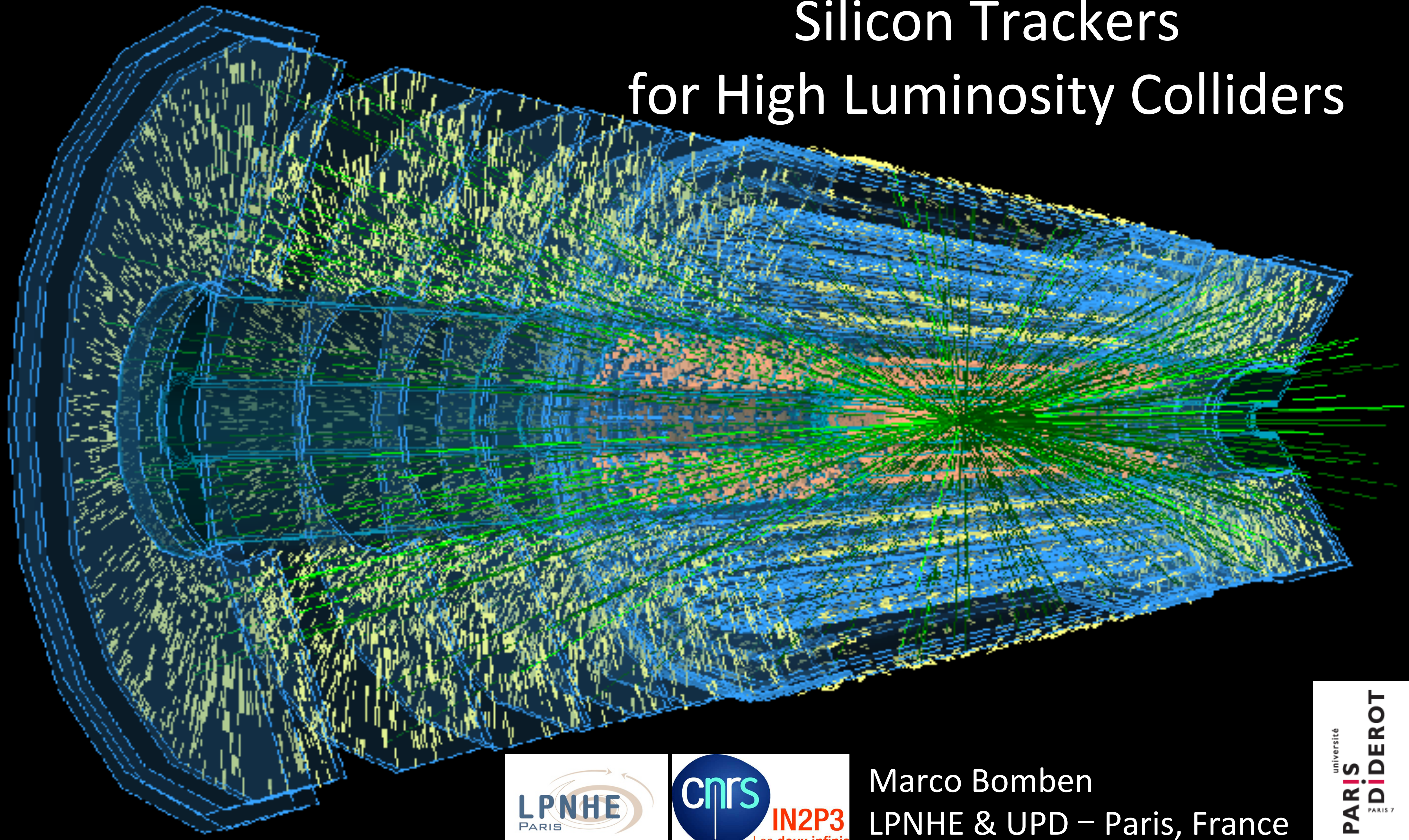
Habilitation à diriger des recherches



Silicon Trackers for High Luminosity Colliders

Marco Bomben
LPNHE & UPD – Paris, France

Outline

- Biography & Context
- Silicon detectors for high energy physics
- The Slim5 Project
- Radiation damage modelling for the ATLAS Pixel detector
- Pixel detectors for the new ATLAS Inner Tracker
- Perspectives
- Summary

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Disclaimer: in what follows
References to original contributions are in red
References to support material are in green

BIOGRAPHY

Education, research and teaching

Università di Trieste & INFN
Laurea, PhD & Post-doc

LPNHE – CNRS – UPD
Post-doc & Maître de Conférences

2003-2007

2007-2009

2010-now

ATLAS EXPERIMENT

Laurea (2003): semileptonic decays of B mesons

PhD (2007): CP violation in b ➔ c decays
+ Silicon Tracker Operations

Silicon sensors for high luminosity e+e- colliders

Silicon trackers for the future high luminosity hadronic colliders

Radiation damage studies on the ATLAS pixel detector

Advising students, from undergraduates to PhD

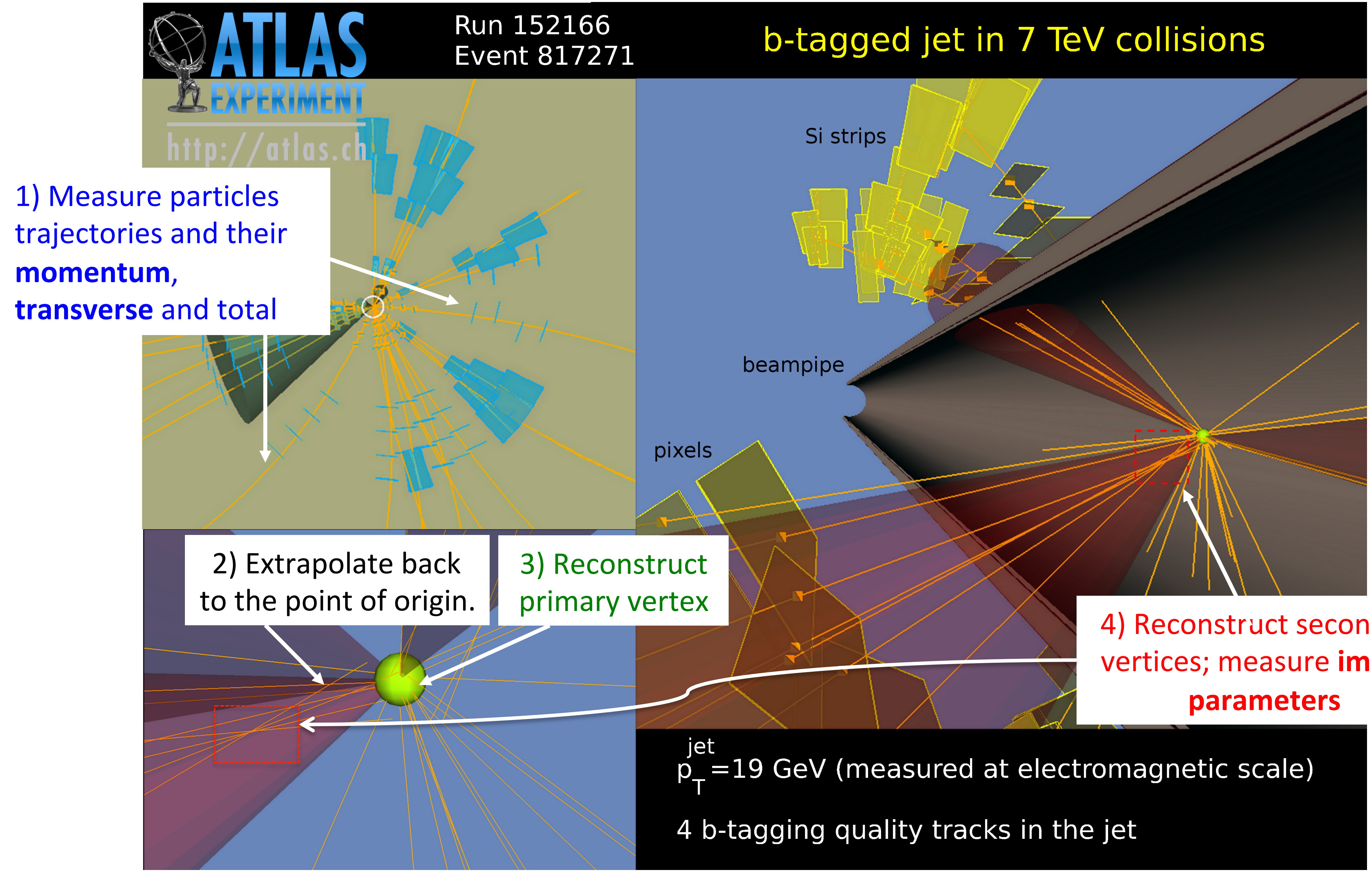
Teaching, in Italy and France
- Università degli Studi di Trieste, Faculty of Engineering, undergraduate program
- Université Paris Diderot, Natural Sc. And Phys. Dept., undergr. and master program

Students supervision

- Gonzague Le Mesre De Pas, stage d'école d'ingénieur, 2011
  - Characterisation and simulation of silicon diodes
- Qu An, M1 stage, 2012
  - Simulation of irradiated silicon sensors
- Audrey Ducourthial, M1 stage, 2014
  - Characterisation of pixel detectors for the ATLAS tracker upgrade
- Audrey Ducourthial, M2 stage, 2015
  - Analysis of testbeam data of pixel detectors for the ATLAS tracker upgrade
- Audrey Ducourthial, PhD Thesis, 2015-ongoing
  - ATLAS Tracking detector upgrade and its importance for H->bb analysis
- Kenji Nardone, stage d'école d'ingénieur, 2017-2018
  - Characterisation and simulation of silicon detectors
- Plus students working at testbeams (Louis D'Eramo, Ilaria Luise, etc.)

CONTEXT

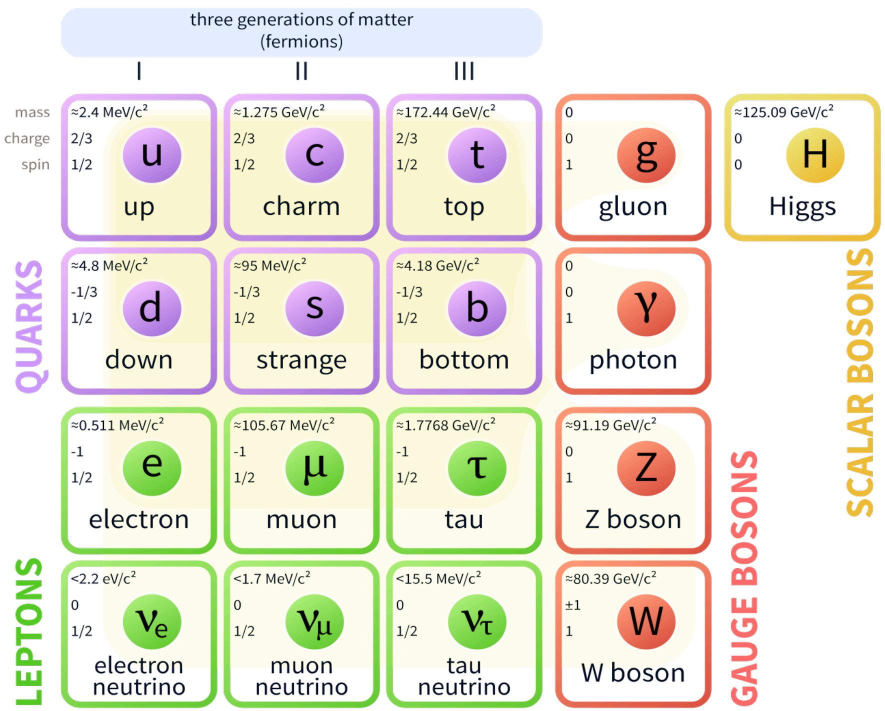
Role of trackers in HEP experiments

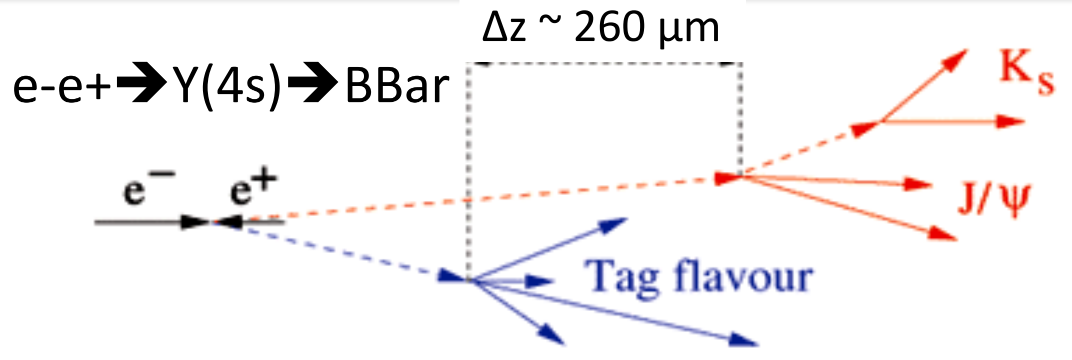


Elementary particles and flavour tagging

+ New Physics…

Standard Model of Elementary Particles





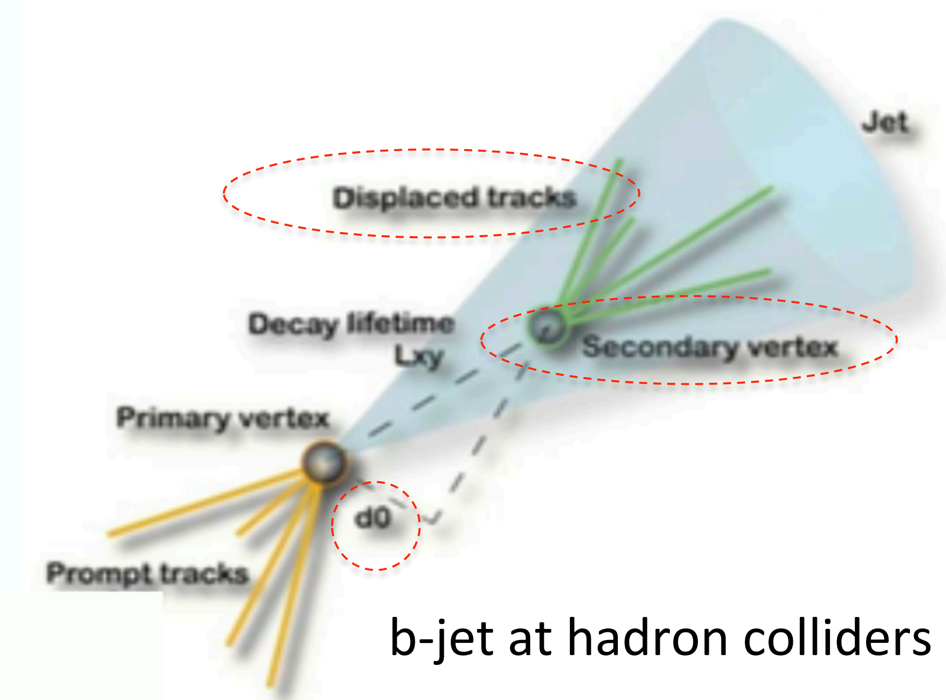
Flavour tagging for CP violation measurement in B mesons system

Lifetimes of tau leptons, charm and beauty hadrons: from 0.2 to 1.5 ps

→

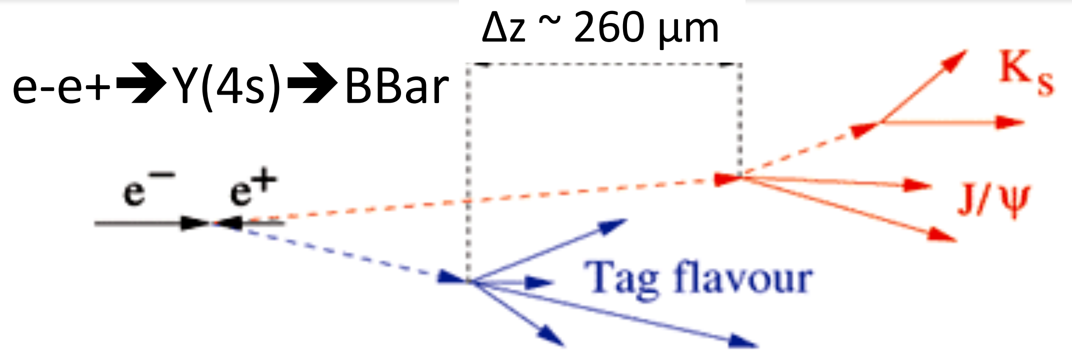
Typically the decay vertex is at a distance of single millimeters from the interaction vertex

→ **sub-millimeter precision needed!**



b-jet at hadron colliders

Flavour tagging at B-factories



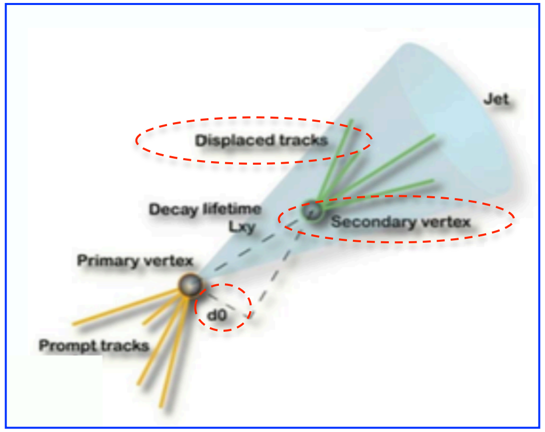
Flavour tagging for CP violation measurement in B mesons system

In order to have a **better than 10% precision in measuring CP violation** the **vertices had to be reconstructed with a 80 μm resolution**, corresponding to about 1/3 of the average vertices distance

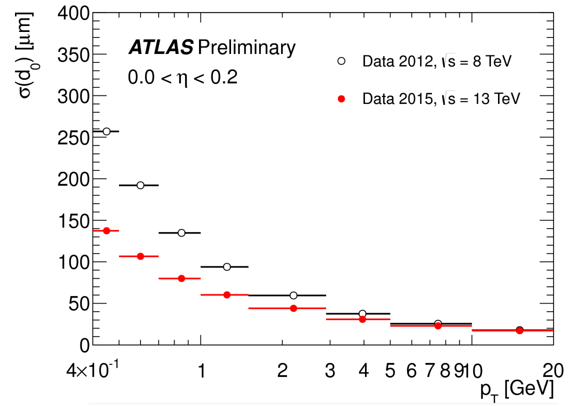
In reality **fully reconstructed Bs had vertex precision of 50 μm**, while for *tag side it was about 100-150 μm*

BaBar tracker performance allowed also to measure precisely τ_B too

Jet tagging at LHC

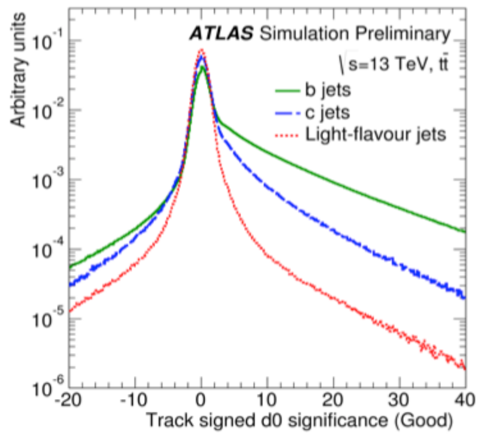


The ability to **identify jets containing b-hadrons** is **important for the high-pT physics program** of a general-purpose experiment at the LHC such as **ATLAS**



Fundamental tool to

- select pure top samples
- search for (SUSY)Higgs coupling to heavy object
- veto large dominant tt background
- **search for new physics**: SUSY decay chains, **heavy gauge bosons**, etc



Transverse momentum resolution

Transverse momentum resolution: need strong ***B***, long path length ***L***, excellent space point resolution $\boldsymbol{\sigma_{point}}$ and **keep material budget at minimum**

$$\frac{\sigma_{p_T}}{p_T} = \left(\frac{p_T\,\sigma_{point}}{0.3|z|\,L^2 B}\sqrt{\frac{720}{N+4}}\right) \oplus \frac{0.054}{\beta B L}\sqrt{\frac{x/\sin\theta}{X_0}}$$

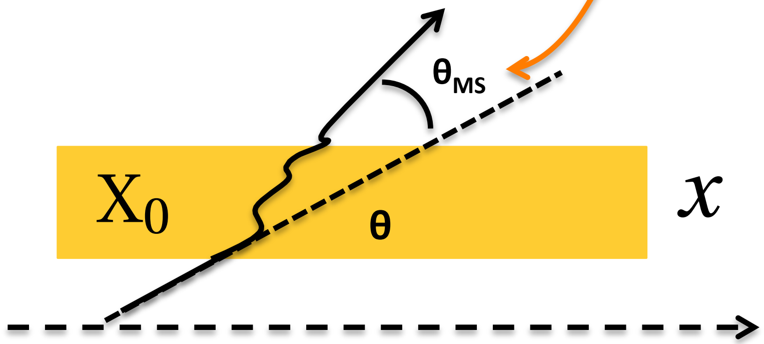
Multiple Scattering

e.g.: arXiv:1705.10150

N: number of equidistant measuring layers

Particle incident on a thin slab undergoes **M**ultiple deflections due to Coulomb **S**cattering (MS)

θ_{MS} depends on material budget and momentum



At normal incidence for 1 layer

$$\theta_{MS} \approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p}\sqrt{\frac{x}{X_0}}$$

Vertexing resolution

The precision on vertexing is linked to the impact parameter resolution

$$\sigma_{d0} \approx \frac{\sigma_{point}}{\sqrt{N}} \sqrt{1 + \frac{12(N-1)}{N+1}\left(\frac{r}{L}\right)^2} \oplus \theta_{MS} r_{pv} \sqrt{\frac{N(2N-1)}{6(N-1)^2}}$$

e.g.: arXiv:1705.10150

- $\boldsymbol{\sigma_{point}}$ is the space point resolution
- **N** is the number of equidistant measuring layers
- **r/L** is the ratio of extrapolation distance over tracker length

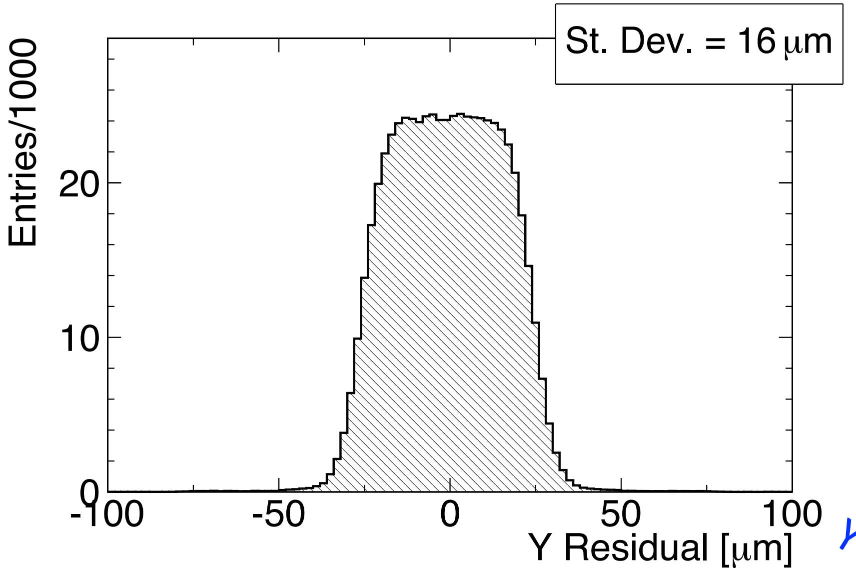
(Limited gain for large N)

$\mathbf{r_{PV}}$ is the distance of the first layer from the primary vertex

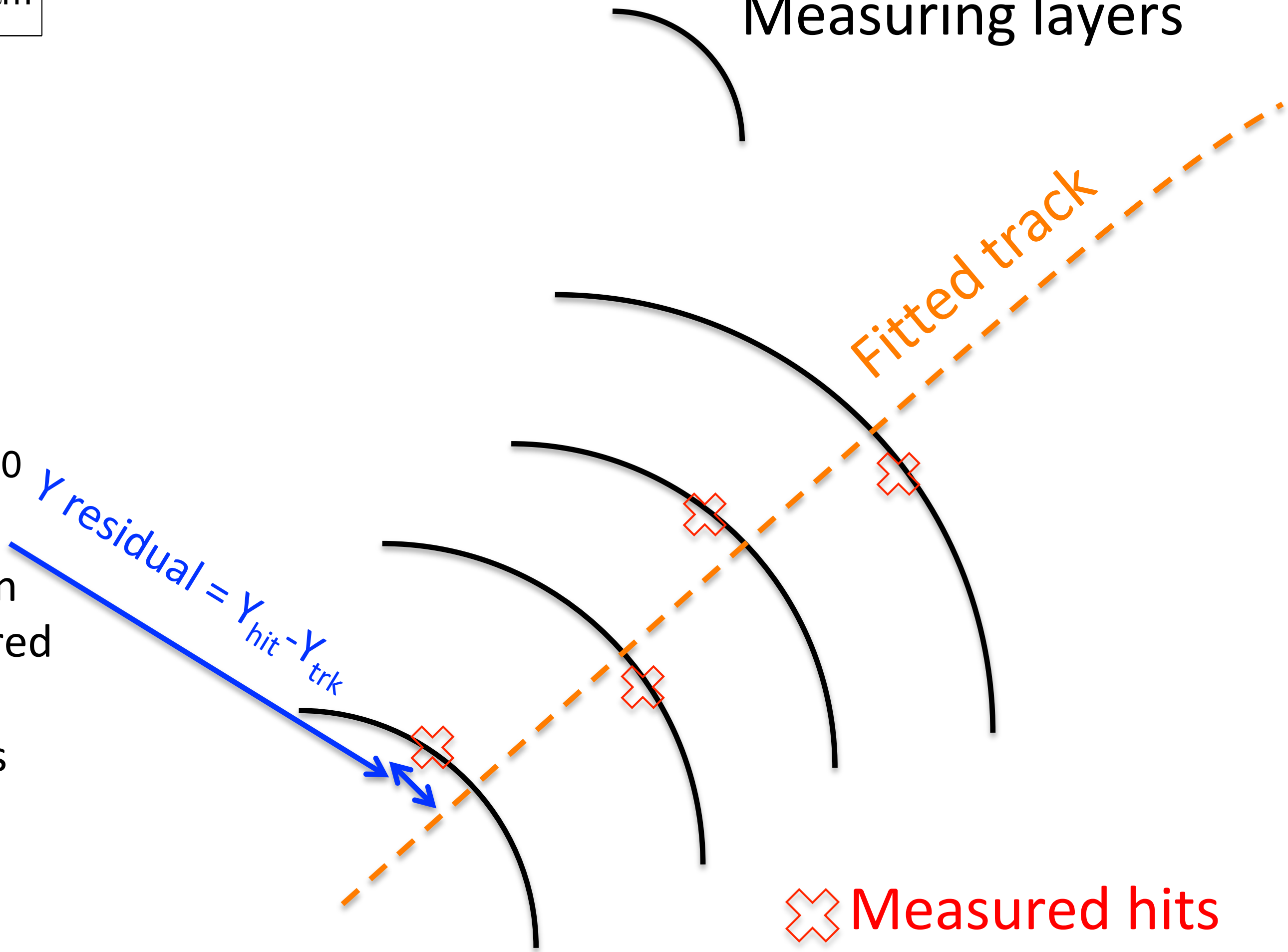
Need for:

- Excellent space point resolution $\boldsymbol{\sigma_{point}}$
- A plane as close as possible to the interaction point (**r**)
- Long lever arm **L**
- Minimize material (**x** and $\mathbf{X_0}$)

How to estimate σ_{point}? Residuals



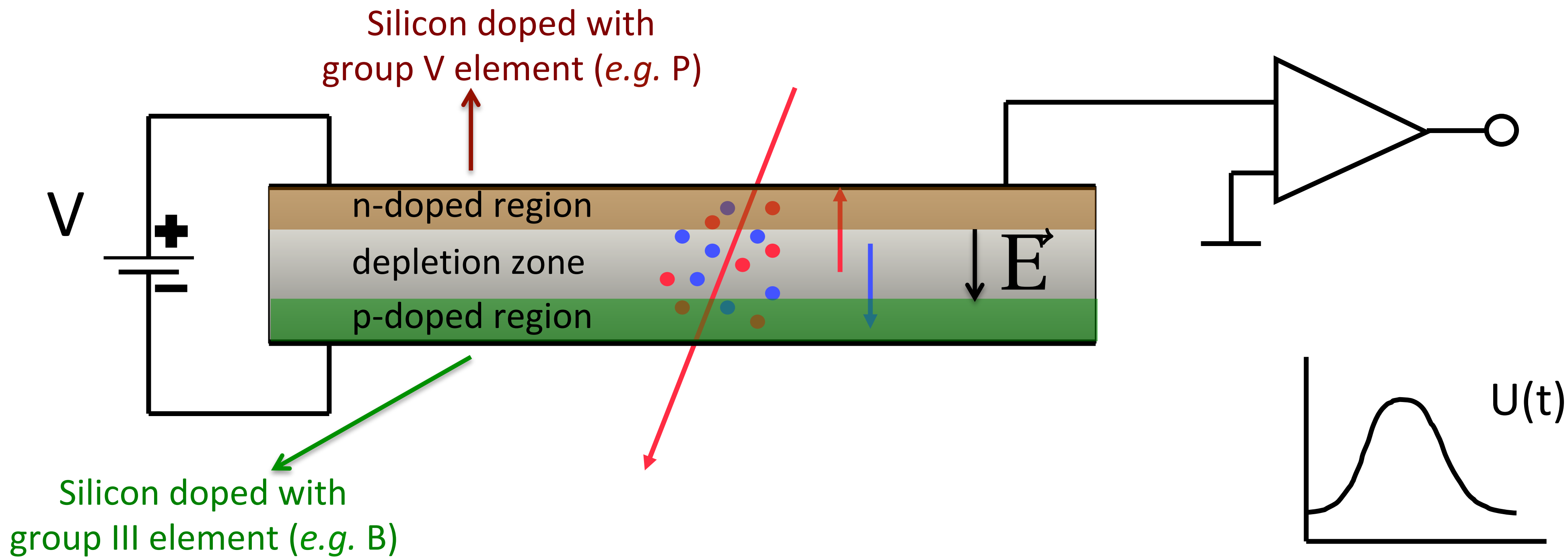
- From the RMS of the residuals distribution the space point resoultion σ_{point} can be inferred
- Several effects enter involved:
  - Statistical fluctuations in energy loss
  - Diffusion
  - Lorentz Angle
  - Sensor pitch
  - Cluster size
  - Analog/Binary r.o.
  - S/N ratio
  - Alignment
  - ...



$$\sigma_{res} = \sigma_{\mathrm{DUT}} \oplus \sigma_{trk}$$

SILICON DETECTORS FOR HIGH ENERGY PHYSICS

The basics: p-n junction in reverse bias

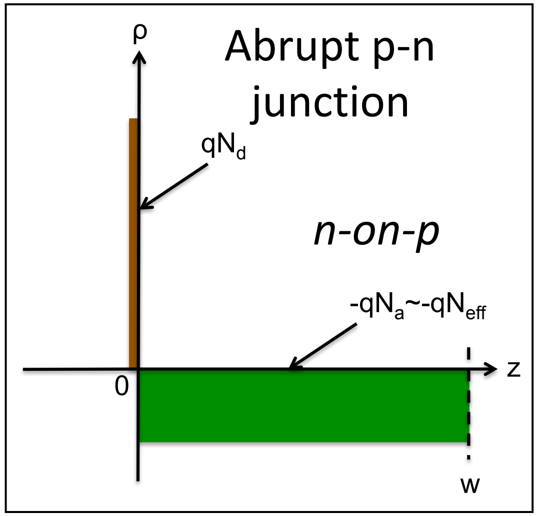


A solid state ionization chamber

Signal given by the drift of charges (electrons and holes) under the effect of the **electric field**

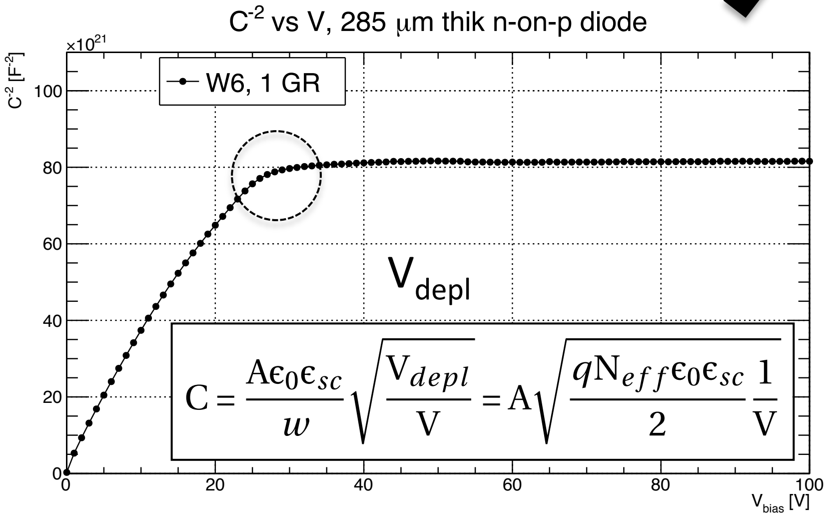
The signal is then amplified and shaped

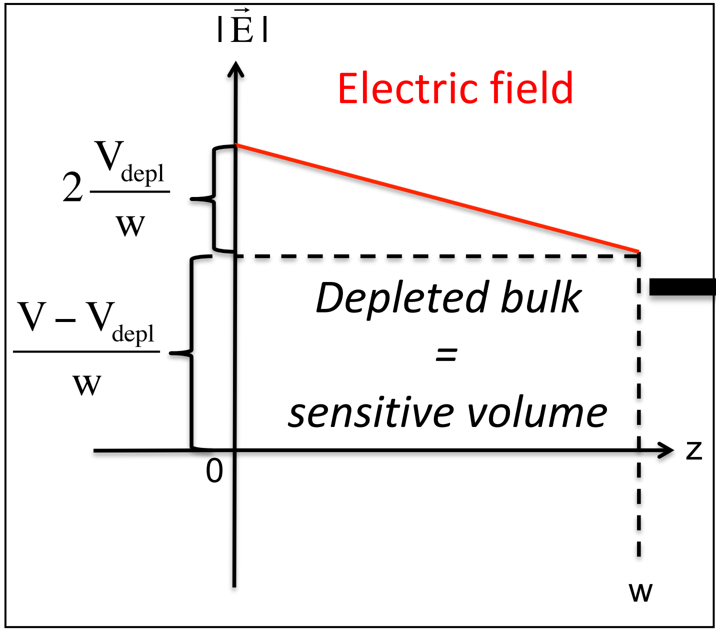
Silicon p-n junction in reverse bias



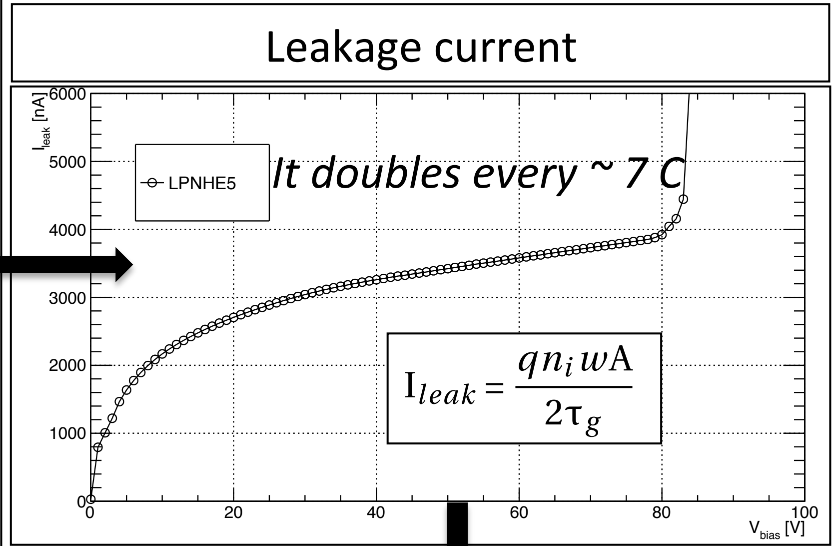
Reverse polarisation

=> Depletion voltage V_{depl}





Leakage current



Why Silicon?

