The R&D for ATLAS pixels for sLHC

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LPNHE

Outline

- The LHC upgrade
- The Pixel upgrade
- The IBL project
- The R&D for a new Inner Detector: the Planar Pixel Sensor Upgrade (PPSU) project
- Conclusions

LHC upgrade

The LHC in the high lumi area

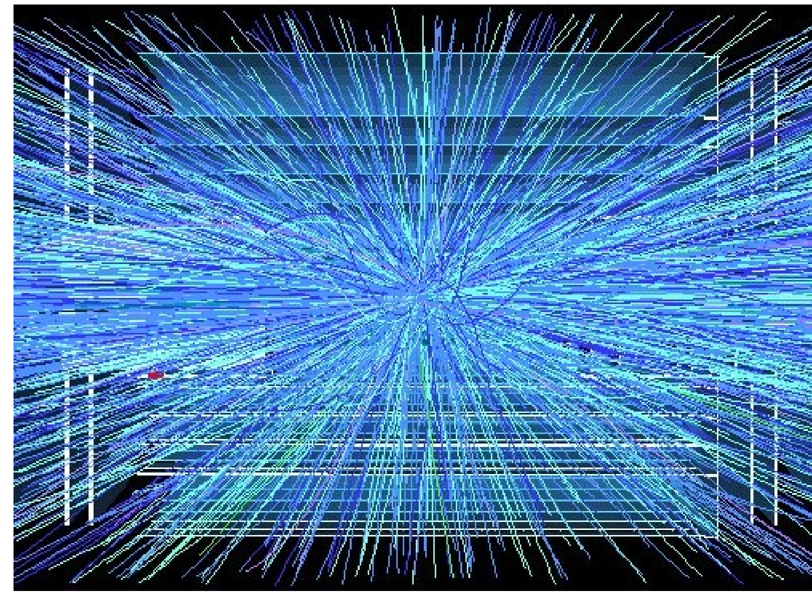
- The LHC is a discovery machine built to study
  - **The ElectroWeak Symmetry Breaking mechanism**
  - **The shortcomings of the Standard Model**
- The discovery potential of the LHC can be enhanced by increasing its luminosity
- Infact, **whatever is discovered**, we'll want, at least, to
  - **Improve the measurement of its properties (masses, couplings, etc)**
  - **Test further predictions of the theories put forward to explain it**

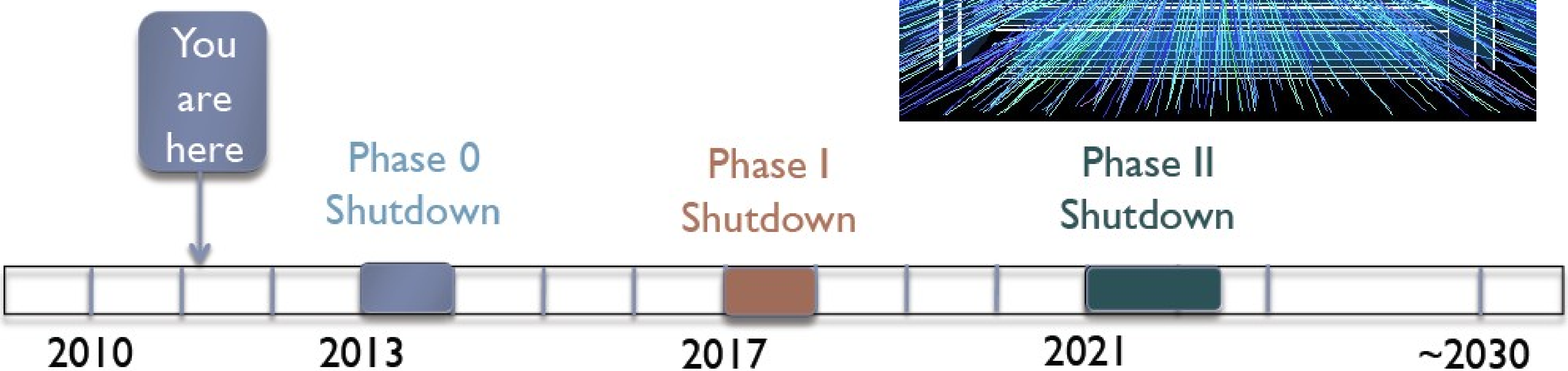
LHC Schedule

- Caveat: this schedule spans decades.

→ Changes to the schedule could be prompted by

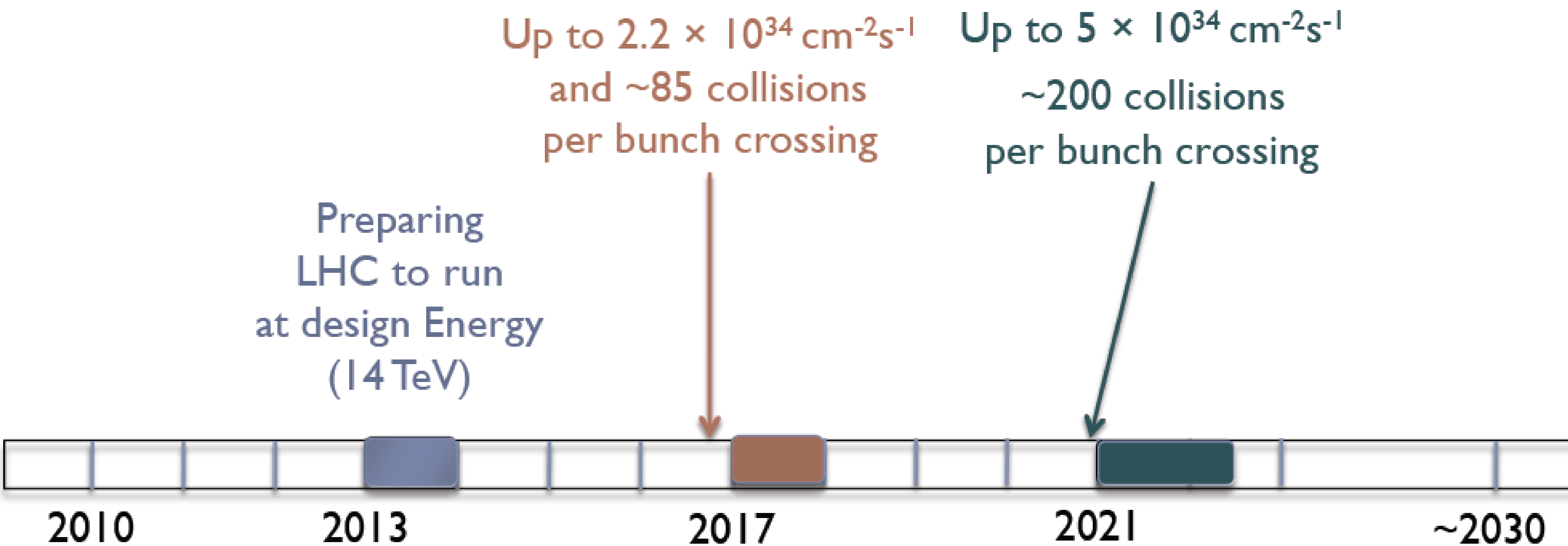
- ✓ Physics landscape
- ✓ Machine needs
- ✓ Detector needs





Luminosity plans

- Depends strongly on how the machine will be run
  - Bunch spacing: 25 vs 50 ns?
  - Leveling?
- Estimates based on current planning



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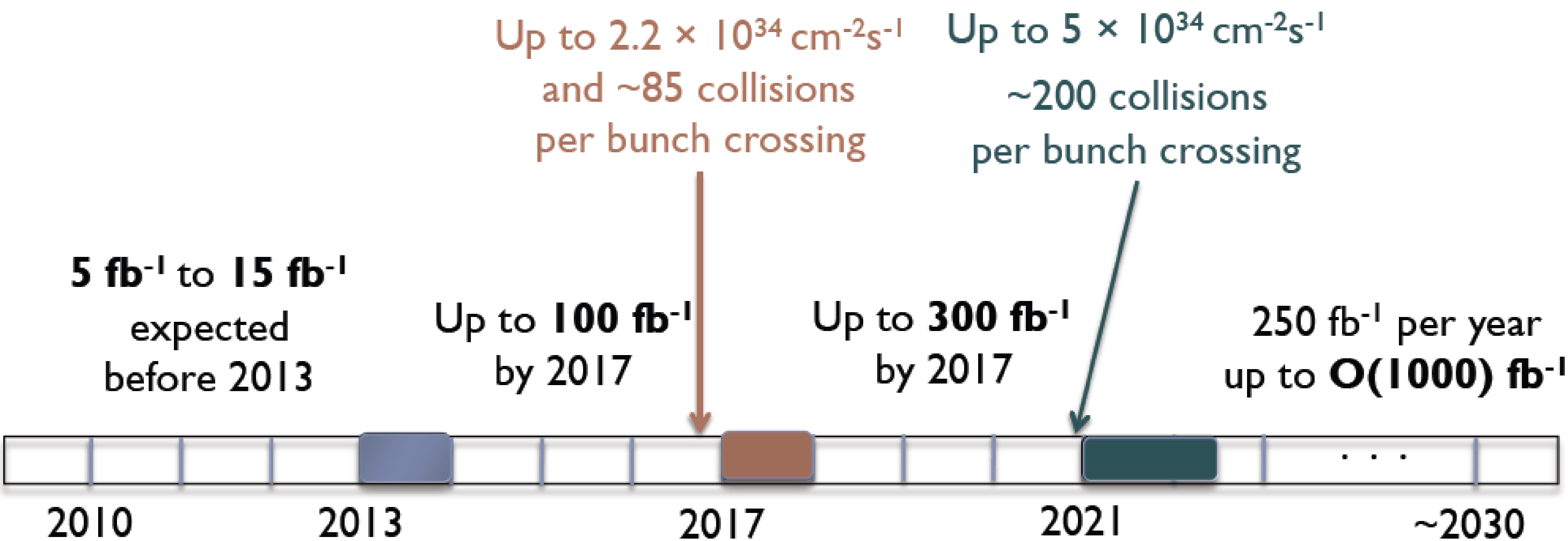
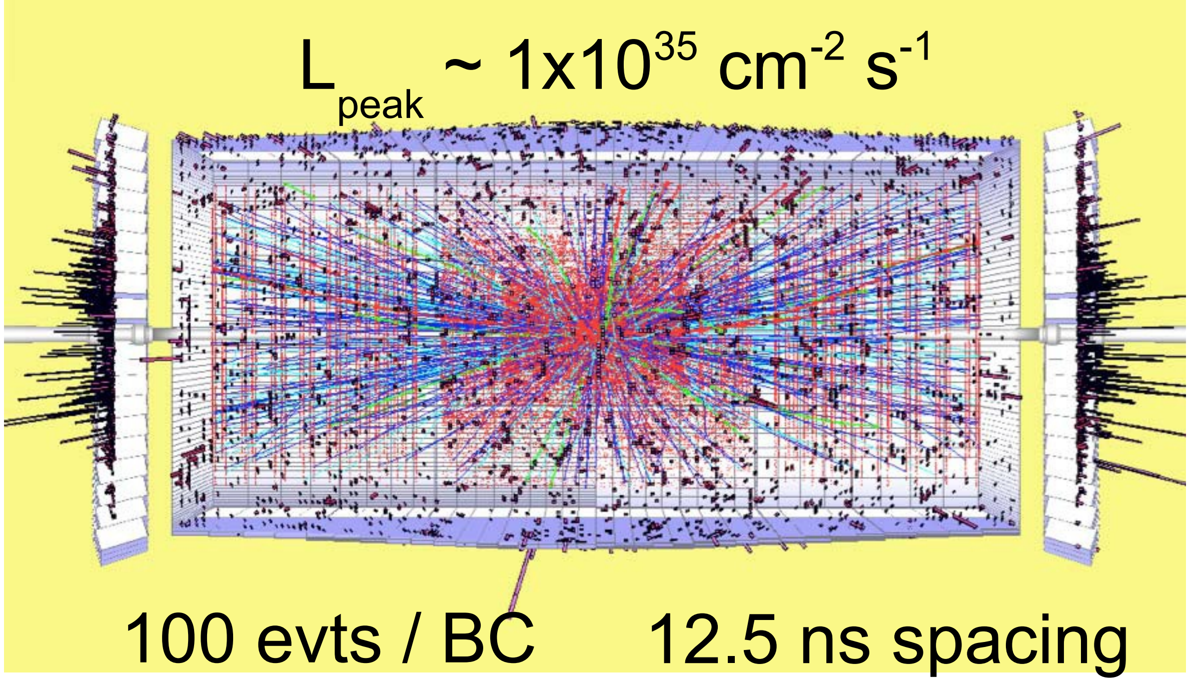


High luminosity implications

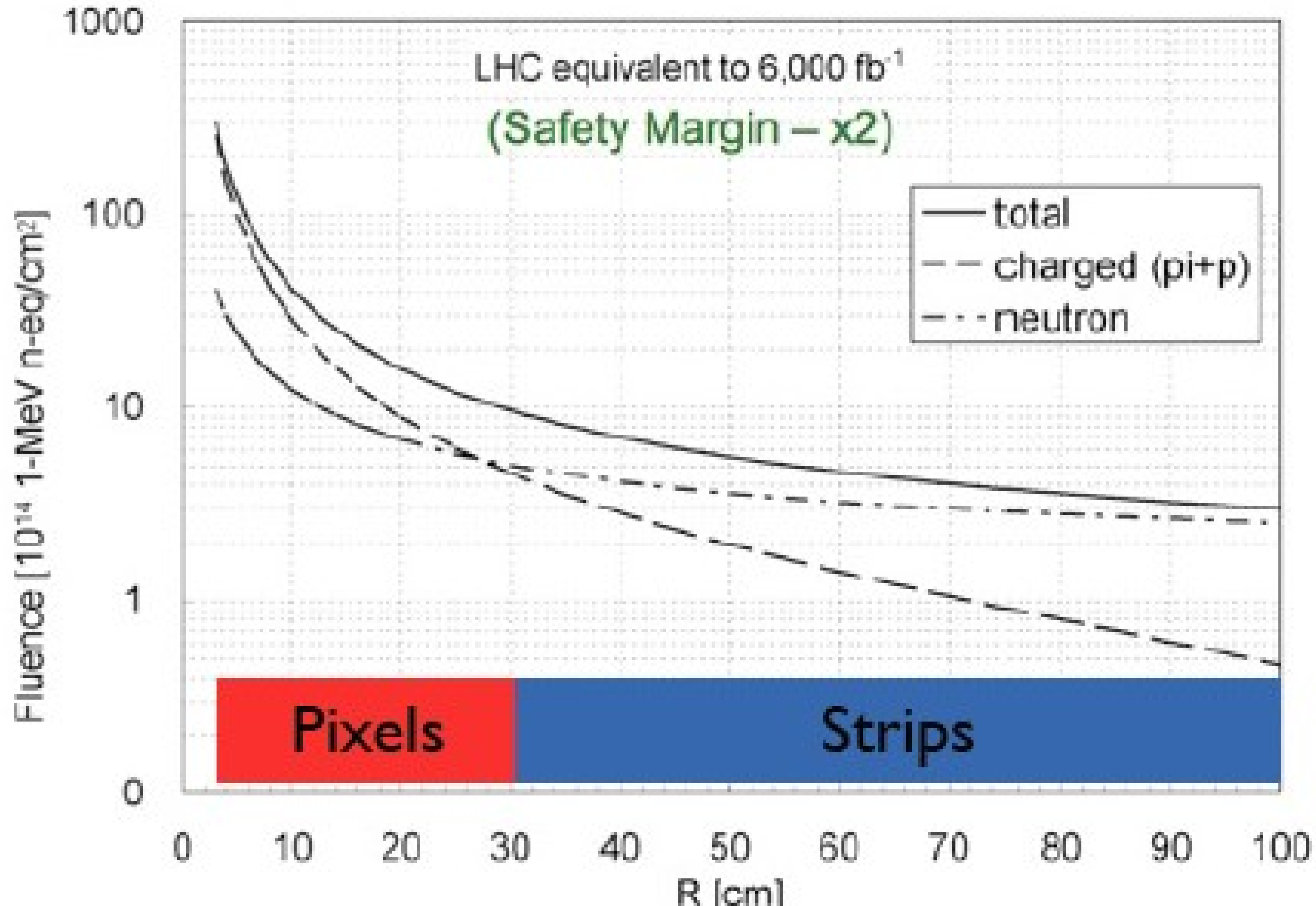


- More pile-up & higher rate events

➔ **Faster electronics**

➔ **Higher granularity subdetectors**

High luminosity implications



- fluences for the innermost pixel layer: **1.5×10^{16} n_{eq}/cm^2 (3 ab^{-1})**

