3D Double-Sided sensors for the CMS phase-2 vertex detector

IX Jornadas de Futuros Colisionadores.
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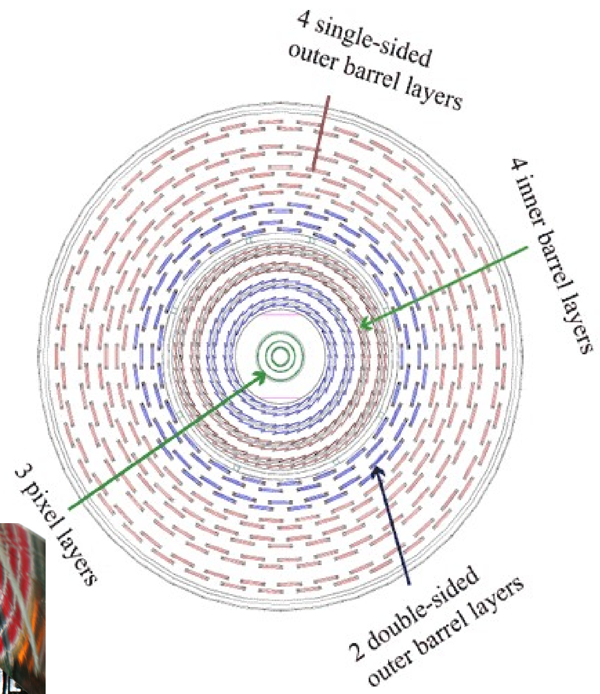
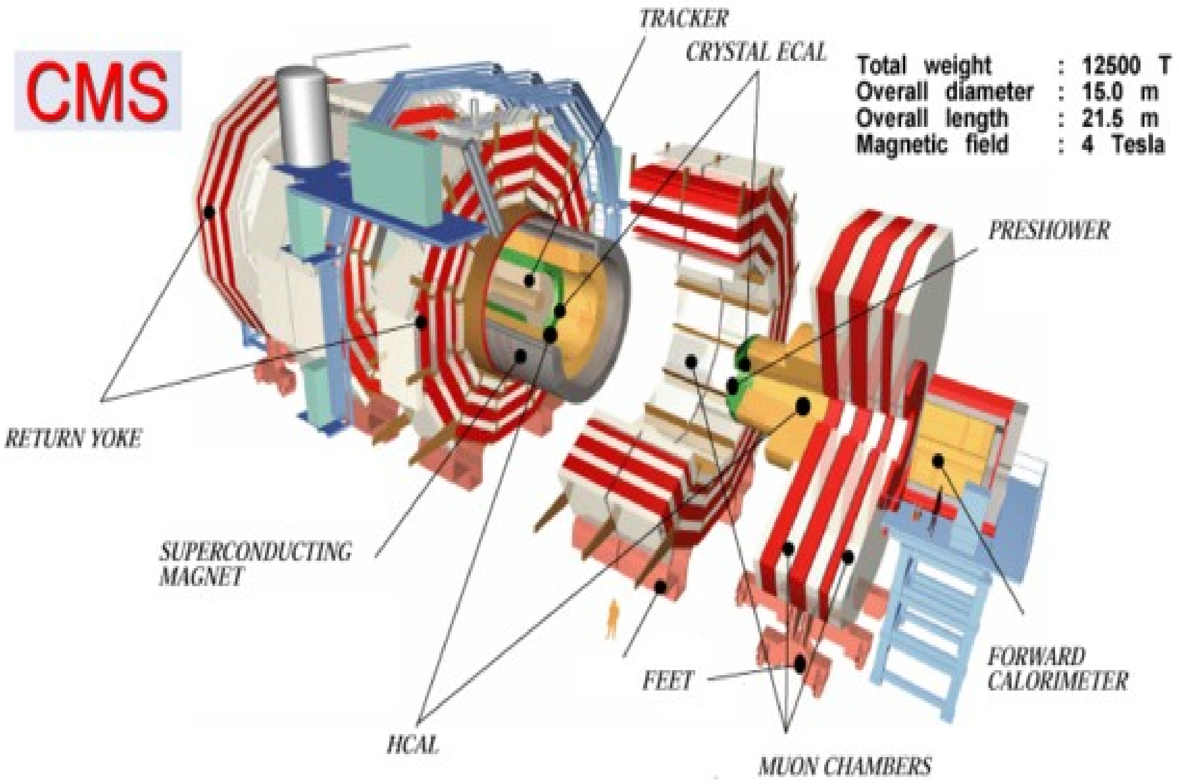
Outline

- Motivation
- 3D silicon technology, production and description
- Electrical characterization
- Read Out Chip in CMS (ROC)
- Bump-bonding
- First Measurements
- Next Steps and Conclusion

CMS. Compact Muon solenoid





LHC to HL-LHC

CMS to S-CMS

2010 ⟹ **~2020**

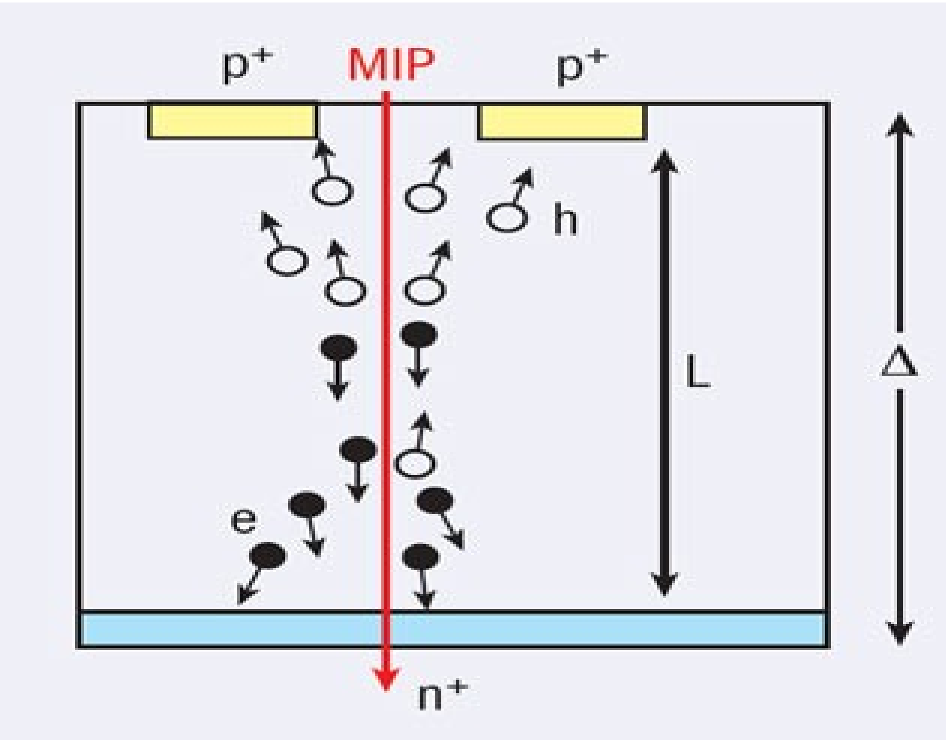
- Luminosity: 10^{34} $cm^{-2}s^{-1}$.
- Fluence: $6x10^{14} n_{eq} cm^{-2}$.
- Inner Radio: 4.4 cm
- Planar sensor

- Luminosity: 10^{35} $cm^{-2}s^{-1}$.
- Fluence: $1.4x10^{16} n_{eq} cm^{-2}$.
- Inner Radio: 3 cm
- 3D ?

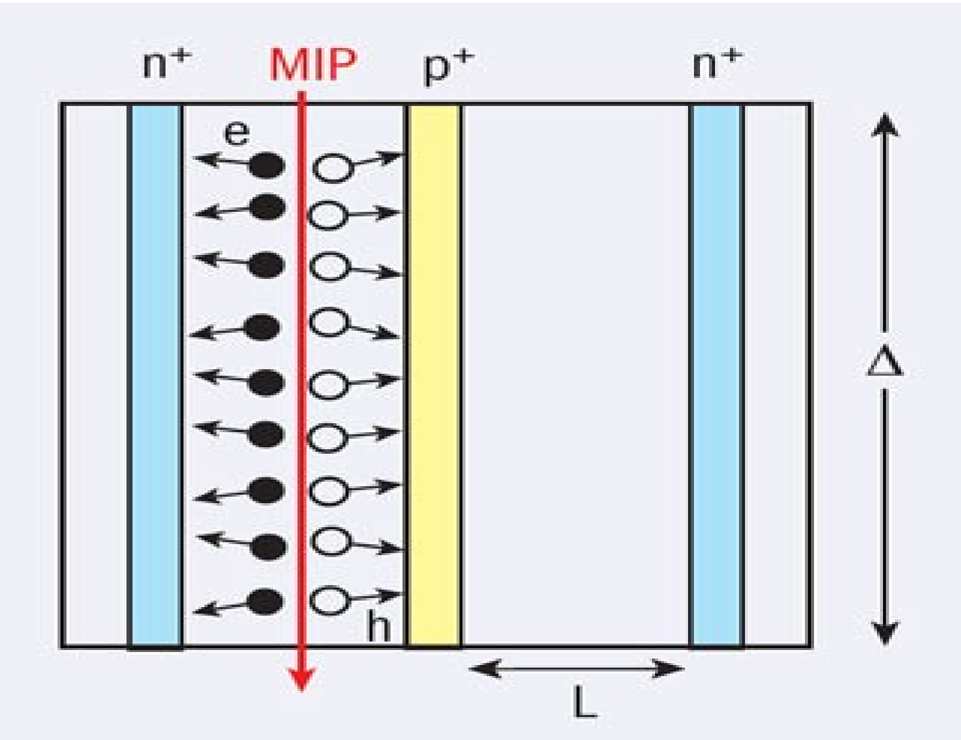
Radiation Damage

- Increasing reverse current proportionally to the particle fluencies
- Change of effective doping concentration. Higher Vfd
- Introduction of defects. Trapping centers. Reducing CCE

Planar Pixel



3D Pixel



$$V_{FD}\ \alpha\ L^{2}$$

3D Detectors {

- **Full depletion of the detector requires lower voltages**
- **Shorter collection distances**

3D- first steps

- 1997. First Proposal of 3D sensors

  S. Parker; “3D - A proposed new architecture for solid-state radiation detectors“

- 1999: first fabrication of 3D sensors

  C. Kenny; “Silicon Detectors with 3-D Electrode Arrays: Fabrication and Initial Test Results”

- 2001: first results with active edge 3D sensors

  C. Kenny; “Results From 3-D Silicon Sensors With Wall Electrodes: Near-Cell-Edge Sensitivity Measurements as a Preview of Active-Edge Sensors“

- 2001: first results irradiated 3D sensors

  S. Parker; “Performance of 3-D Architecture Silicon Sensors After Intense Proton Irradiation“

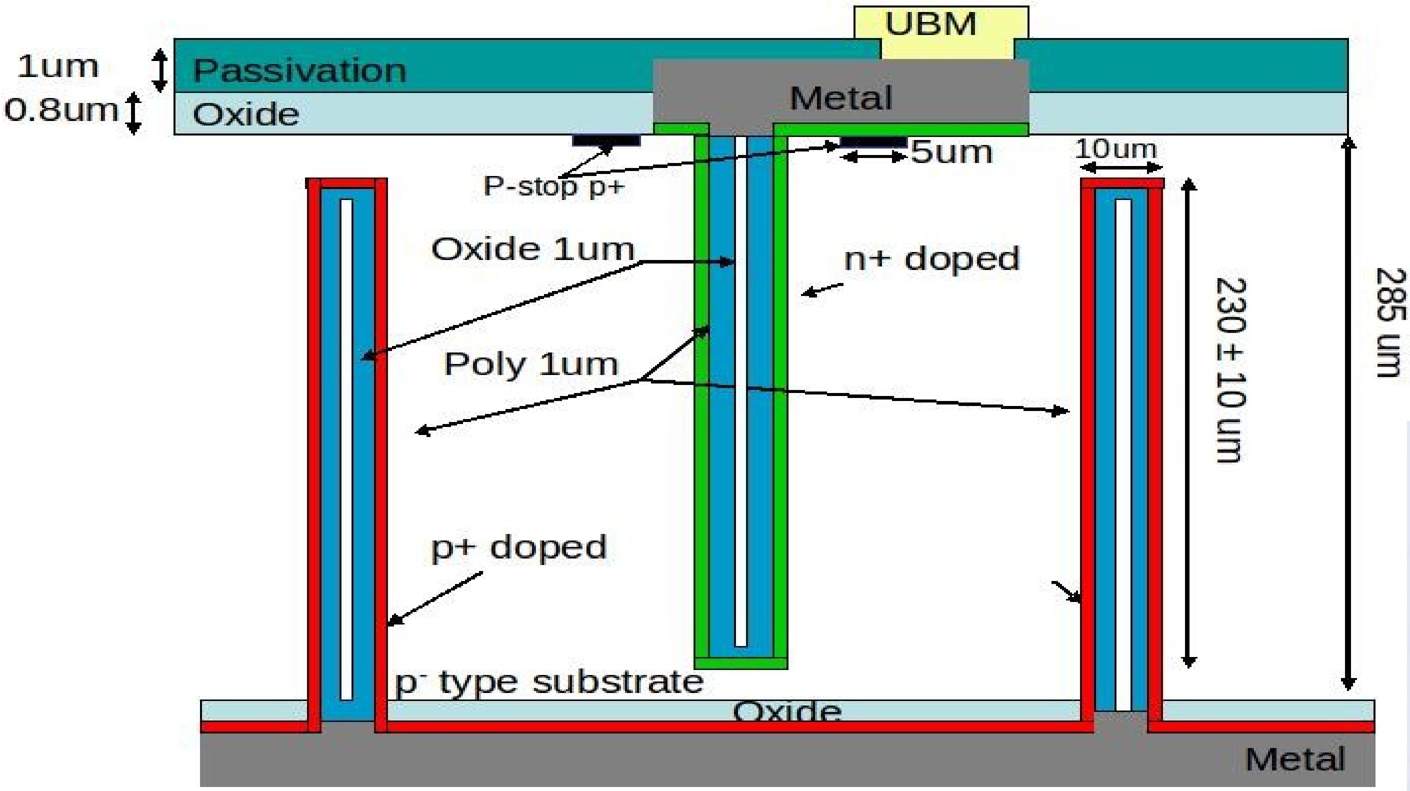
  …

- 2010: 3D sensors become candidate for the ATLAS - IBL Upgrade

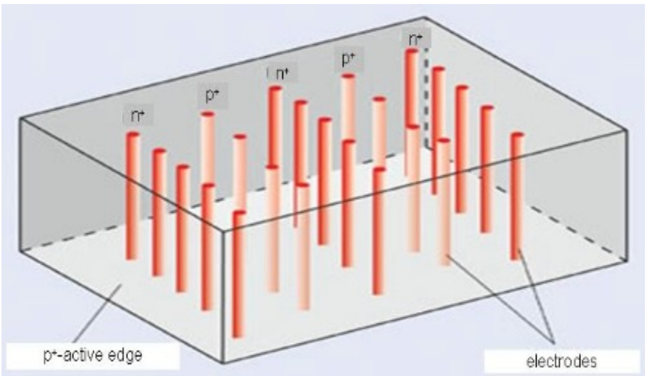
  The ATLAS Collaboration; “ATLAS Insertable B-Layer Technical Design Report”

Technology

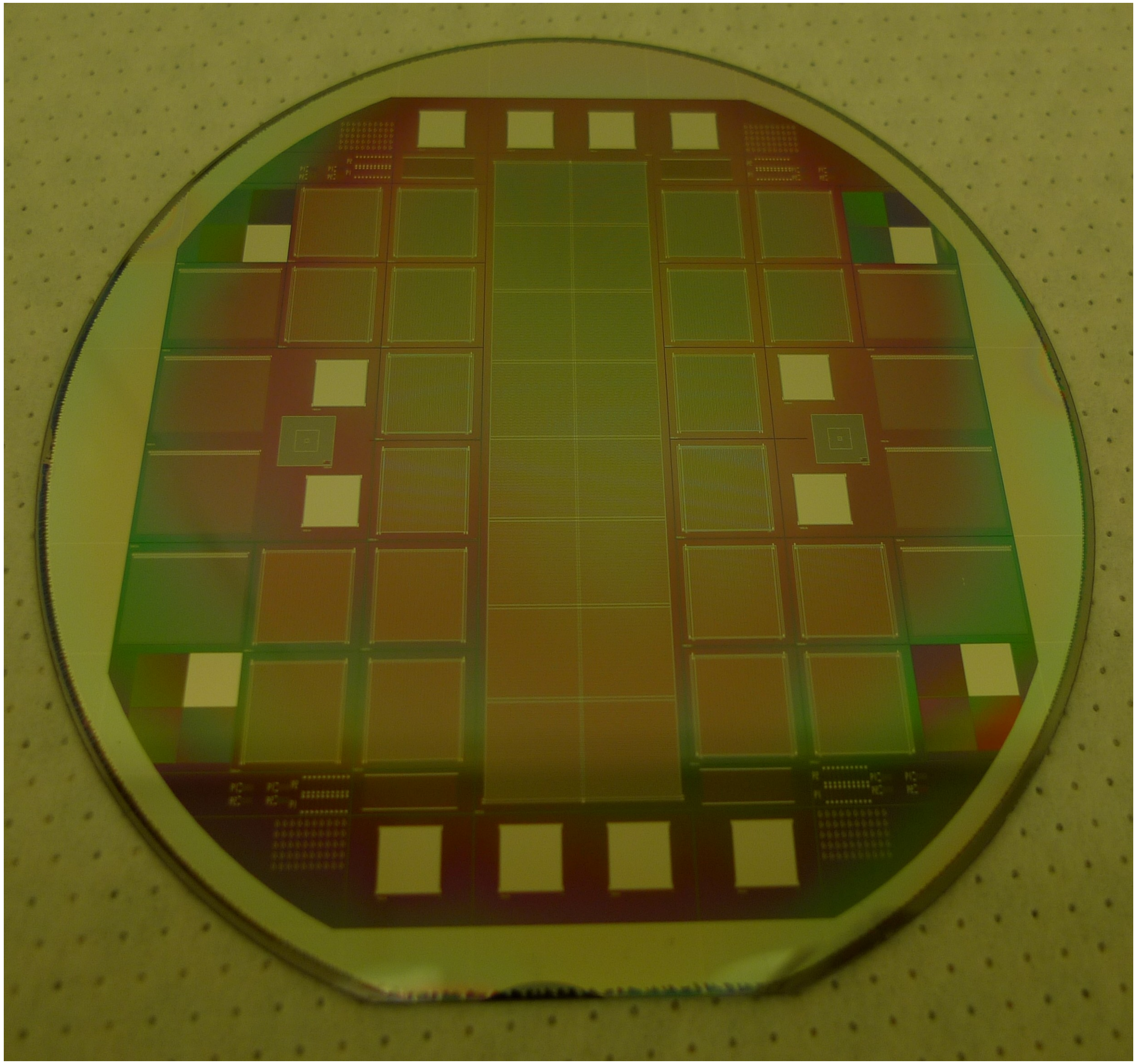
- Double-sided configuration (different doping type on each side)
- Simpler fabrication process
- Photo-lithography to define electrode contacts is only necessary on top surface
- HV biasing on the back side by simple wire bonding