Silicon		
Feature	Value	Comments
Density ρ	2.33 g/cm^3	compact and thin detectors
Energy bandgap E_g	1.12 eV	non-cryogenic operation
Mean ionisation energy ϵ	3.6 eV	large signals
Radiation length X_0	9.37 cm	thin detectors to minimize multiple scattering
Electron mobility μ_e	~1350 cm^{2}V/s	fast charge collection
Saturation velocity v_{sat}	~10^7 cm/s	fast charge collection

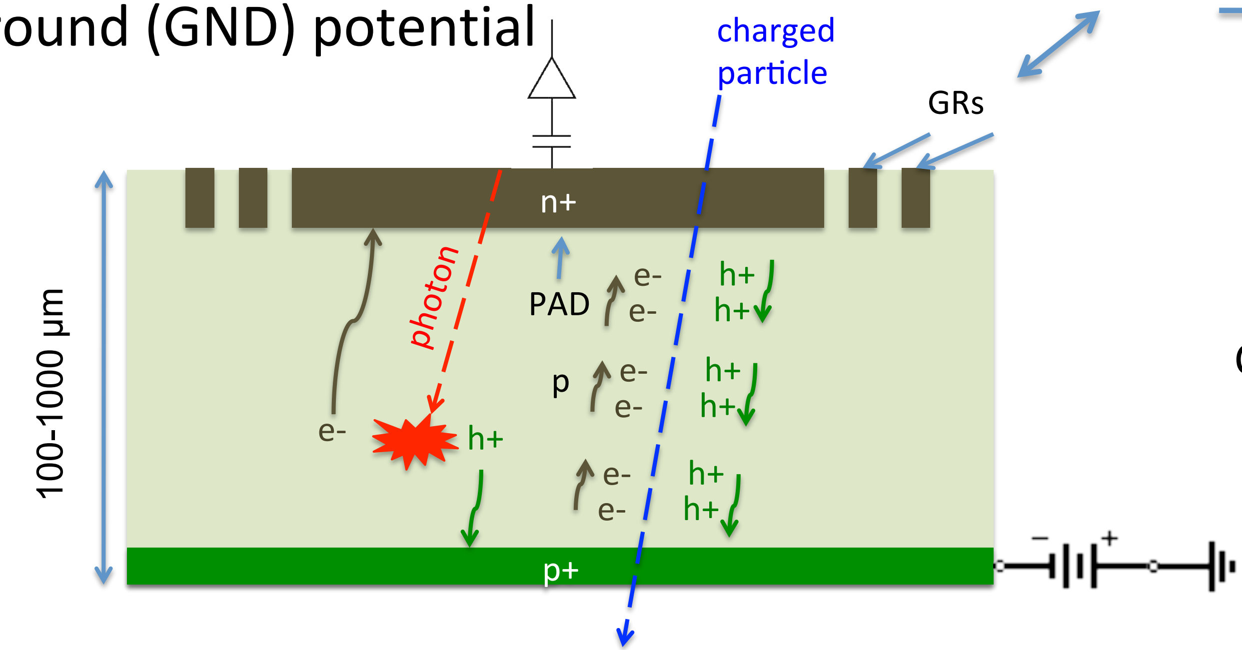
Simplest silicon sensors: the pad diode

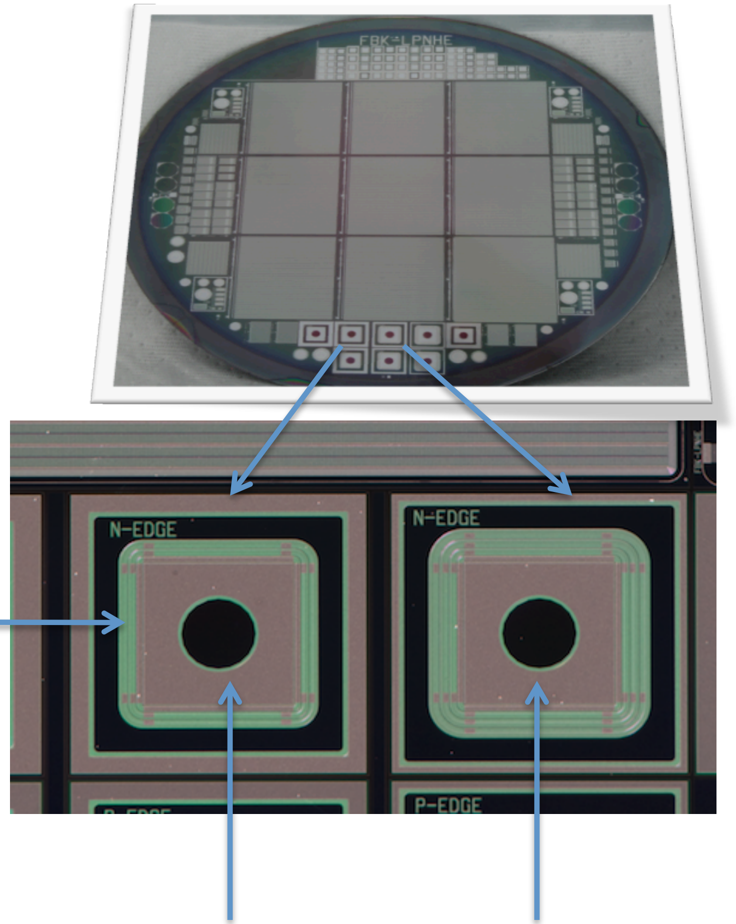
A single p-n diode in reverse bias is the simplest silicon radiation detector
Often it is called pad diode

The size varies between few mm^2 to few cm^2

Guard Rings (GRs) assure a smooth transition between the High Voltage (HV) and the Ground (GND) potential

N-on-p production





GRs

Central openings in the aluminium layer for visible/IR photon detection

Position measurement: Double-sided microstrip detectors (DSSD)

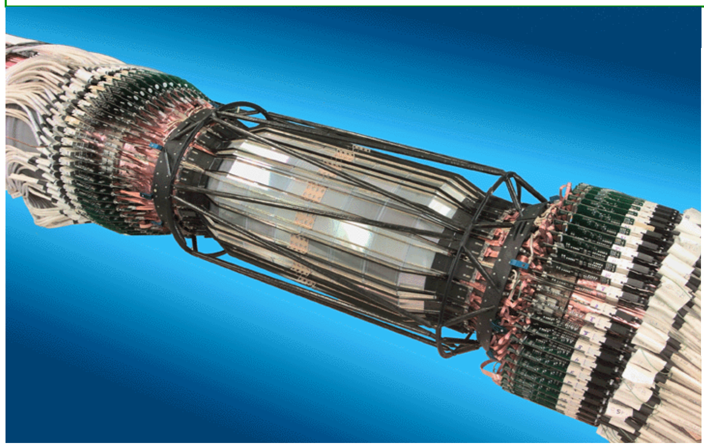
Single sided detector measures only one coordinate. To measure second coordinate requires second detector layer

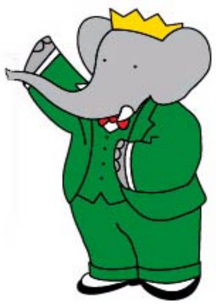
Double sided strip detector measures two coordinates in one detector layer (minimizes material)

In n-type detector the n^+ backside becomes segmented, e.g. strips orthogonal to p^+ strips

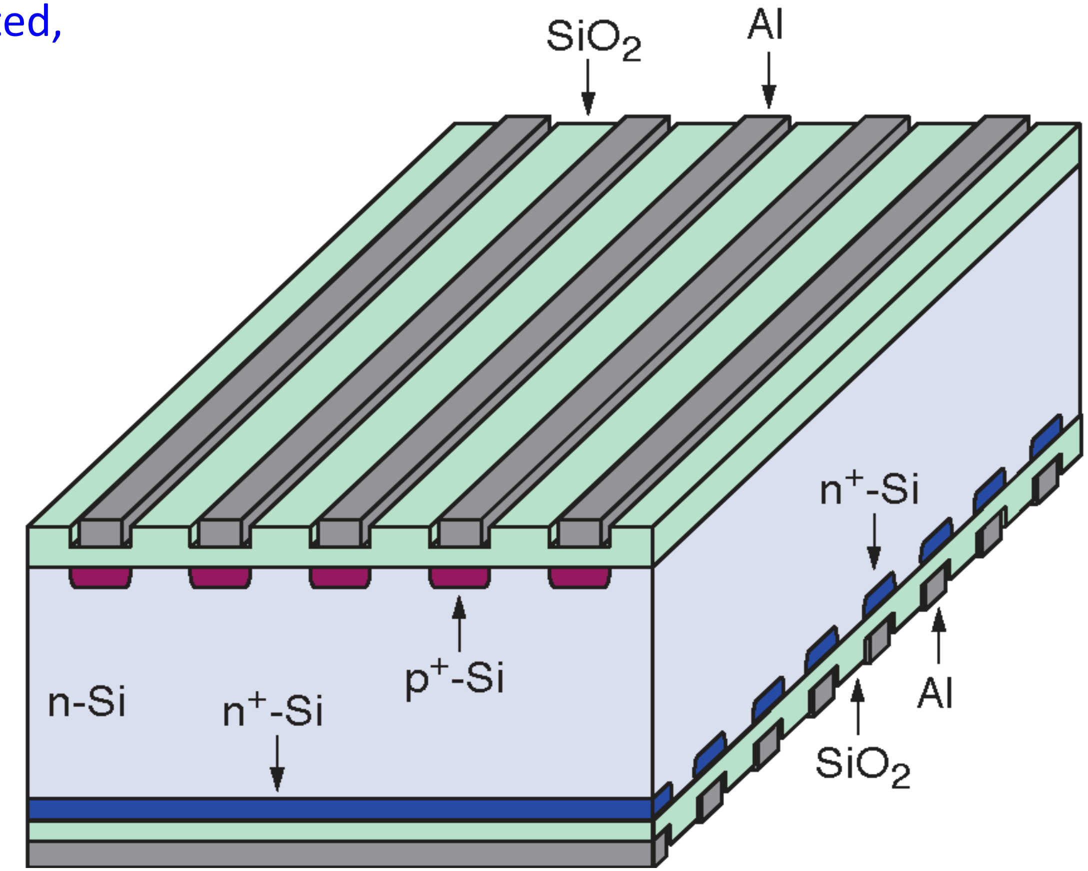
Drawback: expensive as production, handling, and tests are more complicated, and ambiguities!

BaBar SVT





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



Hybrid Pixel Detectors

Originally in planar technology; now 3D too

HPD: Typical size is (50-400) μm x 50 μm

If signal pulse height is not recorded, resolution is the digital resolution: $\sigma = p/\sqrt{12}$

e.g. σ = 14 μm for p = 50 μm

Reminder: better resolution is achieved with analogue readout

Small pixel area ➔ low detector capacitance (~ few fF/pixel) ➔ large SNR (>> 10)

Small pixel volume ➔ low leakage current (~ few pA/pixel)

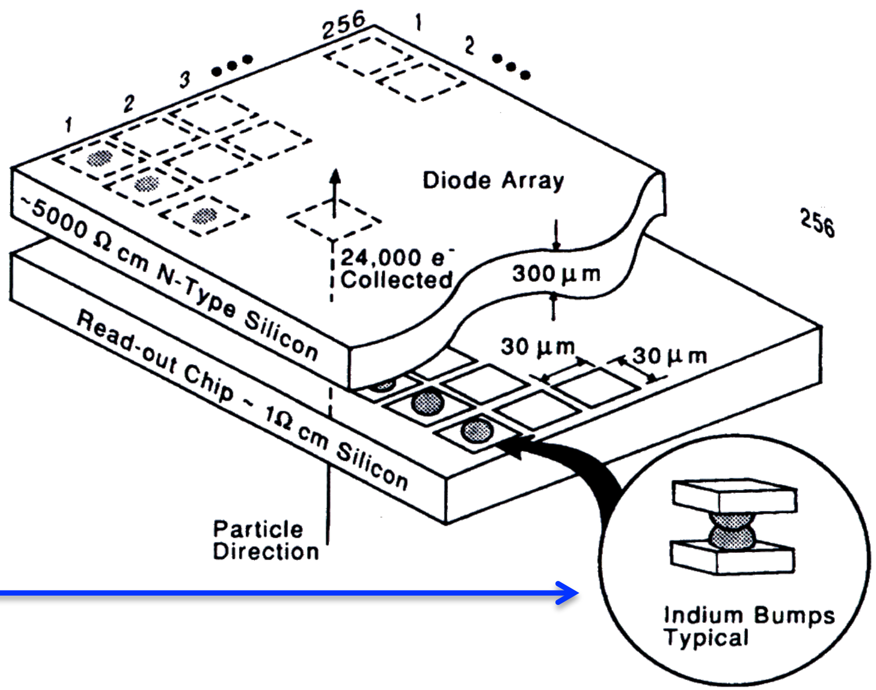
Drawbacks of HPD: large number of readout channels

DSSD ~ 2n

HPD ~ n^2

Large number of electrical connections in case of HPD

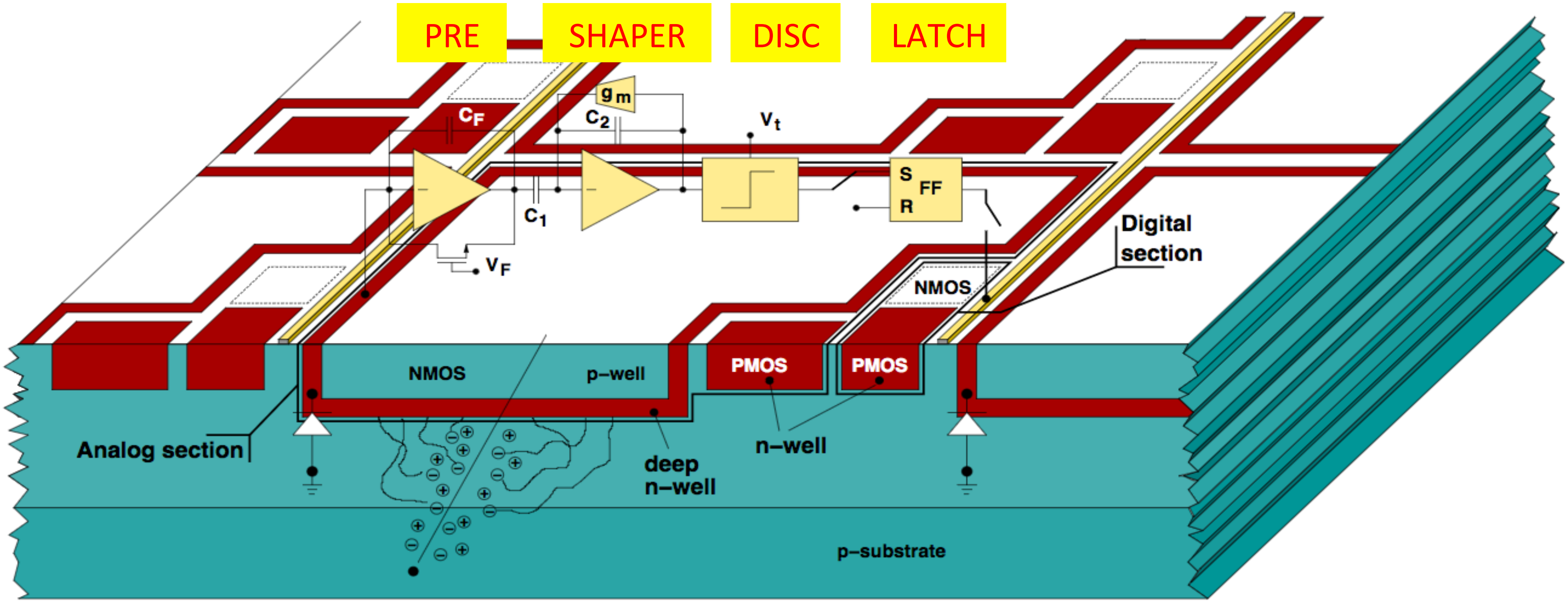
Large power consumptions of electronics



S.L. Shapiro et al., Si PIN Diode Array Hybrids for Charged Particle Detection, Nucl. Instr. Meth. A 275, 580 (1989)

Sensor and electronics together: CMOS MAPS

L. Ratti, IEEE Trans. Nucl. Sci. NS-53 (6) (2006) 3918



Developed for imaging applications

Several reasons make them very appealing as tracking devices :

- detector & readout on the same substrate
- wafer can be thinned down to few tens of μm
- radiation hardness (oxide ~nm thick) (now HV/HR developments)
- Fabrication costs

Important: **maximize** *fill factor* (area of collecting n-well over total sensor area)

Silicon detectors with Low Interaction with Material

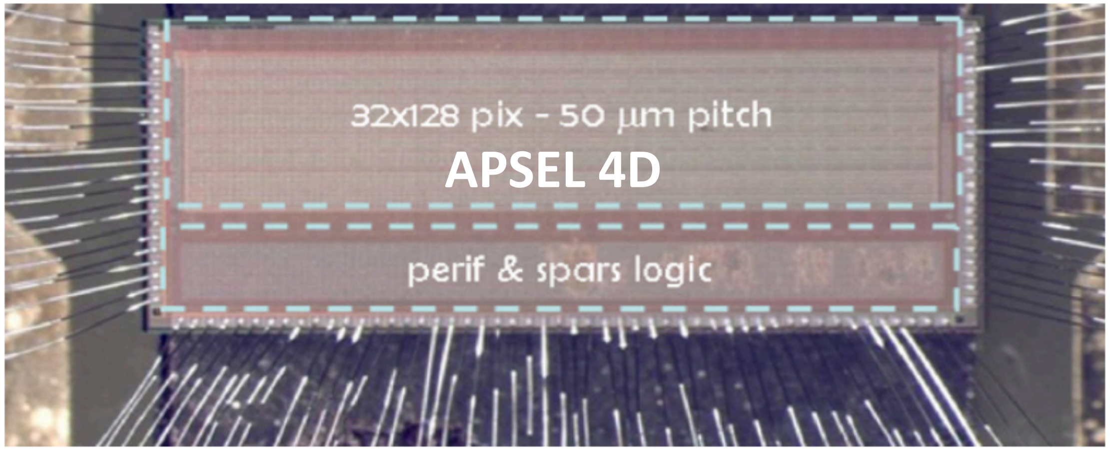
http://www.pi.infn.it/slim5

SLIM5: SILICON SENSORS FOR HIGH LUMINOSITY E+E- COLLIDER EXPERIMENTS

SLIM5 – the project

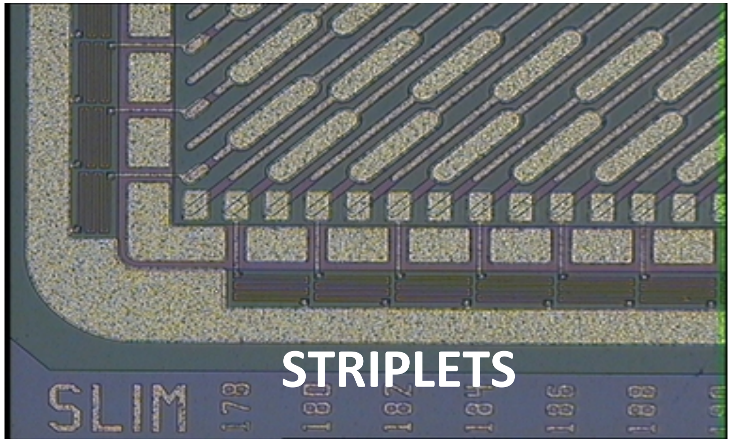
- The SLIM5 project: advance the state-of-the-art of thin tracking systems for high luminosity e^+e^- colliders
- Goal: deliver thin and intelligent (self-triggering/data-driven) silicon tracking detectors for experiments at Super Flavour Factories (SFF) and Linear Collider (LC)
- Typical specifications:
  1. Space point resolution of 10 μm
  2. Material budget below 1% of X_0
  3. Measure $p_T < 100$ MeV/c
  4. Impact parameter resolution of the order of: $\sigma_{ip} = 5\,\mu\text{m} \oplus \frac{10}{p\beta(\sin\theta)^{3/2}}\,\mu\text{m}$
- Two detector concepts were investigated:
- Double sides strip detectors (DSSDs), and
- Monolithic active pixel sensor (MAPS)

SLIM5 silicon sensors



- CMOS MAPS
- Read out up to 40 MHz
- Thinned down to 100 μm
- 50 x 50 μm^2 pitch pixel cells
- Fill factor ~ 90%
- Data sparsification: 4x4 macro pixels (MP) + periphery logic

Nucl. Instr. Meth. A 623 (2010) 942-953

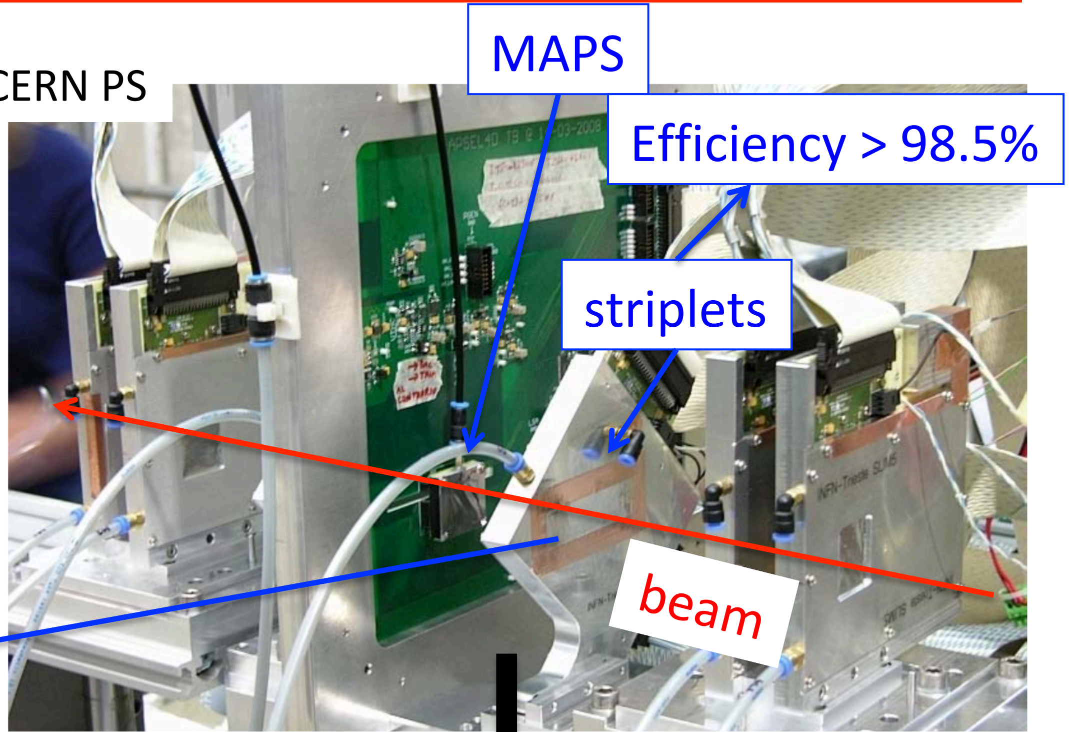


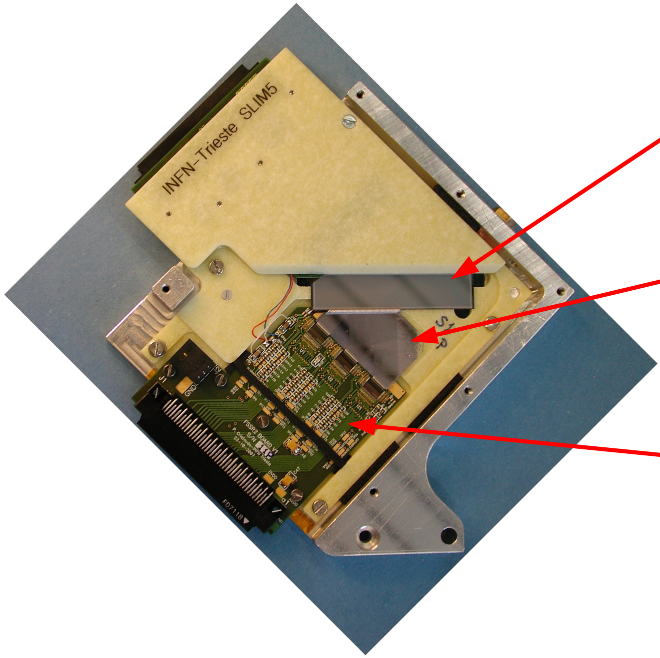
- 200 μm thick double sided strip detector: thinner to reduce multiple scattering effect (0.2%X_0)
- 50 μm pitch strips, tilted by 45^o: less occupancy per channel for the same area
- Data-driven readout chip: data sent out only if above threshold

SLIM5 testbeam

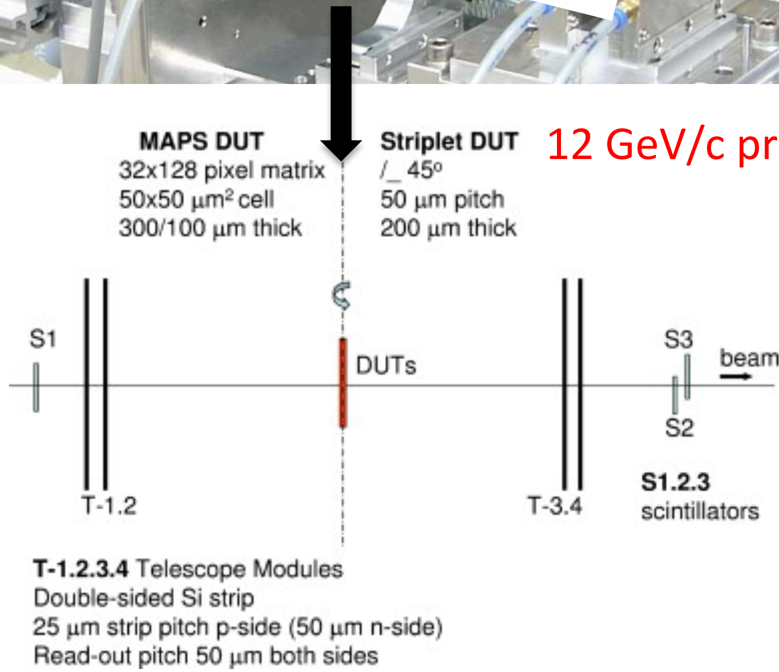
Nucl. Instr. Meth. A 623 (2010) 942-953

2008, CERN PS

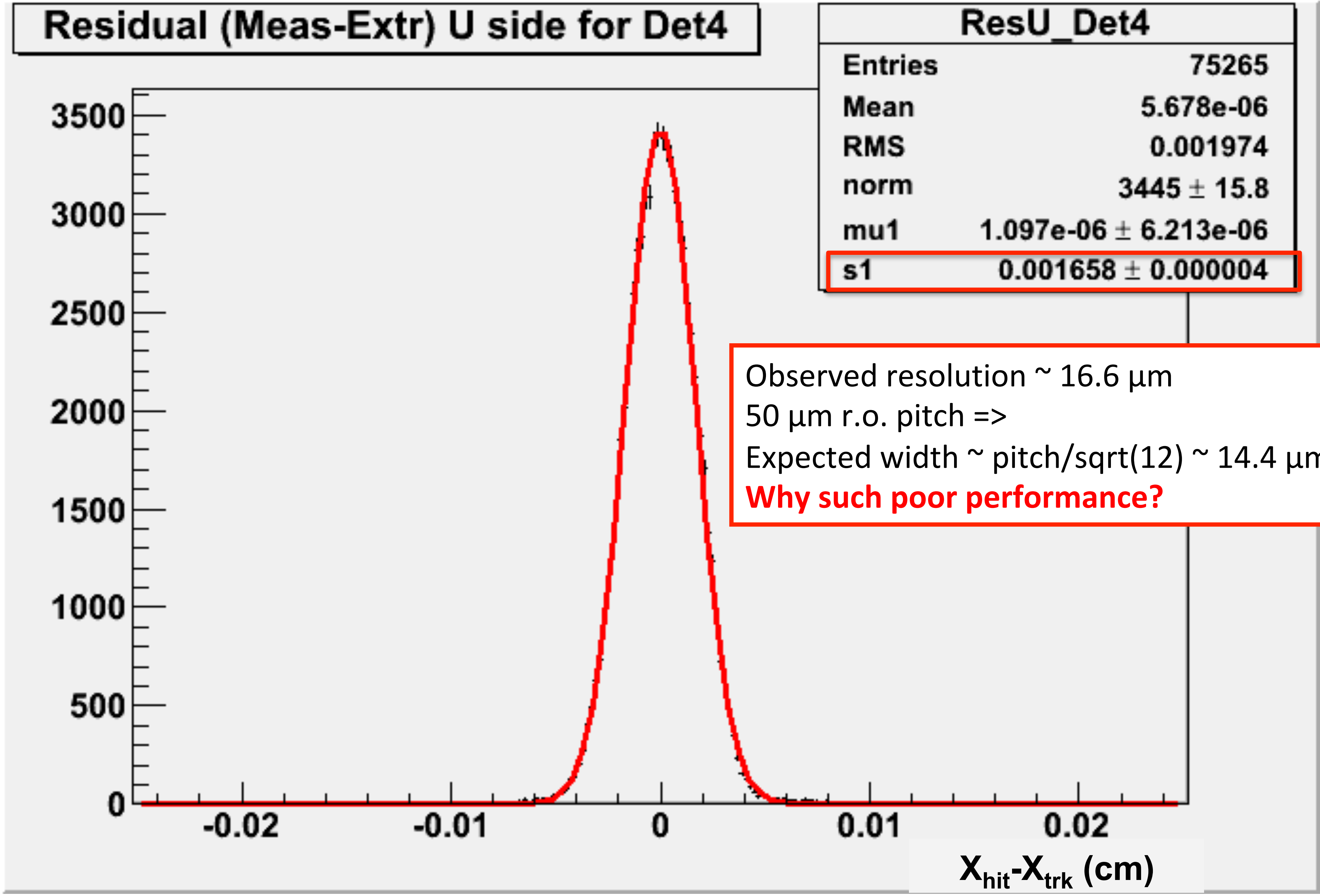




12 GeV/c protons

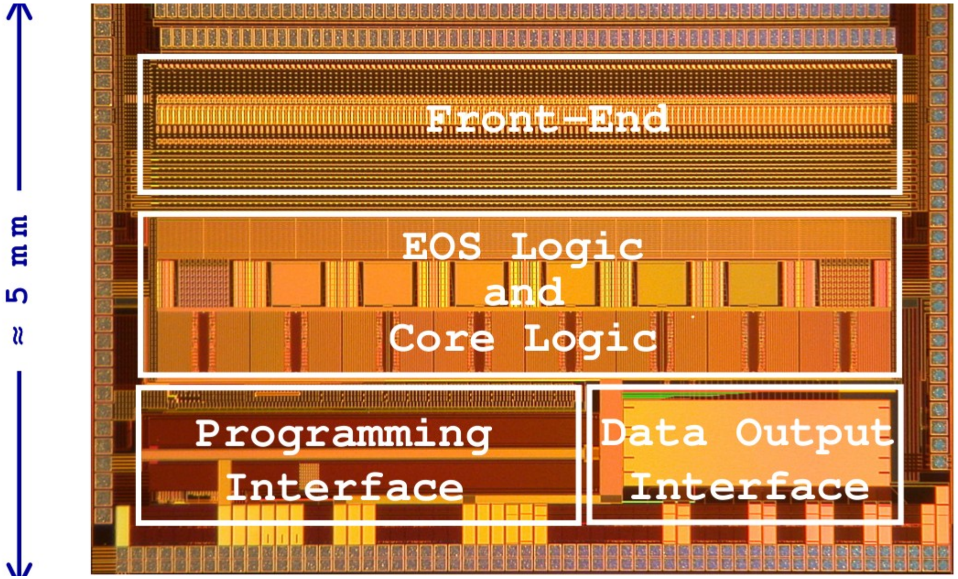


SLIM5 striplets performance: resolution



Observed resolution ~ 16.6 µm
50 µm r.o. pitch =>
Expected width ~ pitch/sqrt(12) ~ 14.4 µm
Why such poor performance?

