Innovative design concepts in P bulk Planar Pixel Sensors R&D project

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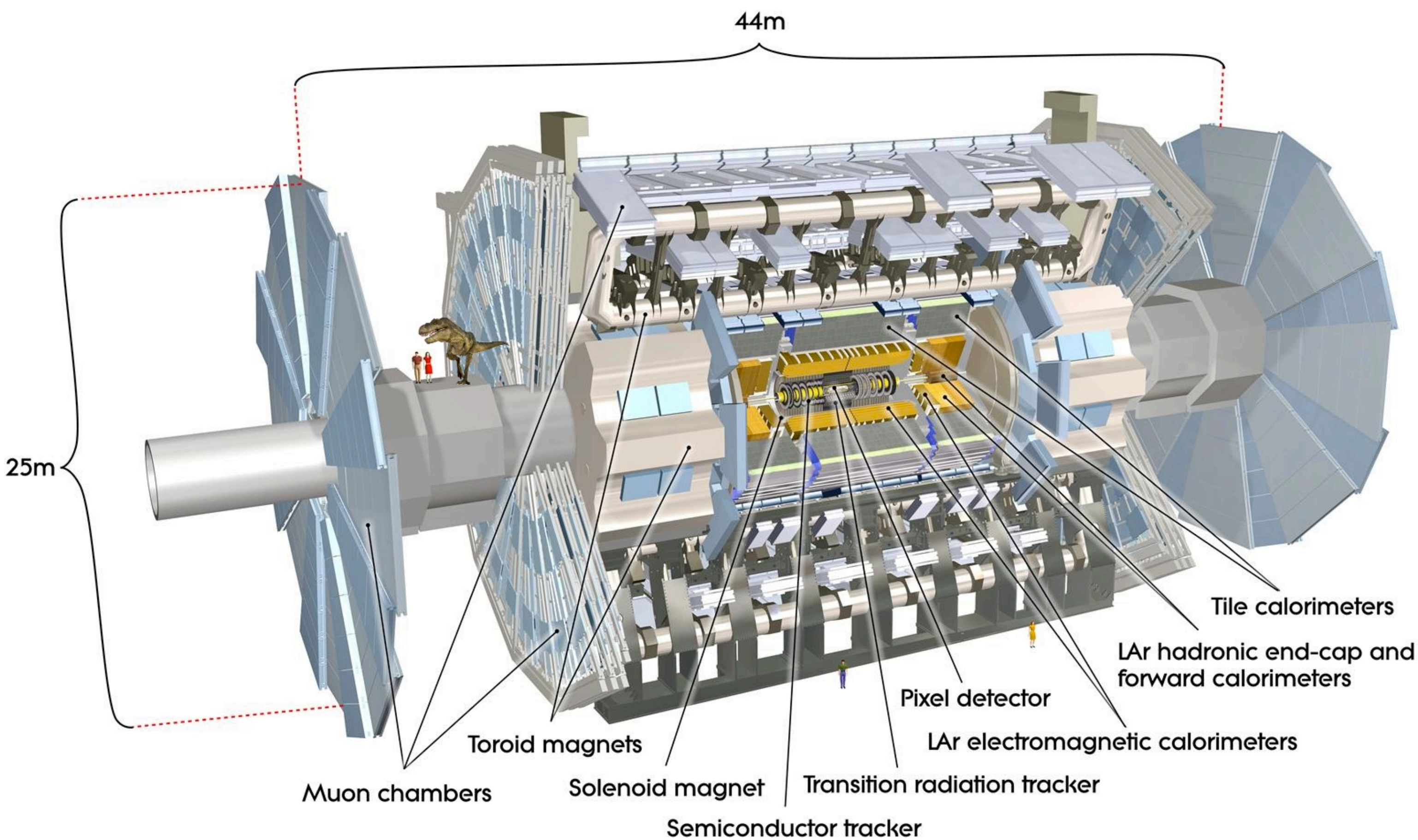
  - Geometrical sensor designs goals
  - Optimized cost effective solutions
- Results from LAL from collaboration with KEK

- Conclusions and budget request

The ATLAS Detector



LAL contribution to ATLAS pixel sensors

- During recent years, our implication was on:
  - Slim edge sensors for edge reduction (simulation of sensor design and detector layout)
  - Radiation damage studies (investigate high charge collection with heavily irradiated sensors)
  - Investigate Bulk material n-on-n-n and n-on-p
  - Contribution to a realistic ATLAS tracking software, including real geometry, irradiation effects ..
- A view on the future : design of edgeless pixels and electronics (Framework of AIDA)
  - 3D pixel electronics (Tezzaron-Chartered): Omegapix…
  - 65 nm electronics and innovative interconnexions

Participating institutes:

- CERN
- AS, Prague
- LAL Orsay
- LPNHE Paris
- Bonn University
- HU Berlin
- DESY
- TU Dortmund
- Goettingen University
- MPP and HLL Munich
- Udine University and INFN
- KEK
- IFAE-CNM Barcelona
- Liverpool University
- UC Berkeley and LBNL
- UNM Albuquerque
- UC Santa Cruz

Tsukuba/KEK to Pixel developments:

- Implication of the Tsukuba/KEK groups on the following subjects:
  - Fabrication and evaluation of Hamamatsu n-on-p pixels
  - Design/fabrication of 2x2 cm and 4x4 cm sensors
  - Assembly modules of 2x2 and 4x4 with bump bonding
  - Proton irradiation at Cyric
  - Test beam (DESY, CERN, SLAC)
  - Development of quality control system
  - TCAD simulation for best sensor design

From the recent past: Common Japan-France scientific experience inside the ATLAS pixel project

- Have shared a lot of experience inside Atlas n-on-p pixel development:
  - Development of the pixel sensors
    - Design issues, optimization...
    - Laboratory characterization and testing (Clean room, Beam tests, irradiation tests.)
    - Simulations.

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Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Development of novel n^{+}-in-p Silicon Planar Pixel Sensors for HL-LHC

Y. Unno [b,*], C. Gallrapp [a], R. Hori [b], J. Idarraga [g], S. Mitsui [h], R. Nagai [i], T. Kishida [i], A. Ishida [c], M. Ishihara [c], S. Kamada [c], T. Inuzuka [c], K. Yamamura [c], K. Hara [j], Y. Ikegami [b], O. Jinnouchi [i], A. Lounis [g], Y. Takahashi [j], Y. Takubo [b], S. Terada [b], K. Hanagaki [f], N. Kimura [k], K. Nagai [j], I. Nakano [e], R. Takashima [d], J. Tojo [b], K. Yorita [k]

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Evaluation of novel KEK/HPK n-in-p pixel sensors for ATLAS upgrade with testbeam

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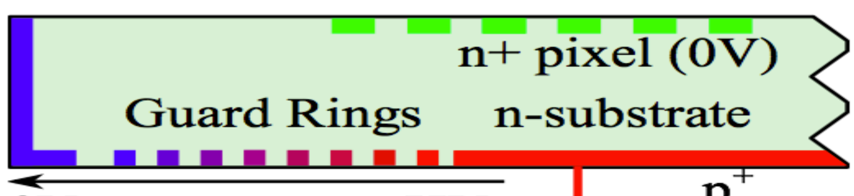
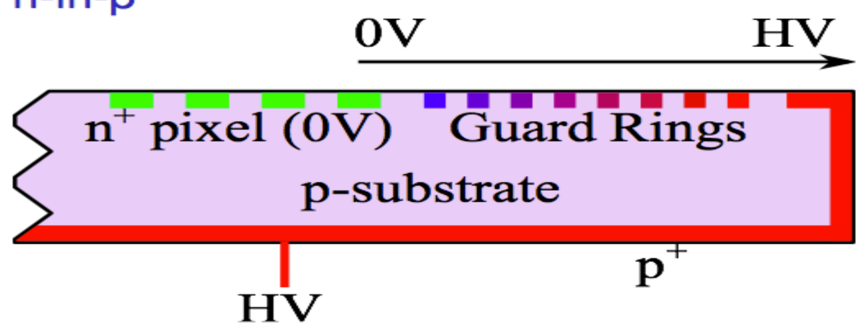
Up to now :The Two planar family options N-on-N vs N-on-P

n-in-n



- Double-sided process
- Pixel can be shifted below guard-rings
- Used already widely

n-in-p

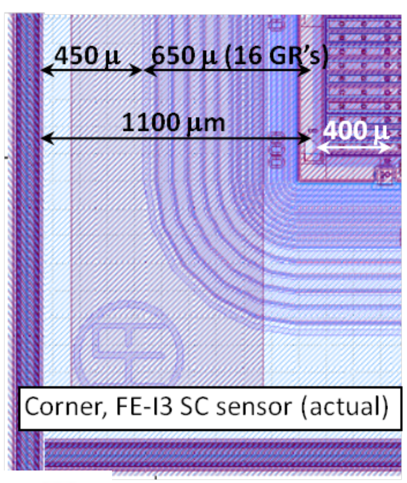


- Single sided process
- No backside-alignment needed

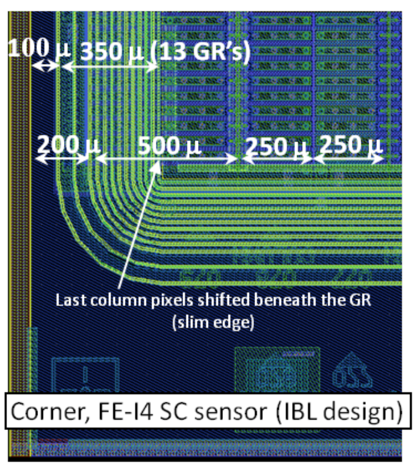
More foundries available
Easier handling/testing, due to lack of patterned back-side implant

- Cost-effective
- Danger of sparks between chip and sensor

Edge inefficiency decrease (effort of last 3 years)



Corner, FE-I3 SC sensor (actual)



Corner, FE-I4 SC sensor (IBL design)

Our aim is built a close partnership for the following Pixel Sensor tasks

Goals

- Performance: evaluate & improve sensor designs
  Up to $2 \cdot 10^{16}$ n_{eq}/cm^2 Operation conditions
- Geometry optimization Slim/Active edges

Productions

- Work on common sensor productions

Use Irradiation facilities:

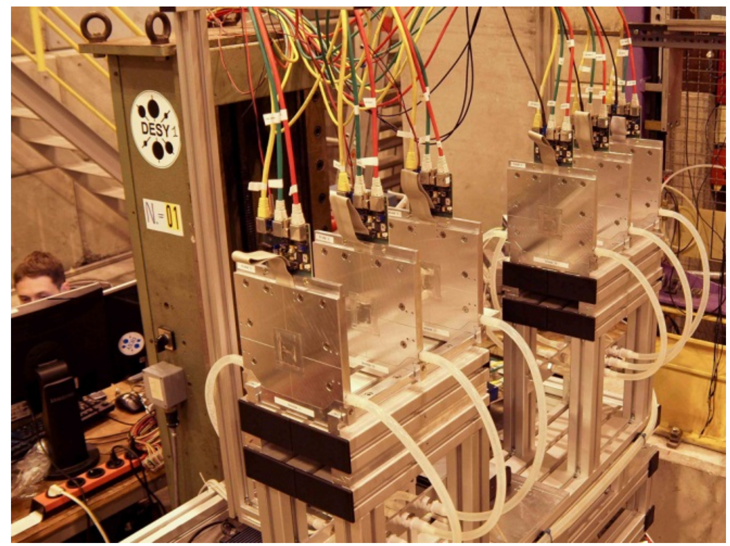
- Reactor neutrons (Ljubljana)
- 26 MeV protons (Karlsruhe)
- 800 MeV protons (Los Alamos)
- 24 GeV protons (CERN)
- Cyclotron and RadioIsotope Center, 70 MeV protons, (CYRIC, Japan)

Share the expertise on TCAD simulations

Silvaco (2D)
Synopsis TCAD (3D)

Contribute to Lab & beam test measurements

Radioactive sources
120 MeV π (CERN)
4 GeV e (Desy)
Eudet telescope



Imagine scenarios for Cost reduction

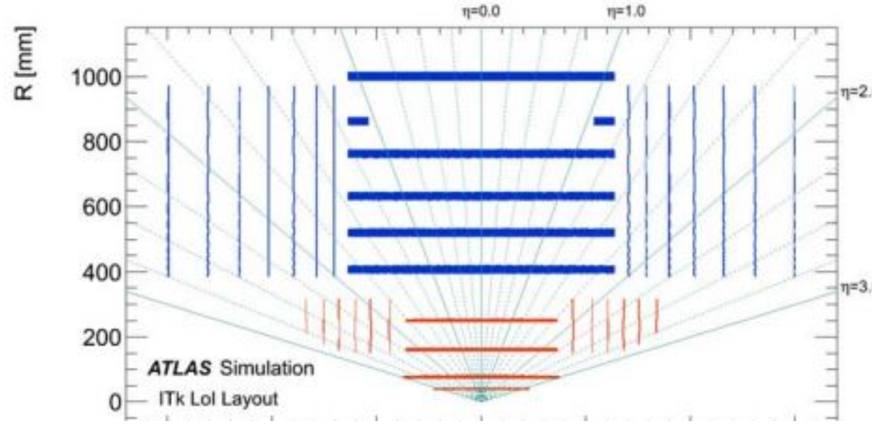
Bulk material: n-on-p rather than n-on-n
Reduce inter-connexion costs (Quad- Hex designs…)

