Solid State Detectors

Semiconductor detectors

Halbleiterdetektoren

Doris Eckstein
DESY

Where are solid state detectors used?

- Nuclear Physics:
  - Energy measurement of charged particles (particles up to a few MeV)
  - Gamma Spectroscopy (precision measurement of photon energies)
- Particle Physics
  - Tracking and vertexing
  - Beam condition monitoring
- Satellite Experiments
  - Tracking, identification of particles
- Security, Medicine, Biology,…

What do we want to do in Particle Physics ?

- Track particles without disturbing them
- Determine position of primary interaction vertex and secondary decays
  - Superb position resolution

    Highly segmented ⇒ high resolution
  - Large signal

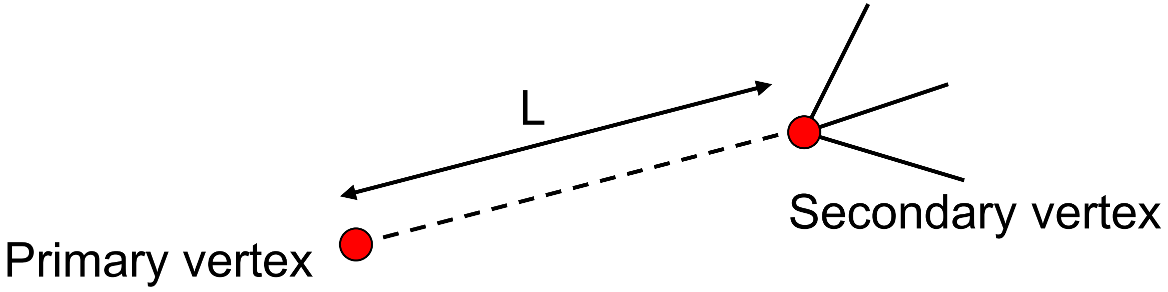
    Small amount of energy to crate signal quanta
  - Thin

    Close to interaction point
  - Low mass

    Minimise multiple scattering
    - Detector
    - Readout
    - Cooling / support

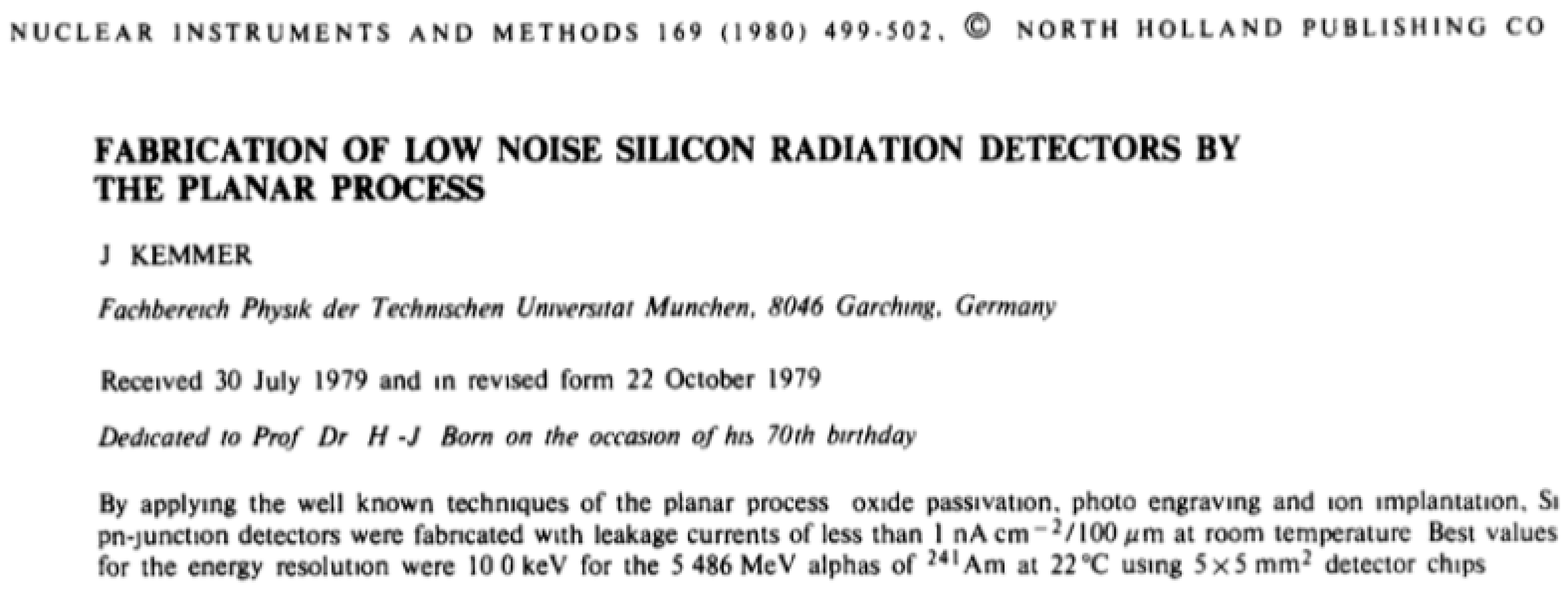
What do we want to do ?

- Measure space points
- Deduce
  - Vertex location
  - Decay lengths
  - Impact parameters
- Reconstruct for example $ttH \rightarrow \bar{b}b$



Historical developments

- J. Kemmer
  - Fixed target experiment with a planar diode*
  - Later strip devices -1980
  - Larger devices with huge ancillary components



NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 499-502, © NORTH HOLLAND PUBLISHING CO

FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

J KEMMER

Fachbereich Physik der Technischen Universitat Munchen, 8046 Garching, Germany

Received 30 July 1979 and in revised form 22 October 1979

Dedicated to Prof. Dr. H.-J. Born on the occasion of his 70th birthday

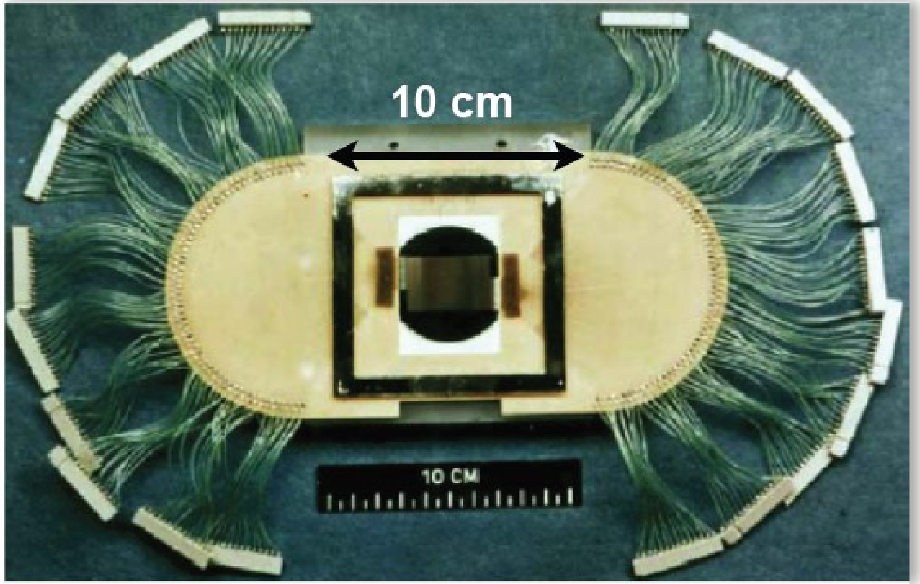
By applying the well known techniques of the planar process: oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than 1 nA $\mathrm{cm}^{-2}/100\ \mu\mathrm{m}$ at room temperature. Best values for the energy resolution were 10.0 keV for the 5.486 MeV alphas of $^{241}\mathrm{Am}$ at 22 °C using $5\times5\ \mathrm{mm}^2$ detector chips.

Historical developments

> NA11 at CERN

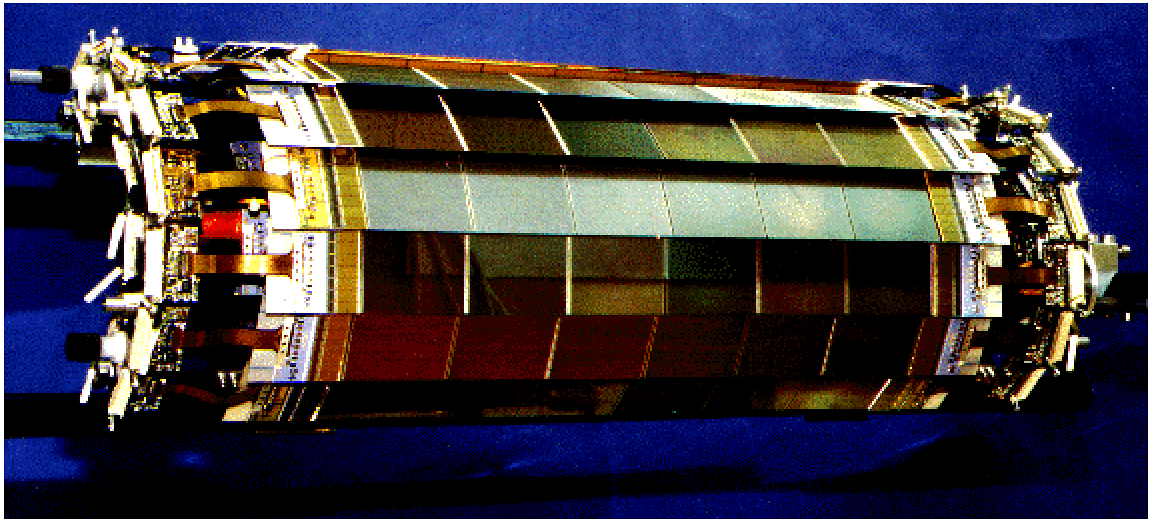
First use of a position-sensitive silicon detector in HEP experiment

- Measurement of charm-quark lifetime
- 1200 diode strips on 24 x 36mm^2 active area
- 250-500 μm thick bulk material
- 4.5 μm resolution



Historical developments

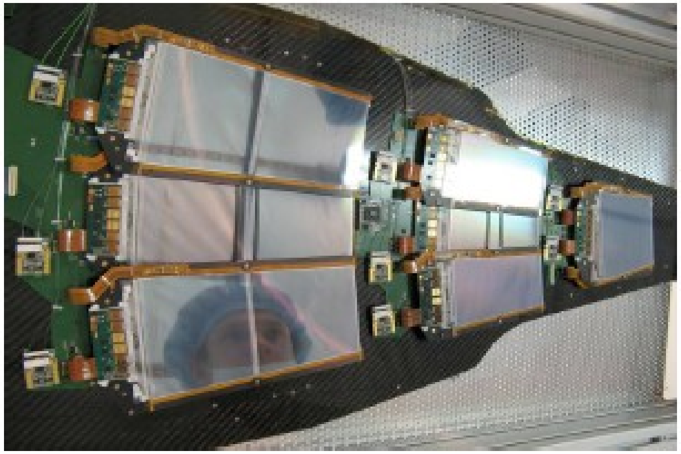
- **LEP and SLAC**
  - ASIC's at end of ladders
  - Minimise the mass inside tracking volume
  - Minimise the mass between interaction point and detectors
  - Minimise the distance between interaction point and the detectors
- Enabled heavy flavour physics i.e. short lived particles



- 2 silicon layers, 40cm long, inner radius 6.3cm, outer radius 11cm
- 300μm Silicon wafers giving thickness of only $0.015X_0$
- S/N rΦ = 28:1; z = 17:1
- $\sigma_{r\phi} = 12\mu m$; $\sigma_z = 14\mu m$

Historical developments

- CDF/D0 & LHC
  - Emphasis shifted to tracking + vertexing
  - Only possible as increased energy of particles
- Cover large area with many silicon layers
- Detector modules including ASIC’s and services INSIDE the tracking volume
- Module size limited by electronic noise due to fast shaping time of electronics (bunch crossing rate determined)

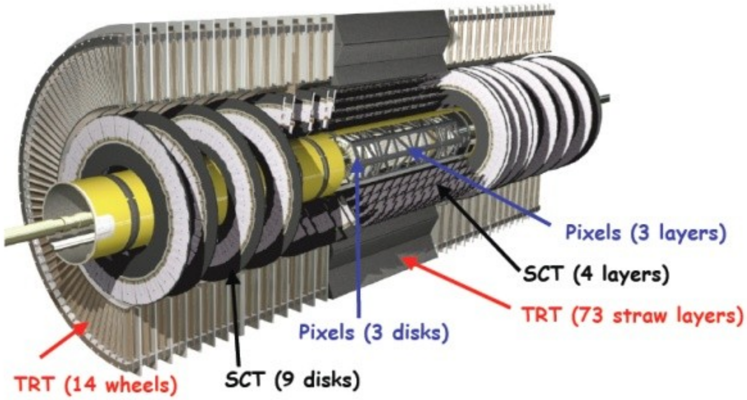


LHC detectors

ATLAS

Strips: 61 m^2 of silicon, 4088 modules, $6x10^6$ channels

Pixels: 1744 modules, 80 x 10^6 channels



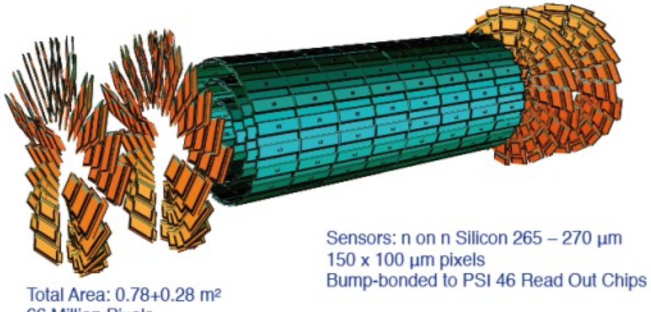
CMS

the world largest silicon tracker

200 m² of strip sensors (single sided)

11 x 10^6 readout channels

~1m² of pixel sensors, $60x10^6$ channels

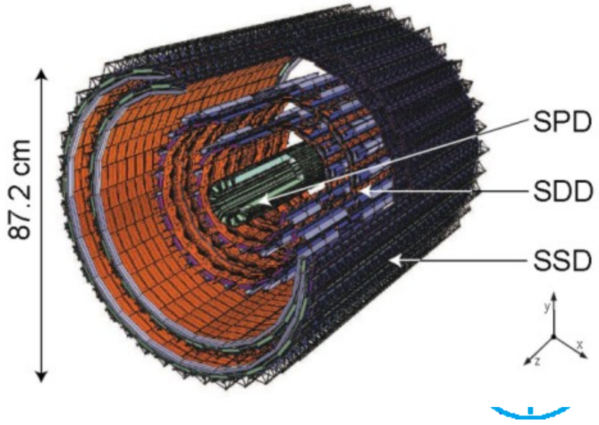


ALICE

Pixel sensors

Drift detectors

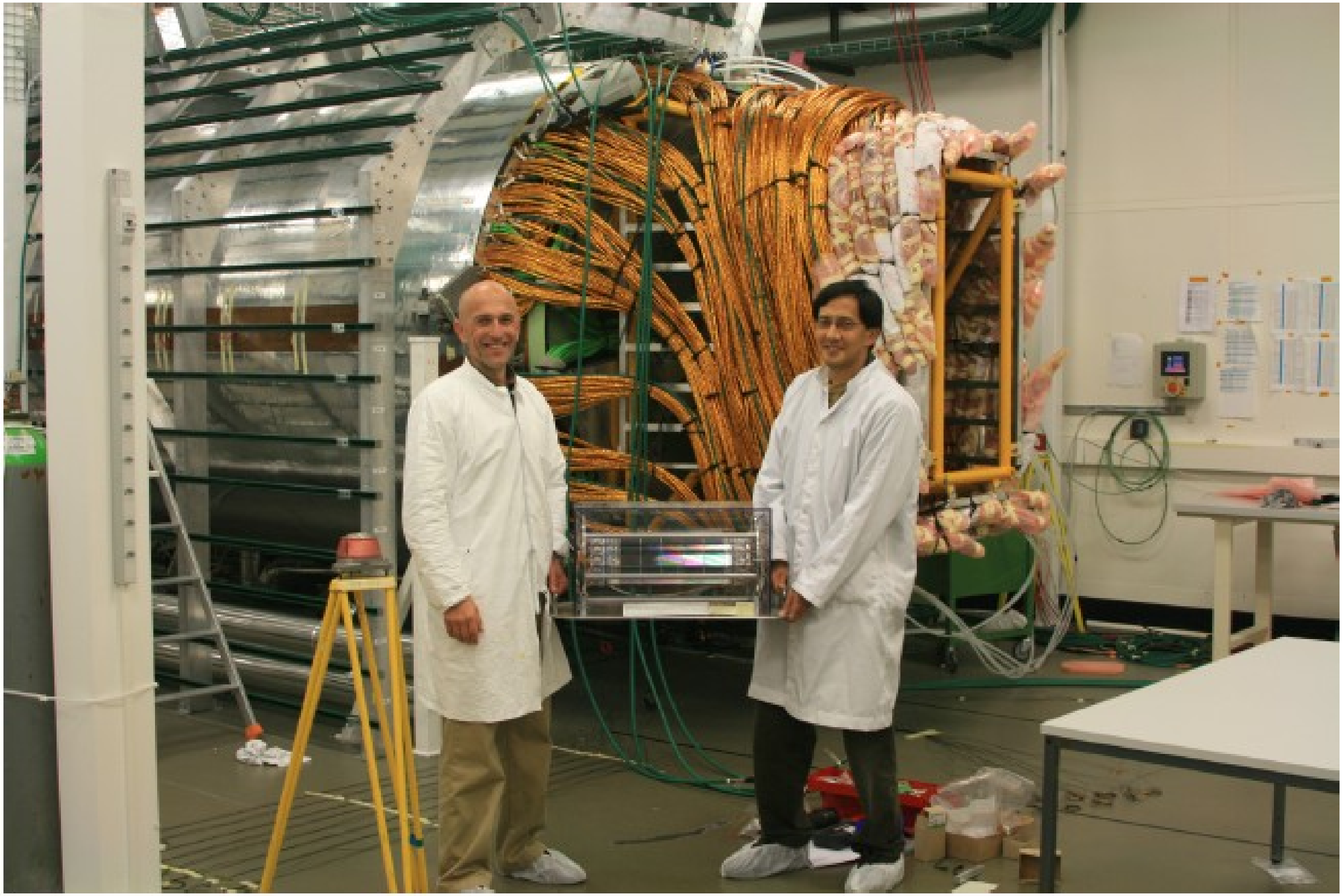
Double sided strip detectors



LHCb

VELO: Si Strips

DELPHI vs. CMS

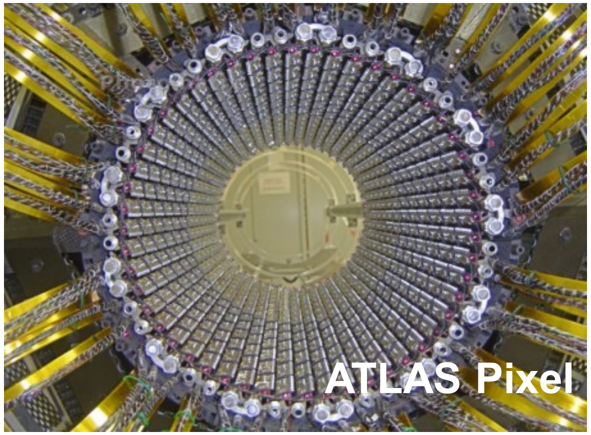


Currently at the LHC

CMS TIB

LHCb VELO

ATLAS SCT



ATLAS Pixel

ALICE Pixel

CMS

Advantages/Disadvantages of semiconductor detectors

- Semiconductor detectors have a **high density**
  - large energy loss in a short distance
  - Diffusion effect is smaller than in gas detectors resulting in achievable position resolution of less than 10 µm
- **Low ionization energy** (few eV per e-hole pair) compared to
  - gas detectors (20-40 eV per e-ion pair) or
  - scintillators (400-1000 eV to create a photon)

- No internal amplification, i.e. small signal
  - with a few exceptions
- High cost per surface unit
  - Not only Silicon itself
  - High number of readout channels
  - Large power consumption □ cooling

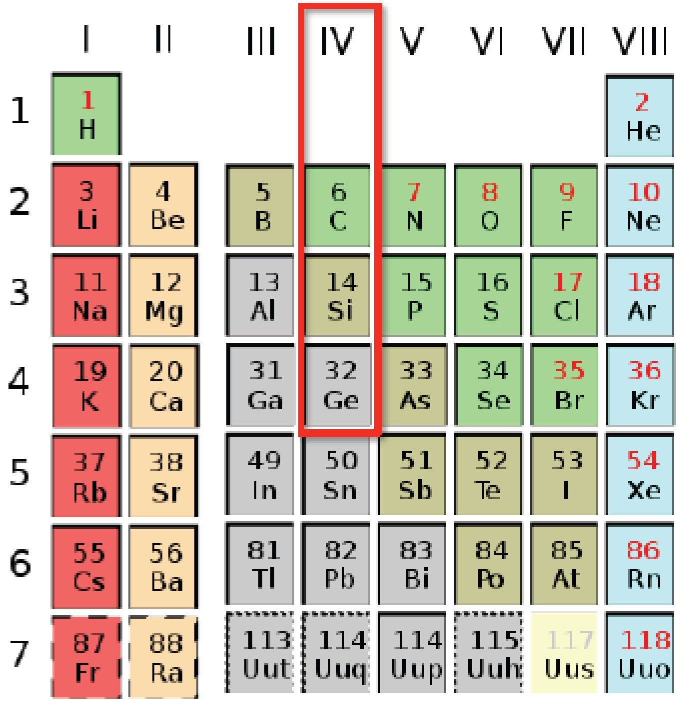
Elemental Semiconductor

- **Germanium:**
  - Used in nuclear physics
  - Needs cooling due to small band gap of 0.66 eV (usually done with liquid nitrogen at 77 K)
- **Silicon:**
  - Can be operated at room temperature
  - Synergies with micro electronics industry
  - Standard material for vertex and tracking detectors in high energy physics
- **Diamond (CVD or single crystal):**
  - Allotrope of carbon
  - Large band gap (requires no depletion zone)
  - very radiation hard
  - Disadvantages: low signal and high cost