➔ **Radiation hard components**

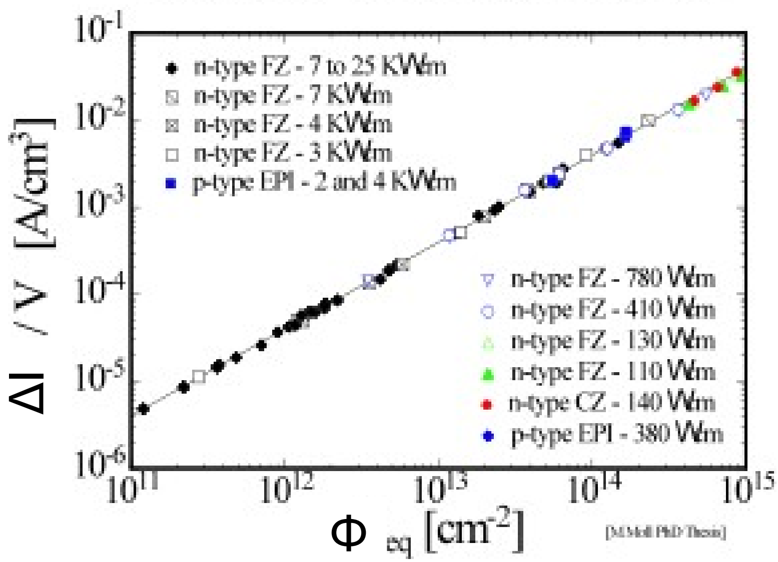
Macroscopic effects

Increase of leakage current
- can be helped with cooling

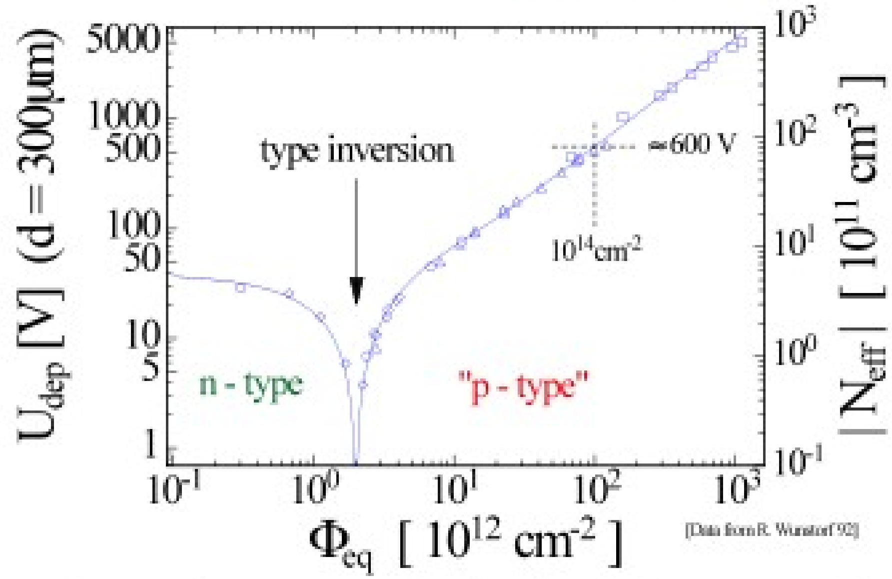
Change of the full depletion voltage V_{dep} (effective doping concentration N_{eff}).
- every p-n-junction has a finite breakdown voltage

Decrease of the charge collection efficiency
- limited by partial depletion, trapping, type inversion

Change of the leakage current:

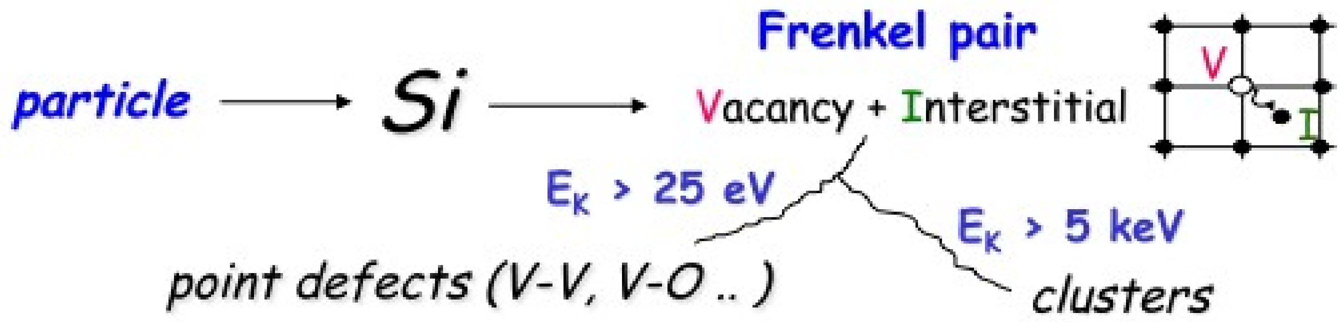


Evolution of the N_{eff} for n-type initial doping:

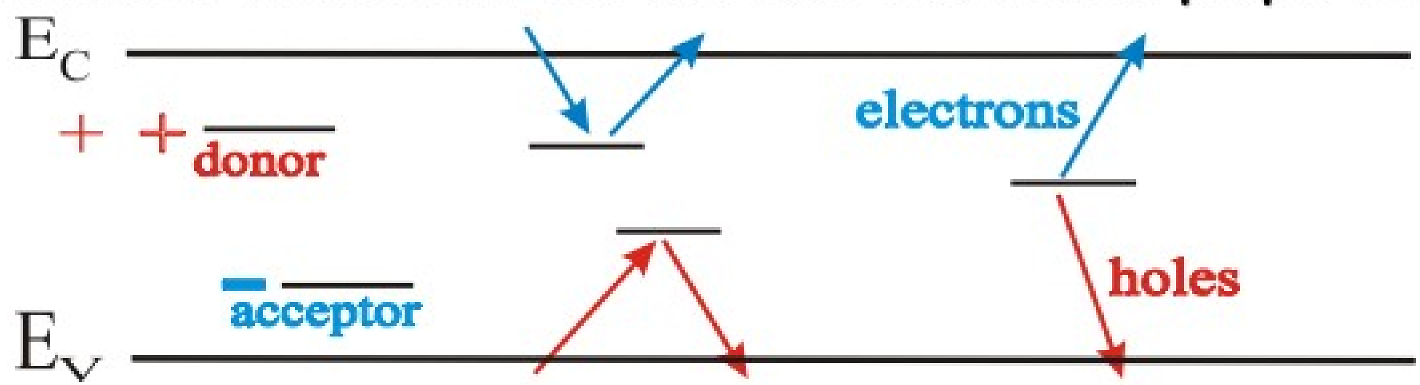


Panja Luukka, The Fifth International Forum on Advanced Material Science and Technology (IFAMST5 2006)

Radiation damage in silicon detectors



Influence of defects on the material and device properties

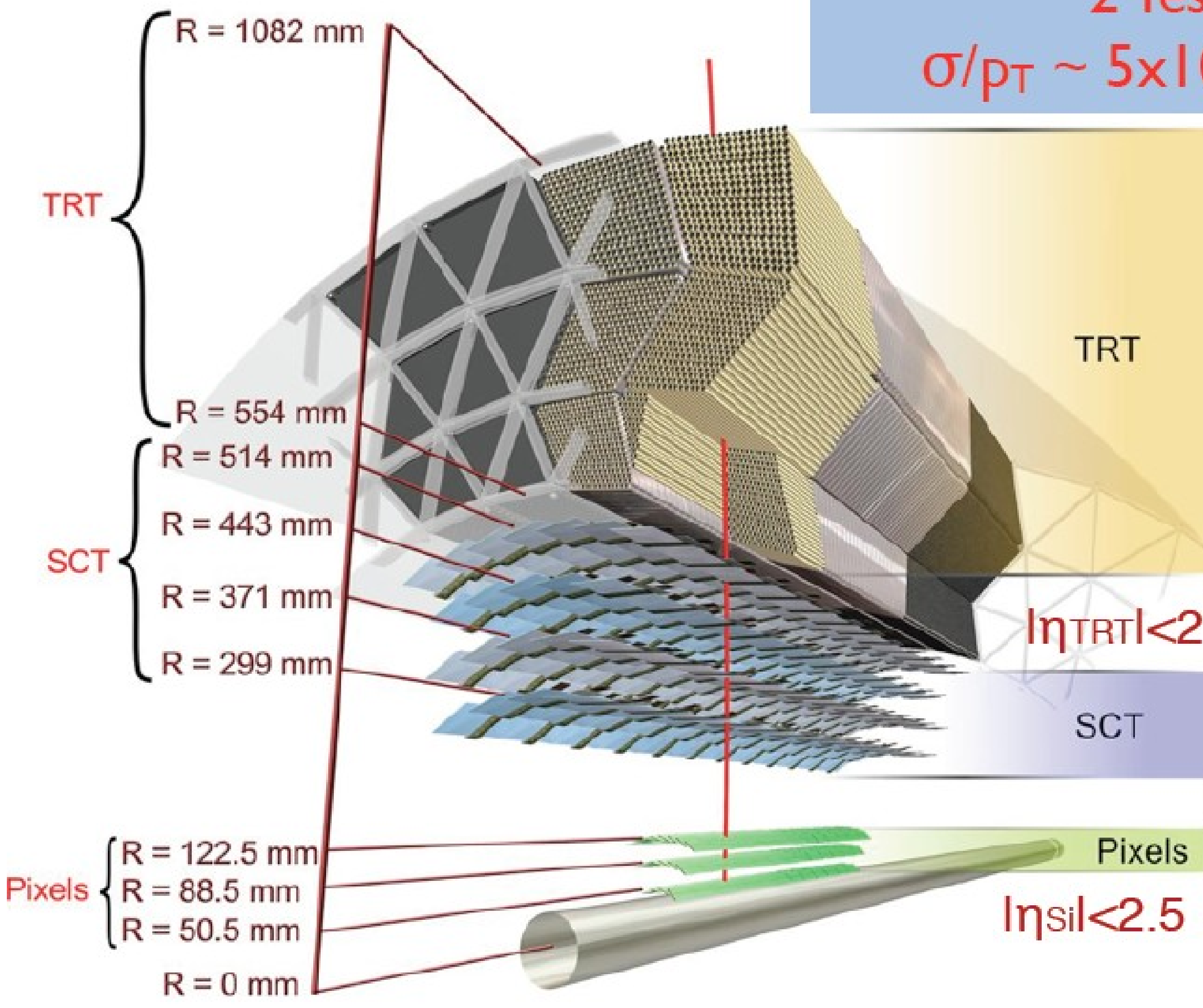


charged defects	trapping (e and h)	generation
⇒ N_{eff} , V_{dep}	⇒ CCE	⇒ leakage current
e.g. donors in upper and acceptors in lower half of the band gap	shallow defects do not contribute at room temperature due to fast detrapping	levels close to middle of the bandgap most effective

Panja Luukka, The Fifth International Forum on Advanced Material Science and Technology (IFAMST5 2006)

THE PIXEL UPGRADE

The current Inner Detector



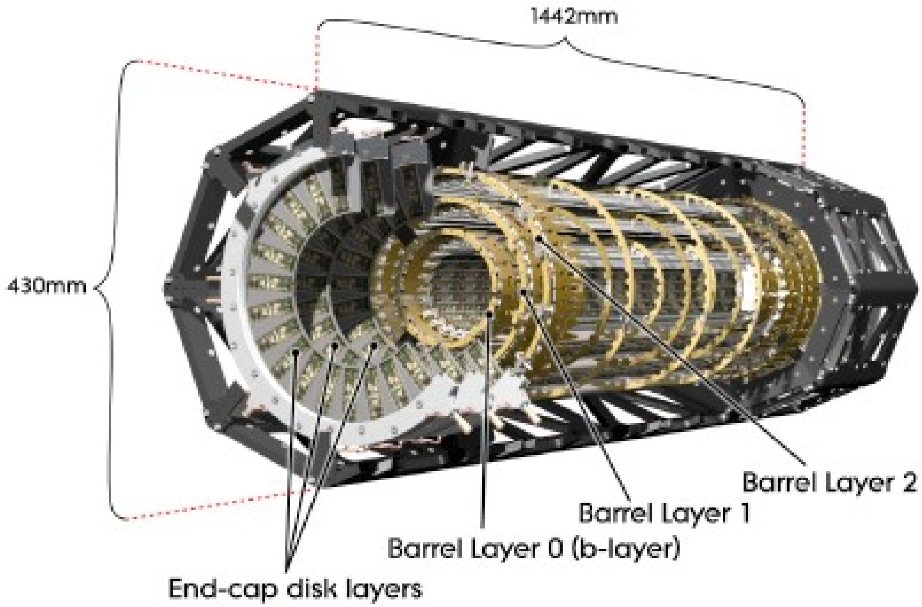
2 Tesla Solenoid
$\sigma/p_T \sim 5\times10^{-4}\, p_T/\mathrm{GeV} \oplus 0.01$