Proposed by G. Pellegrini (2006)

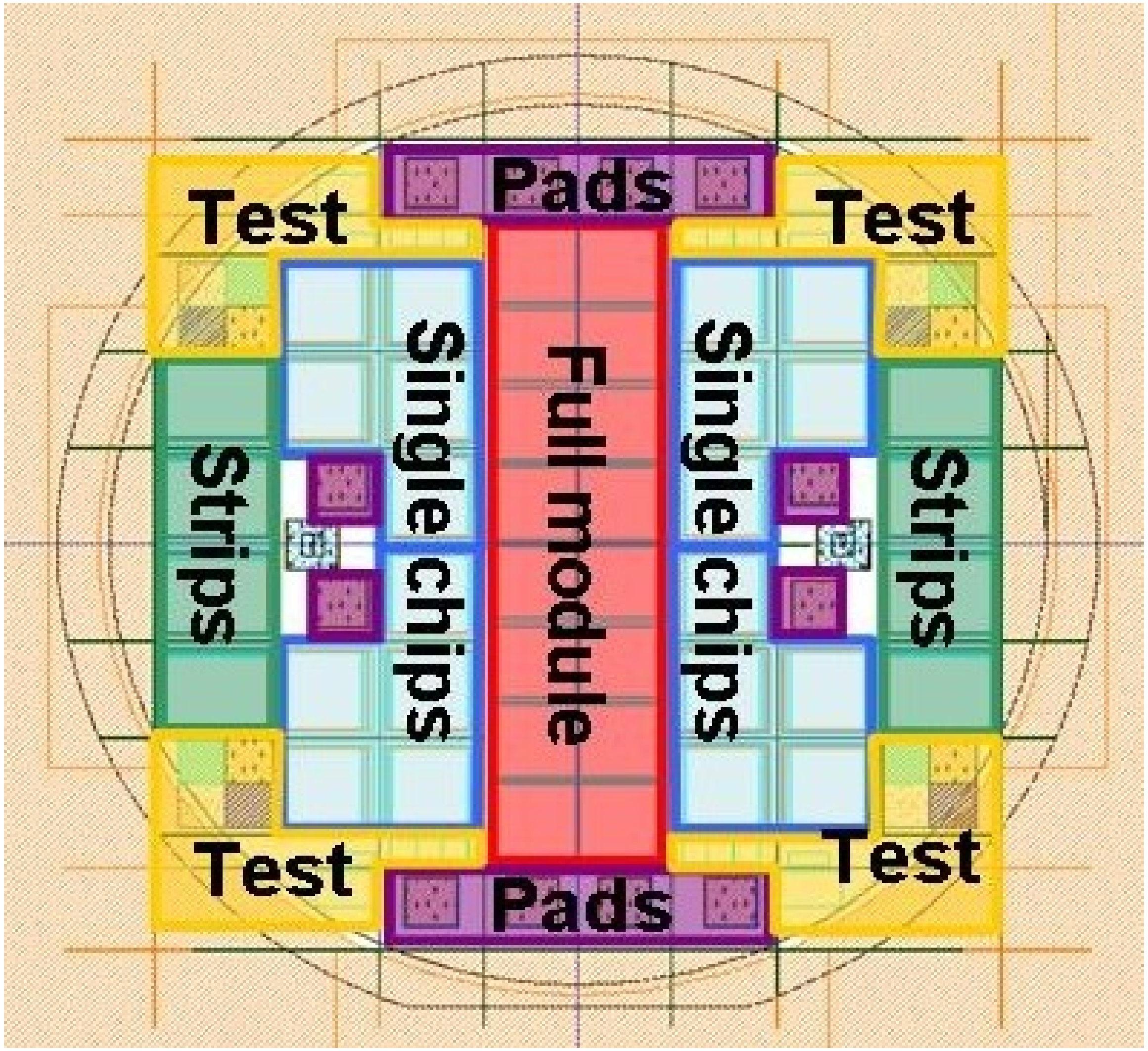


CNM Production



6 wafers:
Wafers 5,6,7,8:
- 285 µm thickness
Wafer 11:
-230 µm thickness
Wafer 3:
- 285 µm thickness
- Resistor bias grid

Wafer description



* Each wafer includes:

1 FM (8x2)

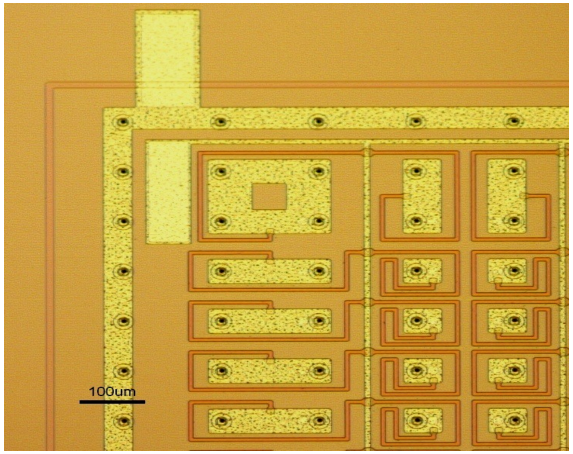
20 Single Chips

8 Strip sensors

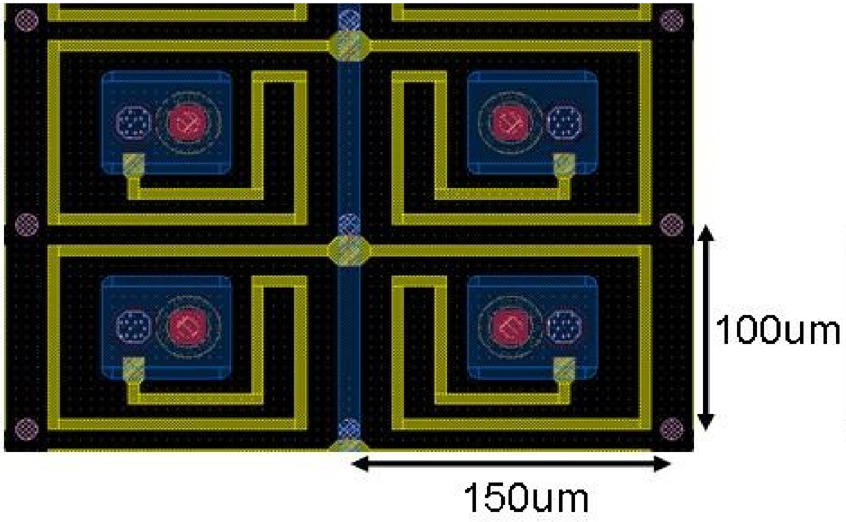
12 Pads

Test structures

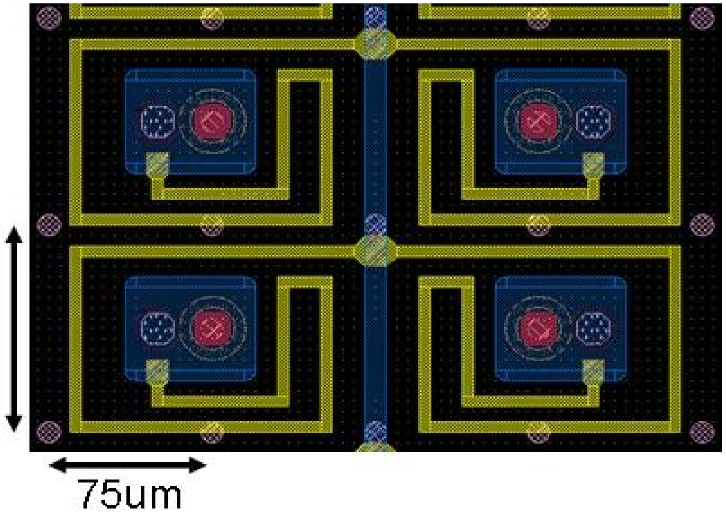
Wafer layout



* In the back side, two columns pattern.
  - Dense → reduced drift distance
    Expected higher radiation resistance
  - Sparse → larger drift distance
    Expected lower noises (lower capacitance)



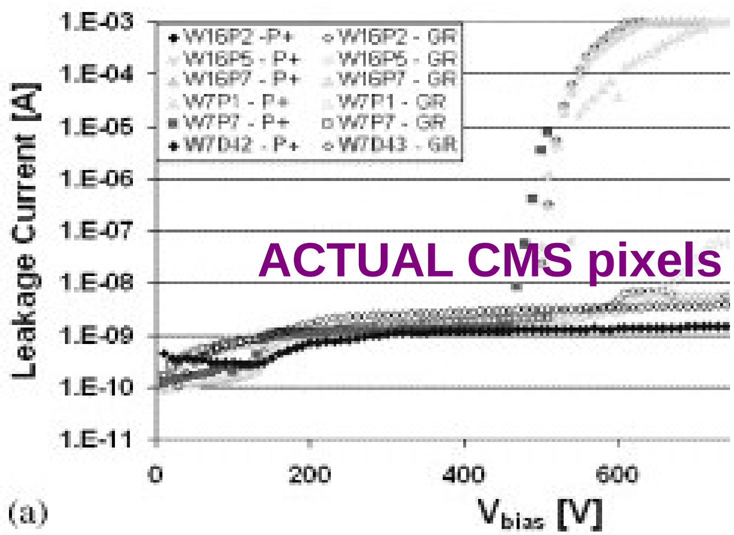
Sparse pattern of holes P:
Rectangular matrix of 150x100um^2

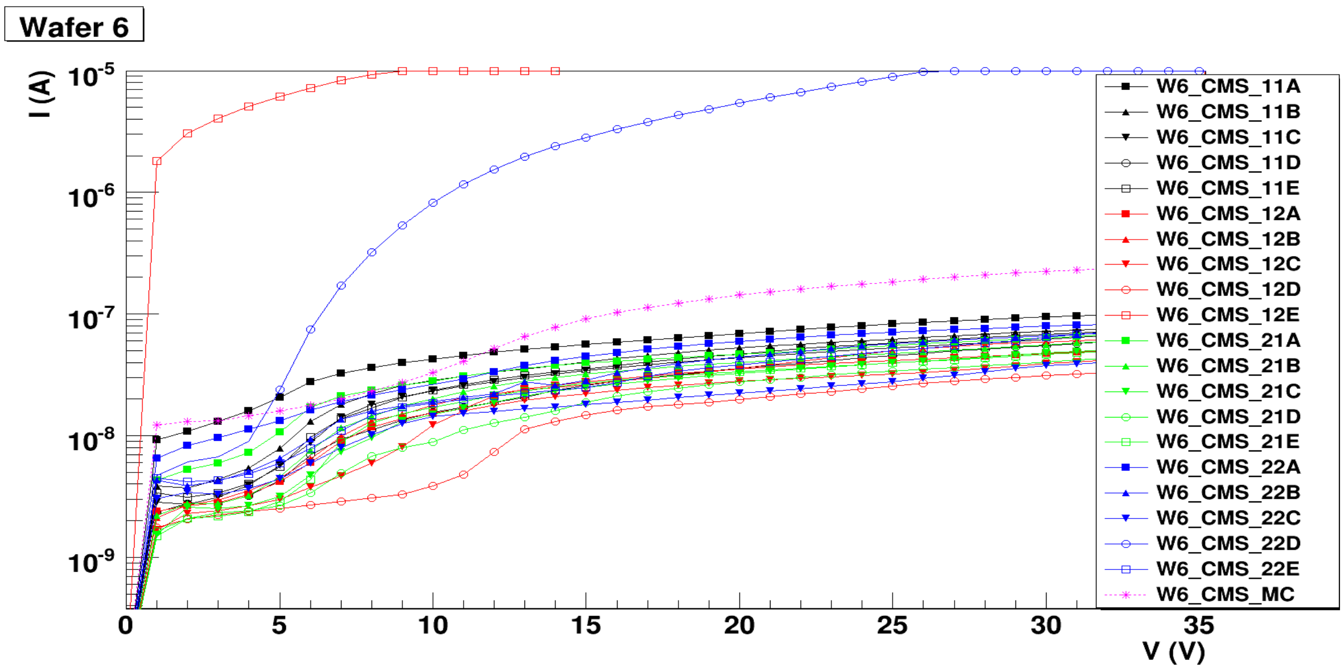


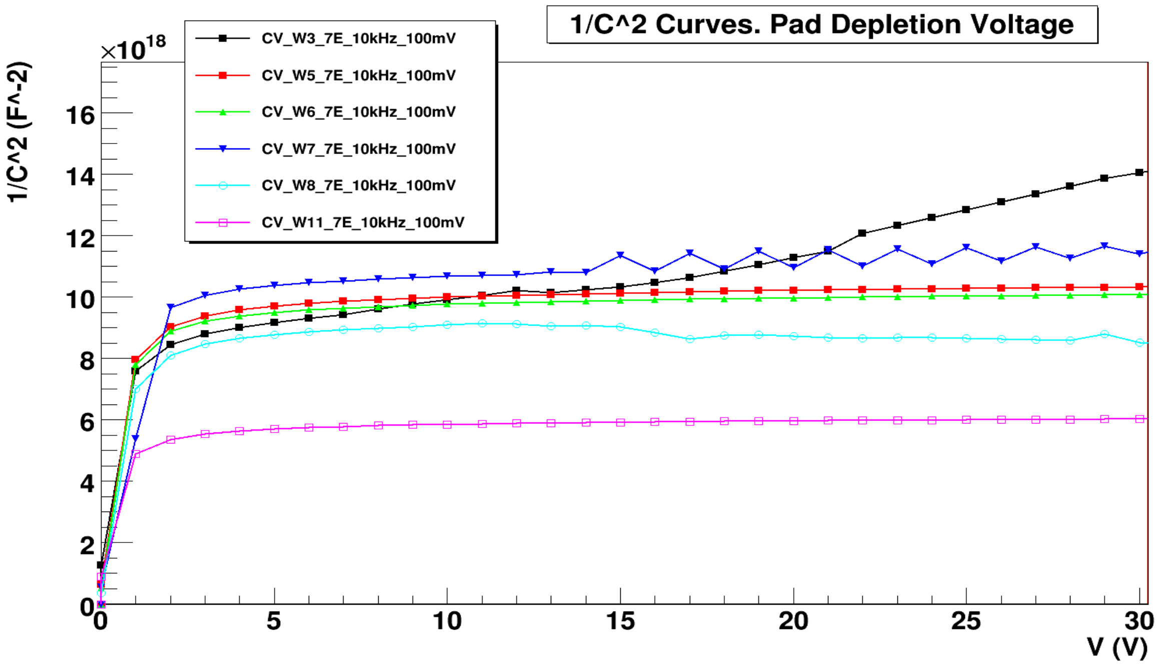
Dense pattern of holes P:
Rectangular matrix of 75x100um^2

* Full module has been designed with sparse pattern and single guard ring
* Wafer with a polysilicon resistor implemented for biasing without ROC

Electrical characterization



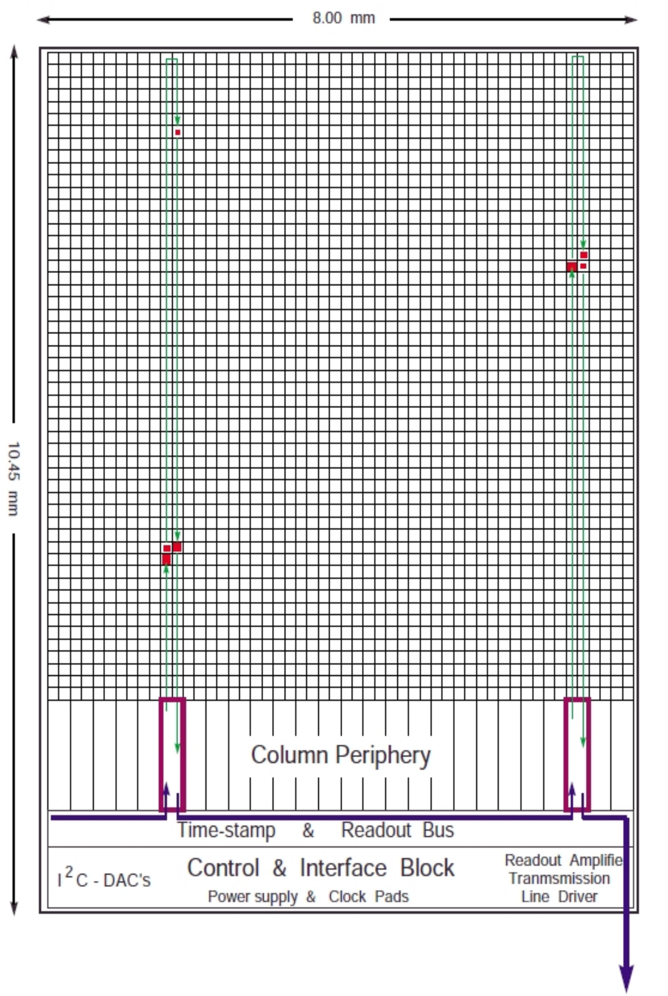




Vfd (3D-Detector) ~ 9 V


Paul Scherrer Institut
With the collaboration of Tilman Rohe

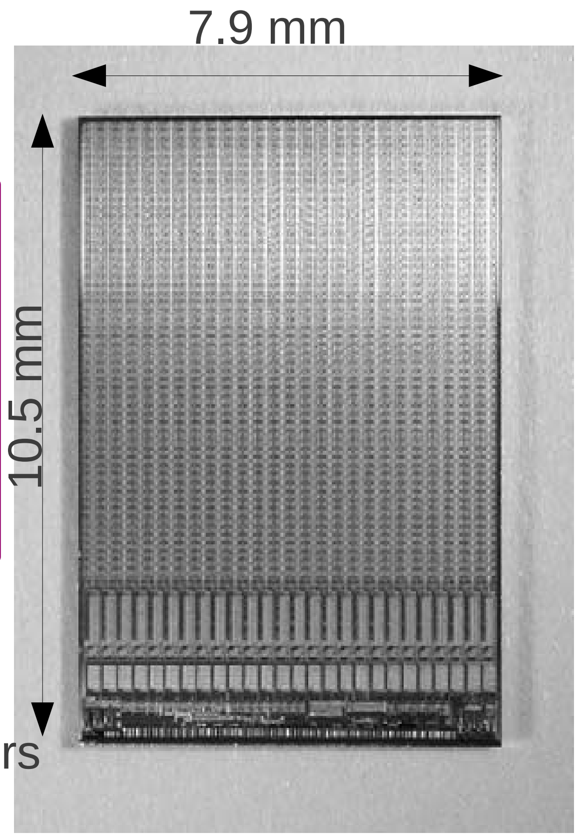
Read Out Chip (ROC) for CMS pixel detector



