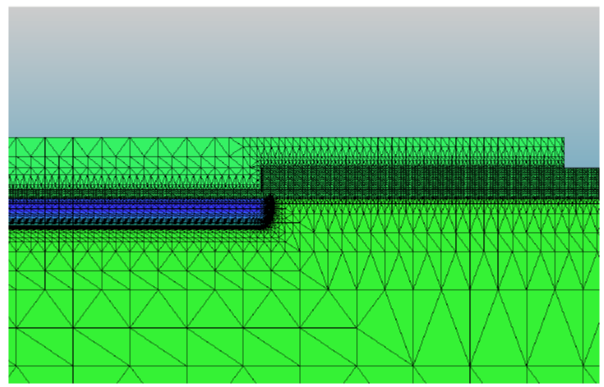
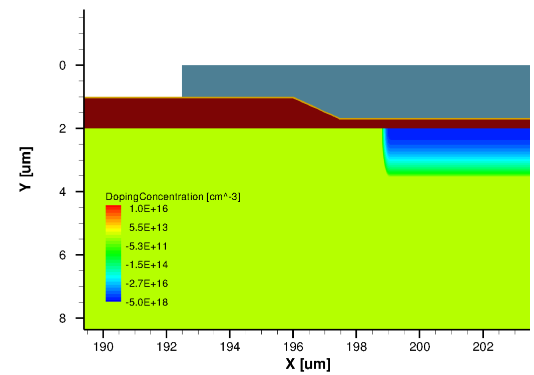
The CMS Phase-II Tracker Upgrade

Testbeam Telescopes

TCAD Simulations



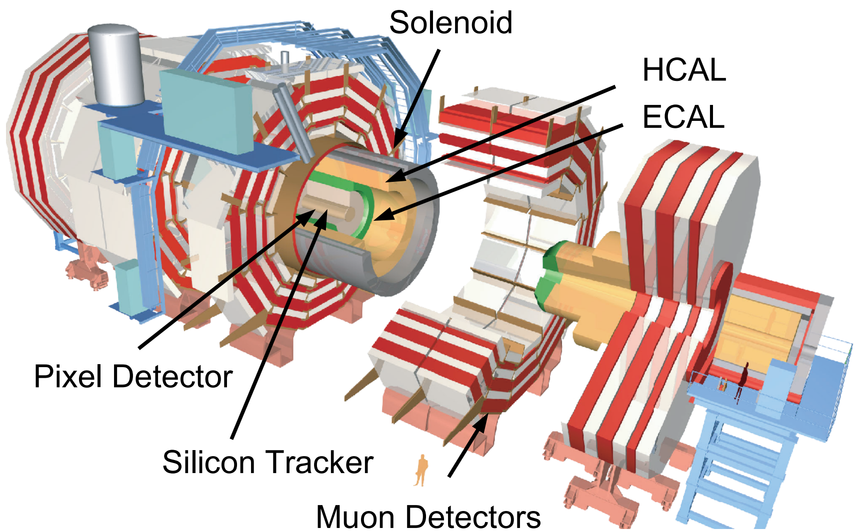


Thomas Eichhorn
DESY Student Seminar on Detector Development
23.05.2013

Outline

- Introduction
  - The CMS Phase-II Tracker Upgrade
  - The DESY-II Testbeam & Pixel Telescopes
  - Sensor Simulations
  - Quick Reminder: Physics of Silicon Sensors
- Simulation Results
  - Sensor Properties in Simulations
  - Modeling Radiation Damage
- Characterising the DESY-II Testbeam
- Summary and Outlook

The CMS Phase-II Tracker Upgrade

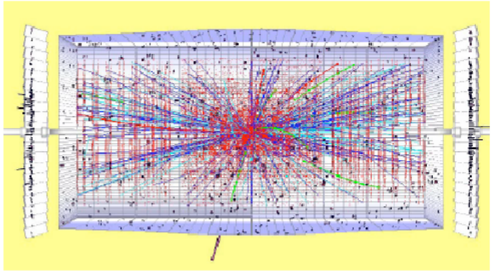


> Current tracker design:

- Built for 10 year run time (500 fb^{-1})
- Peak instantaneous luminosity of 10^{34} $cm^{-2}s^{-1}$

> High luminosity upgrade in 202X:

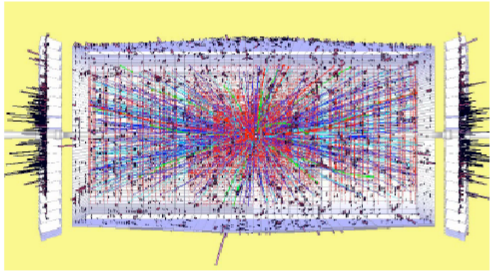
- Increase luminosity by a factor of 5 → higher occupancy
- Even harsher radiation environment



LHC, L = 10^{34} $cm^{-2}s^{-1}$, ~20 MBE

> Upgraded CMS strip tracker requirements:

- Increase granularity to maintain low detector occupancy
- Tracker to contribute to the CMS level-1 trigger
- Radiation hard sensors

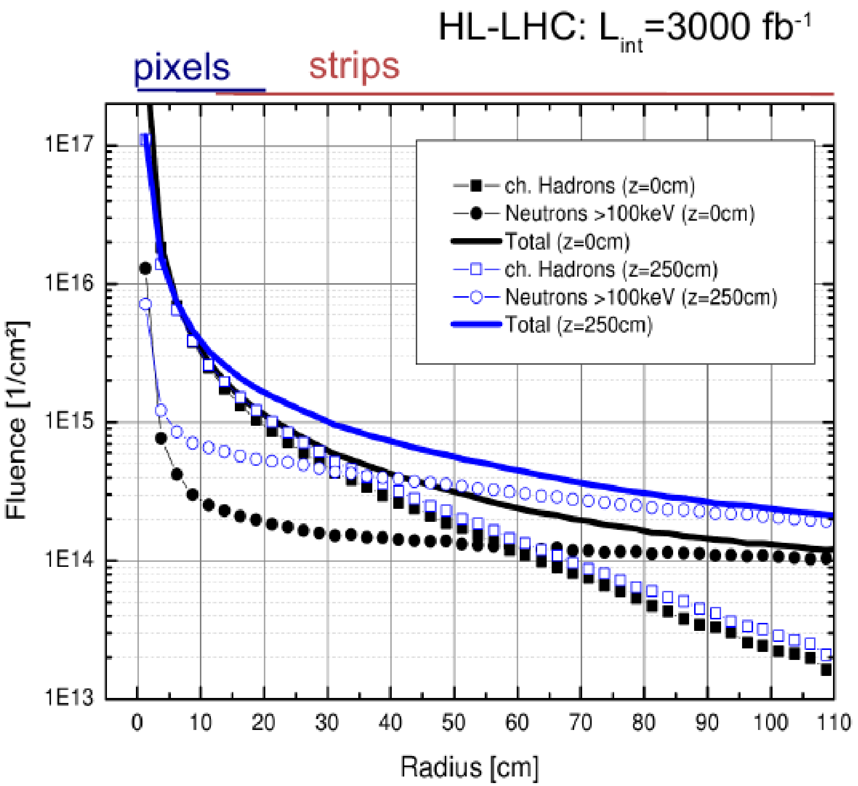


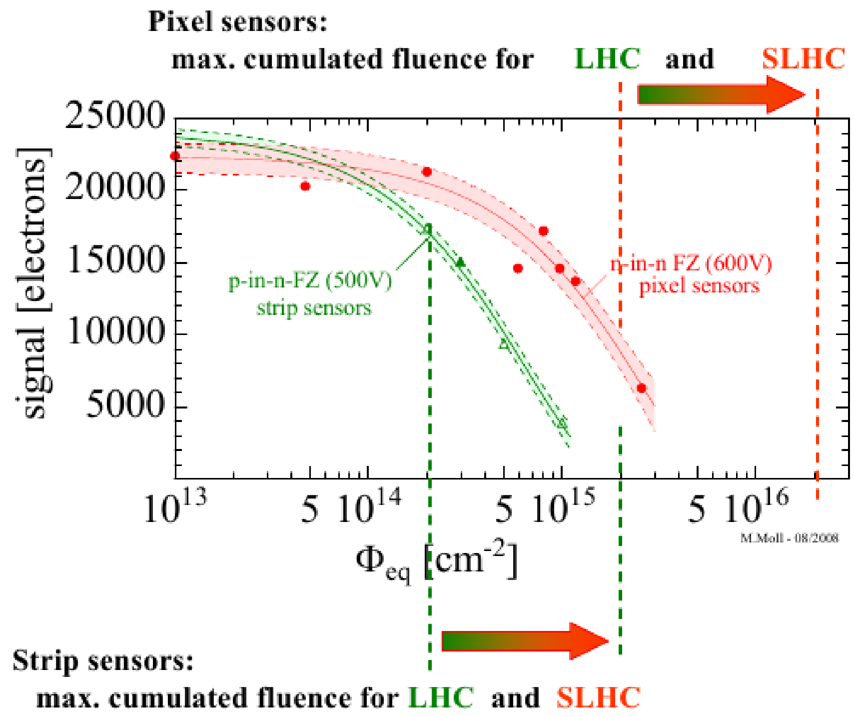
SLHC, L = 10^{35} $cm^{-2}s^{-1}$, ~200 MBE

The CMS Phase-II Tracker Upgrade

- Signal degradation for currently installed sensors

- Mix of irradiations expected

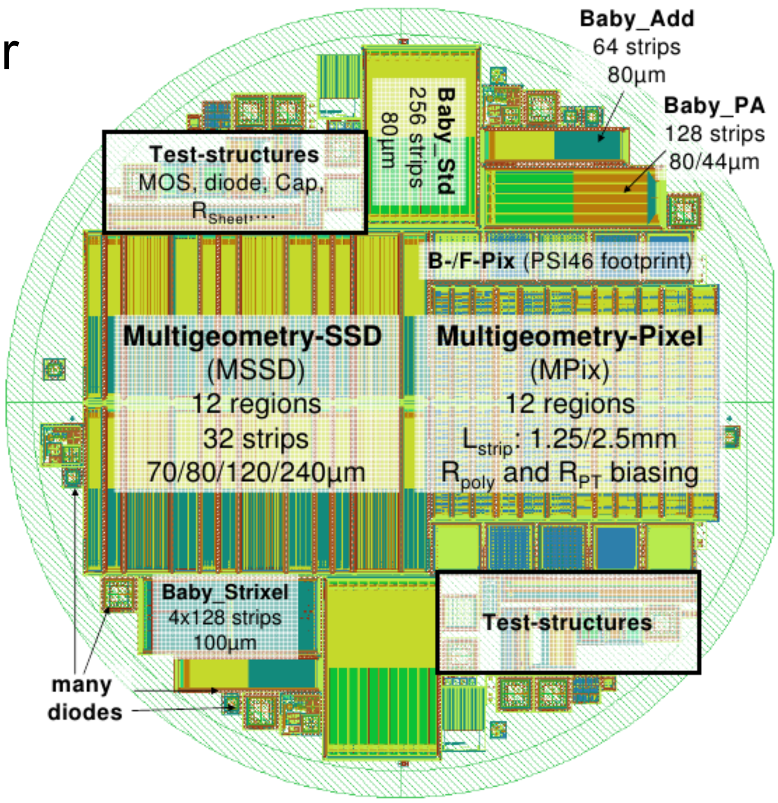




- Detailed and comprehensive studies of possible future sensor materials and technologies needed