Transition Radiation Tracker (TRT) (350k channels) with e/π separation

SemiConductor Tracker (SCT) ~6M silicon strips

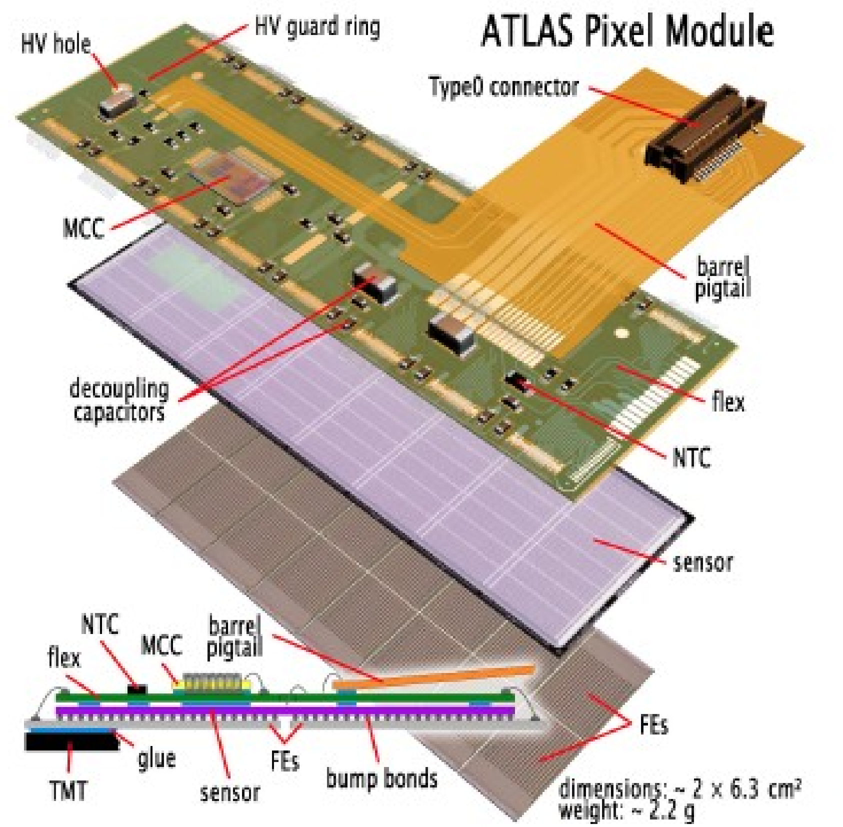
Pixels: 80M channels

The current ATLAS Pixel detector



- ATLAS Pixel Detector
  - 3 barrels + 3 forward/backwarc disks
  - 112 stave and 4 sectors
  - 1744 modules
  - 80 million channels

- **ATLAS Pixel Module**
  - 16 front-end chips (FE-I3) module with a Module Controller Chip (MCC)
  - 46080 R/O channels 50 µm x 400 µm (50 µm x 600 µm for edge pixel columns between neighbour FE-I3 chips)
  - Planar n-in-n DOFZ silicon sensors, 250um tick
  - Designed for 1 x 10^{15} 1MeV fluence and 50 Mrad
  - Optolink R/O: 40÷80 Mb/link

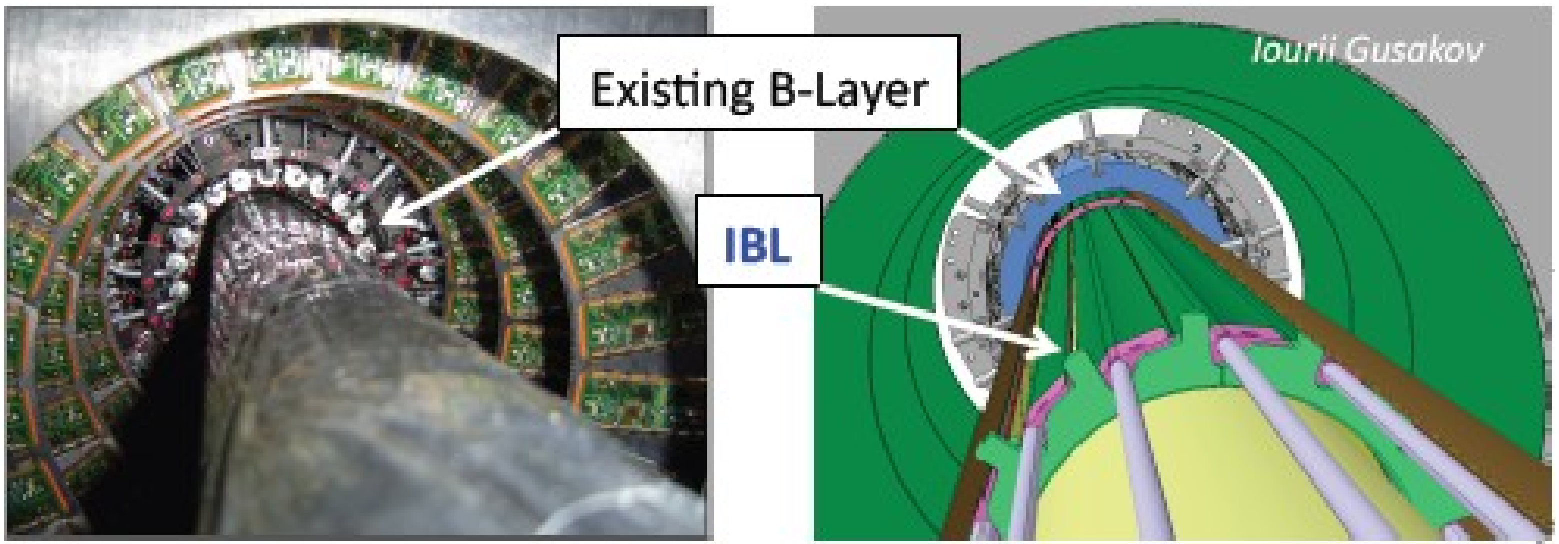


IPRD10, Siena 9.6.2010 - Alessandro La Rosa (CERN)

THE INSERTABLE B-LAYER

A 4th pixel layer: Insertable B Layer

- Add a 4th low-mass Pixel layer inside the present B-layer: the Insertable B-Layer



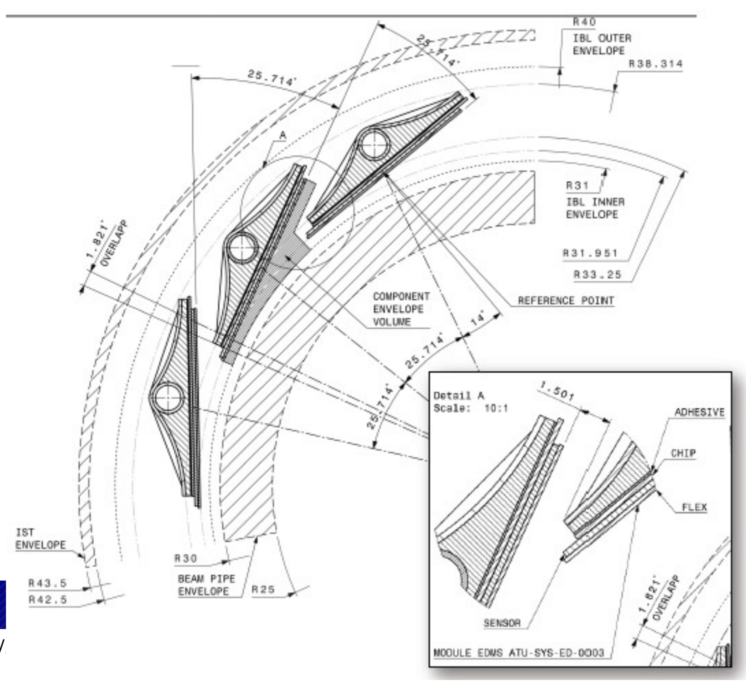
3.2 cm from IP

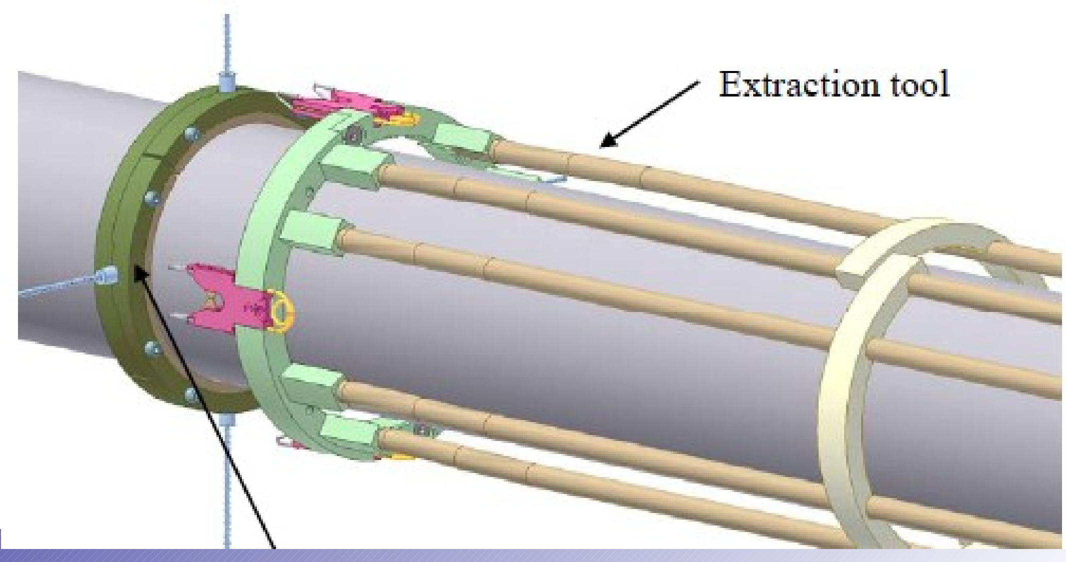
  - To improve performance of existing system
  - To maintain performance of existing system when present B-layer starts degrading

Scheduled for 2013

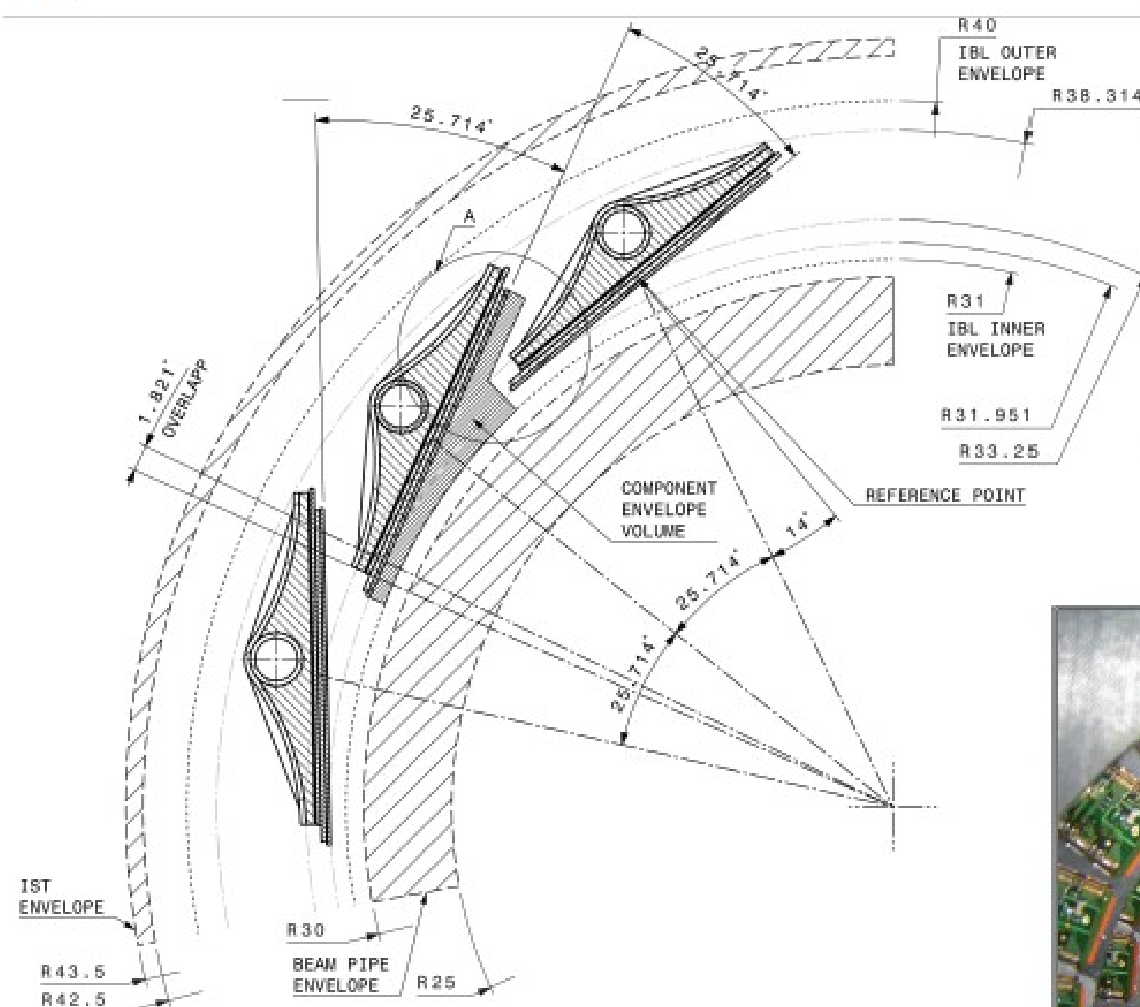
Why is IBL important

- This will be the first real upgrade project in the community
  - ➔ Most of the problems and technologies necessary later for sLHC will be tested and solved already. Excellent test bench for later.
  - ➔ The IBL is the "technology" bridge to sLHC. Its specification required us to develop and use new technologies, which are directly relevant for sLHC