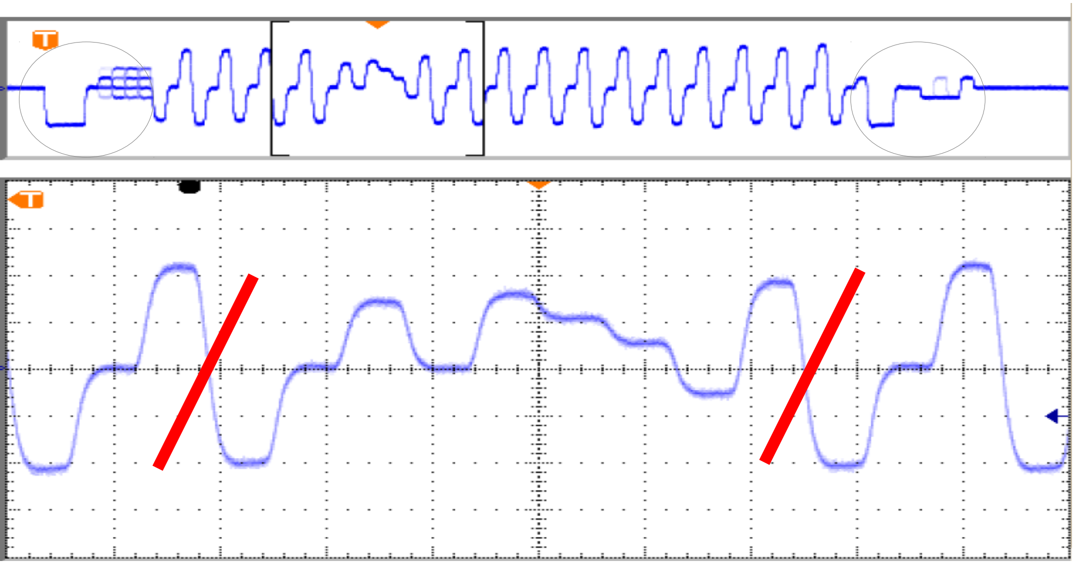
52 x 80 pixel unit cells. 4160 units
150µm x 150µm
26 double columns

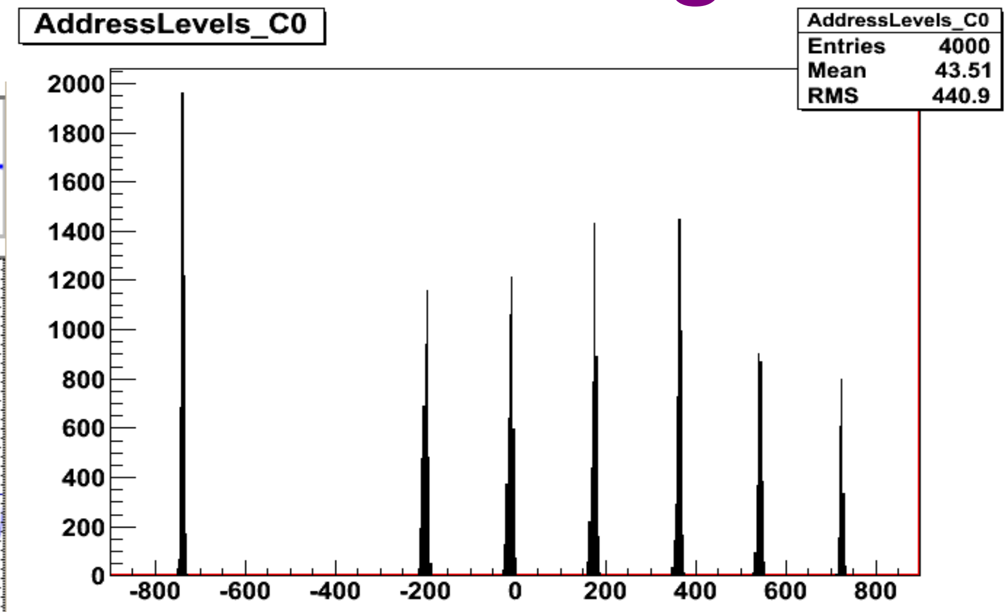
- Pixels without hits are skipped by the token
- Other double columns without hits for this Trigger are not affected and continue data acquisition

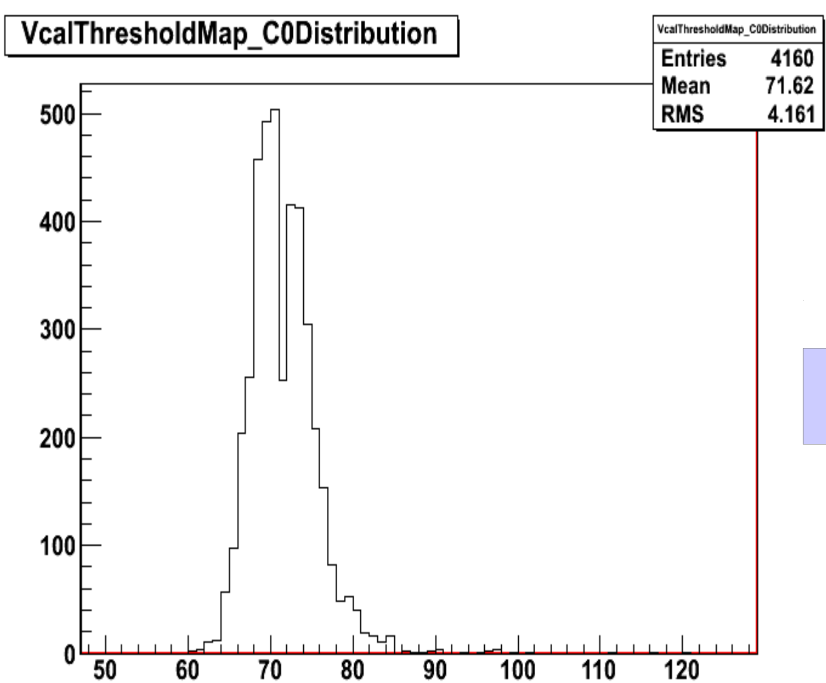
Data buffers
Time stamp buffers
Interface, DAQs and regulators