The CMS Hamamatsu Campaign

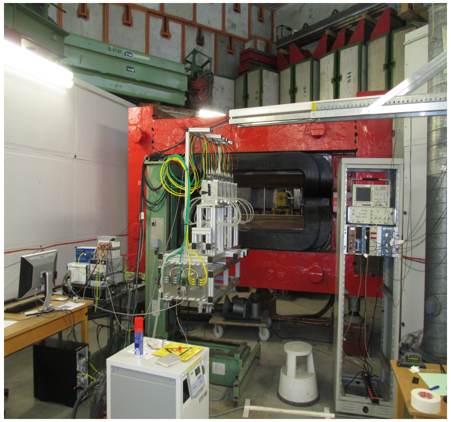
- Goal: identify the technological baseline for the CMS Phase-II strip tracker upgrade
- Single high-quality wafer manufacturer
- Dedicated structures for measurement of specific sensor properties
- Common testing procedures for comparability
- Points under investigation:
  - Radiation damage effects
  - Annealing behaviour
  - Evaluate geometries and materials



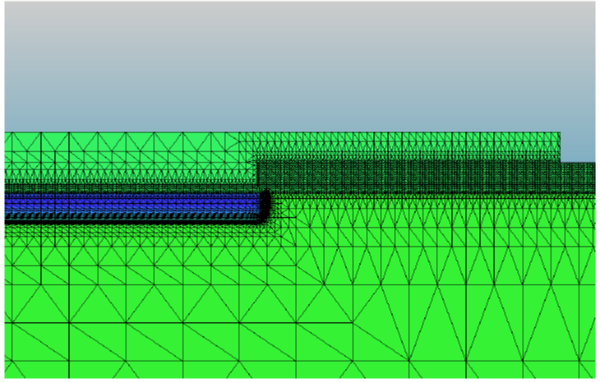
Finding a Sensor for the Future CMS Tracker

- Tools for sensor development

- Testbeam measurements



- TCAD sensor simulations



Finding a Sensor for the Future CMS Tracker

- Tools for sensor development

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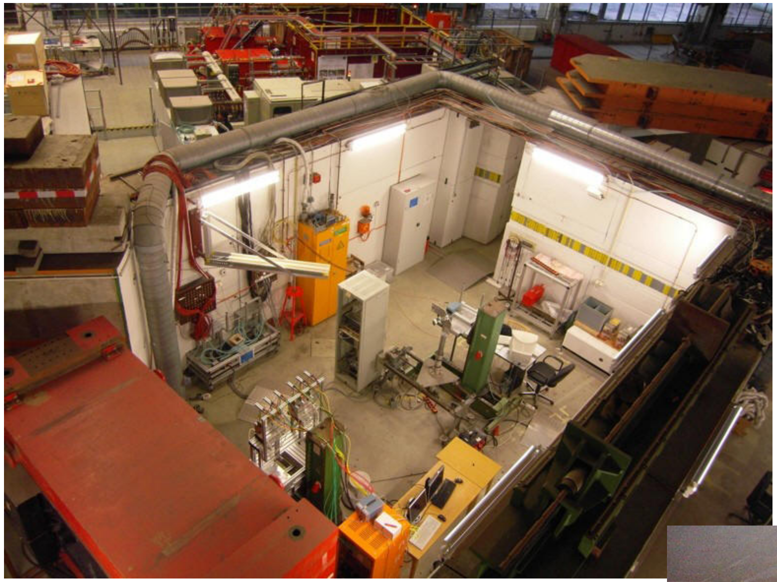
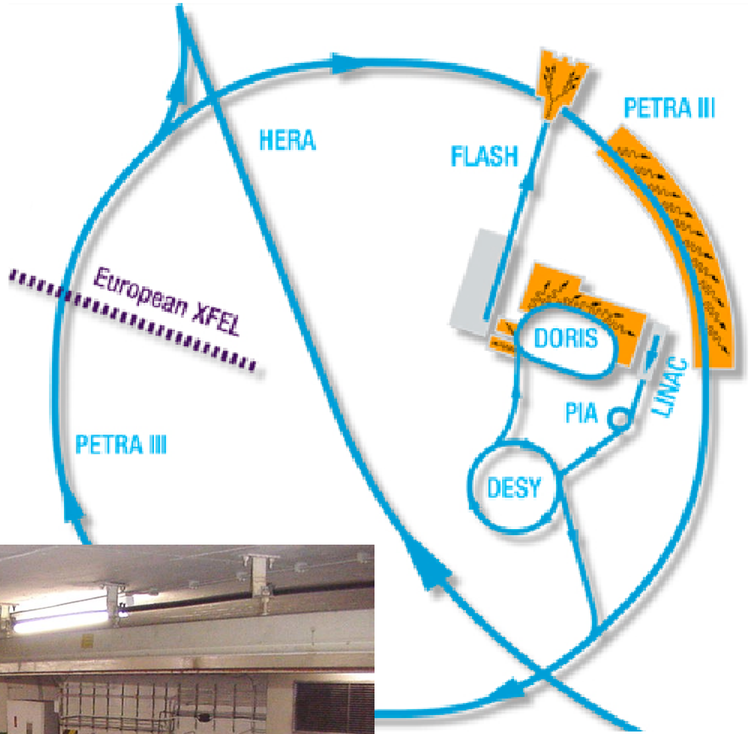
- TCAD sensor simulations

The DESY-II Testbeam

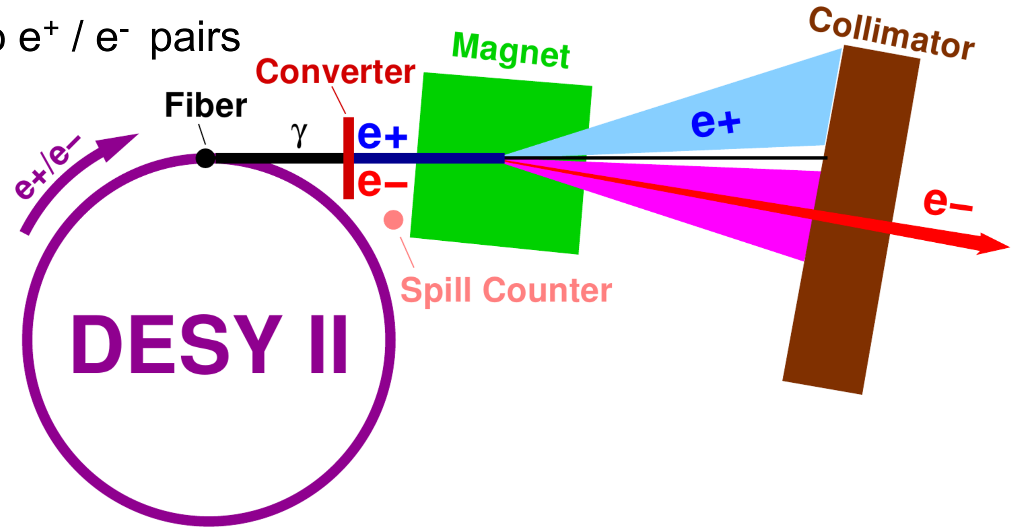




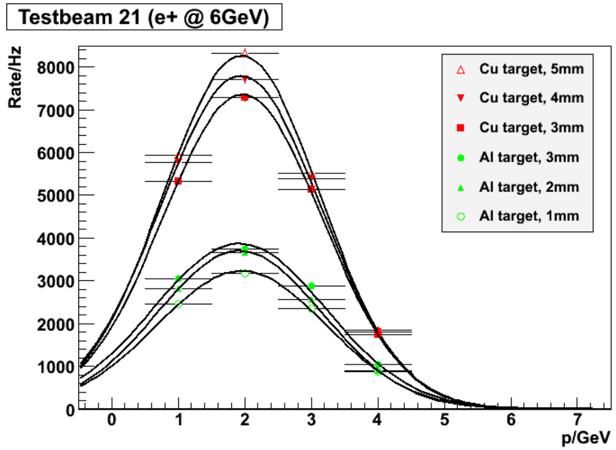
- DESY-II synchrotron
- Pre-accelerator
  - HERA (2007)
  - DORIS (2012)
  - PETRA
- 3 testbeam lines

The DESY-II Testbeam

- Testbeam from DESY-II synchrotron
  - Carbon fiber generates a bremsstrahlung beam
  - Metal target plate converts photons to e^+ / e^- pairs
  - Dipole magnet spreads out beam
  - End collimator cuts out final beam



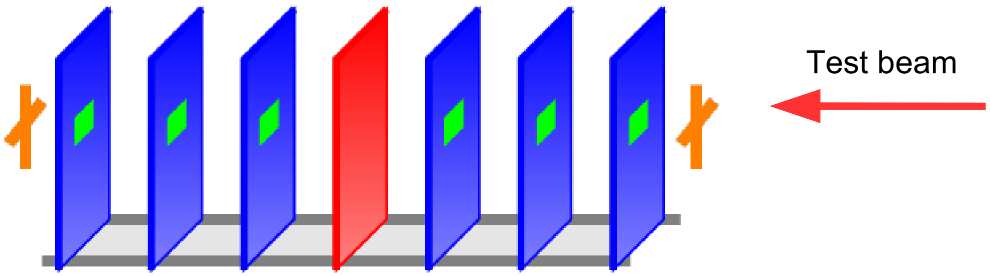
- Beam momentum
  - Changing magnet current allows energies from 1 to 6 GeV
  - Low energies require very thin sensors to reduce multiple scattering

