Silicon Detectors

Frank Hartmann

Historical aspects – Why use silicon?

- Since 50ies large crystals for energy measurements
- Need for fast and precise position measurements

Where are silicon sensors better suited than gas detectors?
Fast ~O(10ns); Precise O(5μm); very good energy resolution ~O(eV)

Take home

- 80ies charm quark tagging
- Late 80ies LEP experiments, vertex tracker
- 90ies in hadron machines FERMILAB
- Today in all LHC experiments

Silicon detectors gives momentum & vertexing, which gives
- b tagging
- lifetimes
- mixing background suppression

…… and a lot of great physics!

Why wasn't silicon used earlier?
- Needed micro-lithography technology ⇒ cost
- Small signal size (need low noise amplifiers)
- Needed read-out electronics miniaturization
  - (transistors, ICs)

Historical aspects II – Why use silicon?

In the post era of the *Z and W discovery, after the observation of Jets at UA1 and* UA2 at CERN, John Ellis visioned at a HEP conference at Lake Tahoe, California in 1983 "To proceed with high energy particle physics, one has to tag the flavour of the quarks!"

CDF; top quark discovery

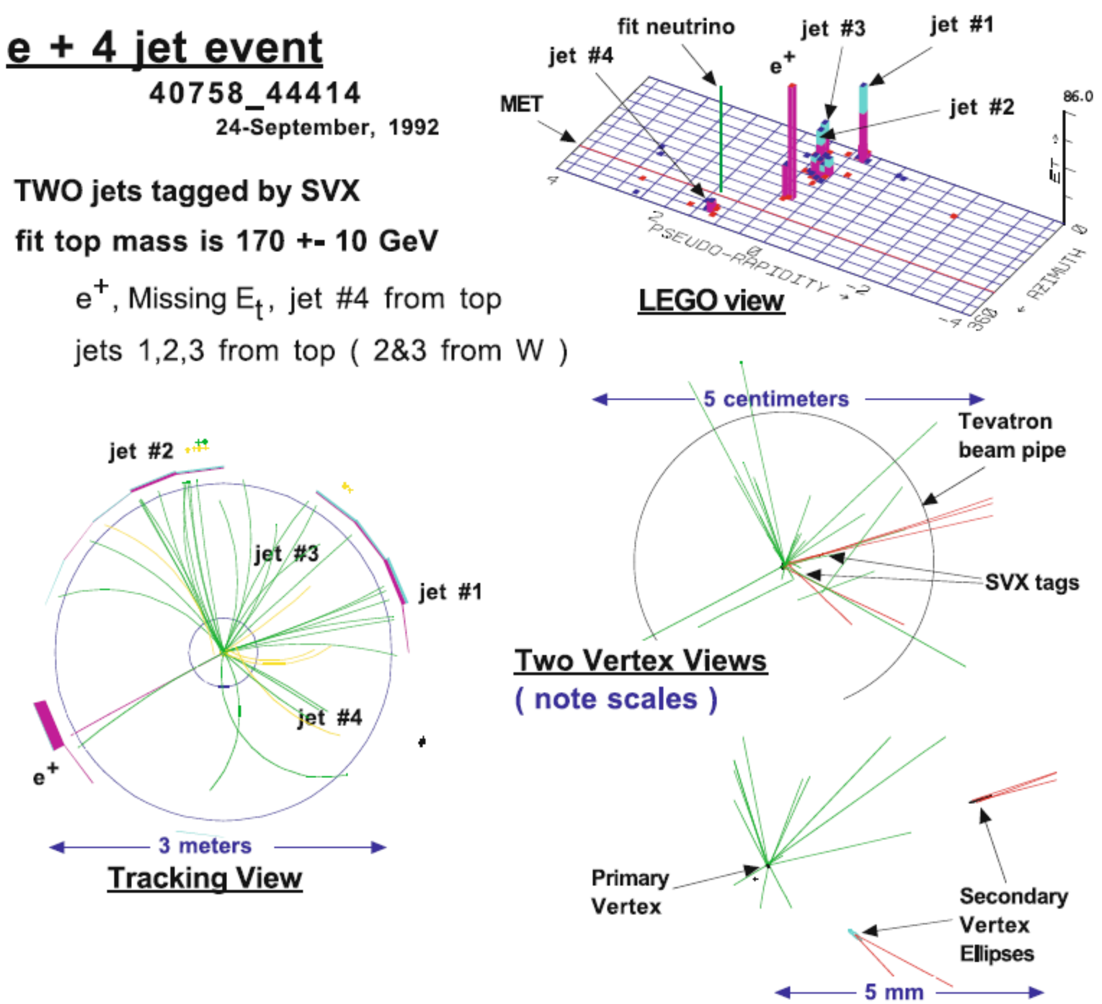
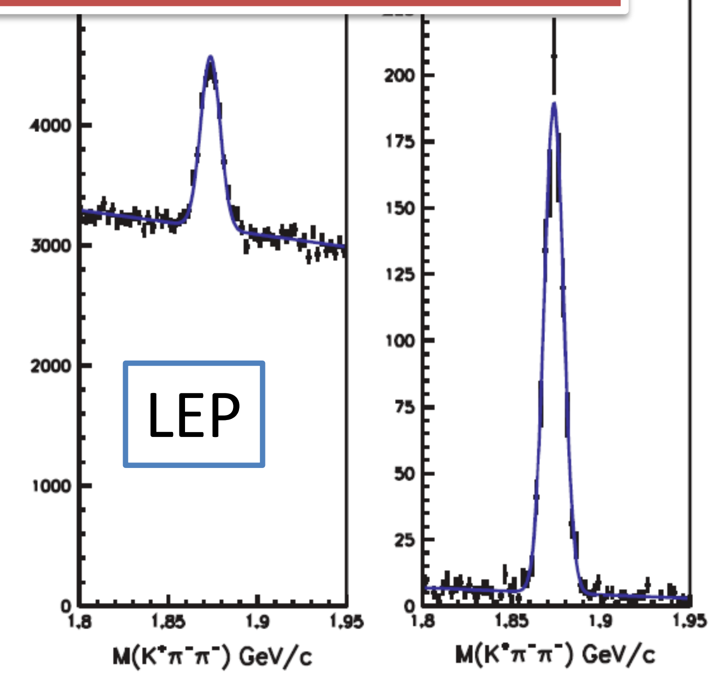
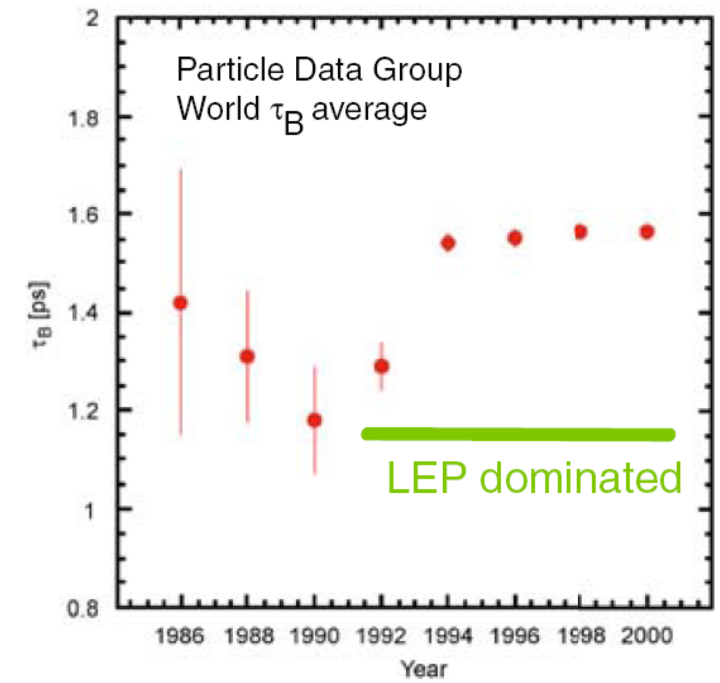
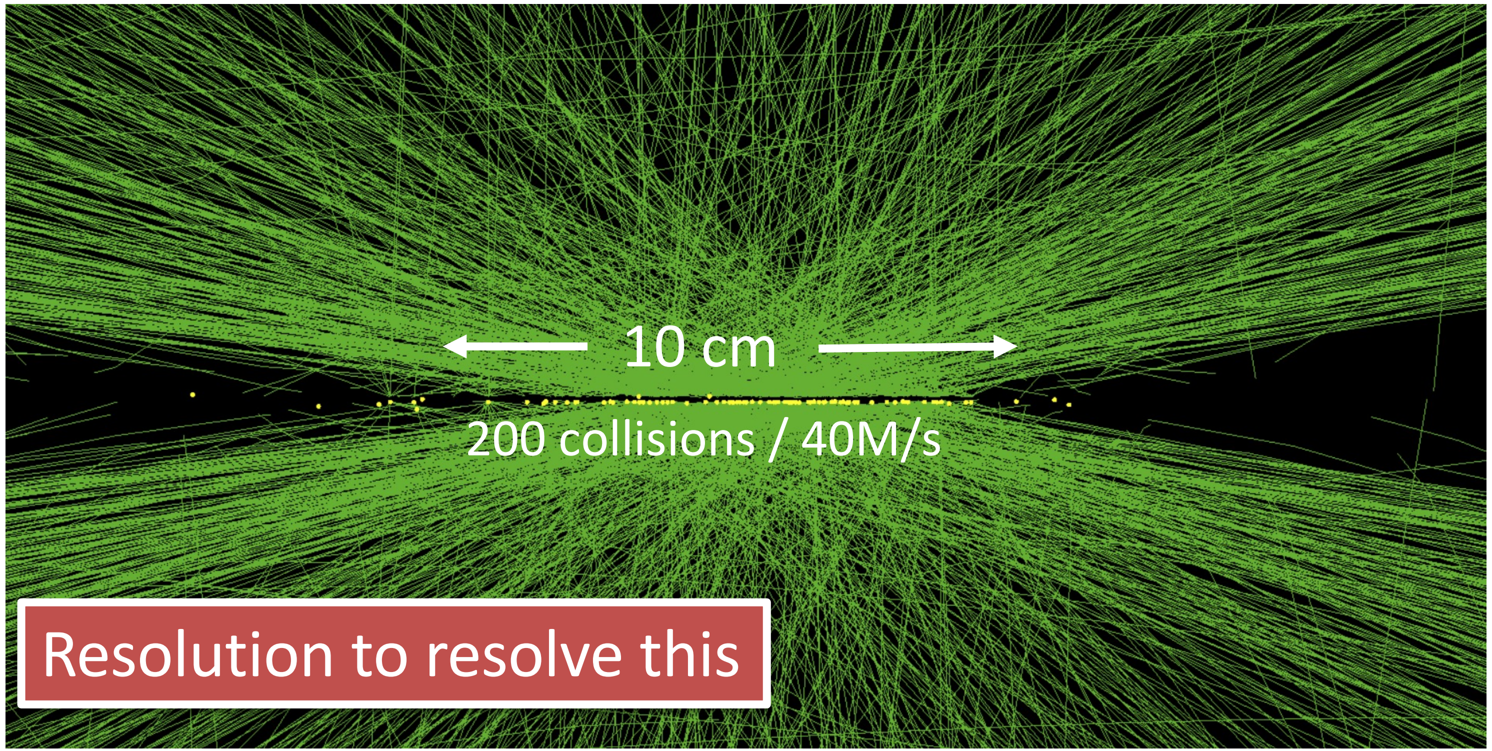


Fig. 4.23 A "Golden" t event. $t\bar{t}$ decaying into W^+b, $W^-\bar{b}$, where one W decays leptonically with the signature lepton ID plus missing energy, the second W decays into $q\bar{q}$ resulting in two jets together with the initial two tagged b jets. In total one lepton, four jets, two tagged b jets and missing energy were reconstructed [151]

Background reduction



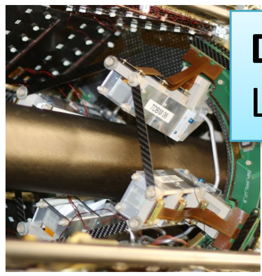




Resolution to resolve this

Everybody is using Silicon in various configurations

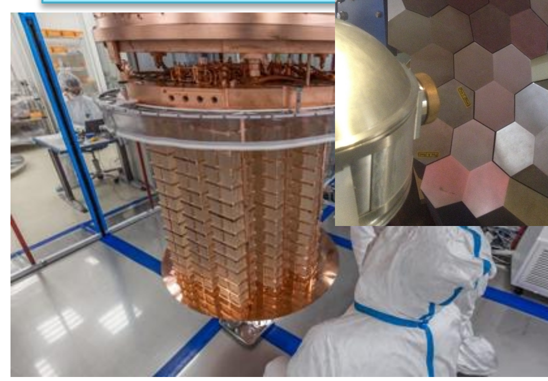
Some of us are also using Germanium, Tellurium, Diamonds

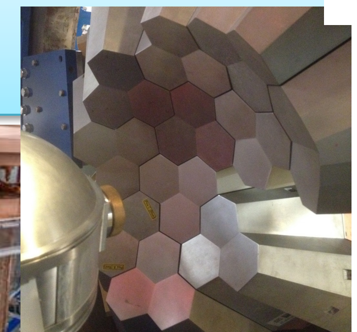


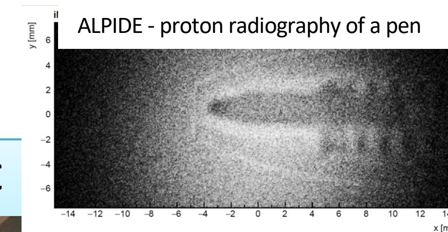
Diamonds – NuPECC; ECFA
LHC, GSI, KEK – *BCM, Lumi, Spectroscopy, timing (ToF)*

Si-Strips – NuPECC; ECFA, ApPEC
LHC, KEK, GSI, ISS, Satellite – *position*

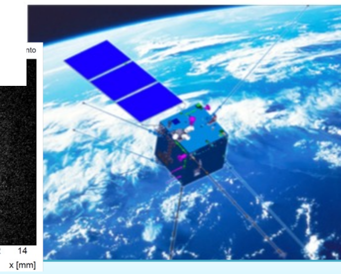
Germanium – NuPECC, ApPEC
γ Tracking
$0\nu2\beta$ decay

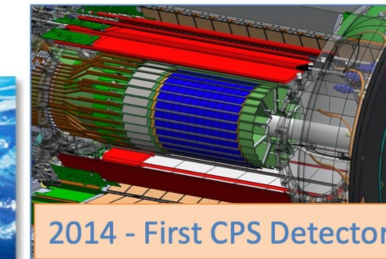






CSES – HEPD2

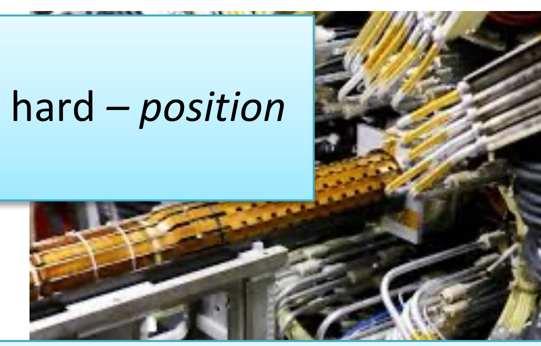




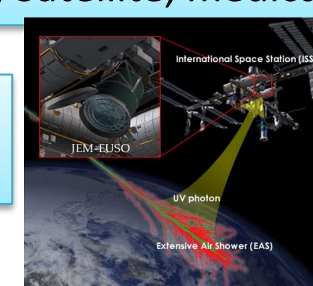
STAR HFT
0.16 m^2 – 356 M pixels

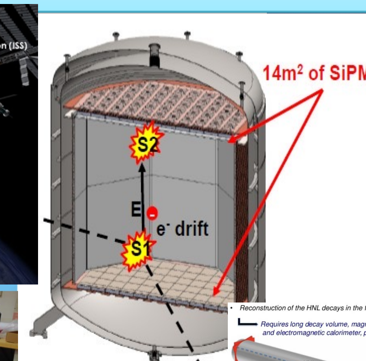
MAPS/CMOS – NuPECC; ECFA, ApPEC
LHC, STAR, PSI satellite, CBM, medical – *position, imaging*

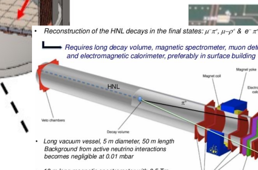
3D silicon – ECFA
Innermost layers - Radiation hard – *position*
ATLAS, CMS, timing

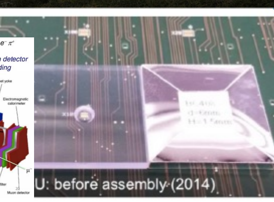


SiPM – NuPECC, ECFA, ApPEC
LHC, GSI, ISS, Satellite, medical (PET, X-ray) – *photons, energy, timing*

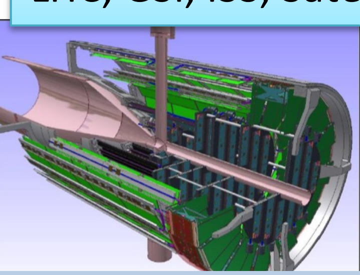


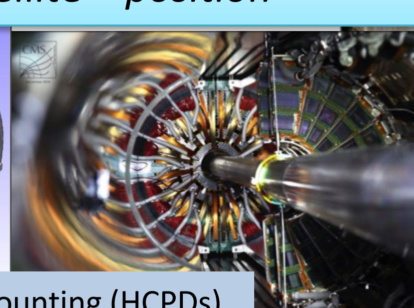


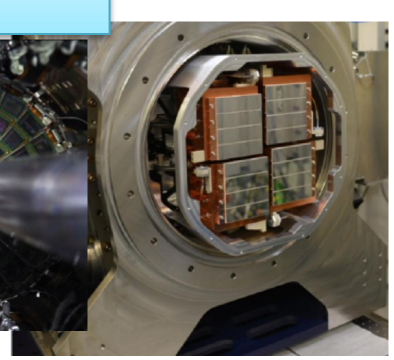




Si-Hybrid Pixel – NuPECC; ECFA, ApPEC
LHC, GSI, ISS, Satellite – *position*

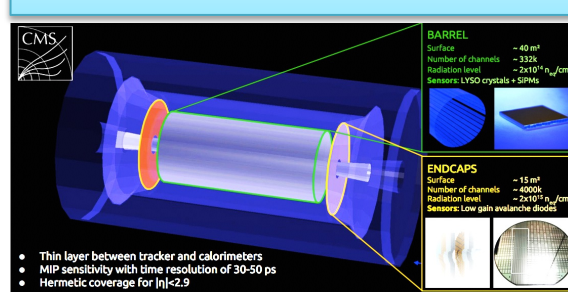






+ synchrotron photon counting (HCPDs)

LGADs – ECFA
ATLAS & CMS – *timing, position*



Content

1. Material Properties – ‘get the numbers’
2. Detector Structures – strips, pads and pixel
   - workhorse
3. Performance
4. Radiation – very brief

Lecture 1

5. More Detector Concepts
6. Detector systems

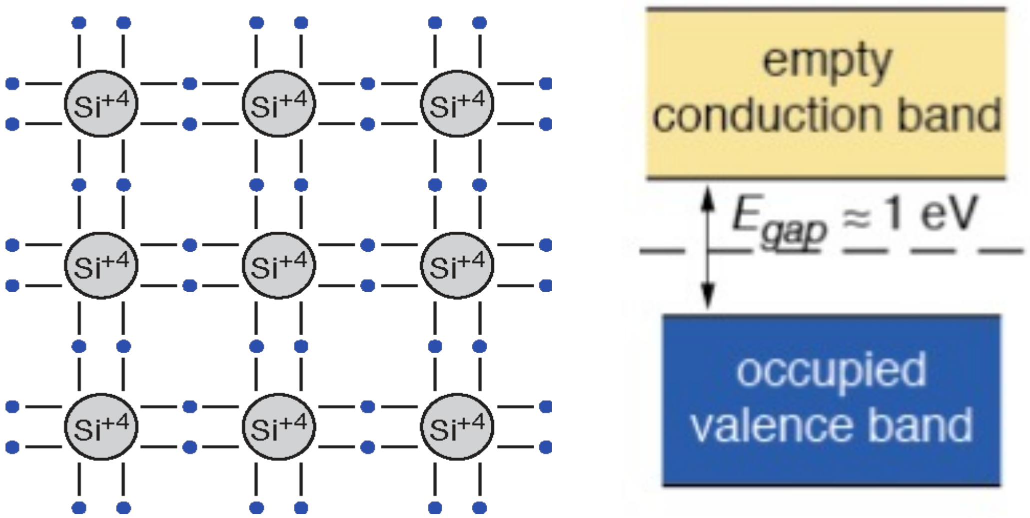
Lecture 2

Homework – learn about signal formation Shockely-Ramo

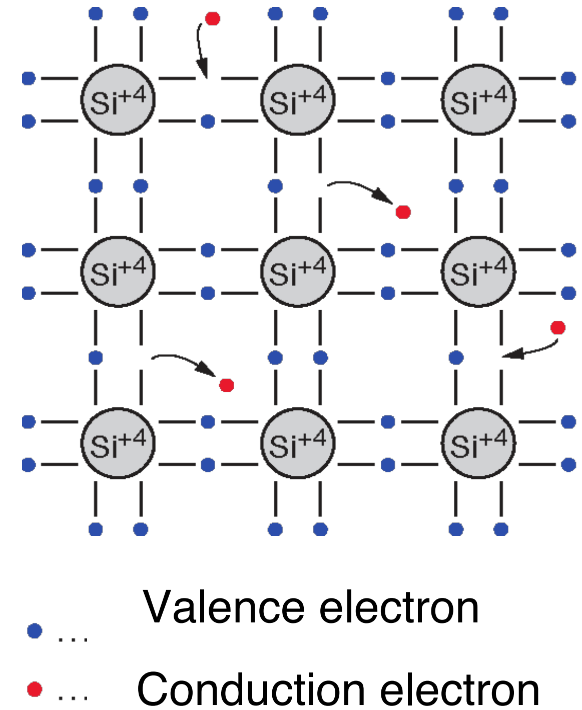
Material Properties

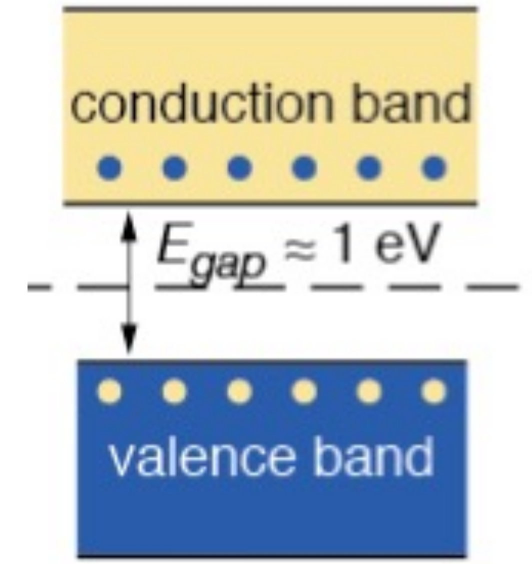
Intrinsic

$T = 0$ K



$T > 0$ K



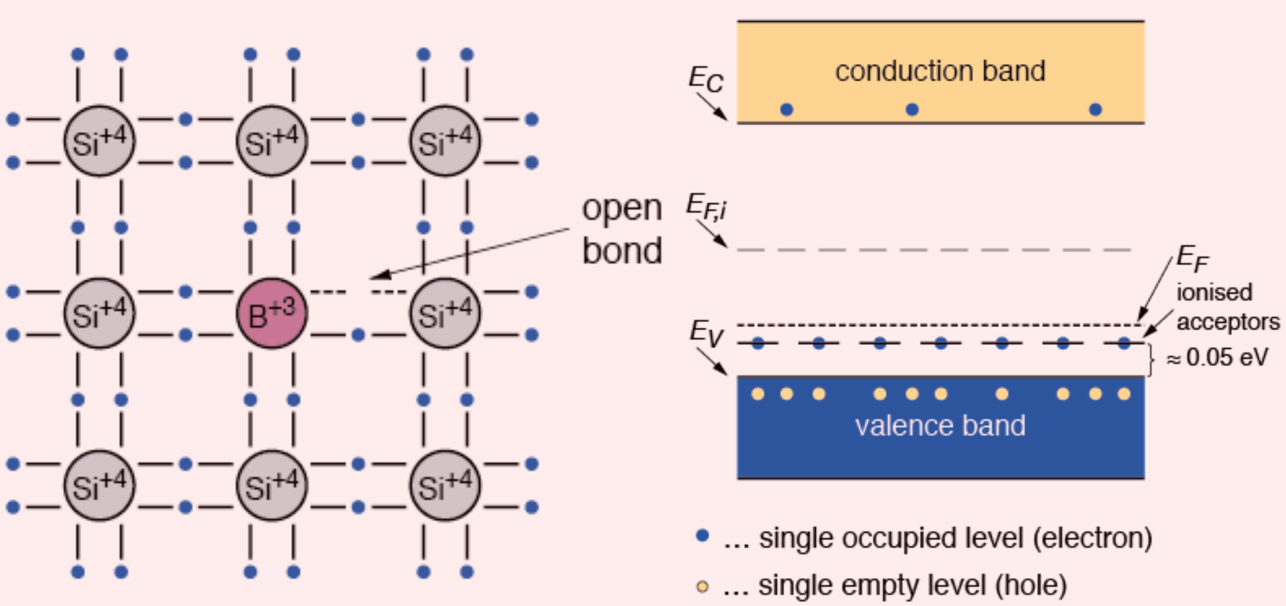


$$n_i = \sqrt{N_C N_V} \cdot \exp\left(-\frac{E_g}{2kT}\right) \propto T^{\frac{3}{2}} \cdot \exp\left(-\frac{E_g}{2kT}\right)$$

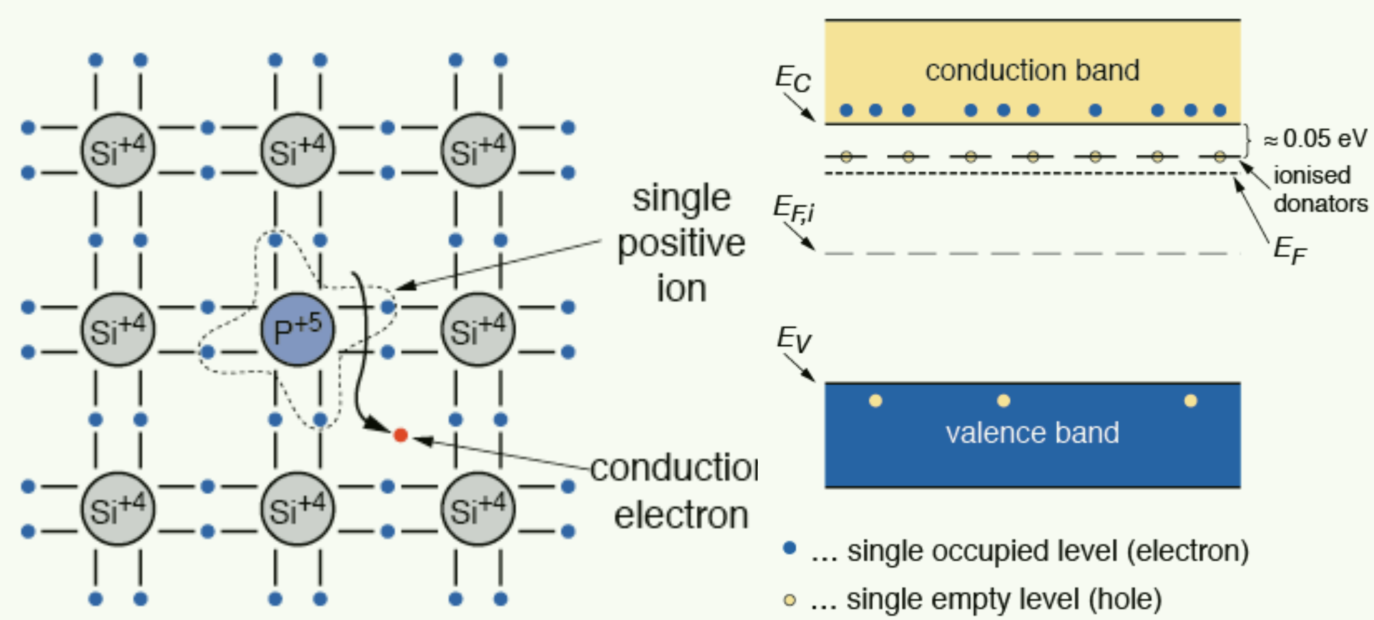
@ RT Approximately $1.45 \cdot 10^{10}$ cm^{-3} intrinsic carieres with 10^{22} Atoms/cm^3 about **1 in 10^{12}** silicon atoms is ionised

Extrinisic = doped

p-Doping - acceptor



n-Doping - donor



Typical doping concentrations for Si detectors are $\approx 10^{12}$ atoms/cm^3 (10^{14} und 10^{18} atoms/cm^3 for CMOS elements)

Material Properties
Drift velocity and mobility

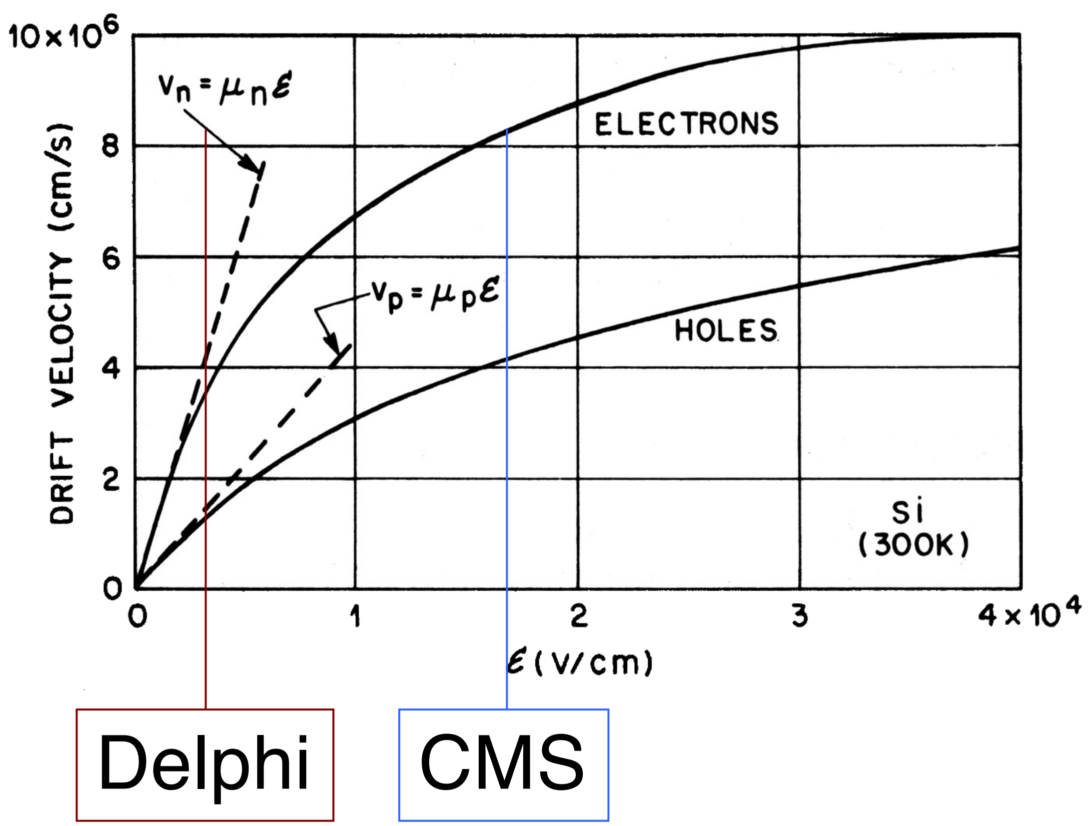
Drift velocity *v*

For electrons: $\boxed{\vec{v}_n = -\mu_n \cdot \vec{E}}$ and for holes: $\boxed{\vec{v}_p = \mu_p \cdot \vec{E}}$

Mobility μ

For electrons: $\boxed{\mu_n = \frac{e\,\tau_n}{m_n}}$ and for holes: $\boxed{\mu_p = \frac{e\,\tau_p}{m_p}}$

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



e …electron charge

ε … 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

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

Constructing a Detector

Estimate Signal to Noise Ratio SNR in an intrinsic silicon detector

Let's make a simple calculation for silicon:

Mean ionization energy $\boldsymbol{I_0 = 3.62}$ **eV**, mean energy loss per flight path of a mip (minimum ionizing particle) $\boldsymbol{dE/dx = 3.87}$ **MeV/cm** (rf. Bethe)

Assuming a detector with a thickness of $d = 300\ \mu$m 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):

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

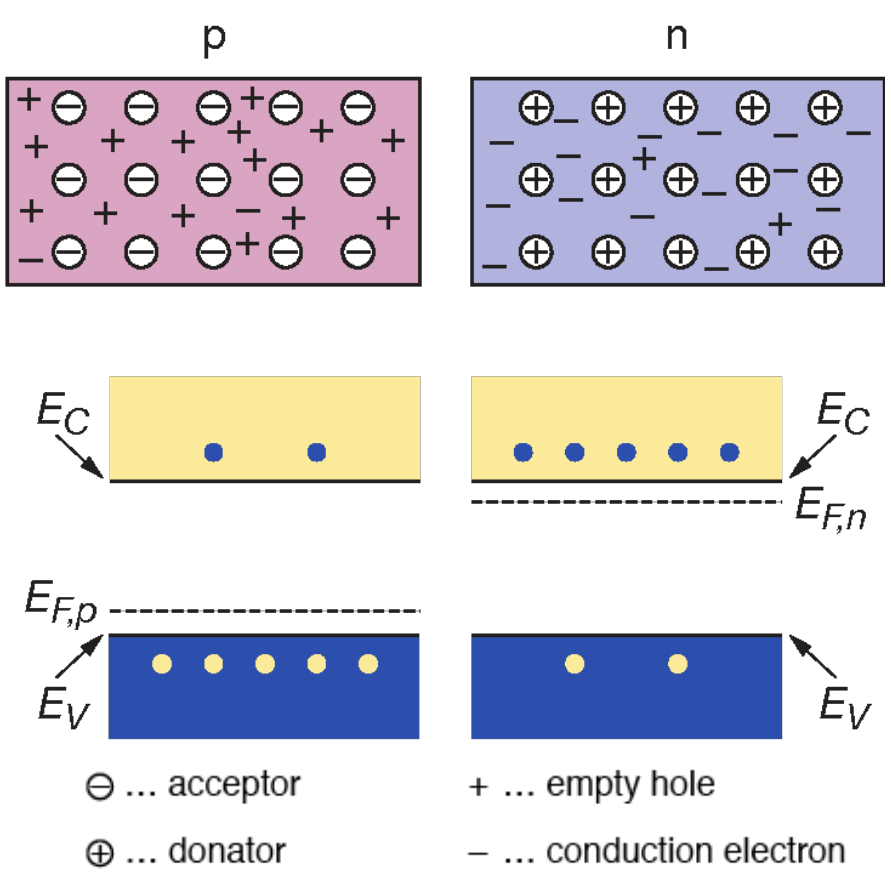
➔ Number of thermal created e^-h^+-pairs is four orders of magnitude larger than signal!!!

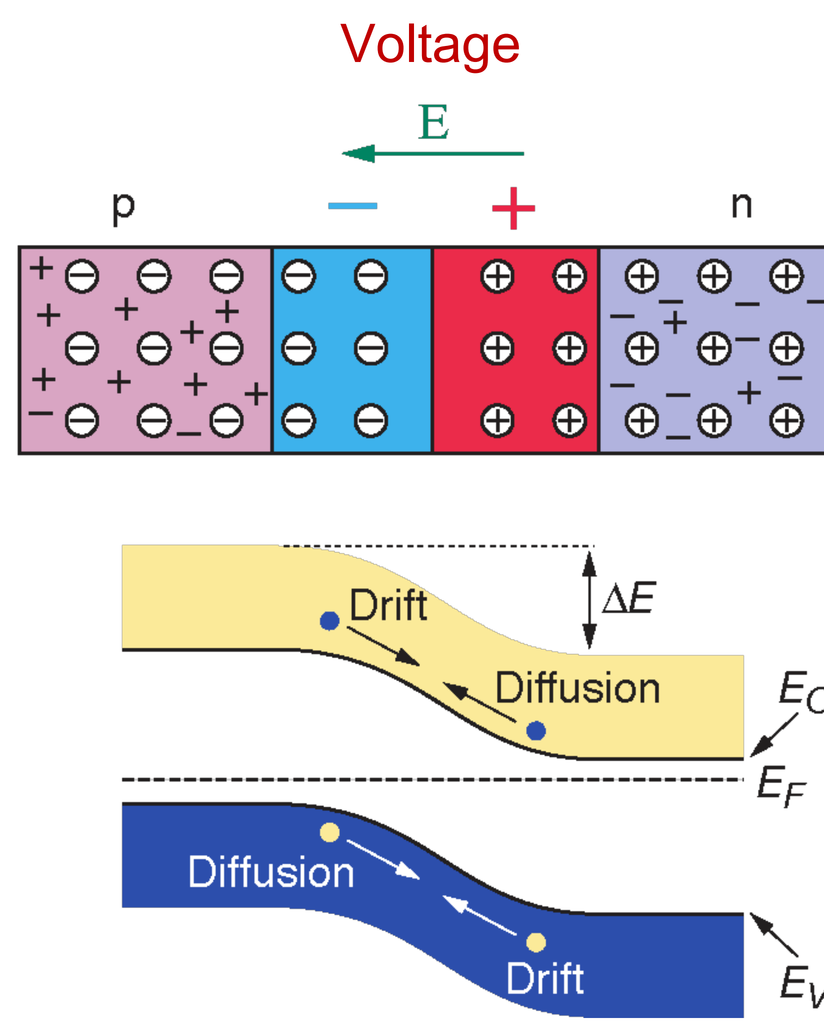
Charge carrier have to be removed!

➔ Depletion zone in reverse biased **pn junction**

The p-n Junction

At the interface of an n-type and p-type semiconductor the difference in the fermi levels cause diffusion of surplus 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 and an electric field stopping further diffusion.
The stable space charge region is free of charge carriers and is called the depletion zone (often also called ‘space charge region’).

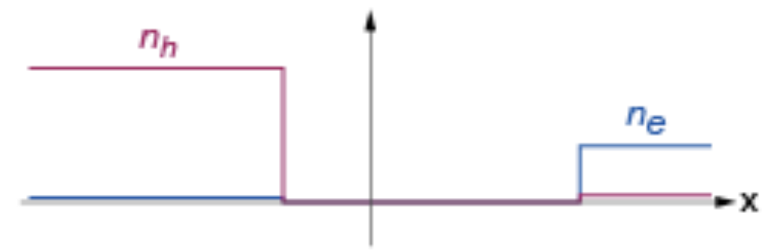




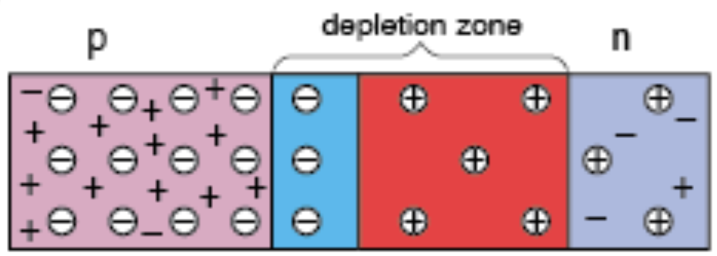
The p-n Junction
Electrical characteristics

Take home:
Fields and potentials completely defined by
doping concentration (& voltage)

concentration of free charge carriers



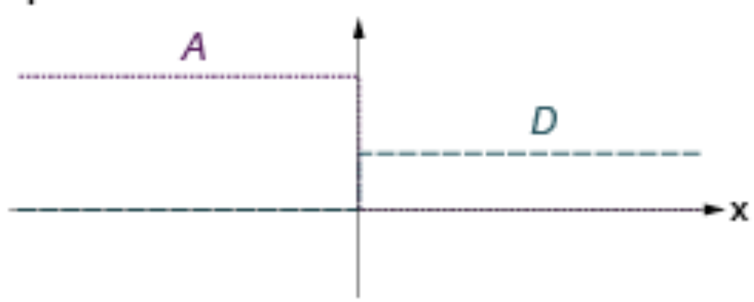
pn junction scheme



Poisson Equation: $\frac{\partial^2 \Phi}{\partial x^2} = -\frac{1}{\epsilon_r \epsilon_0} \rho(x)$

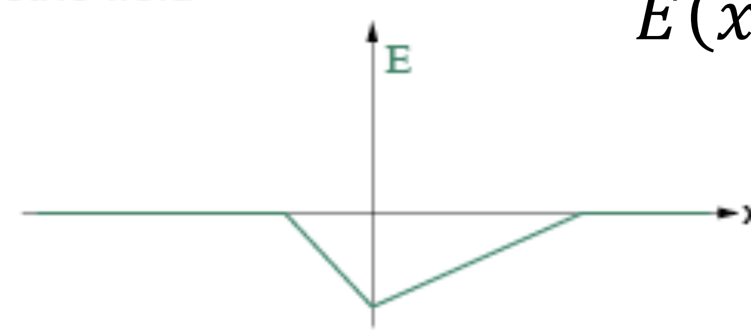
ρ (charge density) is constant in (+/-) depletion zones

acceptor and donator concentration

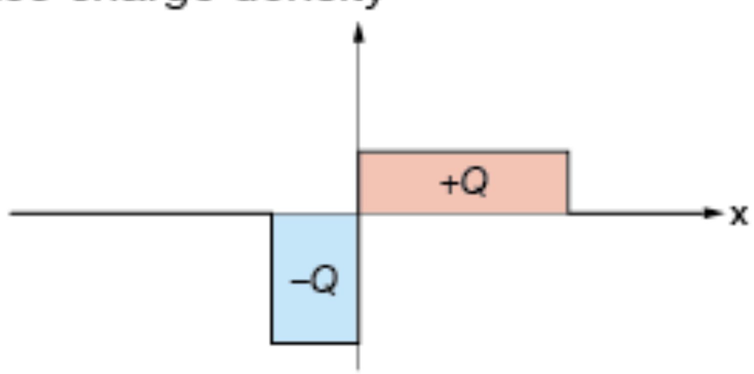


electric field

$E(x) \sim x$

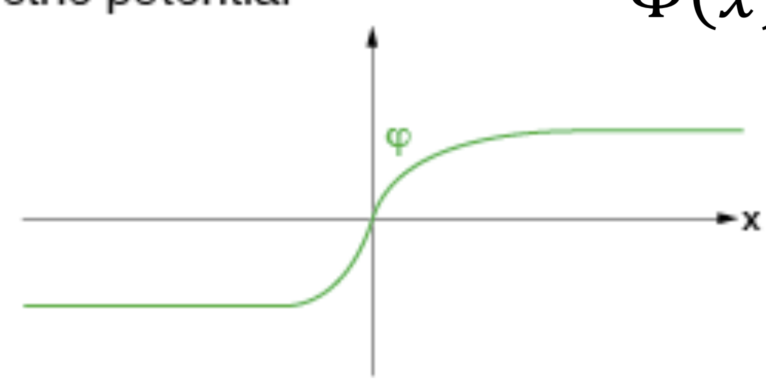


space charge density



electric potential

$\Phi(x) \sim x^2$



⊖ ... acceptor
+ ... empty hole
⊕ ... donator
− ... conduction electron

$V_{diffusion} = \Phi_p(+x_p) - \Phi(-x_n) \sim w^2$

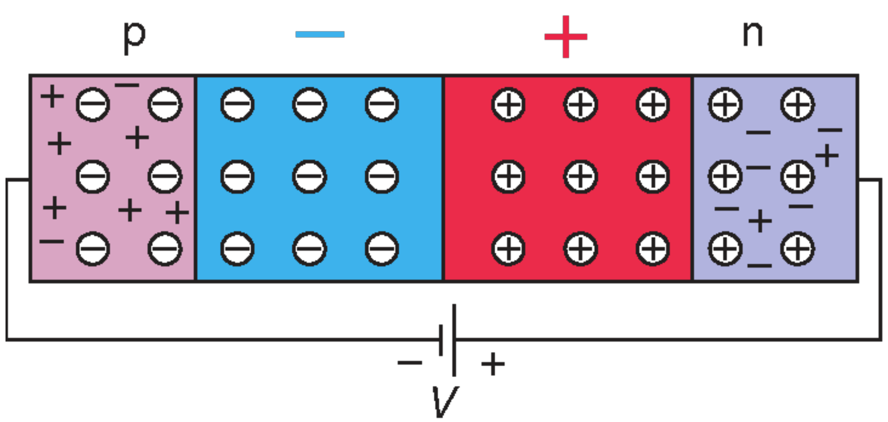
w=width of depletion zone

The p-n Junction

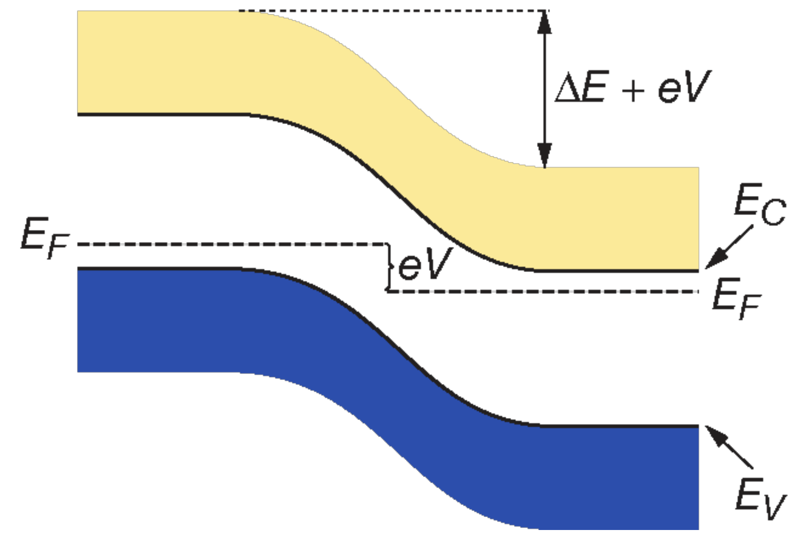
Operation with reverse bias

Take home:
Fields and potentials completely defined by
doping concentration & voltage

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.



The potential barrier becomes higher by *eV* and diffusion across the junction is suppressed. The current across the junction is very small “leakage current”.

➔ That’s the way we operate our semiconductor detector!

Detector Characteristics

Capacitance and Depletion Voltage of a detector

Depletion voltage V_{FD} is the minimum voltage at which the bulk of the sensor is fully depleted. The operating voltage is usually chosen to be higher (overdepletion).

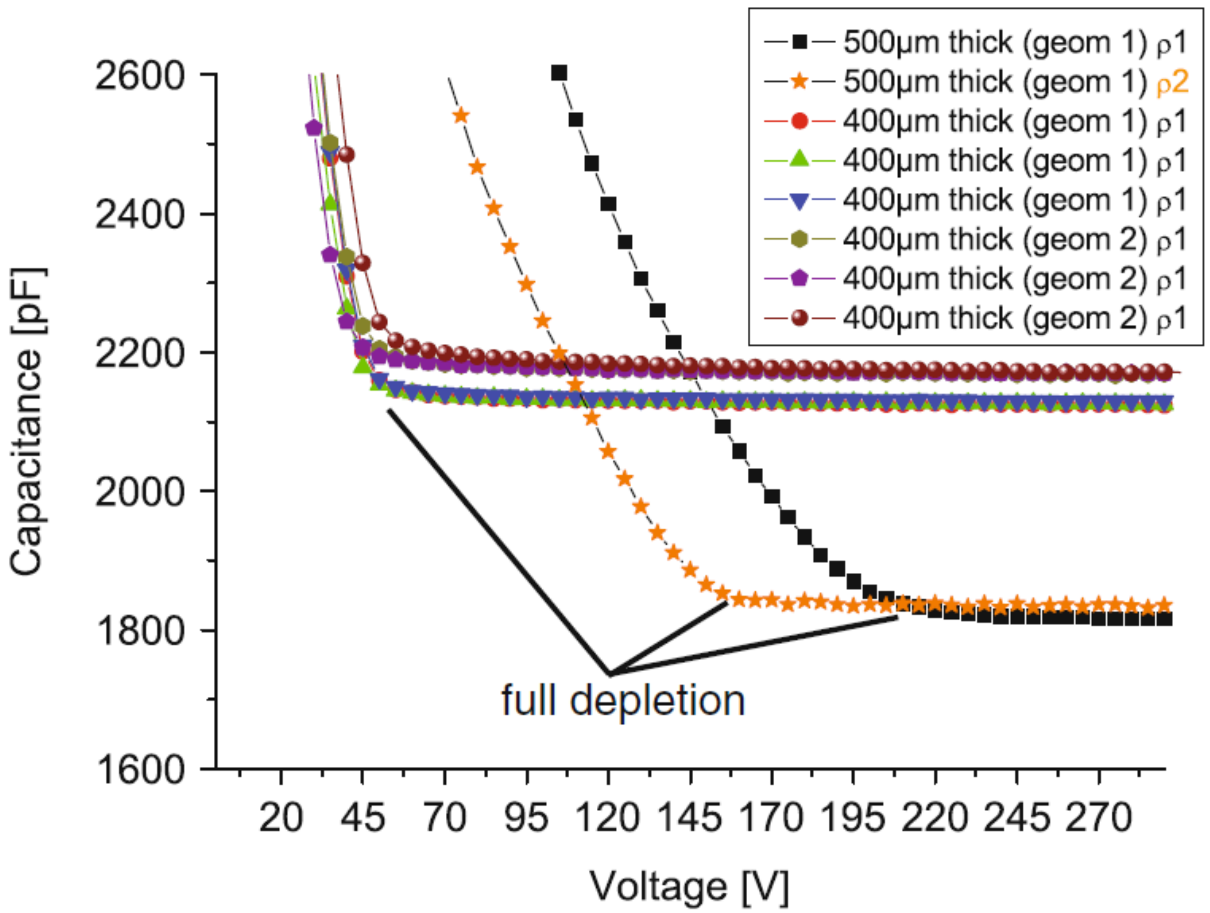
- High resistivity material (i.e. low doping) requires low depletion voltage.

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

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

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

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



Measured detector capacitance as a function of the bias voltage, CMS strip detector:

The p-n Junction
Width of the depletion zone

Example of a typical p^+-n junction in a silicon detector:

Effective doping concentration
$N_a = 10^{15}$ cm^{-3} in p+ region and $N_d = 10^{12}$ cm^{-3} in n bulk.

