Macroscopic Radiation Damage in Semiconductor Detectors

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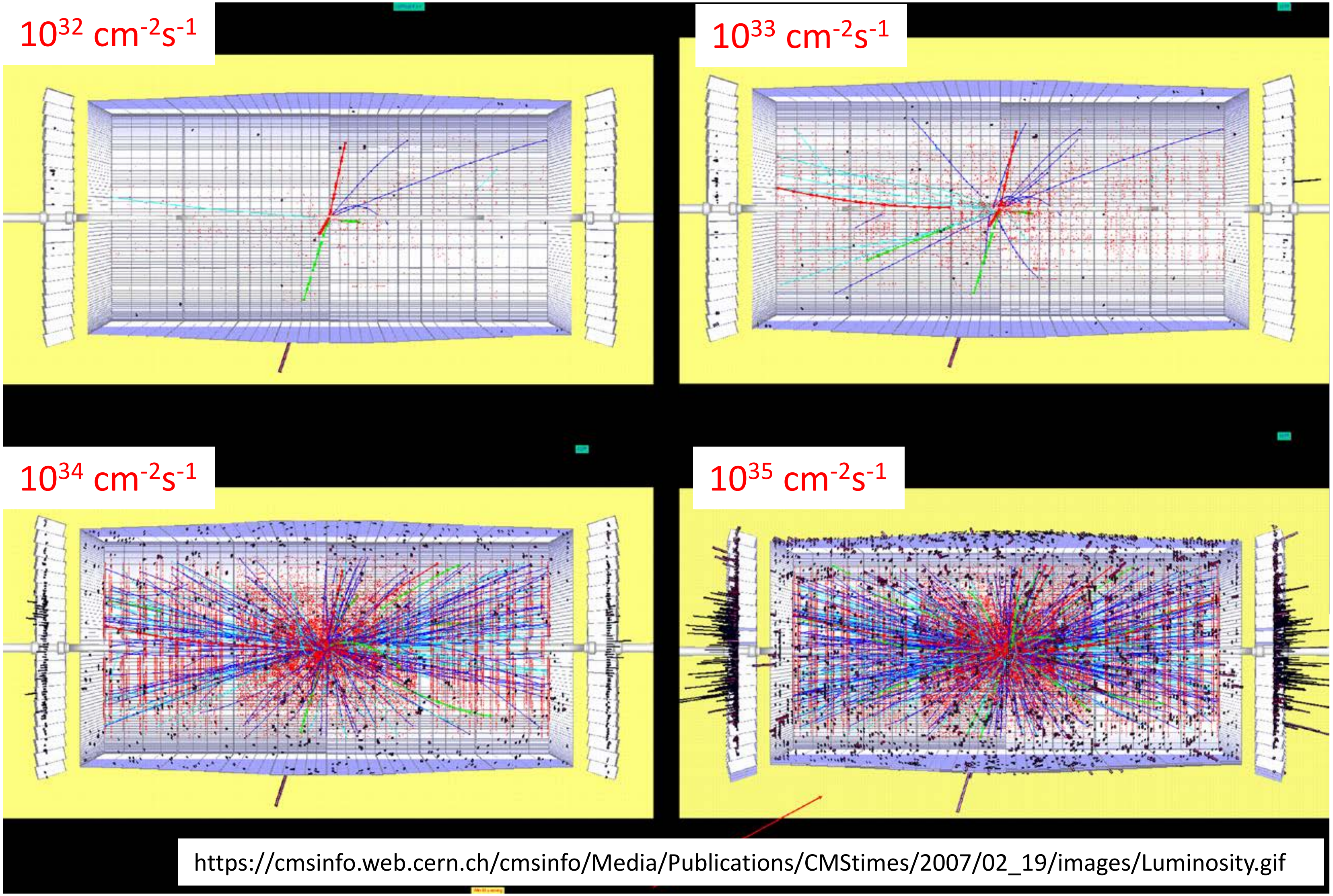
Outline

- Motivations
- Principle of operation of semiconductor detectors
- Macroscopic radiation effects on detector systems
- Possible radiation mitigating techniques
- LHC Silicon detector experience
- Future HI-LHC detectors
- This lecture will cover Silicon pixel and strip detectors only

Why?

- Silicon is, among the materials used to build particle detectors, the one which is most similar to a stone
- But nevertheless its crystal structure is delicate when exposed to high intensity particle fluxes

But this is where we want to use it



The requests for future Silicon based detectors

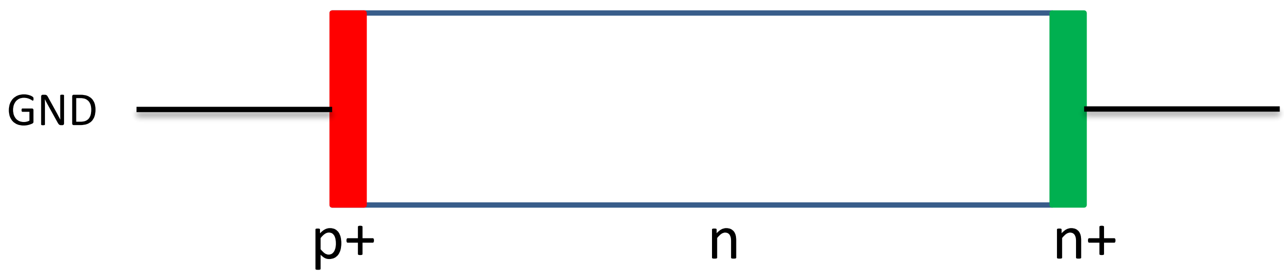
- High Intensity LHC (HI-LHC) will eventually reach instantaneous luminosity close to $\mathbf{10^{35} cm^{-2} s^{-1}}$
- To extract good physics data at this luminosity the detectors should cope with a flux of particles which is ≥10 higher than now, so we need
  - Higher granularity
  - Higher number of channels
  - Higher power
  - Better cooling
- Scaling with the luminosity the radiation damage produced by the particle flux accumulates at a higher rate
- In HI-LHC detectors we expect a flux 10 times the one expected when the present LHC experiments were designed
- Some 100 times the one accumulated during the first two years of operation
- No way: the tracking detectors should be replaced after the first ten years or even before

Principle of operation of a Silicon detector

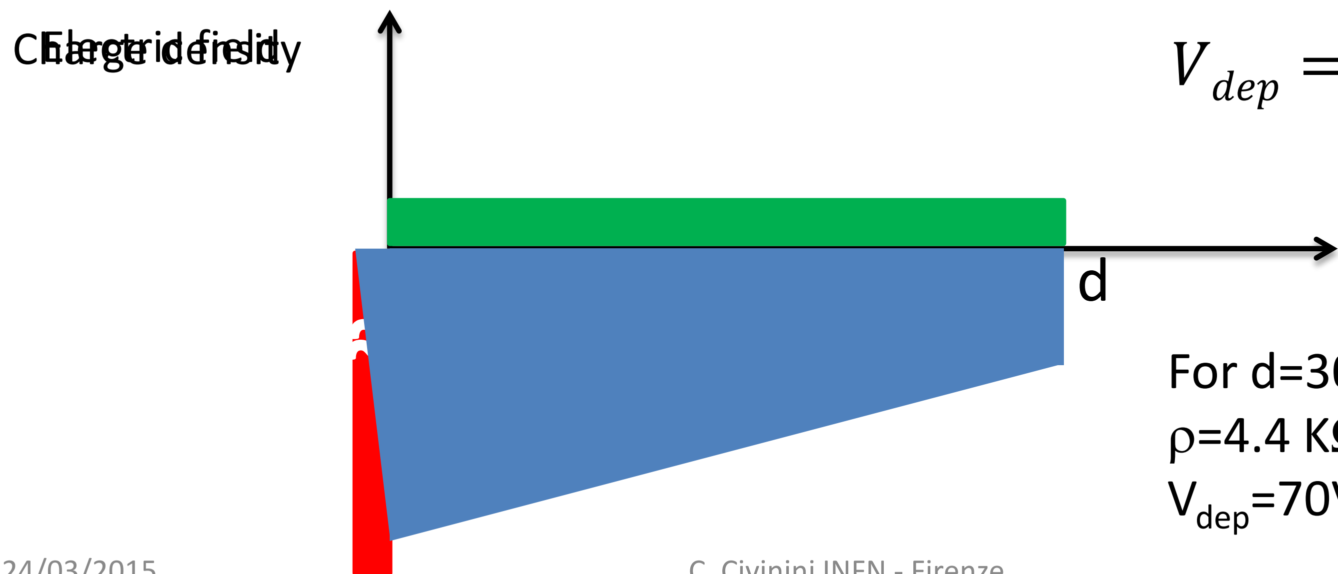
- Reverse diode detectors: a short remind
- Signal formation
- Segmented detectors
- Noise of the detector system: Sensor plus Electronics

Semiconductor detector scheme

- High resistivity (~kΩcm) Silicon layer + ohmic contact + reverse biased asimmetric junction



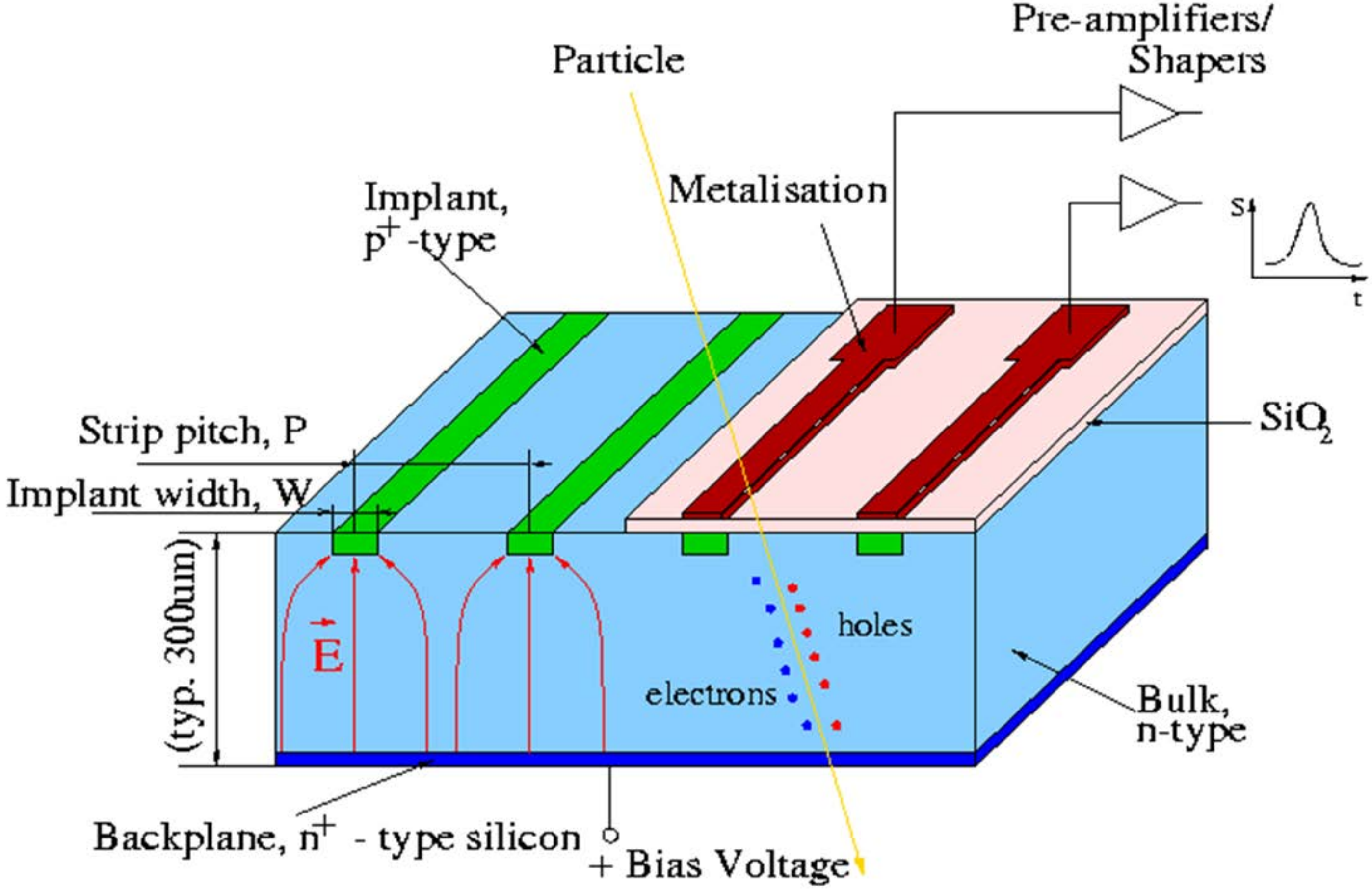
$+V_{bias} > V_{dep}$
Full depletion



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

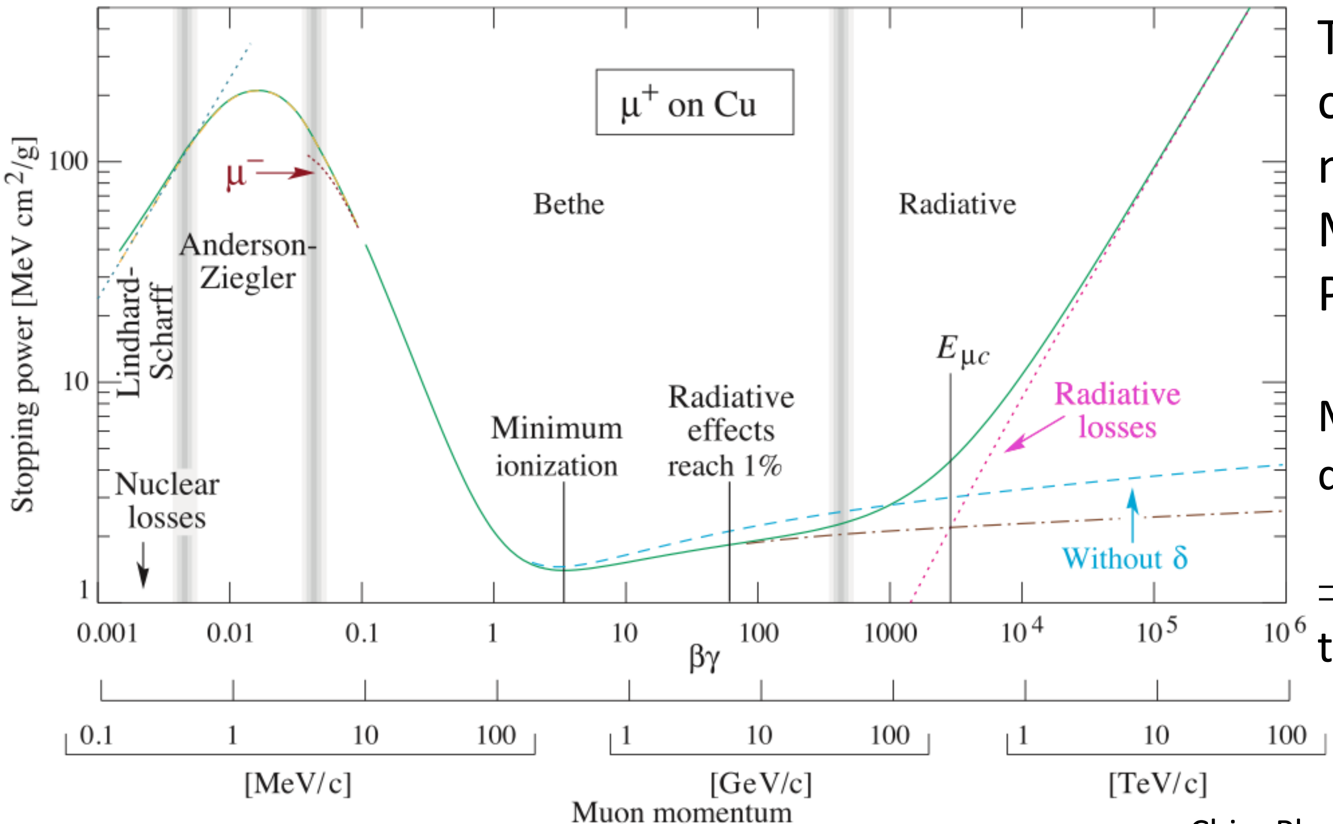
For d=300μm, $N_{eff}=10^{12}cm^{-3}$
ρ=4.4 KΩcm
V_{dep}=70V, E_{max}=4.6KV/cm

Segmented (microstrip) detector



Signal

- Deposited energy / Mean excitation energy



The energy loss of a charged particle has a minimum at p~4mc→ Minimum Ionizing Particles [MIP]

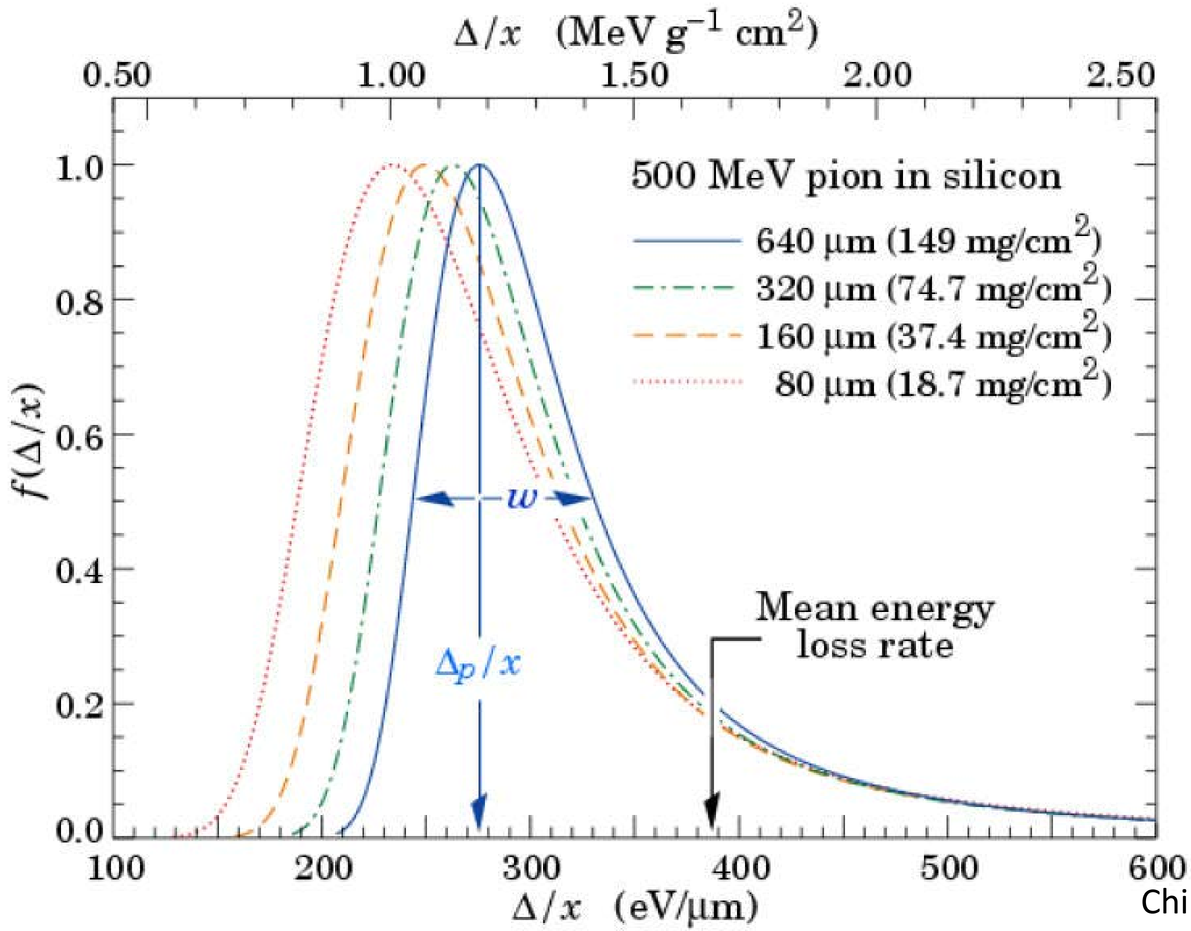
MIP mean energy loss dE/dx (Si) = 388 eV/μm

⇒ 116 KeV for 300μm thickness

Chin. Phys. C, 38, 090001 (2014)

Signal

- <u>Deposited energy</u> / Mean excitation energy

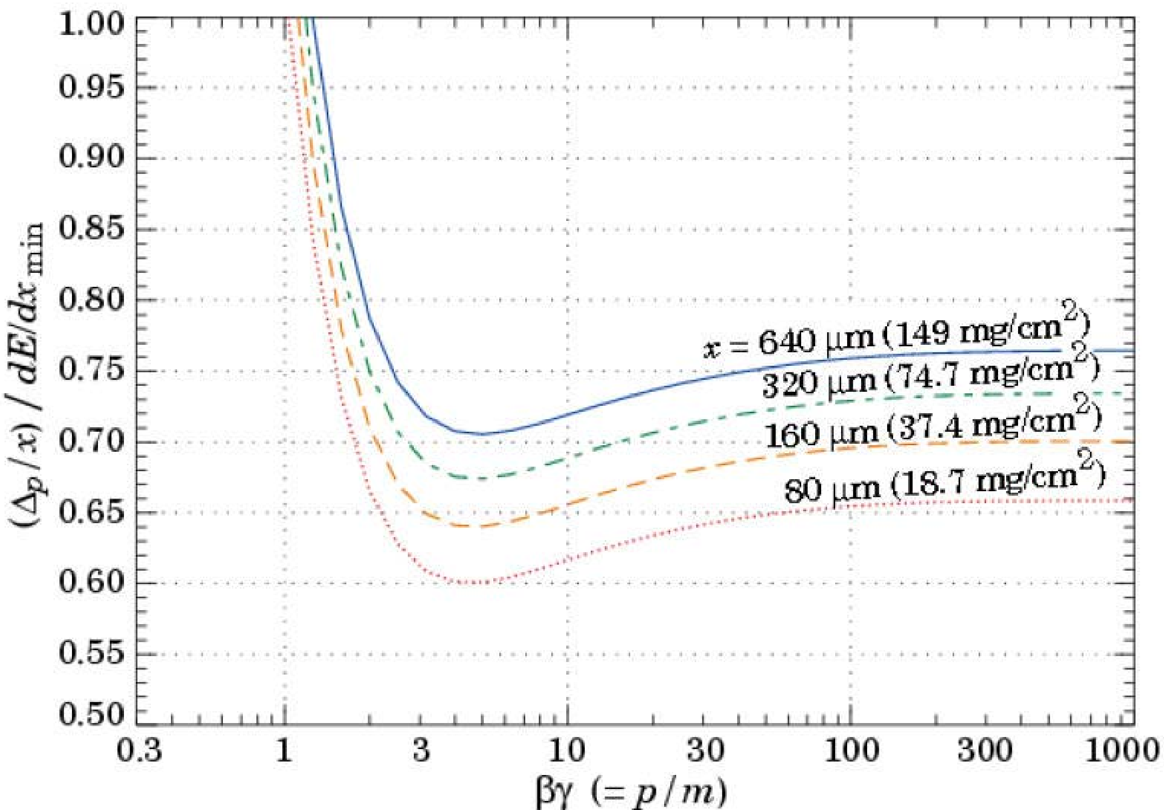


Event-by-event energy loss fluctuations 'follow' the Landau distribution

Chin. Phys. C, 38, 090001 (2014)

Signal

- Deposited energy / Mean excitation energy



The most probable Energy loss depends on detector thickness: About 60-70% of the mean dE/dx

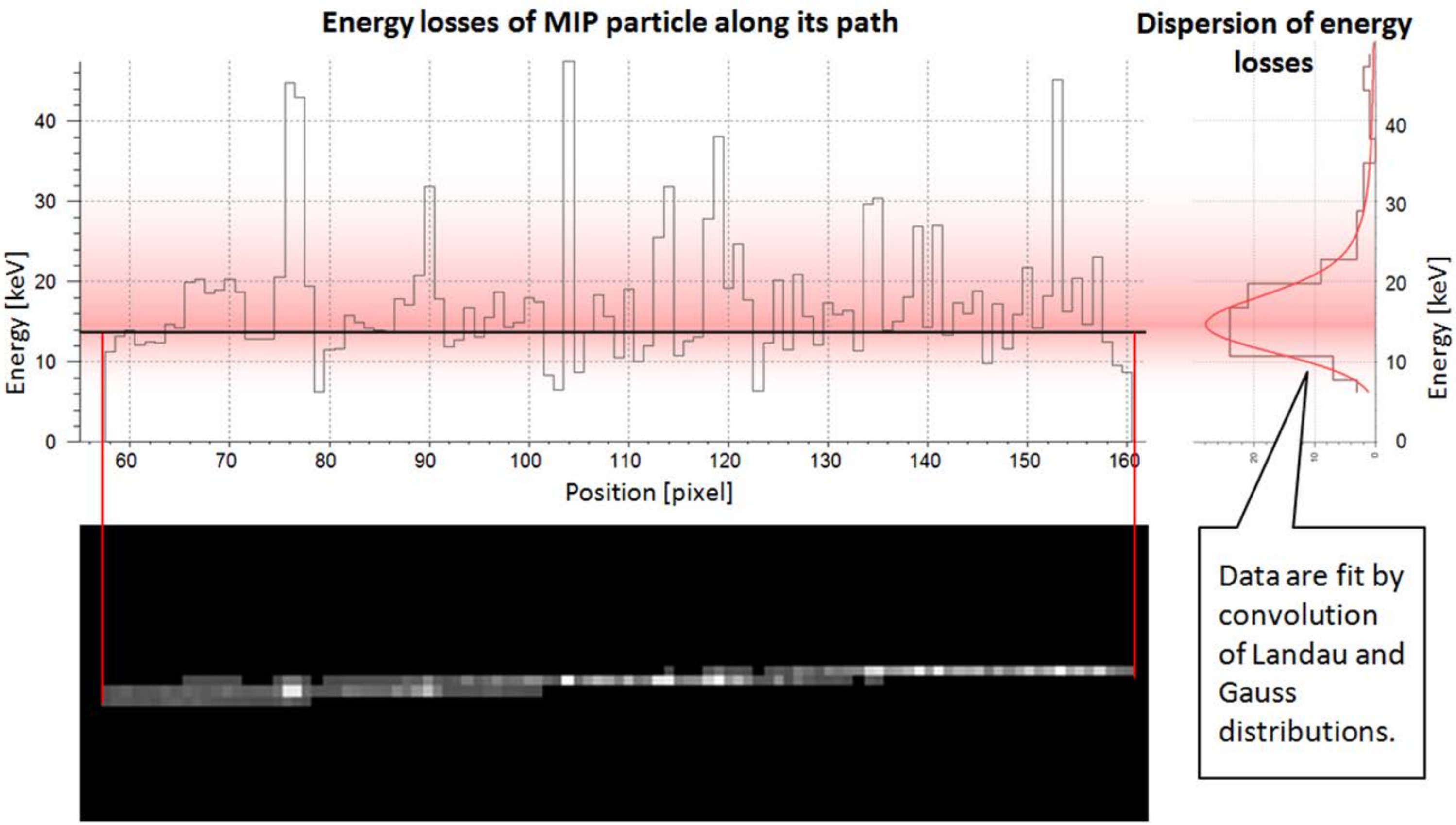
Most probable energy loss in 300μm thick Si For a MIP is:

$\approx 0.67 \times$mean

$\Rightarrow$ 81 keV

Chin. Phys. C, 38, 090001 (2014)

Signal fluctuation visualization



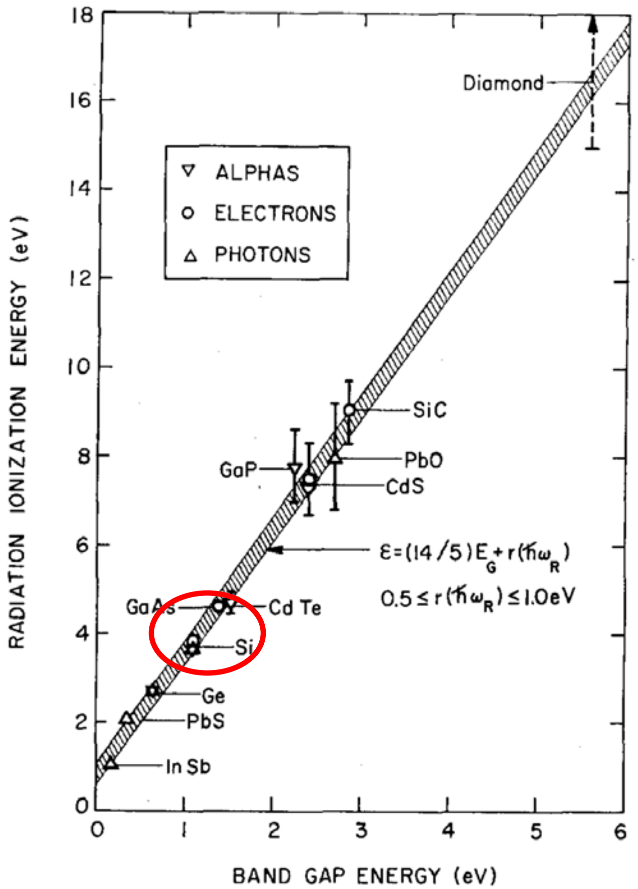
Cosmic ray track viewed by Timepix detector

55μm pixels → measured most probable value = 14 KeV/55μm = 255 eV/μm (as expected)

http://aladdin.utef.cvut.cz/ofat/methods/MIPtracking/index.htm

Signal

- Deposited energy / Mean excitation energy



The average energy to produce an electron-hole pair in Silicon is ~ 3.6 eV

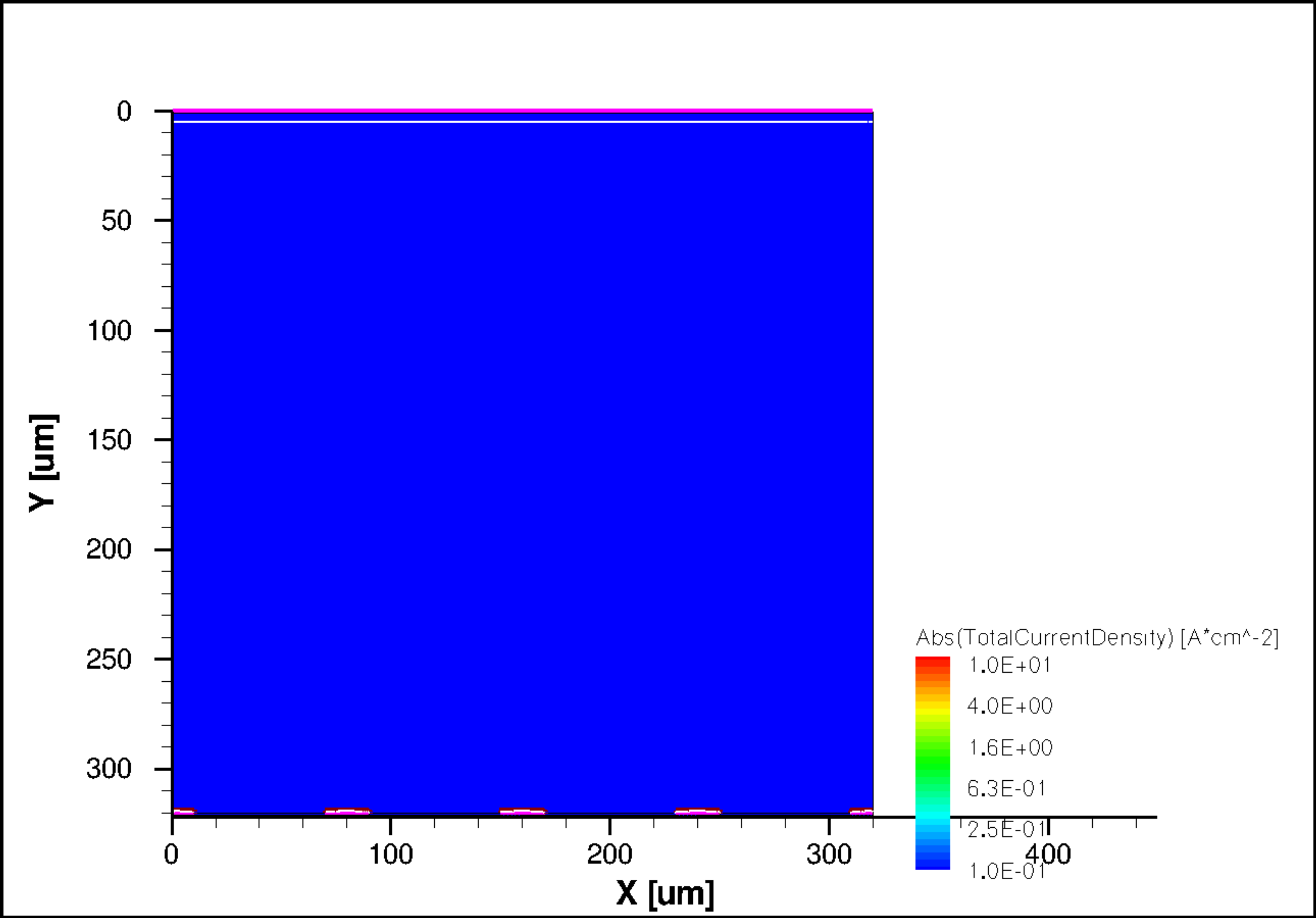
Most probable MIP Signal in 300μm of Silicon → 22500 [e^-] or 3.6 fC (75 e-h couples / μm)

Average MIP Signal in 300μm of Silicon → 32200 [e^-] or 5.2 fC (107 e-h couples / μm)

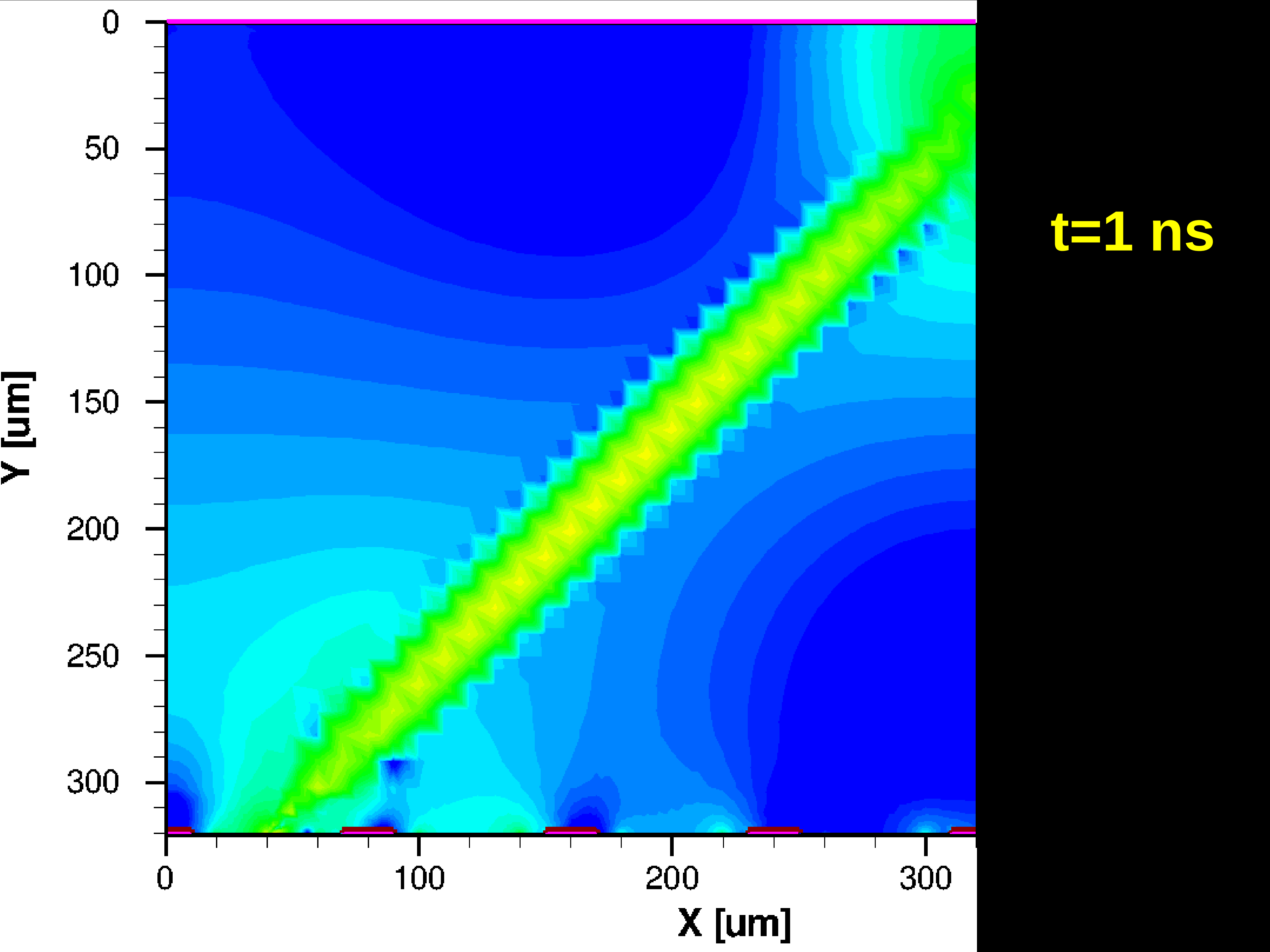
C.A. Klein, J. Applied Physics 39 (1968) 2029