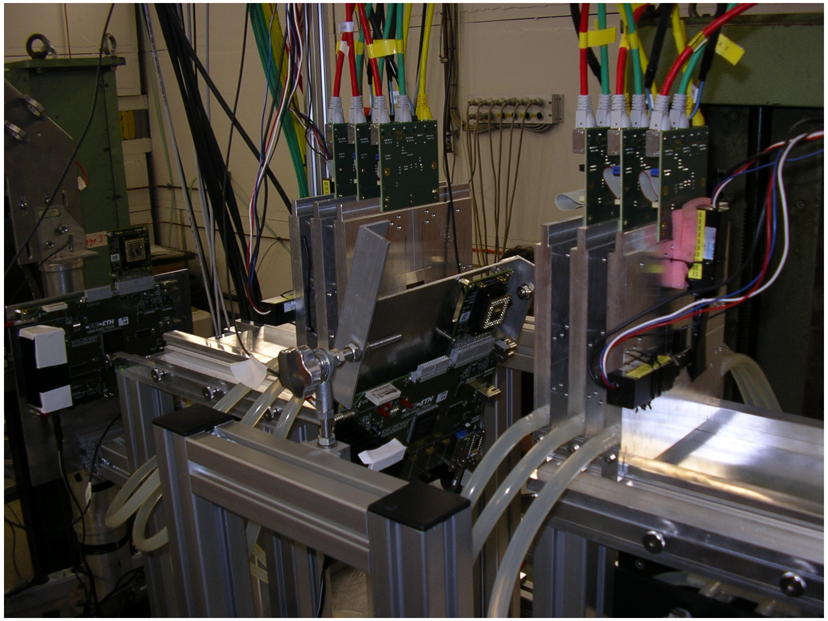


Beam Telescopes – Setup

> What is a beam telescope?

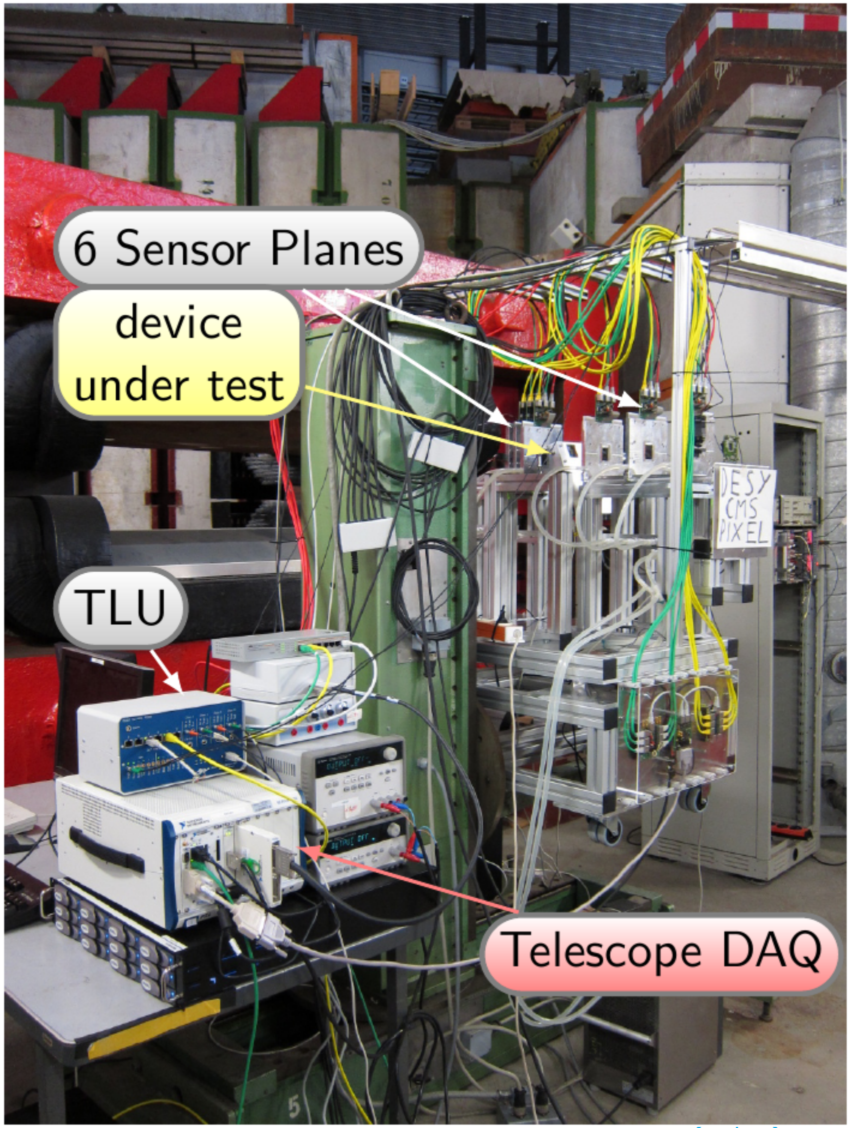
- Series of parallel silicon sensor planes inserted into a particle test beam
- Reconstruct particle tracks through the sensor planes wrt. time and position
- Use gained reference information to evaluate *device under test* (DUT) performance
- Contribution towards the development of future detector systems
- High precision and fast read-out speed needed





Beam Telescopes – Setup

- Datura telescope at DESY:
  - 6 sensor planes
    - Monolithic Active Pixel Sensor
    - Rolling-shutter read-out
    - t ~115 µs
  - Flexible mechanics & cooling
  - Trigger logic unit (TLU)
    - Easy integration of DUTs
  - NI PXIe Telescope DAQ
  - Data analysis with EUTelescope
- Table-top particle physics experiment!



Finding a Sensor for the Future CMS Tracker

- Tools for sensor development

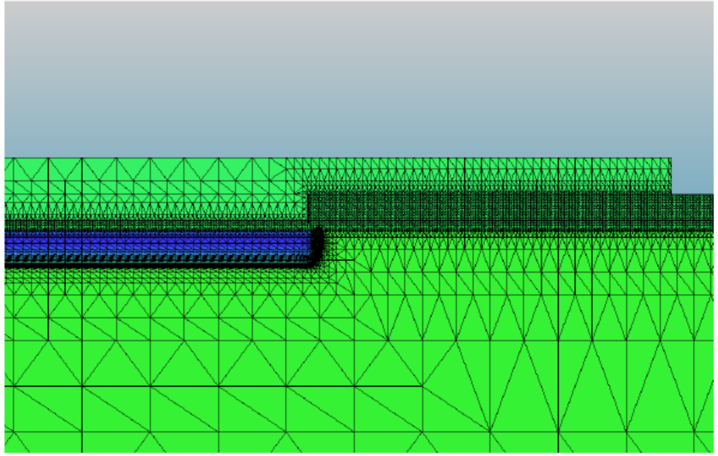
- Testbeam measurements

- TCAD sensor simulations

TCAD Simulations – I

- <u>T</u>echnology <u>C</u>omputer <u>A</u>ided <u>D</u>esign
  - Commercial software for semiconductor simulations
  - Many applications, extensive use in semiconductor industry
  - Two main packages: *Silvaco Atlas*, <u>*Synopsys Sentaurus*</u>

- Standard FEA Framework:
  - Create 2D or 3D structure with materials, doping, etc and generate a mesh
  - Select physical models to be used in simulation:
    - temperature
    - field generation
    - carrier recombination
    - trapping (→ radiation damage)
    - carrier lifetime
    - ...



TCAD Simulations – II

- Standard FEA Framework:
  - Include external effects: electric circuit (SPICE), laser illumination, traversing particle...
  - Specify what kind of simulation: simple I-V, capacitive, or time-dependant
  - Run simulation: at each mesh-point solve
    - poisson's equation

$$\frac{d^2 V(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon_r \ \varepsilon_0}$$

    - carrier continuity equations:

$$\nabla \cdot \vec{J}_n = q \cdot (R_{eff} + \frac{\partial n}{\partial t}) \qquad -\nabla \cdot \vec{J}_p = q \cdot (R_{eff} + \frac{\partial p}{\partial t})$$

  - Derive physical properties:
    - electric field
    - current flows
    - charge distributions
    - ...

The CMS Device Simulation Group

- Working group to streamline and coordinate tasks
  - 5 institutes:
    - Delhi University (India)
    - DESY (Germany)
    - Karlsruhe Institute of Technology (Germany)
    - Helsinki Institute of Physics (Finland)
    - University of Pisa (Italy)

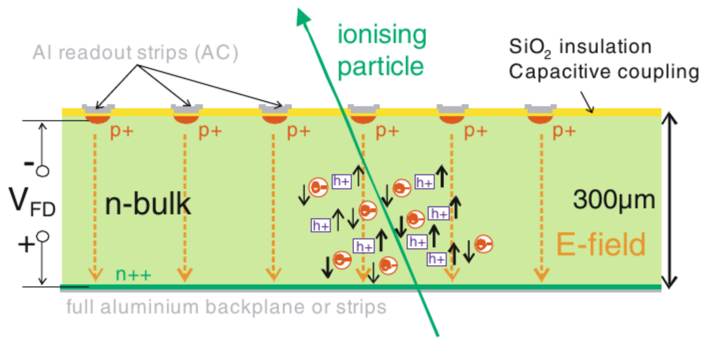
- Group aims:
  - Provide input to the CMS sensor design
  - Points under investigation:
    - Device design – simulate capacitances, verify isolation techniques
    - Charge collection and read-out, research optimal layout
    - Radiation damage → derive a trap model
    - Comparison of simulation tools

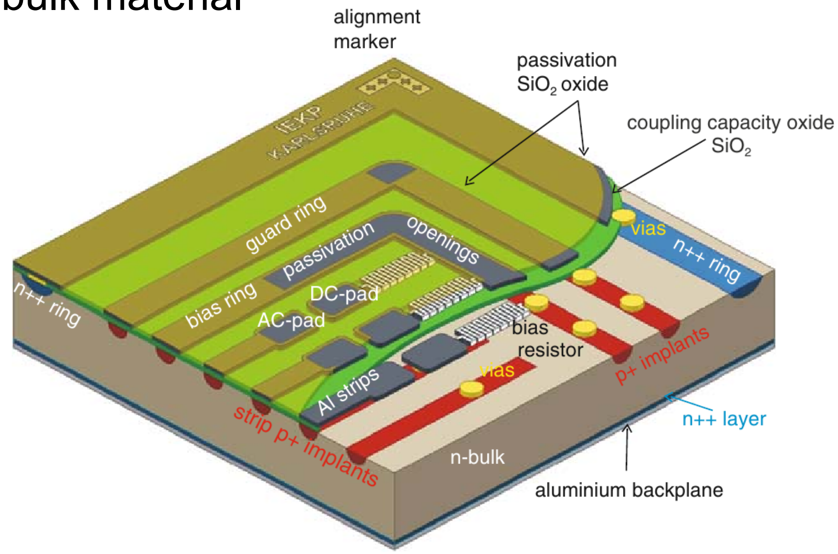
- How does a silicon sensor work?