IBL - layout



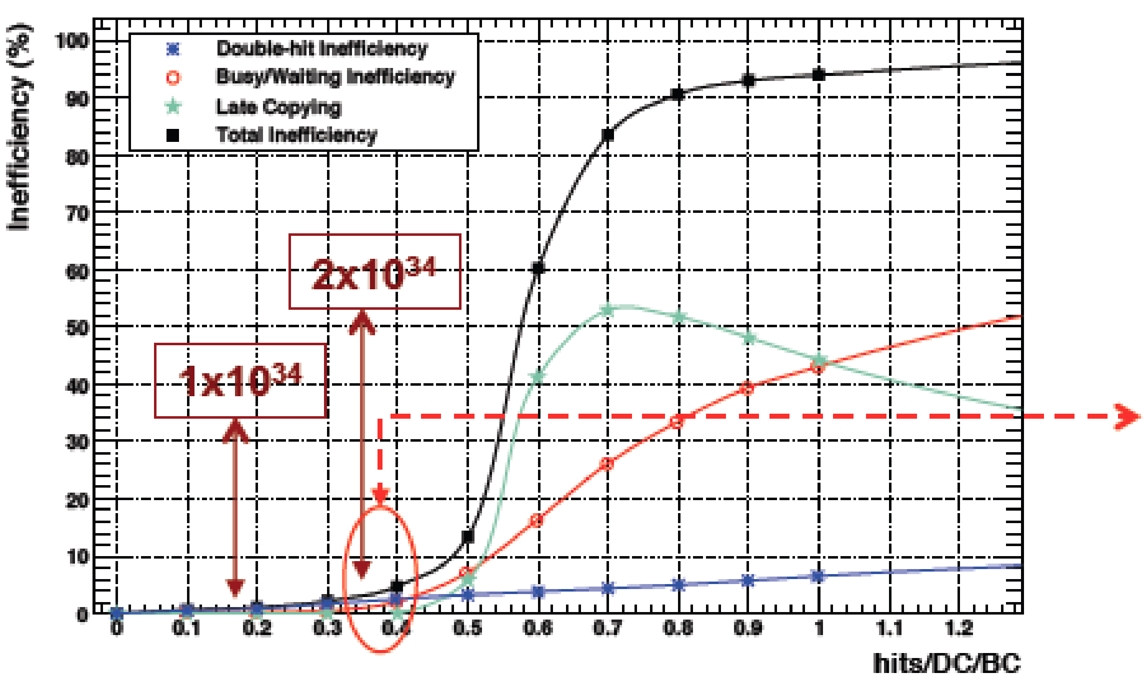
- *Beam-pipe (BP) extracted by cutting the flange on one side and sliding (guiding tube inside).*
- *IBL Support Tube (IST) inserted.*
- *IBL with smaller BP inserted in the IST*

- *Beam-pipe reduction:*
  - Inner R: 29 → 25 mm
- *Very tight clearance:*
  - "Hermetic" to straight tracks in Φ (1.8º overlap)
  - No overlap in Z: minimize gap between sensor active area.
  - Coverage in η (2σ-vertex spread): 2.6
- *Material budget:*
  - Stave, el.serv. Module: 1.16 % X_0
  - IBL Sup.Tube (IST): 0.28 % X_0

IBL - Luminosity effects

- The current Pixel R.O. designed for a peak luminosity of 1 x 10^{34} $cm^{-2}s^{-1}$.
- A luminosity at least twice that high is expected before the sLHC end
- Event pileup: redundancy in track measurement to control the fake rate
- High occupancy: induce readout inefficiencies
- Affects the B-layer more than other layers
- Would thereby limit the *b* tagging efficiency.
- **IBL**: **low occupancy** (with respect to SCT/TRT) **reduces track fakes**
- FE-I4 has higher bandwidth than existing readout.

FE-I3 inefficiency vs occupancy for B-layer

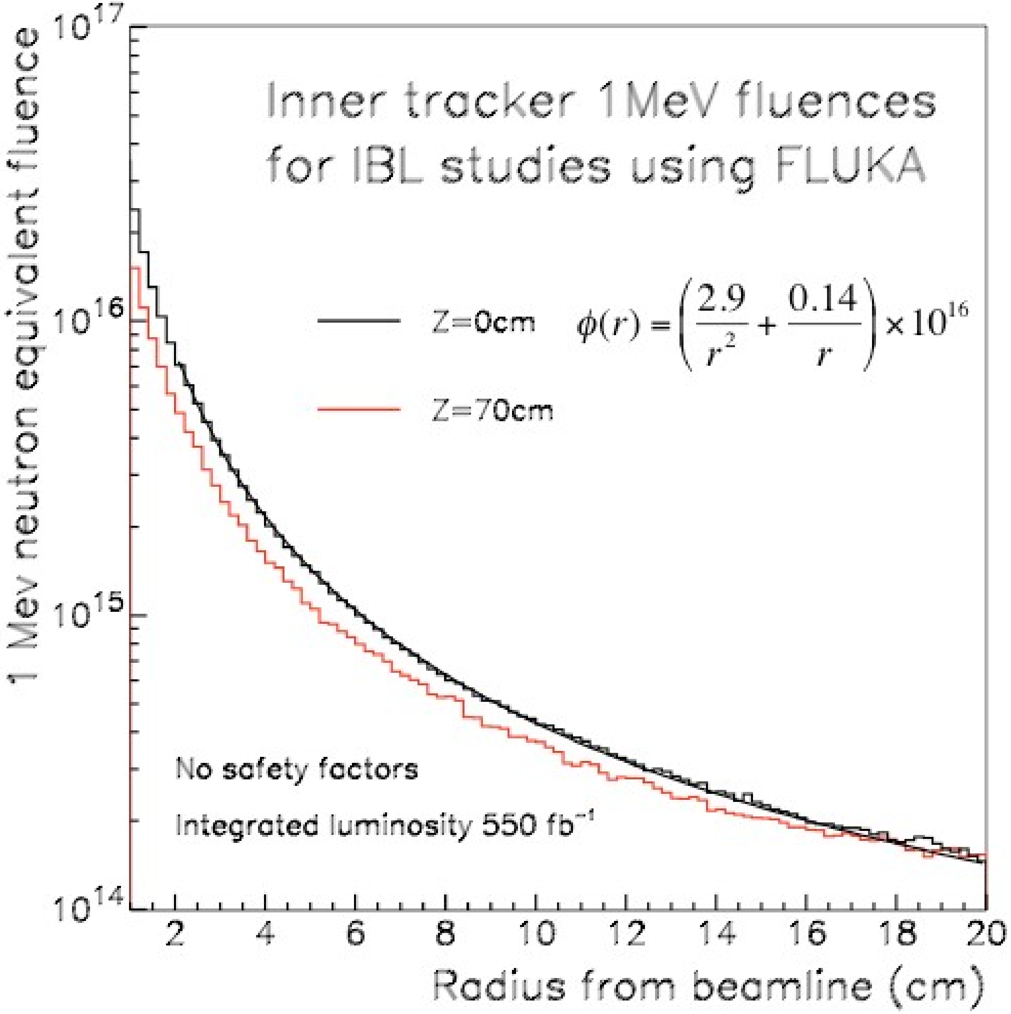


FE-I3 has 5% inefficiencies at the B-layer occupancy for 2.2x10^{34}. Steep rising function of occupancy: no safety margin.

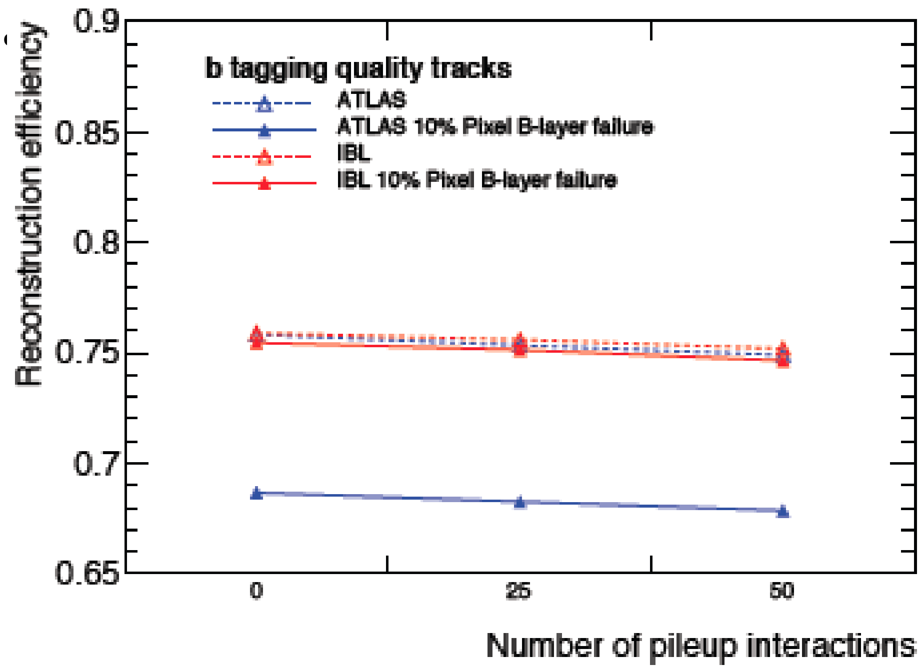
IBL – Radiation effects

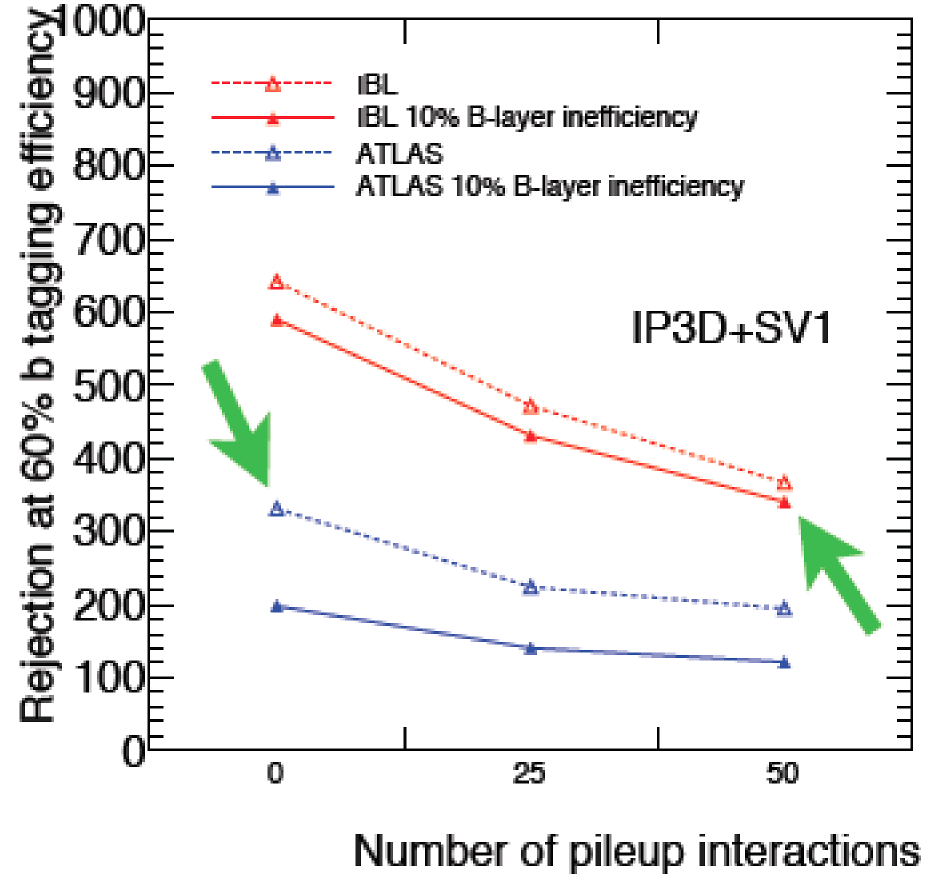
IBL designed for 550 fb^{-1} (provides margin should luminosity evolve more rapidly than expected or should 2020 HL-LHC shutdown be delayed)

- NIEL dose @ 3.2 cm: 3.3 x 10^{15} n_{eq}/cm^2
- Safety factor: 5 x 10^{15} n_{eq}/cm^2
  - TID: 250 Mrad



IBL performances



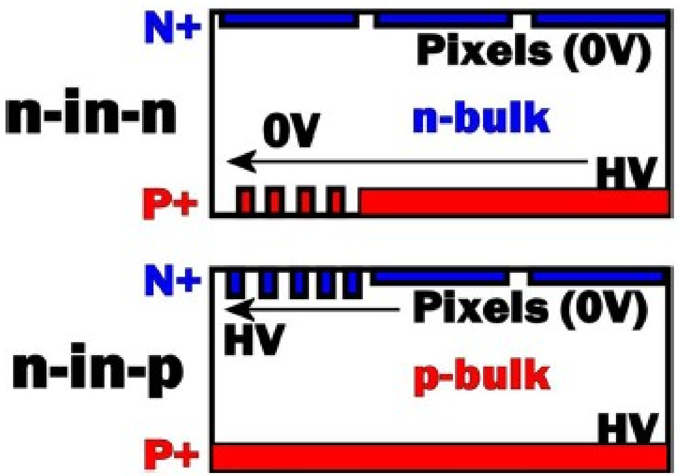


In a scenario with a 10% cluster inefficiency in the actual B-layer, the IBL recovers tracking efficiency and impact resolution

- Only minor effect on b-tagging performances
- Performing better than ATLAS w/o defects and pileup!

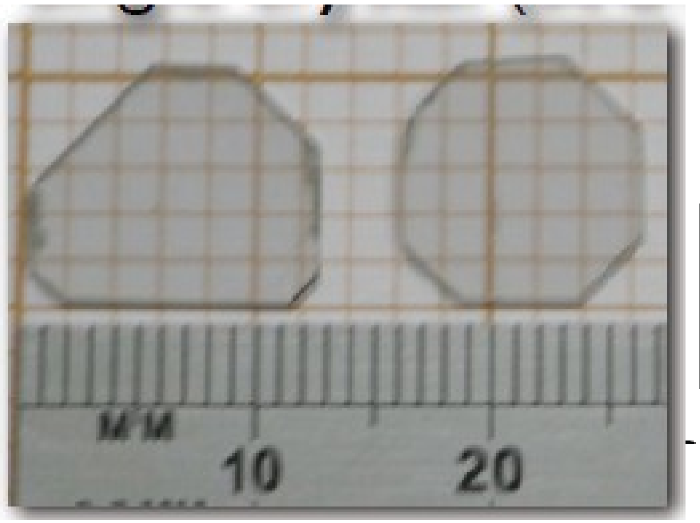
Sensor options for the IBL ...and sLHC

PLANAR



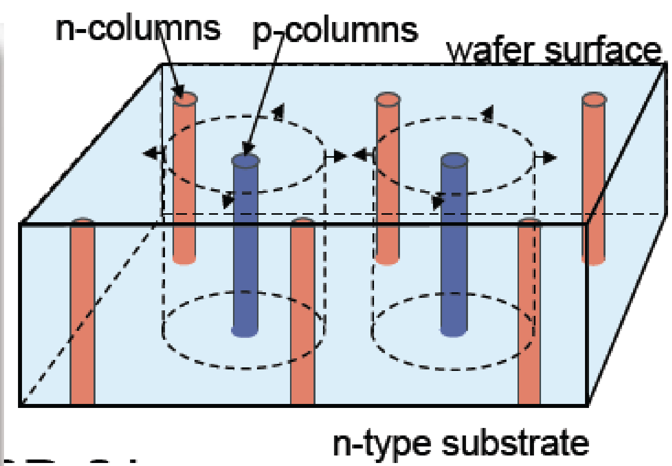
- More details in the next slides

DIAMOND



- Very low noise
- No cooling
- No doping needed
- Low capacitance
- Very high BD field
- Expensive
- Difficult to realize large sample of single crystal sensors

3D



- Implants through the detector
- Highly segmented sensor
- Low depletion voltage
- Fast signal
- High rate capable
- Inefficiency regions correspsing to column
- Low cost large production to be proven