Simulated Current Density

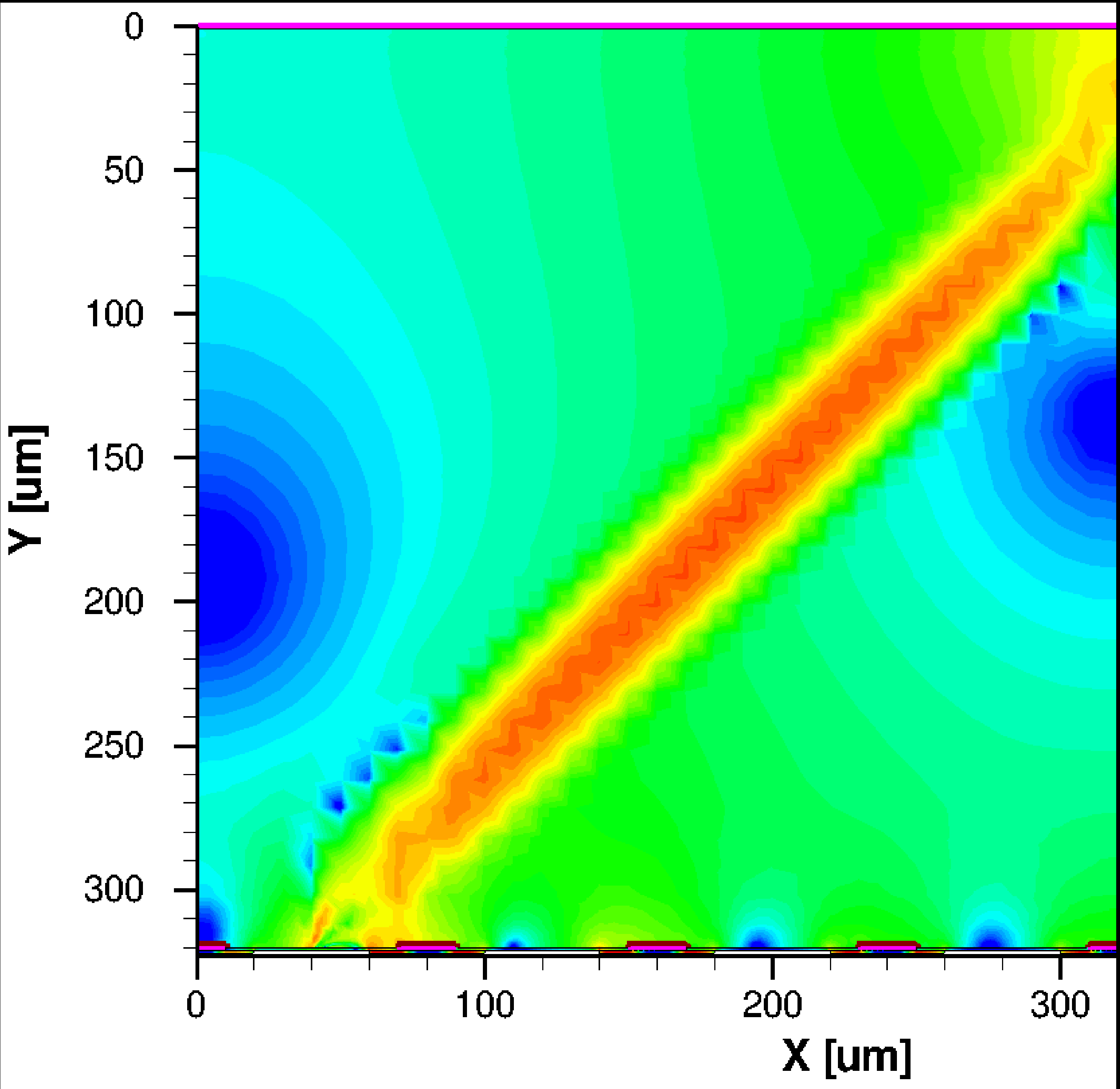
Ionizing particle with 45º angle t=0 s



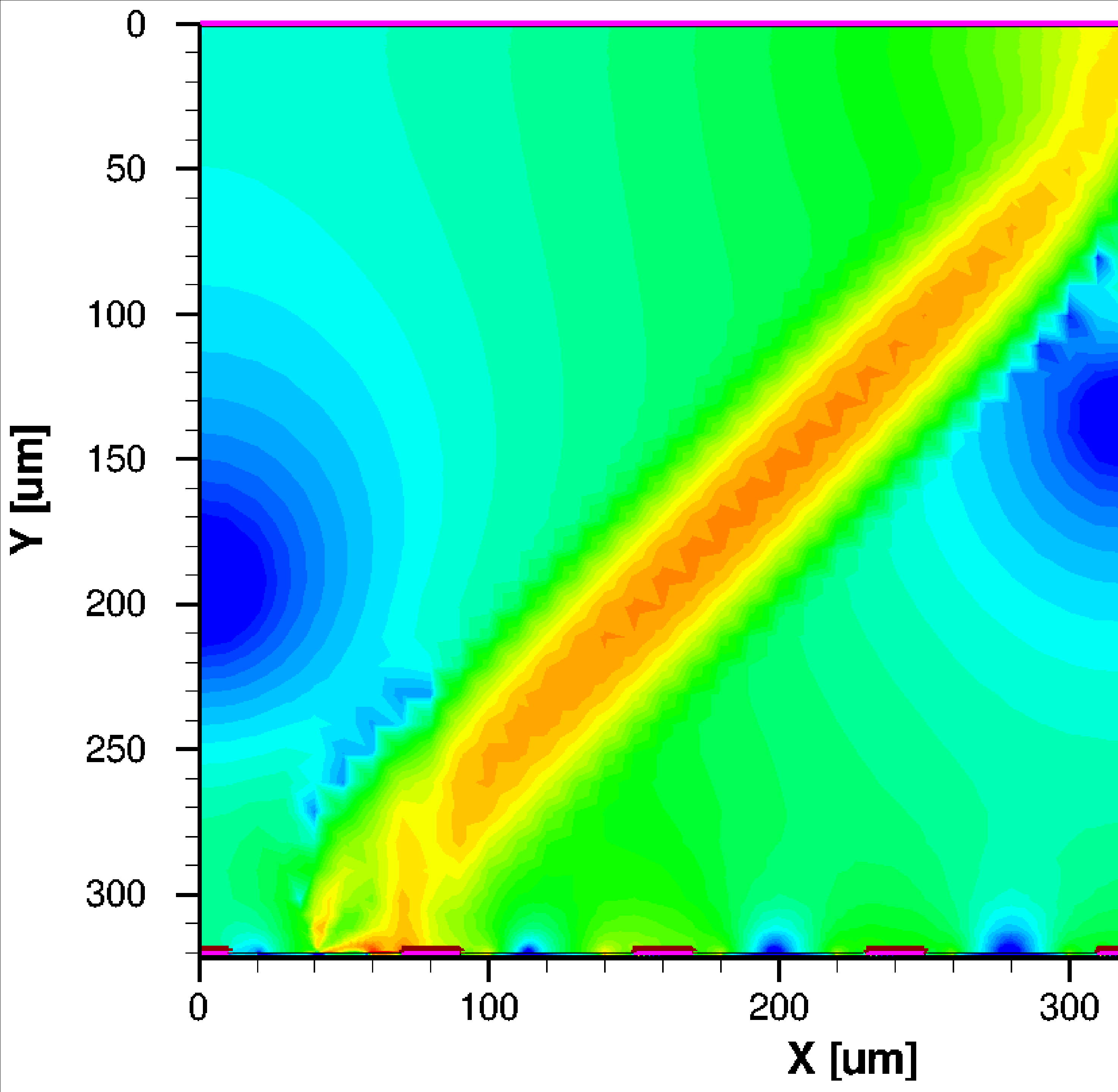
Simulation Thomas.Eichhorn@kit.edu



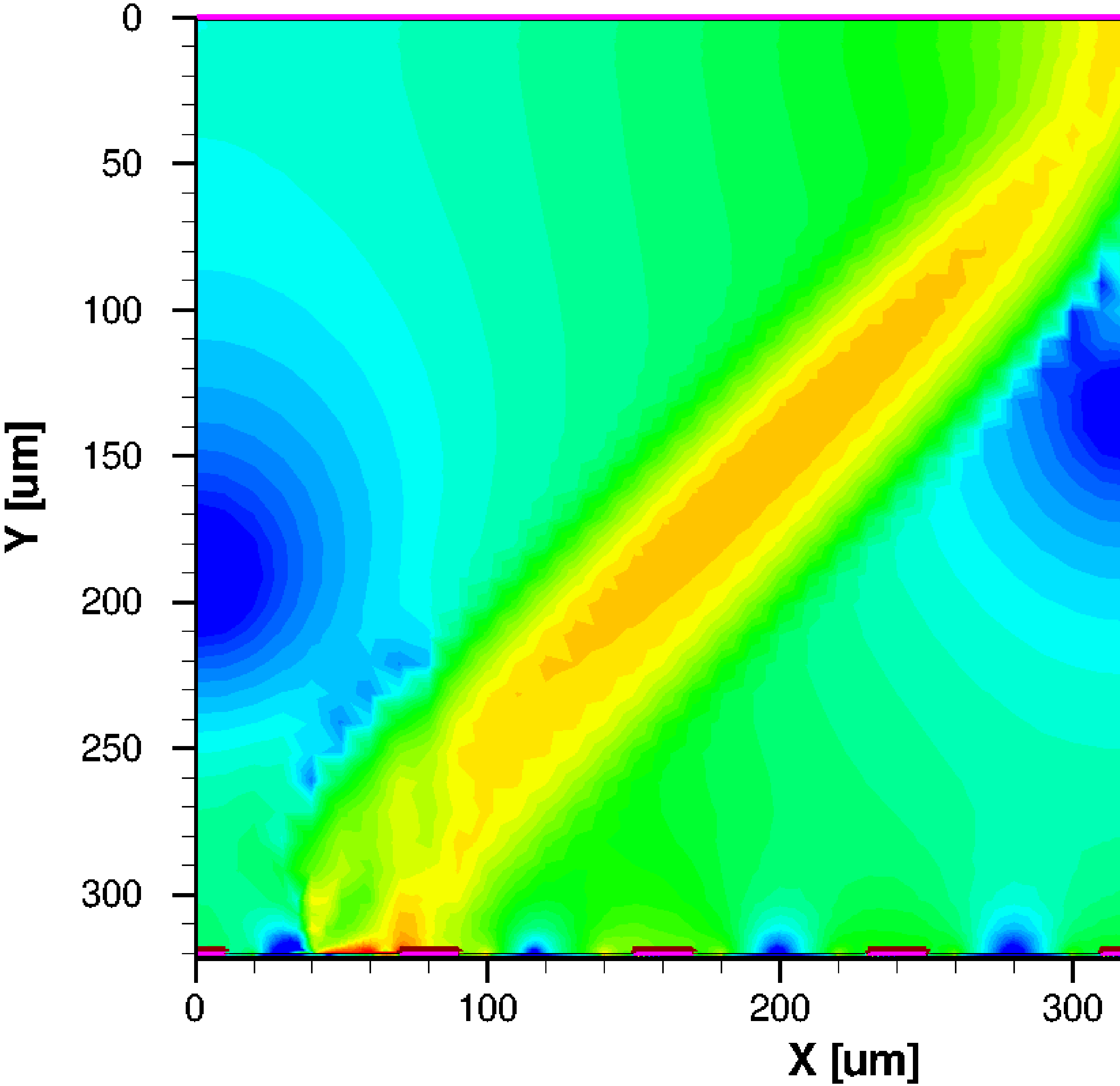
Y [um]
X [um]
0
50
100
150
200
250
300
0
100
200
300
t=1 ns



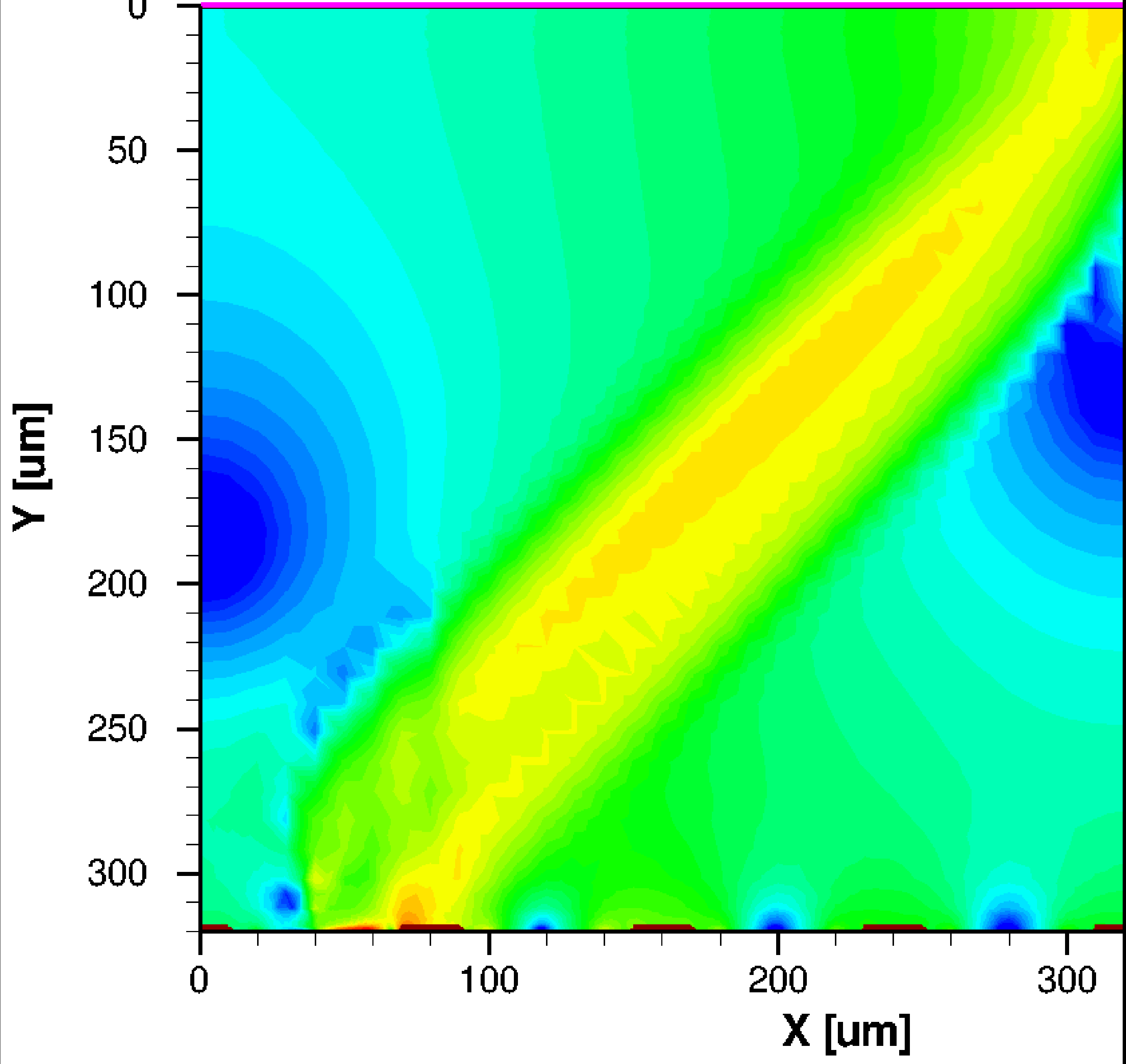
t=1,1 ns



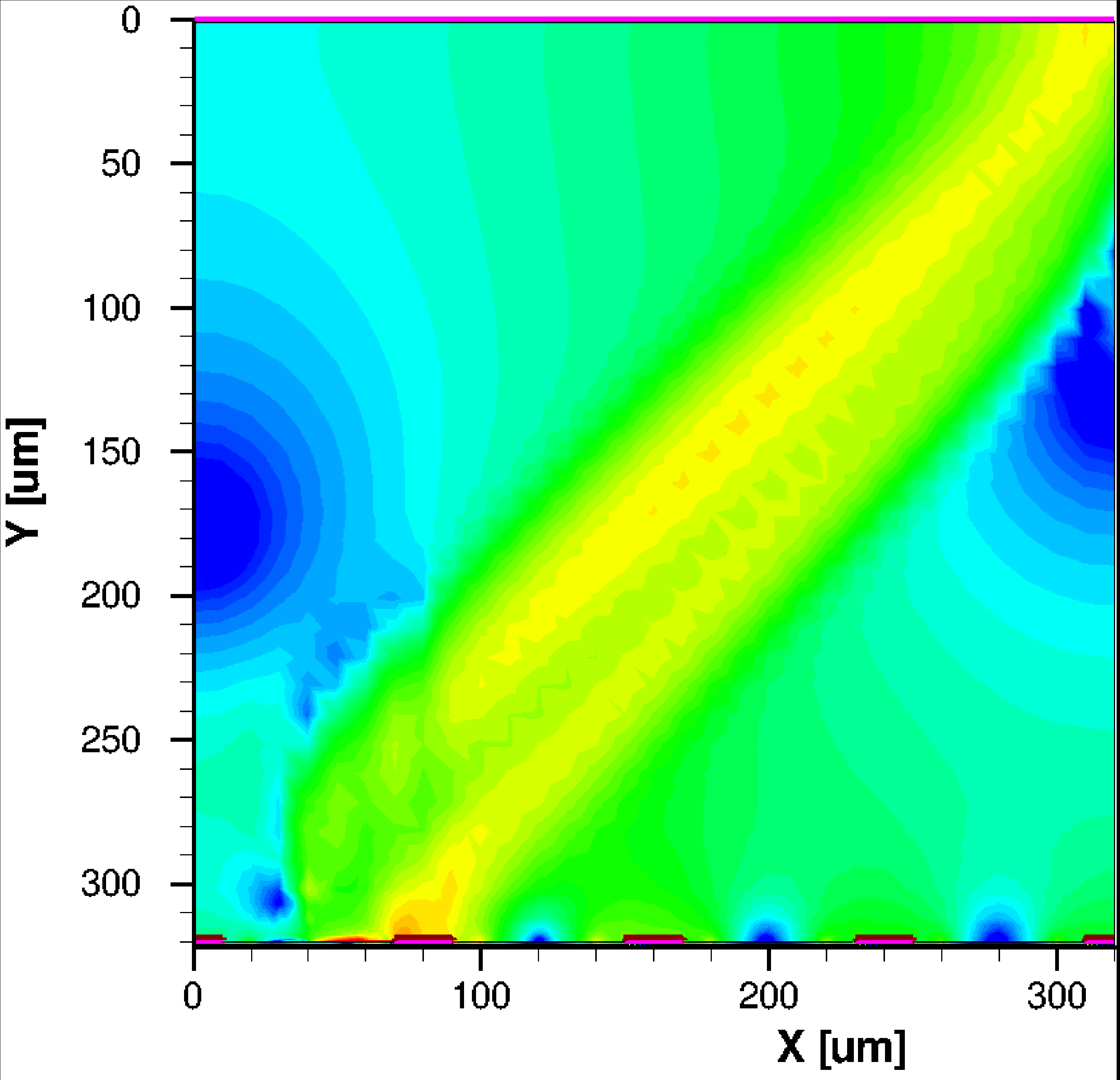
t=1,2 ns



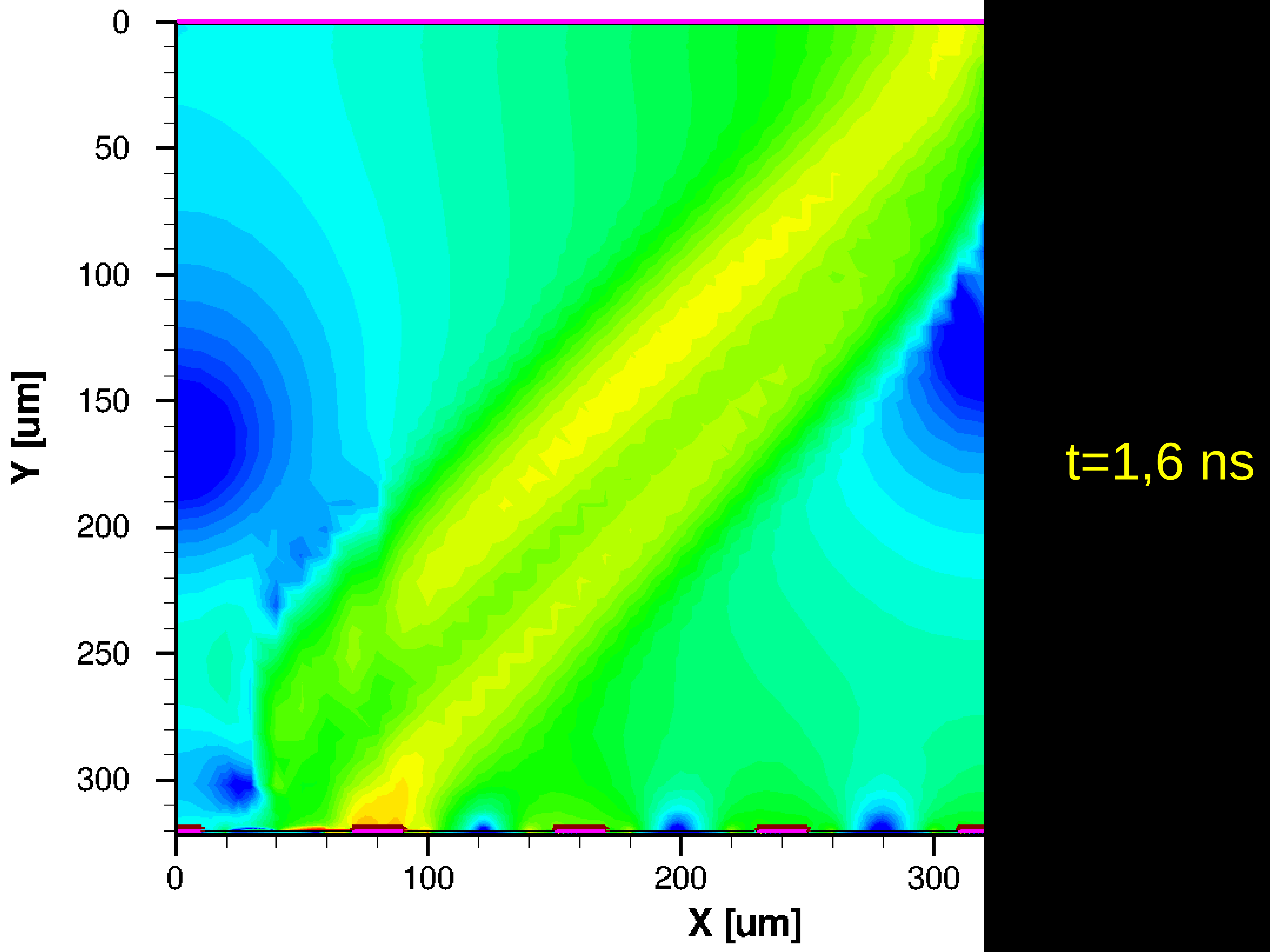
t=1,3 ns



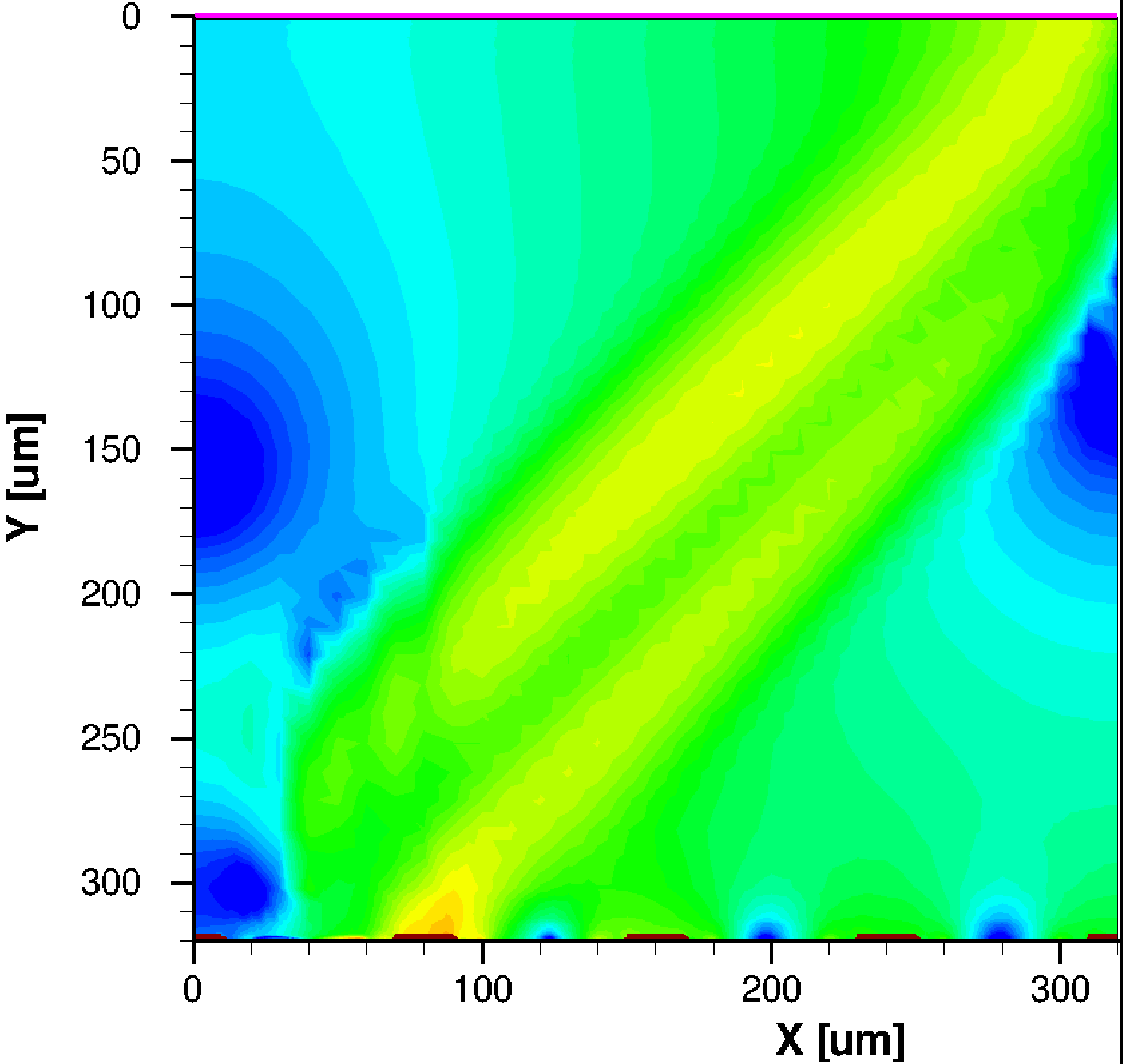
t=1,4 ns



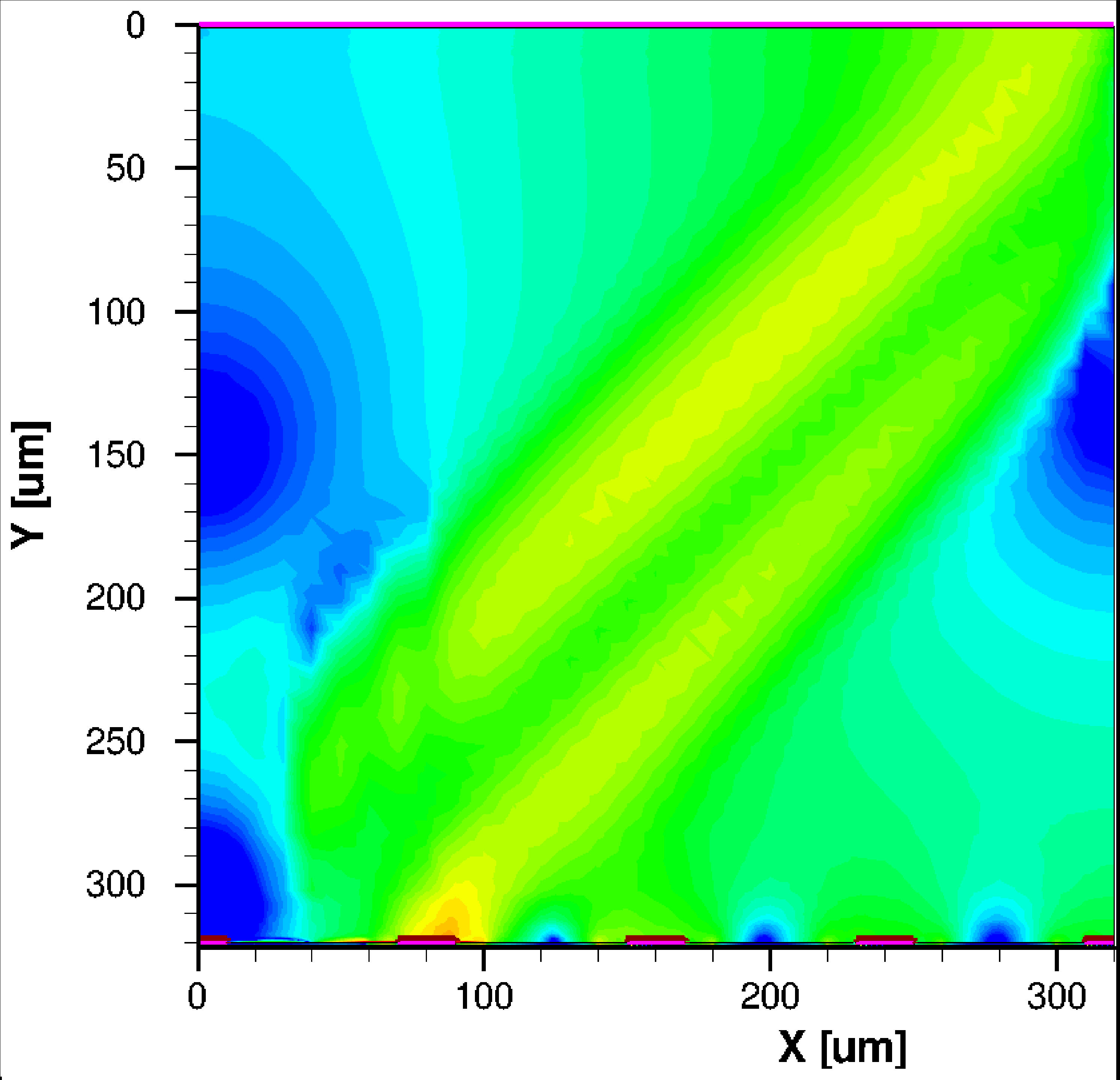
t=1,5 ns



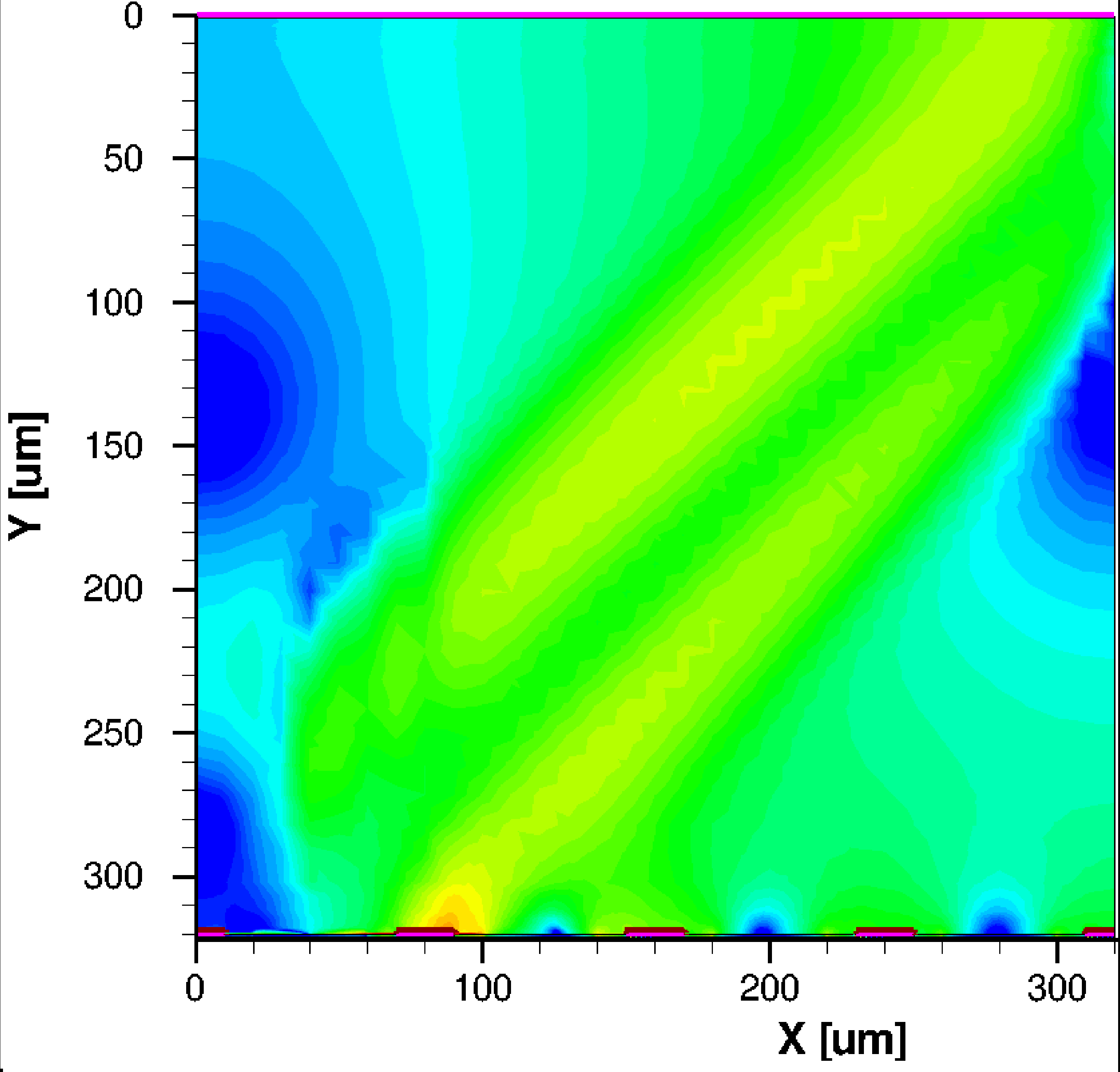
0
50
100
150
200
250
300
Y [um]
0
100
200
300
X [um]
t=1,6 ns