Striplets front end and spatial resolution



Calibration results for striplets during the testbeam

Side	p	n
Noise (e)	630	1020
S/N	25	16
Gain (mV/fC)	96	67
Threshold (e)	4400	6300
Thr.Dis. (e)	880	780

Signal/Thresh. (S/T) 3.6 2.5

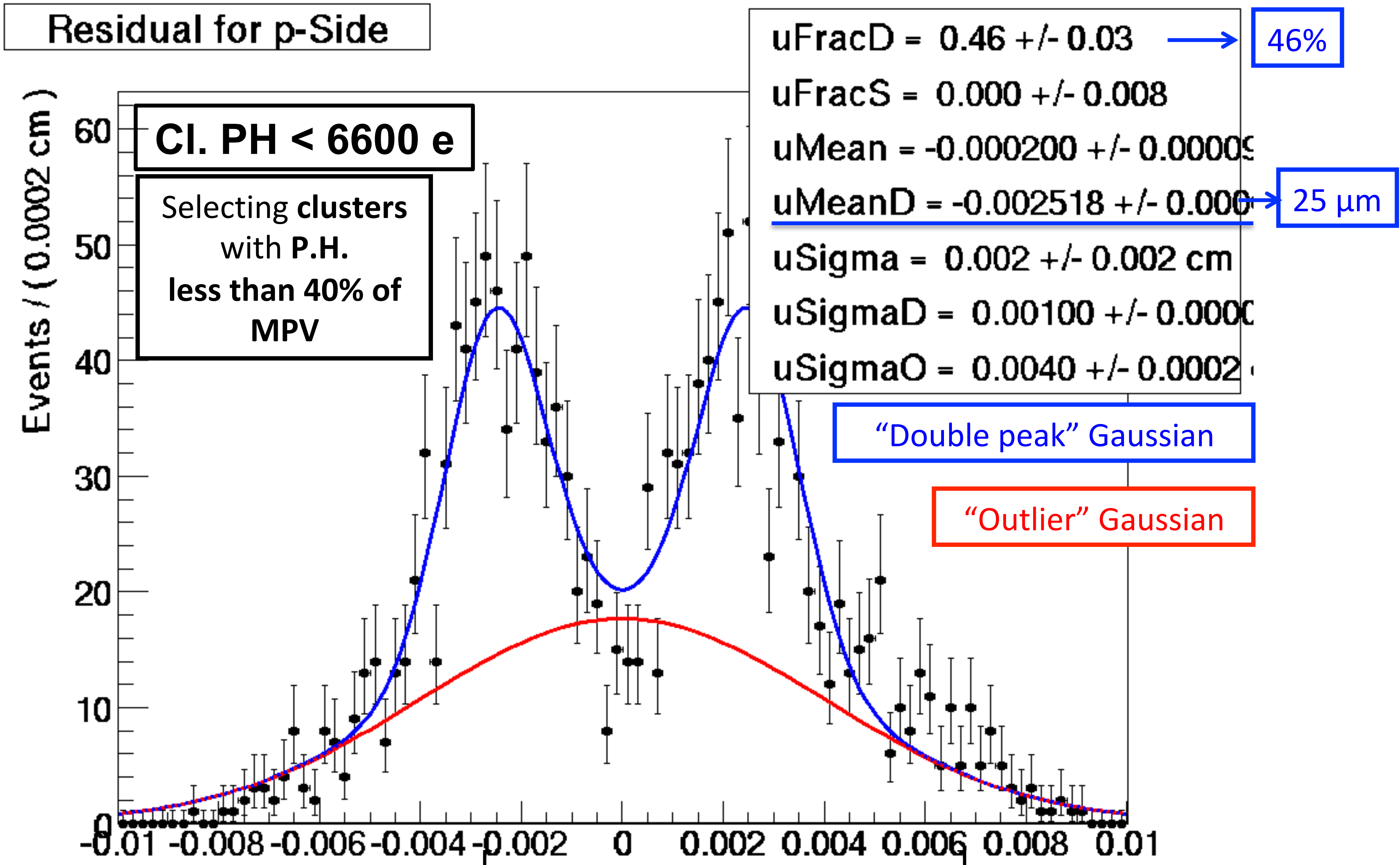
- FSSR2 originally developed for BTeV experiment
- Intended for p-on-n detector => not optimized for ohmic side readout (limited dynamic range)
- Completely datad-driven thanks to
- 8 programmable threshold
- 1st one active as a hit/no-hit discriminator => *zero suppression* mode
- For n-side of striplets only binary information available

IEEE Trans. Nucl. Sci. 53 (2006) 2470–2476

Hypothesis

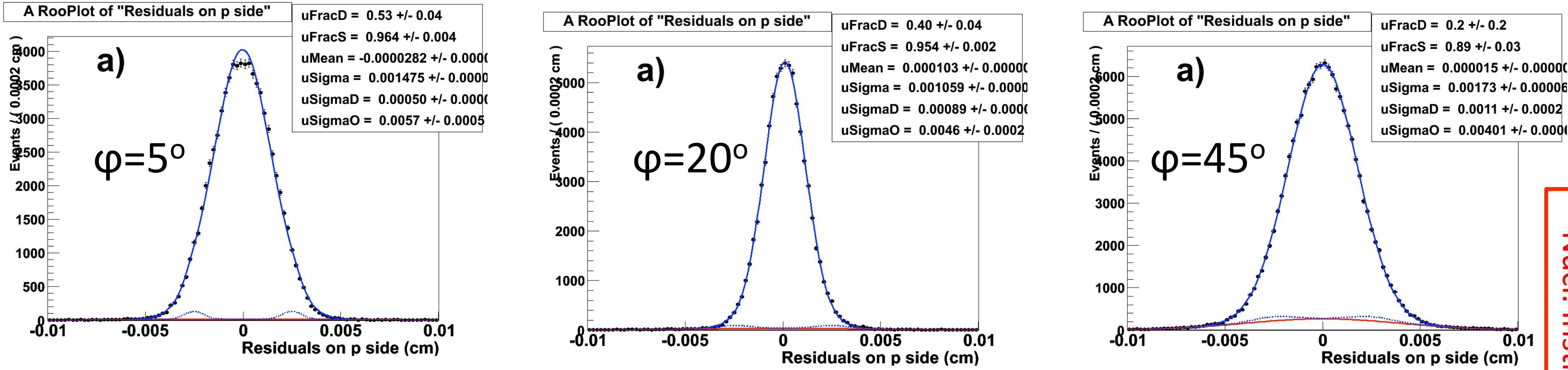
- Due to **marginal S/T small hits** are **below threshold**
- **True clusters of 2 strips reconstructed as 1 strip only**
- Average error on position ~ Pitch/2

Striplets residuals: “double peak”effect

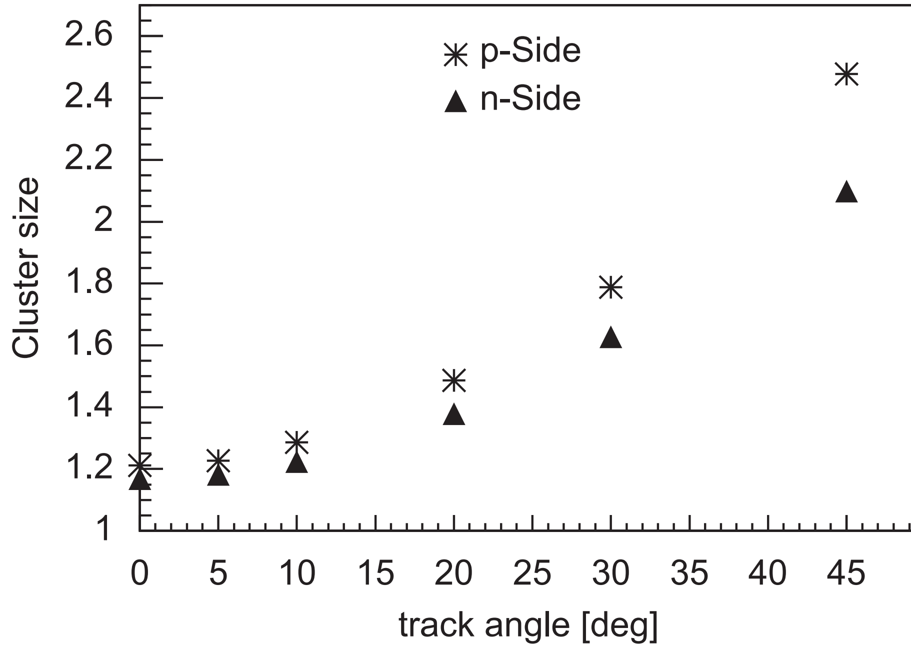


$$f(x) = f_S S(x) + (1 - f_S)\left[f_D D(x) + (1 - f_D) O(x)\right]$$

SLIM5 striplets residuals vs incidence angle

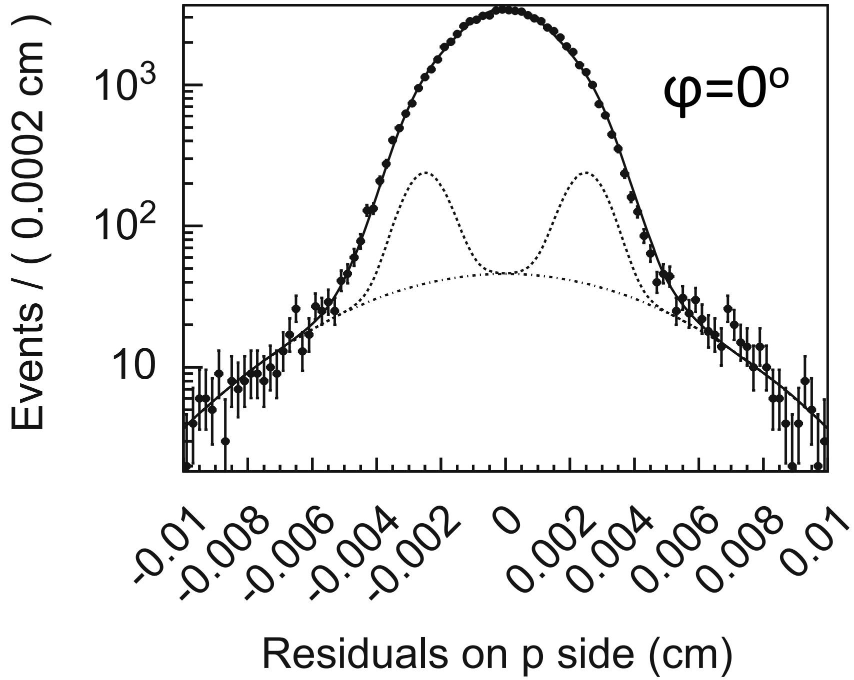


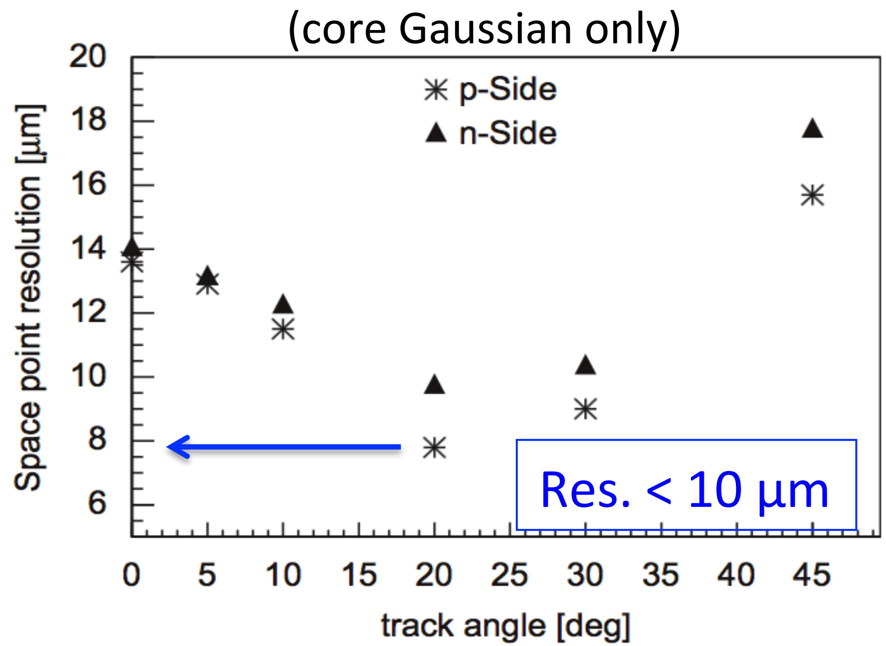
- **Larger incidence angle φ**
- Larger cluster size
- Less chances of mis-reconstructed clusters
- Smaller double peak contribution



Nucl. Instr. Meth. A 623 (2010) 942-953

SLIM5 striplets performance: conclusions





Nucl. Instr. Meth. A 623 (2010) 159 – 161

Nucl. Instr. Meth. A 623 (2010) 942-953

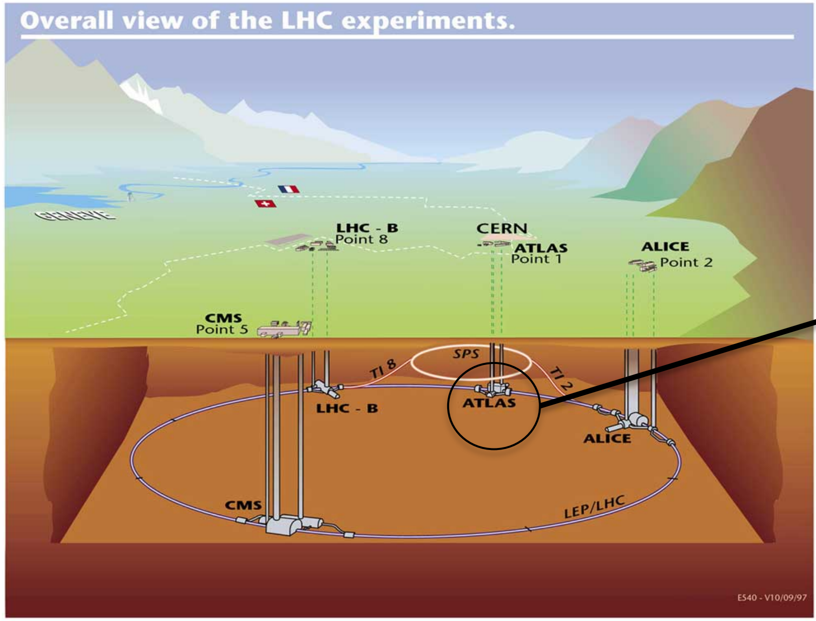
- The **spatial resolution** performance of the **striplets** were severely **impacted by** the sub-optimal functioning of the FFSR2 **readout chip**
- **Ultimate resolution**, measurable once the double peak effect has been identified, **within the specifications**

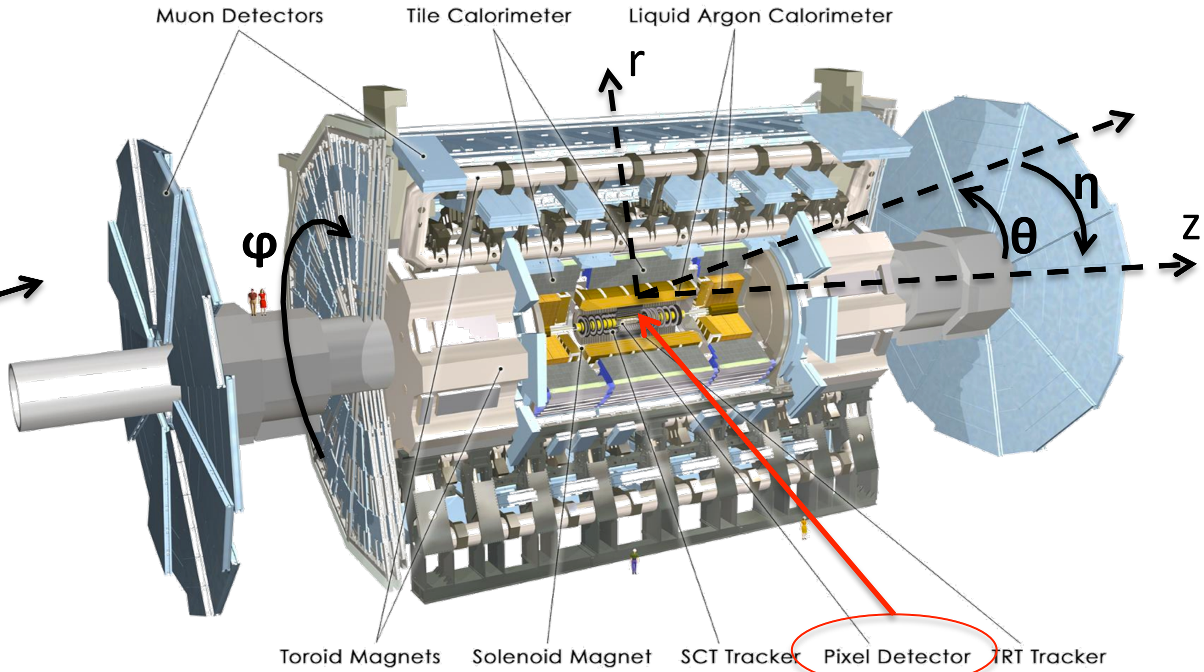
➢ Need for a better readout chip, in terms of noise and speed

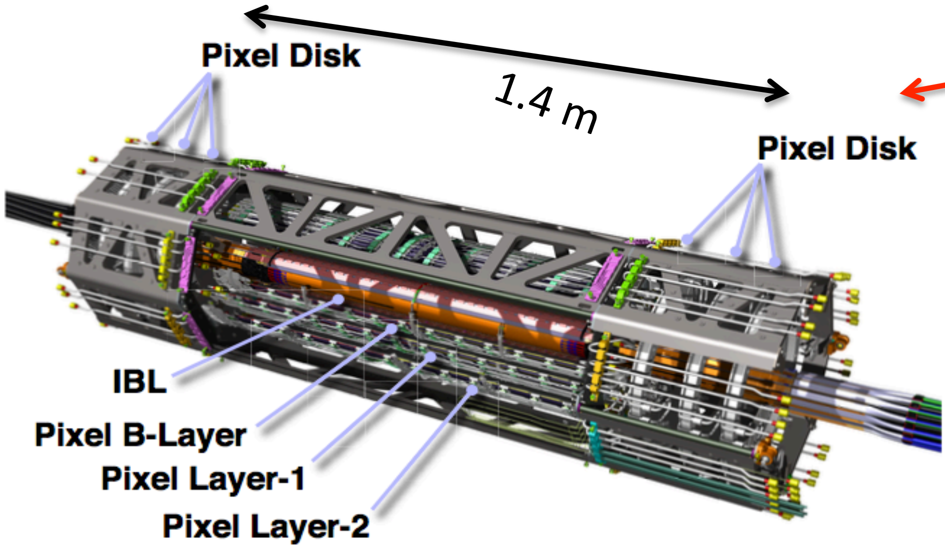
- **Material budget under control (0.2% X_0)**

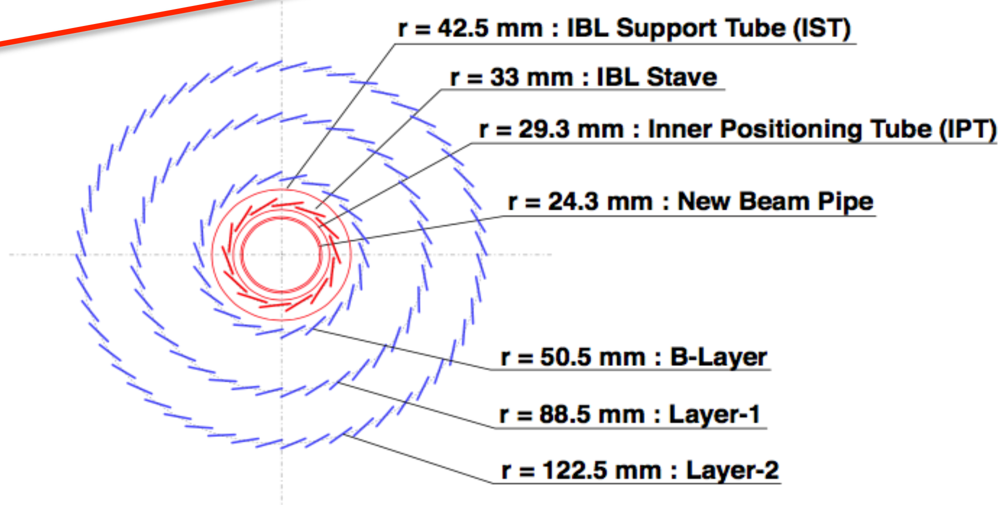
RADIATION DAMAGE MODELLING FOR THE ATLAS PIXEL DETECTOR

Current ATLAS detector @ CERN LHC





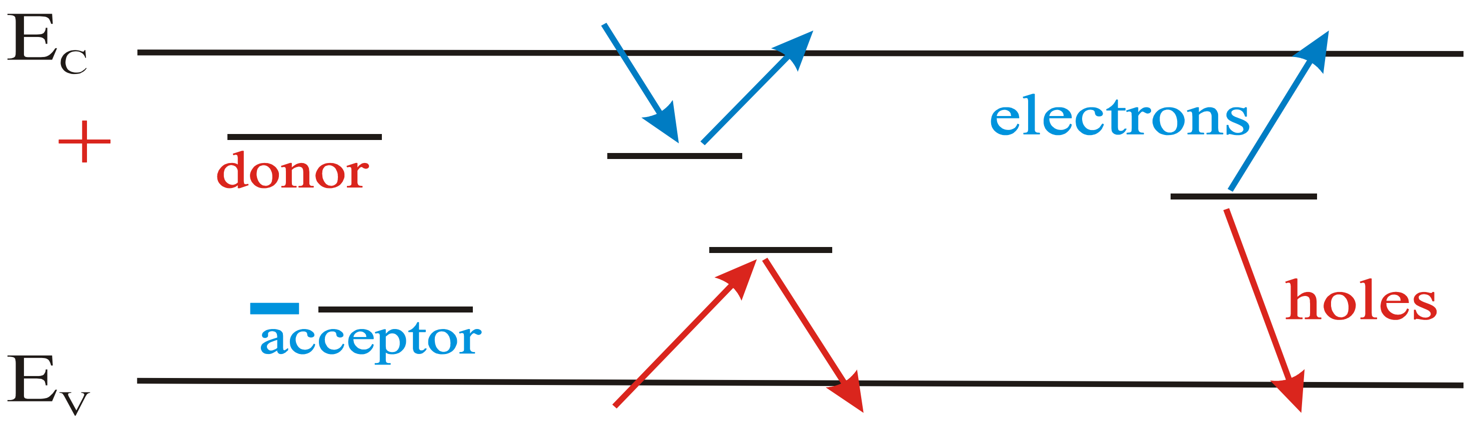




Radiation damage in silicon: microscopic level

M. Moll, Simdet 2016

Shockley-Read-Hall statistics
(standard theory)



charged defects
⇒ N_{eff} , V_{dep}
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)
⇒ CCE
shallow defects do not contribute at room temperature due to fast detrapping

generation
⇒ leakage current
Levels close to midgap most effective

Impact on detector properties can be calculated if all defect parameters are known:

$\sigma_{n,p}$: cross sections **ΔE : ionization energy** **N_t : concentration**

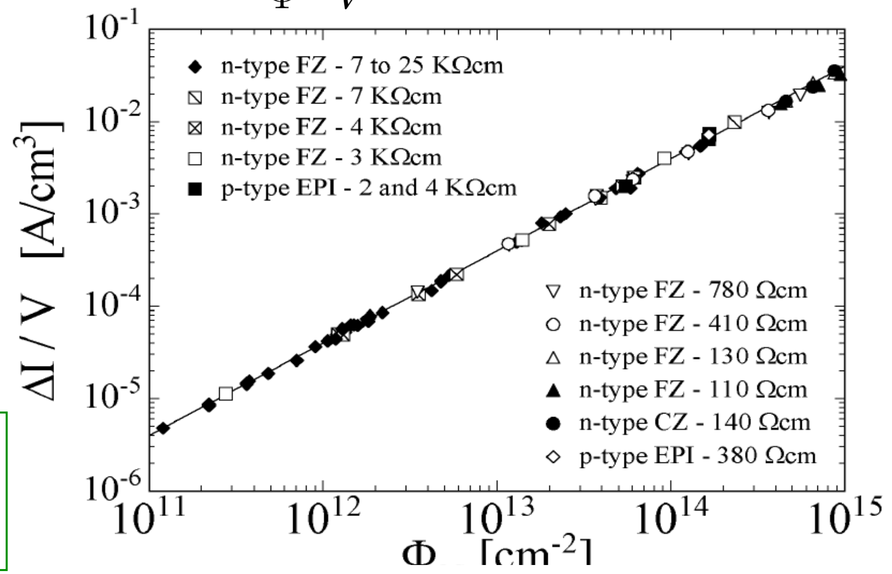
+ annealing...

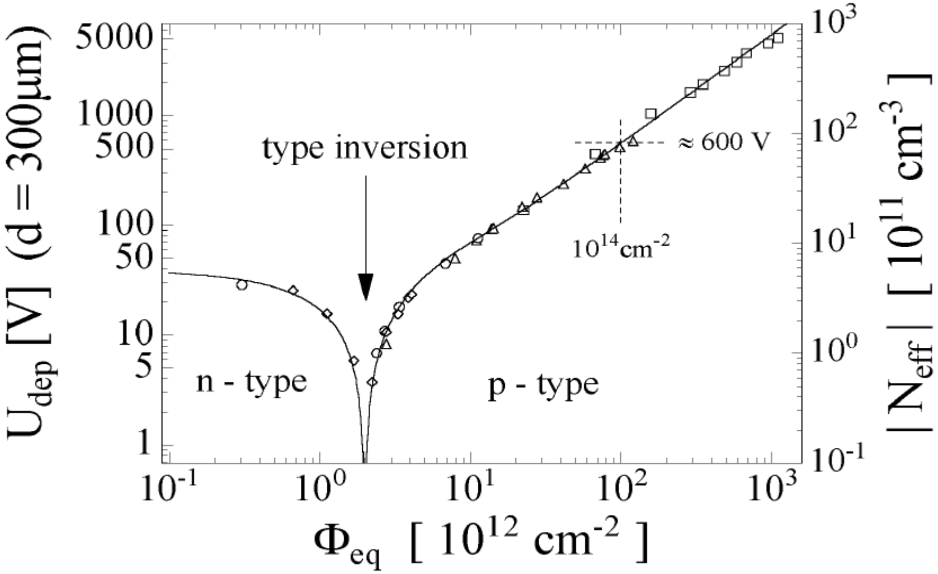
Radiation damage in silicon bulk

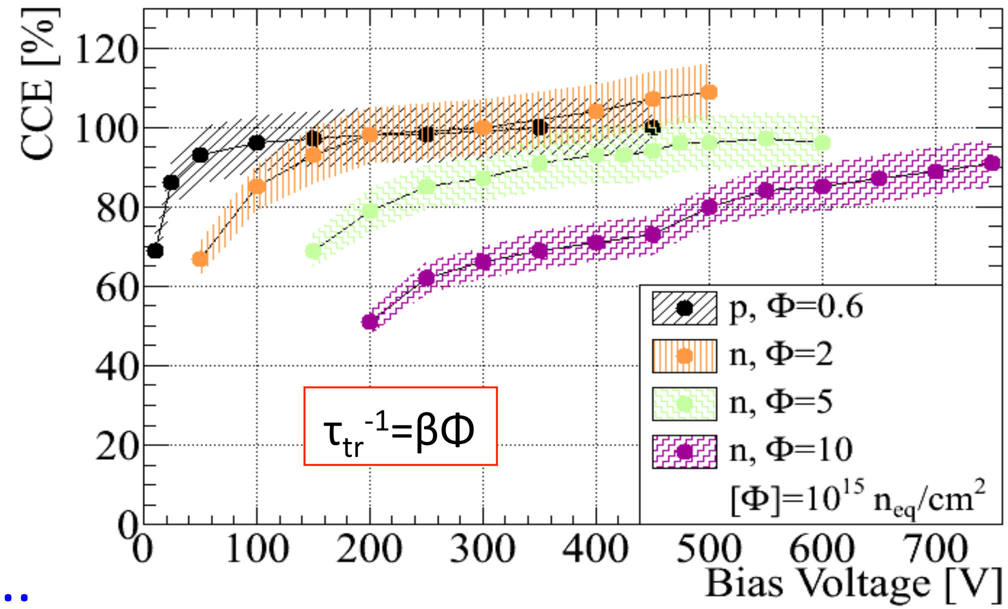
- The leakage current increase is prop. to ϕ
- The U_{dep} increases is prop. to ϕ after type inversion
- The defects acts as trapping centers

M. Moll thesis, MPI group

$$\alpha = \frac{\Delta I}{\Phi \cdot V} \sim 4 \times 10^{-17} A/cm$$







+ annealing...

Defects annealing

Defects **annealing** includes defects migration, formation and dissociation

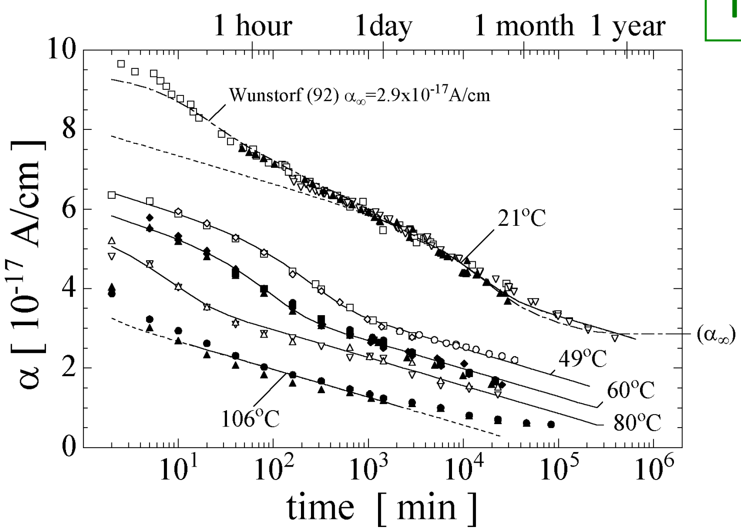
All **phenomena depend on temperature and** show a characteristic **time**, the latter depending on temperature

At first order all annealing processes become quickly negligible below 0º C

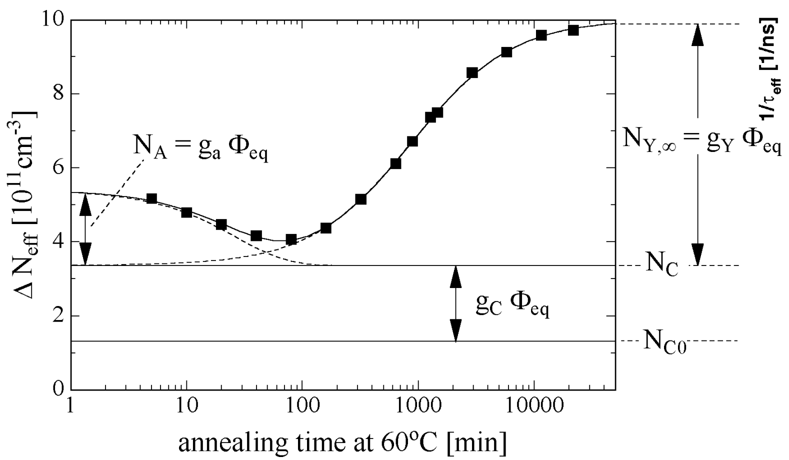
Annealing effects on macroscopic observables:

M. Moll thesis

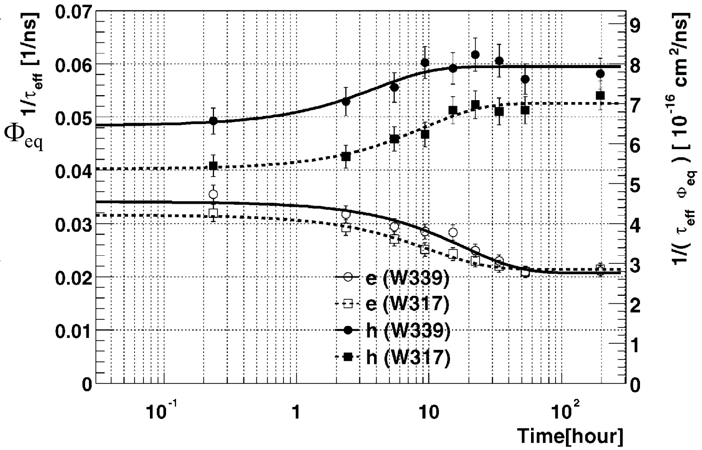
NIM A481(2002)297–305



Leakage current is always **decreasing** with time/ temperature



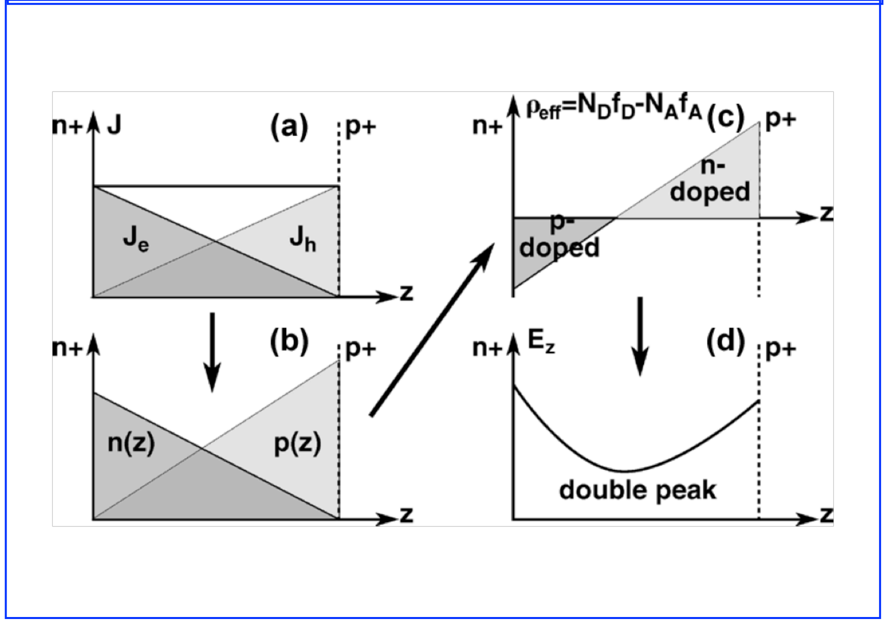
Operational **voltage** decreases at first (**“beneficial annealing”**) then it increases (**“reverse annealing”**)



Trapping constant annealing is **beneficial for electrons** while shows **opposite** behaviour **for holes**

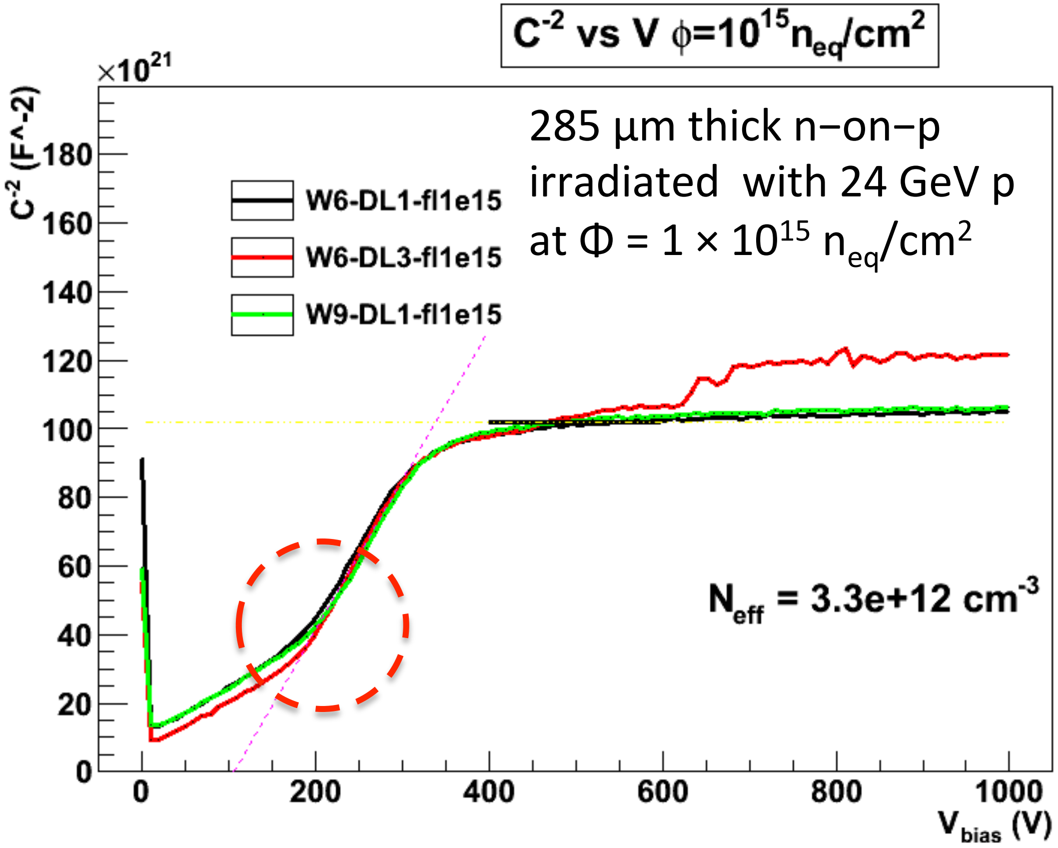
Electric field distribution in irradiated silicon