Working Principle of a Silicon Sensor

Material & structure:

- Boron or phosphorous impurities in silicon → 'doping'
- p/n junction between strip implantation and bulk material
- SiO_2 insulation for capacitive coupling





Operation:

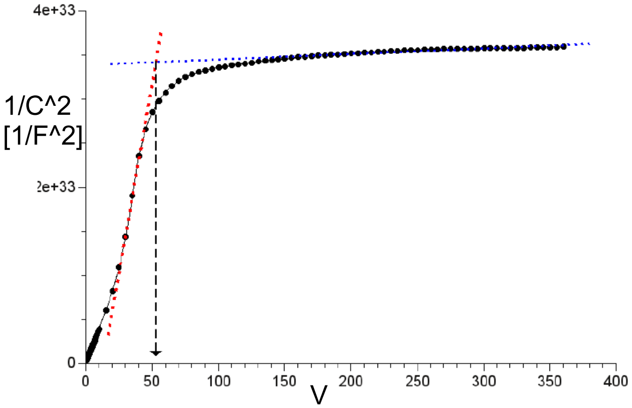
- Bias voltage applied to deplete sensor of free charge carriers → creates electric field
- Traversing ionising particle generates e-/h pairs
- Charge collected at segmented read-out strips

Important Sensor Properties

Depletion voltage

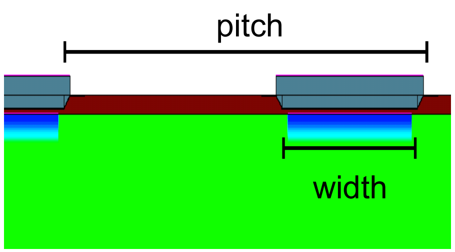
- Voltage needed to deplete sensor of free charge carriers
- Extracted from capacitance – voltage measurements

$$V_d \approx \frac{e \cdot d^2}{2 \cdot \varepsilon_r \ \varepsilon_0} \cdot | N_{eff} |$$



Strip width and pitch

- Pitch: distance between strips
- Strip noise ~ w/p ratio



AC/DC coupling

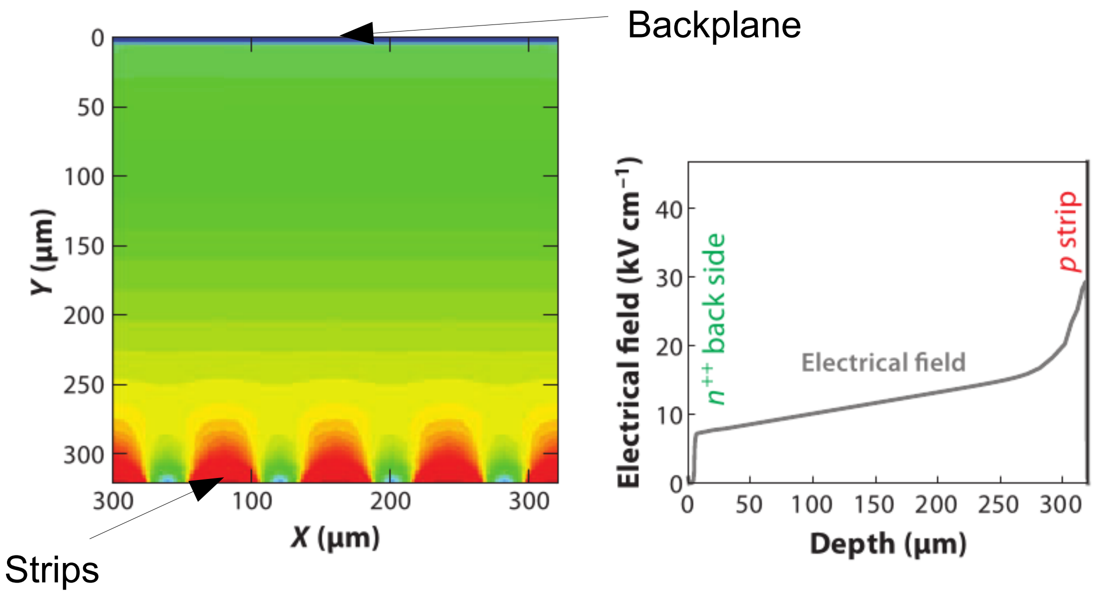
- DC: sensor connected directly to read-out chip → pixel detectors
- AC: capacitive coupling via an oxide → strip detectors

p-in-n or n-in-p?

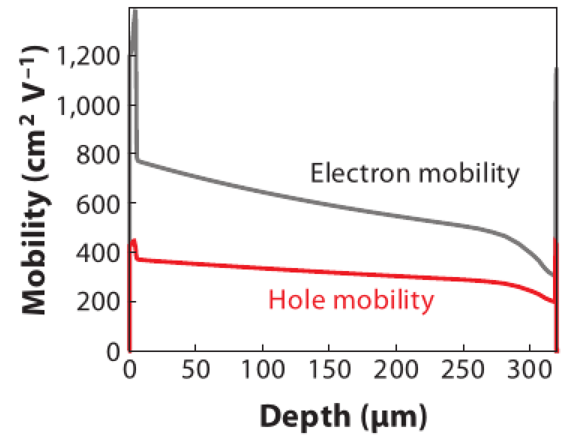
- p-in-n → collects holes
- n-in-p → collects electrons

Sensors in Operation

- Example: traversing minimally ionising particle (*MIP*)
  - → generating ~ 108 e/h pairs / µm Si



Electric field

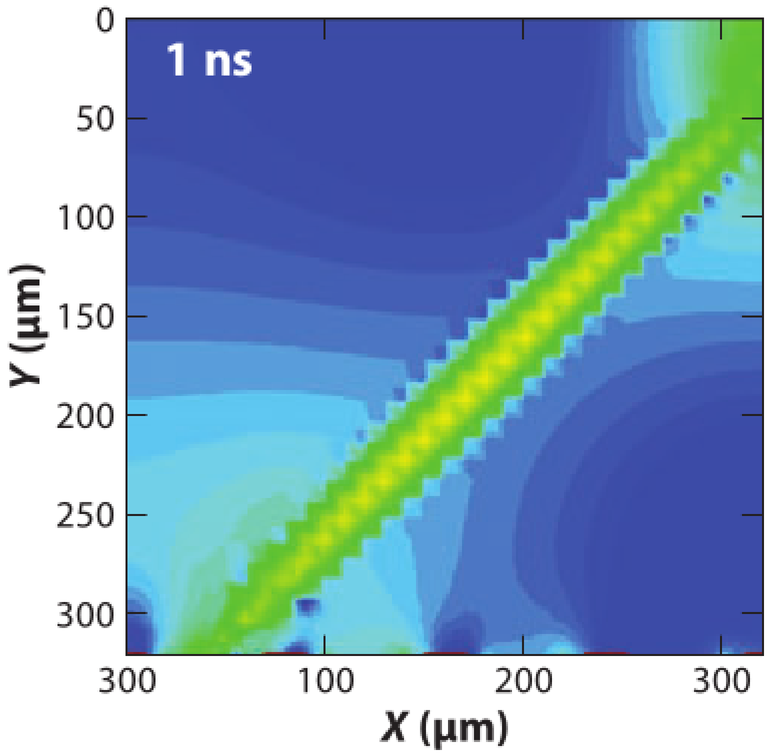


Carrier mobility

Sensors in Operation

- Particle generates electron / hole pairs

- Charge densities



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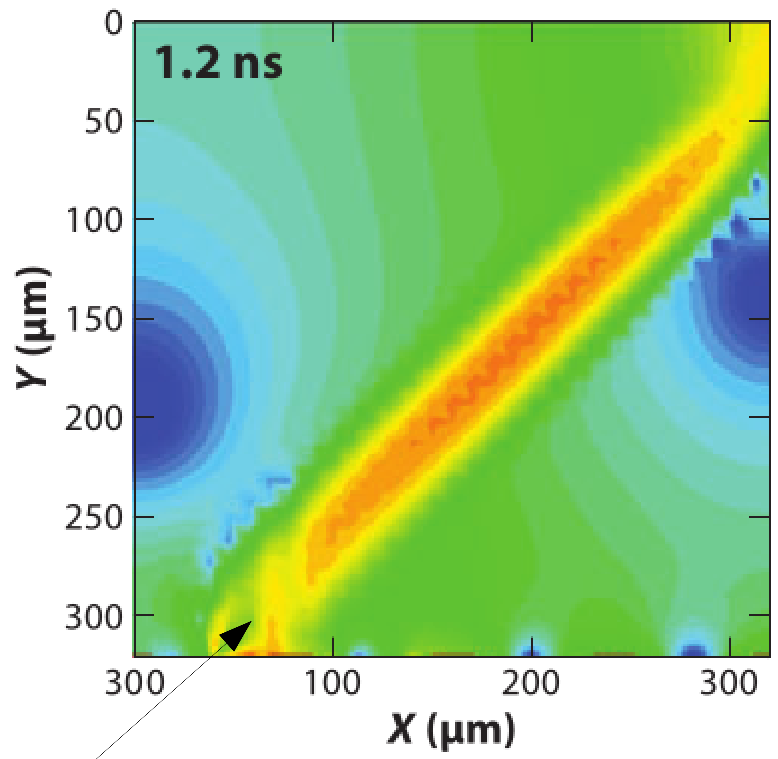
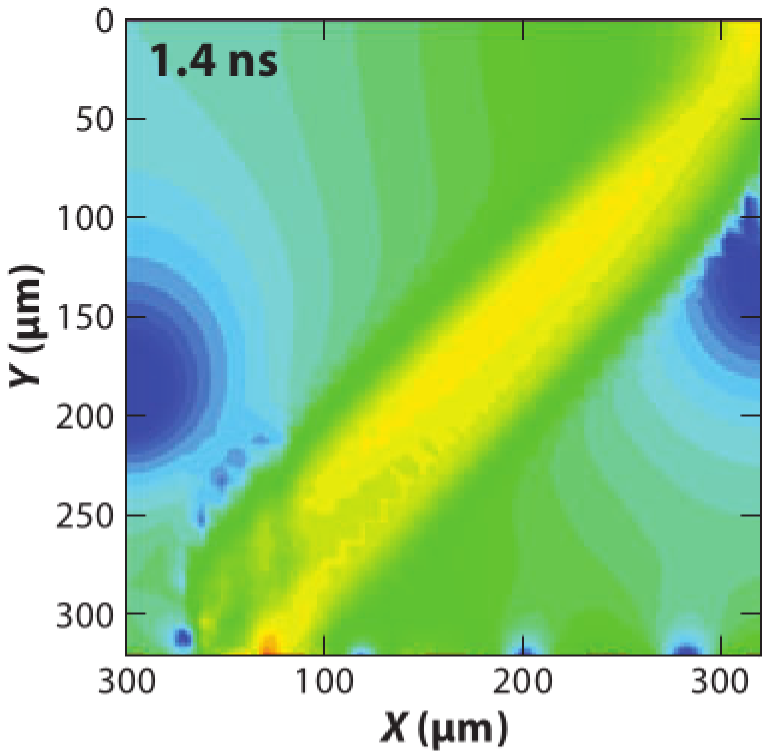