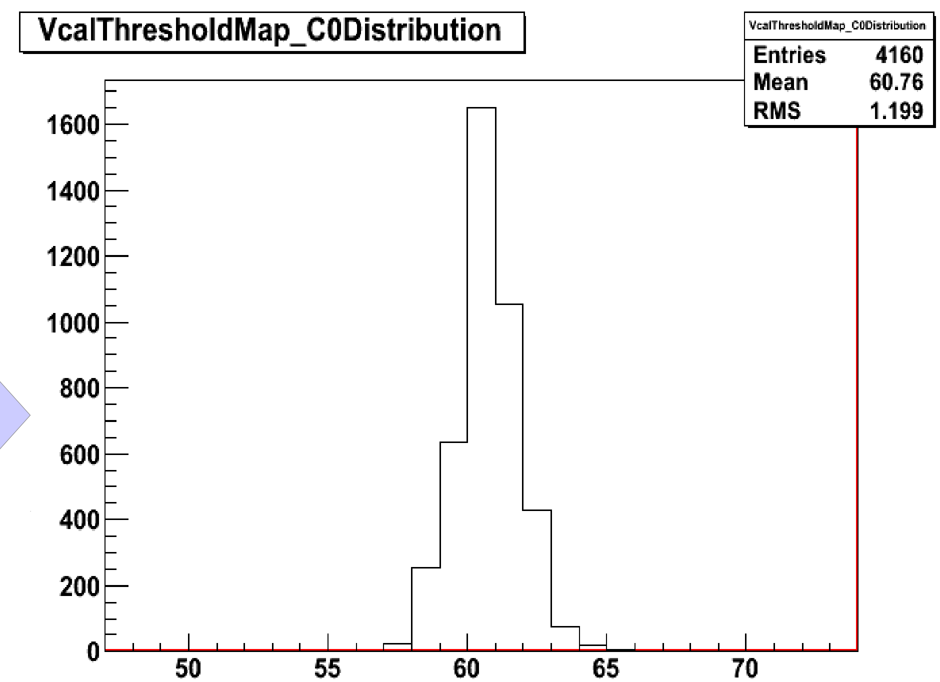
Address levels and trimming



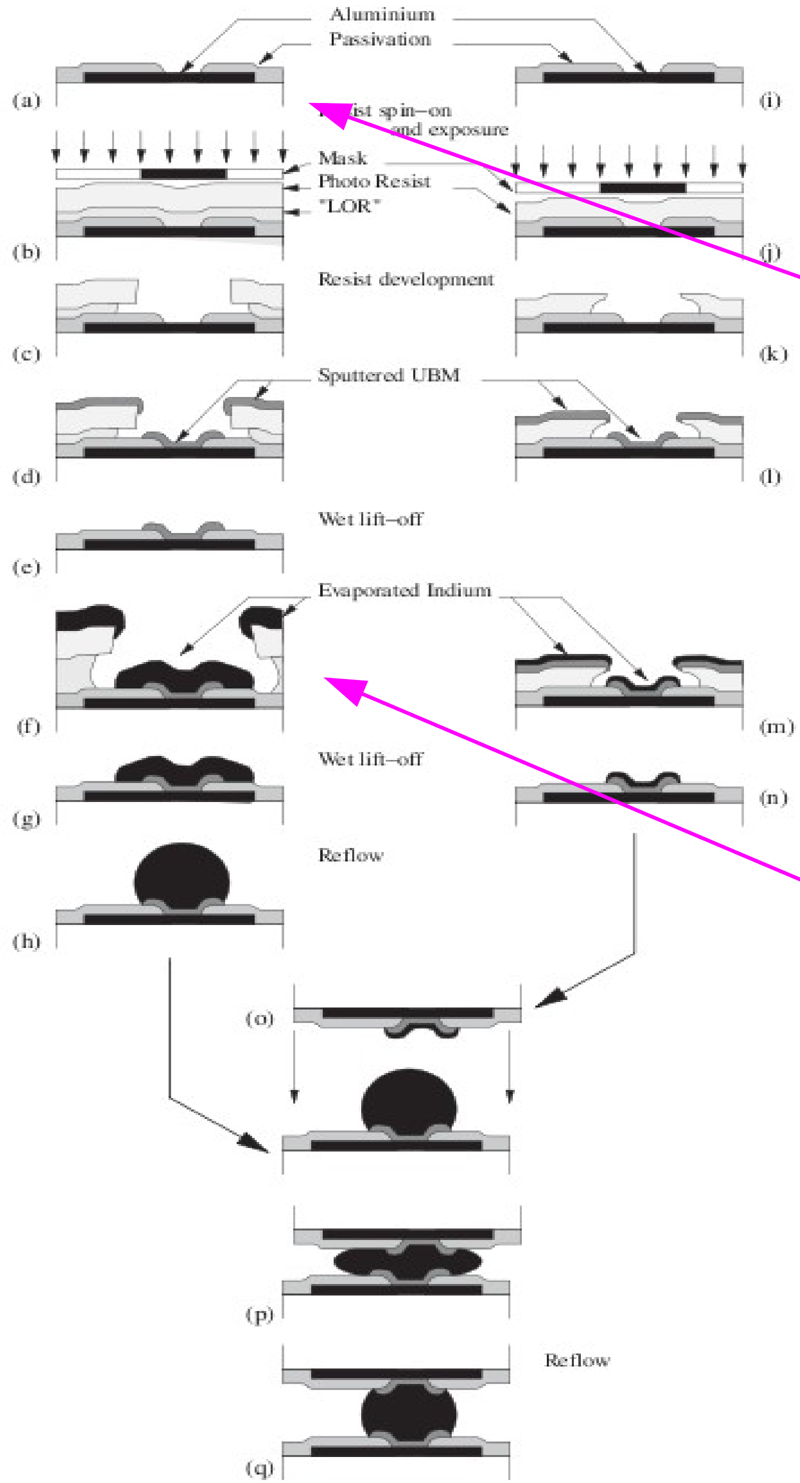


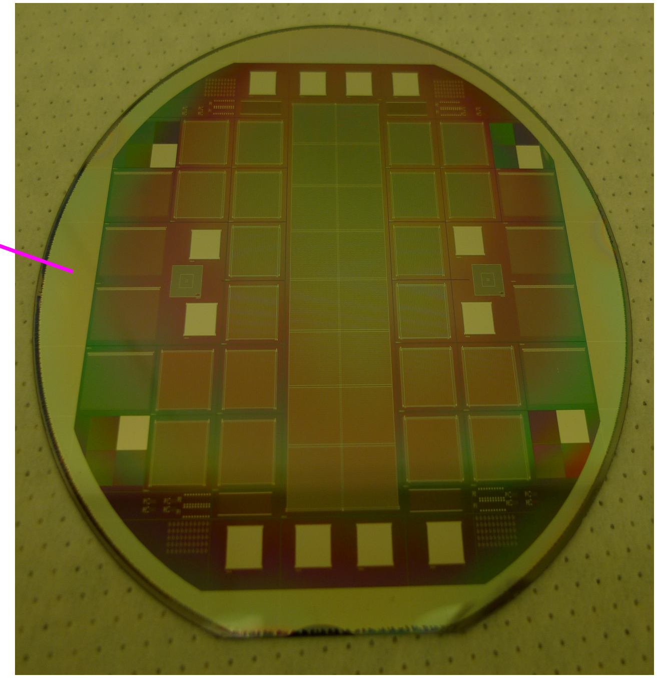


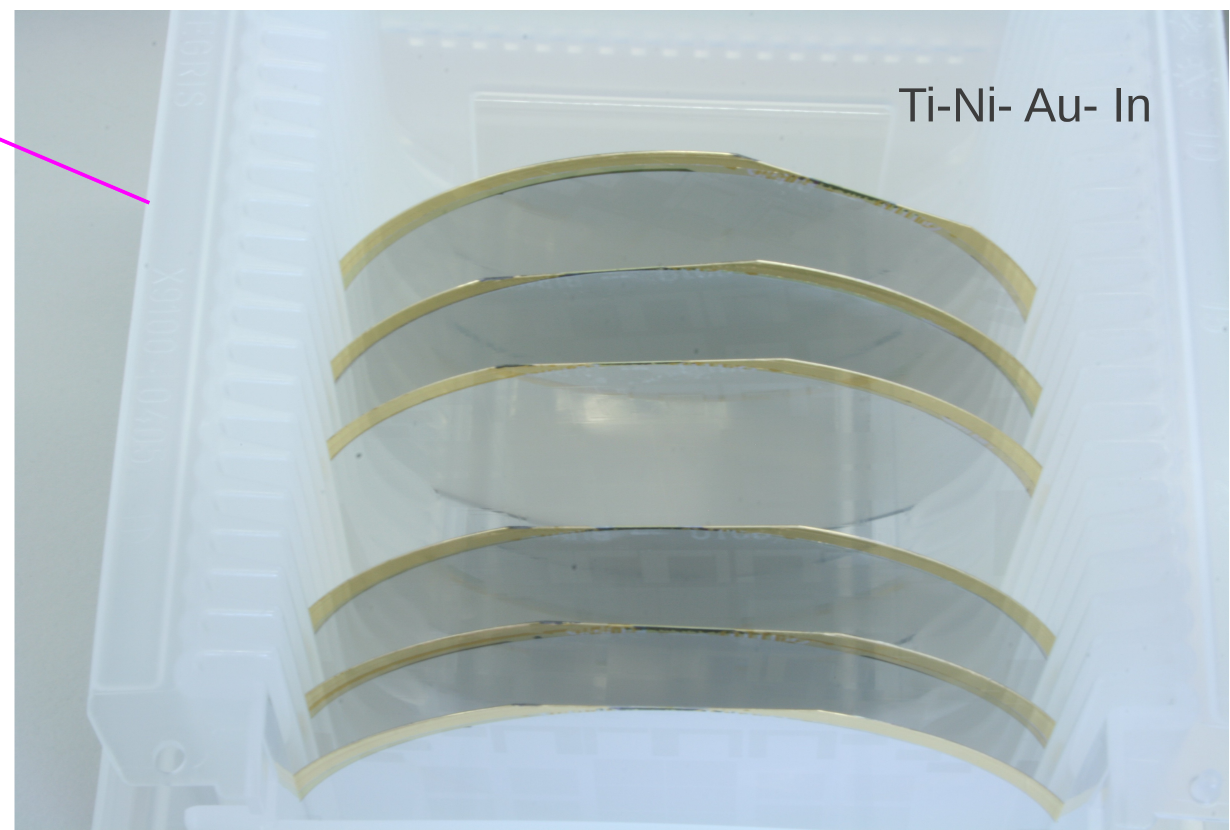
Trimming



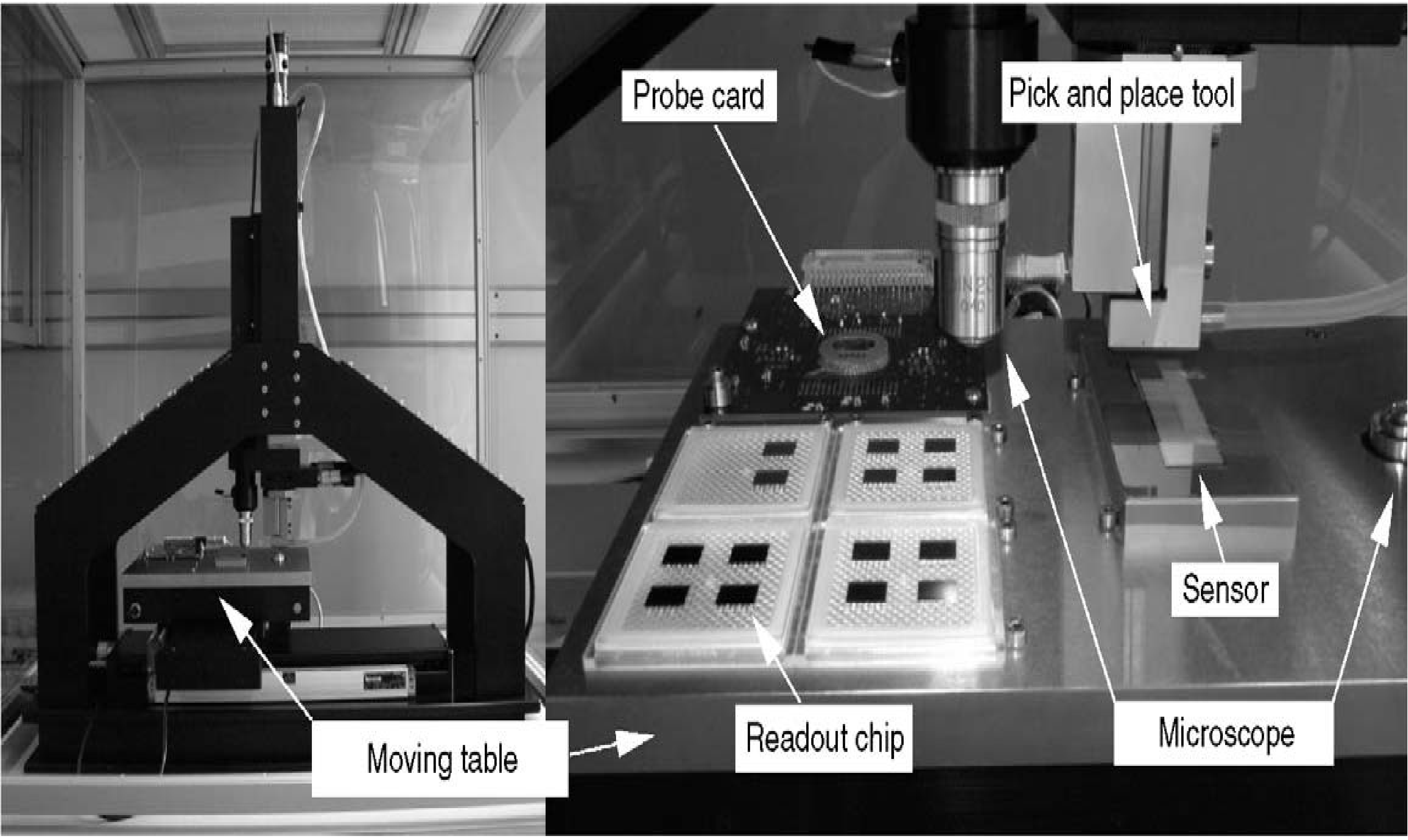
Bump bonding

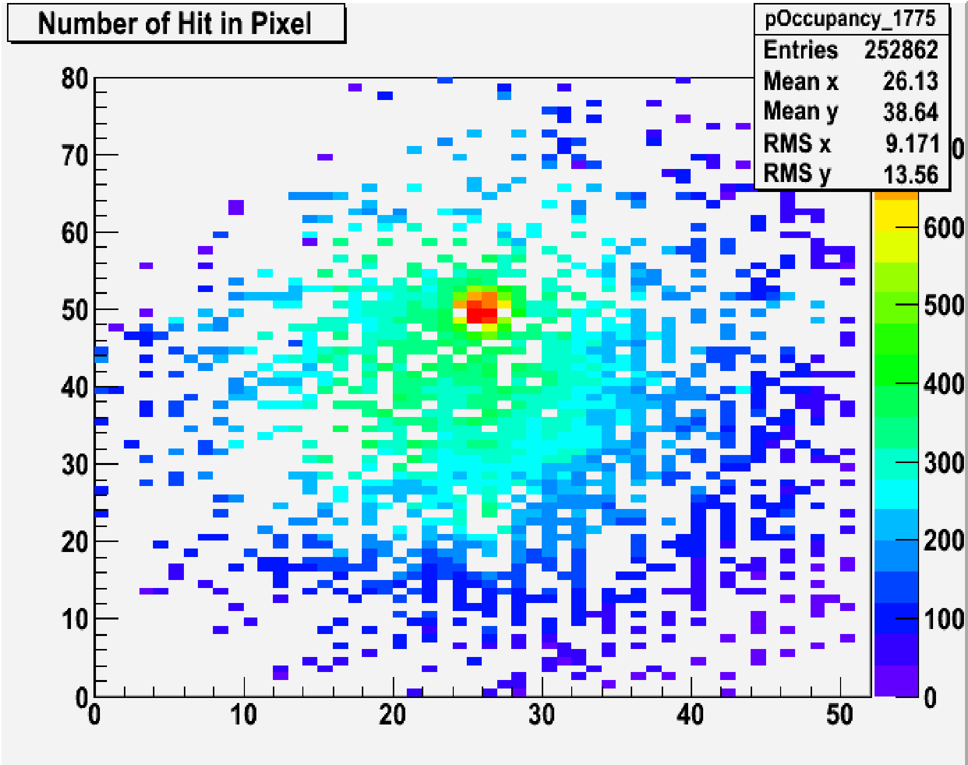






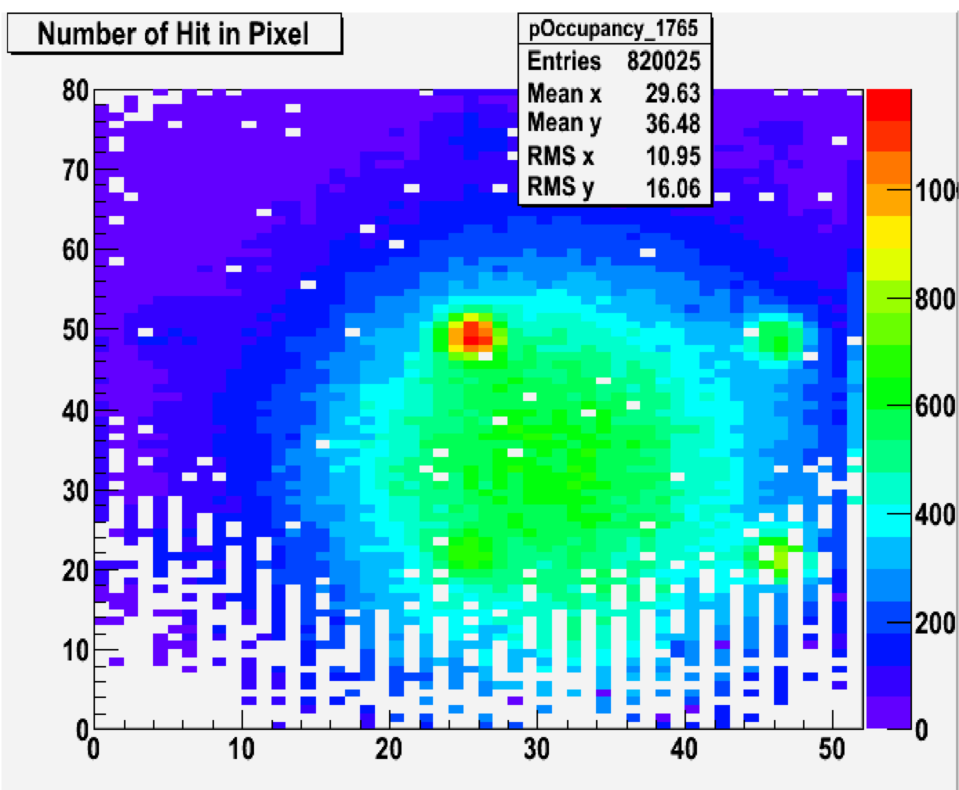
Bump bonding

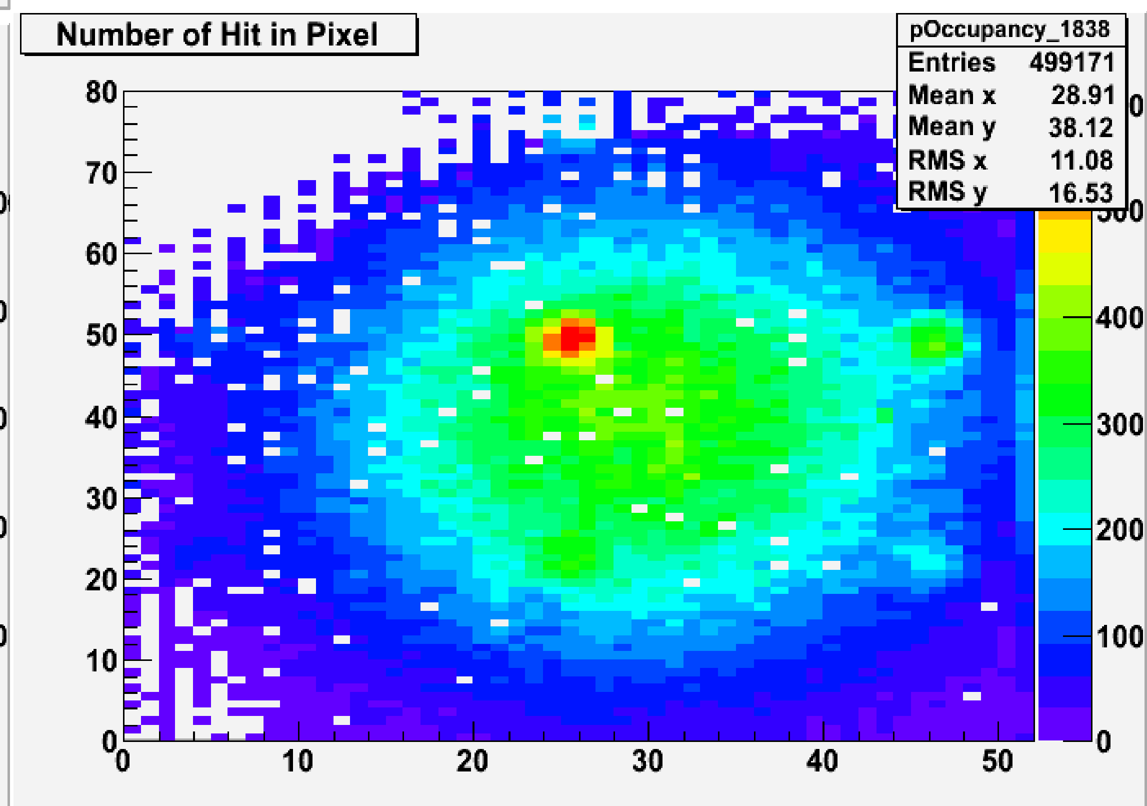




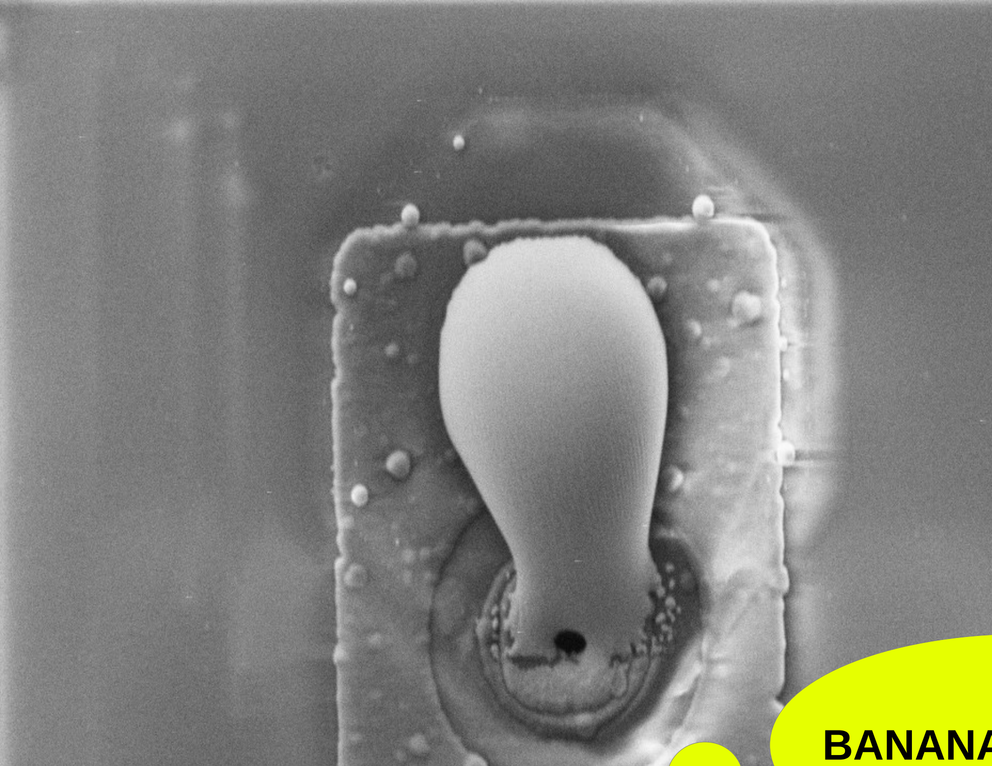
BUMP-BONDING PROBLEM!!

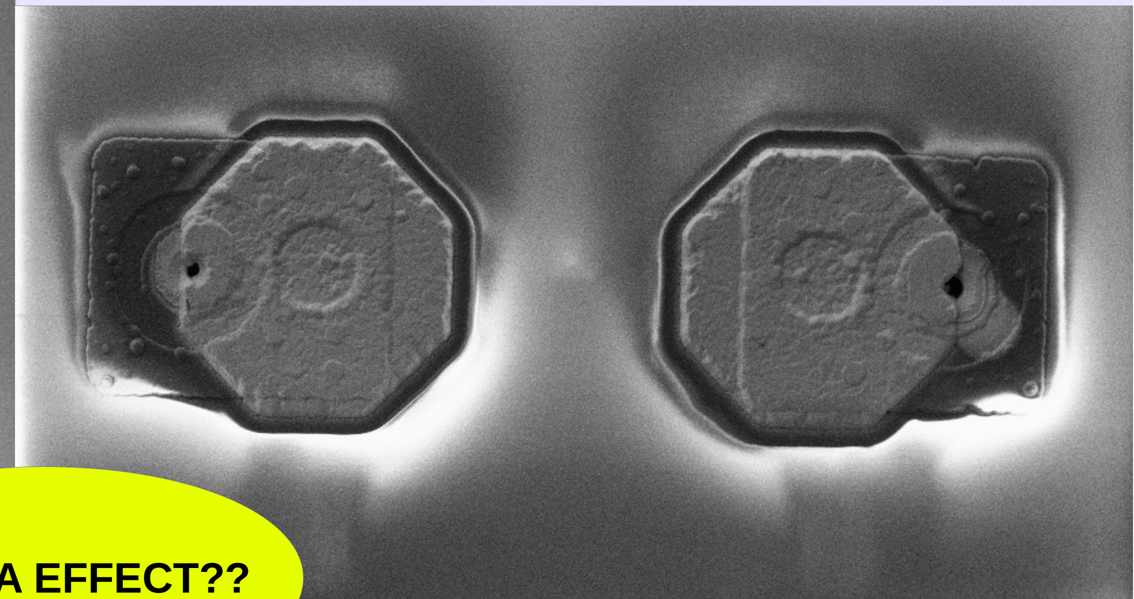
Never in planars

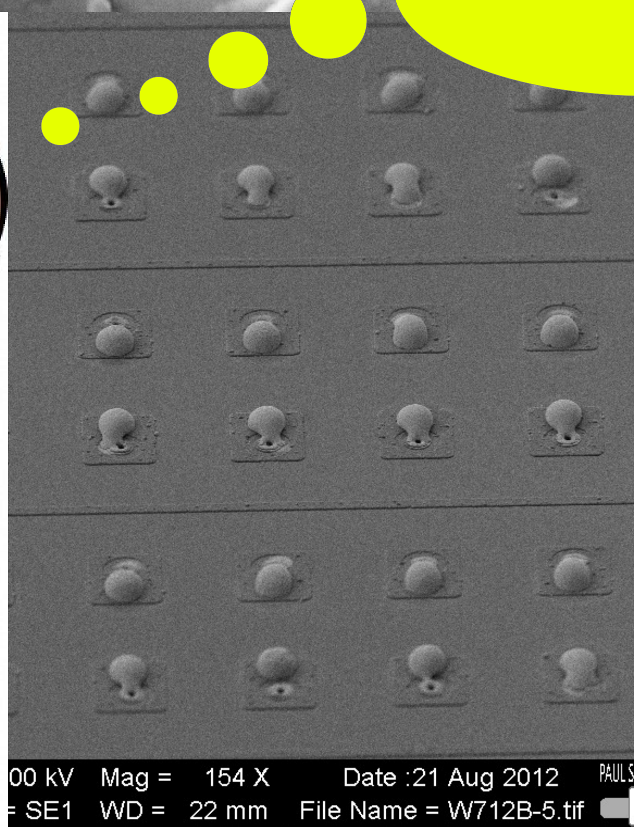


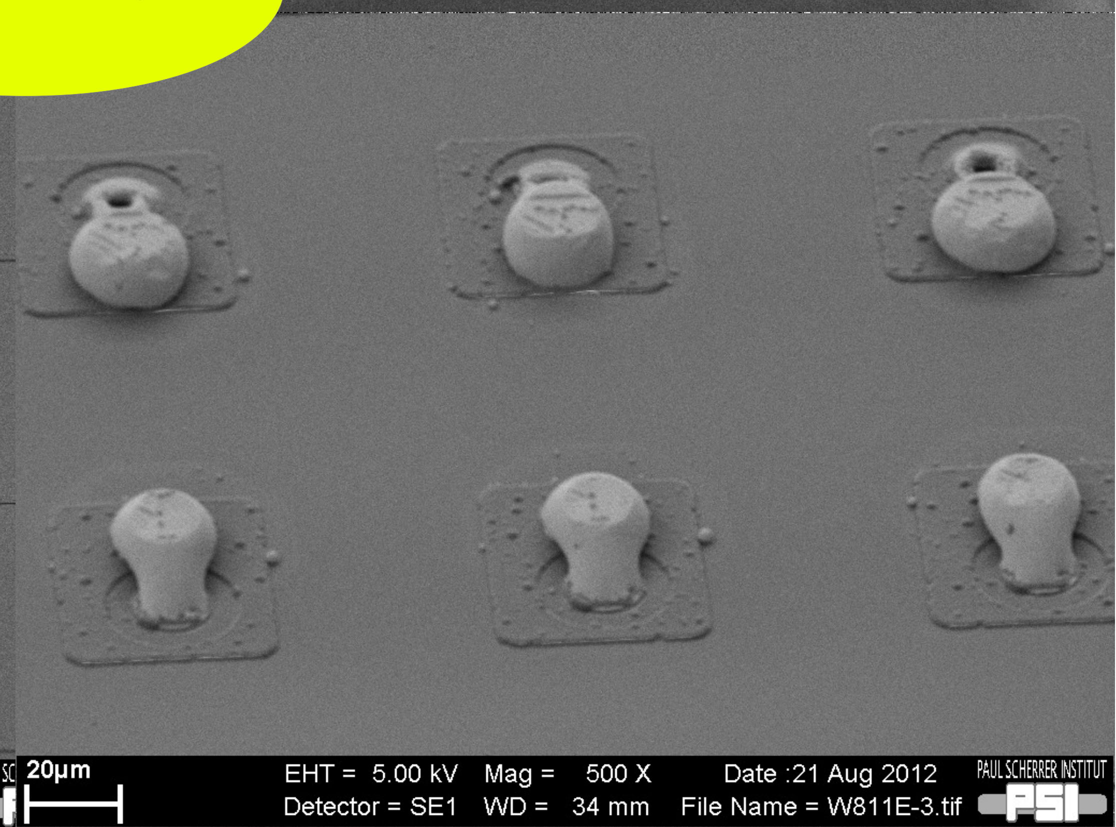


Scanning electron Microscope SEM









IT WAS NOT

BANANAS FAULT

BUT STRESS!