Double peak effect in electric field



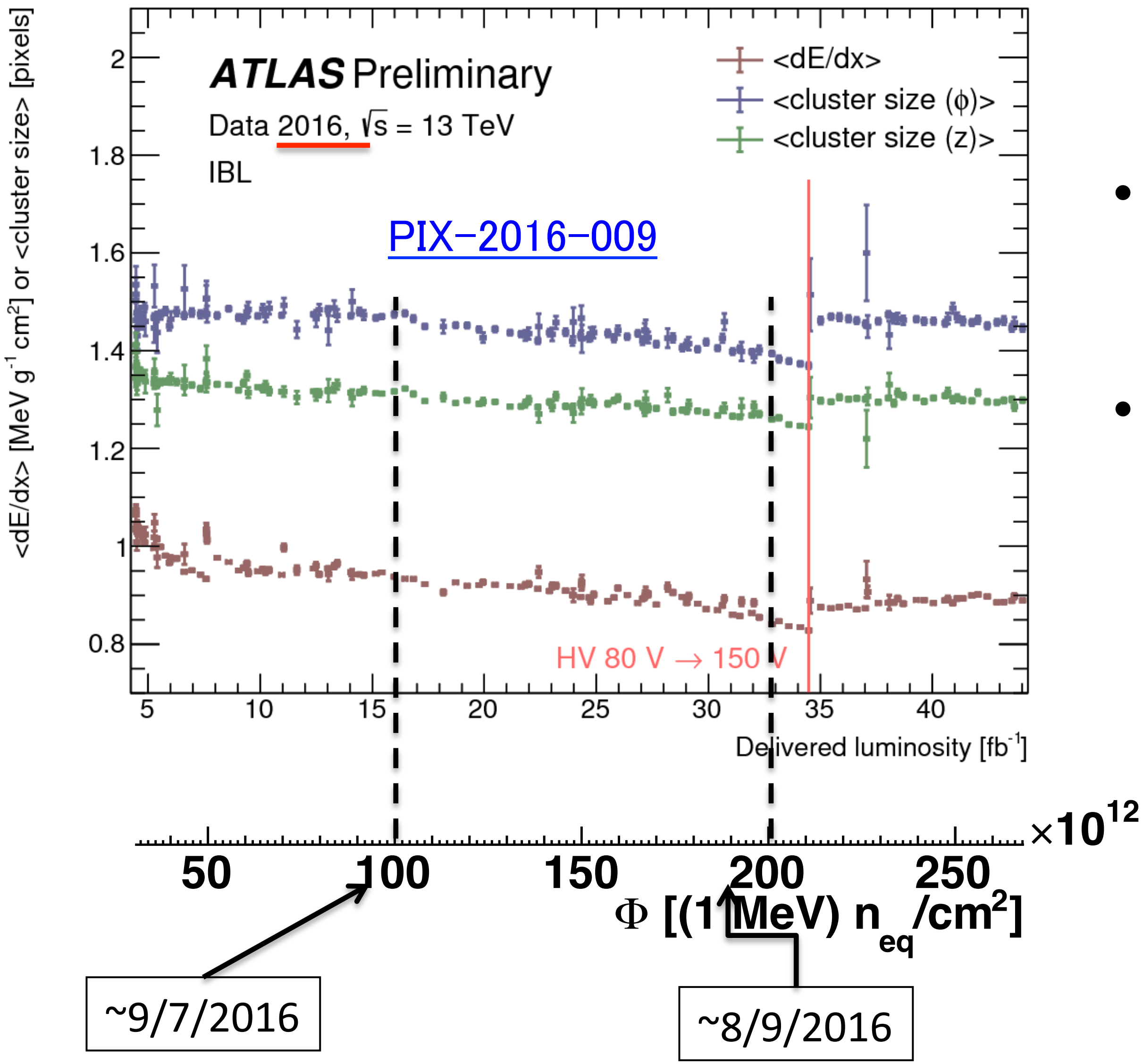
NIMA 476 (2002) 556–564

IEEE TNS 52 (2005) 1067–1075

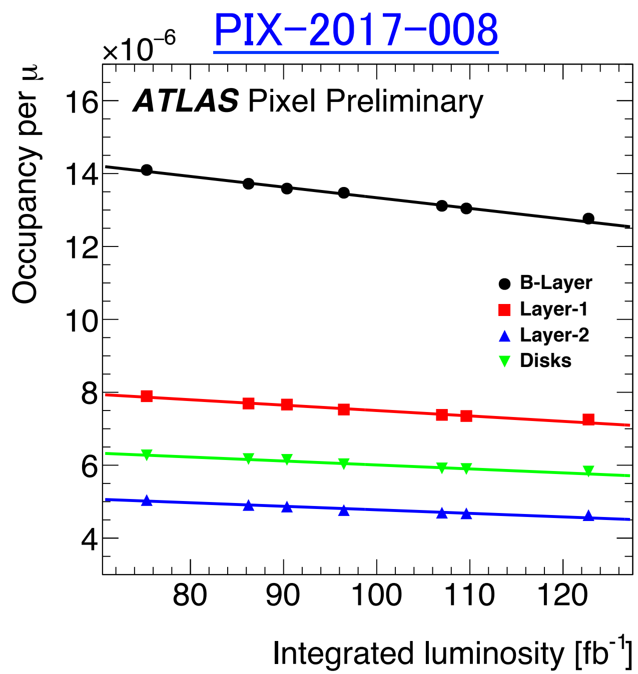


- Thermally generated carriers drift towards collecting electrodes
- Negative/positive space charge builds up approaching n^+/p^+ implant
- ➢ **Space charge distribution is no longer constant**
- ➢ Electric field is no longer linear function of bulk depth
- ➢ Visible in C^{-2} vs V analysis as a change of slope

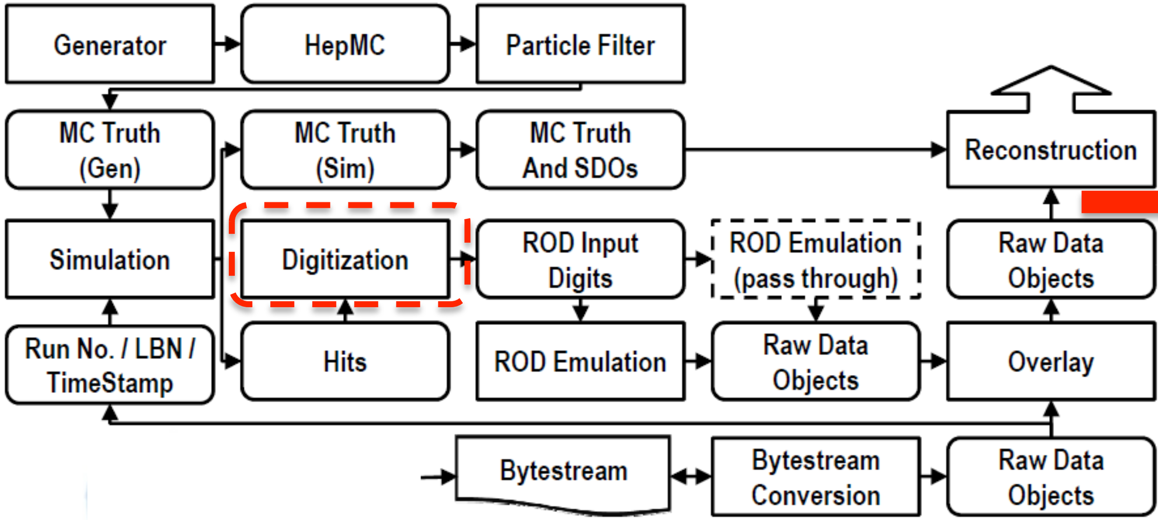
Radiation damage in current ATLAS pixels



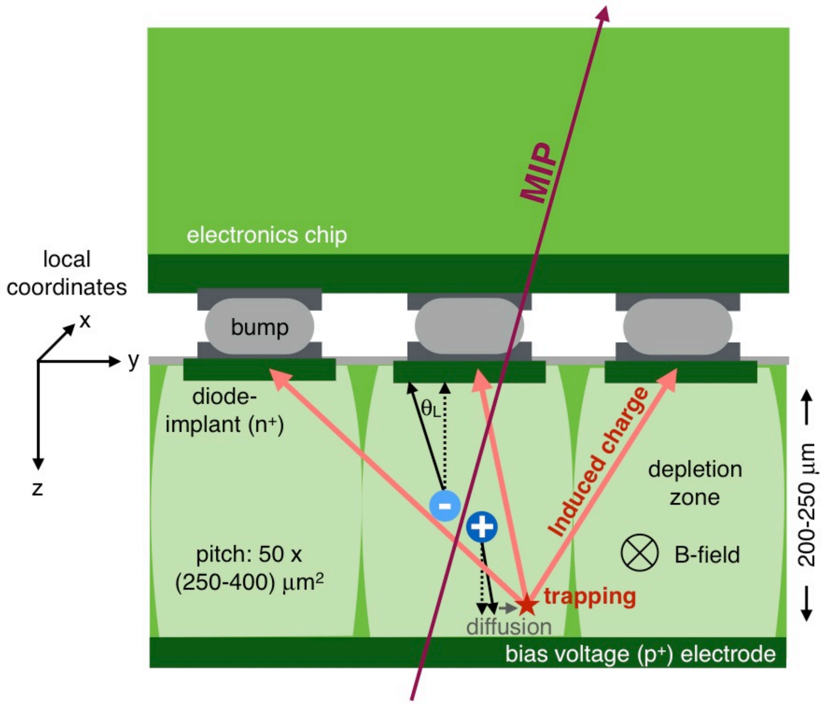
- Significant **decrease of dE/dx and cluster size for IBL**
  - Similar effect for B-Layer
- It was **necessary** to **increase** the **bias voltage** to halt the negative trend
- Occupancy decreasing too



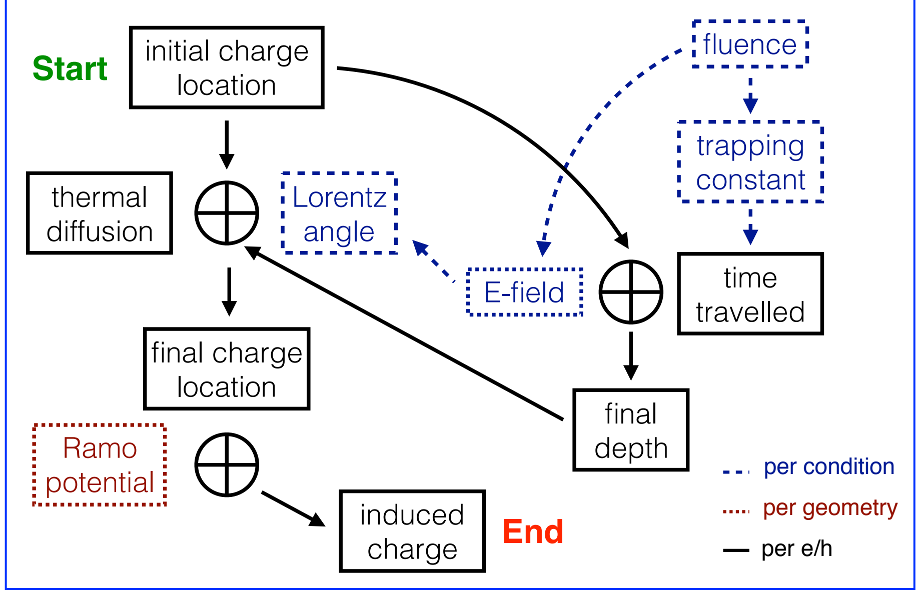
Modelling radiation damage in ATLAS simulations



- **Digitization** step transforms carriers in digital signals on collecting electrodes
- We developed a new digitizer which includes:
  - Deformed electric field (**TCAD**)
  - Signal induced by trapped charges



Digitizer algorithm flowchart



+ procs accepted by Jinst
arXiv:1710.03916

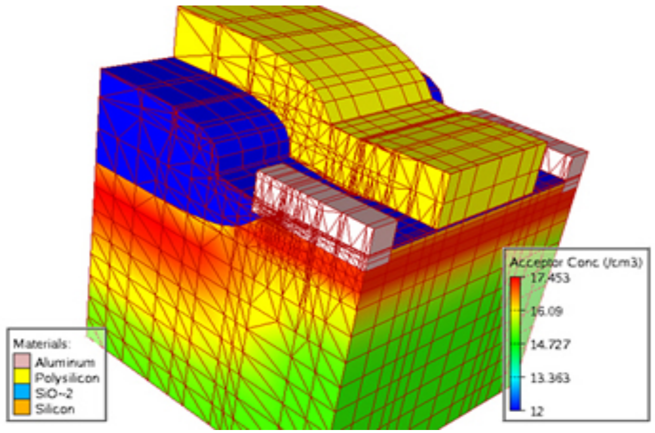
TCAD simulations for ATLAS pixels new digitizer

- Technology Computer Aided Design (TCAD) used to calculate electric field after irradiation (and Ramo potential too) for new digitizer
- Solving drift/diffusion & Poisson equations for electrons and holes:

$$J_n = qn\mu_n E + qD_n \frac{\partial n}{\partial x} \qquad \frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + G_n - R_n$$

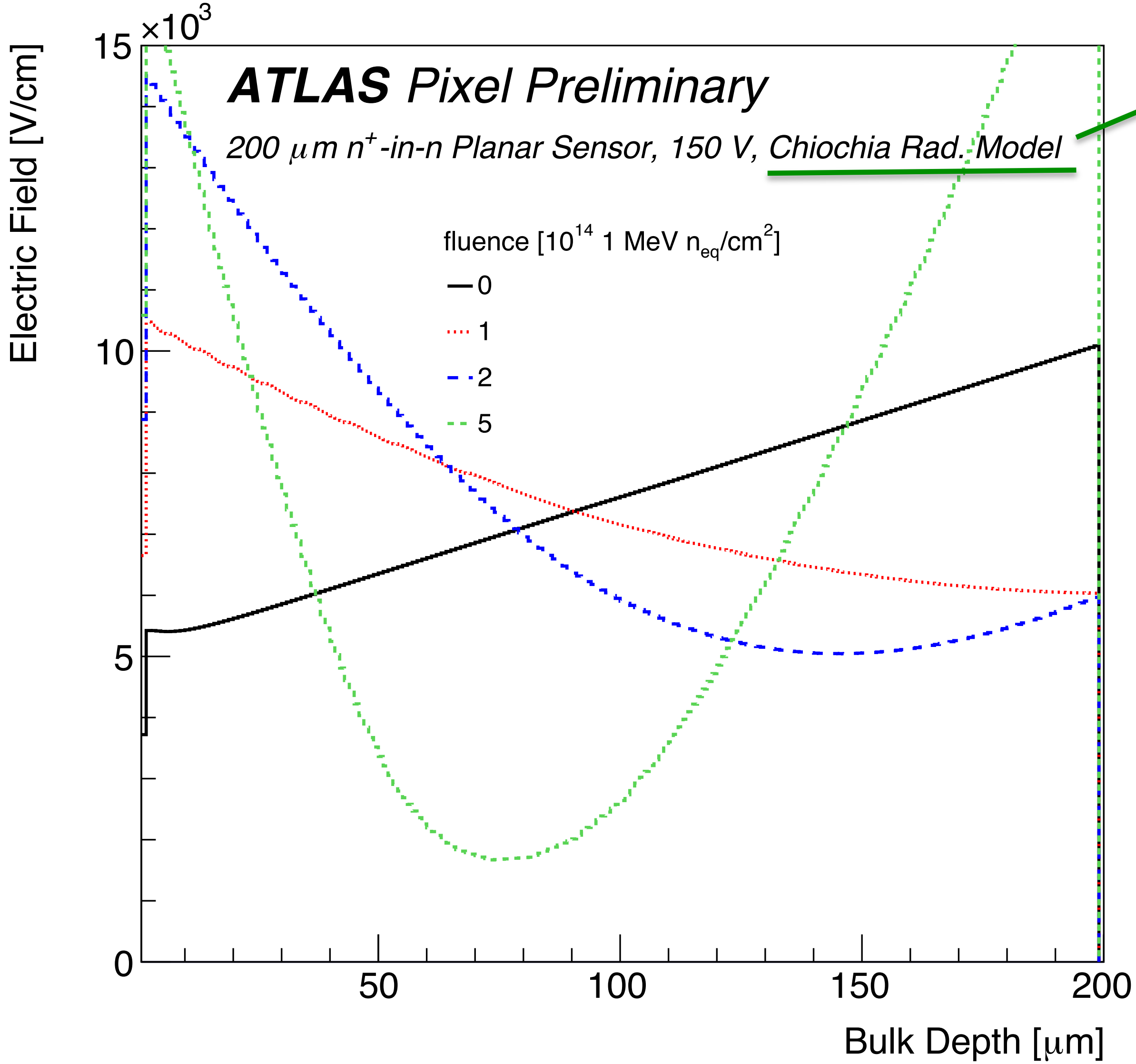
$$J_p = qn\mu_p E - qD_p \frac{\partial p}{\partial x} \qquad \frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + G_p - R_p$$

$$\frac{\partial^2 \psi}{\partial x^2} = -\frac{q}{\epsilon_{Si}\epsilon_0}(N_D + p(x) - n(x) - N_A)$$

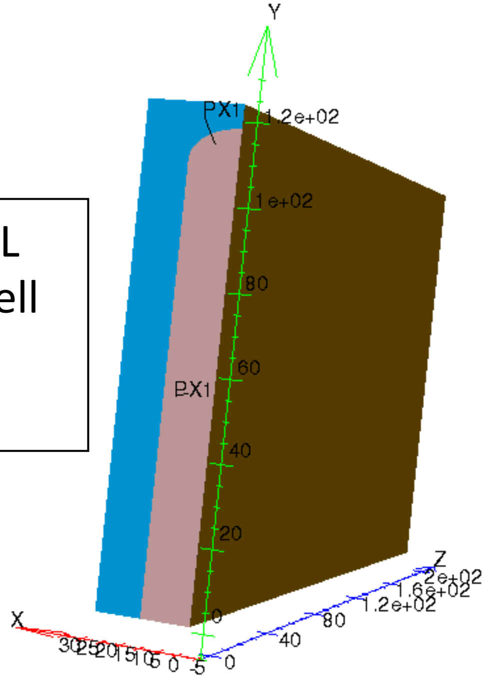


- taking into account **boundary conditions**
  - Electrodes' potentials, interface charges, etc
- on a grid of points
- Powerful **tool to explore and optimize** new **sensors geometries** (*e.g.* edgeless detectors) and performance after irradiation

Electric field predictions for IBL planar sensors



NIM A568 (2006) 51–55



A ¼ of the IBL planar pixel cell has been simulated

After irradiation the **electric field** is **no** longer a **linear** function of the bulk depth

This has an **impact** on:

- **Charge Collection Efficiency**
- **Lorentz Angle**

A word on TCAD radiation damage models

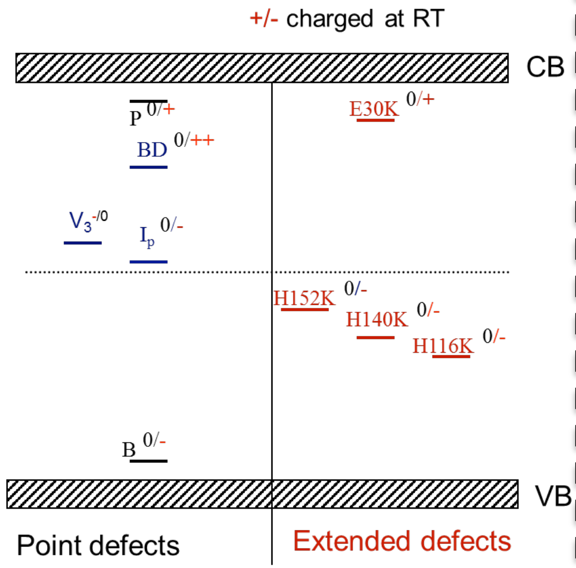
Measured defects

Point defects

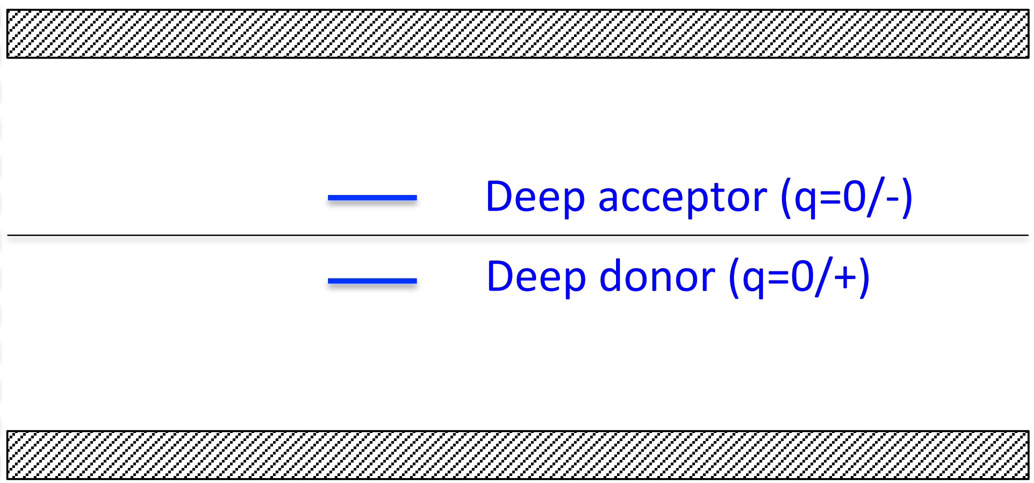
- $E_a^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3\cdot10^{-14}$ cm^2
- $E_a^{V3} = E_c - 0.545$ eV
  - $\sigma_n^{V3} = 1.7\cdot10^{-15}$ cm^2
  - $\sigma p^{V3} = 9\cdot10^{-14}$ cm^2
- $E_a^{Ip} = E_c - 0.545$ eV
  - $\sigma_n^{Ip} = 1.7\cdot10^{-15}$ cm^2
  - $\sigma p^{Ip} = 9\cdot10^{-14}$ cm^2

Extended defects

- $E_a^{H116K} = E_v + 0.33$eV
- $\sigma_p^{H116K} = 4\cdot10^{-14}$ cm^2
- $E_a^{H140K} = E_v + 0.36$eV
- $\sigma_p^{H140K} = 2.5\cdot10^{-15}$ cm^2
- $E_a^{H152K} = E_v + 0.42$eV
- $\sigma_p^{H152K} = 2.3\cdot10^{-14}$ cm^2
- $E_a^{E30K} = E_c - 0.1$eV
- $\sigma_n^{E30K} = 2.3\cdot10^{-14}$ cm^2



Simulated defects (TCAD, Chiochia model)



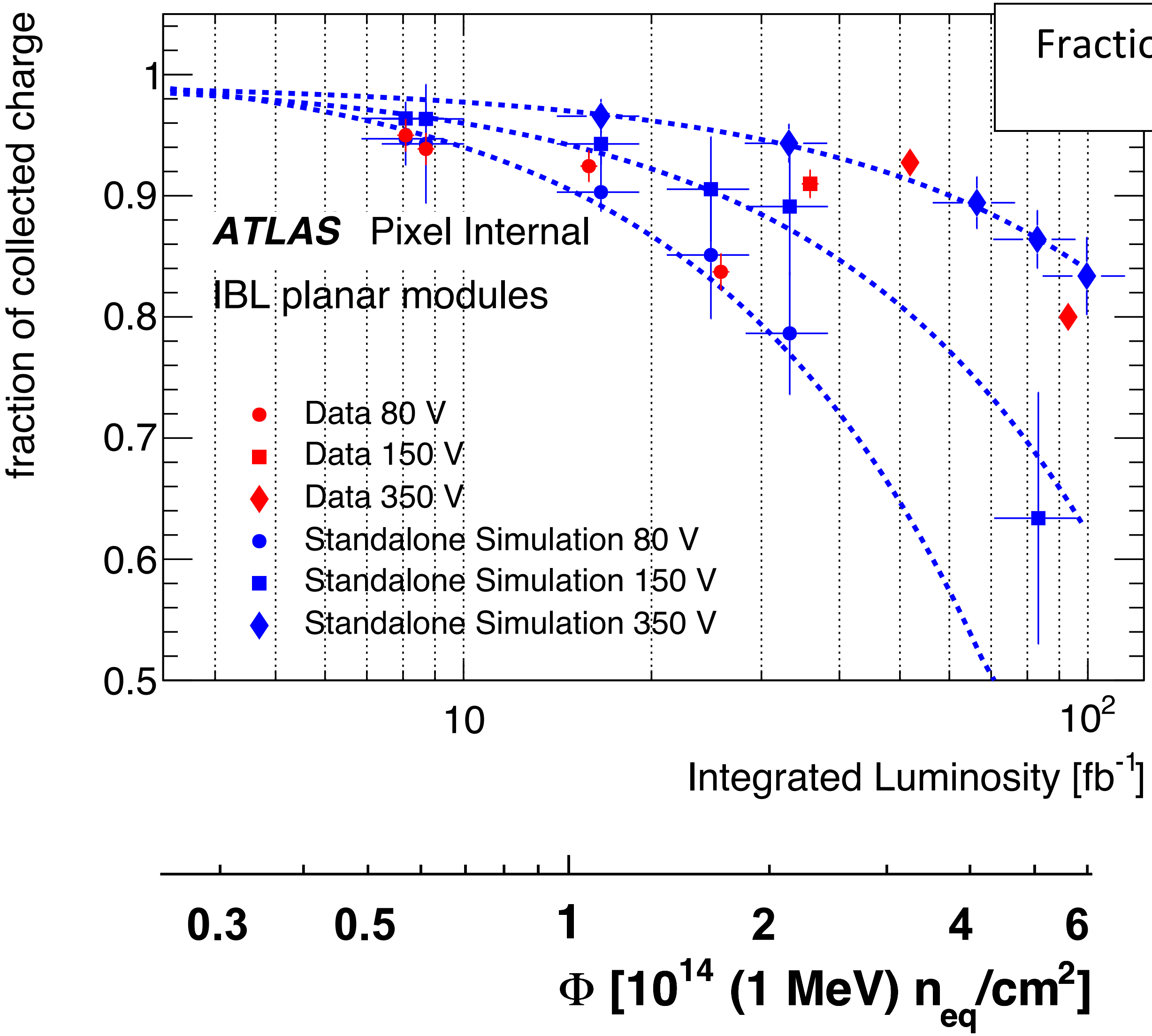
I. Pintilie *(VERTEX2016)*. 25-30 September, 2016.

M. Moll, Simdet 2016

Working with "effective levels" for simulation of irradiated devices

- Most often 2, 3 or 4 "effective levels" used to simulate detector behavior
- Defect densities and cross sections of defects tuned to match experimental data
- Leakage current, signal loss and electric field profile reproducible (with some caveats)

Charge collection efficiency: data vs simulation



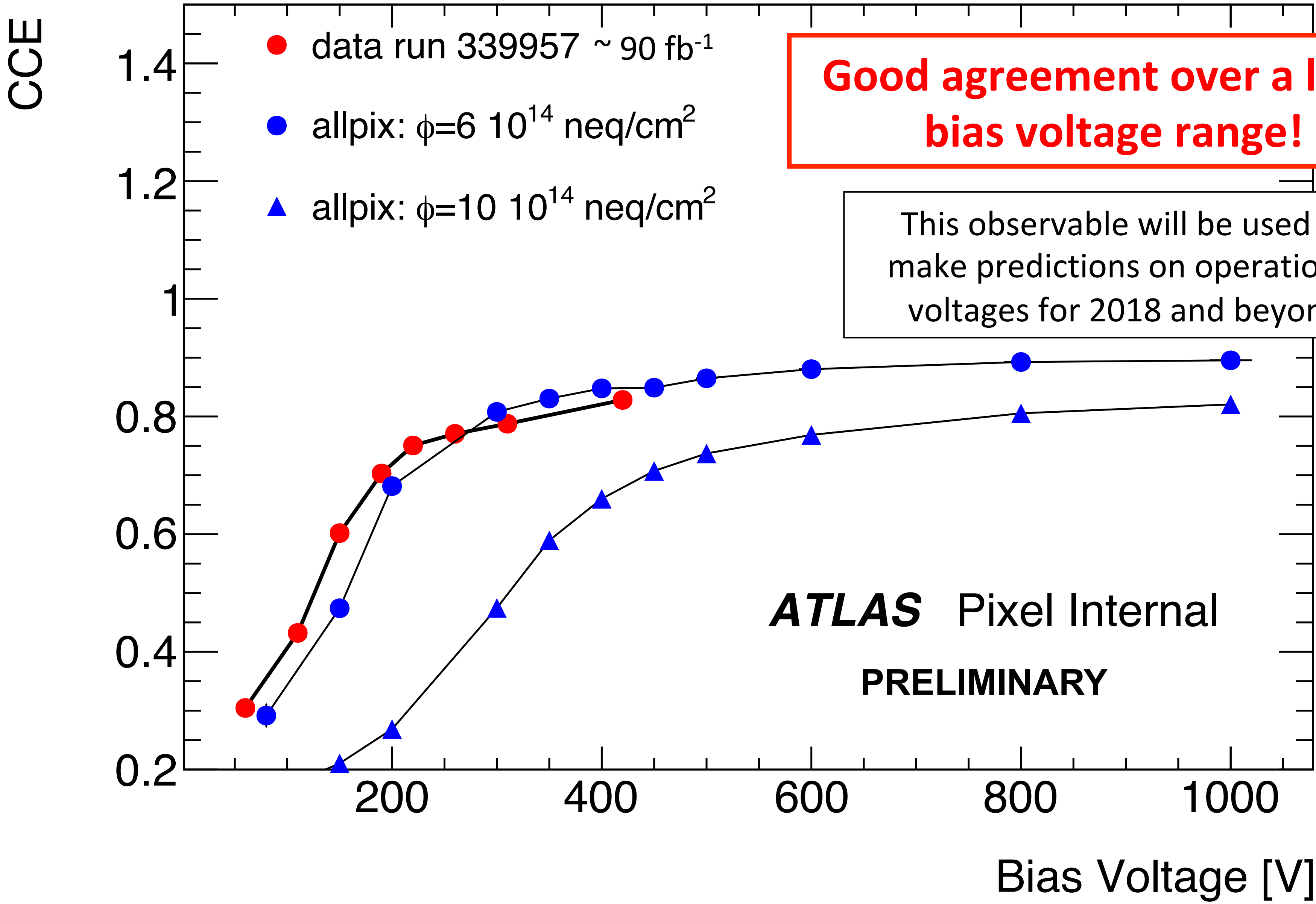
Fraction of collected charge defined as clusters MPV normalised to un-irradiated case

- Good agreement between **collision data** and **our simulation**
- **Essential tool to understand what operational condition to use in the future**
- Error bars H(orizontal) & V(ertical):
  - Data:
    - (H) 2% on luminosity
    - (V) charge calibration drift
  - Simulation:
    - (H) 15% on fluence est.
    - (V) TCAD parameters

Old public version available here: PIX-2017-004

arXiv:1710.03916
+ procs accepted by Jinst

CCE vs Bias Voltage in IBL planar sensors



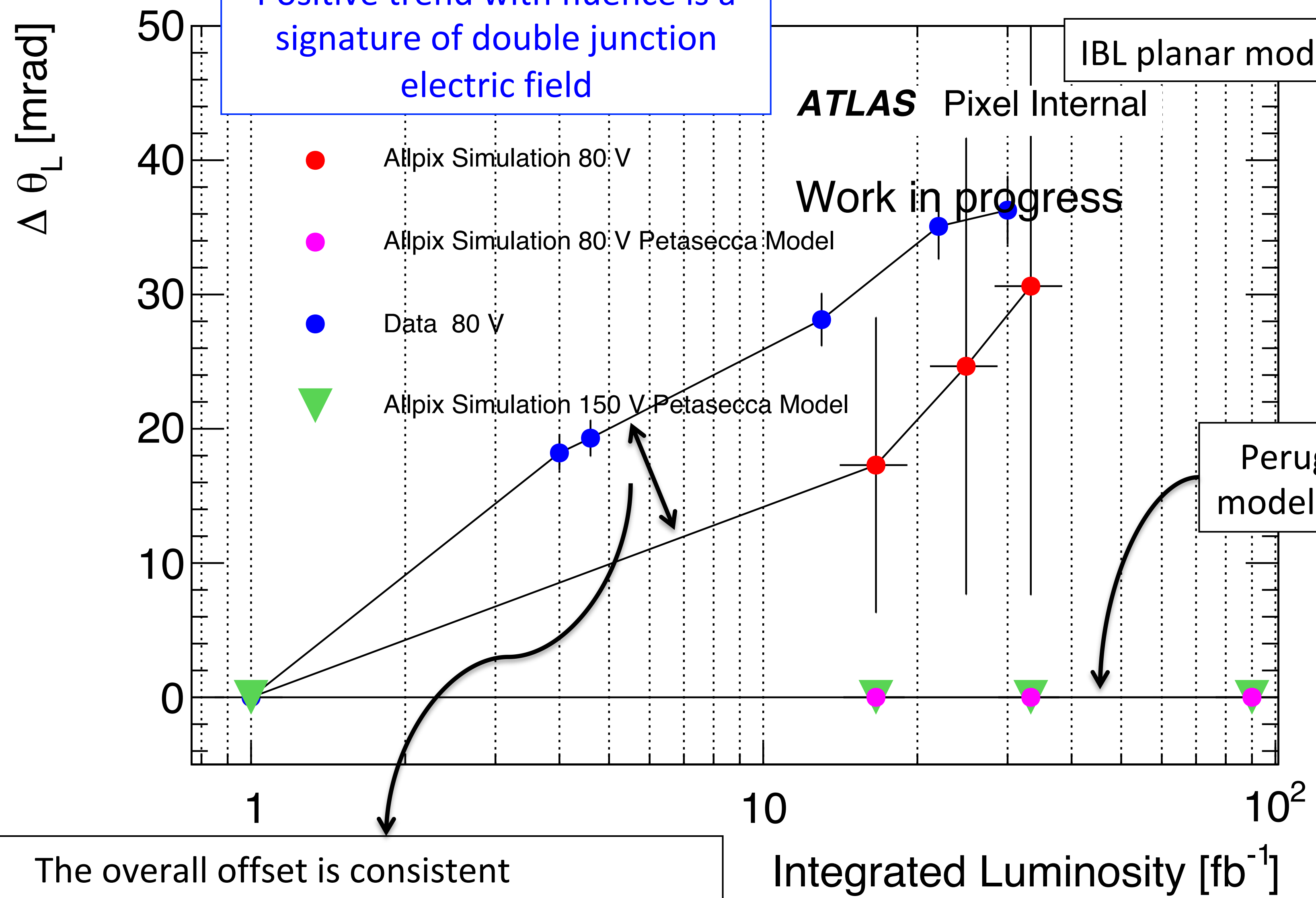
Good agreement over a large bias voltage range!