Compound Semiconductors

- **Compound semiconductors consist of**
  - two (binary semiconductors) or
  - more than two

  atomic elements of the periodic table.
- **Depending on the column in the periodic system of elements one differentiates between**
  - IV-IV- (e.g. *SiGe*, *SiC*),
  - III-V- (e.g. *GaAs*)
  - II-VI compounds (*CdTe, ZnSe*)
- **important III-V compounds:**
  - ***GaAs***: Faster and probably more radiation resistant than Si. Drawback is less experience in industry and higher costs.
  - GaP, GaSb, InP, InAs, InSb, InAlP
- **important II-VI compounds:**
  - ***CdTe***: High atomic numbers (48+52) hence very efficient to detect photons.
  - ZnS, ZnSe, ZnTe, CdS, CdSe, Cd1-xZnxTe, Cd1-xZnxSe



	I	II	III	IV	V	VI	VII	VIII
1	1 H							2 He
2	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	113 Uut	114 Uuq	114 Uup	115 Uuh	117 Uus	118 Uuo

Why Silicon

- Semiconductor with moderate bandgap (1.12eV)
- Energy to create e/h pair (signal quanta)= 3.6eV

plus phonon excitation

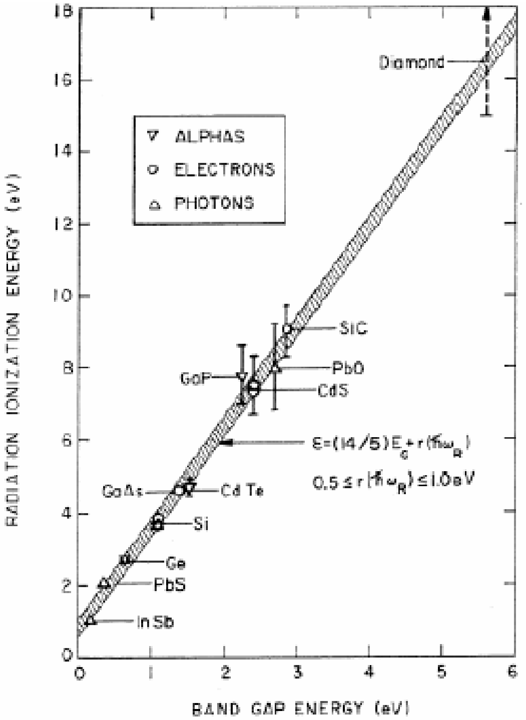
  - (c.f Argon gas = 15eV)
  - High carrier yield
  - Better energy resolution and high signal

  ⇒no gain stage required
- High density and atomic number
  - Higher specific energy loss

  ⇒Thinner detectors

  ⇒Reduced range of secondary particles

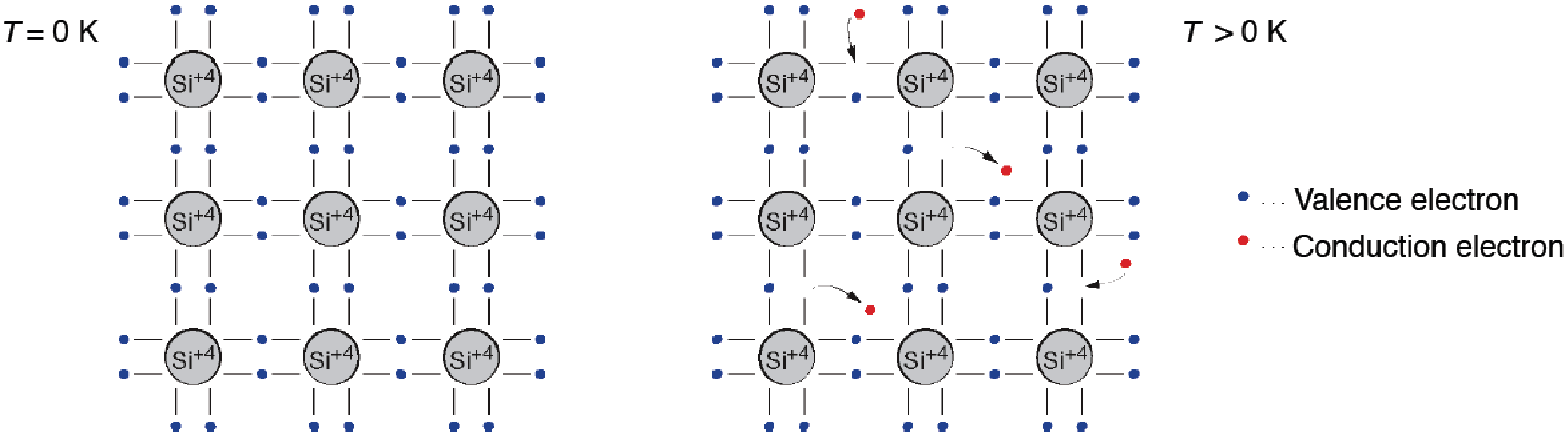
  ⇒better spatial resolution
- High carrier mobility ⇒ Fast!
  - Less than 30ns to collect entire signal
- **Large experience in industry** with micro-chip technology
- High intrinsic radiation hardness



C.A. Klein, J. Applied Physics 39 (1968) 2029

Bond Model

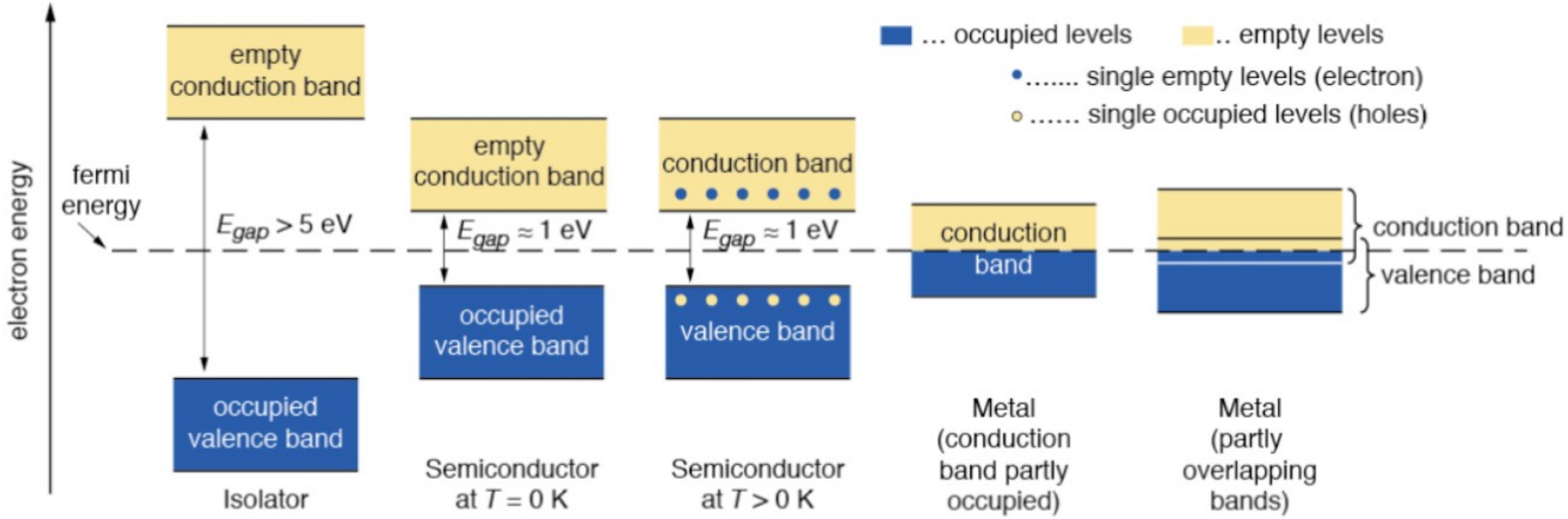
- Example of column IV elemental semiconductor:



- Each atom has 4 closest neighbors, the 4 electrons in the outer shell are shared and form **covalent bonds**.
  - At low temperature all electrons are bound
  - At higher temperature thermal vibrations break some of the bonds
  - free e- cause conductivity (electron conduction)
  - The remaining open bonds attract other e- ➔ The “holes” change position (hole conduction)

Energy Bands

- In an isolated atom the electrons have only discrete energy levels.
- In solid state material the atomic levels merge to energy bands. In **metals** the conduction and the valence band **overlap**, whereas in isolators and semiconductors these levels are **separated** by an energy gap (**band gap**). In isolators this gap is large.



Intrinsic carrier concentration

- Due to the small band gap in semiconductors electrons already occupy the conduction band at room temperature.
- Electrons from the conduction band may recombine with holes.
- A **thermal equilibrium** is reached between **excitation** and **recombination:** charge carrier concentration $n_e = n_h = n_i$

  This is called intrinsic carrier concentration:

$$n_i = \sqrt{N_C N_V} \cdot \exp\left(-\frac{E_g}{2kT}\right) \propto T^{\frac{3}{2}} \cdot \exp\left(-\frac{E_g}{2kT}\right)$$

- In ultrapure silicon the intrinsic carrier concentration is $\mathbf{1.45 \cdot 10^{10}\ cm^{-3}}$.

  With approximately 10^{22} Atoms/cm^3 about 1 in 10^{12} silicon atoms is ionized.

Material Properties: drift velocity, mobility, resistivity

- **Drift velocity** for electrons: $\vec{v}_n = -\mu_n \cdot \vec{E}$

  for holes: $\vec{v}_p = \mu_p \cdot \vec{E}$

- **Mobility** for electrons: $\mu_n = \frac{e\,\tau_n}{m_n}$

  for holes: $\mu_p = \frac{e\,\tau_p}{m_p}$

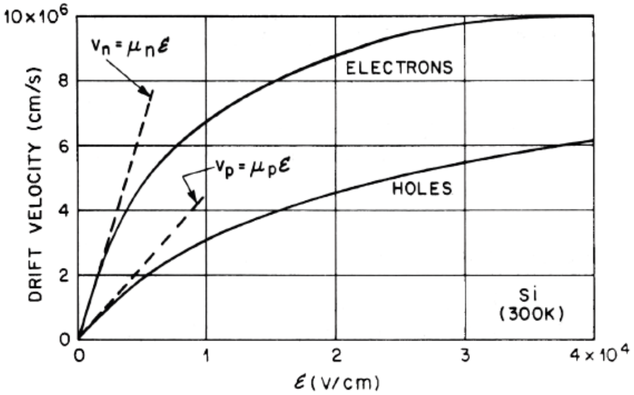
μ_p(Si, 300 K) ≈ 450 cm^2/Vs
μ_n(Si, 300 K) ≈ 1450 cm^2/Vs

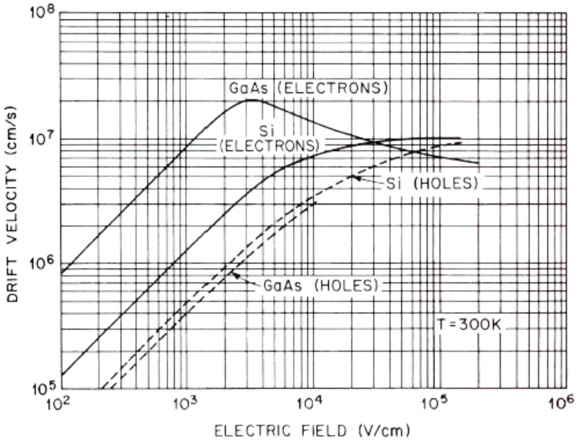
- **Resitivity** $\rho = \frac{1}{e(\mu_n n_e + \mu_p n_h)}$

The charge carrier concentration in pure silicon (i.e. intrinsic Si) for T = 300 K is: $n_e = n_h \approx 1.45 \cdot 10^{10}$ cm^{-3}

This yields an intrinsic resistivity of: **ρ ≈ 230 kΩcm**

e	…	electron charge
E	…	external electric field
m_n , m_p	…	effective mass of e$^-$ and holes
τ_n , τ_p	…	mean free time between collisions for e$^-$ and holes (carrier lifetime)
n_e , n_h	…	Charge carrier density for electrons and holes

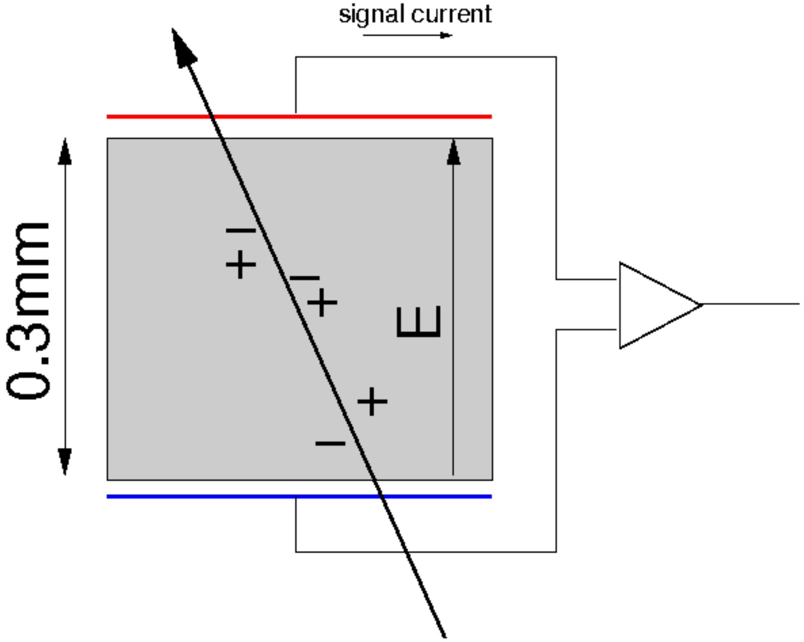




Source: S.M. Sze, Semiconductor Devices, J. Wiley & Sons, 1985

Constructing a detector

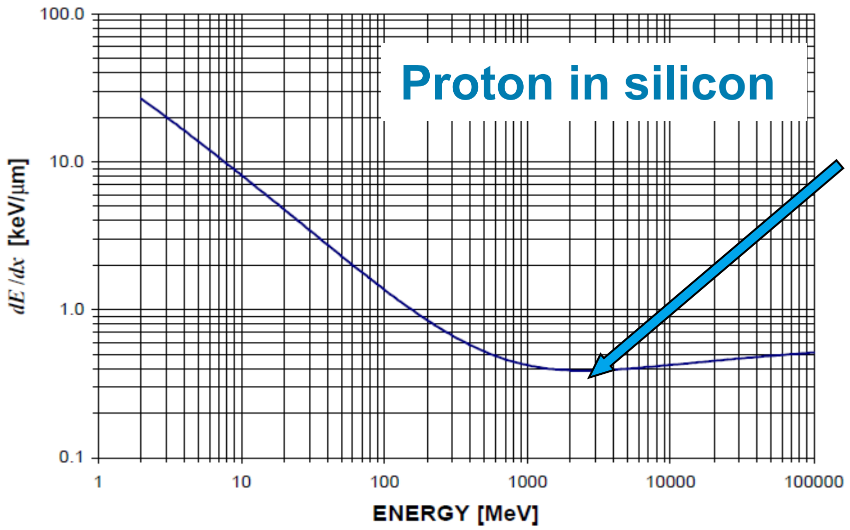
- **Thickness:** 0.3mm
- **Area:** 1cm^2
- **Resistivity:** 10kΩcm
  - Resistance (ρd/A) : 300Ω
- **Mobility (electrons):** ~1400cm^2/Vs
- **Collection time:** ~10ns
- **Charge released:** ~25000 e~4fC



  - Need an average field of

$$E = v/\mu = 0.03\text{cm}/10\text{ns}/1400\text{cm}^2/\text{V} \sim 21000\ \text{V/cm or } V = 60\text{V}$$

Constructing a detector



- Mean ionization energy **I_0 = 3.62 eV**,
- mean energy loss per flight path of a mip **dE/dx = 3.87 MeV/cm**

Assuming same detector with a thickness of d = 300 µm and an area of A = 1 cm^2.

Signal of a mip in such a detector:

$$\frac{dE/dx \cdot d}{I_0} = \frac{3.87 \cdot 10^6 \mathrm{eV/cm} \cdot 0.03\mathrm{cm}}{3.62\mathrm{eV}} \approx 3.2 \cdot 10^4 \, \mathrm{e^- h^+ - pairs}$$

Intrinsic charge carrier in the same volume (T = 300 K):

$$n_i \, d \, A = 1.45 \cdot 10^{10} \mathrm{cm^{-3}} \cdot 0.03\mathrm{cm} \cdot 1\mathrm{cm^2} \approx 4.35 \cdot 10^8 \, \mathrm{e^- h^+ - pairs}$$

Result: The number of thermal created e–h+-pairs (noise) is four orders of magnitude larger than the signal

Creating a pn-junction - doping

- **Doping** is the **replacement of a small number of atoms** in the lattice by atoms of **neighboring columns** from the periodic table
- These doping atoms create **energy levels within the band gap** and therefore alter the conductivity.

Definitions:

- An un-doped semiconductor is called an **intrinsic semiconductor.**

  For each conduction electron exists the corresponding hole.

- A doped semiconductor is called an **extrinsic semiconductor**.

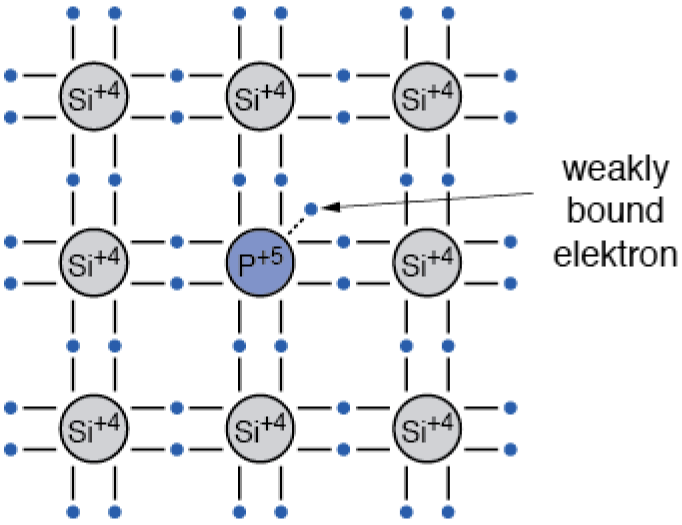
  Extrinsic semiconductors have an abundance of electrons or holes.

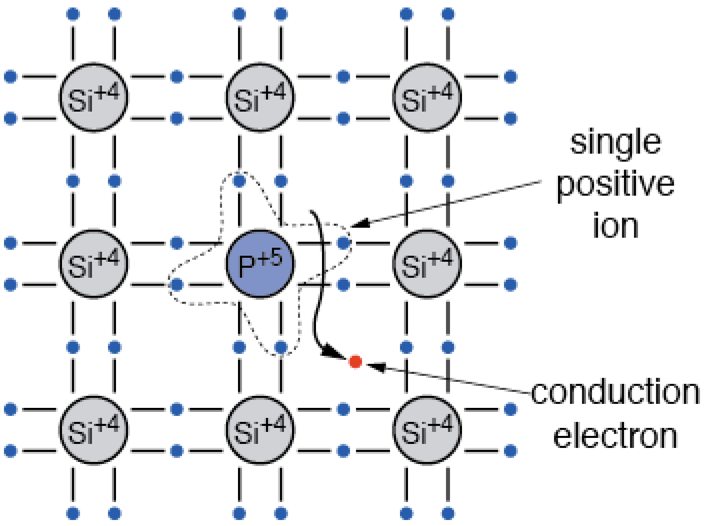
n-type silicon

Doping with an element V atom (e.g. P, As, Sb). The 5th valence electron is weakly bound.

The doping atom is called **donor.**

Negatively charged electrons are the majority carriers and the space charge is positive.

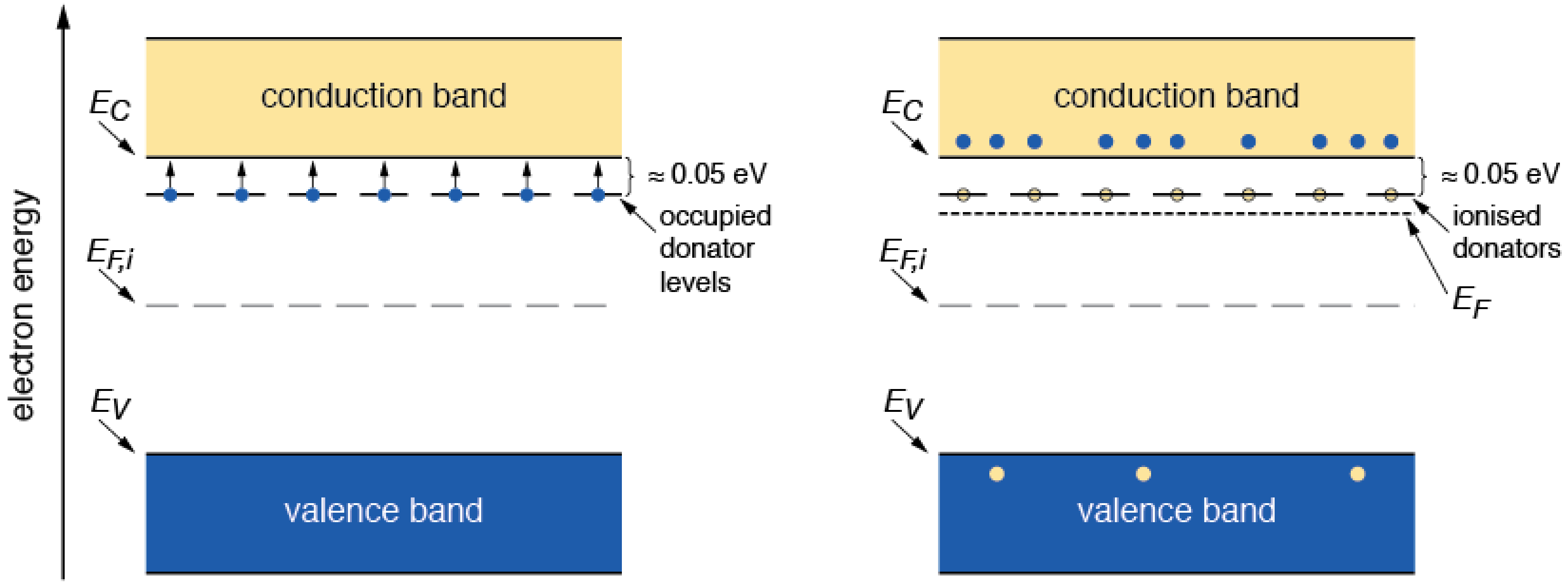




n-type silicon

The energy level of the donor is just below the edge of the conduction band. At room temperature most electrons are raised to the conduction band.