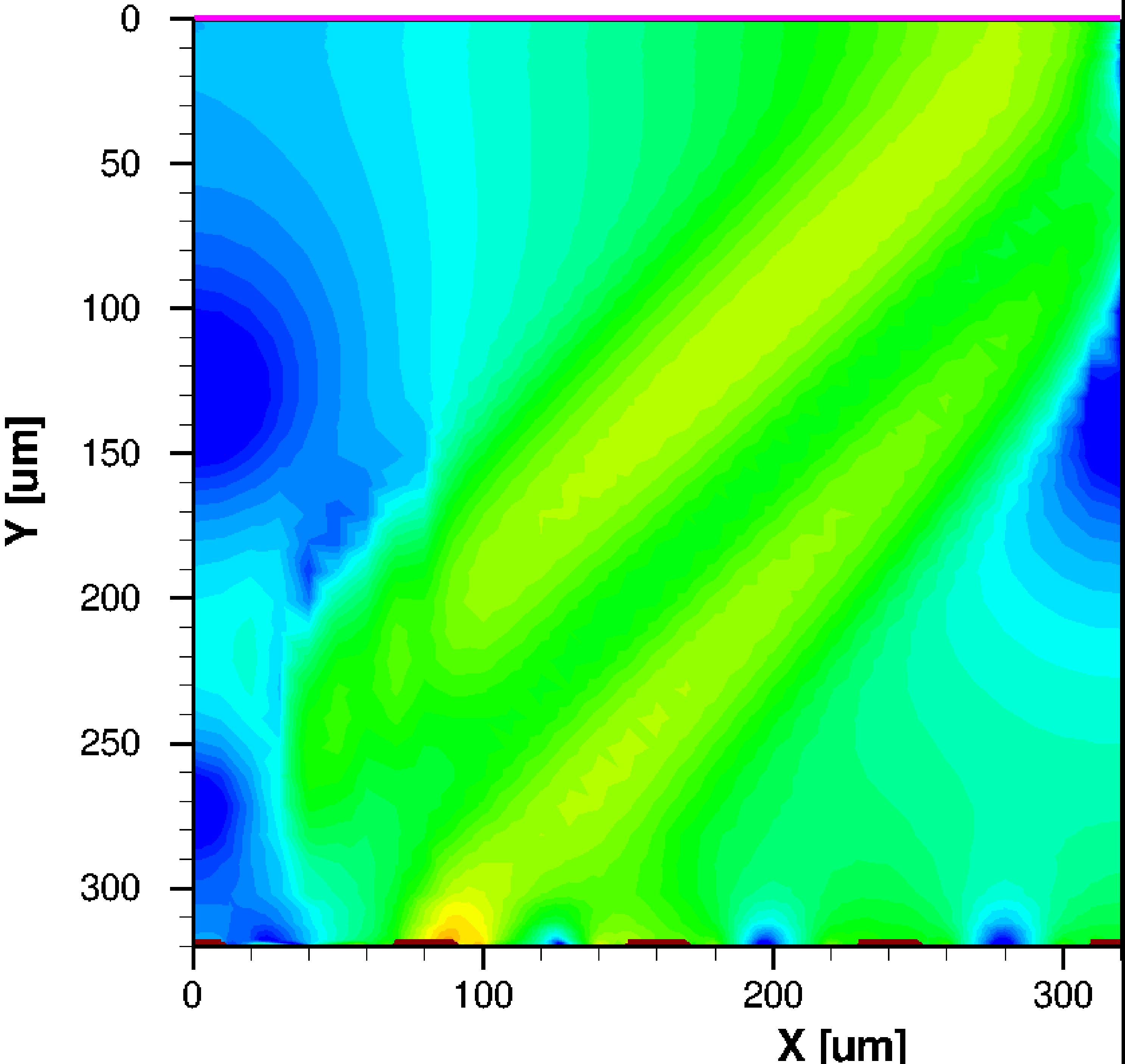
t=1,7 ns



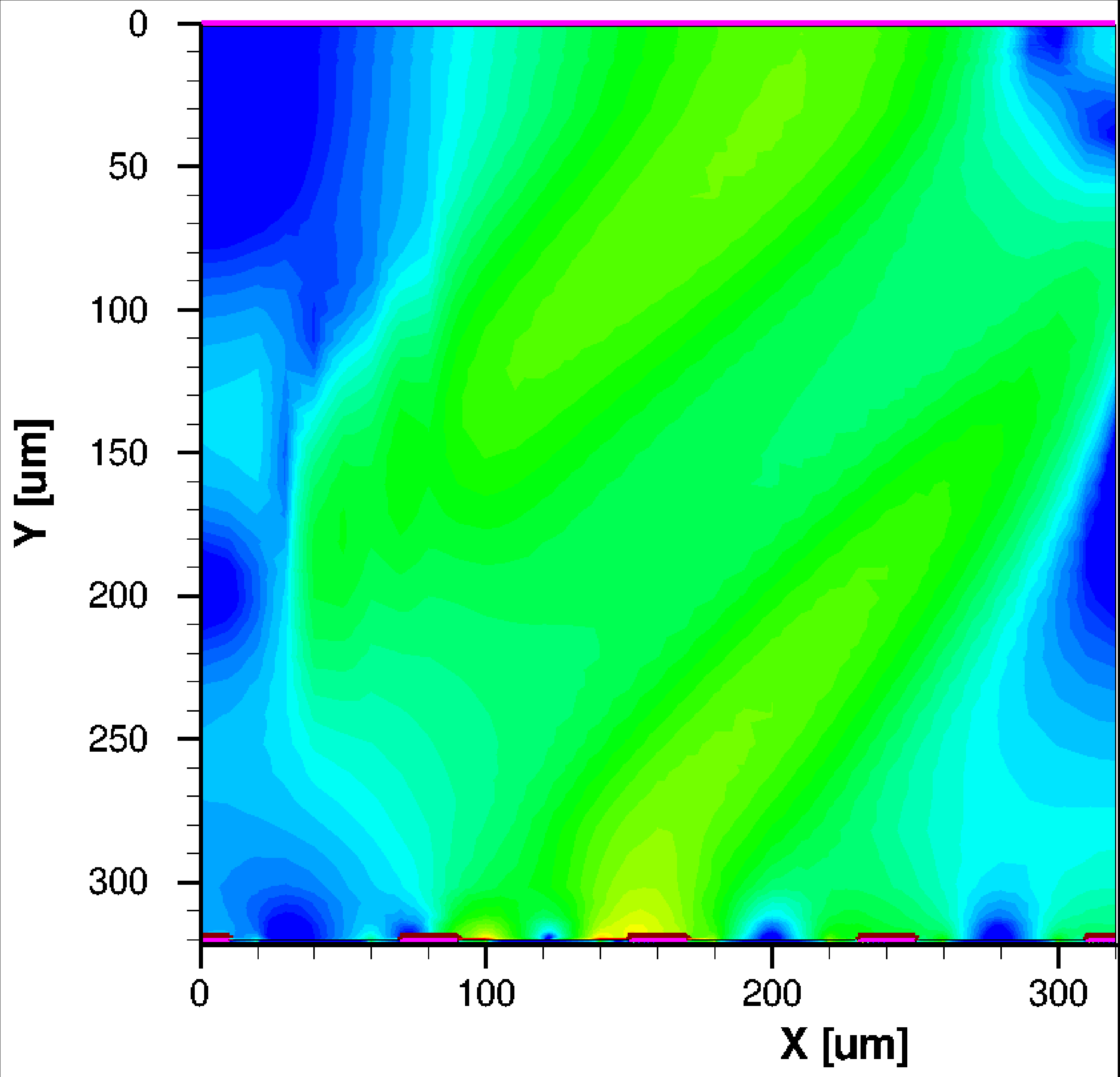
t=1,8 ns



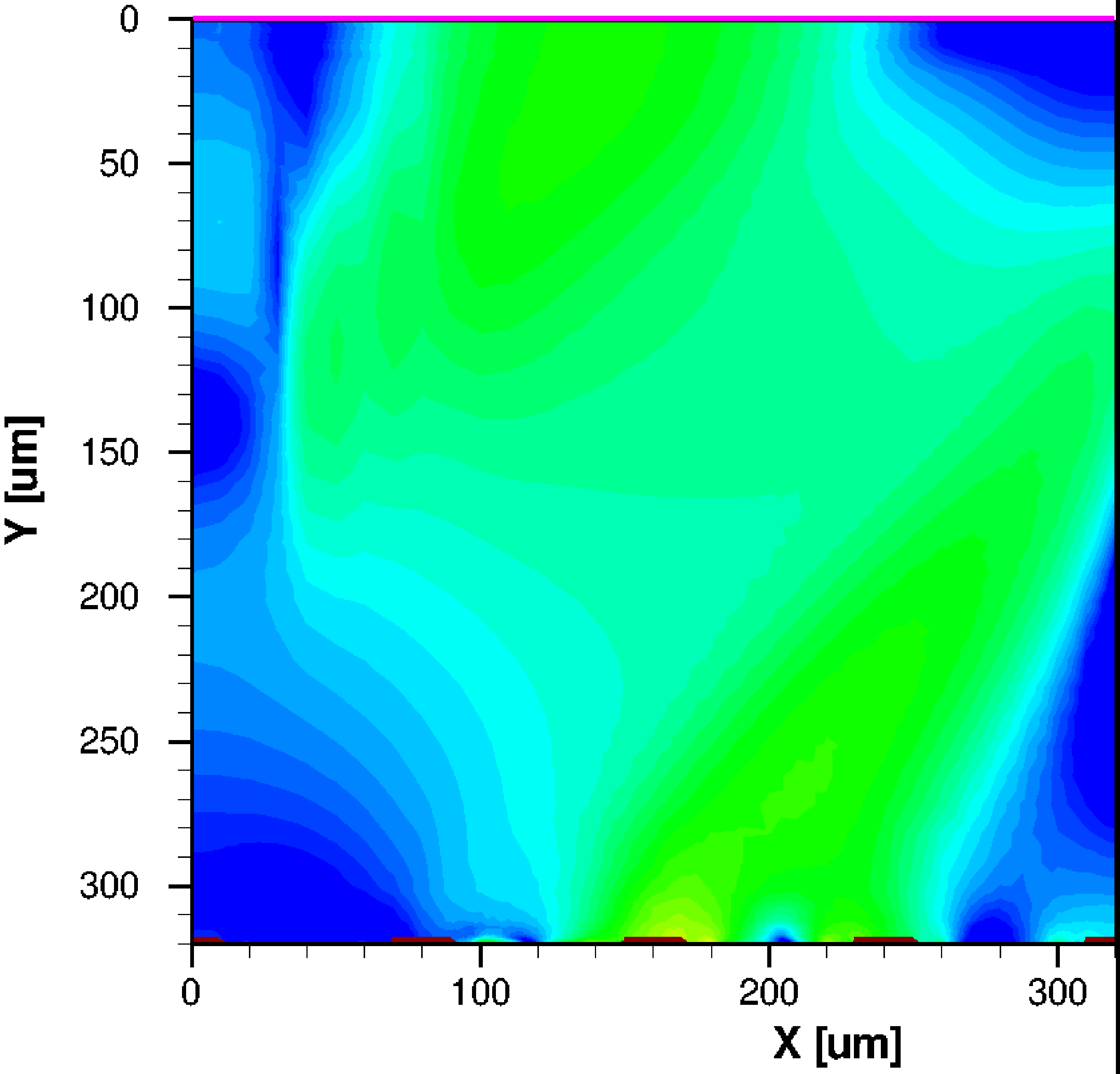
t=1,9 ns



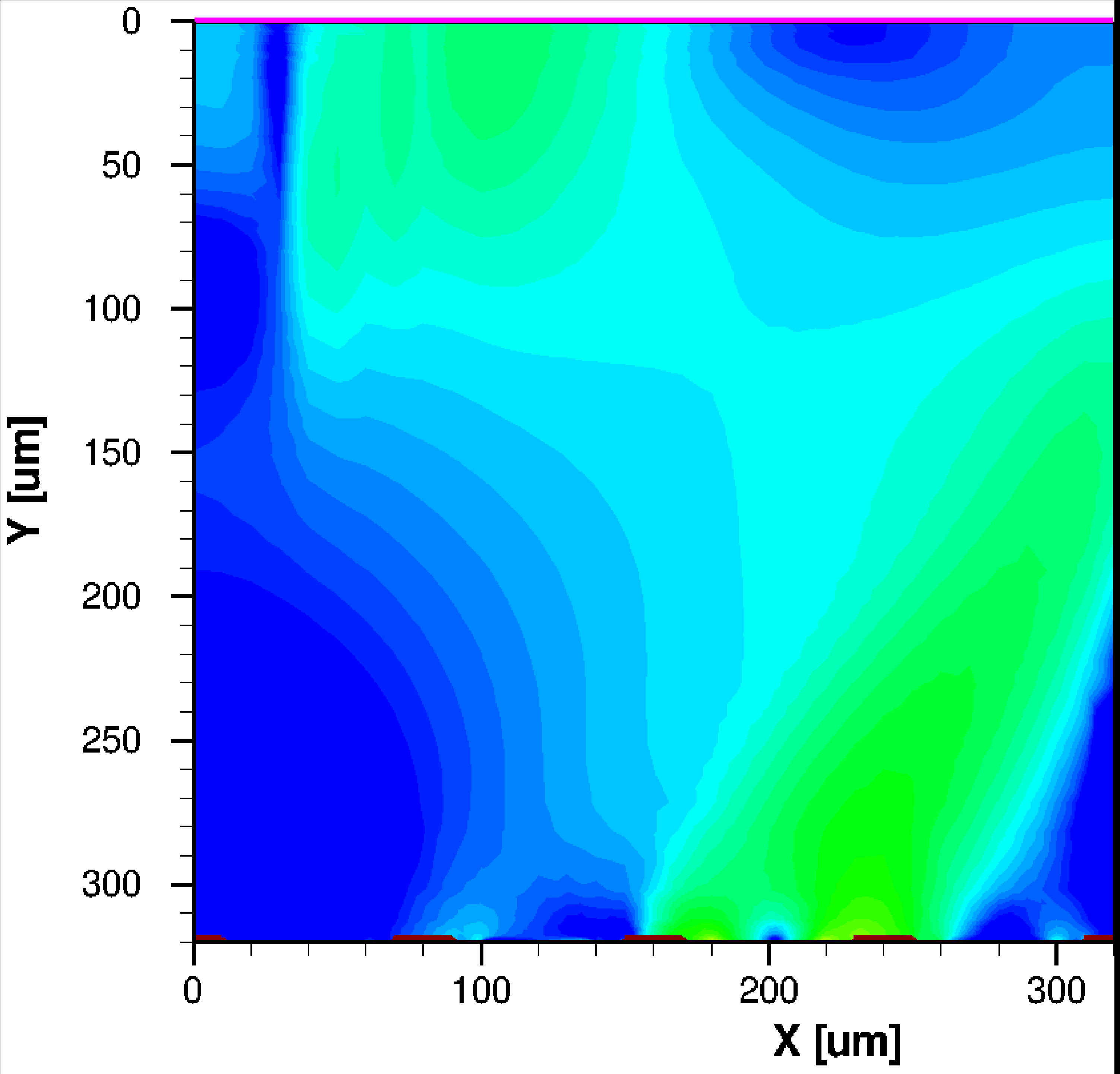
t=2 ns



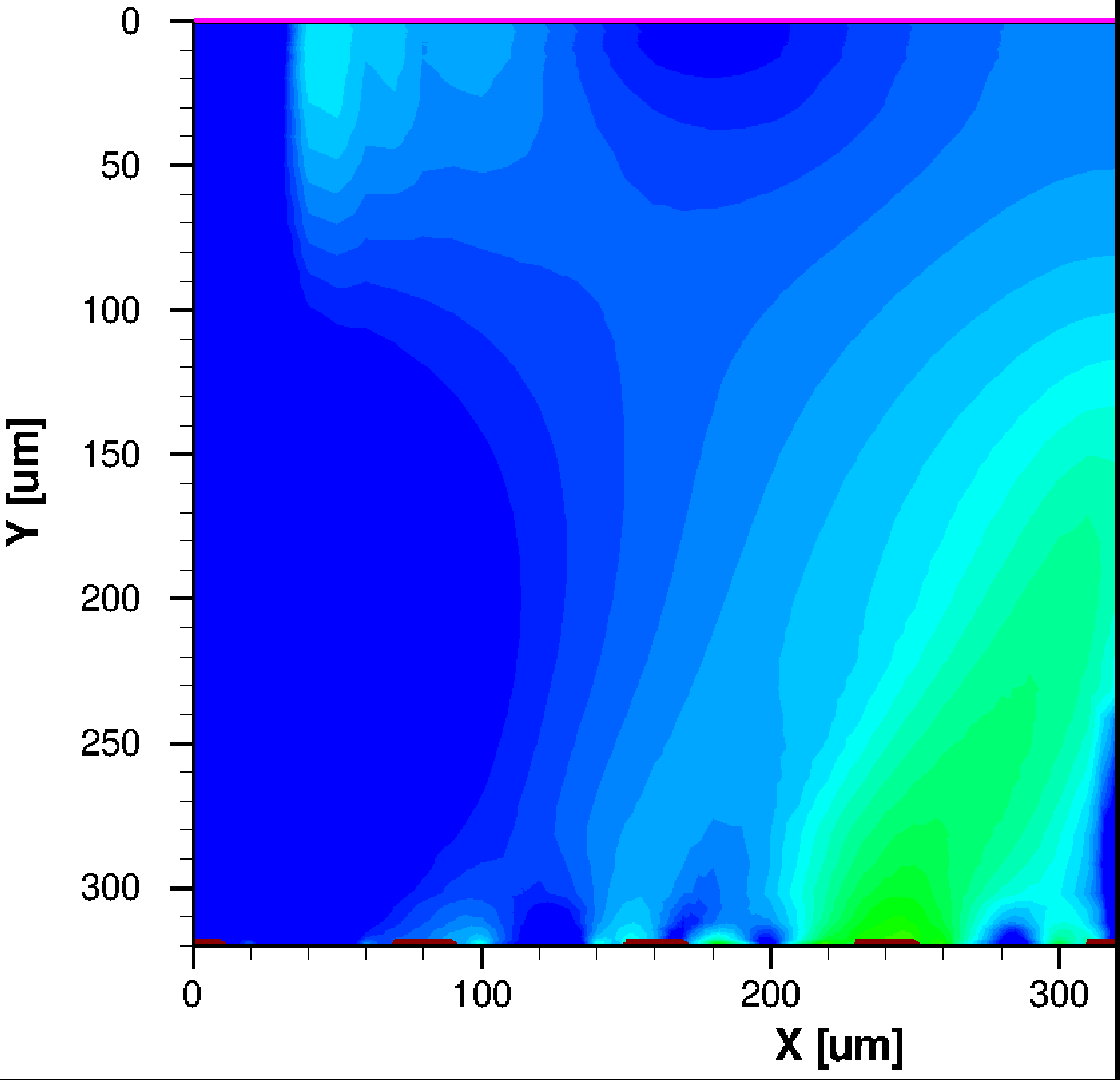
t=3 ns



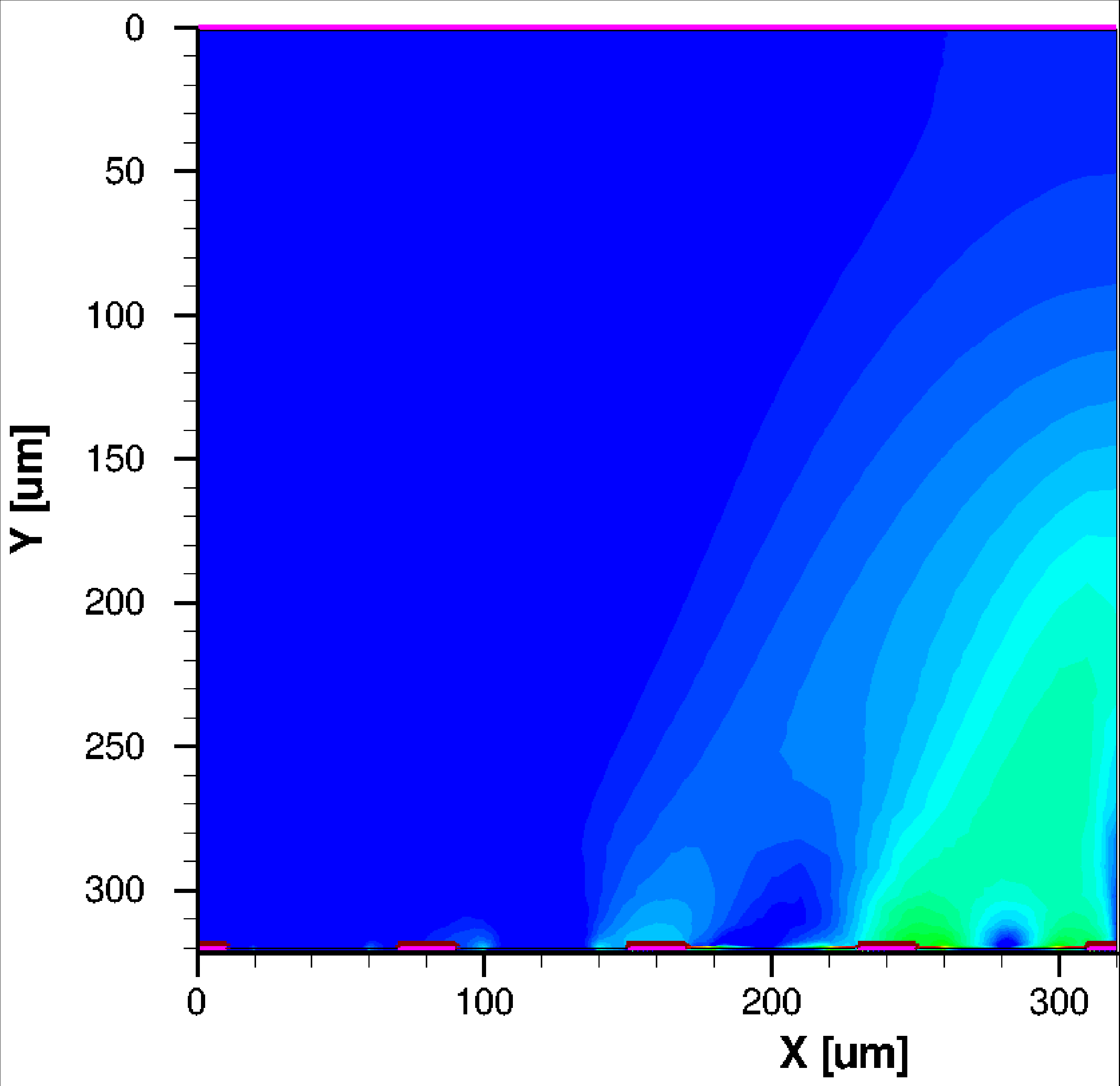
t=4 ns



t=5 ns



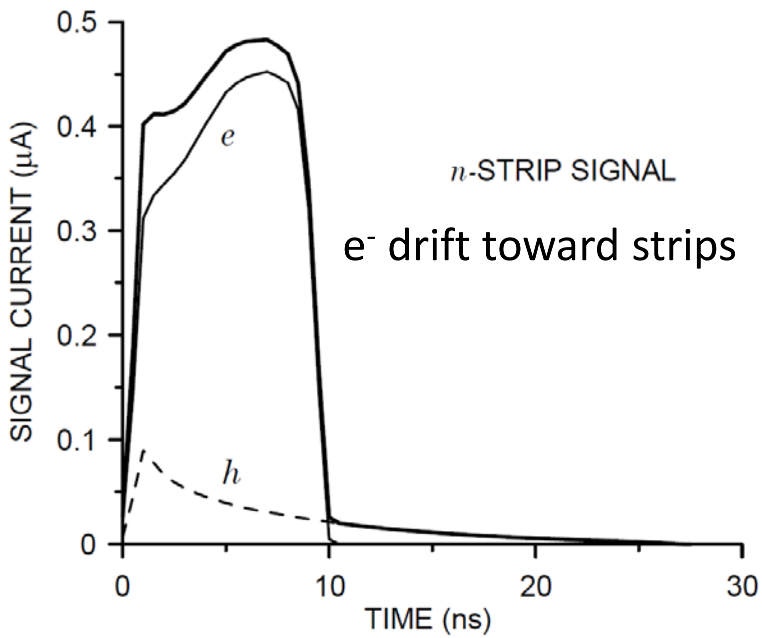
t=6 ns

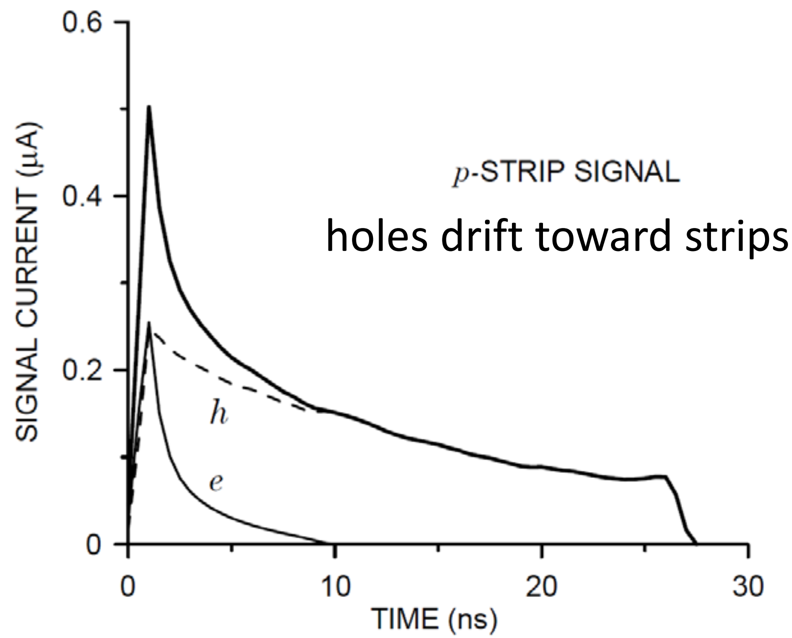


t=7 ns

Mind all electrons collected

Current pulses in strip detectors (track traversing the detector)





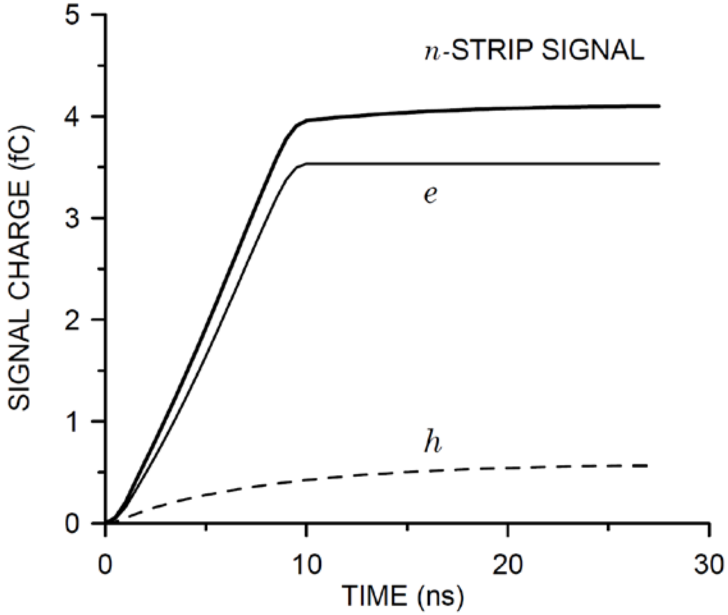
Depletion voltage= 60V Bias voltage= 90V

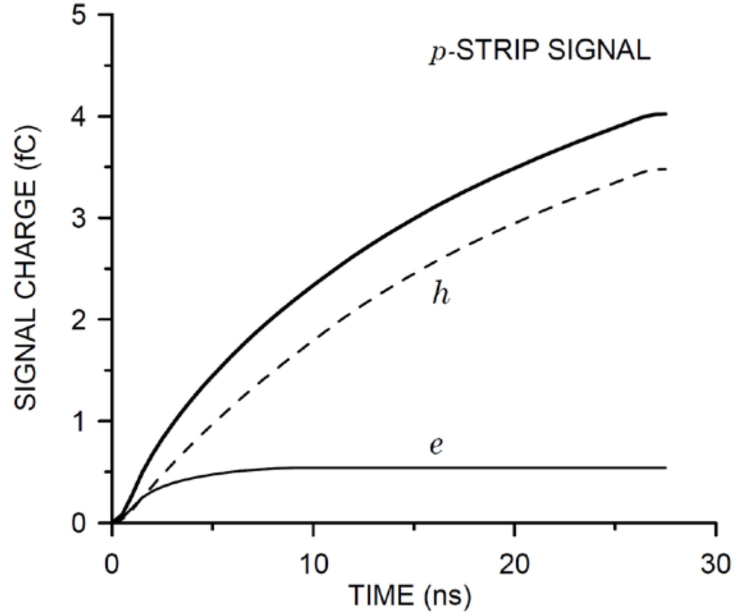
The duration of the electron and hole pulses is determined by the time required to traverse the detector as in a parallel-plate detector, but the shapes are very different.

Silicon Detectors – Refresher Course
2012 IEEE Nuclear Science Symposium, Medical Imaging Conference, Anaheim, CA

Helmuth Spieler

Strip Detector Signal Charge

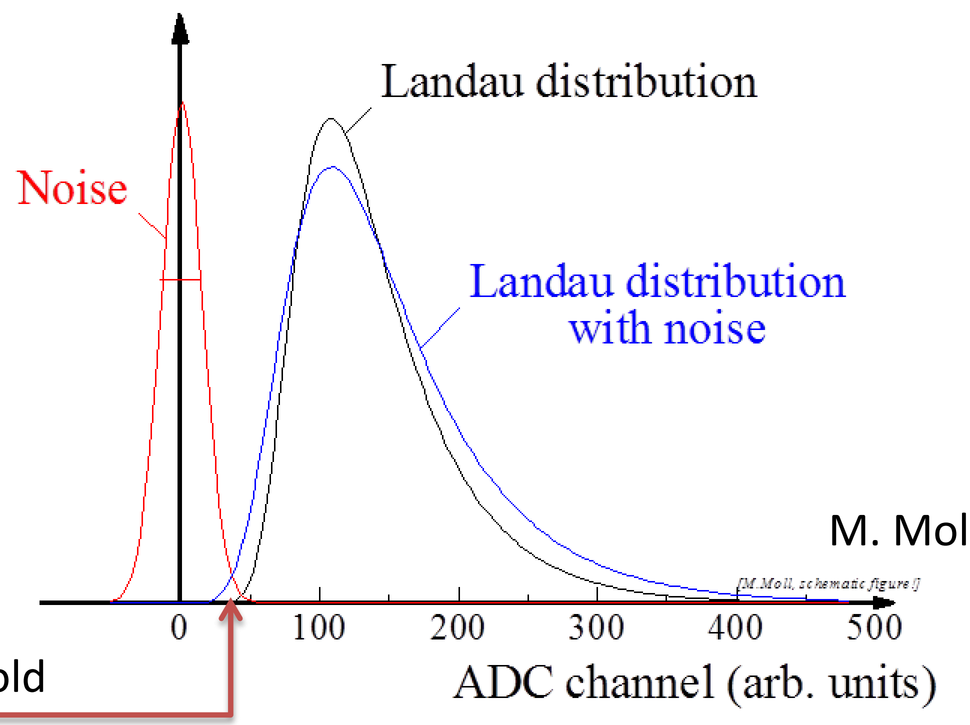




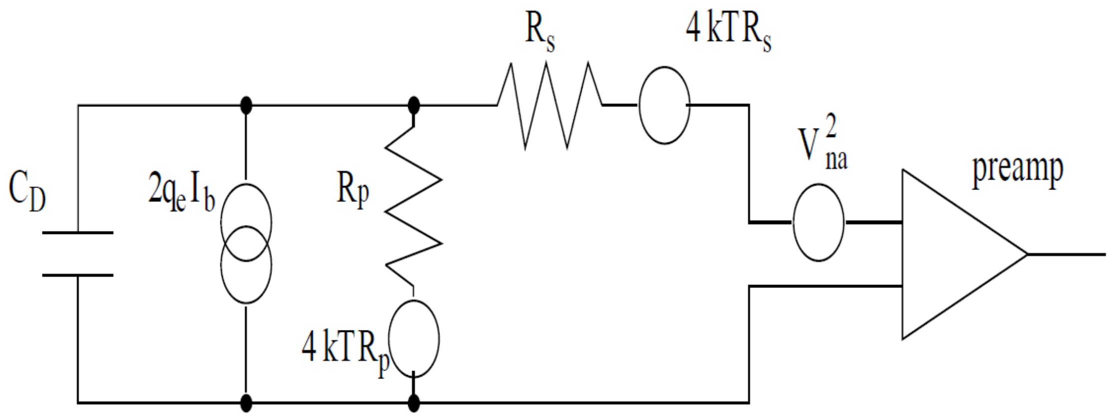
In both electrodes the induced current must be integrated over the full collection time to optimize energy resolution.