Problem:

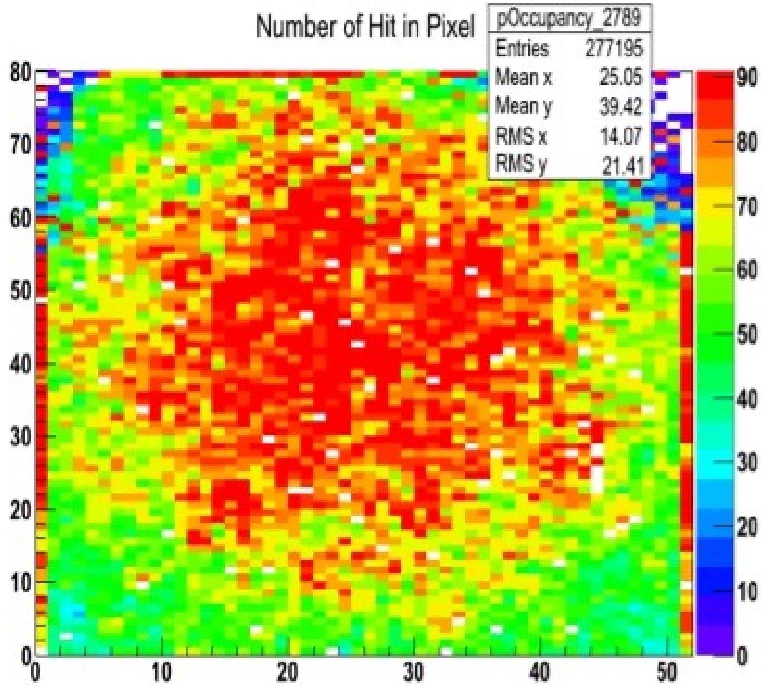
The stress during the second re-flow process, bows the sensor.

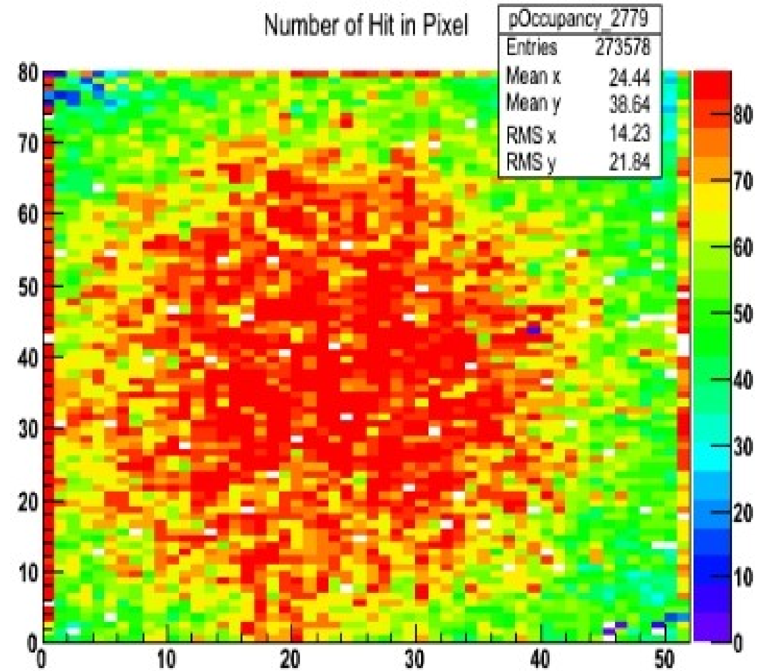
Solution:

Putting some weight on top of the sandwich during 2nd reflow.

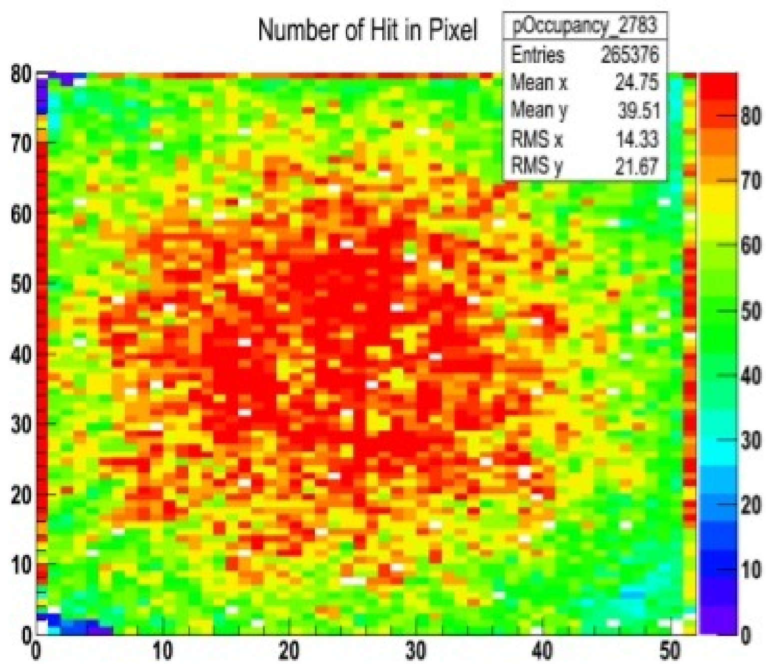
Main Reason:

There are passivation layers only in one side of the wafer.

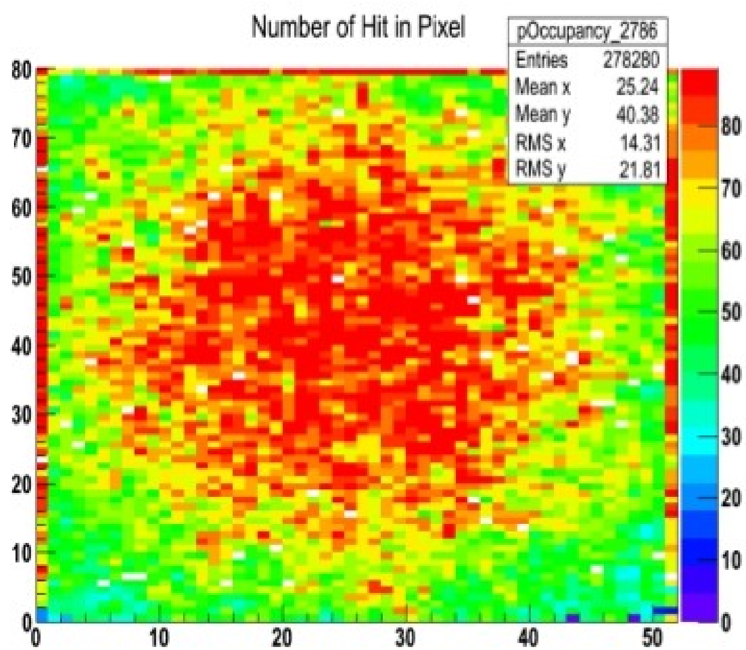




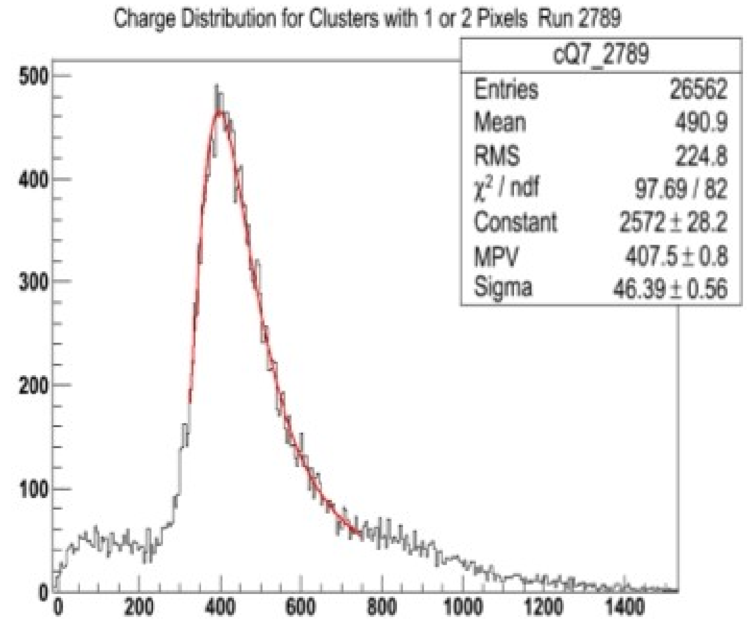
/afer 6. Pixel 21A



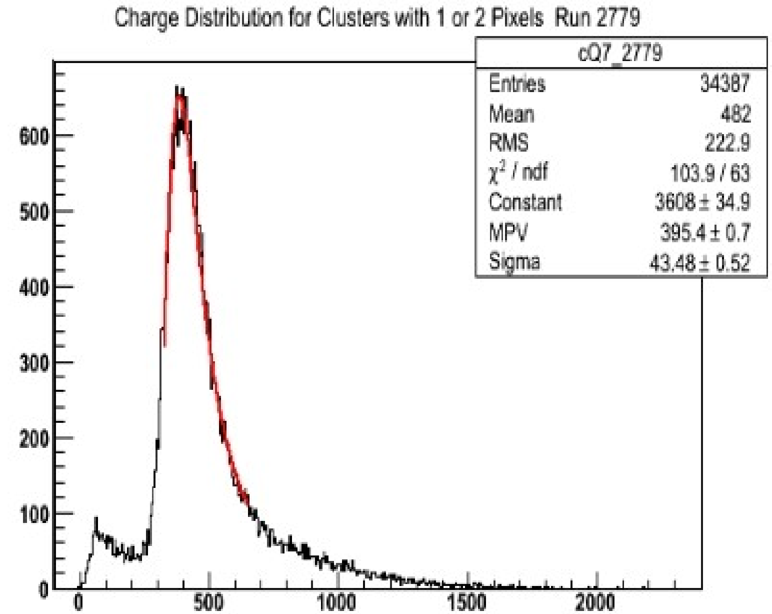
Wafer 6. Pixel 22A



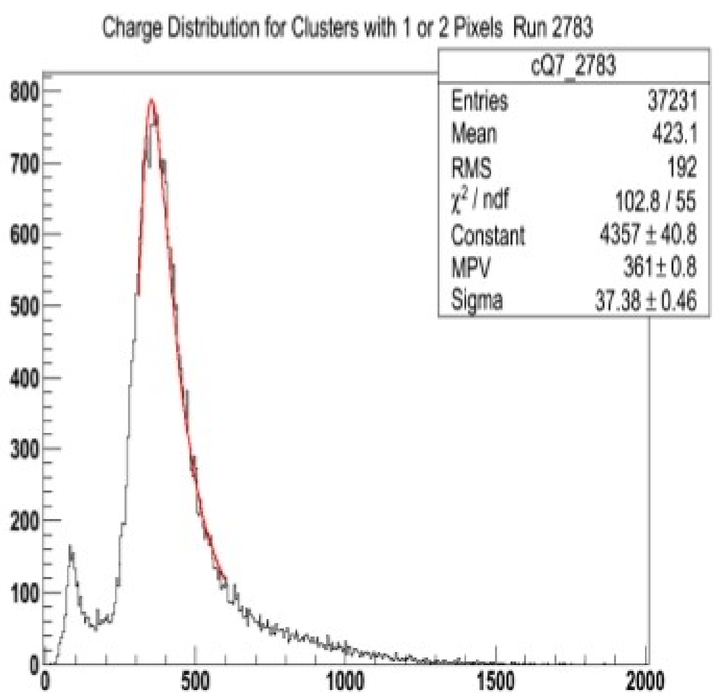
Wafer 6. Pixel 11A:



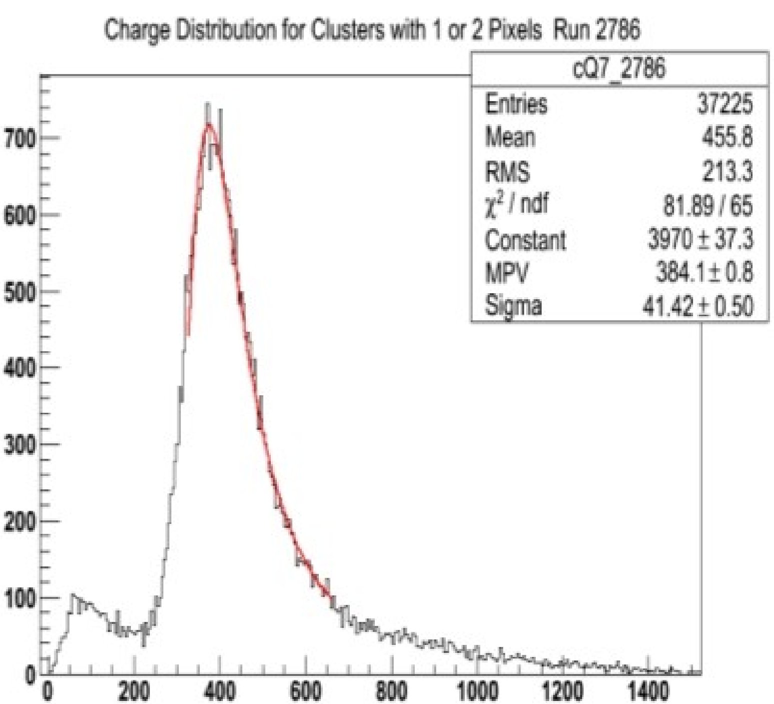
Wafer 6.Pixel 11A:



Wafer 6. Pixel 21A:



Wafer 6.Pixel 22A:

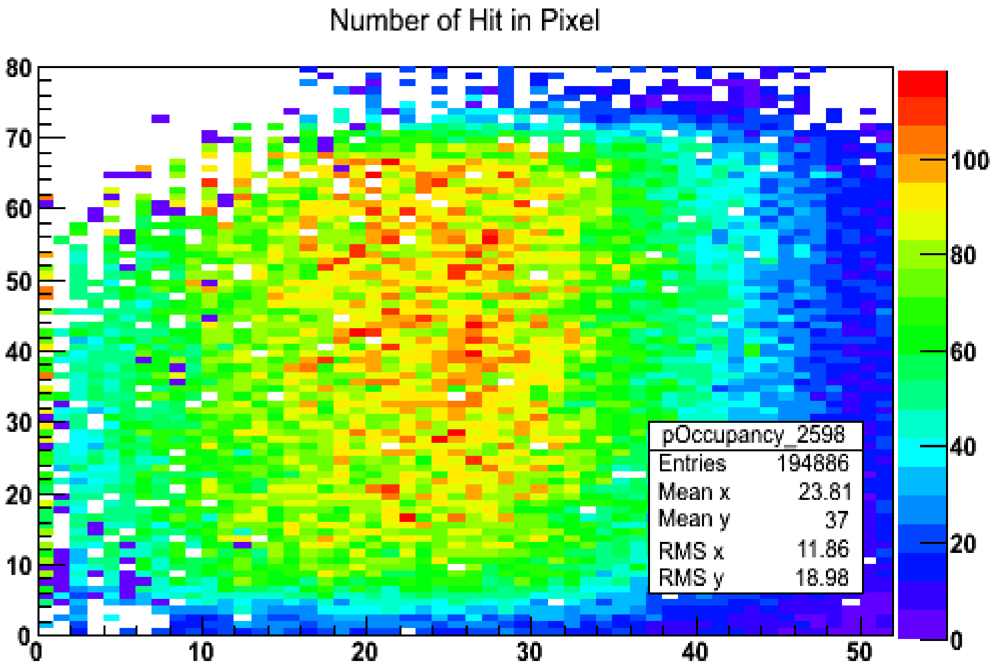


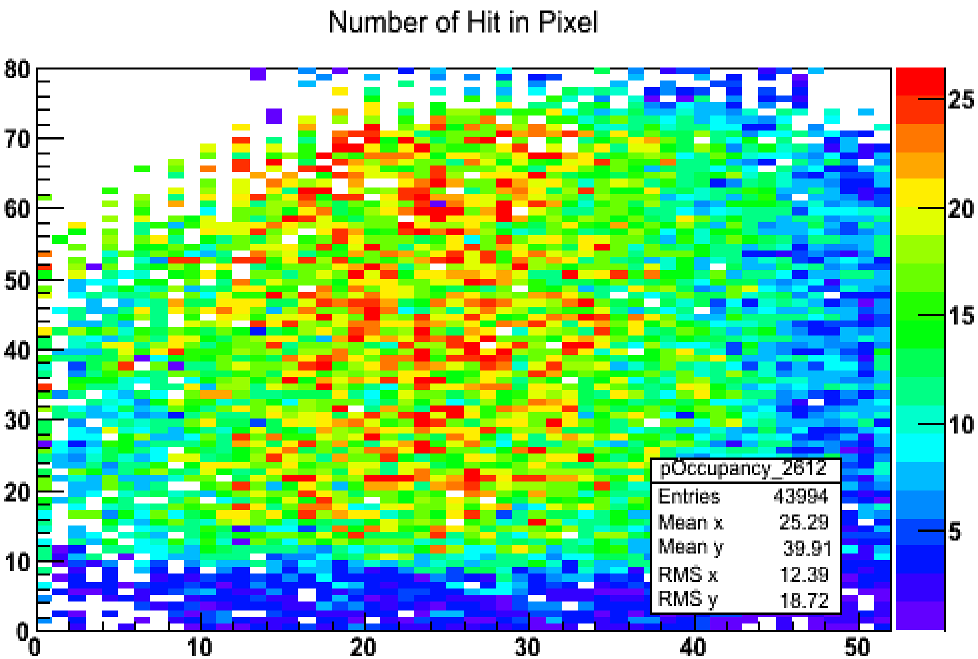
TEST BEAM @ PS Facilities
1-15 Aug. 2012