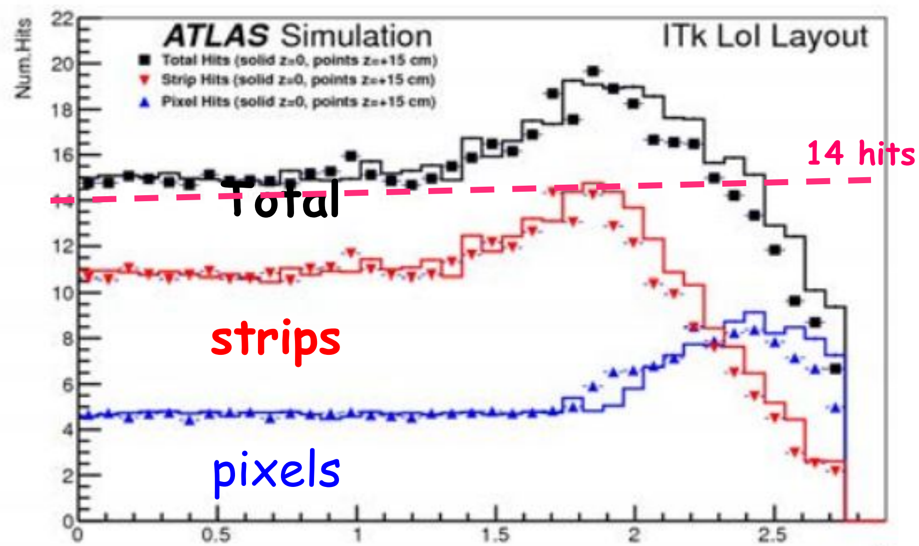
High Luminosity LHC (HL-LHC) framework

- Ambitious program of accelerator upgrade
- This is the « Phase 2 » LHC upgrade
- Peak inst. $\mathcal{L}$: 5-7 10^{34} cm-^{2} s^{-1}
- Integrated $\mathcal{L}$: 250-300 fb^{-1}, 14 TeV pp/ year
- Event with pileup-up up to ~ 200

➢ We aim for a rich physics potential

➔ A need to launch innovative solutions for detectors, mechanics, efficient triggering and advanced analysis technics





ATLAS Tracker Plans

For Phase 2, ATLAS upgrade plans full replacement of Inner Tracker
- All silicon tracker (Pixel and Microstrips)
- Significantly increase granularity
- Minimize material budget within tracker acceptance
- High efficiency of track reconstruction at High pileup level

Some numbers

- Current inner tracker
  - Pixels: R(cm) 5-12
    - **Si area: 2.7 m^2**
    - IBL(2015): 3.3 cm
  - Strips R(cm): 30-51 (Barrel)/28-56 (EndCap)
    - **Si area: 62 m^2**
  - Transition Radiation Tracker R(cm): 56-107
  - Occupancy is acceptable for <3×10^{34} $cm^{-2}s^{-1}$
  - Phase-II at HL-LHC: 5×10^{34} $cm^{-2}s^{-1}$

- Phase-II upgrade (LOI)
  - Pixels: R(cm): 4-25 cm
    - Si area: **8.2** m^2
  - Strips : R (cm): 40-100 (Barrel)
    - Si area: 122 (Barrel)+71(EC)=**193** m^2
- Major changes from LHC
  - **All silicon tracker**
  - Large increase of **Si area**
    - both in Pixels and Strips
    - **~ 3 × LHC ATLAS**

The issue of irradiation levels at the HL-LHC

BULK Damage : High energetic particles will not exclusively interact with the electron cloud producing the electrical signal but also with the nuclei often displacing them out of the lattice. This produces crystal imperfections that may be electrically active and change the electric properties of the material. In the inner regions of high rate hadronic experiments the concentration of crystal defects will after some years of operation exceed the initial substrate doping.

SURFACE Damage : In silicon the surface region is also sensitive to radiation. The term surface damage summarizes all defects in the covering dielectrics, e.g. the silicon oxide and the interface between the silicon and the dielectric. The oxide charge changes the electric field in the silicon bulk close to the surface and induces a compensating electron accumulation layer in *n*-type silicon and a depletion layer in *p*-type material.

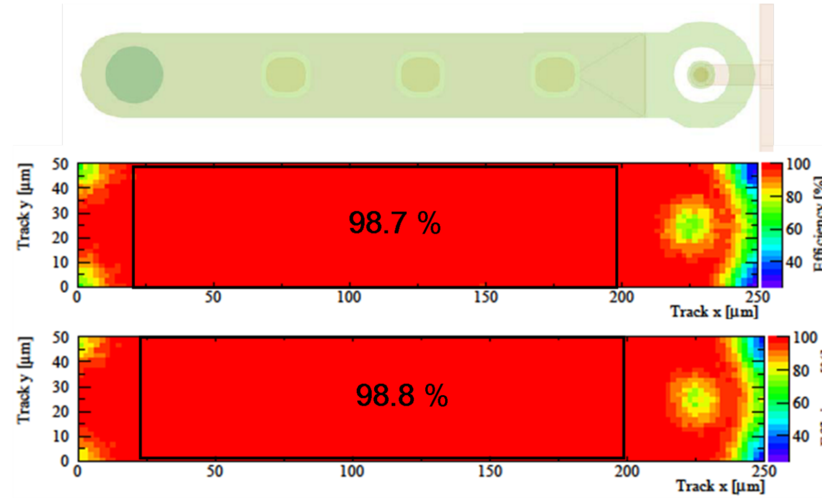
How to build robust and safe working pixel detectors?

Design of the FE-I4 pixel

Optimize the sensor efficiency ?

$F=4\times10^{15}\ n_{eq}\ cm^{-2}$
400 V
Global eff.= 96.5%

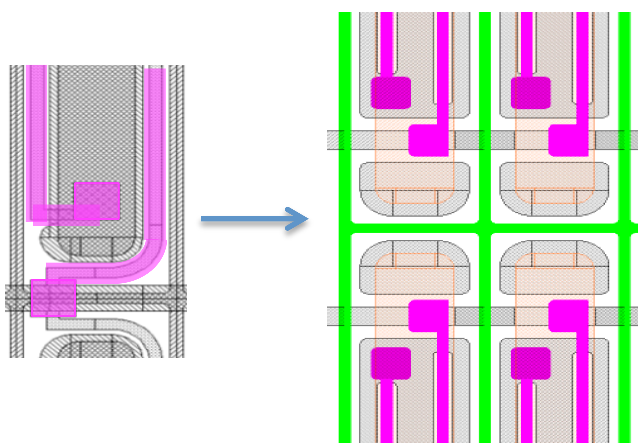
$F=4\times10^{15}\ n_{eq}\ cm^{-2}$
500V
Global eff.= 96.9%



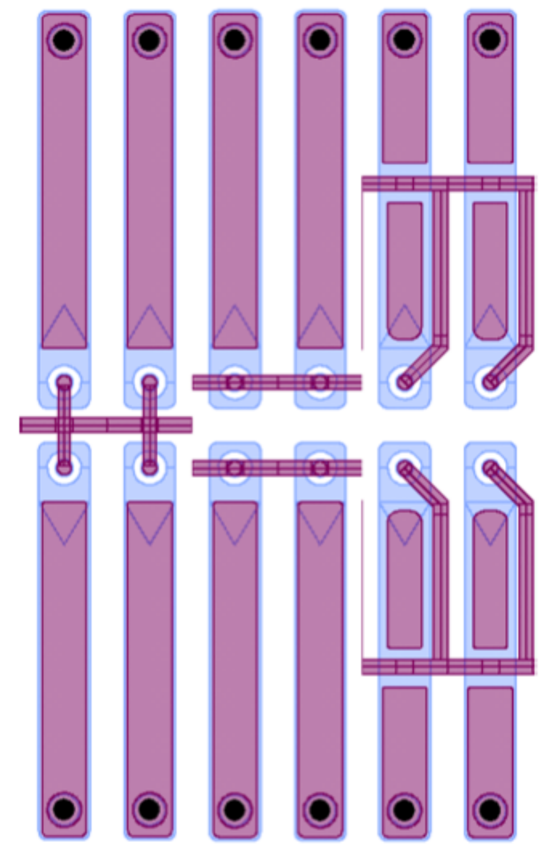
The pixel can be biased using the punch through mechanism in a geometry layout called bias dot.
The bias voltage is brought to the bias dot through a metal bias grid (Bias rail), which is connected to an outside bias ring, common for all the pixels. This biasing scheme has the advantage that it allows sensor testing under full bias conditions before assembling the matrix with the readout chips, minimizing also the bias differences between pixels. Once the sensor has been bump-bonded to its readout chip, the pixel is biased via the electronics. Also, because the bias dot is occupying a fraction of the pixels active area, there is a small signal loss.

Bias Grid Design

To overcome the efficiency loses in the punch through structure for perpendicular tracks, different designs are under investigation: "Bias rail" is a metal over insulator, no implant underneath



KEK design:
PolySi encircling "outside" the pixel implant causes inefficiency by reducing the electric field under the polysilicon, very much similar to the effect of the "bias rail" ➔ solution : Move the routing of the PolySi "inside" the pixel implant

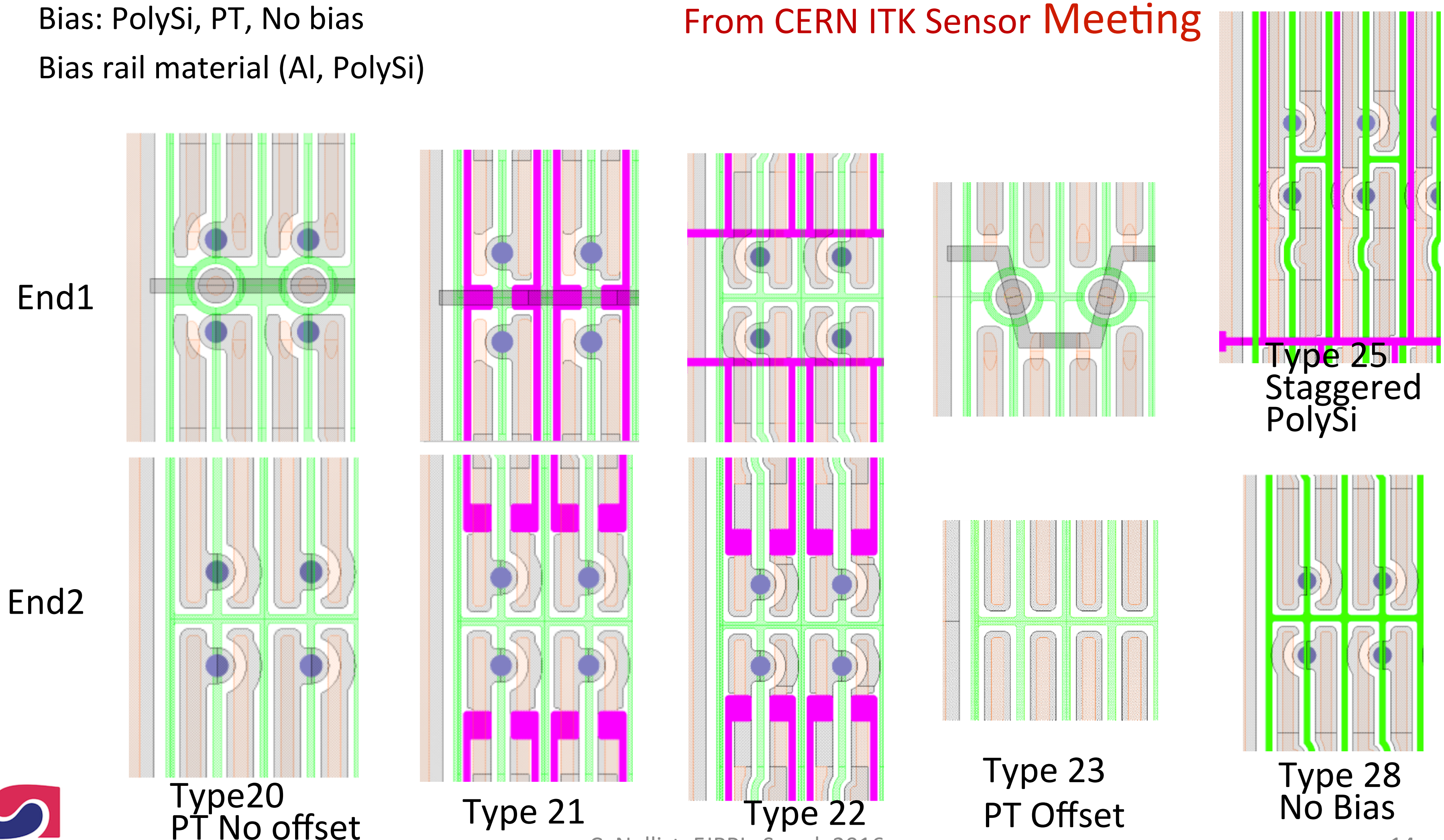


Dortmund design
Bias rail routed differently
2 alternative designs

TCAD simulation needed to explore the design possibilities !