Noise

- What is important to characterize the quality of a detector is its ‘signal-to-noise ratio’
- In a 300μm thick Silicon microstrip detector the minimum charge produced by a MIP is about 70% of the MPV
- If an electronic noise of about MPV/8 is superimposed the minimum charge can mix to the pedestal (signal when no particle crosses the detector) by 3 sigma
- In this condition the detector efficiency starts to decrease and/or the noise contamination becames relevant



Electronic noise



C_d = detector capacitance
I_b = bias current
R_p = bias resistor
R_s = strip resistance
V_{na}^2 = Preamplifier noise

$$ENC^{I_b}_{parallel} \approx 108 \cdot \sqrt{I_b(\mu\mathrm{A})\tau(ns)}e^-,$$
$$ENC^{R_p}_{parallel} \approx 24 \cdot \sqrt{\tau(ns)/R_p(\mathrm{M}\Omega)}e^-,$$
$$ENC^{R_s}_{series} \approx 24 \cdot C_{tot}(\mathrm{pF}) \cdot \sqrt{R_s(\Omega)/\tau(ns)}e^-$$

+ front end electronics: $ENC_{fe} = a + bC_d$

$$Noise = \sqrt{\sum (ENC_i)^2}$$

Radiation damage

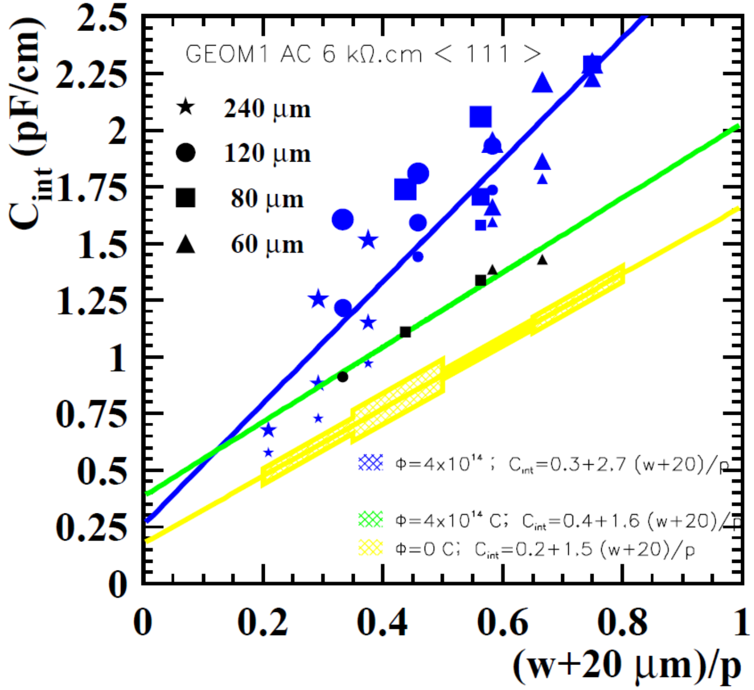
- Surface damage
  - accumulation of charge in the oxide (SiO_2), traps at Si/SiO_2 interface
  - Depends on the ionization energy loss (Dose [rad])
- Volume damage
  - displacement damage → crystal defects
  - Depends on the non-ionization energy loss (NIEL, fluence normalized to 1 MeV neutron)

Surface damage

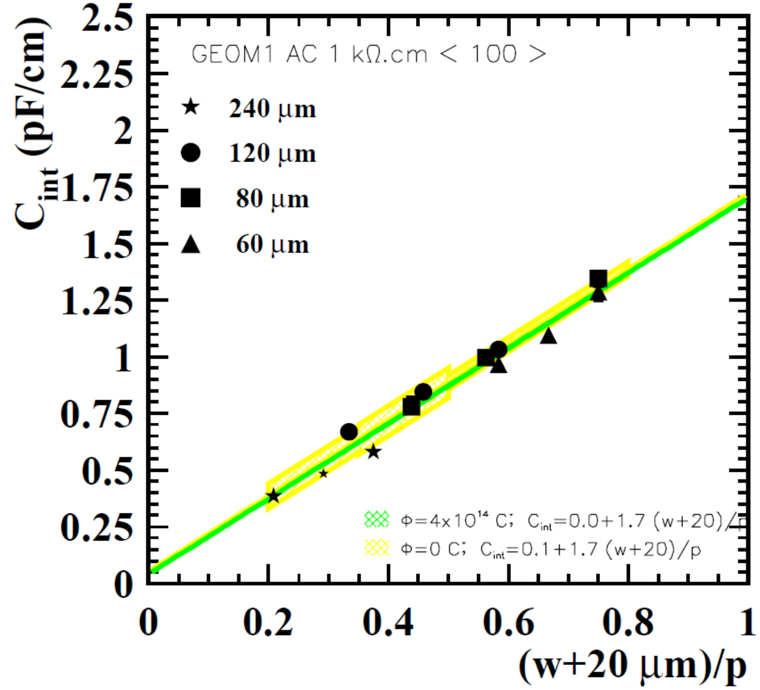
- This effect is due to the presence in the SiO_2 and SiO_2-Si interface of positive charges
  1. Fixed charges → from production process
  2. Mobile positive impurity ions → same as 1.
  3. Trapped holes → from irradiation
- The trapped holes (less mobile than electrons) are generated by ionization
  - Heavy charged particles → high ionization density →high recombination
  - Electrons/photons → low ionization density → low recombination → dominates
- This charged layer changes the electric properties of the segmented side of the detector
  - Increases the interstrip capacitance (C_{int})
  - Increases the surface current
  - Reduce the breakdown voltage
- Depends on the crystal orientation
- Important for Linear Collider and Xfel experiments

Surface damage <111> vs <100>

<u>**<111> silicon**</u>



<u>**<100> silicon**</u>



The C_{int} (main contribution to C_d) increases with irradiation in <111> silicon but stays constant in <100> one

<u>Dangling bonds</u> at the SiO_2-Si interface play an importante role

w = strip width

p = strip pitch

Yellow = no irradiation

Blue and green = 4*10^{14} p/cm^2

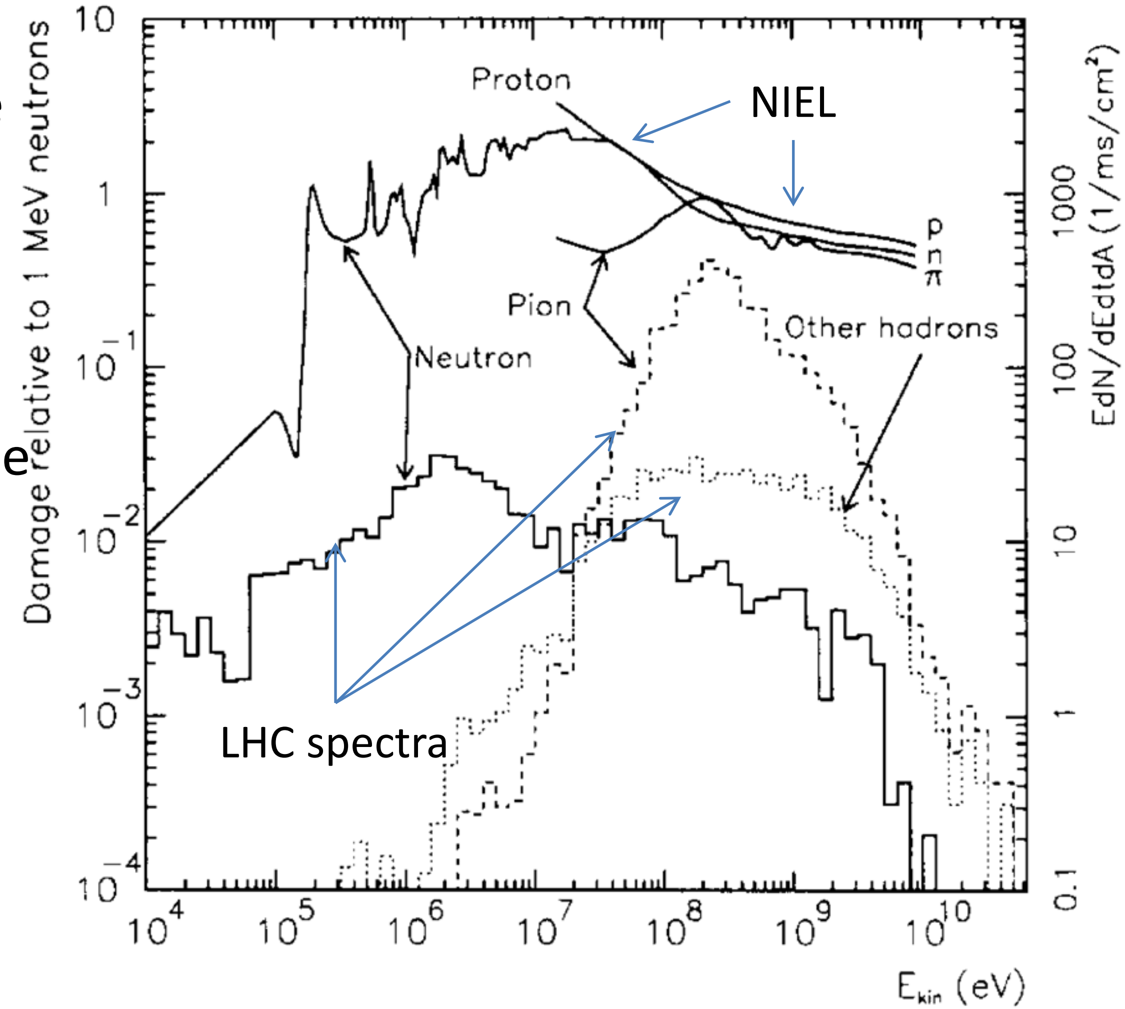
S. Braibant et al., CMS NOTE 2000/011

Volume damage

- Volume (Crystal) damage is due to (*scales* with) Non Ionizing Energy Loss (NIEL) and results in:
  1. Change of effective doping concentration (higher depletion voltage, leading possibly to under-depletion)
  2. Increase of leakage current (increase of shot noise, thermal runaway)
  3. Increase of charge carrier trapping (charge collection efficiency decreases)
- Signal-to-noise ratio could then be reduced substantially
- The sensor total depletion could not be reached
- Safe detector operation is jeopardized by the possible thermal runaway (sensor temperature increased by the bias current, which is increased by temperature, which …) → Positive feedback

NIEL

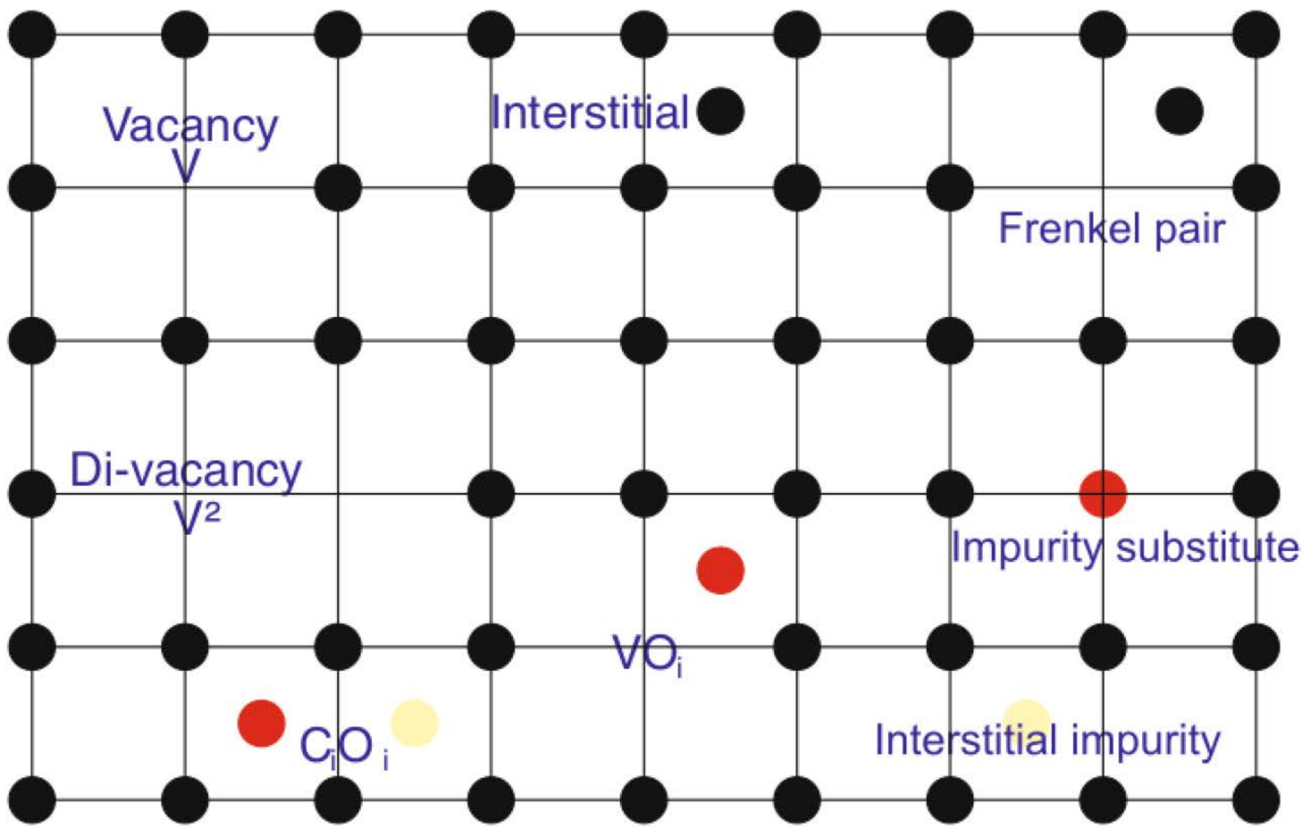
- It is defined as the amount of energy released into the material by an incident particle which is not loss in ionization
- This is the energy which breaks the crystal lattice and introduce defects in the material
- Different particles have different effectiveness in releasing NIEL; to compare irradiation a possible solution is to normalize to the NIEL of a 1 MeV neutron



NIM A 335 (1993) 580-582

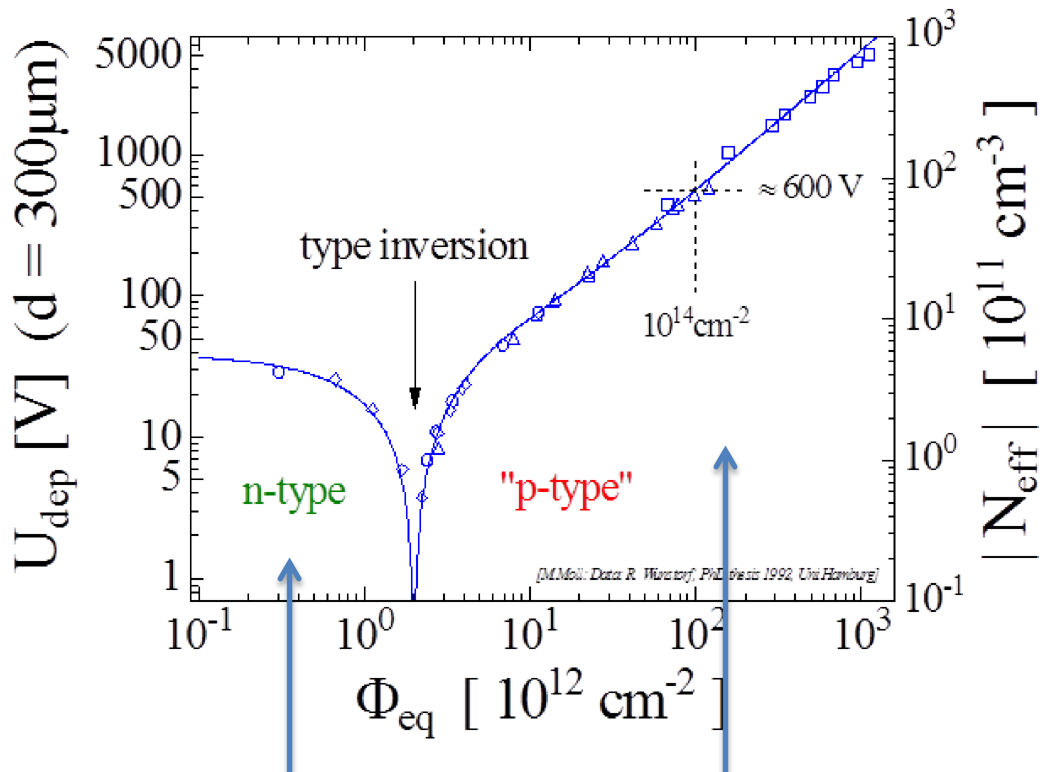
Microscopic view...

The damaged lattice 'zoo'



J. Zhang

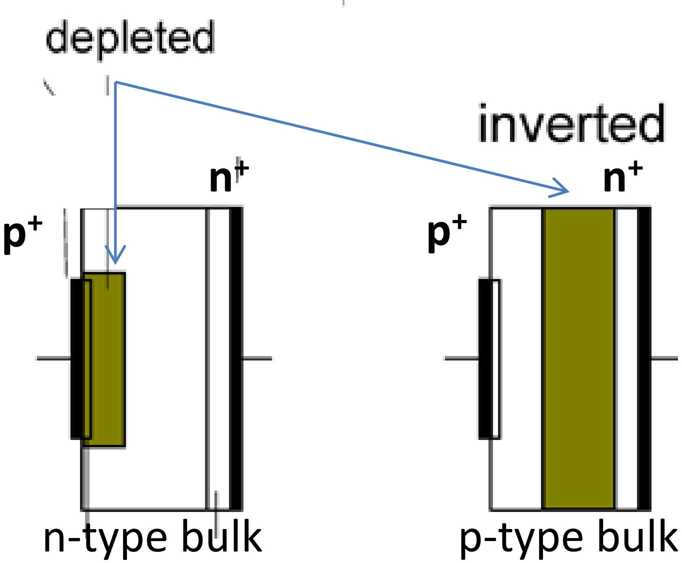
Change of depletion voltage



Donor removal +
Acceptor generation

Acceptor generation

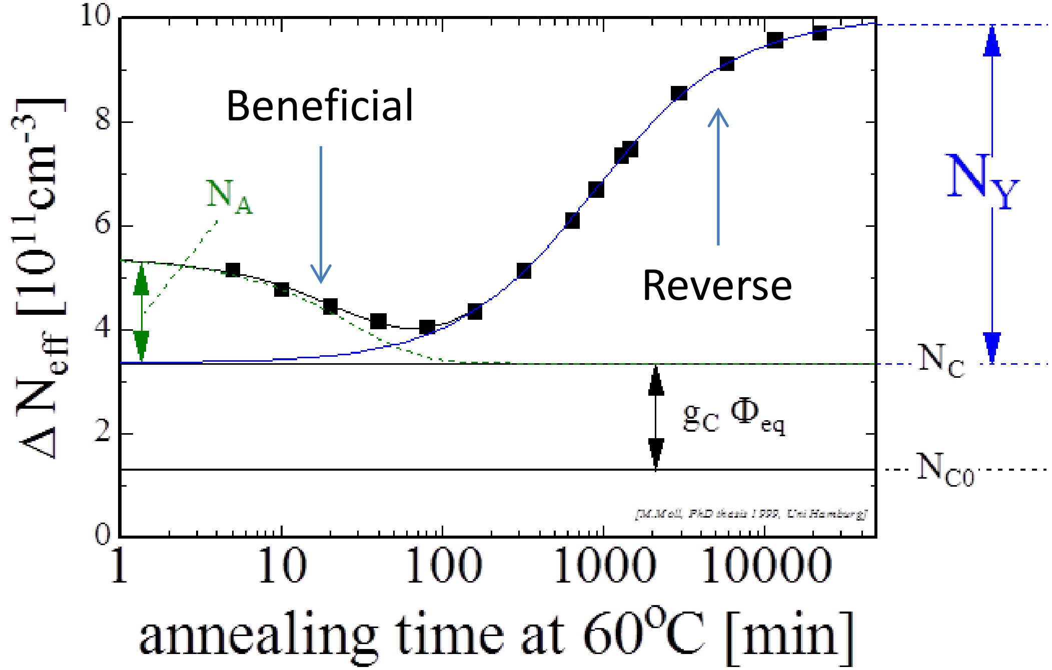
Before inversion, in p-in-n sensors, the junction is on the segmented side (the depletion starts from there).
After inversion the junction moves on the back side and the depletion starts from there.
p+ and n+ layers are unaffected by radiation because their doping concentrations are very high



Keep in mind that 'resonable' bias voltages should be less than 1000V (...and what IV means)

N_{eff} annealing

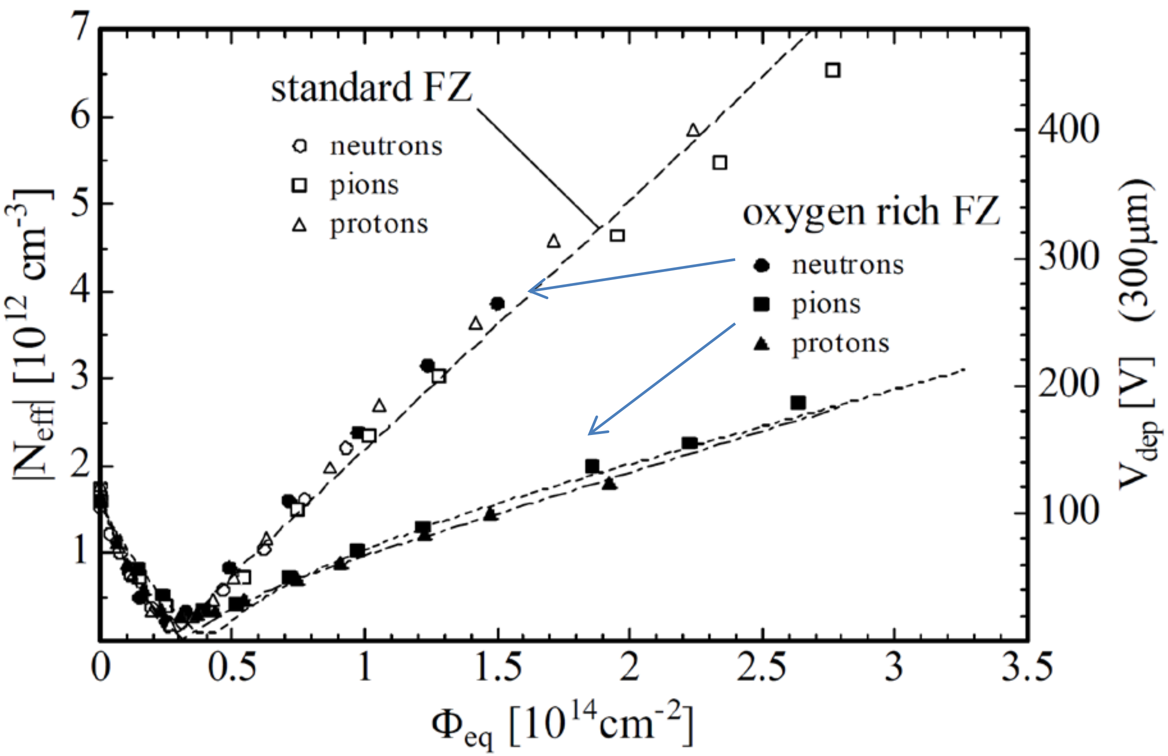
- After irradiation the lattice defects and interstitials start to interact eventually leading to a change in the N_{eff} with time and temperature → annealing



- Essentially two annealing are present:
  - Short term beneficial annealing
  - Long term reverse annealing
    - Time costant 500 years at -10 °C → 500 day at 20 °C → 21 hours at 60 °C
- Irradiated sensors should be keept cool all times

Oxigen enriched silicon

Introducing oxigen in the silicon bulk material a reduced sensitivity to the NIEL released by charged hadrons is obtained



<u>NIEL scaling violation</u>

RD48 Status Report CERN/LHCC 2000-009

Change of leakage current

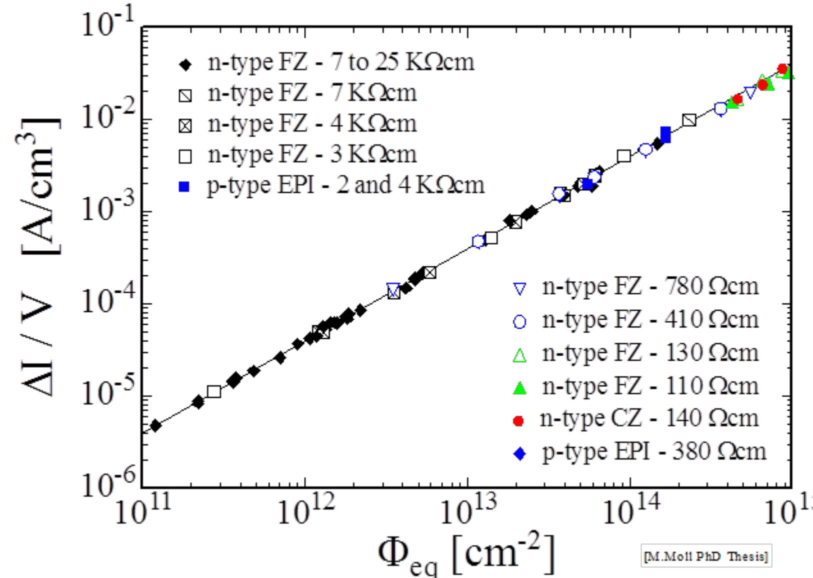
- The leakage current of a sensor, at constant temperature, increase with the NIEL
- The damage parameter doesn't depends on Silicon resistivity, bulk type, fabrication technology, ...

$$\boxed{\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}}$$

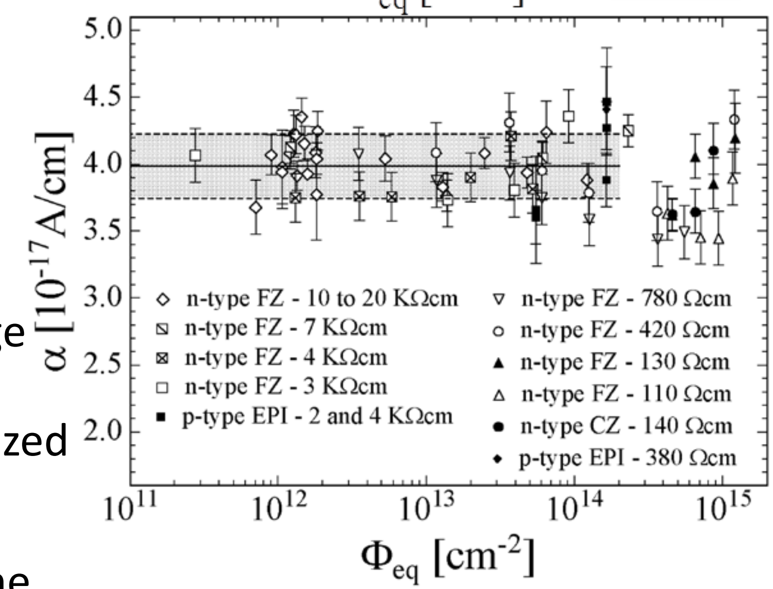
Current change

NIEL normalized Fluence

Detector depleted volume



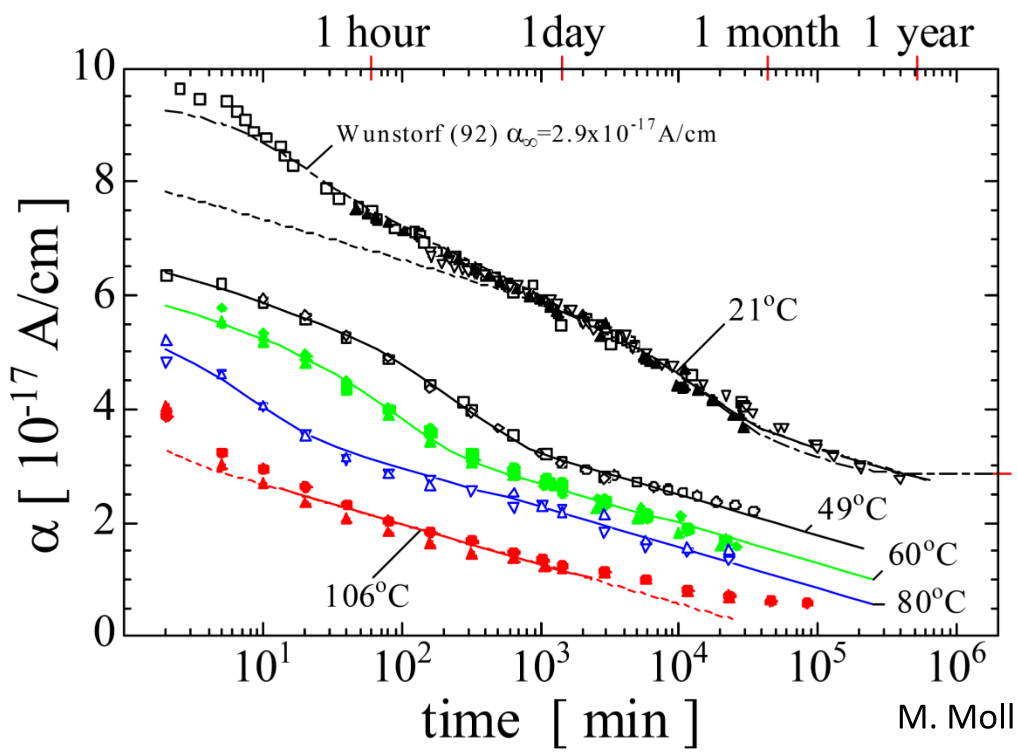
M. Moll



M. Moll

Leakage current annealing

- Also the leakage current is subject to an annealing process
- The measurement of α should be done after a well defined annealing process (temperature and duration)
- Std procedure 80 minutes at 60 °C



M. Moll

- The leakage current has a strong dependence on the sensor temperature: each 7 °C increase of a factor two →
- Irradiated detector should be operated at low temperature

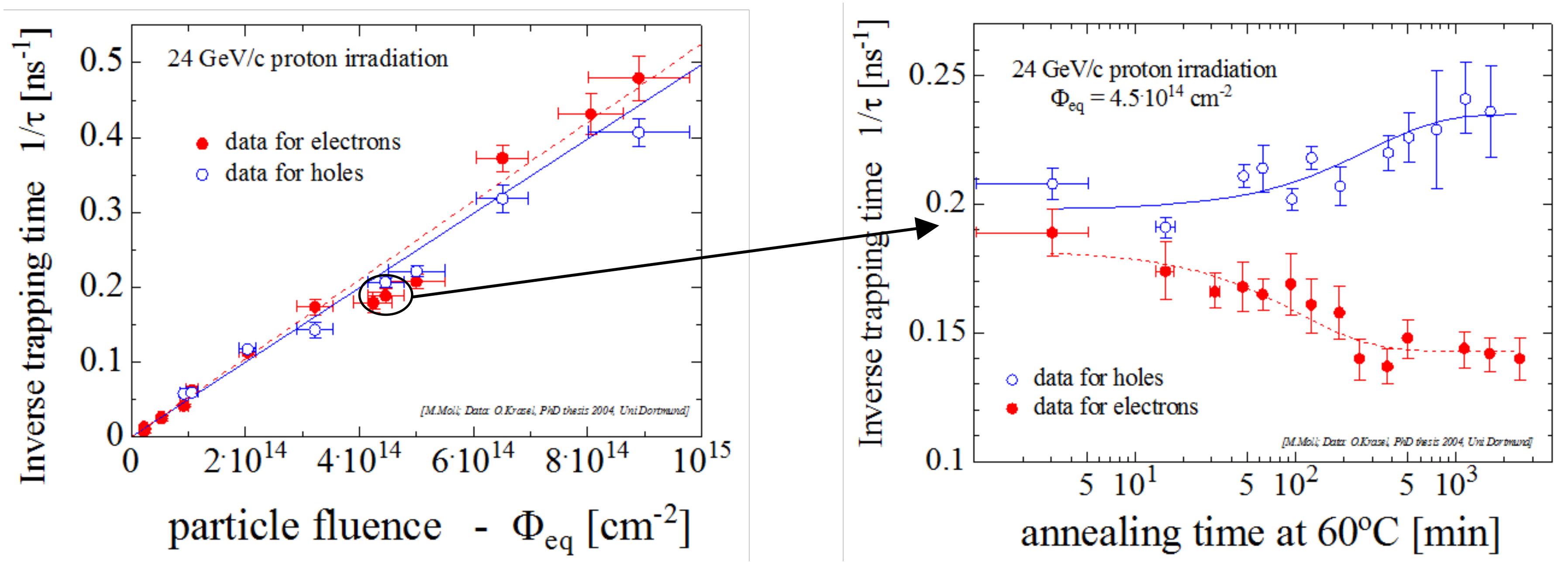
Change of charge collection efficiency

- The irradiation introduces defects which act as trapping center for the charge generated by an ionizing particle
- This reduce the overall signal thus affecting the detector efficiency

$$Q_{e,h}(t) = Q_{0_{e,h}} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t \right) \qquad \frac{1}{\tau_{eff\ ,e,h}} = \beta_{e,h}(T,t)\, \Phi_{eq}$$

- When the effective trapping time becames of the order of the electron/hole drift time (5-20ns) the charge integrated at the electrodes by the front-end electronics is reduced

Change of charge collection efficiency



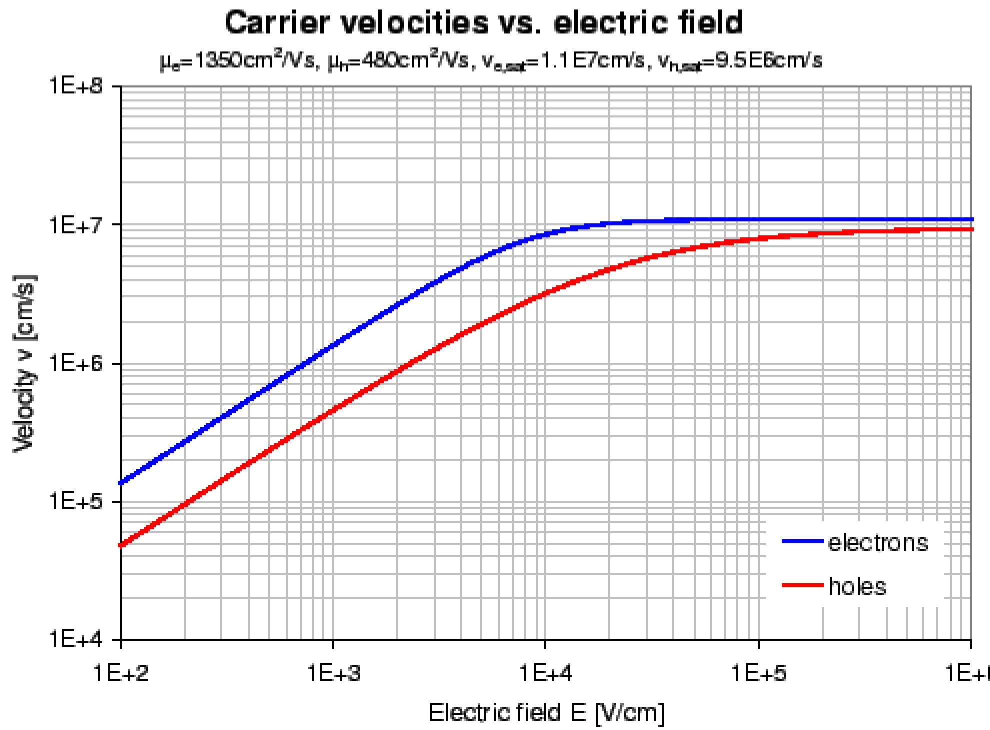
The trapping time too is subjet to an annealing process but with different behaviour for the two carries: the electrons get better, the holes get worse.