Without external voltage:

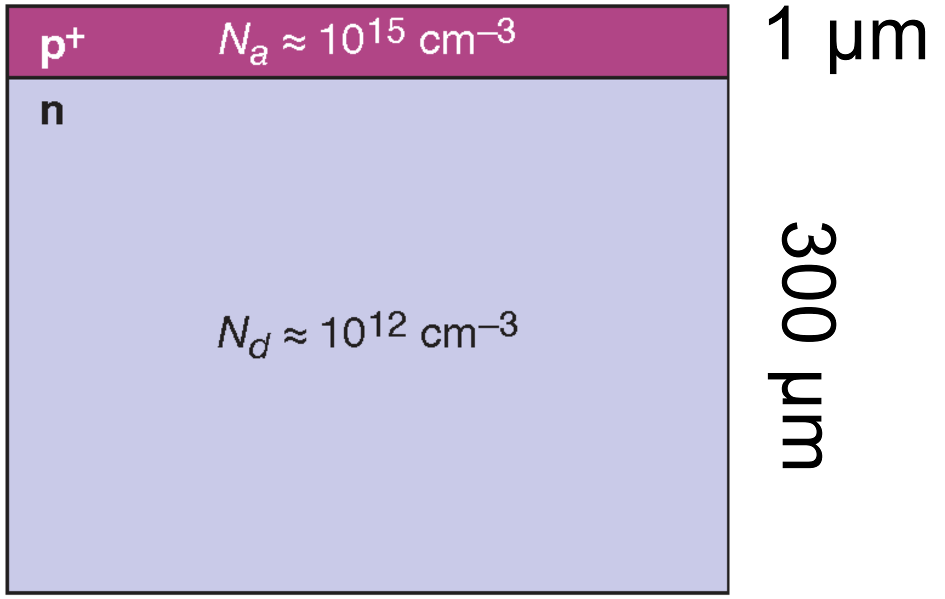
$$W_p = 0.02\ \mu\text{m}$$

$$W_n = 23\ \mu\text{m}$$

Applying a reverse bias voltage of 100 V:

$$W_p = 0.4\ \mu\text{m}$$

$$W_n = 363\ \mu\text{m}$$



p^+n junction

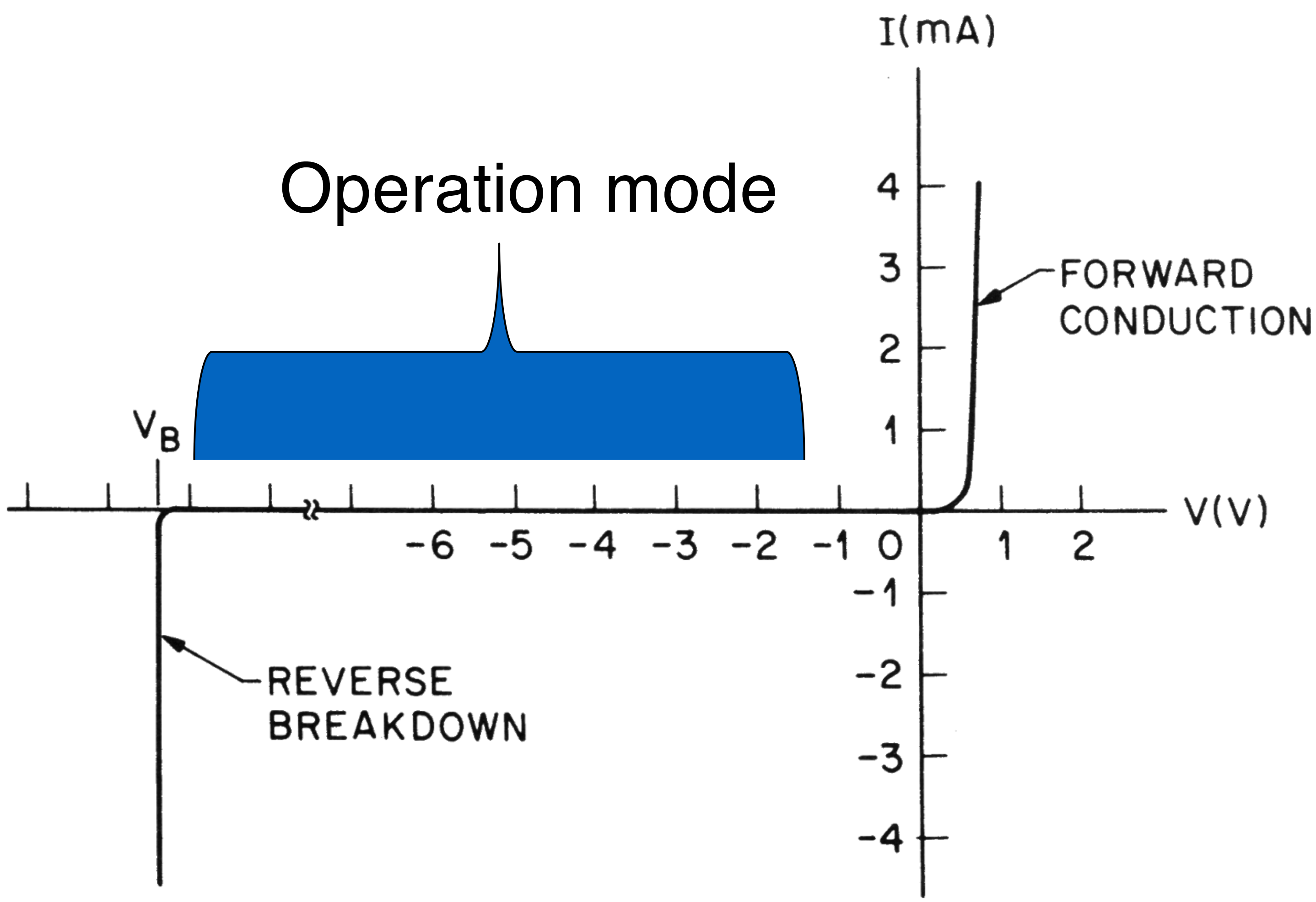
Width of depletion zone in n bulk:

$$\boxed{W \approx \sqrt{2\varepsilon_0\varepsilon_r\mu\rho|V|}} \quad \text{with} \quad \boxed{\rho = \frac{1}{e\mu N_{eff}}}$$

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

The p-n Junction
Current-voltage characteristics

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

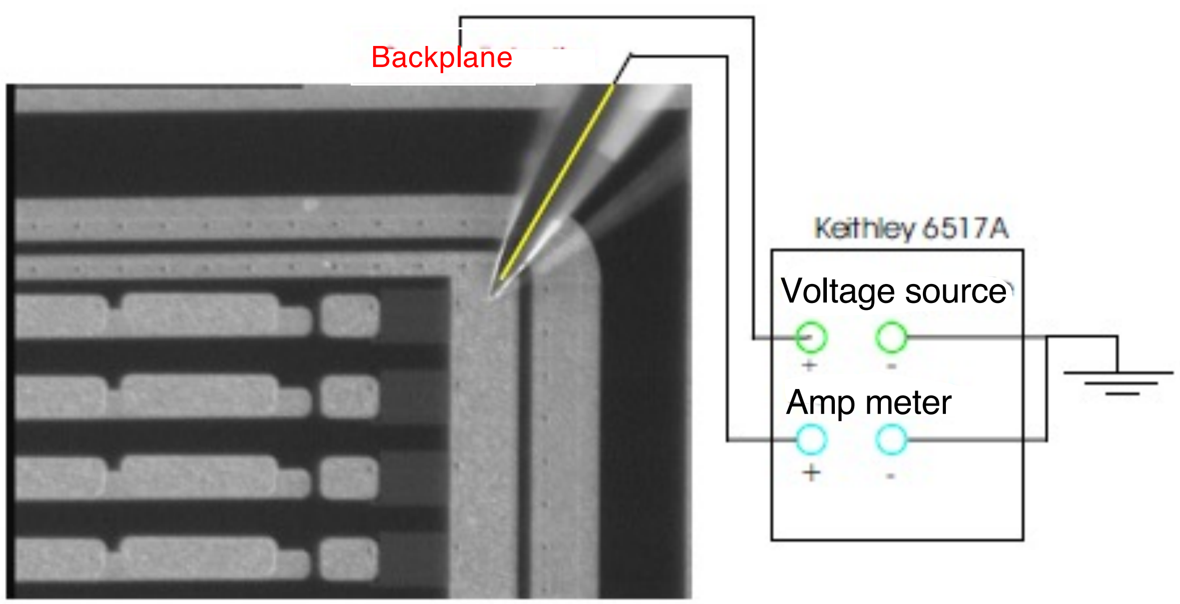


$$I = I_0 \cdot \left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

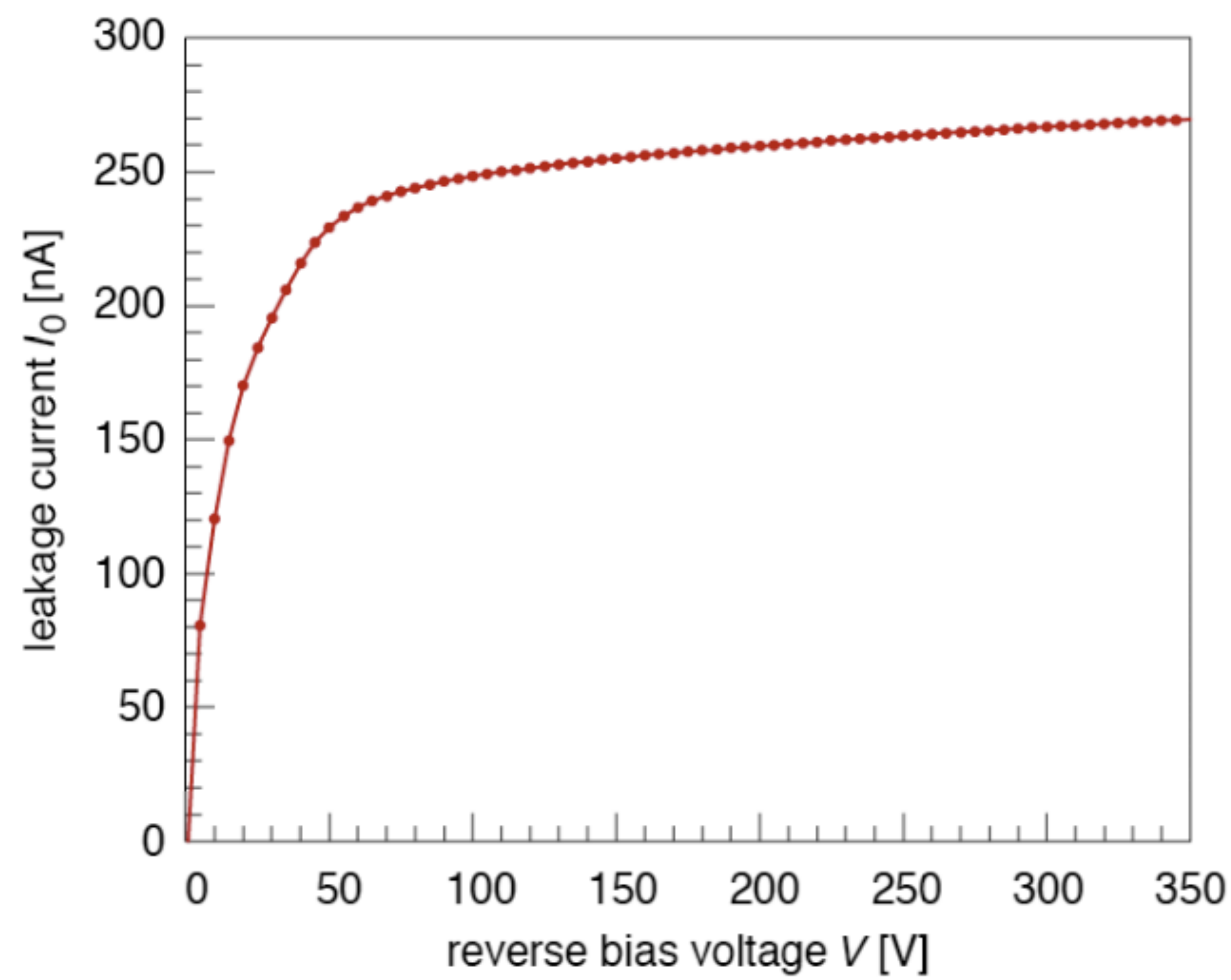
S.M. Sze, *Semiconductor Devices* , J. Wiley & Sons, 1985

Detector Characteristics
Leakage Current

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 *(**totally** dominated by defects)*.
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.



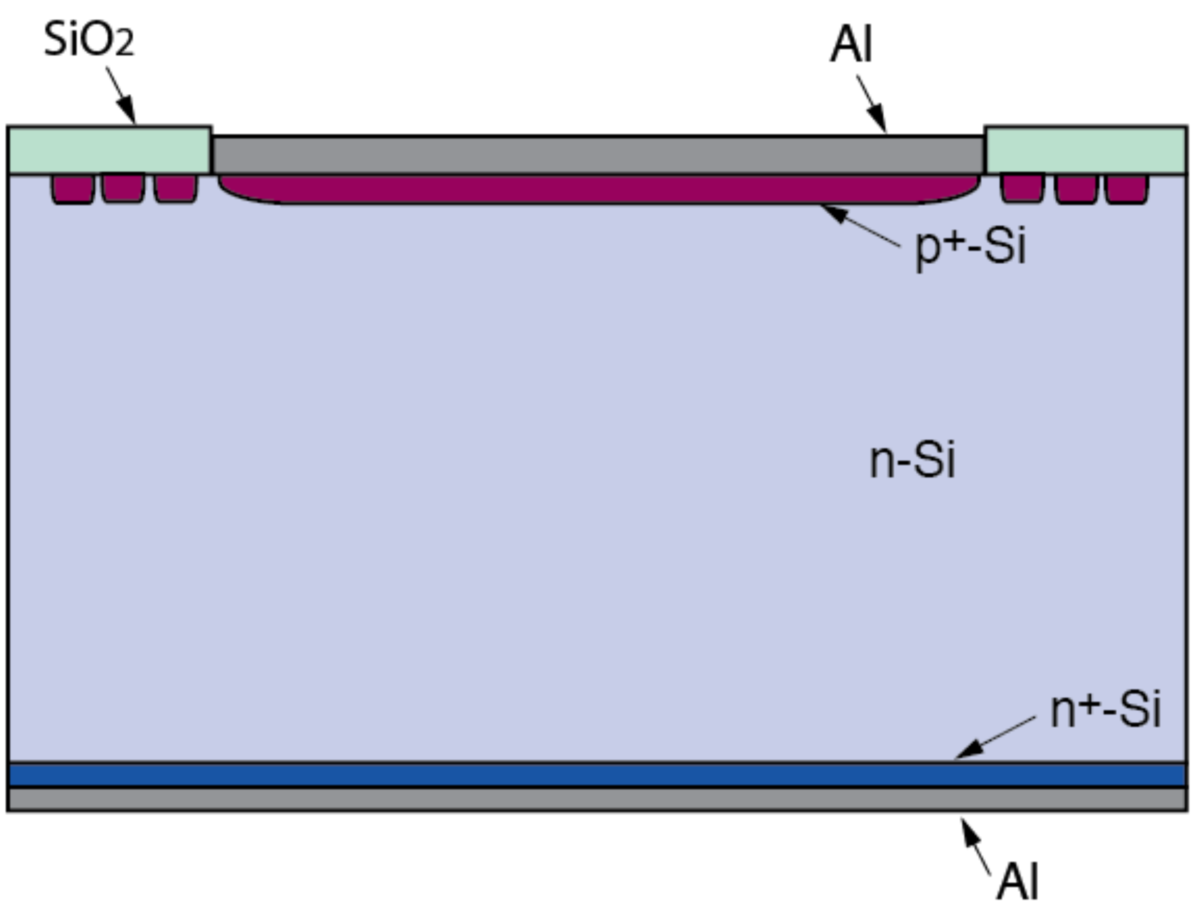
Measured detector leakage current, CMS strip detector (measurement at room temperature):

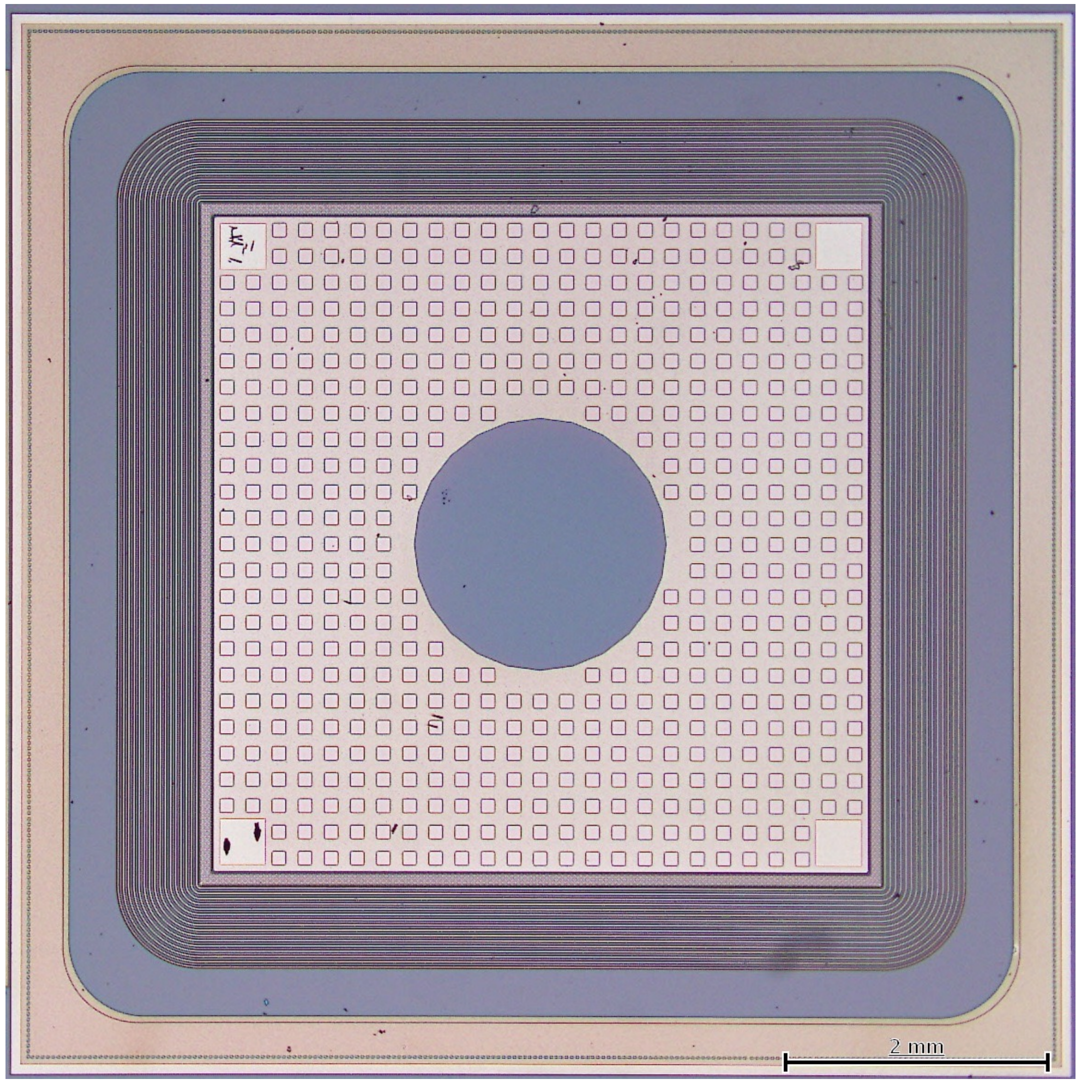


Detector Structures

Pad Detector

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



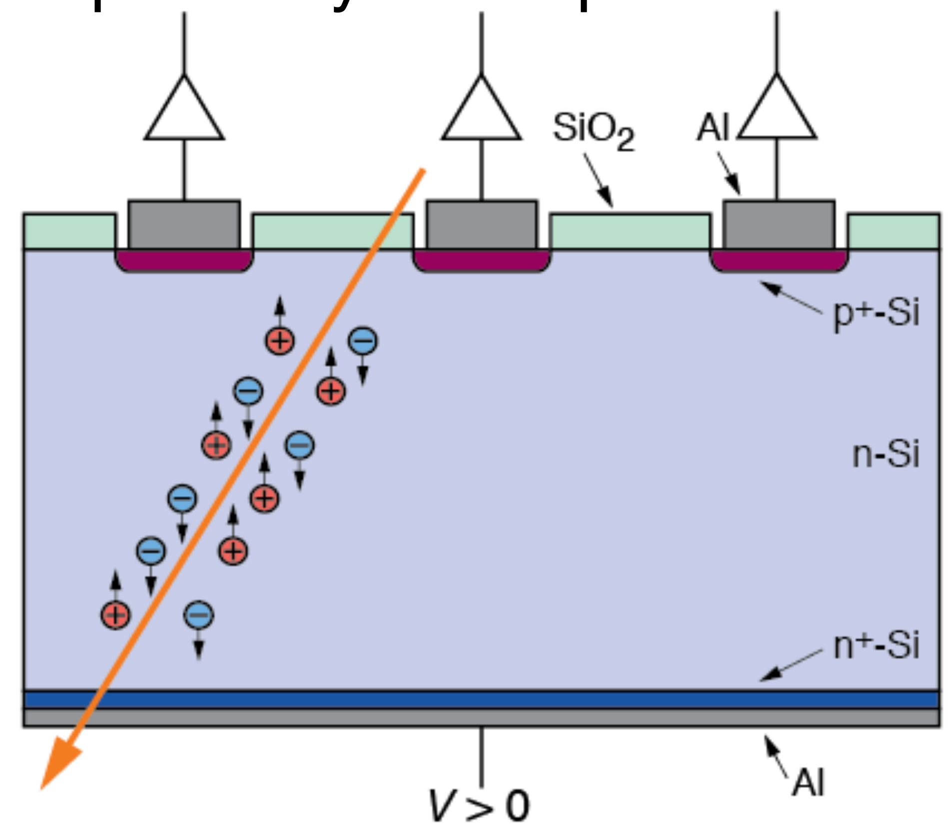


Microstrip Detector

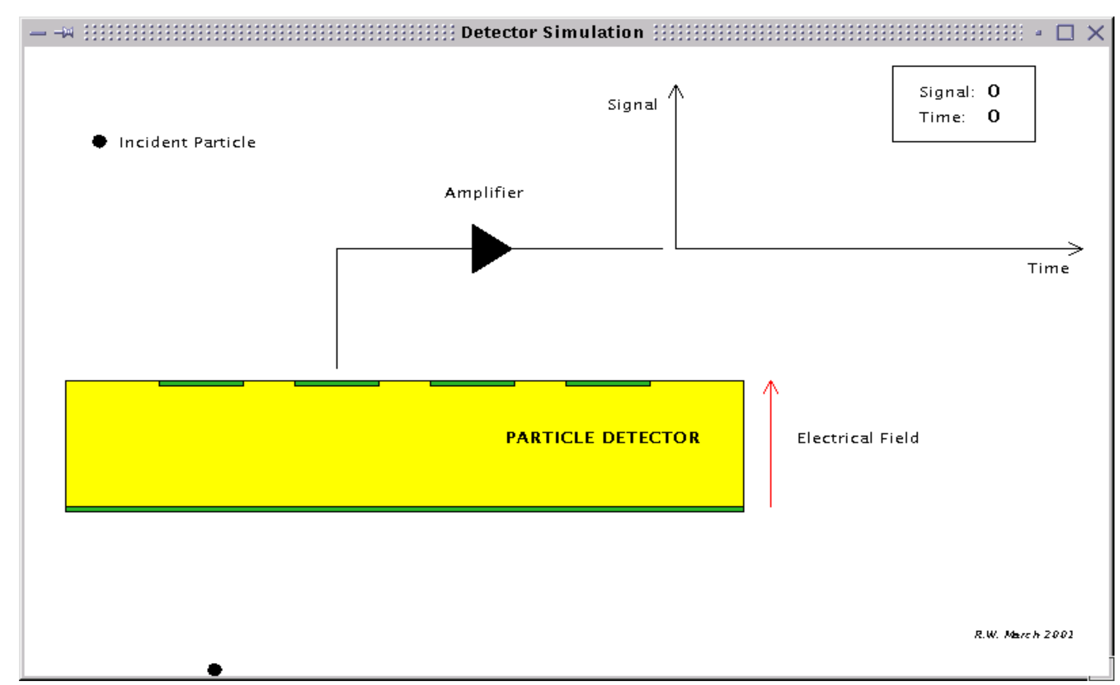
DC coupled strip detector

Traversing charged particles create e^-h^+ pairs in the depletion zone (about 30.000 pairs in 300μm thickness). These charges drift to the electrodes.
The drift (current) creates the signal which is amplified by an amplifier connected to each strip.

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 < 600 V .
- n^+ layer on backplane to improve ohmic contact
- Aluminum metallization



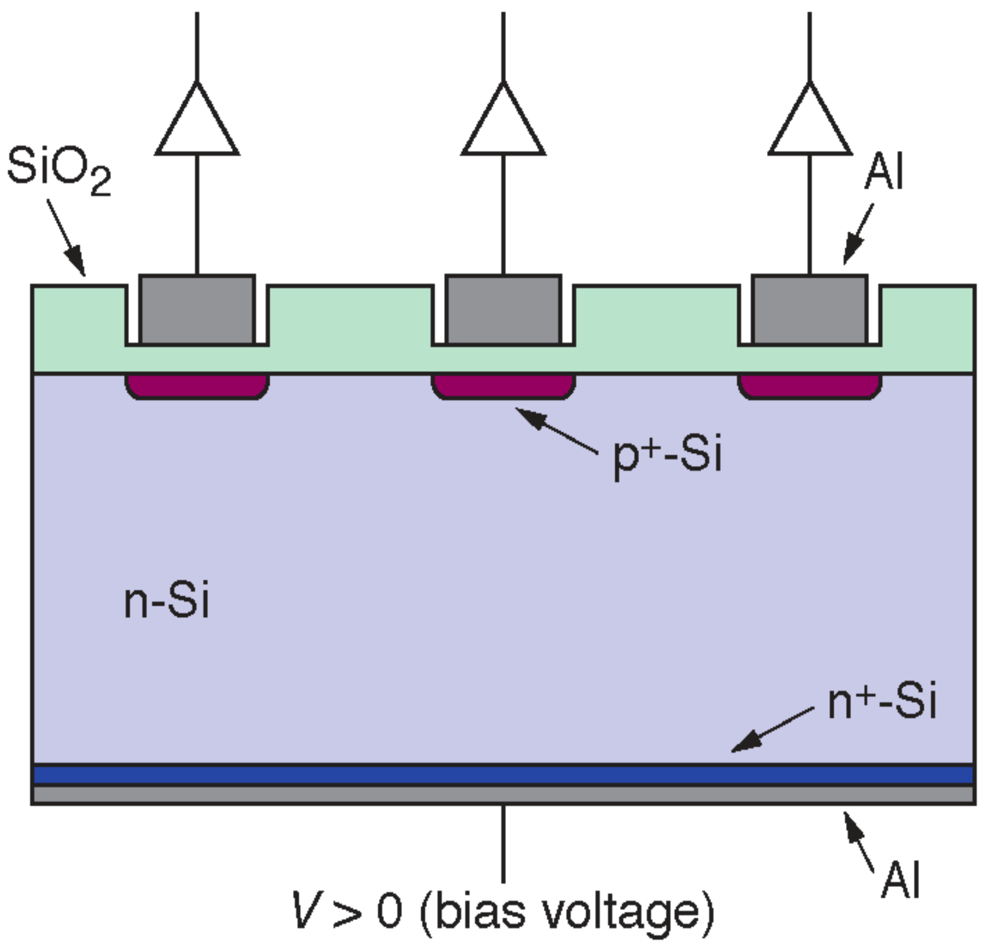
Microstrip Detector

AC coupled strip detector

AC coupling blocks leakage current towards 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.

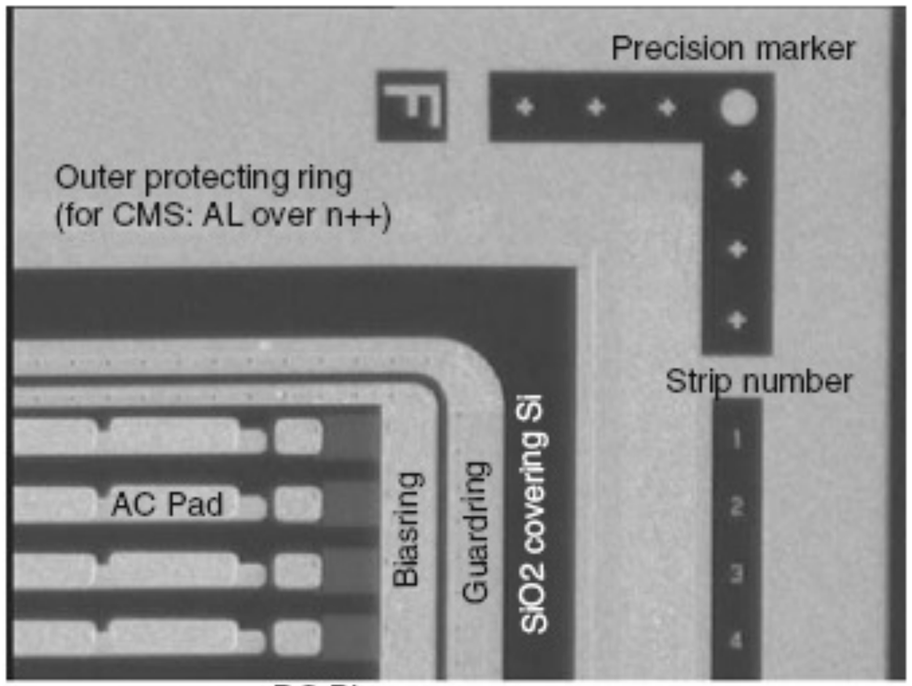
AC coupled strip detector:



However, the dielectric cuts the bias connection to the strips!
Several methods to connect the bias voltage:
polysilicon resistor, punch through bias, FOXFET bias.

Microstrip Detector

a real life case - p-in-n



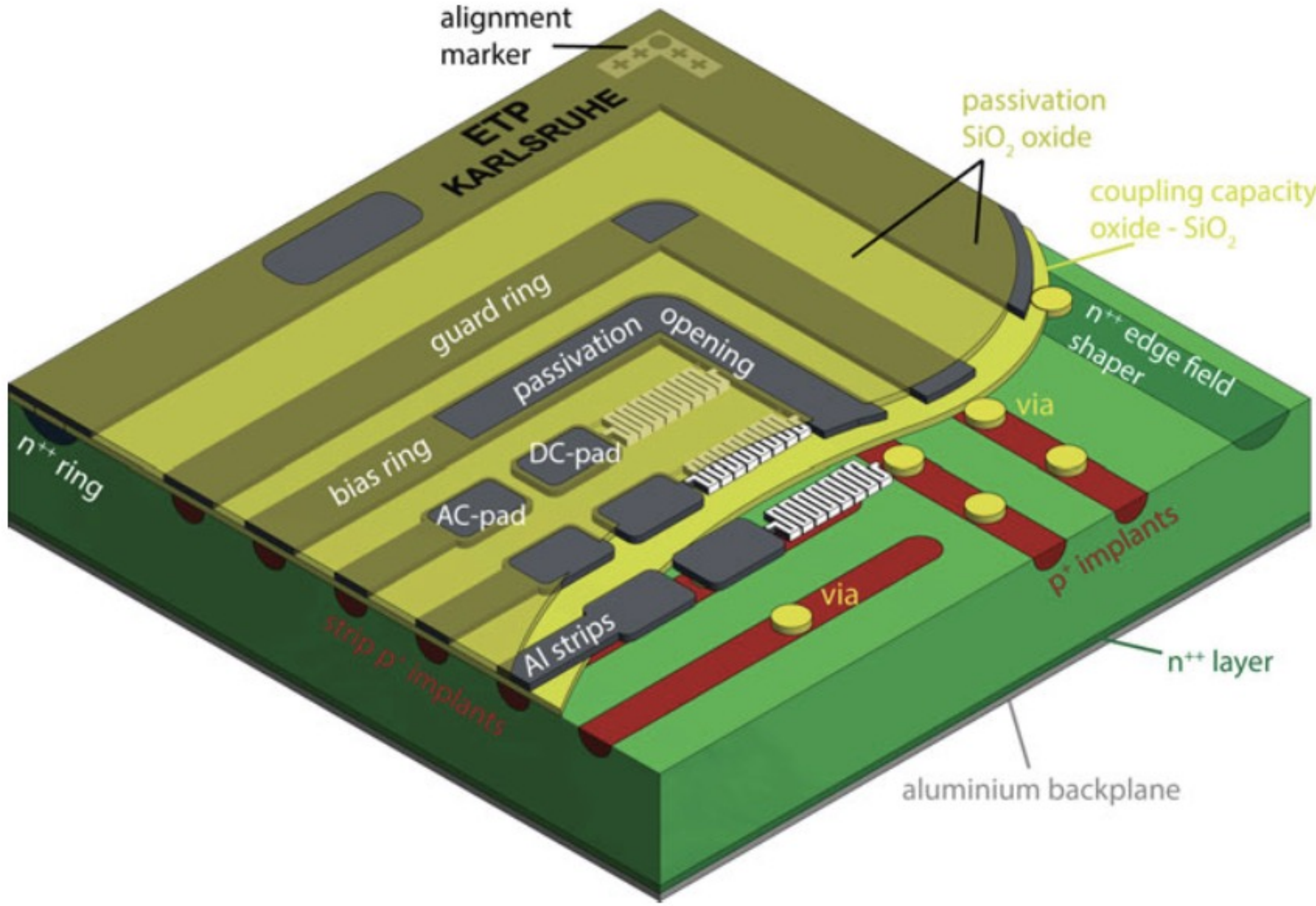
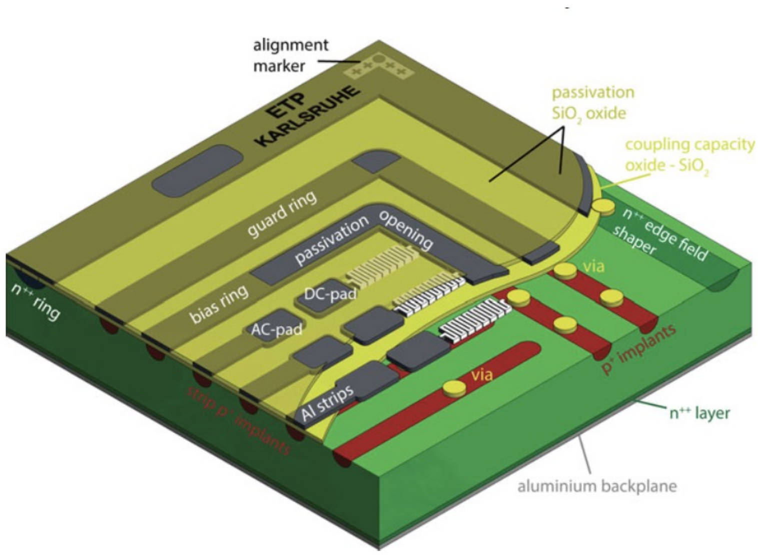
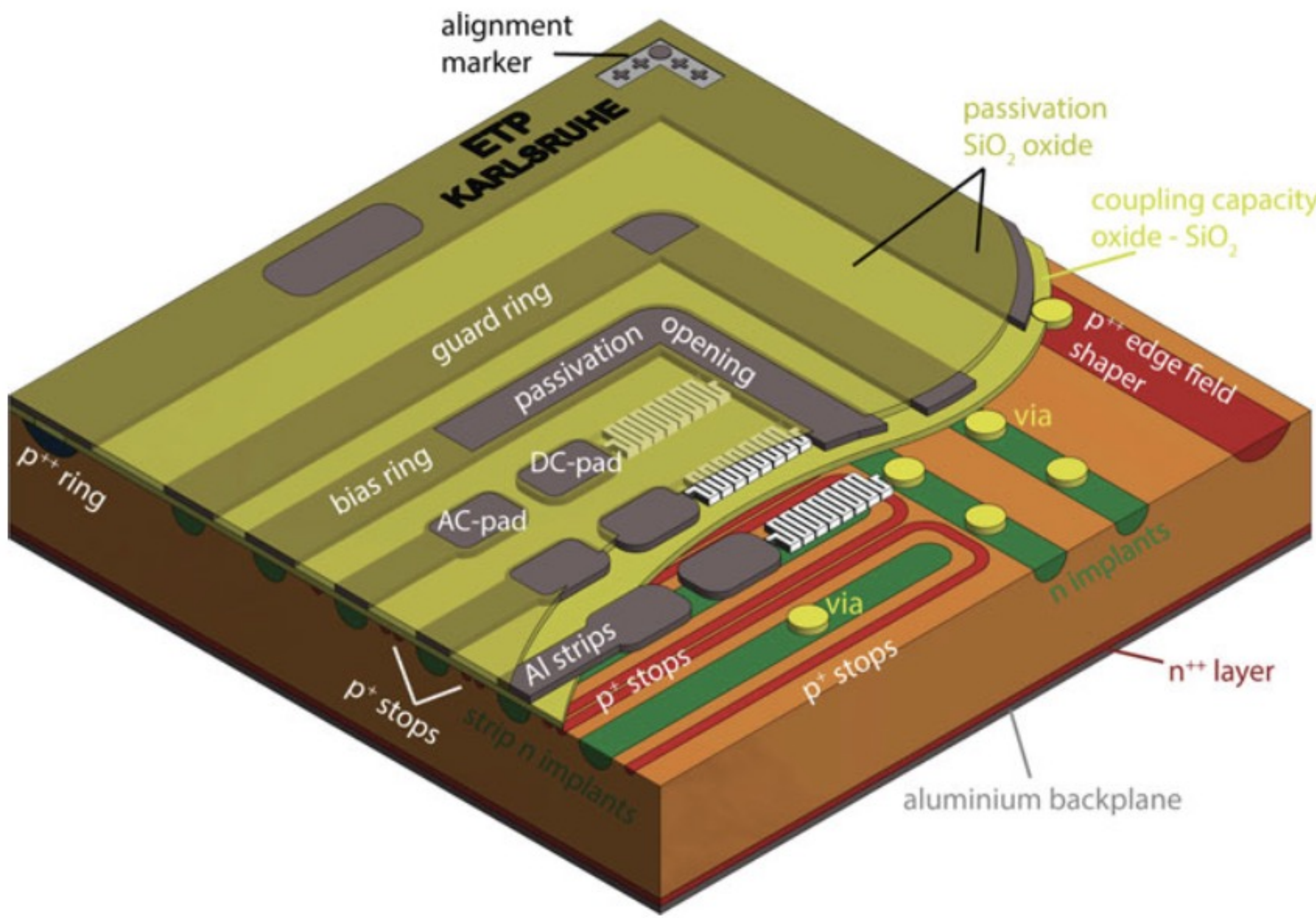


Fig. 1.19 A 3D schematic is sketched. It shows the baseline of the CMS sensor at the LHC in 2008, but could represent basically any single-sided AC-coupled, R_{poly} biased sensor. In operation, the bias ring is connected to GND potential, which is then distributed to the p+ implant strips, while the Al backplane is set to positive high voltage depleting the full n-bulk volume by forming a pn-junction p+ strip to n-bulk. The coupling capacitor is defined between aluminium strip and p+ implant, the inter-strip capacity between neighbouring strips (both p+ and Al part). The guard ring shapes the field at the borders. The n++ ring defines the volume and prevents high field in the real cut edge regions

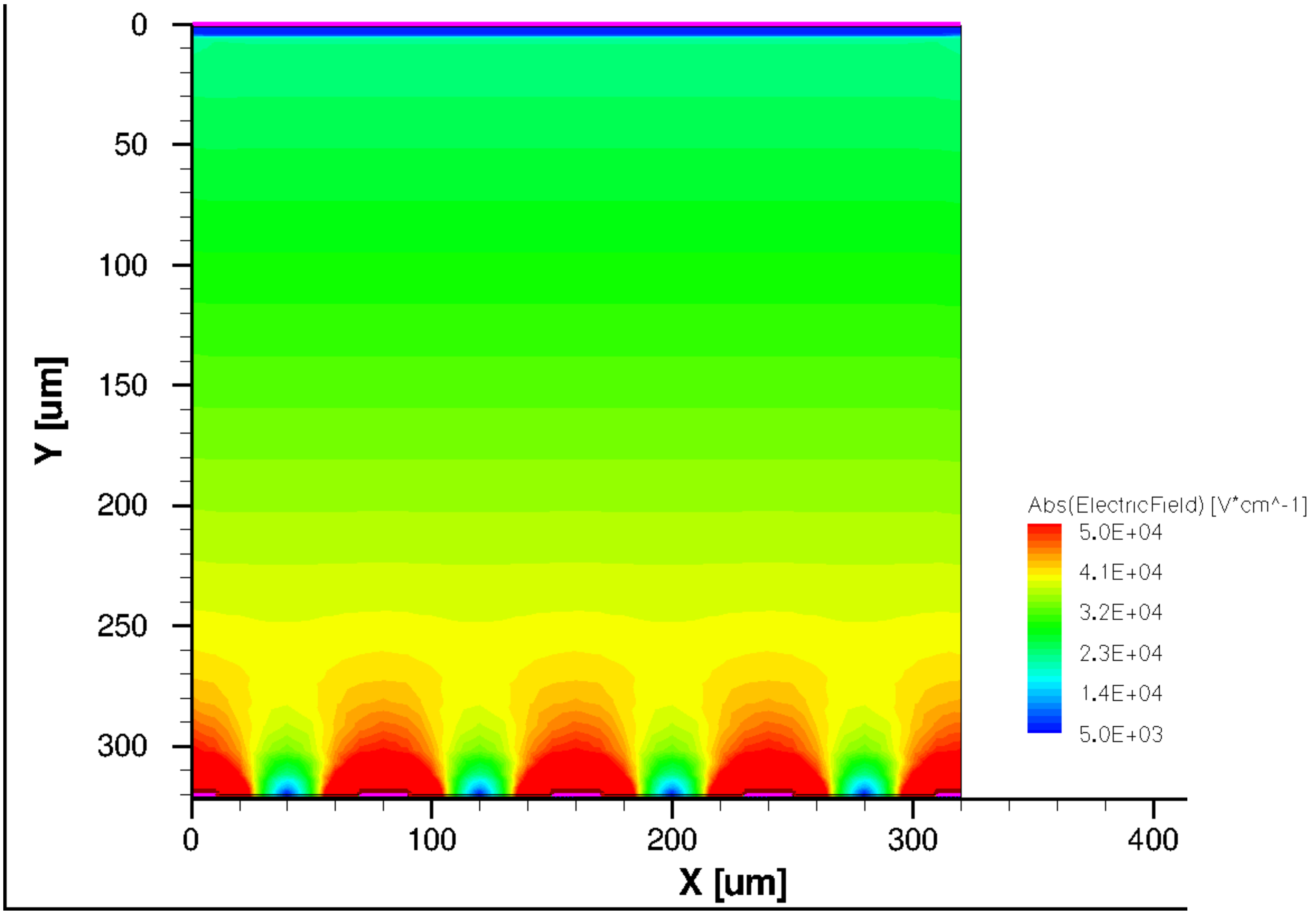
n-in-p sensor (for Phase 2 aka HL-LHC)



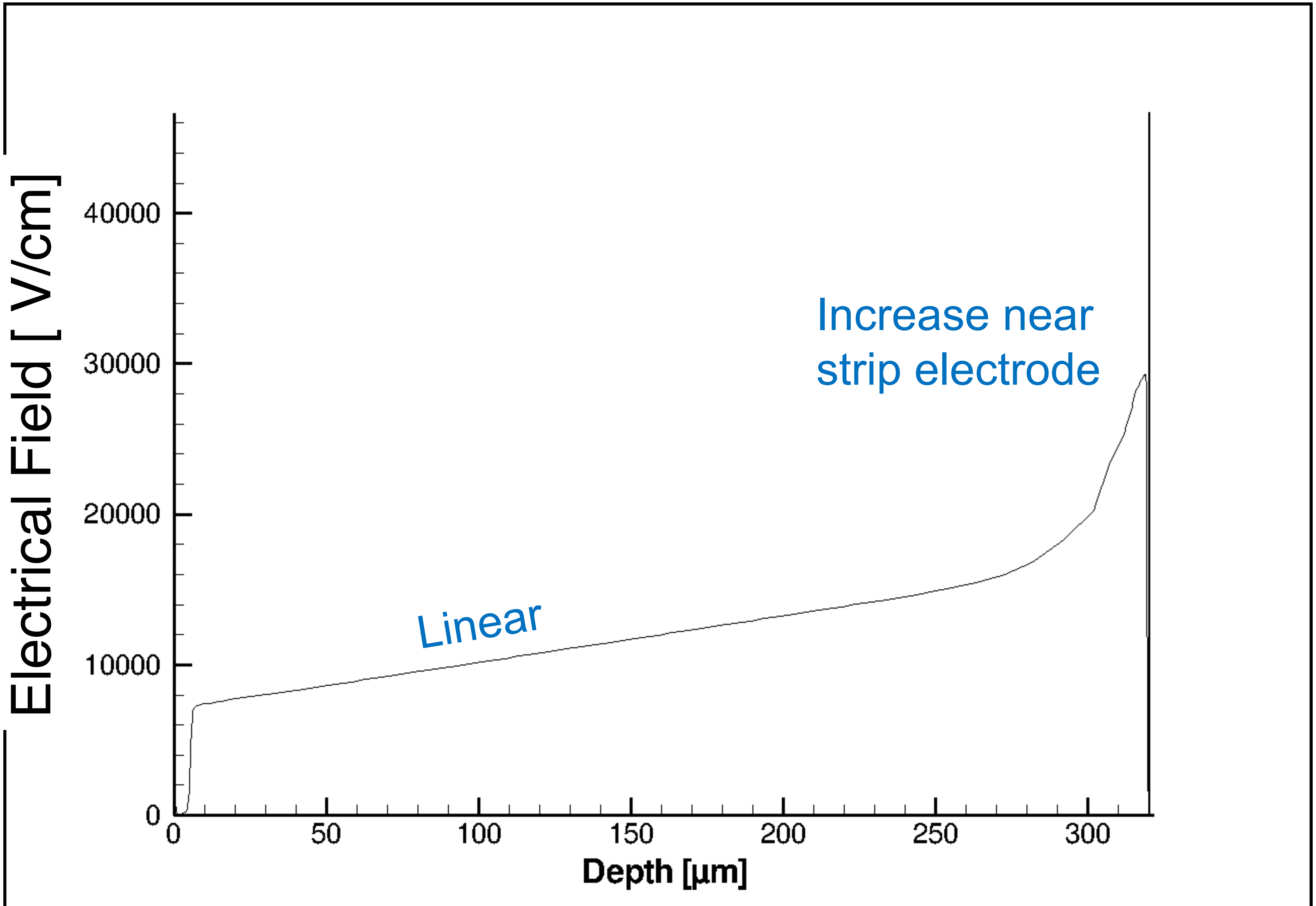
Invert everything
... and add channel isolation (here p-stops)



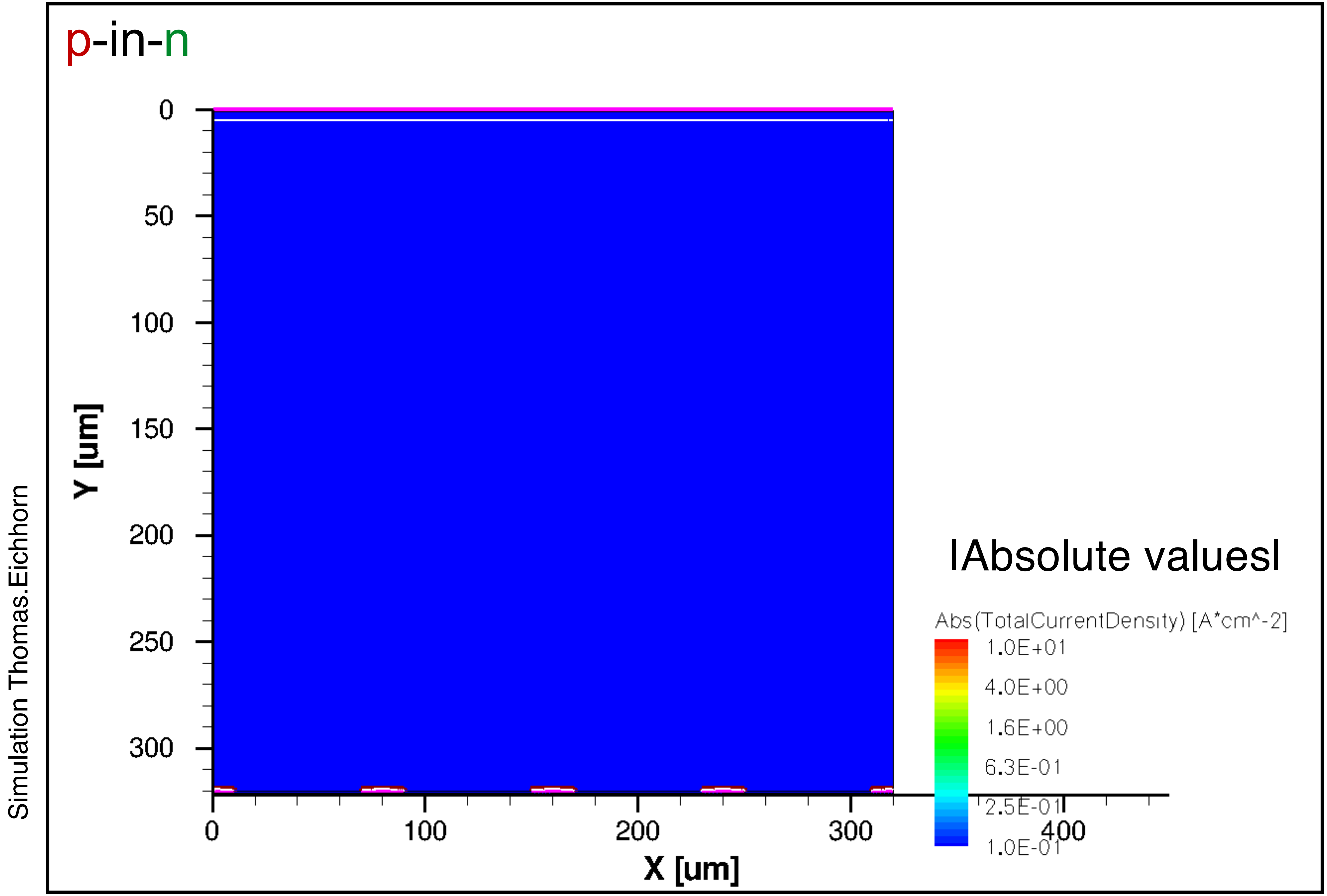
Electrical Field Configuration of a Strip Sensor p-in-n

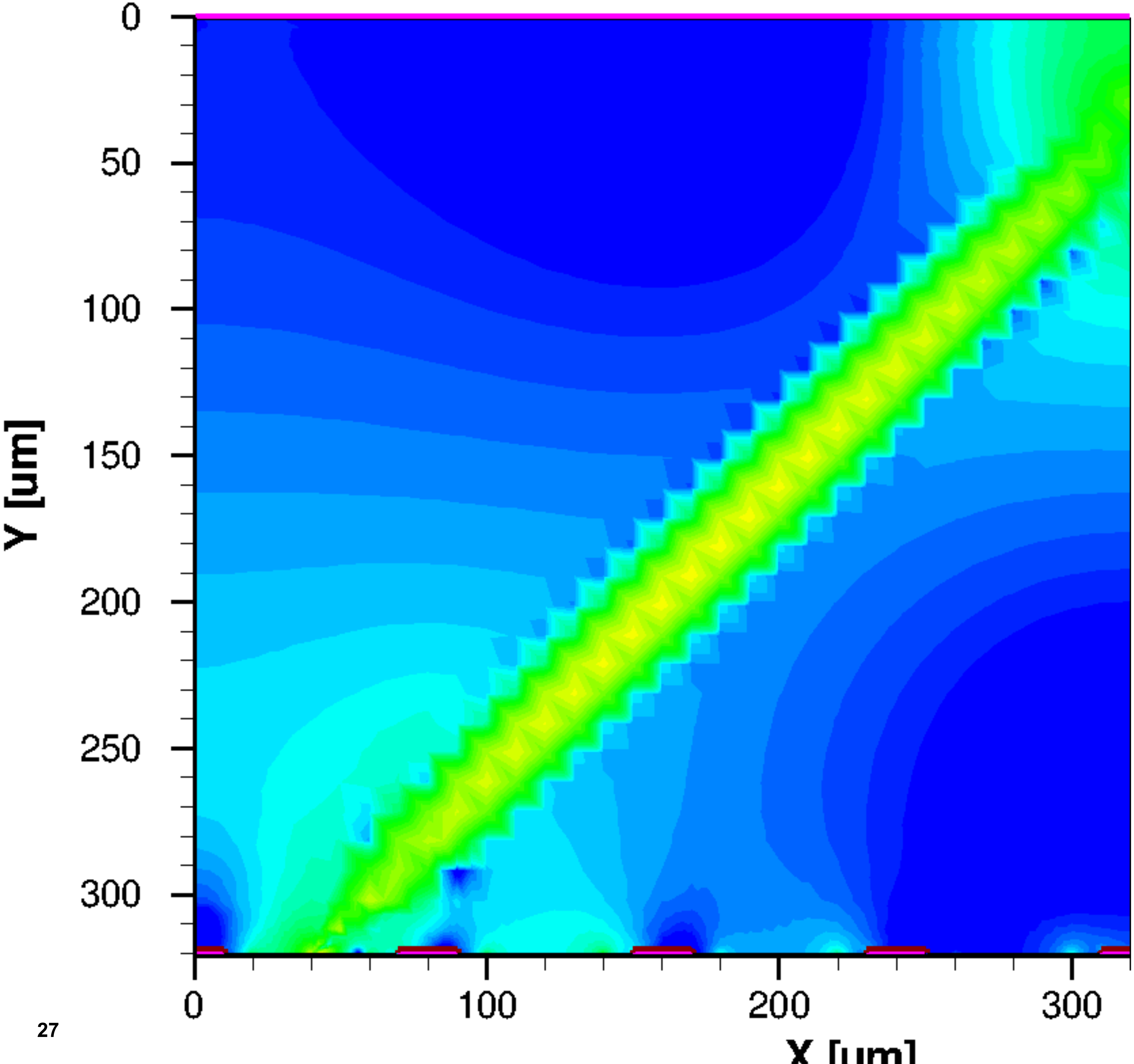


Electrical Field across a Strip

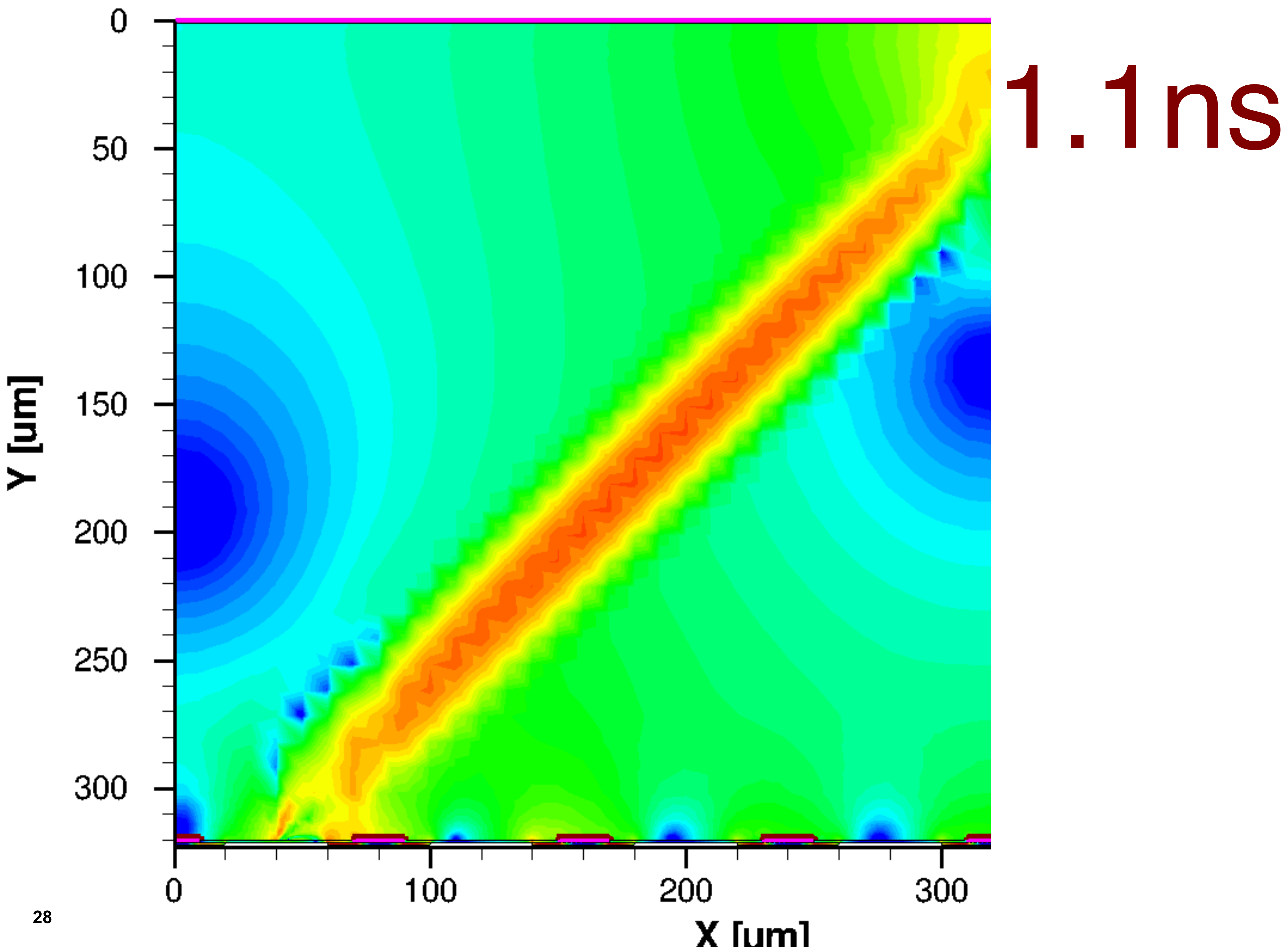


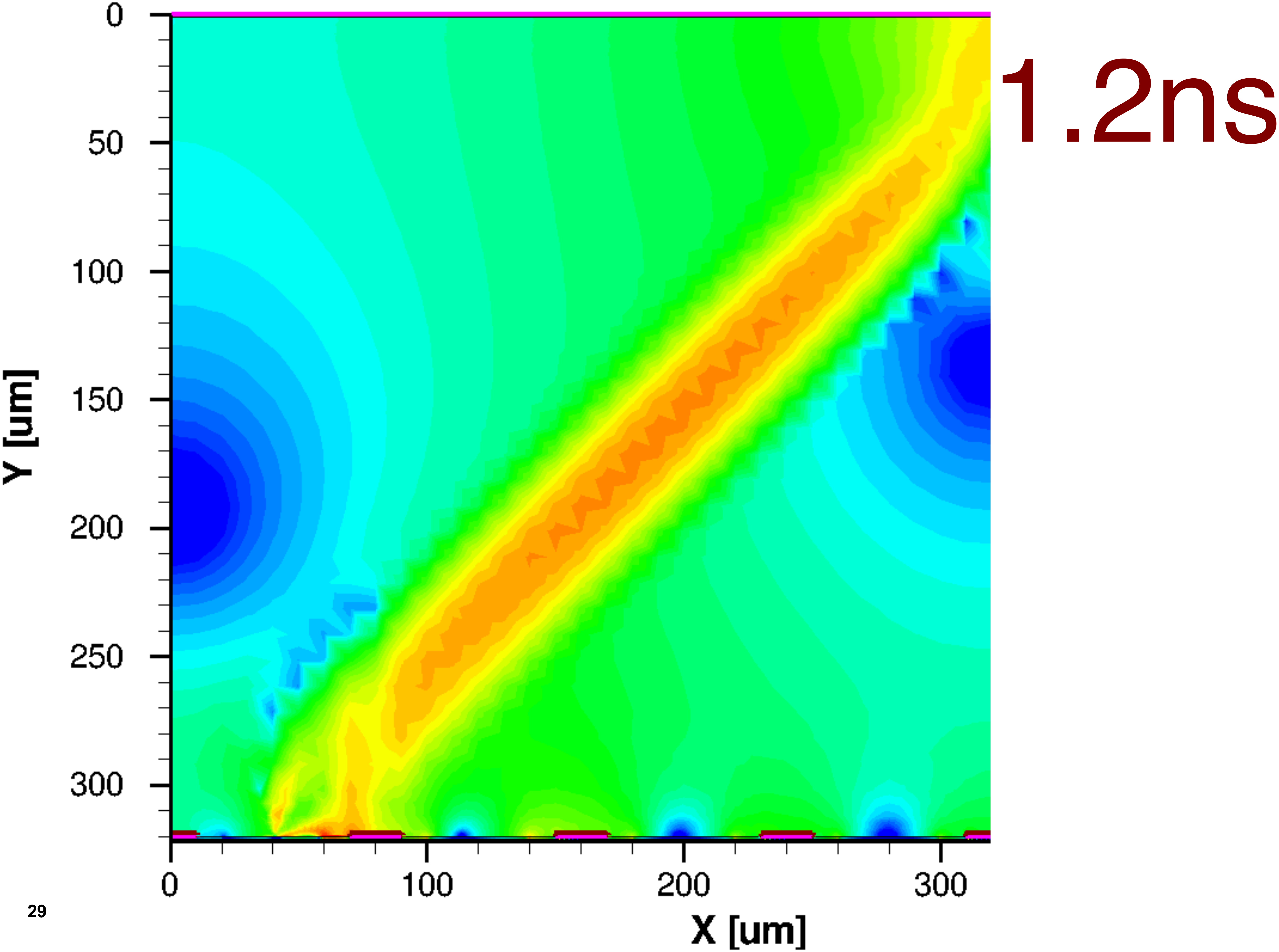
Simulated Current Density
Ionizing particle with 45° angle t=0 s