- Bump pads at the midway of the pixels
- Bias rail offset: No, Offset
- Bias: PolySi, PT, No bias
- Bias rail material (Al, PolySi)

KEK examples of alternative Designs,
Nobu Unno & al.,
From CERN ITK Sensor Meeting

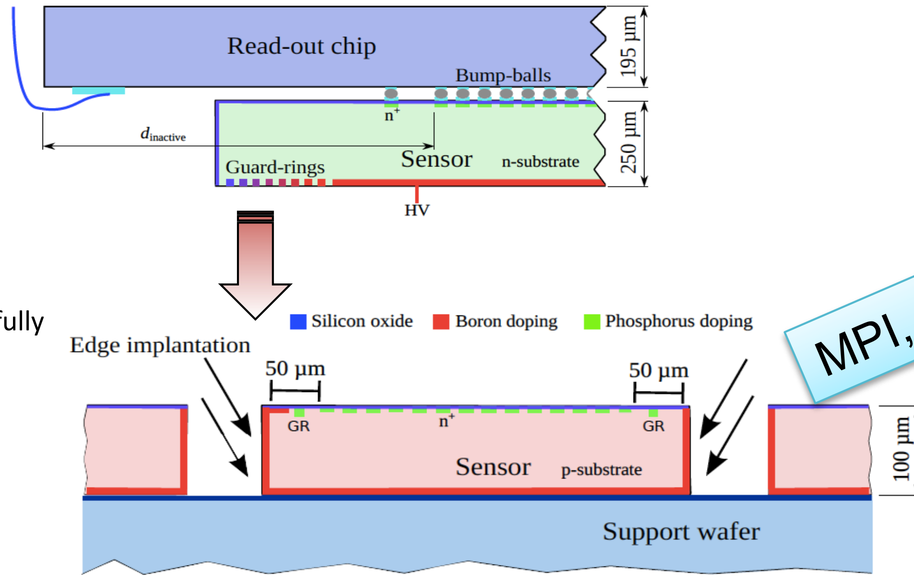


REDUCE THE DEAD AREA AT THE BORDER AND INSIDE THE PIXEL SURFACE

How to build robust and safe working pixel detectors ?

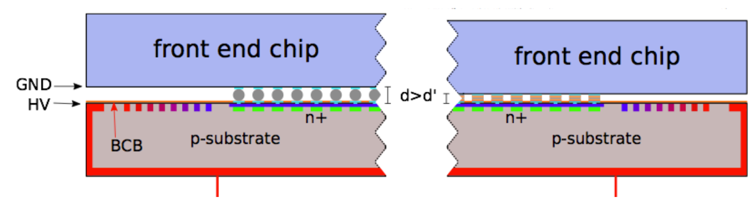
Active edge : designs for planar pixels

Active edge sensors to achieve a fully four- side buttable module, in collaboration with VTT

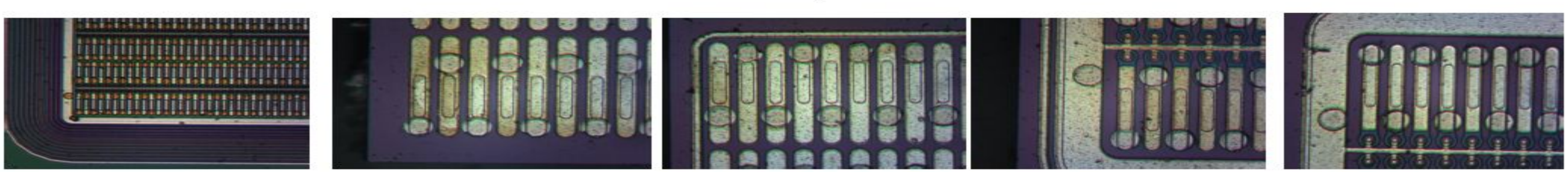


MPI, LAL, VTT, ADVACAM

- ✓ n-in-p pixels on FZ and MCZ material
- ✓ **100 mm** and **200 mm** thickness → together with the active edges makes these sensors very attractive candidates for the inner layers in Phase II
- ✓ Flip-chipping and interconnection should be addressed



C1 C2 C3



12 GR | No GR, No Bias Rails | One GR, No Bias Rails | One GR, Bias Ring +Rails | Bias Ring +Rails

The issue of cost (and cooling) reduction of the future tracker at HL-LHC

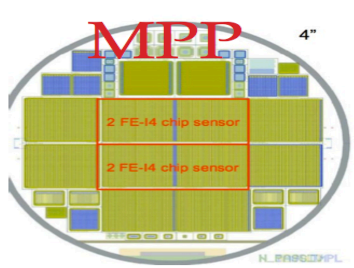
With the major increase in the number of silicon pixel sensor detectors for HL-LHC, it is fundamental to bring down the production costs. One of the main cost driver is the bump bonding, where price depends on the quantity not on the size of the devices. This drives the idea to build large area pixel sensor devices!
Question: Can we get better physics performance with different shape pixels or maintain LOI performance with larger pixels, therefore less channels are needed therefore less power and less cooling ?

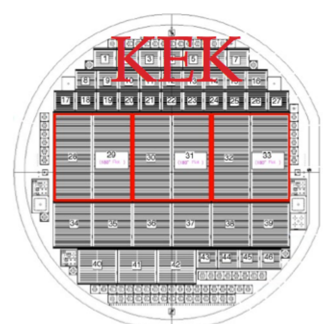
Cost effective modules are mandatory

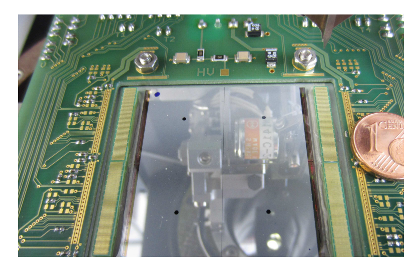
Reduce inter-connection cost: connect one large sensor to four (quad) or even six (hex) FE-I4 chips (2x2 cm, developed or the IBL)

- **KEK/HPK**
- Liverpool/Micron
- MPP/HLL

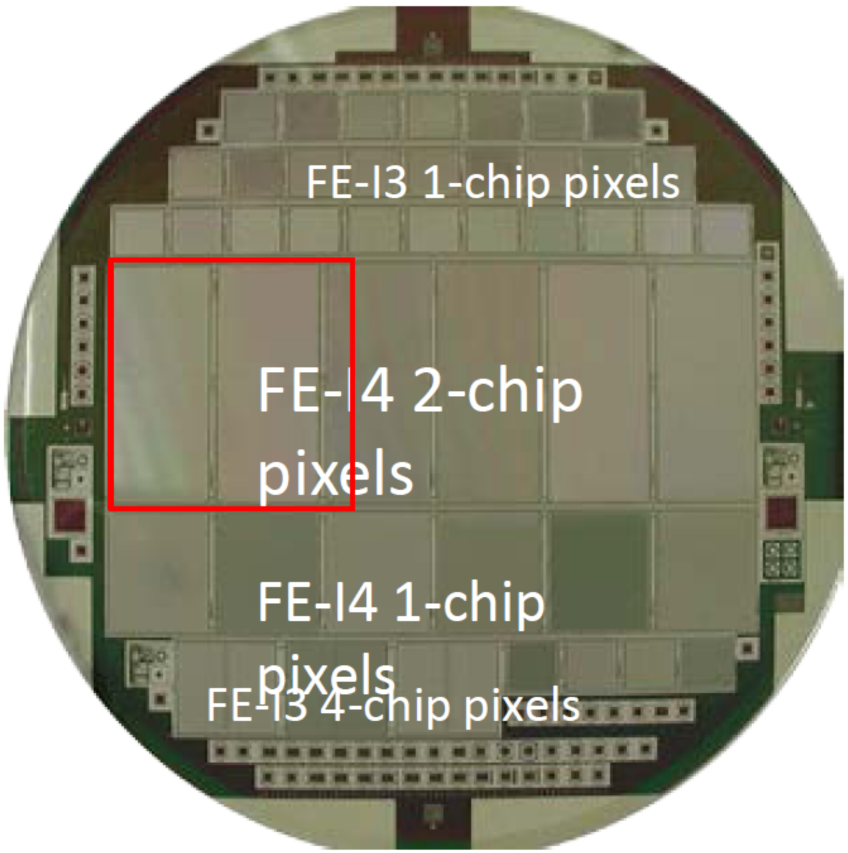
Sensor: 25-40 €/cm² FE chip: 14 €/cm² Bump Bonding: 40-45 €/cm²



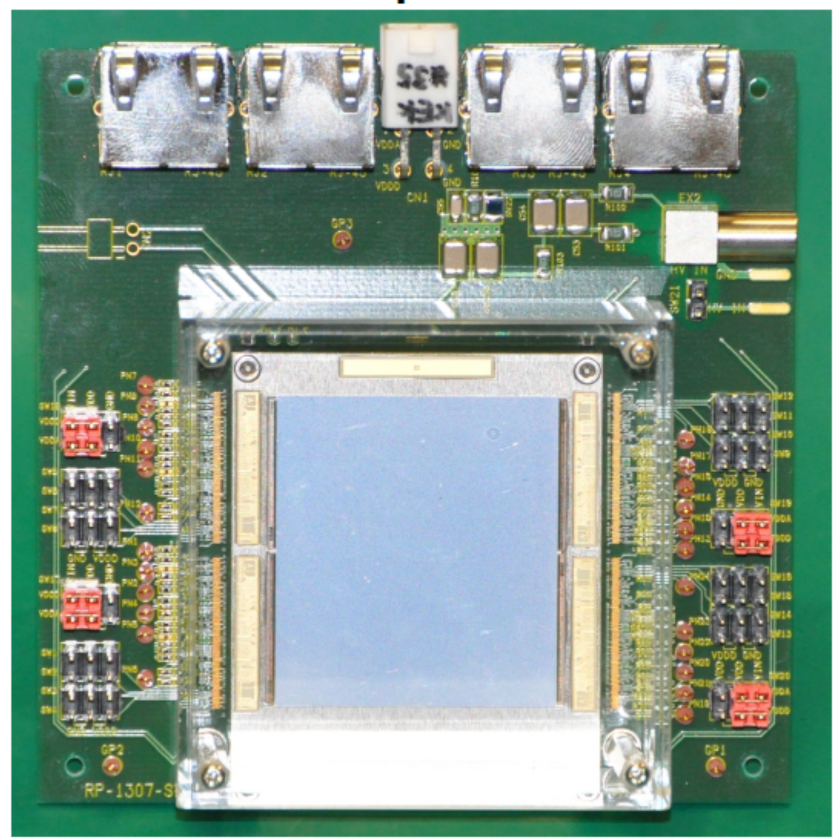




Hamamatsu KEK/Tsukuba : production of sensor wafer and 4chip card

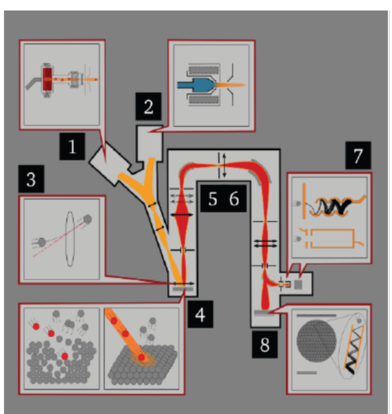


4 Chip Card



Secondary Ion Mass Specrometry (SIMS)

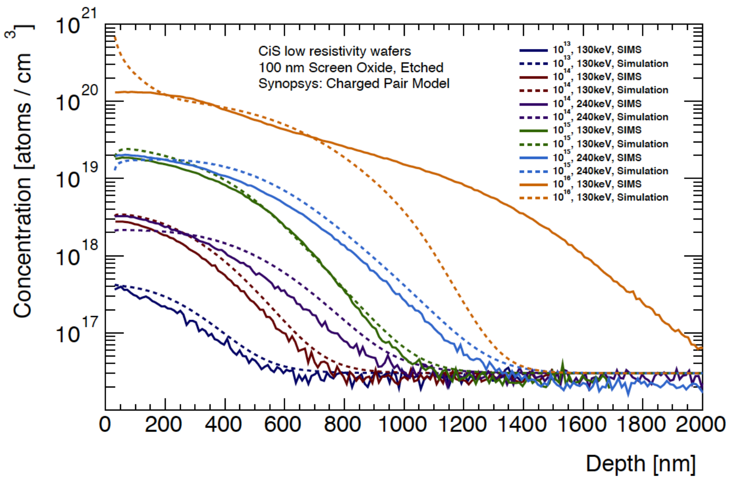
SIMS system at Versailles (Cameca IMS 7F)

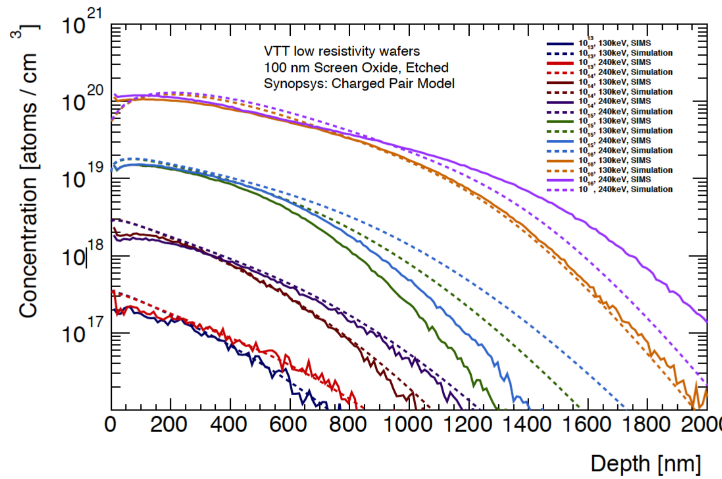


- Analytical technique to characterize the impurities in the surface and near surface (30m) region
- Relies on sputtering of a primary energetic ion beam (0.5-20 keV) on sample surface and analysis of produced ionized secondary particles by mass spectrometry.
- Good detection sensitivity for many elements such as: B, P, Al, As, Ni, O, Si etc.
- It can detect dopant densities as low as 10^{13} cm$^{3.}$
- Has a depth resolution of 1 - 5 nm and can give a lateral surface characterization on a scale of several microns.
- Destructive method, since the act of the removing material by sputtering leaves a crater in a sample
- It determines the total dopant density profile

Example of SIMS and simulation comparision.