* No tracking results, very low data rate in the telescope, most of The beam time debugging the telescope

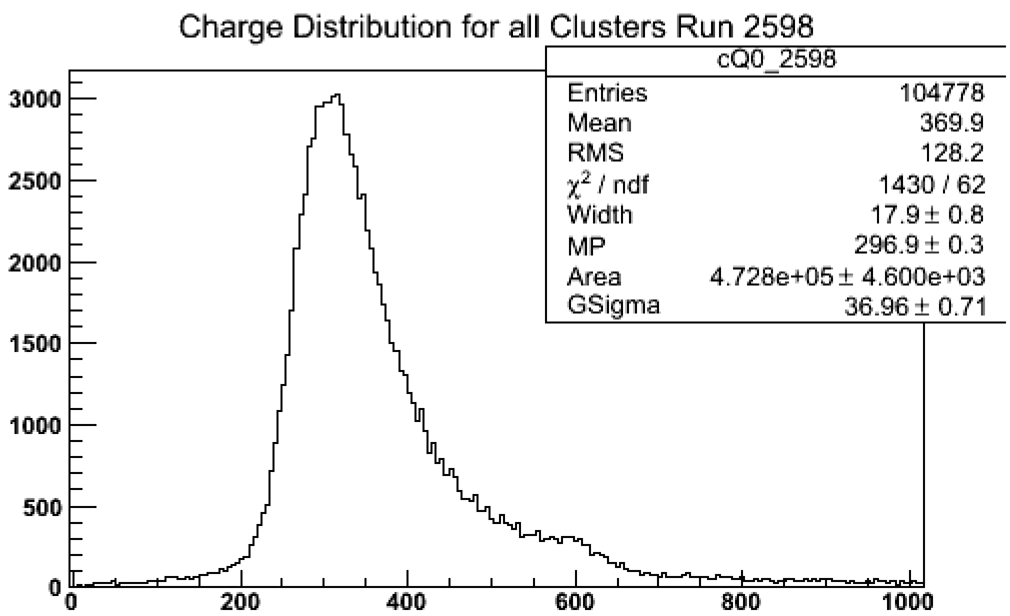
* Irradiated 3D-samples not on time

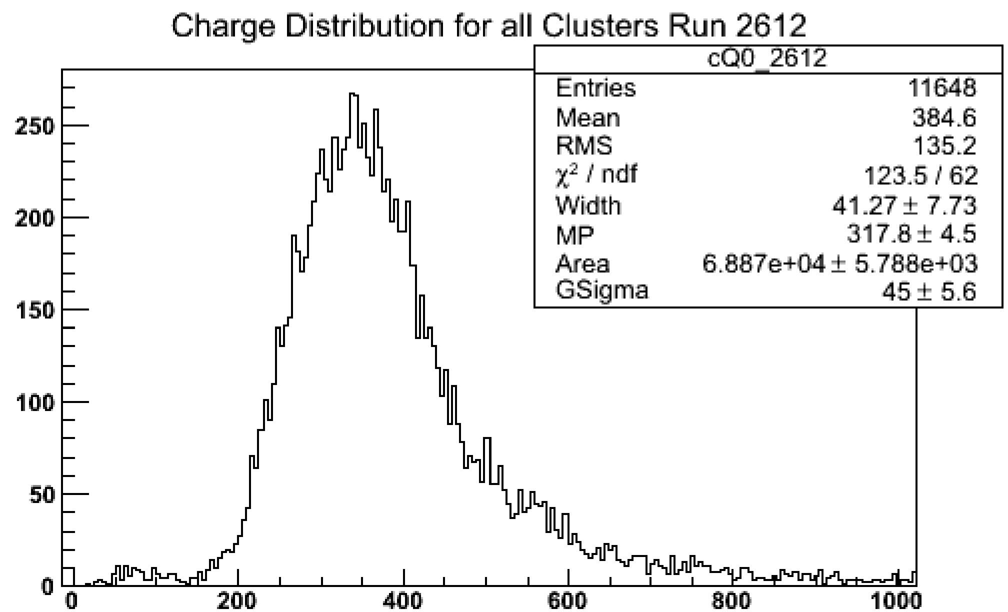
* One Unirradiated 3D sample in 2 different angles





SENSOR 12B: $296.9 = 317.8 * \cos(\alpha) \rightarrow \alpha = 21^{o}$





Irradiation Campaign:

- Karlsruhe fluences: 1×10^{15}, 5×10^{15} n_{eq}/cm^2
- Ljubljana fluences: 1×10^{15}, 5×10^{15}, 1×10^{16} n_{eq}/cm^2

To SPS Test-beam on 18th November 2012

* Karlsruhe and Ljubljana:
  Irradiated samples up to 1×10^{15} n_{eq}/cm^2

*Ljubljana:
  Irradiated samples up to 1×10^{16} n_{eq}/cm^2

TEST BEAM @ SPS Facilities
18-30 Nov. 2012

* Our Program:
    - Testing both patterns:
        Unirradiated
        Irradiated
            - Neutrons: 10^{15} neq/cm²
            - Protons: 10^{15} neq/cm²
            - Neutrons: 10^{16} neq/cm²

⊕ PSI & ETH Program for the TDR
⊕ KIT Program for the HPK Campaign

In a Parasitic Mode!!

TEST BEAM @ SPS Facilities
18-30 Nov. 2012

Effective beam time:

Less than 70 h:

2 days: TDR Campaign sample ---> PSI, ETH
1 day : 3D sample ---> PSI,CNM,IFCA
1 day: HPK campaign sample ---> KIT

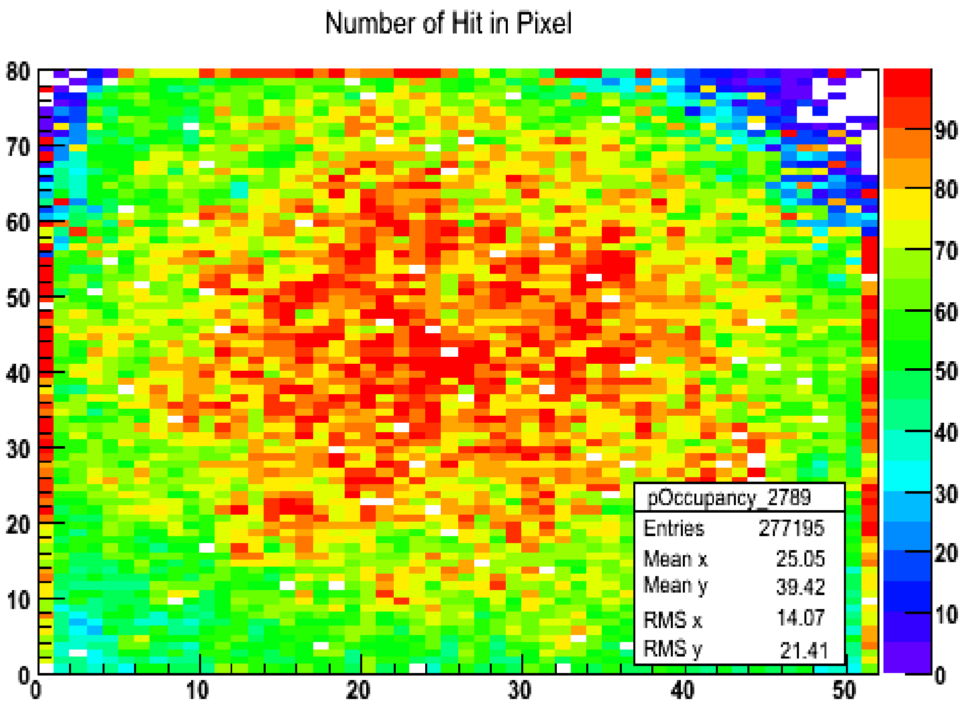
3D sample:

Dose: 10^{15}neq/cm^2 (protons KIT)
Quick voltage rump
Long run @ 100 V

TEST BEAM @ SPS Facilities
18-30 Nov. 2012

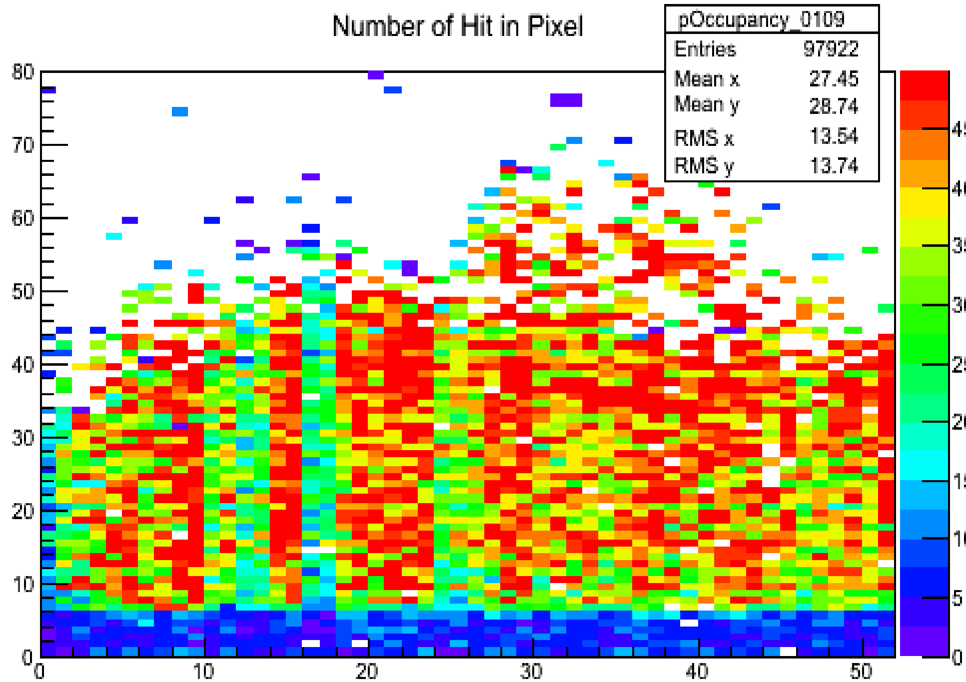
Occupancy map before irradiation in

PSI laboratory



Occupancy map after irradiation in

SPS Test Beam



FUTURE WORK:

- Check the bump bonding yield in all sensors
- Studies on the ROC performance after high irradiation doses

- Reproduction of IBL-ATLAS 3D pixels for irradiated Sensors
- Measurements of Vfd and CCE in irradiated pixels up to **$1x10^{16}$**
- Capacitance meas. In the two different patterns

- Transient Current Technique in 3D strips detectors ?

Conclusions

- Sensors work
- Important technical problem. We need enough area with a good bumps to test them properly

- We have several samples to be characterized, irradiated up to 10^{16} neq/cm²
  - ^{90}Sr Source
  - Capacitance meas

Thank you for your attention!

Backup

Depletion Area in 3D-Pixels

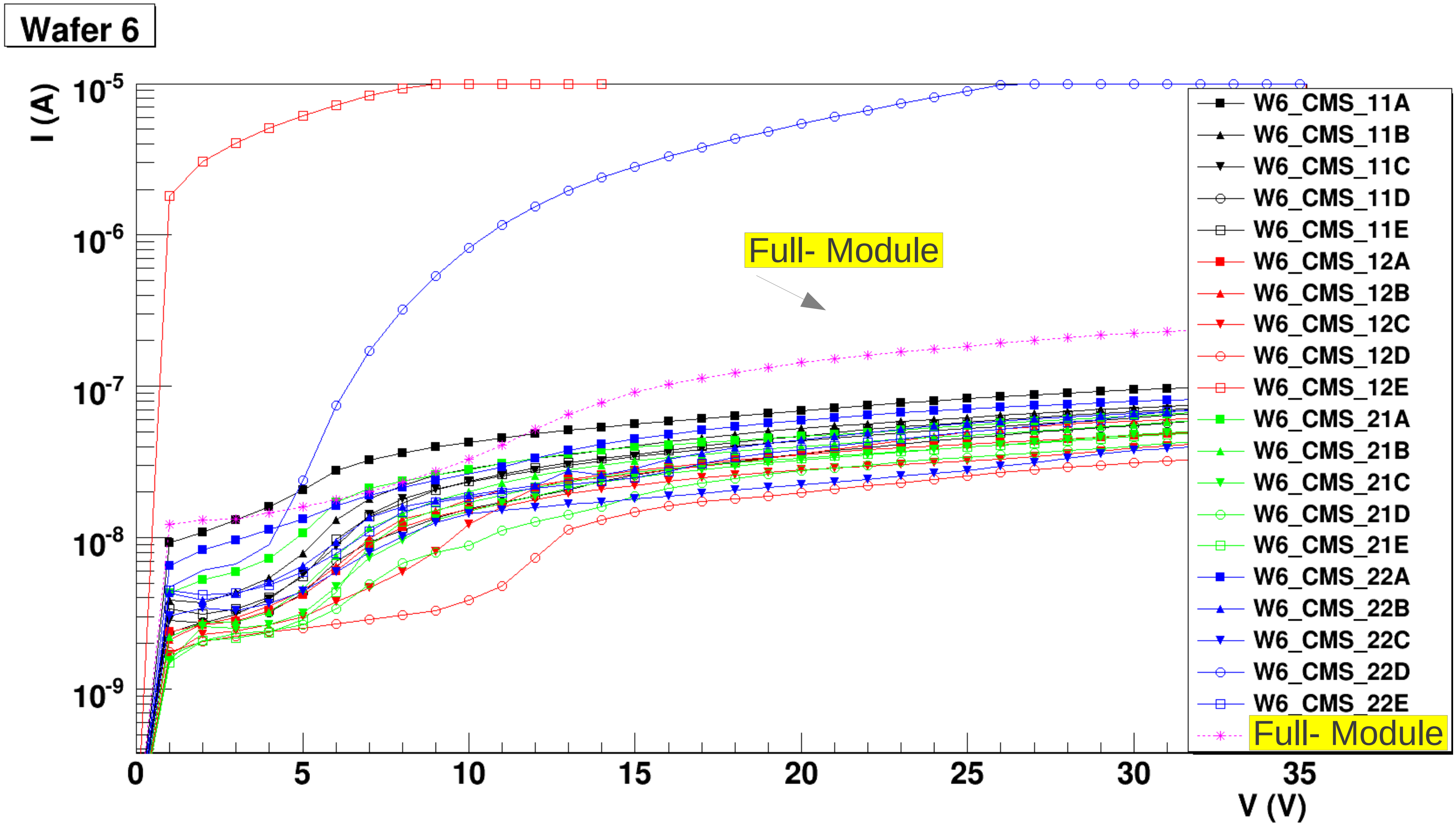
- Coaxial Symmetry
- r1 is the electrode radius
- r2 is the distance between columns
- The depletion voltage is the minimum voltage at which the bulk of the sensor is fully depleted

$$V_{fd} = \frac{1}{2}\frac{Nq}{\varepsilon}\left[r_1^2 Ln\left(\frac{r_2}{r_1}\right) - \frac{1}{2}\left(r_2^2 - r_1^2\right)\right]$$

V_{fd} (coax) = 0.9 · V_{fd} (planar)