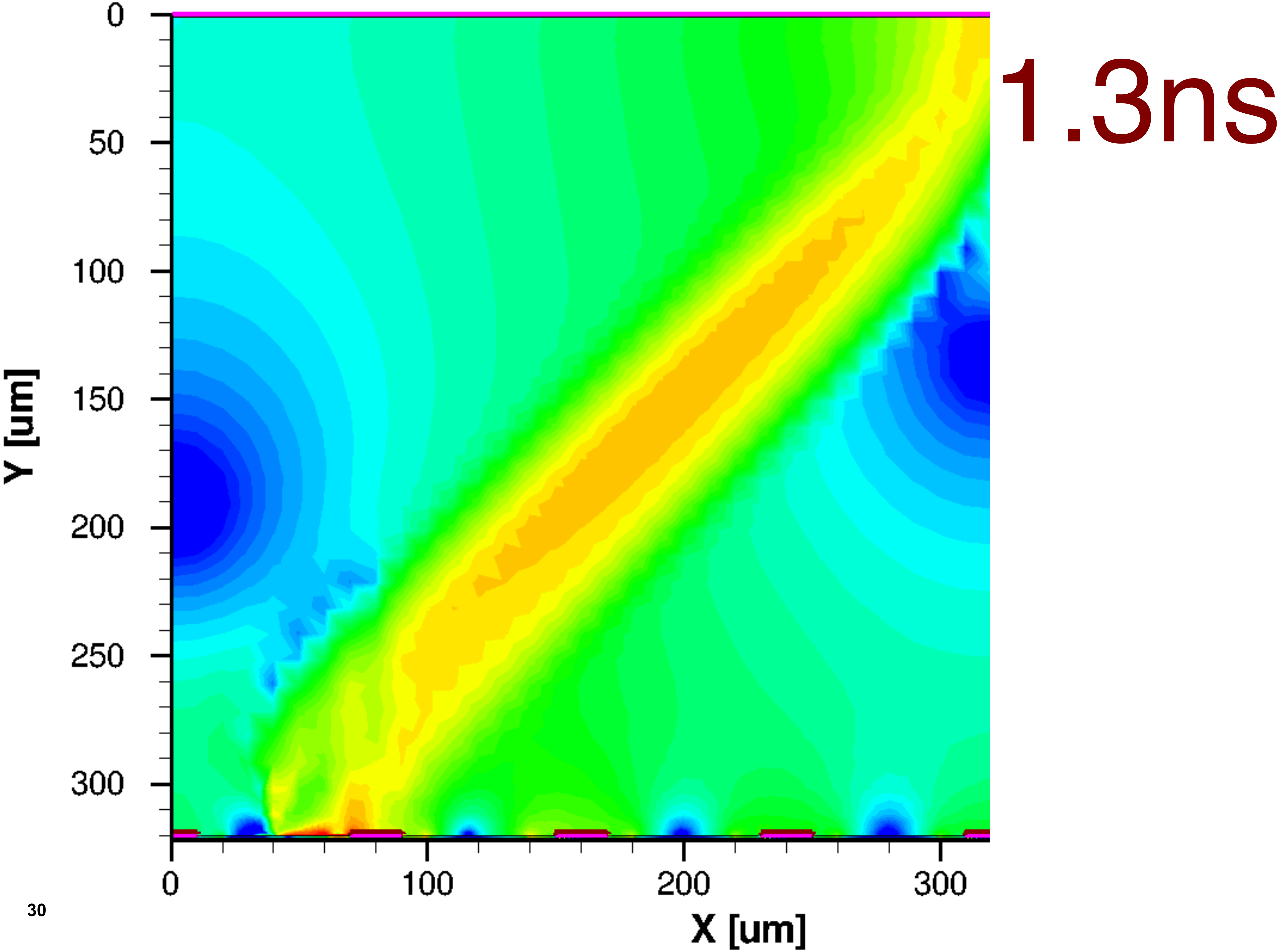




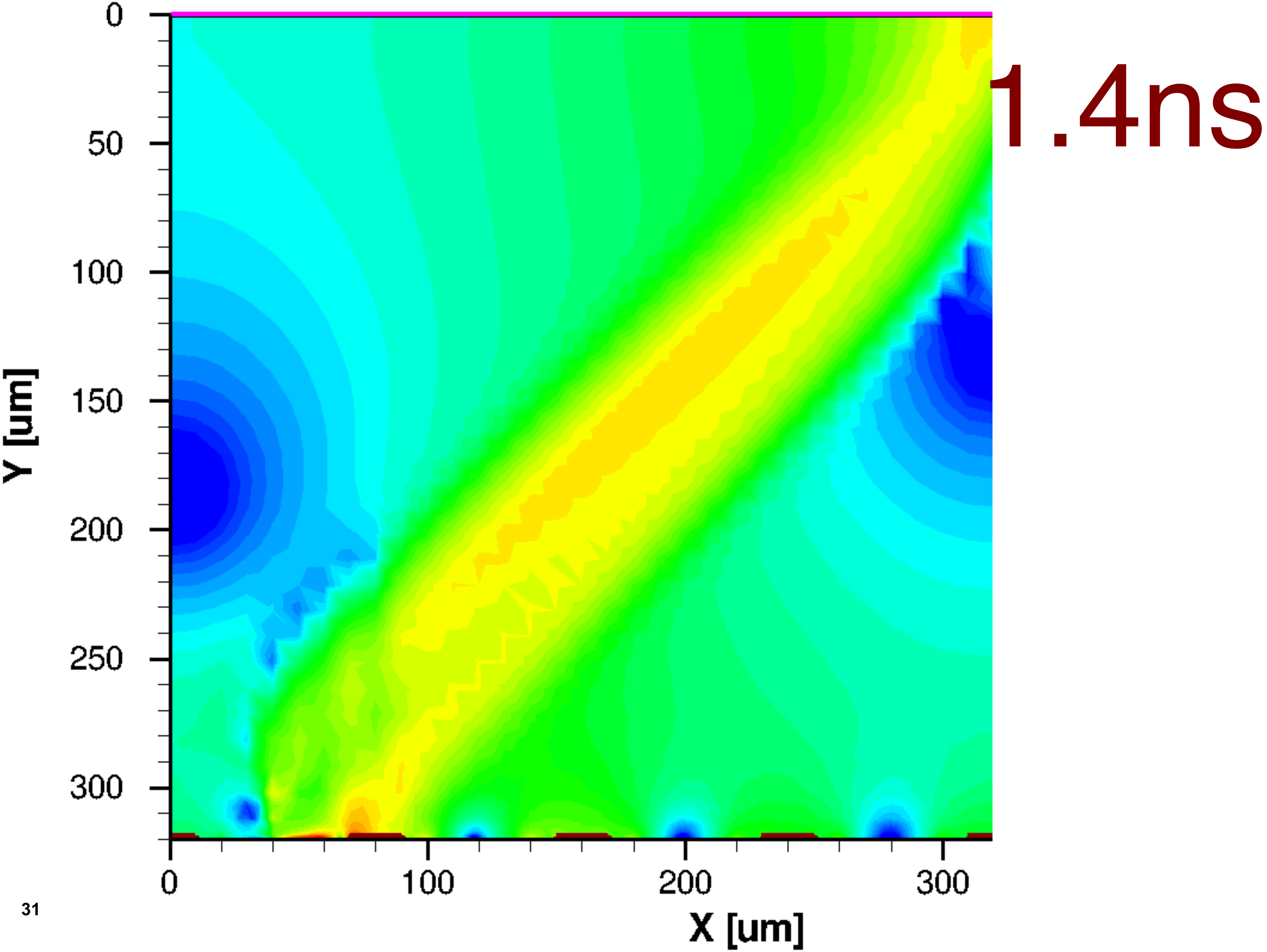
1ns

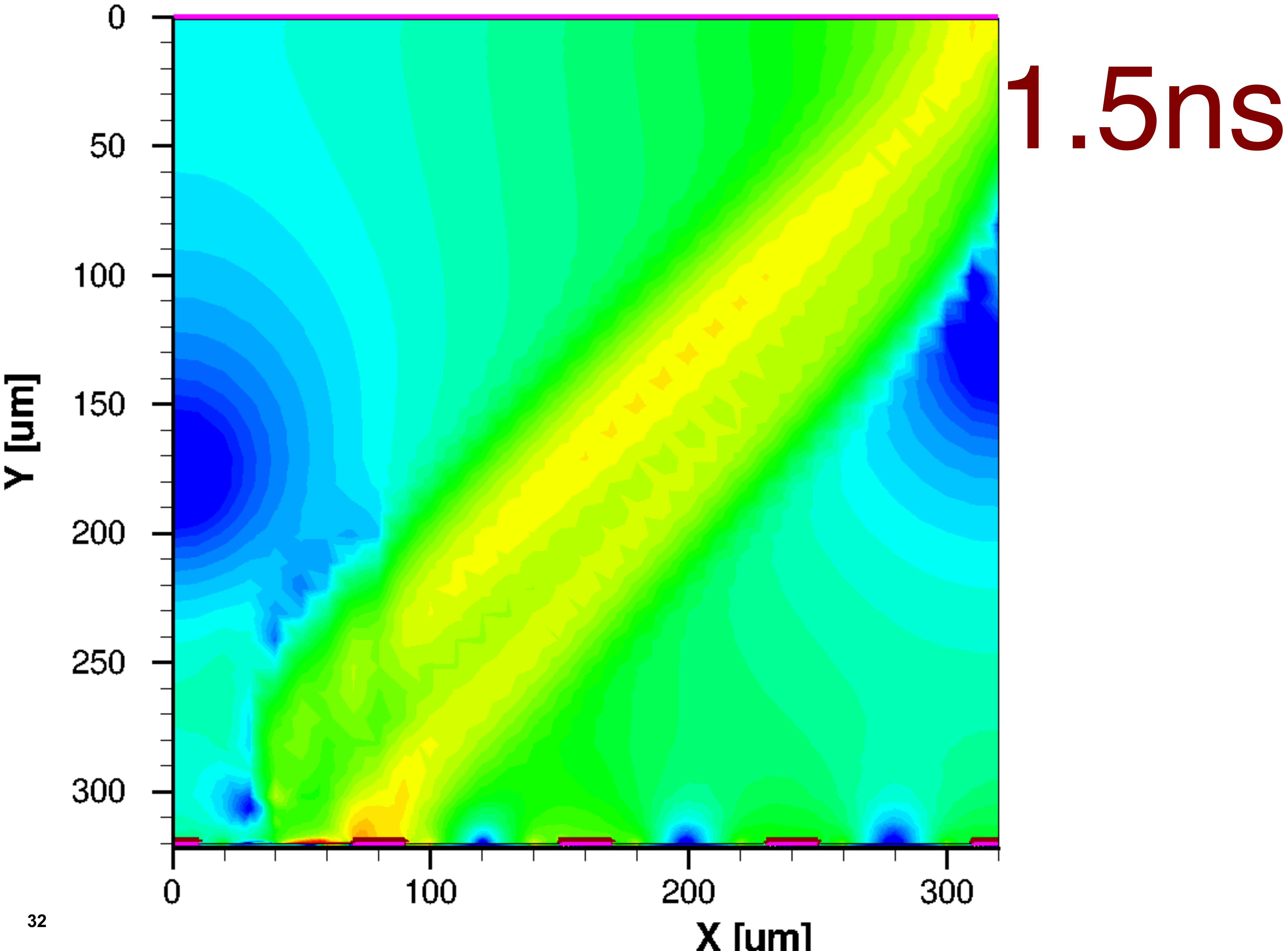

1.1ns
0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]

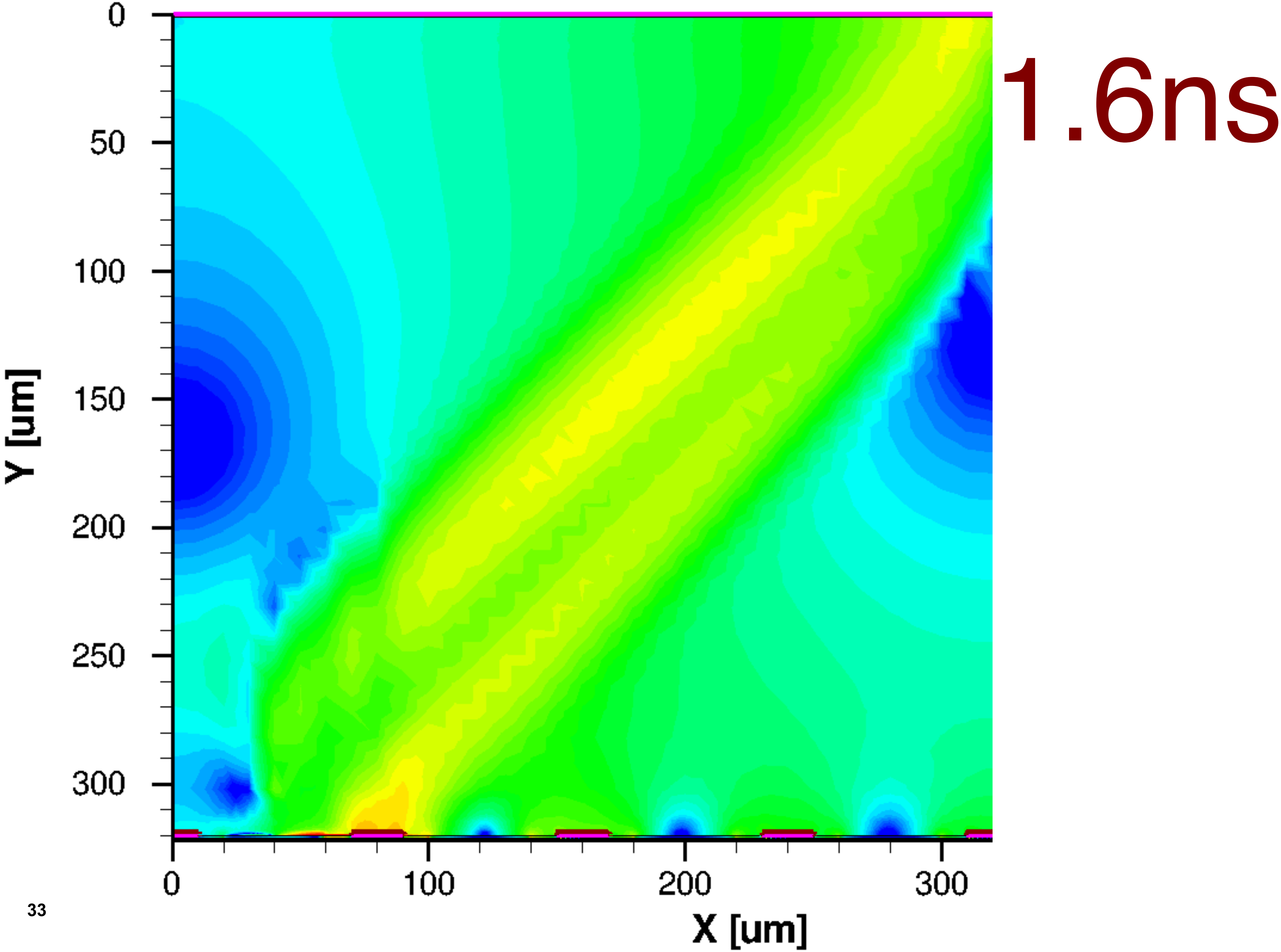

0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]
1.2ns

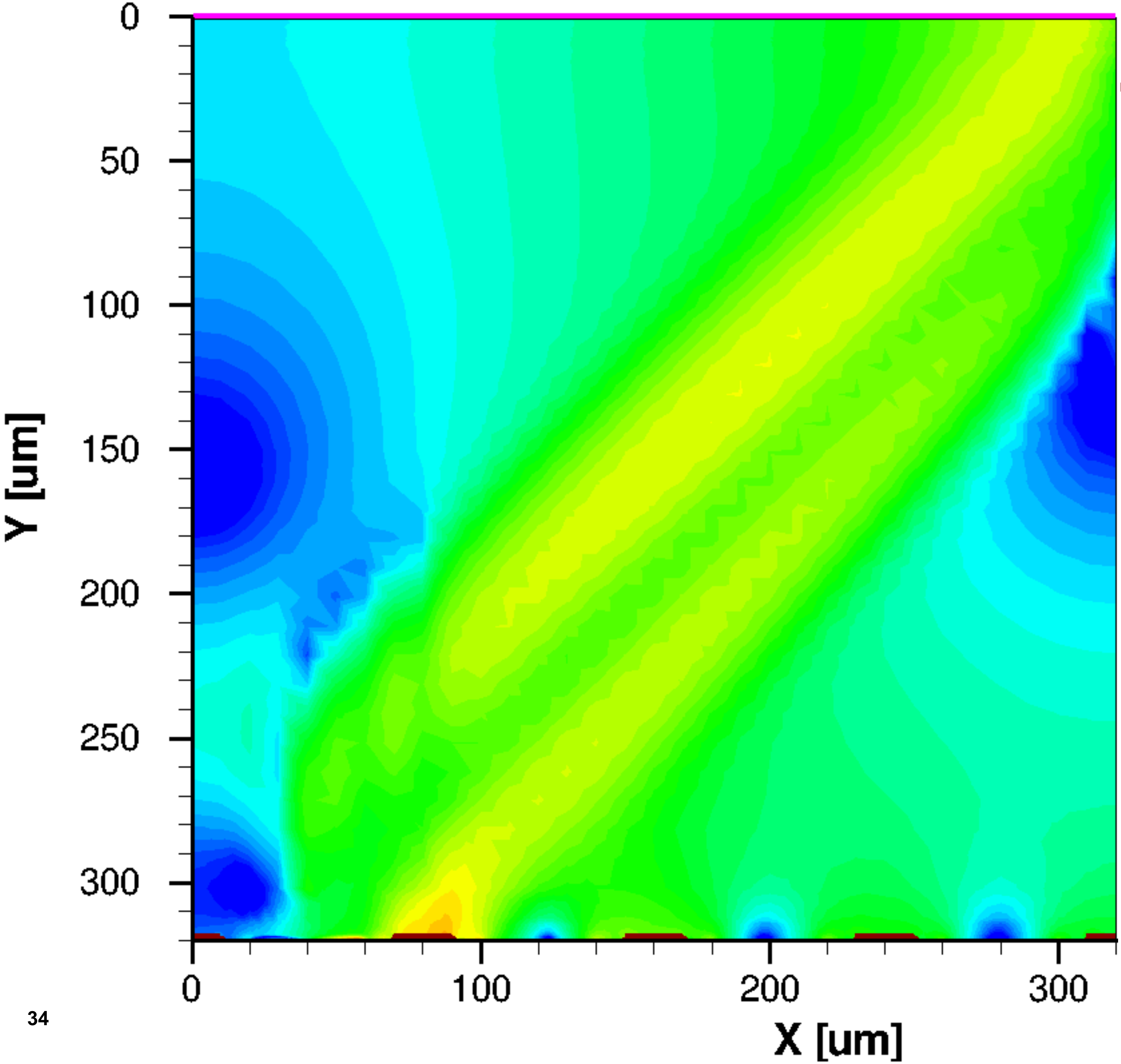


0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]
1.3ns

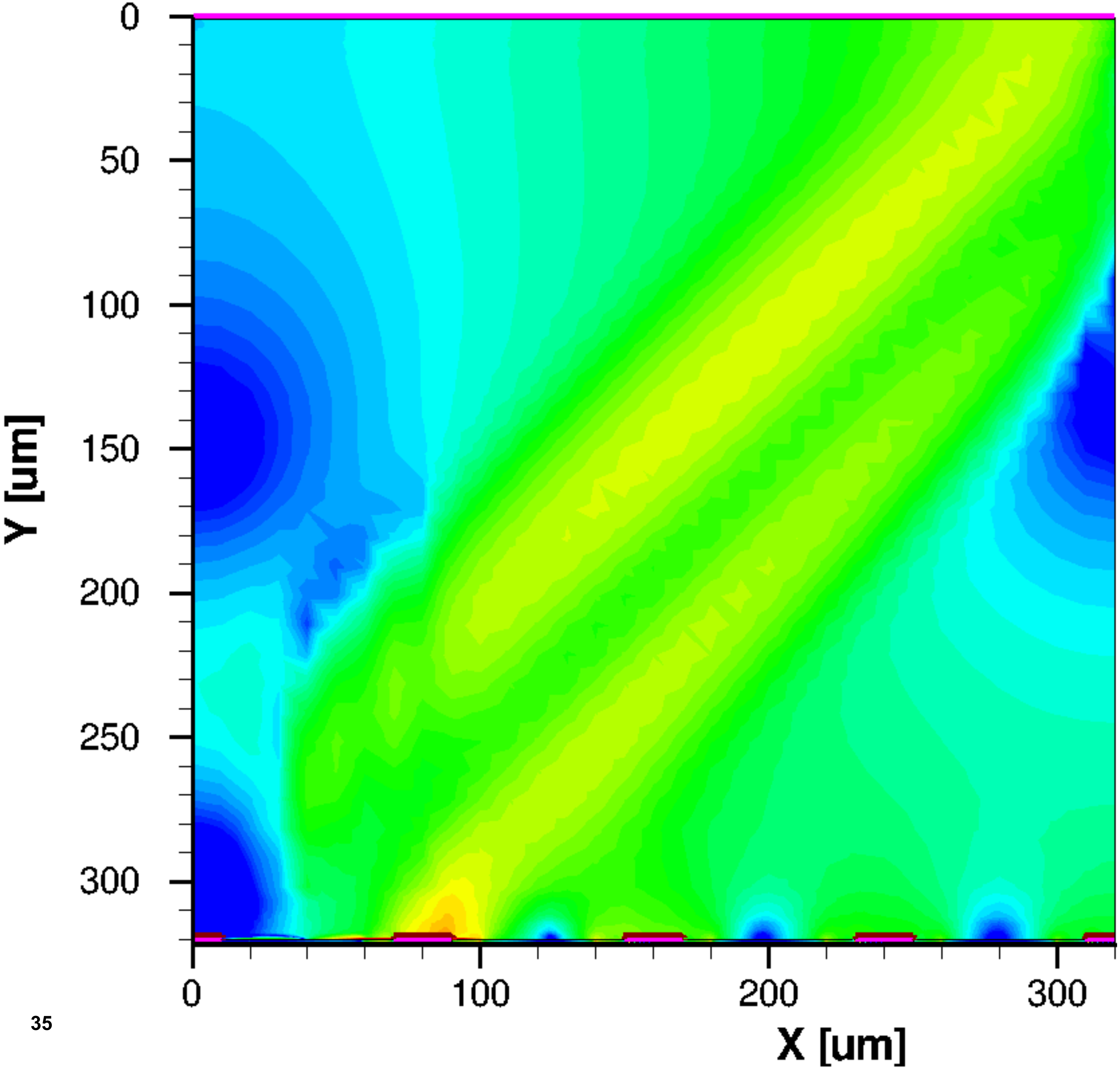

1.4ns
Y [um]
X [um]
0
50
100
150
200
250
300
0
100
200
300


1.5ns
Y [um]
X [um]
0
50
100
150
200
250
300
0
100
200
300

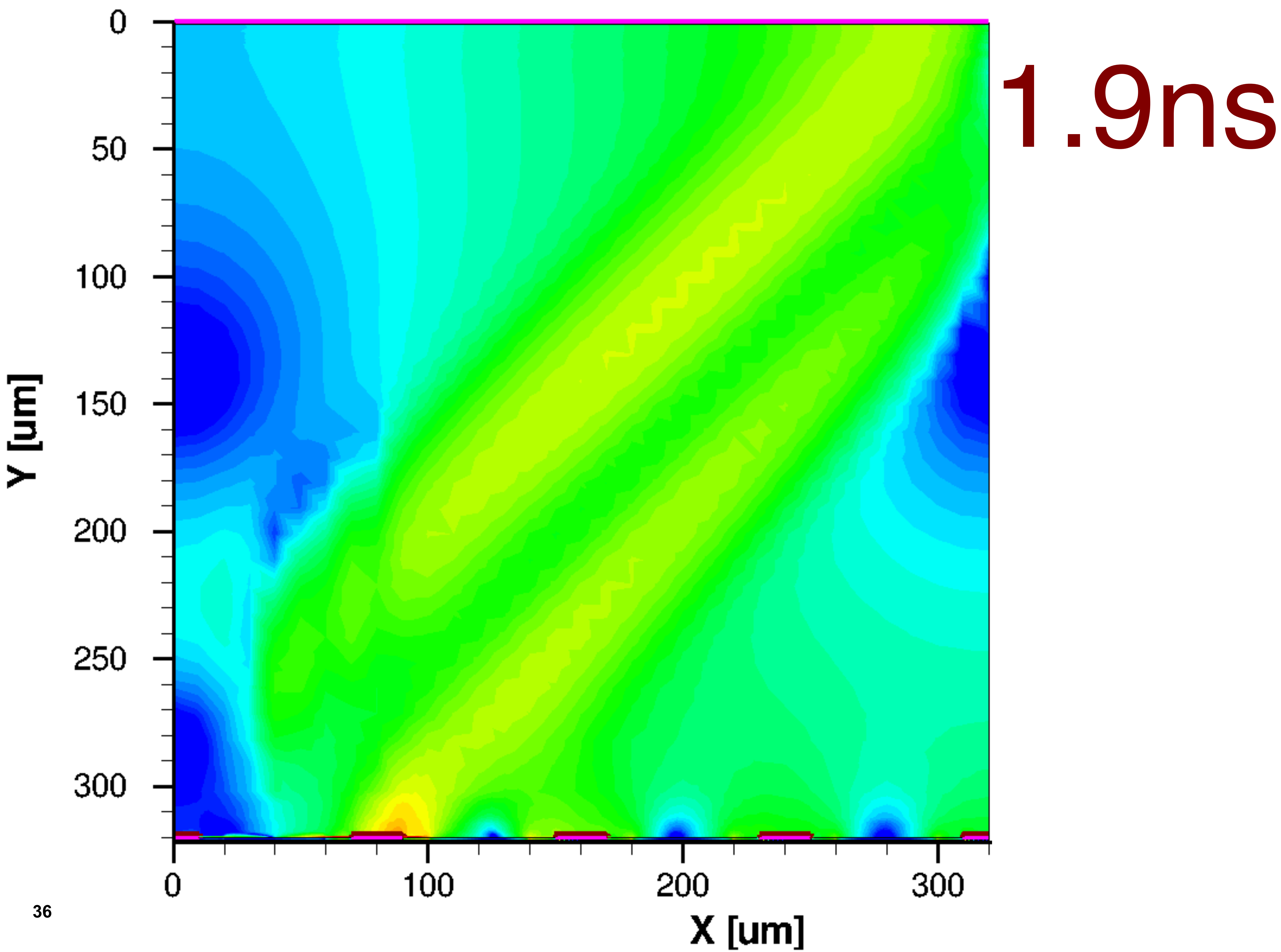

0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]
1.6ns

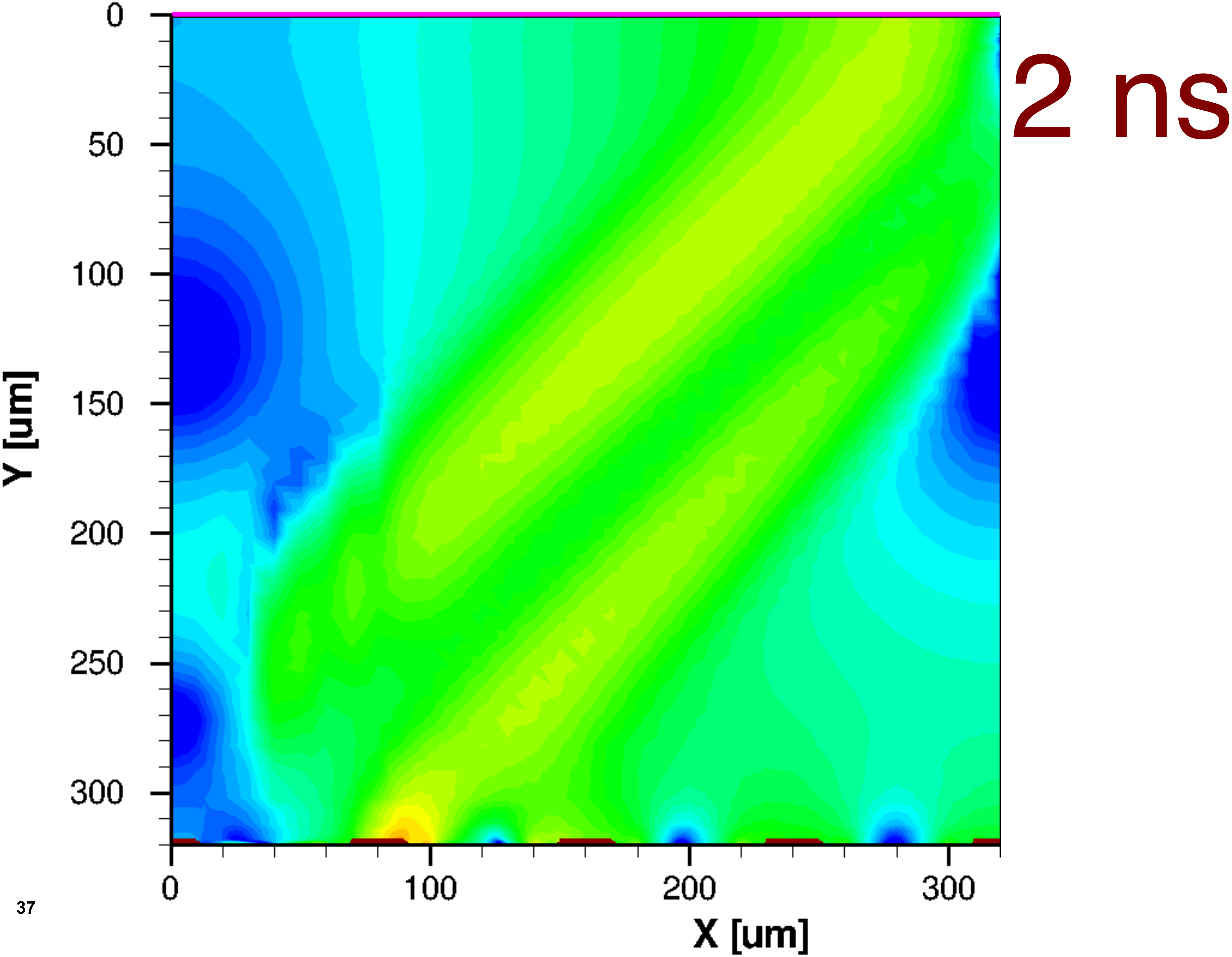


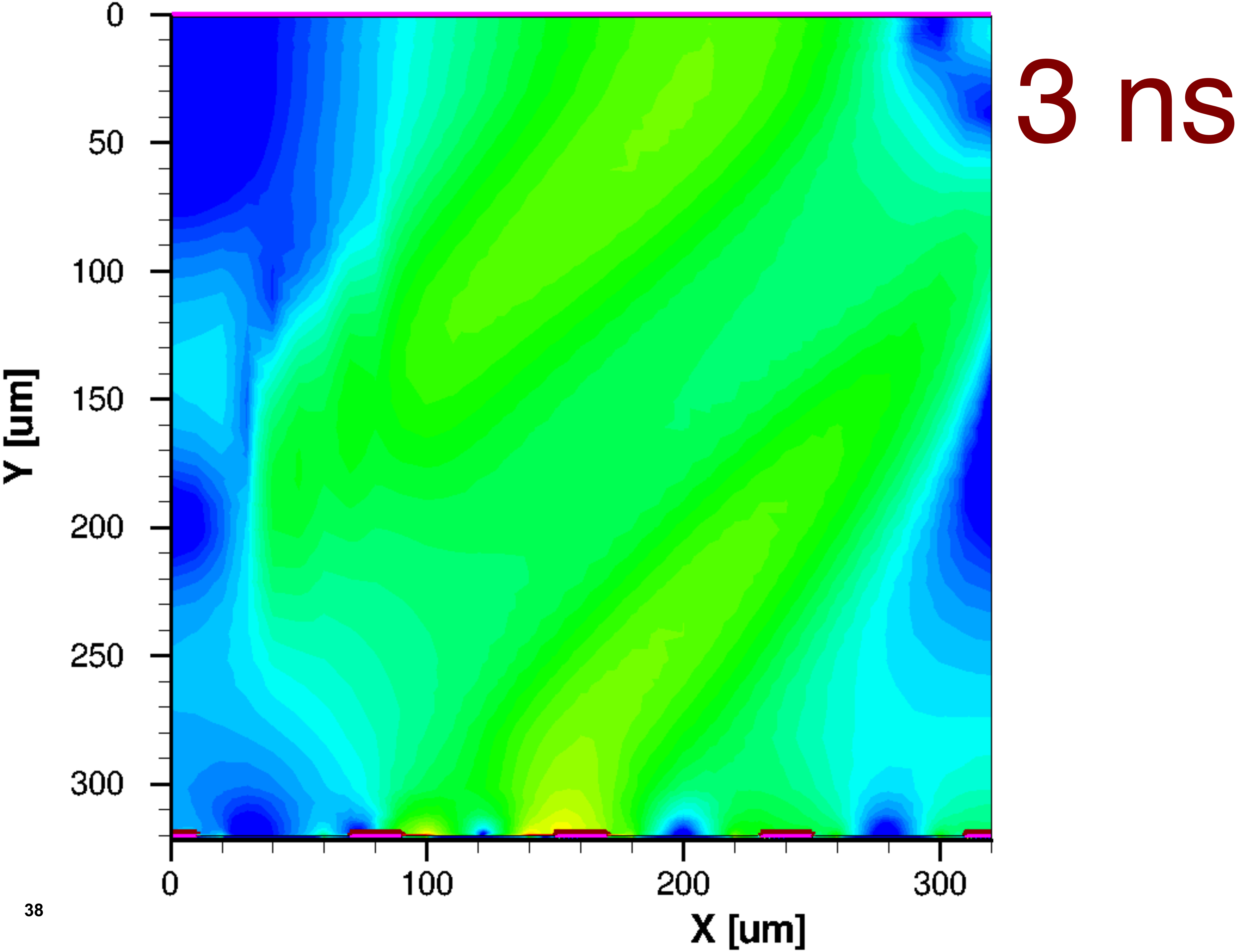
1.7ns

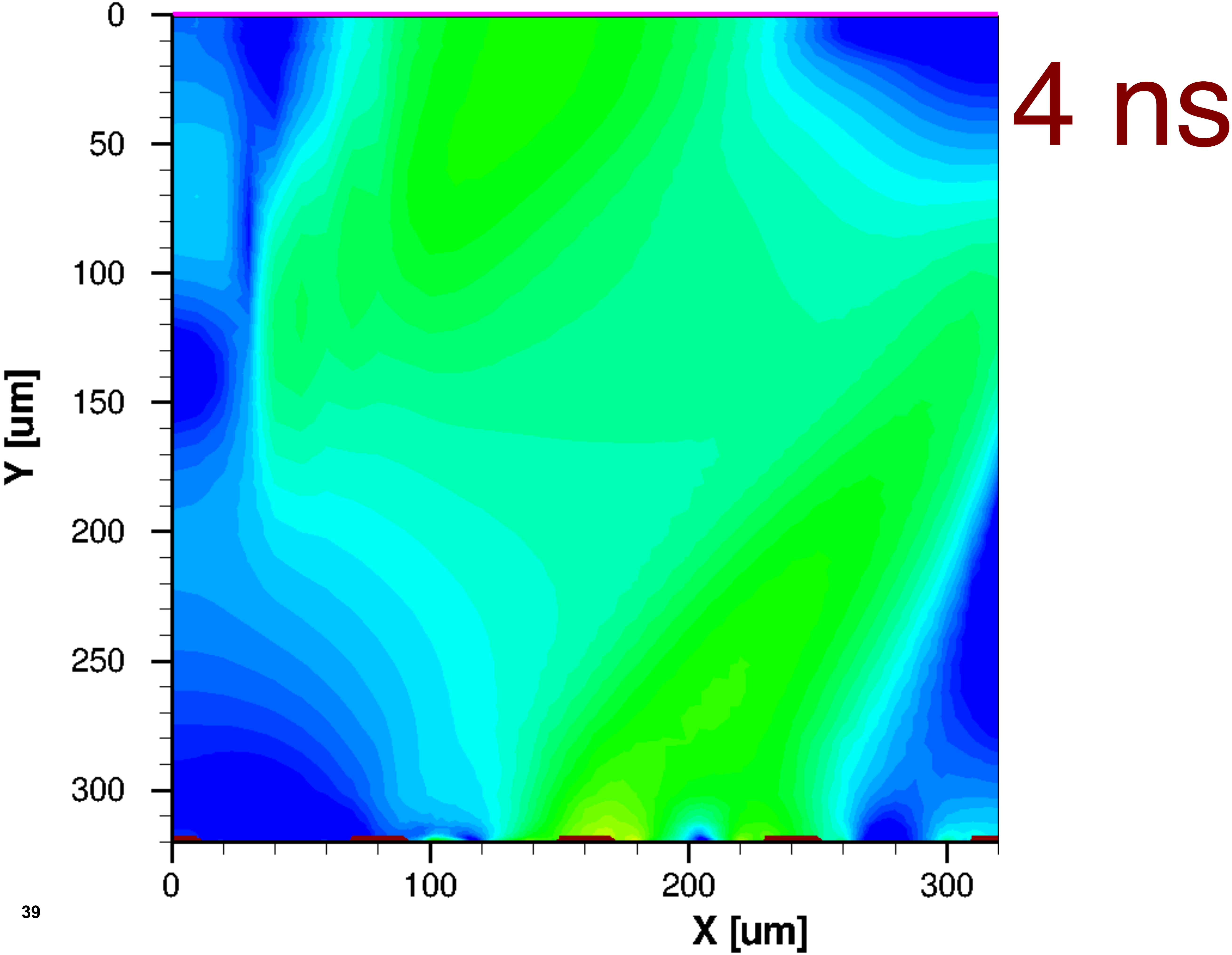


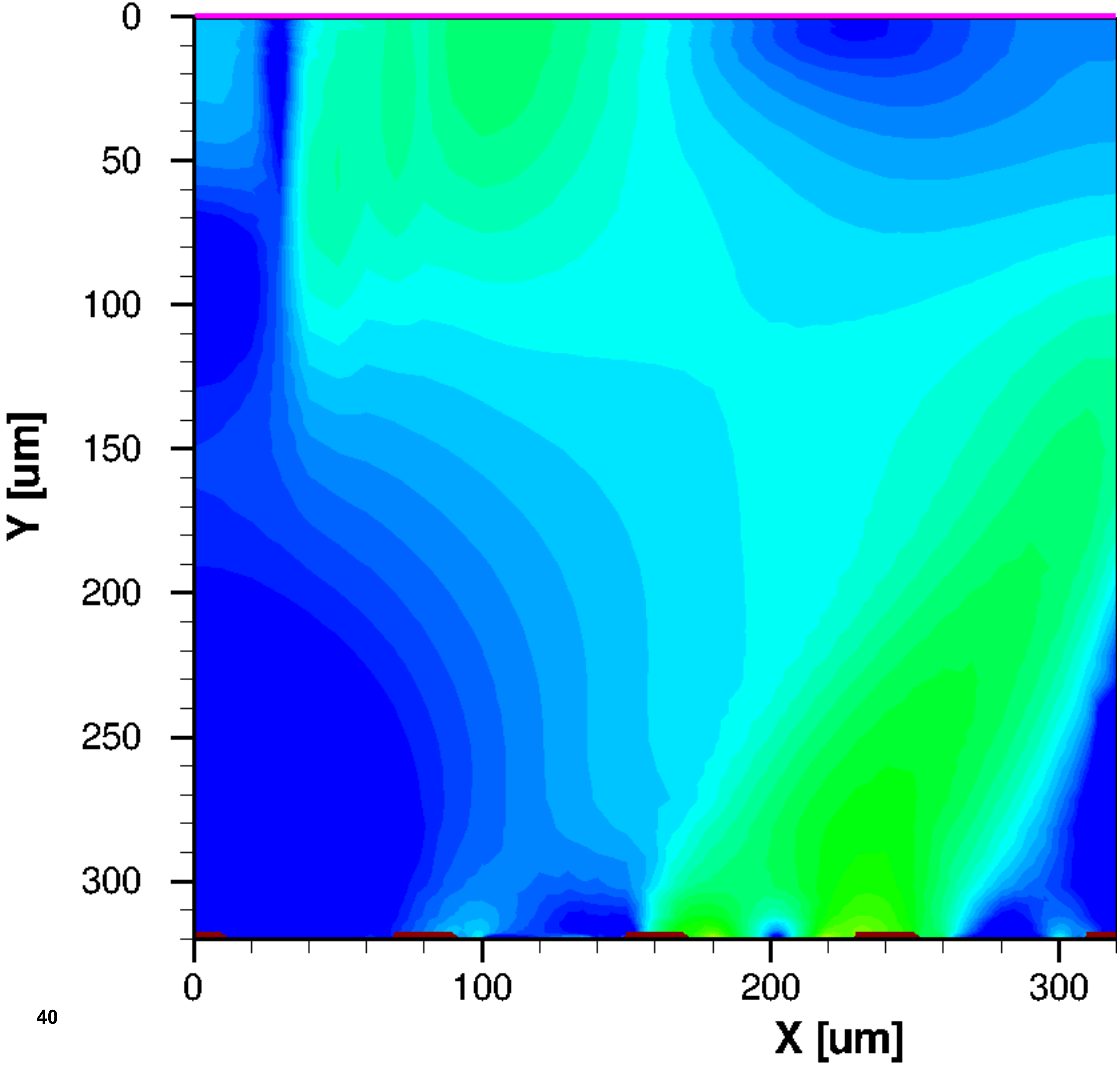
1.8ns


1.9ns
Y [um]
X [um]
0
50
100
150
200
250
300
0
100
200
300

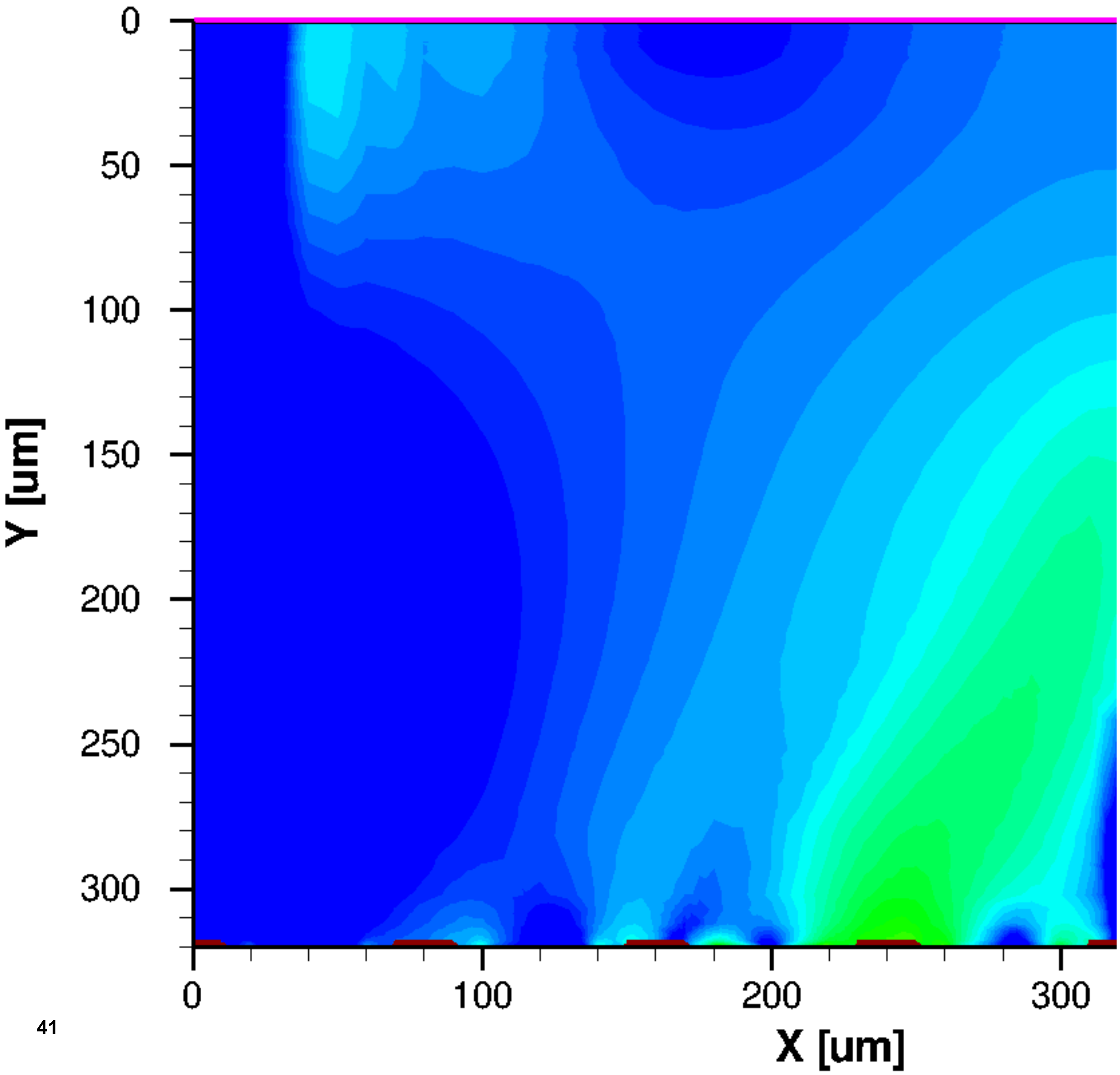

2 ns
Y [um]
X [um]
0
50
100
150
200
250
300
0
100
200
300


0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]
3 ns

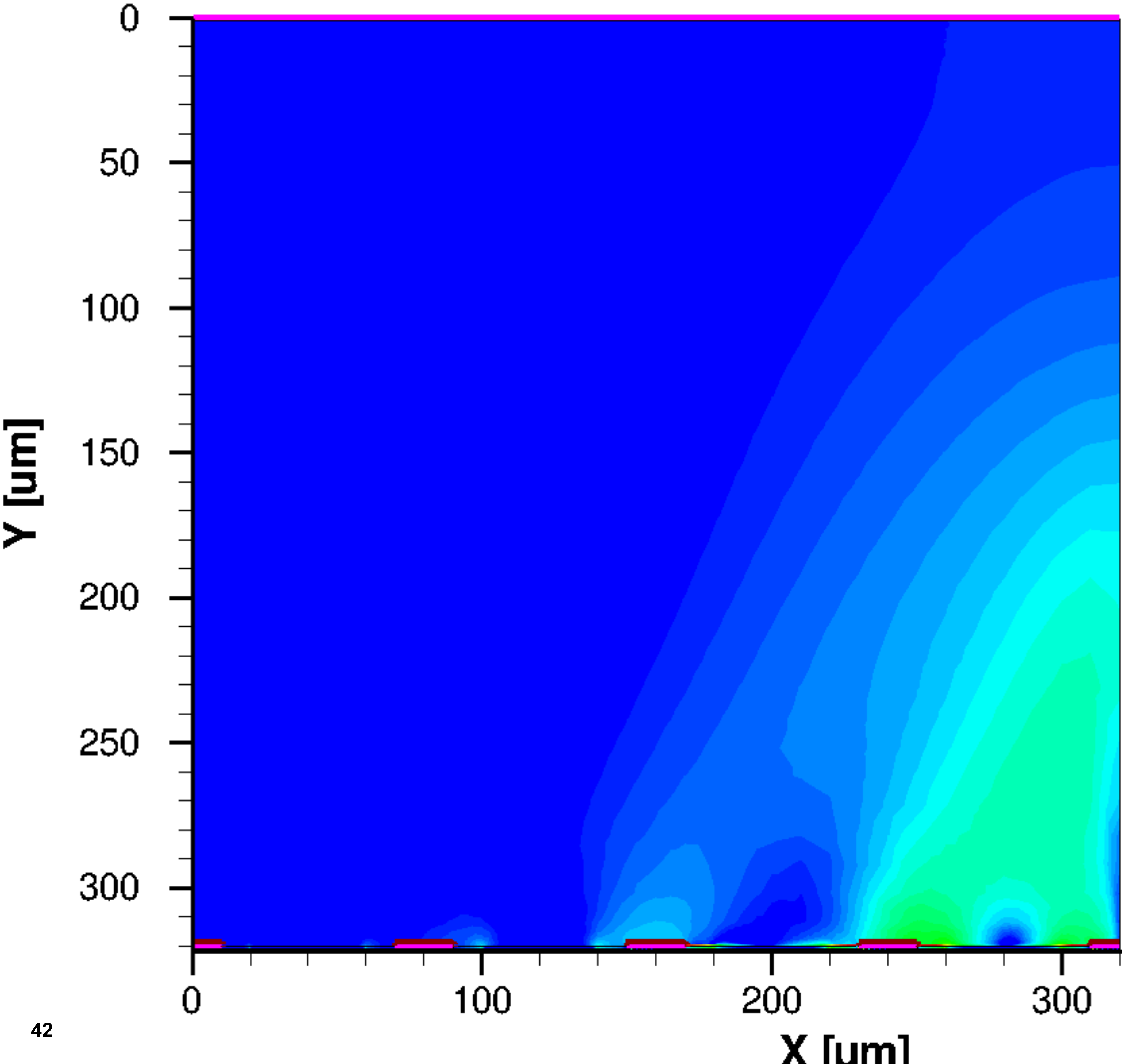

4 ns
Y [um]
X [um]
0
50
100
150
200
250
300
0
100
200
300



5 ns



6 ns



7 ns

Mind:
all electrons
collected

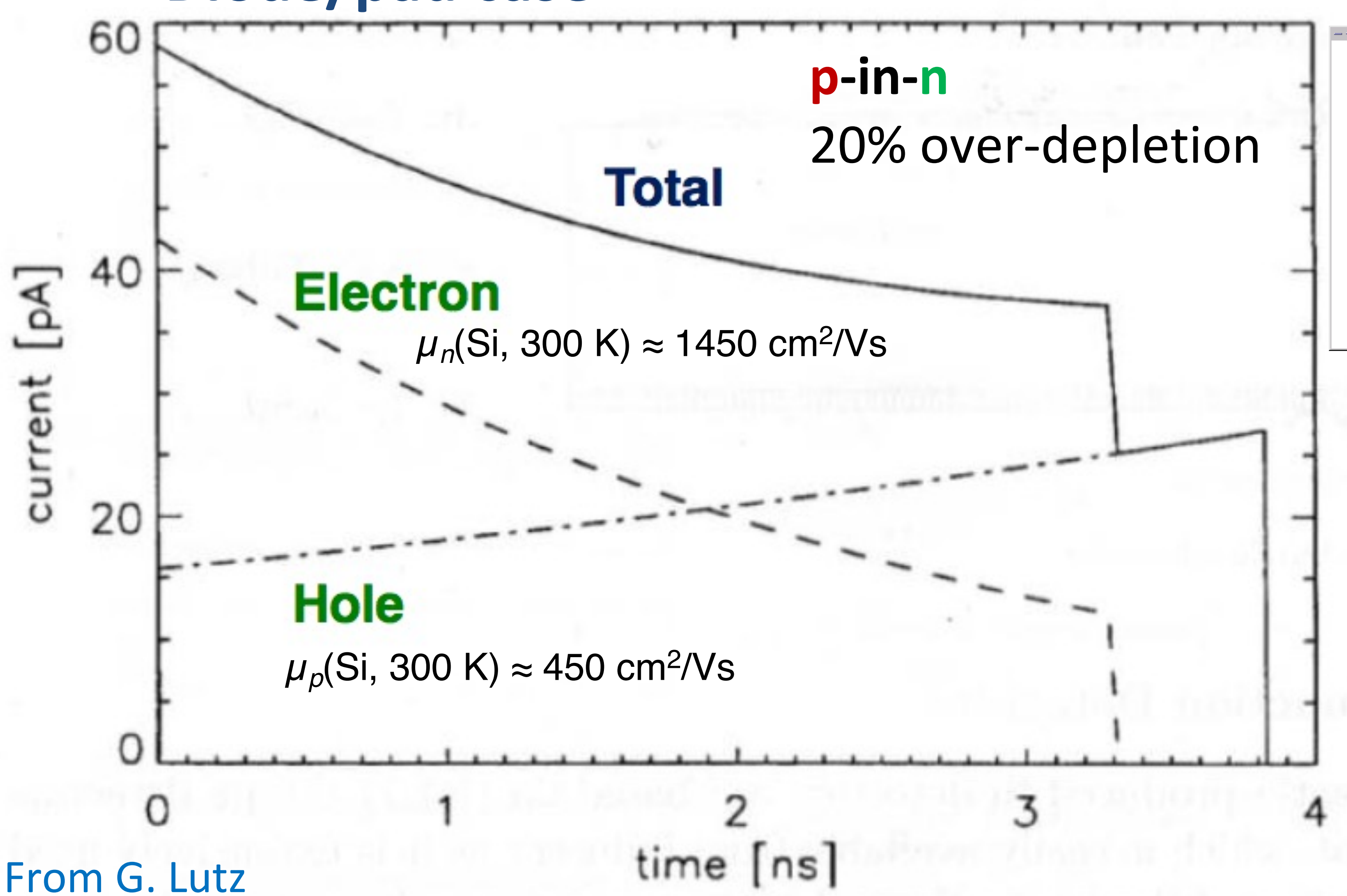
You may blink again

Signal formation - Induced current – Shockley-Ramo

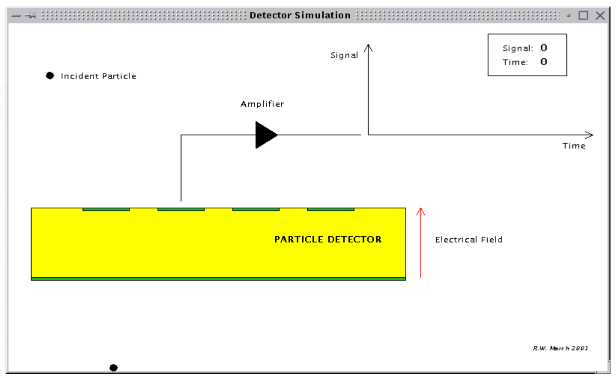
Take home: *All* signals in particle detectors are due to *induction* by moving charges.
Once the charges have arrived at the electrodes the signals are 'over'.
The drift is recorded - the height of the signal is linear proportional to the velocity of the charge

$$i_K(t) = q_P \frac{1}{V_0} \vec{E}_W \cdot \vec{v}\big(x(t), y(t), z(t)\big) = q_P \frac{1}{V_0} \vec{E}_W \cdot \mu \cdot \vec{E}$$

Diode/pad case



From G. Lutz



High
E-field linear
low

In addition:
E_W is called **weighting** field – geometry

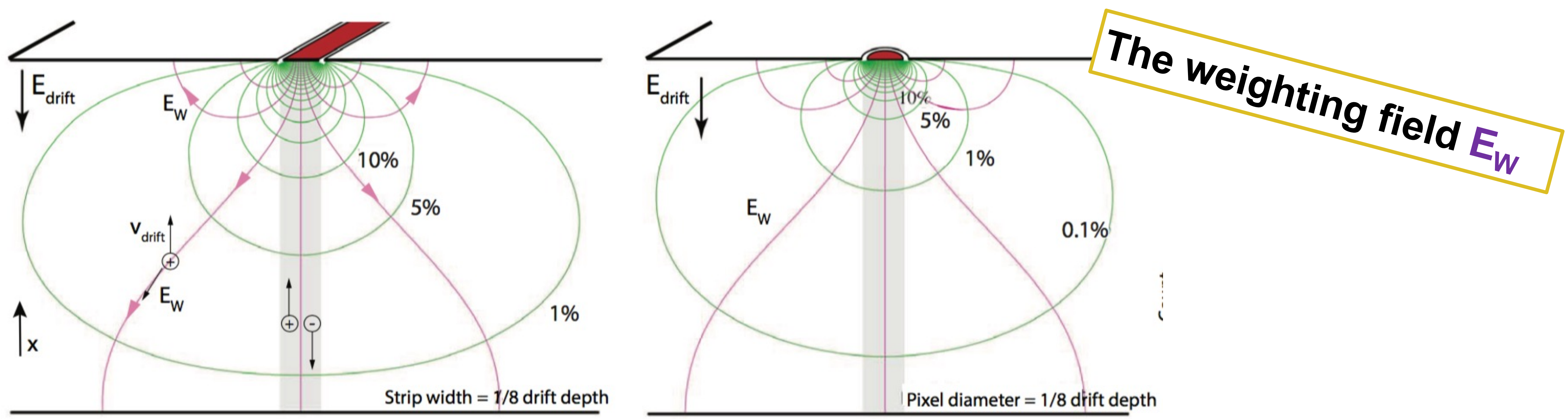
The entire signal is integrated.

