Queen Mary
University of London
Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 7

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Last revised 17 February 2020

What is this lecture about?

- The principles of detection of ionising radiation
    - Interaction of charged and neutral particles with matter
    - Gaseous sensors
    - Semiconductor sensors
    - Scintillators
- Sensor systems used in particle and nuclear physics
    - Calorimeters
    - Tracking detectors
    - Neutrino detectors

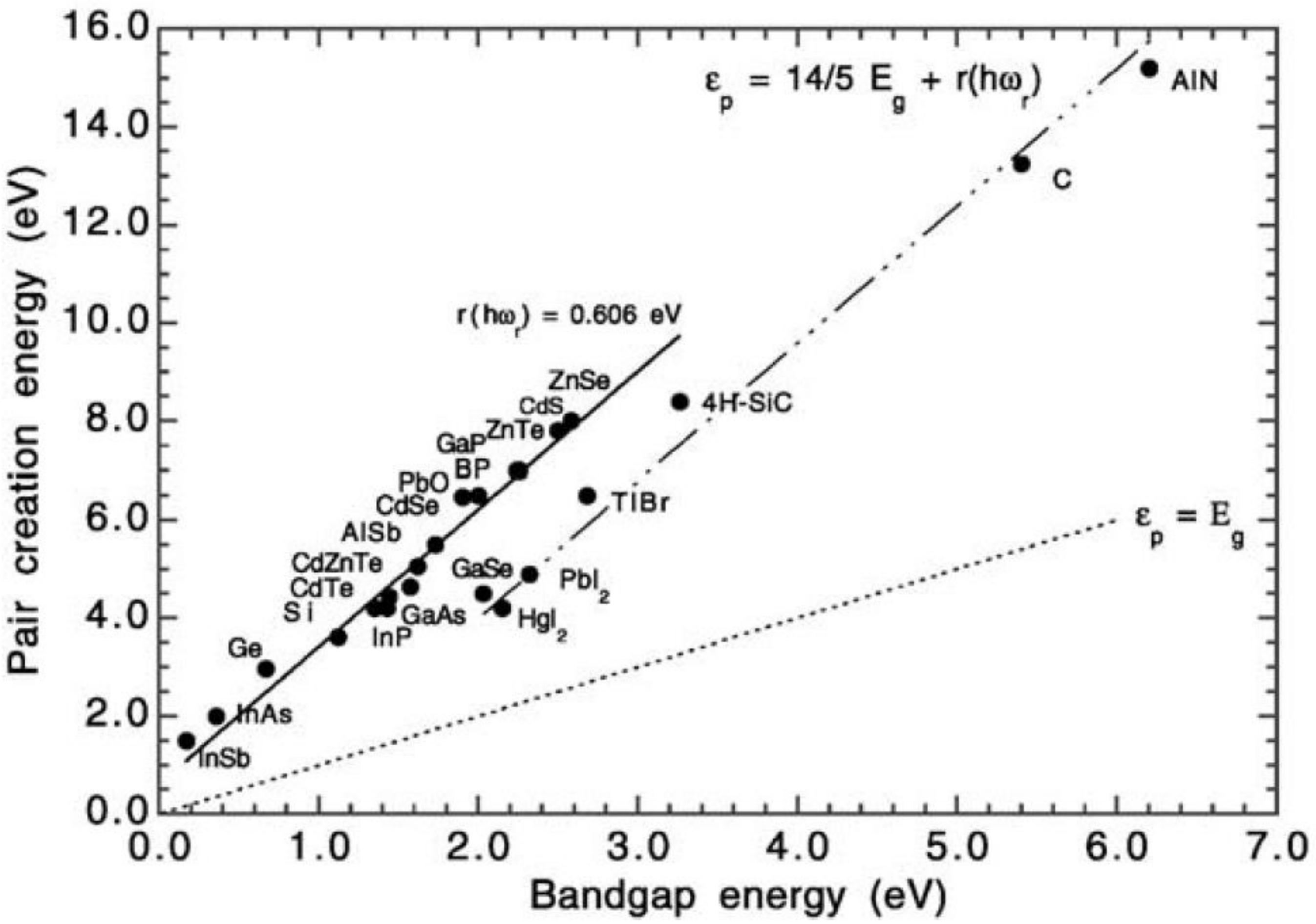
Key points from previous lecture

- Semiconductor properties are defined by doping, “intrinsic” silicon is normally slightly n-type.
- Semiconductor sensors behave like solid state ionization chambers
- Semiconductor bandgap affects the conversion of deposited energy (primarily via ionisation) into e/h pairs.
- e/h pairs separated by external reverse bias in the *depletion* region
- Signal comes from electrons and holes moving under an external electric field.

Pair creation Energy

This is the analogue of the energy required to produce a charged ion and a free electron in a gas. In the case of semiconductors it is the average energy required to produce one e/h pair.

Figure is from Owens and Peacock, *Nuclear Instruments and Methods in Physics Research A* **531** (2004) 18–37



Basic types

- Silicon strips
  - Implanted p on n gives a single sided detector
  - Adding an n^+ implant on the other side makes a double sided detector
  - Typical strips have a pitch of order 0.1 mm
- Pads
  - On single sided detectors. Pads are typically 0.1×0.1 mm^2
- Pixels
  - Smaller than pads. The CCD is a special (but historic) example of a pixel detector e.g. SLD vertex detector at SLAC.

Acknowledgement

- The following slides (up to slide 33) come from a presentation in 2014 from F. Hartman, KIT, Karlsruhe, Germany
- https://indico.cern.ch/event/340296/

The depletion voltage is the minimum voltage at which the bulk of the sensor is fully depleted. The operating voltage is usually chosen to be slightly higher (overdepletion).

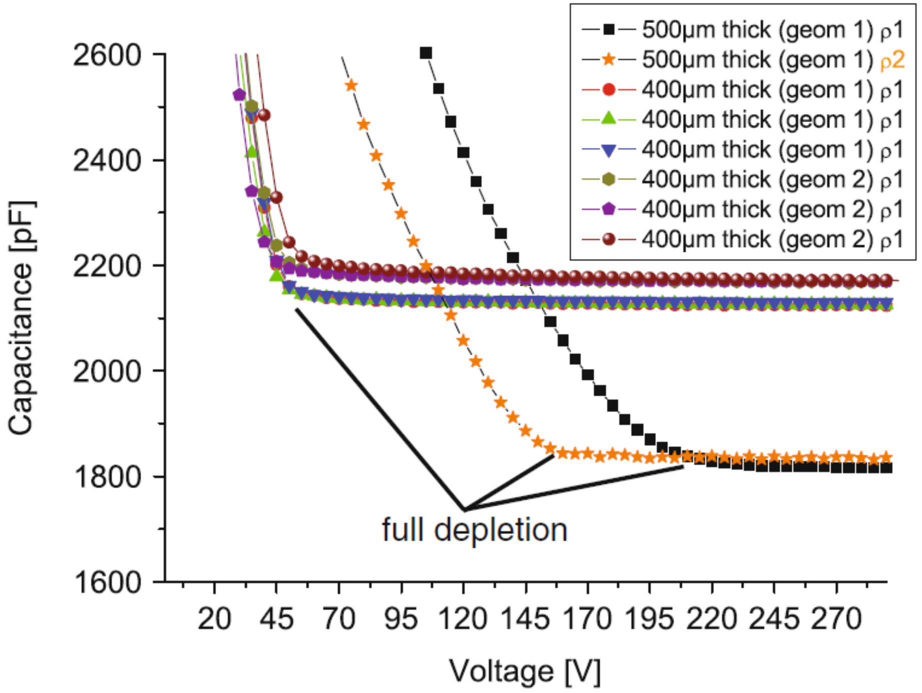
High resistivity material (i.e. low doping) requires low depletion voltage.

$$\boxed{V_{FD} = \frac{D^2}{2\varepsilon\mu\rho}}$$

For a typical Si p-n junction ($N_a \gg N_d \gg n_i$) the detector capacitance given as:

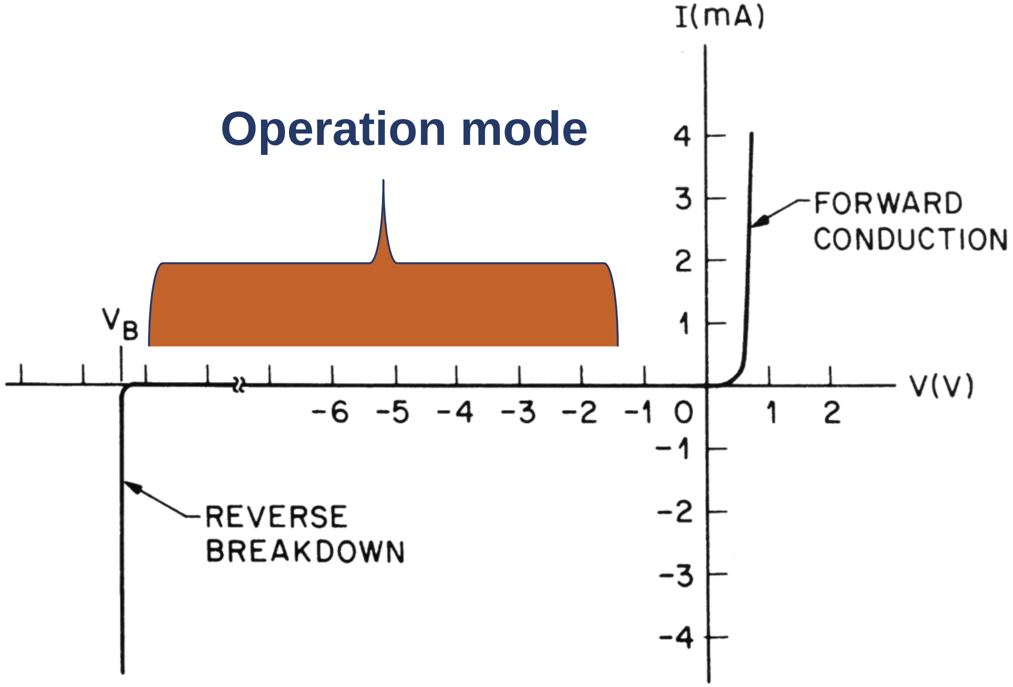
$$\boxed{C = \sqrt{\frac{\varepsilon_0 \varepsilon_r}{2\mu\rho |V|}} \times A}$$

ρ … specific resistivity of the bulk
µ … mobility of majority charge carrier
V … bias voltage
A … detector surface
D … detector thickness



I-V characteristics

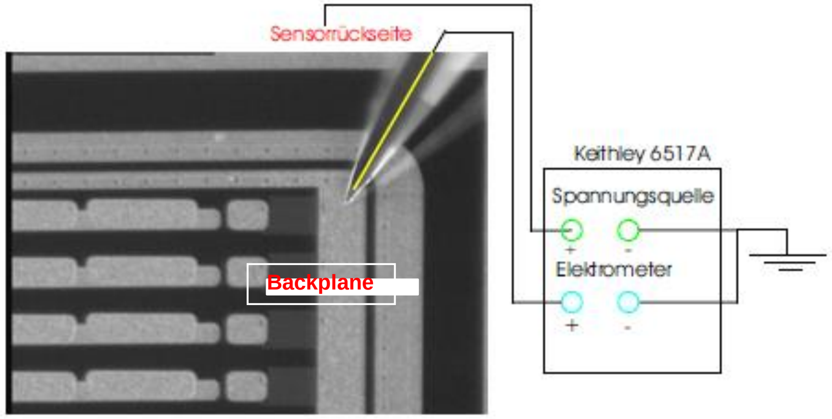
Typical current-voltage of a p-n junction (diode): exponential current increase in forward bias, small saturation in reverse bias.



Operation mode

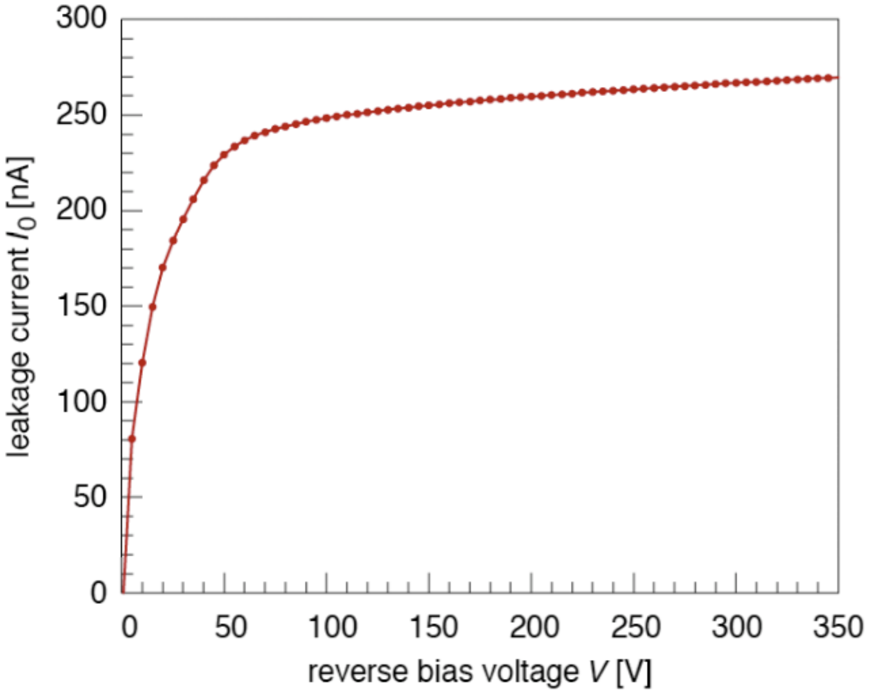
S.M. Sze, *Semiconductor Devices* , J. Wiley & Sons, 1985

A silicon detector is operated with reverse bias, hence reverse saturation current is relevant (leakage current). This current is dominated by thermally generated e^-h^+ pair. Due to the applied electric field they cannot recombine and are separated. The drift of the e^- and h^+ to the electrodes causes the leakage current.



Voltage source

Amp meter

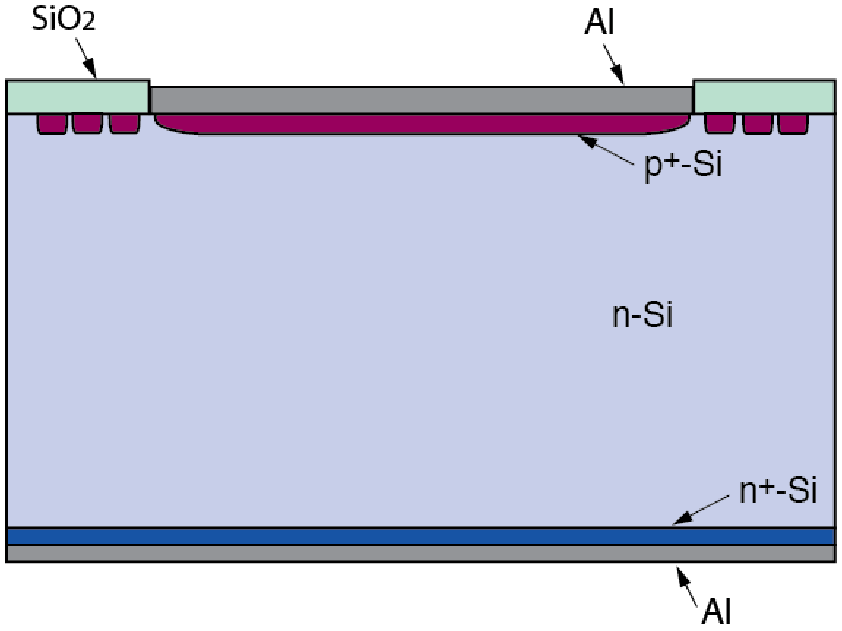


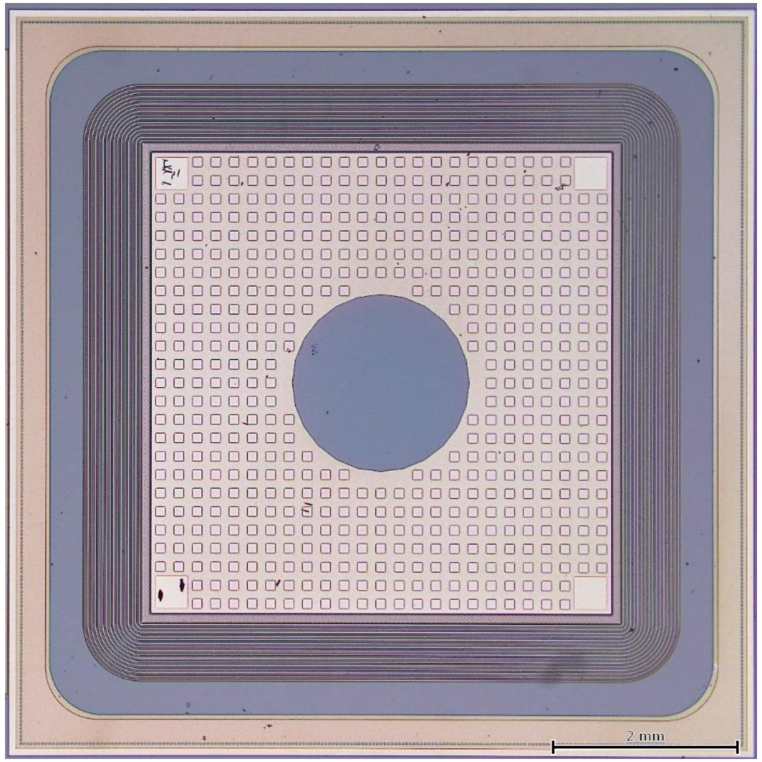
Measured detector leakage current, CMS strip detector (measurement at room temperature):

Detector Structures

The most simple detector is a large surface diode with guard ring(s).