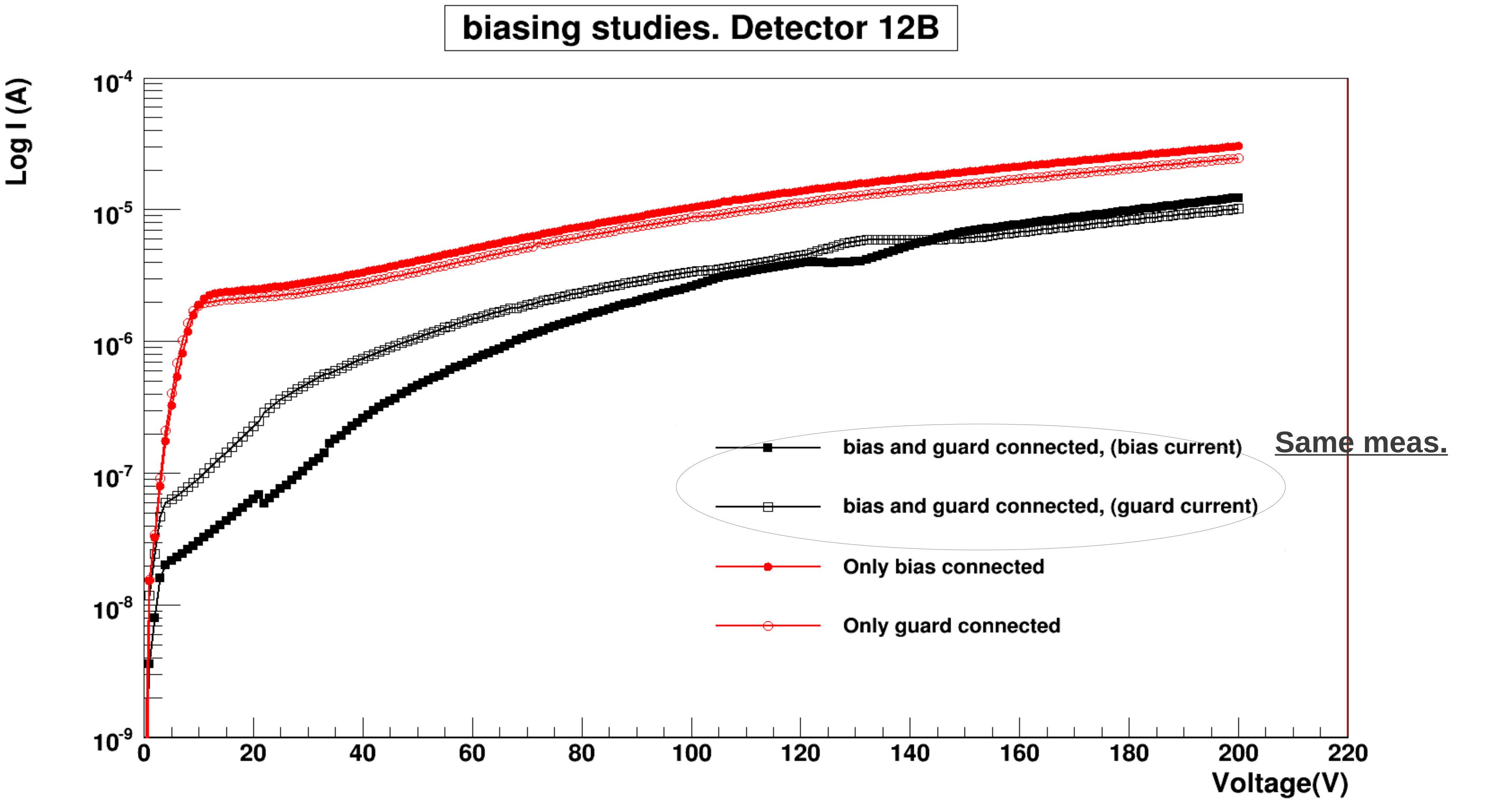
Electrical Characterization. IV Curves

* Homogeneous behavior and acceptable current values

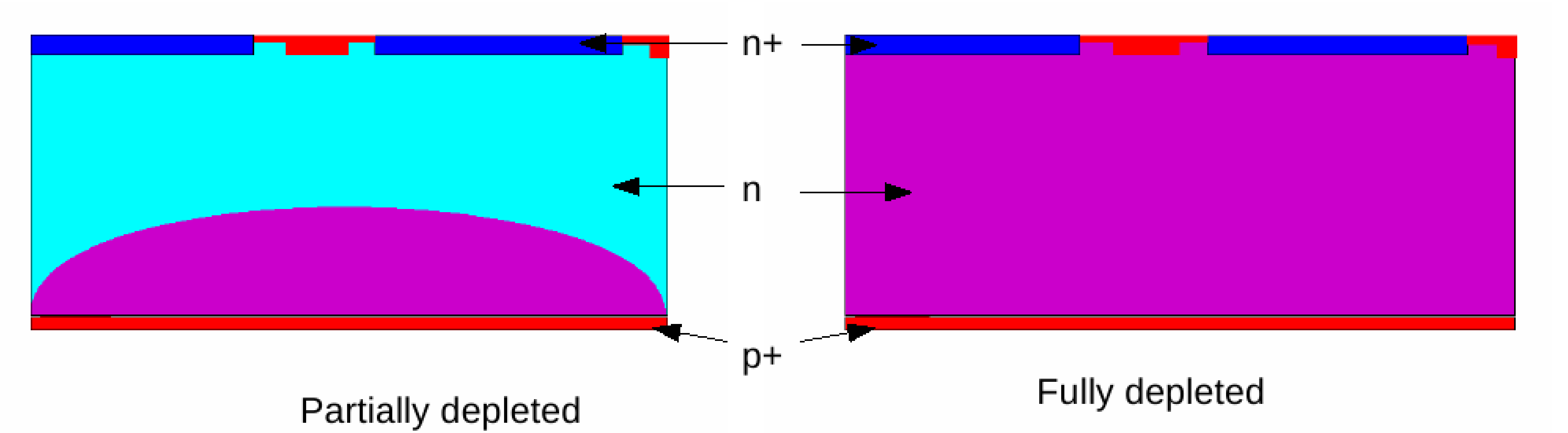


Biasing studies. Wafer 3

Only guard connected → "punch through" polarization
Only bias connected → pixel by pixel polarization

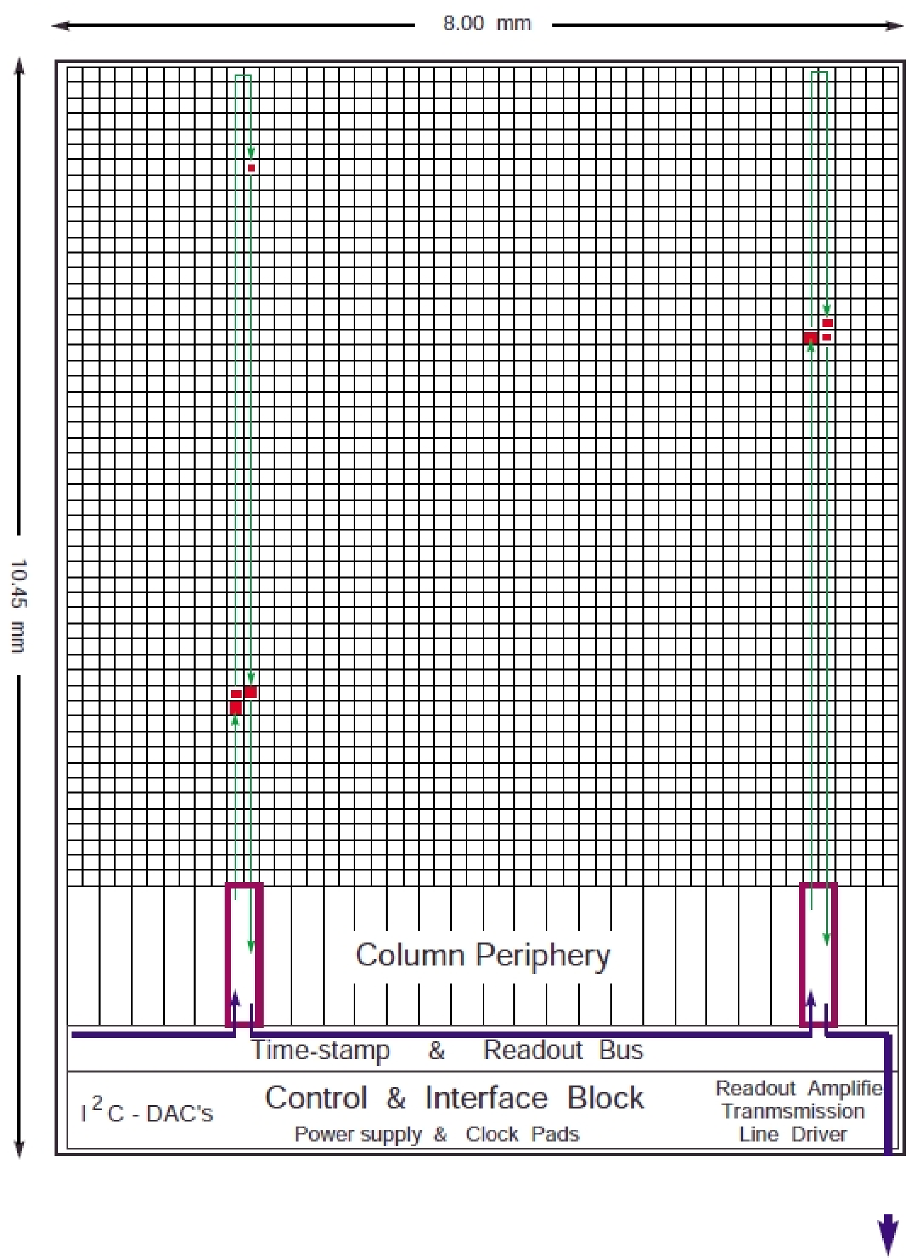


Silicon detectors in HEP



- In CMS pixels (n+ on n), the pn junction is on the bottom, so the depletion region forms from the bottom up
- No signal until full depletion
- Diffusion across the junction is suppressed. Current across the junction is very small "leakage current"!

Readout Chip



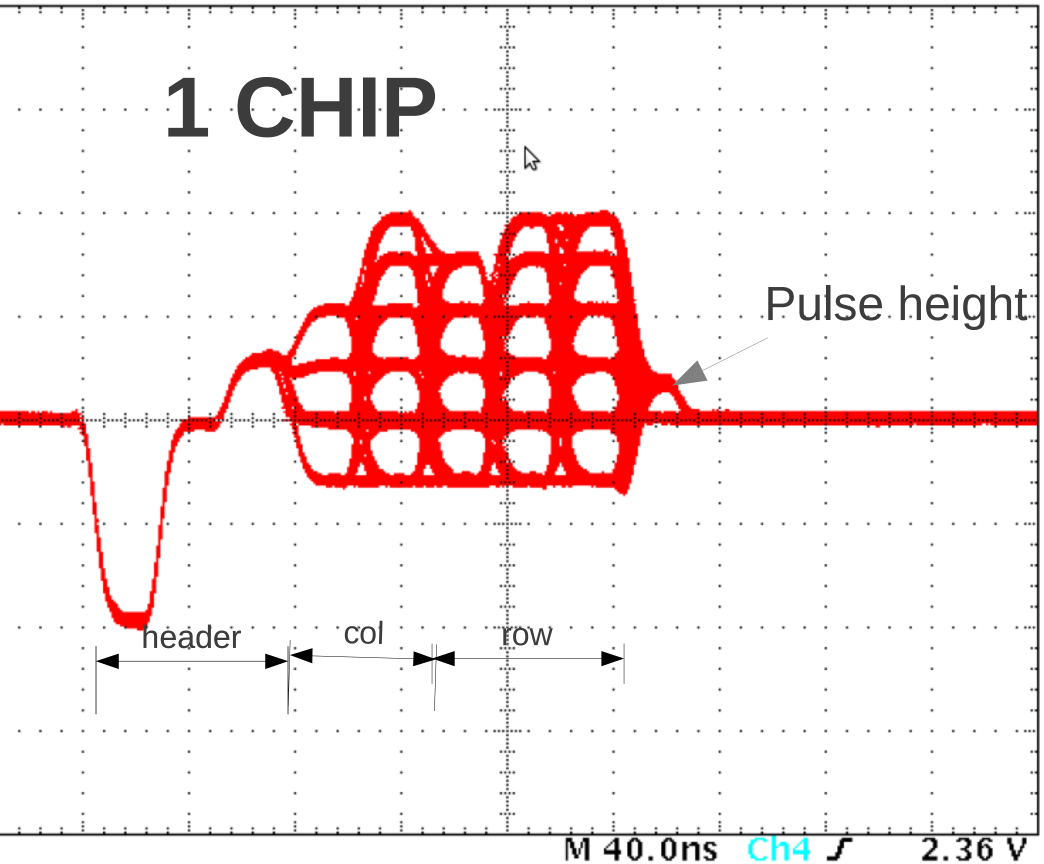
- Paths of column token through double-column (green)
- Paths of the readout Token through the double- column peripheries

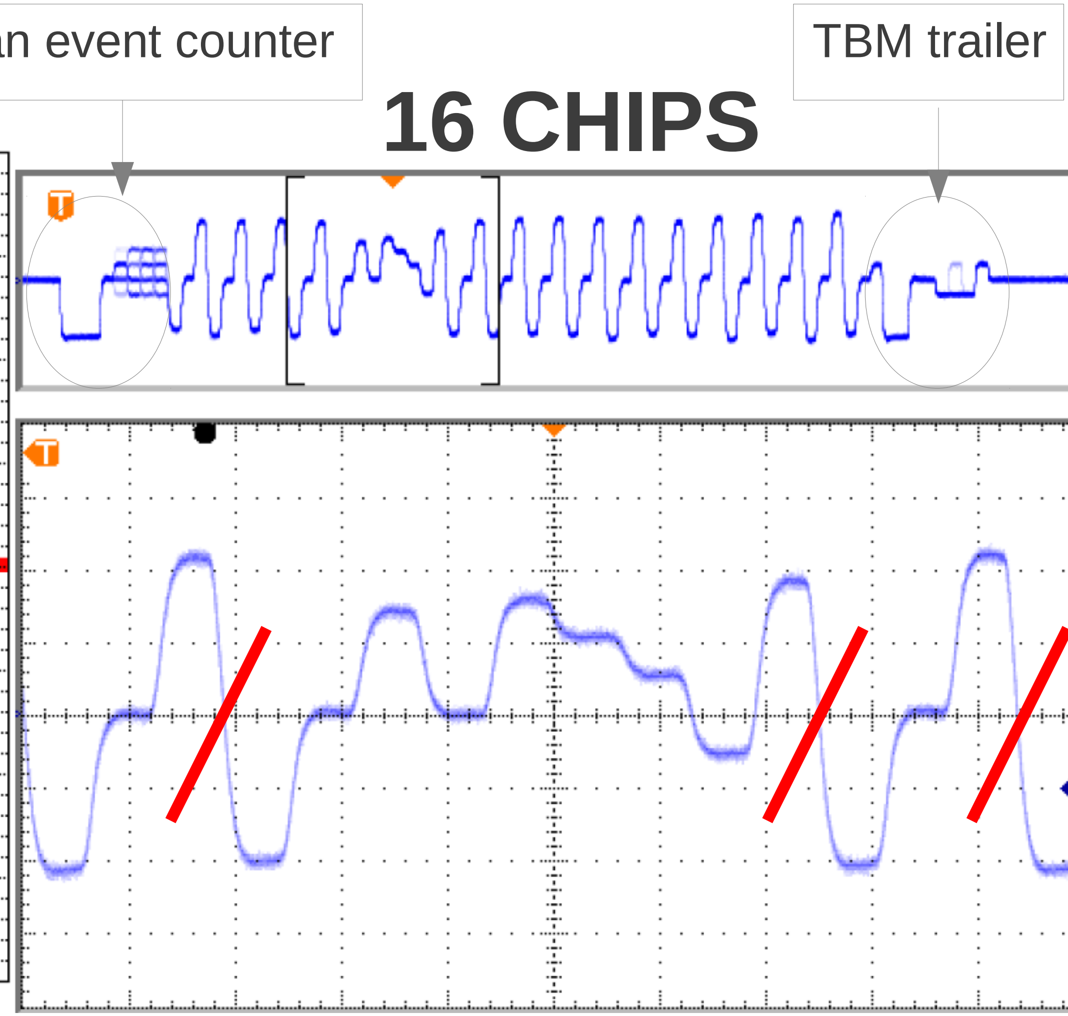
- When the column token stops at a pixel with hits. All hit information (pulse height, address...) is transferred To the column periphery where it is Stored in data buffer

- Pixels without hits are skipped by the token

- Other double columns without hits for this Trigger are not affected and continue data acquisition

Readout format





TOKEN-BIT-MANAGER

Chip 1,2,3,4--> no data
Chip 5--> 1 data
Chip 6--> no data
...

ROC QUALIFICATION

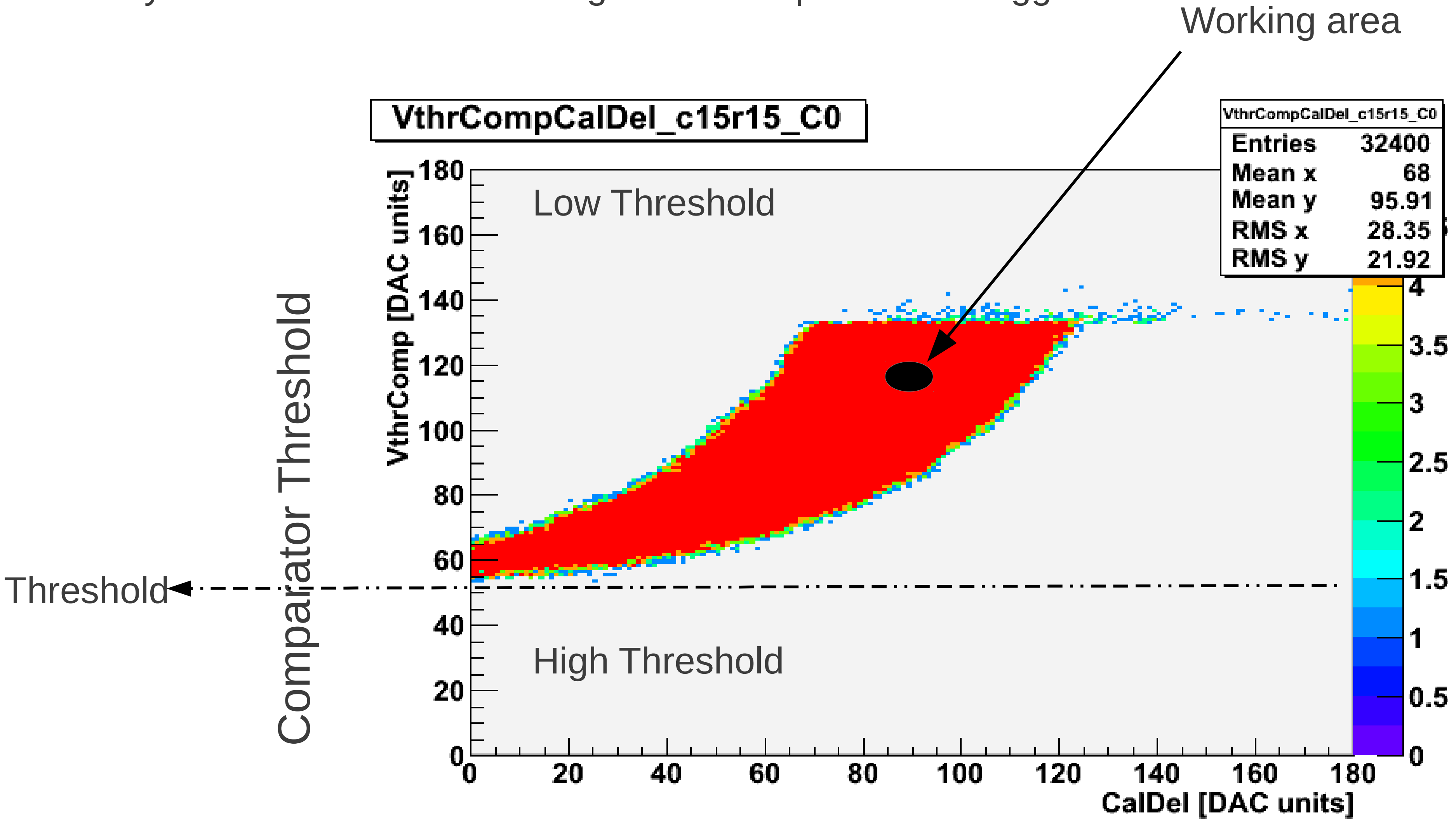
- **Calibrate Signal inputs**
  - Vcal
  - Vana
  - Vthrc
  - CalDel
- **Pixel readout circuits**
  - Pixel
  - Trim bit
  - Bump-Bonding
  - Pixel Address

