RD50 simulations; Summary: T. Peltola, POS, arXiv: 1509.08657v1; 2015]

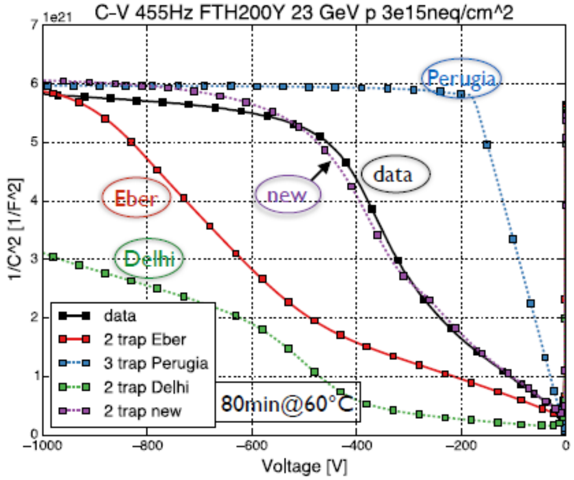
Comparing models and simulators

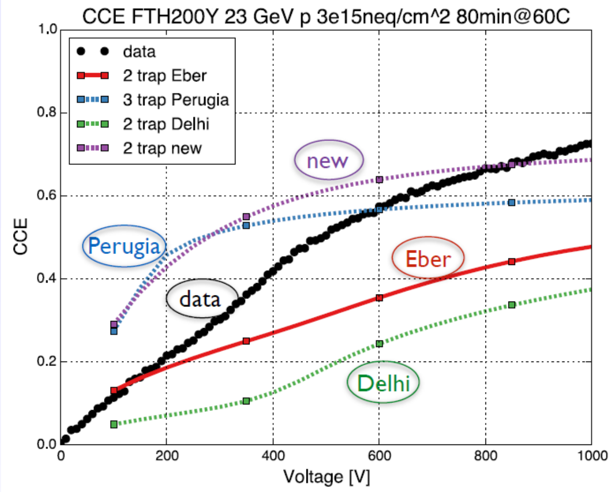
- **Cross checking various models and data fitting within the TCAD simulators**
  - **Many published TCAD models for irradiated sensors**
    - usually optimized for specific data sets with focus on specific parameters (e.g. depletion voltage, reverse current, charge collection)
    - often not applicable to (or not tested for) e.g. different fluence or temperature range !
  - **New RD50 approach:** Understand limits of available models and obtain more consistent parameter set by fitting full data sets (CV,IV, CCE of diodes) within the TCAD simulator.

Minimize difference between measured and simulated IV,CV curves

$$F = w_1 \int_{V_{min}}^{V_{max}} \left(1 - \frac{I_{sim}}{I_{mes}}\right)^2 dV + w_2 \int_{V_{min}}^{V_{max}} \left(1 - \frac{C_{sim}}{C_{mes}}\right)^2 dV$$







Simulation of IV and CV curves & optimization of parameters (“new”)

Compare against CCE (1060nm)

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

Summary

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

Acknowledgements & References

- Most references to particular works given on the slides
  - ***RD50 presentations: http://www.cern.ch/rd50/***
  - ***Conferences:*** *VERTEX, PIXEL, RESMDD*

- Instrumentation Schools
  - ***ICFA, EDIT, ESI, CERN & DESY Summer Student Lectures***

- Books about silicon tracking detectors (and radiation damage)
  - ***Helmuth Spieler, "Semiconductor Detector Systems", Oxford University Press 2005***
  - ***C.Leroy, P-G.Rancoita, "Silicon Solid State Devices and Radiation Detection", World Scientific 2012***
  - ***Frank Hartmann, "Evolution of silicon sensor technology in particle physics", Springer 2009***
  - ***L.Rossi, P.Fischer, T.Rohe, N.Wermes "Pixel Detectors", Springer, 2006***
  - ***Gerhard Lutz, "Semiconductor radiation detectors", Springer 1999***

- Research collaborations and web sites
  - ***CERN RD50 collaboration (http://www.cern.ch/rd50) - Radiation Tolerant Silicon Sensors***
  - ***CERN RD39 collaboration – Cryogenic operation of Silicon Sensors***
  - ***CERN RD42 collaboration – Diamond detectors***
  - ***Inter-Experiment Working Group on Radiation Damage in Silicon Detectors (CERN)***
  - ***ATLAS IBL, ATLAS and CMS upgrade groups***