To find out more about “guarding” (and much more) of circuits this is a useful reference: https://uk.tek.com/document/handbook/low-level-measurements-handbook

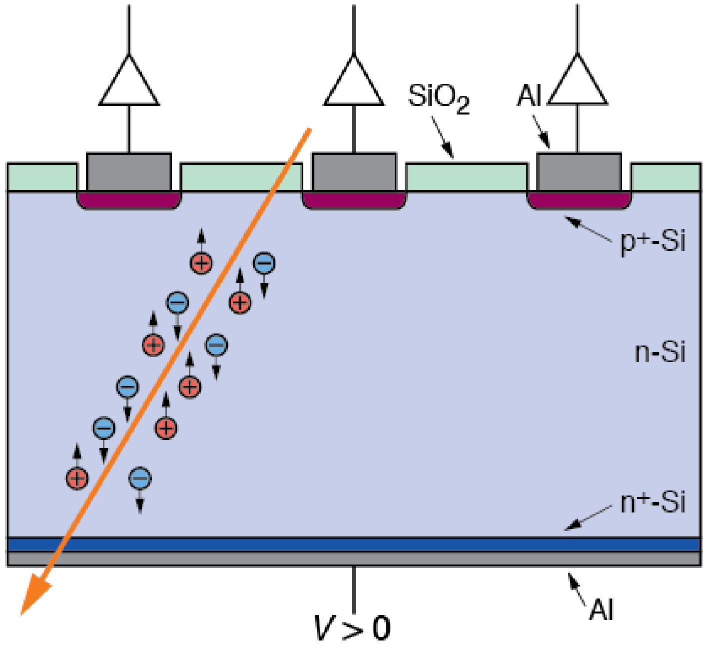




Traversing charged particles create e^-h^+ pairs in the depletion zone (about 30.000 pairs in standard detector thickness). These charges drift to the electrodes. The drift (current) creates the signal which is amplified by an amplifier connected to each strip. From the signals on the individual strips the position of the through going particle is deduced.

A typical n-type Si strip detector:

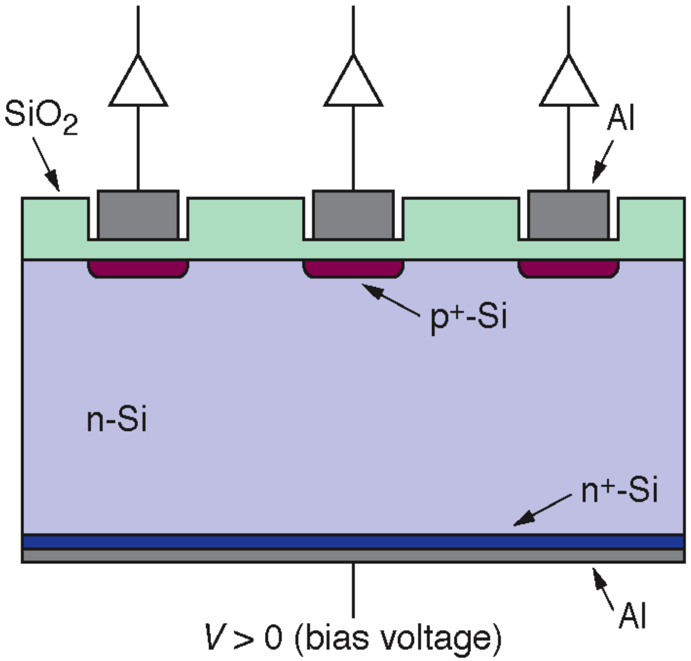
- p^+n junction:
  $N_a \approx 10^{15}$ cm^{-3}, $N_d \approx 1 - 5 \cdot 10^{12}$ cm^{-3}
- n-type bulk: $\rho > 2$ kΩcm
  thickness 300 µm
- Operating voltage < 200 V.
- n^+ layer on backplane to improve ohmic contact
- Aluminum metallization



AC coupling blocks leakage current from the amplifier.

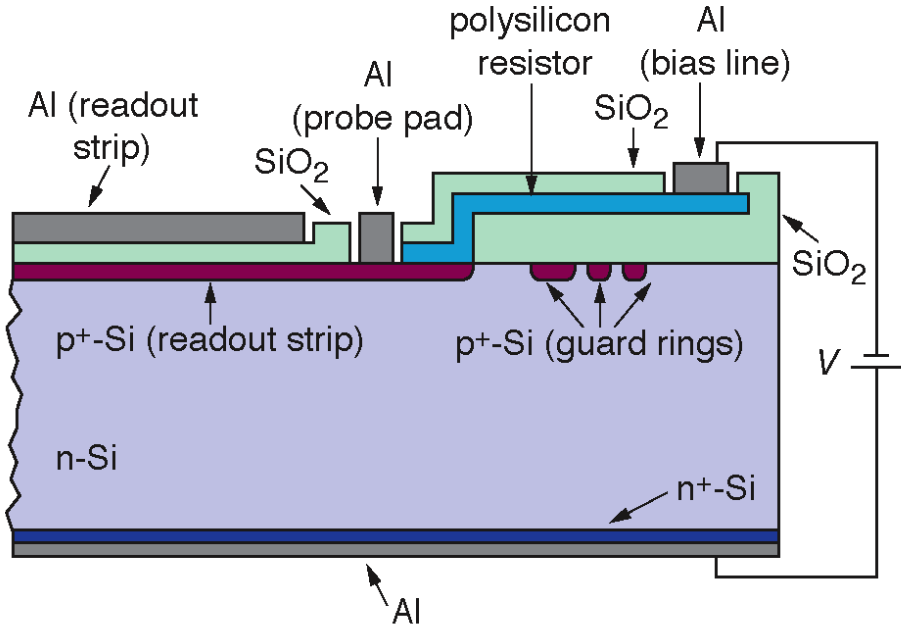
- Integration of coupling capacitances in standard planar process.
- Deposition of SiO_2 with a thickness of 100–200 nm between p+ and aluminum strip
- Depending on oxide thickness and strip width the capacitances are in the range of 8–32 pF/cm.
- Problems are shorts through the dielectric (pinholes). Usually avoided by a second layer of Si_3N_4.

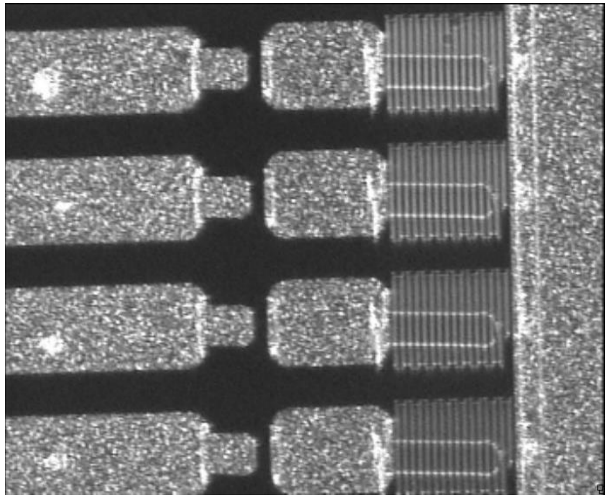
AC coupled strip detector:



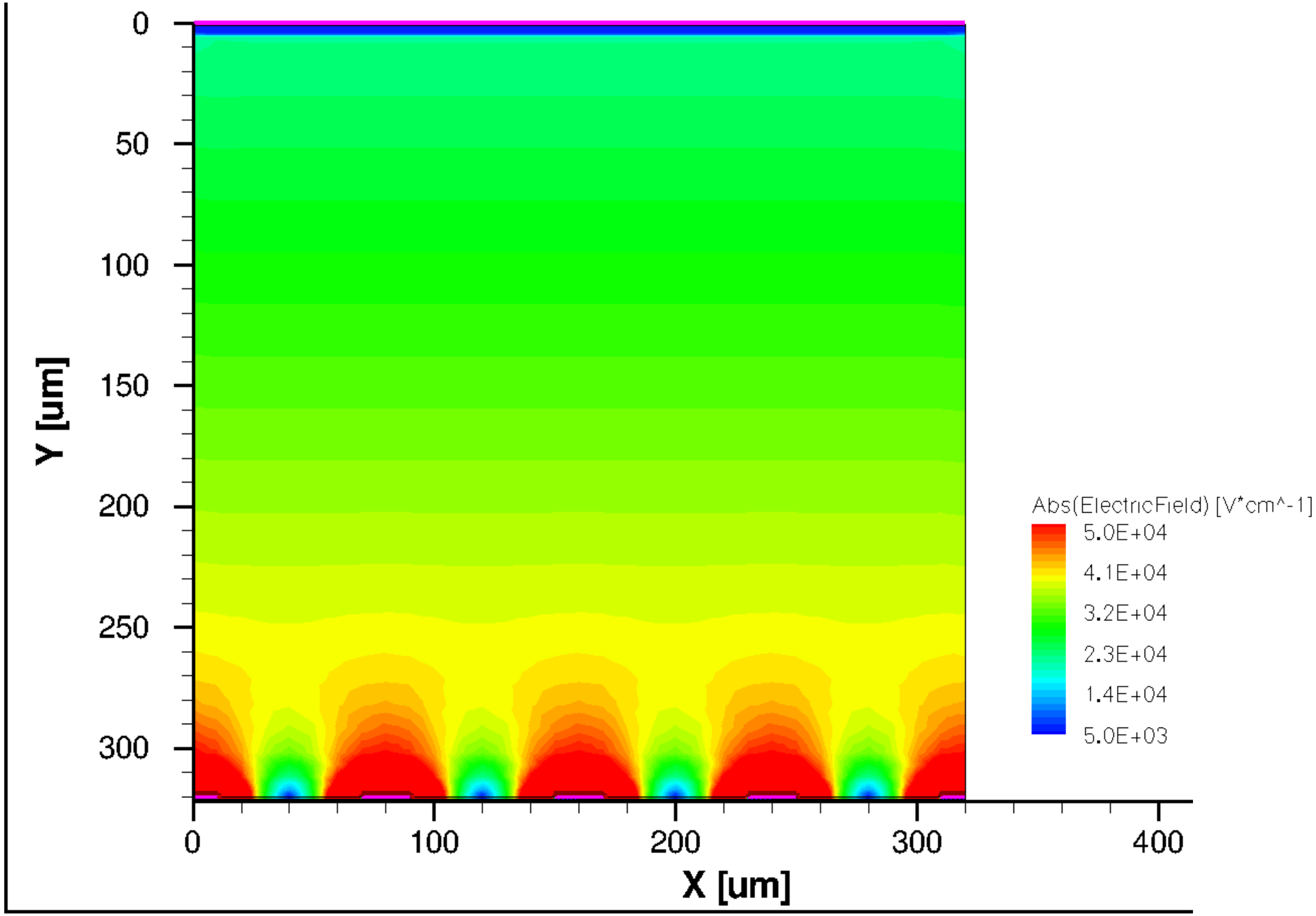
Several methods to connect the bias voltage: polysilicon resistor, punch through bias, FOXFET bias.

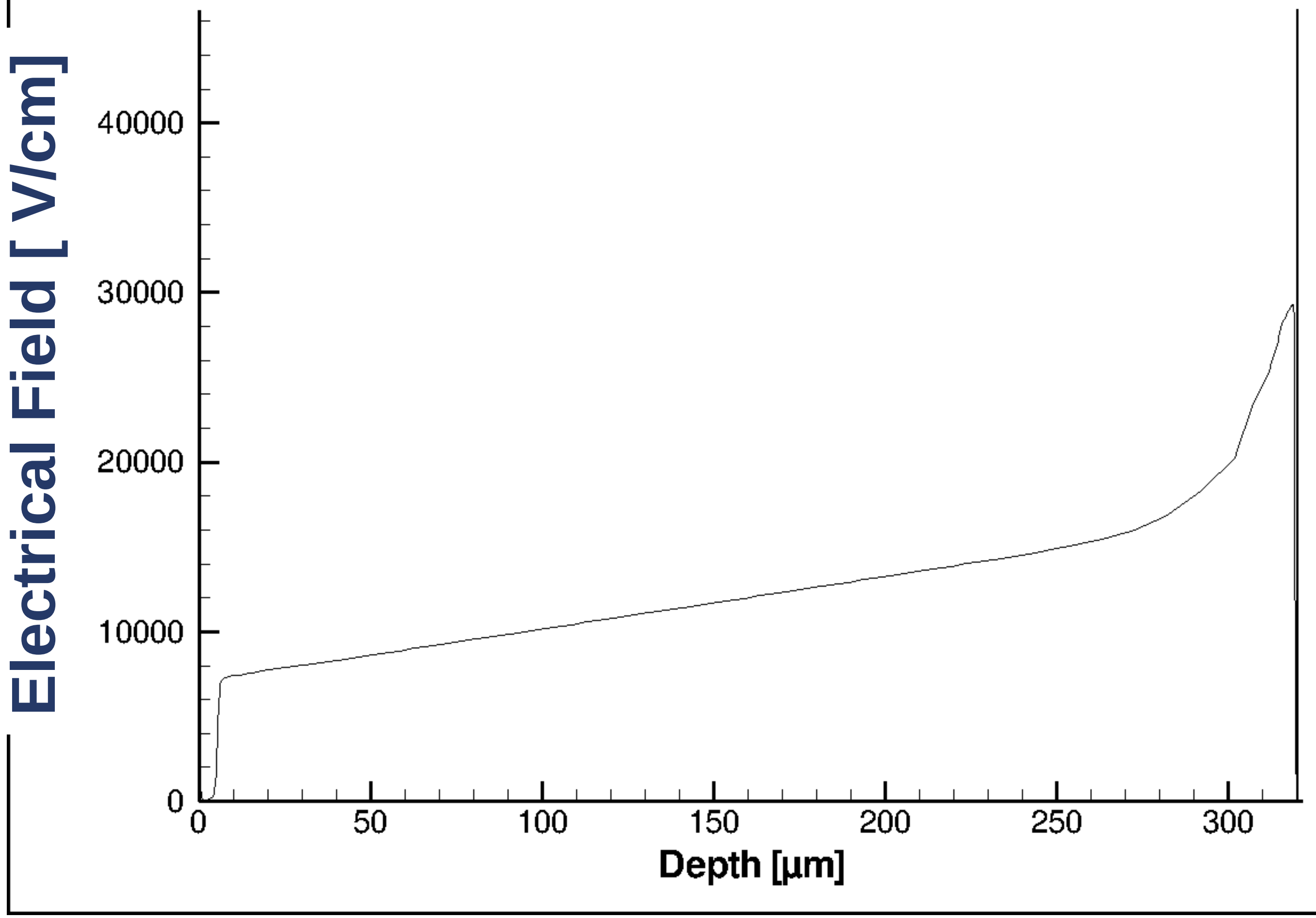
- Deposition of polycristalline silicon between p^+ implants and a common bias line.
- Sheet resistance of up to $R_s \approx 250\ \mathrm{k}\Omega/\square$. Depending on width and length a resistor of up to $R \approx 20\ \mathrm{M}\Omega$ is achieved ($R = R_s \cdot length/width$).
- To achieve high resistor values winding poly structures are deposited.