The Fermi level E_F moves up.



🟨 … empty levels

🟦 … occupied levels

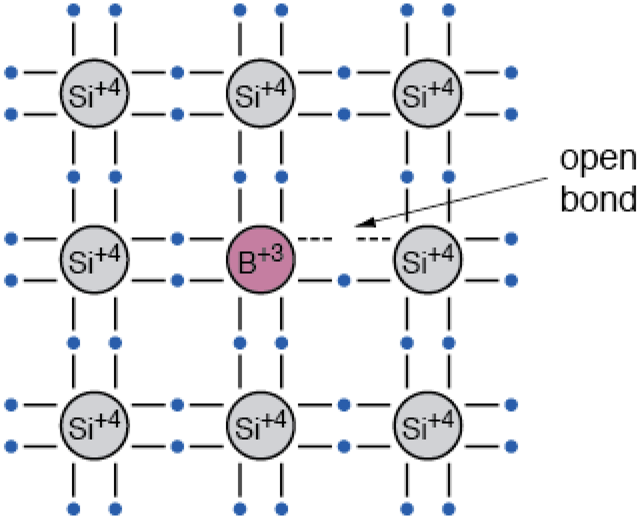
● … single occupied level (electron)

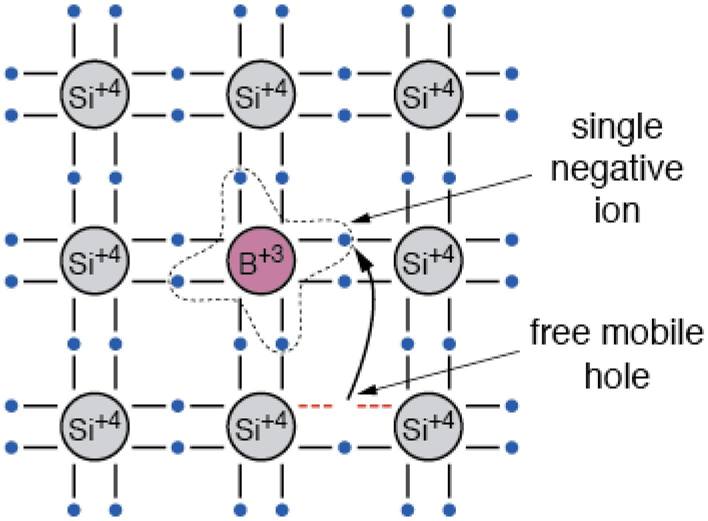
○ … single empty level (hole)

p-type silicon

- Doping with an element III atom (e.g. B, Al, Ga, In). One valence bond remains open. This open bond attracts electrons from the neighbor atoms. The doping atom is called **acceptor**.

Positively charged holes are the majority carriers and the space charge is negative.

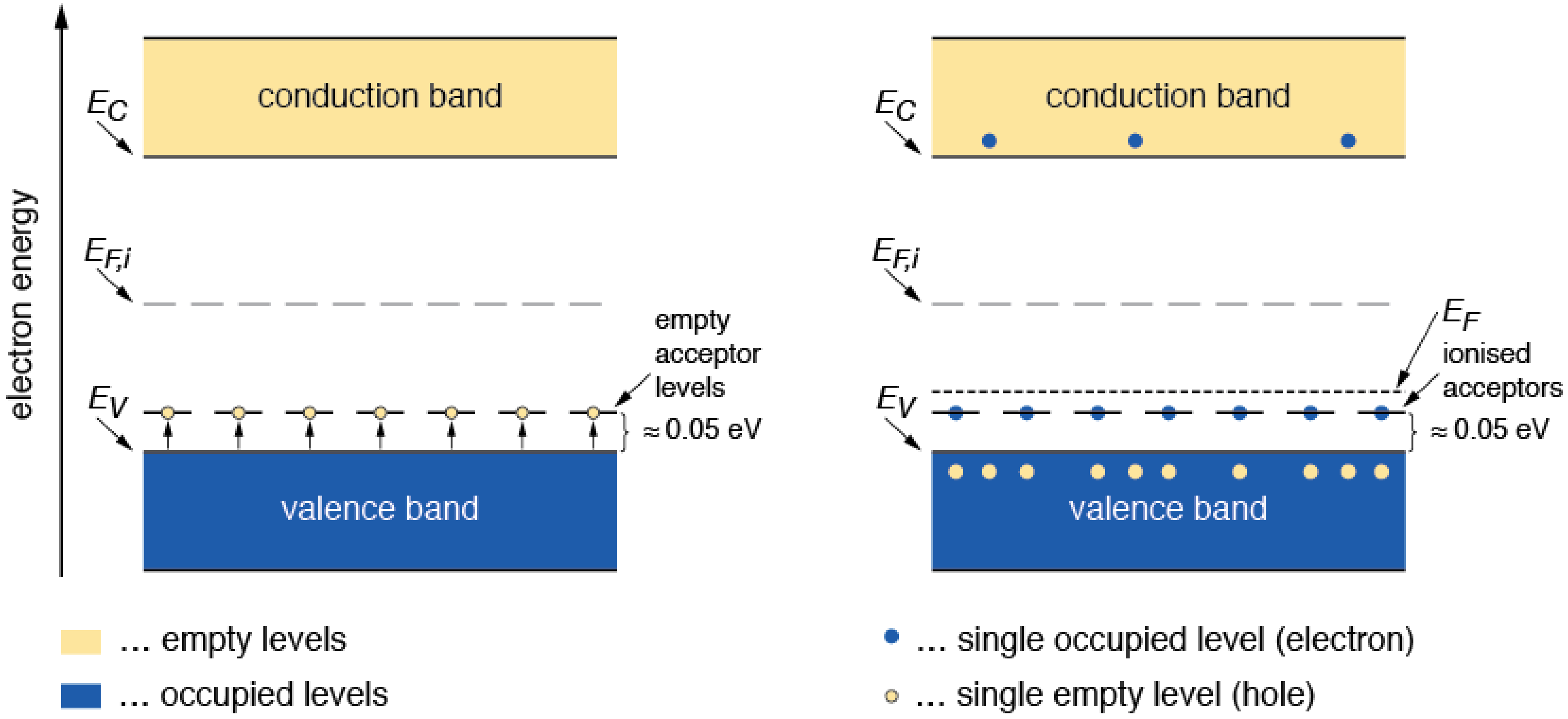




p-type silicon

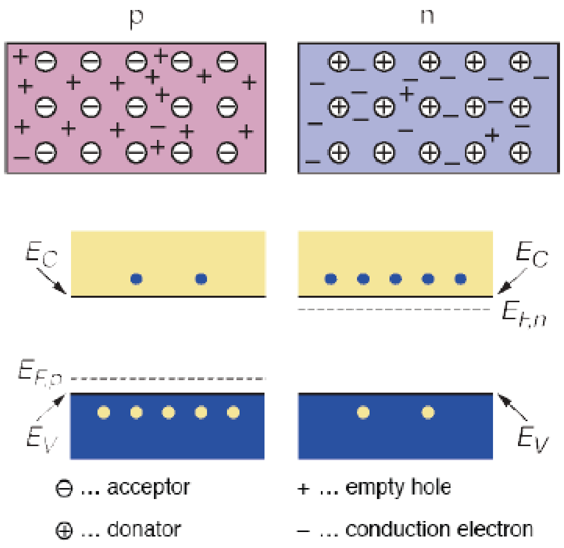
The energy level of the acceptor is just above the edge of the valence band. At room temperature most levels are occupied by electrons leaving holes in the valence band.

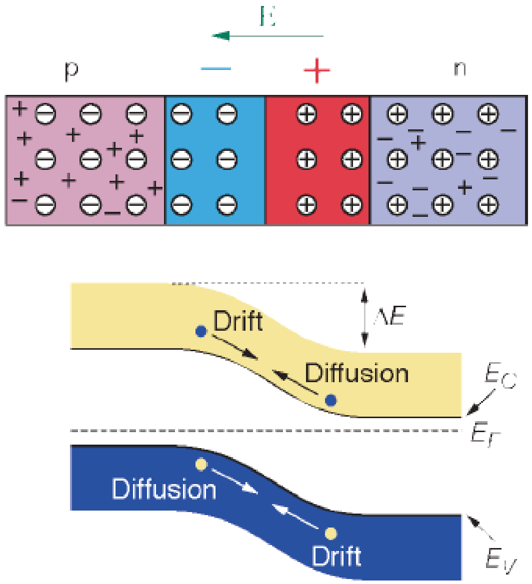
The Fermi level *EF* moves down.



Creating a pn-junction

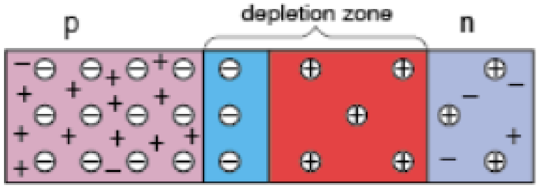
- At the interface of an n-type and p-type semiconductor the difference in the Fermi levels cause diffusion of excessive carries to the other material until thermal equilibrium is reached. At this point the Fermi level is equal. The remaining ions create a **space charge region** and an electric field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



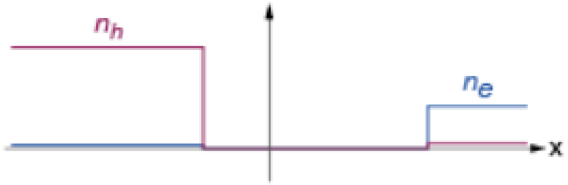


Electrical characteristics of pn-junctions

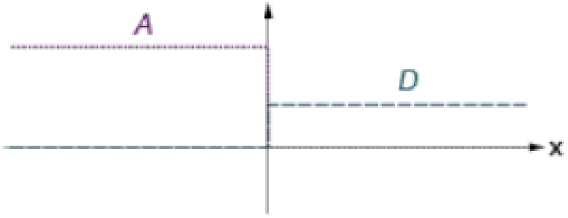
pn junction scheme



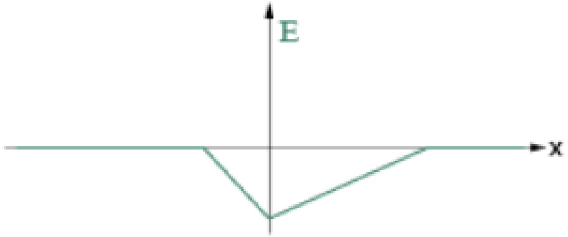
concentration of free charge carriers



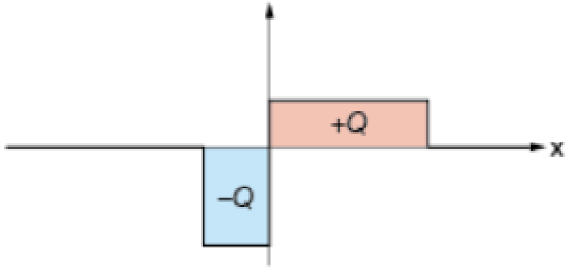
acceptor and donator concentration



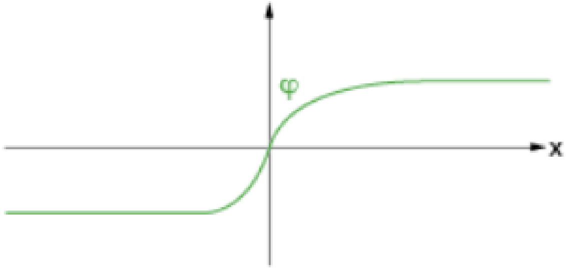
electric field



space charge density



electric potential



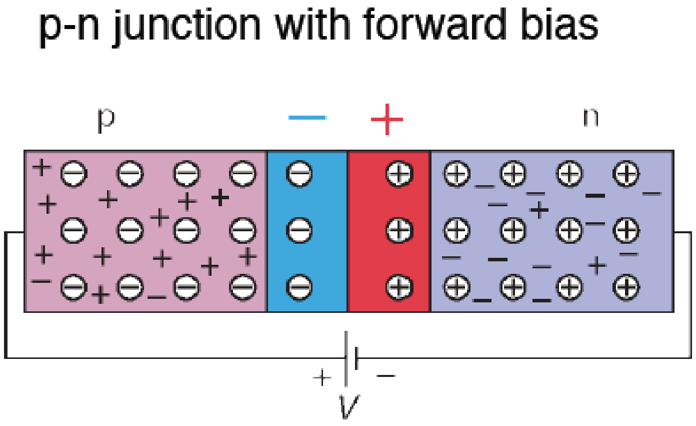
⊖ … acceptor

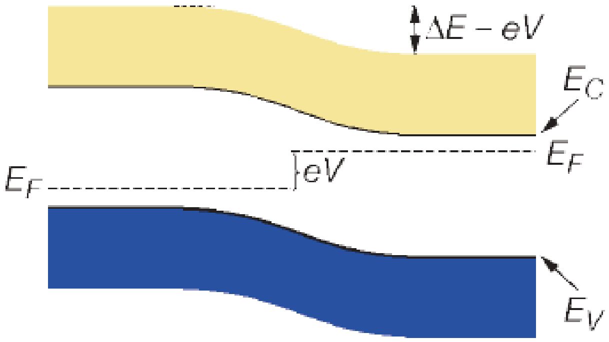
⊕ … donator

+ … empty hole

− … conduction electron

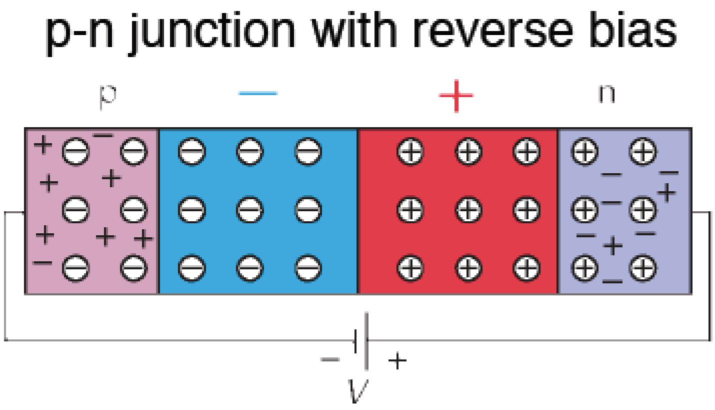
pn-junction with forward bias

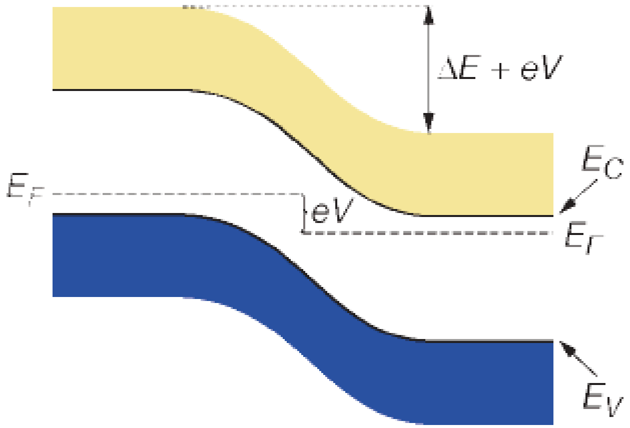

p-n junction with forward bias



- Applying an external voltage V with the anode to p and the cathode to n e- and holes are refilled to the depletion zone. The **depletion zone becomes narrower** (forward biasing)
- **Consequences:**
  - The potential barrier becomes smaller by eV
  - Diffusion across the junction becomes easier
  - The current across the junction increases significantly.

pn-junction with reverse bias


p-n junction with reverse bias

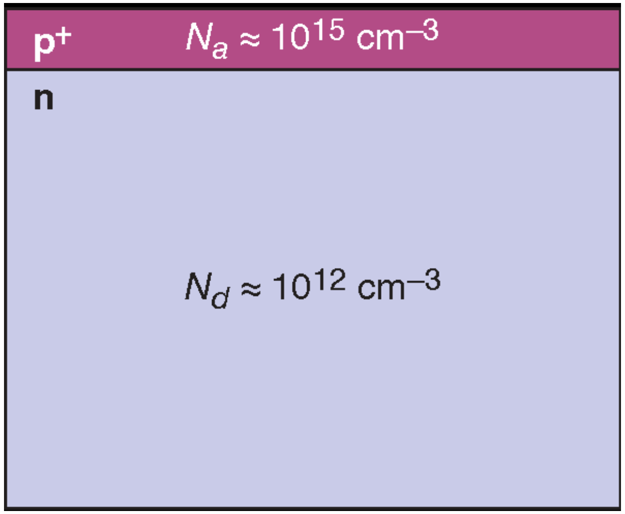


- Applying an external voltage V with the cathode to p and the anode to n e- and holes are pulled out of the depletion zone. The **depletion zone becomes larger** (reverse biasing).
- **Consequences:**
  - The potential barrier becomes higher by *eV*
  - Diffusion across the junction is suppressed.
  - The current across the junction is very small (“leakage current”)

➔ This is the way we operate our semiconductor detector!

Width of the depletion zone

- Effective doping concentration in typical silicon detector with p+-n junction
  - $N_a = 10^{15}$ cm^{-3} in p+ region
  - $N_d = 10^{12}$ cm^{-3} in n bulk.
- **Without external voltage:**
  - $W_p = 0.02$ µm
  - $W_n = 23$ µm
- **Applying a reverse bias voltage of 100 V:**
  - $W_p = 0.4$ µm
  - $W_n = 363$ µm



- **Width of depletion zone in n bulk:**

$$W \approx \sqrt{2\varepsilon_0\varepsilon_r\mu\rho|V|}$$

with

$$\rho = \frac{1}{e\mu N_{eff}}$$

V ... External voltage
ρ ... specific resistivity
μ ... mobility of majority charge carriers
N_{eff} ... effective doping concentration

Derived by solving Poisson equation, $N_a >> N_d$

Depletion Voltage

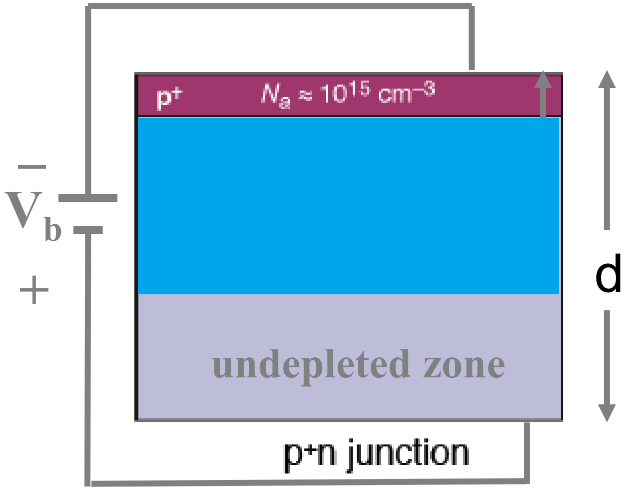
Why do we use high-resistivity Silicon ?