- Simulation and data compared for CiS (left) and VTT (right) samples for Synopsys Charged Pair simulation model:

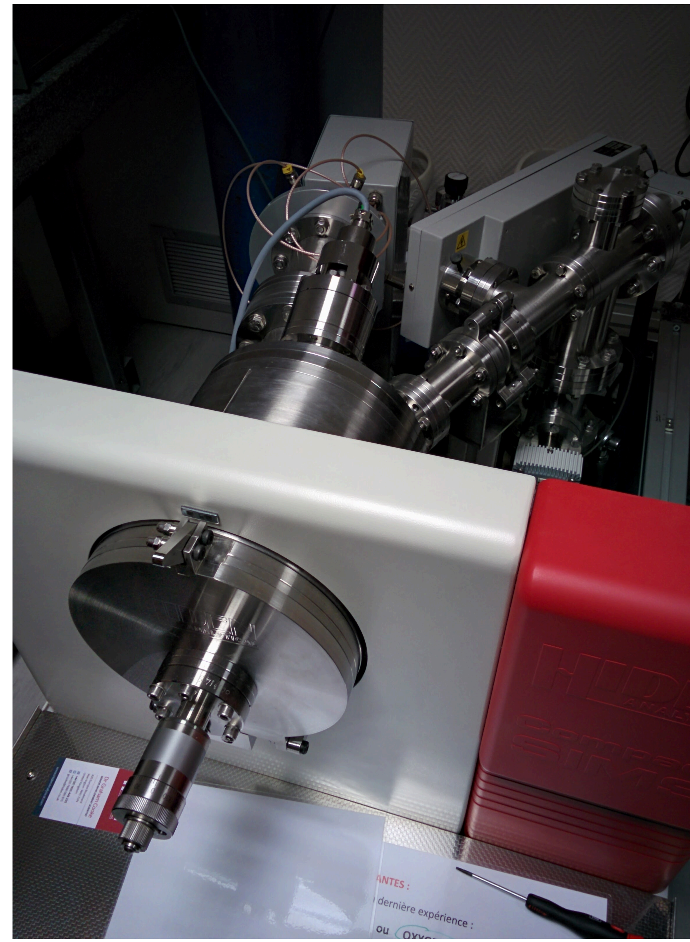




- Simulation by Vagelis Gkoukgoussis. Results presented at Pixel 2014.
- Generally good agreement between simulation and SIMS data for lower doses.
- Large discrepancy with the highest dose (10^{16}) for CiS sample.
- Comparison with various diffusion models in Synopsys and Silvaco, but no single model accounts for data.

New compact SIMS machine in-house at LAL

- Compact SIMS machine complementary to current collaboration with Versailles.
- Training on the machine and first measurements to begin this month.
- Interest from our colleagues at KEK to utilise this machine.

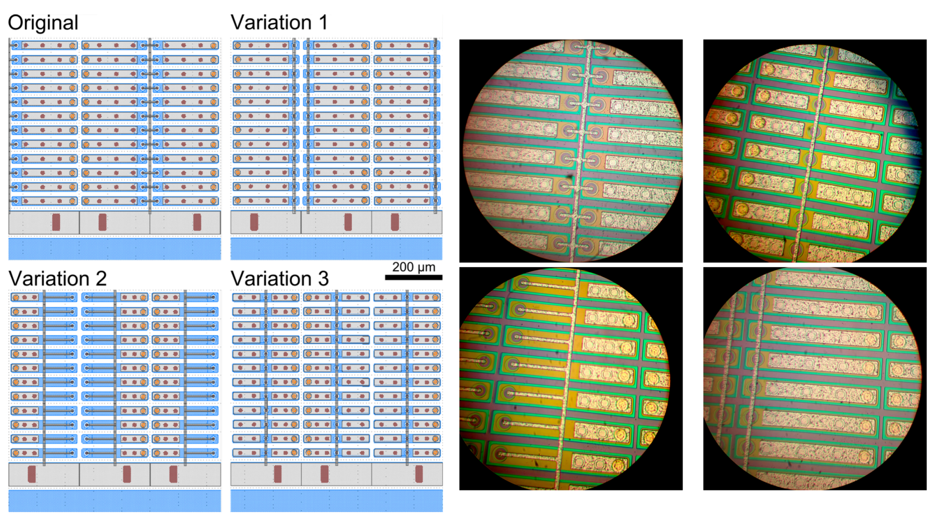


Results from LAL from collaboration with KEK

Many thanks to Koji Nakamura, Kazuyuki Sato, Junki Suzuki and Hiromi Sawai for the collaboration and hospitality!

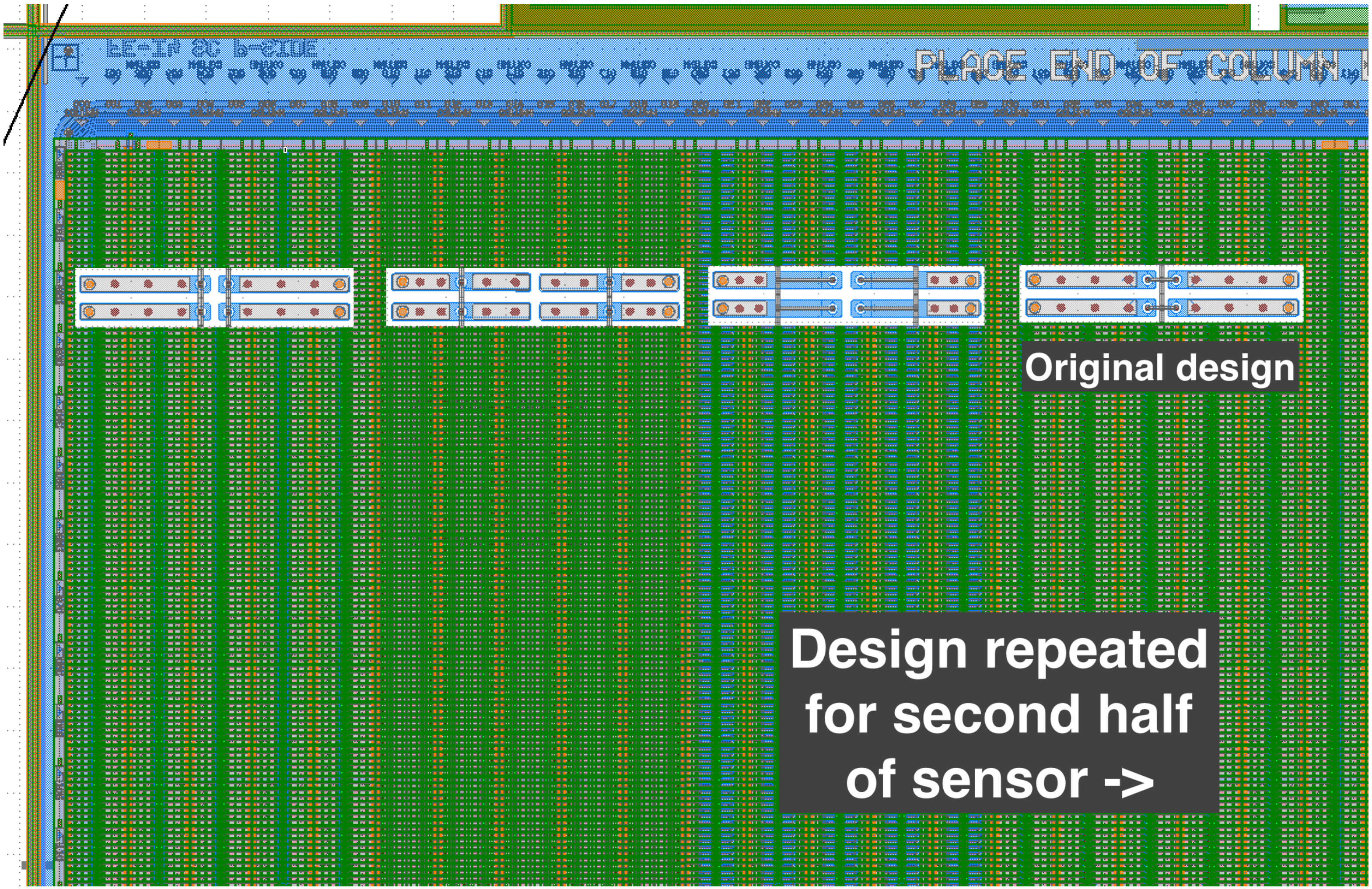
CiS Bias Rail Design

- It is a known issue with planar pixel sensors that there is an efficiency loss under the bias rail after irradiation.
- This could be solved by removing the bias rail entirely.
  - The sensor could not then be tested before bonding to a readout card.
  - Possibly leading to a lower yield.
- Instead investigate alternative routing of the bias rail to see if a different design could improve the efficiency.
- Studies are done through tuning in the clean room and test beams both before and after irradiation.



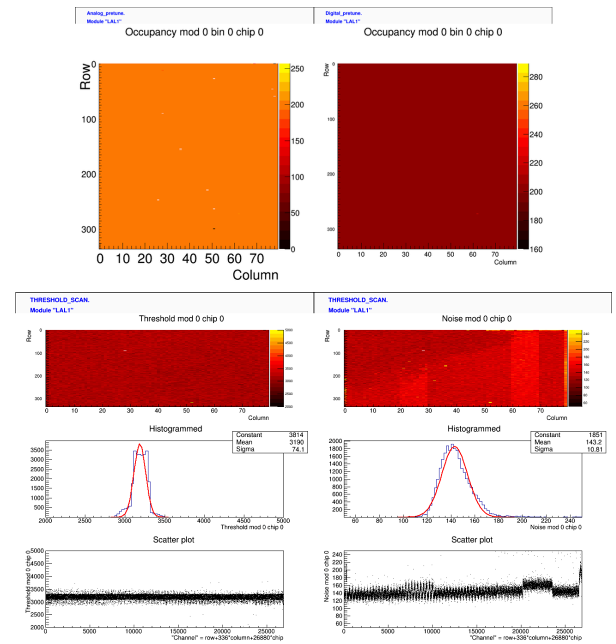
CiS Bias Rail Design

4 designs in 1!



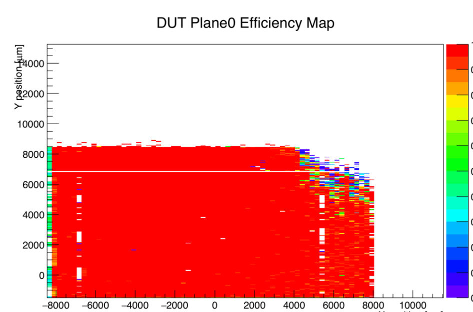
Summary of tests performed before collaboration with KEK

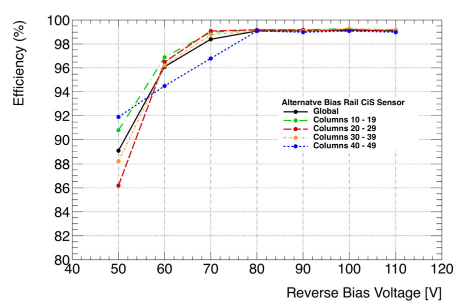
- **LAL 1:**
  - Clean room measurements (known bump-bonding issue seen.)
  - CERN test beam
  - Irradiated to 5 x 10 ^{15} n_{eq} cm^{-2} at CERN PS.
  - Further bump-bonding disconnection, but large region working fine after irradiation.
  - After cooling to -40º, can no longer measure the device due to all but ~20 pixels being disconnected.