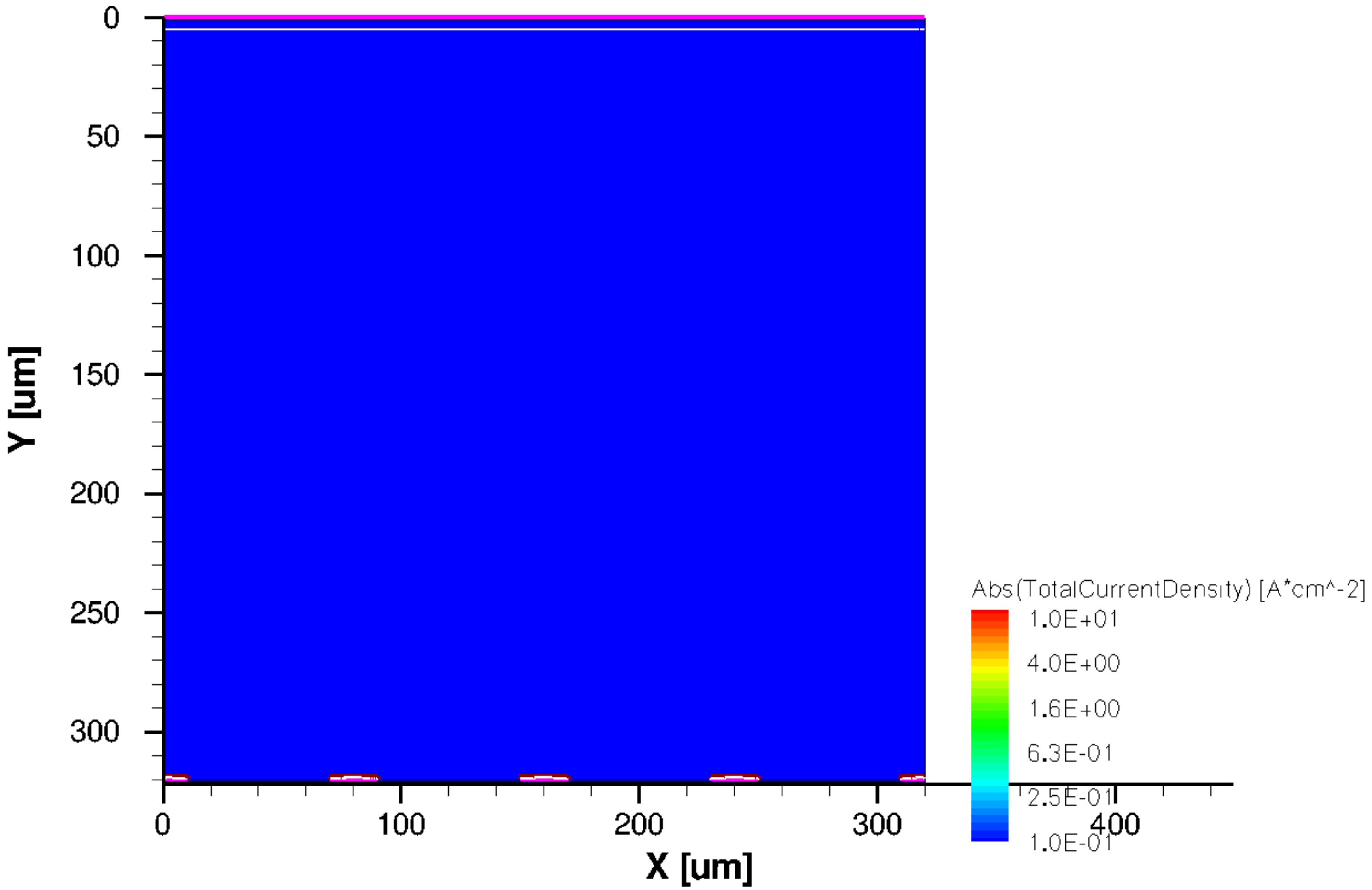




Cut through an AC coupled strip detector with integrated poly resistors:

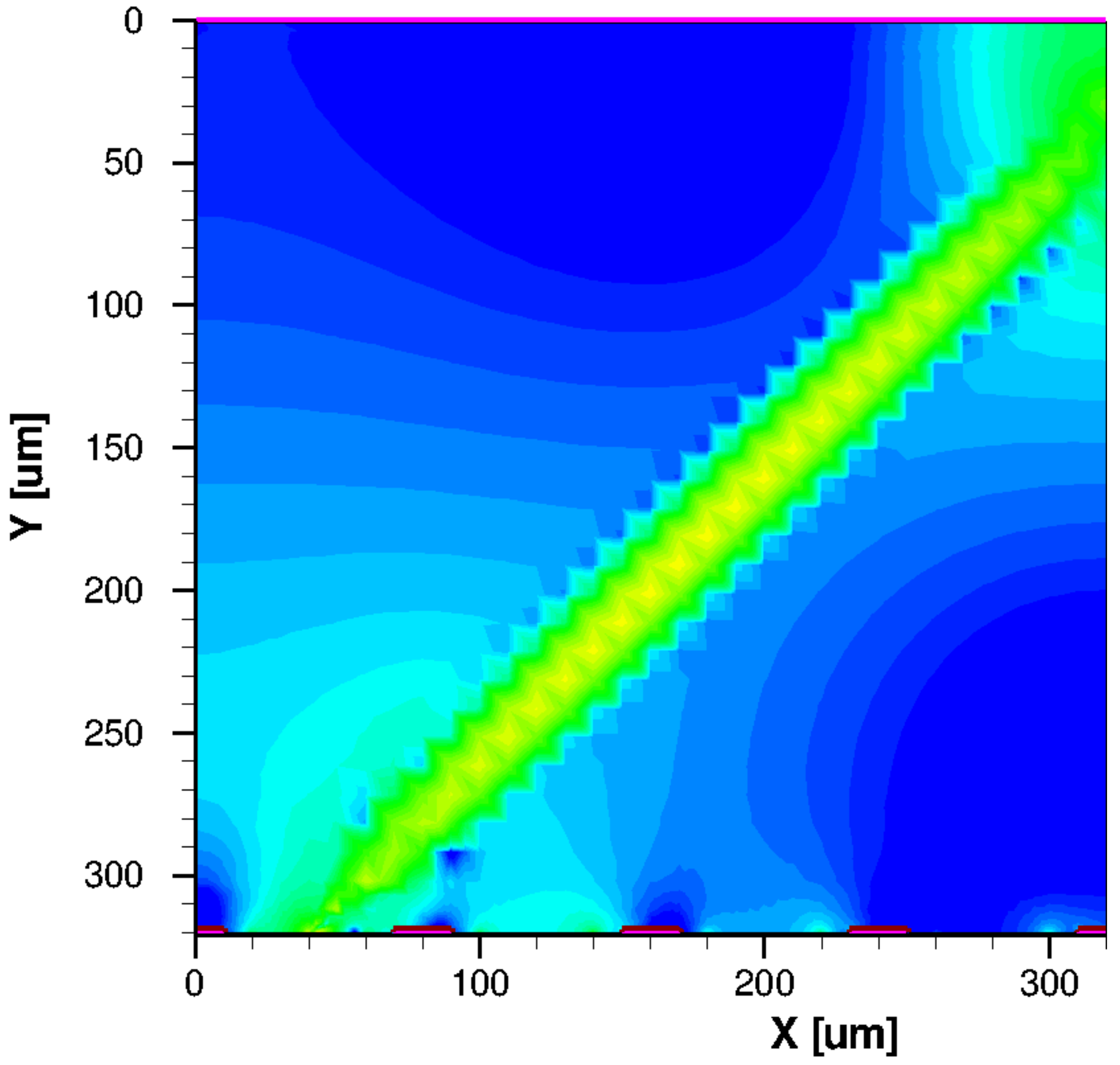

0
50
100
150
200
250
300
Y [um]
0
100
200
300
400
X [um]
Abs(ElectricField) [V*cm^-1]
5.0E+04
4.1E+04
3.2E+04
2.3E+04
1.4E+04
5.0E+03


Electrical Field [V/cm]
40000
30000
20000
10000
0
0
50
100
150
200
250
300
Depth [μm]



Simulation Thomas.Eichhorn@kit.edu

Simulated Current Density
Ionizing particle with 45^o angle t=1 ns



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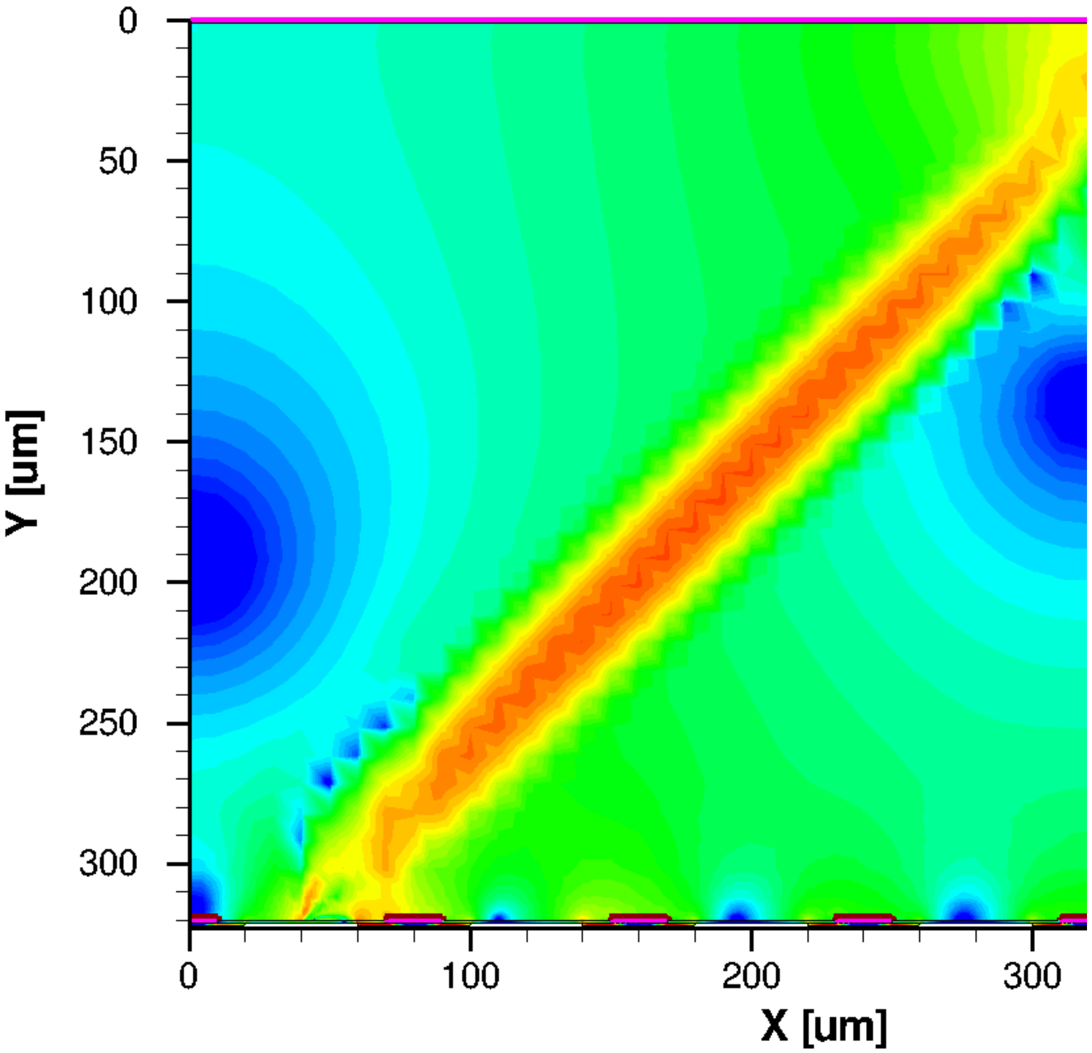

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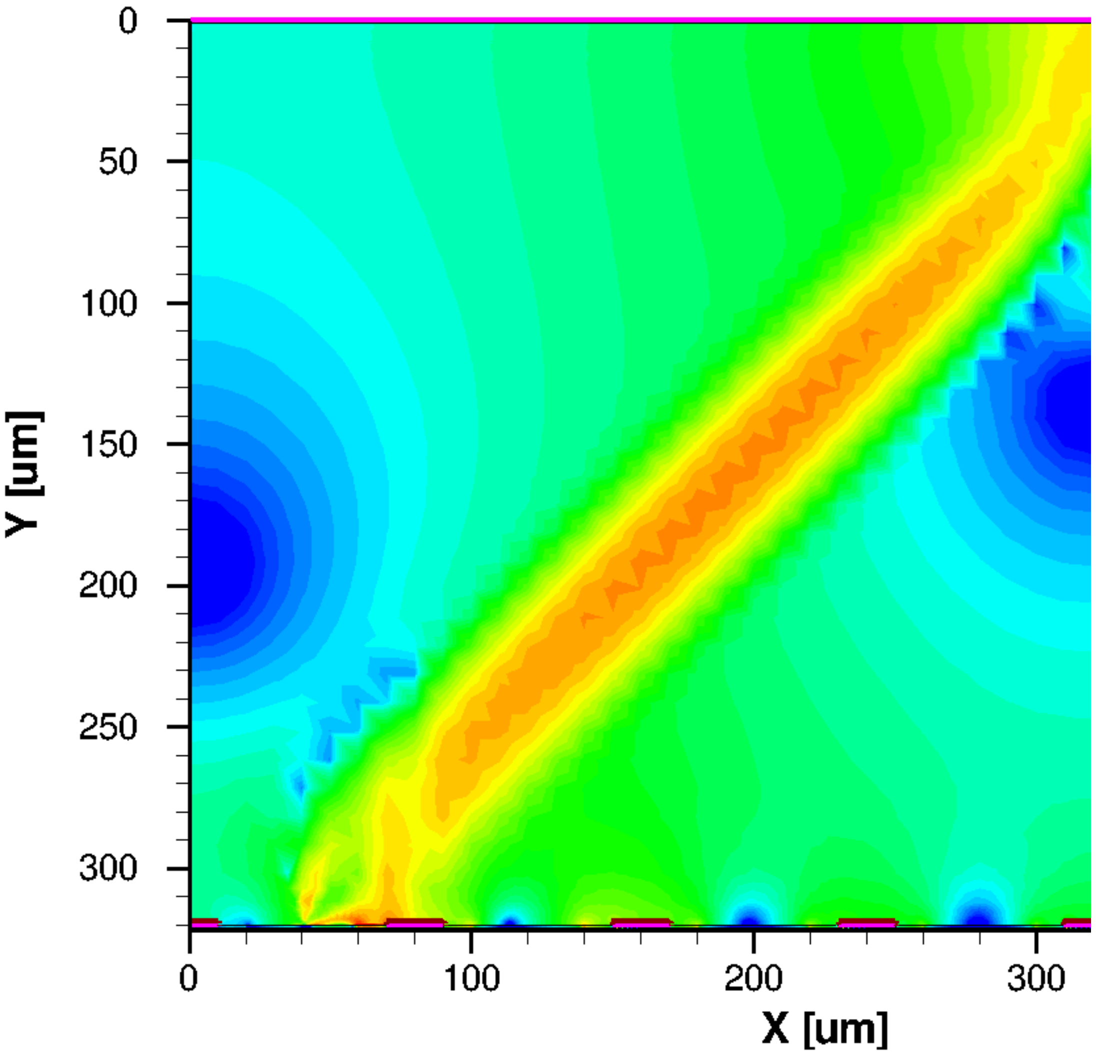