This observable will be used to make predictions on operational voltages for 2018 and beyond

Lorentz Angle in ATLAS pixels: data vs simulation

Positive trend with fluence is a signature of double junction electric field

IBL planar modules



Perugia 2006 model ruled out

The overall offset is consistent with previous studies and appears even without radiation damage (zero fluence)

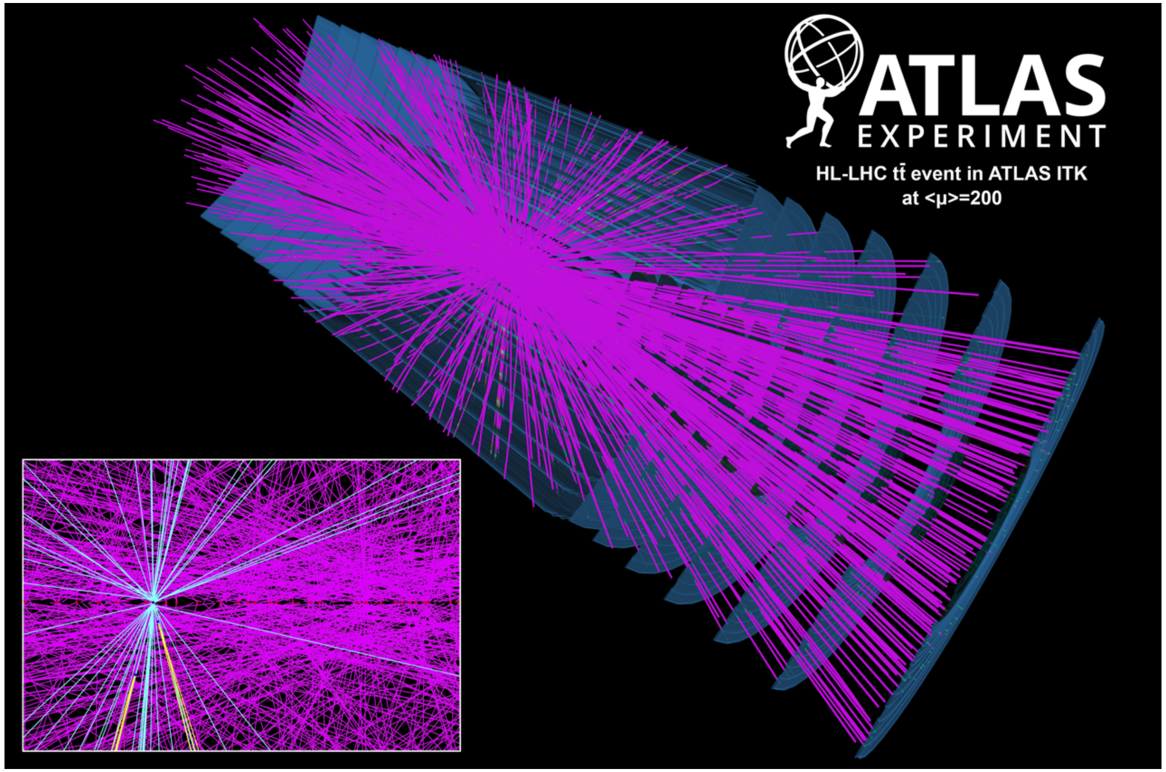
Comments and Summary

- Radiation damage is already impacting ATLAS Pixel detector:
- ➢ Reduction of signal, cluster size, dE/dx, occupancy; drift of Lorentz Angle (LA)

- Two-fold action:

1. **Reproduce radiation damage effects in ATLAS digitizer**
2. Make predictions for optimal future data taking conditions

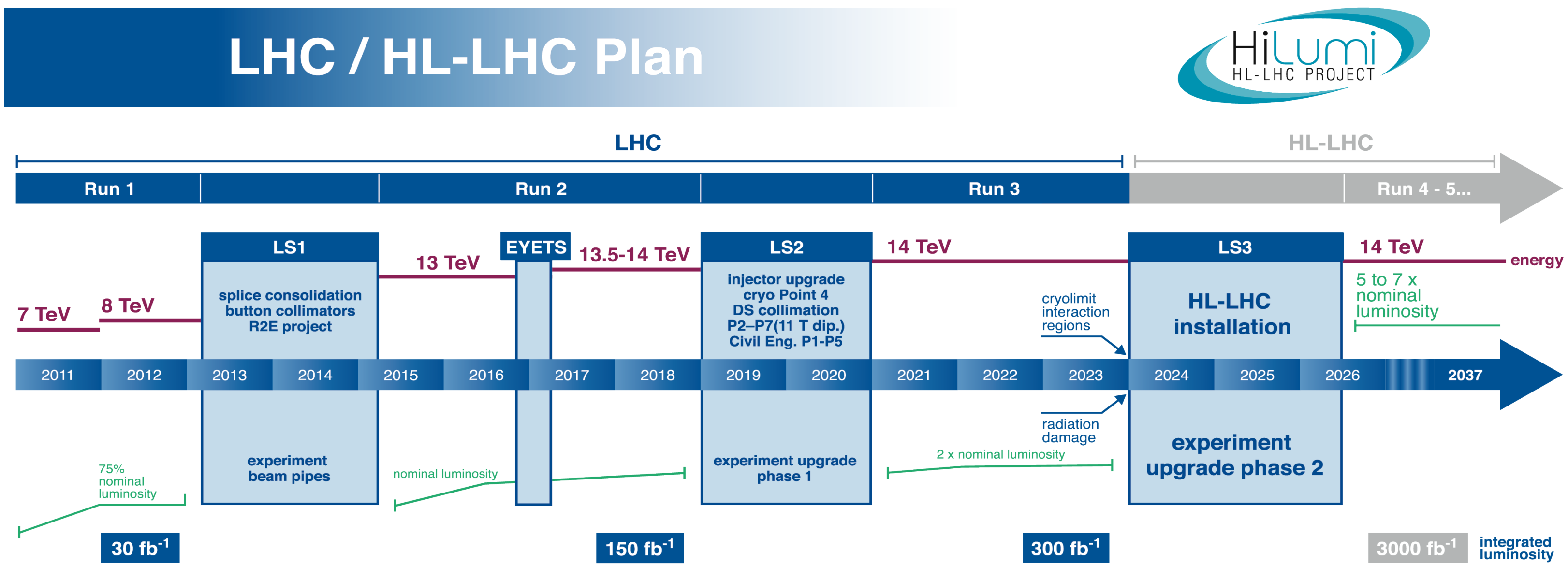
- ➢ New ATLAS pixel digitizer calculate signal induced on electrodes taking into account deformed electric field and trapping
- ✓ Model validated on collision data for what concerns CCE and LA
- Extrapolation for end of 2018 (expected ~ $1x10^{15} n_{eq}/cm^2$) on-going



PIXEL DETECTORS FOR THE NEW ATLAS INNER TRACKER

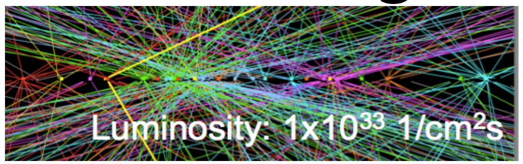
High Luminosity LHC

- To fully exploit its physics reach, CERN plans to upgrade LHC into an High Luminosity collider (HL-LHC)
- With $L = 5\text{-}7 \times 10^{34}/cm^2/s$ and about $4ab^{-1}$ of final data set observation of rare SM mechanism will be eventually possible (one example: Higgs self-coupling) and the physics reach for several BSM scenarios will be significantly extended
- Such large instantaneous and integrated luminosities translate into an unprecedented level of events rate and radiation fluence.
- **The ATLAS Inner Detector needs to be replaced**

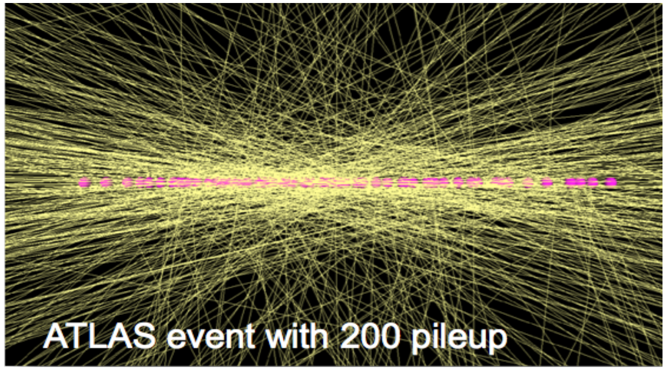


Challenges for the future ATLAS tracker

- Instantaneous luminosity : L_{inst} = 5-7x10^{34} cm^{-2}s^{-1}
  - x7 more than today
- Events-pile up: μ ≈ 140 – 200 events/*Bunch Crossing*
  - x8-10 more than today



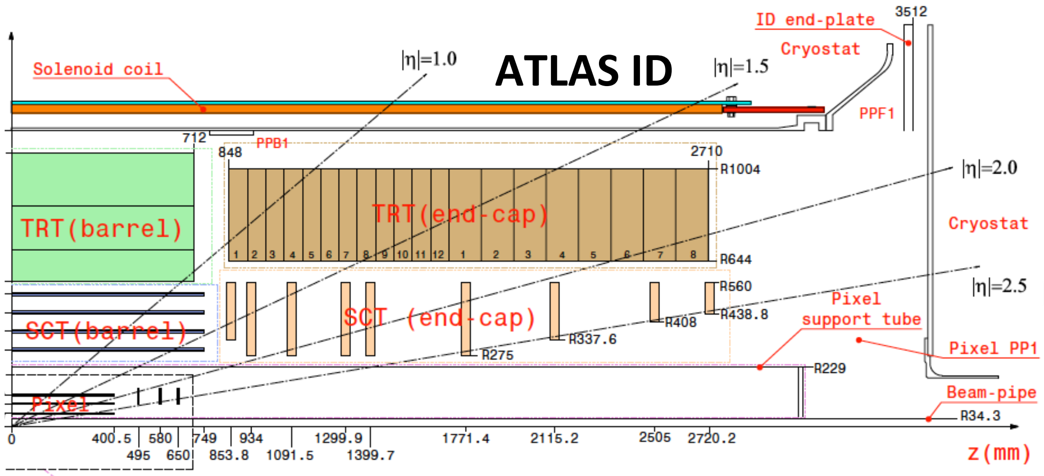
➢ **Need to increase the pixel granularity**
  - Actual pixel size: 50x(250-400) μm^2
- Expected fluence: ϕ = 2x10^{16} n_{eq}/cm^2
  - x5 more the actual sensor lifetime limit

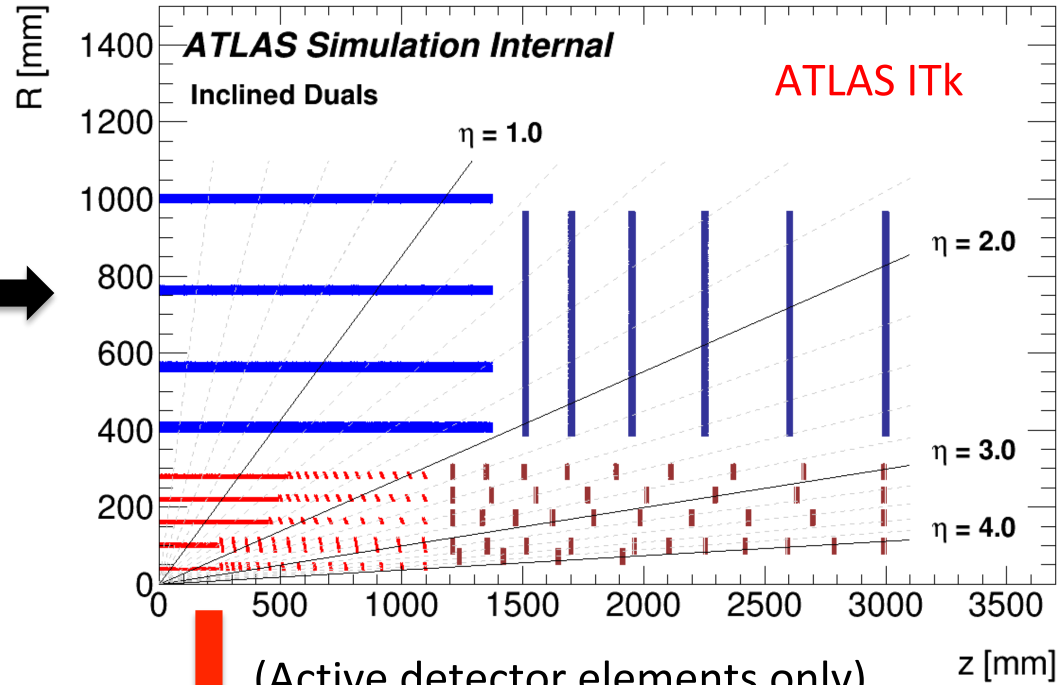


➢ **Need radiation-hard detectors**

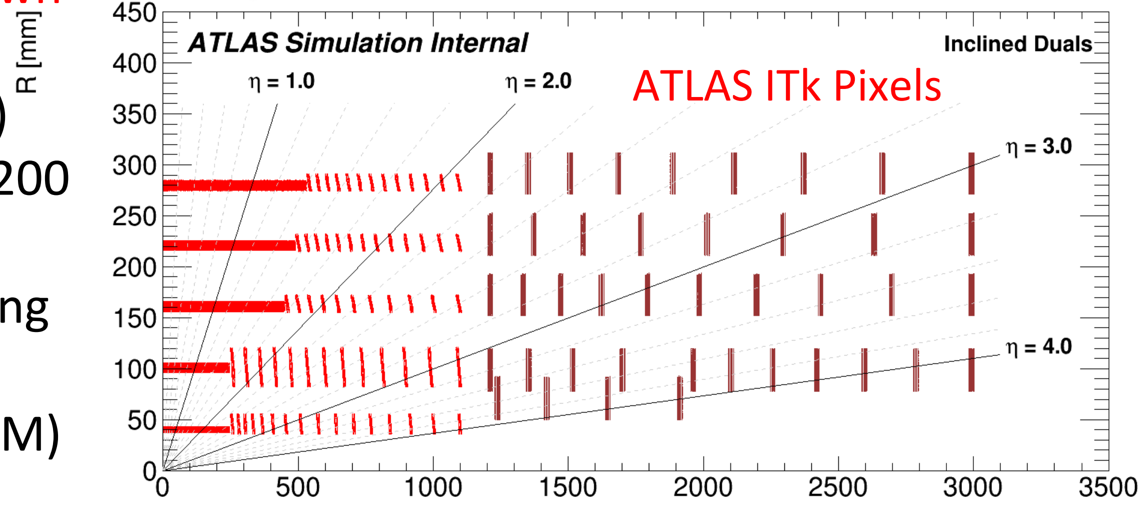
➢ **Goal: better performance in a harsher environment!**

From ATLAS Inner Detector to Inner Tracker





(Active detector elements only)



3D for innermost layers, HVCMOS for outermost

The new **ATLAS** Inner Tracker (**ITk**) will be an **all silicon tracking system**, composed of:

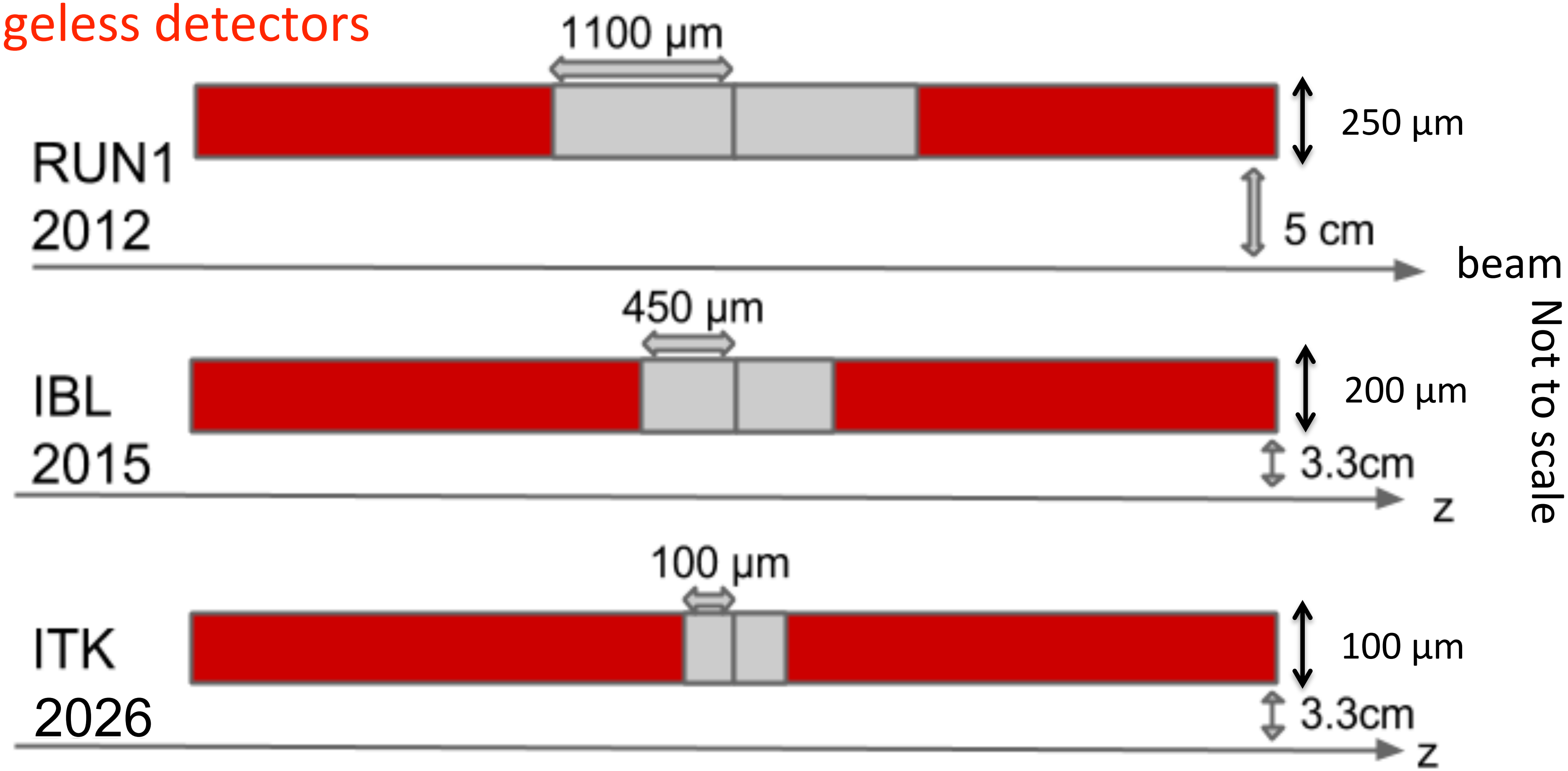
- 5 pixel barrel layers with *inclined modules*, down to |η|~4 , plus several pixel rings
- **Pixel pitch: 50µm x 50µm** (it was 50x250-400)
- Small pitch to keep occ. at 0.1% even with µ=200
- Pixel thickness: 100-150µm (it was 200-250)
- Reduced thickness to cope with charge trapping
- Total pixel surface: ~ 13 m^2 (it was 1.6 m^2)
- Total number of channels ~ 5.2 G (it was ~ 90 M)

ATLAS-TDR-025 + ITk Pixel TDR (internal)

Edgeless (and thin) detectors

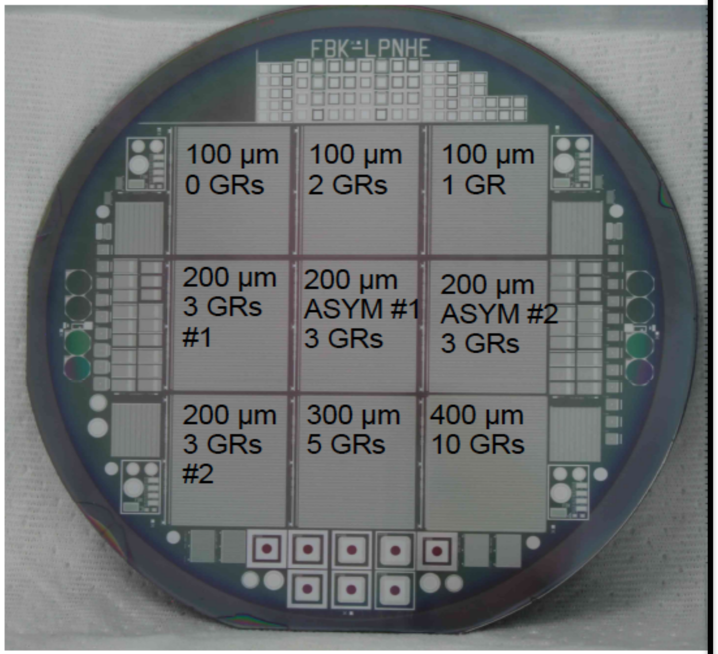
- To maintain (and improve) the flavour tagging performance we have to place detection modules as close as possible to the beam interaction point
- Detectors dead areas are to be reduced to maximize acceptance

➢ Edgeless detectors



LPNHE planar pixel productions

PAE1 – active edge

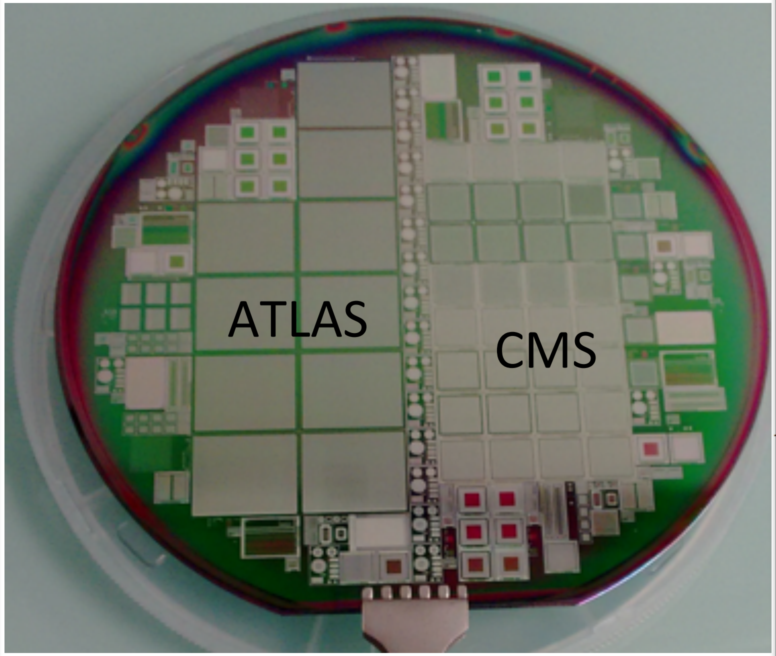


4” 200 µm thick n-on-p
Active Edge technology
Pixel-to-edge down to 100 µm
Tested extensively on beam

NIM A 712 (2013) 41–47

JINST 12 P05006 (2017)

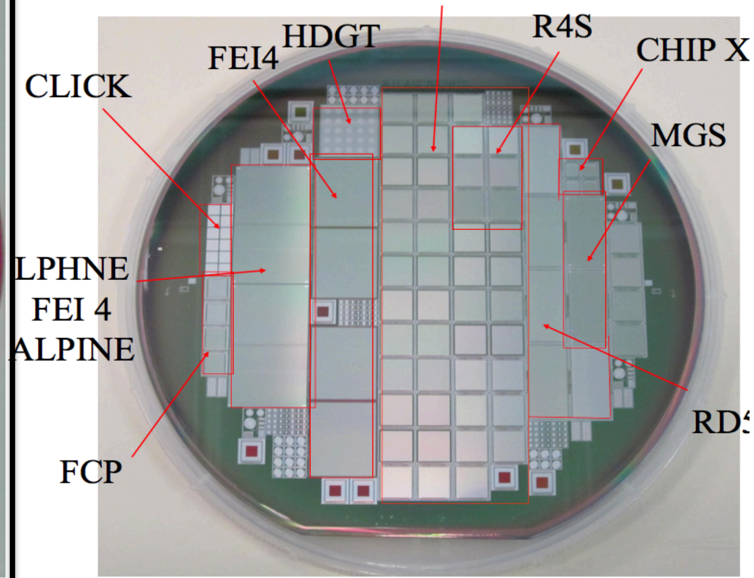
P2 - thin



6” 100 µm thick n-on-p
INFN ATLAS/CMS project
Tested extensively on beam, after irradiation too

2017 JINST 12 C12038

PAE3 - thin and active edge



6” 100 µm thick n-on-p
INFN ATLAS/CMS project
Active Edge technology
Pixel-to-edge down to 50 µm
<u>50x50 µm pitch sensors</u>
Tested on beam,
after irradiation too

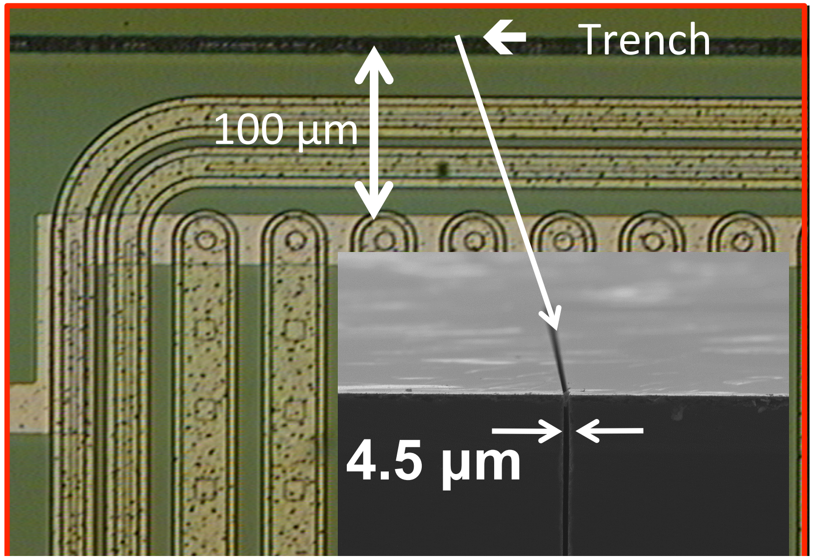
13th Trento Workshop, 2018

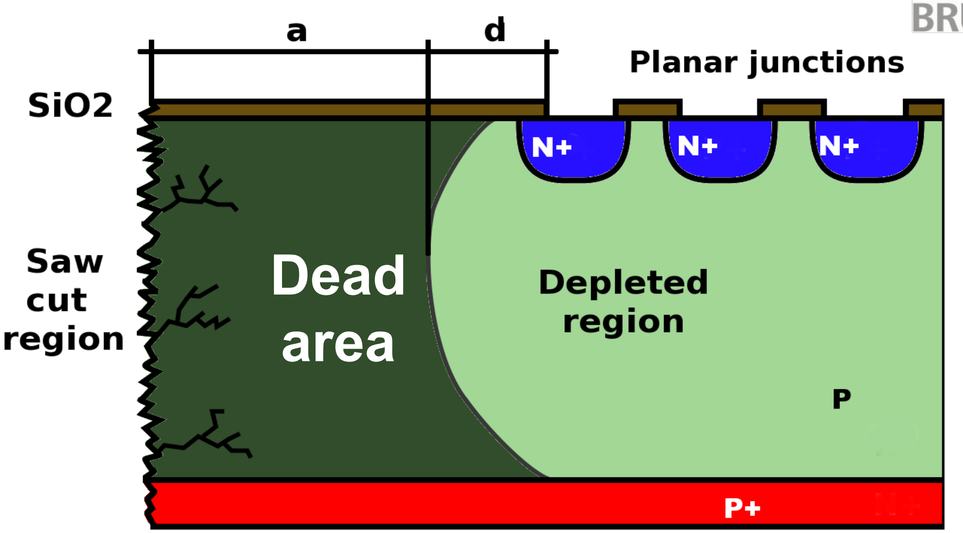
The FBK/LPNHE PAE1 pixel production

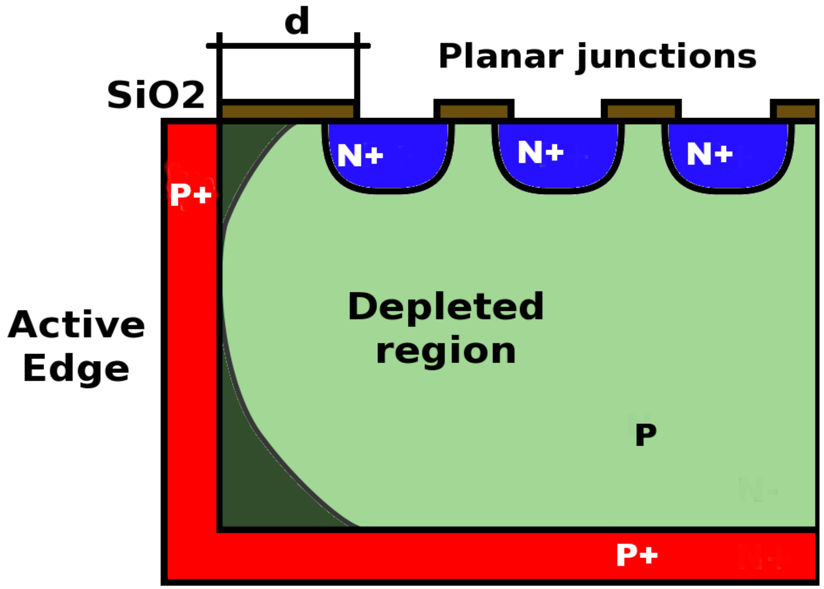
An FBK-LPNHE production

- 200 µm thick, n-on-p sensors
- **Challenge: reduce the dead area at the detector periphery** (Atlas: 1100 µm)
- Technique: *Deep reactive Ion Etching*

✓ **Inactive region down to: 100 µm**

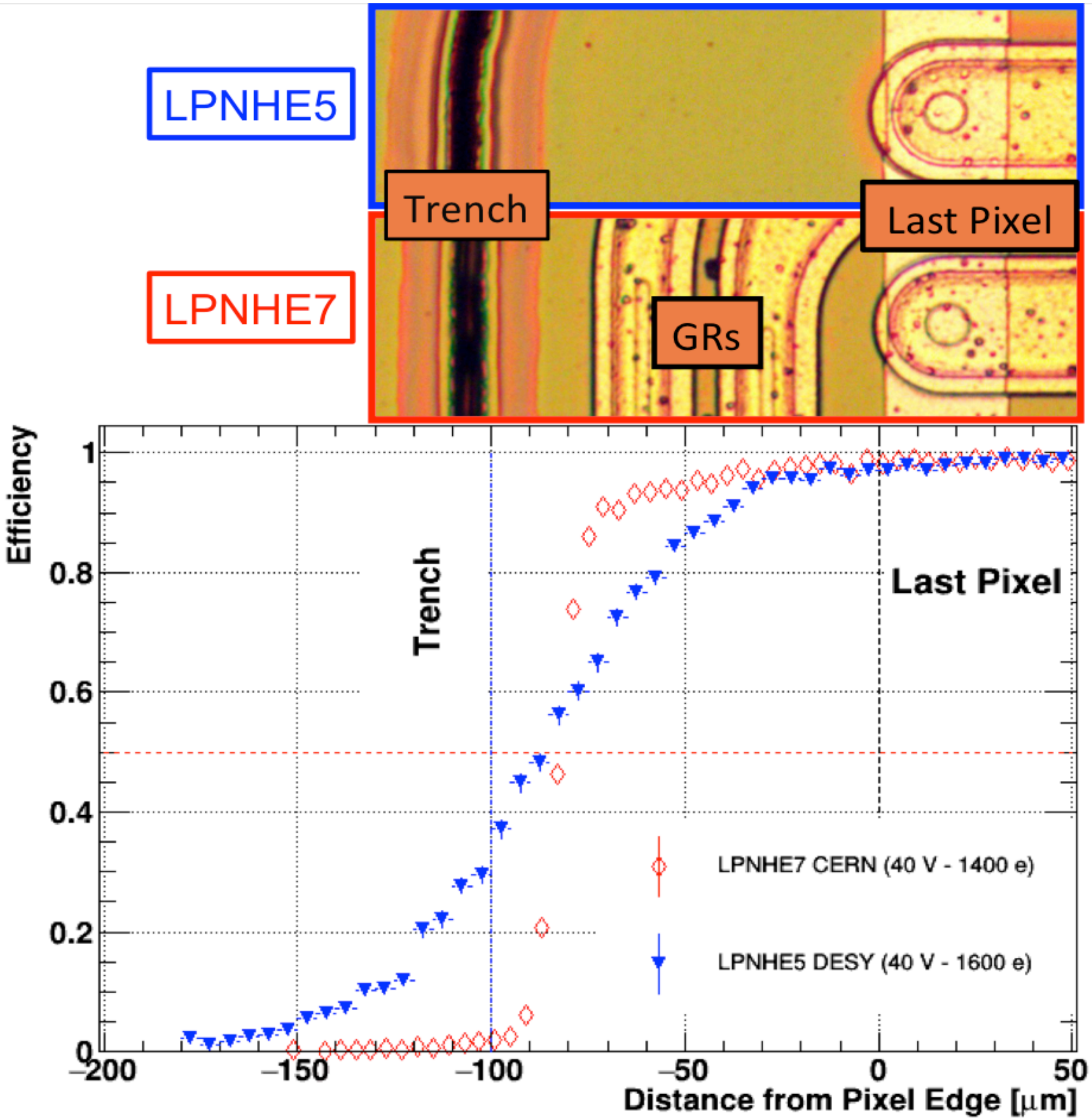






NIM A 712 (2013) 41–47

Testbeam performance of edgeless detectors

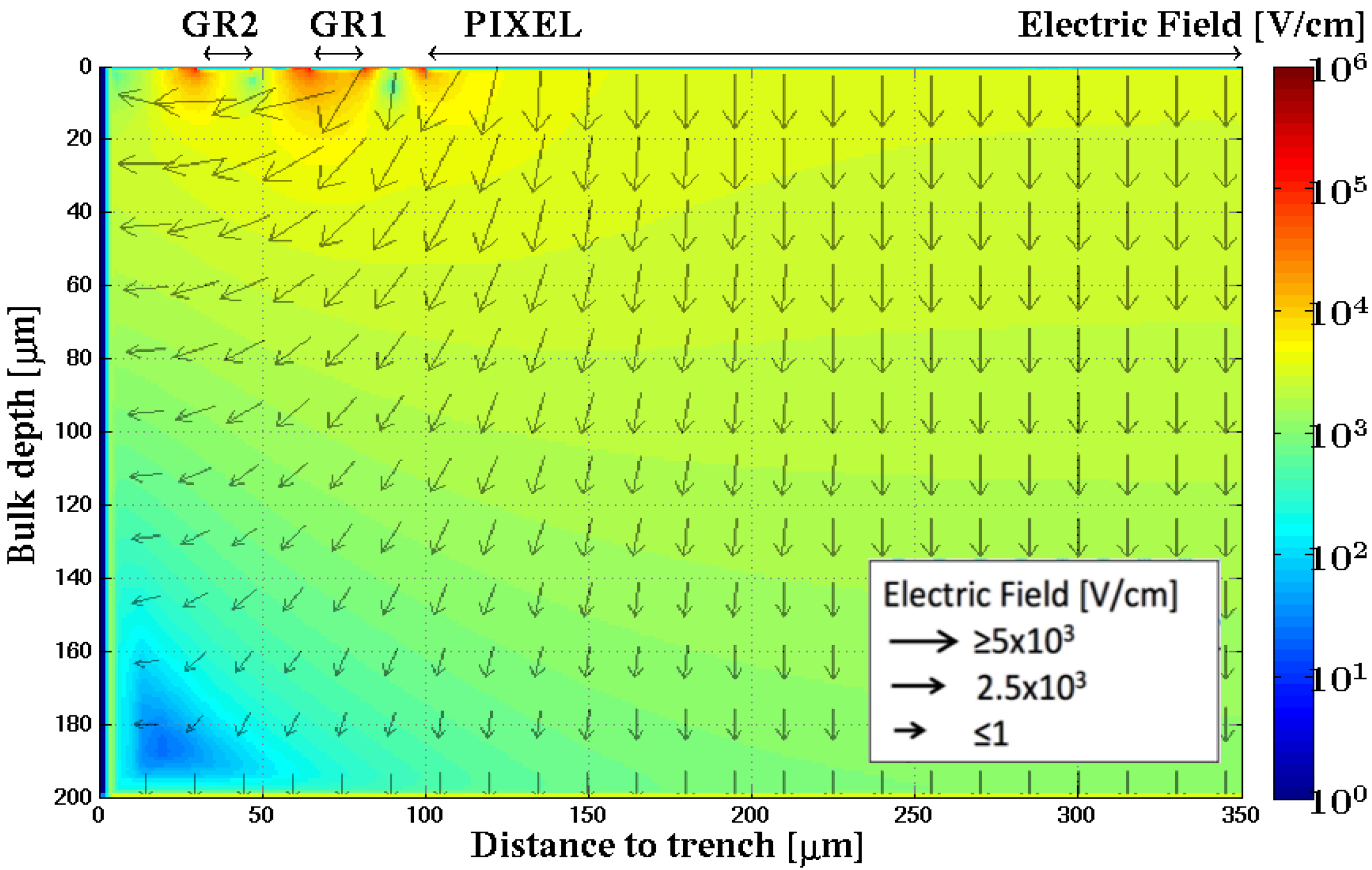


- The detector is efficient beyond the last collecting electrode
- Efficiency is > 90% up to 80 μm away from the last pixel
- The dead area is no longer dead!