THE PLANAR PIXEL UPGRADE

The ATLAS Planar Pixel Sensor R&D

- Aim: Explore the suitability of planar pixel sensors for highest fluences
- Approved ATLAS R&D project since 2009: 17 institutes, > 80 scientists

IBL + Long Term (2017 or 2020)

ATLAS project	R&D on Planar Pixel Sensor Technology for the ATLAS Inner Detector Upgrade		
ATLAS Upgrade Document No:	Institute Document No.	Created: 10/01/2008	Page 1 of 19
		Modified: 07/05/2009	Rev. No.: 1.1

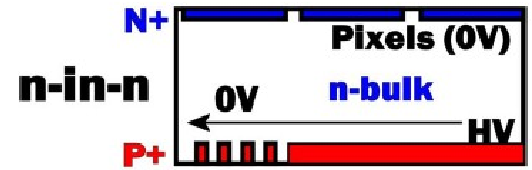
D. Dobos, B. Di Girolamo, H.Pernegger, S. Roe, A. La Rosa[1], V. Vrba, P. Sicho, J. Popule, M.Tomasek, L. Tomasek, J. Stastny, M. Marcisovsky, M. Havranek, J. Bohm[2], A. Lounis, N. Dinu, M. Benoît, R. Tanaka[3], G. Calderini, D. Lacour, H. Lebbolo, G. Marchiori, J. Ocariz, P. Schwemling[4], M. Barbero, F. Hügging, H. Krüger, N. Wermes[5], H. Lacker[6], I. M. Gregor, U. Husemann, P. Kostka[7], C. Gößling, R. Klingenberg, D. Münstermann, A. Rummler, G. Troska, T. Wittig, R. Wunstorf[8], J. Grosse-Knetter, M. George, A. Quadt, J. Weingarten[9], L. Andricek , M. Beimforde, A. Macchiolo, H.-G. Moser, R. Nisius, R. Richter, P. Weigell[10], D. Cauz, M. Cobal, C. del Papa, D. Esseni, M. P. Giordani, P. Palestri, G. Pauletta, L. Selmi[11], Y. Unno, S. Terada, Y. Ikegami[12], M. Cavalli, I. Korolkov, M. Lozano, C. Padilla, G. Pellegrini, M. Ullan[13], T. Affolder, P. Allport, G. Casse, T. Greenshaw, I. Tsurin[14], M. Battaglia, T. Kim, S. Zalusky[15], I. Gorelov, M. Hoeferkamp, S. Seidel, K. Toms[16], V. Fadeyev, A. Grillo, J. Nielsen, H. Sadrozinski, B. Schumm, A. Seiden[17]

17 institutions:

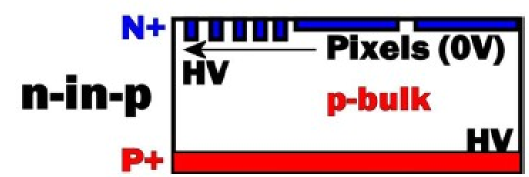
[1]CERN, [2]AS CR, Prague, [3]LAL Orsay/ University Paris-sud XI, [4]LPNHE / University Paris VI, [5]University of Bonn, [6]HU Berlin, [7]DESY, [8]TU Dortmund, [9]University of Goettingen, [10]MPP and HLL Munich, [11]Università degli Studi di Udine – INFN, [12]KEK, [13]IFAE-CNM (Barcelona), [14]University of Liverpool, [15]UC Berkeley/LBNL, [16]UNM, Albuquerque, [17]UCSC, Santa Cruz

Why planar sensors?

- Planar pixel is a proven technology
  - the current n-in-n pixel detector.
  - Modules shown to work after 10^{15} neq/cm2
  - If strips not adequate any more, pps would be the natural option



- Potential for a low-cost large-area production with n-in-p
  - Only one side is patterned



- Research directions
  - Radiation damage studies
  - Active area optimization and geometry redesign
  - Advanced simulation studies
  - High rate capable electronics
  - Low cost module production

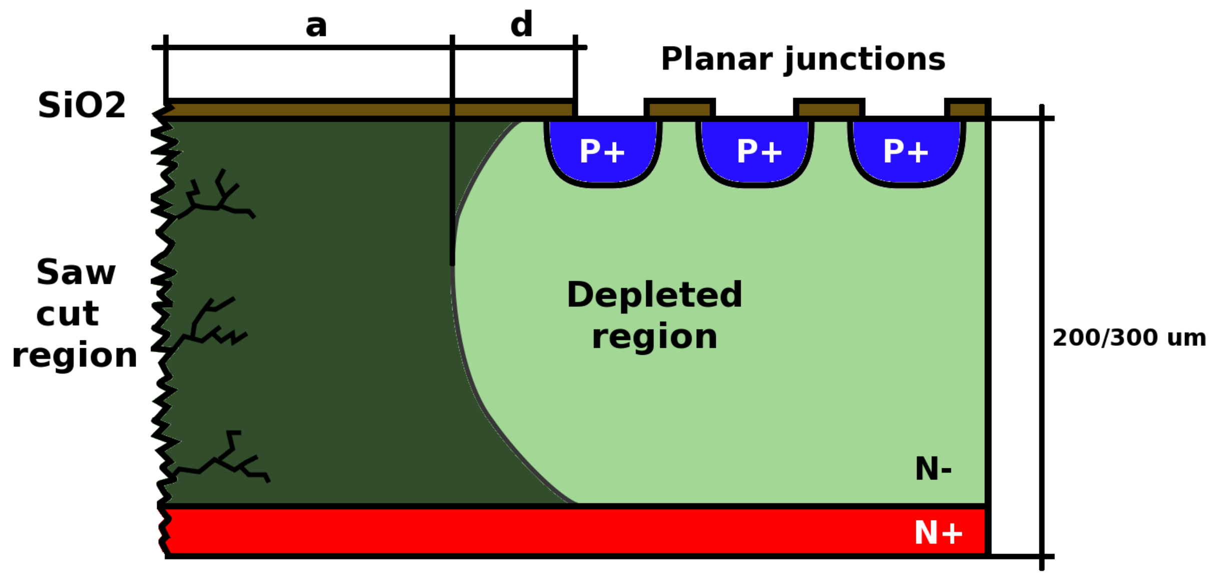
TCAD simulation

- Technology Computer Aided Design offers the possibility to simulate the behavior of a sensor under several conditions
  - Reverse bias
  - Illuminated by light
  - At high/low temperature
  - As been exposed to high fluences
- And monitor the interesting quantities
  - IV / CV curves
  - GR potentials
  - CCE
  - Electric field

Simulation saves you money but needs very precise inputs to produce reliable information

Geometry - Dead edge

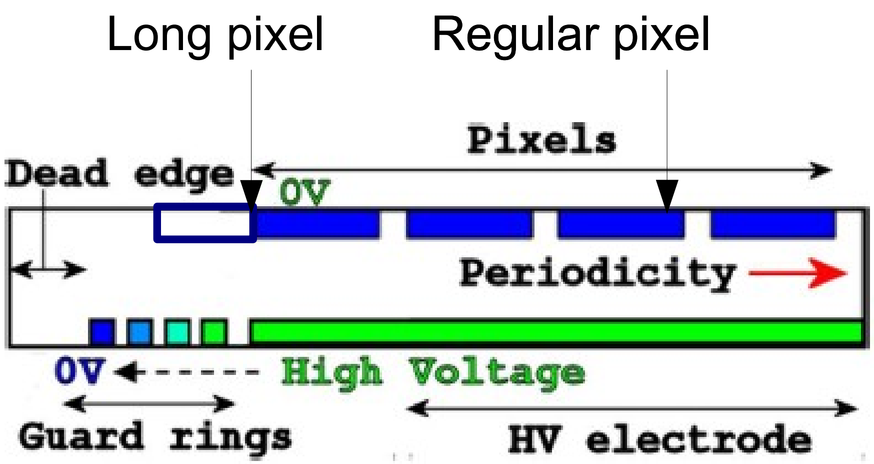
Dead edge is an inactive area whose porpouse is to protect the cut area (full of generation centers) from high electric field



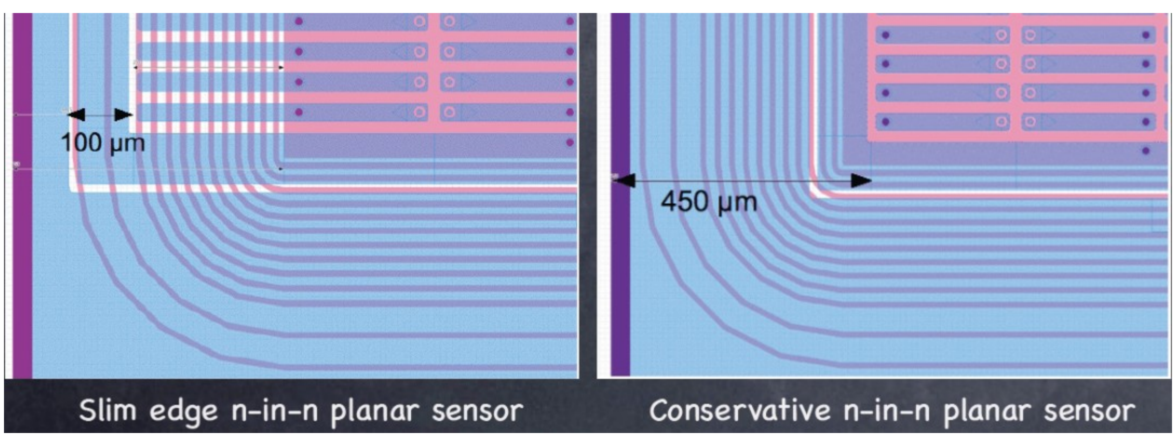
- “It is not possible to obtain the full geometrical coverage in z as the Pixel detector does, where modules are tilted in z and are partially overlapped, because there is not enough space. However the gap between modules is minimized using a sensor design with active or slim edges.” IBL TDR

Geometry optimizations

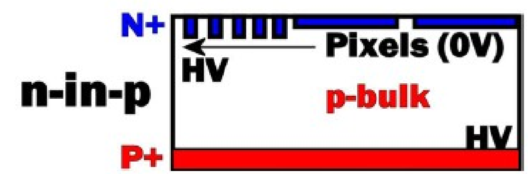
Attempt to recover active area



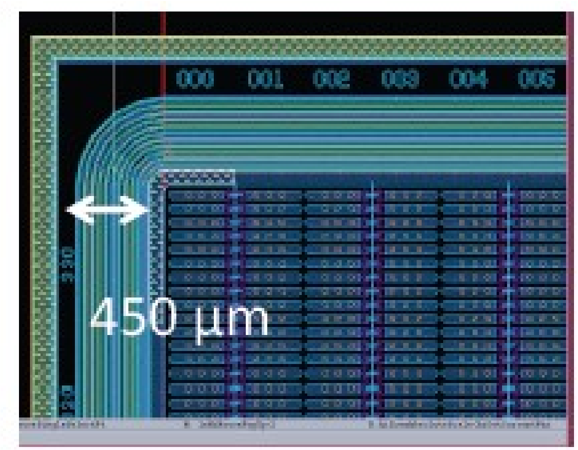
n-in-n



Longer pixel "under the guard-ring"



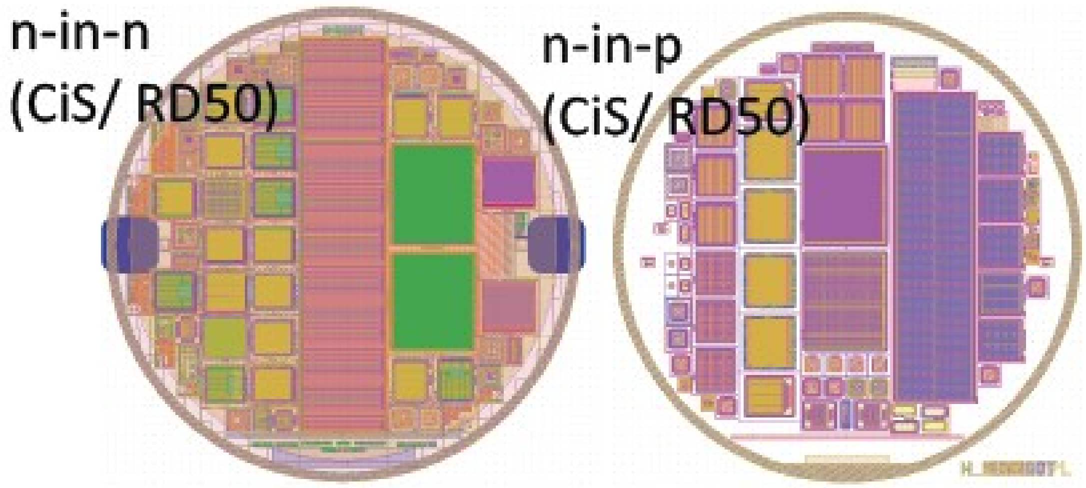
n-in-p



Reducing GRs structure width

First PPS sensor submission

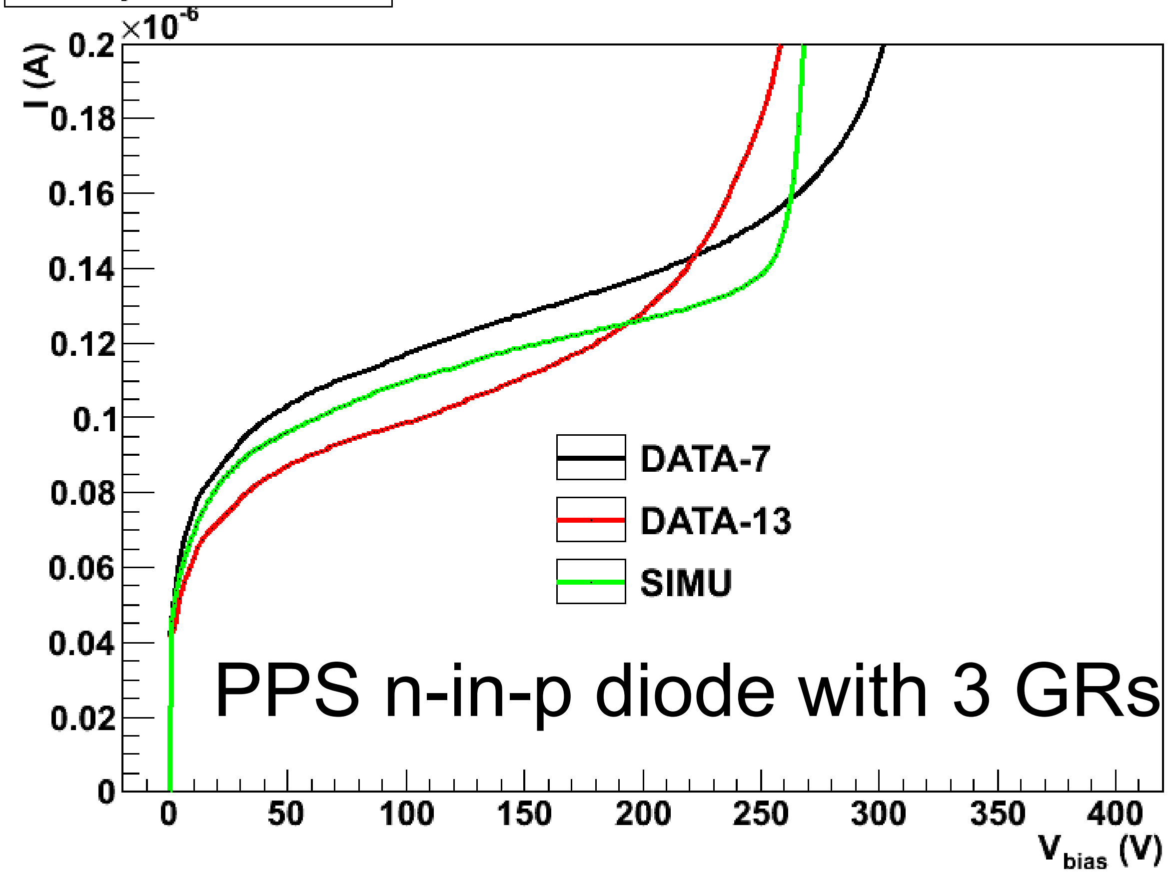
- Based on an intense design and simulation work, a first submission of planar sensors was made