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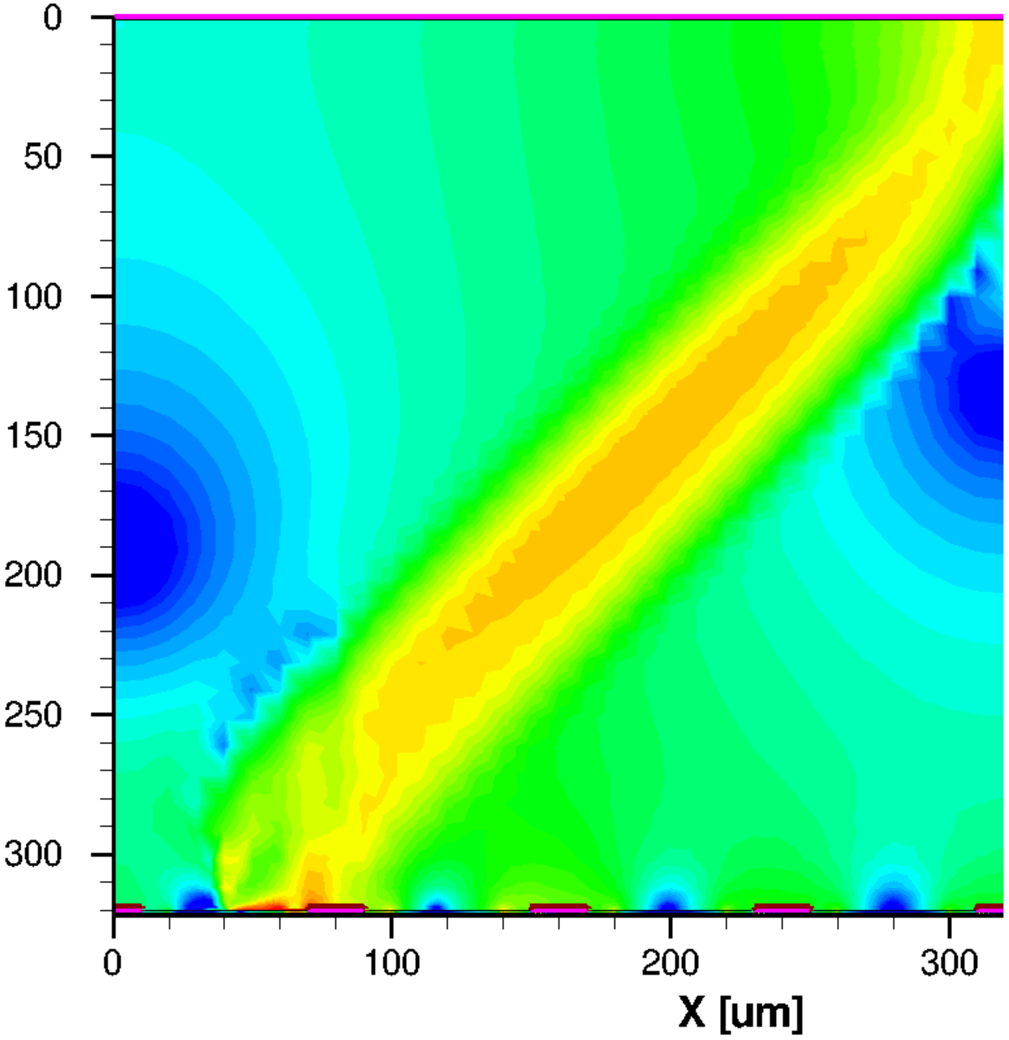

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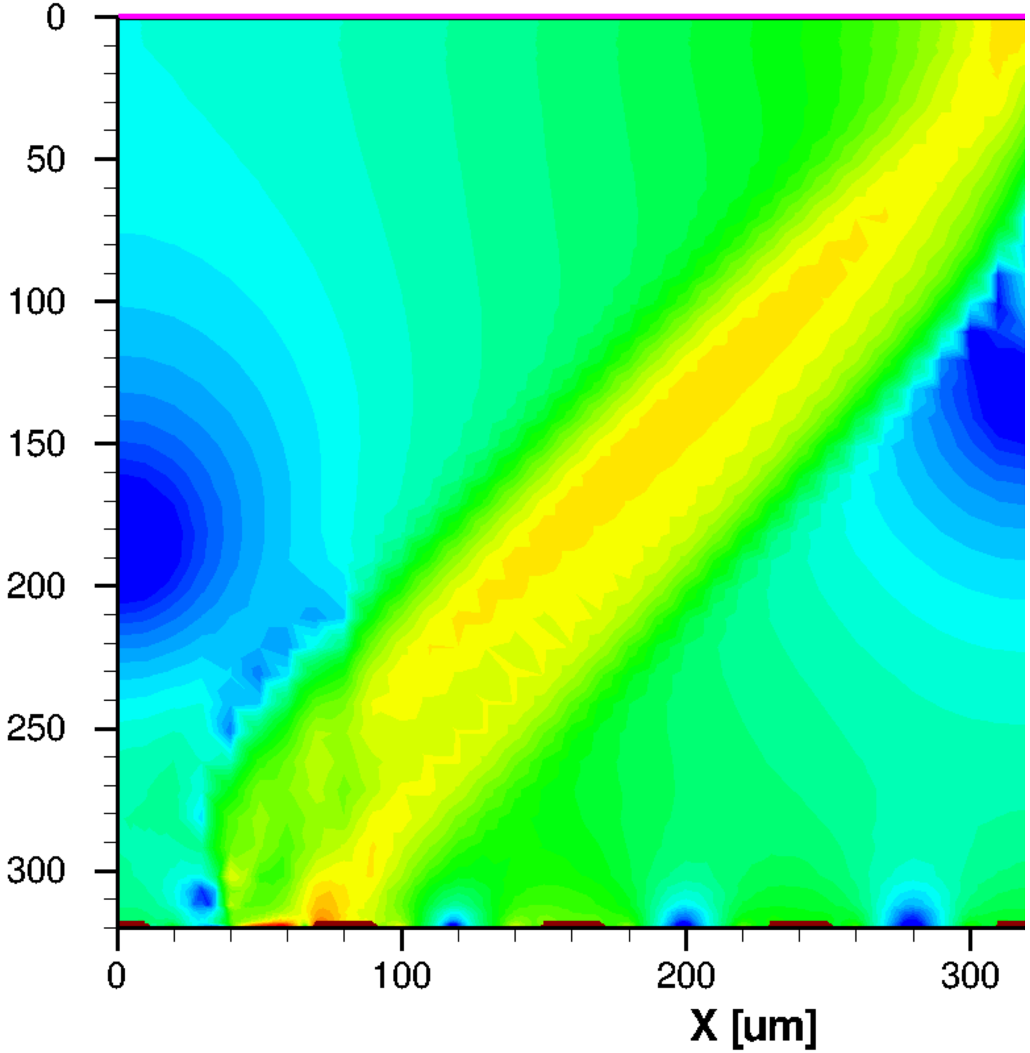

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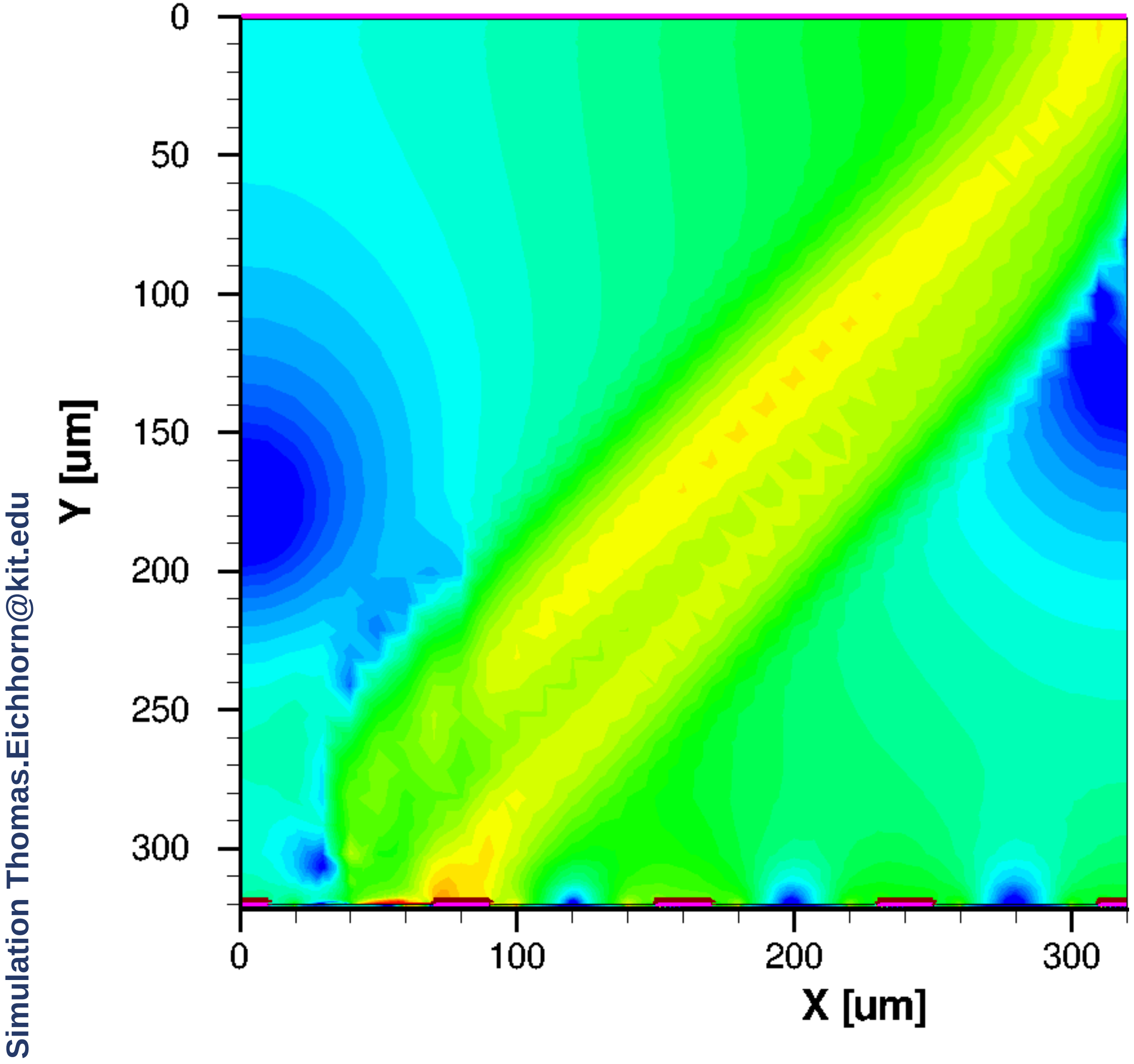

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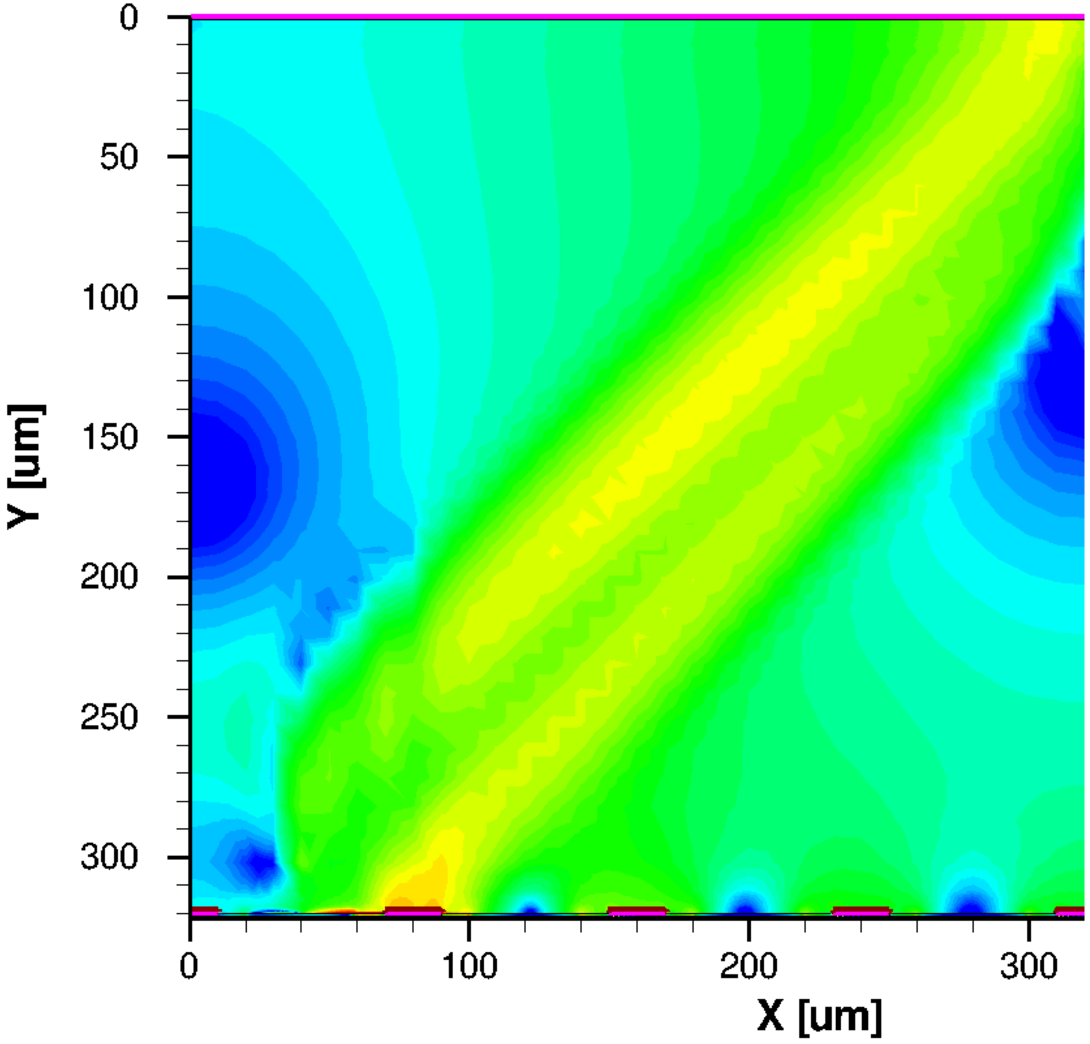

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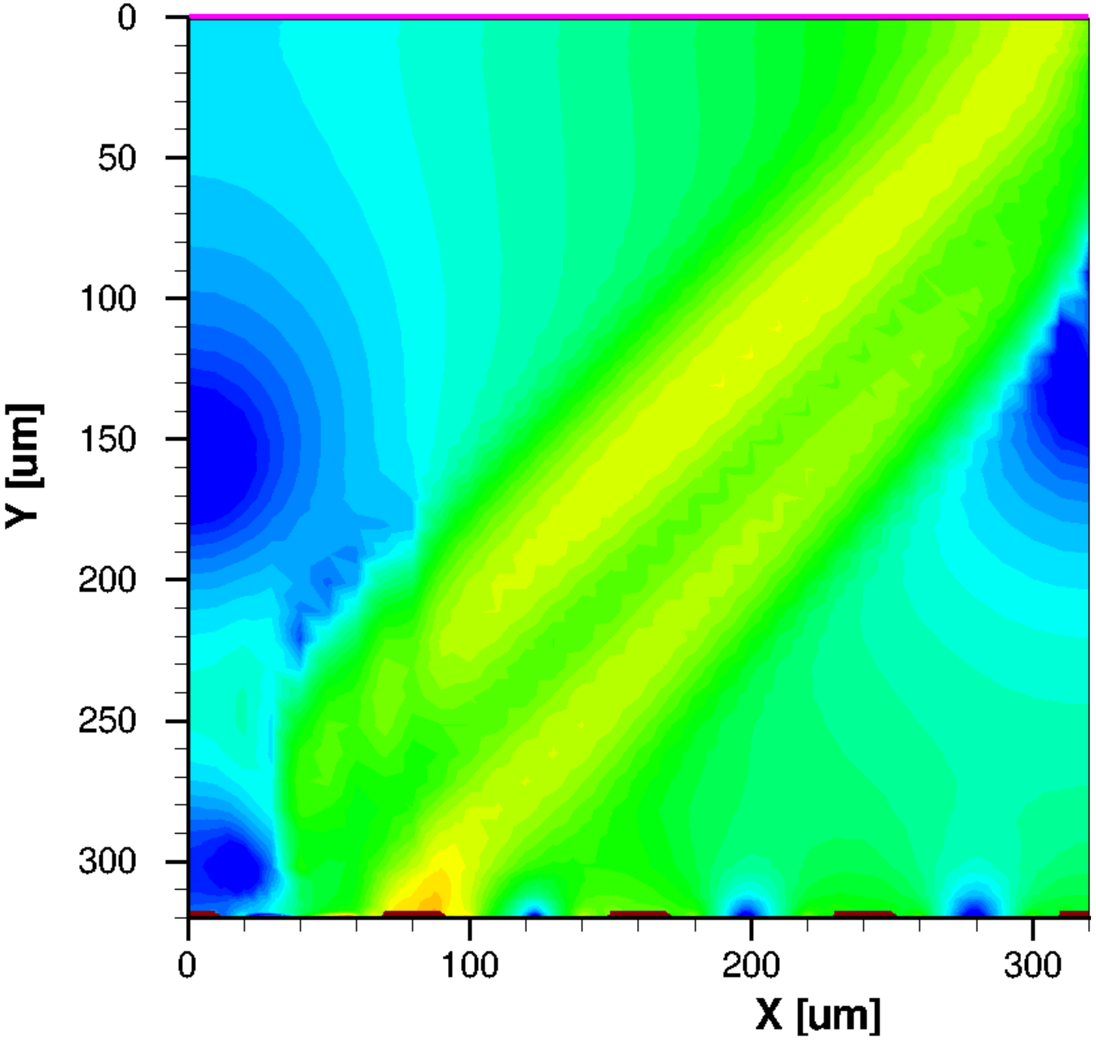