- But how is it possible that charge is collected beyond the last pixels?
- TCAD simulations can shed light here!

JINST 12 P05006 (2017)

TCAD simulations and edgeless detectors

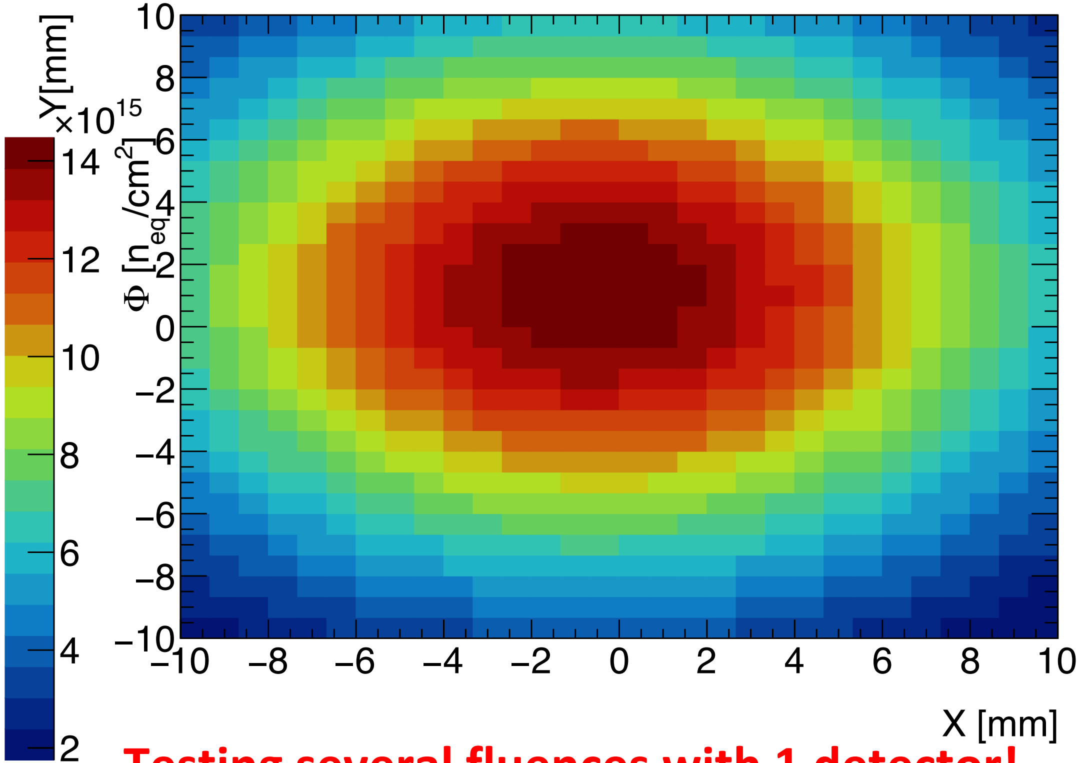


Charges are not collected and re-emitted by the GRs
apart from few μm below the surface

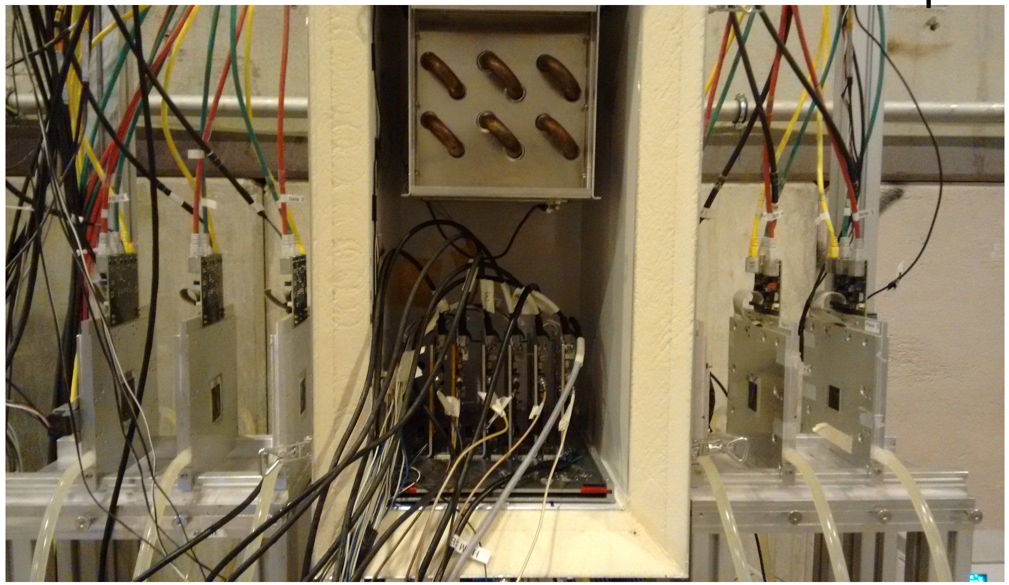
JINST 12 P05006 (2017)

P2 - Thinner detectors for the HL-LHC phase

Two n-on-p pixels **sensors** from **P2 production** were **irradiated** with 24 GeV protons at CERN in subsequent irradiation steps with a **Gaussian beam profile**



Tested on beam after each irradiation step

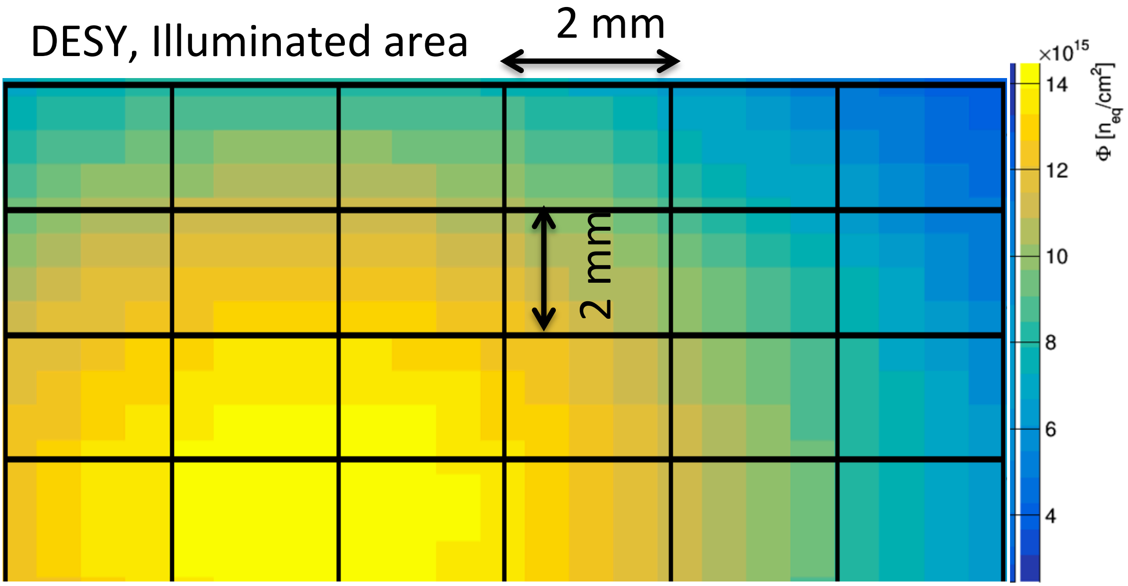


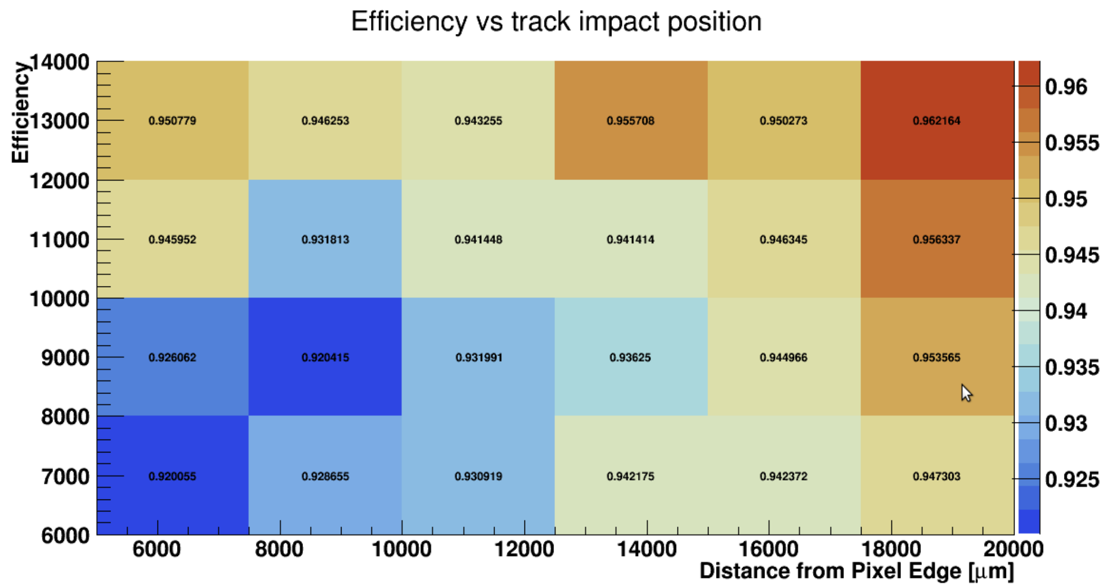
Testing several fluences with 1 detector!

Module name (thickness [μm], # of GRs)	Beam spot size (FWHM - [mm^2])	Fluence ϕ [10^{15} n_{eq}/cm^2]	Cumulative fluence at peak Φ [10^{15} n_{eq}/cm^2]
W80 (130, 2)	20×20	3	same
W30 (100, 5)	12×12	4	same
W80 (130, 2)	20×20	7	10
W30 (100, 5)	20×20	7	11

2017 JINST 12 C12038

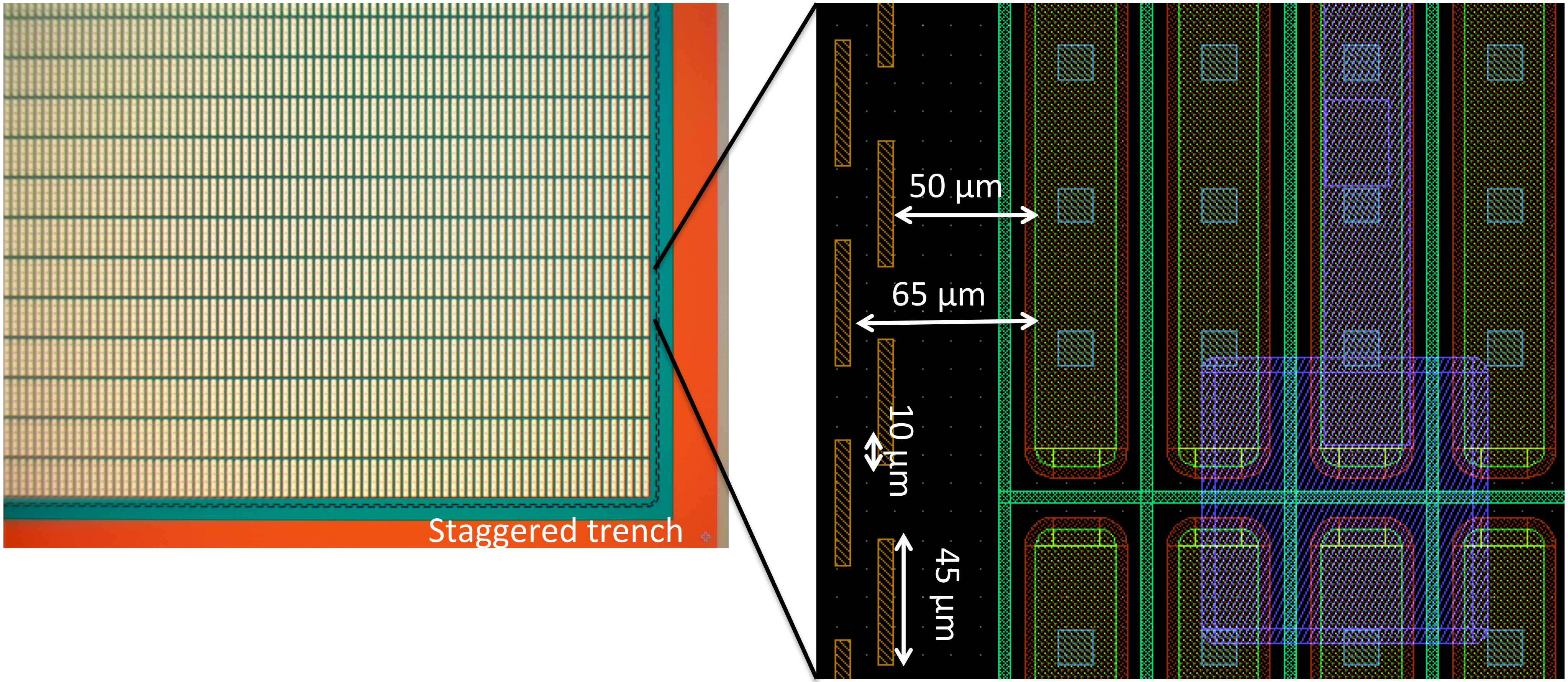
P2 – Hit efficiency after HL-LHC like fluence





- Module tested up to 600 V at t = -40º C
  - at DESY (4 GeV/c electron beam) and CERN (120 GeV pion beam)
- Hit-efficiency is ~ 92-94% at 1.4x10^{16} n_{eq}/cm^2
- Hit-efficiency is ~ 96-98% at 5.5x10^{15} n_{eq}/cm^2
- Average hit-efficiency is ~94-96% at 1x10^{16} n_{eq}/cm^2 (ITk specs. require 97%)
- **Uncertainties** on irradiation **map alignment**, **threshold** and **gain** uniformity
- *To be used to tune the digitizer for HL-LHC fluences*

PAE3 – thin and active edge sensors



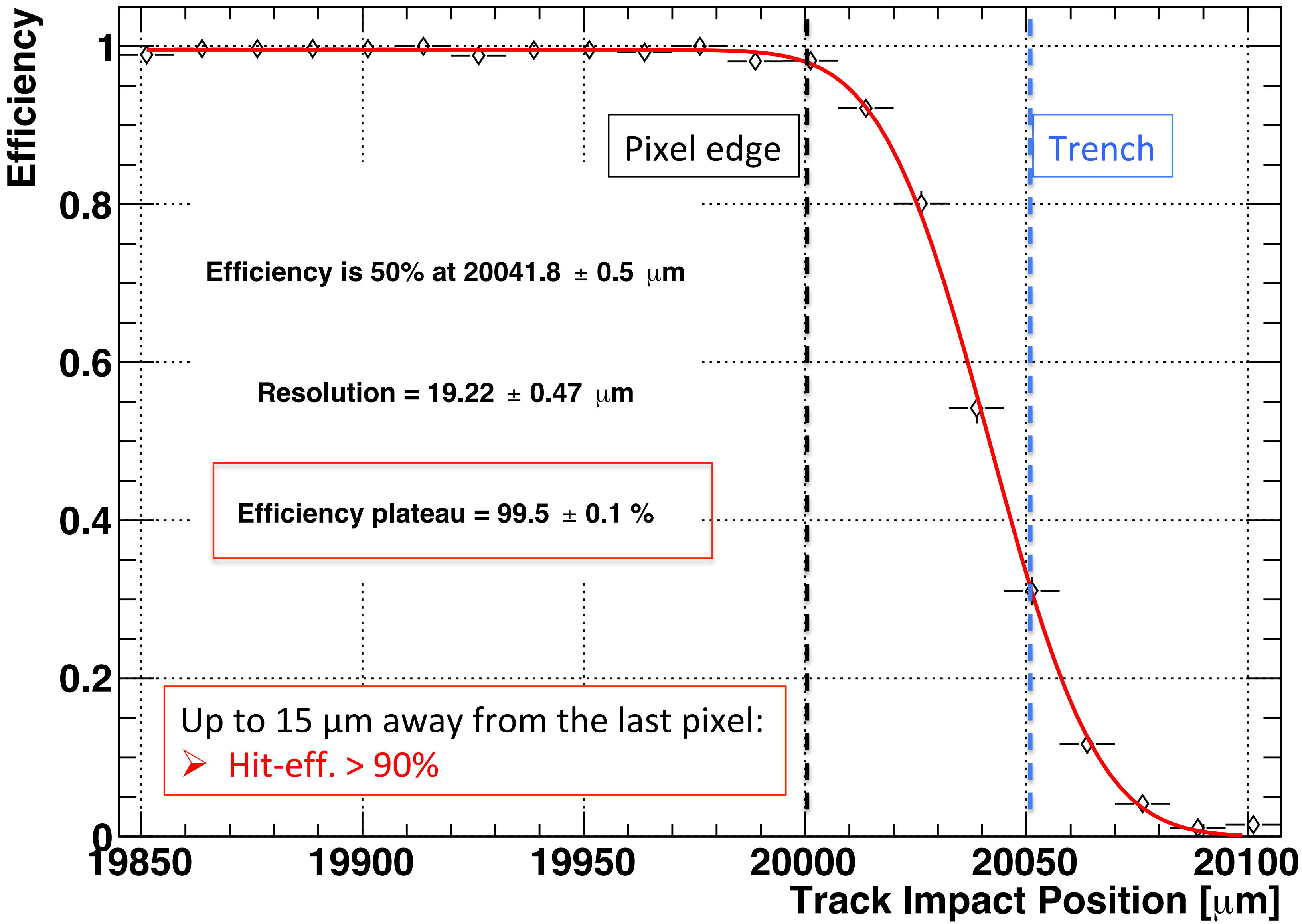
Sensor taken from **130 µm** SiSi wafer

50 µm minimal **pixel-to-edge** distance and **no Guard Rings**

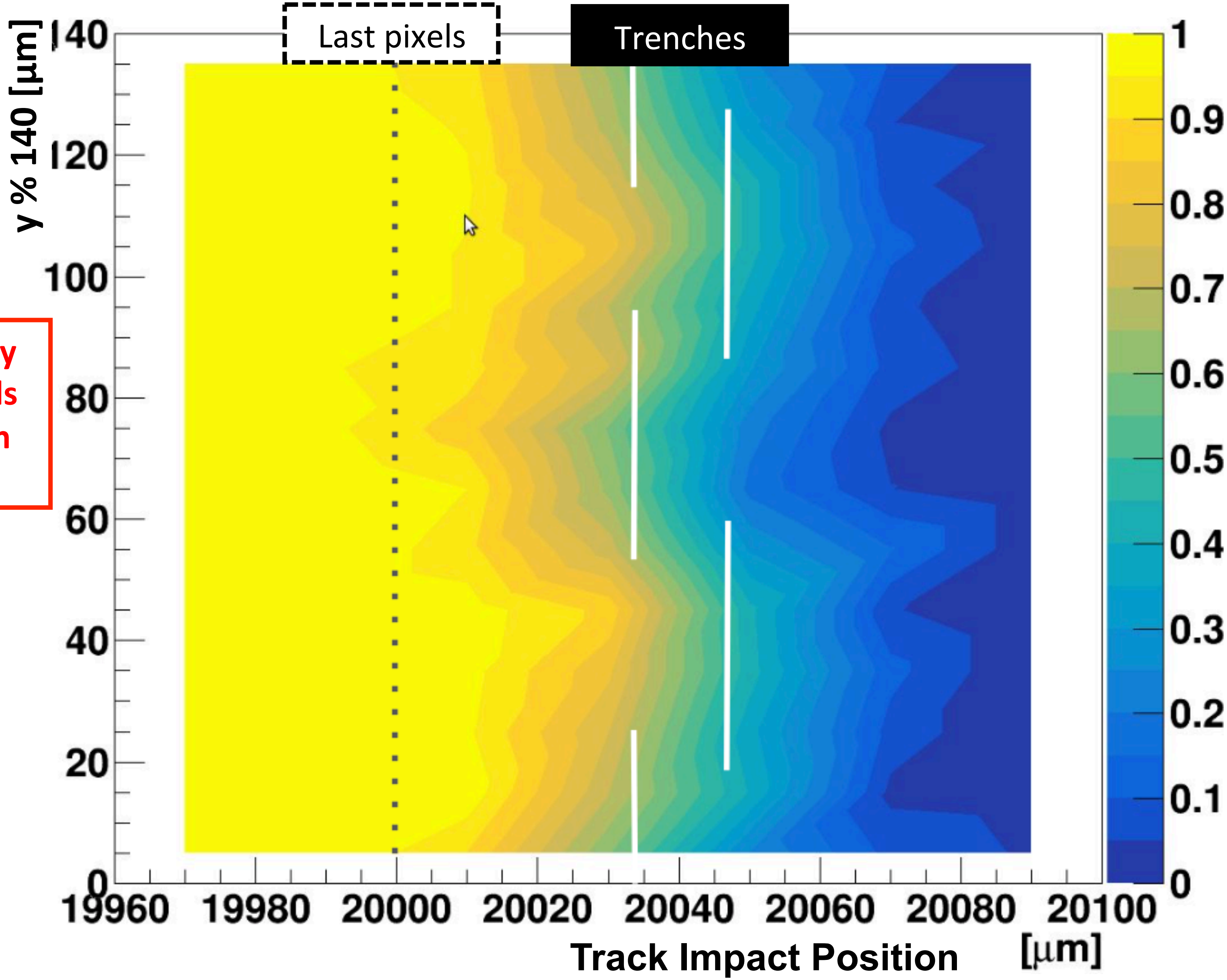
Irradiated uniformly with low energy protons (KIT) at **2.7×10^{15} n_{eq}/cm^2** (average fleunce for ITk Pixel intermediate layers)

Tested on beam (DESY) **before and after irradiation**

PAE3 – Edge efficiency for un-irr. sensors

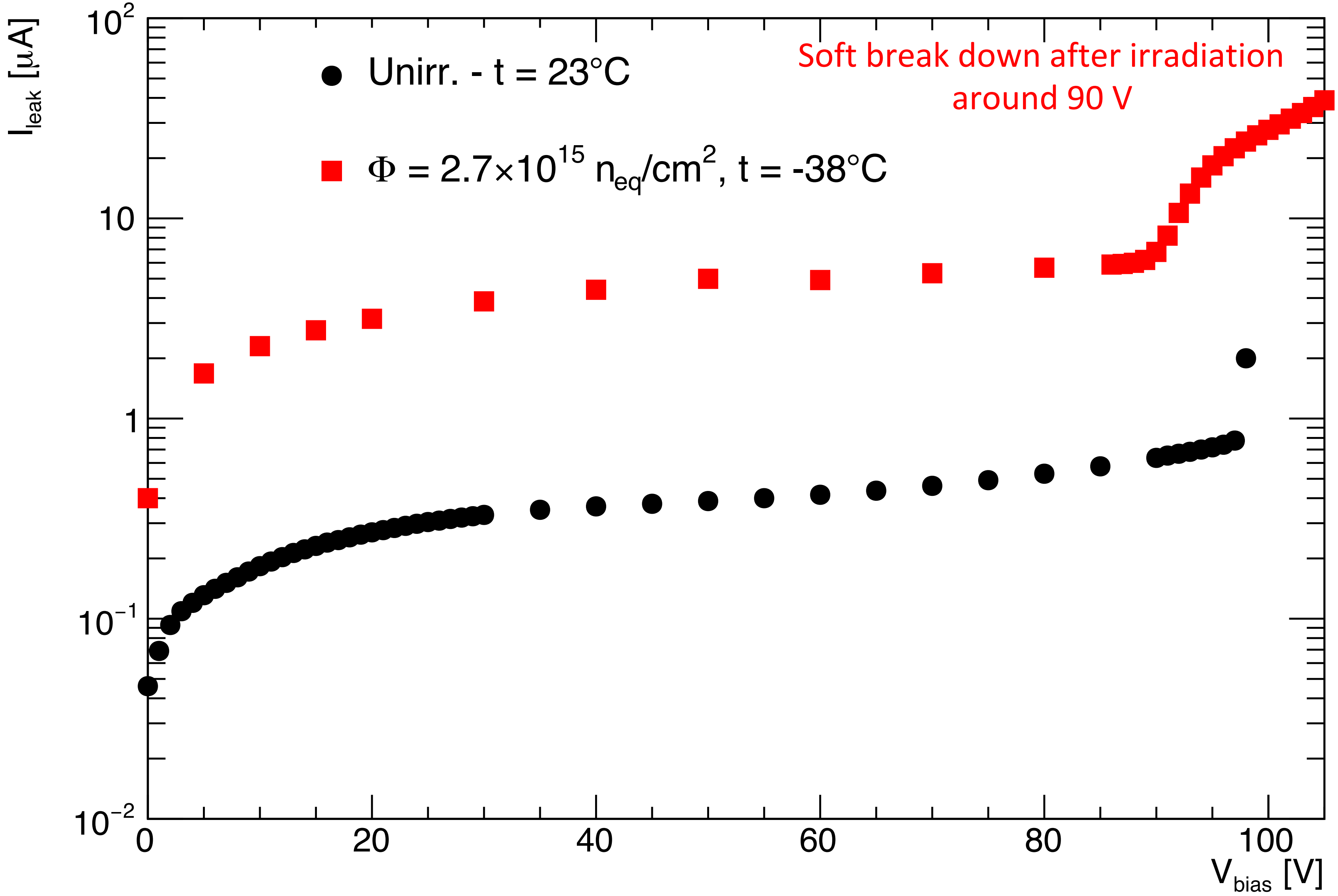


PAE3 – Edge efficiency for un-irr. sensors

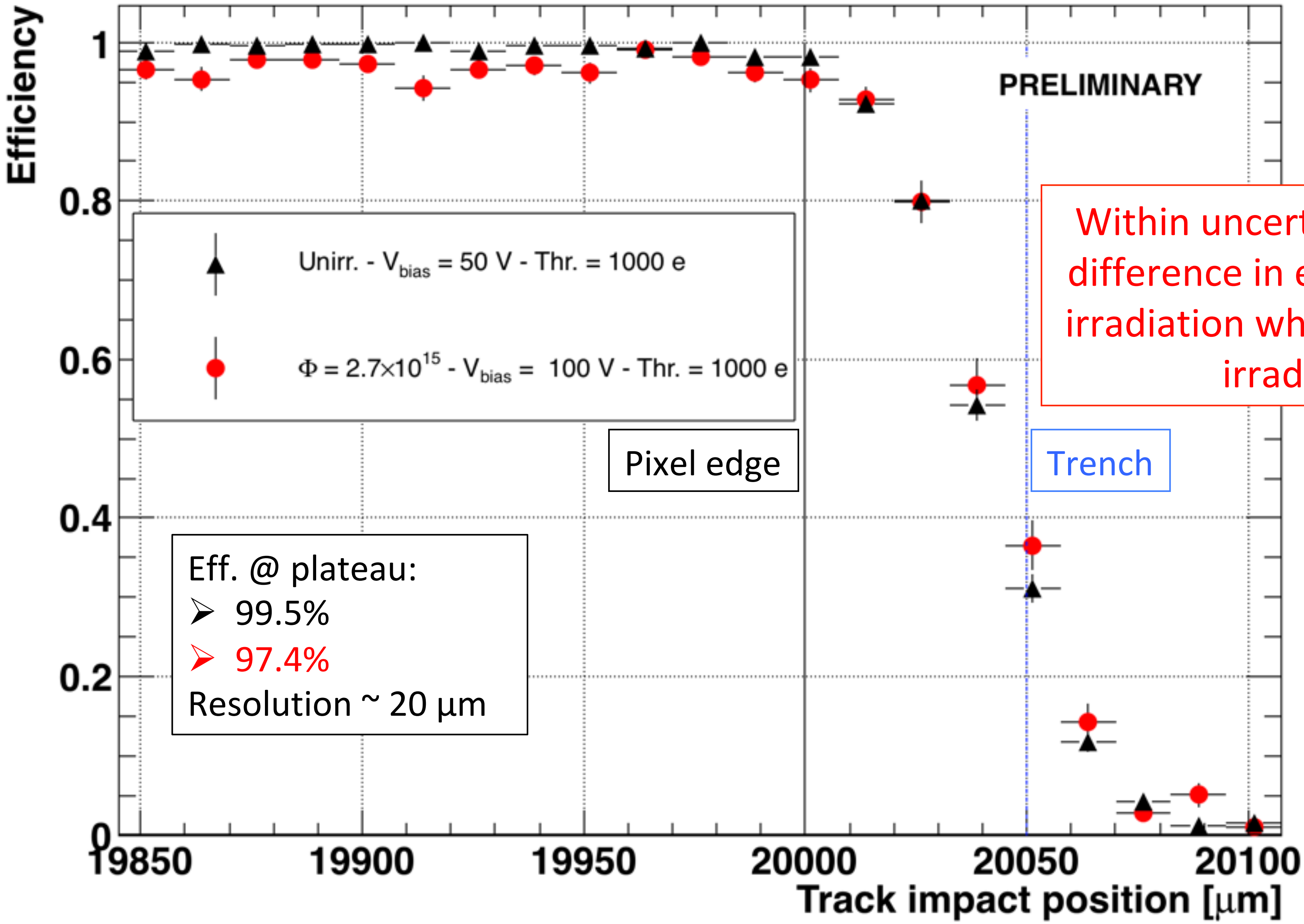


High efficiency region extends among trench segments

PAE3 - IV curves before and after irradiation



Efficiency at edge: irr. vs unirr. modules



Within uncertainties, no sizeable difference in edge efficiency after irradiation when compared to un-irradiated case!

Eff. @ plateau:
- 99.5%
- 97.4%

Resolution ~ 20 μm

Summary and Outlook

- The planned **increase luminosity of LHC** translates into **unprecedented** levels of event rate, pile-up and **radiation damage**
- A complete new inner tracking system is under development within the ATLAS community, the ITk
- **Pixels**, at the core of the ATLAS ITk, will have to **assure the performance of current detectors in a much more harsh environment**
- Planar thin and edgeless pixel sensors are excellent candidates for intermediate ITk layers thanks to their performance and cost effectiveness
- **Active edge technology to be retested at larger fluences**

PERSPECTIVES

Development of the ITk pixel system

- Hybrid pixels are the sensors candidates for the innermost layers of the ATLAS Inner Tracker
- **My expertise in designing, simulating and testing silicon sensors** will allow me to **keep making important contributions** for the development of the **ITk**:

1. I am contributing to new pixel productions, based on results achieved in the last years
2. We are now entering the phase of **module construction**, and within the ATLAS ITk French group, I will be in charge of **coordinating** some of the **modules construction** phases
3. As ATLAS ITk testbeam coordinator I will play an important role in the final sensor decision for the new ATLAS Pixel detector

Improved TCAD and Monte Carlo simulations

- The data collected in laboratory and on beam with highly-irradiated sensors are vital to model the radiation damage in silicon at the fluences expected at the HL-LHC

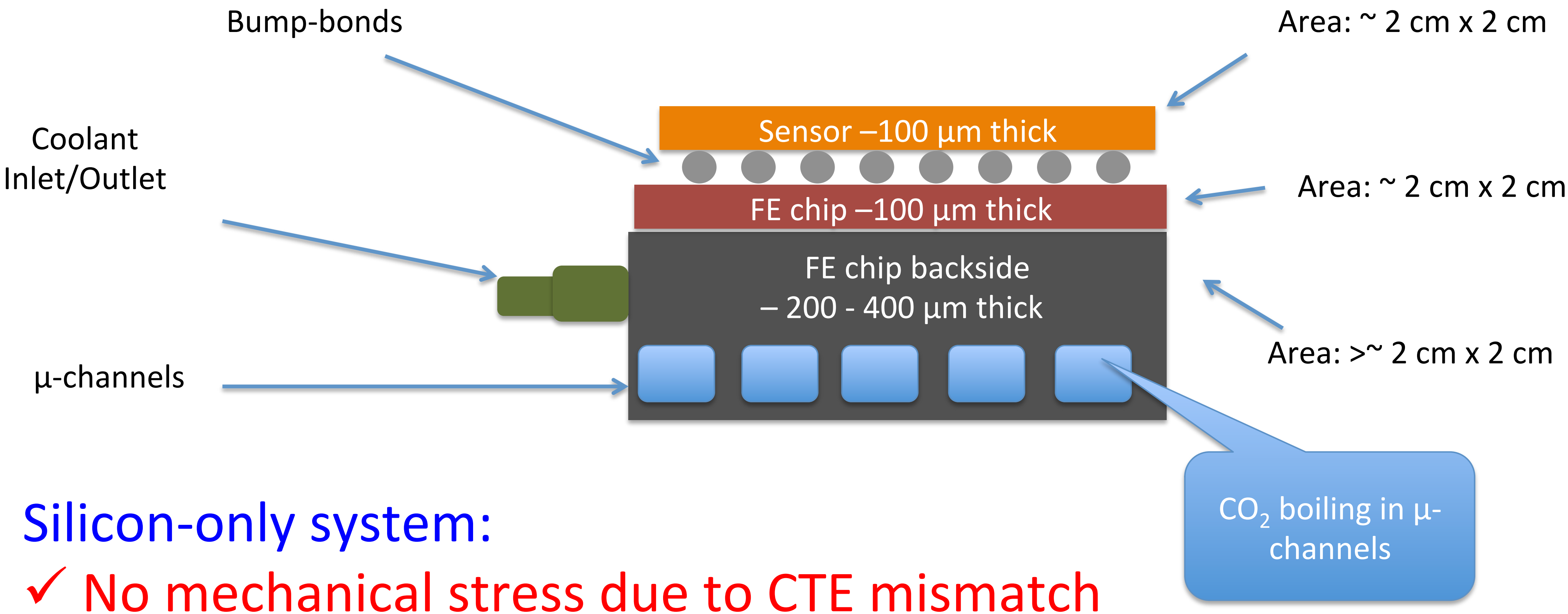
- As **coordinator of the Radiation Damage Pixel Digitizer** group I will make use of ITk-like modules data to further **develop** first **TCAD and** then **Monte Carlo simulations**

➢ The natural continuation of such a program is the further development of the ATLAS Monte Carlo simulations to correctly model the degraded detector at the fluences expected HL-LHC, work I started already for the ITk Pixel TDR

From tracker radiation damage to performance

- **Radiation damage** is **already impacting** actual **ATLAS** data taking
- It is important to follow closely tracker and tracking observables to quickly re-establish optimal data-taking conditions
- Hit-efficiency is one of the most important variables to monitor but cluster size is even more important for tracking resolution which impacts on a large part of the ATLAS physics program
- **Monte Carlo studies** based on different scenarios for what concerns radiation damage are **being prepared** and will be vital **to predict future performance** of tracks and high-level **physics objects**
- New and better algorithms for clustering, tracking, vertexing and flavour-tagging will be developed on this work
- I see myself coordinating this effort together with tracking experts, mentoring students that will have the opportunity to understand in deep the performance of the ATLAS tracking system

The µ-channels solution (option for HL-LHC)



Silicon-only system:

✓ No mechanical stress due to CTE mismatch

✓ Low mass

✓ Customizable layout of the channels → more efficient and uniform cooling

Coefficient of **T**hermal **E**xpansion

REFLECS & REFLECS2 project (financed by CNRS)