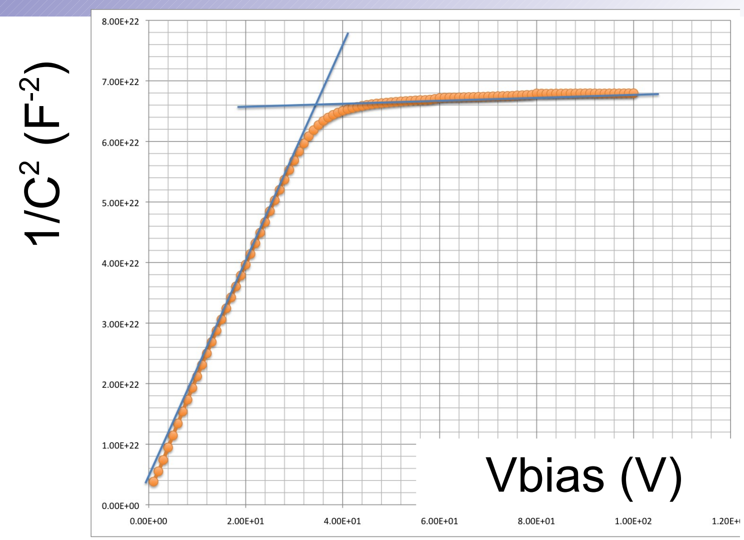
  - Current ATLAS R.O.C. (“FE-I3”) compatible sensors
  - New ATLAS R.O.C. (“FE-I4”) compatible sensors
  - Diodes, test structures

Test on prototypes

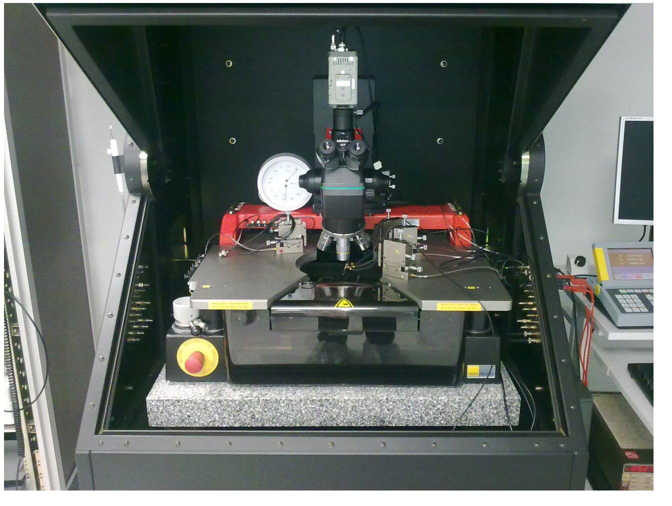
n-in-p with 3 GRs



Tuning for bulk concentration and generation lifetime for simulation

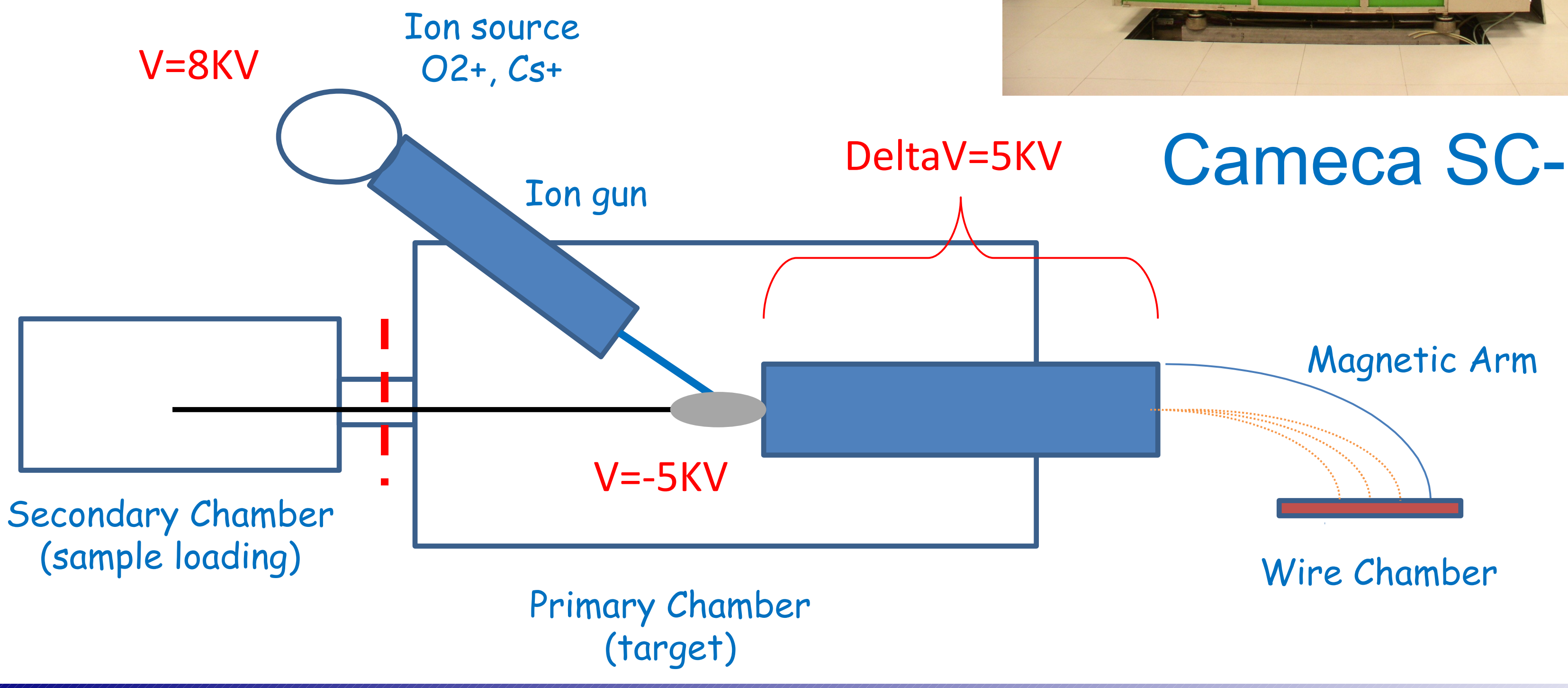


Measures were taken in our clean room



SIMS measurements

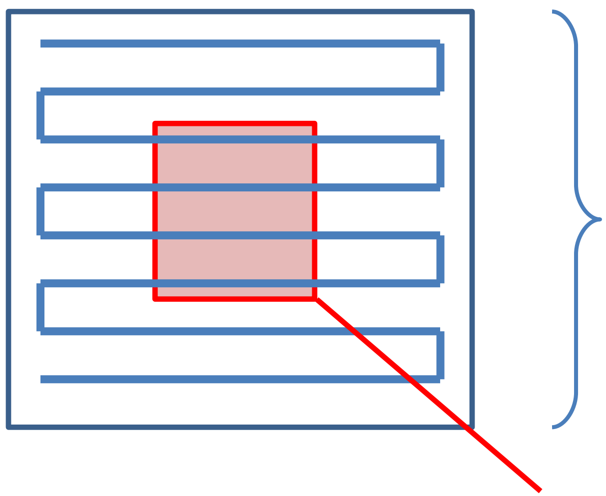
- SIMS: Secondary Ion Mass Spectroscopy



Cameca SC-Ultra

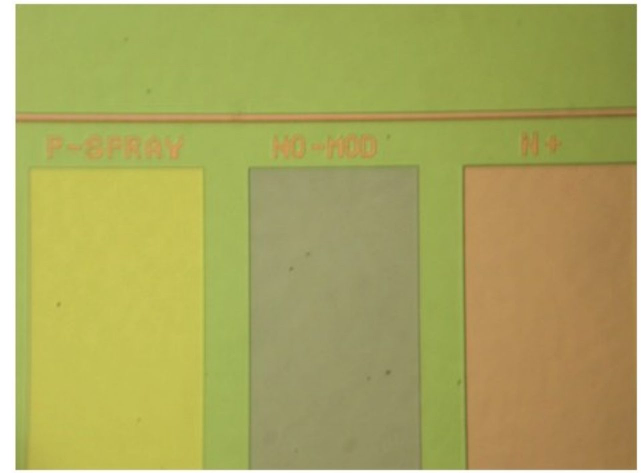
SIMS principle

- An ion beam is scanning (and escavating the sample)

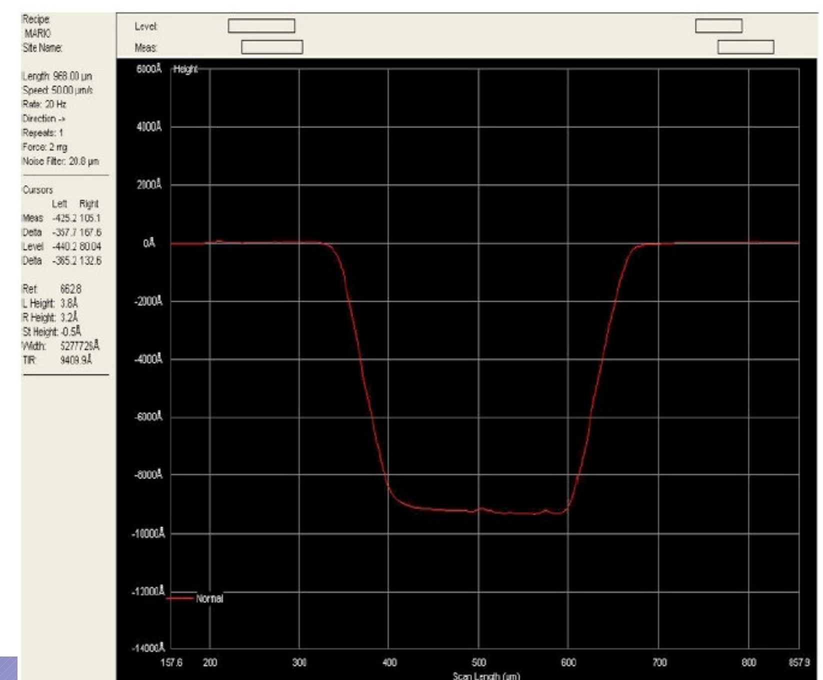


200-250 um

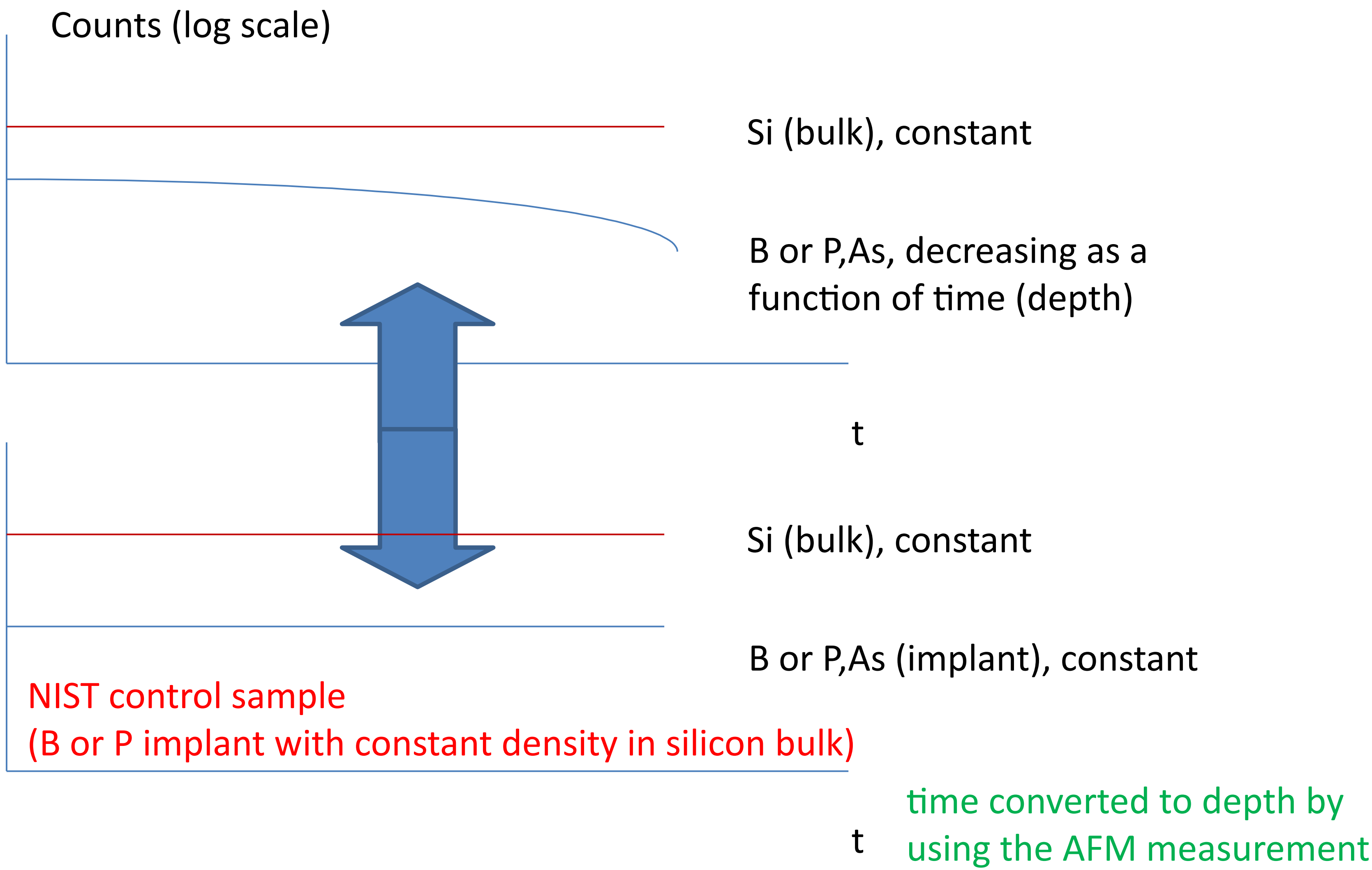
Restricted region analyzed
(to avoid scattering from walls)