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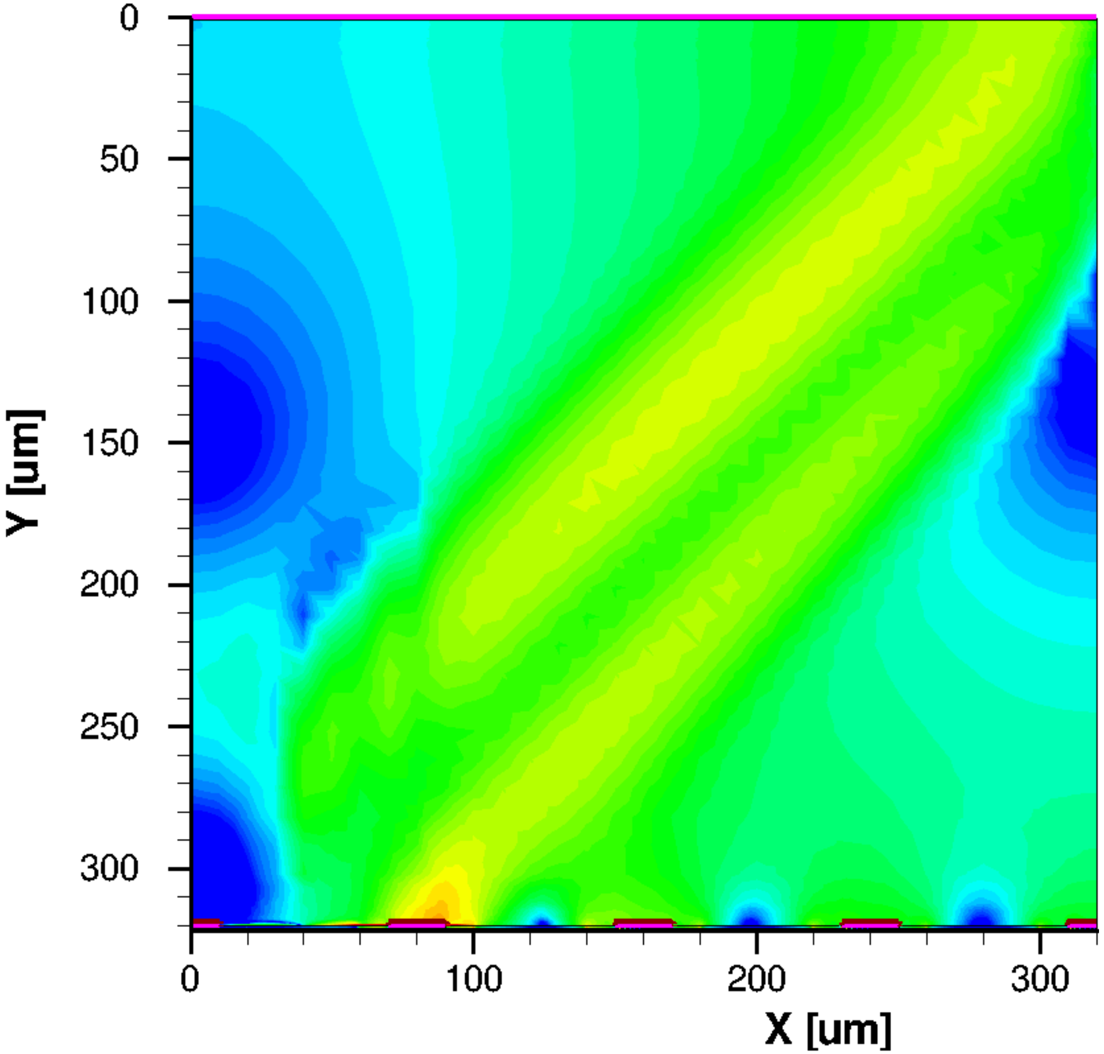

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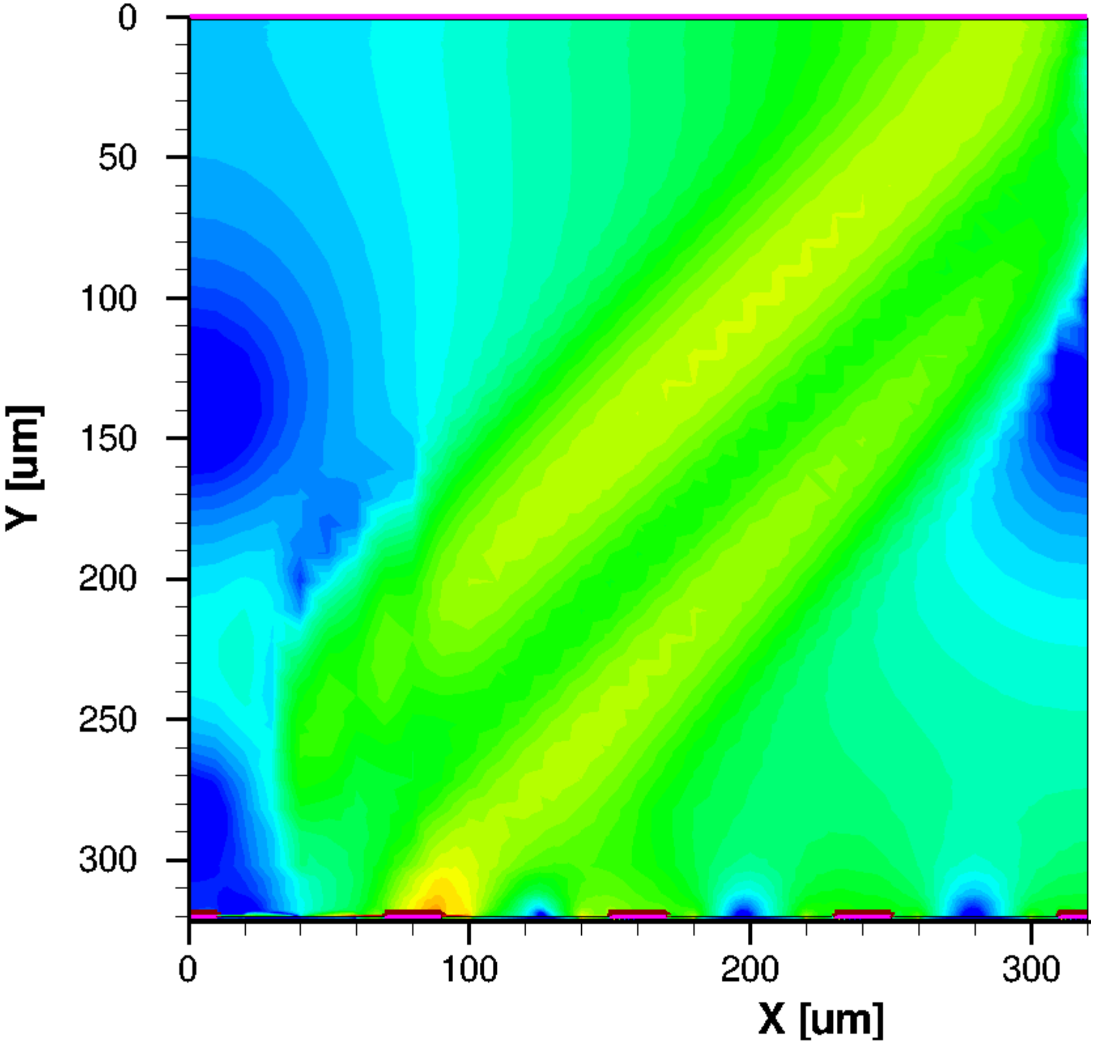

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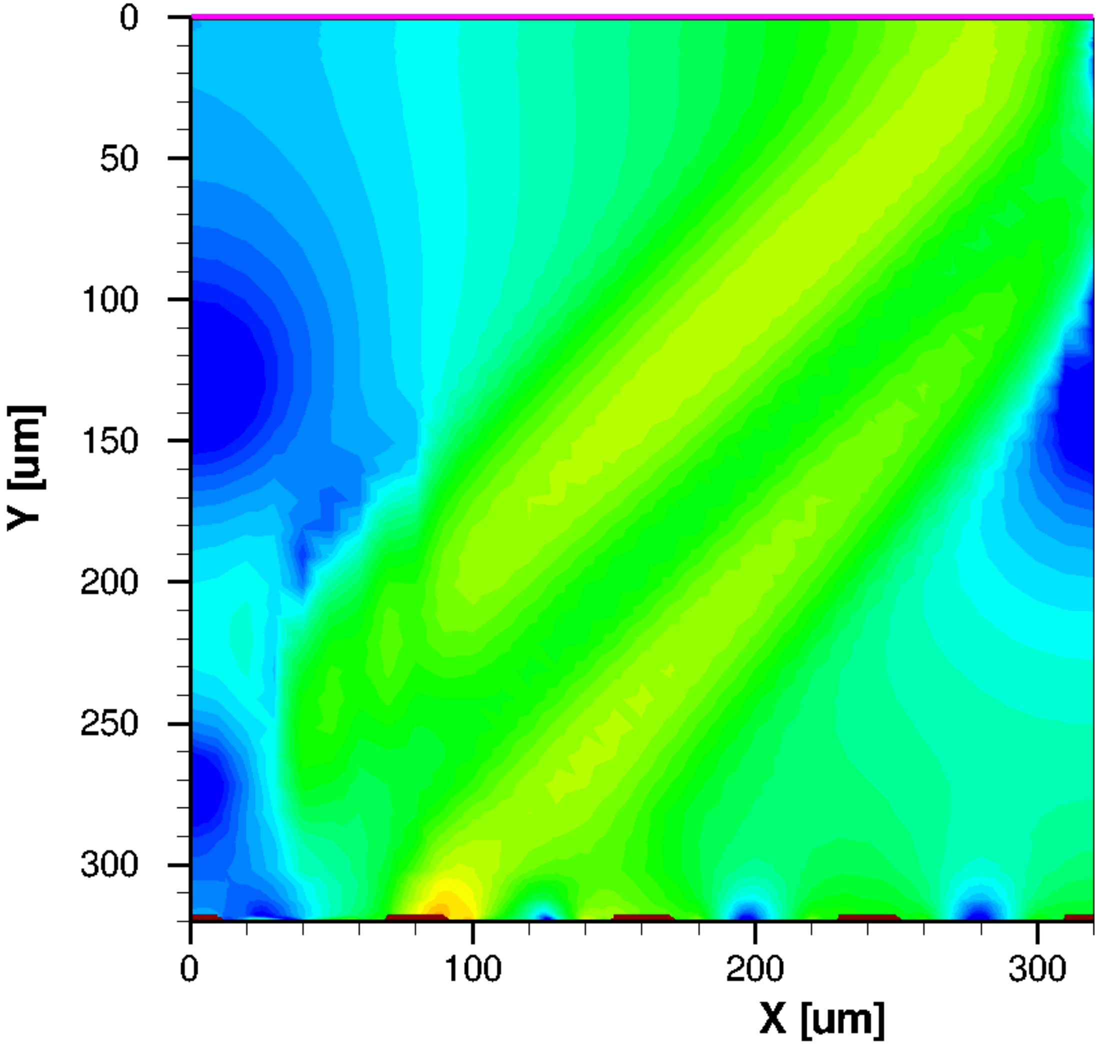

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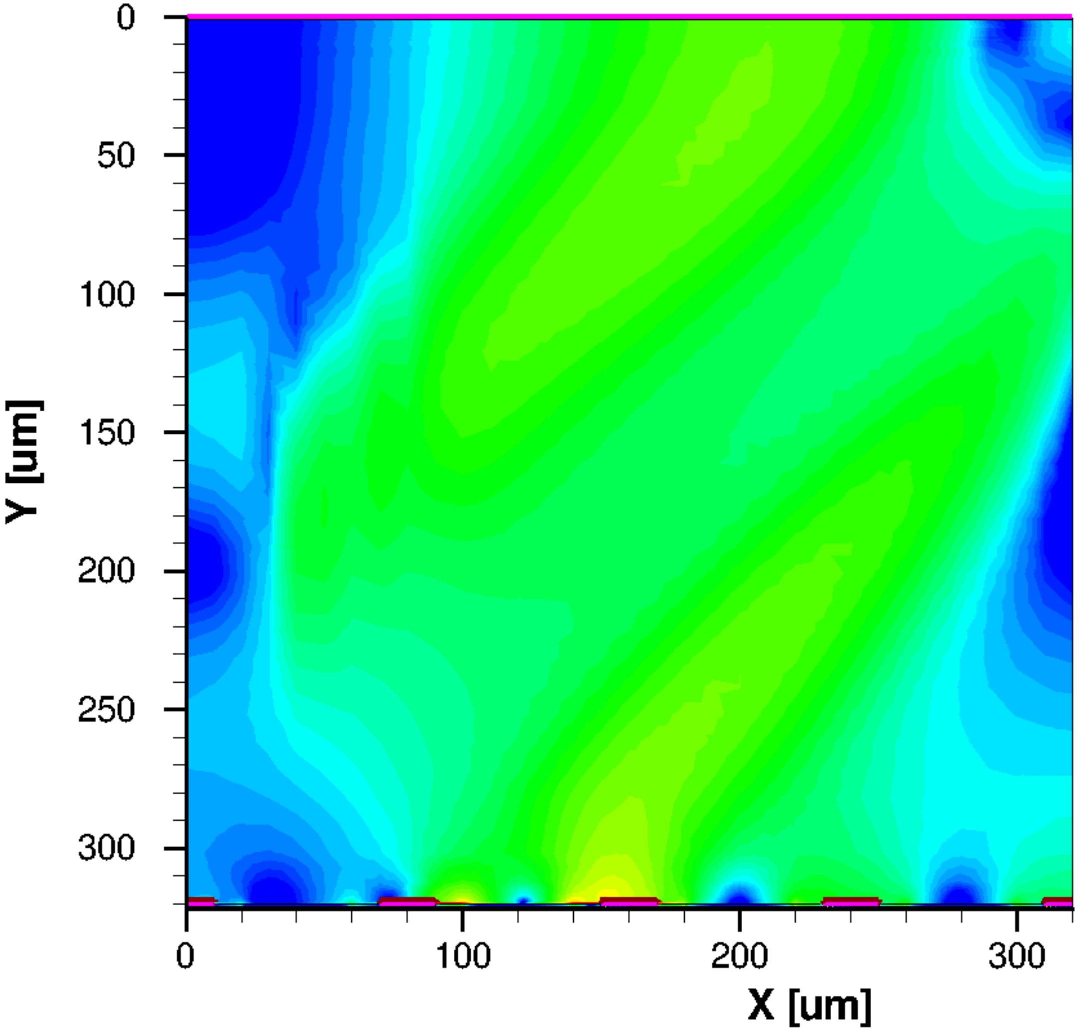