Radiation hard Silicon detector

- Approach on two sides
  - Microscopic: material engineering (Oxigenated Silicon, crystal grown: FZ-MCz-Epi)
  - Macroscopic: device engineering
    - p-type sensors
    - Thin sensors
    - 3D sensors

p-type detectors

- The electrons mobility in Silicon is higher (factor ~3) than the holes one
- The charge trapping times (see slide 47) are more or less the same (remember that annealing help electrons)

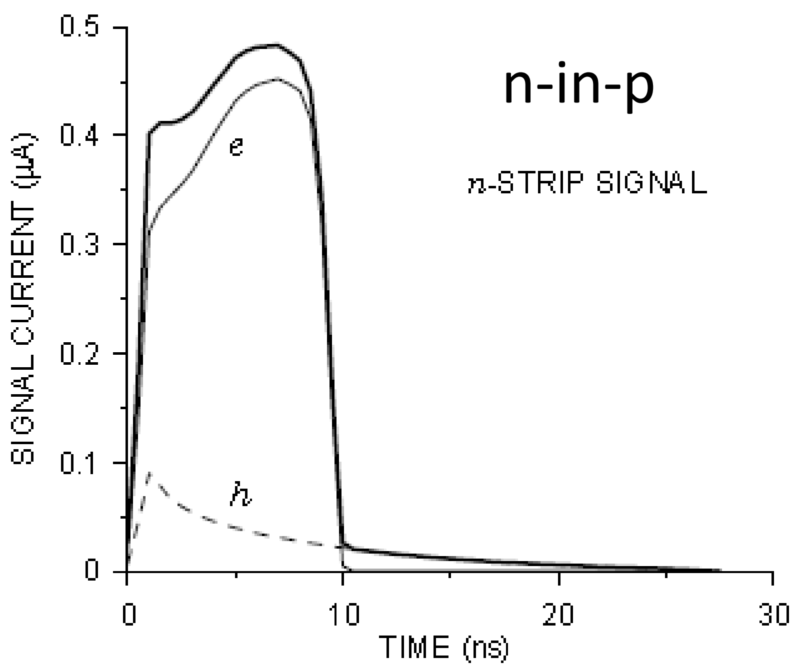


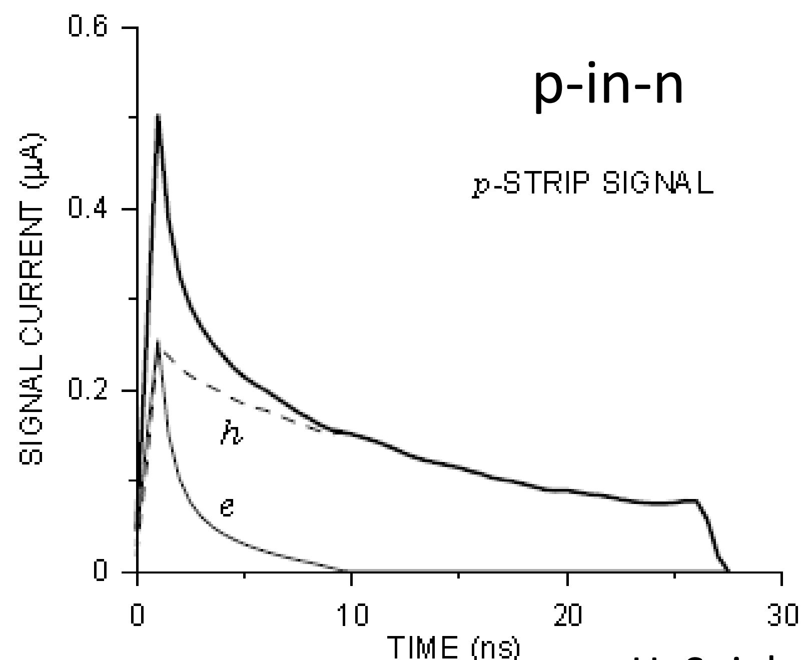
http://www.hephy.at/user/friedl/diss/html/node11.html

Using a detector configuration with a signal produced mainly by electrons should reduce the radiation induced trapping effects

Signal formation (i)

- The current pulse shape originating from a MIP orthogonally crossing the sensor its very different in n-in-p with respect to p-in-n devices

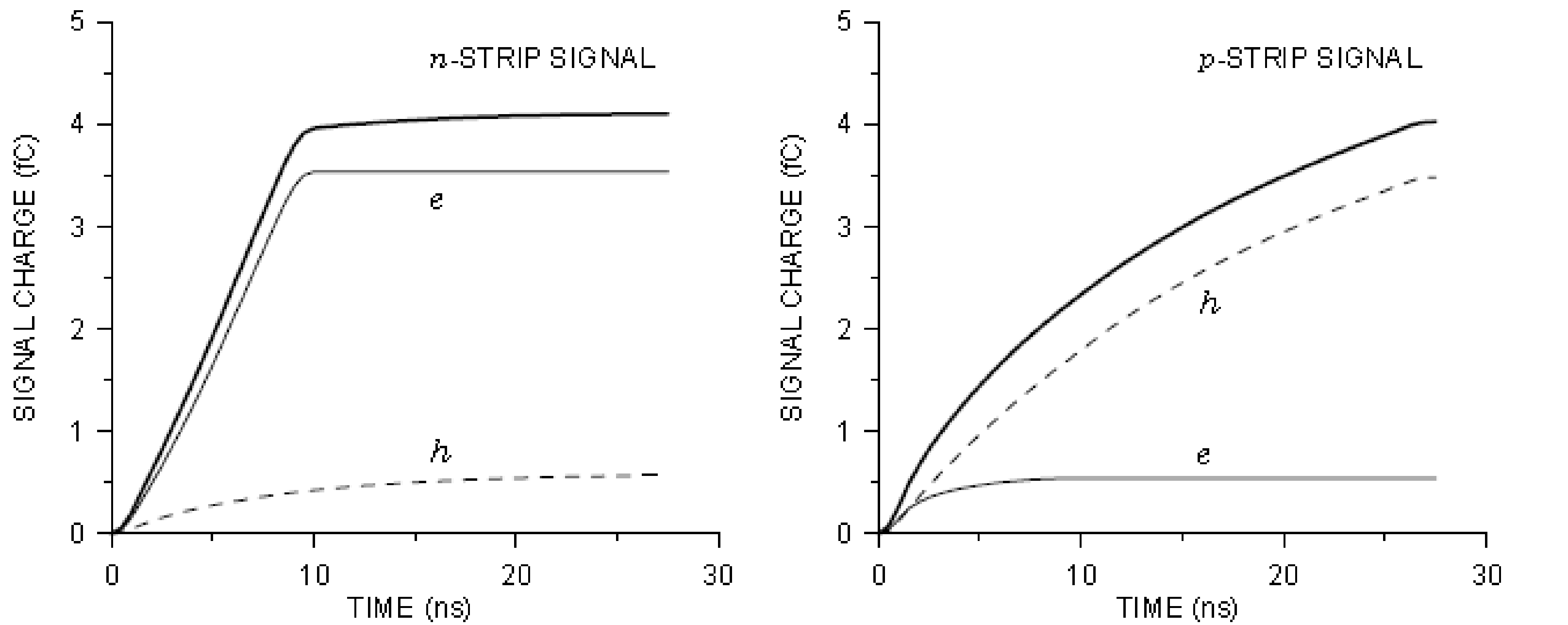




H. Spieler

Signal formation (ii)

- For p-in-n detectors the signal is mainly produced by the electron drifting to the strips
- For p-in-n detectors the majority of the signal is produced by the holes and it is much slower that the other

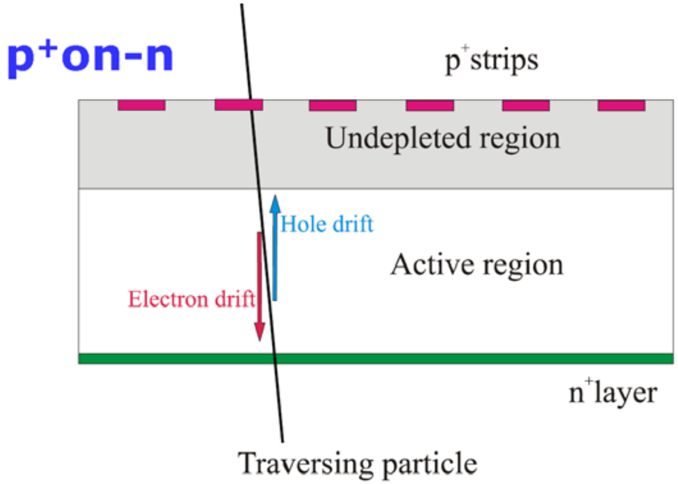


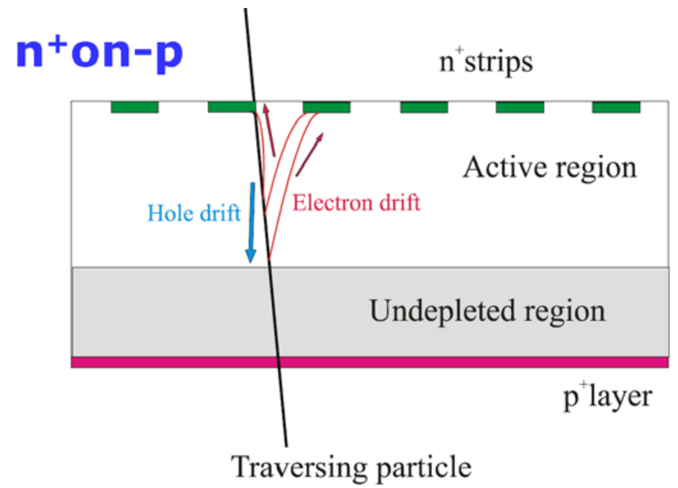
H. Spieler

Device engineering

- p-in-n detectors
  - After some value in fluence the bulk type is inverted

- n-in-p or n-in-n detectors
  - No inversion at all





p-on-n silicon, under-depleted:

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

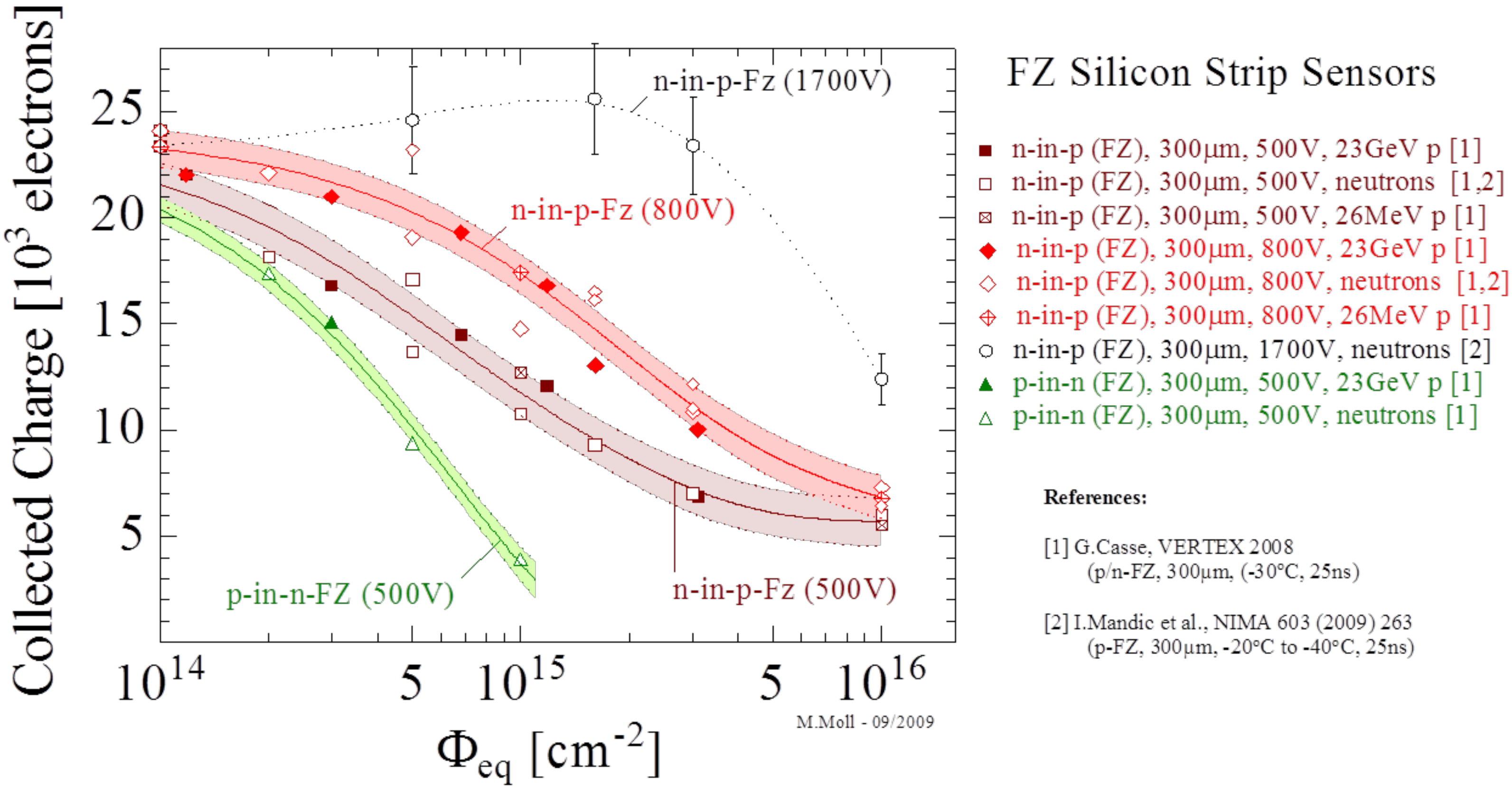
Be careful, this is a very schematic explanation, reality is more complex !

n-on-p silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **<u>Collect electrons</u> (fast)**

M. Moll

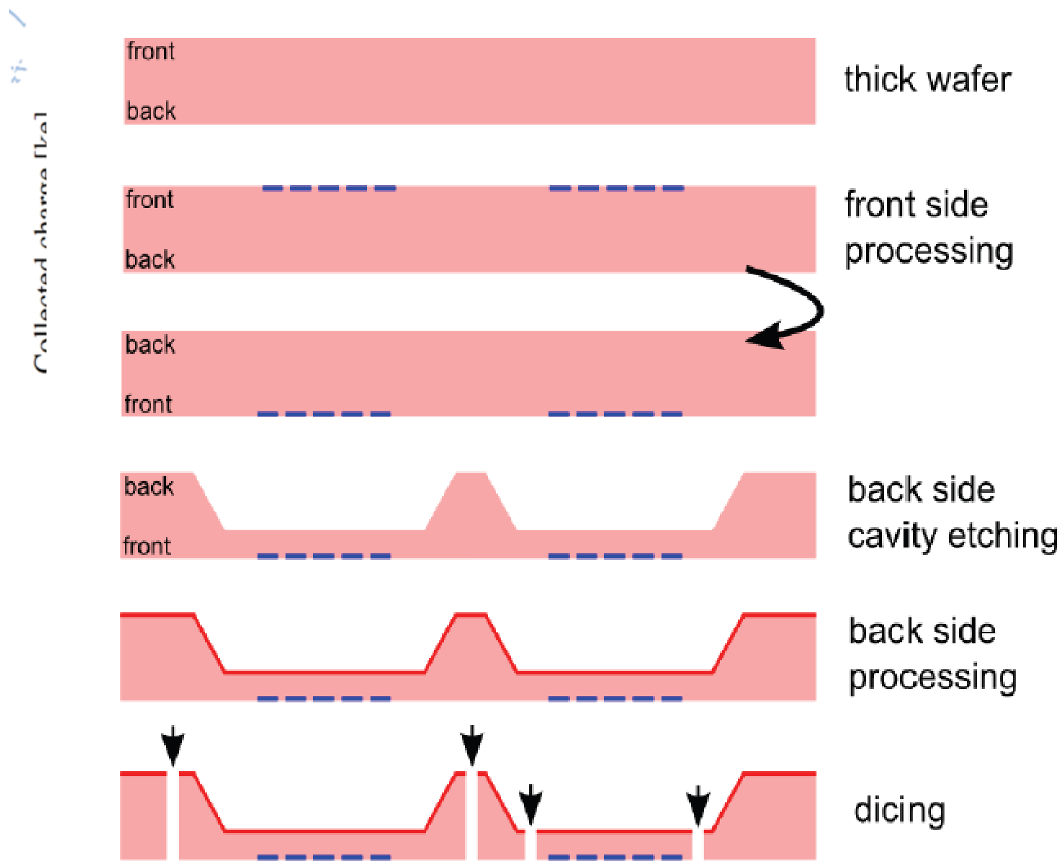
n side read-out behaviour

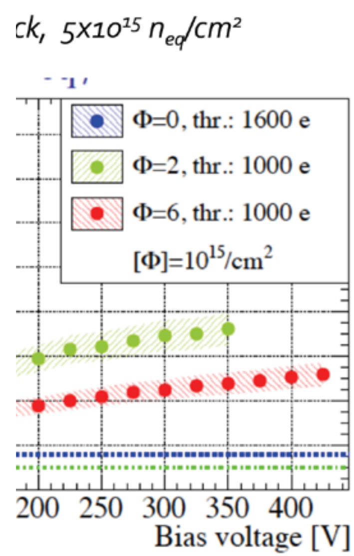


15000 e^- signal:
from $3*10^{14}$ 1MeV n_{eq}/cm^2 in p-in-n up to
$2*10^{15}$ 1MeV n_{eq}/cm^2 n-in-n

Thin sensors

- Very thin (100μm) n-in-p pixel sensors have been tested resulting in an almost full efficiency at $5*10^{15}n_{eq}/cm^2$



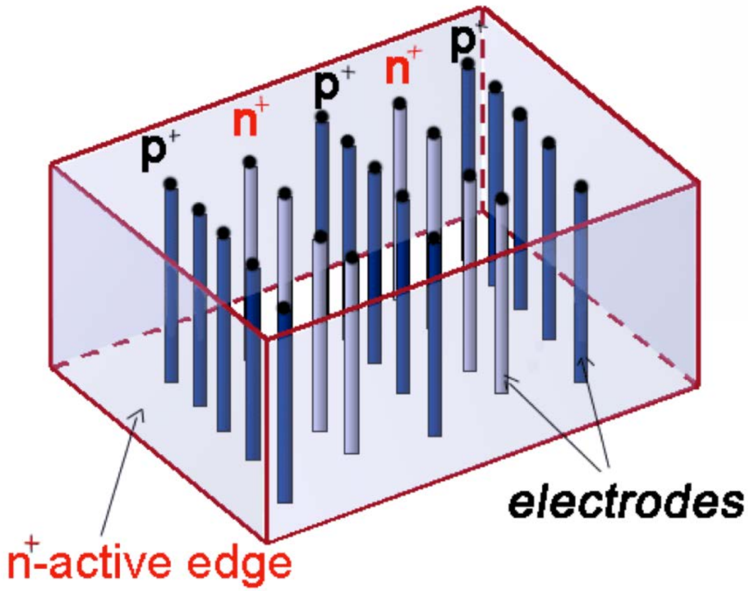


A. Macchiolo, Trento 2015

3D sensors

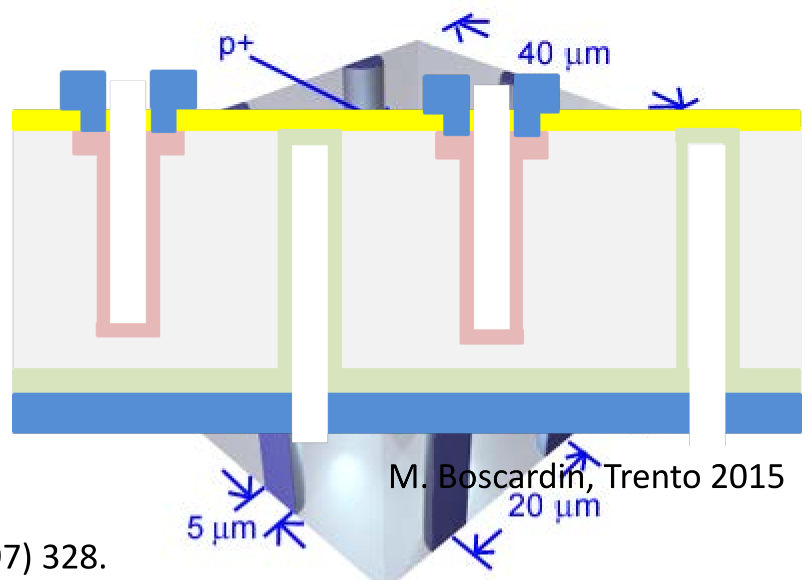
- So far planar technology applied to sensor:
  - J.A. Hoerni (Fairchild Semiconductors) 1957-58
  - Signal proportional to detector thickness
  - A planar detector is depleted starting from junction towards the opposite side (whole thickness)
- 3D technology:
  - Signal proportional to detector thickness
  - Depletion from column to columns (different type) with a distance decoupled from detector thickness
  - Example: 300μm thick sensor and (order of) 50μm columns pitch

3D sensors layout



Depletion voltages order of 10V or less even at high fluences
Fast charge collection when the read-out is connected to n+ colums

Some dead volumes inside the columns → not critical if the particle trajectories are not too collimated and orthogonal to the sensor (tilted detectors)
Some regions with low electric field, poor charge collection
High intercolumn capacitance, higher noise



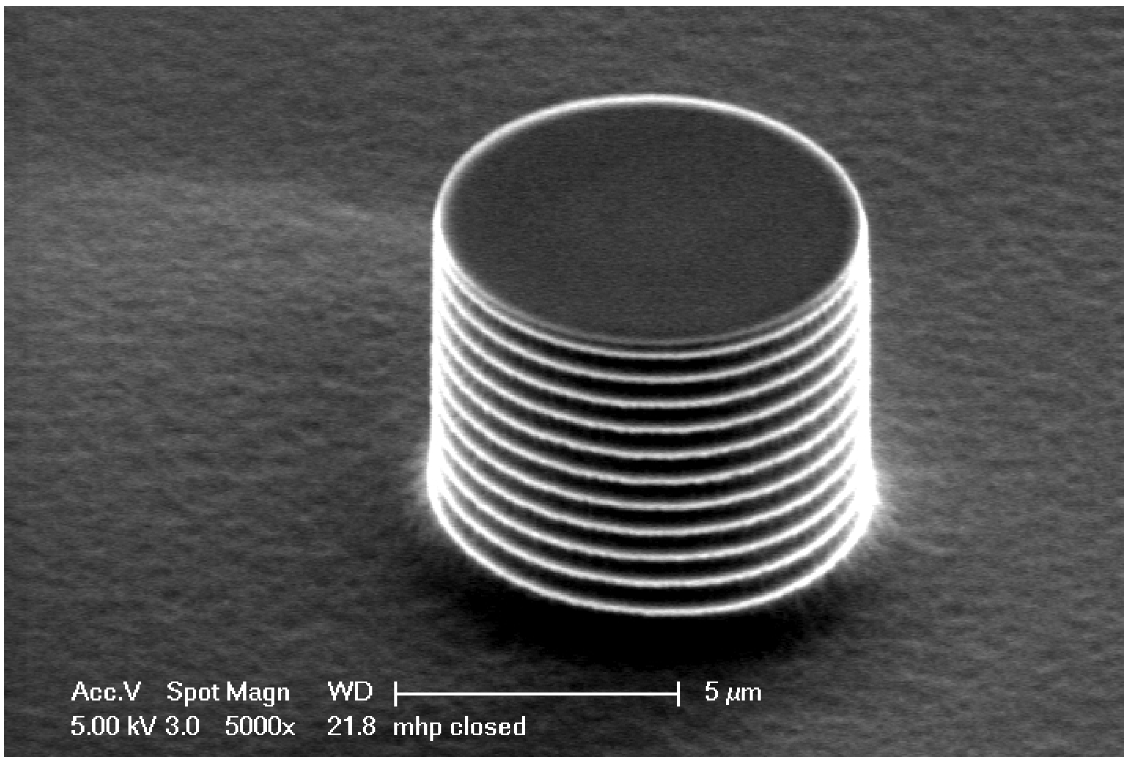
S.I. Parker, C.J. Kenny, J. Segal, Nucl. Instr. and Meth. A395 (1997) 328.

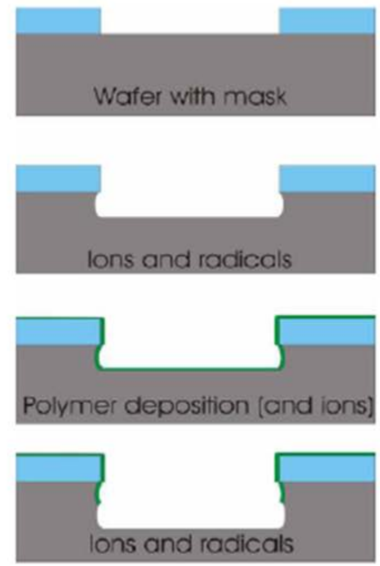
How to ‘drill’ a hole into Silicon?

M. Boscardin : “Rivelatori 3D & SiPM”

FONDAZIONE BRUNO KESSLER

Deep Reactive Ion Etching





"Bosch process PILLAR" by Pgalajda - Own work. Licensed under Public Domain via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Bosch_process_PILLAR.jpg#/media/File:Bosch_process_PILLAR.jpg

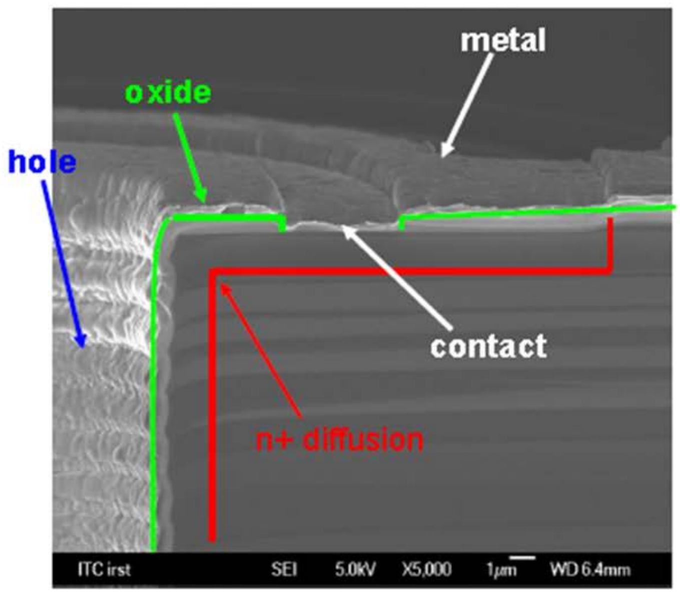
The 3D column structure

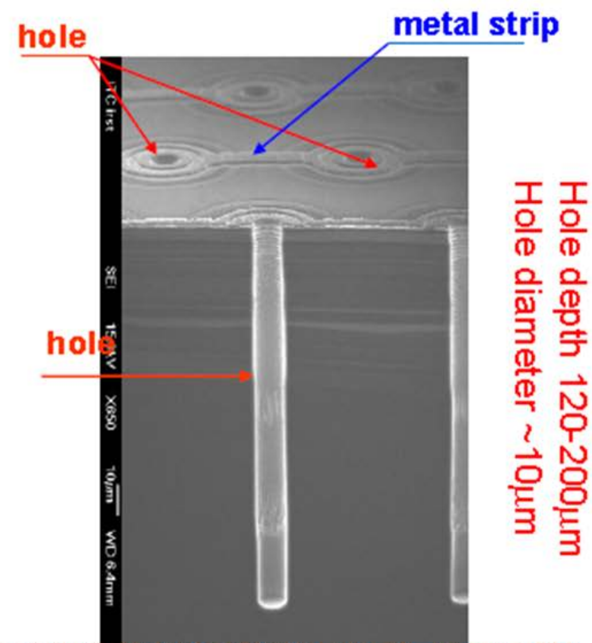
M. Boscardin : "Rivelatori 3D & SiPM"

FONDAZIONE BRUNO KESSLER

3D-STC detectors - FBK technology

- Hole etching with Deep-RIE technology
- Wide superficial n+ diffusion in which the contact is located
- Passivation of holes with oxide





- Si High Resistivity, p-type, <100>
- Surface isolation: p-stop *or* p-spray
- Holes are "empty"

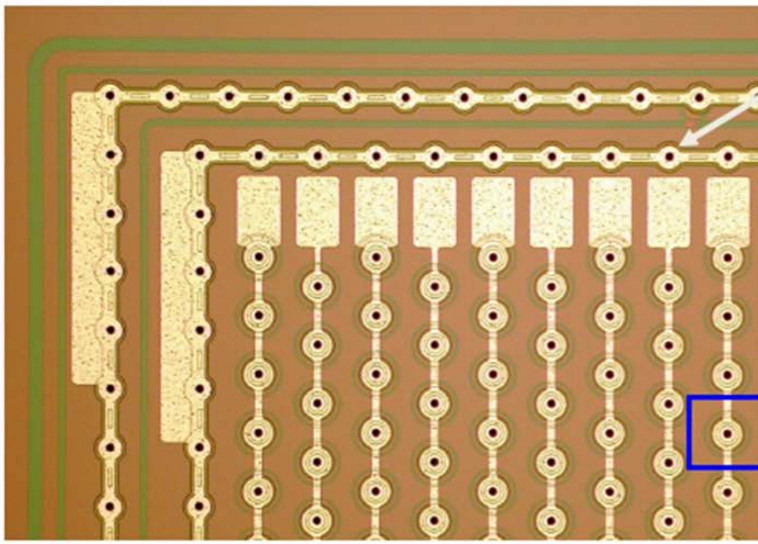
Scuola Nazionale "Rivelatori ed Elettronica per Fisica delle Alte Energie, Astrofisica ed Applicazioni Spaziali", INFN – LNL, 20 – 24 aprile 2009

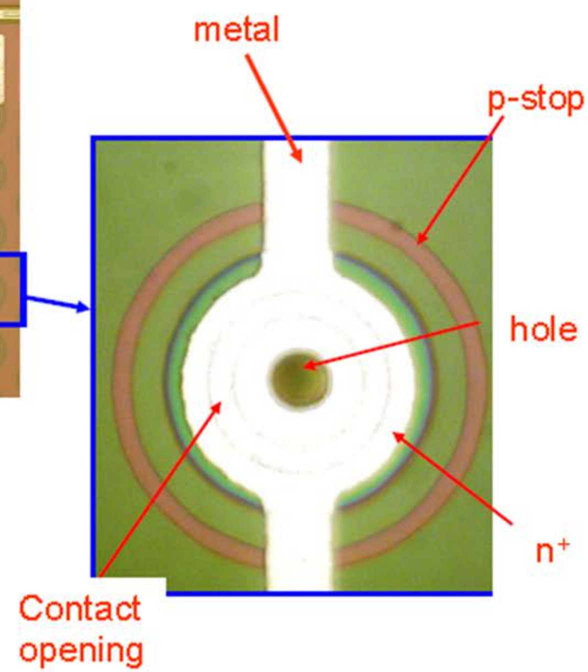
3D: from pixels to strips

M. Boscardin : "Rivelatori 3D & SiPM"

FONDAZIONE BRUNO KESSLER

3D-STC detectors - Strip detectors



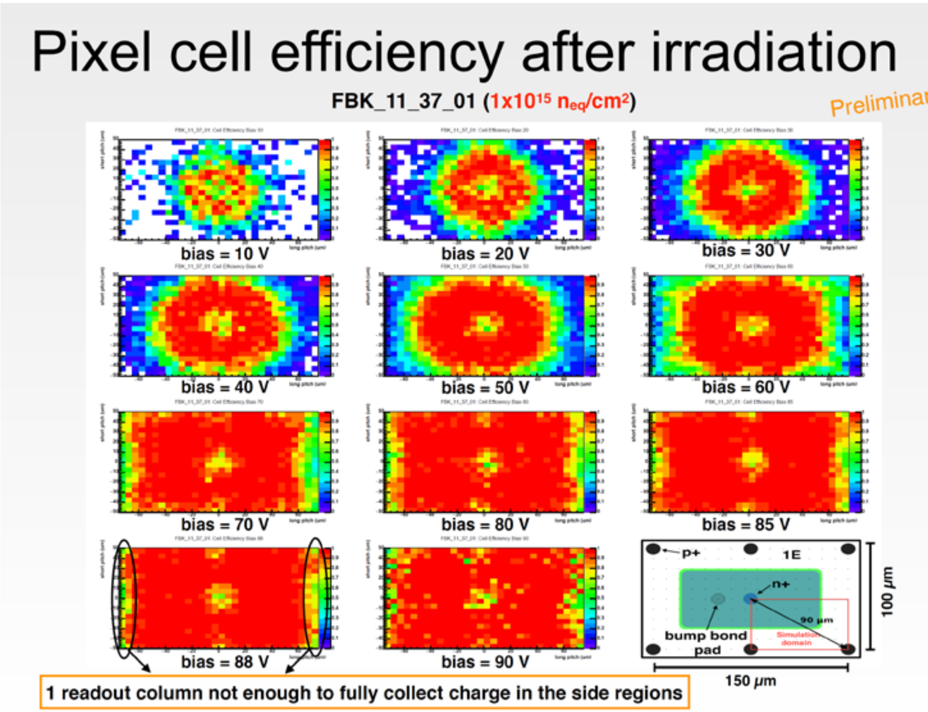


Different strip-detector layouts:

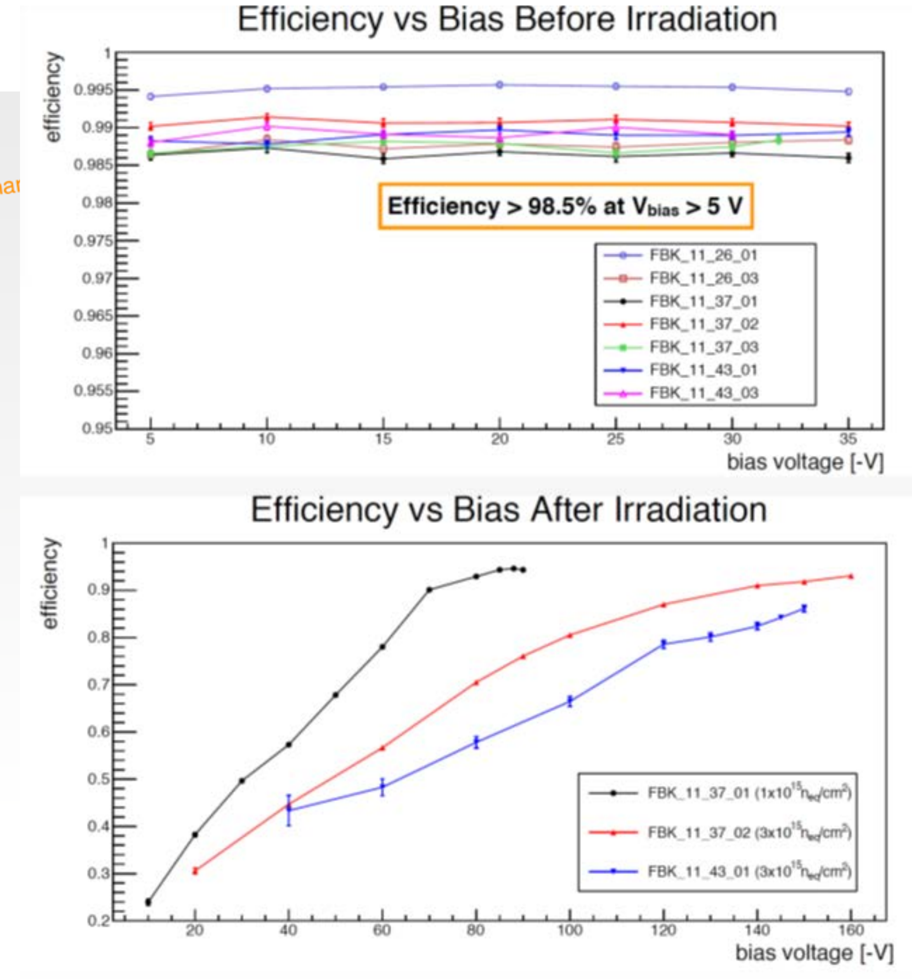
- Number of columns from 12000 to 15000
- Inter-columns pitch 80-100 μm
- Holes Ø 6 or 10 μm

Scuola Nazionale "Rivelatori ed Elettronica per Fisica delle Alte Energie, Astrofisica ed Applicazioni Spaziali", INFN – LNL, 20 – 24 aprile 2009