Detectors:

Doping concentrations: 10^{12}–10^{15}cm^{-3}
Resistivity ~ 5 kΩcm

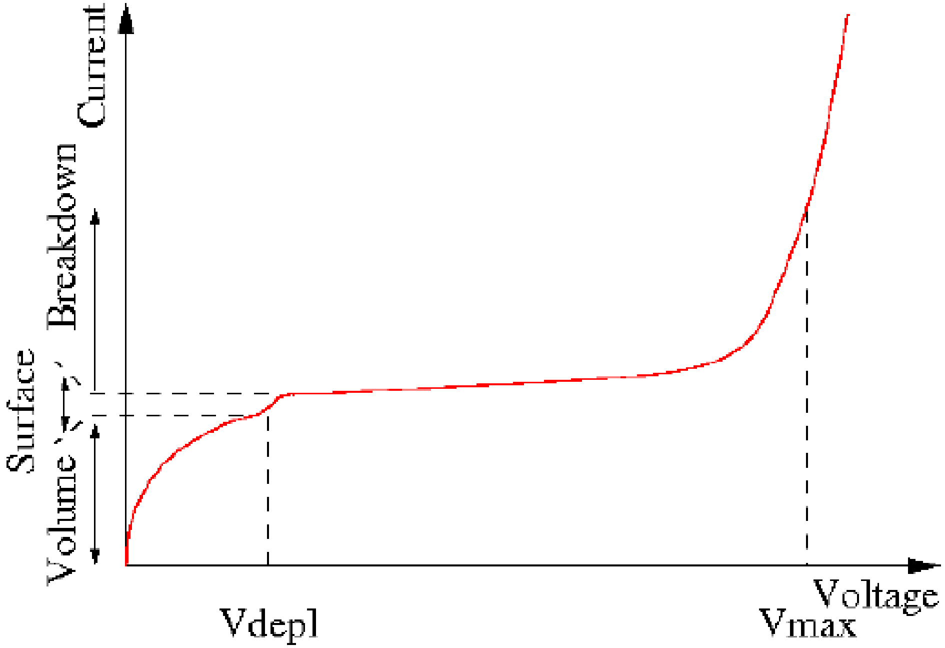
CMOS:

Doping concentrations: 10^{17} –10^{18} cm^{-3}
Resistivity ~ 1 Ωcm



The voltage needed to completely deplete a device of thickness d is called the depletion voltage

Properties of the depletion zone – reverse current



Diffusion current

- From generation at surface, interfaces
- Negligible for a fully depleted detector

Generation current

– From thermal generation in the depletion region

– Reduced by using pure and defect free material

- high carrier lifetime

– Must keep temperature low & controlled

$$j_{gen} \propto T^{3/2} \exp\left(\frac{1}{2kT}\right)$$

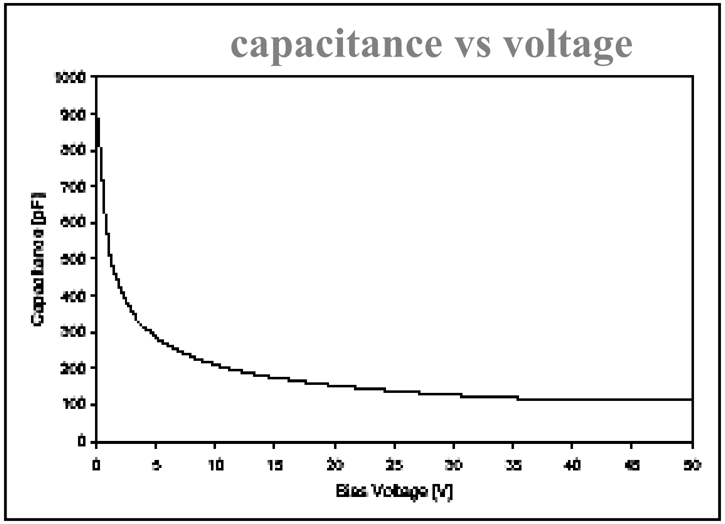
Factor 2 every $\Delta T = 8^\circ C$

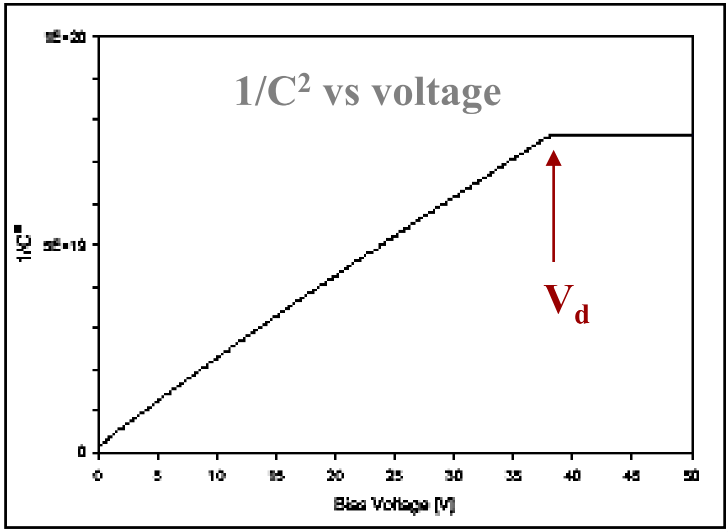
Detector Capacitance

- Capacitance is similar to parallel-plate capacitor
- Fully depleted detector capacitance defined by geometric capacitance

$$C = \sqrt{\frac{\varepsilon_0 \varepsilon_r}{2\mu\rho|V|}} \cdot A$$

One normally measures the depletion behaviour (finds the depletion voltage) by measuring the capacitance versus reverse bias voltage.





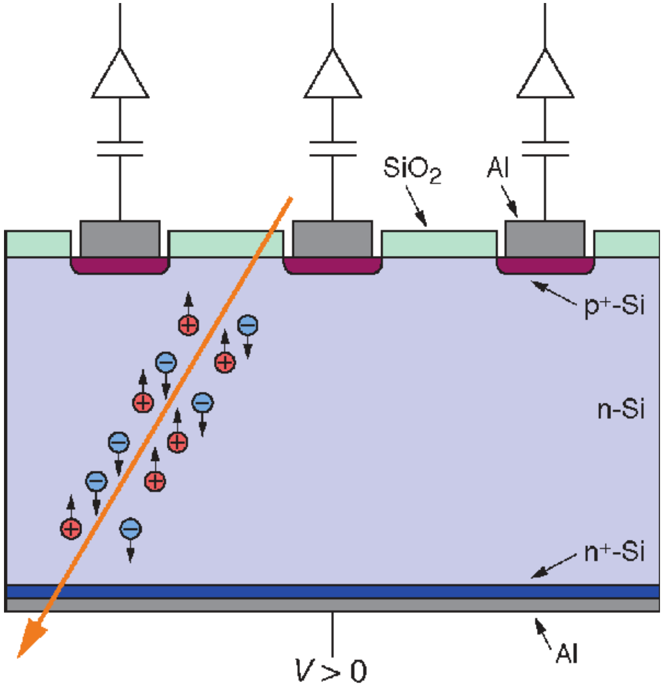
Position Resolution – Strip Detector (DC coupled)

- By segmenting the implant we can reconstruct the position of the traversing particle in one dimension
- DC-coupled strip detector – simplest possible

  realisation of a position sensitive Silicon detector
- Strips are Boron implants
- Substrate is Phosphorous doped (~2-10 kΩcm)

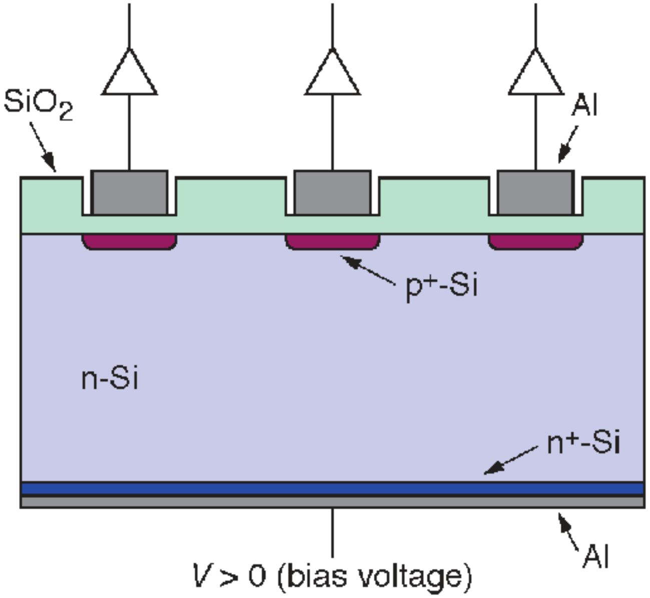
  and ~300µm thick
  - $V_{dep} < 200$V
- •Backside Phosphorous implant to establish

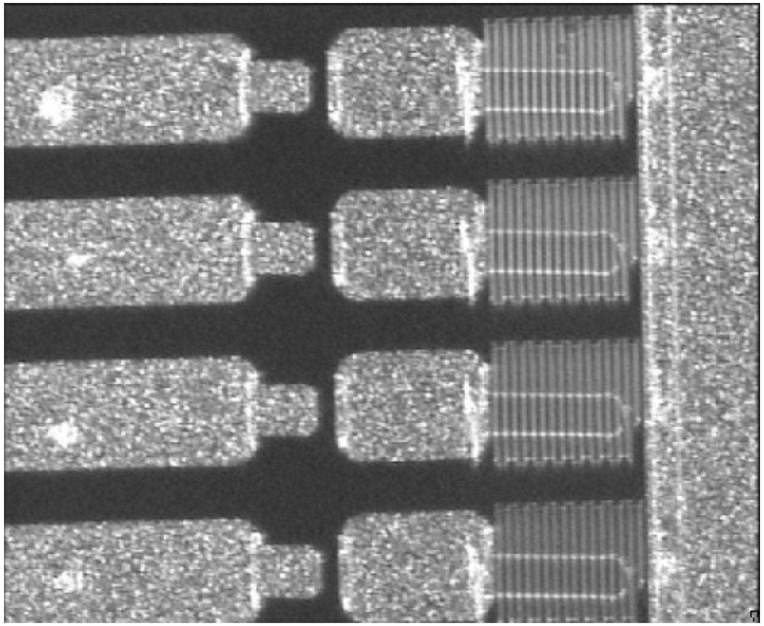
  ohmic contact and to prevent early breakdown
- Highest field close to the collecting electrodes where most of the signal is induced



Position Resolution – Strip Detector (AC coupled)

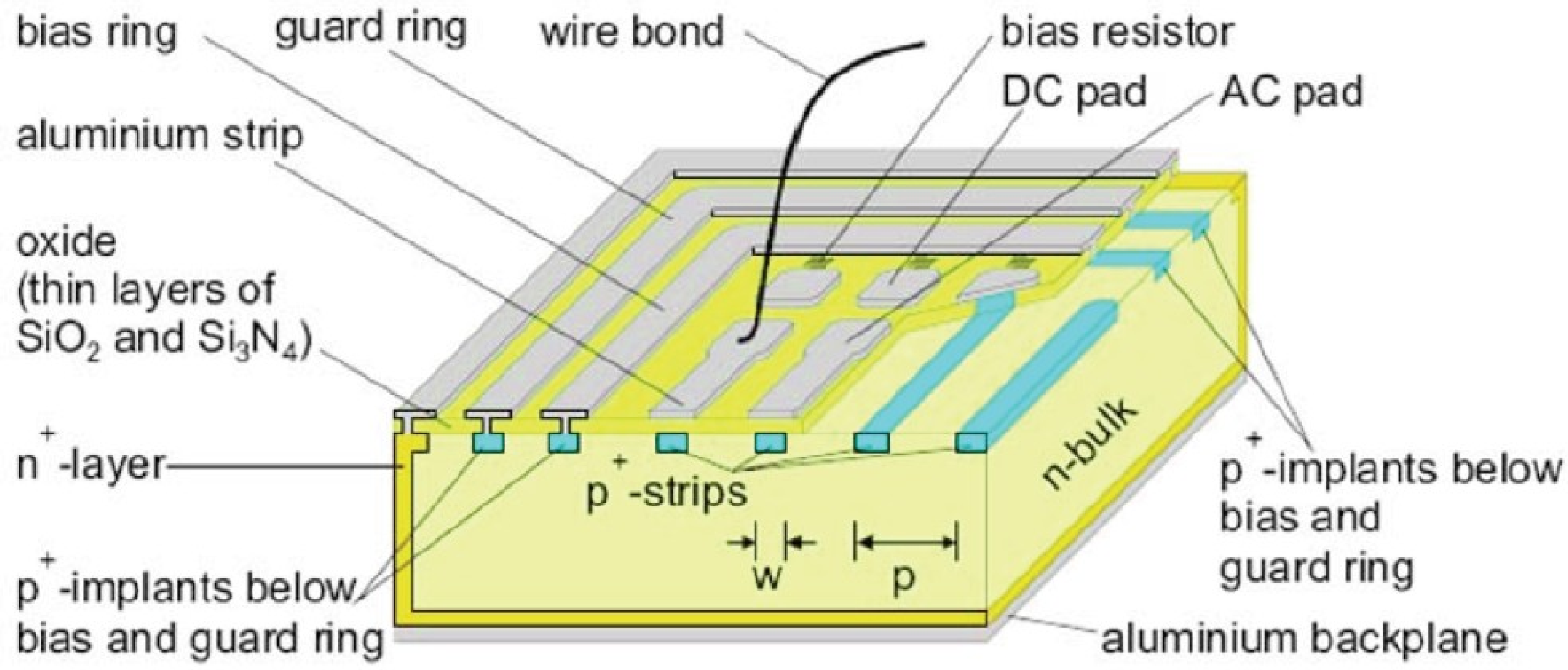
- AC coupling blocks leakage current from the amplifier
- Integration of coupling capacitances in standard planar process.
- Deposition of SiO_2 with a thickness of 100–200 nm between p+ and aluminum strip
- Increase quality of dielectric by a second layer of Si_3N_4.





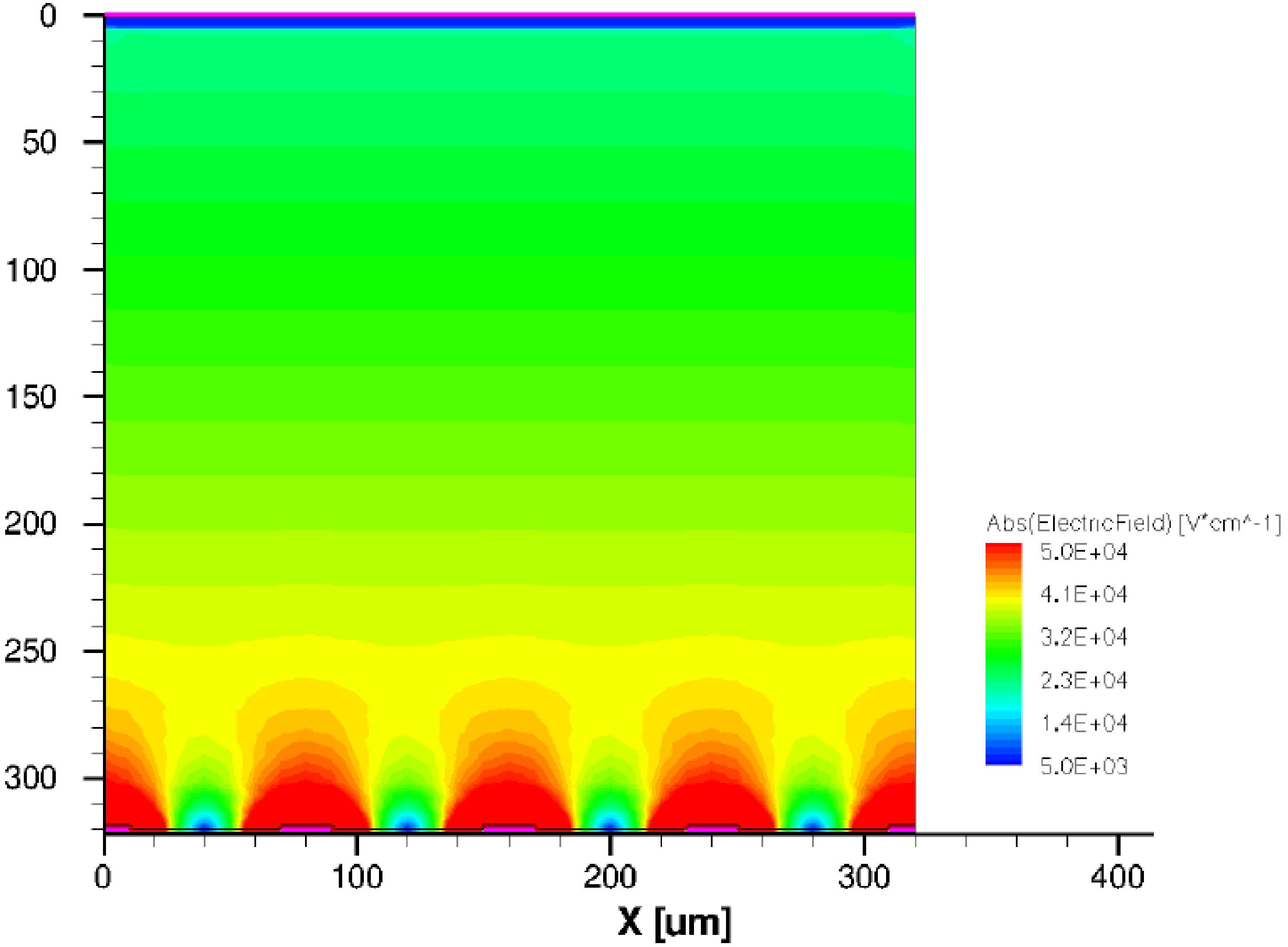
- to connect the bias voltage to the strips:
  → Long poly silicon resistor with R>1MΩ

A typical AC-coupled strip sensor



Typical thickness: 300µm
Typical strip-pitch: 50-100µm

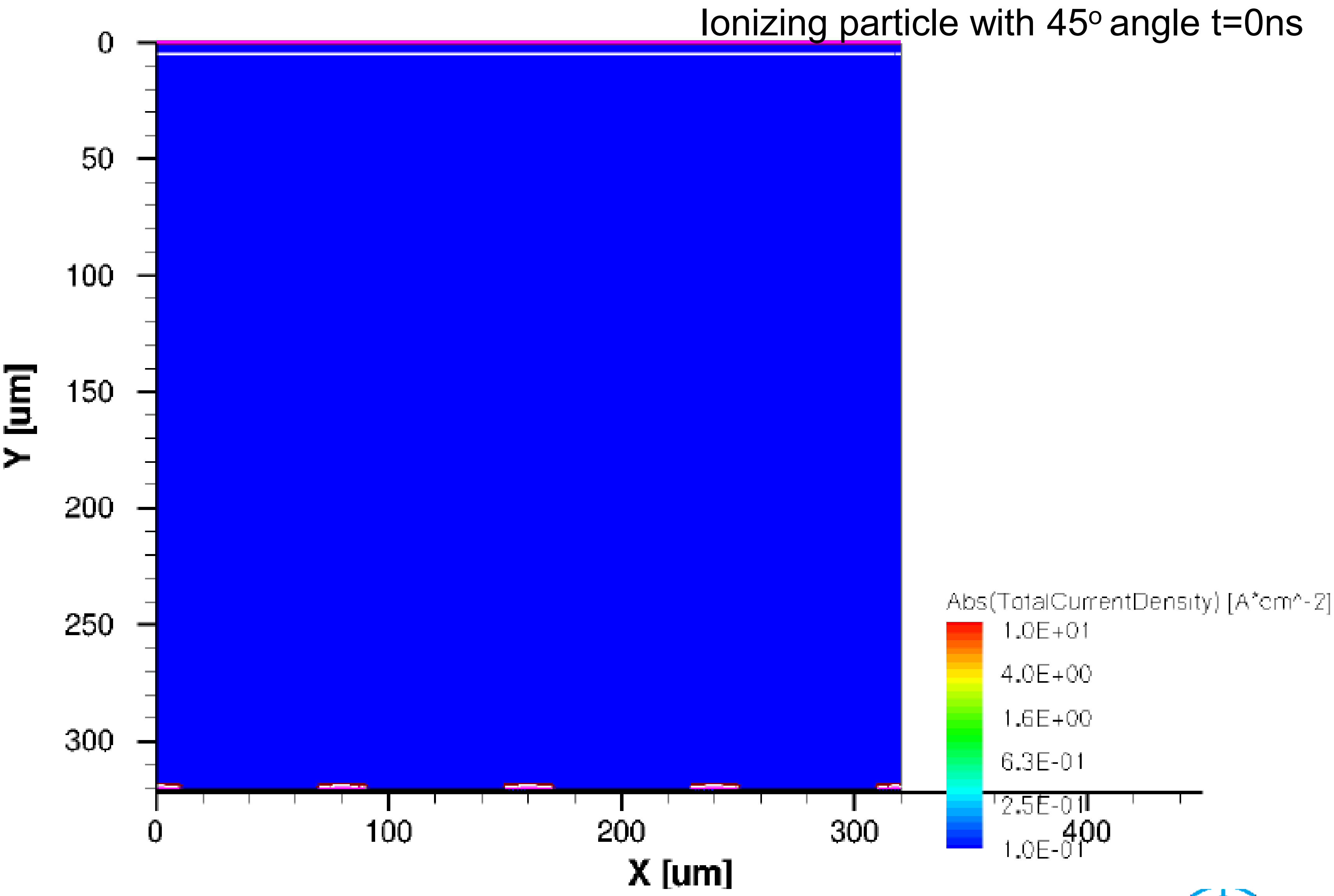
A Simulation Result – Electrical Field Configuration