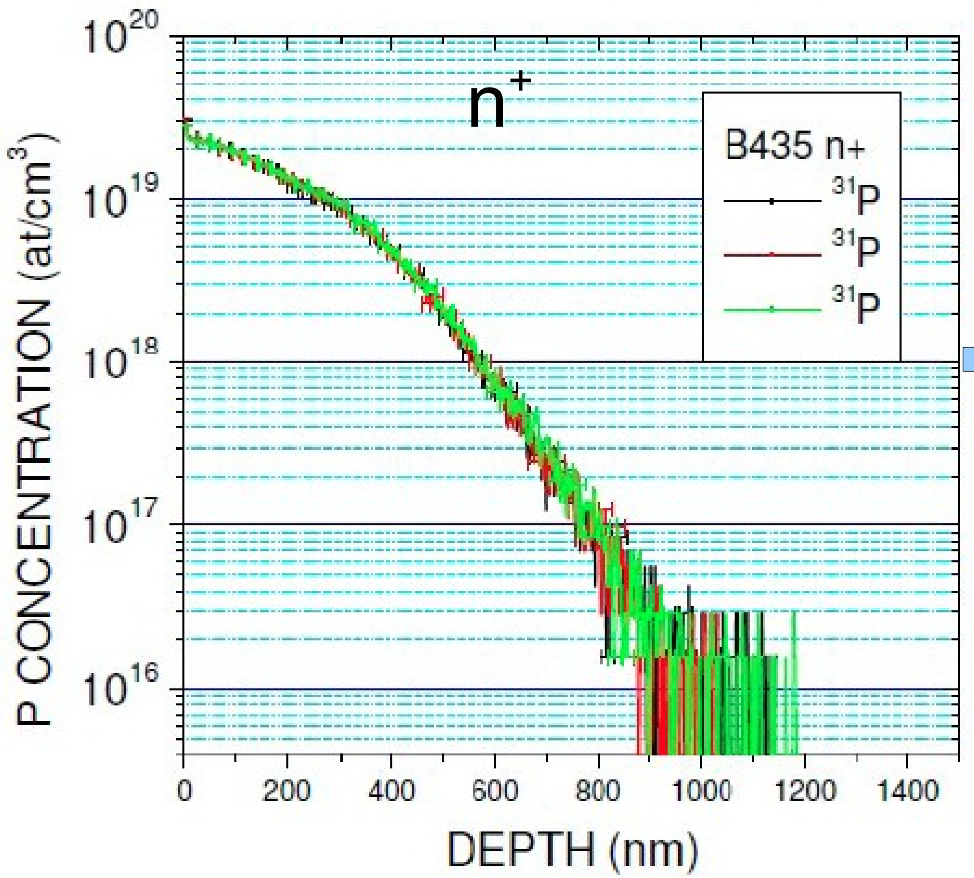
Measured with AFM

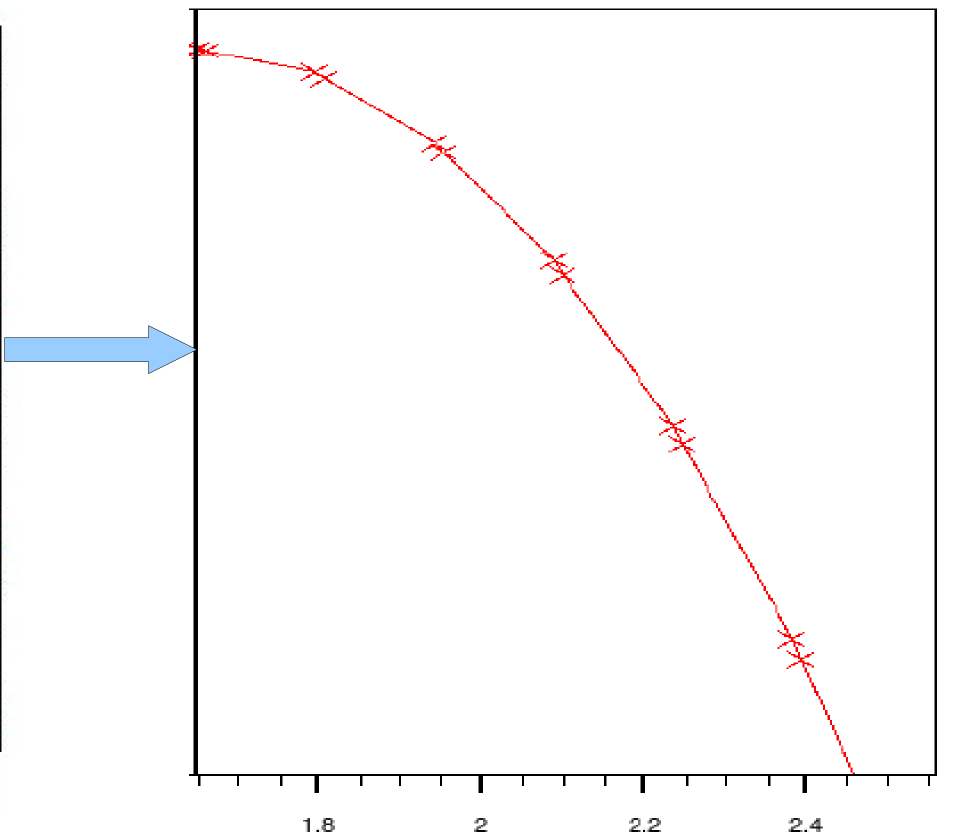


Doping profile measurement



Example: pixel implant



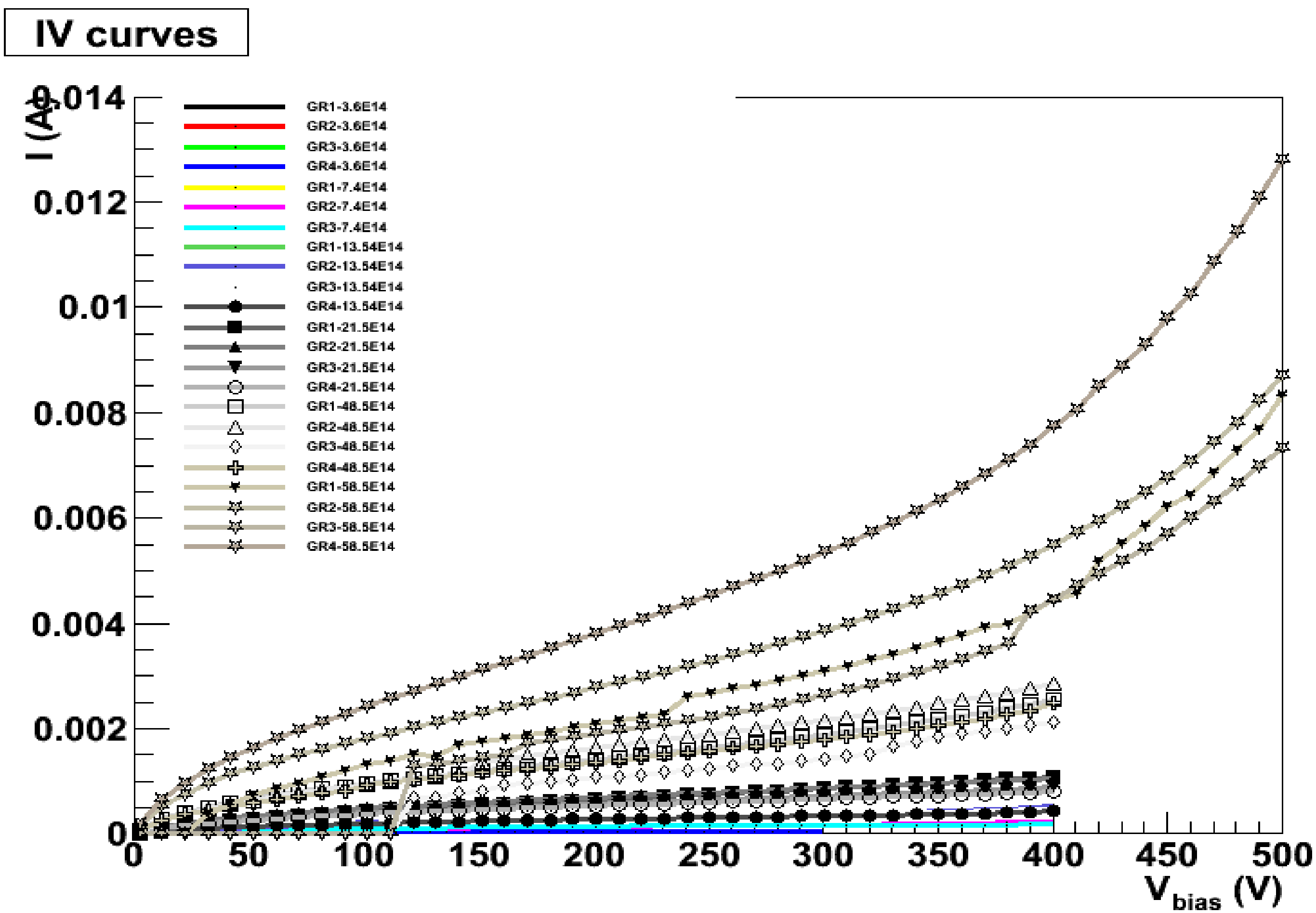


3 points per sample

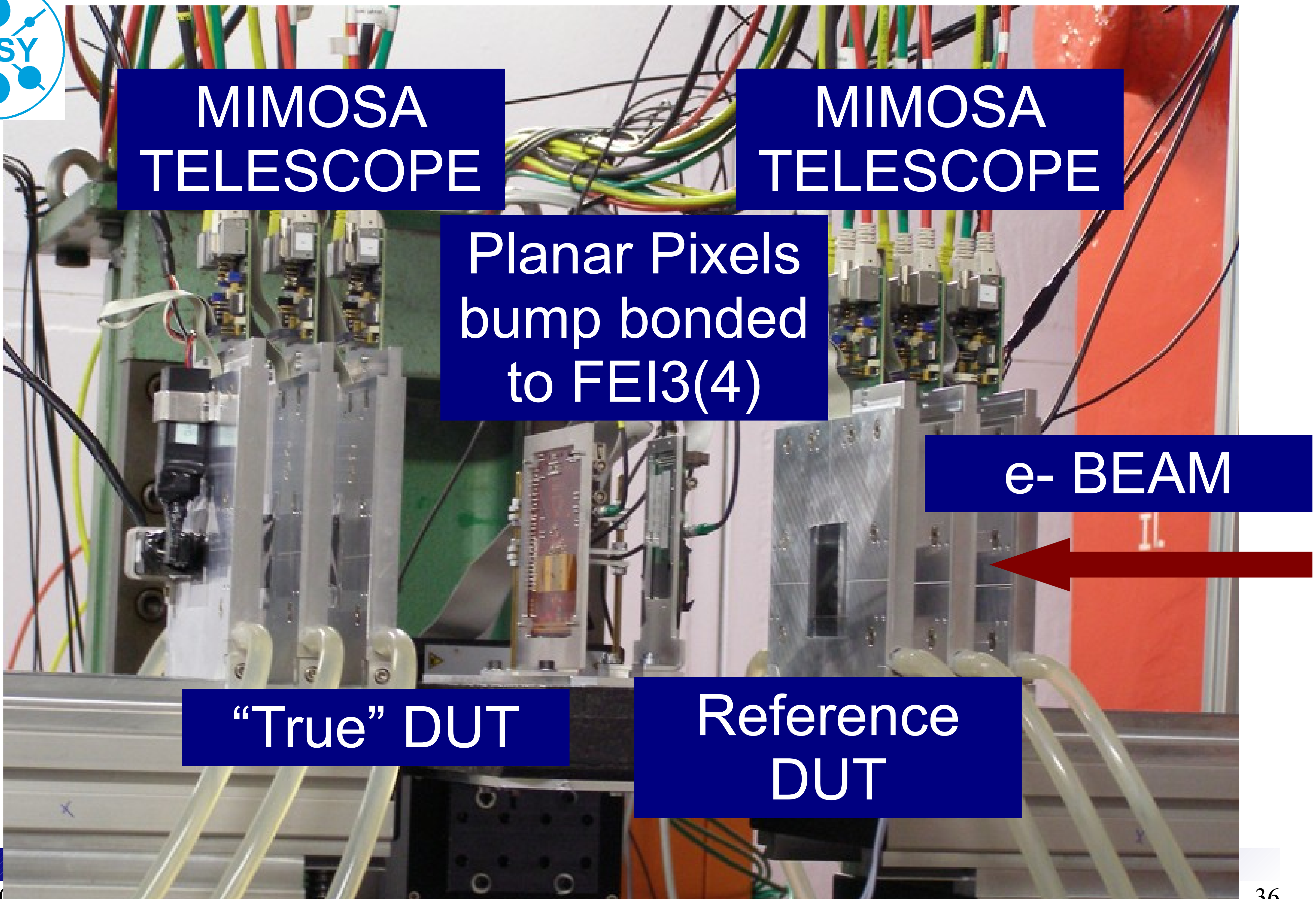
- Concentration profiles are used inputs for the simulation
  - Same for p+, moderate and non-moderate p-spray

Irradiation campaings

- 24 GeV/c proton at CERN (with step of fluence 2×10^{14} to $4 \times 10^{15}\ n_{eq}/cm^2$)
- MeV neutrons irradiation in Ljubjiana (Up to $1 \times 10^{16}\ n_{eq}/cm^2$)