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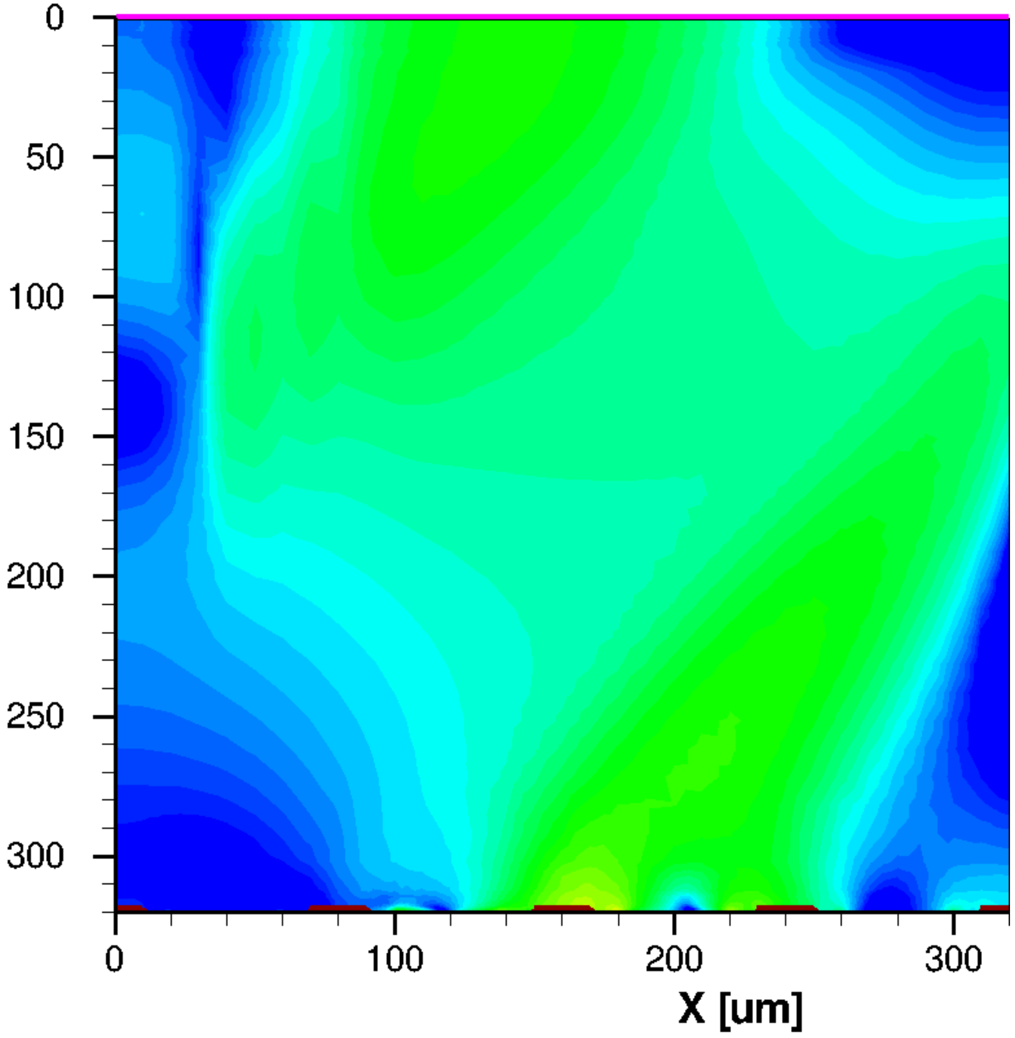

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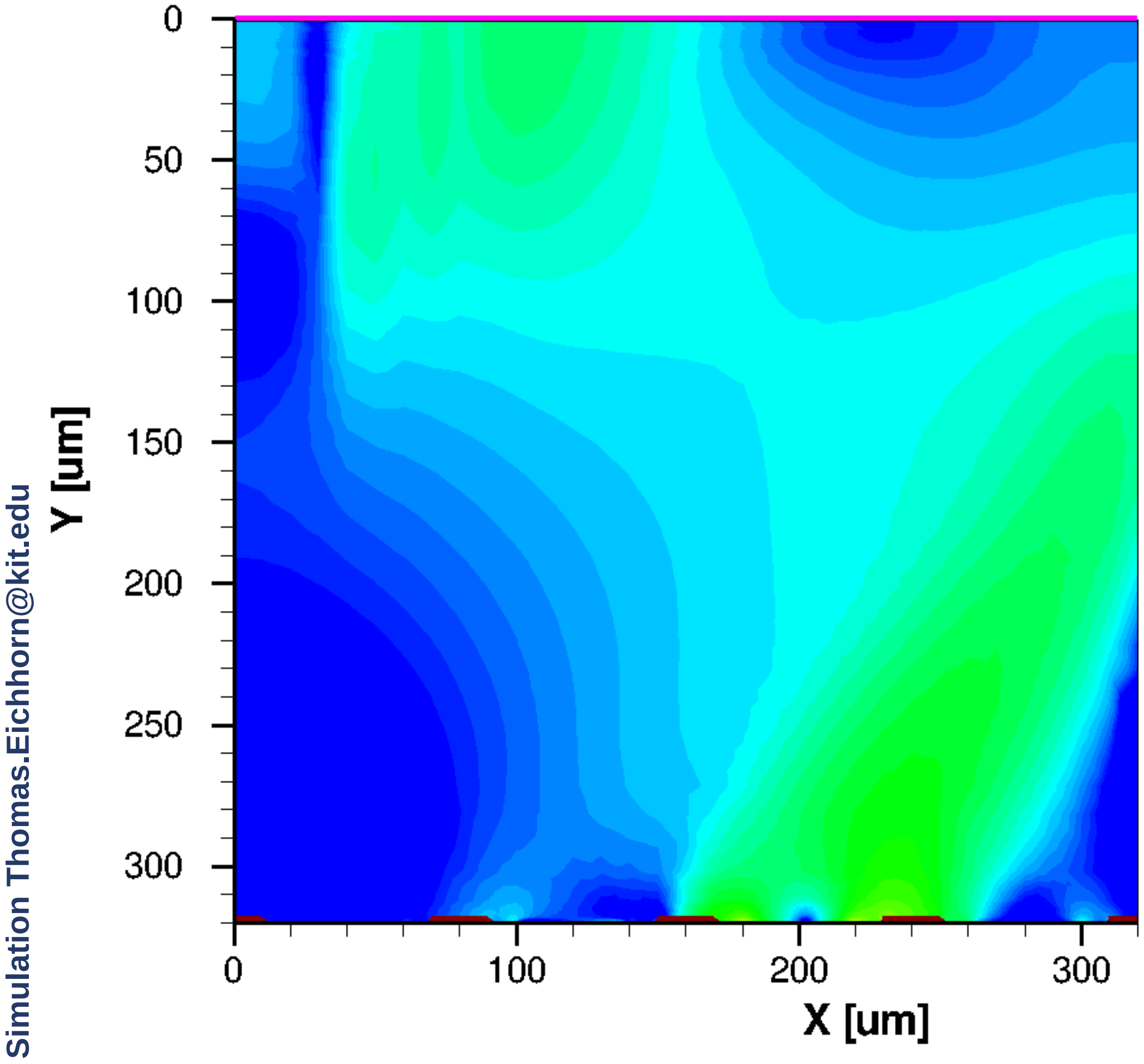
Simulation Thomas.Eichhorn@kit.edu
Y [um]
0
50
100
150
200
250
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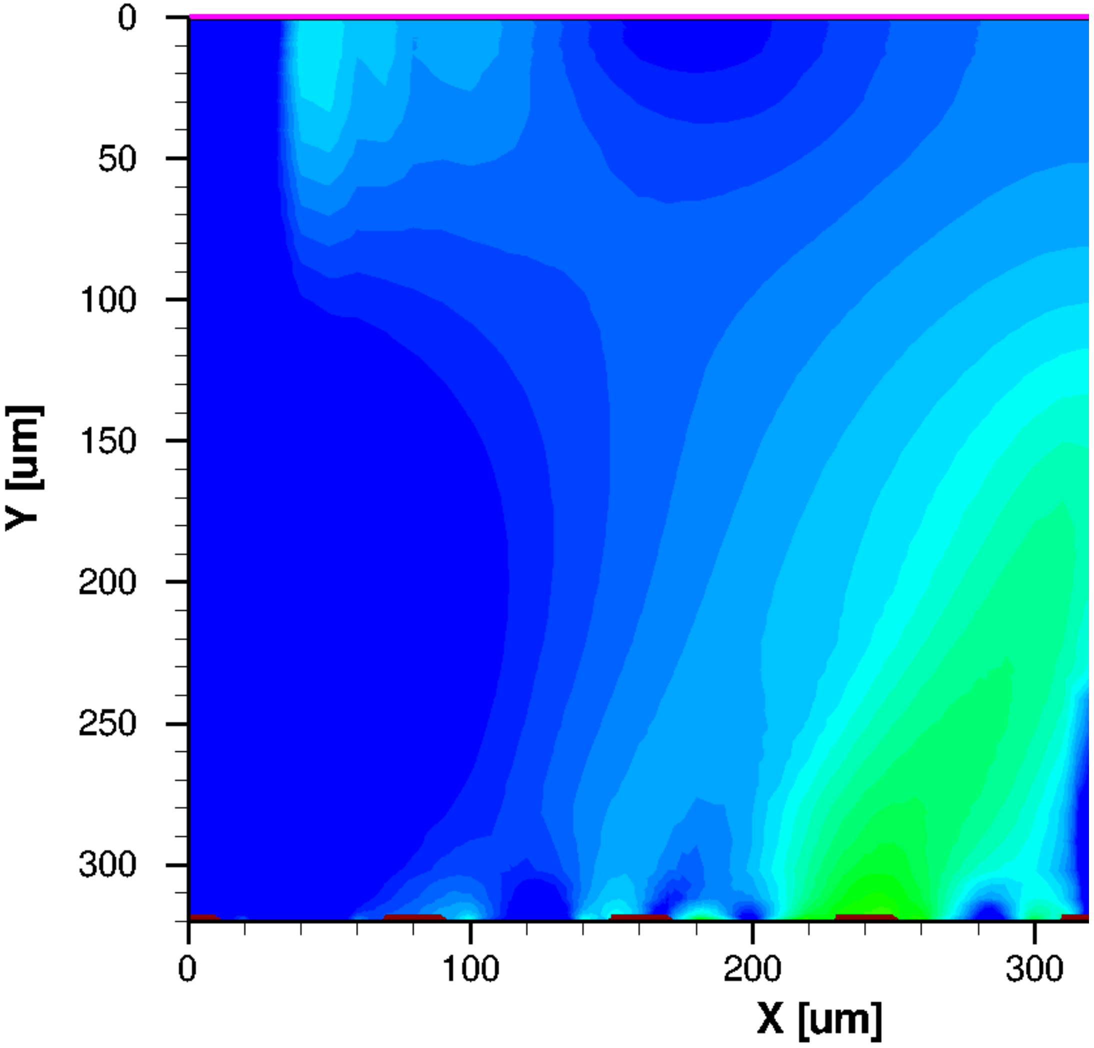
X [um]
0
100
200
300



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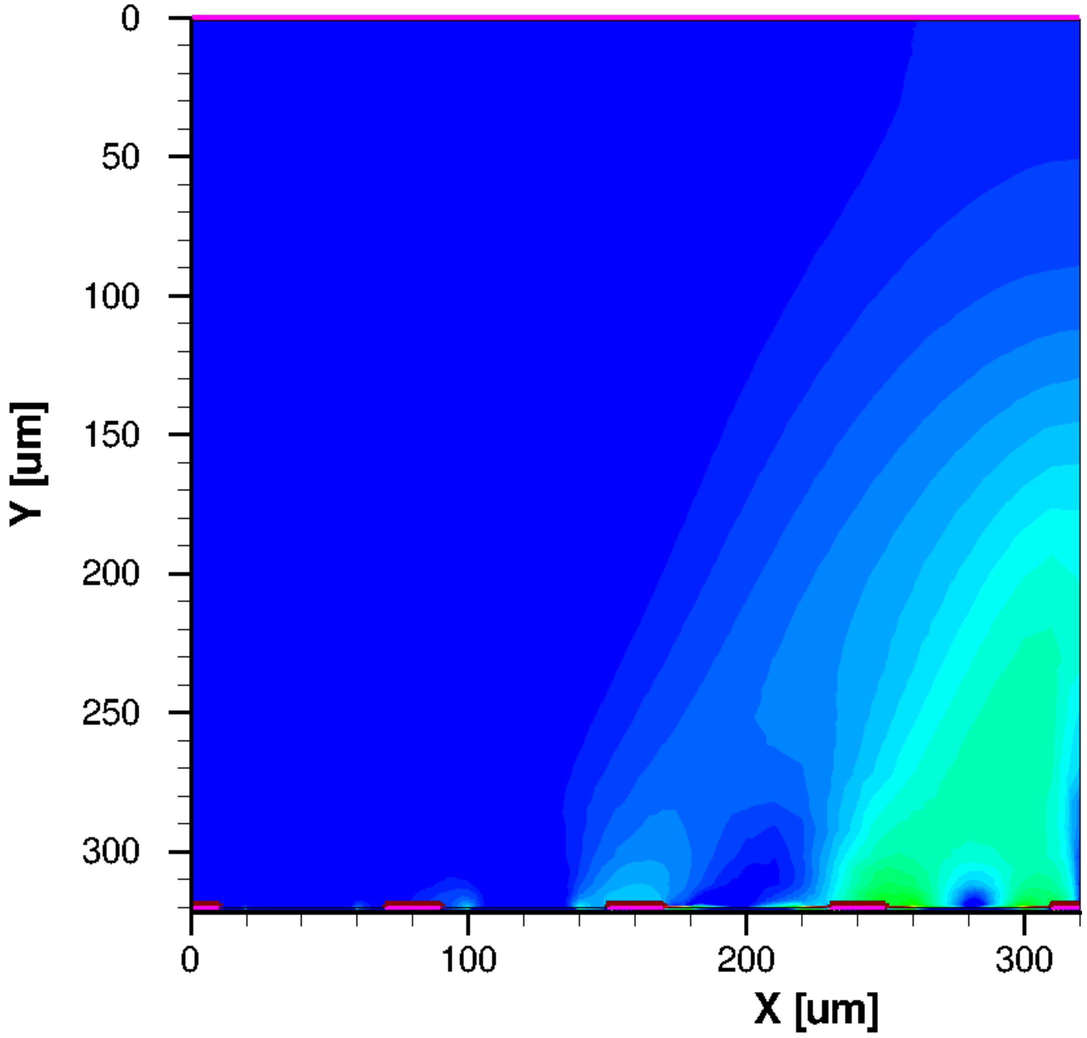
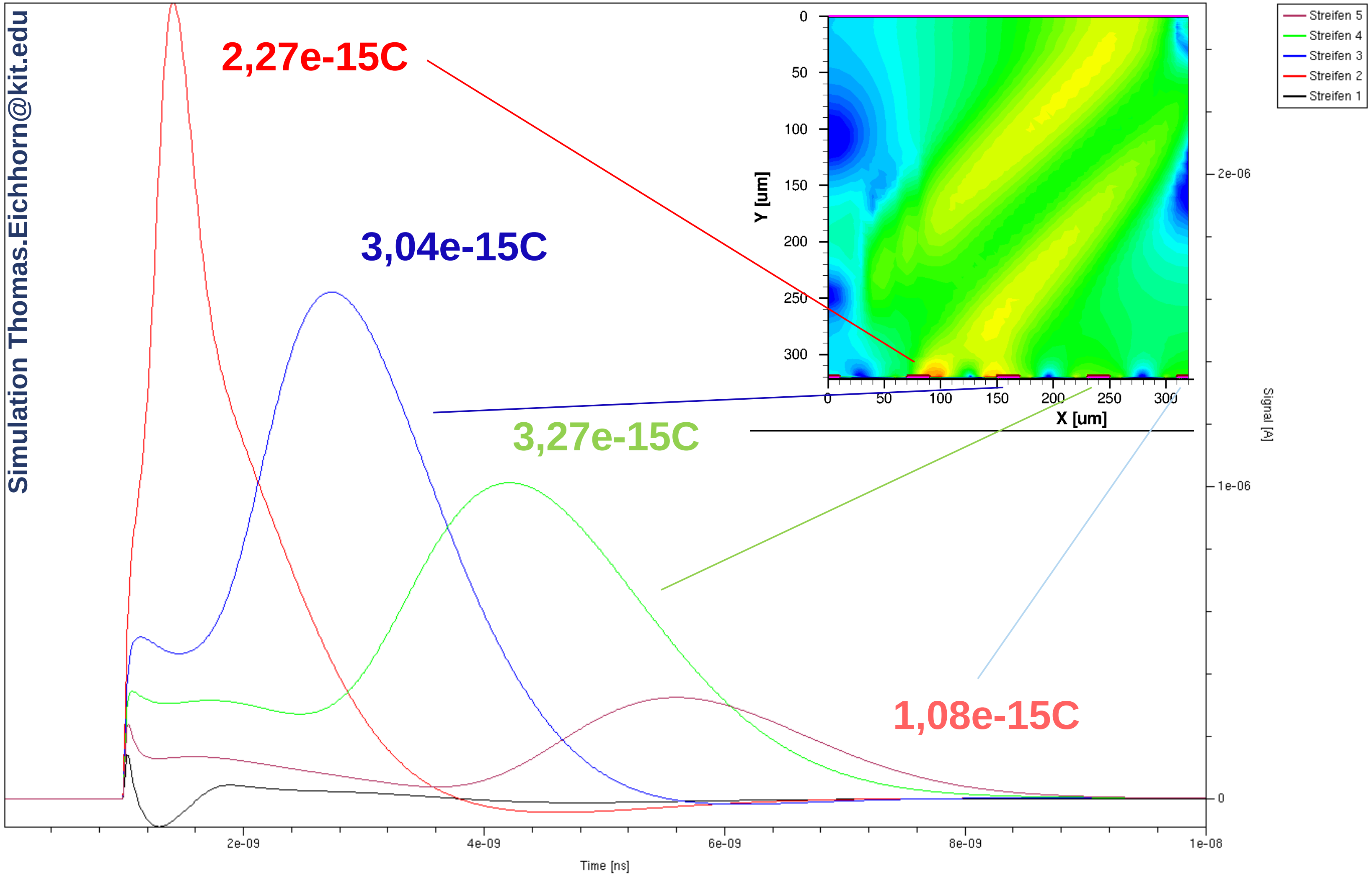