Simulation Thomas.Eichhorn@kit.edu

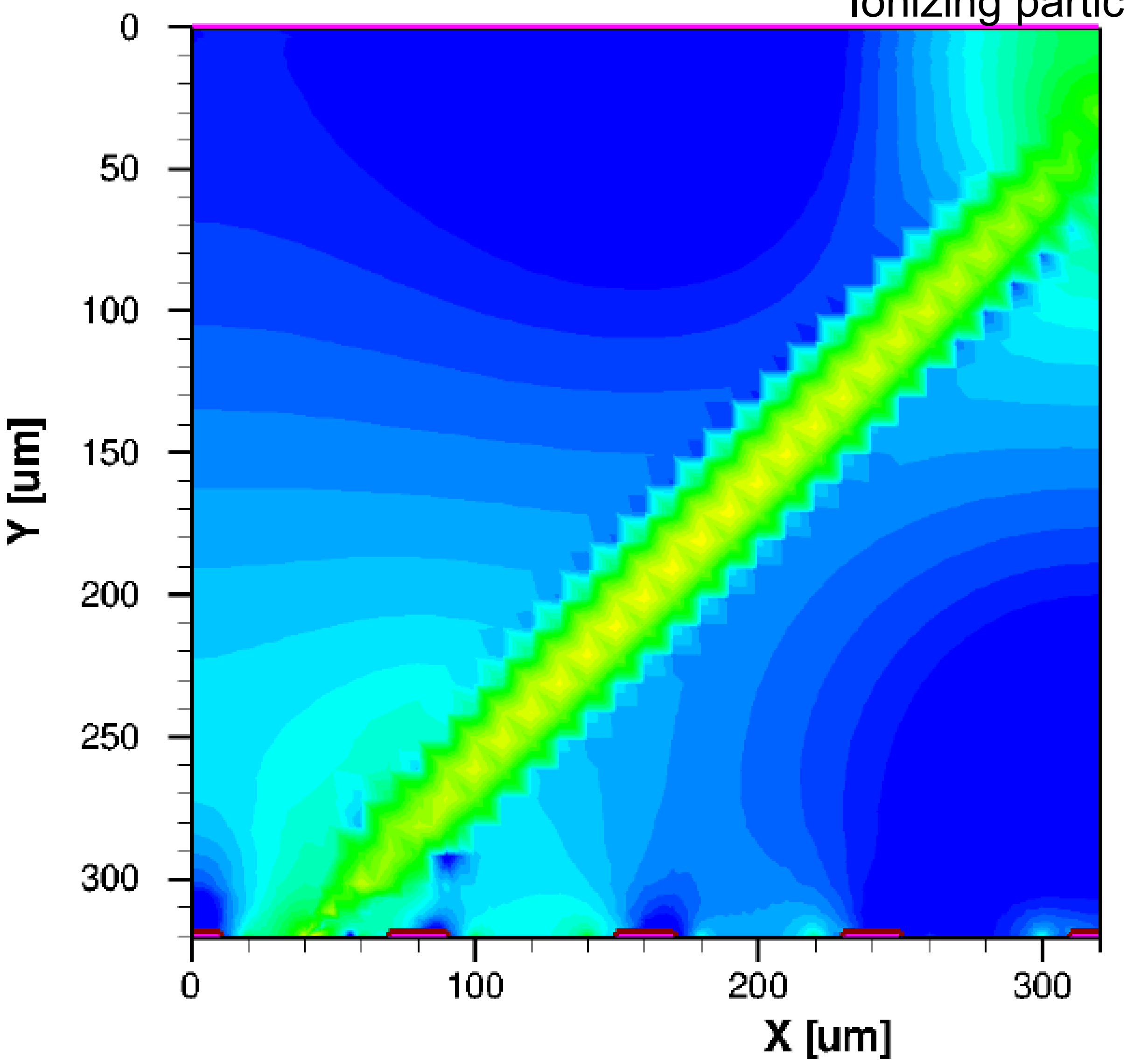
Current Density

Simulation Thomas.Eichhorn@kit.edu



Current Density

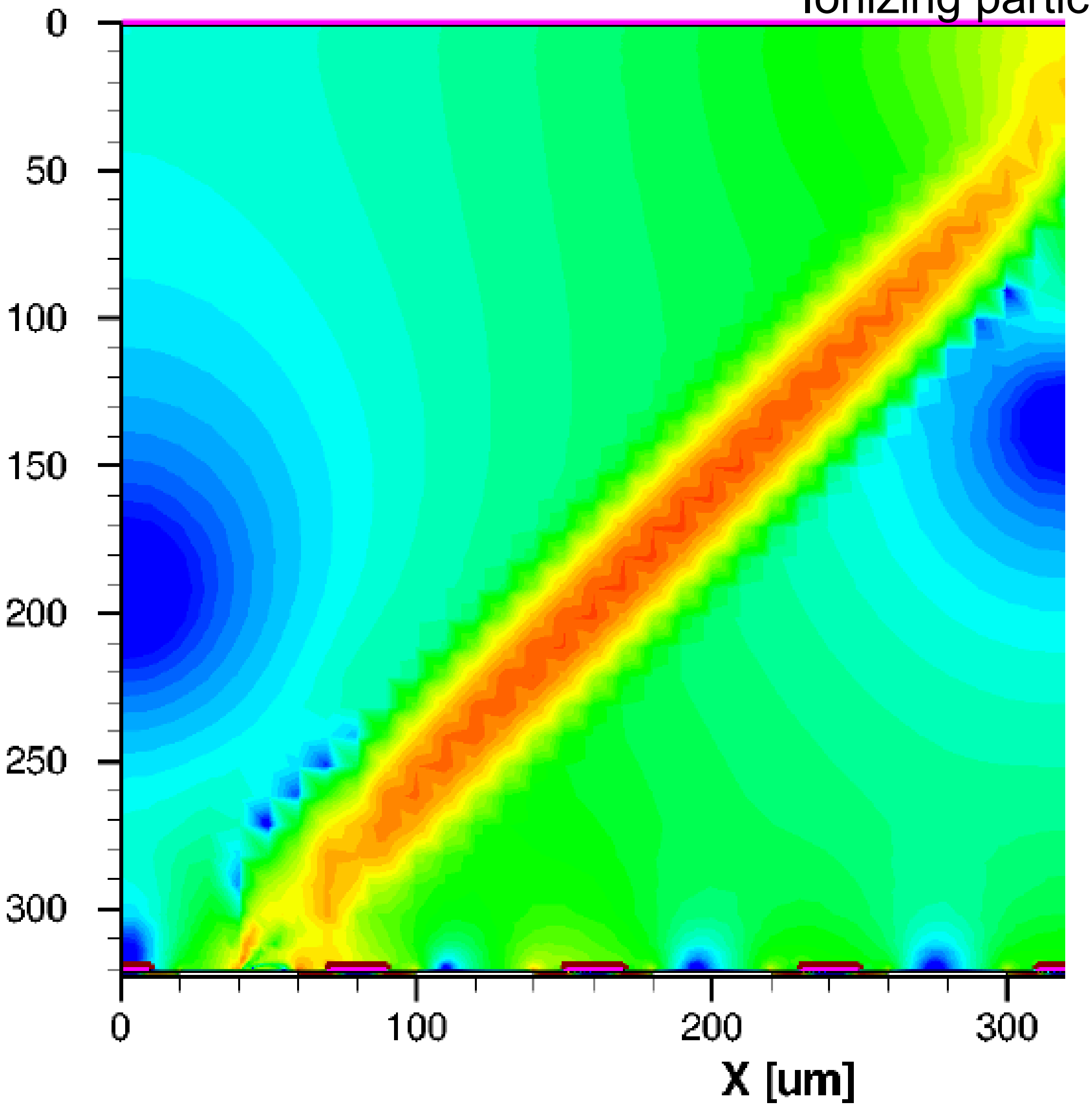
Ionizing particle with 45° angle t=1ns



Simulation Thomas.Eichhorn@kit.edu

Current Density

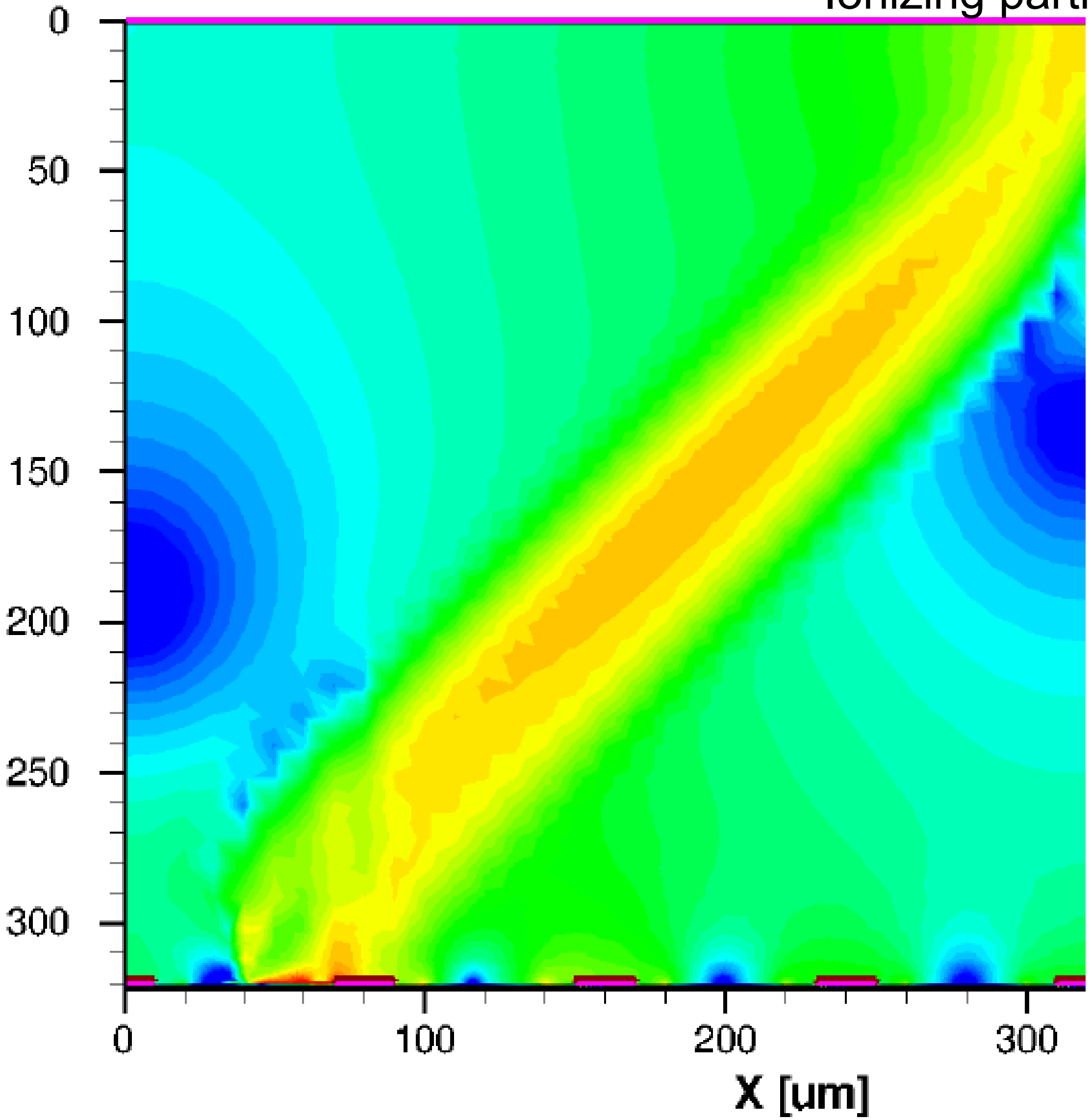
Ionizing particle with 45° angle t=1.1ns



Simulation Thomas.Eichhorn@kit.edu

Current Density

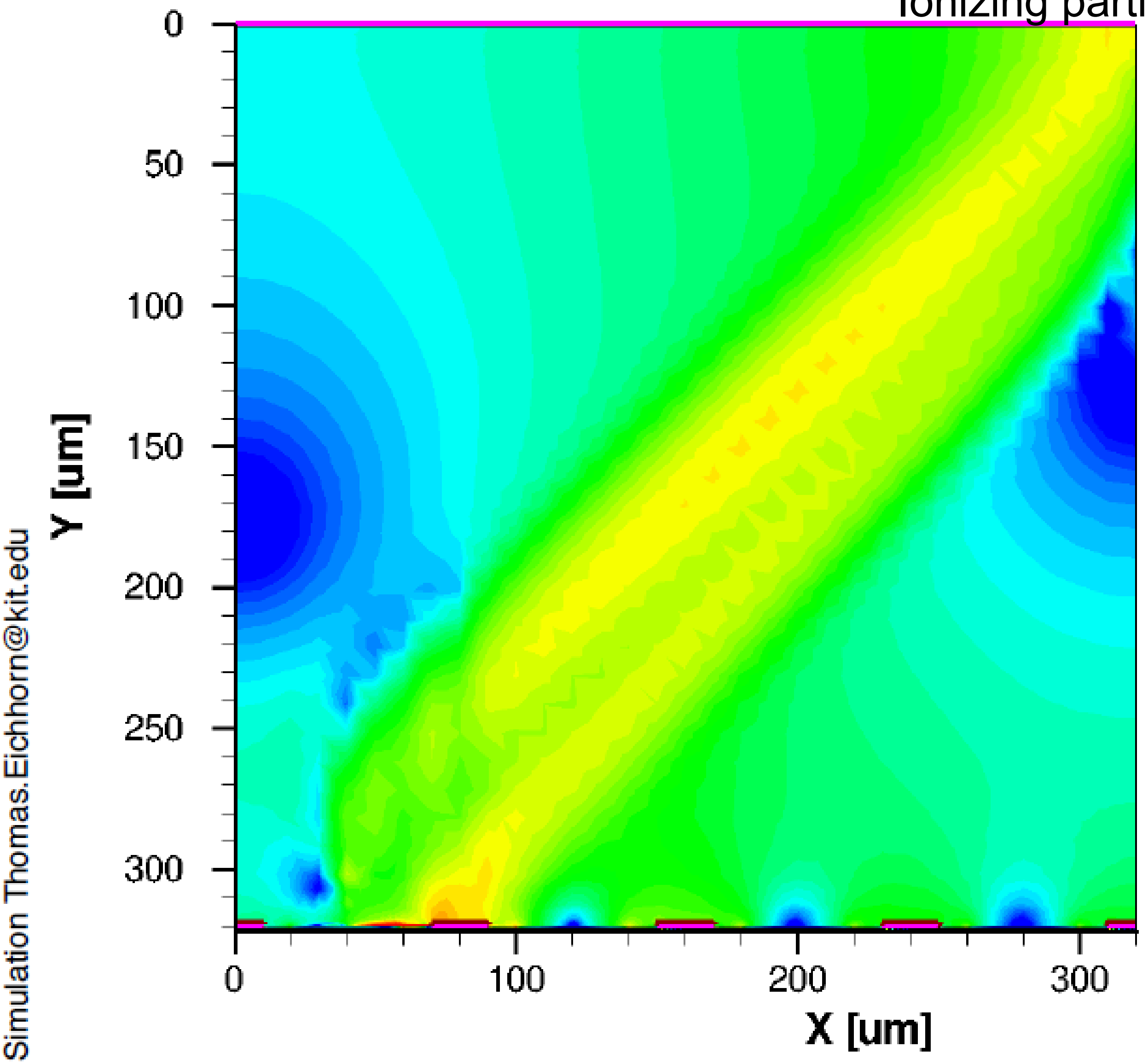
Ionizing particle with 45° angle t=1.3ns



Simulation Thomas.Eichhorn@kit.edu

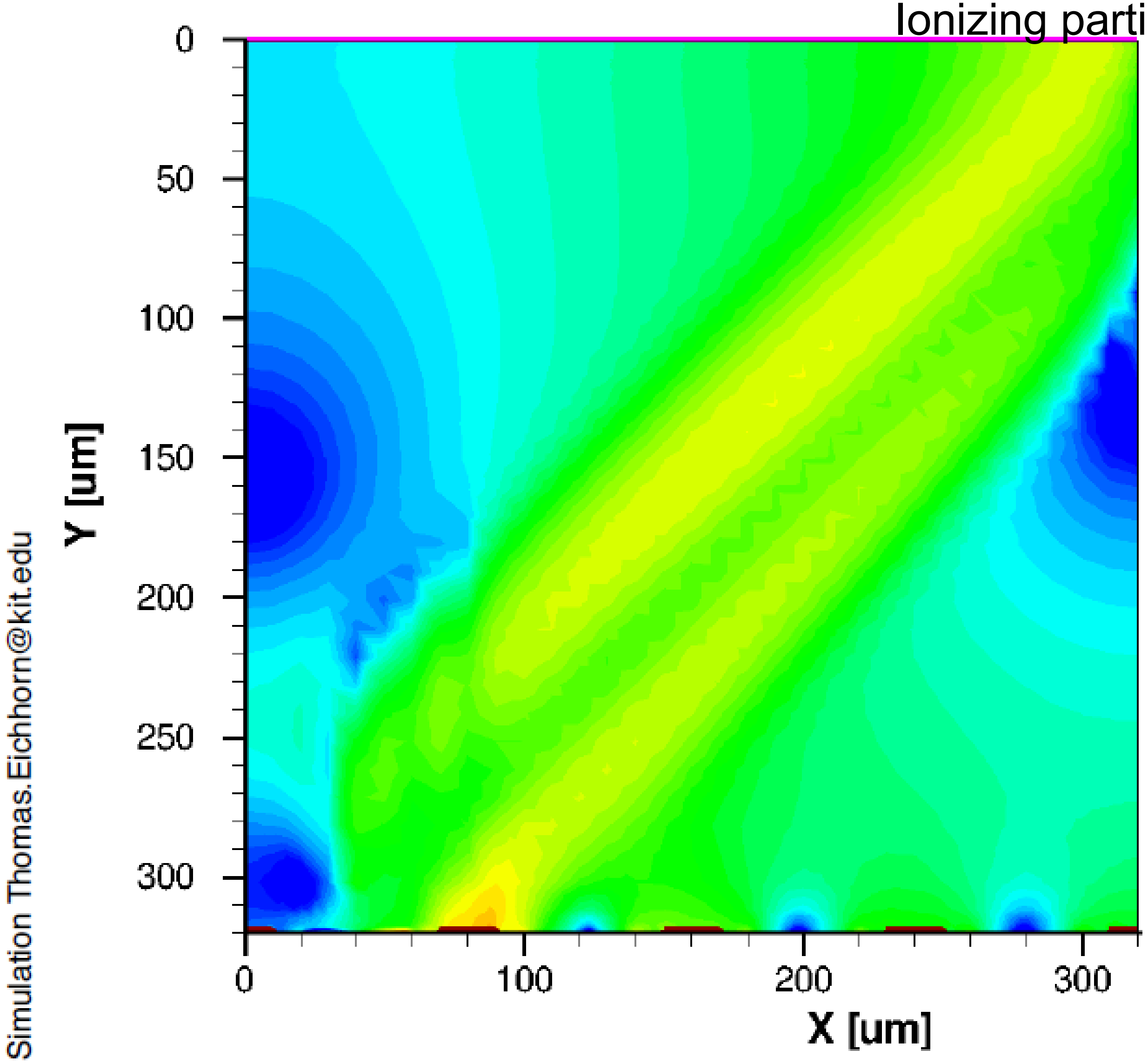
Current Density

Ionizing particle with 45^{o} angle t=1.5ns



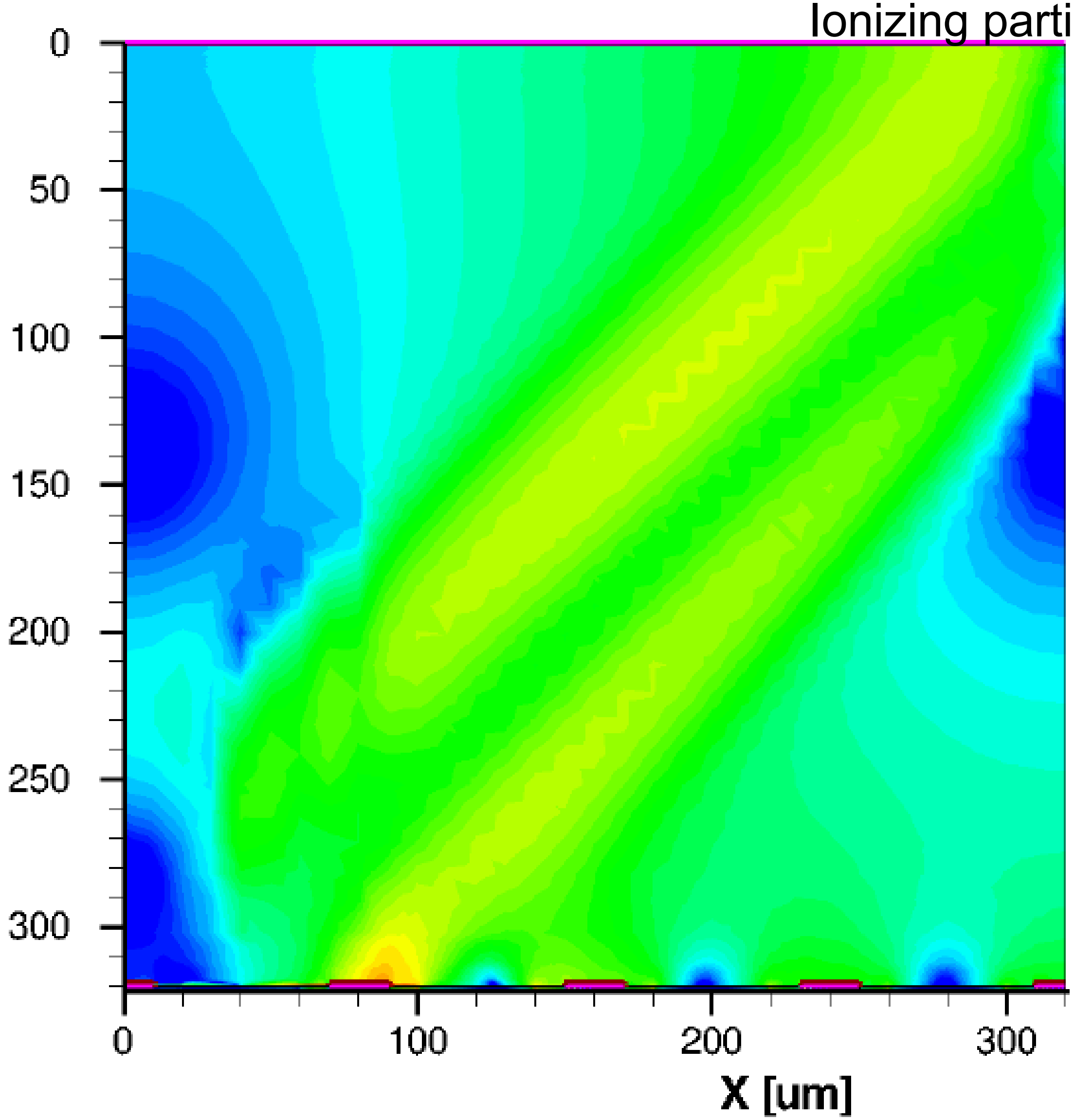
Current Density

Ionizing particle with 45° angle t=1.7ns



Current Density

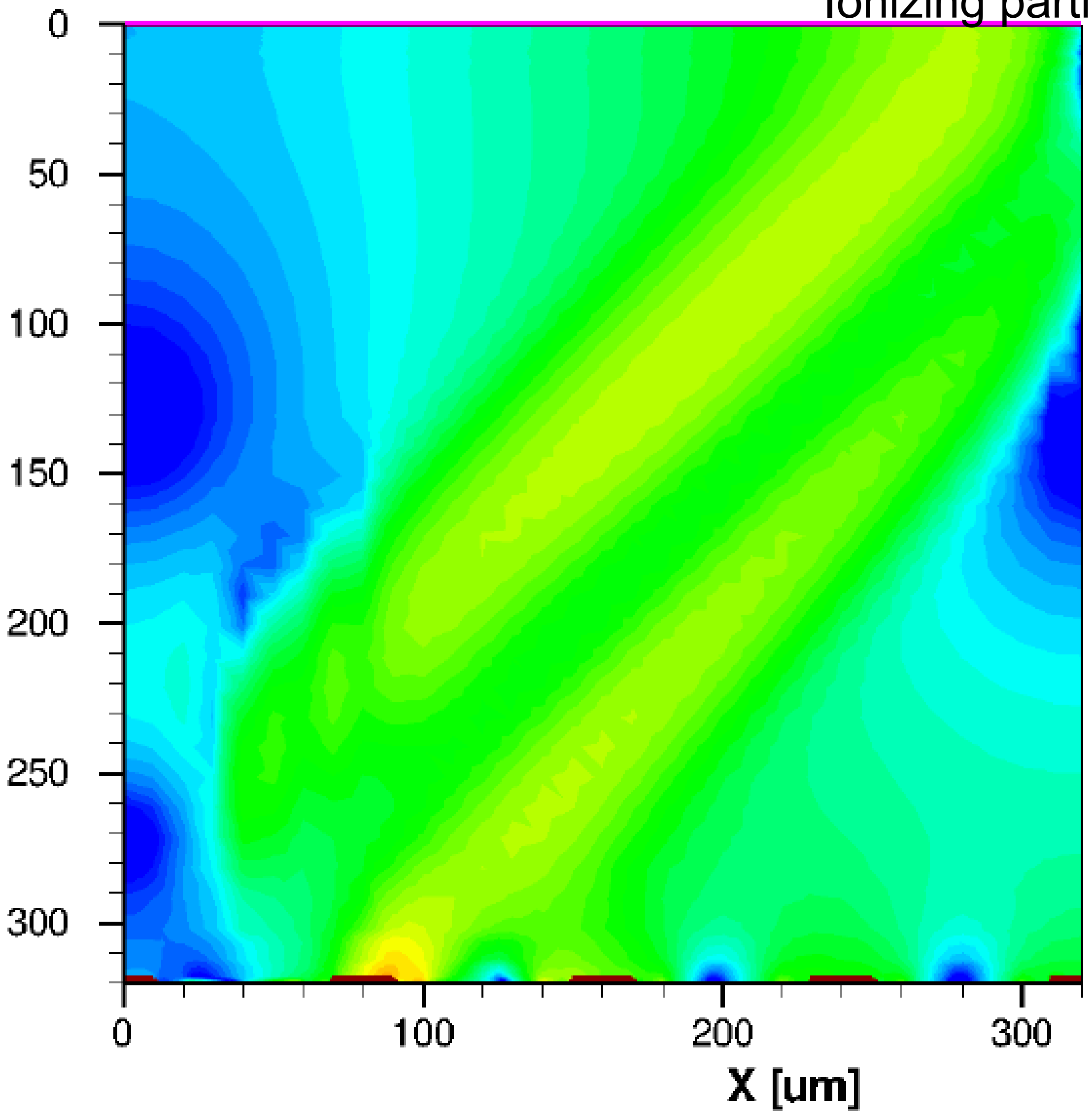
Ionizing particle with 45° angle t=1.9ns