Holes collected at sensor strips

Sensors in Operation

- Electric field separates charge carriers
- Electrons drift to backplane
- Holes collected at strips

- Charge densities



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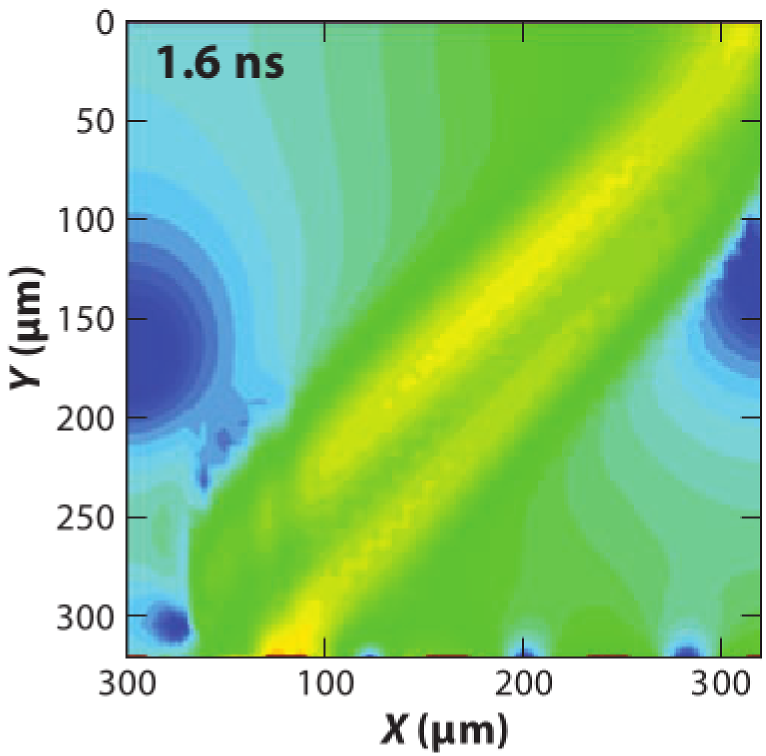

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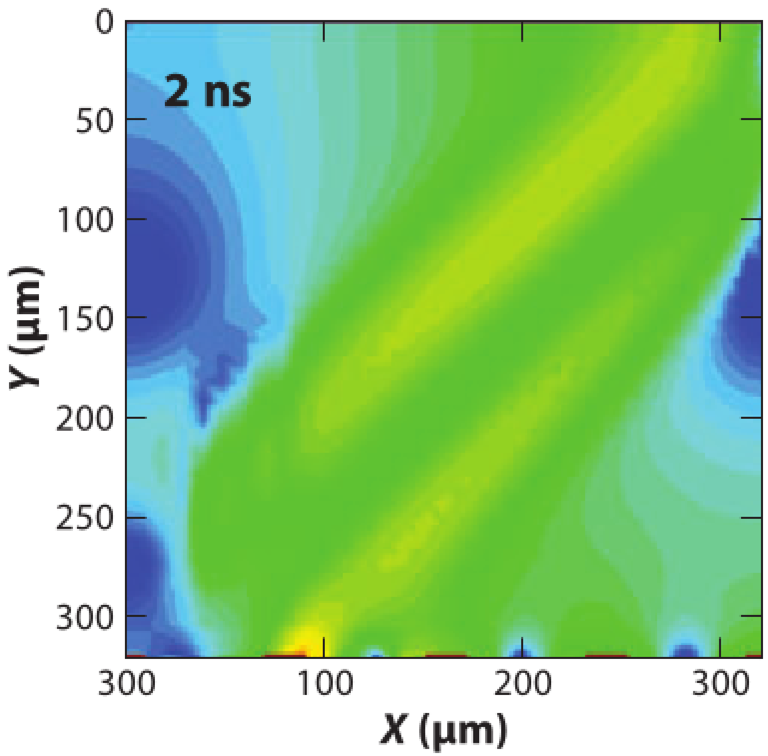

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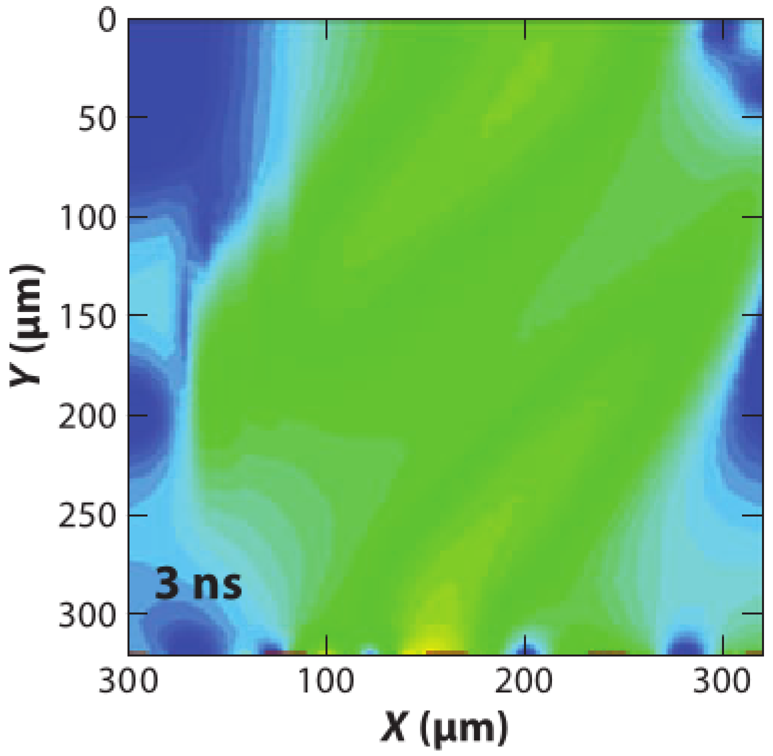
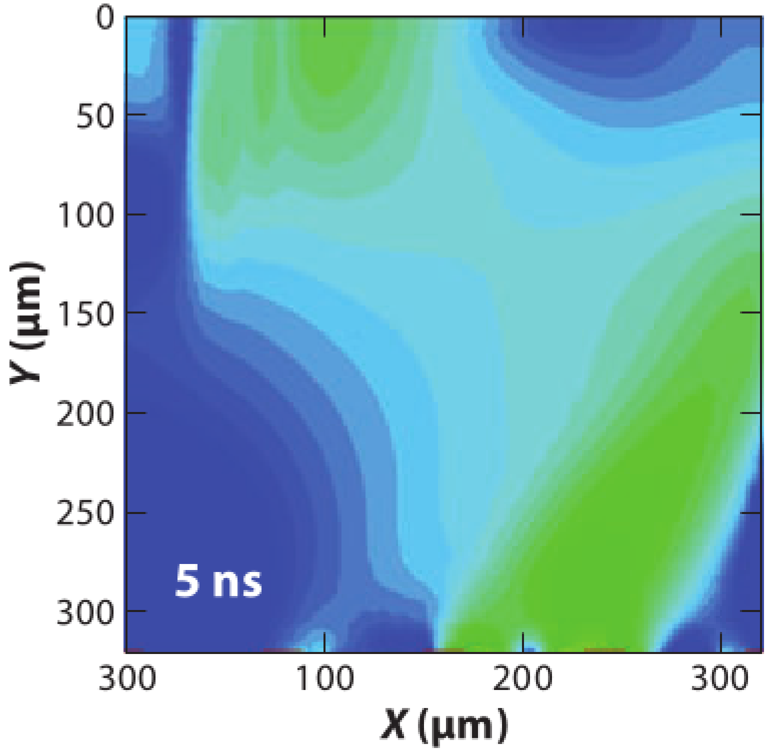


Sensors in Operation

- Electric field separates charge carriers
- Electrons drift to backplane
- Holes collected at strips
- $\mu_e > \mu_h \rightarrow$ electrons faster