3D pixel efficiency and irradiation



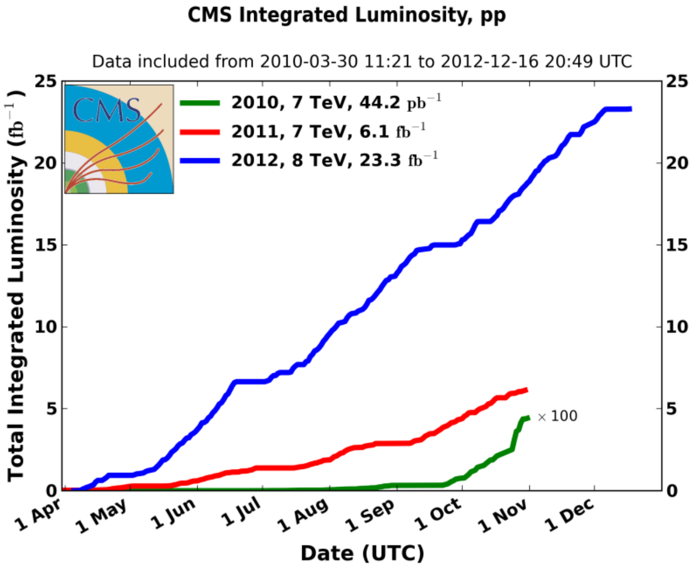
F. Ravera, Trento 2015

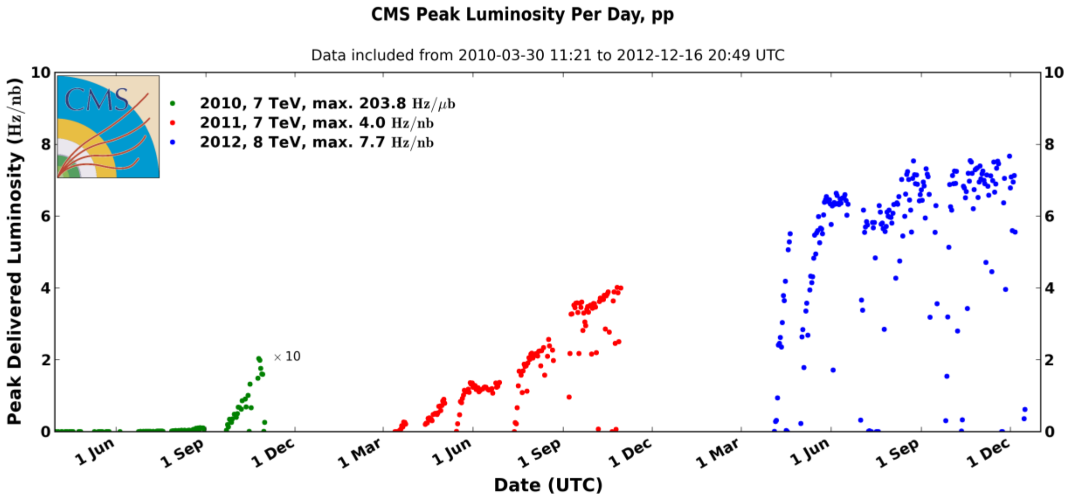


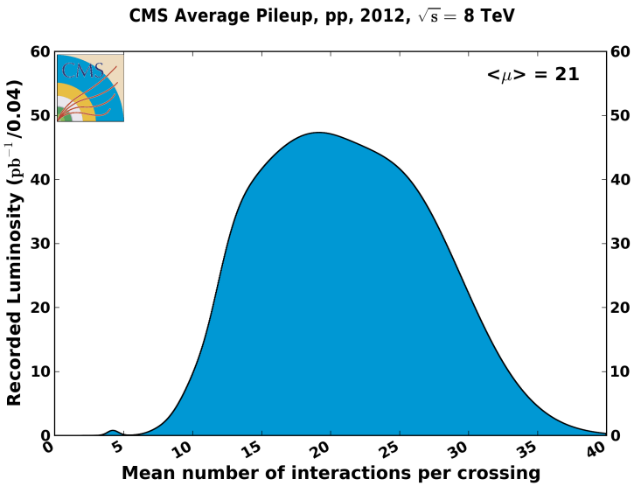
F. Ravera, Trento 2015

Radiation effects measured on LHC Silicon detectors

- A review of the status of the Silicon detectors, pixel and strips, installed in Atlas, CMS and LHCb experiments
- Mainly data from leakage current and depletion voltage measurements
- LHC Integrated luminosity near to 30 fb^{-1}

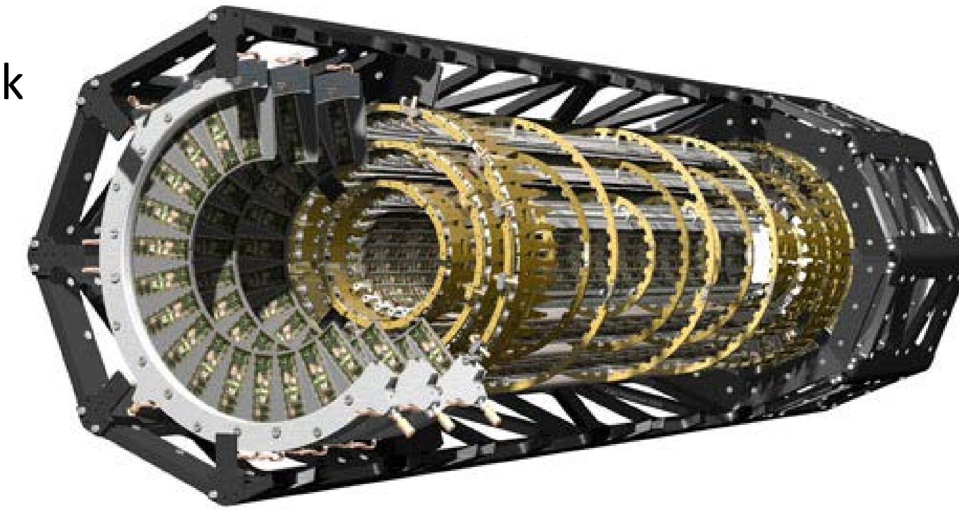


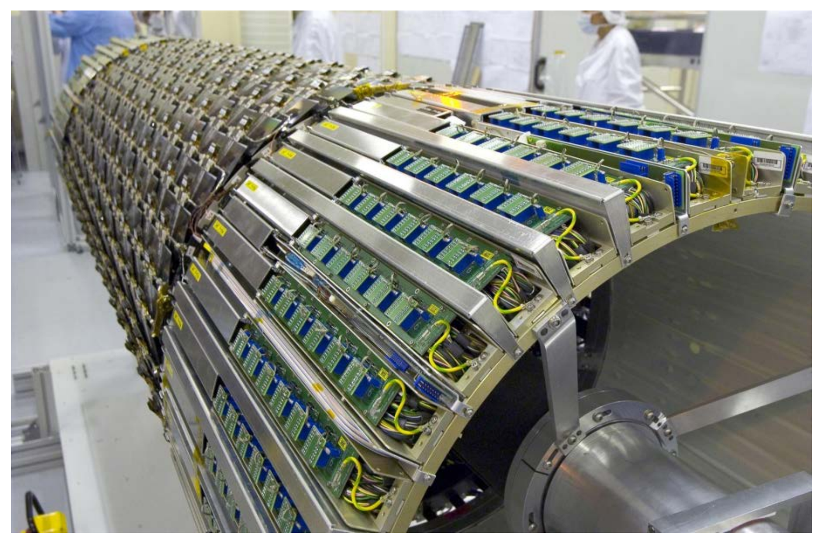




Atlas Pixel Detector

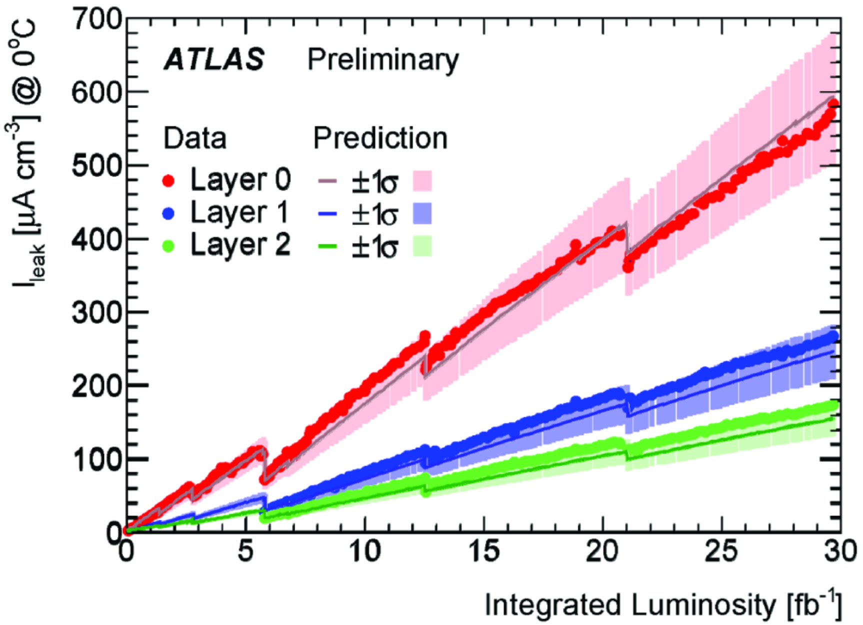
- 3 barrel layers and 3+3 endcap disk
- Coverage $|\eta|<2.5$
- Innermost barrel layer at r=5cm
- n+-in-n 250 μm thick, oxigenated Silicon material
- 1744 modules with $80*10^6$ pixels, for a total of 1.7 m^2
- 8 μm resolution r-ϕ
- 75-80μm resolution in z
- Evaporative C_3F_8 cooling (average temperature -13 ^oC)
- Additional layer (IBL) in 2015: mixed technology planar + 3D sensors

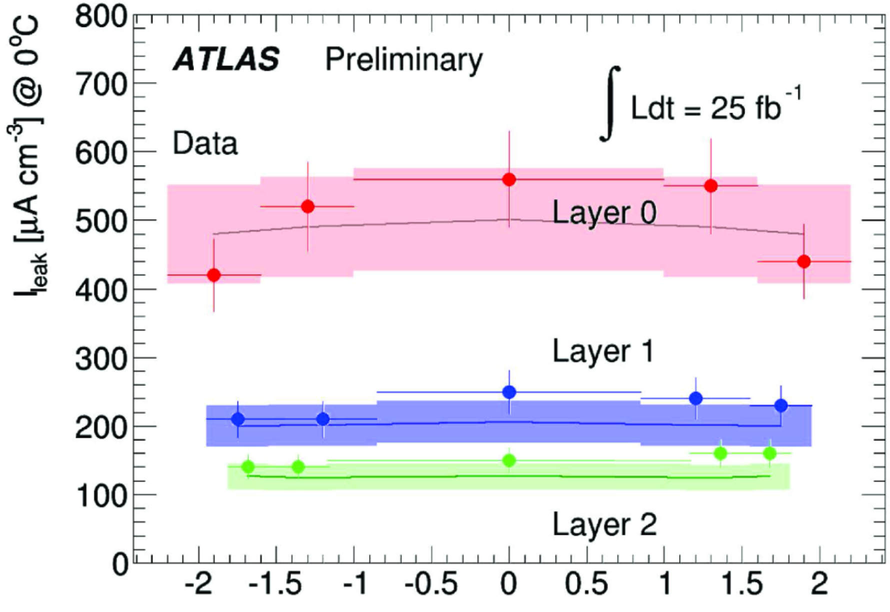




www.atlas.ch

Leakage current evolution



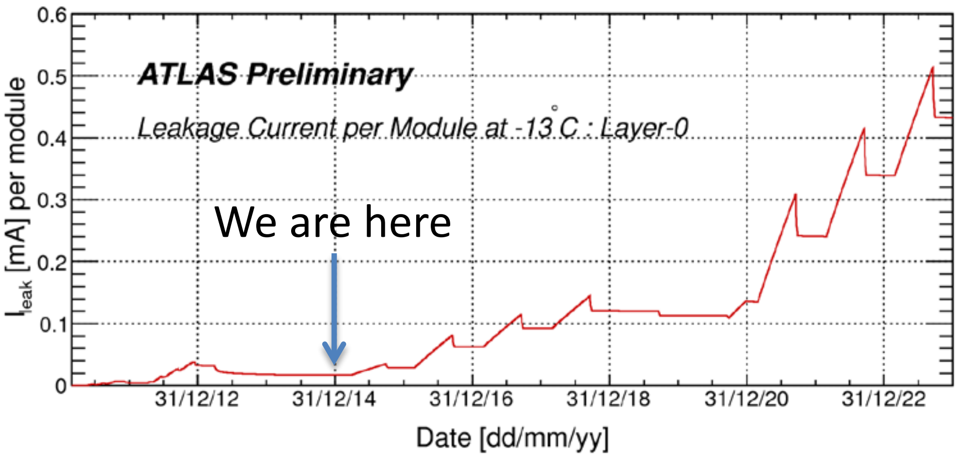


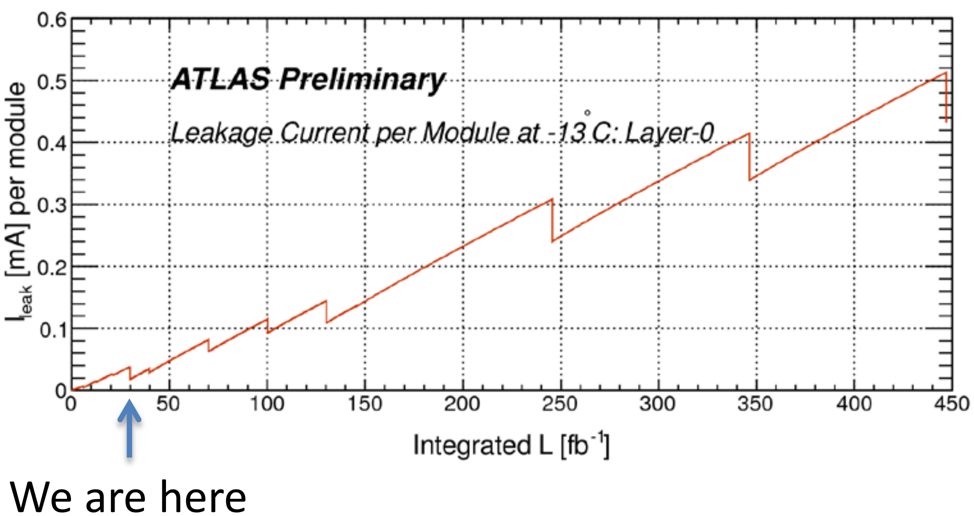
ATL-INDET-PUB-2014-004

- The Atlas pixel sensors have been kept at -13 ^{o}C during most of the time with some periods at room temperature (annealing is clearly visible)
- The measured leakage current is compatible with the predictions

10 years forecast on Leakage current

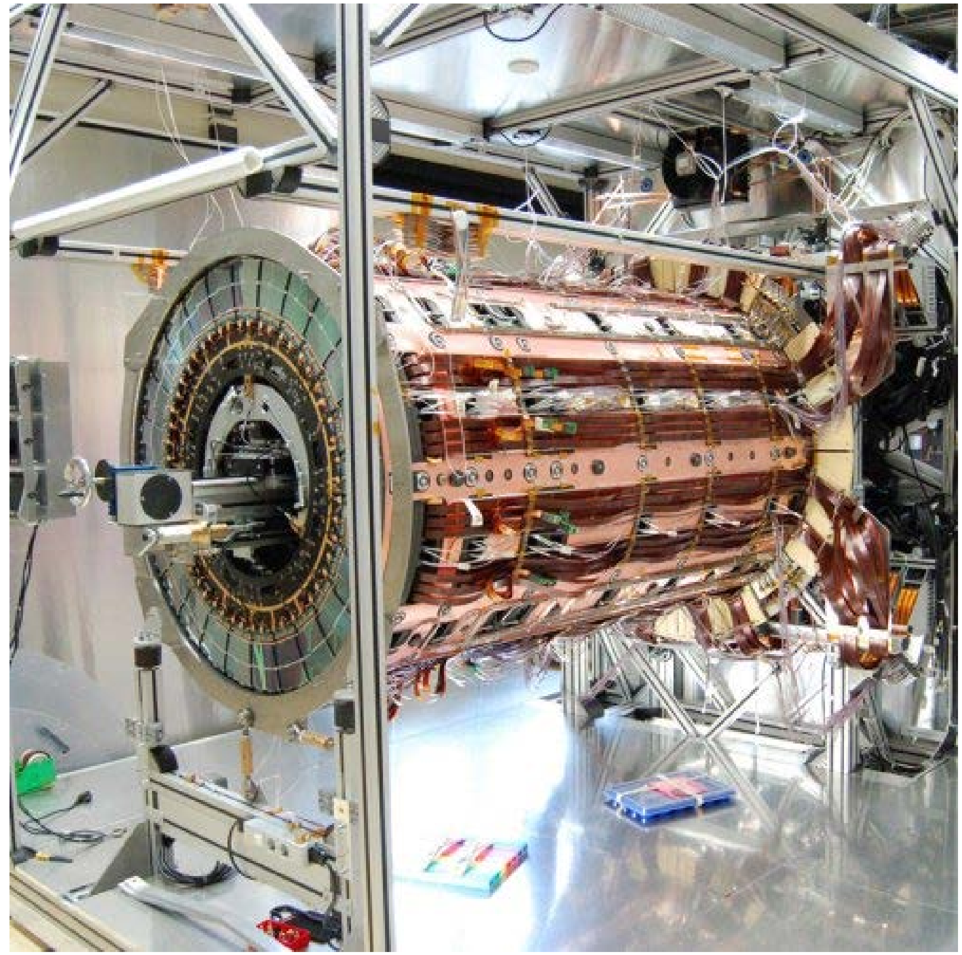
- The evolution of the leakage current with the following scenario: 10 days at 20 °C every year, otherwise -13 °C
- The temperature is of paramount importance
- Annealing is an important ingredient too



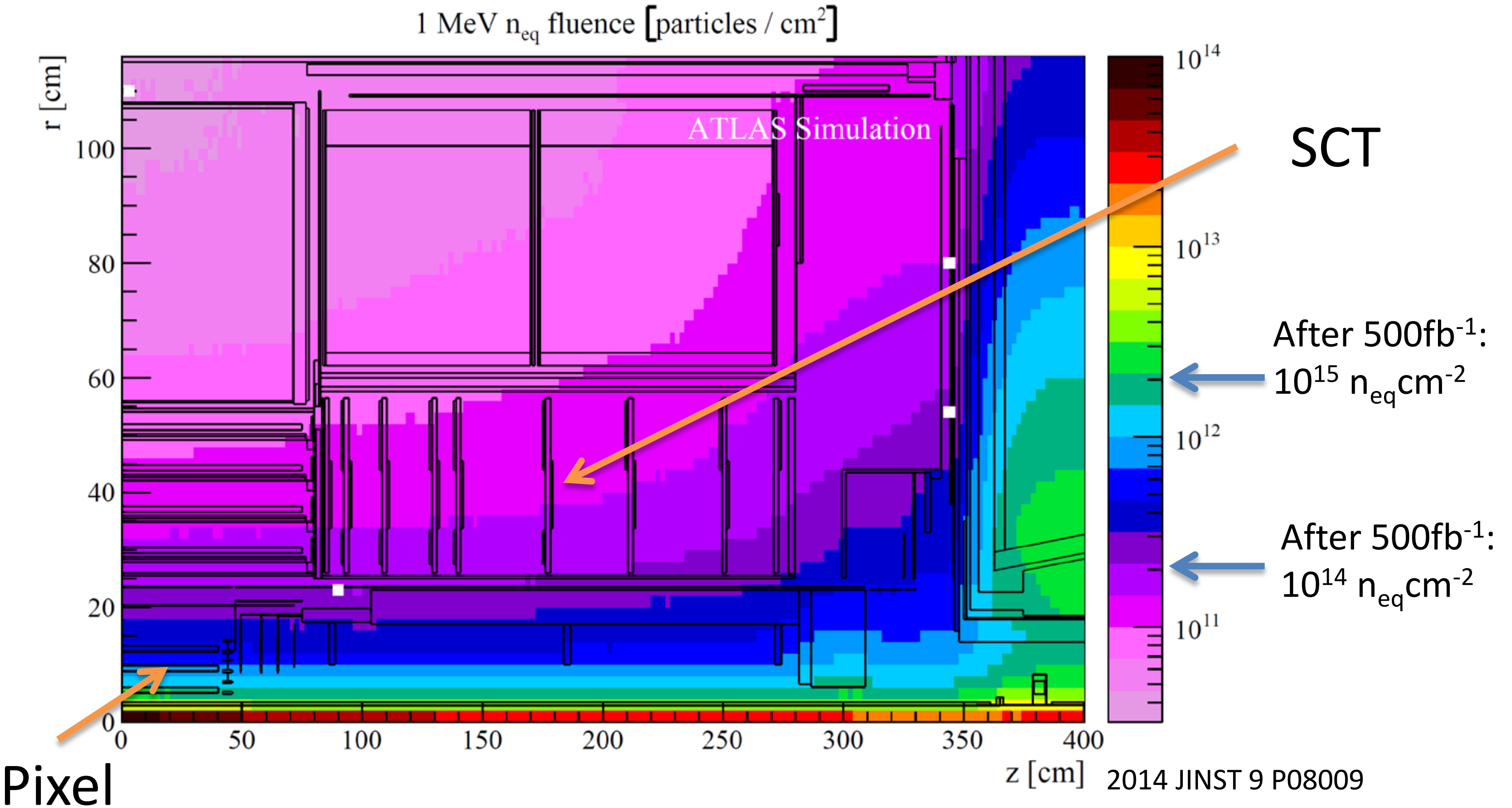


Atlas Semiconductor Tracker (SCT)

- 4 barrel layers and 9+9 endcap disks
- Coverage $|\eta|<2.5$
- 4088 p-on-n microstrip modules, 285μm thick
- $6.2*10^6$ channels, 61 m^2 of active area
- -7°C operating temperature



Atlas fluence estimation

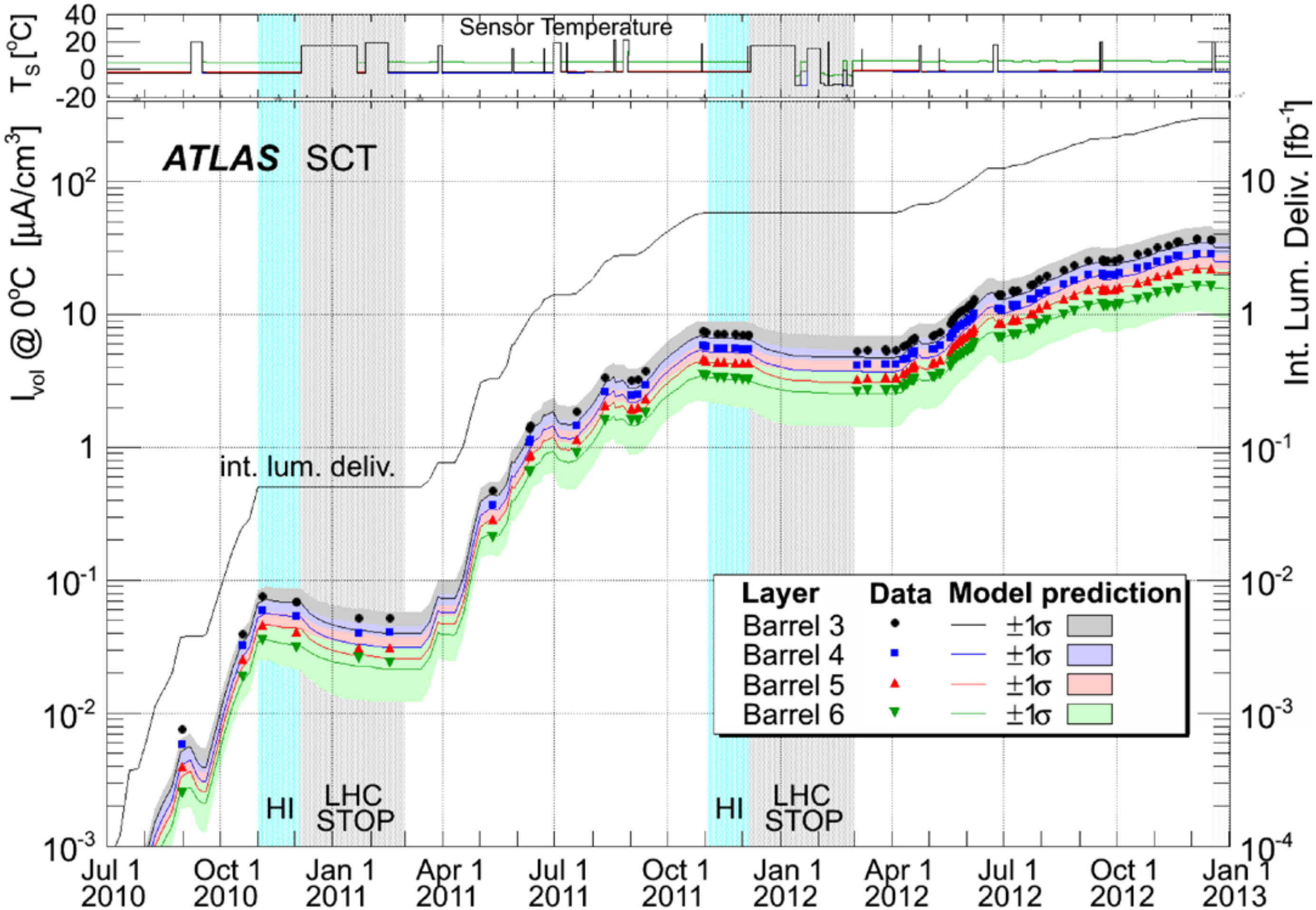


2014 JINST 9 P08009

- 1 MeV neutron equiv. /cm^2 for 1fb^{-1} of integrated luminosity

Atlas SCT: leakage current evolution

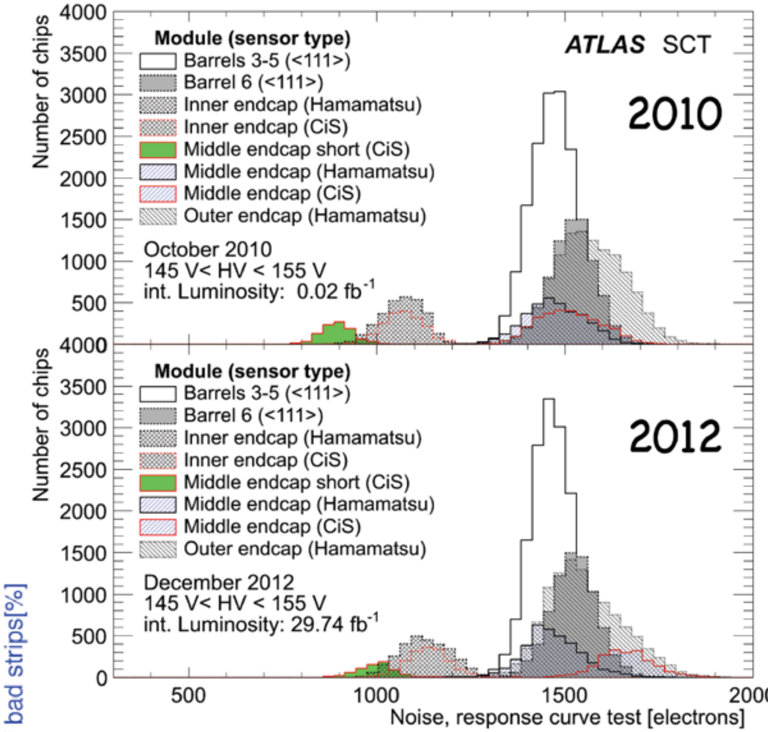
- Also in SCT the leakage current is in agremeent with the expectations
- Annealing during the LHC shutdowns and technical stop periods is visible

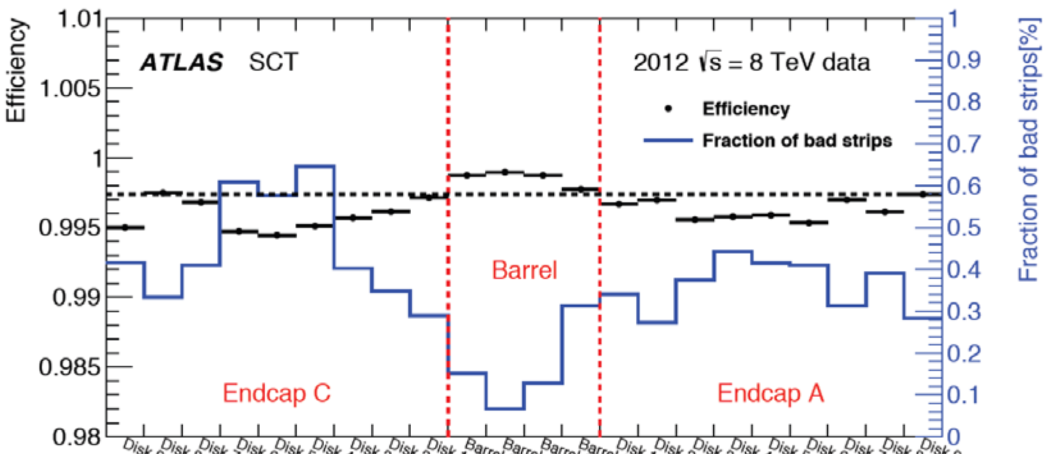


2014 JINST 9 P08009

SCT noise performance

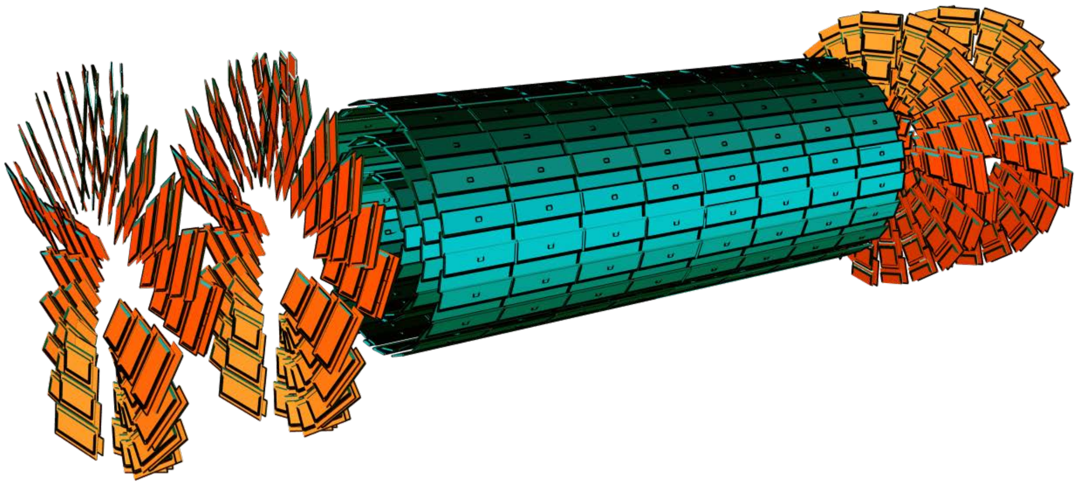
- The radiation effects are still very low: the noise is practically unaffected and the efficiency is close to full

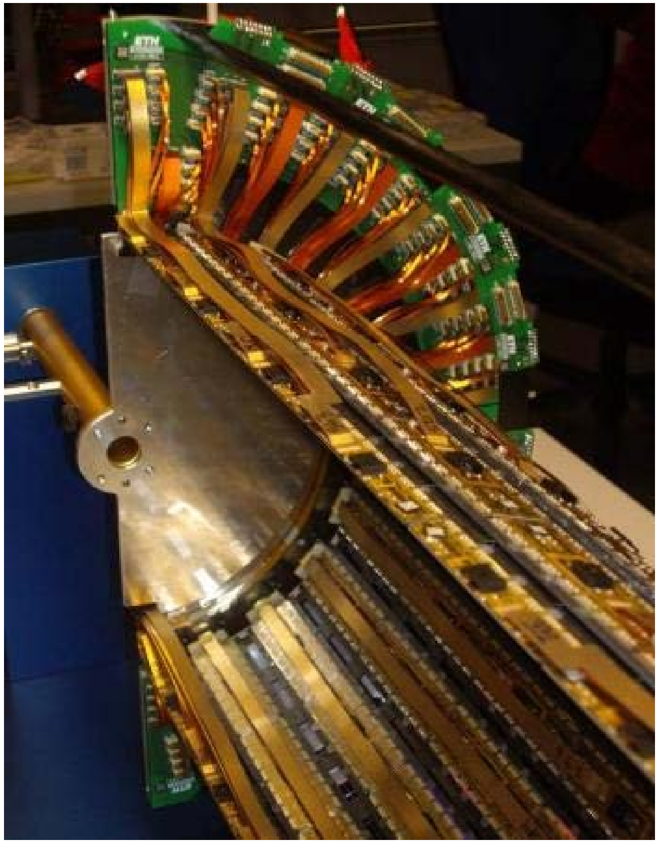




Koichi Nagai, Vertex 2014

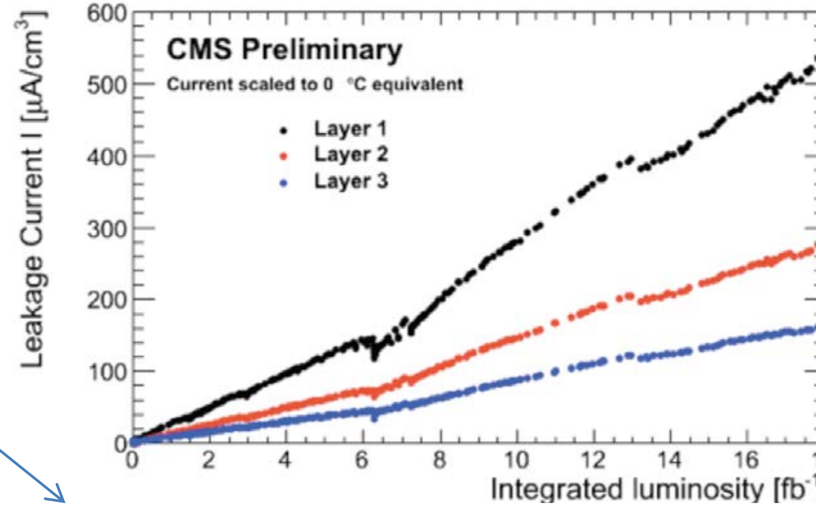
CMS Pixel detector





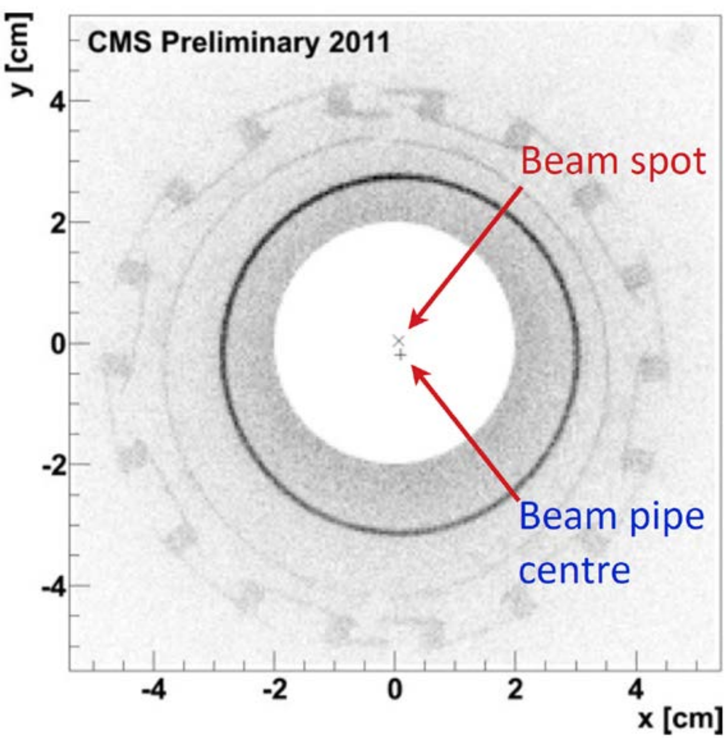
- 3 barrel layers and 2+2 endcap disks
- Coverage $|\eta|<2.5$
- Barrel layers at r = 4.3, 7.2, 11 cm
- n+-on-n
- 10 μm resolution r-ϕ
- 100x150μm^2 pixel size