Velocity~E-field & E_W

Gas detector work the same, though the **electric field** in gas is **constant** and in Silicon is **linear**

Signal Formation – weighting field ~ geometry

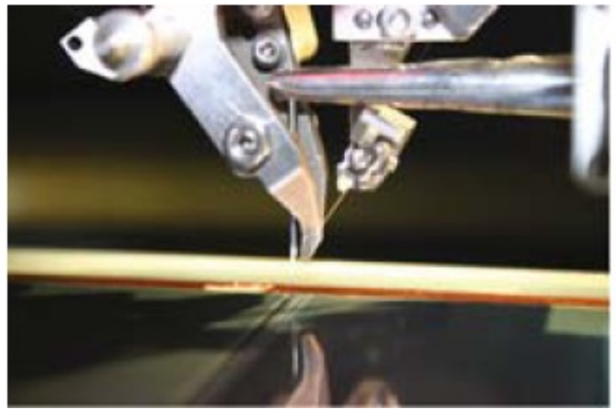
- An interesting fact is that for diodes (or large pad detector) with an entirely linear field
  - electrons and holes contribute the same to the electrode (pad)
- For fine segmented sensors pixel and strip one charge type contributes much more; because the electrical fields concentrate at the electrodes;
  - the drift velocity there is much higher thus the **induced** signal is much higher
  - Weighting field is higher too
  - We therefore often **say we collect** holes, or we collect electrons ☺

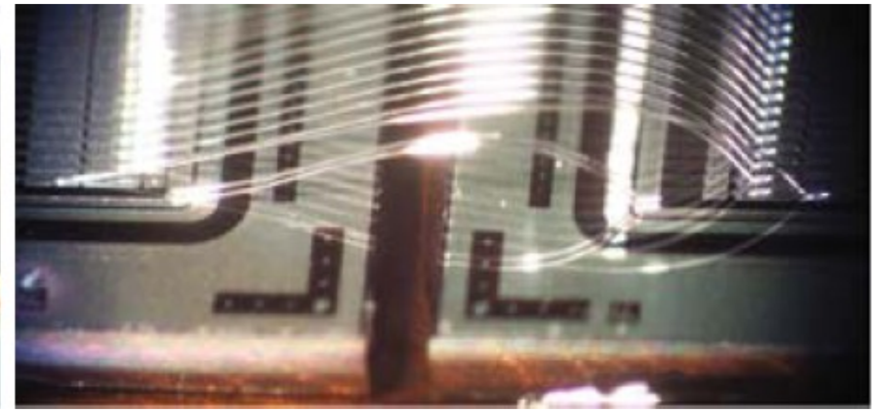


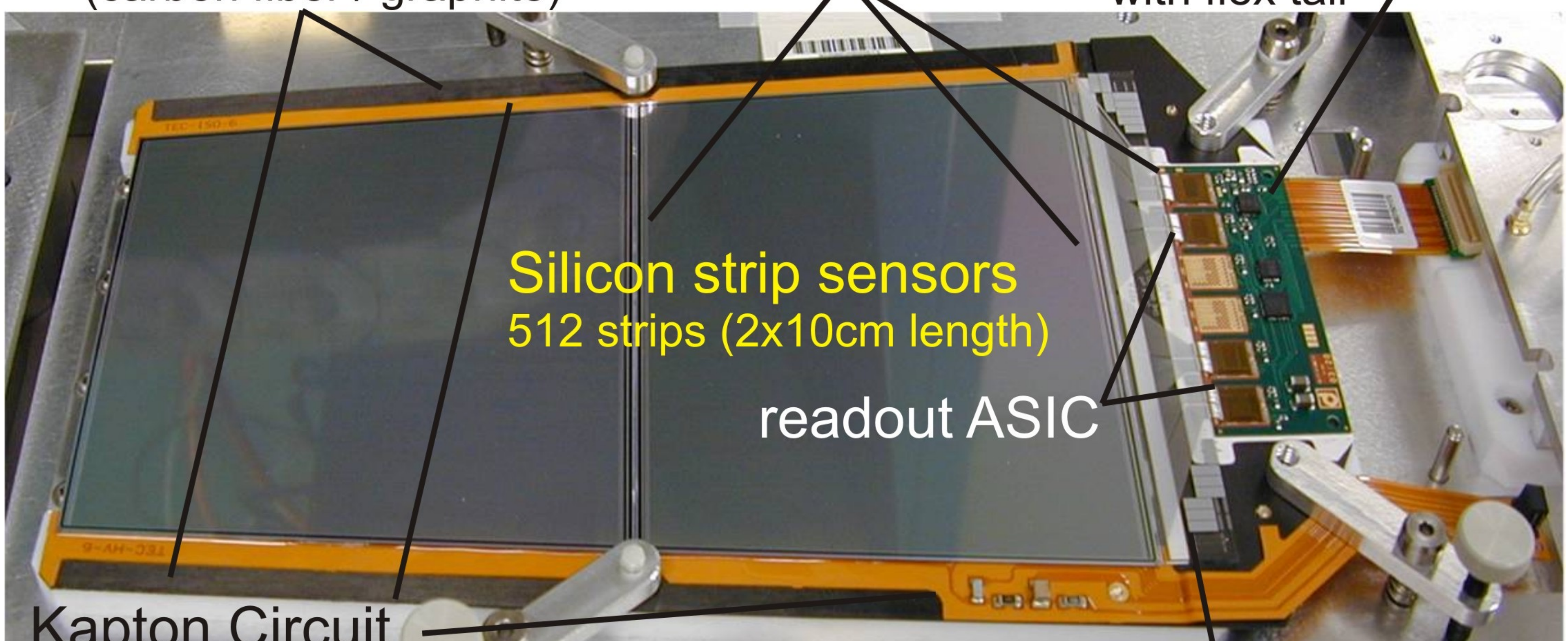
- **The future CMS High Granularity Calorimeter will register both** electrons and holes
  - Basically a pad detector (with many pads)
- **The future HL-LHC tracker will register electrons (mainly)**
  - **The current one registers holes**

V. Radeka, *Low-Noise Techniques in Detectors*, Ann. Rev. Nucl. Part. Sci

Strip Sensor to Module







Position Resolution

Threshold (binary) readout versus analogue readout

- Threshold (**binary**) readout:

➔position: $\boxed{x = \text{strip position}}$

➔resolution:

$$\boxed{\sigma_x \approx \frac{p}{\sqrt{12}}}$$

p …distance between strips (readout pitch)

x …position of particle track

- **Analogue** readout with interpolation (signal on two strips):

➔Position (charge center of gravity):

$$\boxed{x = x_1 + \frac{h_1}{h_1 + h_2}(x_2 - x_1) = \frac{h_1 x_1 + h_2 x_2}{h_1 + h_2}}$$

➔resolution:

$$\boxed{\sigma_x \propto \frac{p}{SNR}}$$

x_1, x_2 … position of 1st and 2nd strip

h_1, h_2 … signal on 1st and 2nd strip

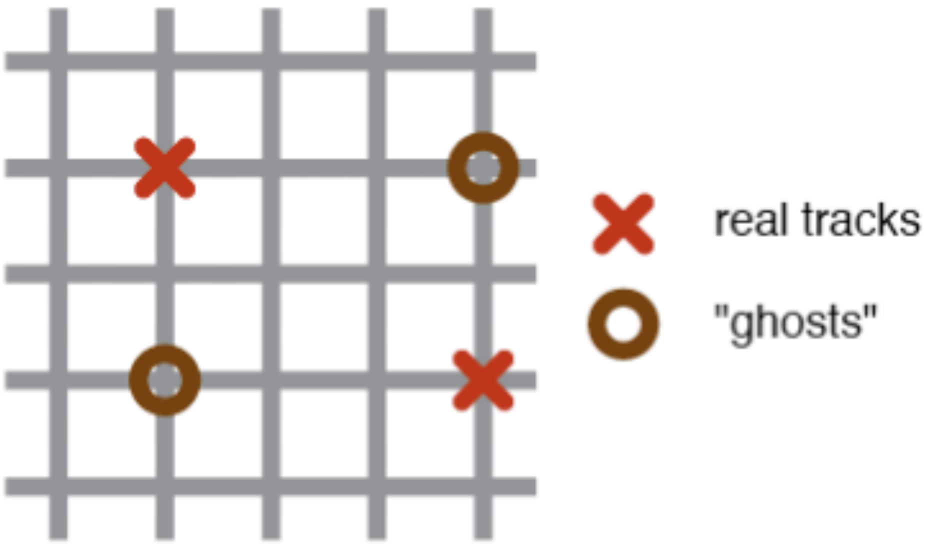
SNR … signal to noise ratio

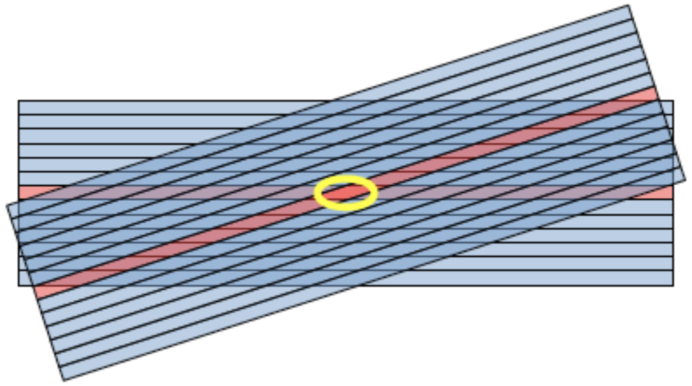
A position resolution of a few μm is achievable with analogue readout !

Strip vs. Pixel Detectors

- A strip detector measures 1 coordinate only. Two orthogonal/angled arranged strip detectors could give a 2-dimensional position of a particle track. However, if more than one particle hits the strip detector the measured position is no longer unambiguous. “Ghost”-hits appear!

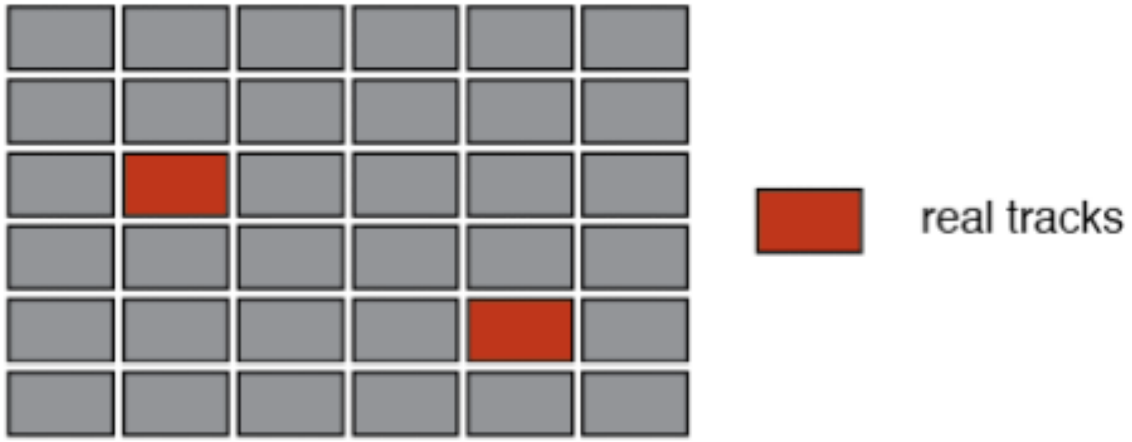
True hits and ghost hits in two crossed strip detectors in case of two particles traversing the detector:





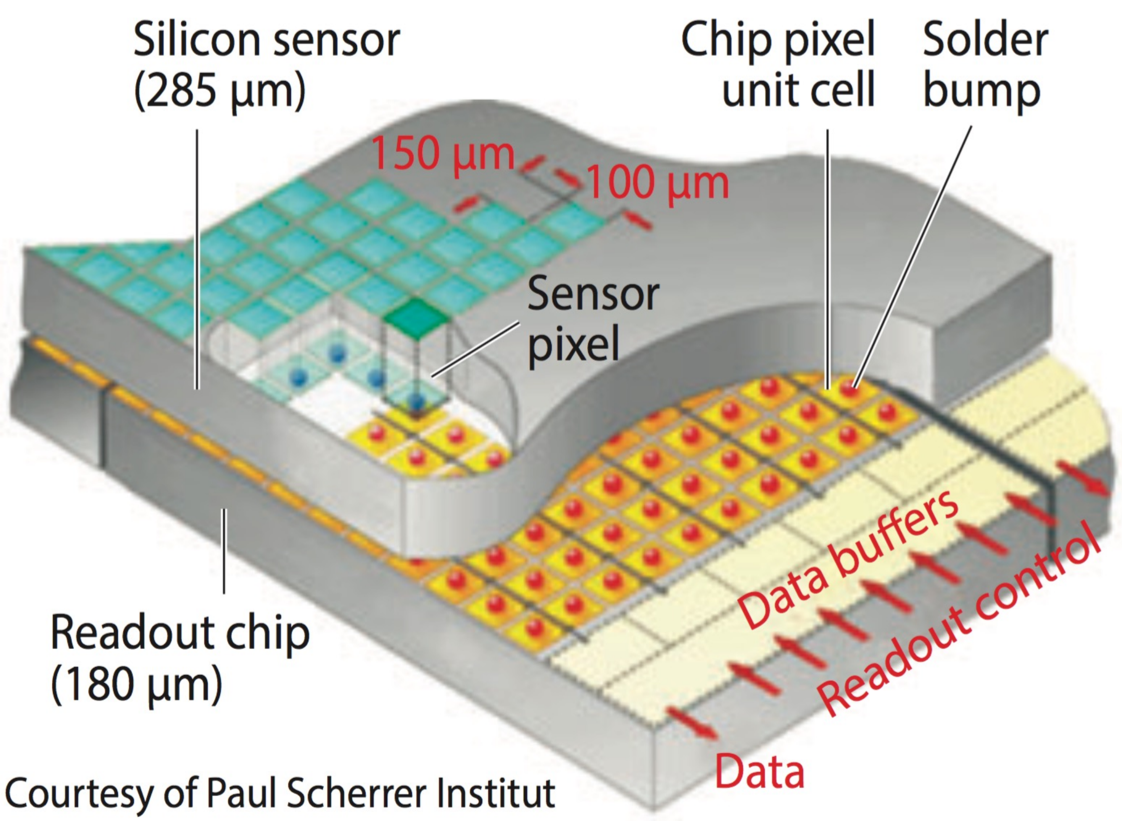
- Pixel detectors produce unambiguous hits!

Measured hits in a pixel detector in case of two particles traversing the detector:

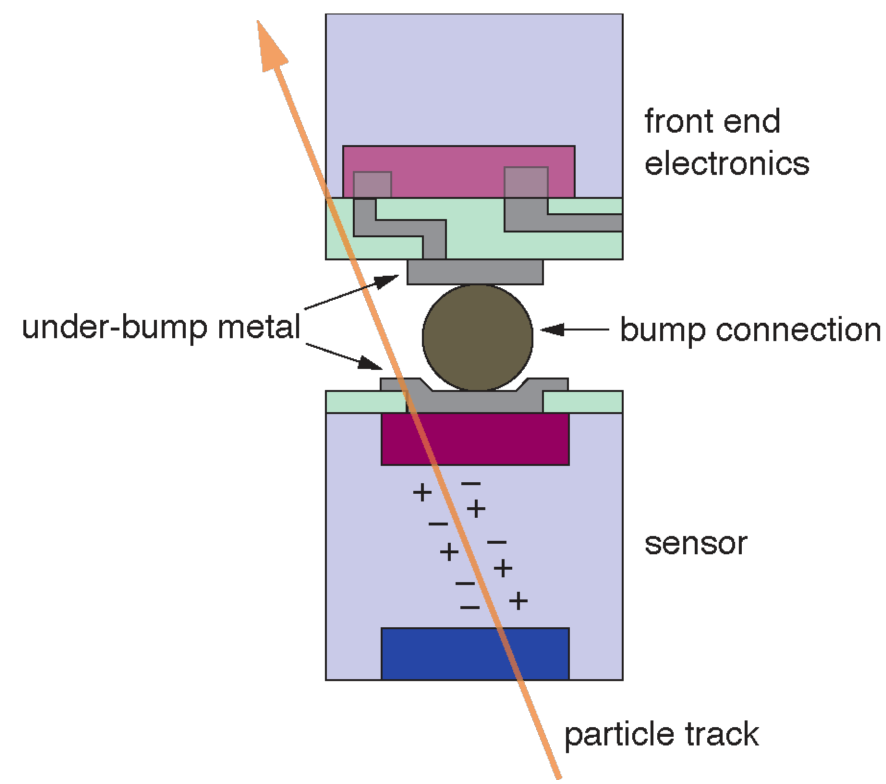


Hybrid Pixel Detectors
Principle

“Flip-Chip” pixel detector:
On top the Si detector, below the readout chip, bump bonds make the electrical connection for each pixel.



Detail of bump bond connection. Bottom is the detector, on top the readout chip:



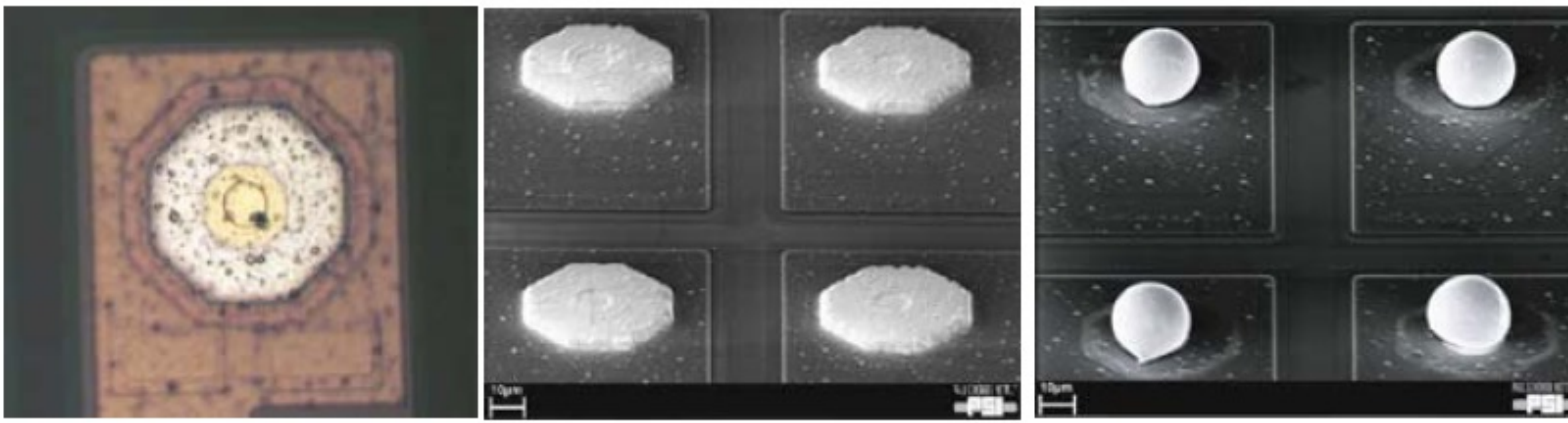
L. Rossi, *Pixel Detectors Hybridisation*, Nucl. Instr. Meth. A **501**, 239 (2003)

Drawback of hybrid pixel detectors: Large number of readout channels

→Large number of electrical connections and large power consumption.

Hybrid Pixel Detectors
Bump bonding process

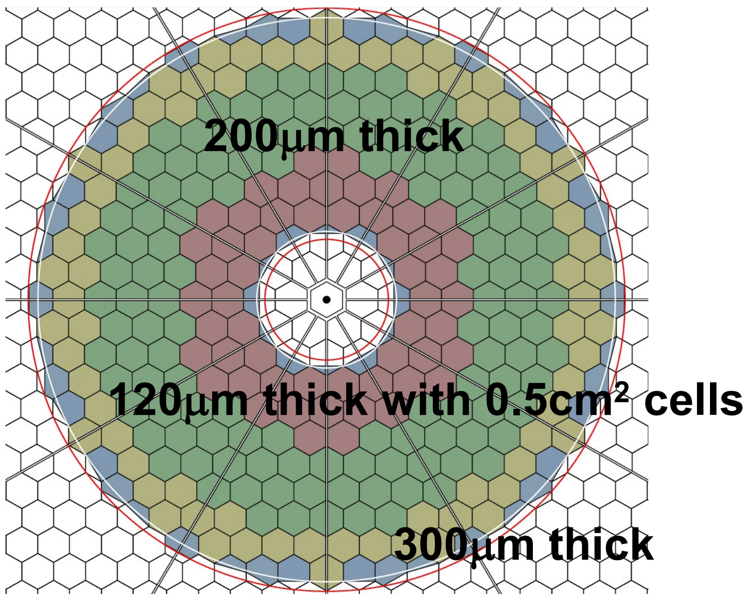
Electron microscope pictures before and after the reflow production step.
In bump, The distance between bumps is 100 µm, the deposited indium is 50 µm wide while the reflowed bump is only 20 µm wide.

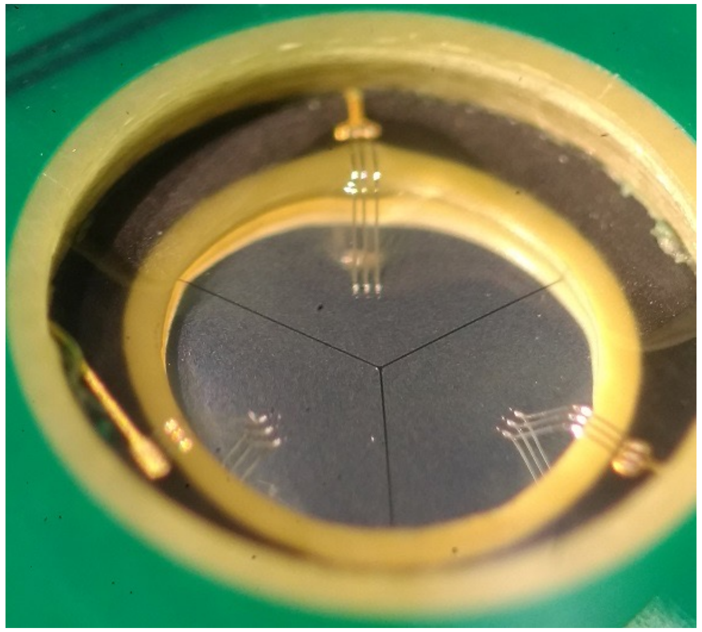


C. Broennimann, F. Glaus, J. Gobrecht, S. Heising, M. Horisberger, R. Horisberger, H. Kästli,J. Lehmann, T. Rohe, and S. Streuli, *Development of an Indium bump bond process for silicon pixel detectors at PSI, Nucl. Inst. Met. Phys, Res. A565(1) (2006) 303–308 82*

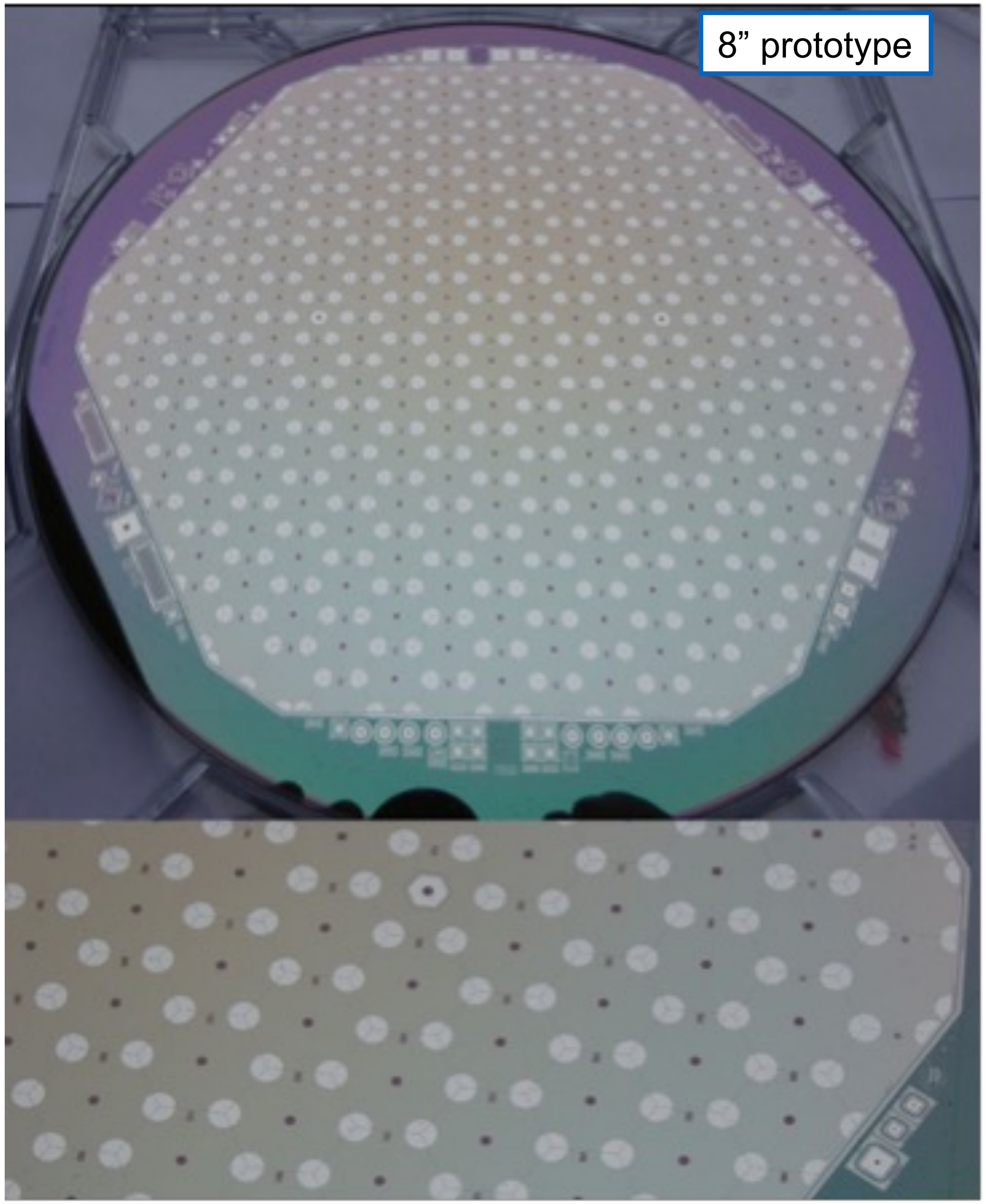
Silicon Pad detectors – for calorimeter CALICE & CMS HGCAL

- **Hexagonal** sensors to maximize use of wafer area
- 120, 200, 300 μm thick n-in-p pad sensors
    - Thickness defines radiation tolerance
- Cell size ~0.5 or ~1 cm^2
    - Smaller cell size in central region
        - High occupancy and noise reduction
- Cells are wire-bonded to a PCB on top with holes





n-in-p more radiation tolerant than p-in-n; thinner = radiation tolerant
Higher radiation at lower radius



8" – a first in HEP High Energy Physics

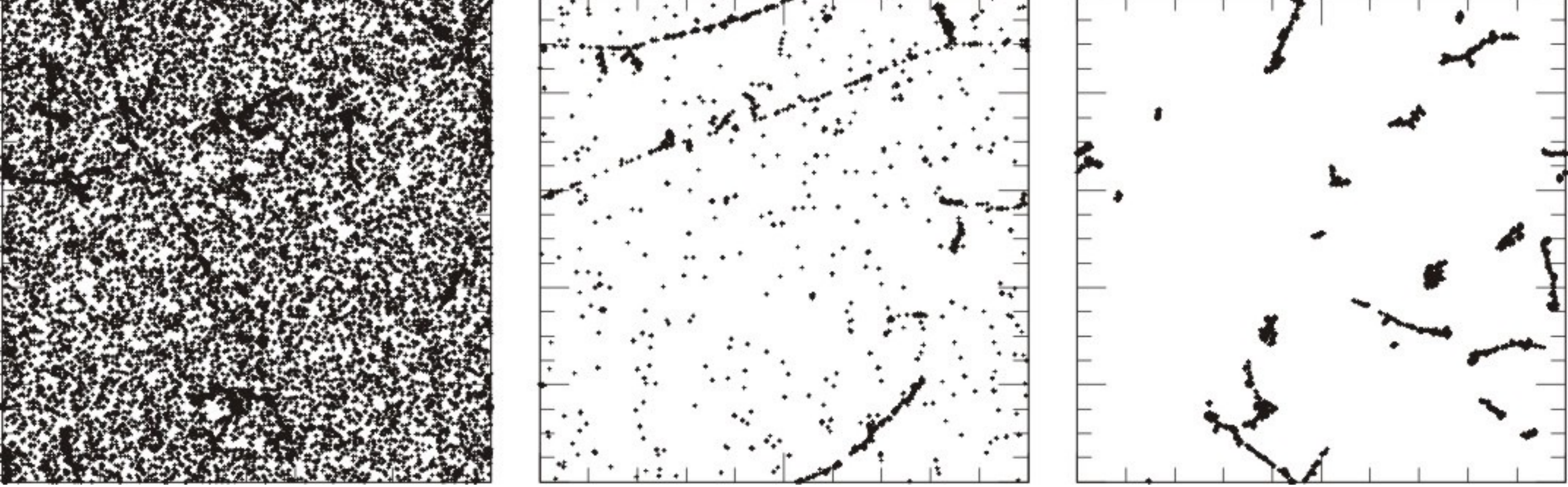
Silicon properties
– the numbers are simply right

Table 1.1 Silicon properties

Parameter	Symbol	Unit	Value
Atomic number			14
Relative atomic weight			28.0855
Structure			diamond
Lattice constant	a_0	Å	5.4307
Lattice orientation			$\langle 111 \rangle$
Electron configuration:			$1s^2 2s^2 2p^6 3s^2 3p^2$
Density	ρ	gcm^{-3}	2.328
Melting point	T_m	°C	1414
Boiling point	T_b	°C	2355
Gap energy (300 K)/(0 K)	E_g	eV	(1.124)/(1.170)
Dielectric constant	ε_r		11.7
Intrinsic carrier density	n_i	cm^{-3}	1.45×10^{-10}
Mobility			
– of the electrons	μ_e	$cm^2\,[Vs]^{-1}$	1350
– of the holes	μ_h	$cm^2\,[Vs]^{-1}$	450
Effective density of states			
– of the conductance band	N_c	cm^{-3}	3.22×10^{19}
– of the valence band	N_v	cm^{-3}	1.83×10^{19}
Max. electrical field	E_{max}	$V\mu m^{-1}$	30
Thermal expansion coefficient		1/°C	2.5×10^{-6}
Intrinsic resistivity		kΩ cm	235

And detector relevant:

- Dense: the average energy loss and high ionized particle number with 390eV/*µm* ~ *108 (electron–hole pairs)/µm is effectively high due to the high* density of silicon.
  - **No charge amplification needed**
- very good intrinsic energy resolution: for every 3.6 eV released by a particle crossing the medium, one electron–hole pair is produced. (30 eV to ionize a gas molecule)
- Very fast O(10ns)
- Mechanical stability
  - Self supporting



Radiation damage in silicon sensors

A very very brief glimpse

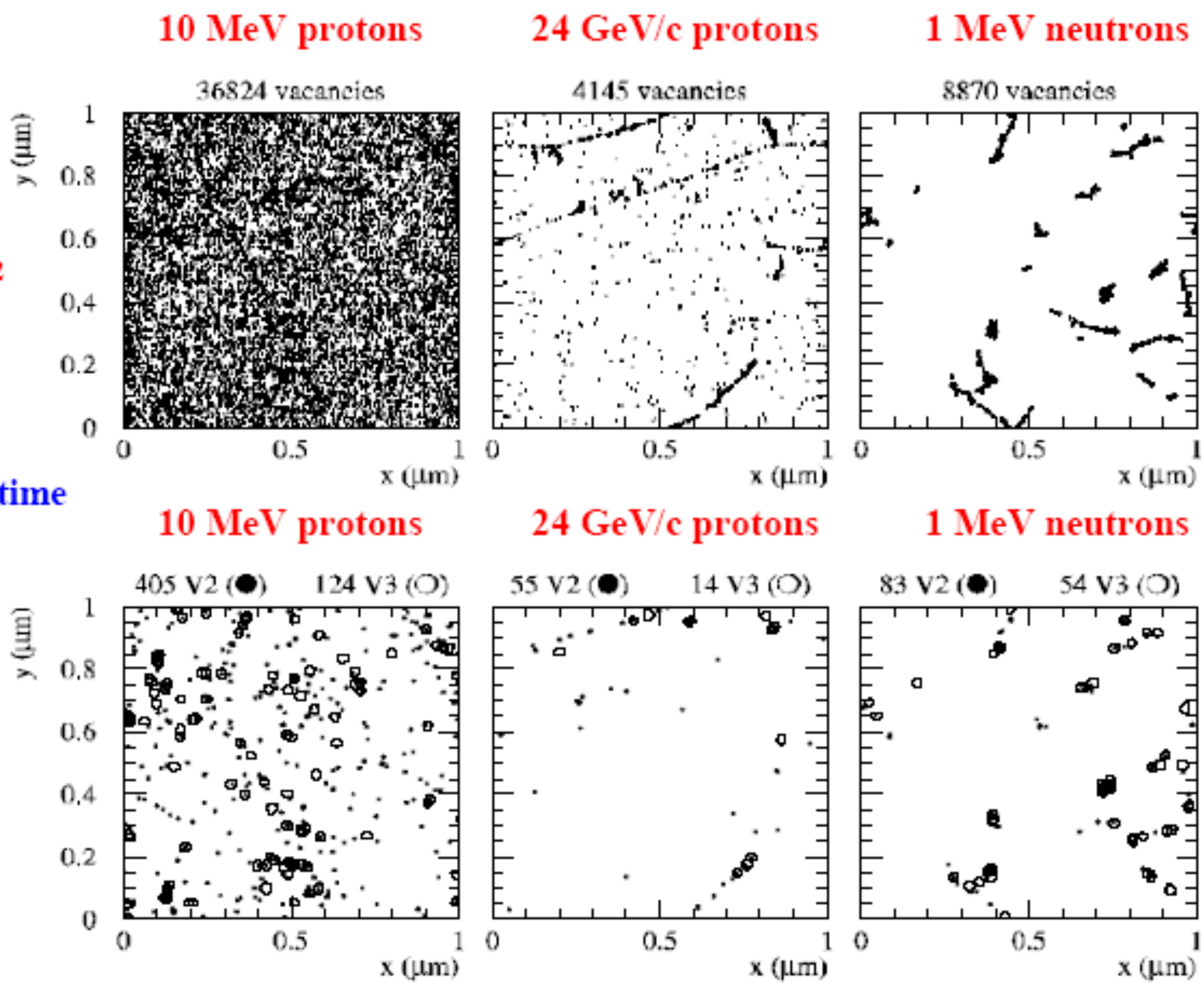
Then there is „diffusion“ (annealing)

Initial distribution of vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2

I,V random walk
+
recombination or defect formation

time

Final constellation of V_2 and V_3



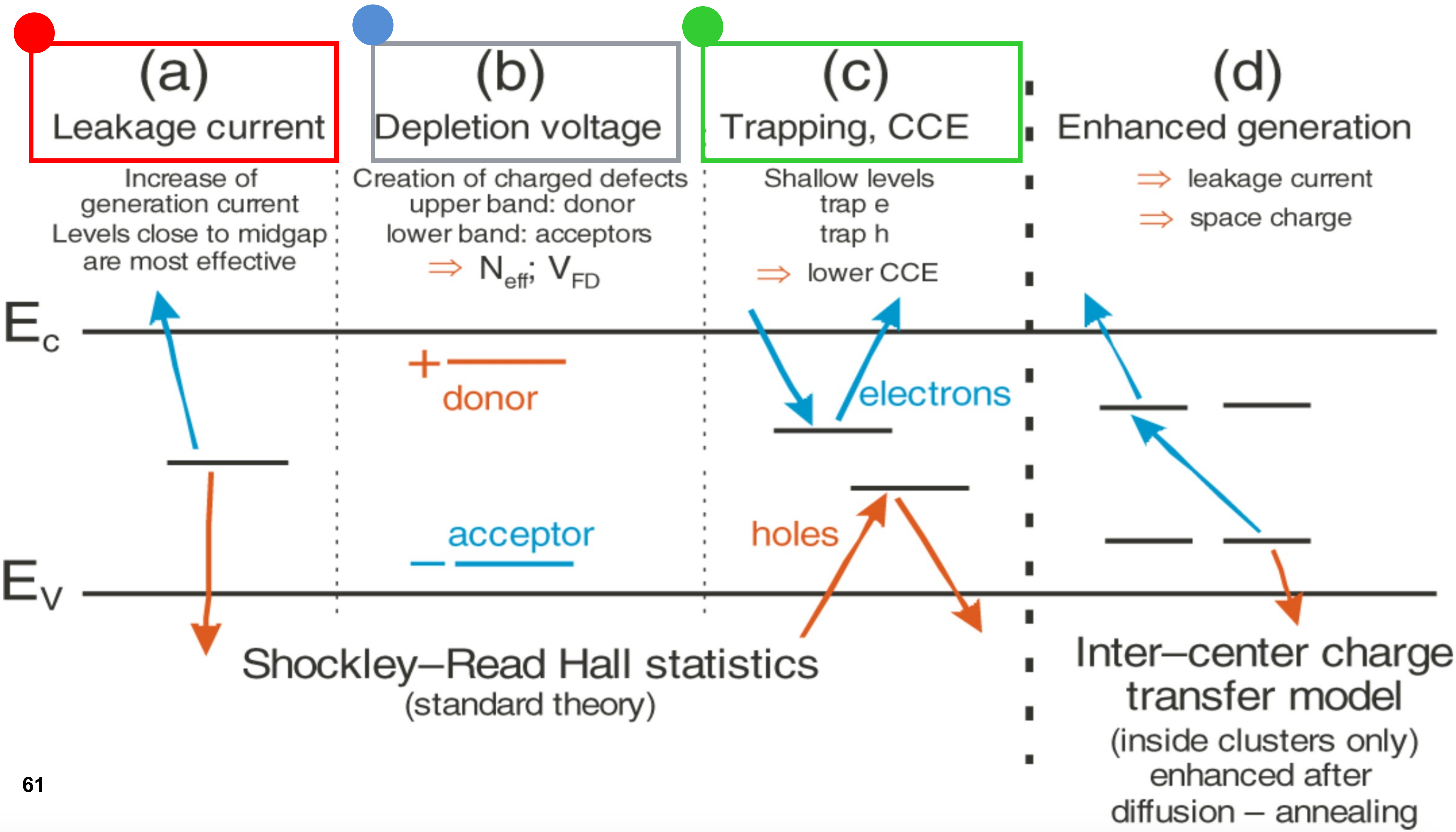
[Mika Huhtinen ROSE TN/2001-02]

The term **“diffusion”** used here is more a descriptive one combining effects like diffusion, migration, break-up, re-configuration of defects – also often summarized by the term **“annealing”**

Mind 'the Gap'

Rule of Thumb:

- Leakage Current - Relevant from **E13** 1MeVN_{equiv} onwards – LHC
- Depletion voltage - Relevant from **E14** 1MeVN_{equiv} onwards - LHC
- Trapping - Relevant from **E15** 1MeVN_{equiv} onwards – HL- LHC

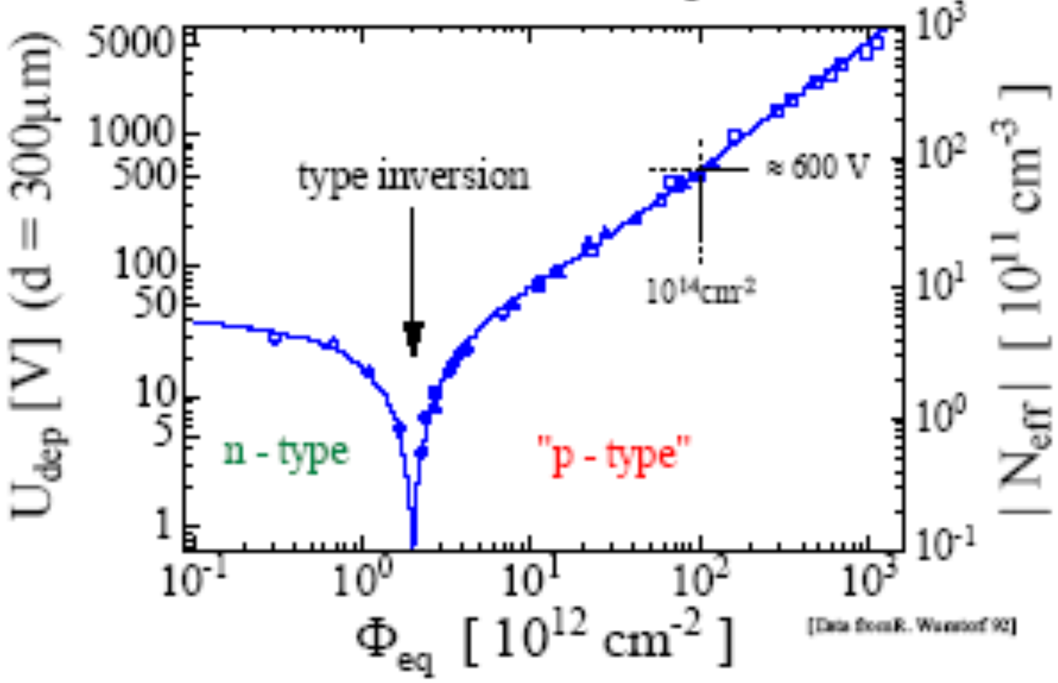


Defects are simply add. levels in the band gap

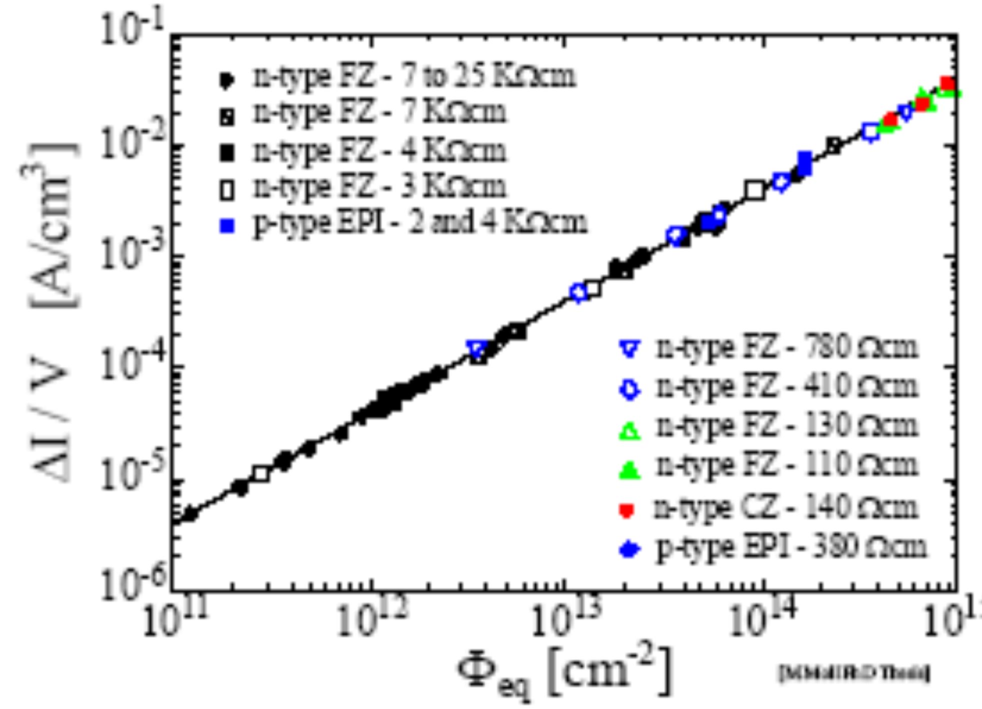
Macroscopic parameters (in n-bulk FZ sensors)

Irradiation

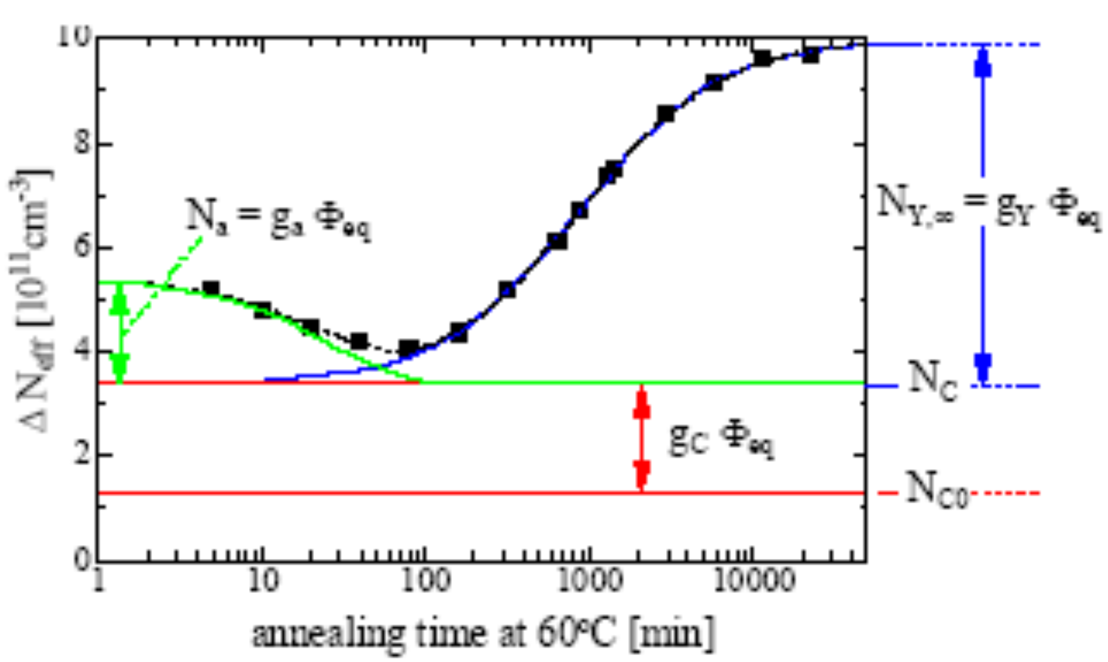
1. Change of V_{dep} (N_{eff})

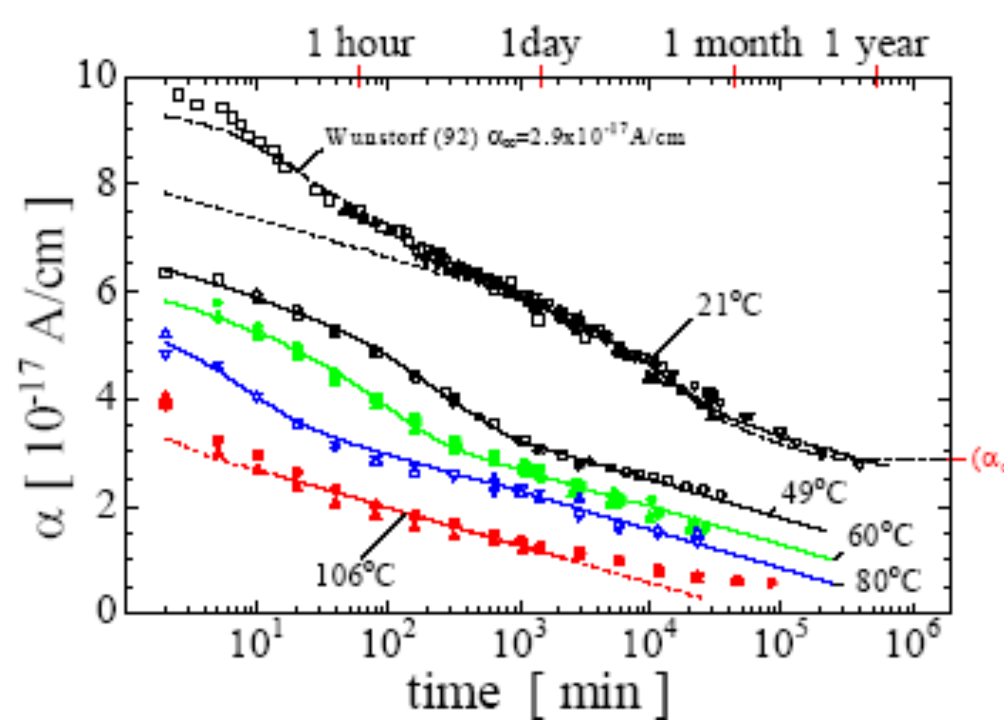


2. Increase of leakage current



Annealing (e.g. at 60°C)