Simulation Thomas.Eichhorn@kit.edu

Current Density

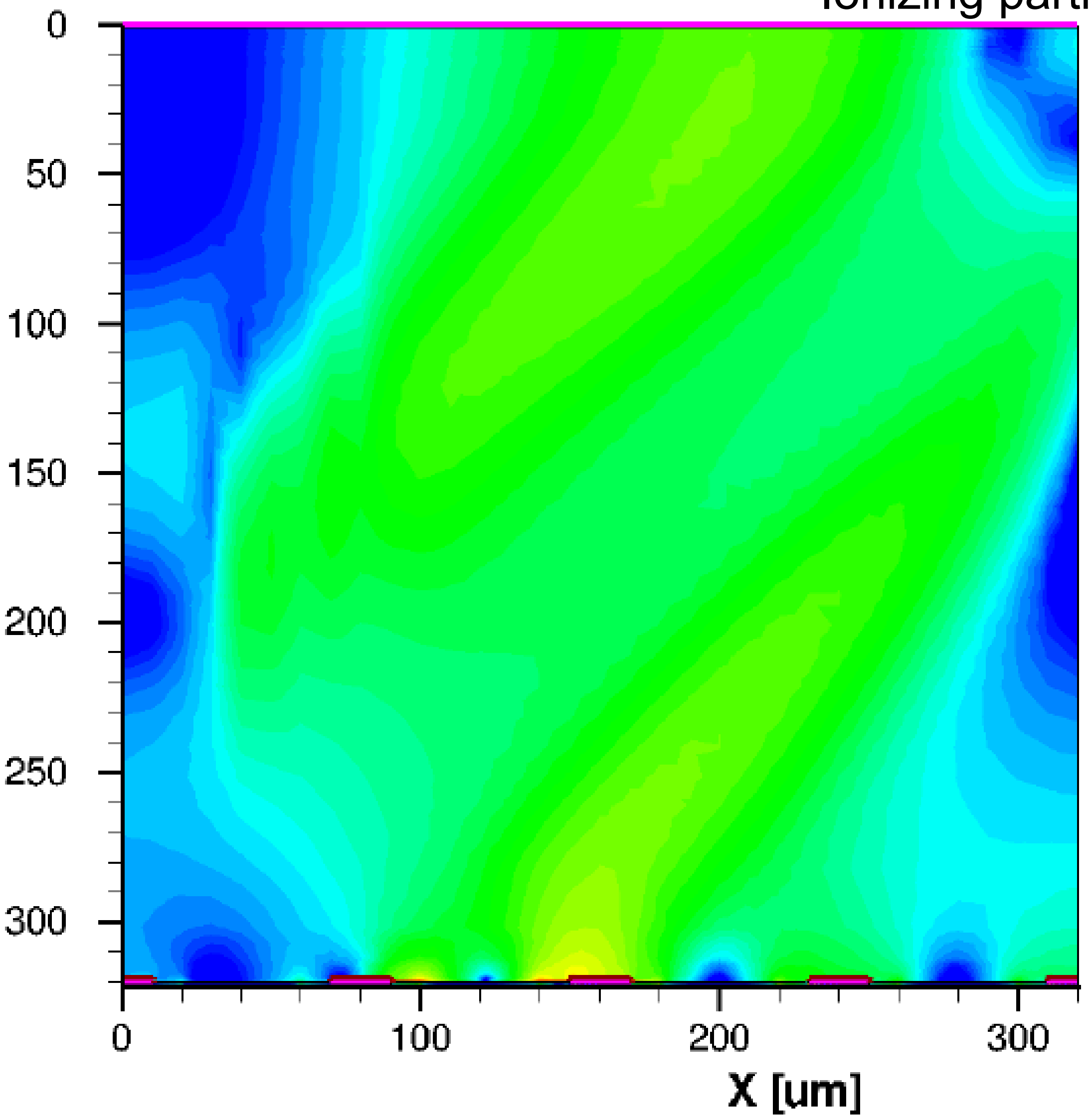
Ionizing particle with 45° angle t=2ns



Simulation Thomas.Eichhorn@kit.edu

Current Density

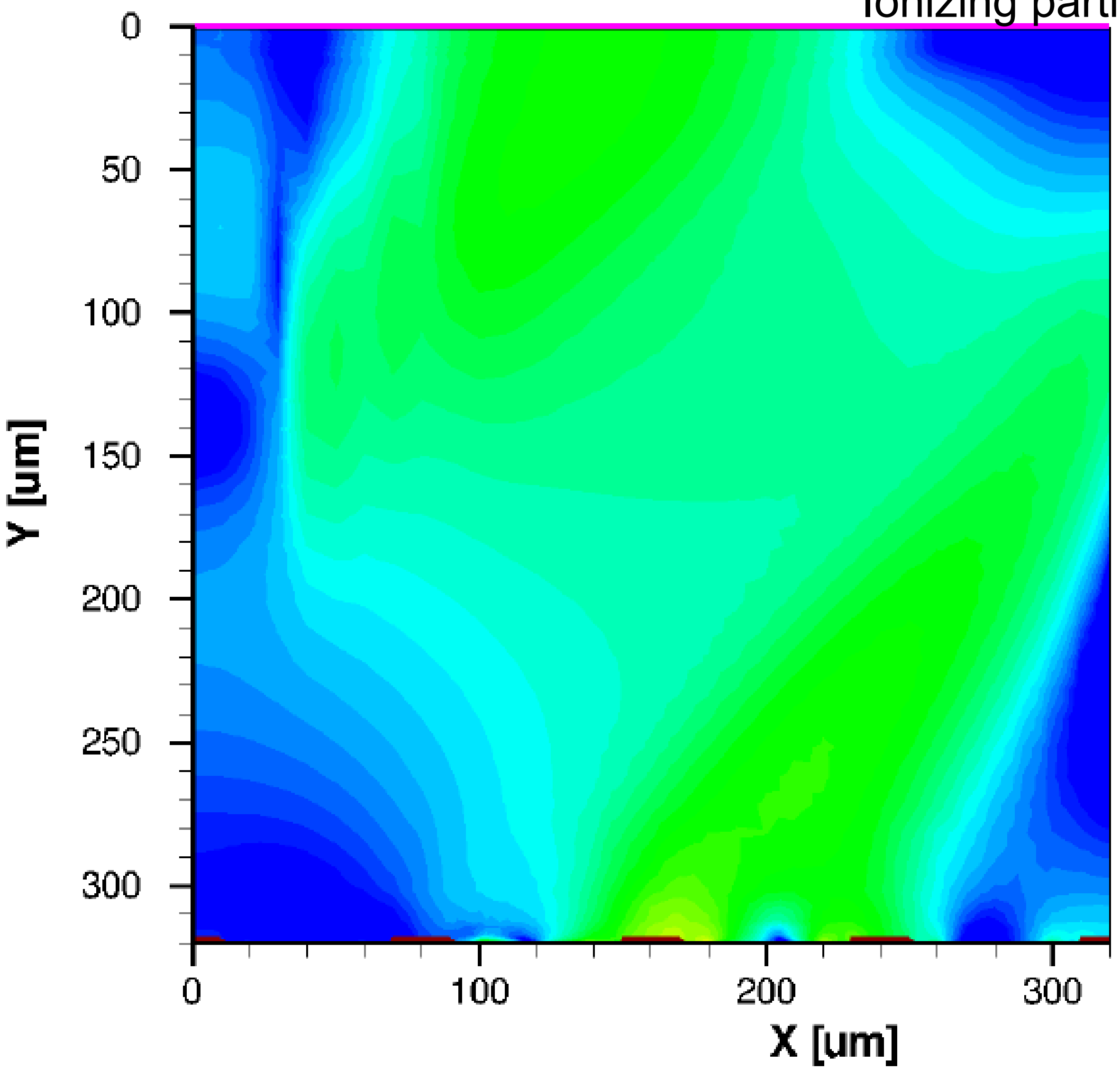
Ionizing particle with 45° angle t=3ns



Simulation Thomas.Eichhorn@kit.edu

Current Density

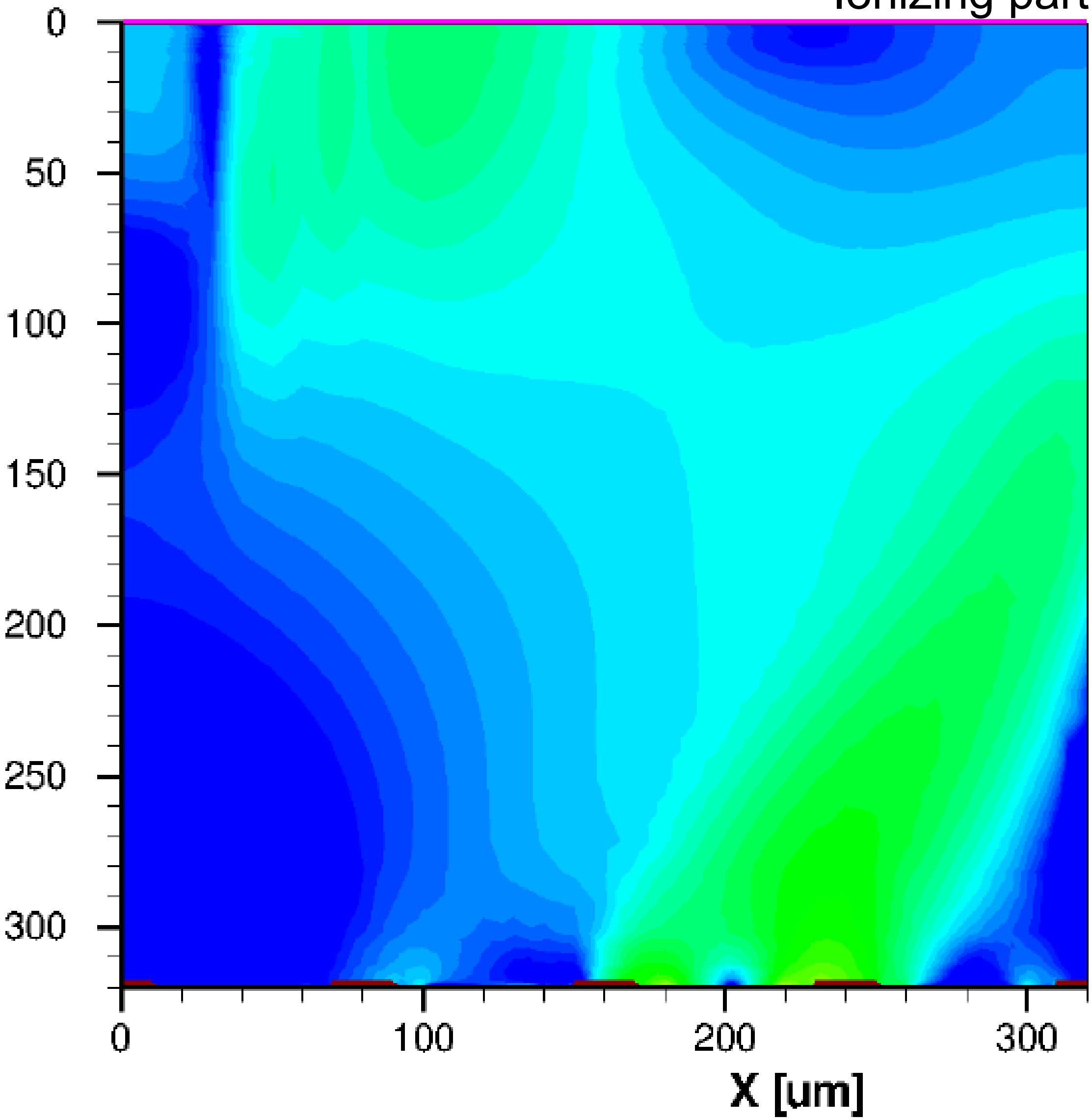
Ionizing particle with 45° angle t=4ns



Simulation Thomas.Eichhorn@kit.edu

Current Density

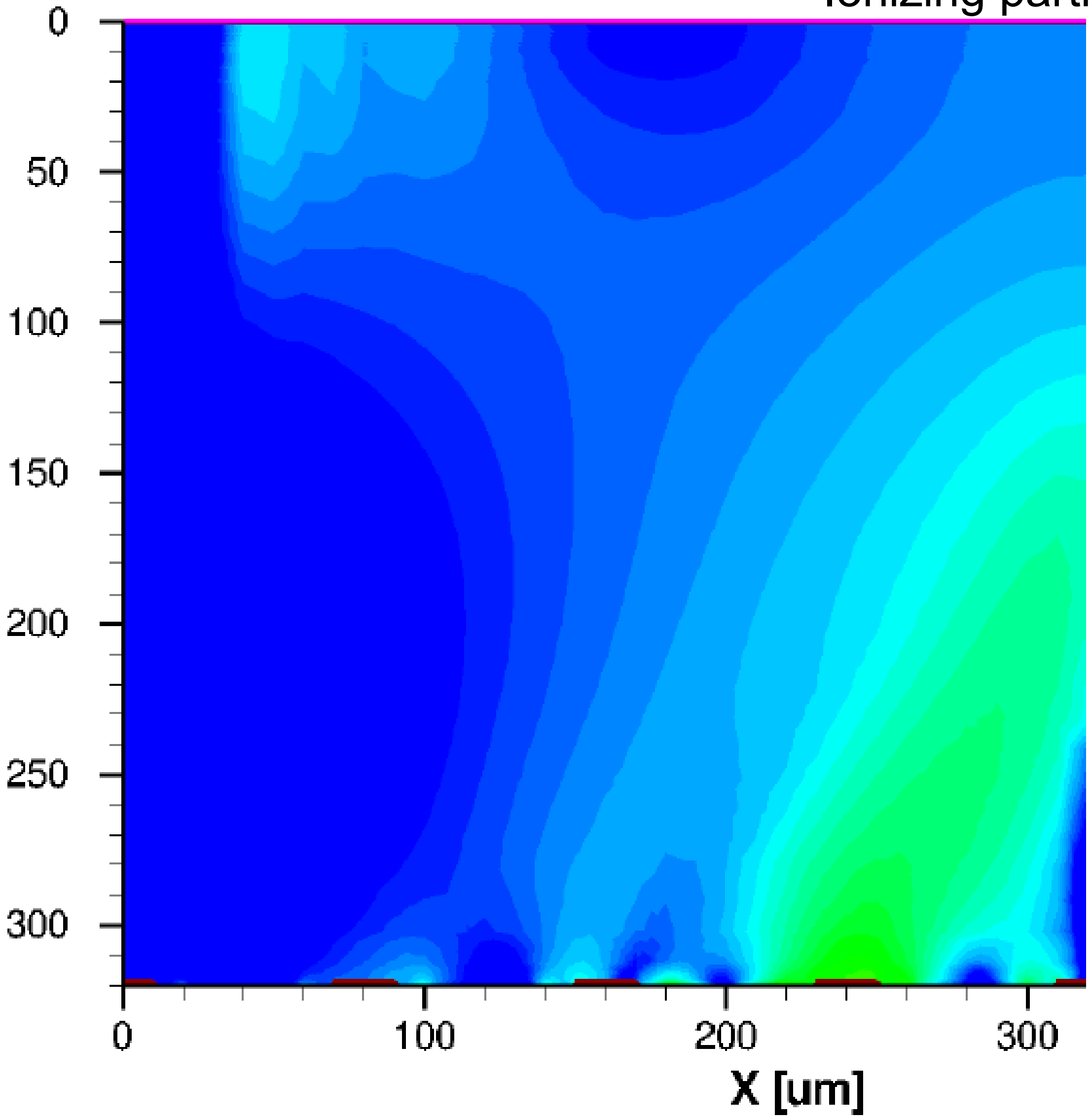
Ionizing particle with 45° angle t=5ns



Simulation Thomas.Eichhorn@kit.edu

Current Density

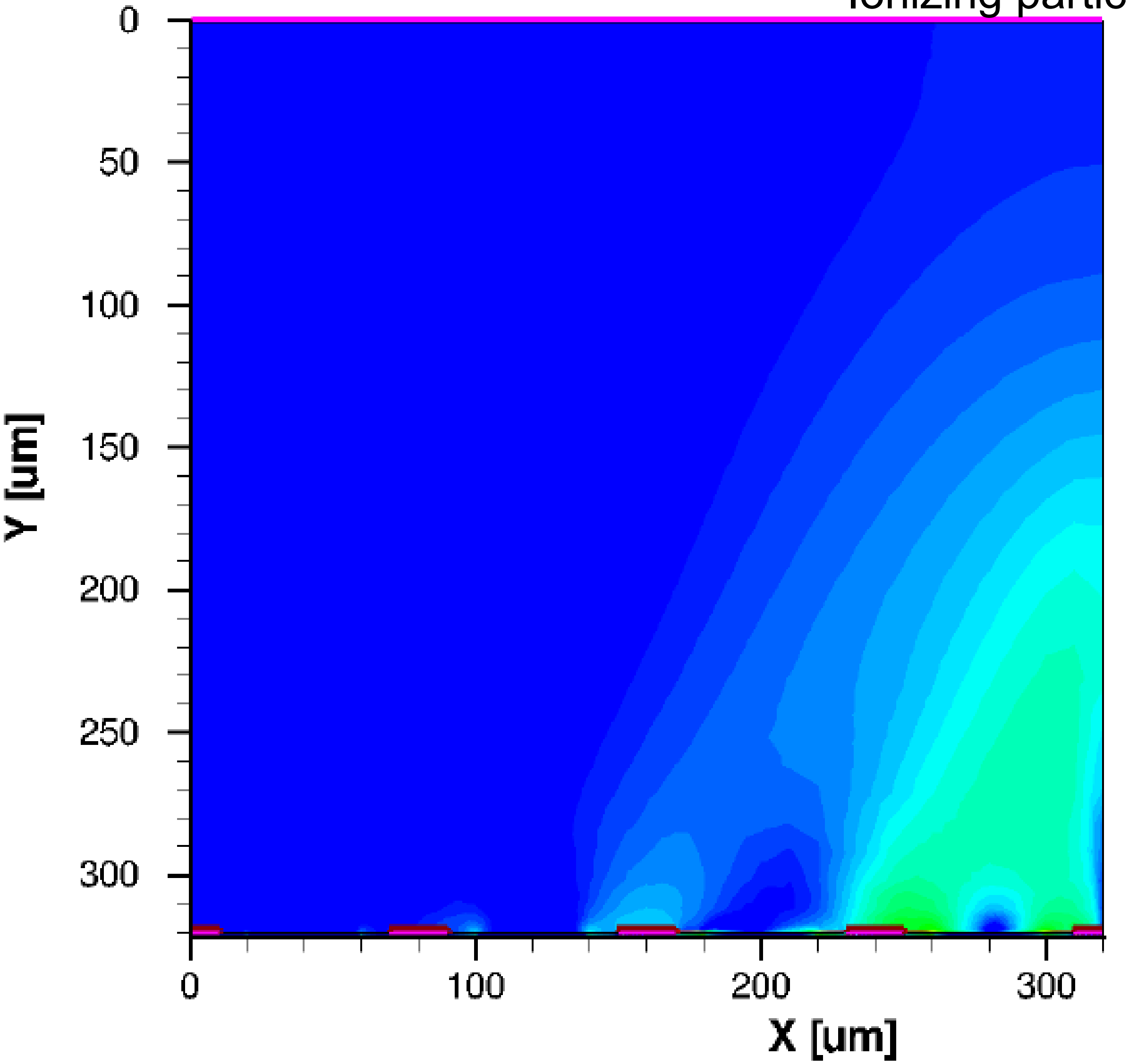
Ionizing particle with 45° angle t=6ns



Simulation Thomas.Eichhorn@kit.edu

Current Density

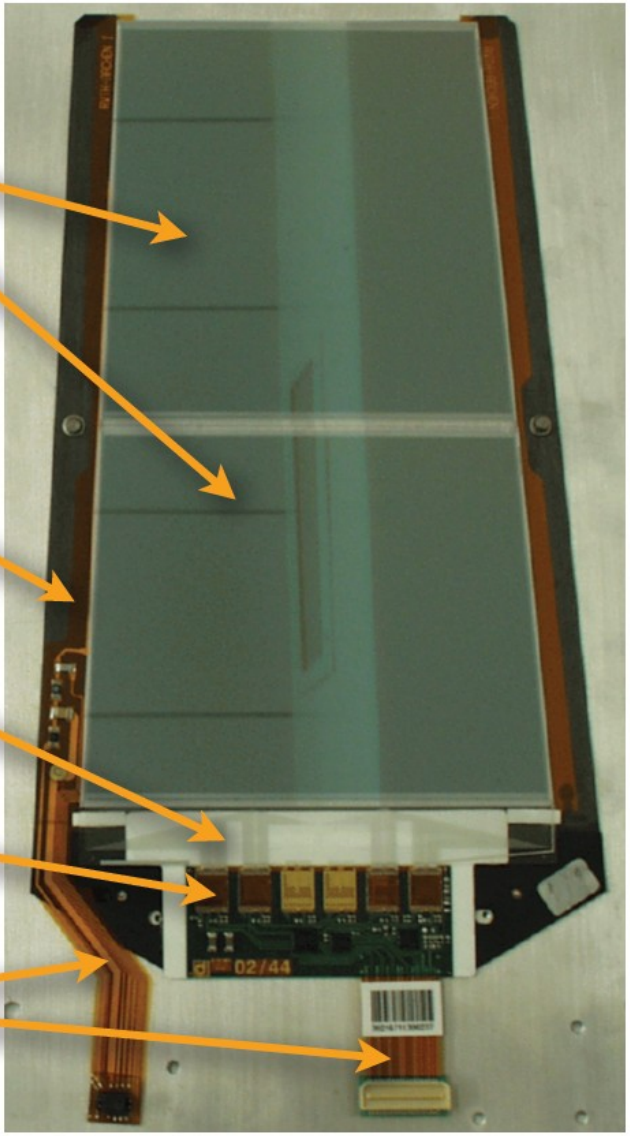
Ionizing particle with 45° angle t=7ns



All electrons collected

Simulation Thomas.Eichhorn@kit.edu

A typical strip module (CMS)