- Charge densities



Sensors in Operation

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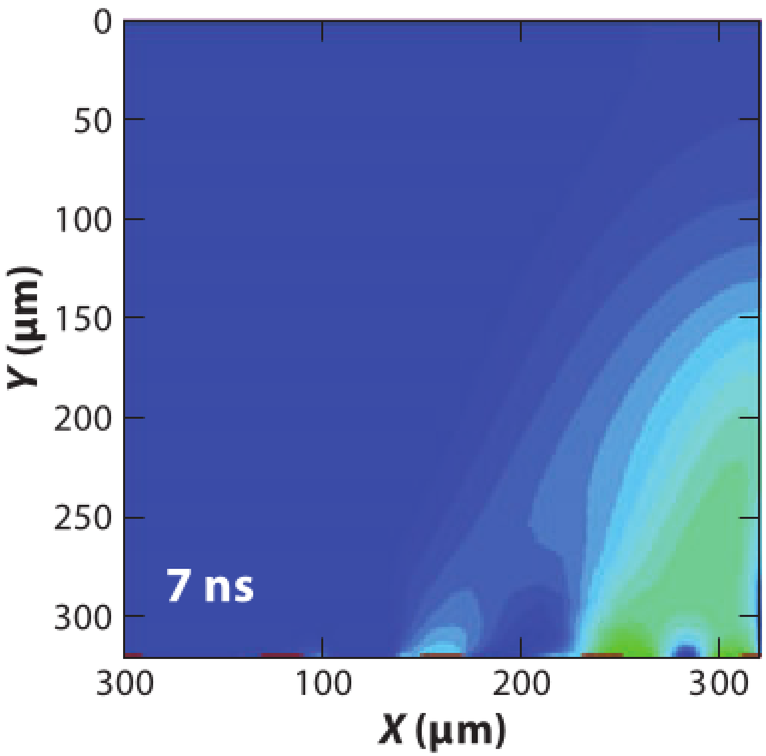
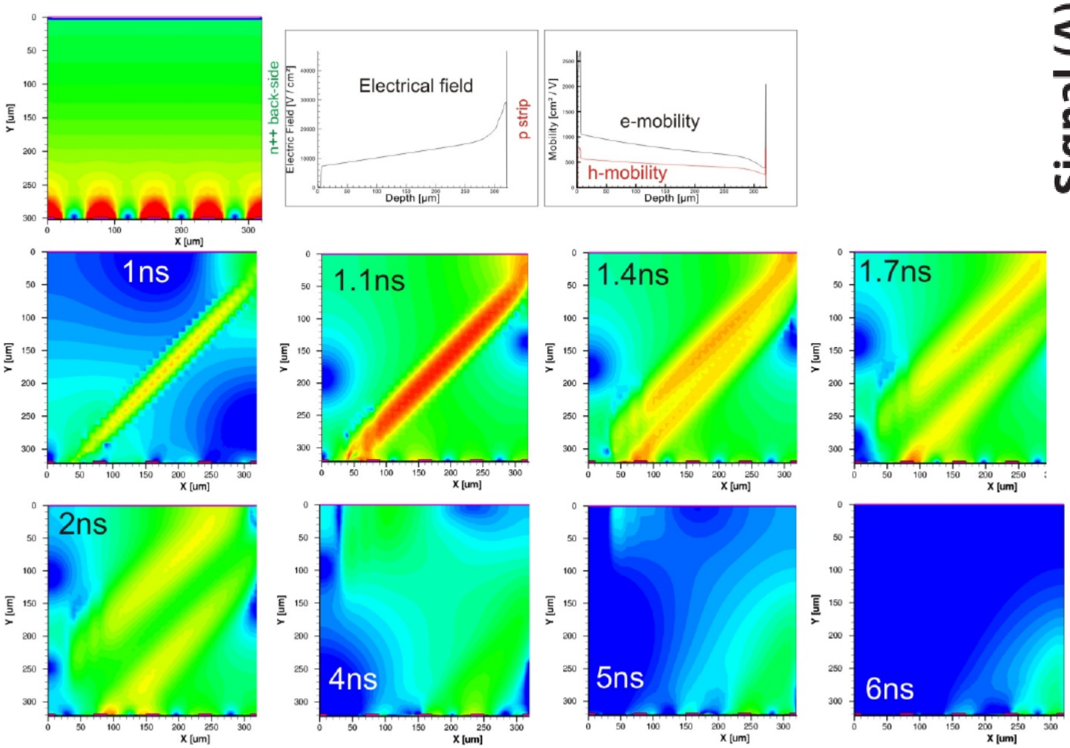
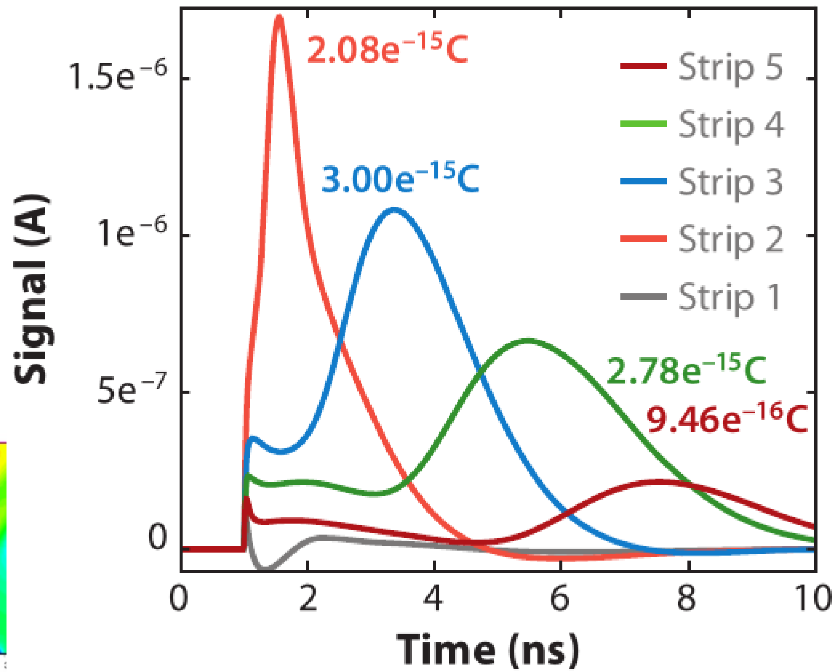


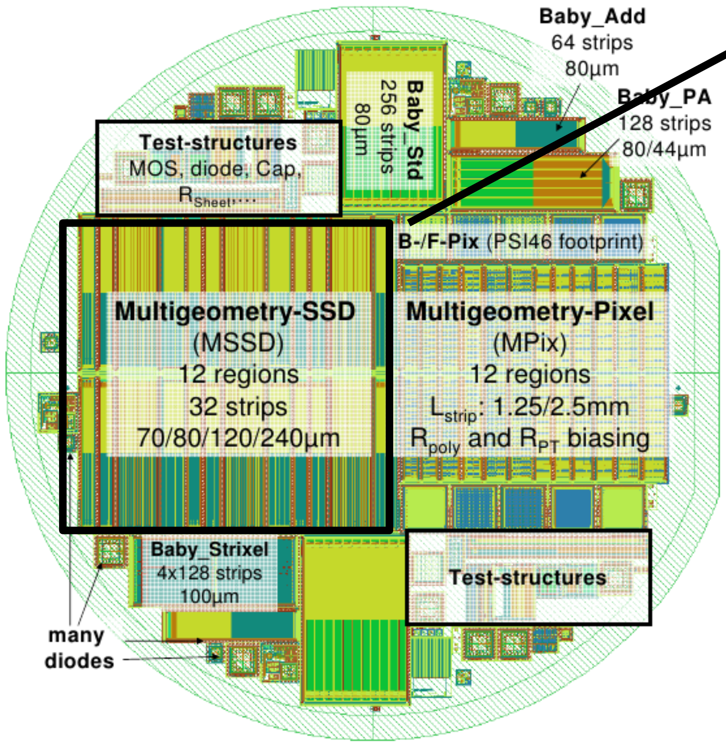
- Recieved signals
- Inner strips collect most charge



- Collected charge over time



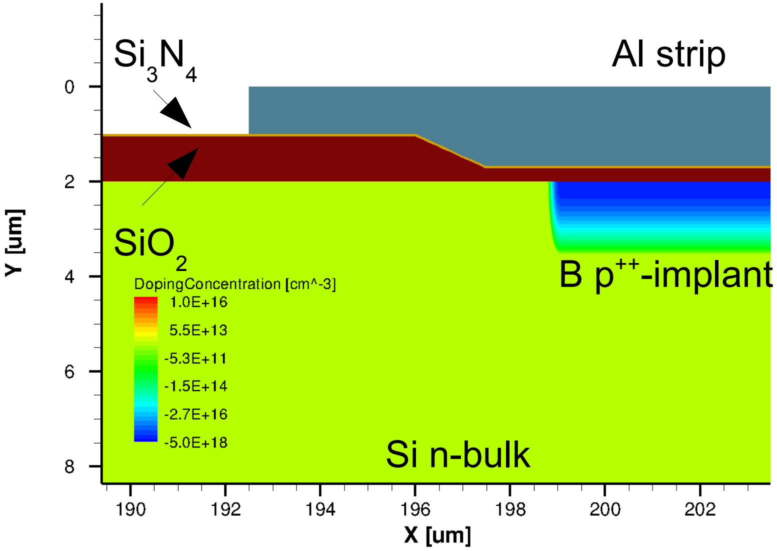
- MSSD sensors (Multi-geometry silicon strip detectors):
  - 12 regions on wafer, 32 strips each, with 70 / 80 / 120 / 240 µm pitch
  - Main source of strip noise: inter-strip capacitance C_{int}
  - Can measurements be verified by simulations?



Sensor	Pitch [µm]	Implant width [µm]	Alu width [µm]	w/p
1	120	18	26	0.15
2	240	36	44	0.15
3	80	12	20	0.15
4	70	10.5	18.5	0.15
5	120	30	38	0.25
6	240	60	68	0.25
7	80	20	28	0.25
8	70	17.5	25.5	0.25
9	120	42	50	0.35
10	240	84	92	0.35
11	80	28	36	0.35
12	70	24.5	32.5	0.35

Simulations of Unirradiated Sensors – II

- Not all sensor parameters known or released by manufacturer
  - Doping profile, concentration and depth, oxide thickness, etc.



- Include diagonal aluminium strip component to model etching
- 50 nm Si_3N_4 layer
- 270 – 680 nm SiO_2
- Implant depth depends on type (pnn/npp) and sensor thickness (120 / 200 / 320 μm)
- p-spray isolation concentration 1e16 cm^{-3}

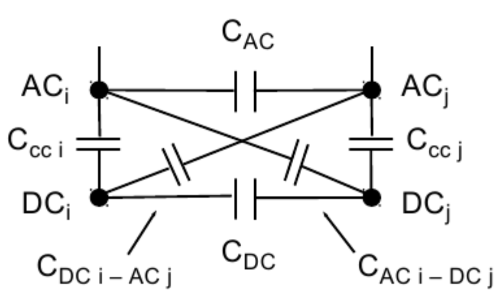
- Compare simulations with measurements to get these parameters
  - Approximate simulated structure to the actual sensor geometry
  - How do these parameters influence sensor properties?