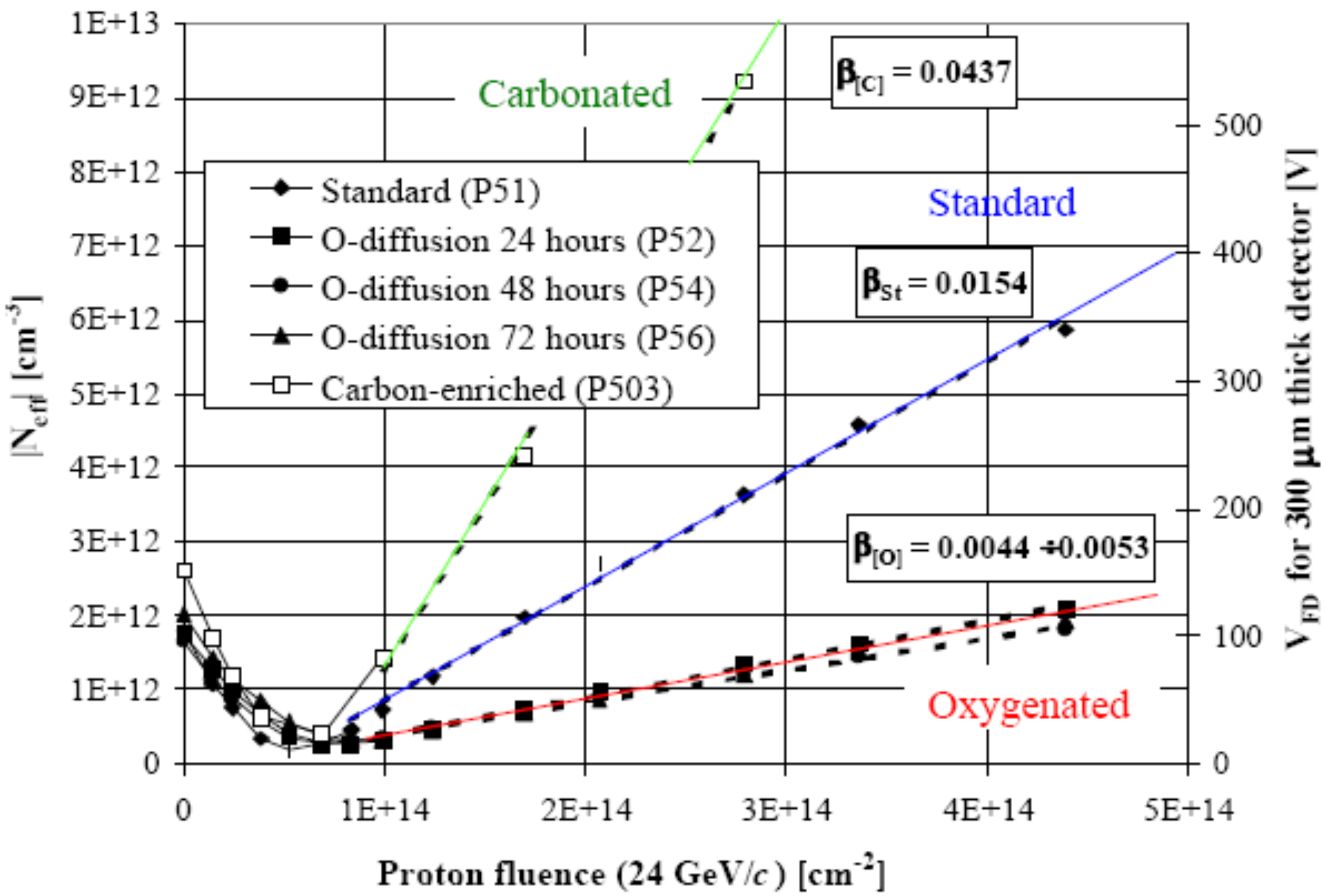




Defect Engineering – RD50

Influence of Carbon and Oxygen concentration

24 GeV/c proton irradiation



Introduced in CMS & ATLAS pixel

Compared to standard silicon:

- **High Carbon ⇒ less radiation tolerant**
- **High Oxygen ⇒ more radiation tolerant**

Oxygen is good

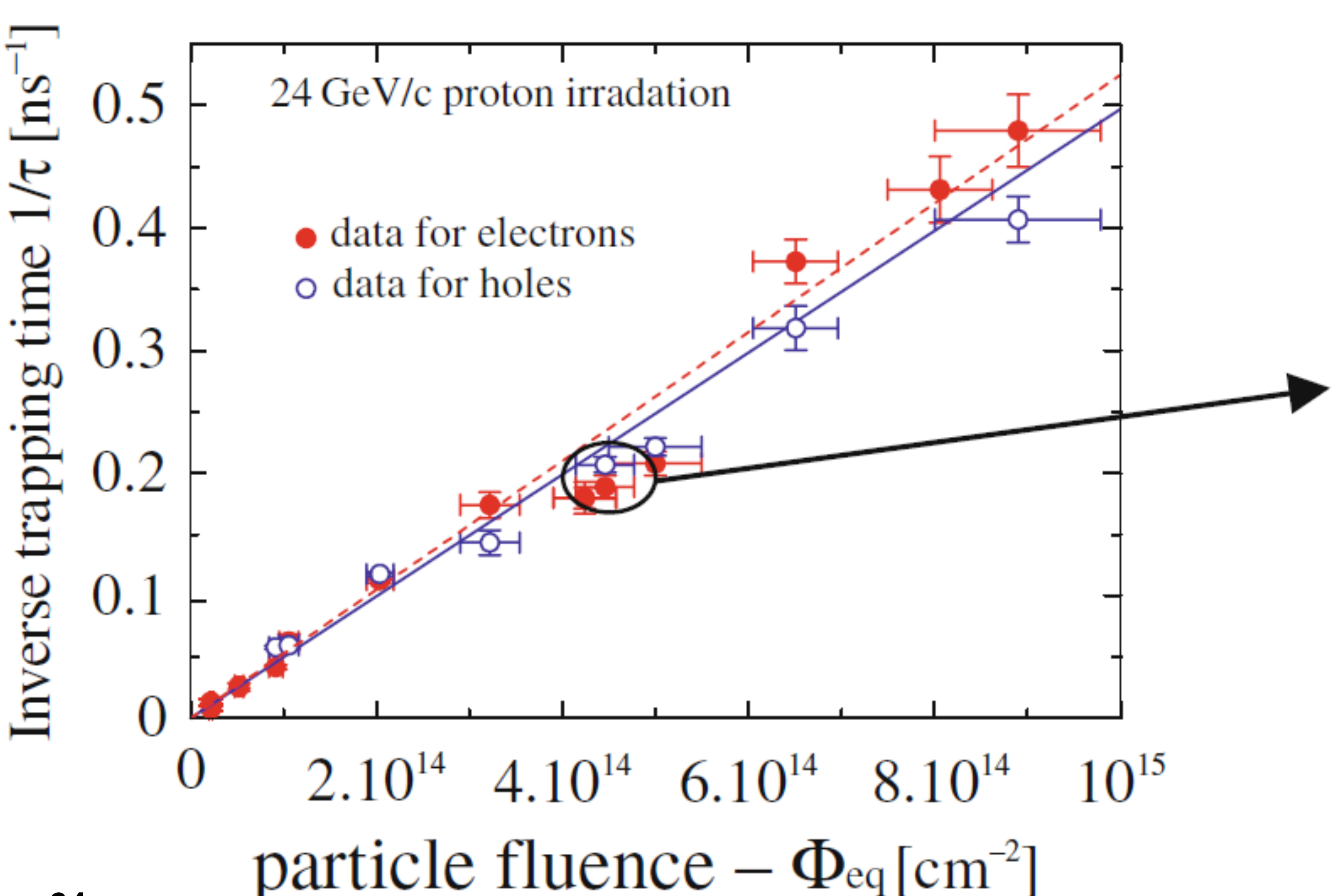
Michael Moll - CERN EP-TA1-SD Seminar - 14.2.2001

Radiation Damage – Trapping

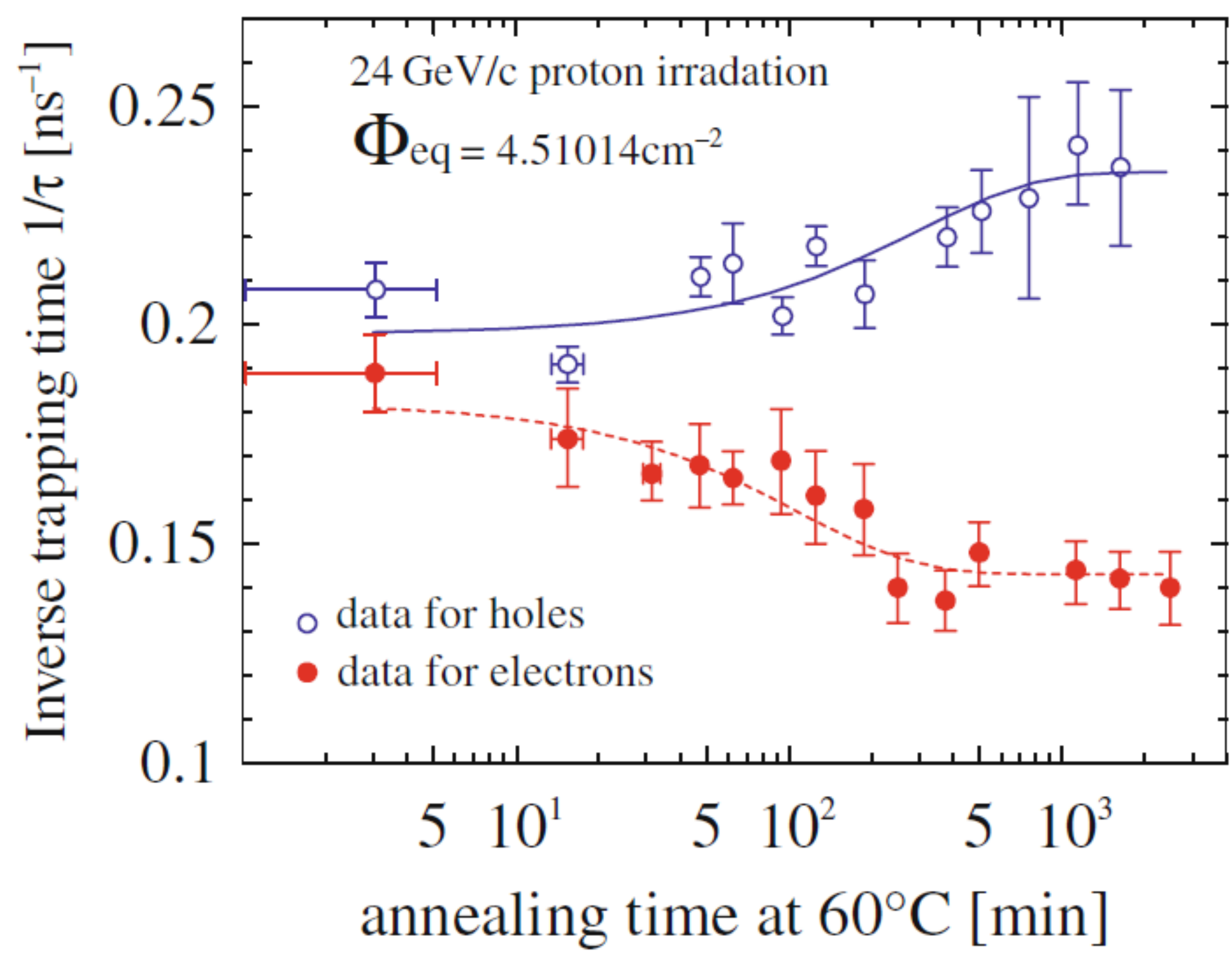
- Trapping τ_{eff} changes with Φ_{eq}
- Different materials behave differently (n, p, FZ, MCz, oxygenated)
- Rule of thumb: dominant damage item up to 10^{16} $1MeV_{eq}$
- $\tau_{eff}\ (10^{15}\ n1\ MeV/cm2) = 2\ ns$: $x = (10^7\ cm/s) \cdot 2 \cdot ns = 200\mu m$
- $\tau_{eff}\ (10^{16}\ n1\ MeV/cm2) = 0.2\ ns$: $x = (10^7\ cm/s) \cdot 0.2 \cdot ns =$ **20μm**

Annealing effect small

Increase of inverse trapping time (1/τ) with fluence



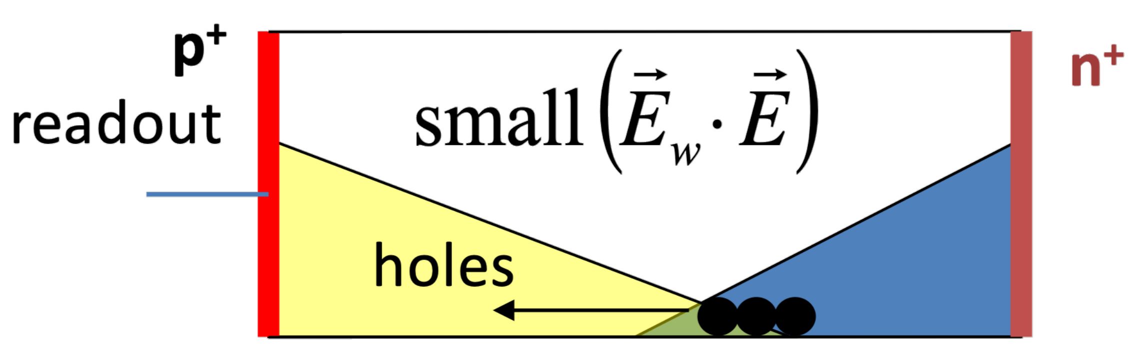
..... and change with time (annealing):

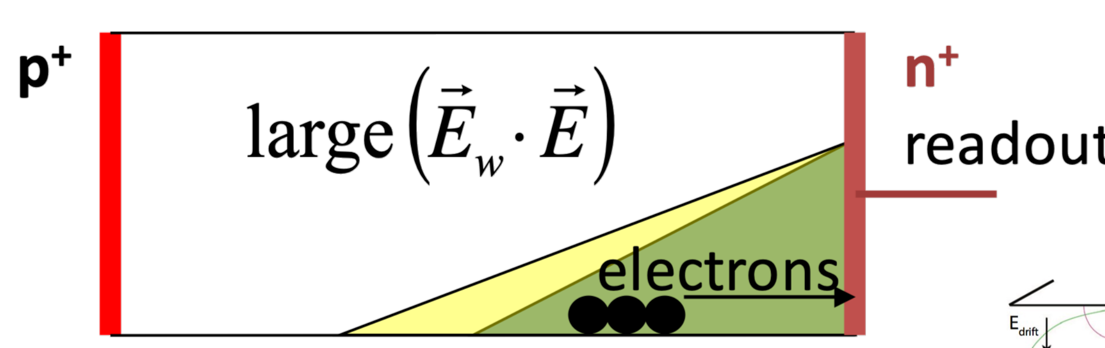


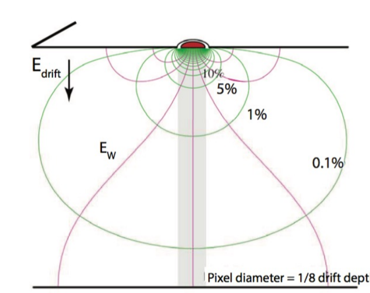
→signal decreases

Is this all on irradiation? Not really

- The content of impurities is important and different particles and different energies damage differently wrt V_{FD} / E-field
  - create also donors, not only acceptors – oxygen helps
- You need high field to get a signal, **thinner sensor** help (~d^2)
  - This also reduces the path length, thus trapping
- n-in-n or **n-in-p** sensors ‘*register*’ **electrons** which are faster and the *electric and weight field is higher* at the n-electrode → larger signal







Thin – electrons - n-electrode - oxygen

Everybody still alive?

Ready for coffee?

NEXT: Other Silicon Detector Structures

Strips-, pad- and hybrid pixel detectors are mature technologies employed in almost every experiment in high energy physics **‚work-horse‘**

Additional interesting silicon detector structures are:

- ~~Charged Coupled Devices~~ (CCD) – older tech
- ~~Depleted Field Effect detectors (DEPFET)~~ – used in Belle-2
- ~~Silicon Drift Detectors (SDD)~~ – in ALICE Phase 0
- ~~Silicon On Oxide (SOI)~~

If time allows, we can come back to the omitted ones

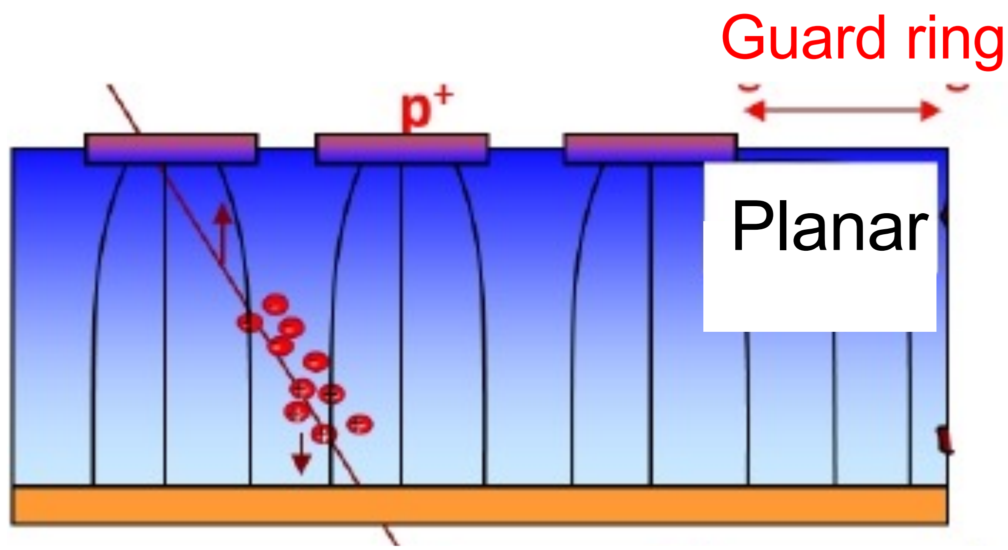
- **3D detectors** – radiation tolerant
- **Low Gain Avalanche Detector (LGADs)** – precise timing
    - **And new/future developments RSD**
- **Silicon Photomultiplier (SiPM)** – photo detection
- **Monolithic Active Pixels (MAPS)** – nice, not very rad tolerant, ‚slow‘
- **HV-CMOS / depleted MAPS (DMAPS)** – monolithic, very interesting

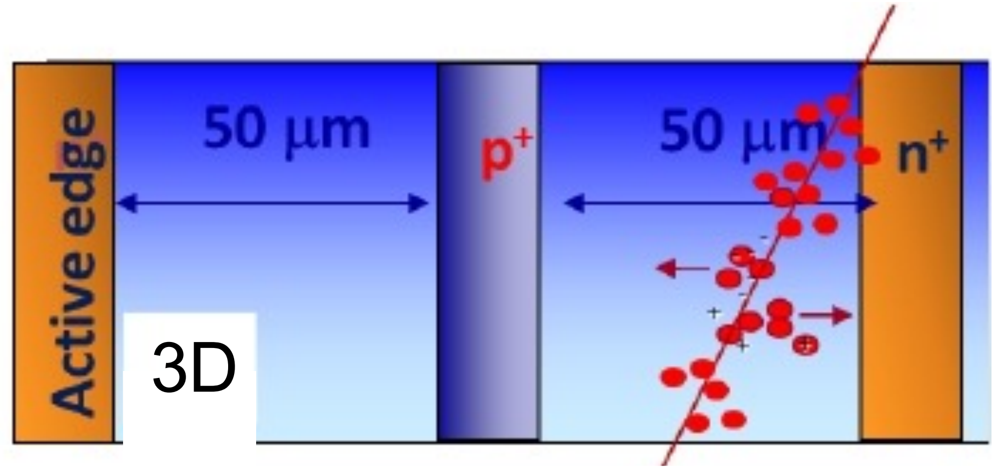
~~Also very intersting but not enough time~~

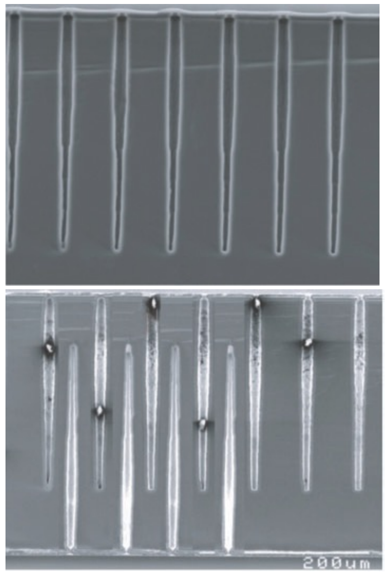
And if thin sensors are not rad tolerant enough for HL-LHC innermost pixel layers?

Use 3D sensor:

Common advantages: **Short drift path** (less trapping), **Higher fields** at same V_{bias}

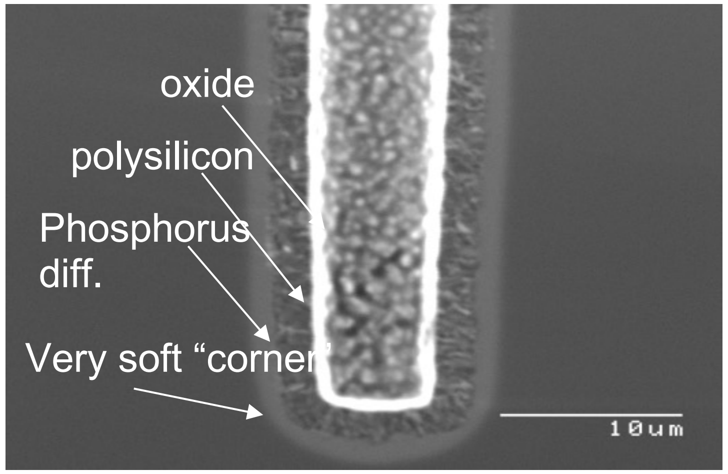






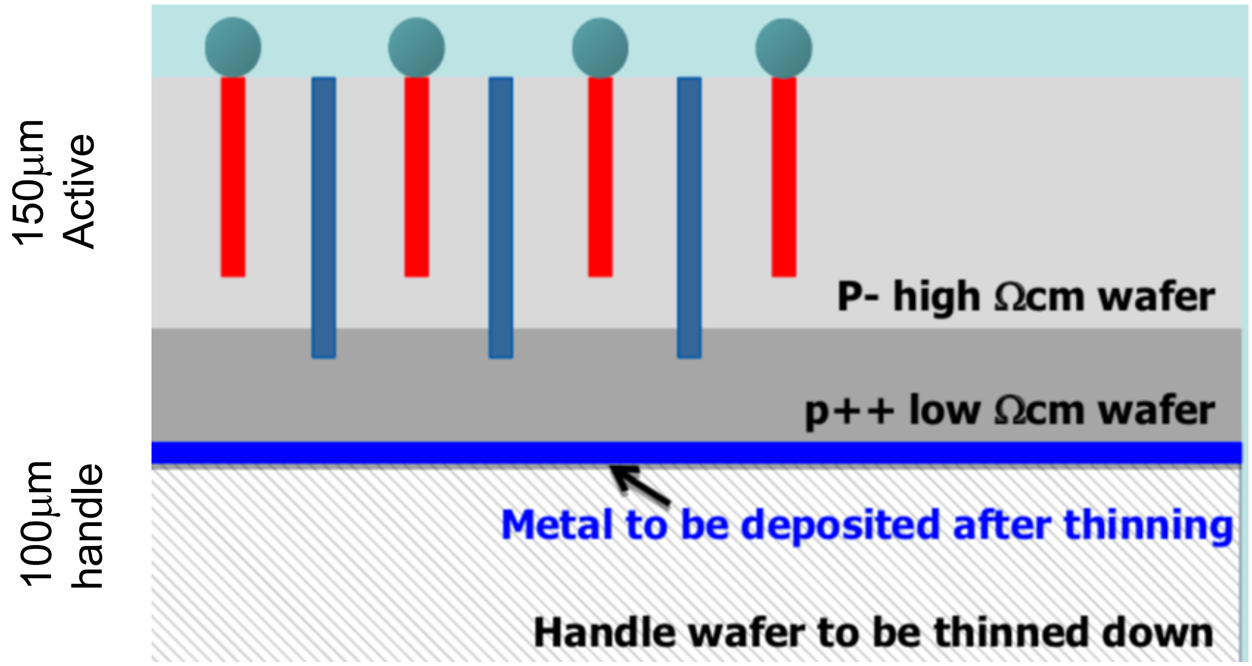
- **Thin** planar sensors:
  - Low total leakage after irradiation
- Drawback:
  - Smaller initial signal

- 3D sensors:
  - Thick sensor possible with **low depletion voltage**
    - **Less power**
- More rad tolerant (less trapping)
- Drawback:
  - Higher Capacity
  - Low yield

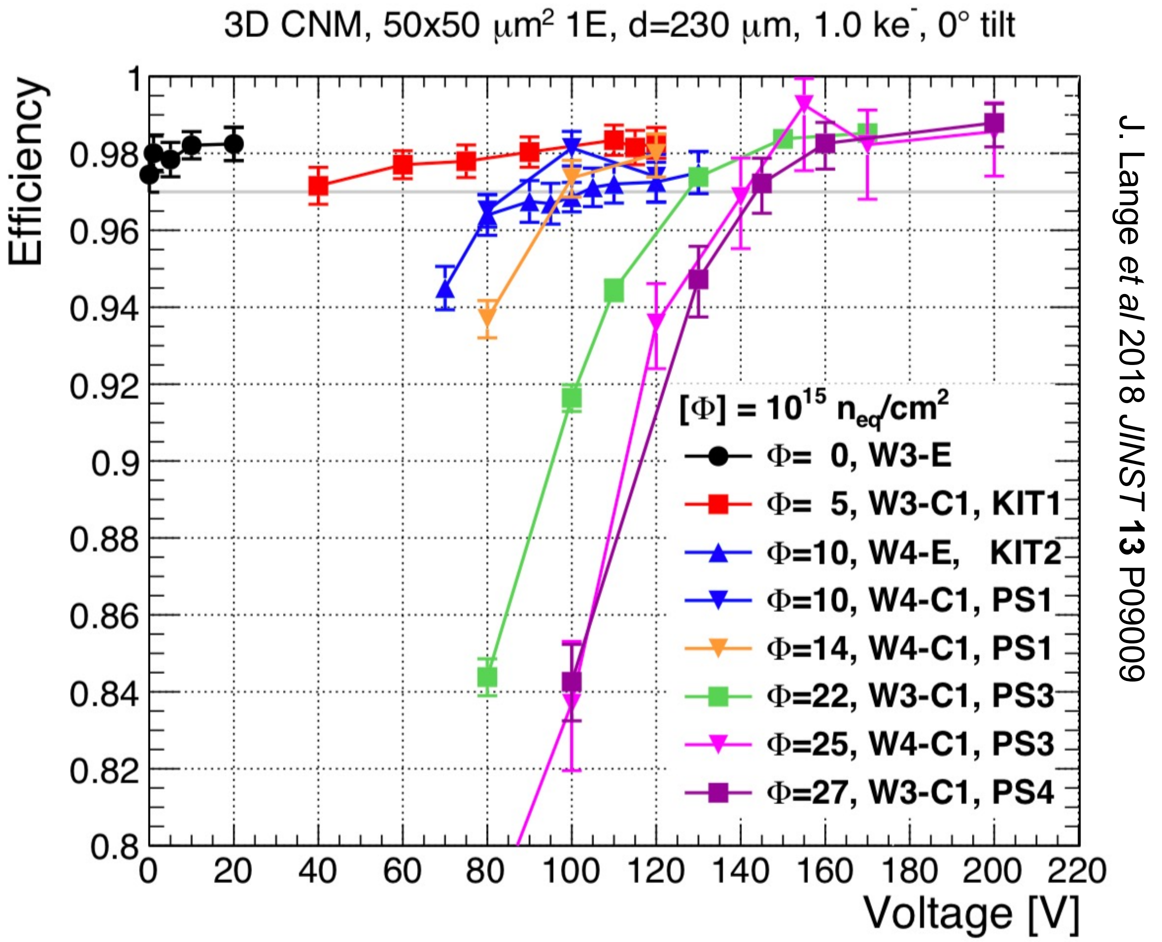


Take Home:
The trick lies in the short drift length!
And the lower voltage – remember d^2

3D Silicon Sensors for HL-LHC

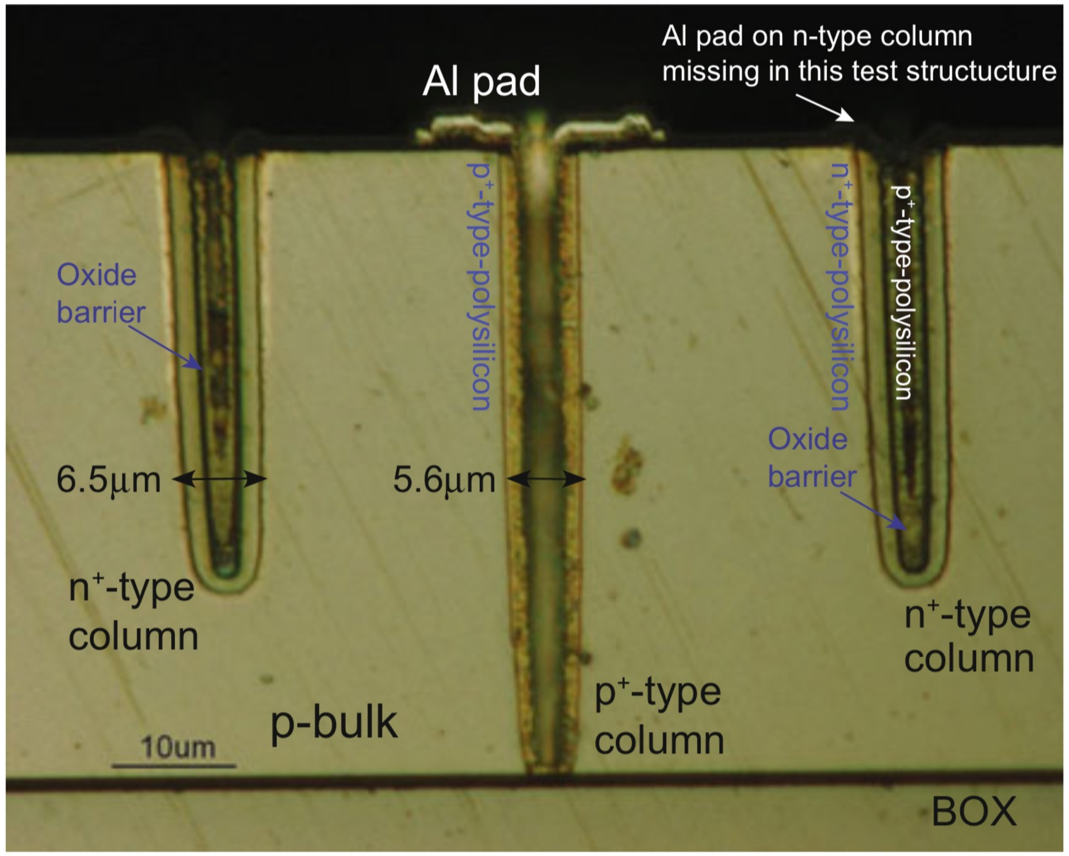


Made possible by Direct Wafer Bonding (Si-Si-DWB)



They work after $3*10^{16}$ n_{eq}/cm^2

- rad tolerant

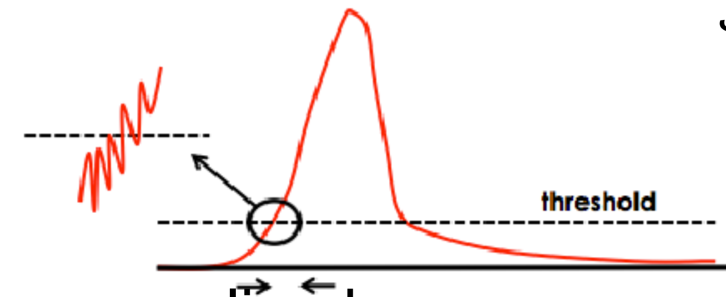


Close to this one…

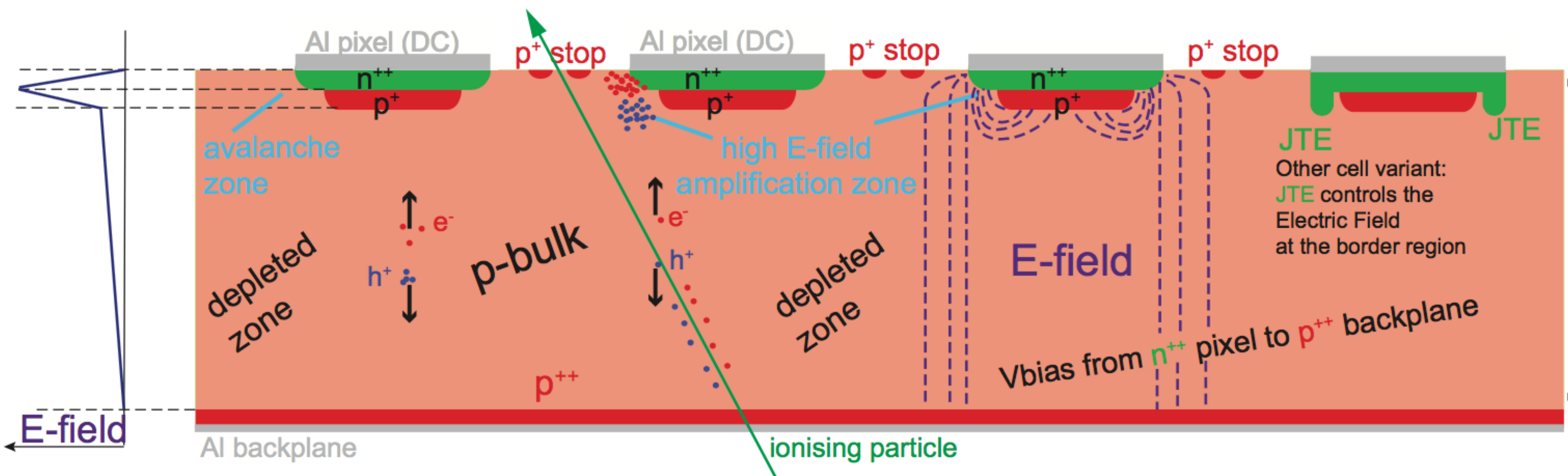
LGAD – timing detectors
Low Gain Avalanche Detector

Finally: amplification

- Concept of a Silicon Photomultiplier (SiPM) / avalanche photdiode (APD)
- Generally, electric field strengths above $2 \cdot 10^5$ V/cm activate the impact ionising multiplication **- avalanche**
- high gain - high signal - faster rise - smaller ”jitter”
- for gain values of 20 – 30 a time resolution of σ_t=30 ps has been realized
- **Spatial resolution?? Fill factor!?! ‘Dead’ zones!?!**

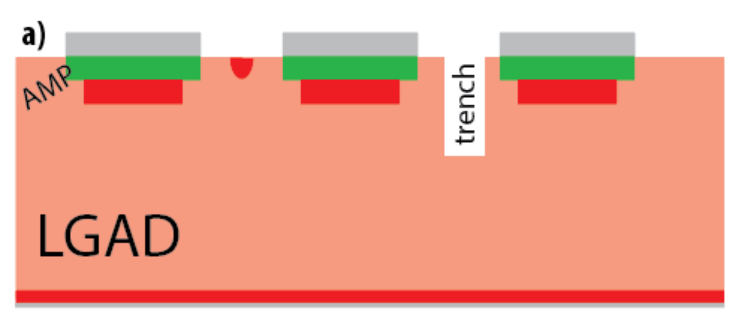


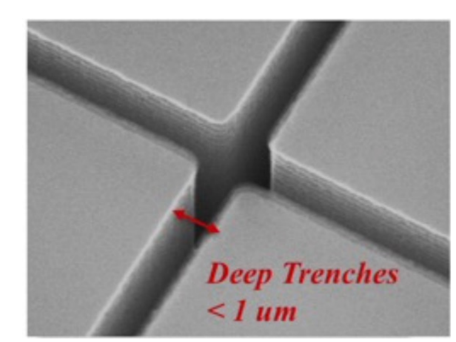
Very active field/evoltuion – see recent summary:
https://indico.cern.ch/event/829863/contributions/4479396/attachments/2565397/4423107/Pixel2022_Novel%20Detectors%20for%20Tracking%20and%20Timing_final_s.pptx



Remember: doping concentration defines field strength

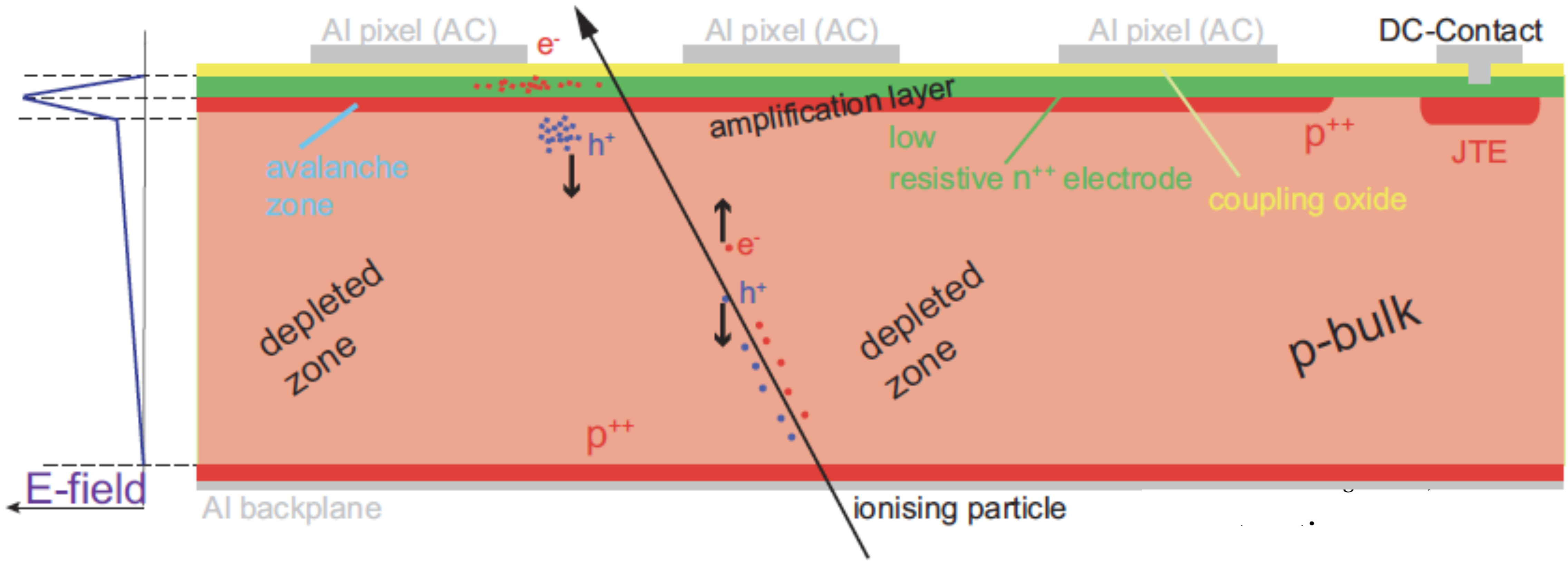
NEW: Trench Isolation LGAD: ~50 → 5 µm dead zone



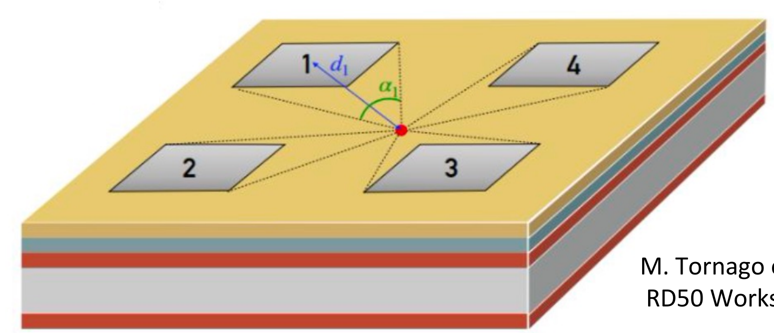


Precise timing -Evolving further
AC-LGADs or Resisitive Silicon Sensors RSD

First results very encouraging **(IMHO great)**



- Timing ~30 ps 
- 100% fill factor 
- ~5 µm spatial resolution with *150 µm pitch*
  - *Excellent ratio*
  - Due to charge distribution and sharing in intrinsic low resistivity n++ layer with ~4 AC pads as smallest impedance to ground



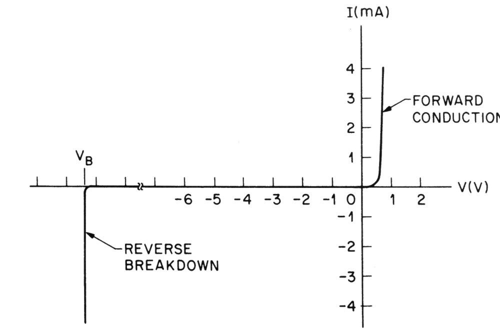
M. Tornago et al., RD50 Workshop (2020)

- Fresh idea; next do DC-RSD

→11m² TOF for EiC?

Soon state-of-the-art?

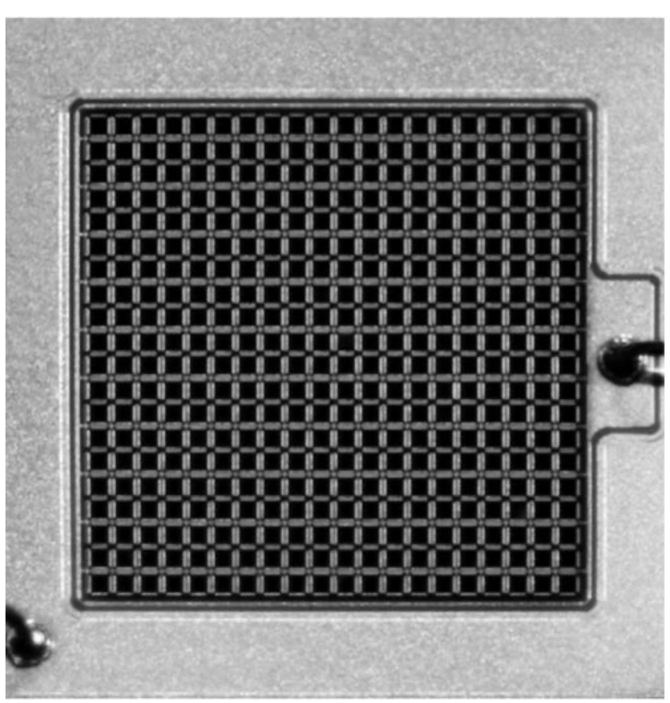
Semiconductor Photon Detectors

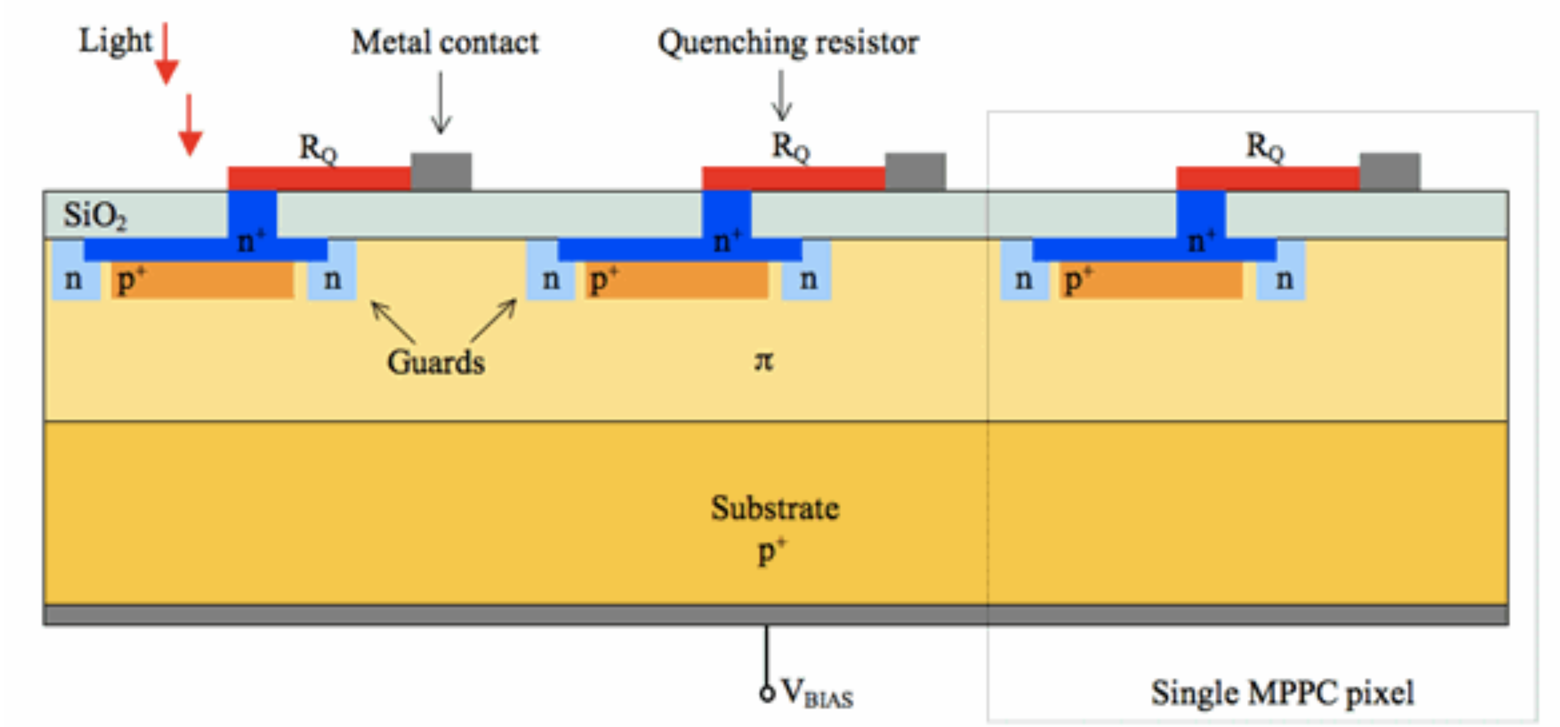


- **Silicon photomultiplier** (SiPM):

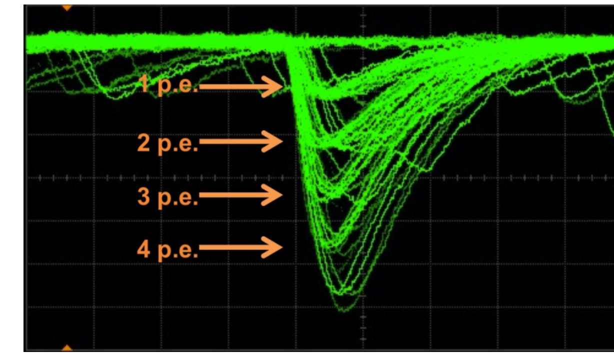
  Again: amplification

  - Multi-pixel photon counter = 2D array of APDs operated in **Geiger mode** (voltage above breakdown voltage → discharge independent of light input)
  - Single pixel: **binary** device, energy = sum of photons detected in all pixels
    - Cell sizes are small enough to only 'see' single photons
  - Gain and PDE similar to PMT, but: very compact design, insensitive to magnetic fields, low afterpulsing → replacement for traditional PMTs
  - Challenges: temperature stability, dark current, cross talk of pixels

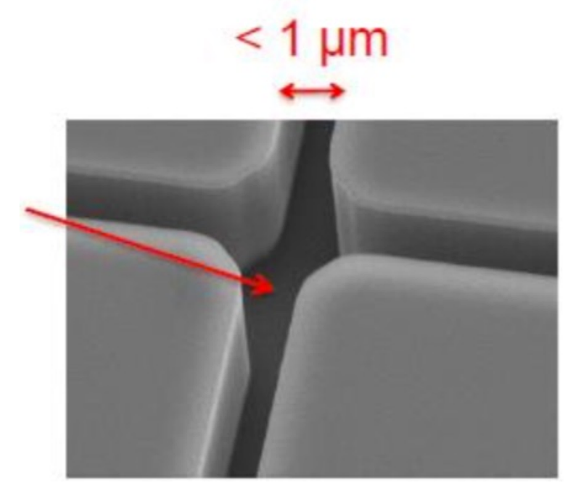


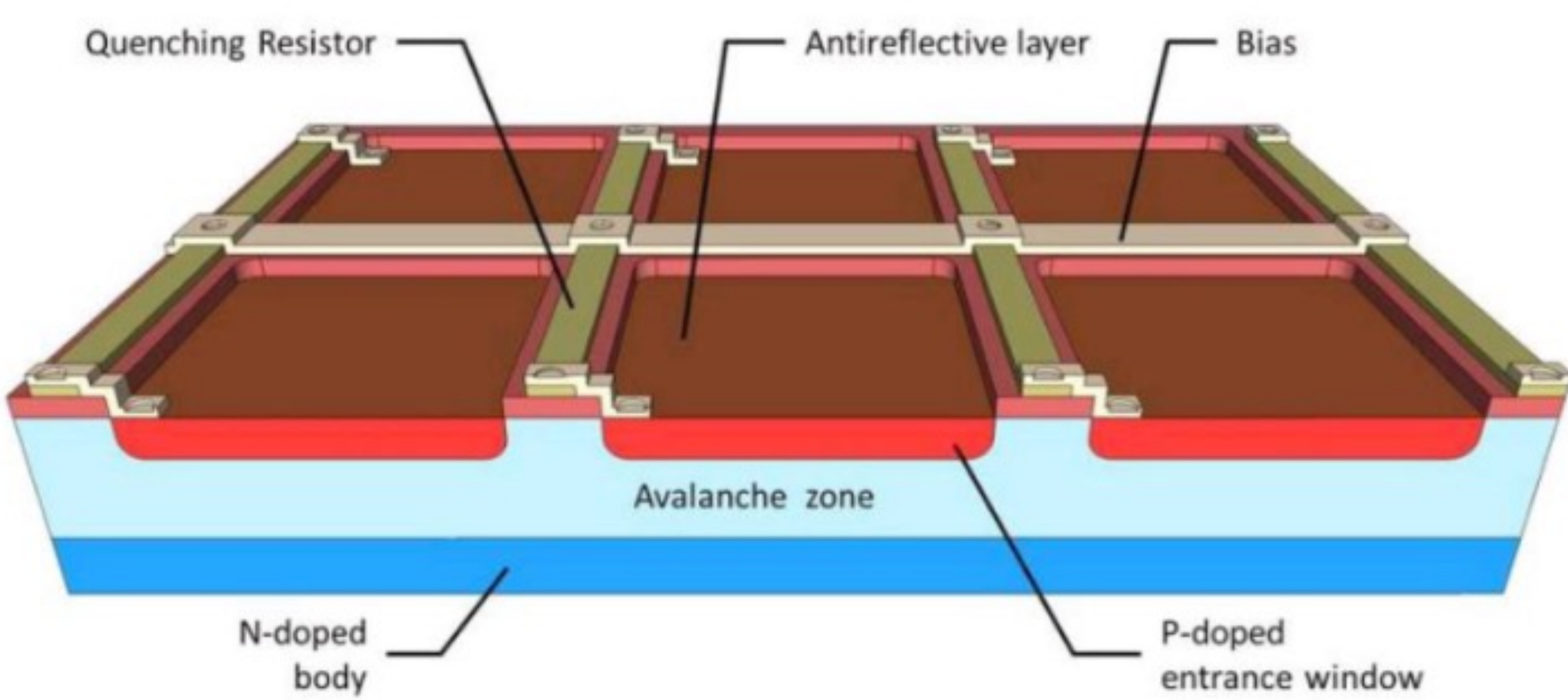


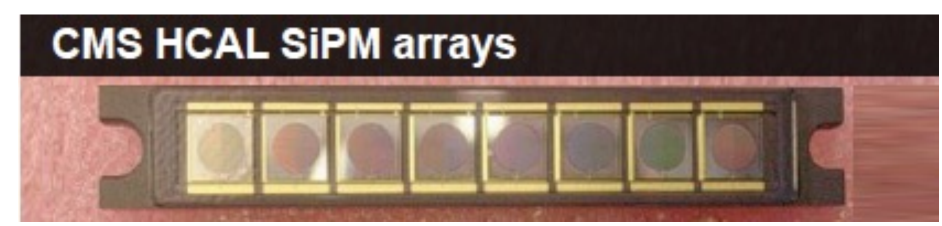
SiPM Silicon Photomultiplier

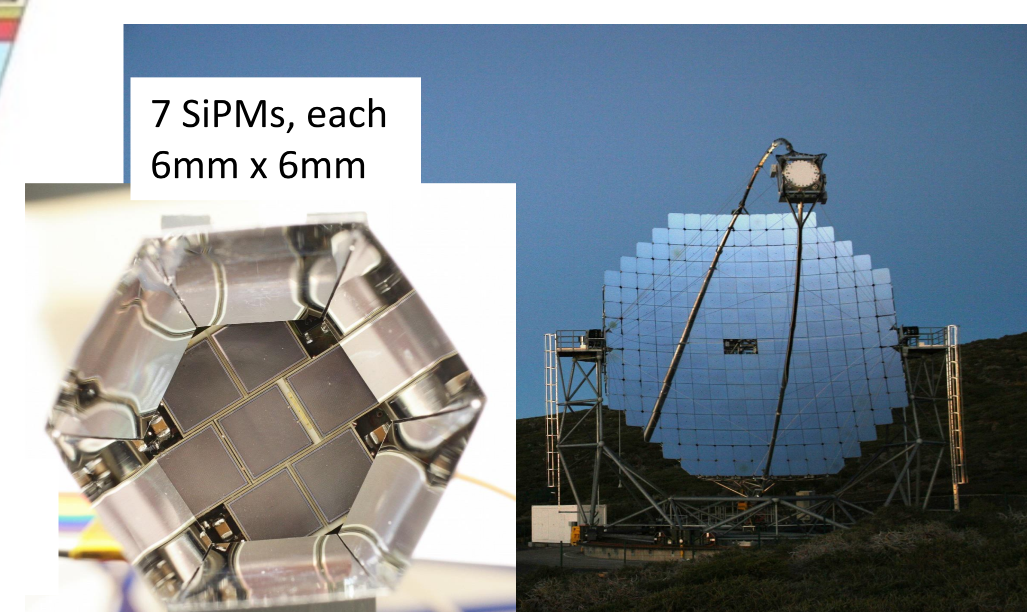


- Gamma-ray cameras, PET scanners, X-Ray detection, calorimetry, LIDAR, neutrino detection (DUNE, …), radiation monitoring, space application (EUSO, AMS), SHiP, SiFi (LHCb), nEXO, timing@LHC (up to $3*10^{14}$ n_{eq}/cm^2), telescope (e.g. MAGIC), Darkside, etc.
  - Limit on radiation tolerance due to DCR (cooling helps)









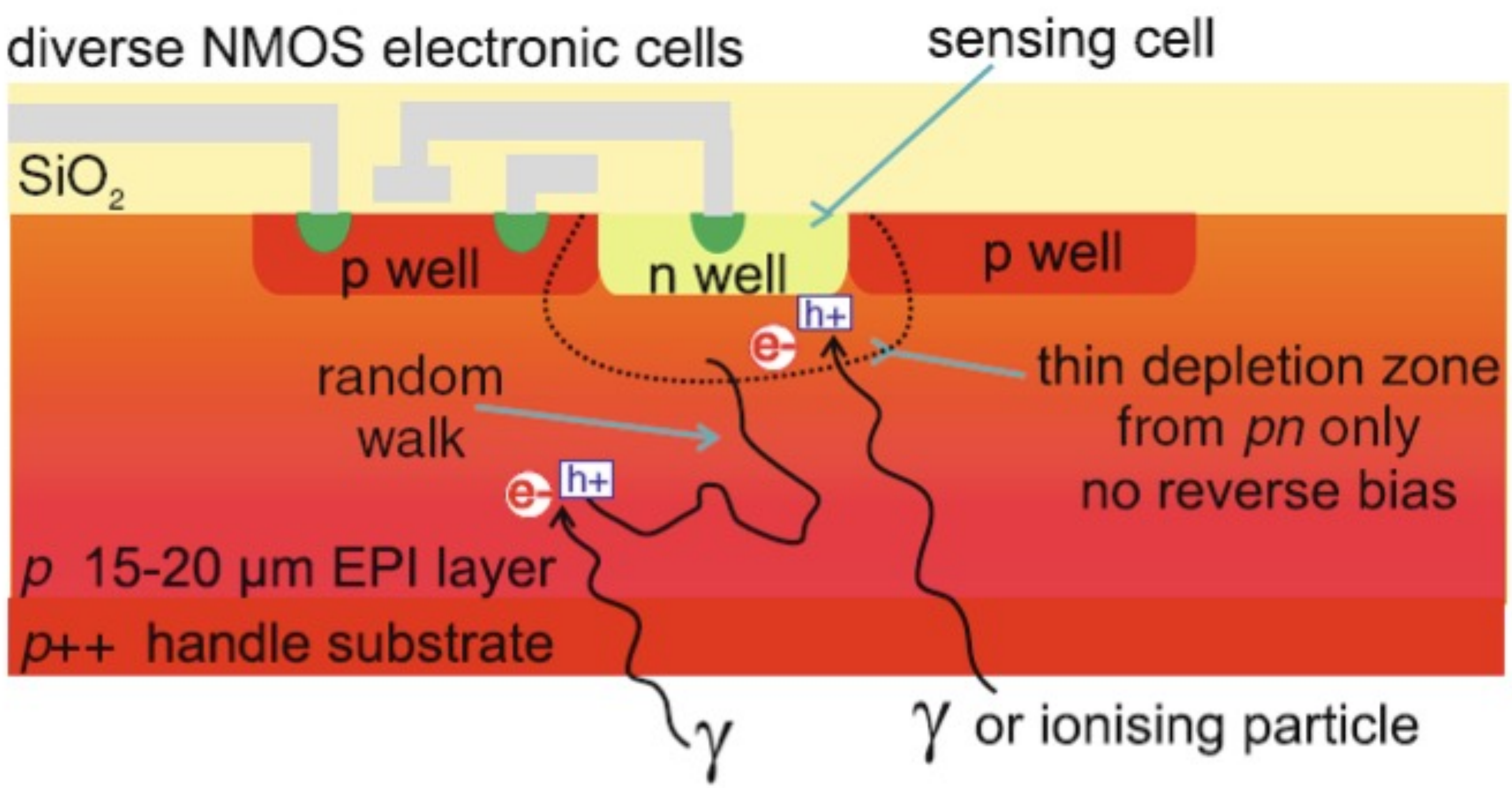
SHiP: **S**earch for **Hi**dden **P**article: Dark matter search behind SPS beam dump facility 10^{20} Protons on Target (PoT) (3500 SiPMs)
EUSO Extreme Universe Space Observatory
nEXO = (next) Enriched Xenon Observatory (digital SiPMs - **3DdSiPM**)

Monolithic Active Pixels (MAPS)

CMOS

Monolithic

Scheme of a CMOS monolithic active pixel cell with an NMOS transistor.
The N-well collects electrons from both ionization and photo-effect.
Electronics and sensor fully integrated – MONOLITHIC!