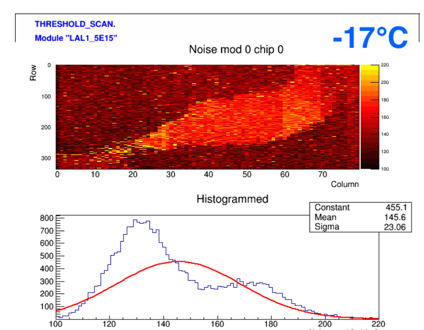


- **LAL 2:**
  - Clean room measurements.
  - CERN test beam.

Plots for LAL 1

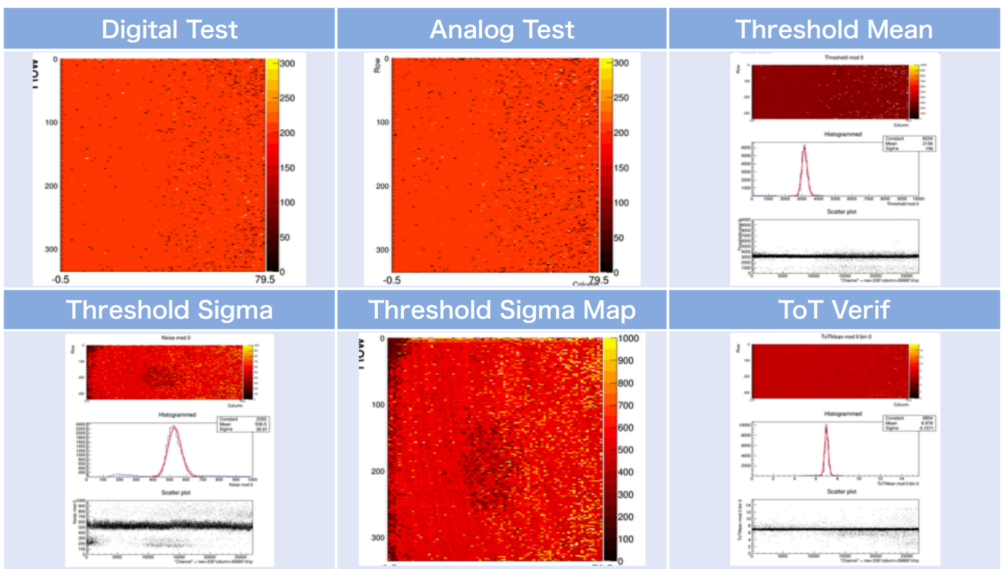


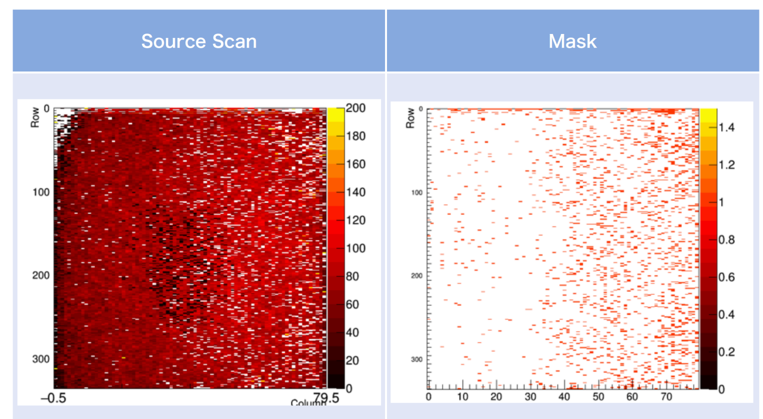




Measurements at KEK

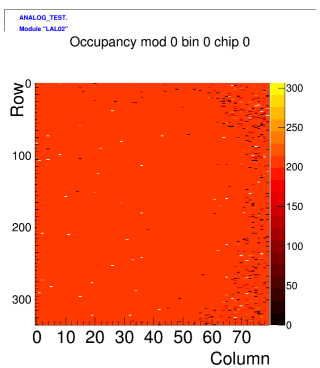
- LAL 2:
  - Sample arrived safely in Japan and was tested prior to irradiation.
  - Tuning parameters:
    - Threshold of 3000e, TOT tuned to 7 at 20ke.
    - Many thanks to Hiromi Sawai for performing these measurements.

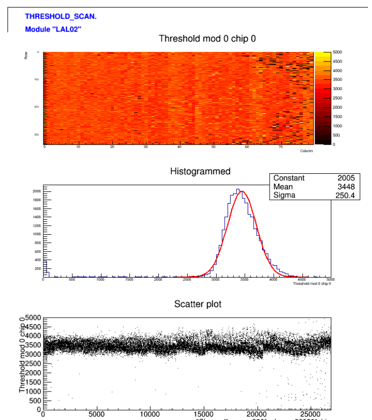


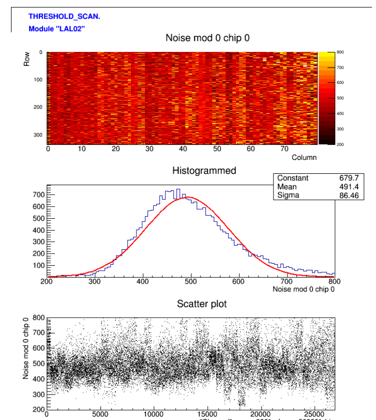


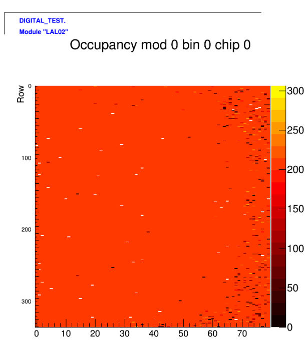
After irradiation at KEK

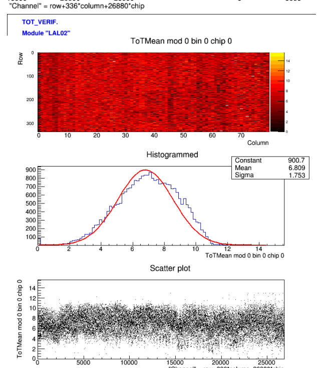
- Sample was irradiated to 3 x 1015 and kept in the freezer afterwards. Tuning parameters: Threshold of 4000, TOT tuned to 7 at 5ke.
- Cooled to -30◦.
  Many thanks to Kazuyuki Sato for working with me to perform these measurements.

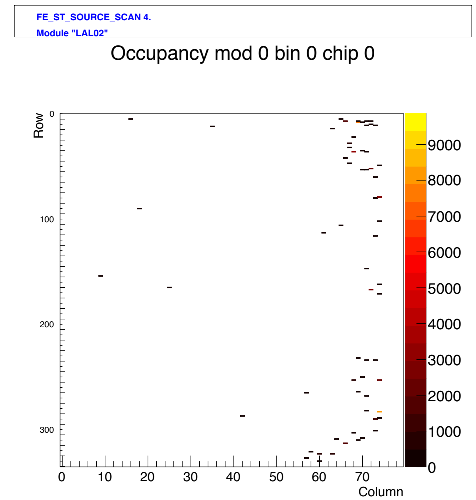


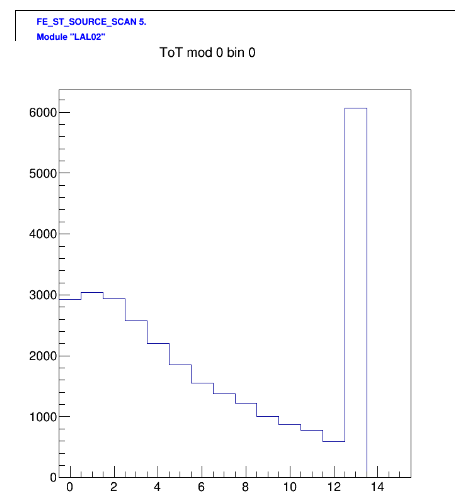












Conclusion from KEK studies and further work

- Results suggest that only a handful of pixels are connected. Since the irradiation is not unusually high, and the chip can be tuned successfully, our conclusion is that the bumps are disconnected due to thermal cycling. This can be tested by performing an x-ray scan of the sample.

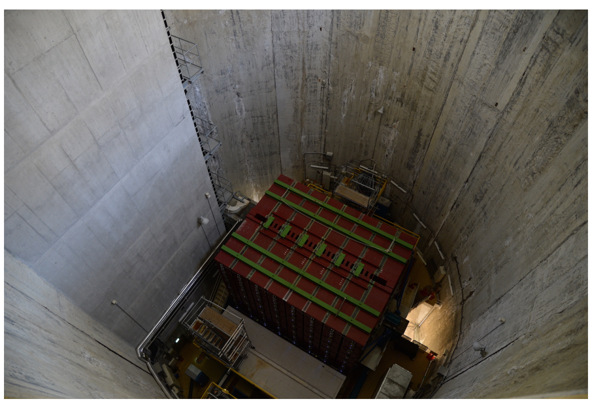
Further work:

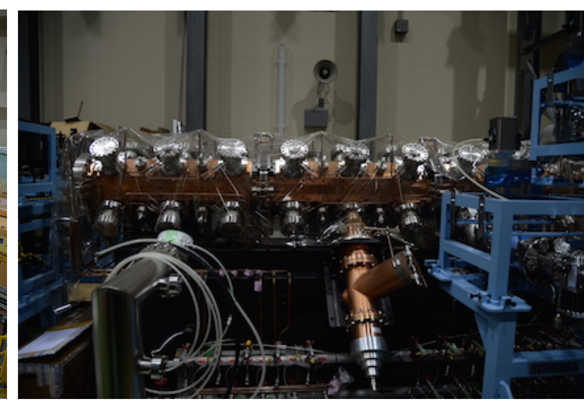
- Two additional samples with alternative bias rails have been prepared for the next CERN test beam (end of May) and subsequently will be irradiated at KEK.
- We have a non-alternative-bias-rail sample, also bump-bonded at LETI, which we can thermal-cycle to test if this is the reason for the disconnection.
  - Important feedback for community which will chose the laboratories and parameters for bump-bonding ATLAS ITK modules.
- X-ray scans of two irradiated modules and then a tear-and-pull procedure to photograph the shape of the bumps.

ATLAS EXPERIMENT

Visit to JPark, Japan

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE





프랑스 FRANCE CORÉE 한국 2015 2016

Conclusions

LAL and Japanese Groups are committed in an ambitious R&D program inside the ATLAS ITK effort for HL-LHC, where we will face challenging issues:

Major issue is to Built an innovative granular thin pixel planar detector

- Find the best sensor layout ingredients for high charge collection efficiency.
- Explore productions with active edges which will exhibit the best performance.
- Develop robust radiation hard solutions to cope with HL-LHC irradiation fluences.

Thus, our aim is to enhance and reinforce LAL-FR/ JAPAN collaboration to build the future P bulk Planar Pixel Sensors for ATLAS tracker for phase 2 of HL-LHC

We intend to increase the:

- Synergy in terms of P bulk sensor design, characterization and testing (Clean room, Beam-tests, irradiation tests).
- Understand the behavior of heavily irradiated Planar Pixel sensors.
- Share expertise and efforts in TCAD simulation and Secondary Ion Mass Spectrometry (SIMS).