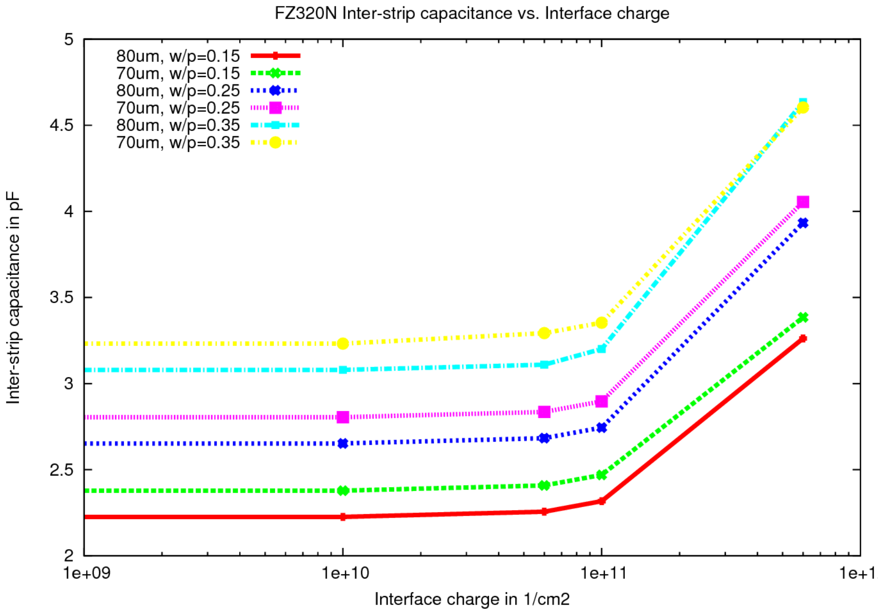
Insights from Simulations

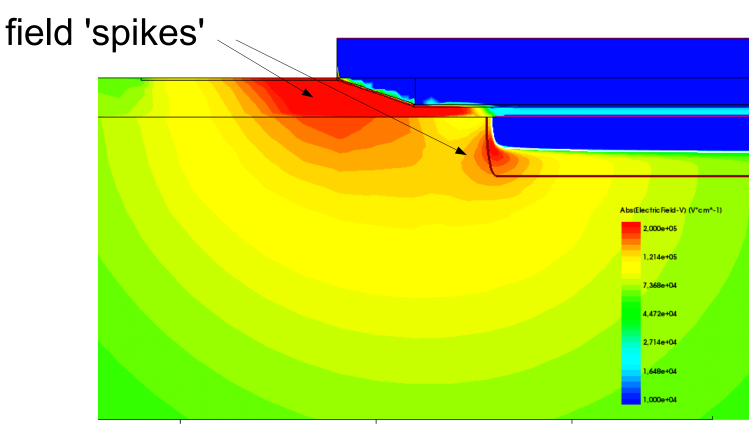
- Simulations can visualise how parameters influence sensor properties
  - Interface charge Q_f increases C_{int}
  - Resulting changes to electric field

- Some discrepancies to reality
  - Simulation requires 'additional' capacitances in the calculation:

$$C_{int} = C_{AC} + C_{DC} + 2 * C_{ACDC}$$

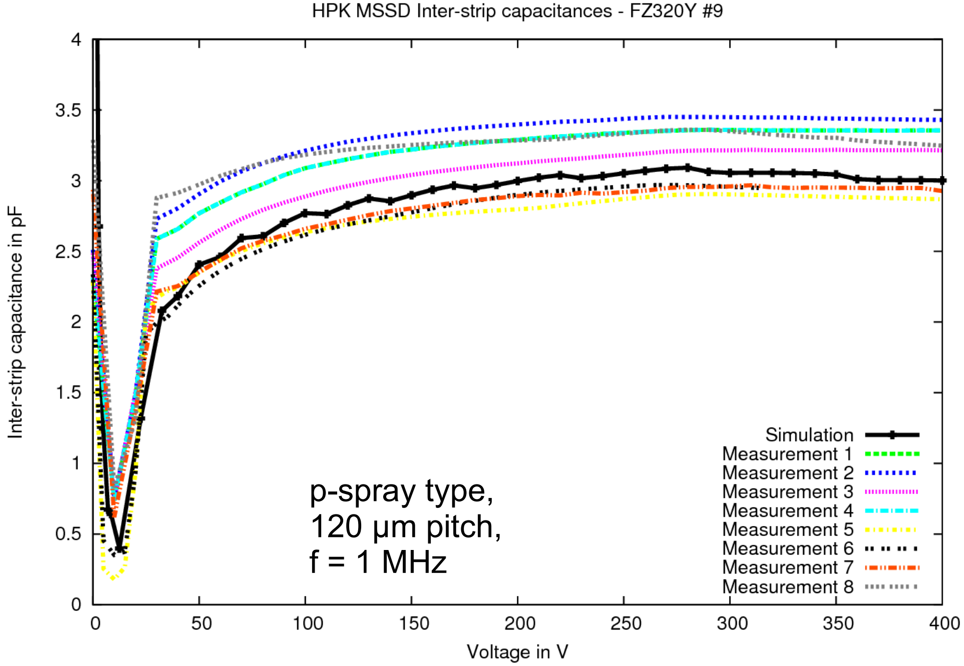


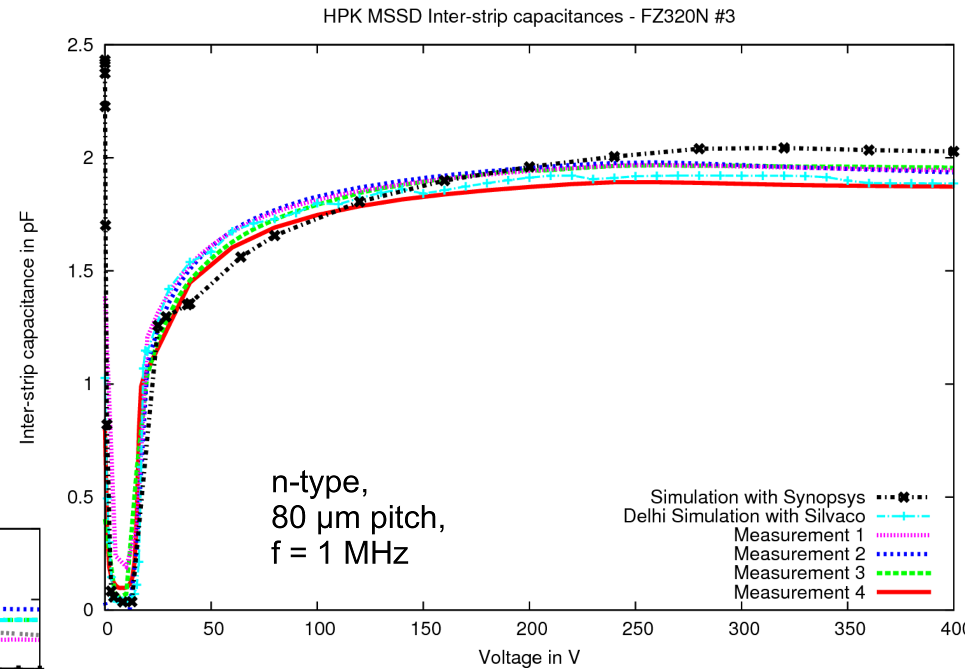




Comparison with Measurements

- Simulated C_{int} in good agreement with measurements for all materials and geometries
- Both main simulation packages give comparable results



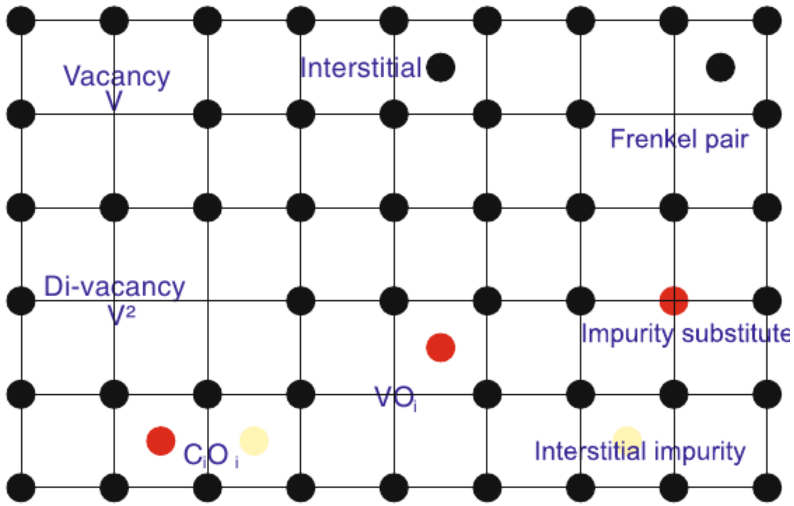


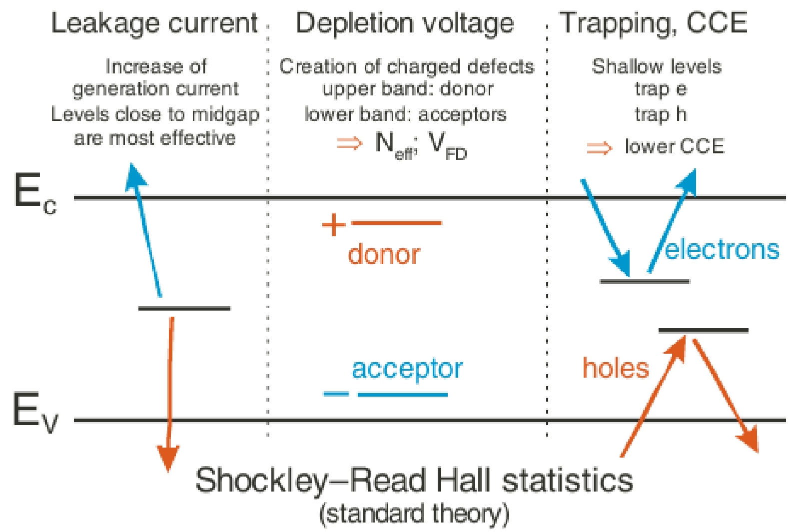
- Measurement spread due to different wafers and institutes

  → Minor variations in temperature and relative humidity

Radiation Damage in Silicon Sensors

- Radiation damage creates point- and cluster defects
- Influence on sensor properties through states in the Si band-gap
  - Increase in leakage current
  - Change in depletion voltage
  - Reduction of charge collection efficiency by trapping
- Defect types and concentrations depend on material and radiation type (ch. hadron, neutron, gamma irradiation)