- No depletion voltage
- Very thin
- Very low noise
- **Random walk – no drift**
- In cell signal processing
- Very high resolution

- ALICE upgrade will build 10m^2 out of this (**with some V_{bias}**)
- Not radiation hard enough for CMS or ATLAS
- Not fast enough for CMS or ATLAS – random walk

That's what you have in your camera (mobile phone)

HV-CMOS

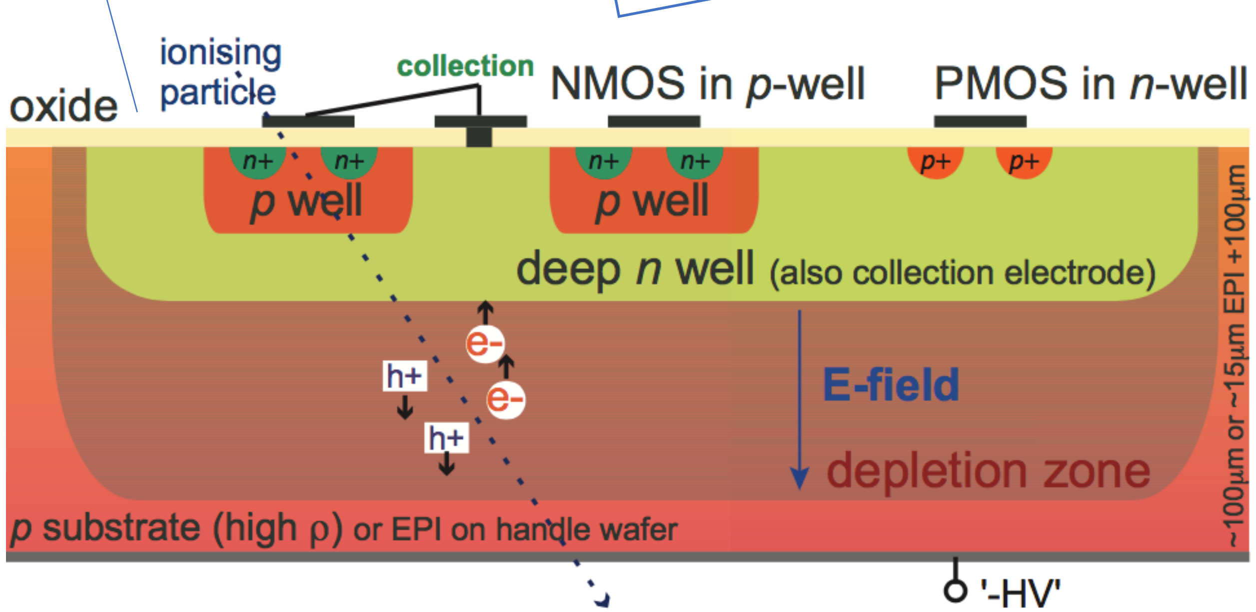
A very interesting detector concept

- ‘From’ high power and automotive industry
  - **Not available in all FABs**
- Quite radiation tolerant
- **Protect** NMOS and PMOS circuits INSIDE deep-wells - NESTING
- **Allows to apply ‘high’ voltage thus <u>deplete</u> the bulk**
  - **Voltage = field = drift NOT random walk**
  - Need backside contact

Monolithic

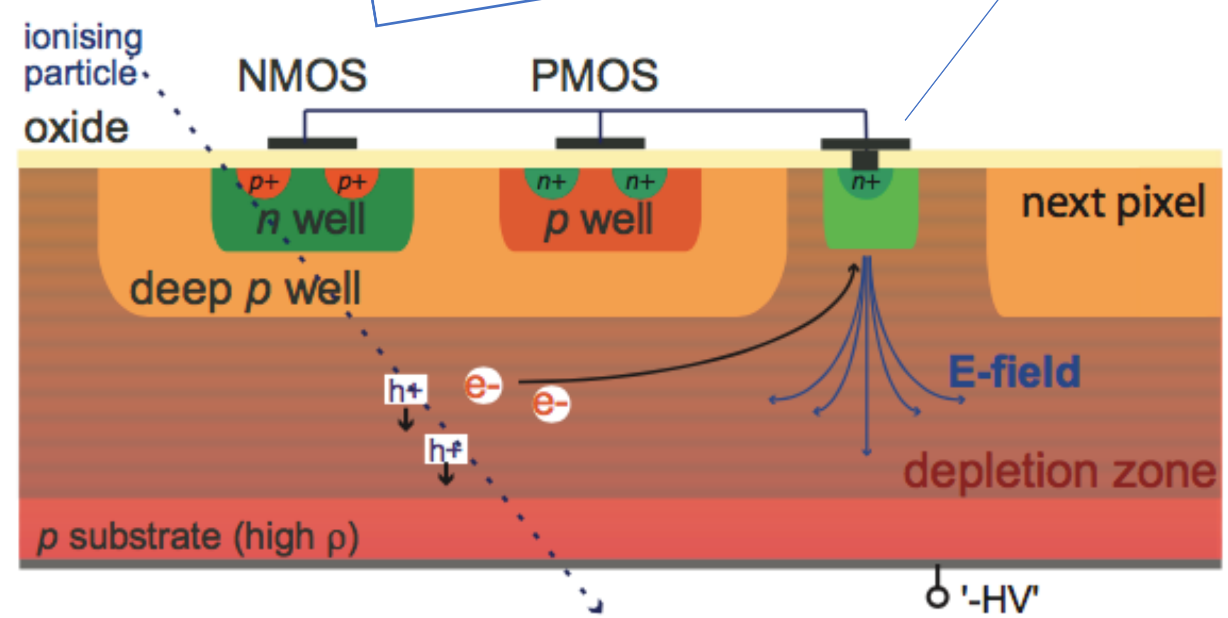
e.g. 50-60 μm (for RD50)

BIG electrodes



SMALL electrodes

e.g. 3 μm (for Malta)

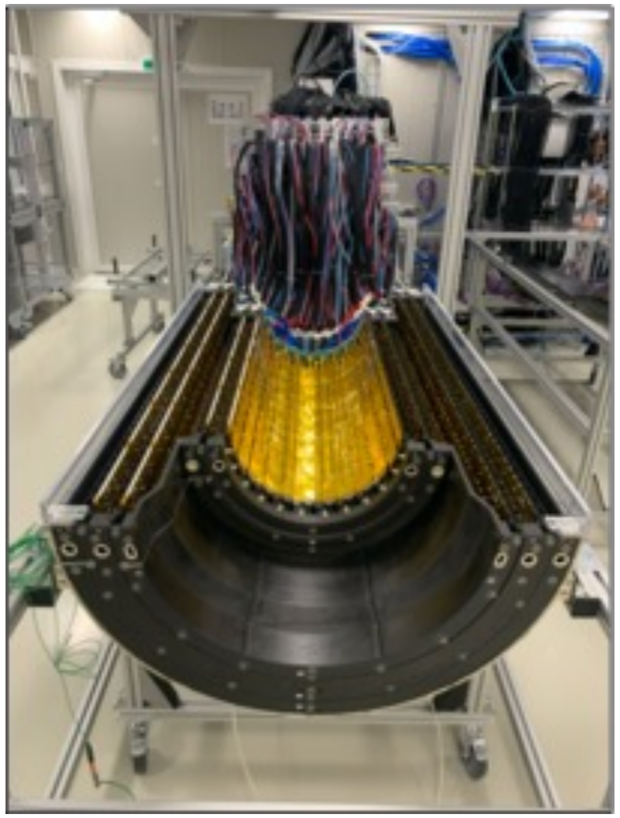


- Short drift path (faster ‘*collection*’)
- High C - higher noise O(100 e$^-$)
- Homogeneous weighting field
- High homogeneous electrical field
- *E.g. MUPIX, RD50, MONOLITH, LF-MONOPIX, ATLASPIX*

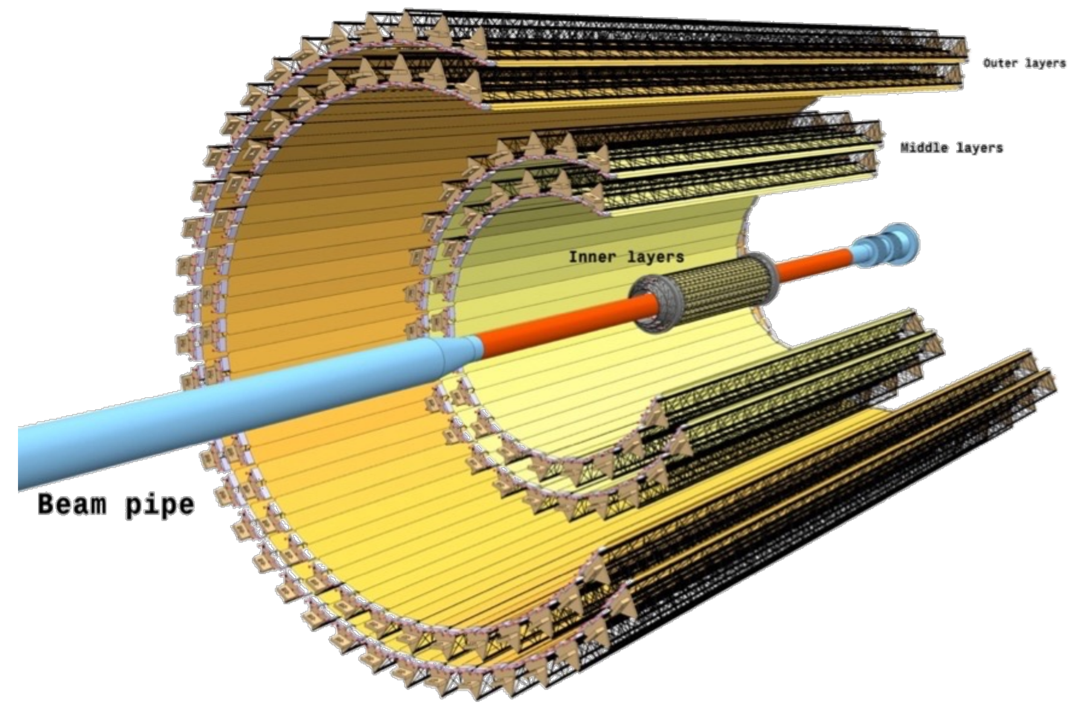
- Long drift path
- Very low C - reduced noise (~10 e$^-$ & low power)
- δ weighting field – arrival
- *Some adaptions help further – electrical field*
- *E.g. ALPIDE, MALTA, TJ-MONOPIX. CLICTD, FASTPIX*

2D - superb resolution and granularity && can do 12” wafers && radiation tolerance $10^{15}\ \Phi_{eq}$

The ‘big’ example of MAPS - ALICE



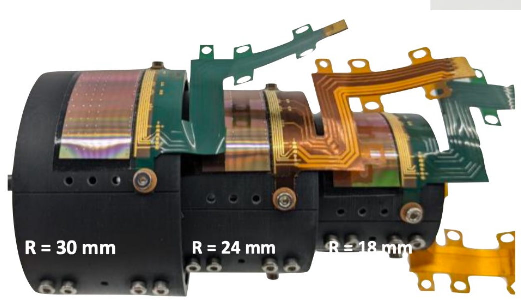
- **LS2:** 3+4 layers of MAPS (CMOS) **~10m^2**
  - 27x29 μm^2 pixels - **12.5 G-pixels**
  - MAPS thinned to 50 μm
    - ~0.3 % X_0 per layer

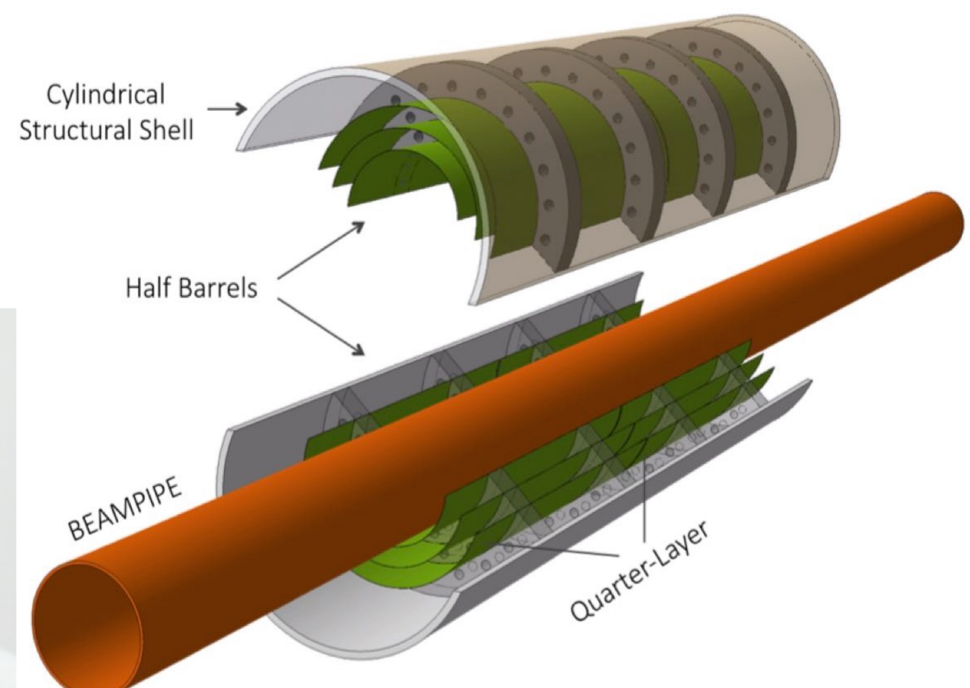


ALICE ITS Upgrade TDR CERN-LHCC-2013-024

- **Future:** ALICE upgrade (ITS3) – HR/HV CMOS
  - Push technology further: **thinner,** large sensors through stitching
  - Faster signal, more radiation hard
  - Pixel sizes 10x10μm^2 → 3μm position resolution
  - X/X_0 per layer 0.05%
  - **CURVED**

In test beam
Bent ALPIDE





Truly cylindrical vertex detector

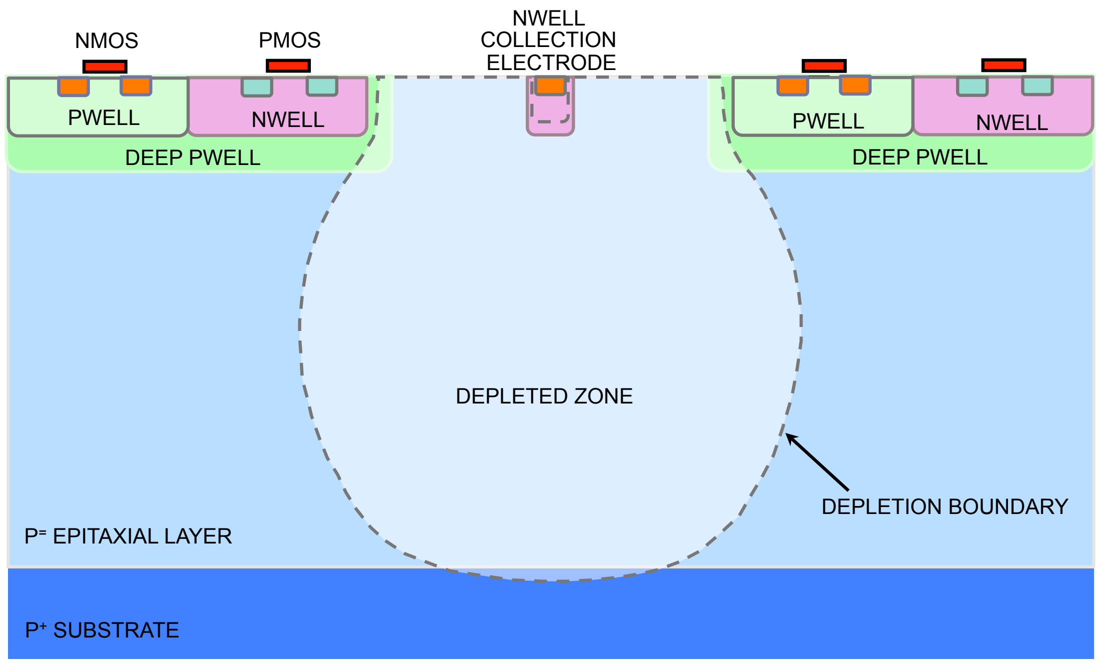
ALICE-PUBLIC-2018-013

HV-CMOS

Monolithic

SMALL electrodes II

ALICE ITS Upgrade
TDR CERN-LHCC-2013-024



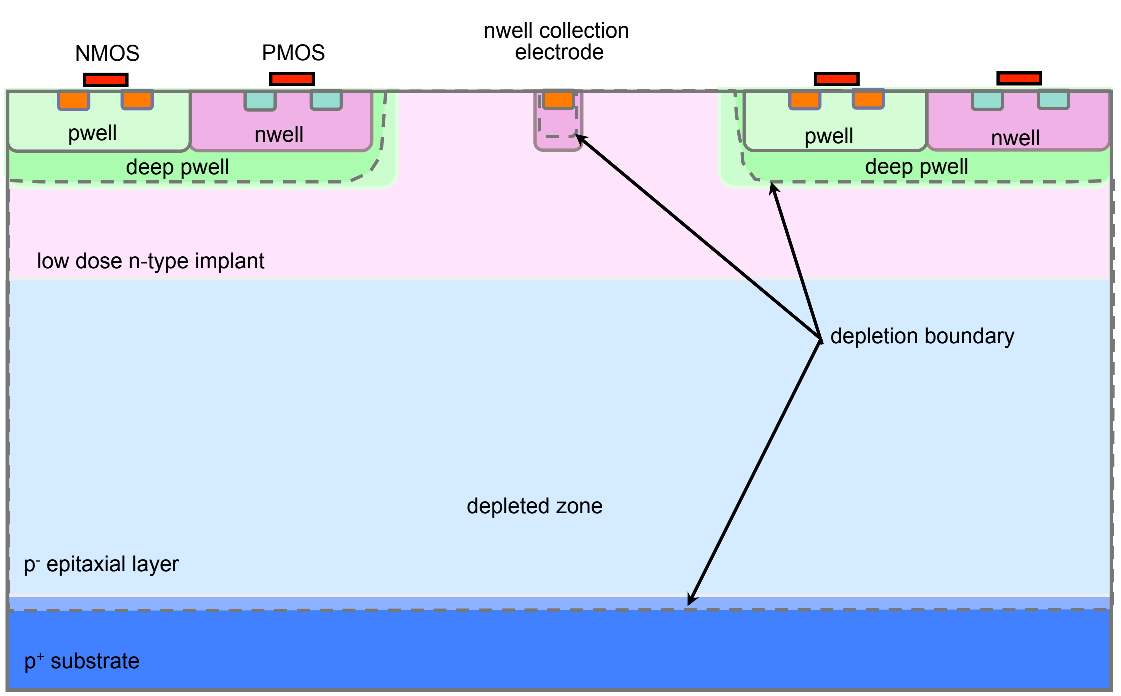
Vertical full depletion

Lateral partial depletion

Collection time < 30 ns (V_{bb}=-3V)

Suitable for up to 10^{14} n/cm^2

Foundry Standard Process



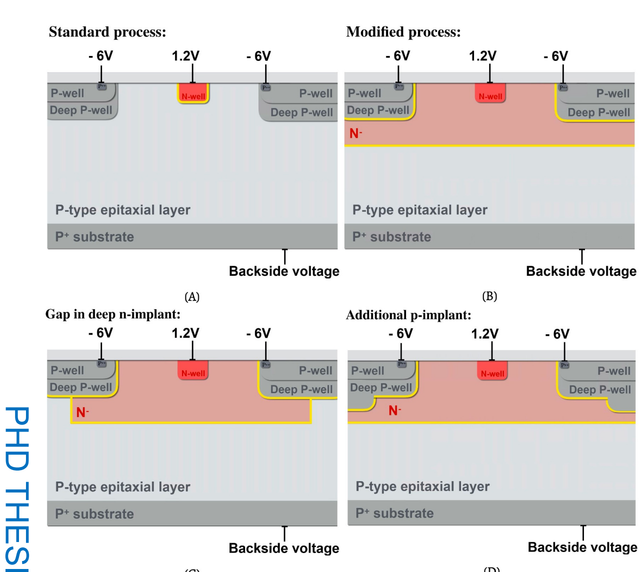
Epi-layer fully depleted

Collection time < 1 ns

Operational for up to 10^{15} n/cm^2

No lateral depletion – full vertical

E.g. Modified process CERN/Tower



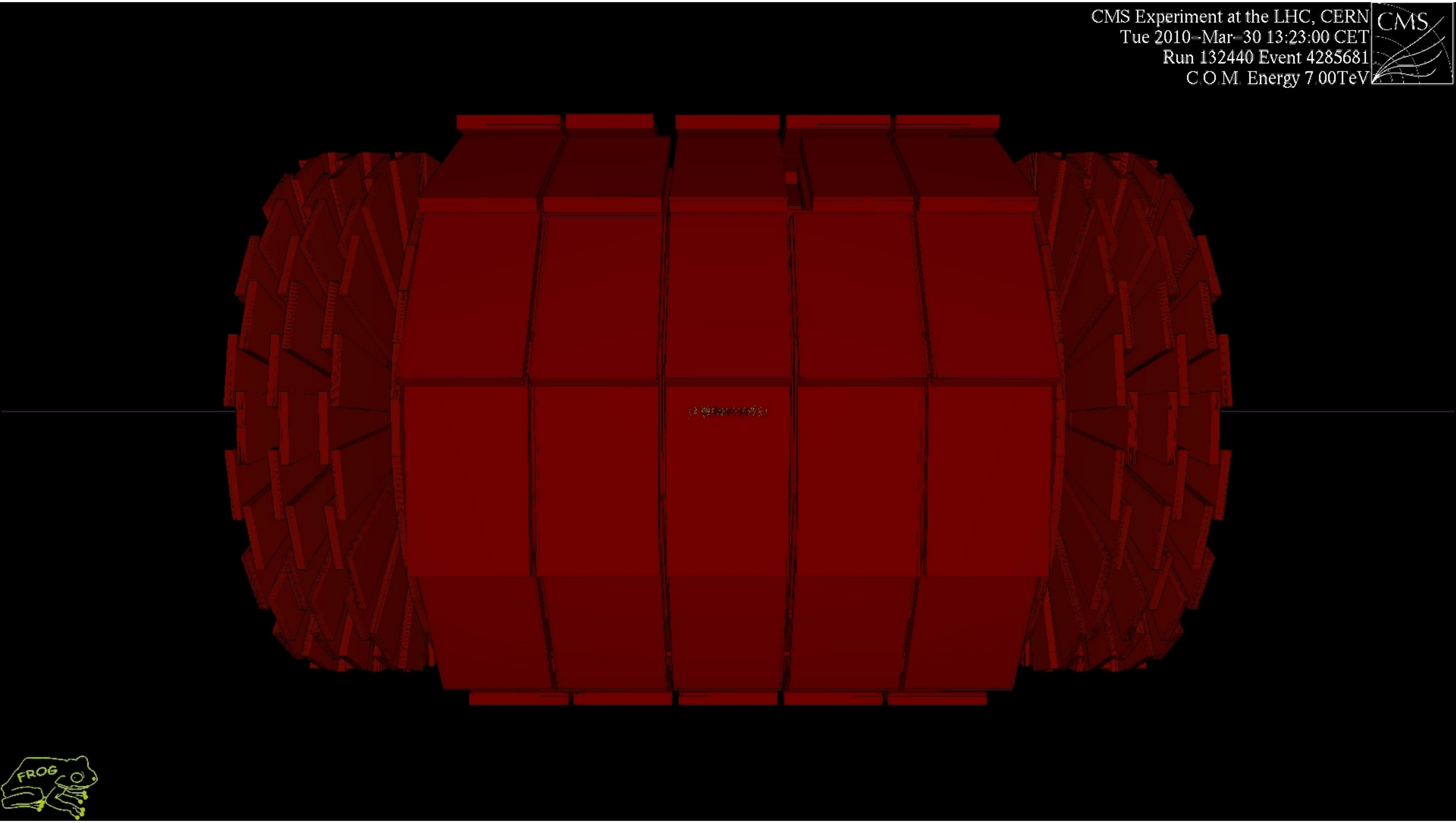
PHD THESIS Jan
HASENBICHLER

Snoeys, W. and others, 2017 NIMA 871, p=90 - 96, DOI=10.1016/j.nima.2017.07.046

Joint ALICE & ATLAS Pernegger, H. and others, 2017, JINST P06008, DOI = 10.1088/1748-0221/12/06/P06008

Systems

A pp interaction at CMS



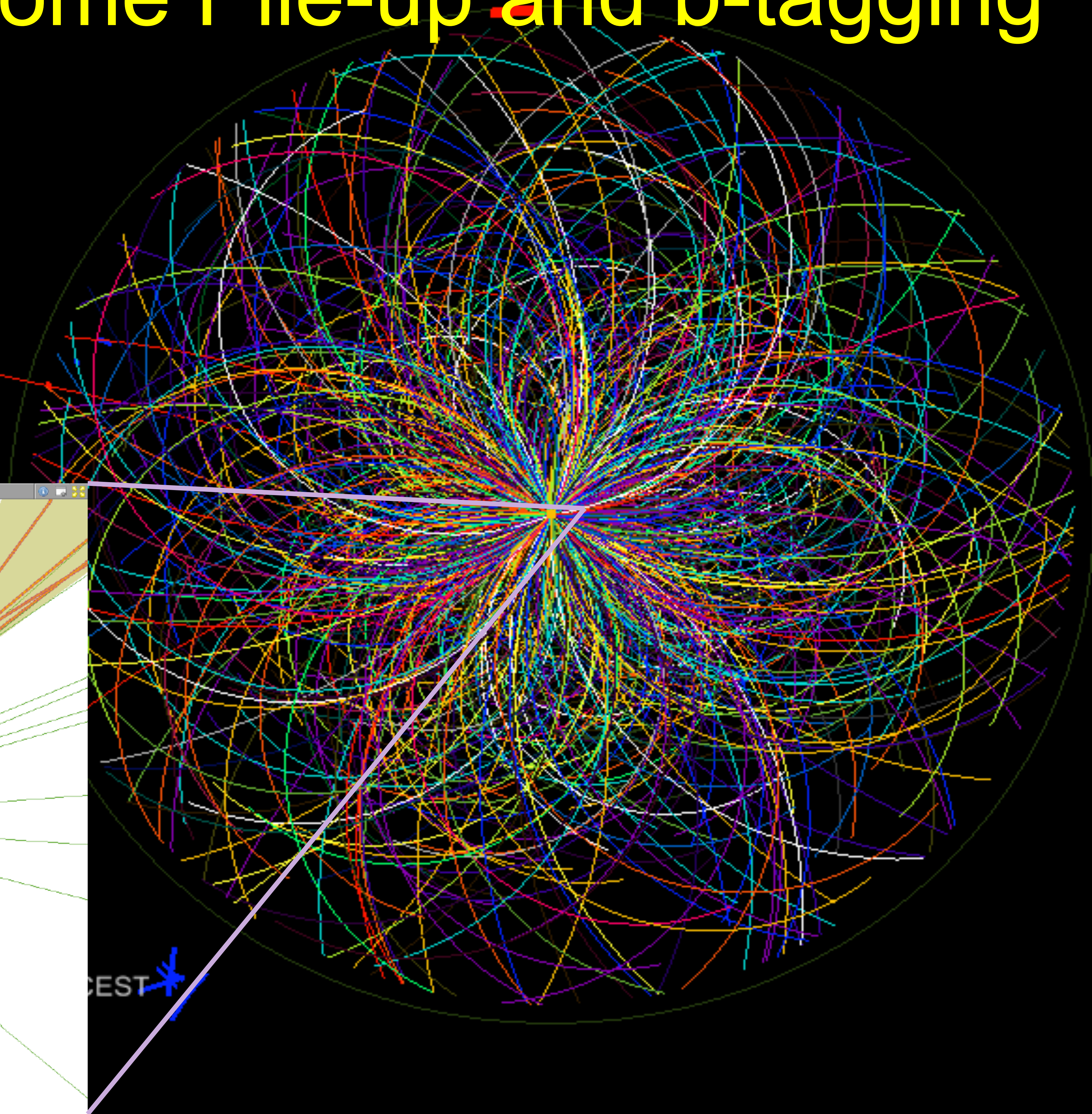
http://www18.i2u2.org/elab/cms/event-display/

The experimental reason for radiation and the need for high precision…

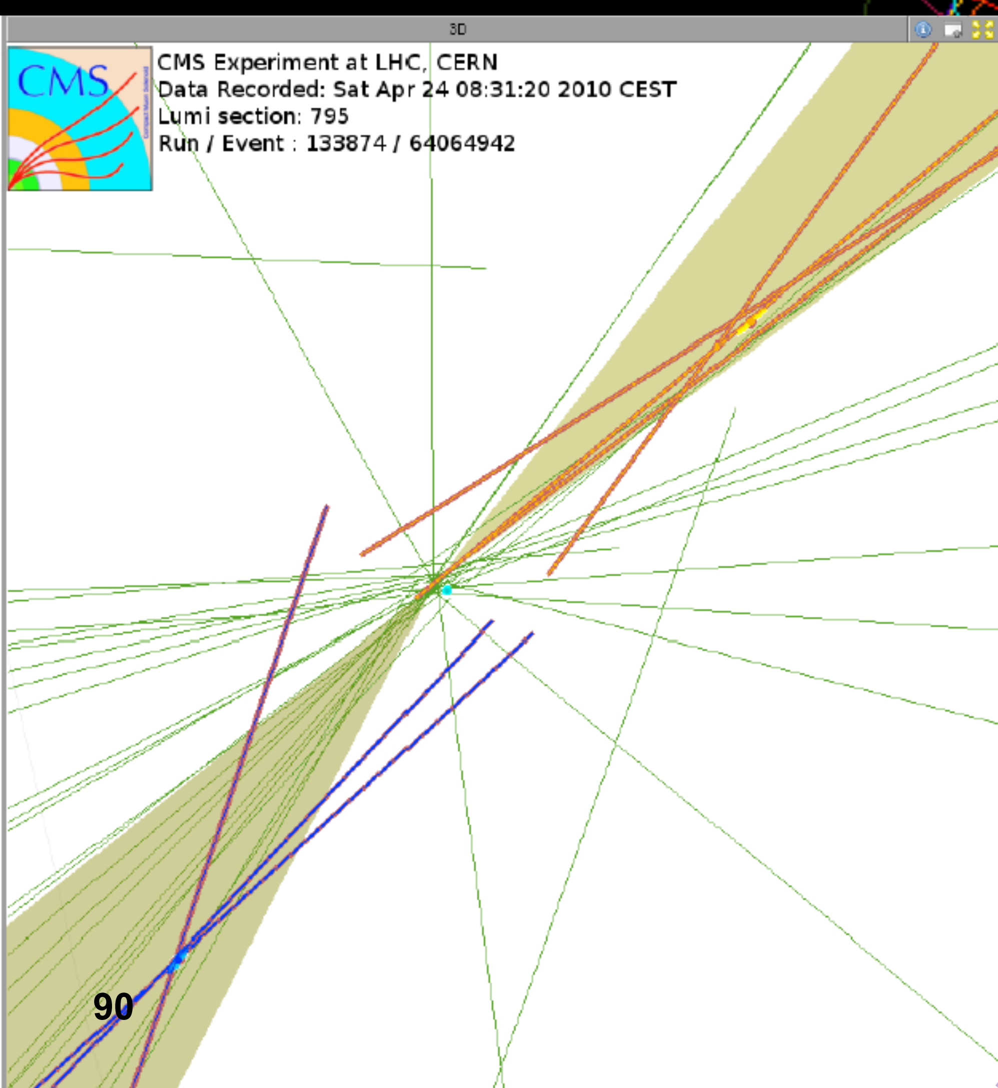
THE REAL WORLD

THE PROBLEM PILES UP ..

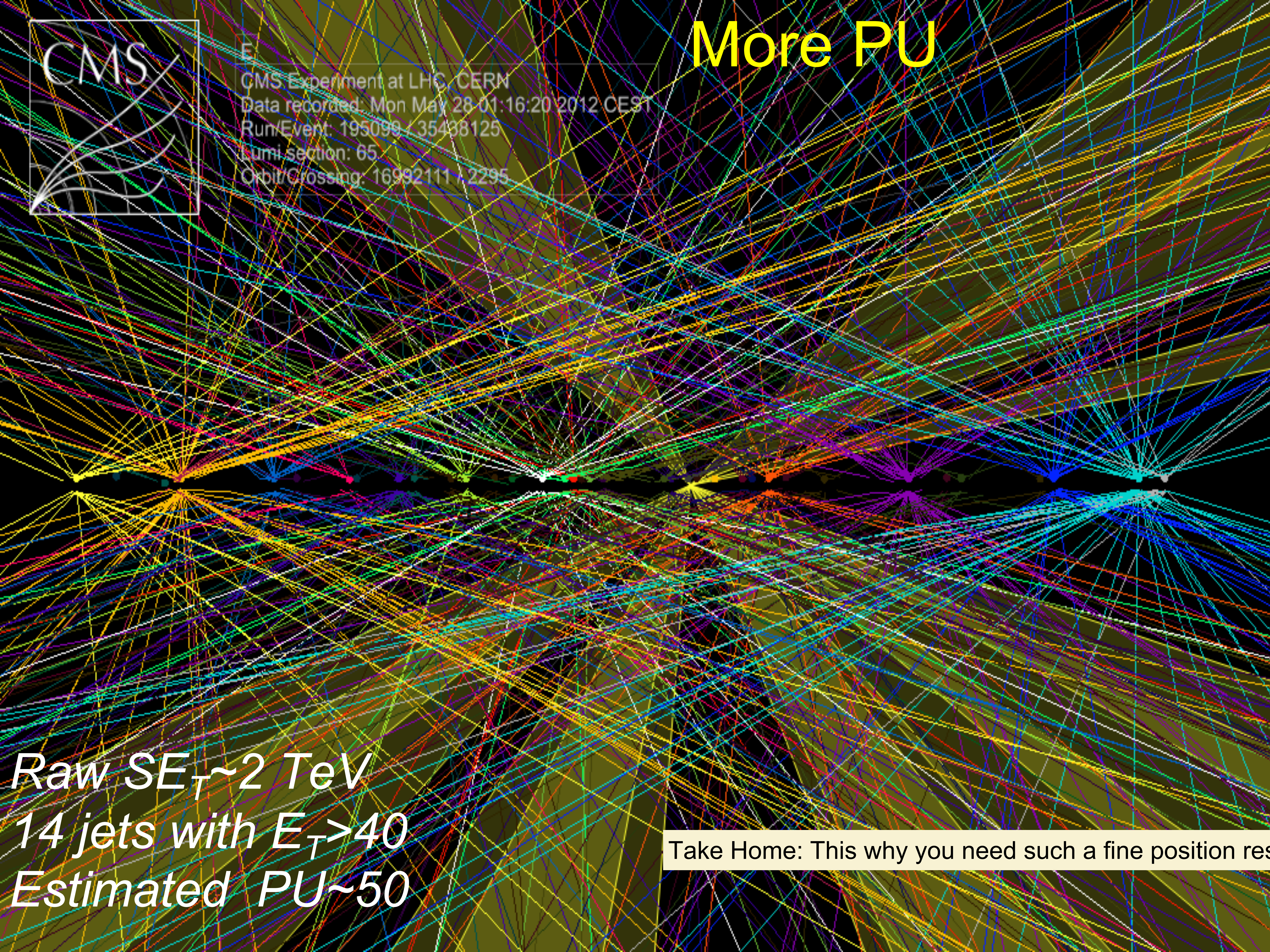
Some Pile-up and b-tagging



Precision allows secondary vertex identification



More PU



Raw SE_T~2 TeV
14 jets with E_T>40
Estimated PU~50

Take Home: This why you need such a fine position res

NA11

CDF

DELPHI

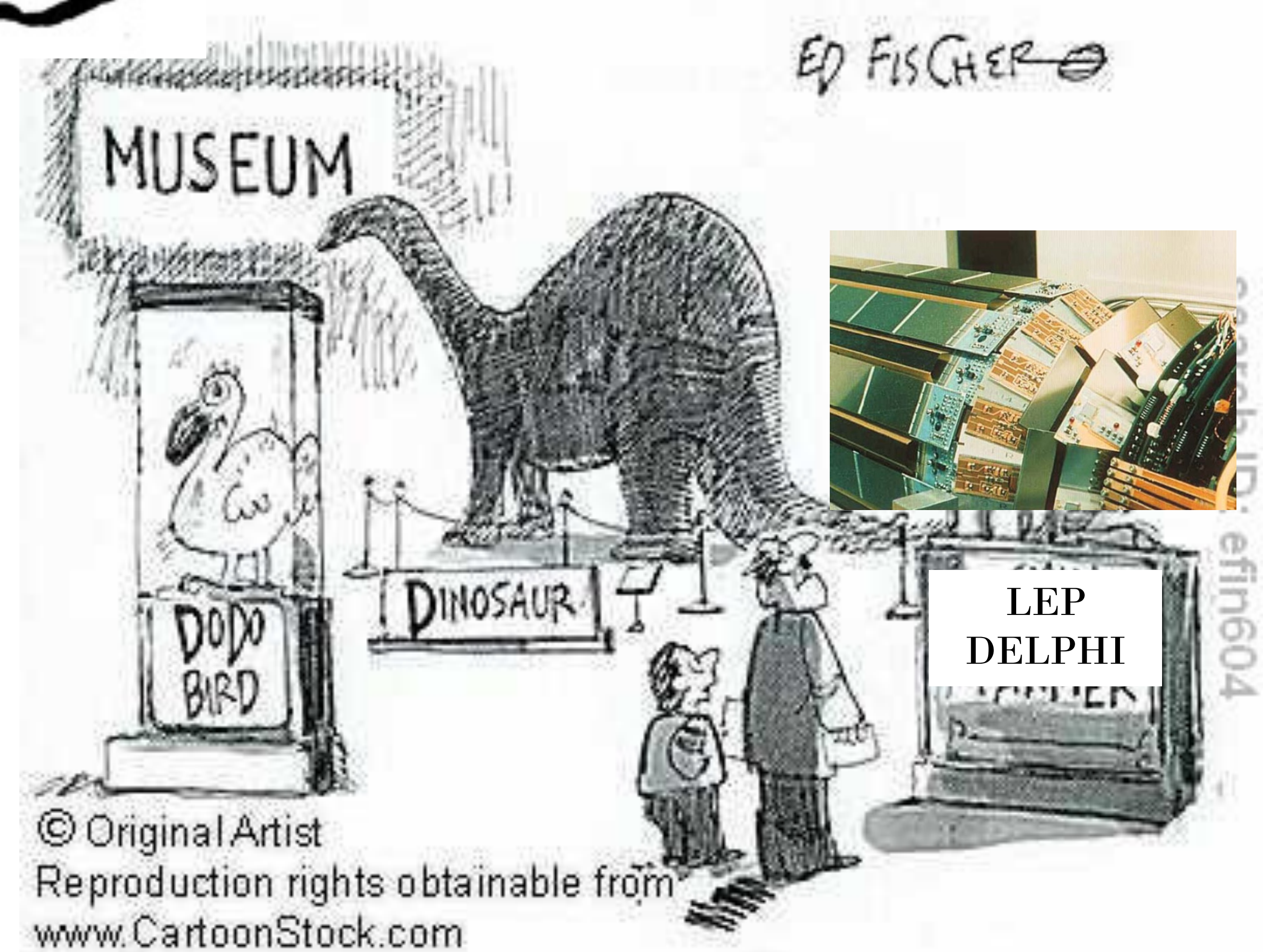
CMS

LHCB (upgrade)

~~CMS/ATLAS upgrade~~ (backup only)

@FCC

EXAMPLES



First Strip Sensor

NUCLEAR INSTRUMENTS AND METHODS 97 (1971) 465-469;

STRIPED SEMICONDUCTOR DETECTORS FOR DIGITAL POSITION ENCODING

E.L. HAASE, M.A. FAWZI*, D.P. SAYLOR and E. VELTEN

Institut für Experimentelle Kernphysik der Universität und des Kernforschungszentrums Karlsruhe, Germany

The counters are large area ion-implanted detectors with a common aluminium contact and a front contact consisting of five or twelve gold strips separated by 0.2 mm.

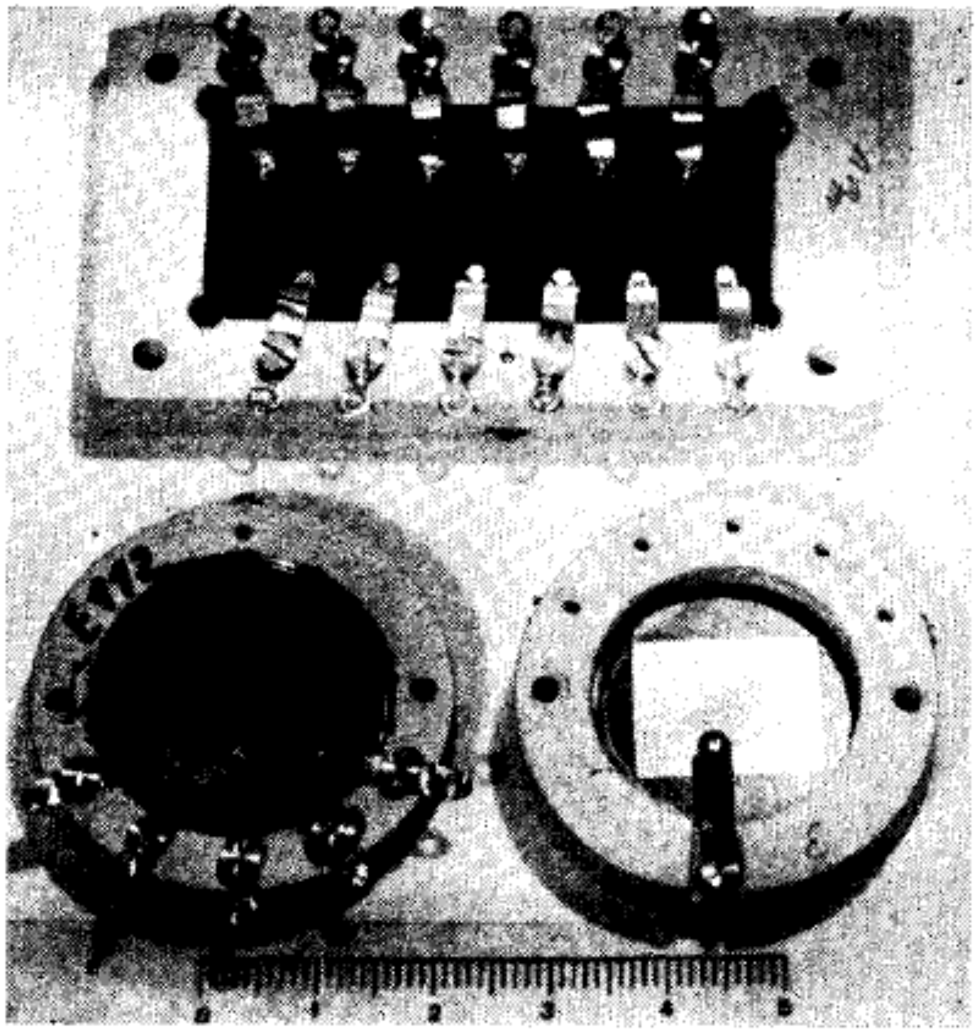


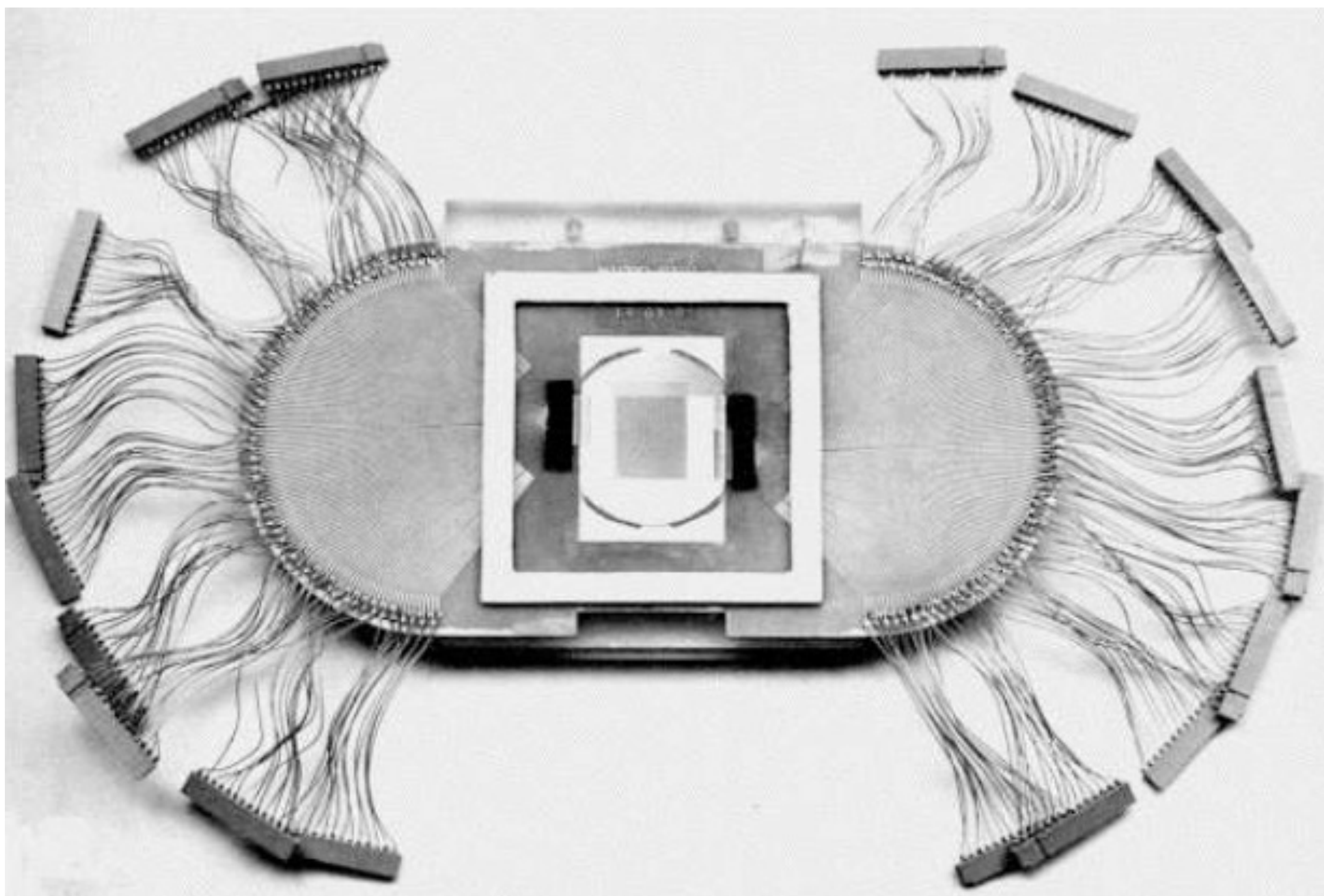
Fig. 1. Ion-implanted semiconductor detectors with subdivided front-contact and common back-contact.

First Silicon Strip Detector in HEP

The NA11 silicon detector 1983

Experiments NA11/NA32 at CERN

Goal: Measure lifetime and mass of the charm mesons D^0, D^-, D^+, D^+_s, D^-_s



NIM205 (1983) 99

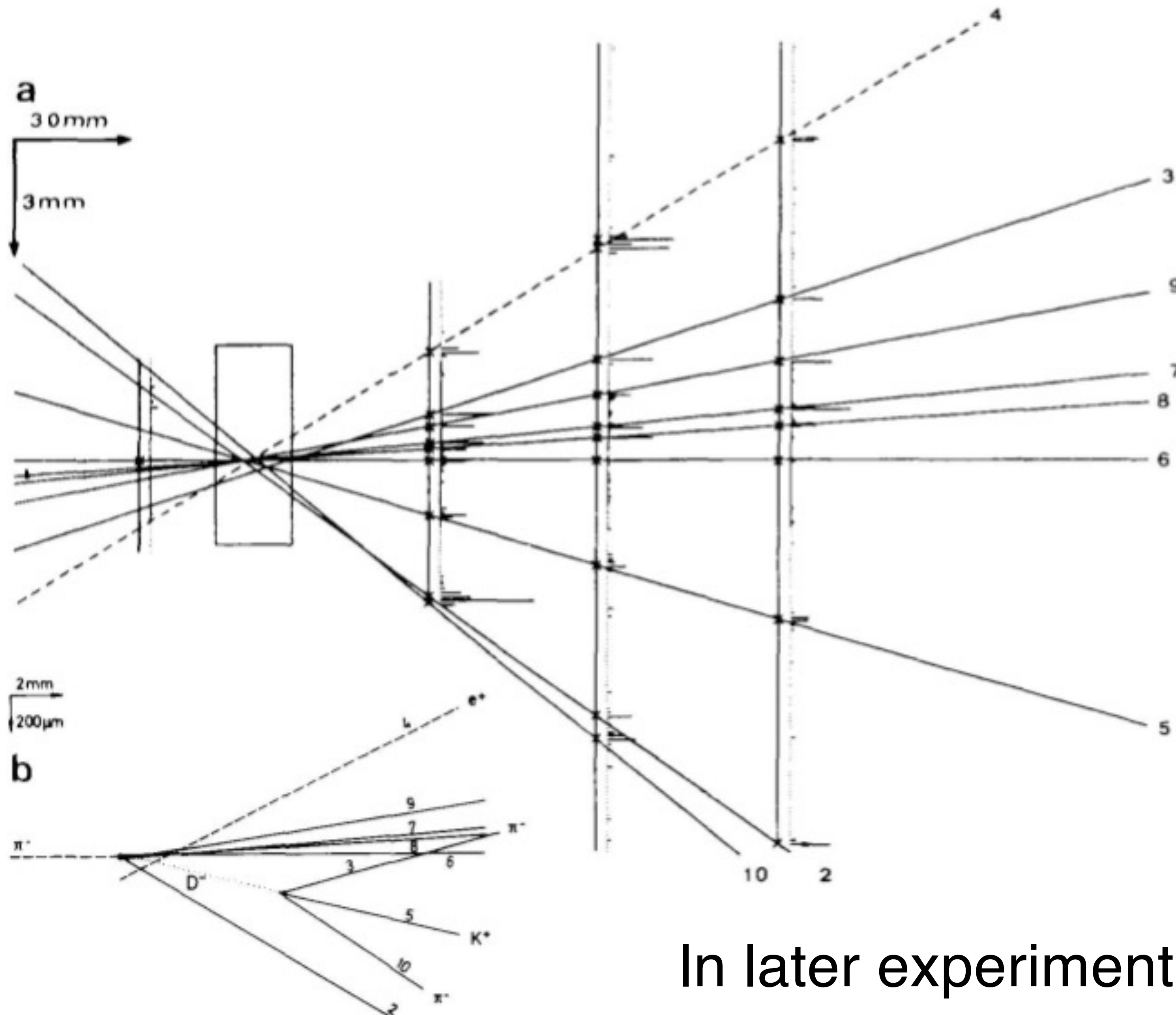
Surface 24 cm^2 (2″ wafer)
1200 strip, 20 μm pitch
Ever 3rd/6th strip connected.
Precision 4,5 μm !

8 silicon detectors
(2 in front, 6 behind the Target)

Ratio detector surface to nearby electronics surface 1:300 !

First Silicon Strip Detector in HEP

Event from NA11



Computer reconstruction of a decay of $D^- \rightarrow K^+\pi\pi$

Flight path length ($c\tau\gamma$) used to deduce the lifetime of the particle.

In later experiments these dislocated vertices are used to identify - **tag** - heavy quarks.