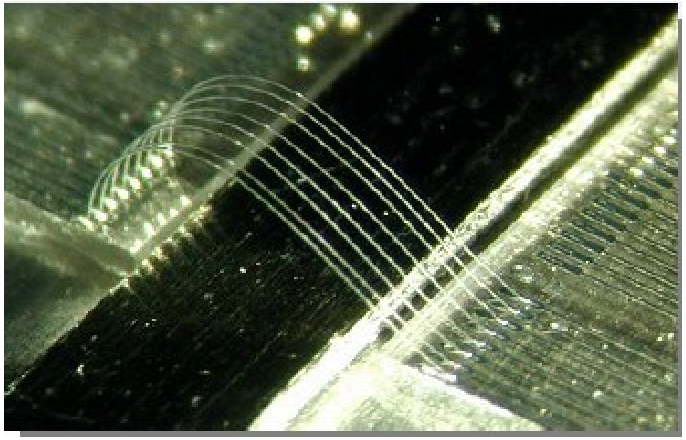
silicon sensors
~20 cm strip length

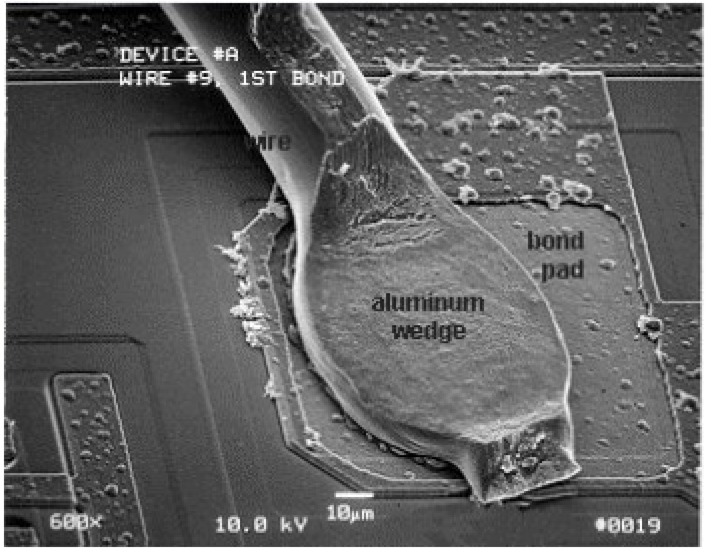
carbon fibre
support

pitch adapter

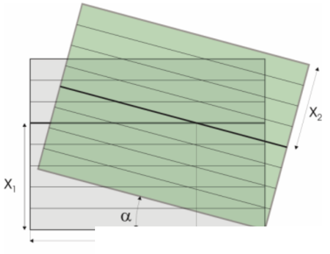
hybrid
front-end electronics
with read-out chips

kapton flat cables
for power and data





Double Sided Silicon Detectors (DSSDs)

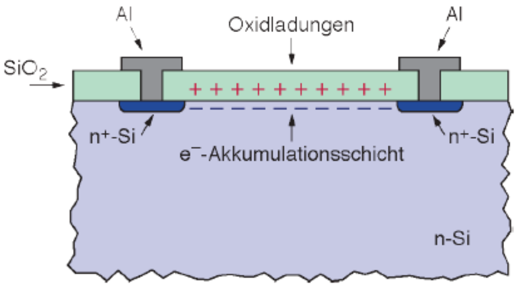


> Advantages:

- More elegant way for measuring 2 coordinates than using stereo modules
- Saves material

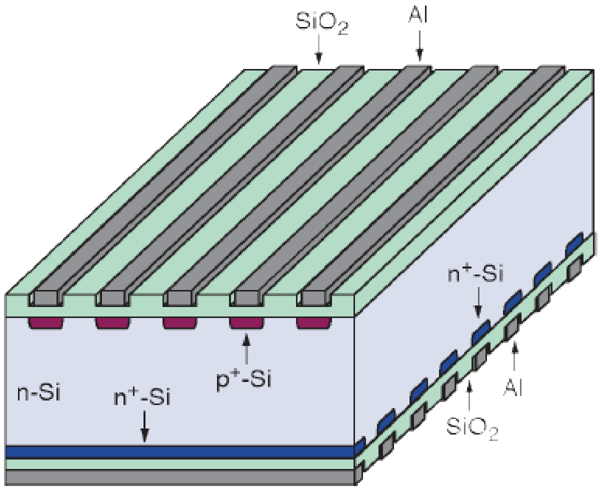
> Disadvantages:

- Needs special strip insulation of n-side (p-stop, p-spray techniques)
- Very complicated manufacturing and handling procedures
  ⇒ expensive

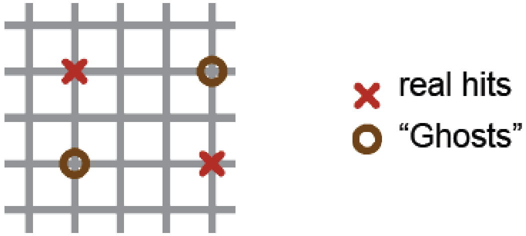


Positive oxide charges cause electron accumulation layer.

- Ghost hits at high occupancy



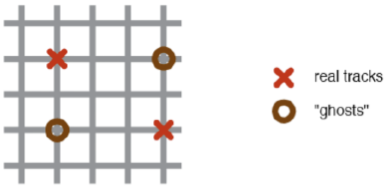
Scheme of a double sided strip detector (biasing structures not shown)

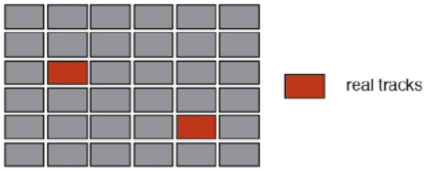


(Hybrid) Pixel Detectors

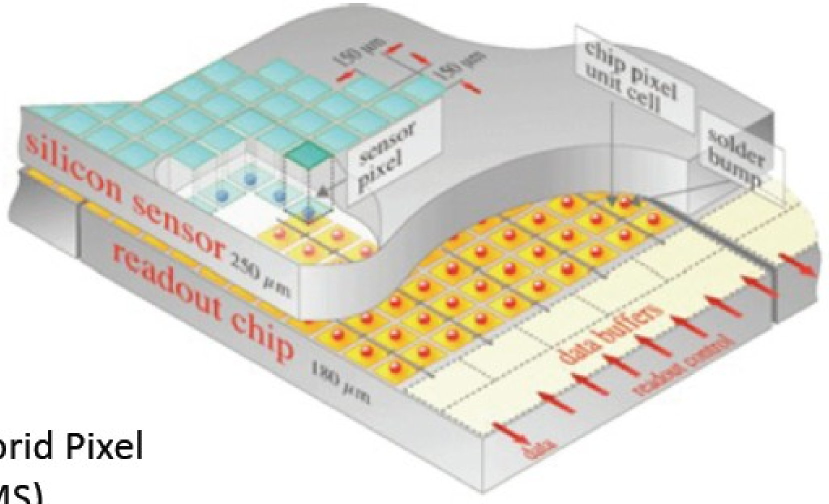
Advantages:

- Pixel detectors produce unambiguous hits





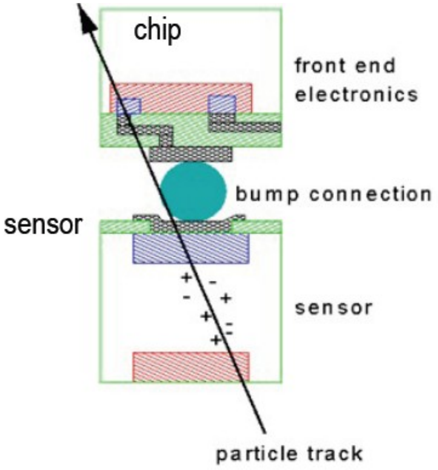
- Small pixel area
  - →low detector capacitance (≈1 fF/Pixel)
  - →large signal-to-noise ratio (e.g. 150:1).
- Small pixel volume
  - →low leakage current (≈1 pA/Pixel)



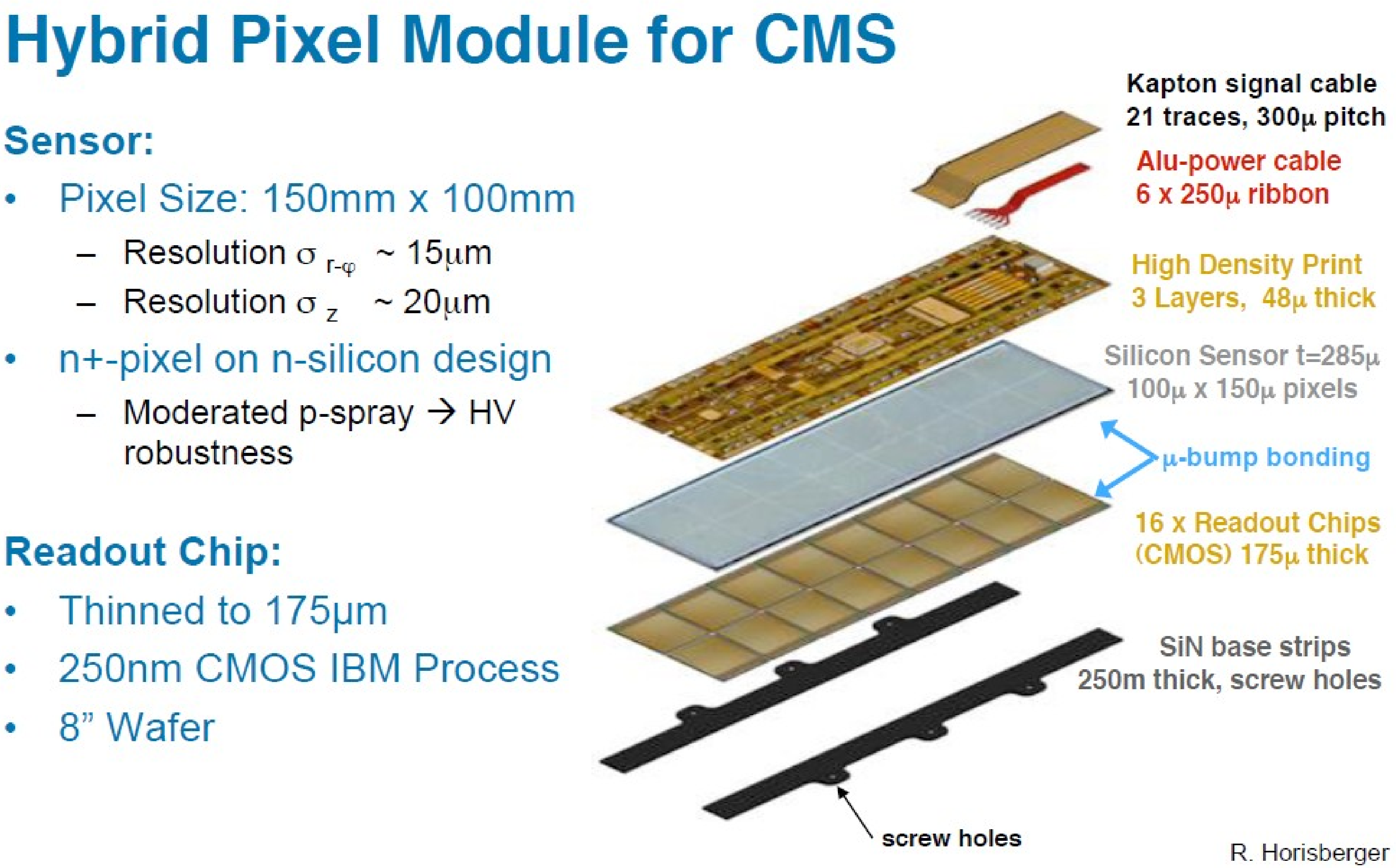
Hybrid Pixel (CMS)

Disadvantages:

- Large number of readout channels
  - →Large number of electrical connections
  - →Large bandwidth
  - →large power consumption



Example hybrid pixel module



Hybrid Pixel Module for CMS

Sensor:

- Pixel Size: 150mm x 100mm
  - Resolution $\sigma_{r\text{-}\varphi}$ ~ 15μm
  - Resolution σ_{z} ~ 20μm
- n+-pixel on n-silicon design
  - Moderated p-spray → HV robustness

Readout Chip:

- Thinned to 175μm
- 250nm CMOS IBM Process
- 8” Wafer

Kapton signal cable
21 traces, 300μ pitch

Alu-power cable
6 x 250μ ribbon

High Density Print
3 Layers, 48μ thick

Silicon Sensor t=285μ
100μ x 150μ pixels

μ-bump bonding

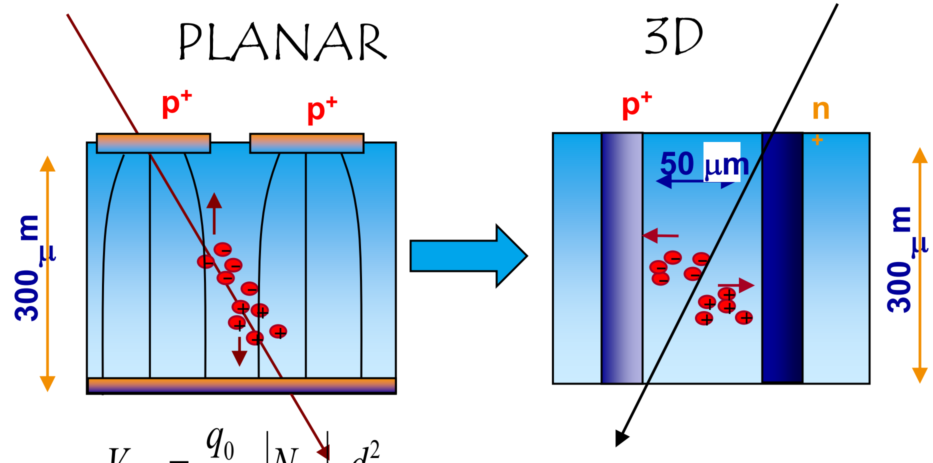
16 x Readout Chips
(CMOS) 175μ thick

SiN base strips
250m thick, screw holes

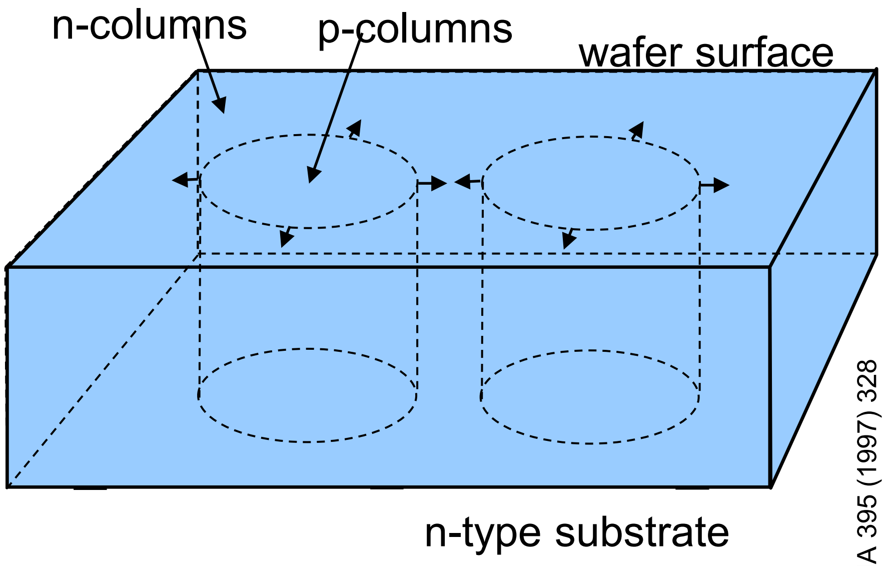
screw holes

R. Horisberger

3d detectors - concept



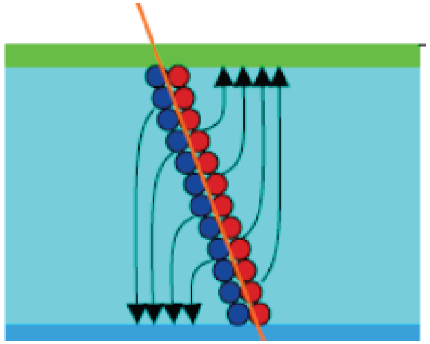
$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0} \cdot |N_{eff}| \cdot d^2$$



Introduced by: S.I. Parker et al., NIMA 395 (1997) 328

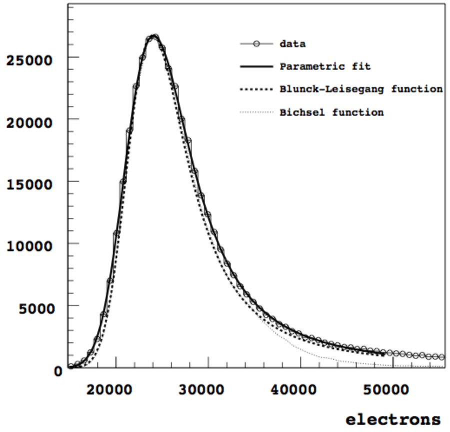
Signal to Noise

- **The signal** generated in a silicon detector depends essentially only on the thickness of the depletion zone and on the dE/dx of the particle.



- Reminder:
  - mean energy loss per flight path of a mip ***dE/dx*** **= 3.87 MeV/cm**
  - Fluctuations give the famous “Landau distribution”
  - The “most probable value” is 0.7 of the peak
  - For 300 µm of silicon, most probable value is

    ~23400 e- / h pairs

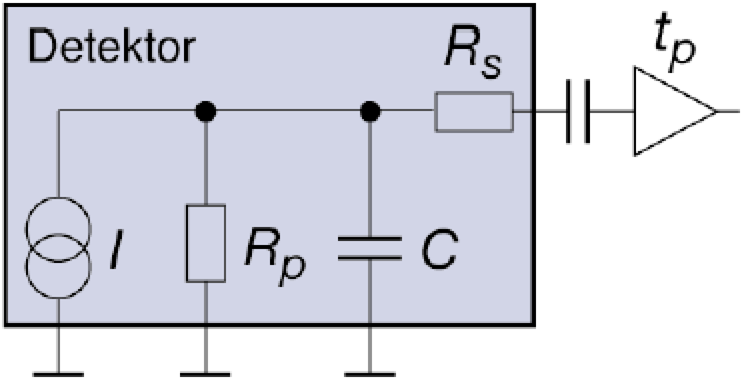


- **The noise** in a silicon detector system depends on various parameters: geometry of the detector, the biasing scheme, the readout electronics, etc.
- Noise is typically given as “equivalent noise charge” ENC. This is the noise at the input of the amplifier in elementary charges.

Noise

> The most important noise contributions are:

- Leakage current (ENC_I)
- Detector capacitance (ENC_C)
- Detector parallel resistor (ENC_{Rp})
- Detector series resistor (ENC_{Rs})



Equivalent circuit diagram of a silicon detector.