Budget request 2016 summary

Funding Request from France				
Description	**€/unit**	**Nb of units**	**Total (€)**	**Requested to:**
Visit to KEK/ Tsukuba (3seniors)	150/day	5 days	2250	FJPPL
Student Stay in KEK/ Tsukuba	1000/month	2 weeks	500	KEK / TSUKUBA
PostDoc stay in KEK	100/day	7 days	700	FJPPL
Travels	800	3	2400	FJPPL
Total			5850	

Funding Request from Japan				
Description	**k¥/Unit**	**Nb of units**	**Total (k¥)**	**Requested to:**
Visit to LAL (3 seniors), per diem	45/day	5 days	225	KEK
Student (1) Stay at LAL, per diem	150/month	2 months	300	KEK
Travels	160	4	640	KEK
Total			1,165	

Additional Funding from France			Additional Funding from Japan		
Provided by/ Requested to	**Type**	**€**	**Provided by/ Requested to**	**Type**	**k¥**
LAL/ATLAS PIXEL/ANR	TCAD SIM licence	400	KEK / ATLAS (JSPS)	Silicon sensor production	1,000
LAL/ATLAS PIXEL,CNRS ANR	Silicon sensor production	5000	KEK / ATLAS (JSPS)	CYRIC irradiation	500
Total		5400	Total		1,500

Thank you for your attention

Merci pour votre attention

本当にありがとう

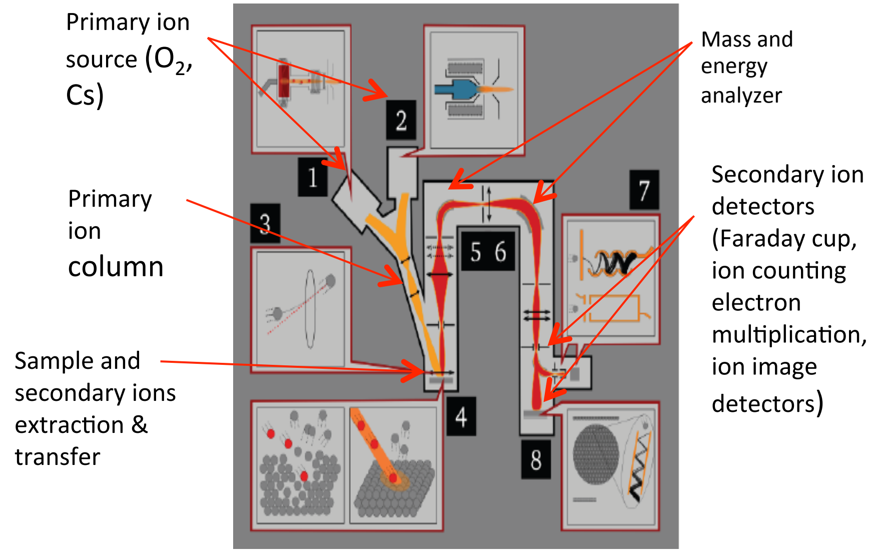
여러분의 관심에 감사드립니다

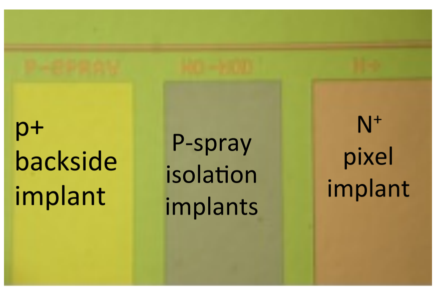
Back up slides

Tools: synopsis 3D & doping profile measurements

- To overcome the problem of non-accessibility of Technology parameters :
  - charge carrier distribution, doping profiles, density of defects and Impurities etc…
- TCAD simulation is absolutely needed
  - Tool for studying relationship: semiconductor physics - device characteristics
  - Process simulator: oxidation, ion implantation, diffusion, etching etc.…
  - Device simulator: electrical parameters by solving eq.: Poisson, current density , continuity etc..
- Experimental methods used for TCAD calibration
  - Secondary Ion Mass Spectrometry (SIMS) – atomic doping profile
  - Spreading Resistance Profiling (SRP) – charge carriers doping profile

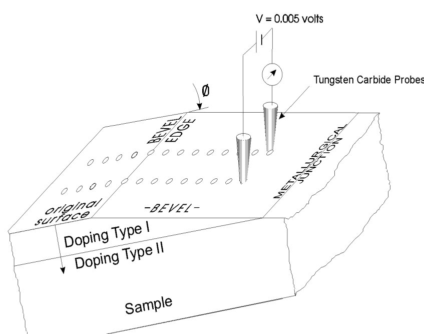
SIMS

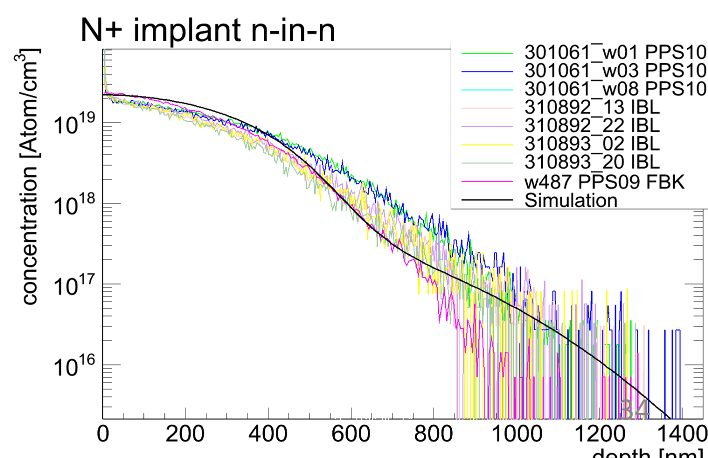




- Optimization of implantation & annealing parameters:
  - energy and dose, oxide thickness, annealing time and temperature

SRP : It relies on stepping a pair of small probes across the bevel surface of a sample and the measurement of a resistance when 5 mV are applied across the probes at each step

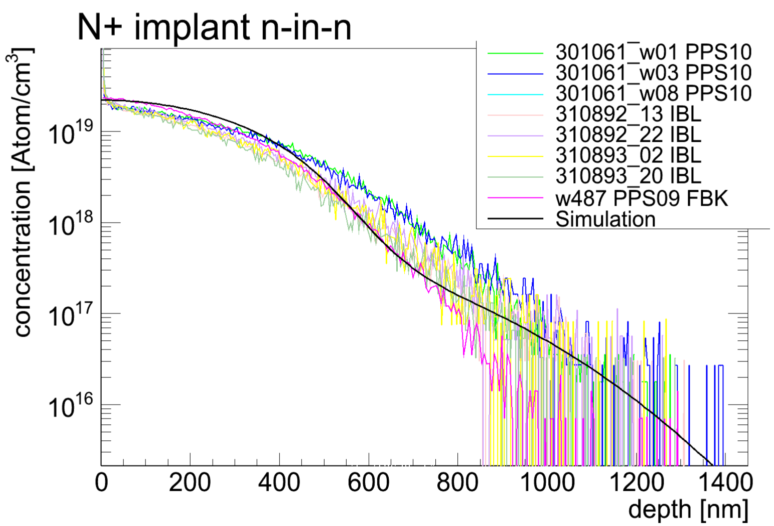


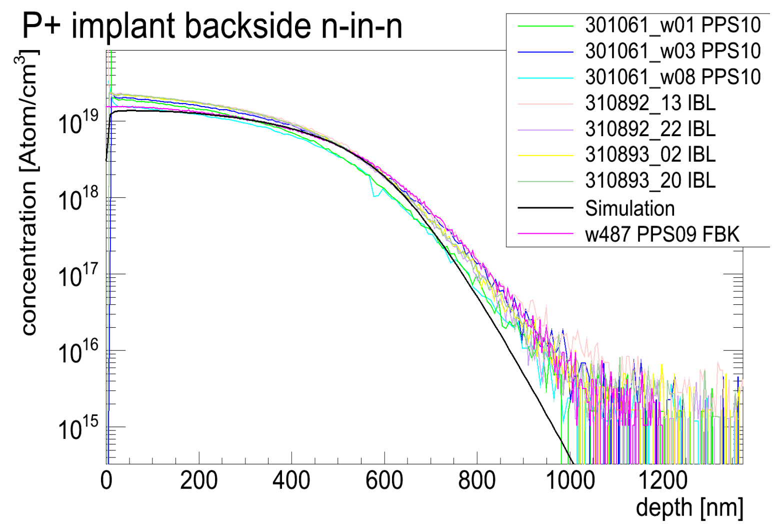


Doping profile for f IBL pixel sensor ATLAS

Comparison: experimental measurements / TCAD simulations

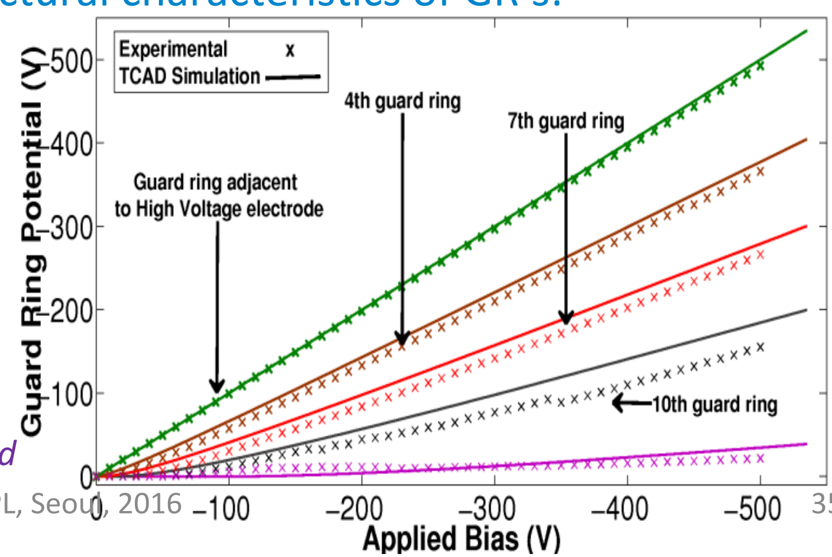
- Optimization of implantation & annealing parameters:
  - energy and dose, oxide thickness, annealing time and temperature



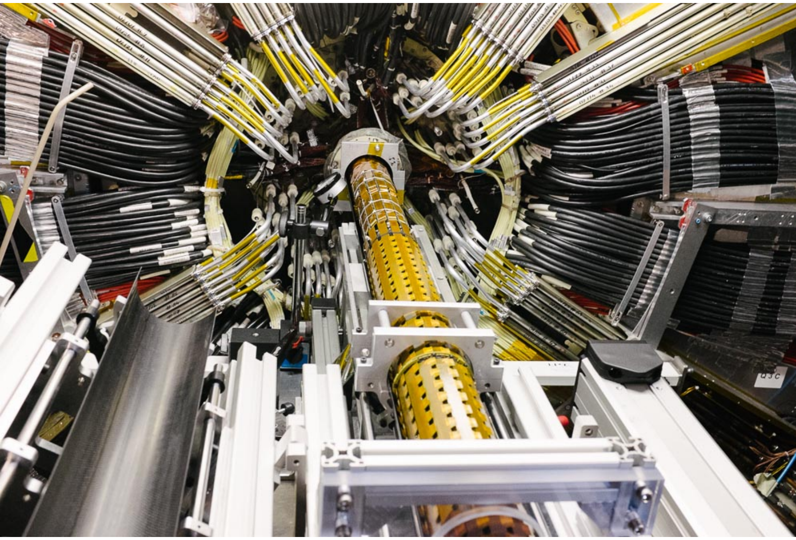


- Optimization of geometrical and structural characteristics of GR's:
  - number & width, gap size, metal overhang width