Very Precise – Very Close

DELPHI @ LEP

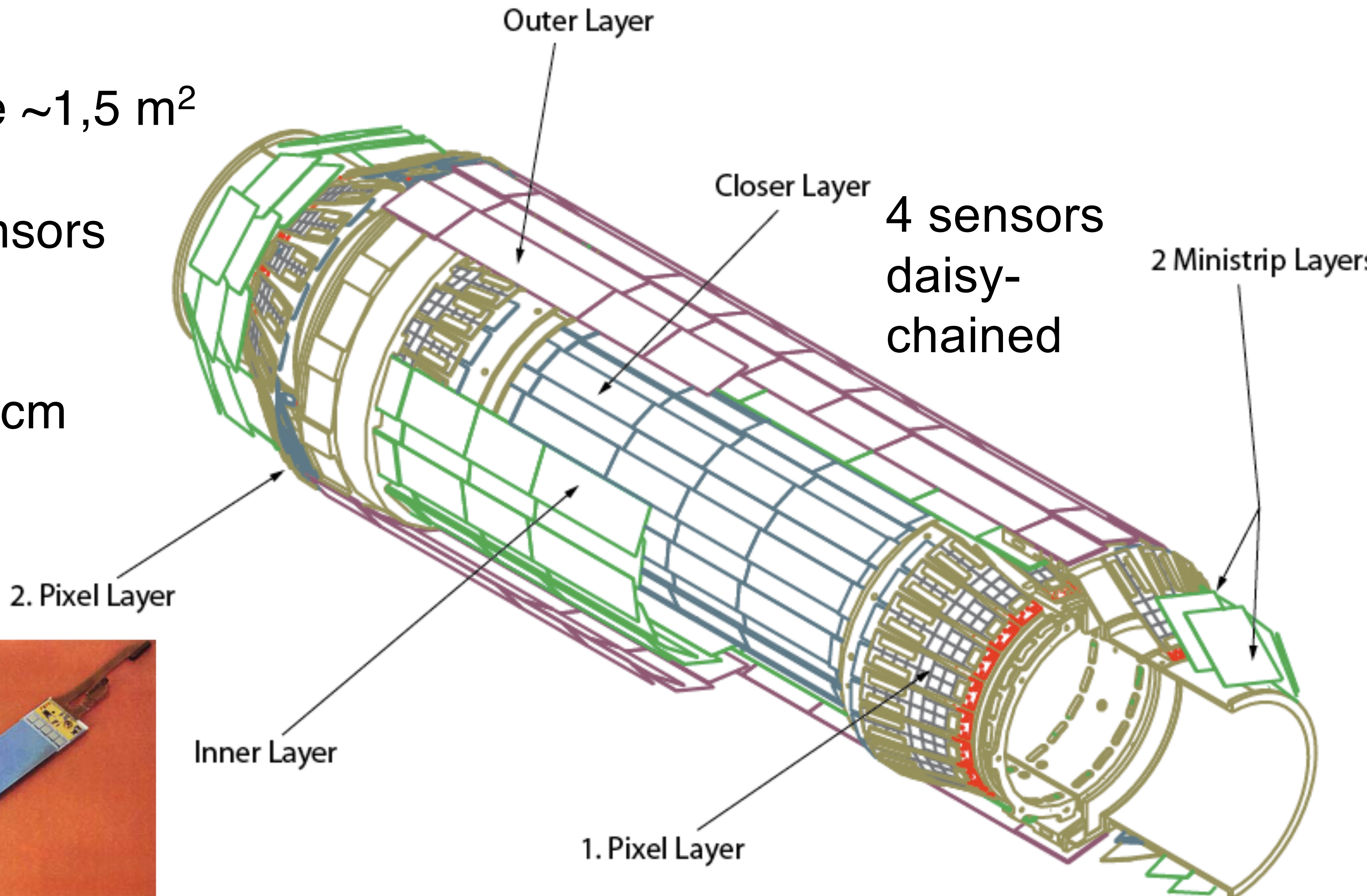
Si Detectors in Collider Experiments

The DELPHI Vertex Detector

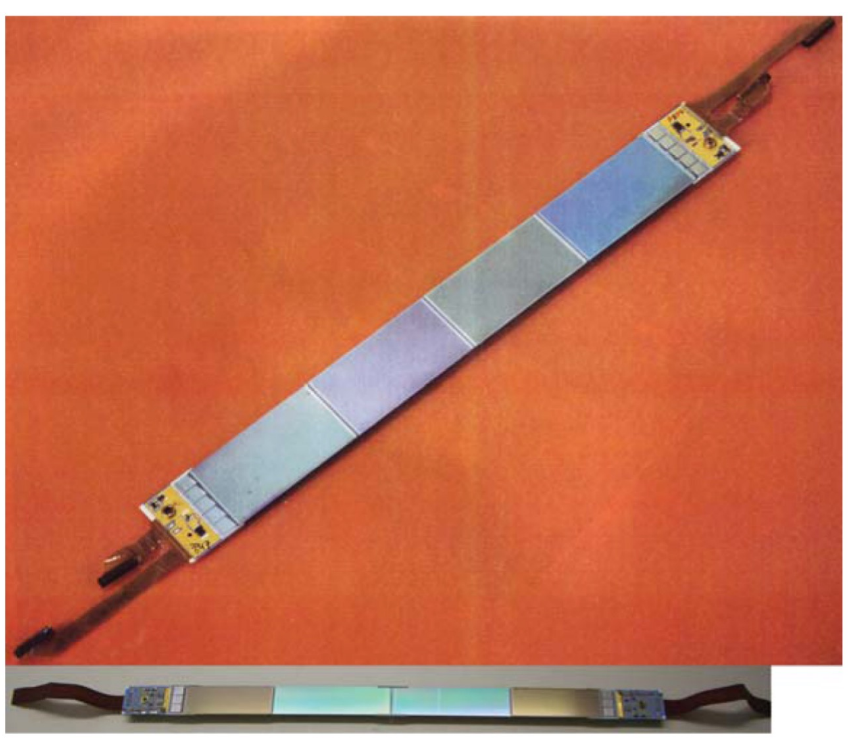
Sensor surface ~1,5 m^2

888 Silicon sensors

Length ~1 m
Diameter ~ 20 cm

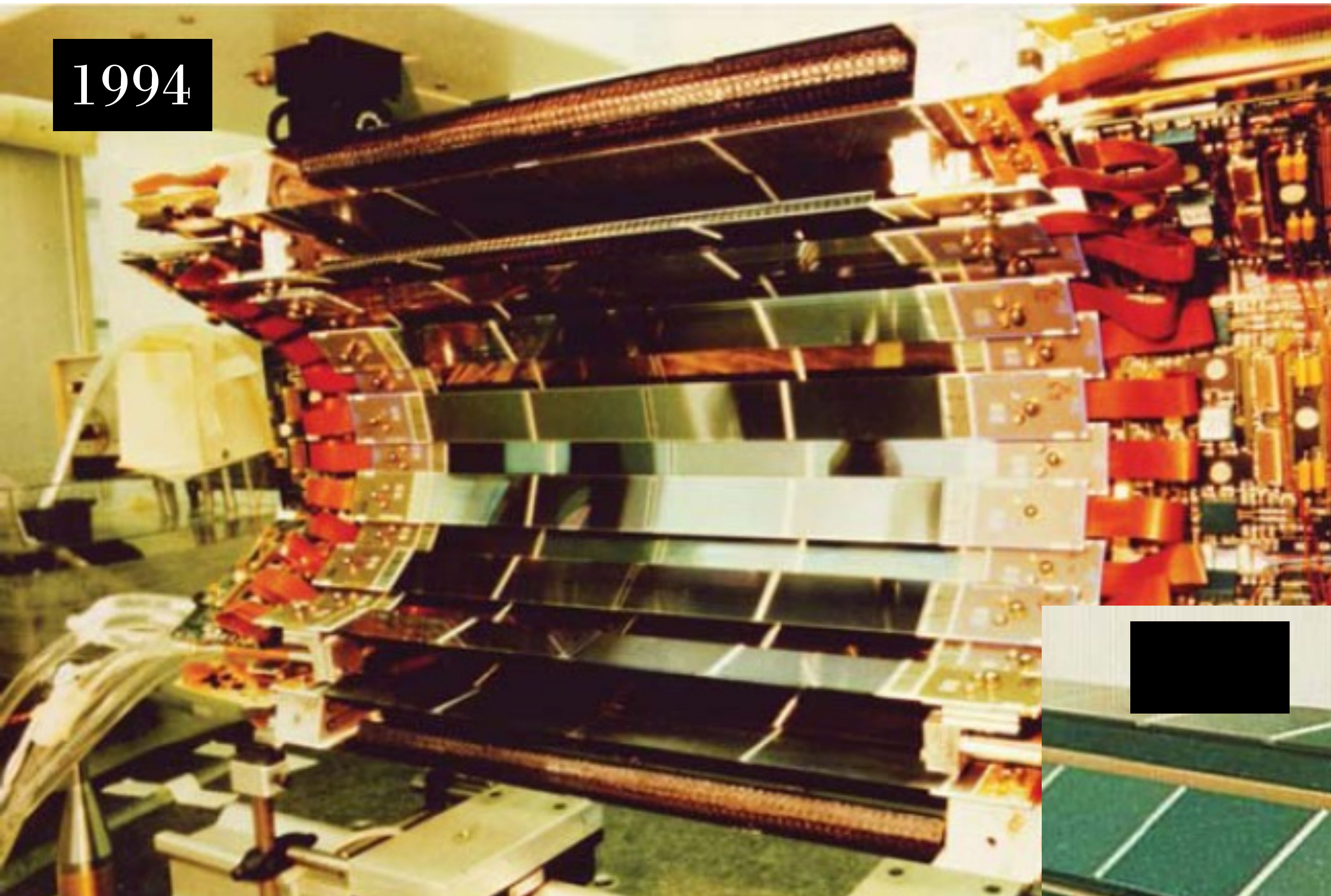


4 sensors daisy-chained

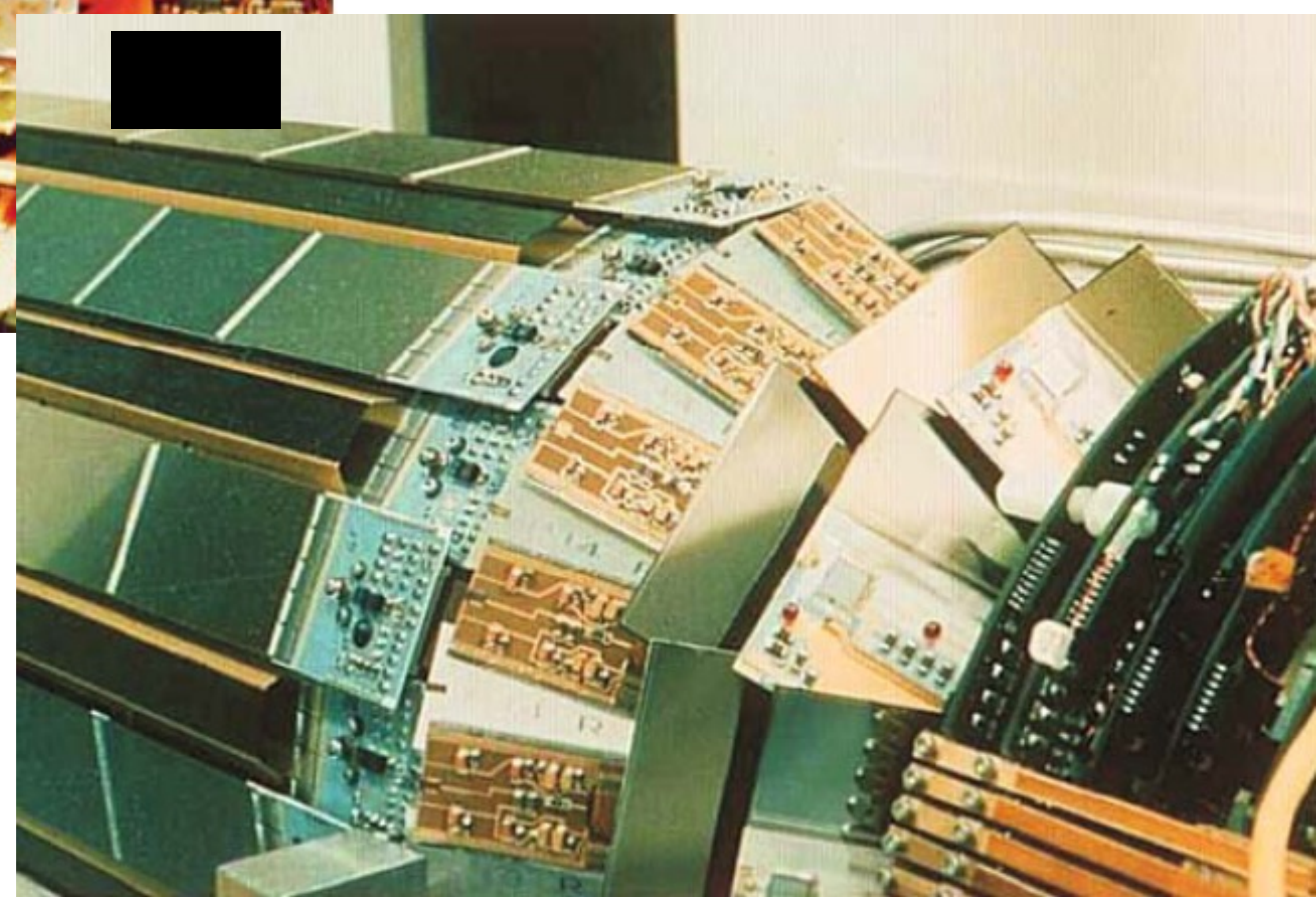


I call it a boutique detector, everthing is dedicated!

LEP: DELPHI



1997
3 double sided layers Rϕ, Rz
Extra forward strip sensors
Extra forward pixel



Even with the large size still clear bifurcation:

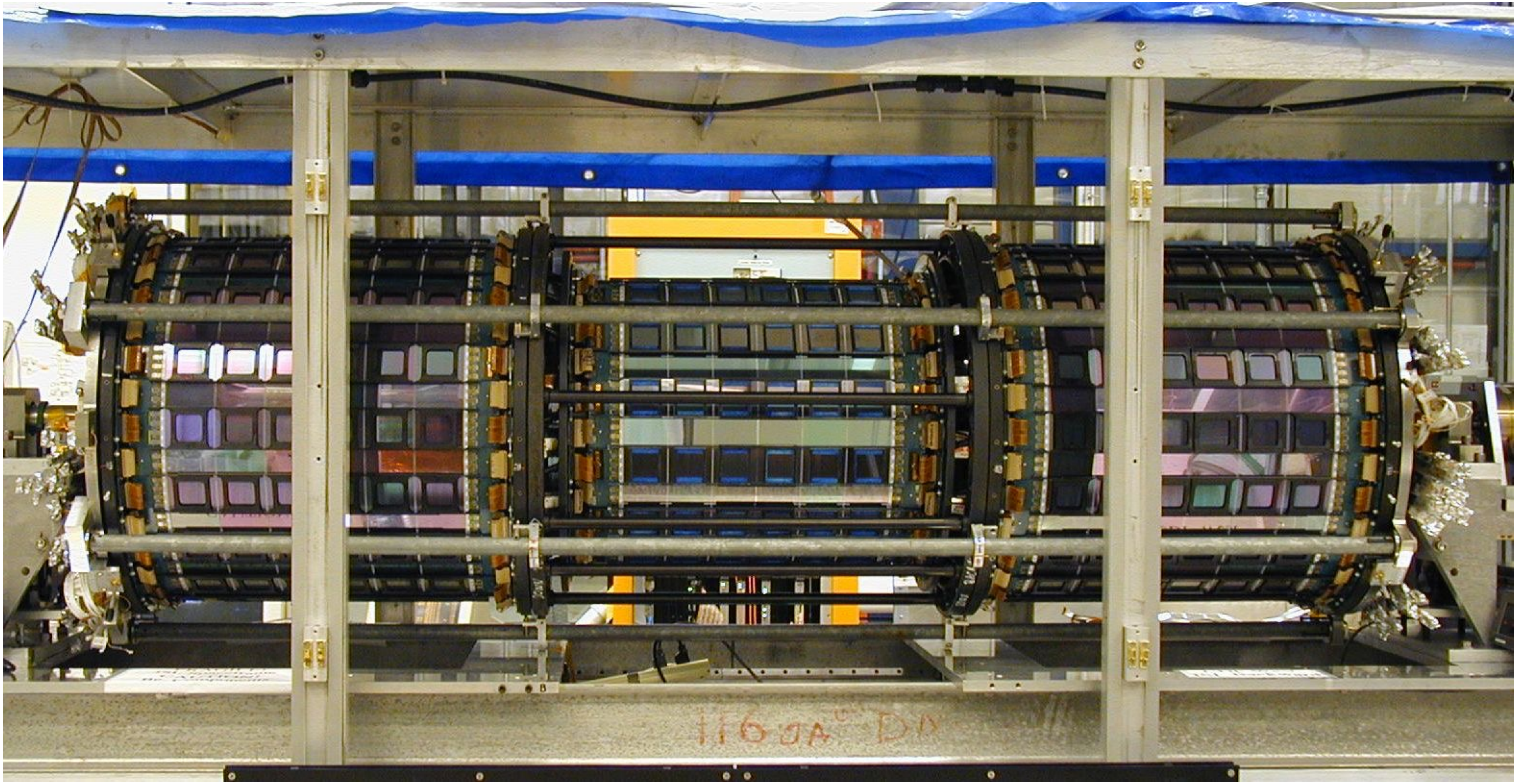
- Silicon gives Vertexing
- Gas gives Tracking

CDF @ TEVATRON

Collider Detector at Fermilab
CDF@TEVATRON

First ever $10m^2$ detector

Intermediate Silicon Layers Detector

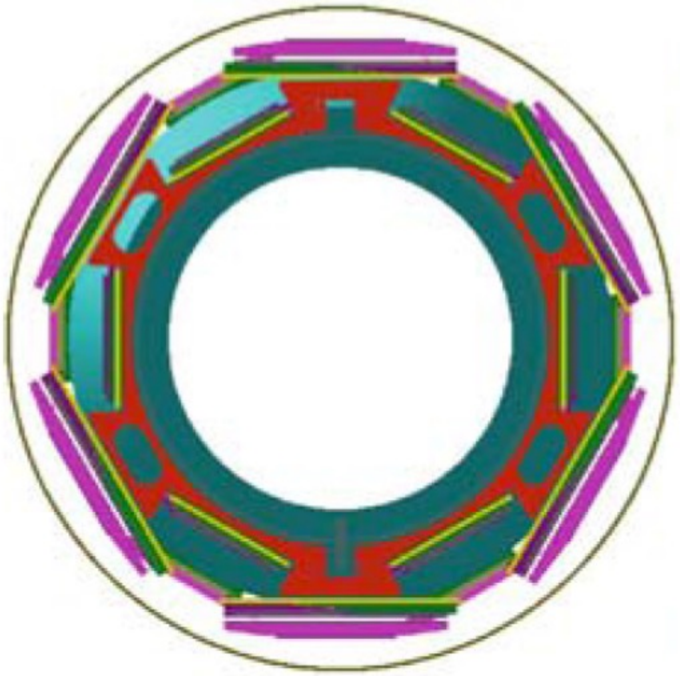


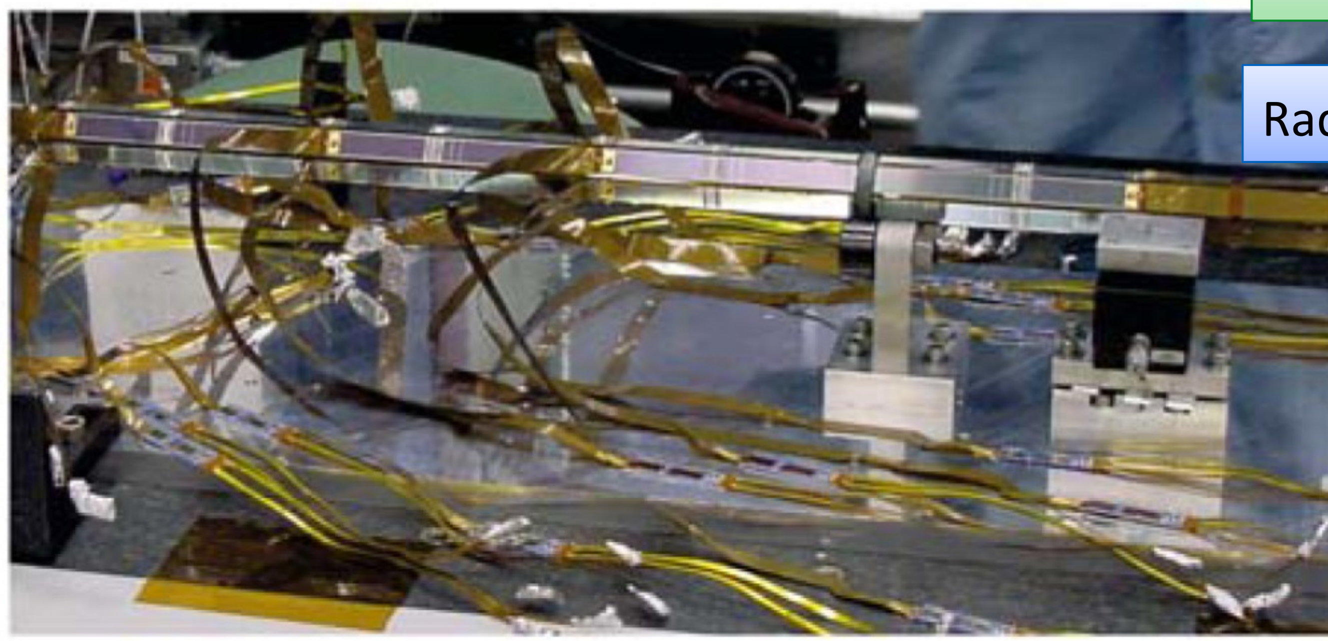
$10m^2$ with fully double sided strip – first use of 6" wafer in HEP
First time with silicon as stand-alone-tracking

Radiation tolerance> $10^{13}\ \Phi_{eq}$

Collider Detector at Fermilab DCF @TEVATRON

First use of LHC radiation tolenrant sensor recipe

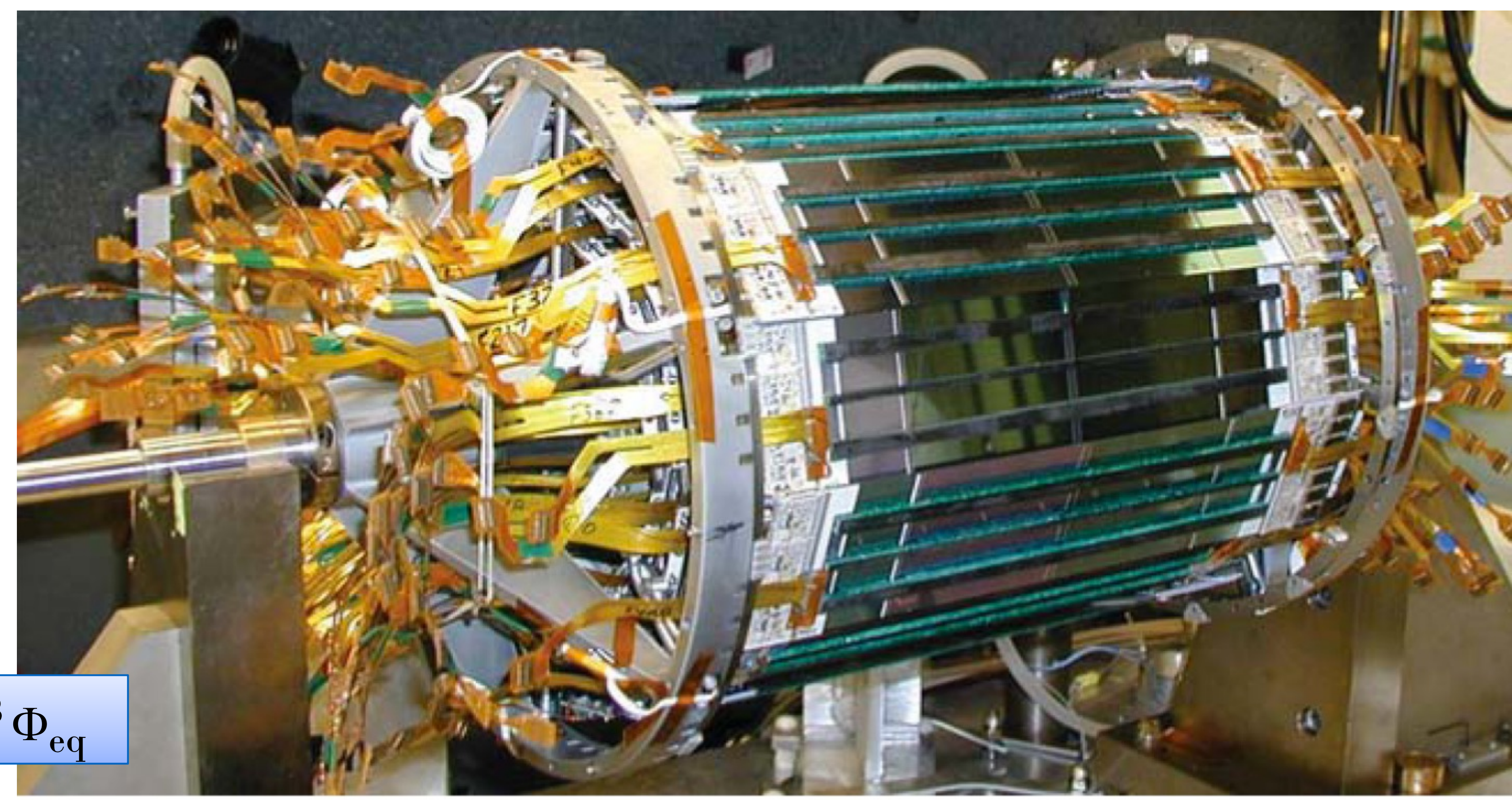




Radiation tolerance> $10^{14}\ \Phi_{eq}$

SVX Silicon Vertex Detector

As close as possible → mount it directly ON the beam pipe



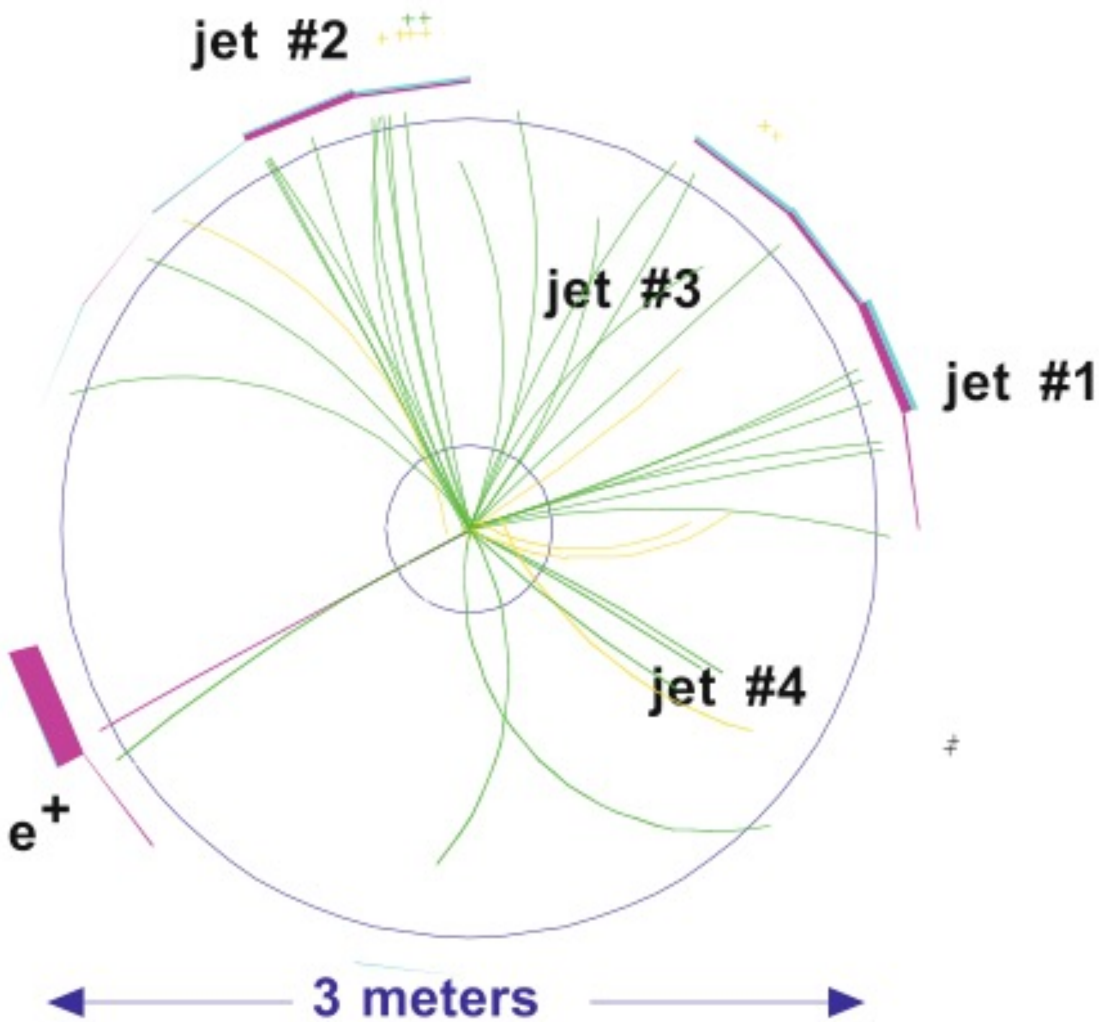
Radiation tolerance> $10^{13}\ \Phi_{eq}$

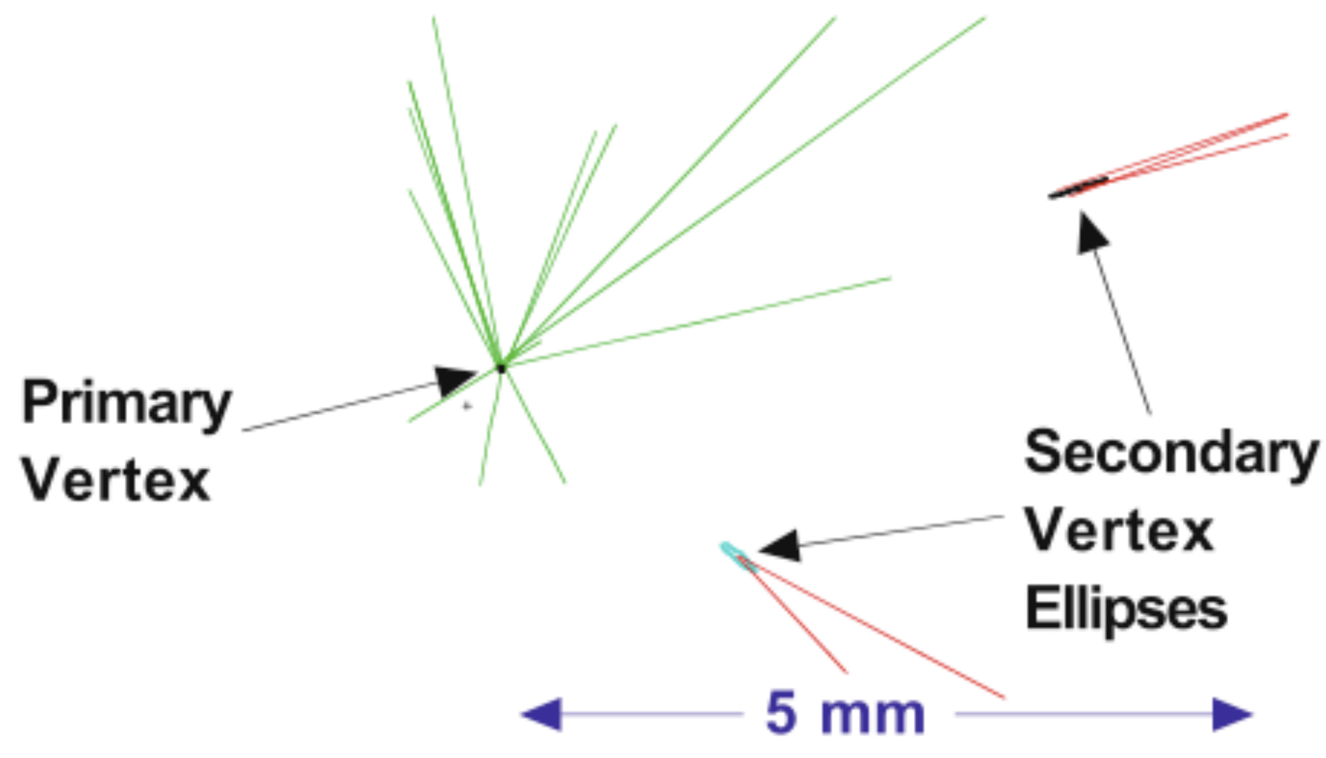
Fig. 5.8. The SVX II detector, one barrel [27]

No top quark discovery without the vertex detector

A "Golden" Top Event

tt(bar) ➔ W^+b, W^-b(bar)
One W decays leptonically showing one lepton plus missing energy
Second W decays into qq(bar) producing two jets
Signature: one lepton, four jets of which two tagged b jets and missing energy



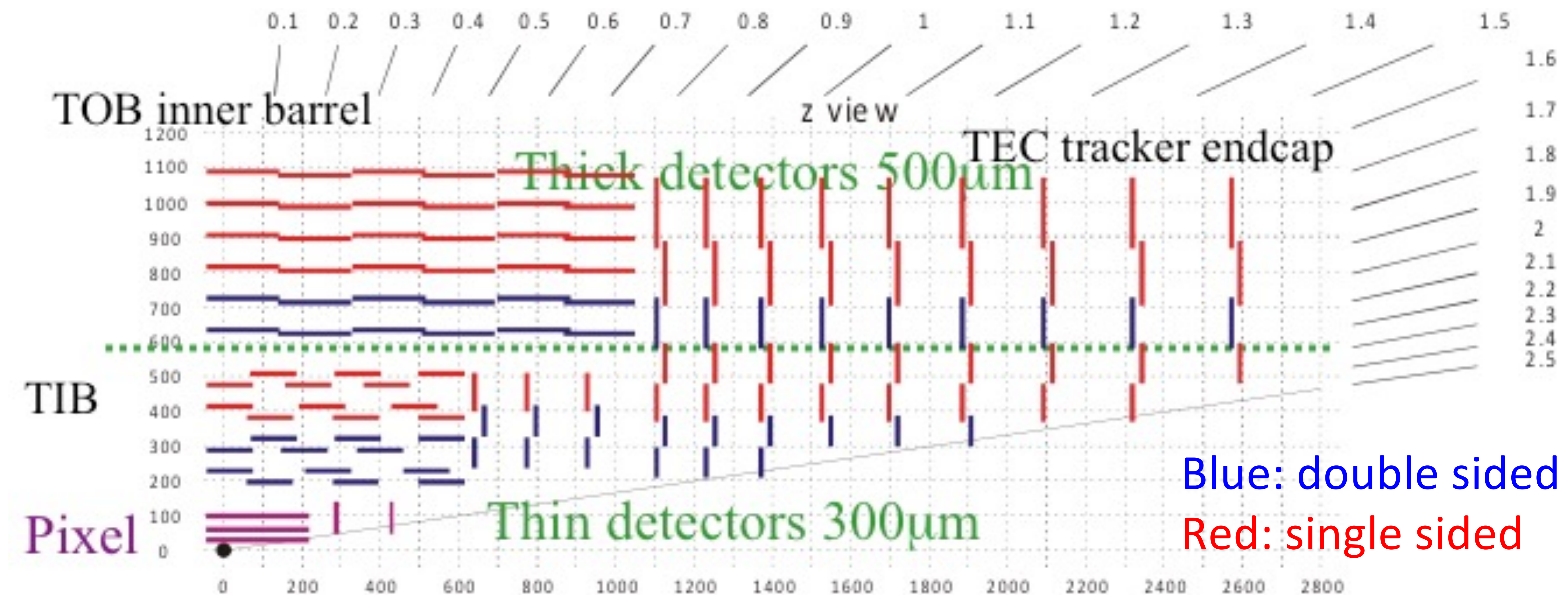


In 1994 the evidence of the top quark was published!
Phys. Rev. D50 (1994) 2966

→ Enjoy the photos

CMS

CMS - Silicon Strip & Pixel Tracker



- Strips Outer cell size ~20cm x 100-200µm
- Strips Inner cell side ~10cm x 80µm
  - Design occupancy 1-2% - resolve & isolate tracks
  - Sensor Technology **p-in-n** Radiation tolerance> $10^{14}\,\Phi_{eq}$

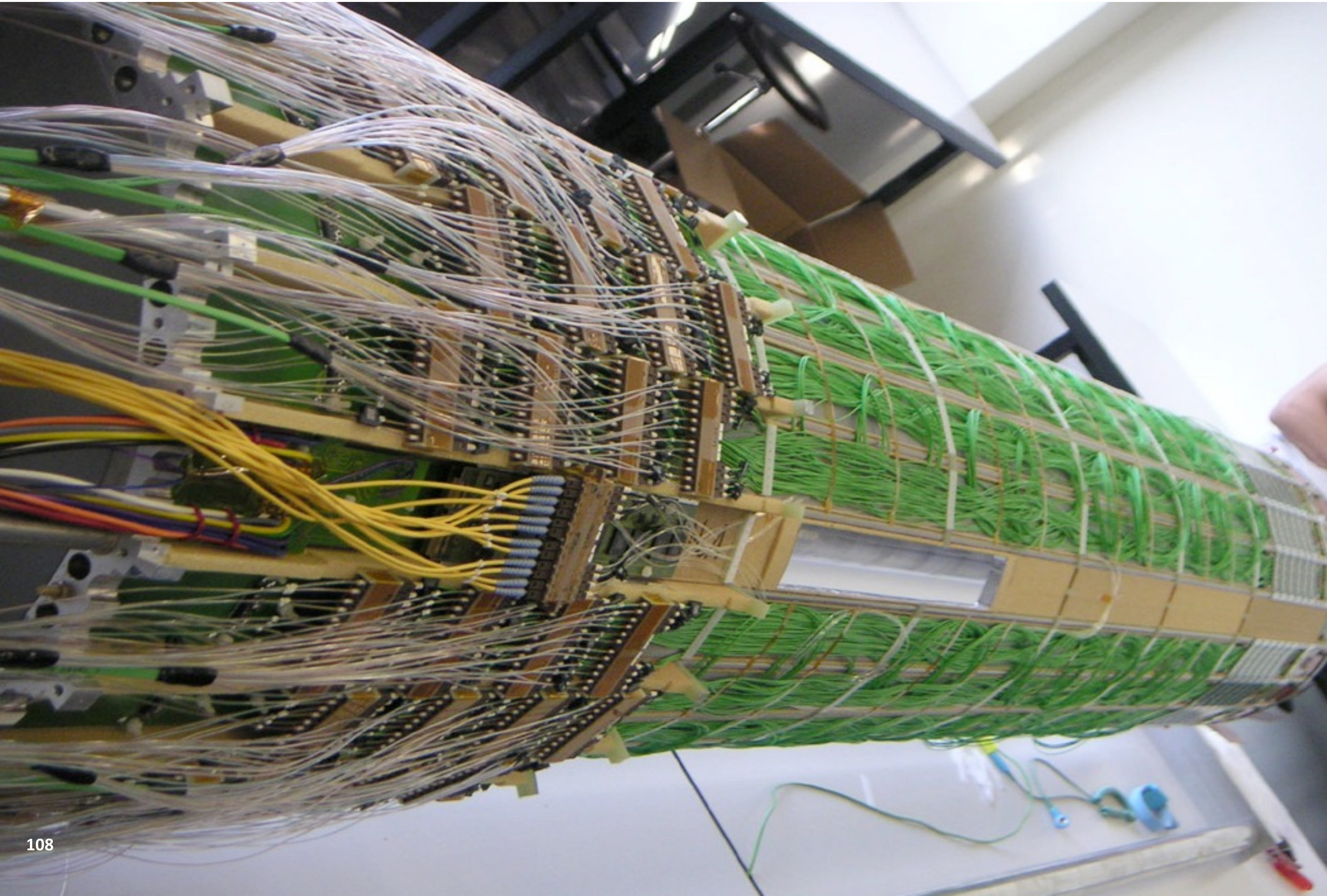
First ever 200m² detector

- Pixel 100x150 µm²
  - Occupancy: 10^{-4}
  - Sensor Technology **n-in-n**: Radiation tolerance> $10^{15}\,\Phi_{eq}$

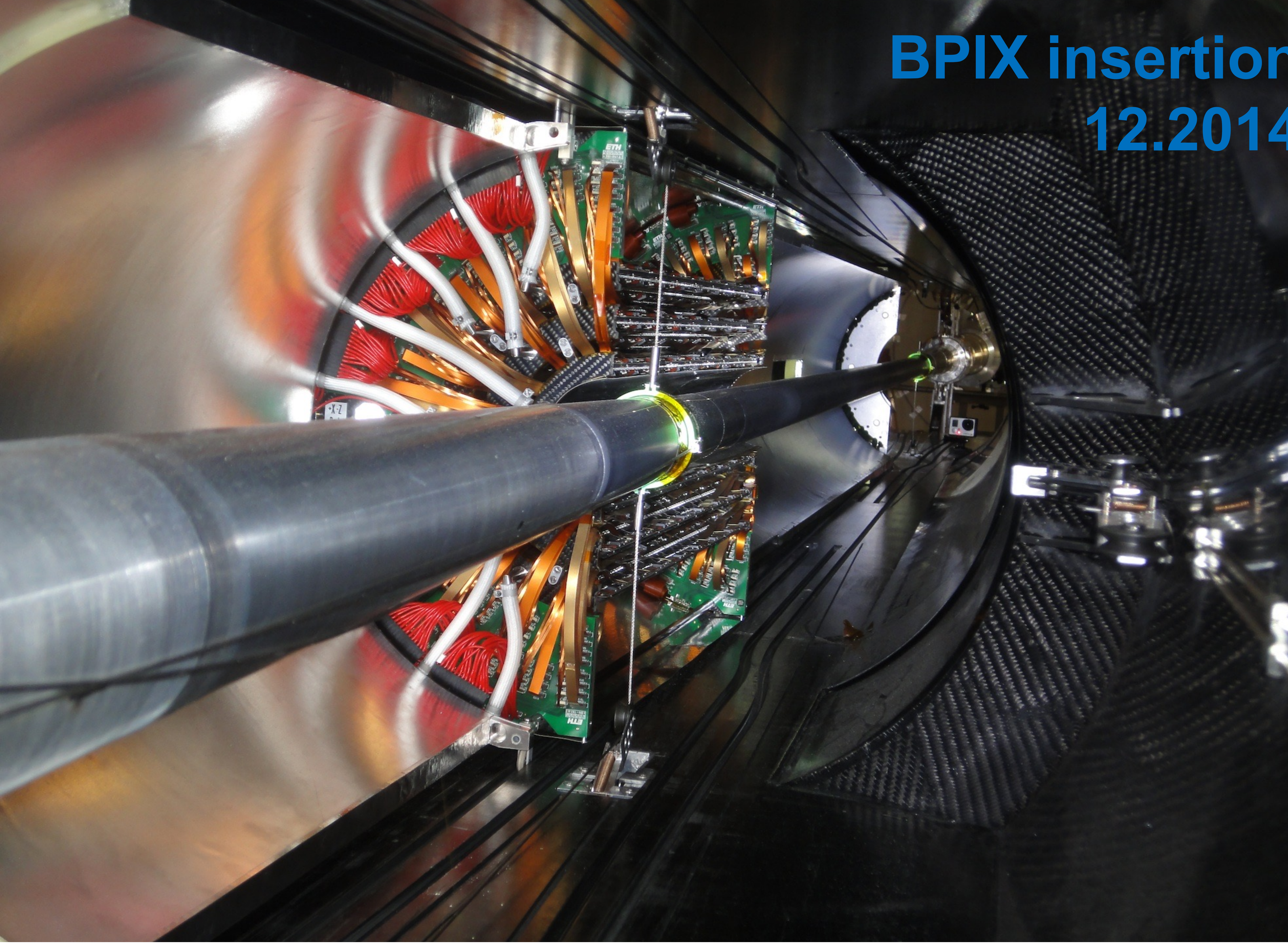
Half disc of Forward Pixels

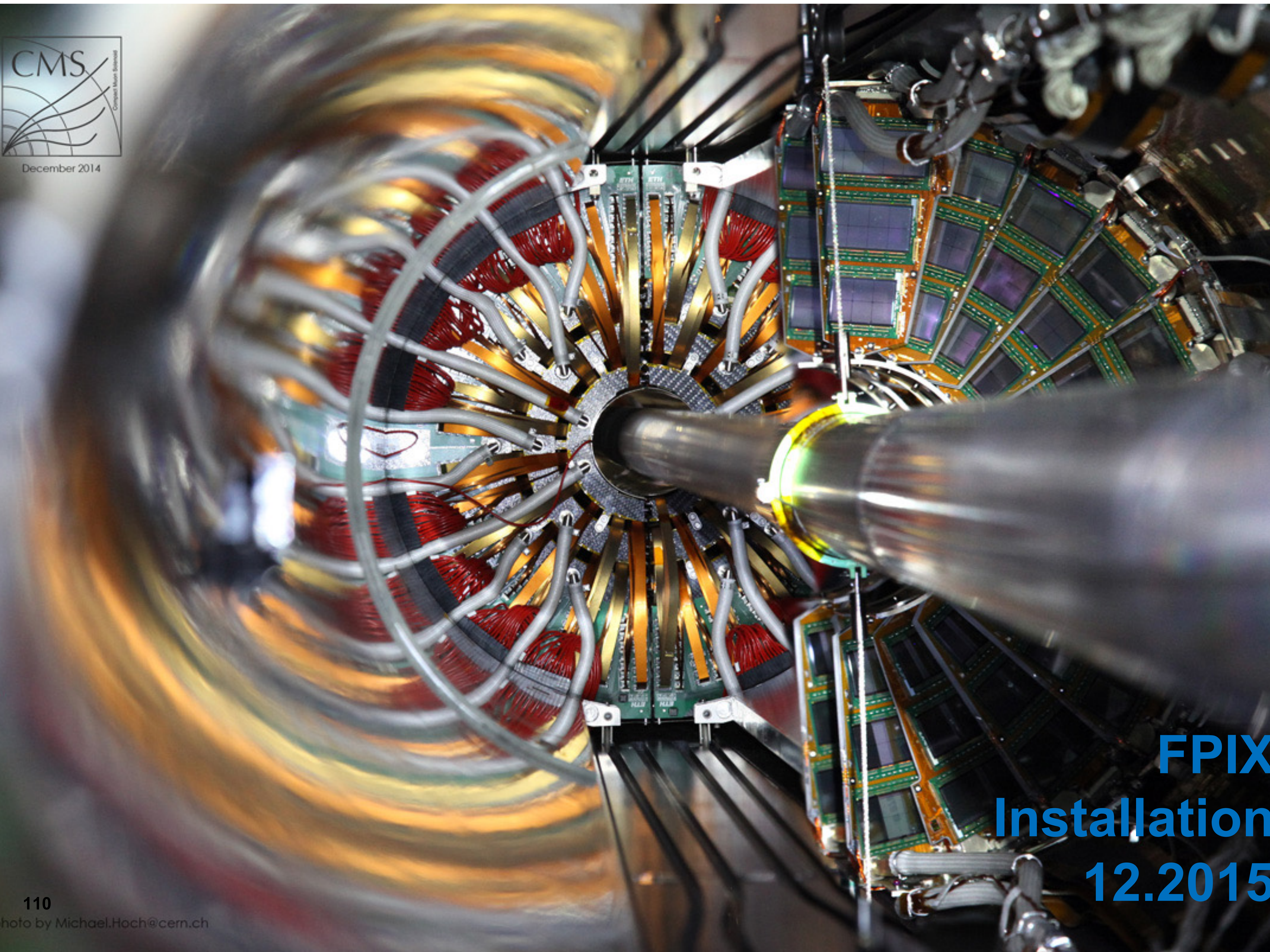
Forward Pixel: 672 plaquettes

Pixel Barrel plus Endcaps



BPIX insertion
12.2014

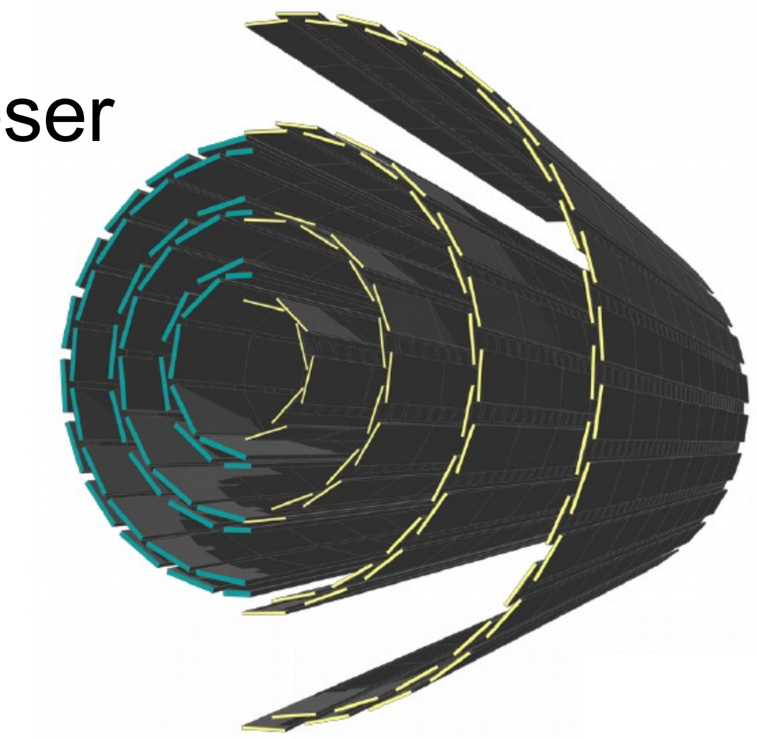



CMS
December 2014
FPIX
Installation
12.2015
hoto by Michael.Hoch@cern.ch

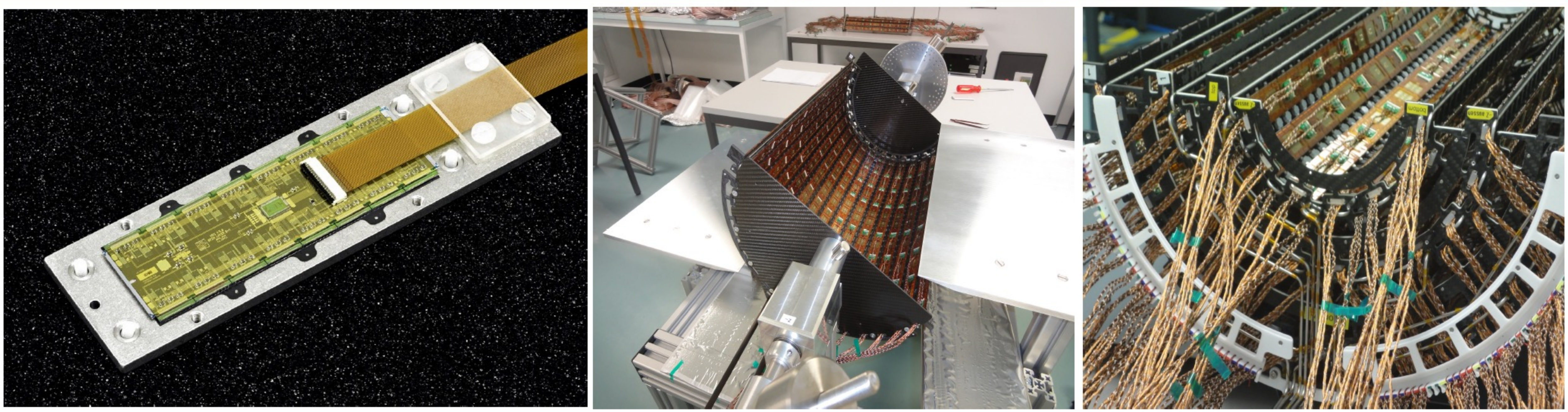
The CMS new pixel – Phase 1 – since 2017

- 3 → 4 layers   2→ 3 disks
- Add layer at r=20cm and inner layer moves 2cm closer

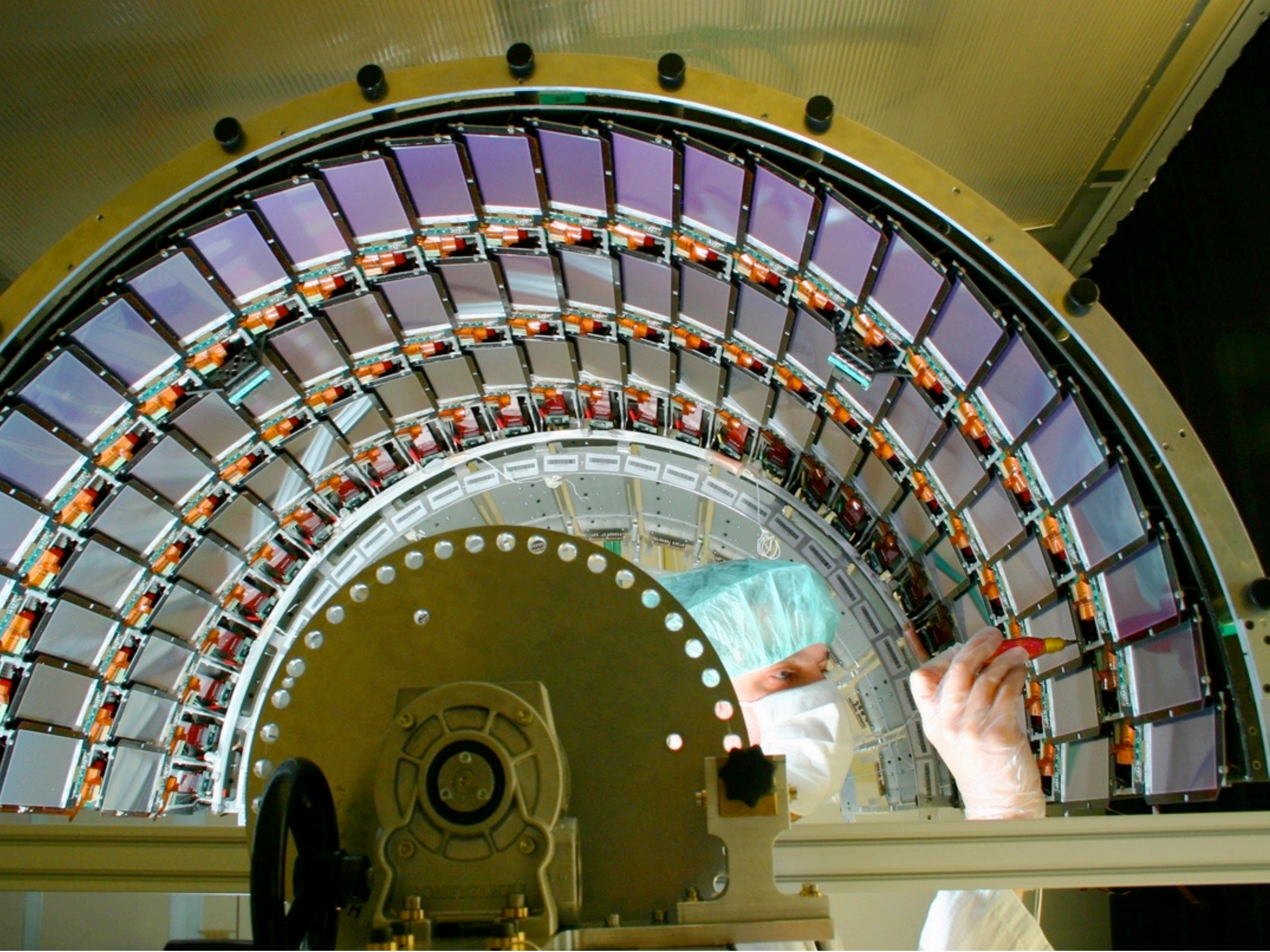
Lower inner radius
Lever arm **L** much improved
More layers better pattern recognition