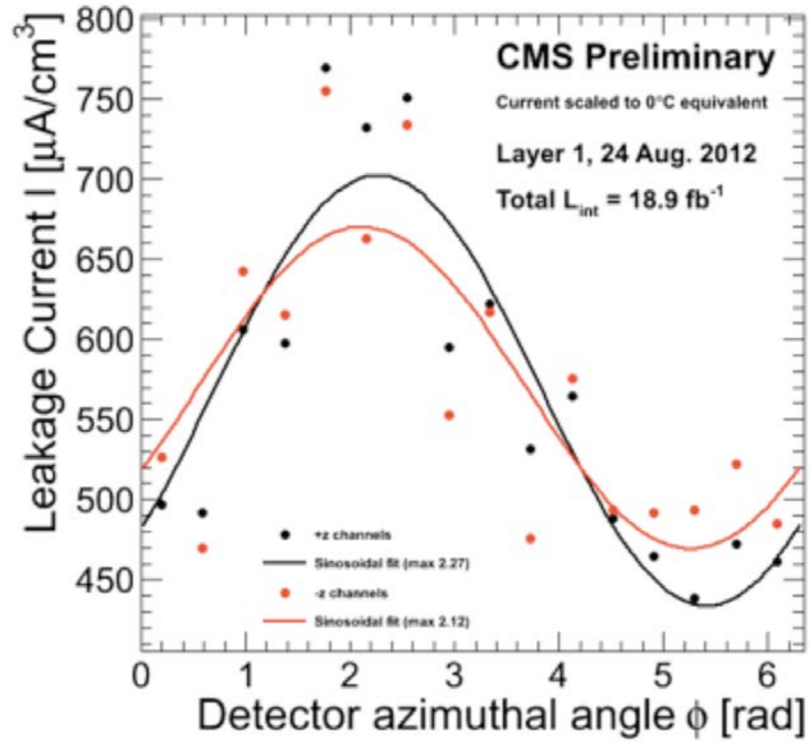
Total leakage current vs luminosity



Leakage current vs ϕ (off-center detector position)

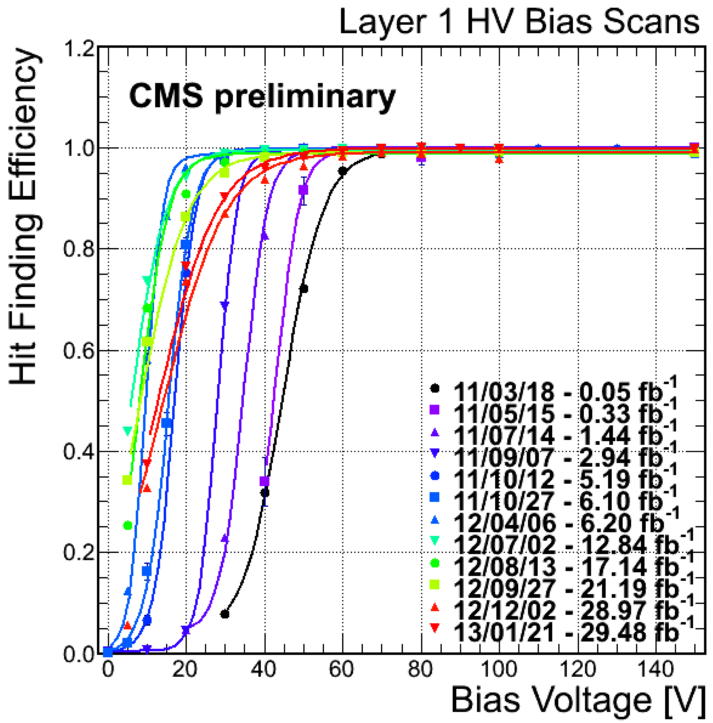
CMS pixel position s seen from nuclear interaction vertices



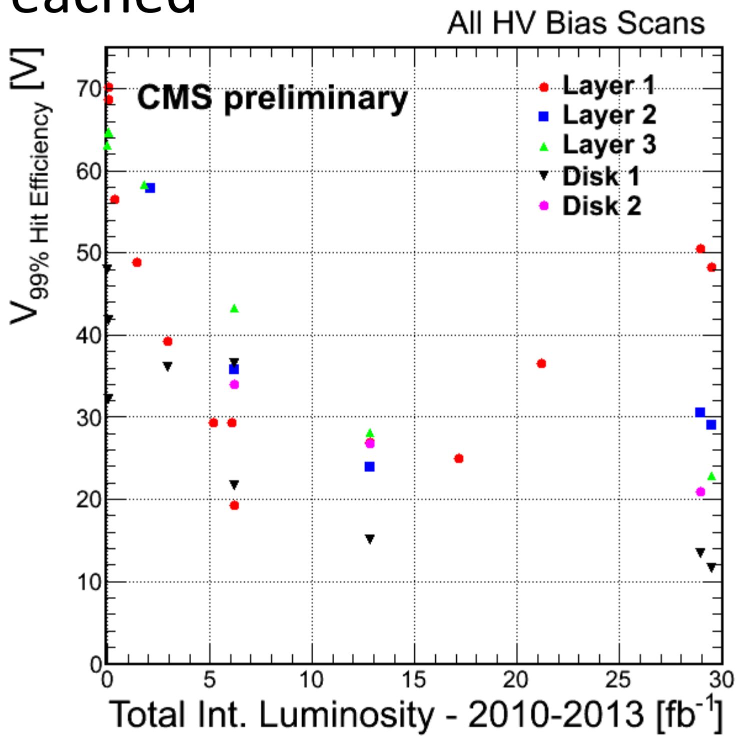


CMS Pixels: Depletion voltage evolution

- Method: measure the Voltage at which the Hit Finding Efficiency is 99% of the plateau value

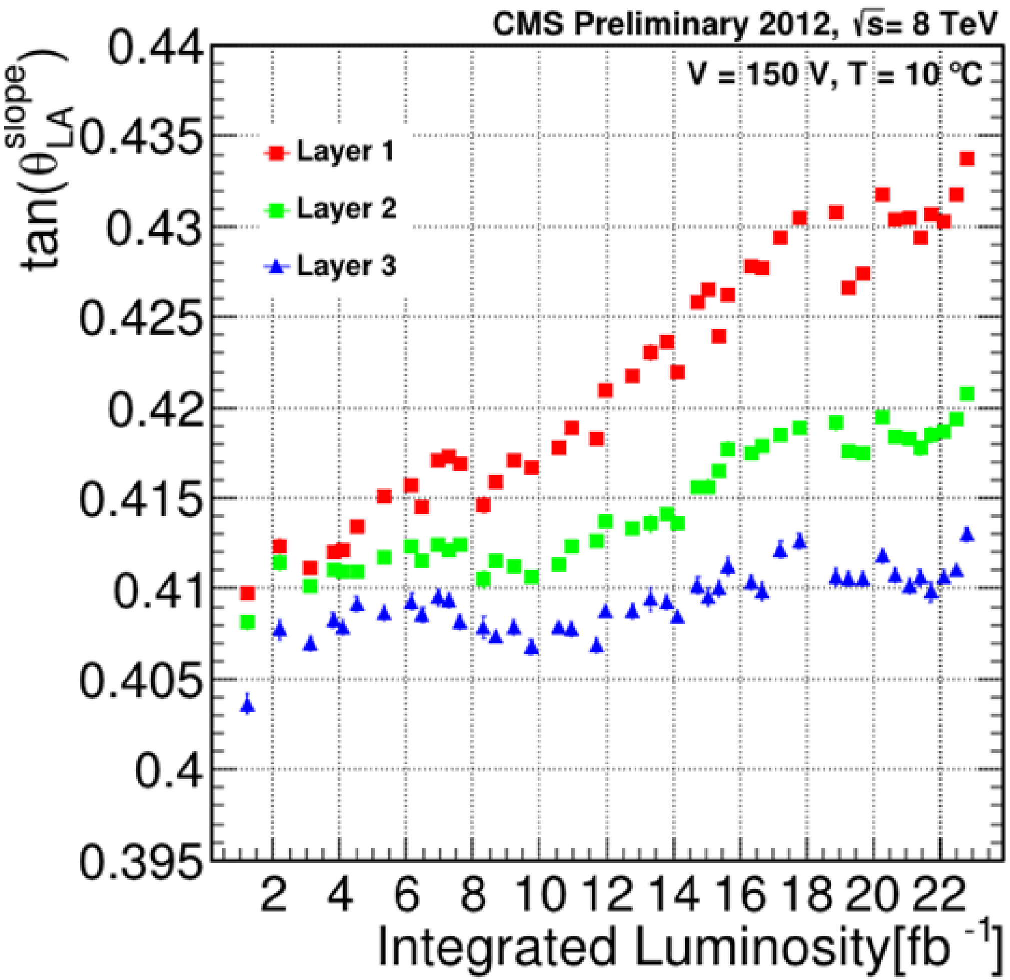


- Plot it as function of the integrated luminosity
- At least for layer 1 the type inversion point has been reached



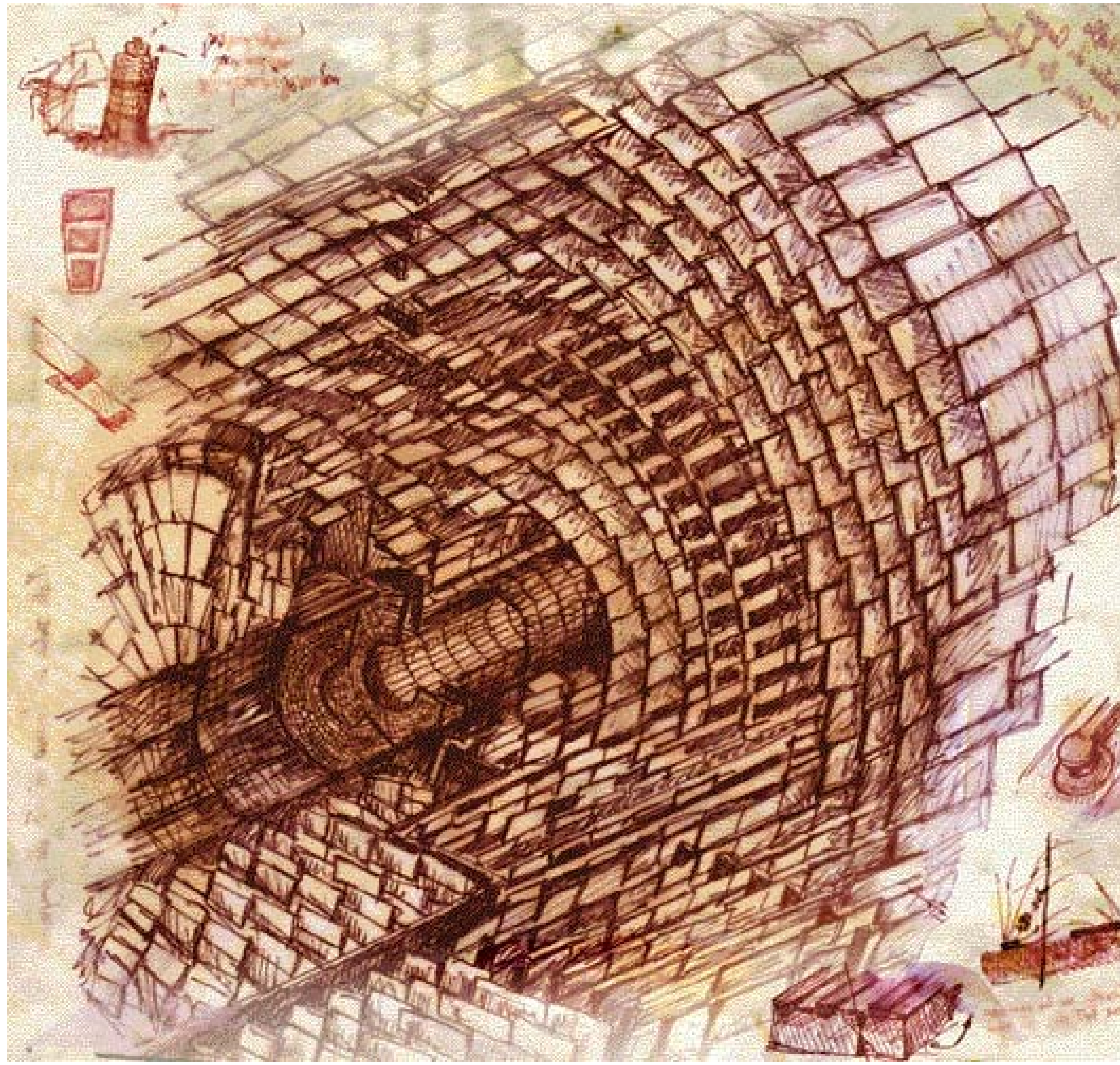
Lorentz angle vs fluence

- The Lorentz angle depends on the fluence
- Should be constatly monitored beacause it has an influence on the local hit position recontraction



CMS strip tracker

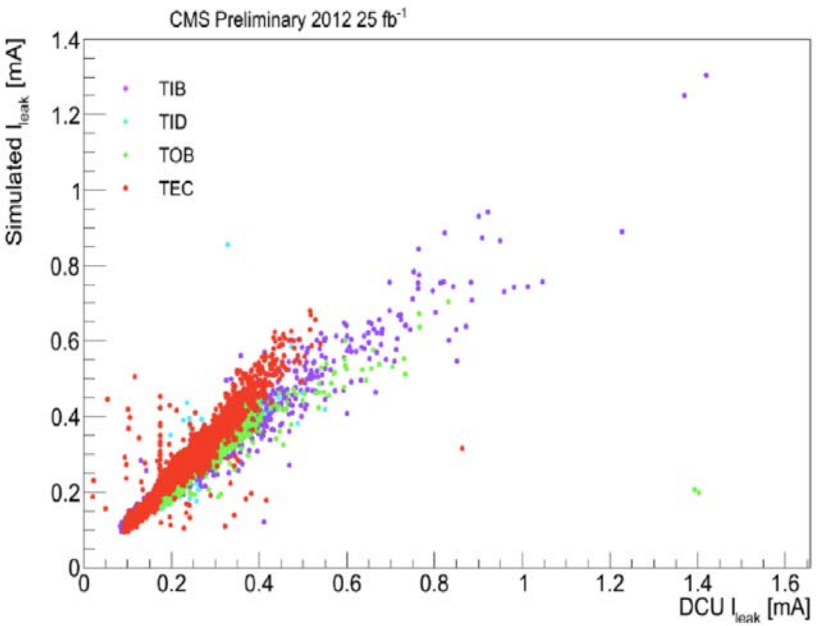
- 4+6 barrel layers
- 3+9 endcap disks
- 200 m^2 of silicon
- p-on-n sensors
- 15148 modules, 320-500μm thick
- 9.6*10^6 channels



S.Cittolin

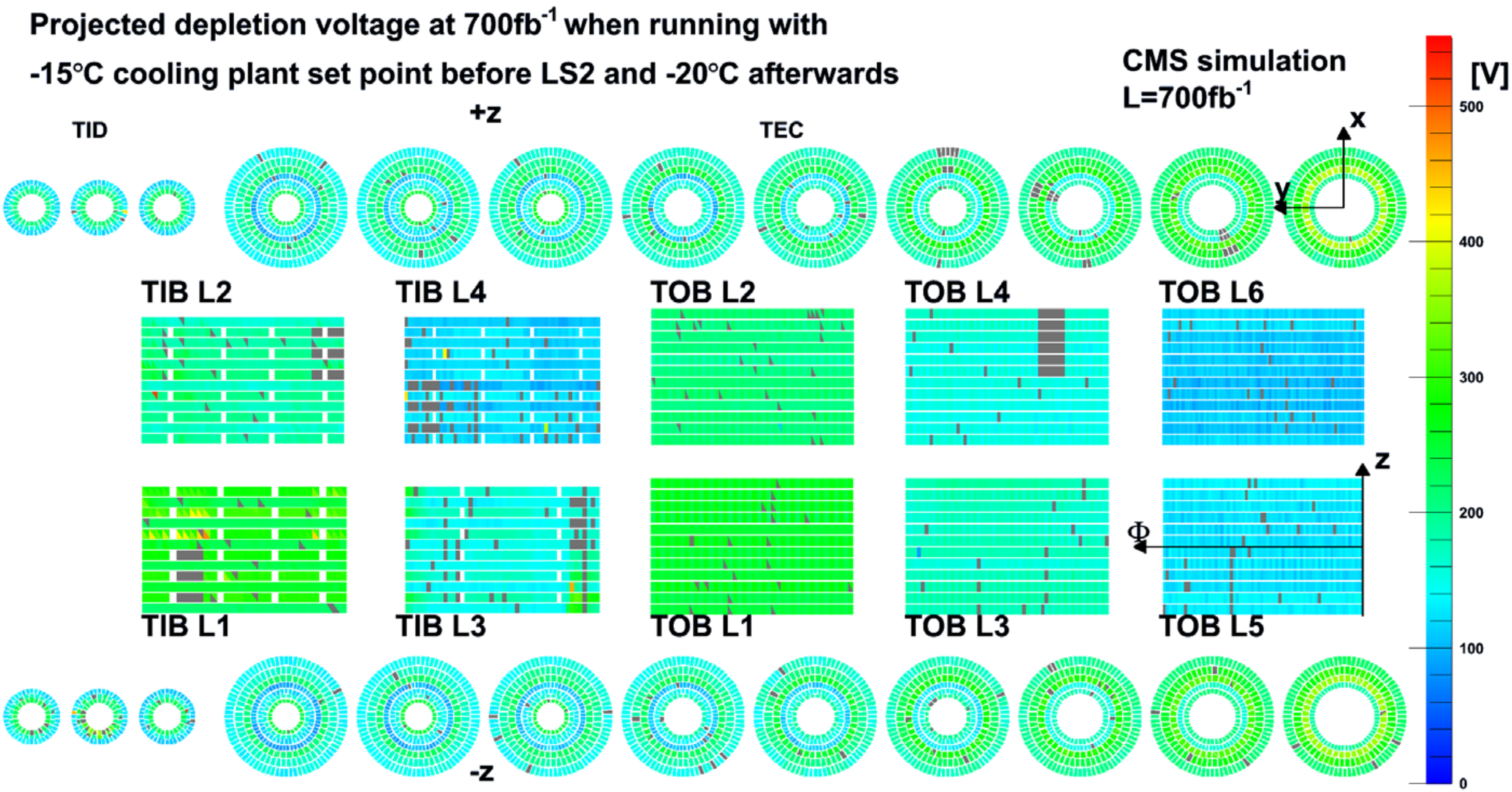
CMS strip leakage current

- The detector has been operated at +4 ^{o}C (dew point in tracker quite high)
- In some cases already 30% of the HV power supply limit (12mA)
- After an intervention to seal the tracking volume now -20^{o}C could be reached (-15^{o}C has been choosen for operation)



E. Butz, Vertex 2014

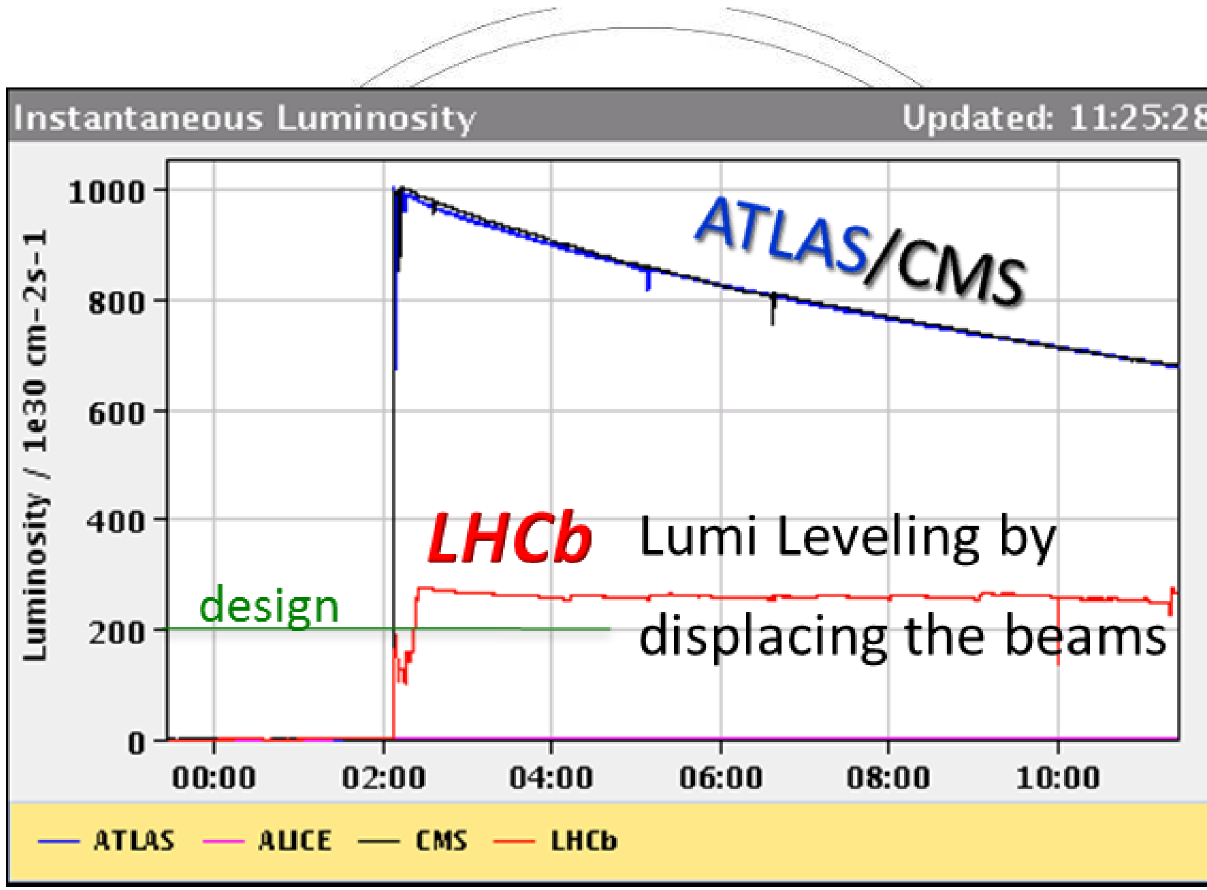
CMS strip: foreseen depletion voltage



https://twiki.cern.ch/twiki/pub/CMSPublic/StripTrackerCommissioningPlots2014/total_VDEP_15_20_700.png

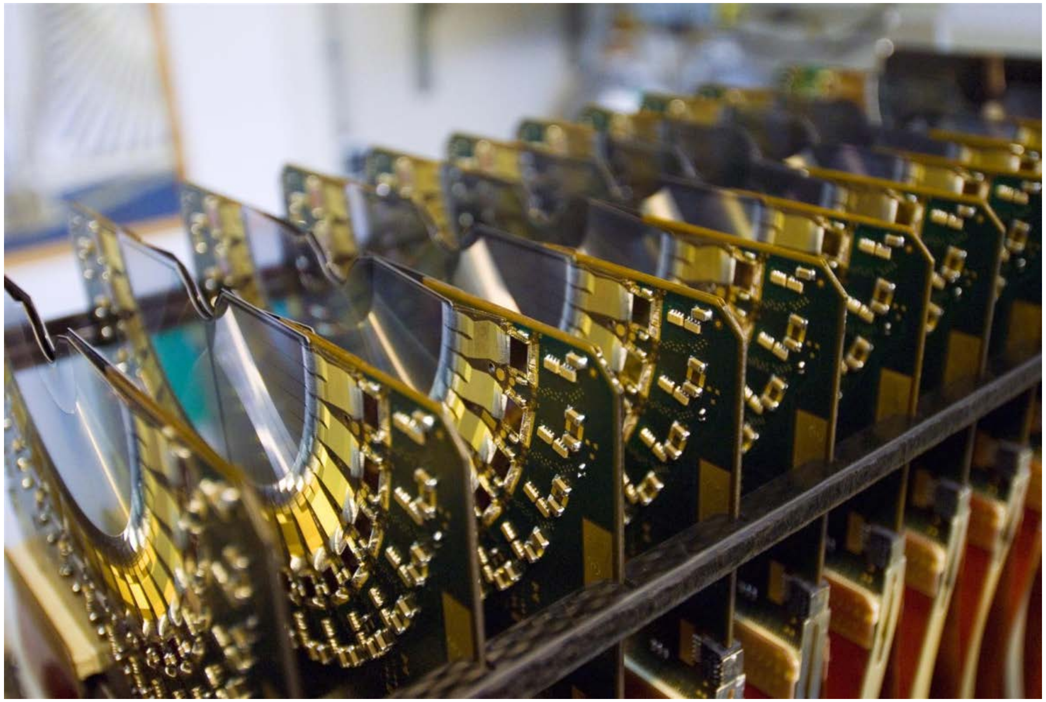
LHCb

- Single arm spectrometer for b physics
- $2 < \eta < 5$
- Silicon strip detectors:
  - VELO
  - TT/IT
- Less luminosity than Atlas/CMS



LHCb Vertex Locator (VELO)

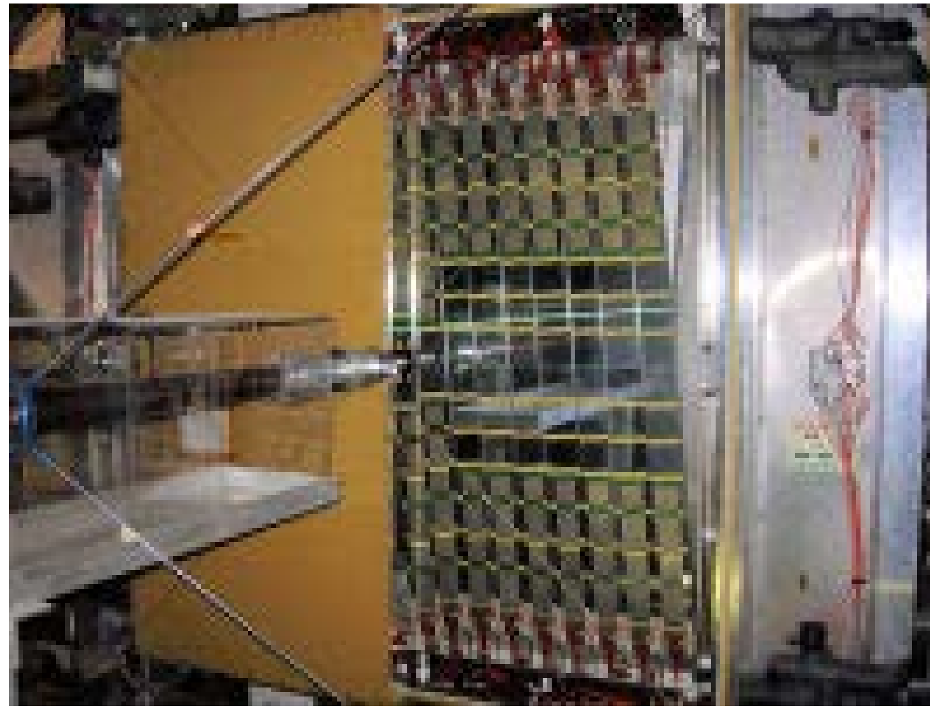
- Two single-sided sensors (r-strips, ϕ-strips) glued back-to-back
- Sensors: n+-in-n, n+-in-p on the most upstream modules
- 300μm thick
- Double metal for signal routing
- T=-10° C



Two halves opened during LHC filling and acceleration phases, then closed for data taking

LHCb Tracker Turicensis (TT)

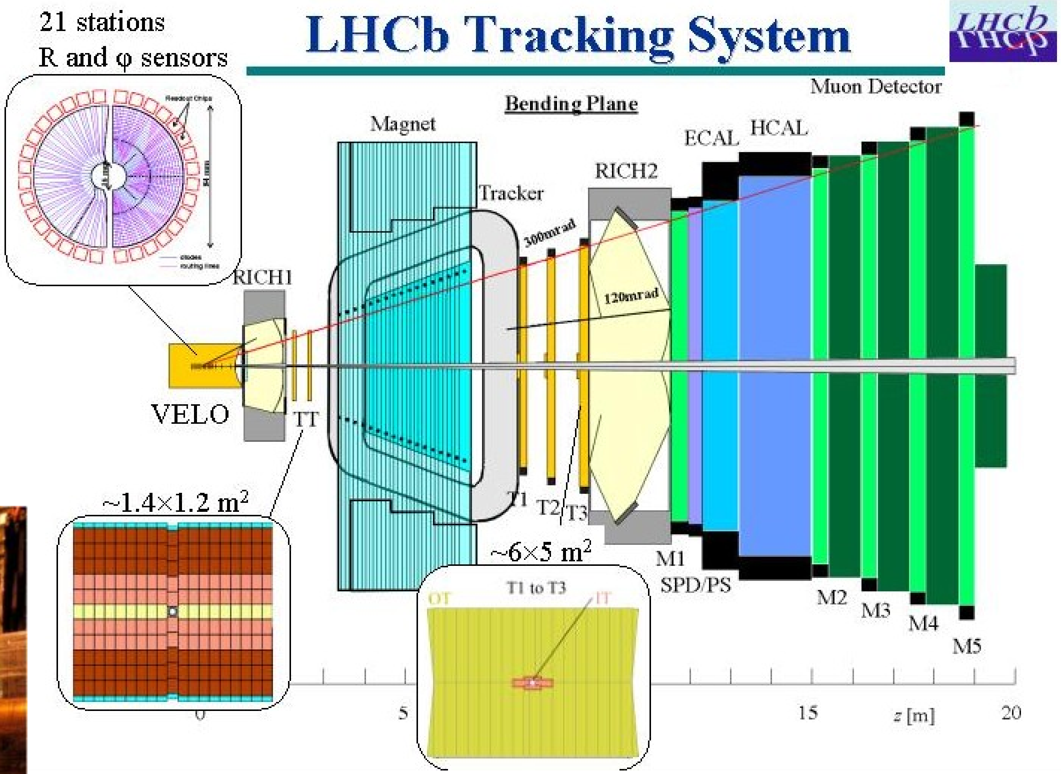
- p+-in-n sensors
- 500μm thick
- 183μm pitch
- Long readout strips (up to 37 cm → 60pF)
- T=8° C
- 144k channels, 8m²



http://lhcb.physik.uzh.ch/

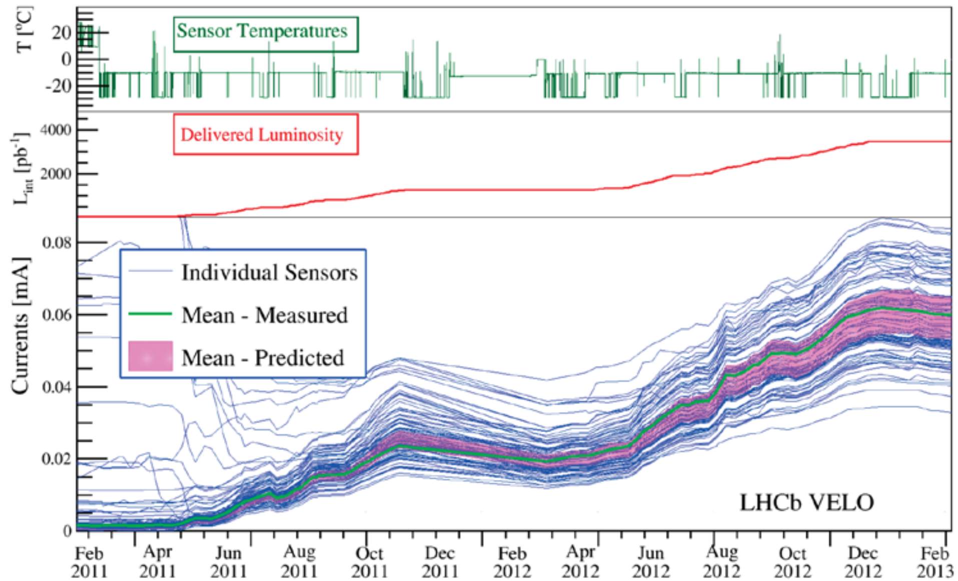
LHCb: Inner Tracker (IT)

- p+-in-n sensors
- 12 layers
- 320/410μm thick
- 198μm strip pitch
- 130k channels, 4.2m²
- T=8° C

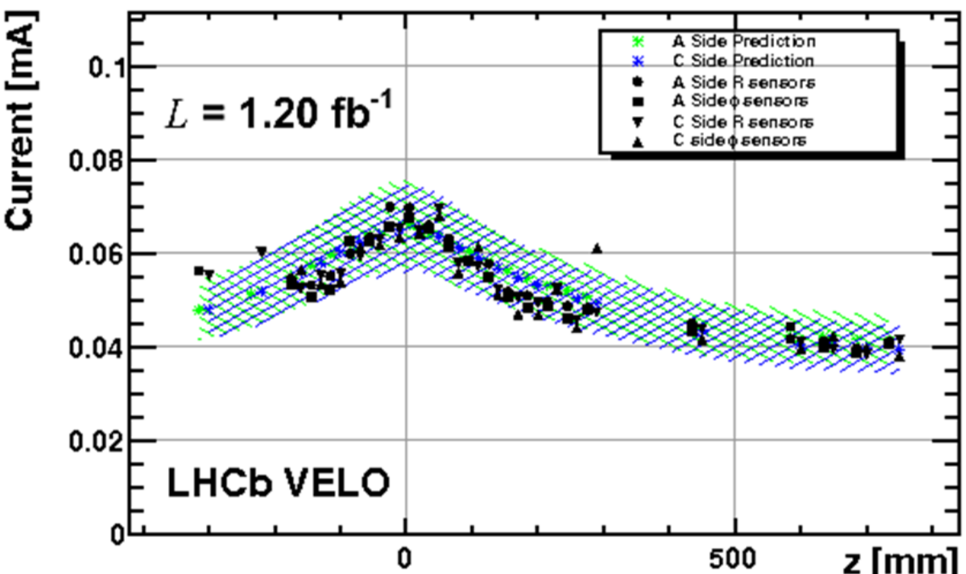


VELO leakage current

- Current normalized to -7°C
- In agreement with predictions



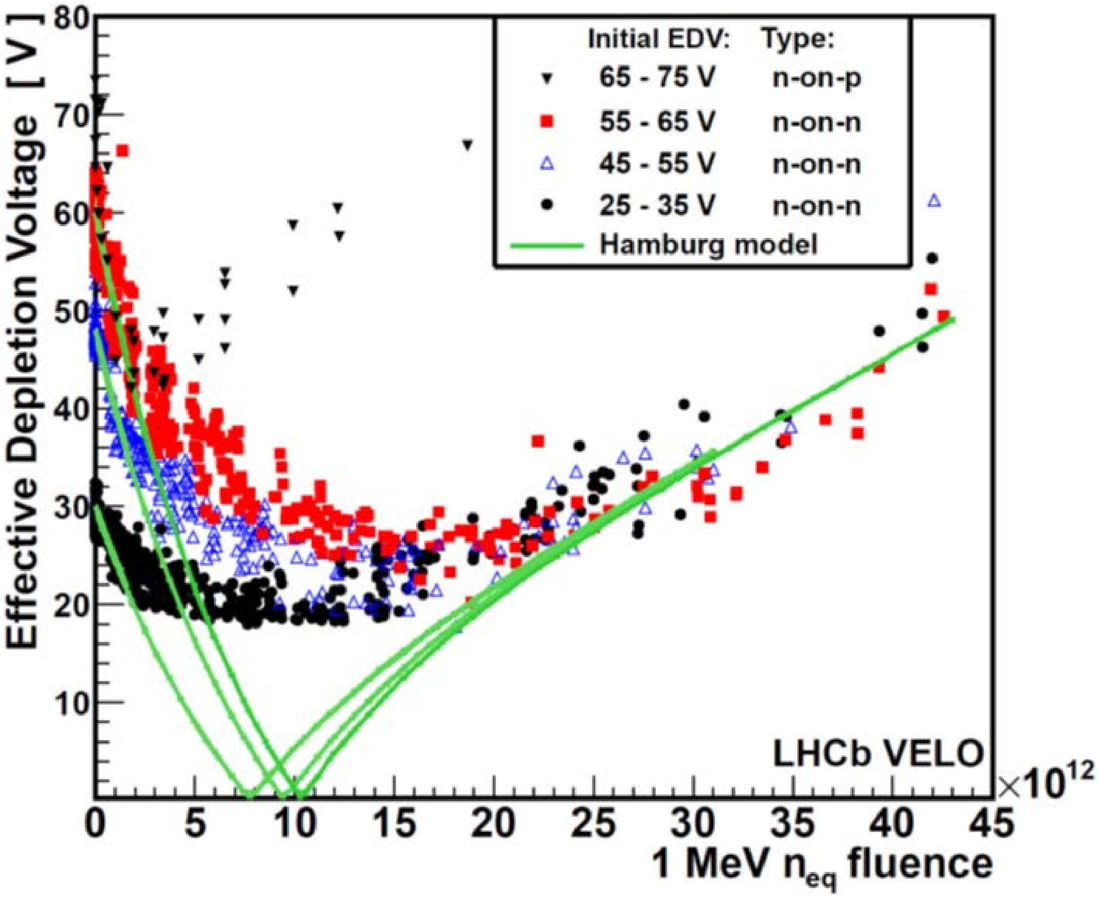
Current [mA]