6“ wafer µ-channel production

FONDAZIONE BRUNO KESSLER

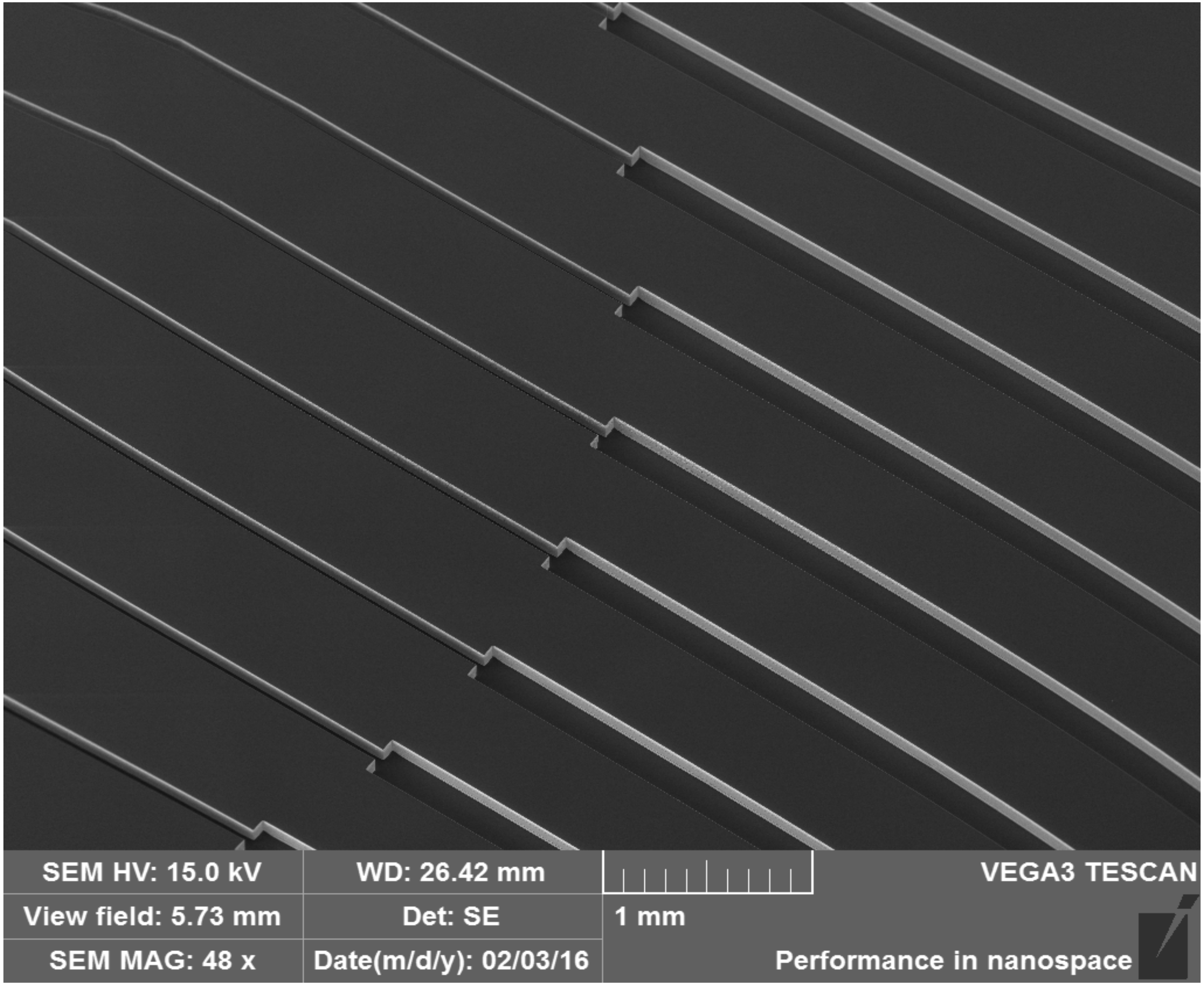
www.cnrs.fr

REFLECS & REFLECS2 project (financed by CNRS)

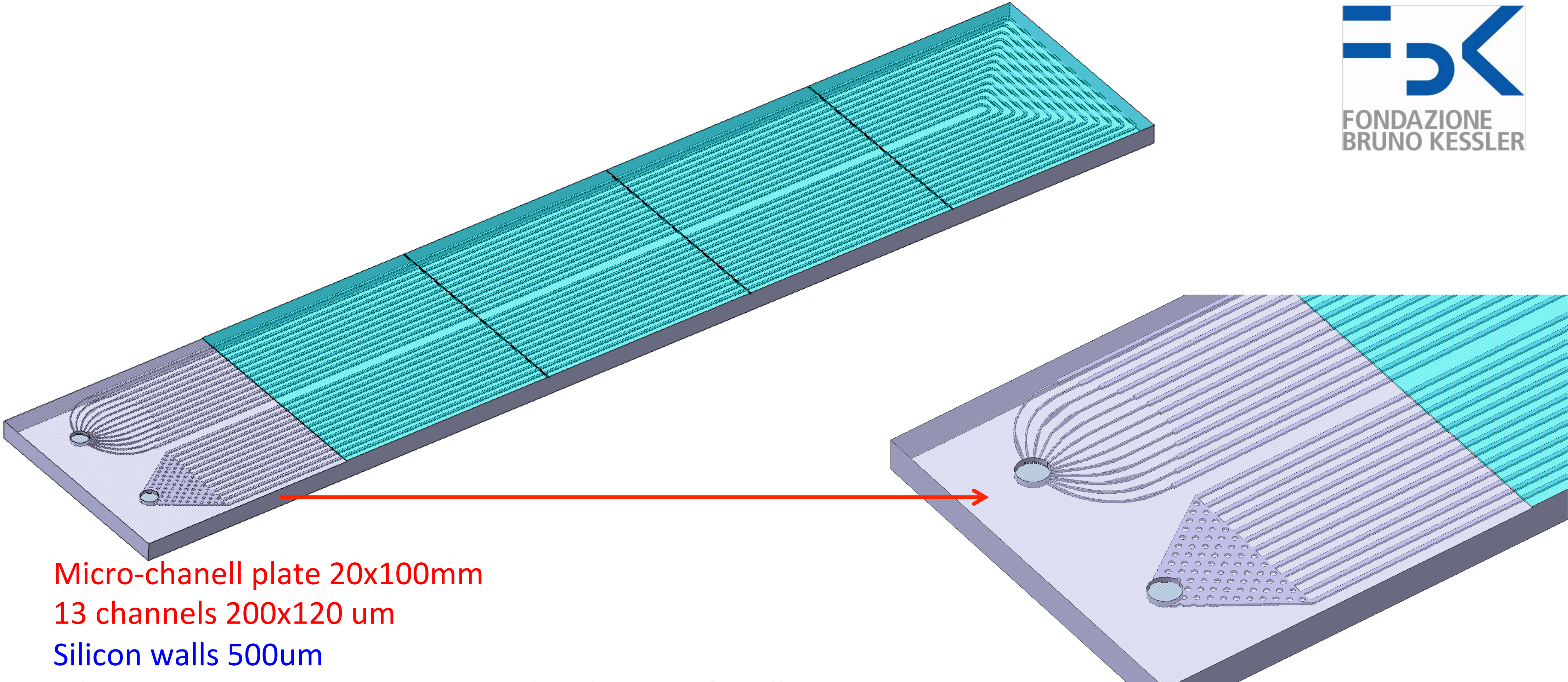
13 channels 200x120 µm
Silicon walls 500um
Inlet restrictions 60x120µm

FONDAZIONE
BRUNO KESSLER

www.cnrs.fr



FBK production: mini-stave for 4 modules



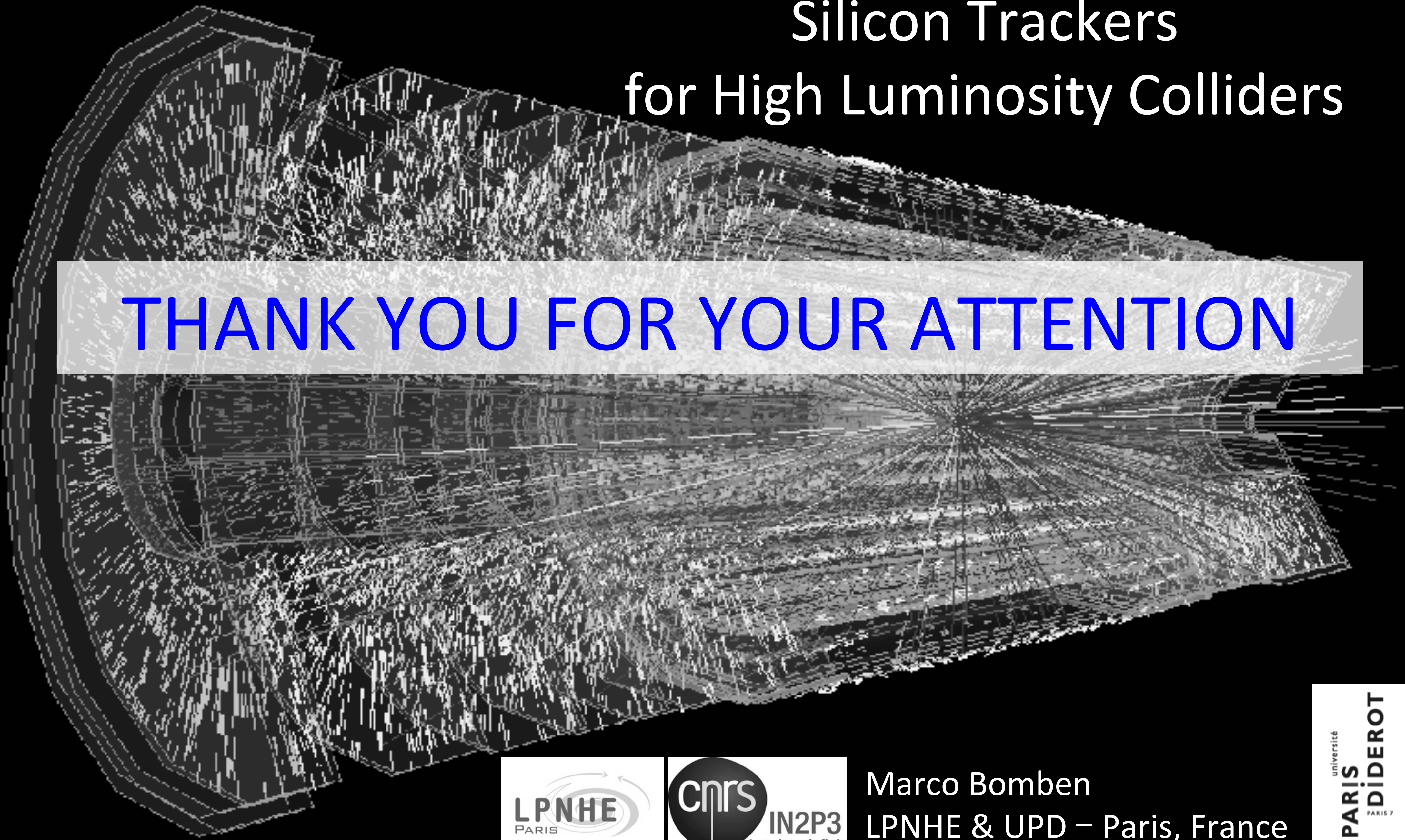
Micro-chanell plate 20x100mm
13 channels 200x120 um
Silicon walls 500um
Inlet restrictions 60x120um: same lenght 6mm for all
Inlet outlet holes 1.6 mm diameter
Pillars in the outlet: 350um diameter
Shortest channel: 165 mm
Longest channel: 199 mm

SUMMARY

Summary

- Silicon detectors for High Energy Physics were born almost 40 years ago with the goal of measuring heavy flavour particles
- Today they are the standard choice for the innermost layers of experiments at high energy colliders
- Rare phenomena and high precision measurements require high luminosity colliders
- The main challenges for future silicon detectors are high data rates and radiation damage
- Further detector segmentation and more "intelligence" at the pixel level are crucial, together with accurate performance predictions
- An all-silicon system is the final goal
- I am happy to be one of the actors in this field, able to contribute from design to performance studies and eager to enter the "High-Lumi" era

Silicon Trackers for High Luminosity Colliders



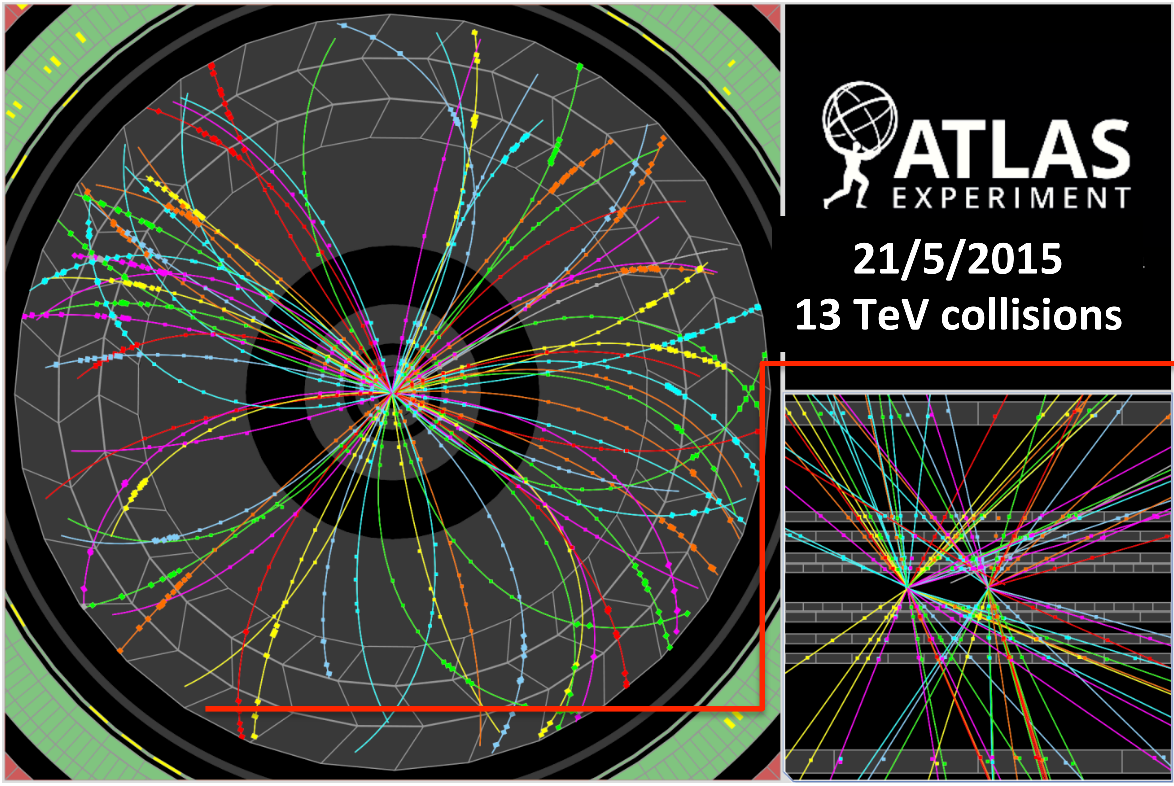
THANK YOU FOR YOUR ATTENTION

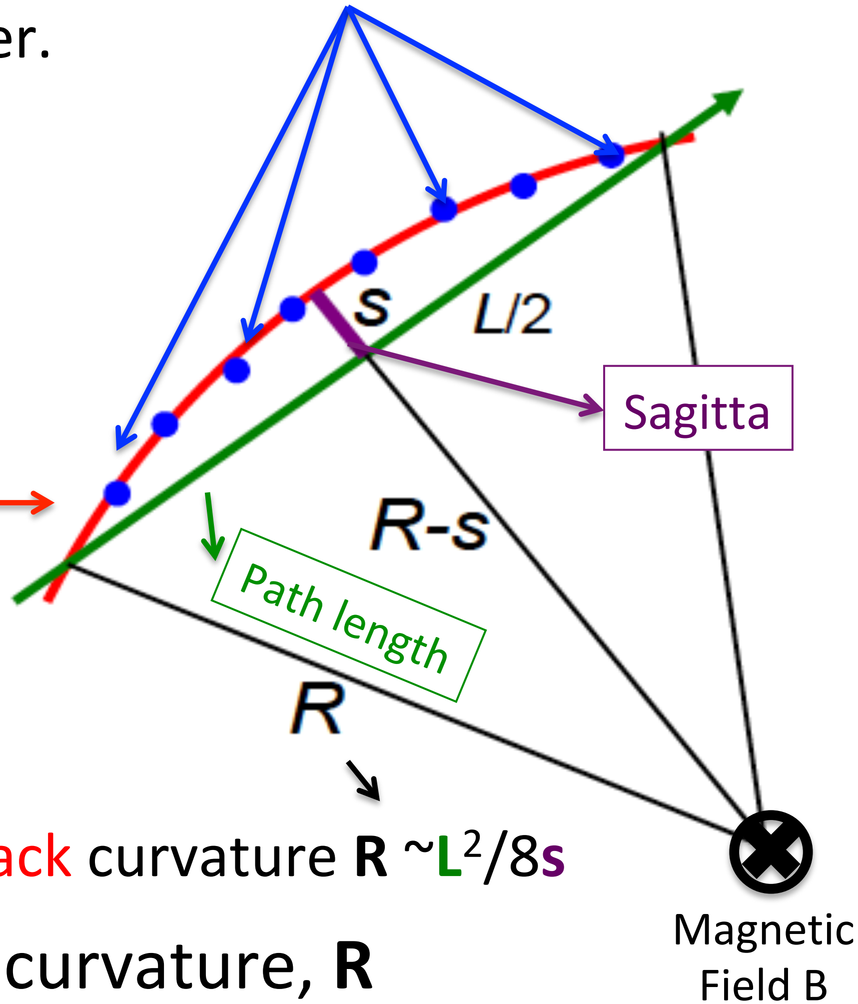
Marco Bomben
LPNHE & UPD – Paris, France

Backup

Transverse momentum measurement

The base of tracking and vertexing is the measurement of space-points, *i.e.* the 3D position of the track traversing the sensing layer.





Track curvature **R** ~$L^2/8s$

Measure sagitta, **s**, from track arc -> get curvature, **R**

From curvature **R** transverse momentum $\mathbf{p_T}$ can be determined:

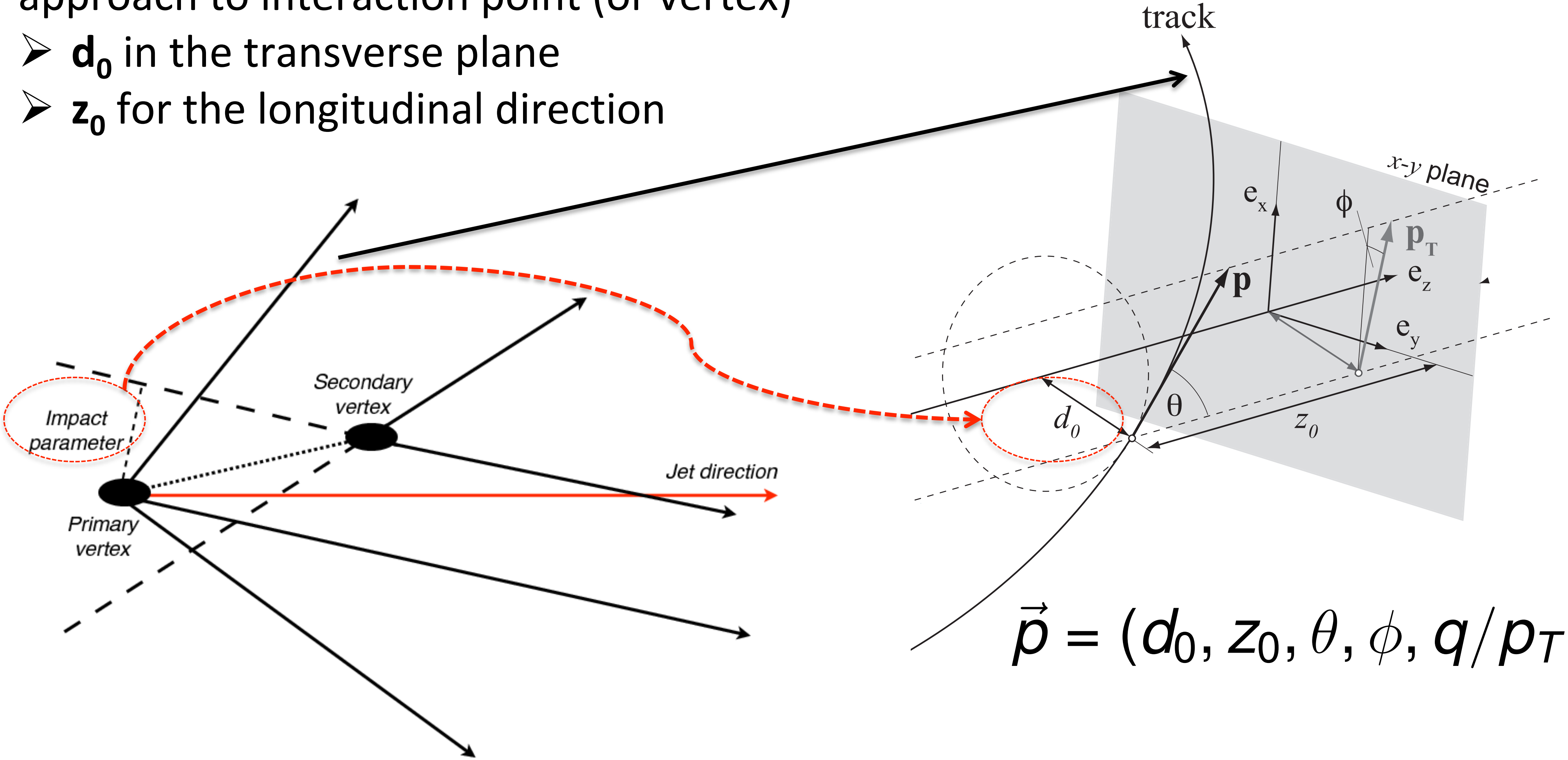
$$p_T[\text{GeV/c}] = 0.3\ |z|\ B[\text{T}]\ R[\text{m}]$$

Vertexing measurement

Task: find a common point in space for tracks' origin

Fundamental ingredient: distance of closest approach to interaction point (or vertex)

- $\mathbf{d_0}$ in the transverse plane
- $\mathbf{z_0}$ for the longitudinal direction

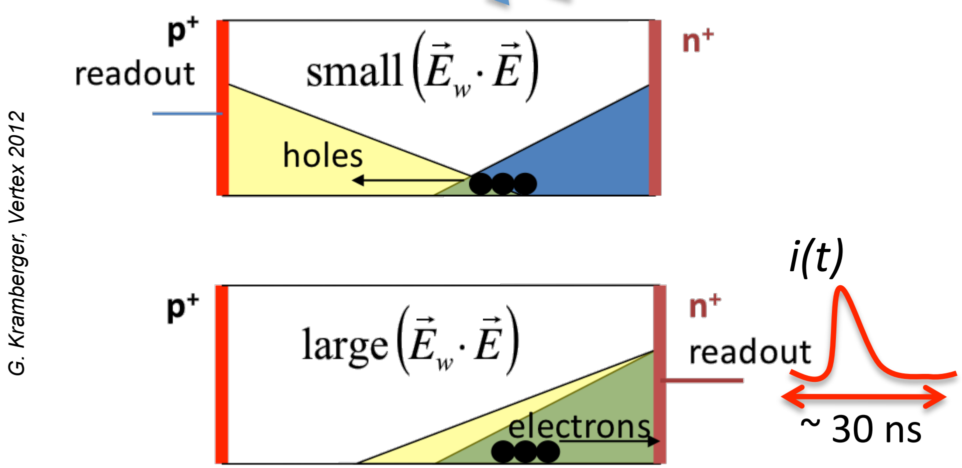


$$\vec{p} = (d_0, z_0, \theta, \phi, q/p_T)$$

P-n Junction – Signal formation

The charged carriers created by the interaction of a photon or of a charged particle drift towards the respective electrodes under the effect of the *electric field E*

The carrier velocity *v* depends linearly on the electric field *E* through the mobility *μ*: $\vec{v} = \mu\vec{E}$

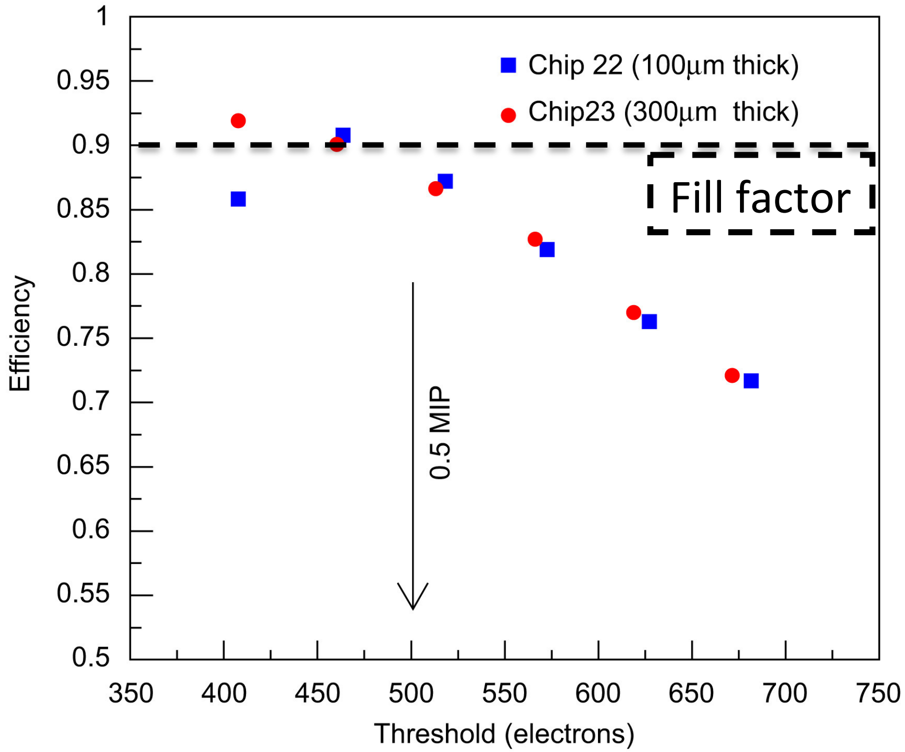


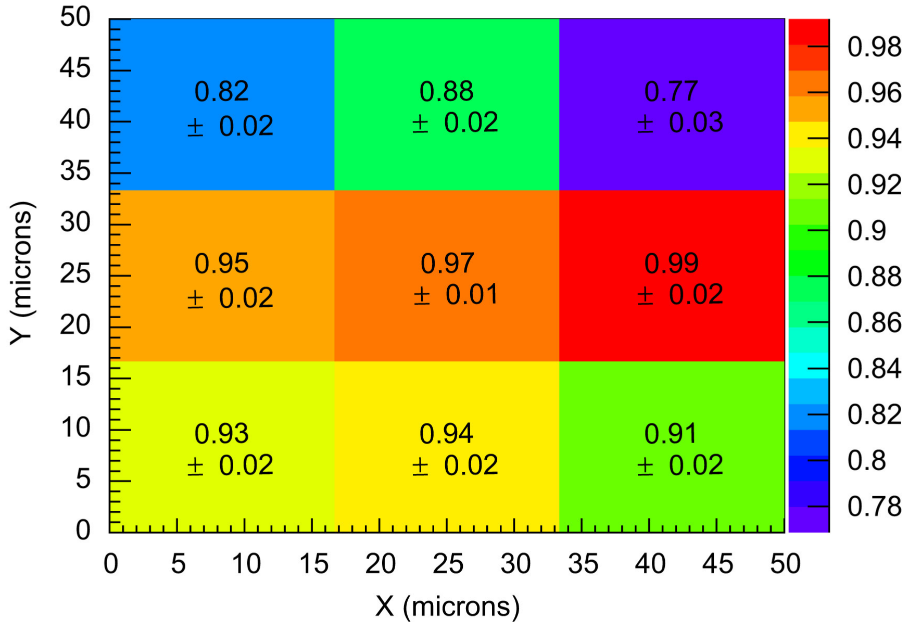
The charged carriers drifting towards the respective electrodes induce a transient current on them

For a single carrier with charge *q* this current *i(t)* depends on the carrier velocity v and on the *weighting field* E_w: $i(t) = q\vec{v} \cdot \vec{E}_w$
(For a MIP: *i(0) ~ O(μA)*)

The weighting field E_w is related to the the *weighting potential* V_w by the relation: $\vec{E}_w = -\nabla V_w$
where V_w is the solution of the Laplace equation: $\nabla^2 V_w = 0$
with unit potential to one of the electrodes and zero for the others

SLIM5 APSEL 4D performance





Nucl. Instr. Meth. A 623 (2010) 942-953

Figure 3.9: (left)Efficiency results for two MAPS detectors, taken from a single threshold scan. The statistical uncertainty on each point is smaller than the size of the plotting symbol. The point of low efficiency at the lowest threshold was probably due to temperature fluctuations during the measurements.(right) MAPS hit efficiencies measured as a function of position within the pixel. The picture, which is not to scale, represents a single pixel divided into nine sub-cells. The values are the efficiencies obtained in each sub-cell after taking into account track migration among cells. The uncertainties include the statistical uncertainty plus a systematic contribution coming from the track migration.

SLIM5 striplets performance; efficiency

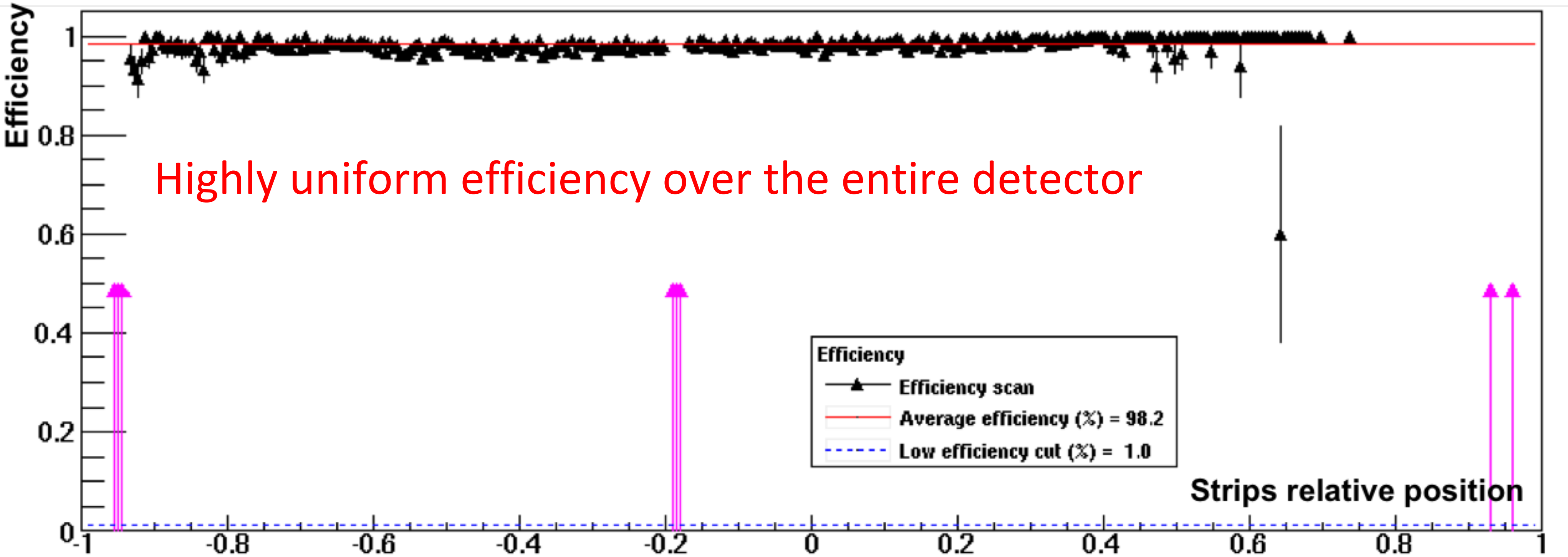
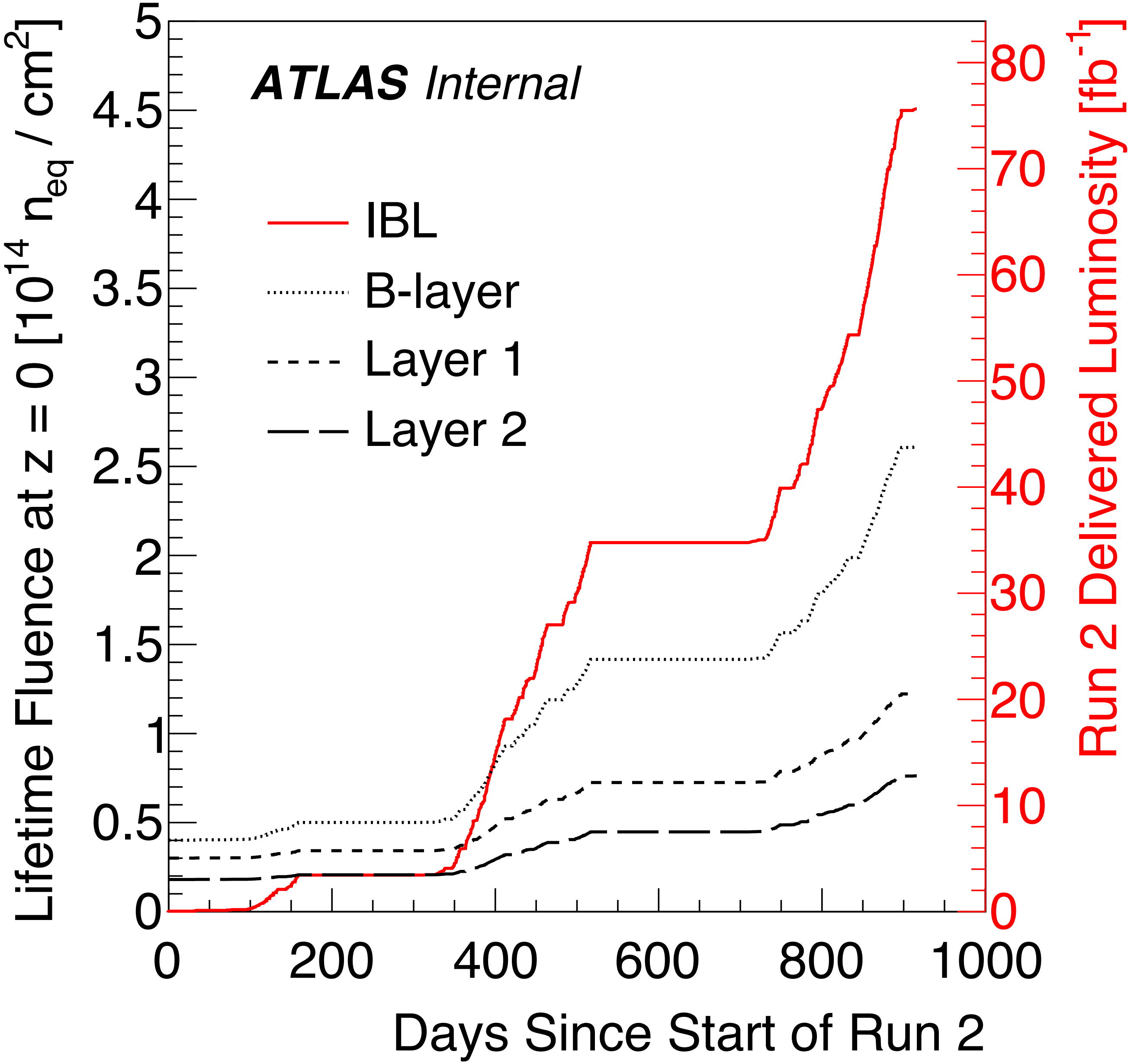


Figure 3.11: Efficiency of a striplet module as a function of the track impact position. Dead strips where removed from the analysis by selecting strips with efficiency greater than 1.0%; dead strips position is marked by magenta arrows.