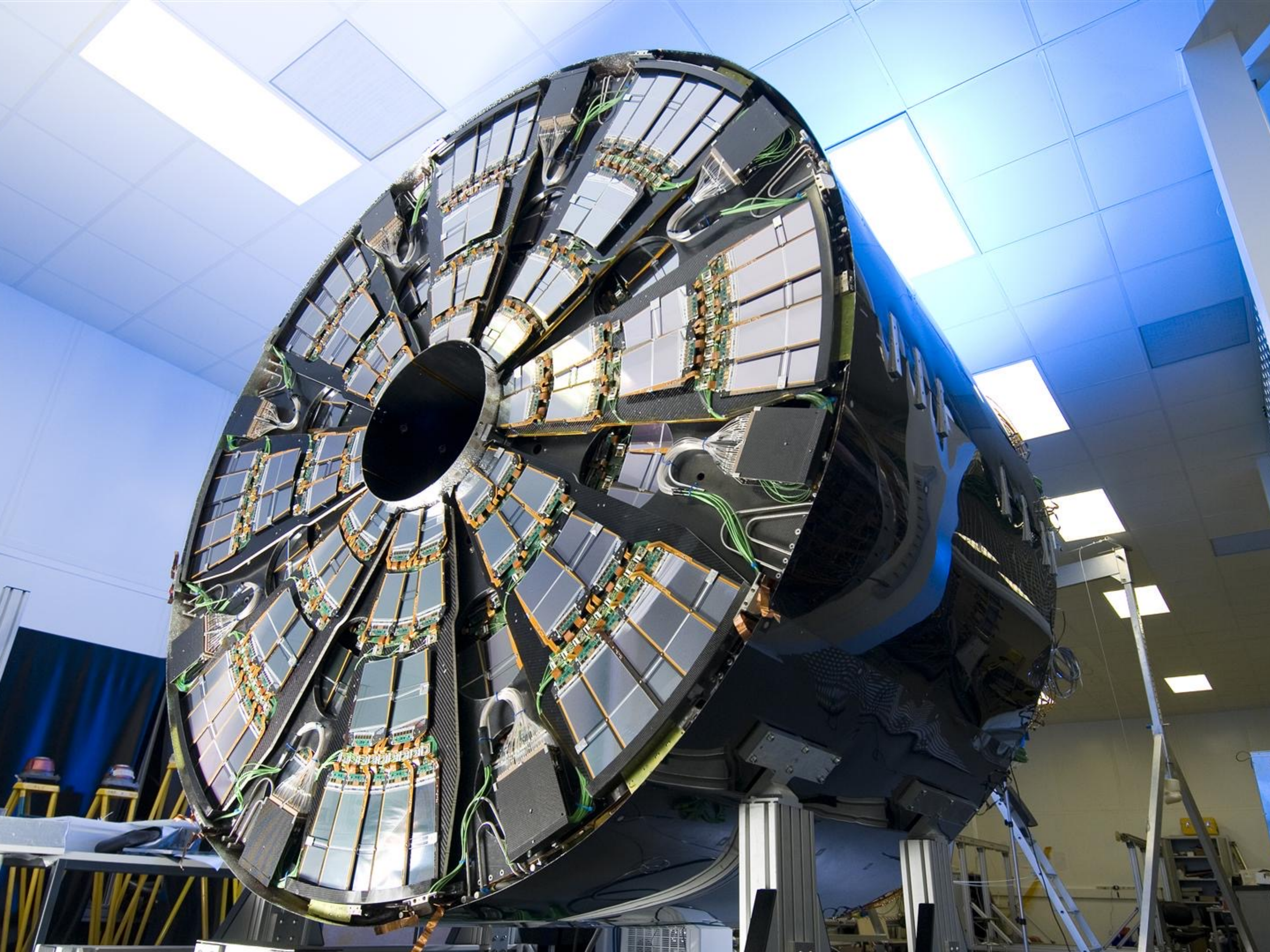


Detector

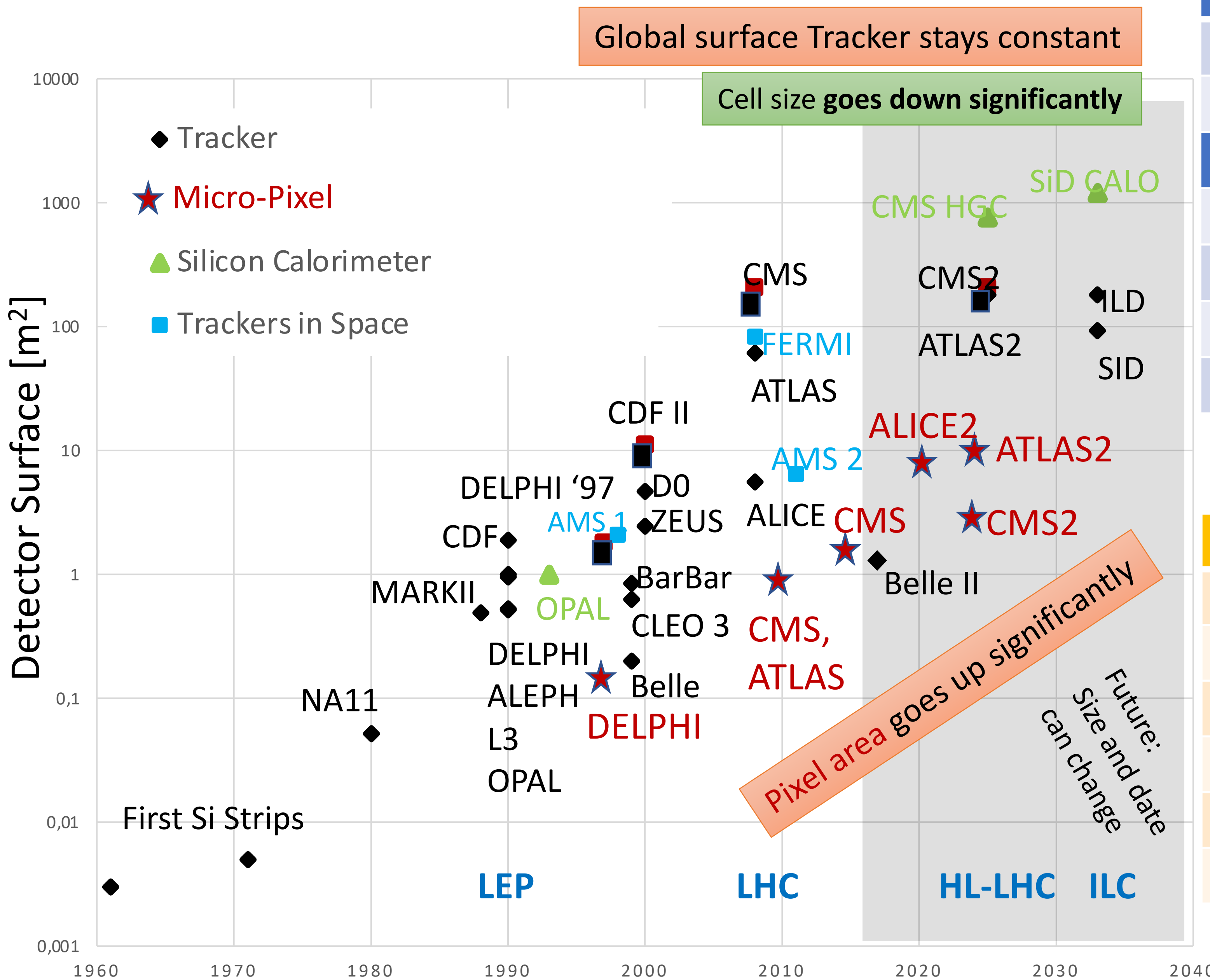


NB.: we replaced layer again 2022 due to radiation damage





Size matters! Does it?



Detector	Strip length [cm]	Strip length [cm]	ratio
ATLAS strips barrel	12.6	2.4 / 4.8	> 5 / 2.5
CMS strips barrel	20 / 10	5 / 2.5 / 0.15	4 / 4 / **66**
	pixel size [μm²]	**pixel size [μm²]**	**ratio**
ATLAS pixel	50x400	25x100 (50x50)	8
CMS pixel	150x100	50x50 (25x100)	6
VELO	1 to 7 cm	55x55	180 - **1300**
ALICE	50X425	**28x28**	27

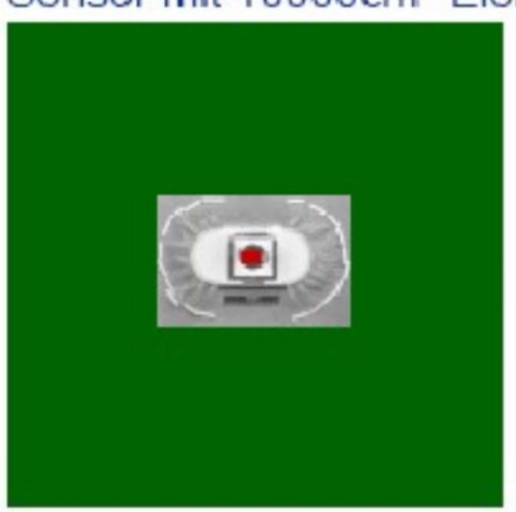
Yes, size matters – small is sexy!

Detector	Channels	Channels
CMS strips	9.8M	42M + **172M**
CMS Pixels	127M	2GP
ATLAS strips	6.3M	60M
ATLAS pixels	92M	**5GP**
VELO	171k	41M
ALICE	12.5M	**12.5G**

Fun fact:
CMS macro-pixel just factor 1.4 wrt Delphi pixel

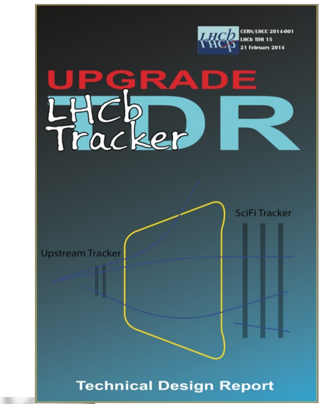
Cell granularity, the weapon against high-PU keeping occupancy at a reasonable level

9 cm² Sensor mit 10000cm² Elektronik



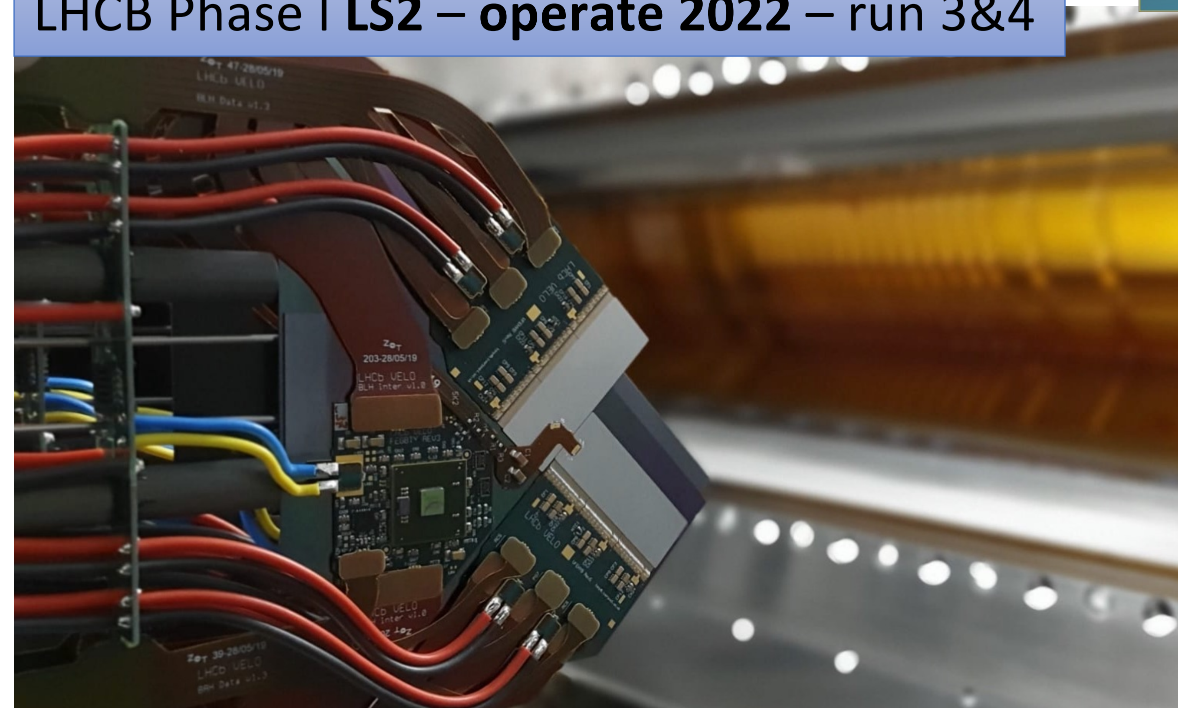
160 cm² Sensor mit 20cm² Elektronik

Hey LHCB, what did you do to your lovely custom round sensors? I liked them so much!



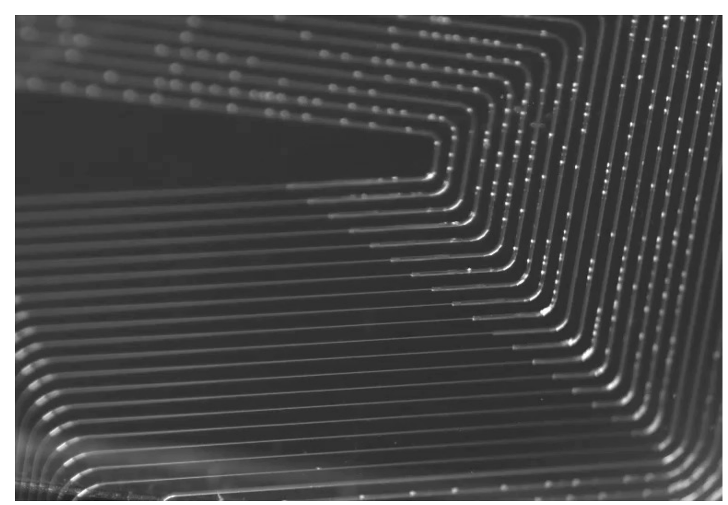
LHCB – run 1&2

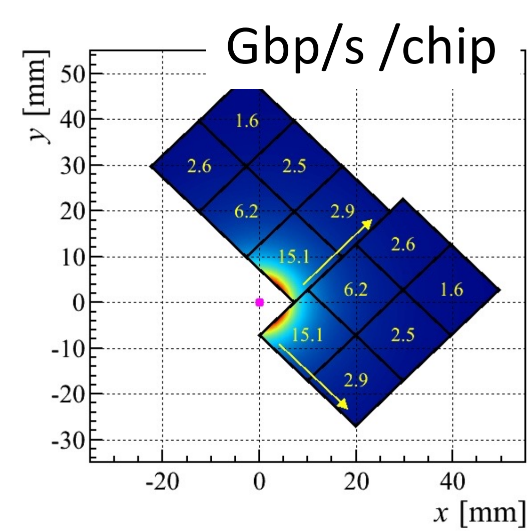
LHCB Phase I **LS2 – operate 2022** – run 3&4



Each sensor (43mm x 15mm) bump-bonded to three VELOPIX ASICs

- All-pixel detector 55x55 μm^2 n-in-p 200 μm thick pixels sensor, readout with VELOPIX
  - Very high ($8x10^{15}$ n_{eq}/cm^2 for 50 fb^{-1}until LS4) & non-uniform irradiation (~ $r^{-2.1}$)
- Go closer: distance to beam 51 mm instead of 8.2 mm
- Sensors on CO_2 micro-channel cooling
- No hardware trigger
  - **Full 40 MHz readout**
  - 20 Gbit/s for central ASICs

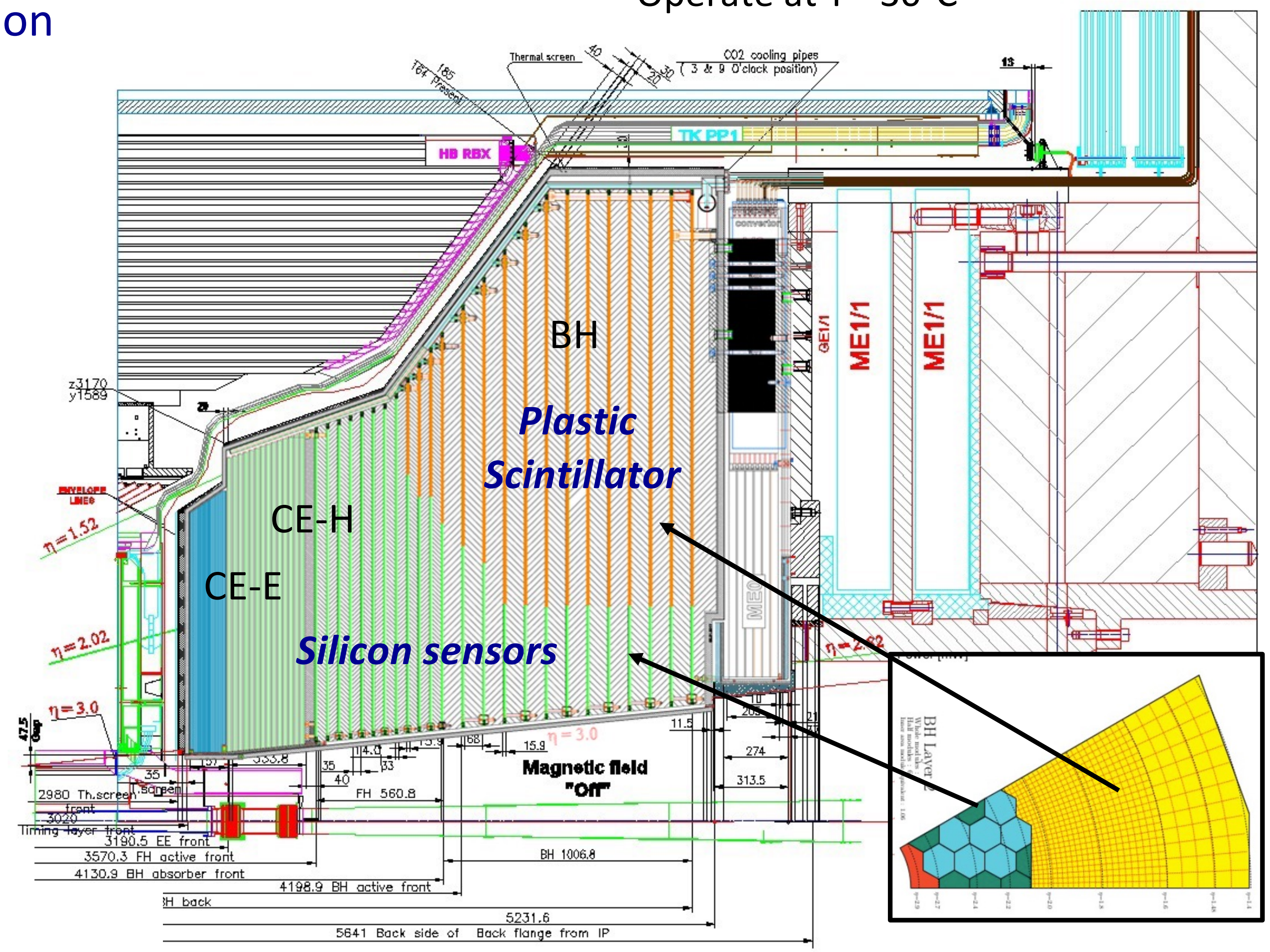




Silicon enters calorimetry on large scale – World's first

- 3D shower topology and time resolution of ~ 30 ps (p_T > few GeV) - **5D**
  - E.g. 2% energy resolution for γ
- **The silicon part** (*more rad tolerant*)
  - 600 m^2 of silicon
  - 8" wafers – a first in HEP
  - 6M channels, 0.5 or 1 cm^2 cells
  - 25000 modules
- **Plastic scintillator** (*less rad tolerant*)
  - 500 m^2 of scintillators
  - ~400k scintillator & SiPMs on tile
- High granularity
  - A dream for Particle Flow concept (PF)

Operate at T=-30°C



Cu/CuW/Pb stainless steel

*CE-E: **28** sampling layers – 26 X_o + ~1.7 λ*

***22** sampling layers – 9 λ*

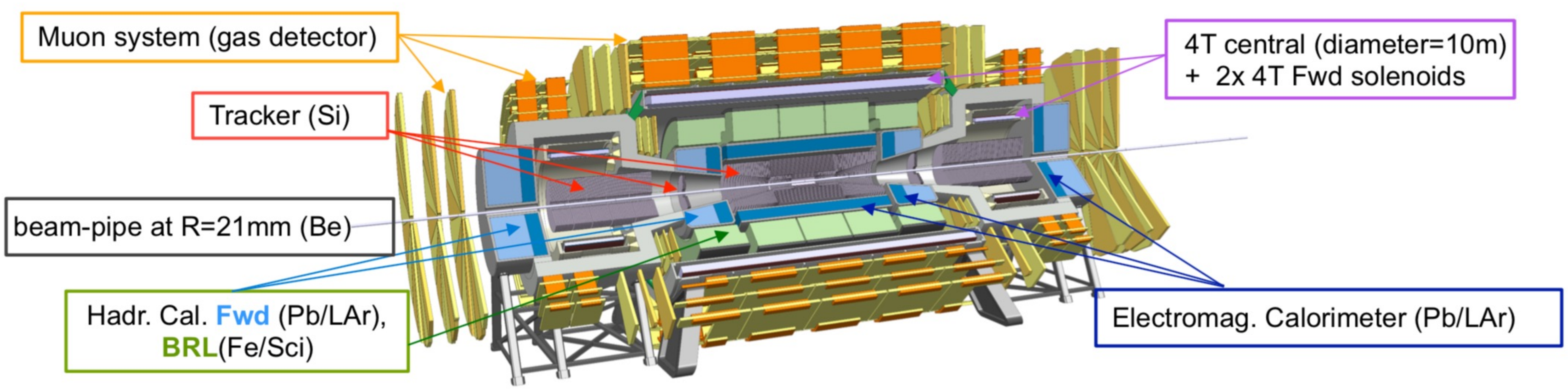
CERN-LHCC-2017-023 CMS-TDR-019

HEP: High Energy Physics

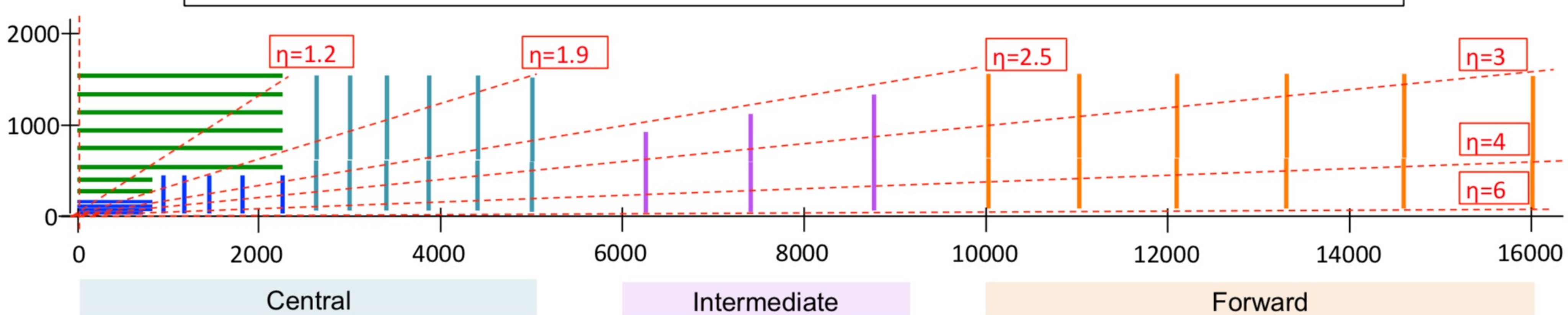
The far future in HEP - FCC

FCC-hh - Reference Detector Layout

- FCC- hh: Sensor $10^{18} n_{eq}/cm^2$
- Spatial resolution 10μm everywhere
- And timing – 5 ps



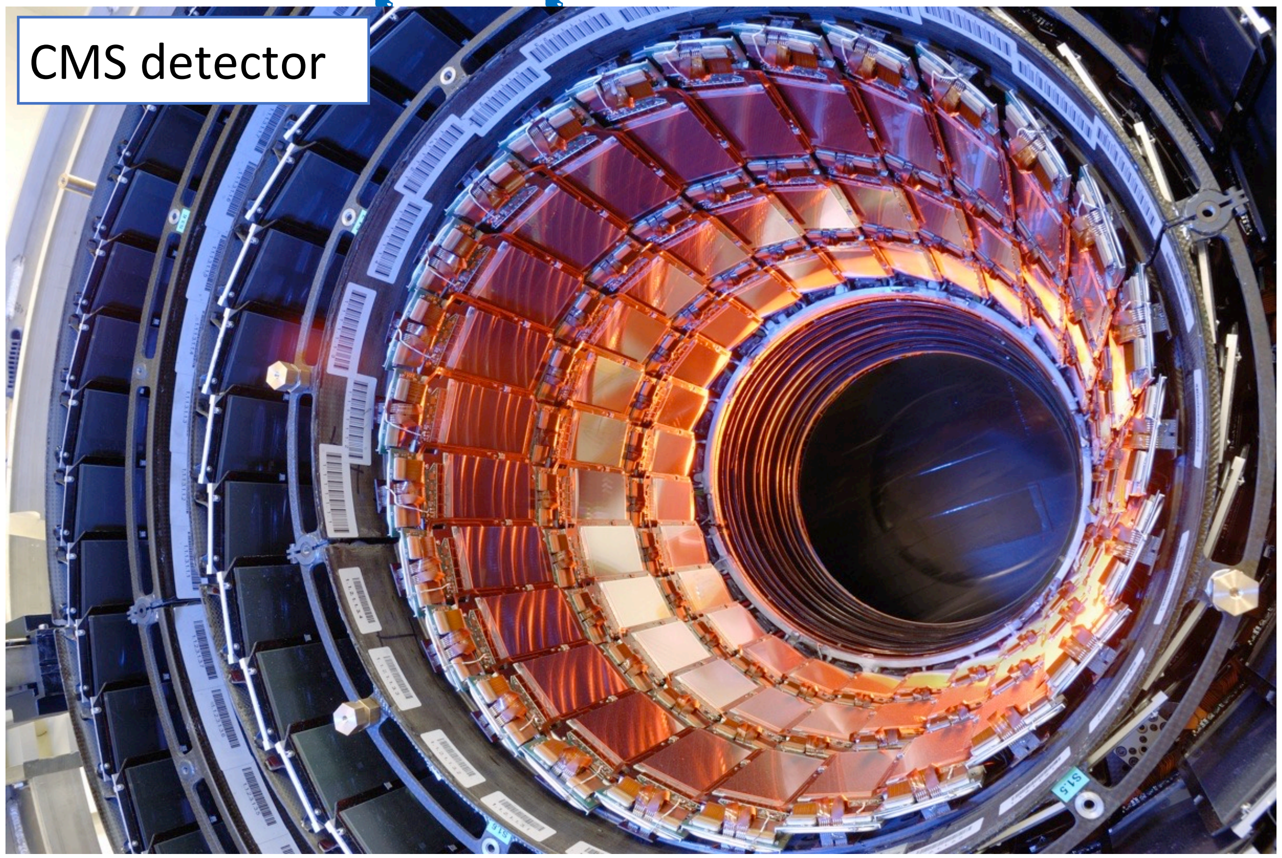
Tracker radius: 1.6m , half-length: 16m , 4T solenoidal B-field



https://fcc-cdr.web.cern.ch

- G. Lutz: Semiconductor Radiation Detectors: Device Physics Springer (1999)
- H. Spieler: *Semiconductor Detector Systems*, Oxford University Press (2005)
- L. Rossi, P. Fischer, T. Rohe, N. Wermes: *Pixel Detectors: From Fundamentals to Applications*, Springer (2006)
- F. Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*, Springer (2017; 2nd edition)

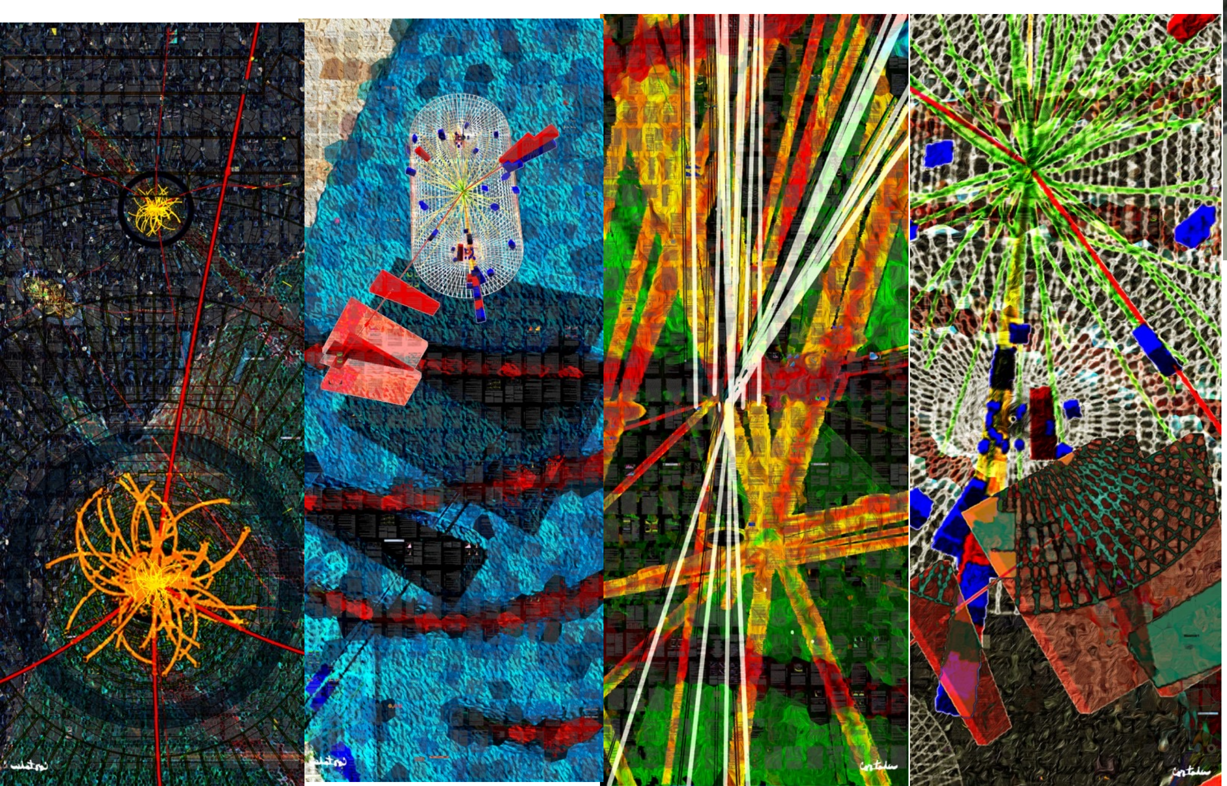
and pop - culture

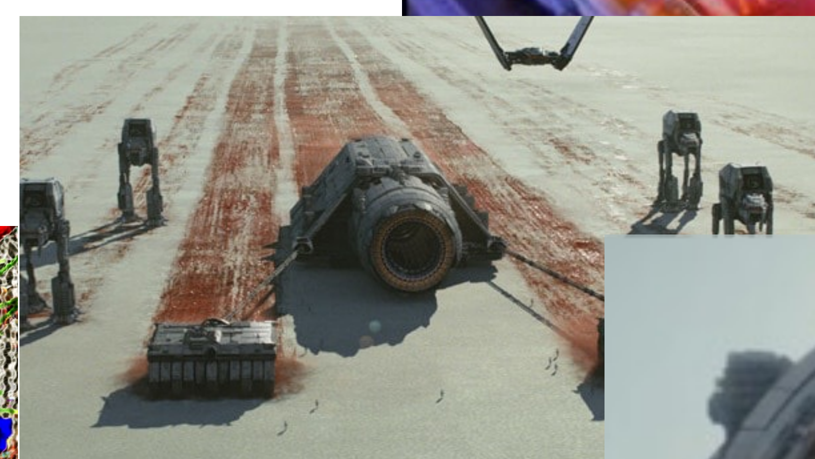


CMS detector

CD cover

and art

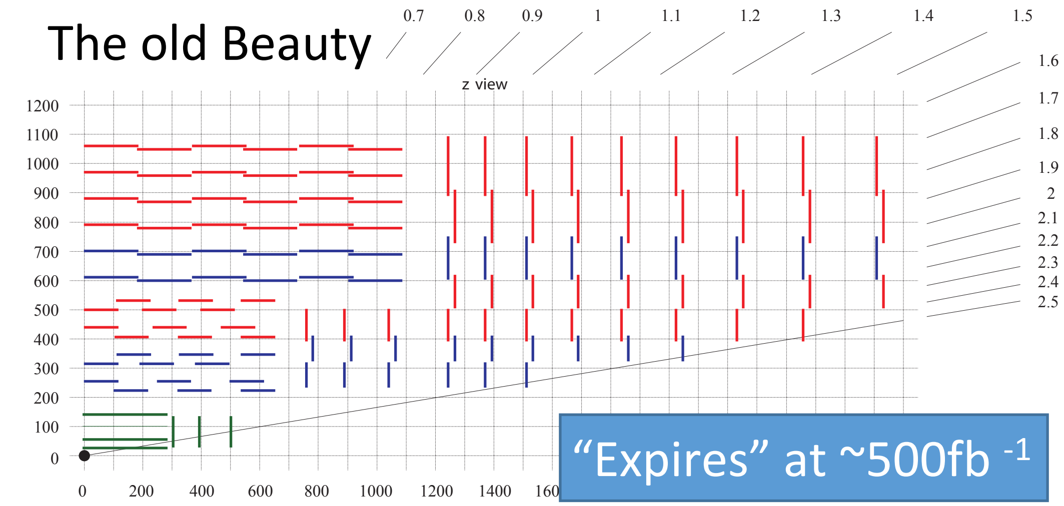


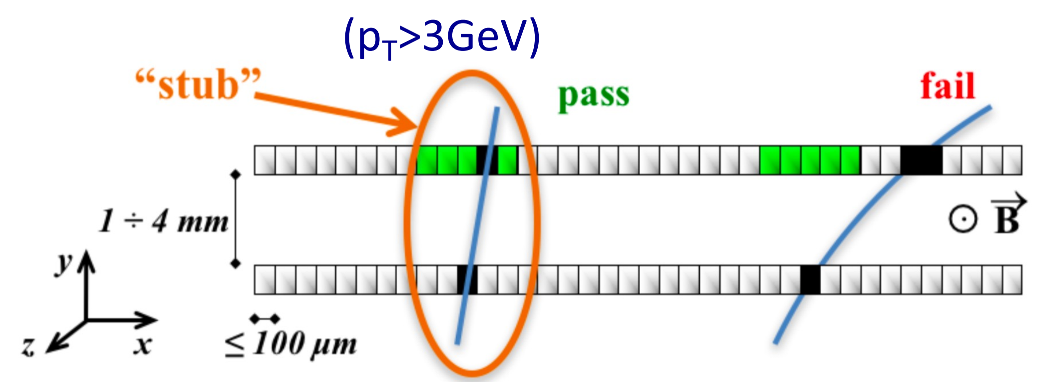


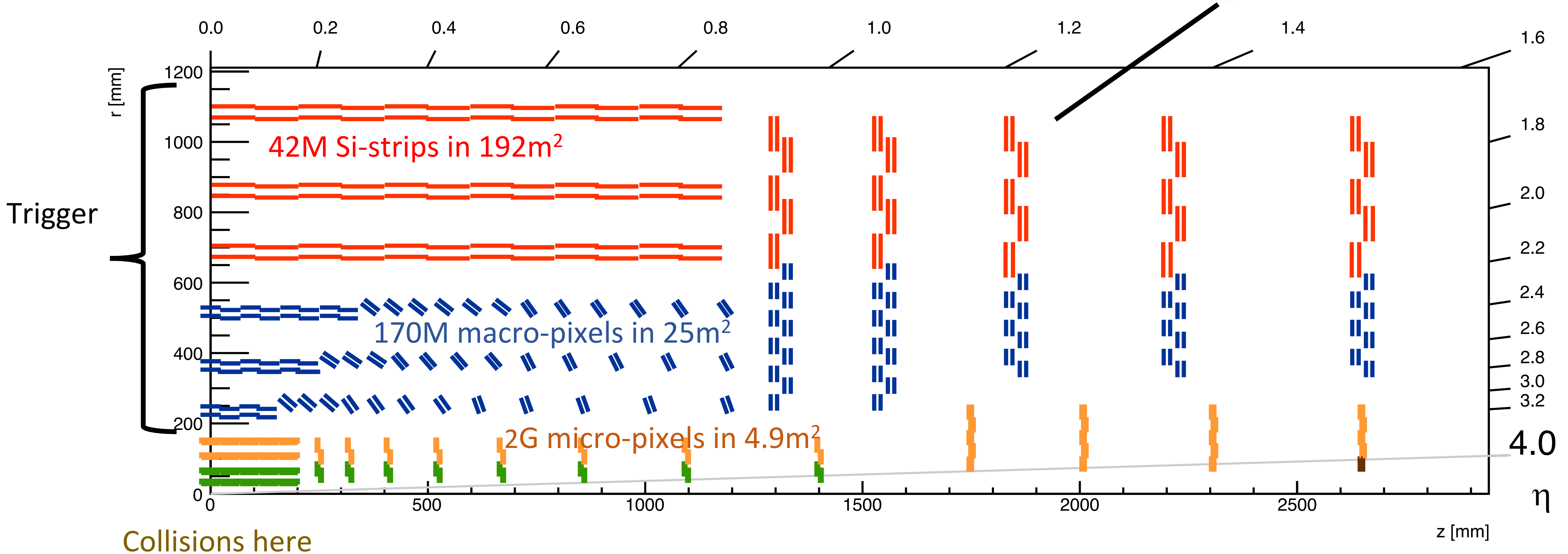
Starwars super laser siege cannons

The new Beauty
– CMS Phase-2 Tracker

- Outer Tracker design driven by ability to provide **tracks at 40 MHz to L1-trigger** (p_T>3GeV)
  - World's first
- Tilted modules in three OT layers
- Inner Tracker (pixel) extend coverage to $\eta \simeq 3.8$
- Half the material as the current tracker
  - DCDC conversion, CO_2 cooling, ultralight structures







CERN-LHCC-2017-009 CMS-TDR-17-001

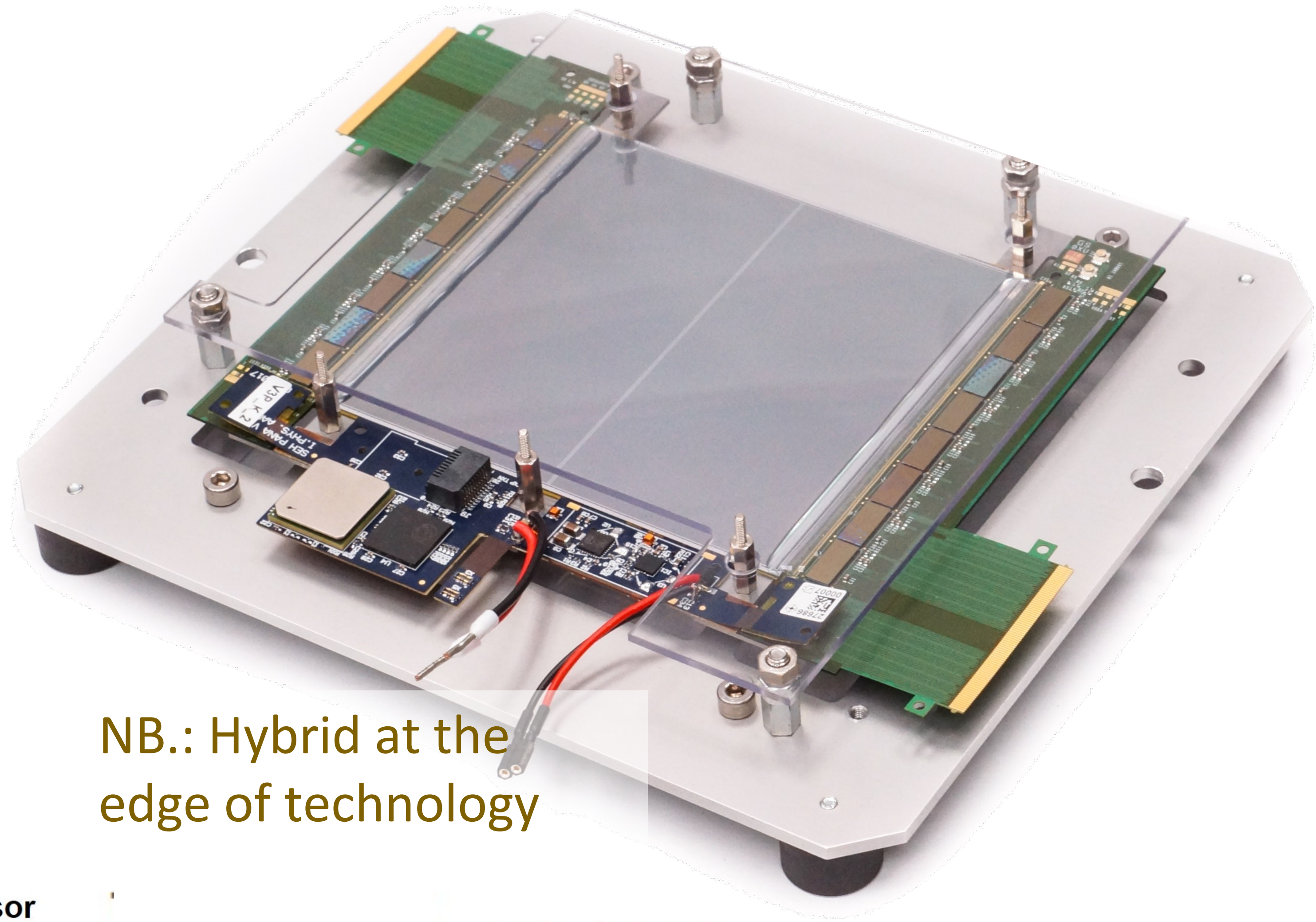
p_T transverse momentum

n-in-p sensors: Radiation tolerance $>10^{16}\,\Phi_{eq}$

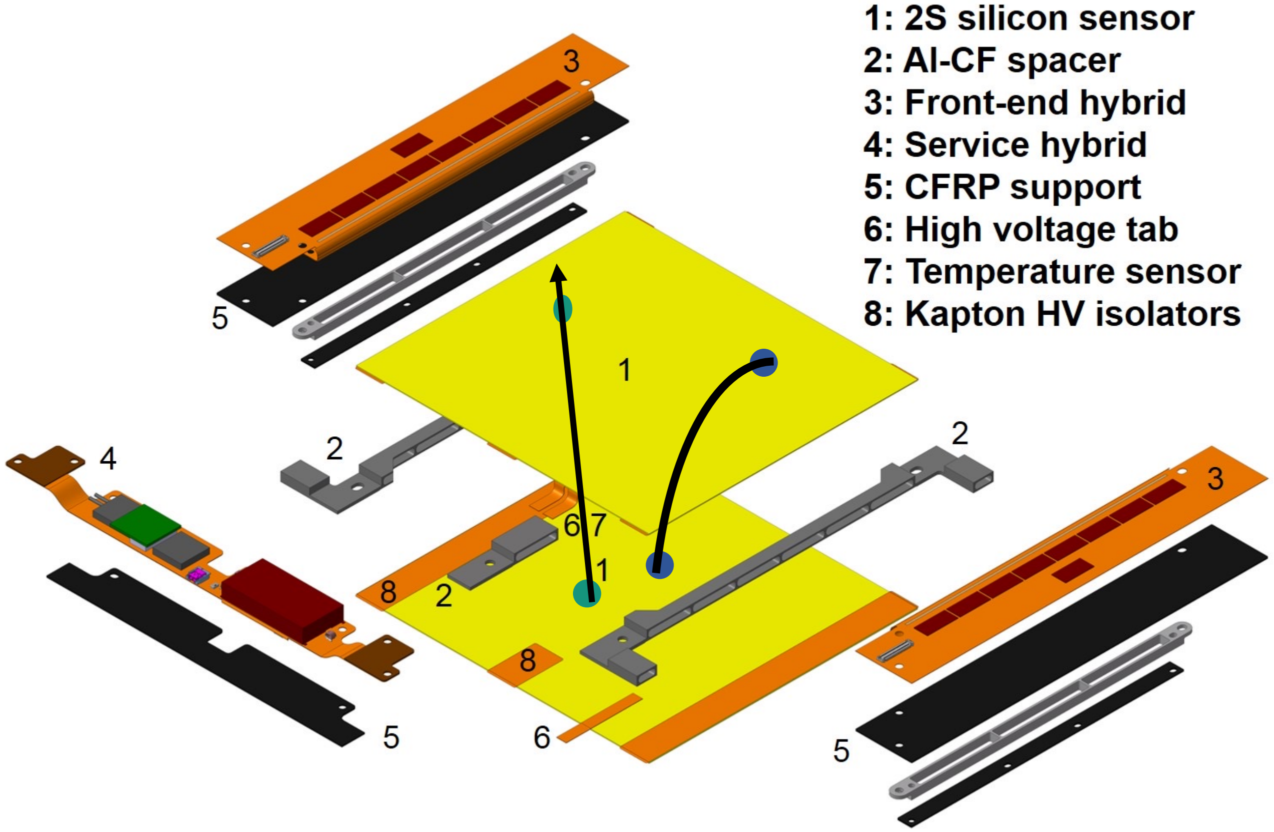
New Technologies – Tracker Module

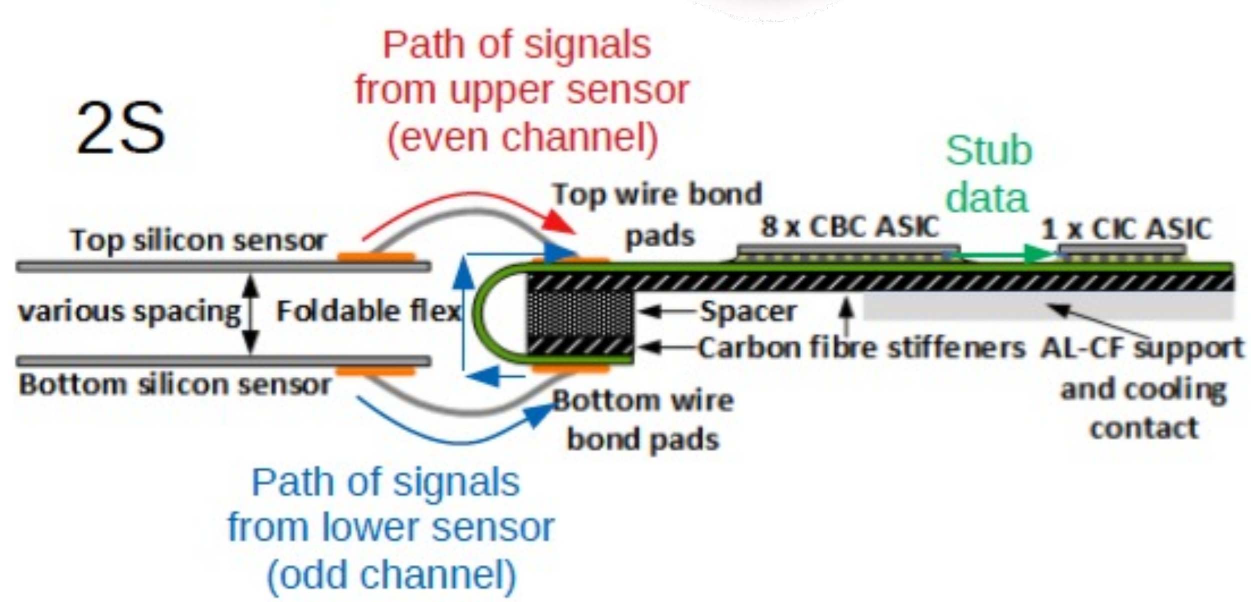
New concept

- Contains ALL electronics = full system
- Effective way to have 2 space points in single mechanics – lightweight
- Gives ‘vectors’ instead of points
- Tag high p_T segments



NB.: Hybrid at the edge of technology

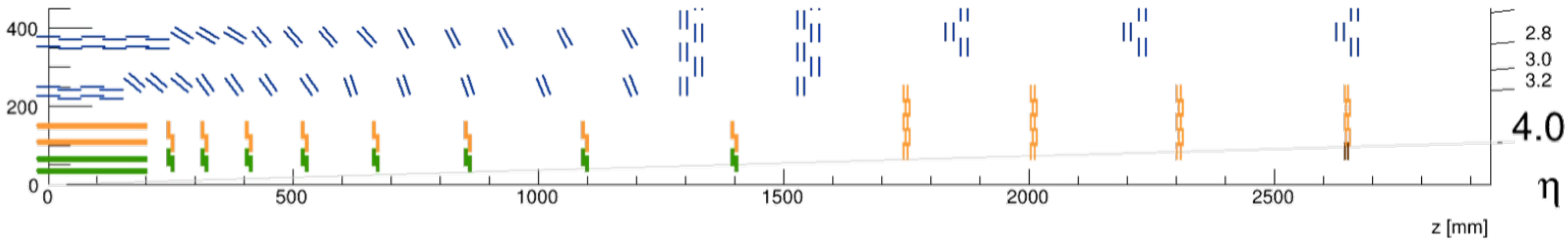




NB.: ~10 years of engineering and modelling

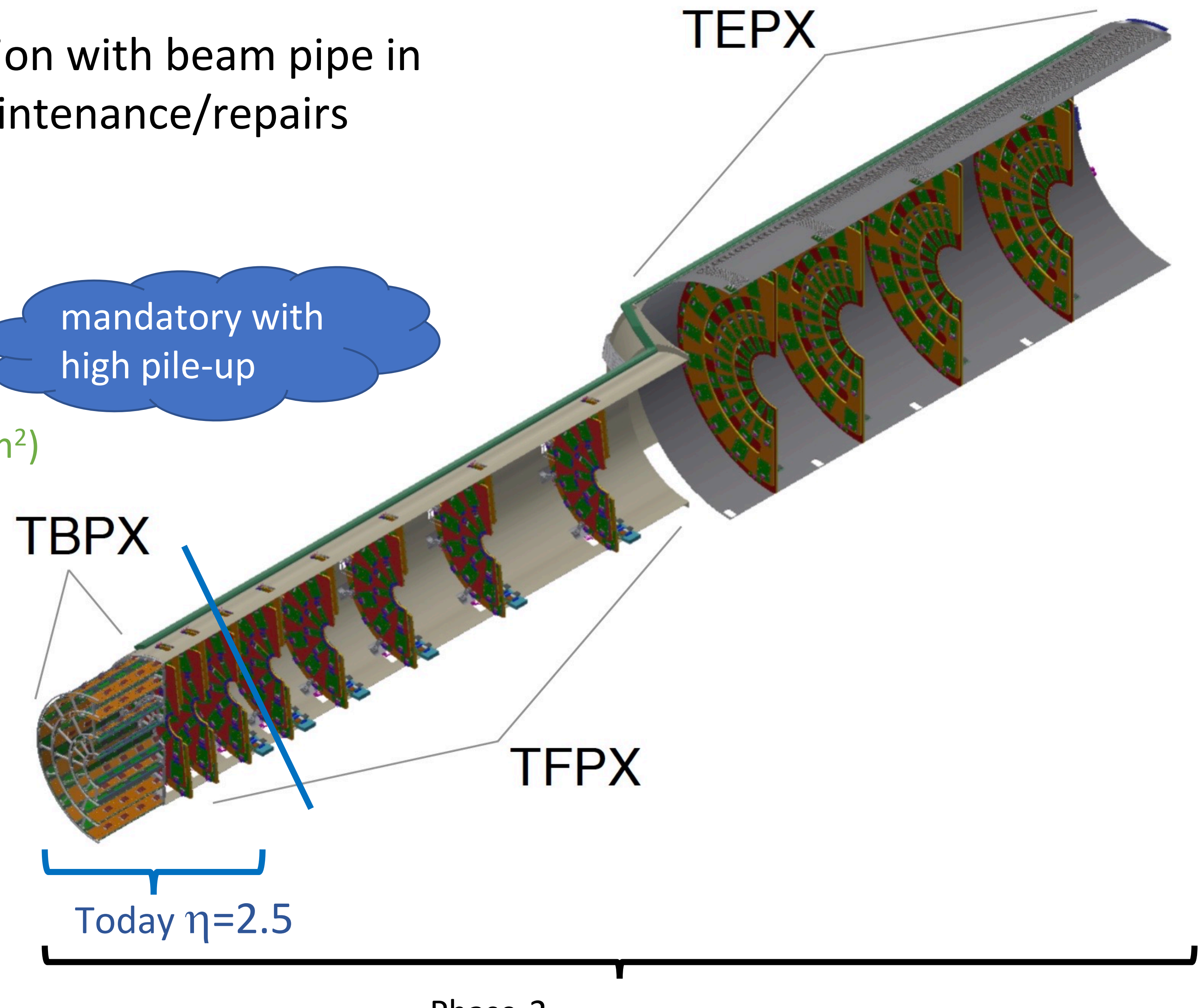
n-in-p sensors: Radiation tolerance $>10^{15}\,\Phi_{eq}$

We extend into the forward region



- Half-shells permit installation/extraction with beam pipe in place – **BIG** advantage as it allows maintenance/repairs
  - Low radius helps excellent b-tagging
  - Coverage up to $\eta=4$
  - 3.900 modules = 2 billion pixels
  - Surface: 4.9 m^2 (today 1.75)
  - Pixels: 25x100 μm^2 (today 100x150 μm^2)
  - Hit rate: 3 GHz/cm^2

mandatory with high pile-up



→VBF
→b-tagging
→PU mitigation

NB.: Pixel chip development:
24 institutes - 5 years of work

For the innermost layer, we will use 3D pixels - see earlier slides