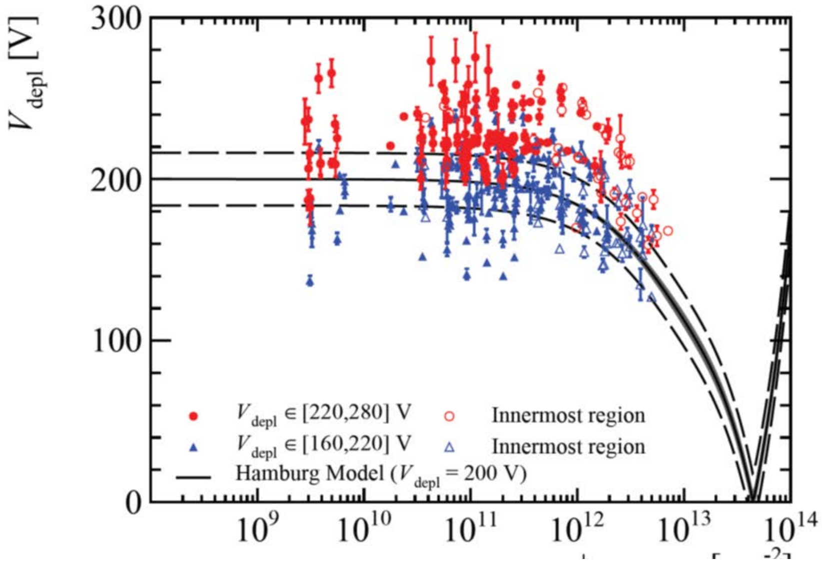
A. Affolder et al 2013 JINST 8 P08002

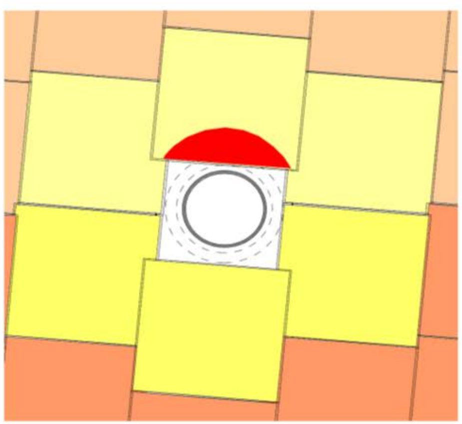
VELO Depletion Voltage

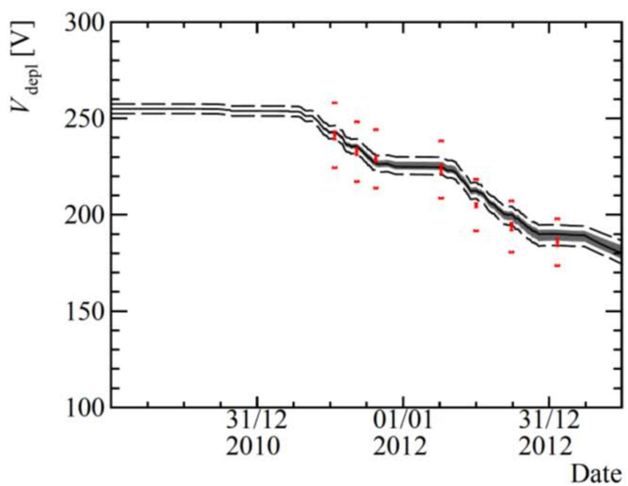
- n+-in-n sensors invert bulk type after (7÷10)*10^{12} n_{eq}/cm^2
- The few n+-in-p sensors have a depletion voltage which increase (as expected p type bulk material)



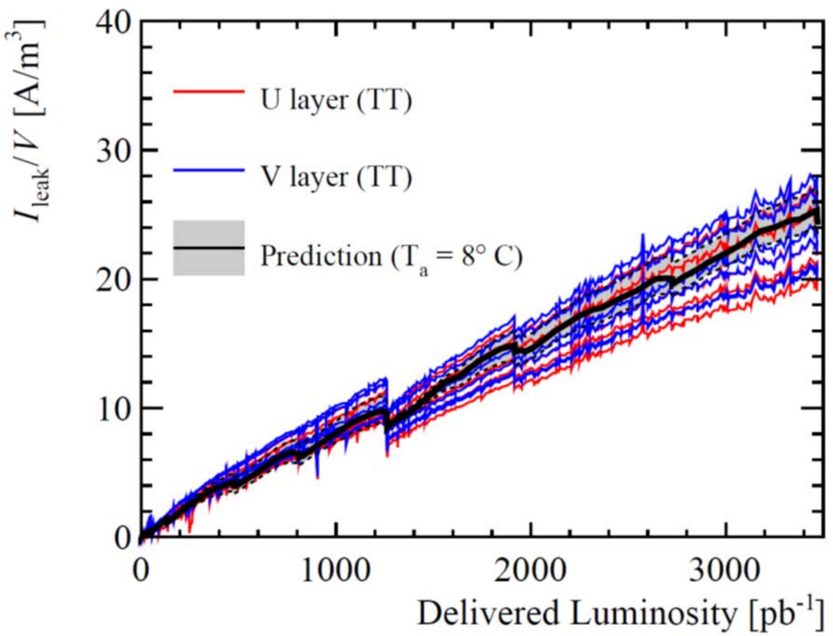
LHCb: IT Depletion Voltage

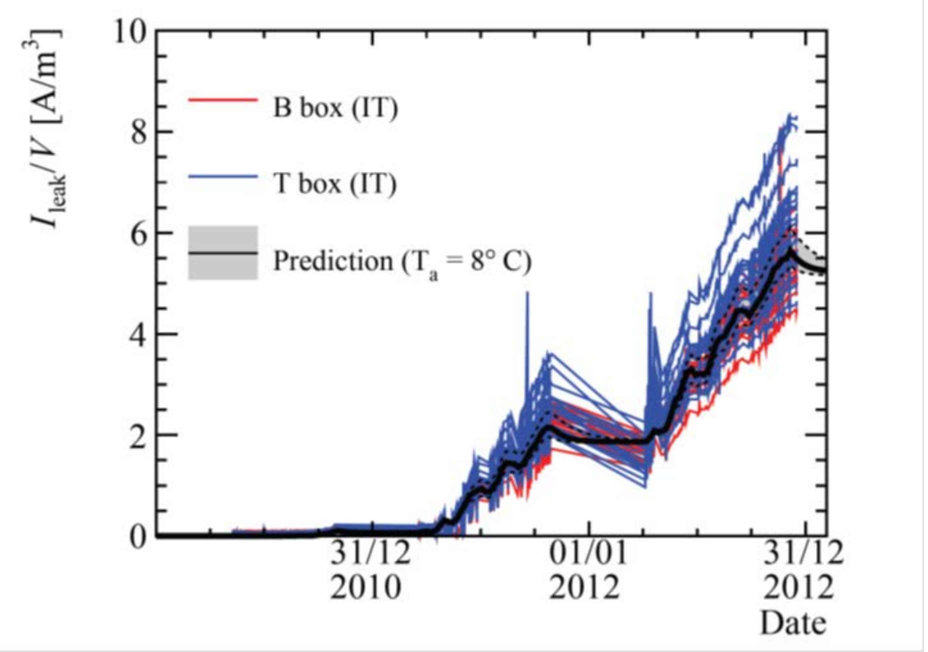






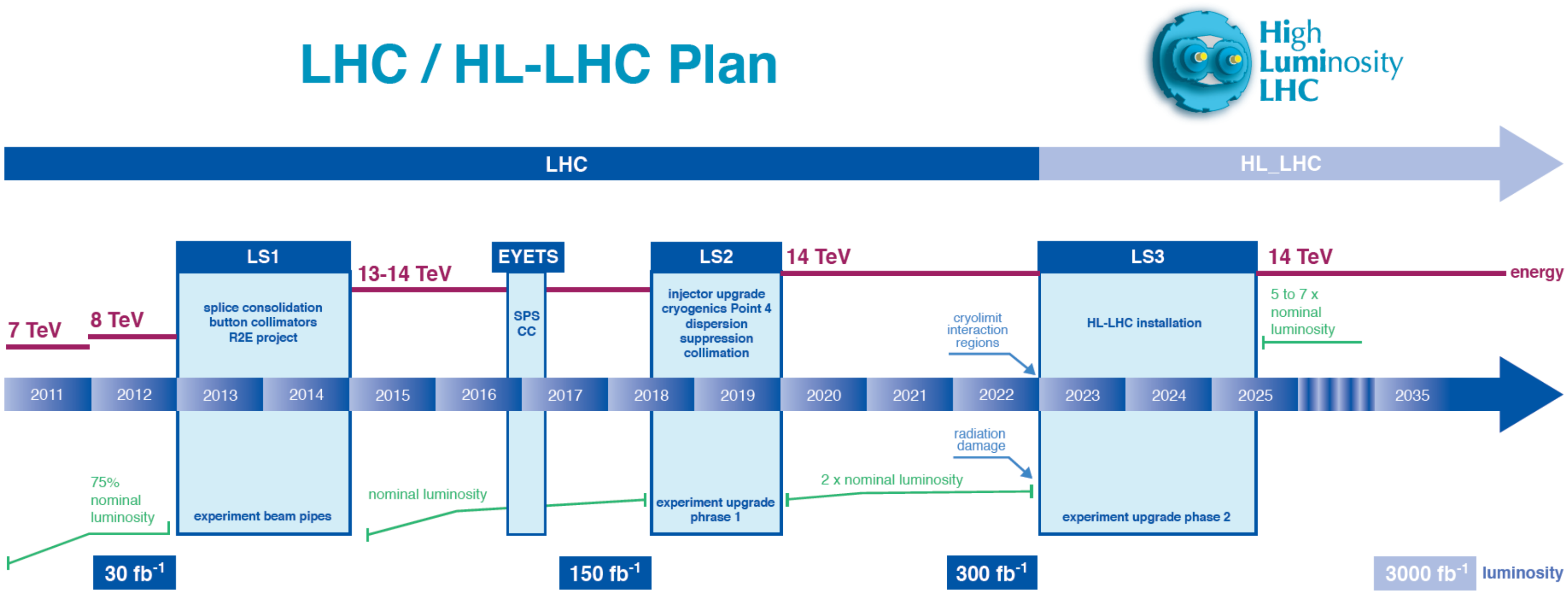
LHCb: TT and IT leakage current





HL-LHC

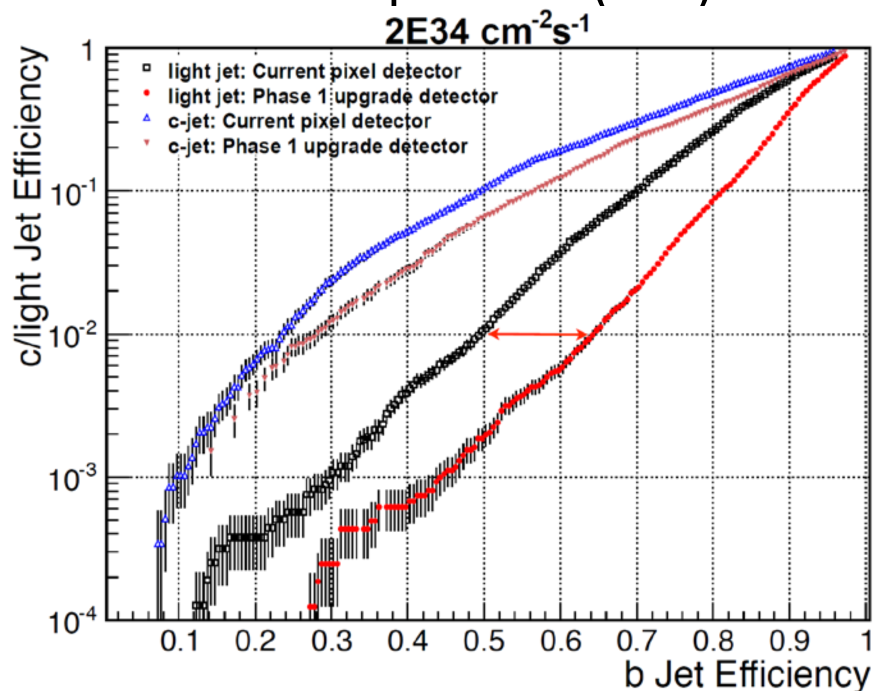
- LHC is an evolving infrastructure which will be improved over decades to exploit its full potential
- During these days the machine is restarting after a period of two year during which the magnet electrical connections have been redone to permit reaching both the energy and luminosity design specifications



https://cds.cern.ch/record/1975962/files/new_timeplan_24Sept2014_1_image.png

CMS Phase 1 Pixel upgrade

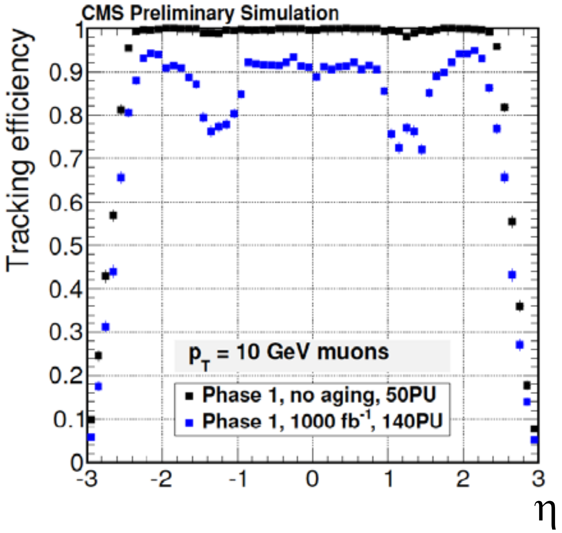
- The present CMS pixel detector was designed to sustain 500 fb^{-1}
- But the instantaneous luminosity evolution will soon exceed the rate capability of read-out chips and data links
- The new detector will have the same sensor type (n-in-n), a new read-out chip (evolution of the present one) and more redundancy → one more barrel layer (4) and one more disk per side (3+3)
- The new beam pipe with a radius of 22.5mm, instead of 30mm, will allow to place the innermost barrel layer at 29mm, instead of 43mm) with important improvements on the b-tagging capabilities of the system

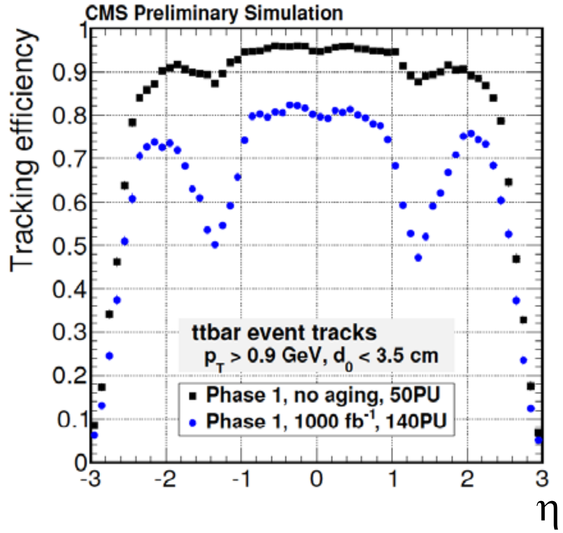


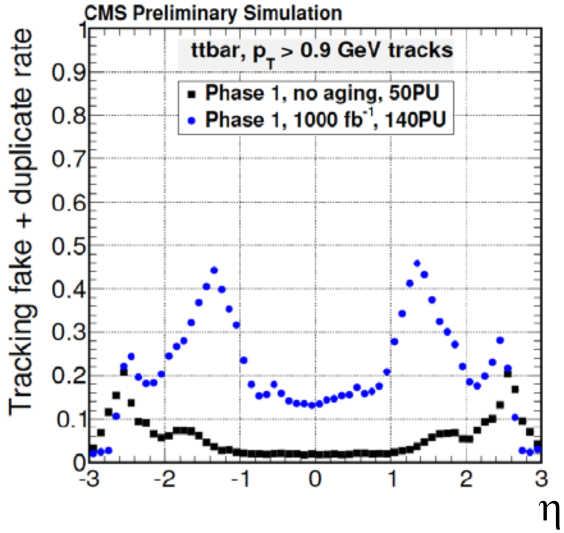
CERN-LHCC-2012-016

CMS Phase 2 Pixel upgrade

- After 500 fb^{-1} also the phase 1 detector starts to loose some of its key performance on tracking
- A full replacement of the pixel detector, together with the external microstrip detector, is foreseen starting from 2022

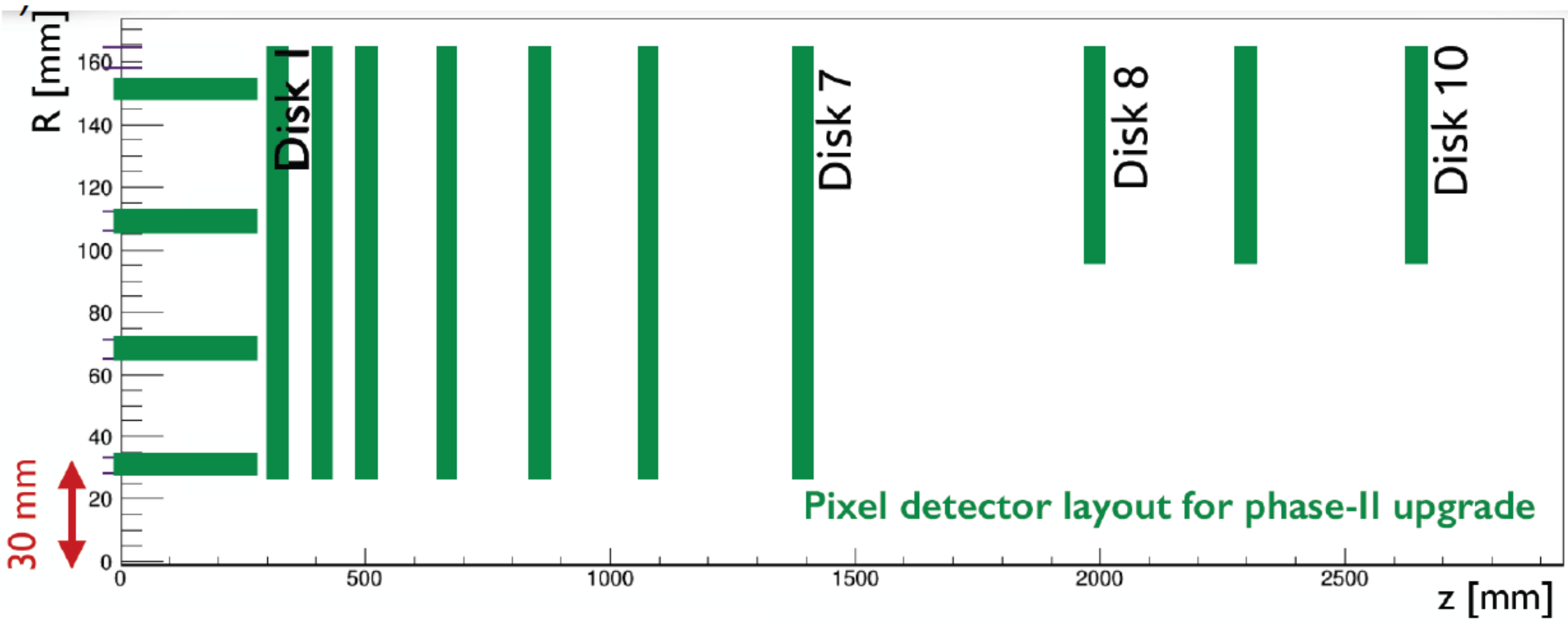






M. Musich, Vertex 2014

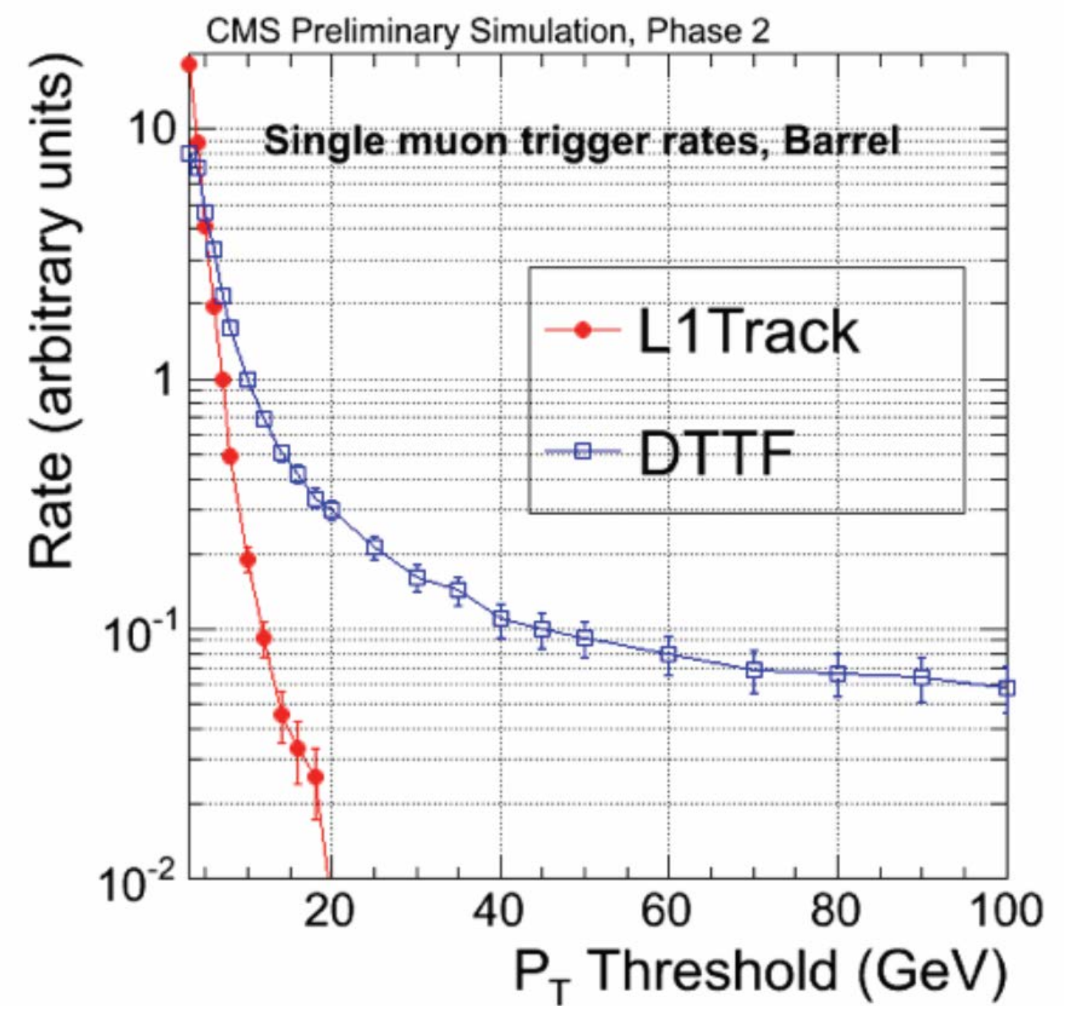
CMS phase 2 pixel layout



- Improve the resolution at high p_t → higher granularity
- Improve the resolution at low p_t → reduce the material
- Increase acceptance up to $|\eta|<4$ → 10+10 endcap disks
- Pixels dimensions: 25x100 μm^2 (50x200 μm^2 external layers)
- Sensor choice: planar n-in-p thin or 3D

The phase 2 tracker upgrade

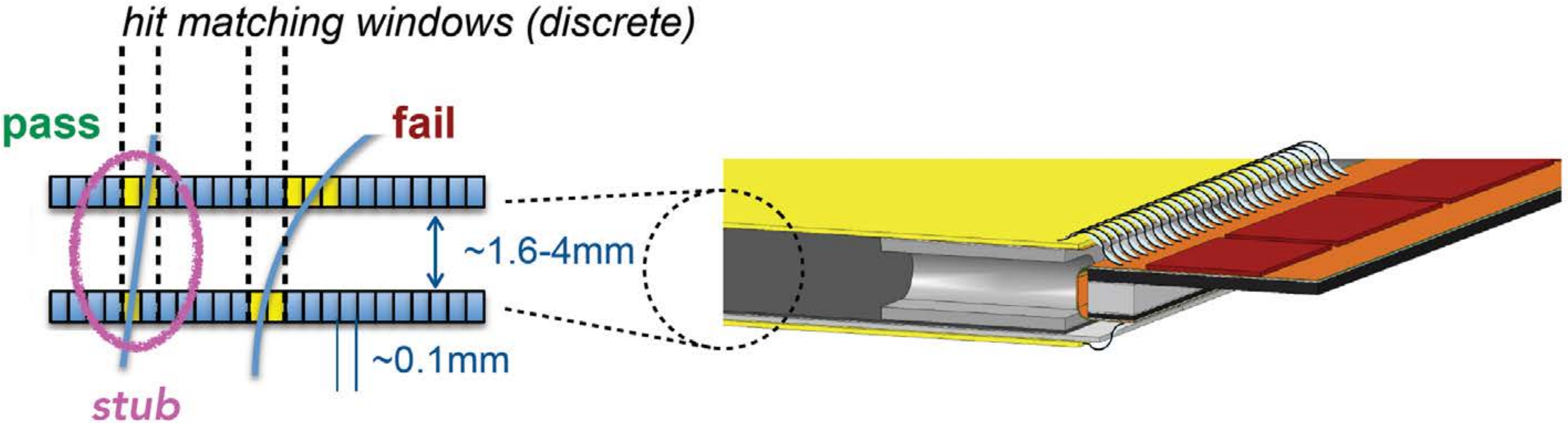
- Aside the radiation problems, at HI-LHC luminosities the whole CMS level-1 muon trigger system will not be more able to reduce the rate selecting high p_t events
- The phase 2 tracker should be able to provide information already at level 1 trigger (within few μs from the interaction time)



G. Sguazzoni, Vertex 2014

p_t module concept

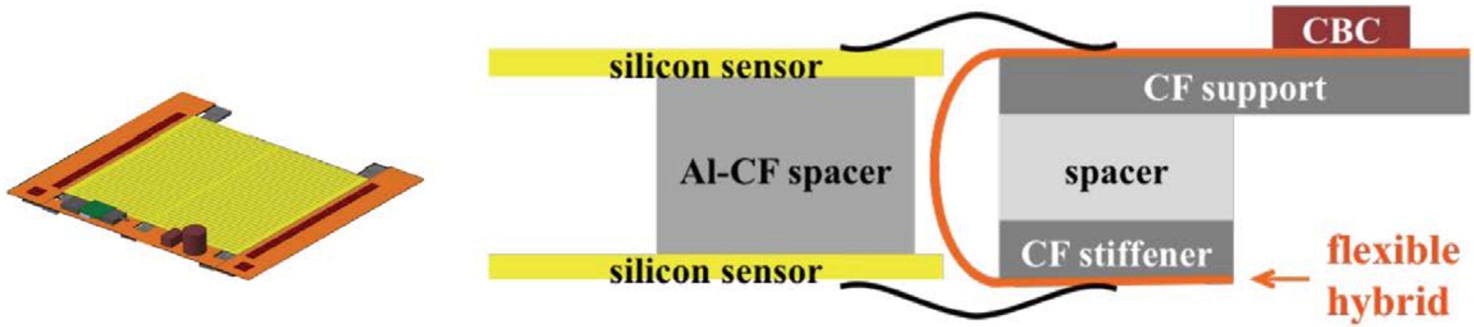
- The pt discrimination is done locally using appropriate hit position correlation in two closely spaced detectors
- Only interesting data are sento out at 40MHz to ease an online fast track reconstruction

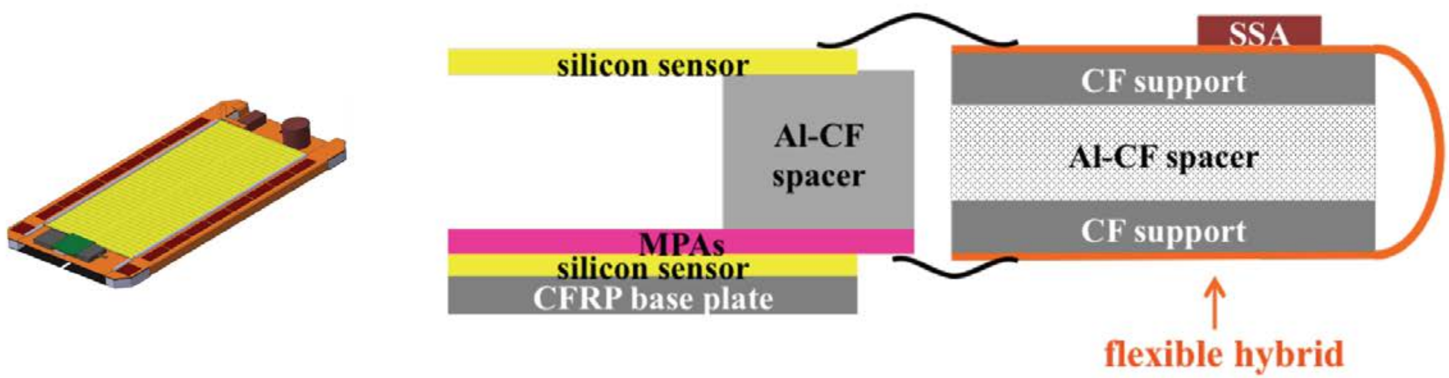


G. Sguazzoni, Vertex 2014

p_t modules

- Two kind of modules: strip-strip (outer), strip-pixel (inner)
- Fluences up tp 1.5×10^{15} n_{eq}/cm^2
- Probably n+-in-p 200μm thick sensors





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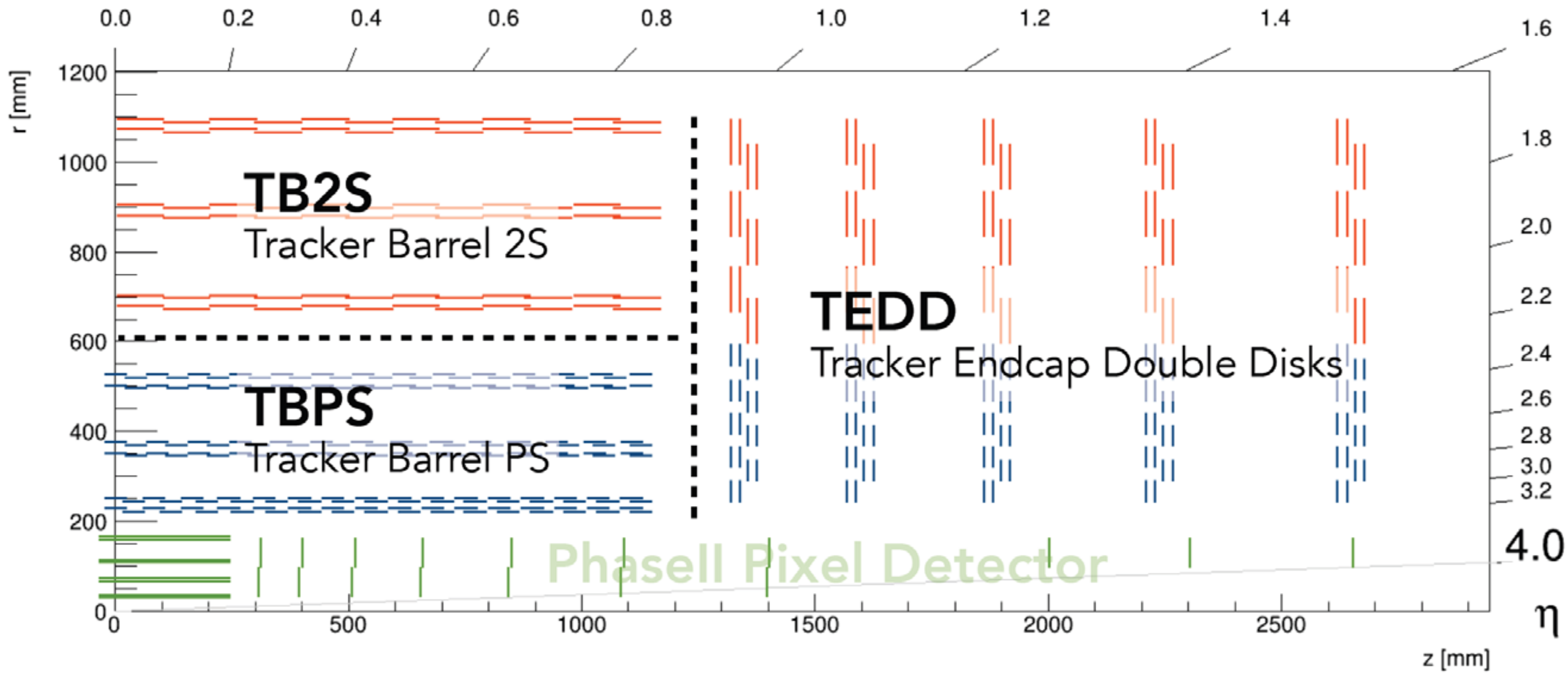
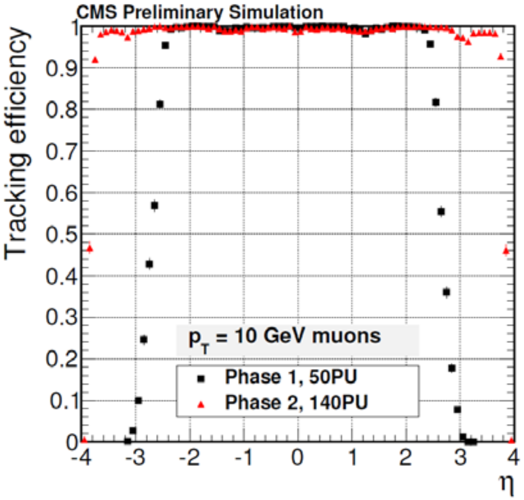
The Phase 2 CMS tracker

- 6 barrel layers
- 5+5 endcap disks



The Phase 2 CMS tracker: performance



Single muon efficiency
P_T = 10GeV