Simulation Thomas.Eichhorn@kit.edu

2.2. Hole Charge Collection (strip & time resolved)



Simulation Thomas.Eichhorn@kit.edu

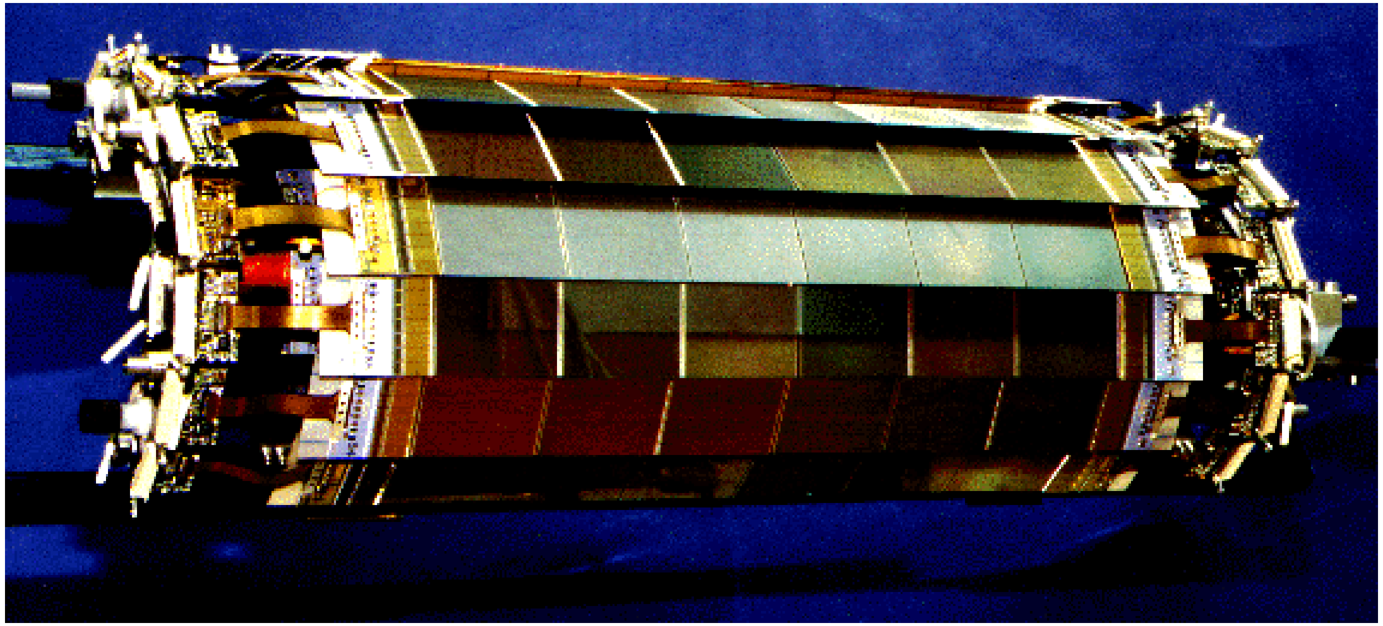
2,27e-15C

3,04e-15C

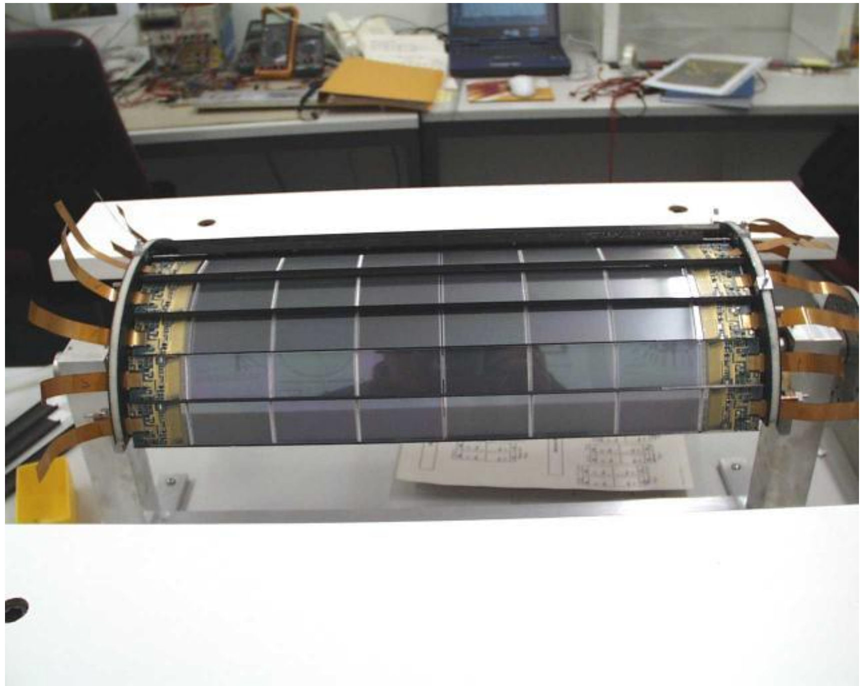
3,27e-15C

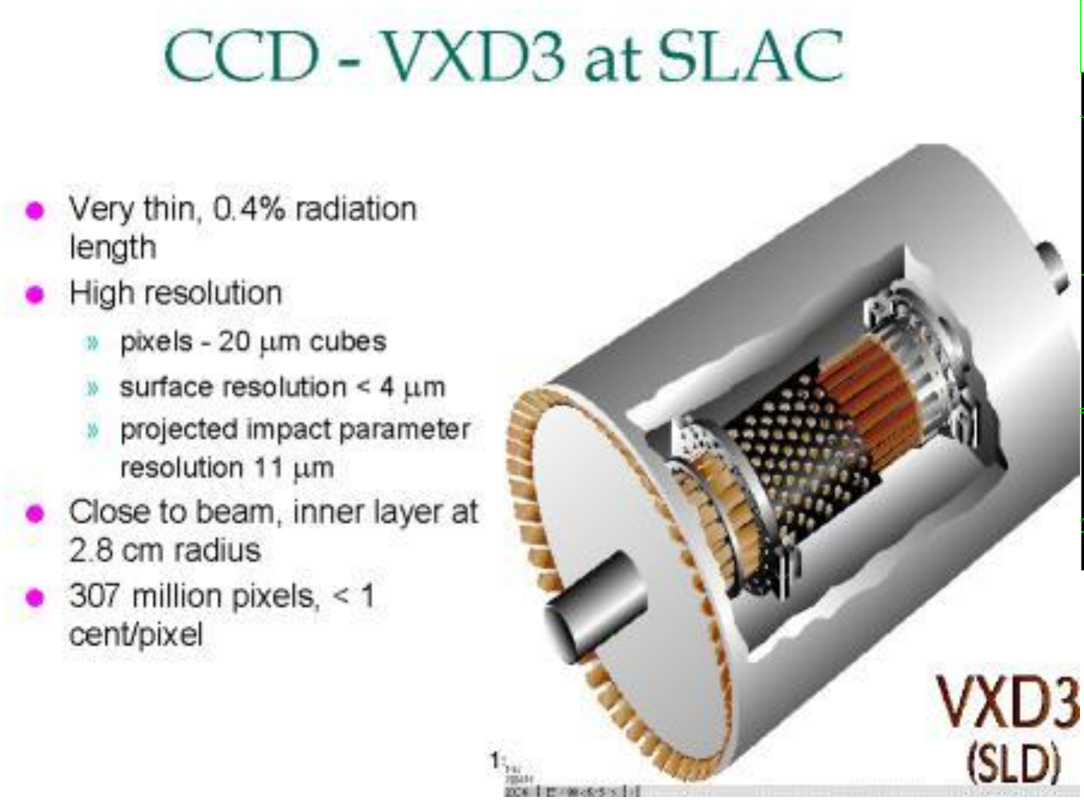
1,08e-15C

- ALEPH:The silicon vertex detector, 1995 version



Aleph WWW site publicity picture

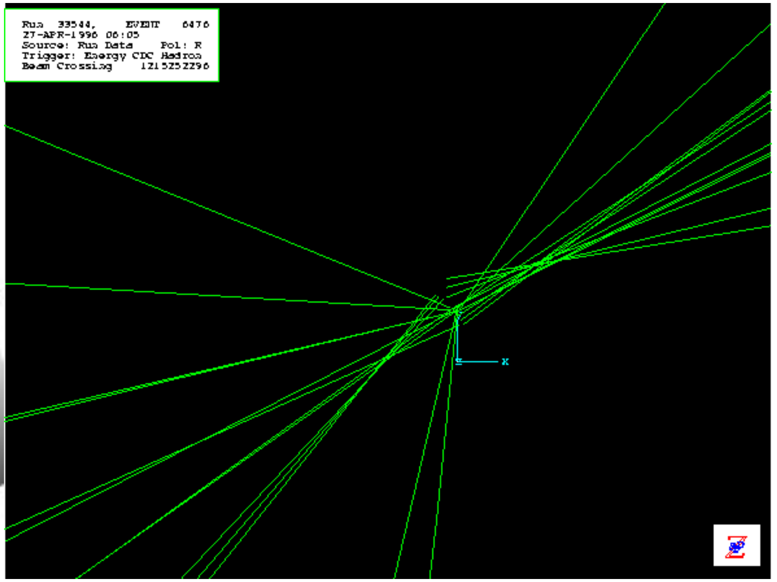




CCD - VXD3 at SLAC

- Very thin, 0.4% radiation length
- High resolution
  - pixels - 20 µm cubes
  - surface resolution < 4 µm
  - projected impact parameter resolution 11 µm
- Close to beam, inner layer at 2.8 cm radius
- 307 million pixels, < 1 cent/pixel

VXD3
(SLD)

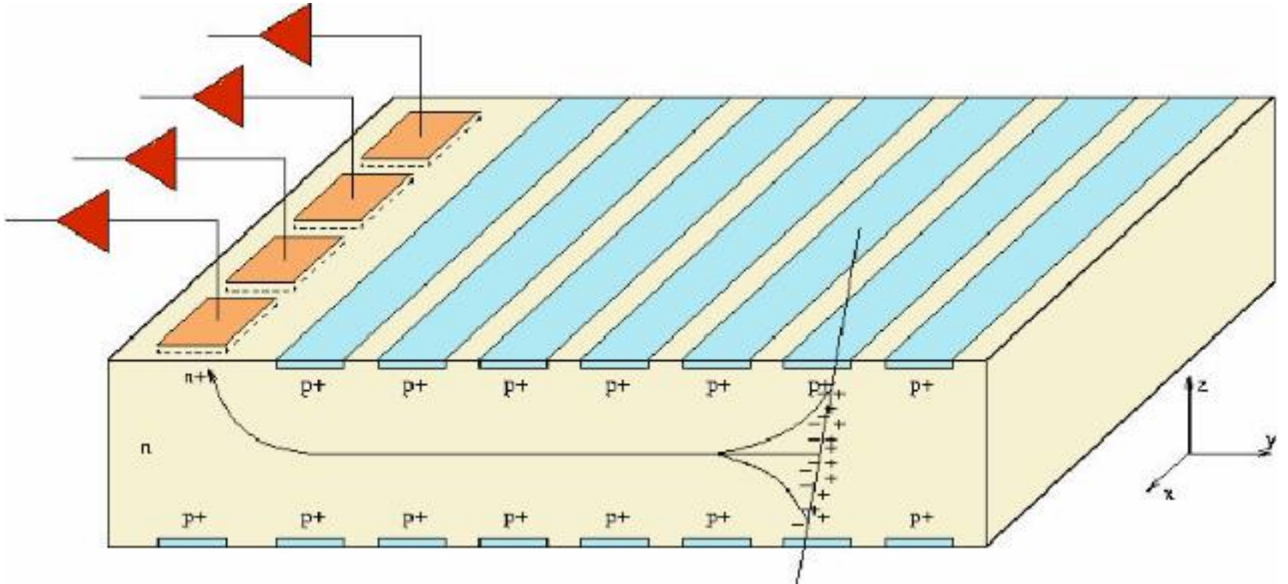


```
Run  33544,     EVENT   6476
27-APR-1996 06:05
Source: Run Data    Pol: R
Trigger: Energy CDC Hadron
Beam Crossing    1215252296
```

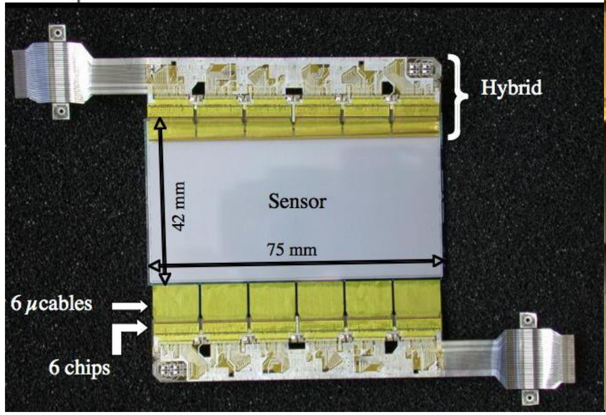
bb event from SLD WWW site

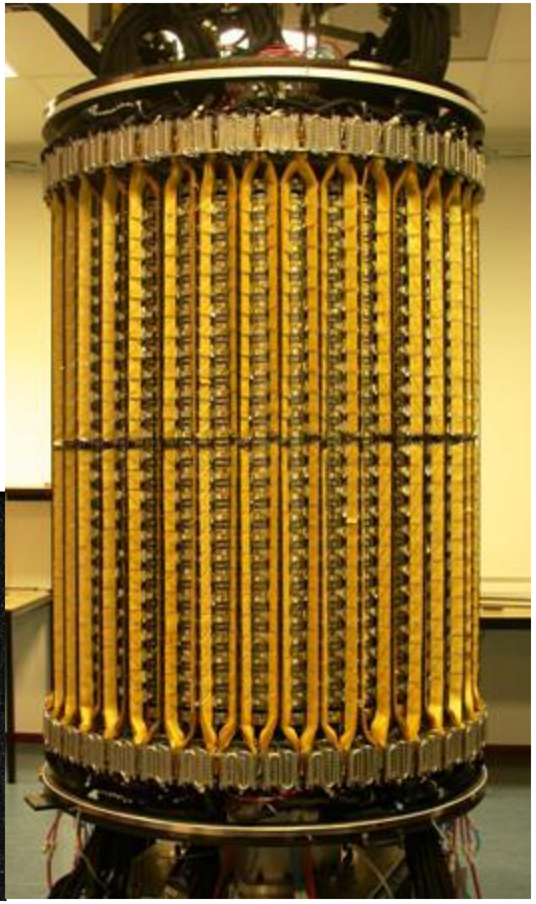
Figure from talk by H Wieman at Vertex 2000

Silicon Drift Detector



The Inner Tracking System of the ALICE experiment at LHC uses Silicon Drift Detectors in two cylindrical layers located at radial distance of ≈ 15 and ≈ 24 cm from the beam axis.