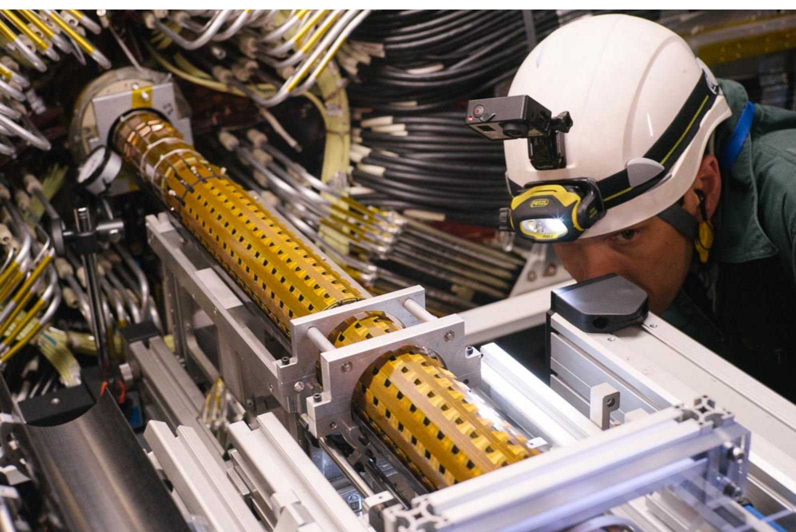
M. Benoit, PhD thesis, 2011

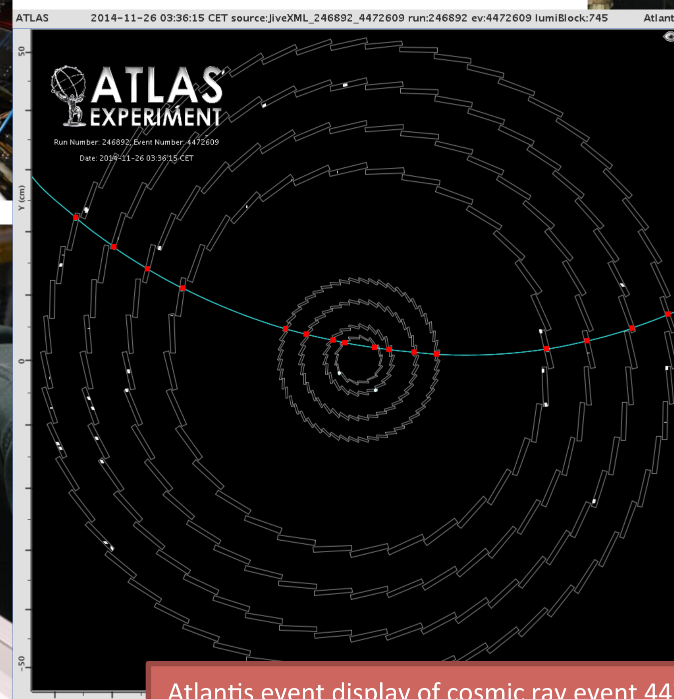


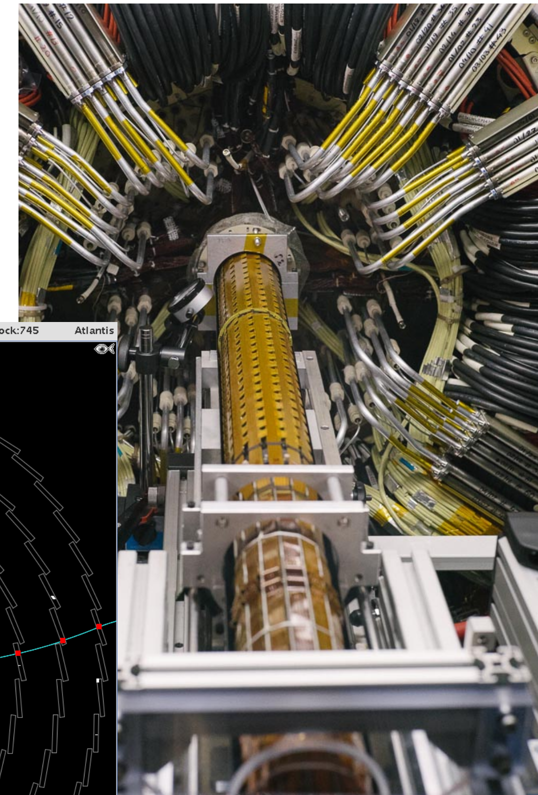
Collaboration: TU-Dortmund



May 7th , 2014
The successful IBL insertion phase

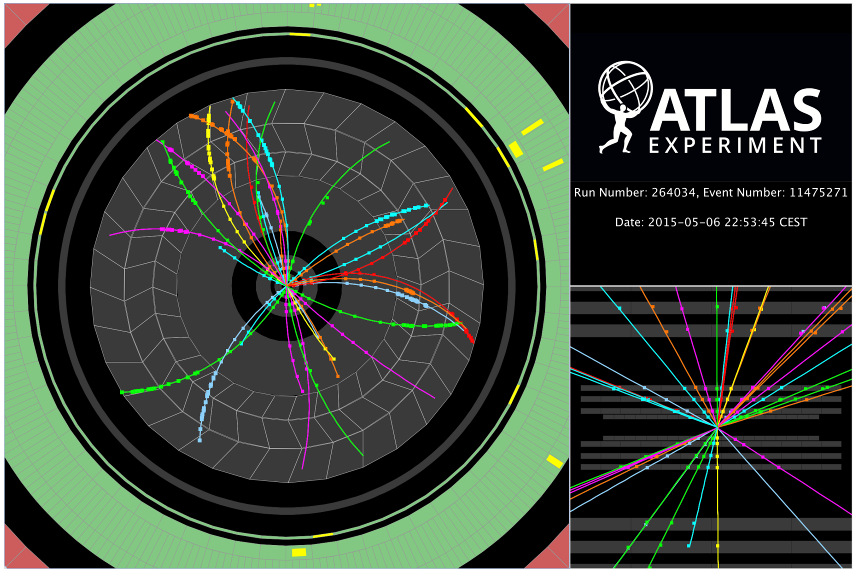


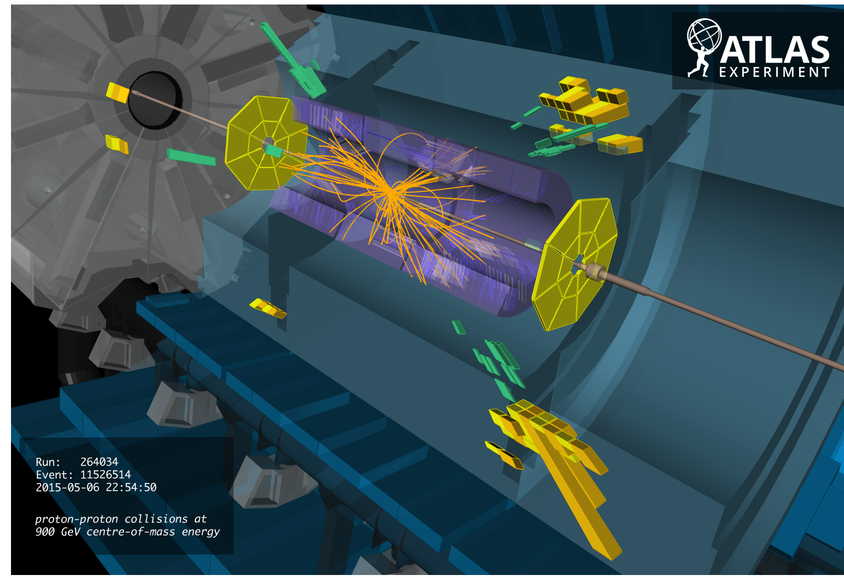


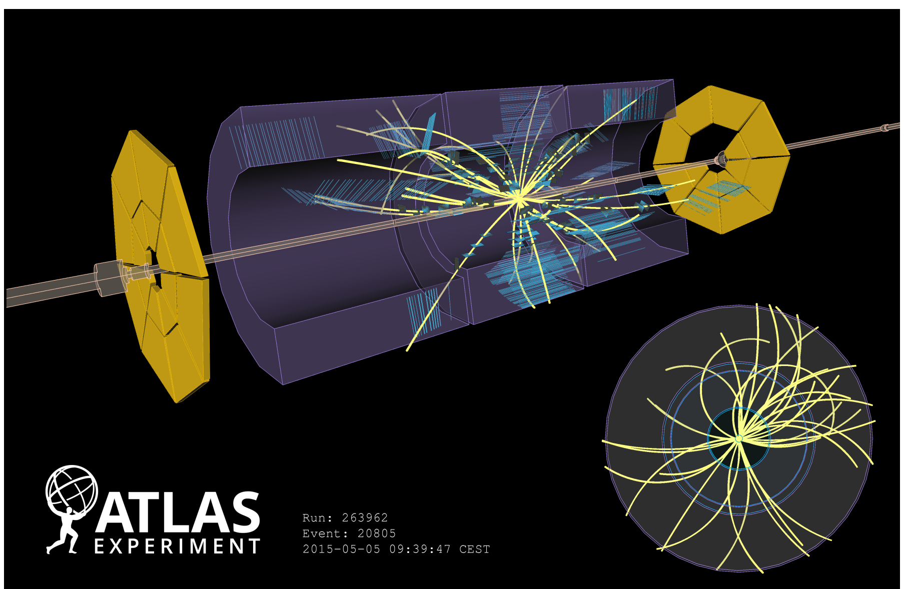


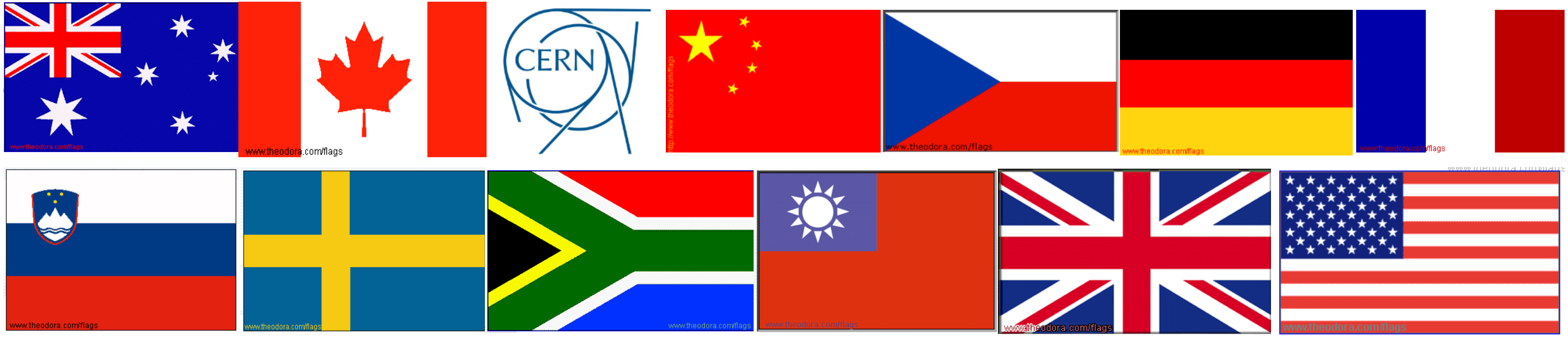
Atlantis event display of cosmic ray event 4472609 from run 246892. A cosmic ray is shown passing through the IBL, the newly installed pixel layer of the ATLAS detector, in the presence of a solenoidal magnetic field. The IBL is the inner-most layer in the display.

ATLAS has been running with four pixel layers since May 2015.









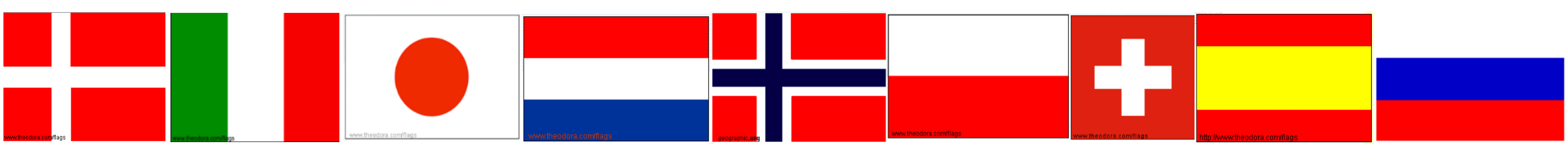
The present and future environment KEK and LAL inside :

The ATLAS ITk

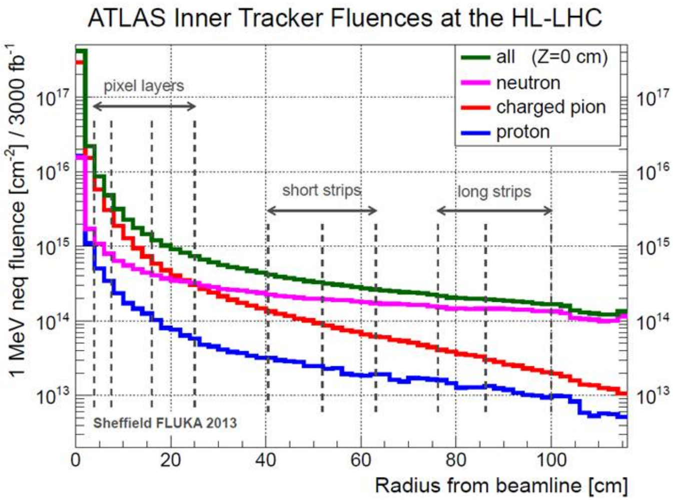
21 Countries : 93 Institutions

https://twiki.cern.ch/twiki/bin/view/Atlas/ITK

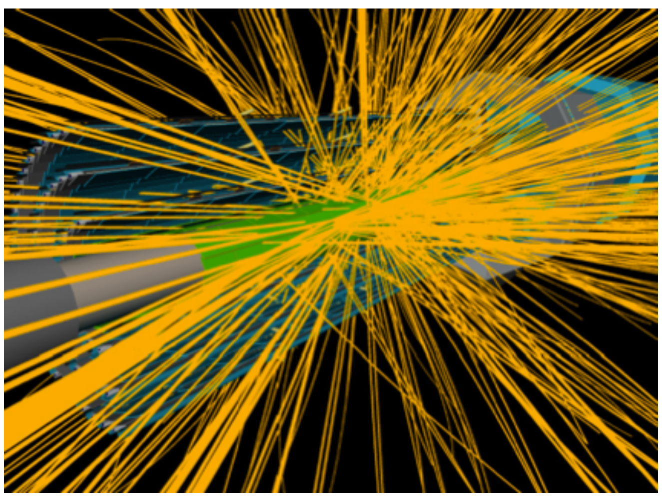
ATLAS EXPERIMENT



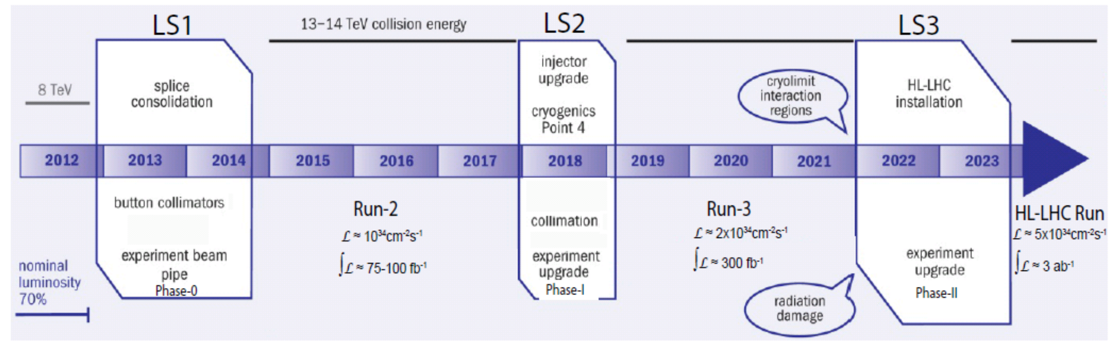
HL-LHC :The issue of IRRADIATION LEVELS :