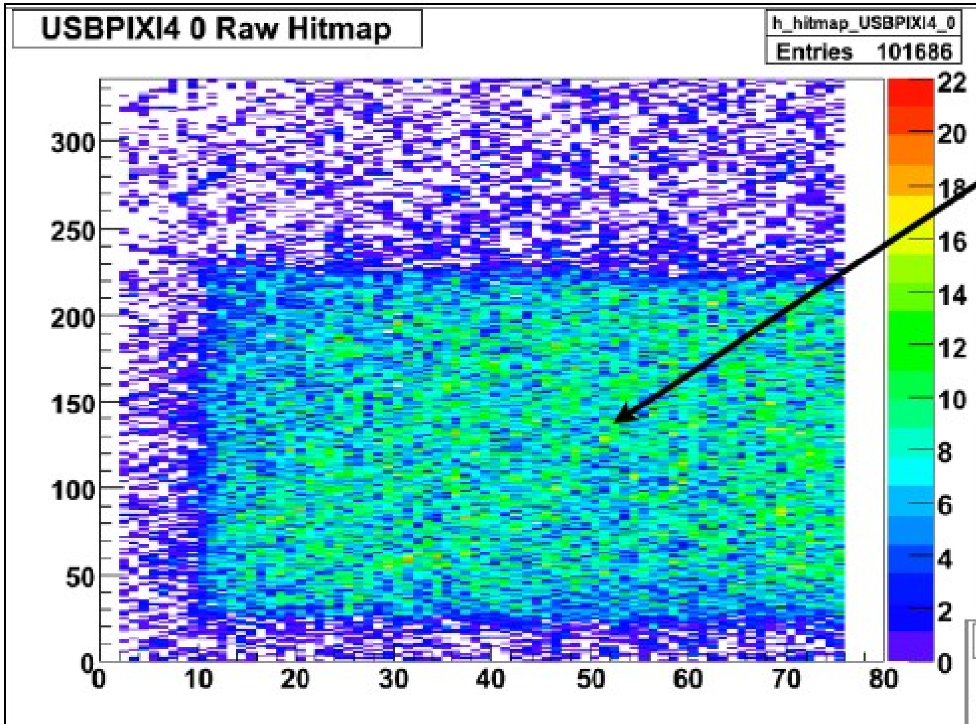


Test beams


MIMOSA TELESCOPE
MIMOSA TELESCOPE
Planar Pixels bump bonded to FEI3(4)
e- BEAM
"True" DUT
Reference DUT

Pictures from a test beam

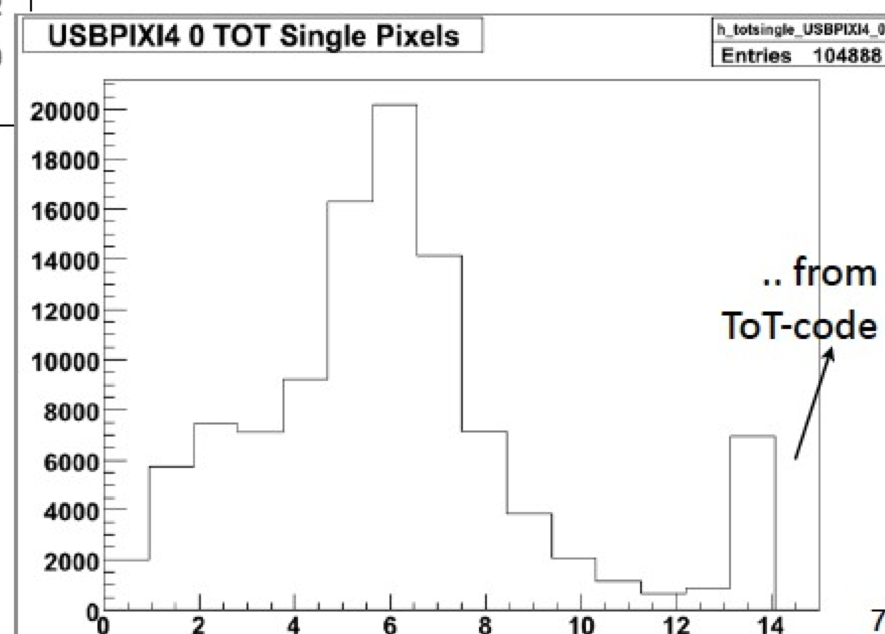
FIRST Highlight from data-taking



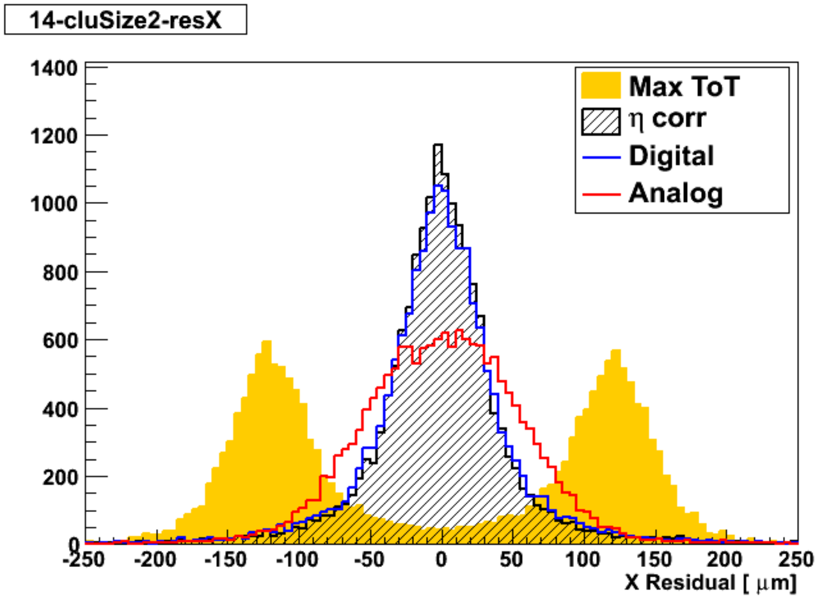
First beam seen with FE-I4 Module !!!!

FE-I4 Module SCC-17 (slim edge)

➡ See Expected peak !

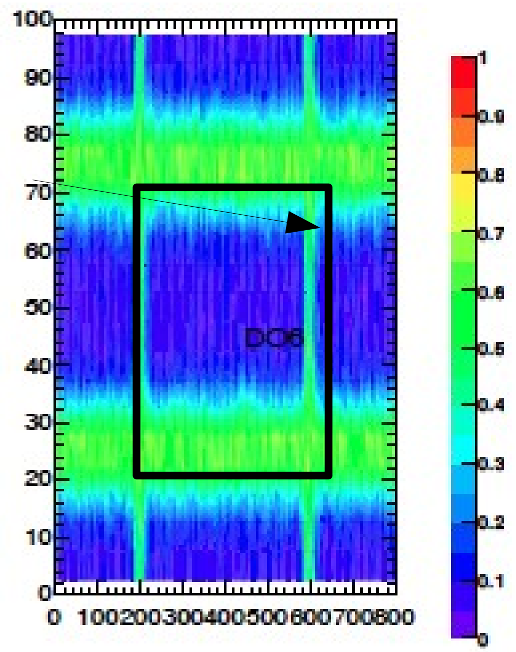


Test beam data analysis

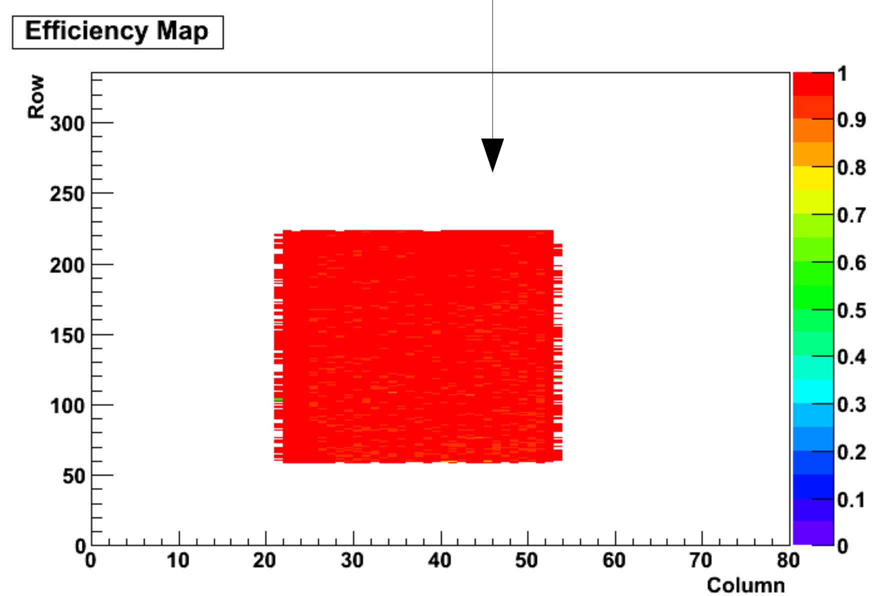


- Space point resolution
  - Different cluster-algorithms are compared

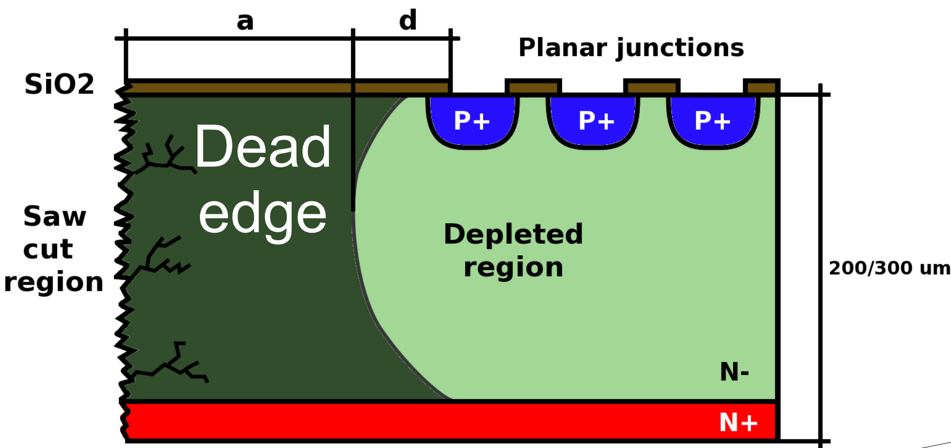
- Charge sharing among pixel cells

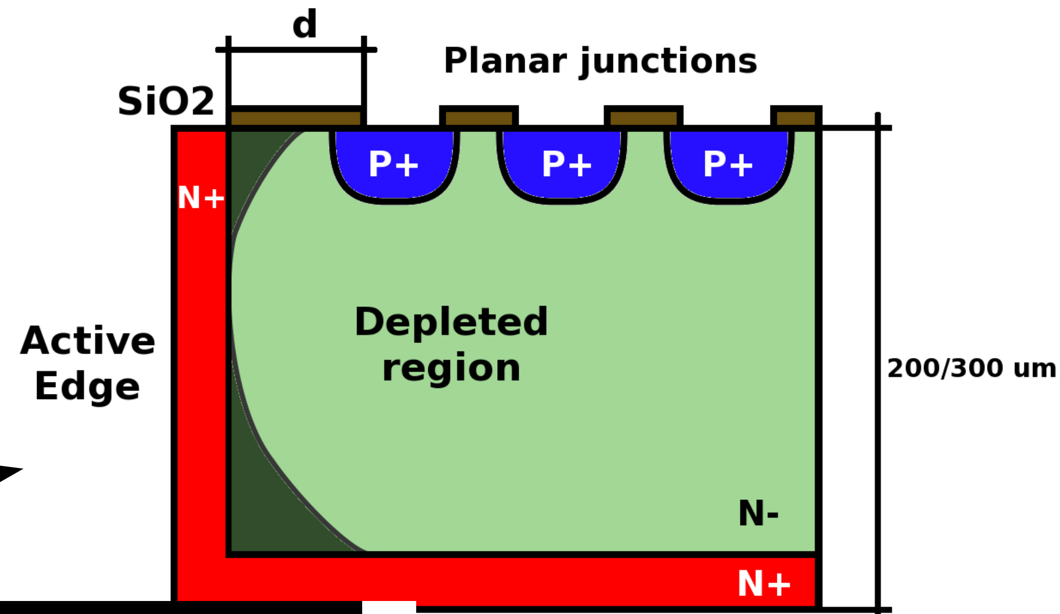


- Efficiency

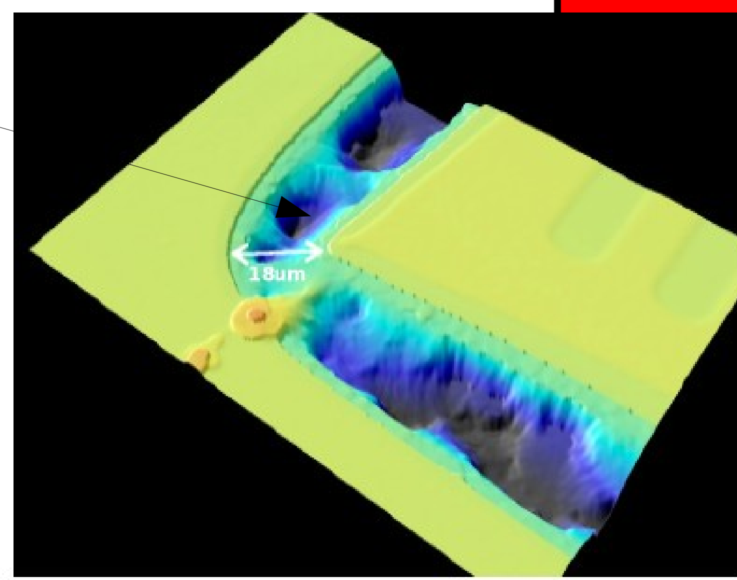


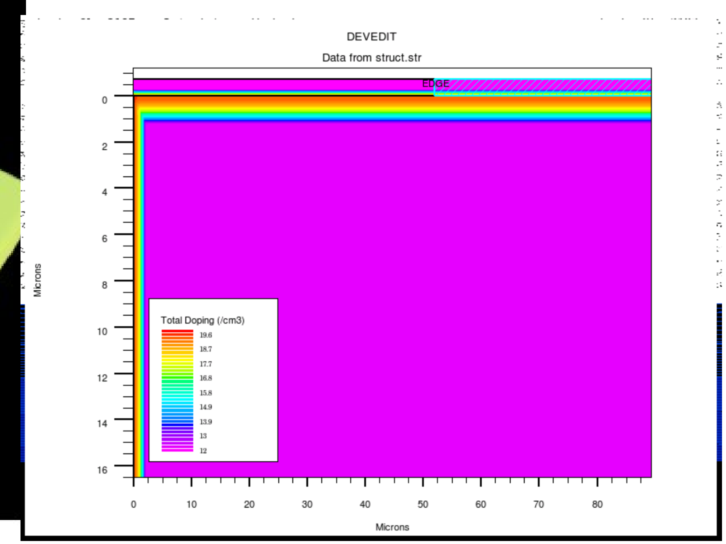
Ideas for new submission





Cut lines etched with Deep Reactive Ion Etching (DRIE) and doped





[C. Kenney, et al., IEEE TNS 48-6 (2001) 2405]

CONCLUSIONS

Conclusion & Outlook

- LHC will turn into a High Luminosity machine after 2017
- A completely new detector is needed, coping with higher rates and large radiation fluence
- The PPSU R&D group is working on the new Pixel Tracker for ATLAS
- Key parameters for the new detector are
  - Radiation hardness
  - Low material budget and optimized geometry
  - Charge collection efficiency
- Detailed simulations, and measurements, performed at test beams, after irradiations and on test structures, are driving the new pixel design

That's it!