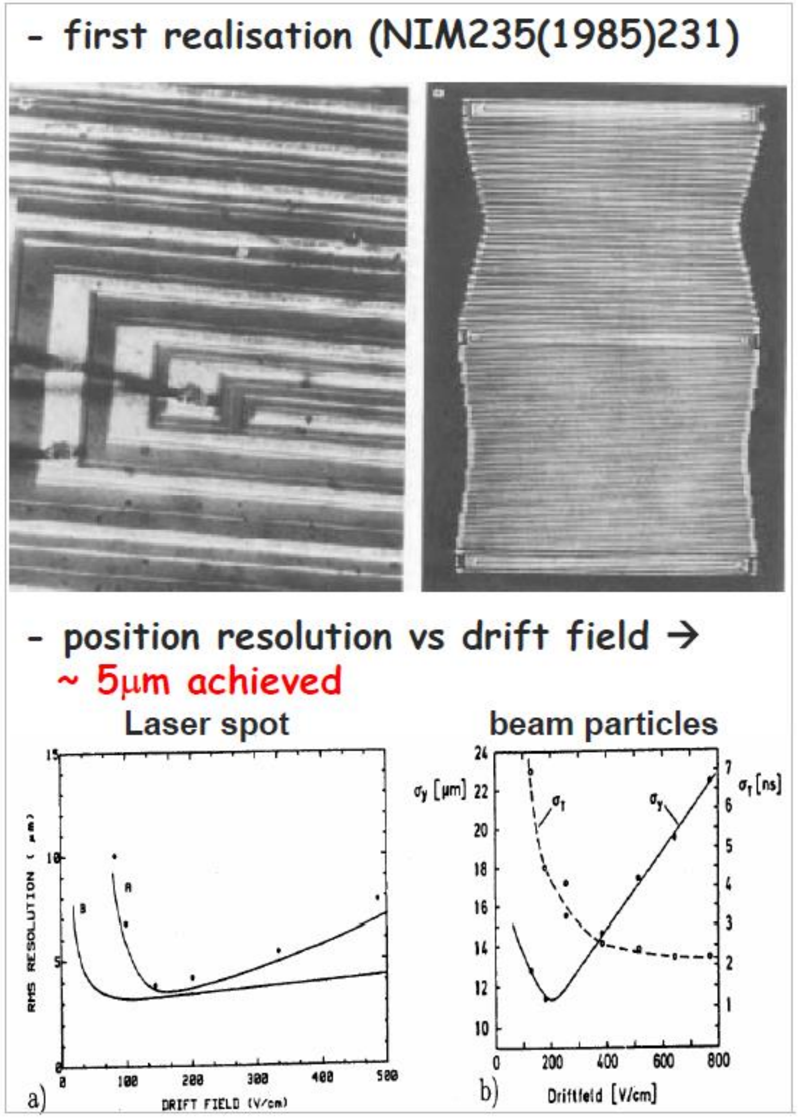




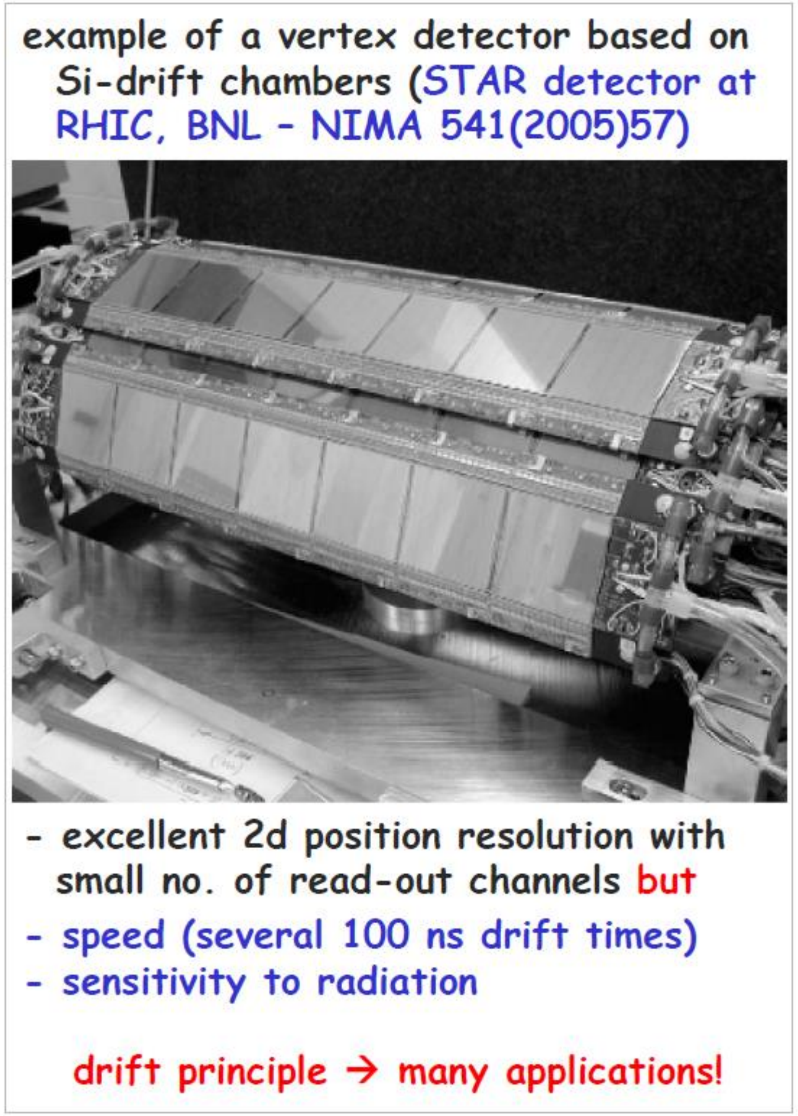
SDD for ALICE

Pictures taken from G.Contin “The Silicon Strip Detector (SSD) for the ALICE experiment at LHC: construction, characterization and charged particles multiplicity studies.” PhD thesis, Trieste, 2008

Silicon Drift - examples



- first realisation (NIM235(1985)231)
- position resolution vs drift field →
  ~ 5μm achieved



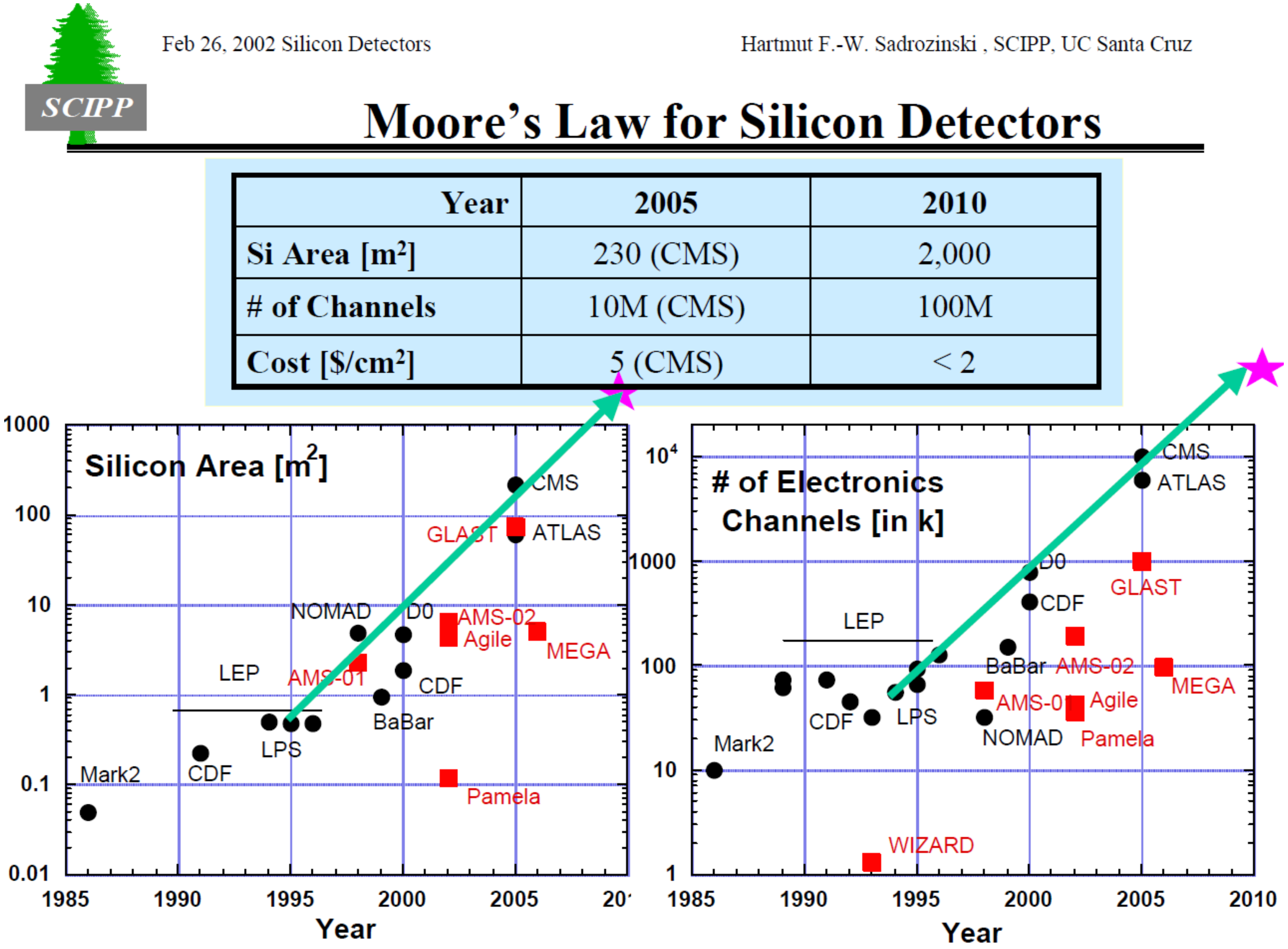
example of a vertex detector based on Si-drift chambers (STAR detector at RHIC, BNL - NIMA 541(2005)57)

- excellent 2d position resolution with small no. of read-out channels but
- speed (several 100 ns drift times)
- sensitivity to radiation

drift principle → many applications!

From a lecture by Robert Klanner, Univ. Hamburg

Evolution of scale



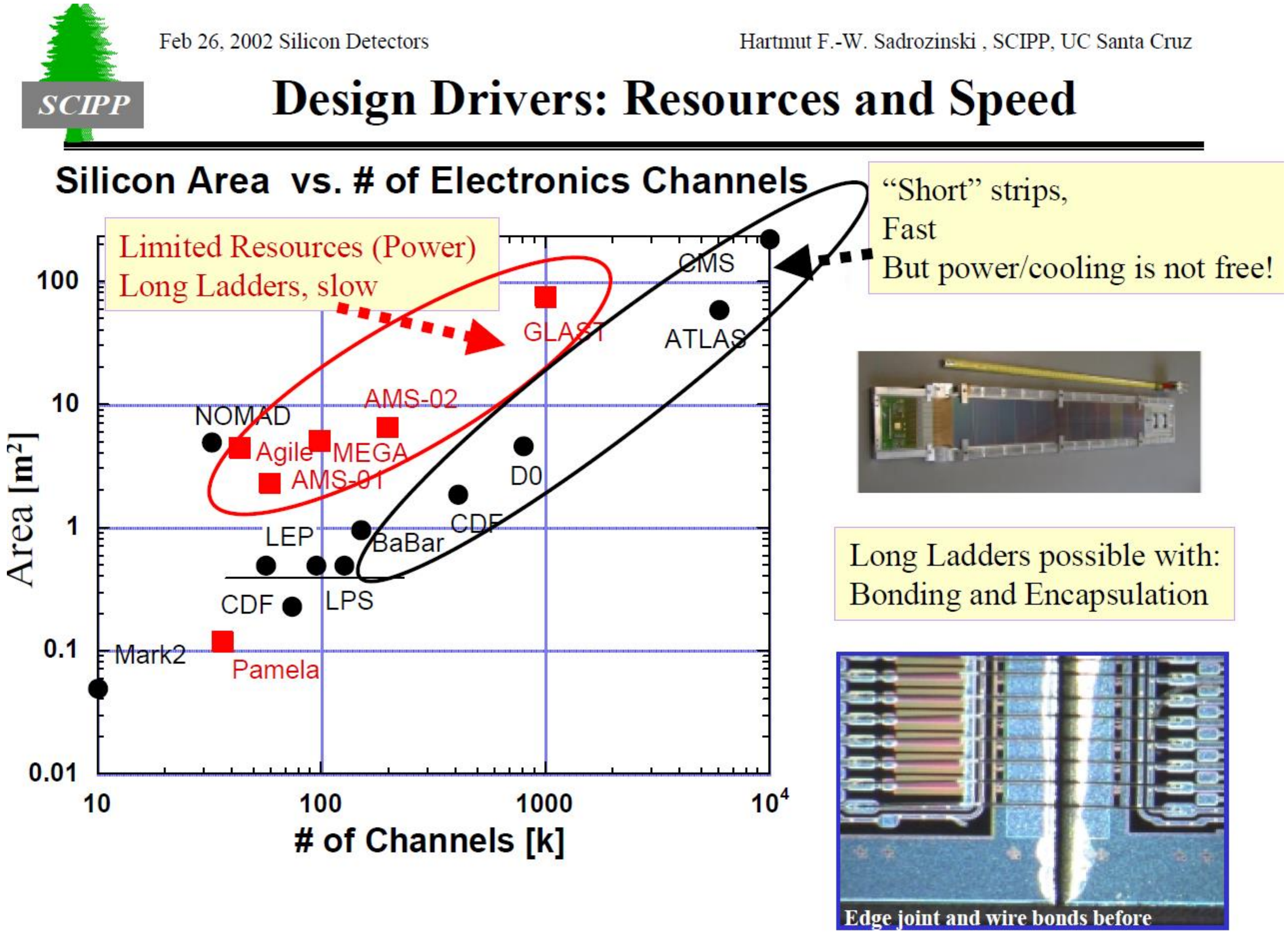
Feb 26, 2002 Silicon Detectors

Hartmut F.-W. Sadrozinski , SCIPP, UC Santa Cruz

Moore’s Law for Silicon Detectors

Year	2005	2010
Si Area [m²]	230 (CMS)	2,000
# of Channels	10M (CMS)	100M
Cost [$/cm²]	5 (CMS)	< 2

Growth with time



SCIPP

Feb 26, 2002 Silicon Detectors

Hartmut F.-W. Sadrozinski , SCIPP, UC Santa Cruz

Design Drivers: Resources and Speed

Silicon Area vs. # of Electronics Channels

Limited Resources (Power)
Long Ladders, slow

"Short" strips,
Fast
But power/cooling is not free!

Long Ladders possible with:
Bonding and Encapsulation

Edge joint and wire bonds before