I. Dawson, P. S. Miyagawa, Sheffield University, Atlas Upgrade radiation background simulations



Increase luminosity to extend physics reach of LHC



Higher fluences (up to $2 \cdot 10^{16}$ n_{eq}/cm^2) Radiation hard material

- Thinner bulk –lower X_0;
- Abbutable devices (no dead space), innovative designs
- Lower chip threshold, consumption → deep submicron technologies
- Decrease the overall cost & keeping high performance
- Master the behavior of sensors after SCSI
- Understand the Charge amplification for Heavily irradiated detectors

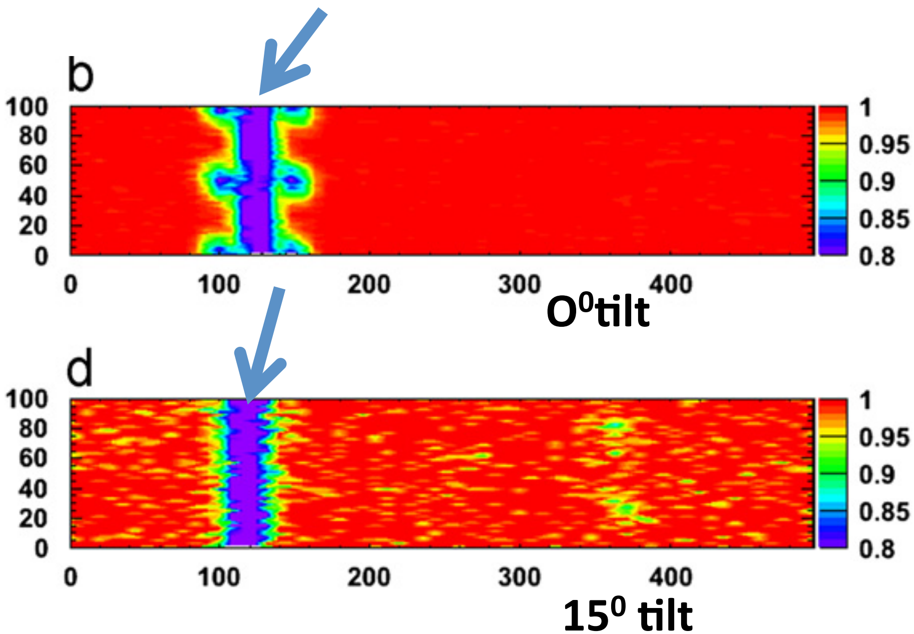
Higher pile-up

- Challenging reconstruction
- Finer pixel granularity

Matters to improve ?

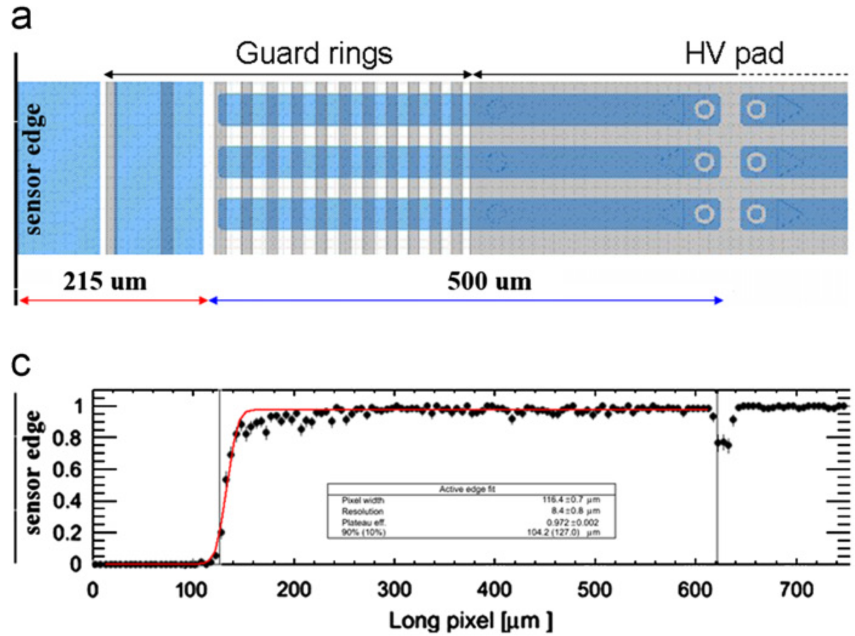
what could we learn from the recent past ?

Bias Rail position

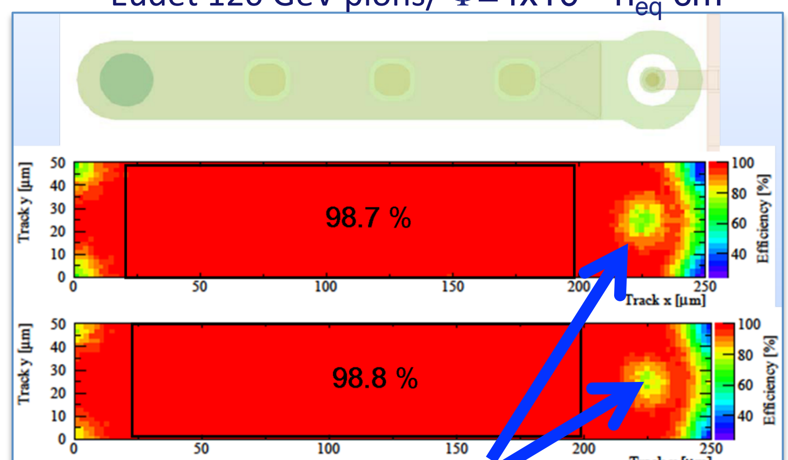


Pixel efficiency map for the sensors irradiated to 5. 10^{15} neq/cm^2 and cooled to -15^{0}c.

Igor Rubinski, Nuclear Instruments and Methods in Physics Research A 699 (2013) 67–71



Eudet 120 GeV pions/ Φ=4x10^{15} n_{eq} cm^{-2}



Is there a way to improve this situation ?

Main loss of efficiency in the bias dot and in the bias rail

The question of the high radiation at HL-LHC

Why new sensors for HL-LHC ?

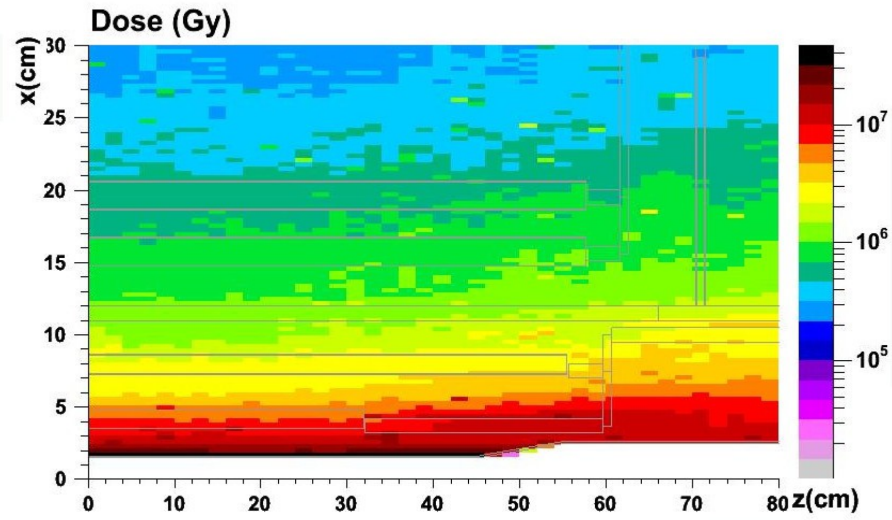
- Integrated luminosity: 3000 fb^{-1}, including safety factor of 2 for all uncertainties,

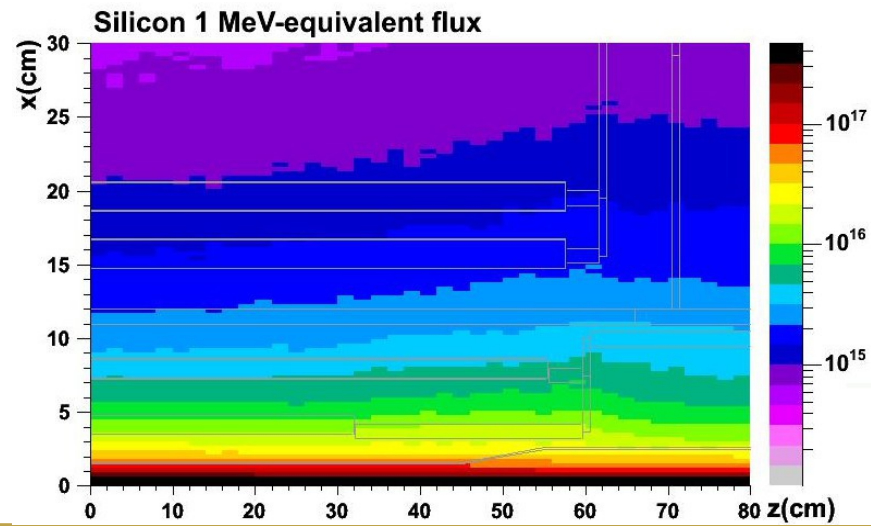
so : for low radius area (<5 cm radius):
  - 2×10^{6} n_{eq} cm^{-2} (1500 Mrad) : *severe irradiation damage*
- For higher radius (25 cm) :
  - Up to 10^{15} n_{eq} cm^{-2} (100 Mrad)
  - Several m^2 of silicon

For outer region > 25 cm radius ~ 10^{14} n_{eq} cm^{-2}
  - Up to 200 m^2 of silicon

Drive to idea to construct a new inner tracker

- Radiation damage =➔ material with more radiation tolerance for bulks
- Radiation tolerant ASIC readout
- Higher occupancy =➔ granularity

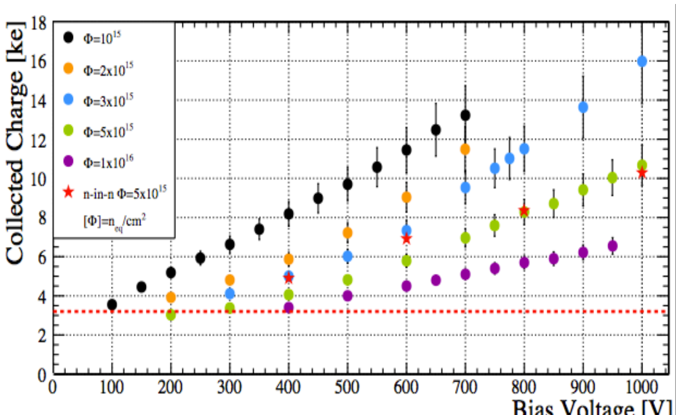




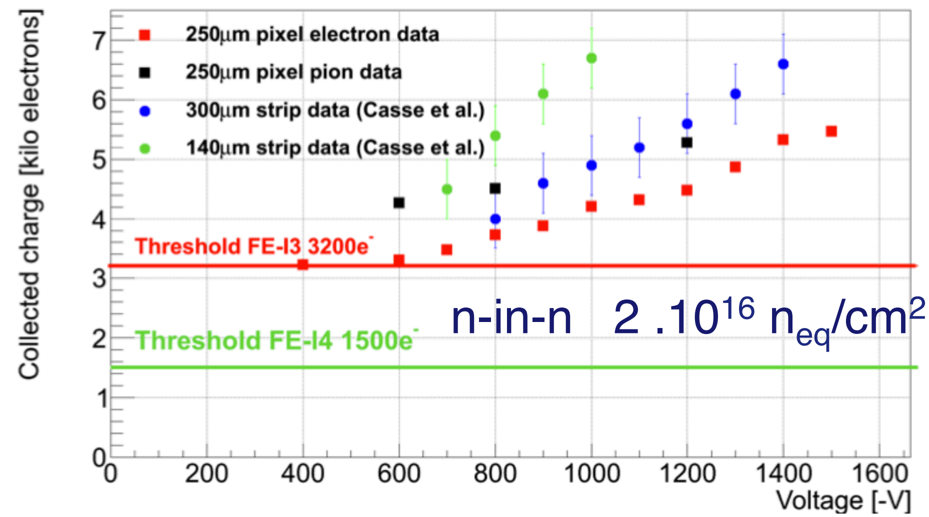
Under heavy irradiation levels : the charge Multiplication issue

- ***Charge Multiplication observed and characterized** after high levels of irradiation with different techniques and in several different types of devices*

Intense activity lead by RD50 collaboration



C. Gallrapp et al., "Performance of novel silicon n-in-p planar Pixel Sensors ", Nucl. Instrum. Meth. A679 (2012) 29



T. Wittig, "Radiation hardness and slim edge studies of planar n+-in-n ATLAS pixel sensors for HL-LHC", PIXEL2012

Question:

- **Are existing models have all the ingredients to be able to predict the charge multiplication phenomenon ? Do we have the possibility to simulate the Charge multiplication (impact ionization and trap to band tunneling) (see M. Benoit, PhD dissertation, Université de Paris Sud XI, Orsay) ?**
- **Can one imagine how to better exploit charge multiplication (design);**
- **TCAD effort mandatory ?**