Implementing Radiation Damage

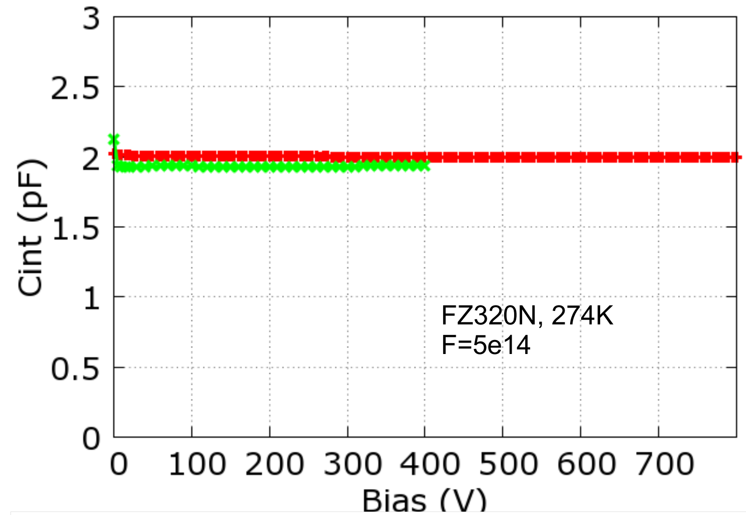
- Implemented into simulations by including traps
  - Energy states in the silicon band-gap
  - Characterised by:
    - Energy
    - Concentration
    - Capture cross-section for electrons and holes
  - Various existing models for different materials and irradiations
  - Search for a trap model that fits best to measured data
  - CMS Simulation Group has used the *EVL-4* model by V. Eremin to cross-check simulations

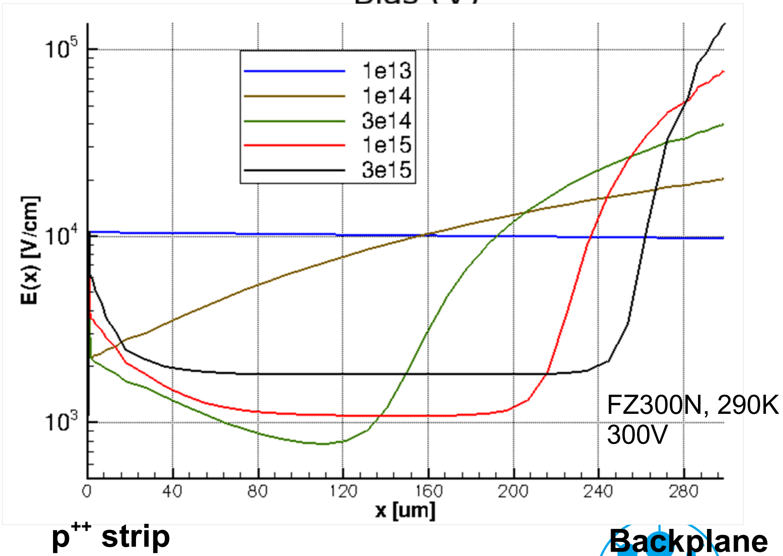
- Preliminary trap model
  - Simulate the double-peak electric field observed in irradiated sensors
  - Defects approximated into two 'effective' traps

Defect	Energy [eV]	σ_n [cm^{-2}]	σ_p [cm^{-2}]	g [cm]
Acceptor	$E_C - 0.525$	4e-14	4e-14	0.8
Donor	$E_V + 0.48$	4e-14	4e-14	0.8

Simulated Radiation Influence

- First tests: basic 2-trap model can reproduce some measurements
  - Interstrip Capacitance
  - Double-peak in electric field
    - Trapped charge carriers contribute to field
- Ongoing work:
  - Compare other sensor properties after irradiation with measurements
  - Other trap models currently being tested to include further defects
  - Ongoing search for a trap model describing all effects





Finding a Sensor for the Future CMS Tracker

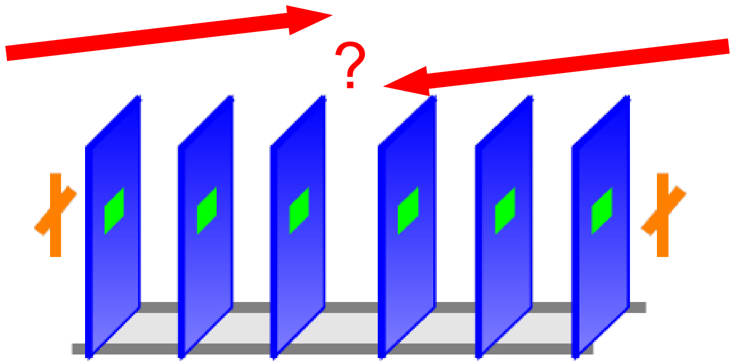
- Tools for sensor development

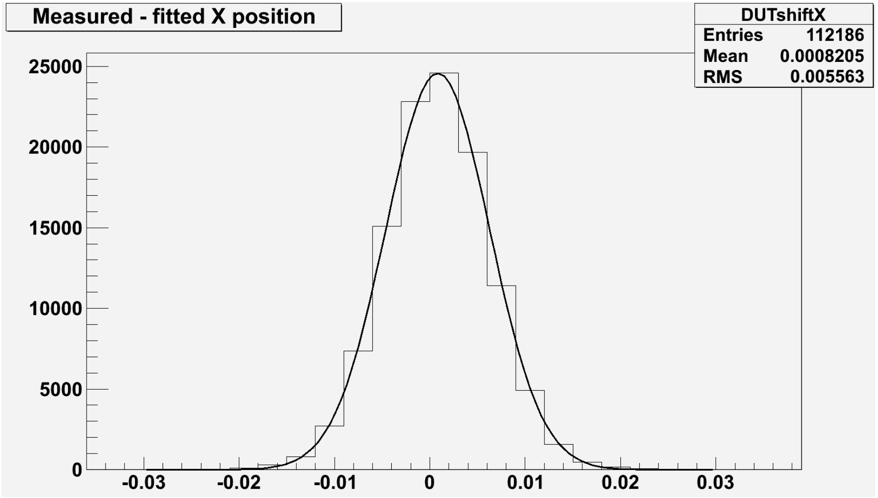
- Testbeam measurements

- TCAD sensor simulations

Characterising the DESY-II Testbeam

- Goal: use the testbeam to evaluate performance of future sensors
- Prerequisite: measure beam properties and telescope capabilities
- Telescope figure of merit: intrinsic tracking resolution
- Use each telescope plane as a DUT for residuals



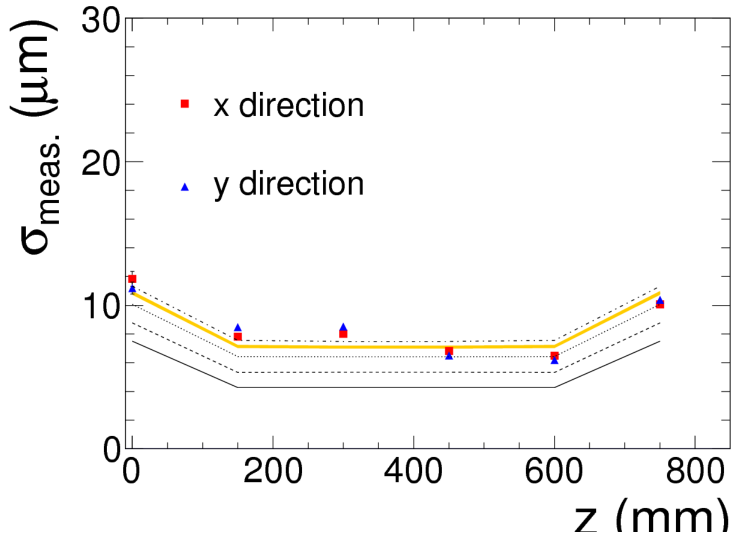


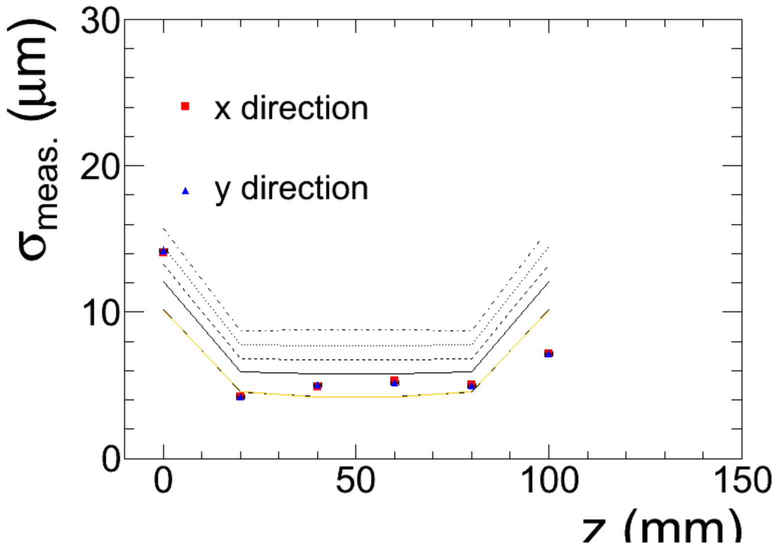
Intrinsic Resolution of the Datura Beam Telescope

- **Resolution depends on:**
  - beam energy (1 to 6 GeV)
  - sensor distance (20 to 150 mm)

  → suffers greatly from multiple scattering

- **First results – 2 GeV:**
  - σ ~ 8 µm at 150 mm sensor distance
  - σ ~ 5 µm at 20 mm sensor distance





Summary and Outlook

- CMS Phase-II upgrade requires a new silicon tracker
  - Sensors to withstand higher radiation dose → investigate new materials and layouts
  - Cope with increased occupancy → improve granularity
  - New modules, ROCs, cooling, contribute to the Level-1 trigger, …

- Beam telescopes as a powerfull tool to test sensors
  - Pin-point a particle track → evaluate *device under test* performance

    → DESY beam telescopes & testbeam used by a variety of groups

- TCAD simulations
  - Powerful tool to see the inner workings of silicon sensors
  - Unirradiated sensor measurements can be reproduced
  - Ongoing search for a defect model to implement radiation damage

Backup

Beam Telescopes – Data Analysis

- EUTelescope software framework
  - Group of processors to convert raw detector data into particle tracks
  - Actively maintained and supported at DESY

http://eutelescope.desy.de