> The overall noise is the quadratic sum of all contributions:

$$ENC = \sqrt{ENC_C^2 + ENC_I^2 + ENC_{Rp}^2 + ENC_{Rs}^2}$$

Signal to Noise Ratio Summary

- To achieve a high signal to noise ratio in a silicon detector system the
- following conditions are important:
  - Low detector capacitance (i.e. small pixel size or short strips)
  - Low leakage current
  - Large bias resistor
  - Short and low resistance connection to the amplifier
  - Long integration time

- Obviously some of the conditions are contradictory. Detector and front end electronics have to be designed as one system. The optimal design depends on the application

Signal Diffusion

- Diffusion is caused by random thermal motion
- Width of charge cloud after a time t given by

$$\sigma_D = \sqrt{2Dt} \qquad \text{with:} \qquad D = \frac{kT}{e}\mu$$

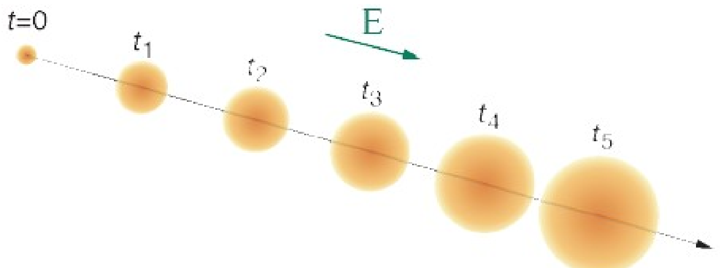
σ_D … width "root-mean-square" of the charge carrier distribution
t … drift time
k … Boltzmann constant
e … electron charge
D … diffusion coefficient
T … temperature
μ … charge carrier mobility

Note: $D \propto \mu$ and $t \propto 1/\mu$, hence σ_D is equal for e^- and h^-

- So drift times for: d=300 mm, E=2.5Kv/cm:

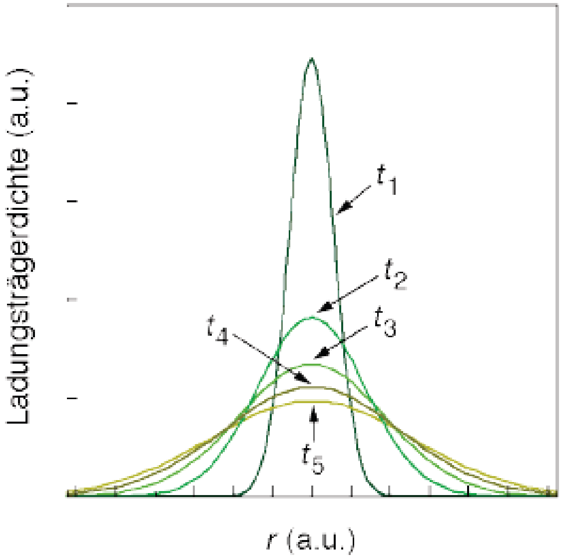
$t_d(e)$ = 9 ns, $t_d(h)$=27 ns

- Diffusion:Typical value: 8 µm for 300 µm drift.
- Can be exploited to improve position resolution



Drift in E-field + diffusion

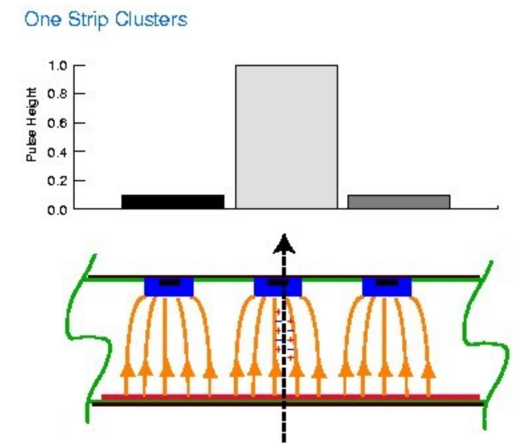
Charge density distribution for 5 equidistant time intervalls:



Position resolution

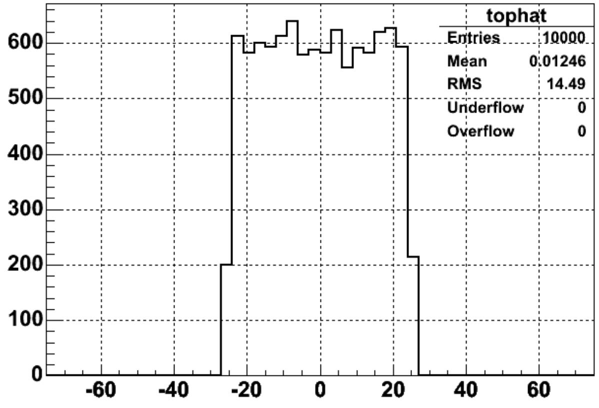
Resolution is the spread of the reconstructed position minus the true position

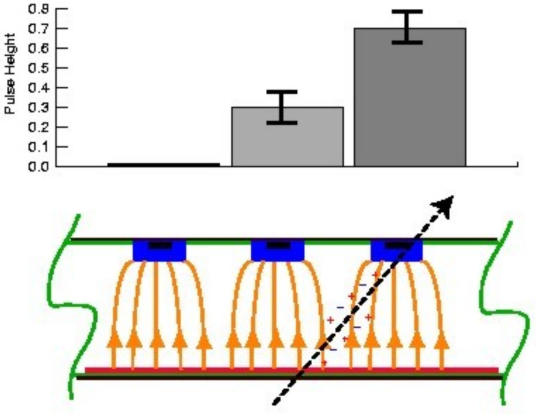
For one strip clusters



$$\sigma = \frac{\text{pitch}}{\sqrt{12}}$$

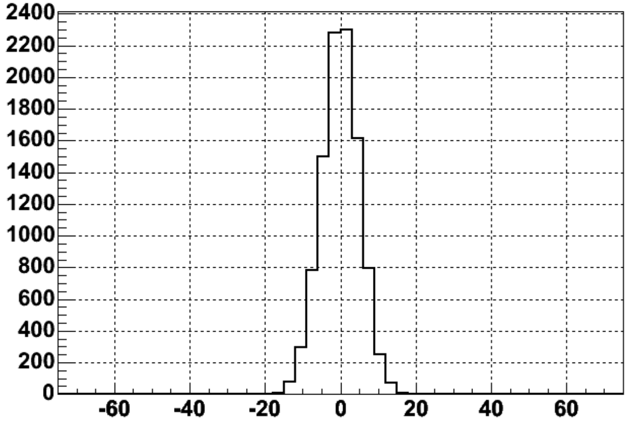
“top hat” residuals





$$\sigma \approx \frac{\text{pitch}}{1.5 * (S/N)}$$

“gaussian” residuals

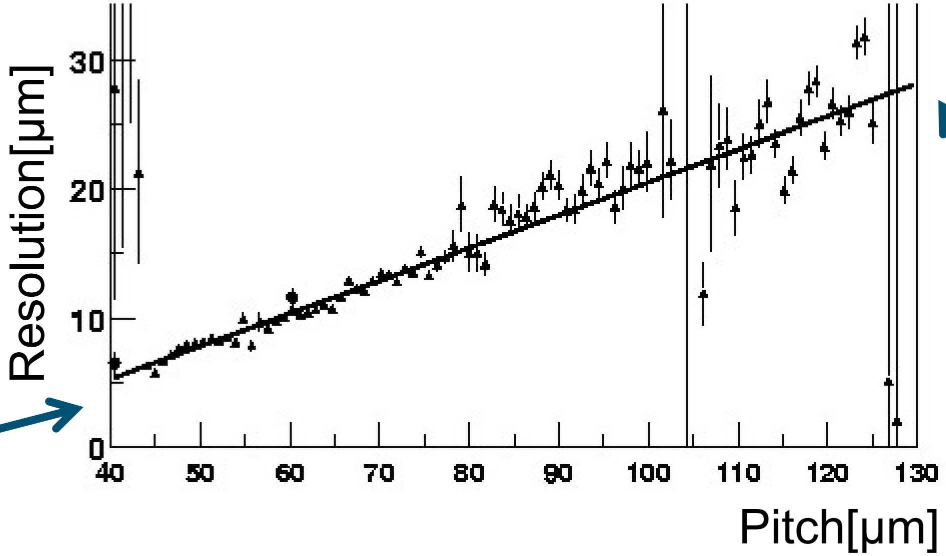


Position resolution

- In real life, position resolution is degraded by many factors
  - relationship of strip pitch and diffusion width

    (typically 25-150 mm and 5-10 mm)
  - Statistical fluctuations on the energy deposition

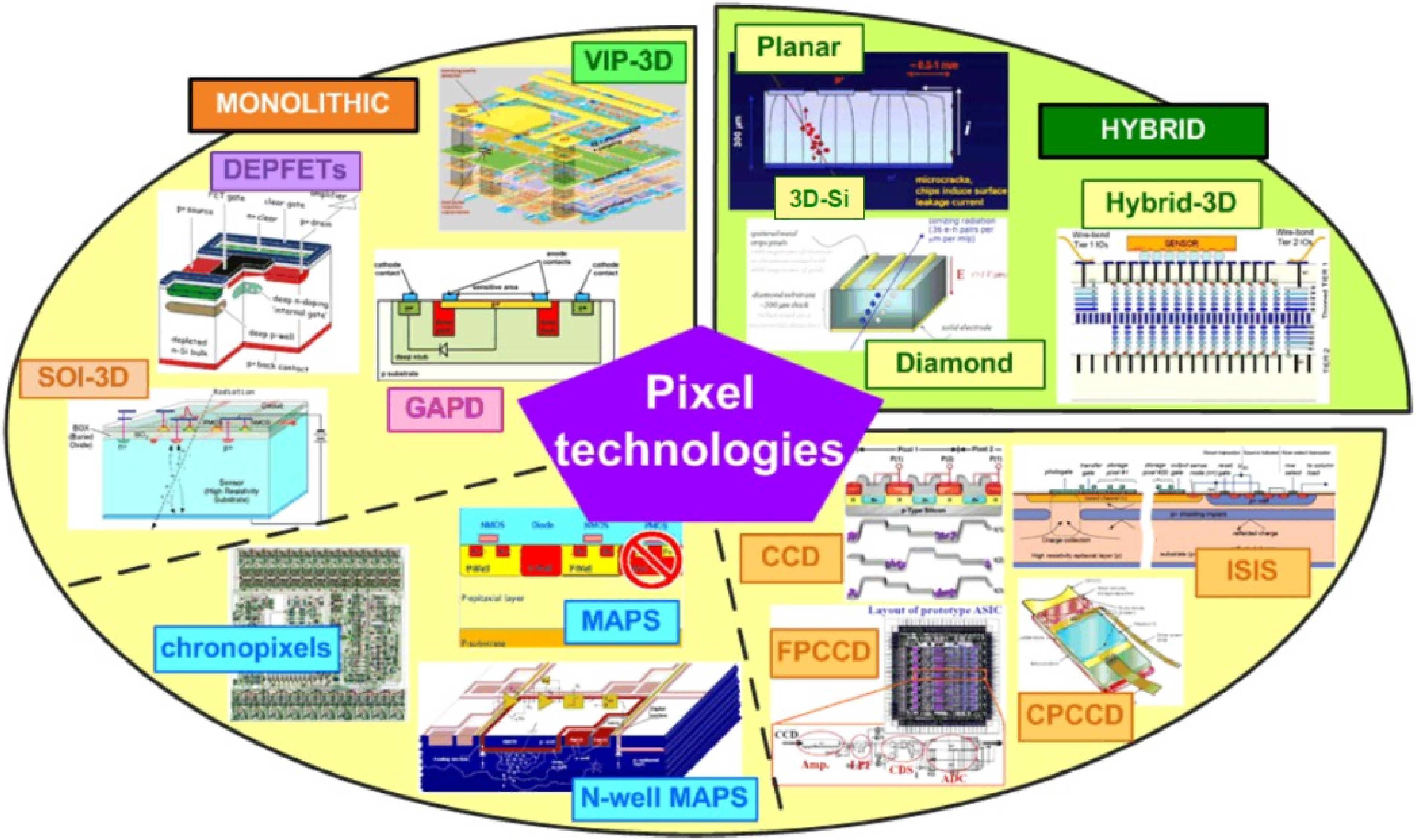
Typical real life values for a 300mm thick sensor with S/N=20



Here charge sharing dominates

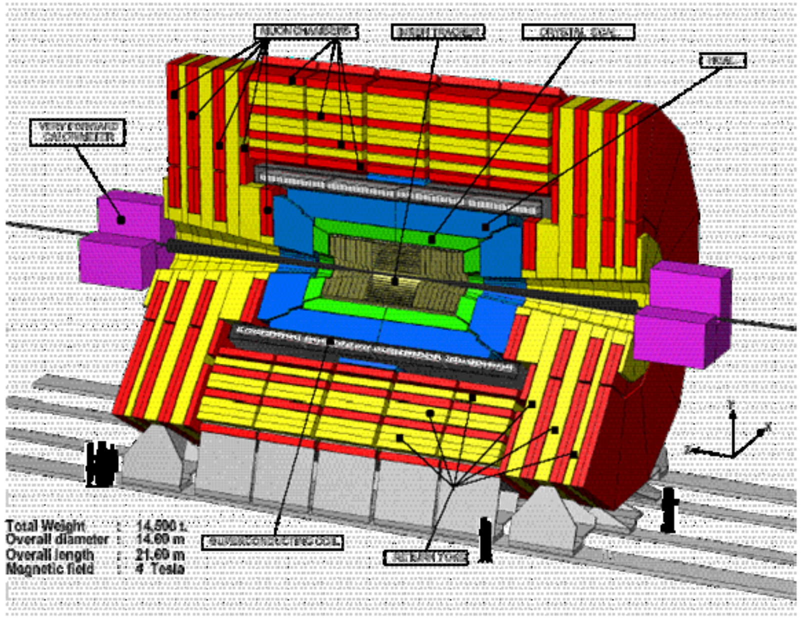
Here single strips dominate

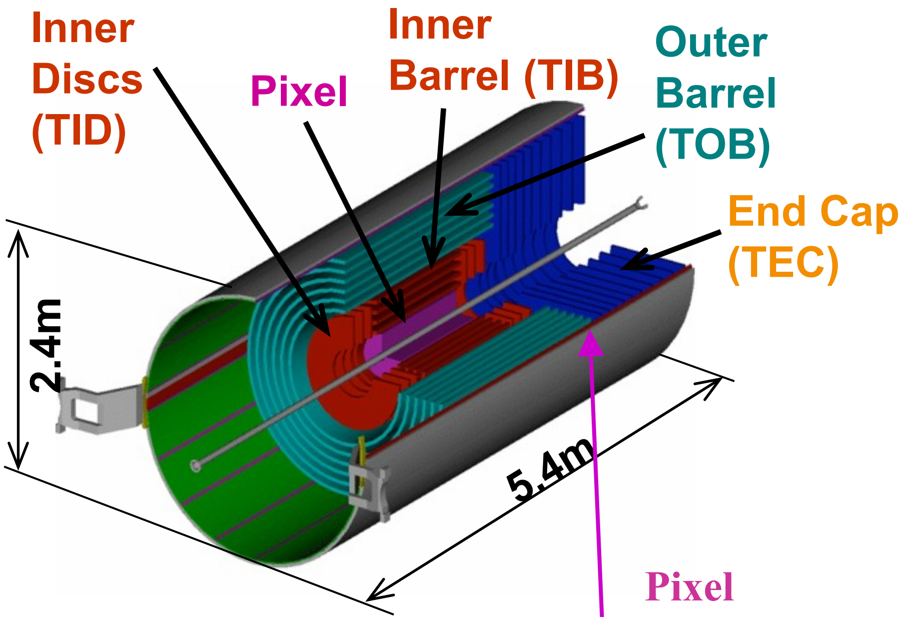
The variety of pixel technologies



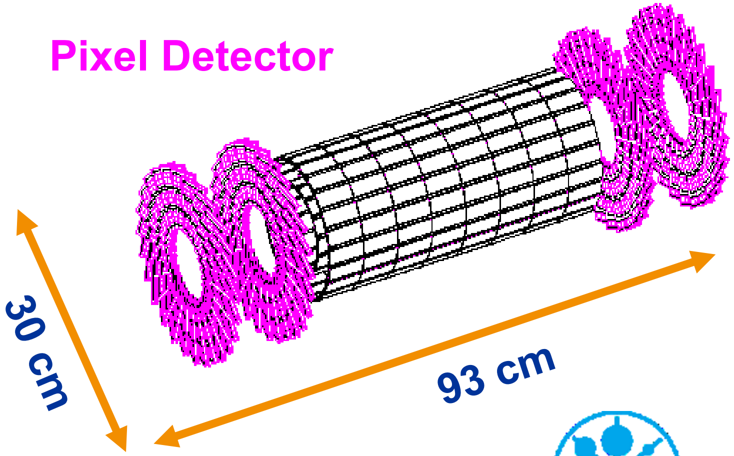
Slide: N.Wermes at annual workshop of the Helmholtz Alliance Dec.2011, Bonn

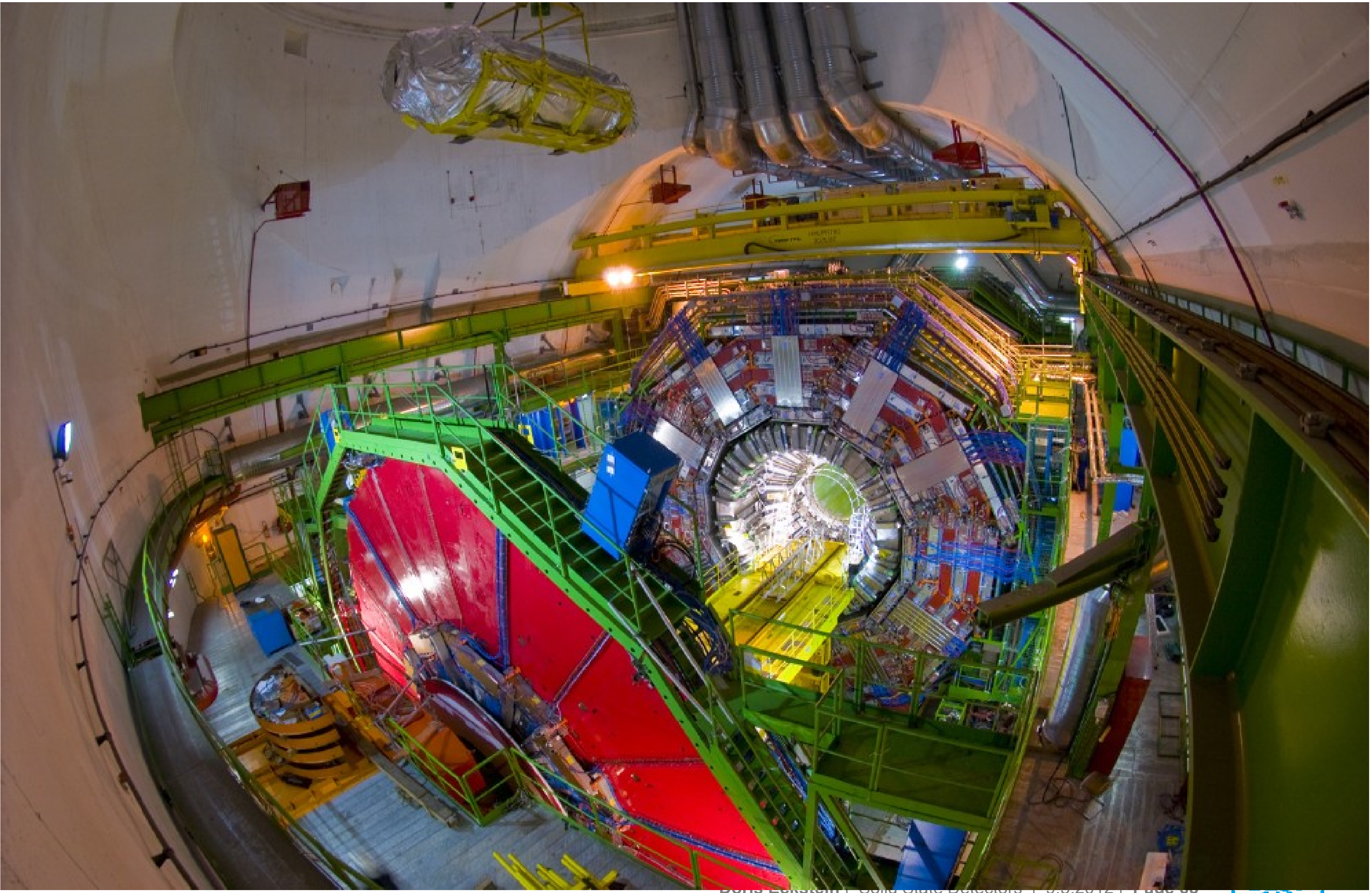
Example – CMS Tracker





- **Largest silicon tracker**
  - **Micro Strip Tracker:**
  - ~ 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)





- Thanks to:
  - Thomas Bergauer, Richard Bates, Tilman Rohe, Ingrid Gregor
- You can find a great lecture here: http://www.hephy.at/fileadmin/user_upload/Lehre/Unterlagen/Praktikum/Halbleiterdetektoren.pdf

Suggestions for further reading

- H. Spieler, Semiconductor Detector Systems, Oxford Science Publications, 2005
  See also: http://www-physics.lbl.gov/~spieler/
- G. Lutz, Semiconductor Radiation Detectors: Device Physics , Springer (July 11, 2007)
- G. Knoll, Radiation Detection and Measurement Wiley; 4 edition (August 16, 2010)
- A.S. Grove, Physics and Technology of Semiconductor Devices, (1967) John Wiley & Sons; ISBN: 0471329983
- S.Sze, Physics of Semiconductor Devices, J.Wiley, 1981
- T. Ferbel, Experimental Techniques in High Energy Nuclear and Particle Physics, World Scientific, 1992
- K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010)
  http://pdg.lbl.gov/2009/reviews/rpp2009-rev-particle-detectors-accel.pdf

...and references therein