ATLAS Pixels: Fluence and Luminosity



Example of TCAD radiation damage models

Perugia 2006

TABLE I
THE RADIATION DAMAGE MODEL FOR P-TYPE

Level	Ass.	$\sigma_{n,p}$ (cm^2) Exp.[2]	σ_n (cm^2)	σ_p (cm^2)	η (cm^{-1})
E_c-0.42eV	$VV^{(-/0)}$	$2\cdot10^{-15}$	2×10^{-15}	2×10^{-14}	1.613
E_c-0.46eV	$VVV^{(-/0)}$	$5\cdot10^{-15}$	5×10^{-15}	5×10^{-14}	0.9
Ev+0.36eV	CiOi	2.5×10^{-15}	2.5×10^{-14}	2.5×10^{-15}	0.9

TABLE II
THE THREE LEVELS RADIATION DAMAGE MODEL FOR N-TYPE

Level	Ass.	$\sigma_{n,p}$ (cm^2) Exp.[2,9]	σ_n (cm^2)	σ_p (cm^2)	η (cm^{-1})
Ec-0.42eV	$VV^{(-/0)}$	2×10^{-15}	2×10^{-15}	1.2×10^{-14}	13
Ec-0.50eV	VVO(?)	5×10^{-15}	5×10^{-15}	3.5×10^{-14}	0.08
Ev+0.36eV	C_iO_i	2.5×10^{-15}	2×10^{-18}	2.5×10^{-15}	1.1

IEEE TNS, VOL. 53, NO. 5 (2006)

IEEE TNS, VOL. 63, OCTOBER 2016

Perugia 2016

TABLE III
THE RADIATION DAMAGE MODEL FOR P-TYPE (UP TO 7×10^{15} N/CM^2)

Type	Energy (eV)	σ_e (cm^{-2})	σ_h (cm^{-2})	η (cm^{-1})
Acceptor	Ec-0.42	1×10^{-15}	1×10^{-14}	1.613
Acceptor	Ec-0.46	7×10^{-15}	7×10^{-14}	0.9
Donor	Ev+0.36	3.23×10^{-13}	3.23×10^{-14}	0.9

Nota Bene: Perugia 2006 p-type and Perugia 2016 are very similar

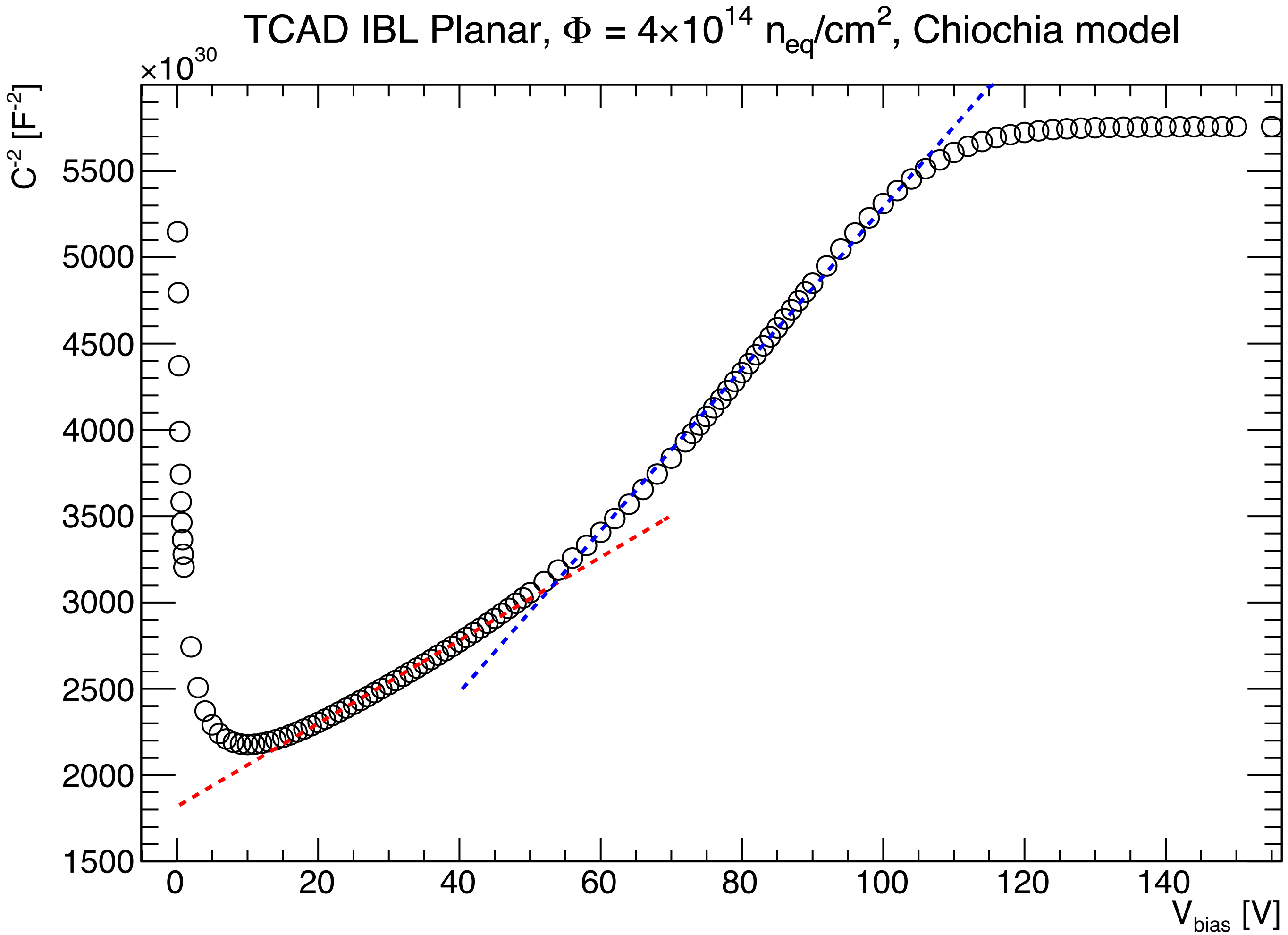
NIM A568, (2006) 51 — Chiochia 2006; E_A: Ec−0.525 eV; E_D: Ev+0.48 eV

Used for ATLAS digitizer

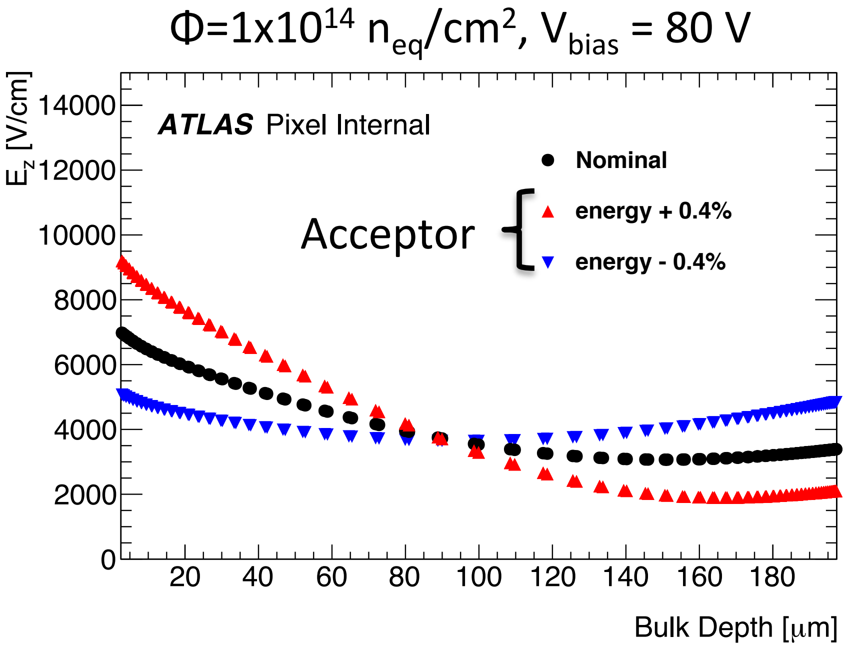
Table 1
Double trap model parameters extracted from the fit to the data

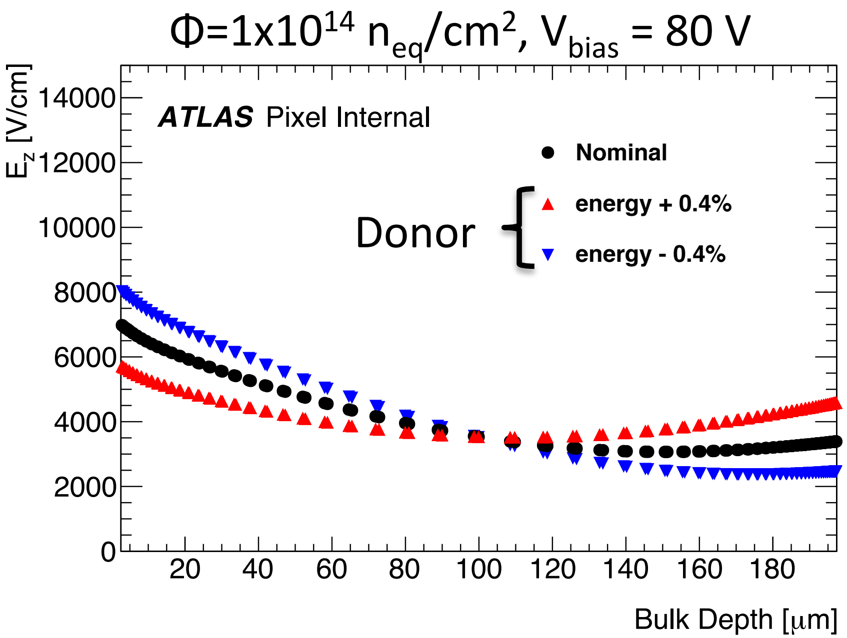
Φ (n_{eq}/cm^2) ($\times10^{14}$)	N_A(cm^{-3}) ($\times10^{15}$)	N_D(cm^{-3}) ($\times10^{15}$)	$\sigma_e^{A/D}$(cm^2) ($\times10^{-15}$)	σ_h^A(cm^2) ($\times10^{-15}$)	(cm^2) σ_h^D ($\times10^{-15}$)
0.5	0.19	0.25	6.60	1.65	6.60
2	0.68	1.0	6.60	1.65	6.60
5.9	1.60	4.0	6.60	1.65	1.65

Simulated CV curve after irradiation



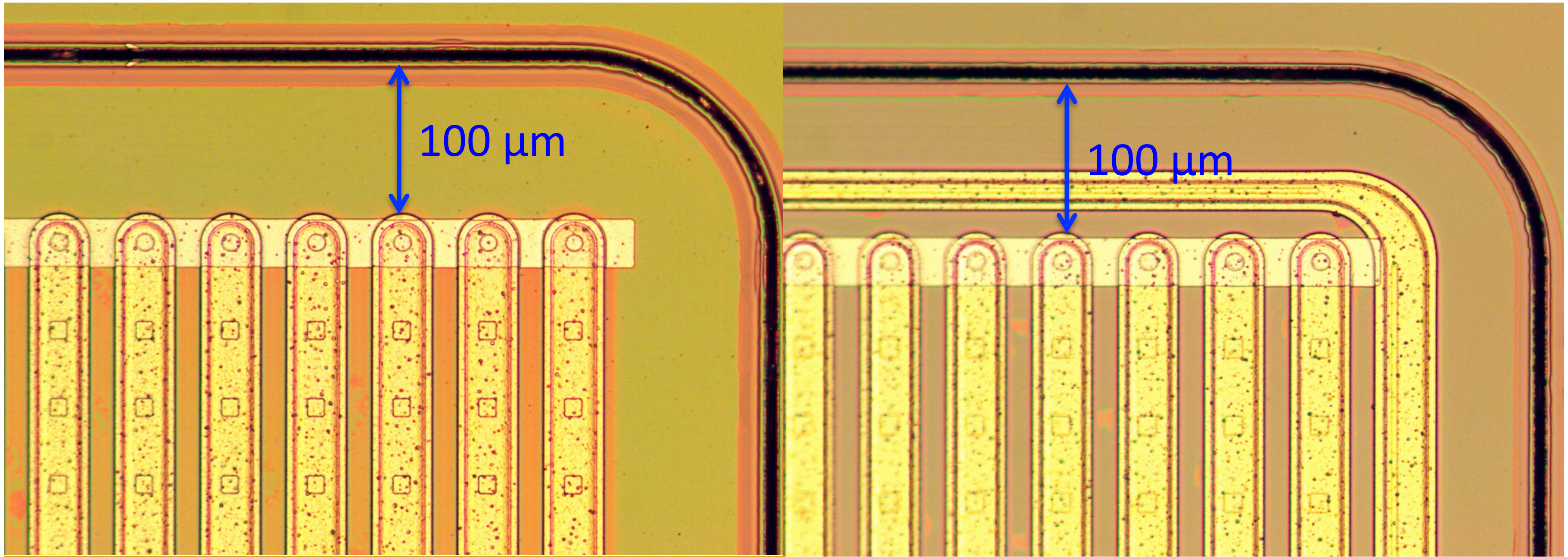
Systematic uncertainties from TCAD models

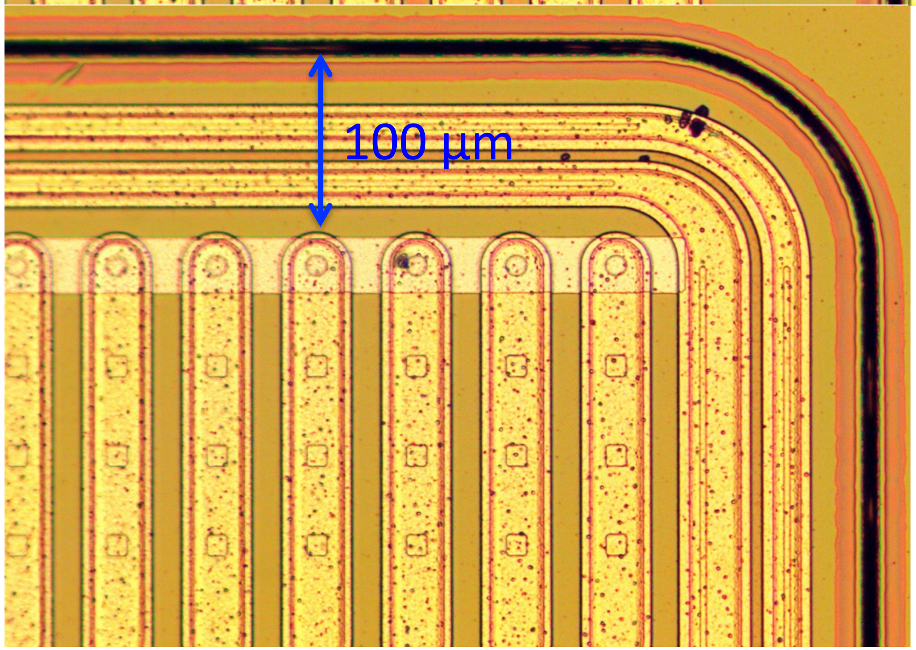


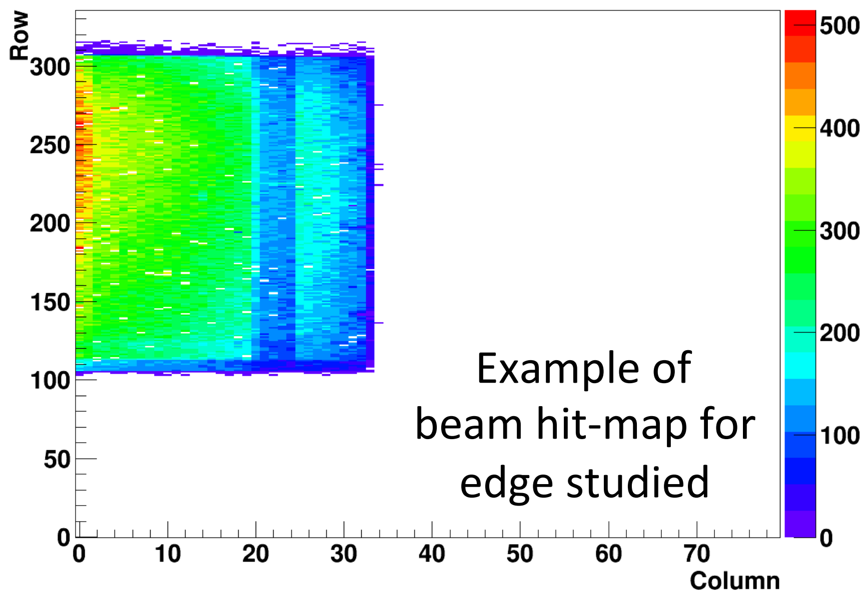


- As shown in the previous slide, TCAD radiation damage **models parameters** come with **no uncertainties**
  - Motivation: limited computing power/time, at least for early 2000s models
  - Authors provided no guidance at all
- We decided to **vary each trap parameter by a certain fraction** of its value and **see the effect on the electric field profile**
- Trap occupation probability P_t depends exponentially on trap energy E_t and linearly on the other parameters, so the following uncertainties were assigned:
  - **E_t: +/- 0.4% (~1/10 of k_BT)**
  - **Trap density N_t, cross sections $\sigma_{e,h}$: +/- 10%**

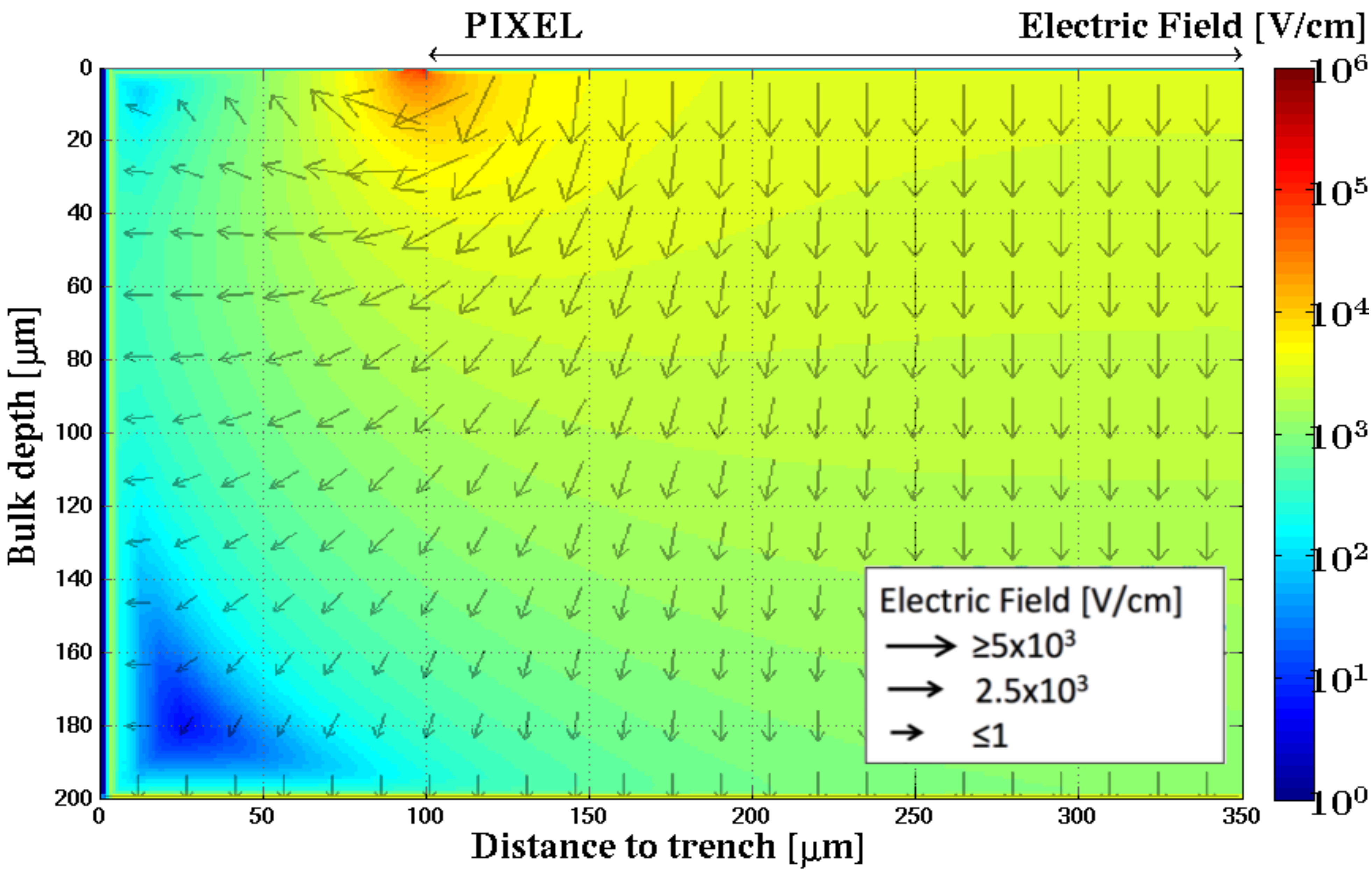
PAE1 pixel production: edge studies







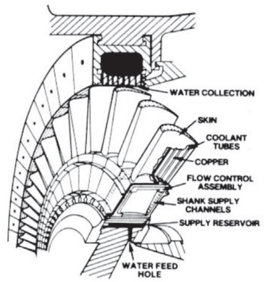
TCAD simulations – 0 GRs

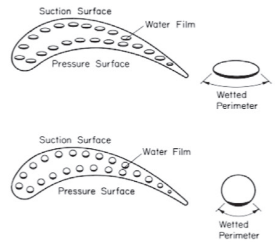


μ-channels cooling applications

Sung-Min Kim, Issam Mudawar, International Journal of Heat and Mass Transfer 77 (2014) 74–97

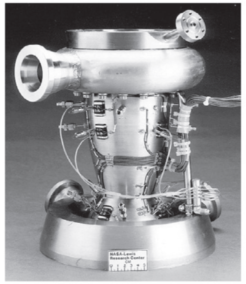
Water cooling of turbine blades

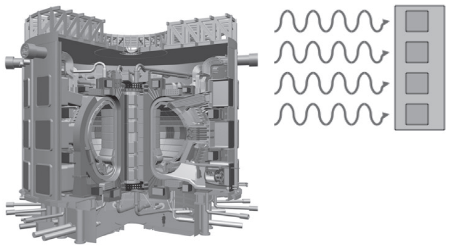




Computer data centres

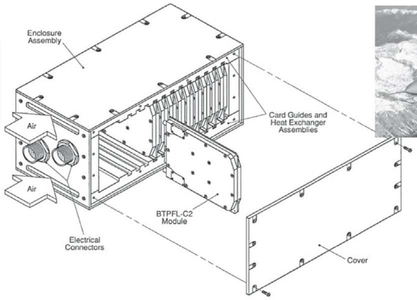
Rocket engine noozle cooling

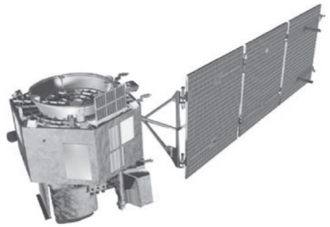




Fusion reactor blanket

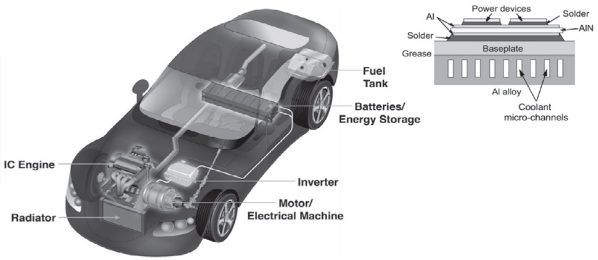
Avionics cooling

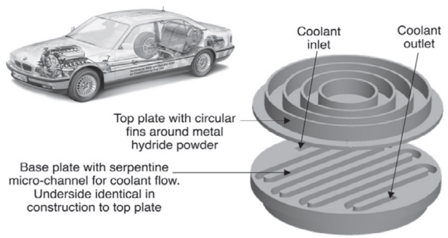




Cooling of satellite electronics (*e.g.* HEP: *AMS)*

Hybrid veichles data centres





Heat exchange for hydrogen storage

Motivations

Many modern devices are faced with two conflicting trends

- the need to dissipate increasing amounts of heat,
- and the quest for more compact and lightweight designs

Most present air cooling and single-phase liquid cooling solutions virtually obsolete

Paradigm shift from single-phase to two-phase cooling strategies to capitalize upon the coolant's sensible and latent heat rather the sensible heat alone

- CO_2 boiling

Sung-Min Kim, Issam Mudawar, International Journal of Heat and Mass Transfer 77 (2014) 74–97

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- CO_2 boiling
- into micro-channels!

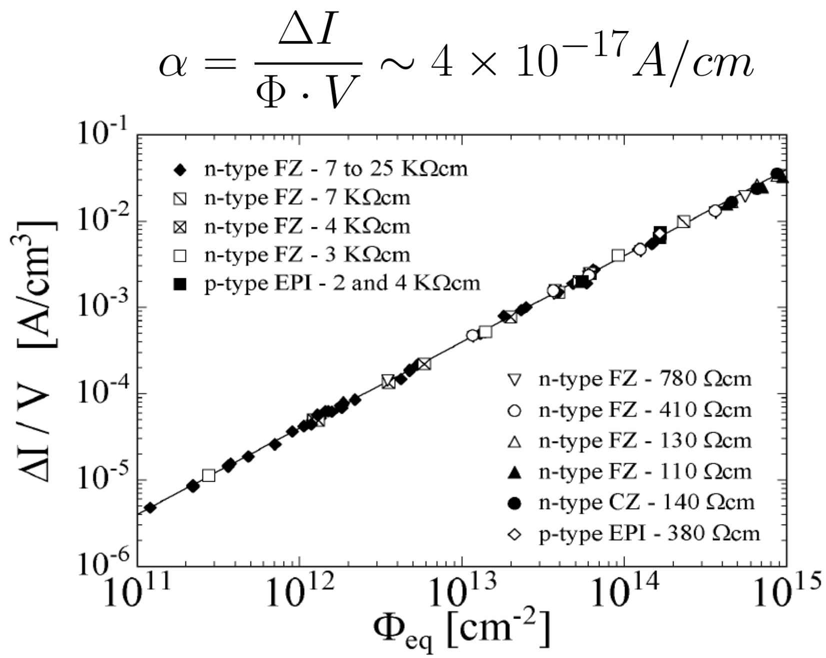
Sung-Min Kim, Issam Mudawar, International Journal of Heat and Mass Transfer 77 (2014) 74–97

New cooling system for ITk

- The leakage current increase is prop. to ϕ

$\Delta I/V(\Phi=1e16/cm^2) \approx 0.4\ A/cm^3$

16 mA if $V = 4cm^2$ x 100µm



Efficient and powerful thermal management needed

HEP Experiments at Colliders and in Space

- **@Future Hadronic Colliders**
- To avoid thermal runaway future sensors must be operated well below 0 °C ➔ ideally: -20 °C
- Sensor+chip will dissipate ≈ W/cm^2
- A very efficient cooling system is needed
- Important constraint: very low material budget (< 1% X_0 envisaged)

- **Space-Born experiments**
- Silicon detectors require:
- a high degree of temperature homogeneity across the apparatus
- a cooling system capable of working for several years without possibility of intervention during the space mission

Promising solution:
micro-channel based cooling using CO_2

Evaporative CO_2 in silicon μ-channels

LHCb

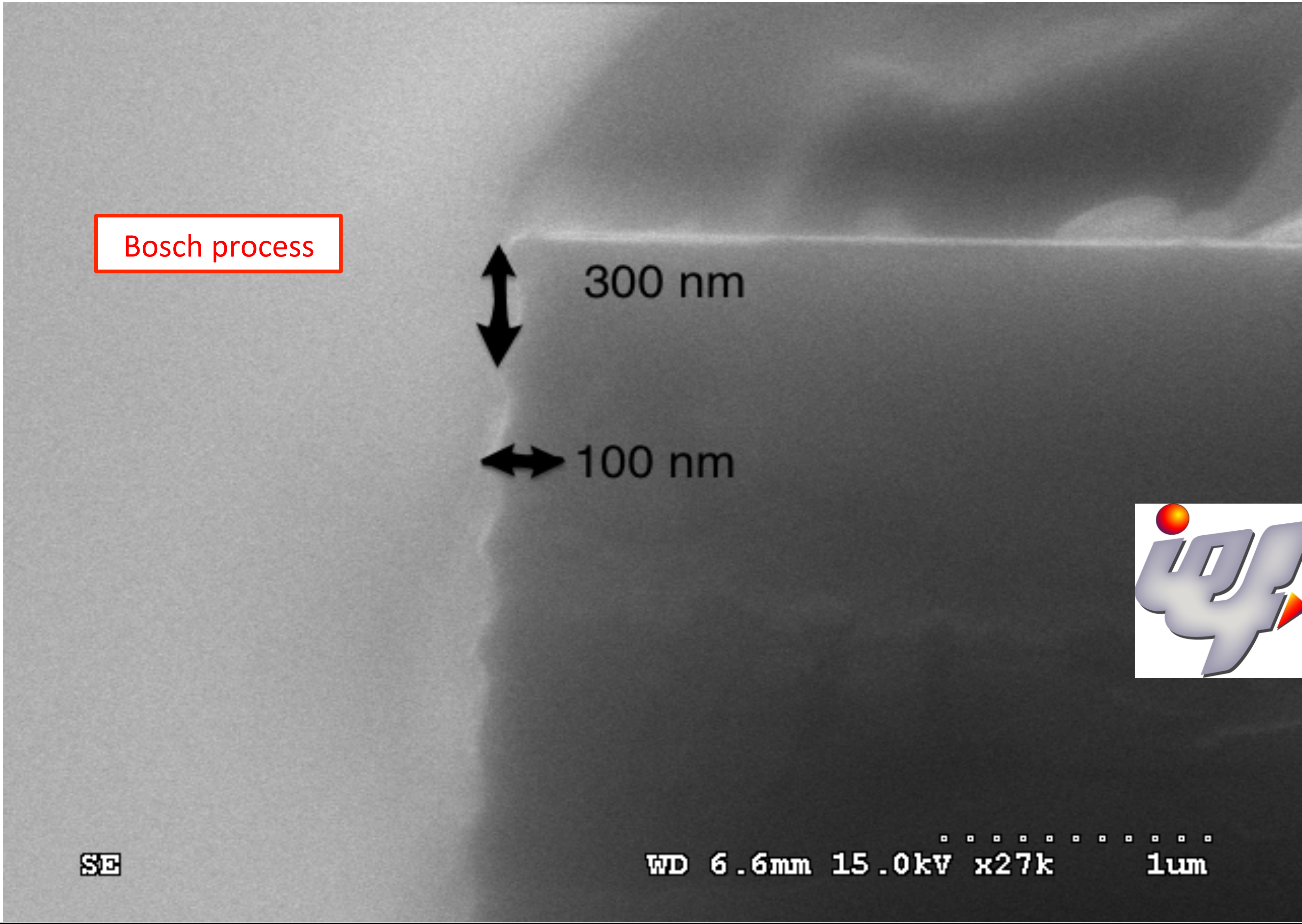
Advantages of evaporative CO_2 microchannel cooling in silicon

- Evaporative Cooling
  - Isothermal (low temperature gradient)
  - Easy to control by regulating the pressure
  - Very Stable: Temperature is quite insensitive to the variation of heat load

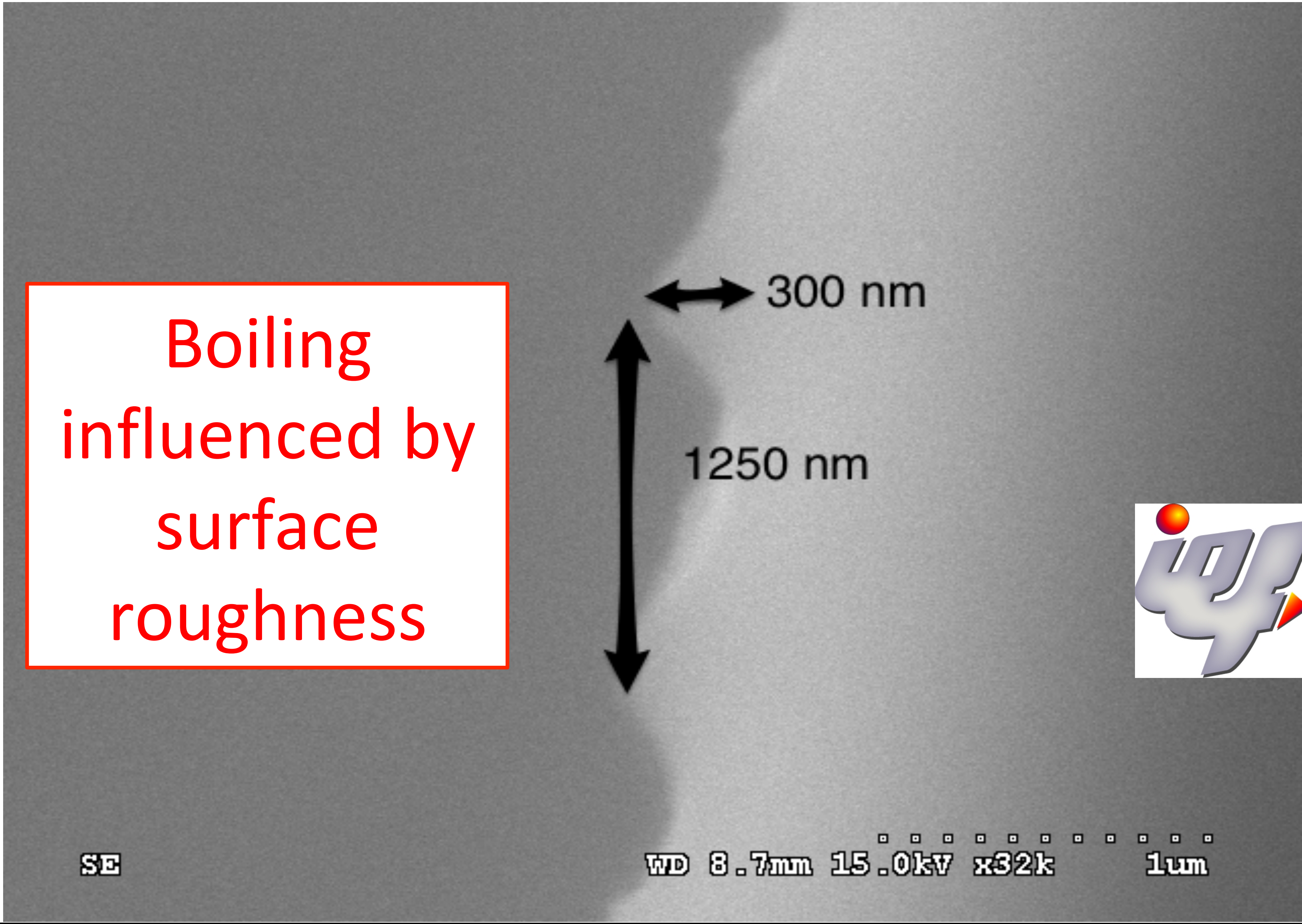
- CO_2
  - High latent heat
  - Low viscosity
  - Non-toxic and environment friendly
  - Chemical inert
  - Radiation hard

- Microchannels in Silicon
  - Cooling fluid is immediately underneath the heat source
  - Low mass – The cooling substrate is also the mechanical support
  - No mismatch of expansion coefficients

Scalloping



Scalloping



Boiling influenced by surface roughness

Ceramic connectors (and microchannels)