- **Functionality of the module**
  - Noise
  - Trimming
  - Gain and Pedestal
  - IV
  - Thermal Cycle

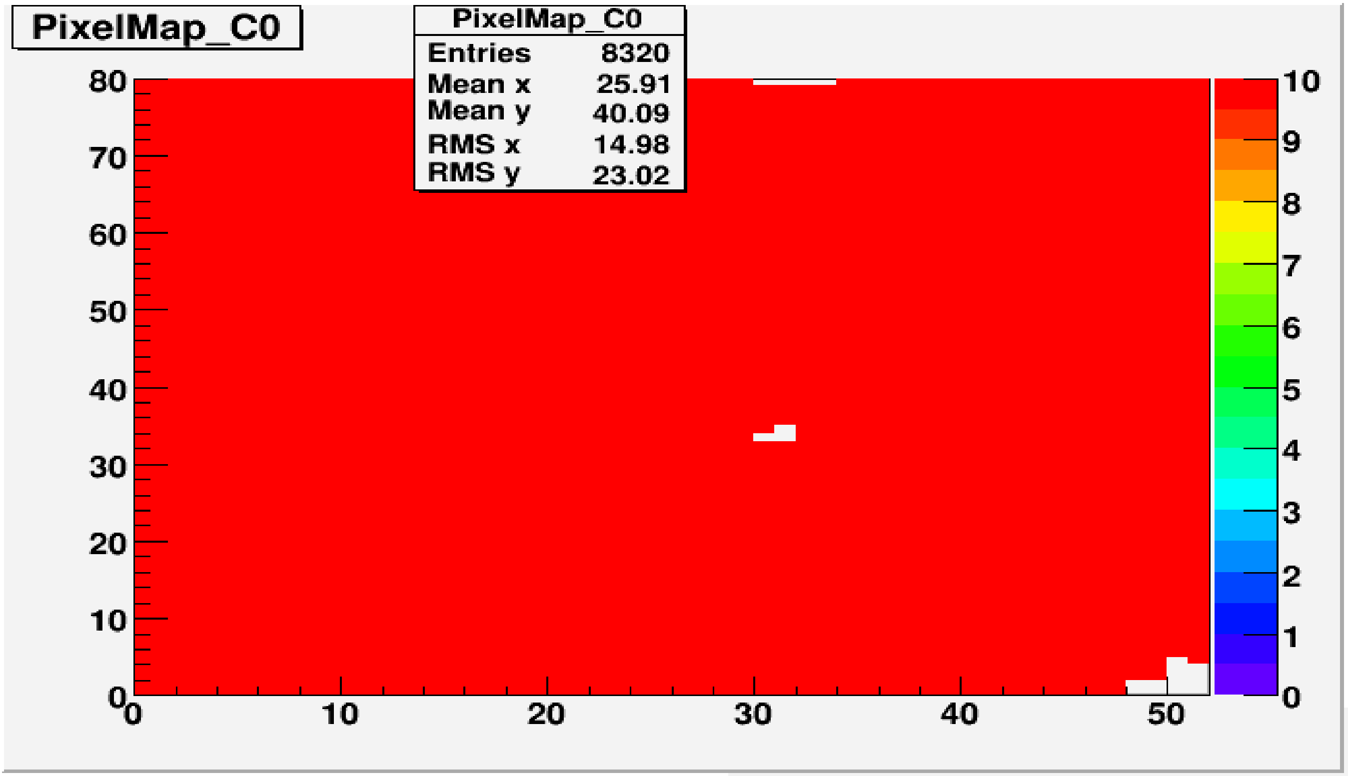
VthrComp vs CalDel

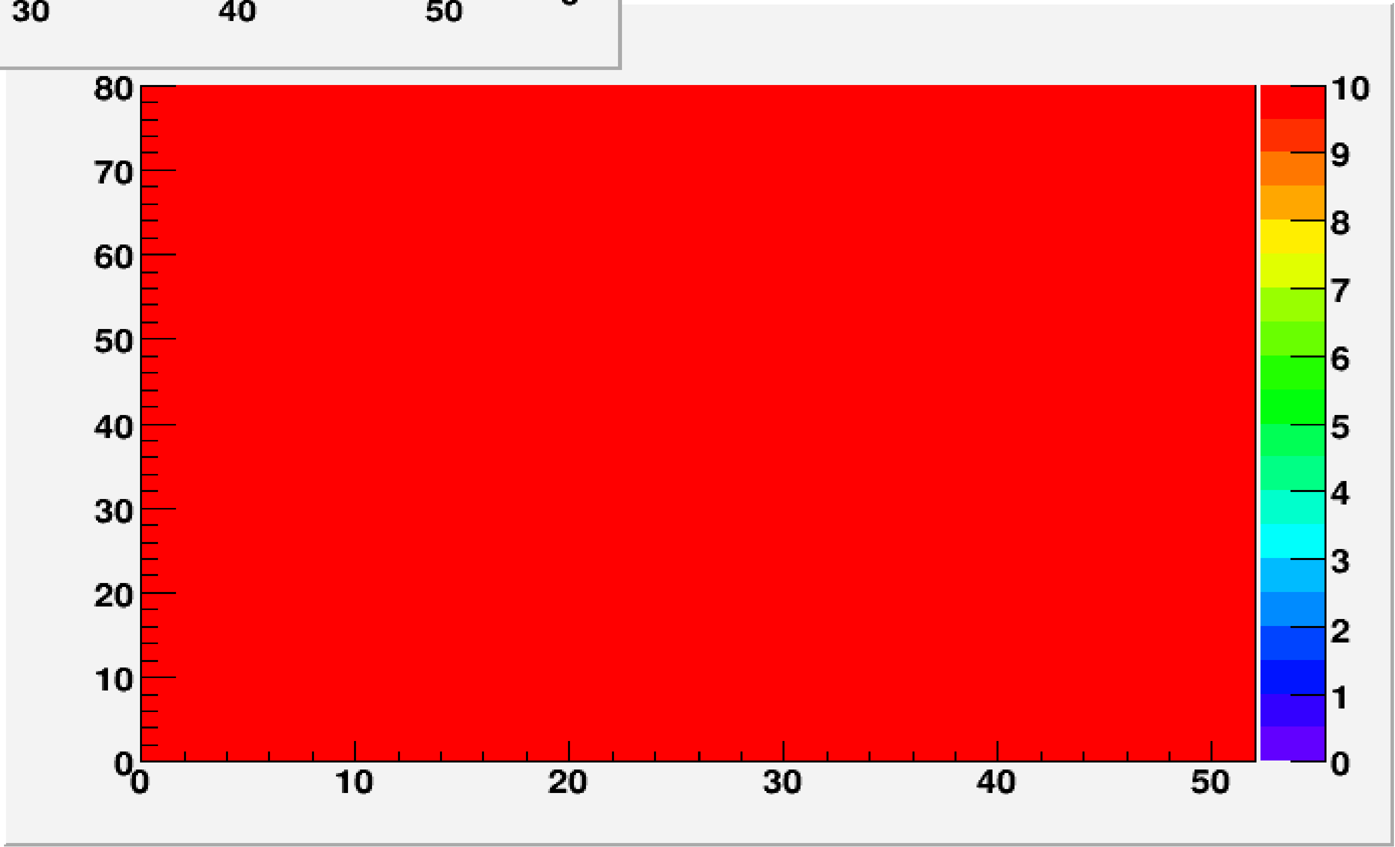
VthrComp →Injecting a signal with fixed amplitude (Vcal), finding the value at the comparator at which this signal is above threshold

CalDel → Delay of the internal calibrate signal with respect to the trigger



Pixel test

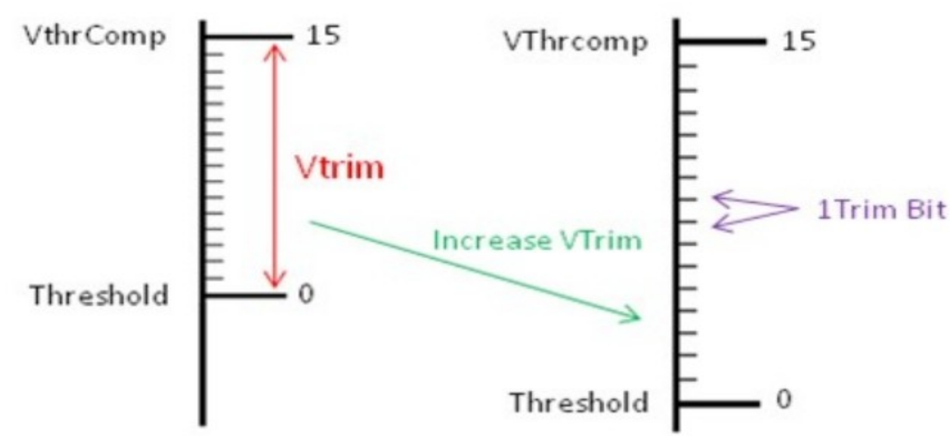

PixelMap_C0
PixelMap_C0
Entries 8320
Mean x 25.91
Mean y 40.09
RMS x 14.98
RMS y 23.02



VthrComp, Vtrim and the Trim Bits

- These are the DAC's used to adjust the thresholds of the comparators of the PUC
- VthrComp adjusts the threshold for every pixel on the ROC
- Vtrim sets range of thresholds the trim bits can be used to program the PUC to have
- Higher VthrComp and Vtrim translates into lower thresholds
- Trim Bits of 0 gives the lowest possible threshold for a given VthrComp and Vtrim
- Increasing Vtrim gives more range of threshold, yes it increases the step size of a trim bit

- The goal of setting Vtrim and the trim bits is to make up for the small differences in transistors due to limitations of IBM process used to manufacture the ROC
- These differences vary from pixel to pixel, and it is important to have the same threshold across the entire ROC



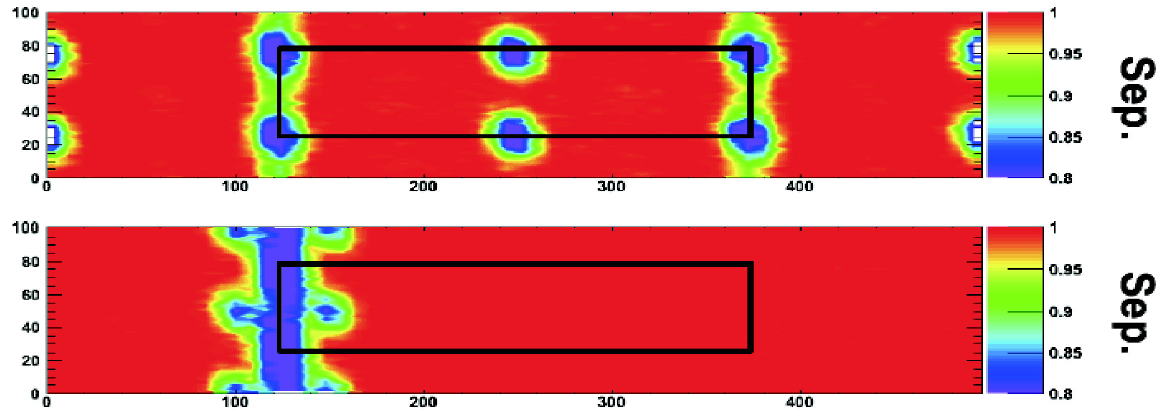
Source: Cameron Bravo's Talk, PIRE program Student
PSI, Summer 2012

Latest results. IBL-ATLAS

Test-beam Results: planar and 3D

CNM-81 (3D), $5*10^{15}$ n-irrad, HV=160V Eff=97.46

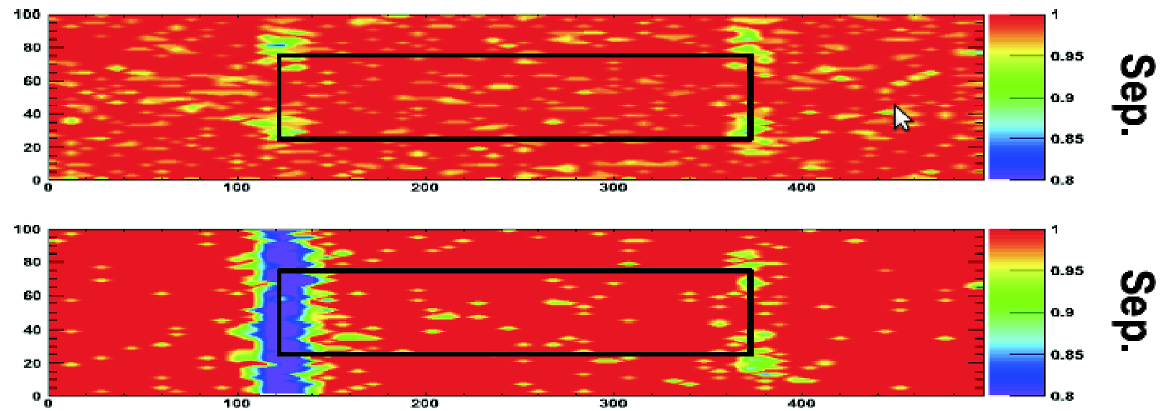
LUB4 (Planar), $5*10^{15}$ n-irrad, HV=1000V Eff=97.90



Batch4, 0 degree (B.E. = 80 GeV)

SCC34 (CNM-3D), $5*10^{15}$ p-irrad, HV=160V Eff=98.96

SCC60 (Planar), $5*10^{15}$ p-irrad, HV=940V Eff=97.65



Batch1, 15 degree (B.E. = 120 GeV)

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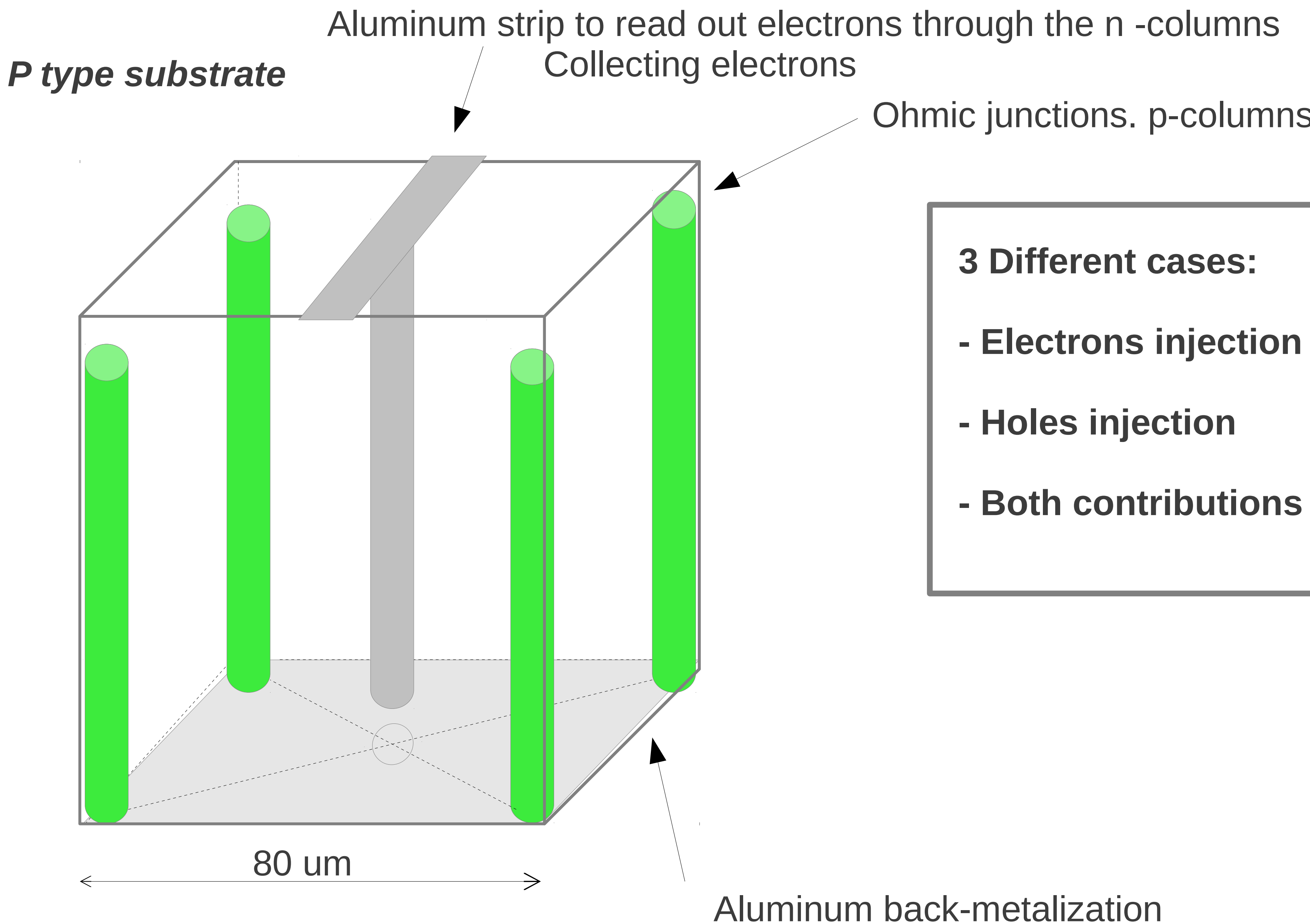
TCT Measurements

- To study the field profile within the detector, using laser generated carriers:

$$j = \frac{Nq\,v}{d} = \frac{Nq\,\mu\,E}{d}$$

TCT in ONE cell in 3D-strips



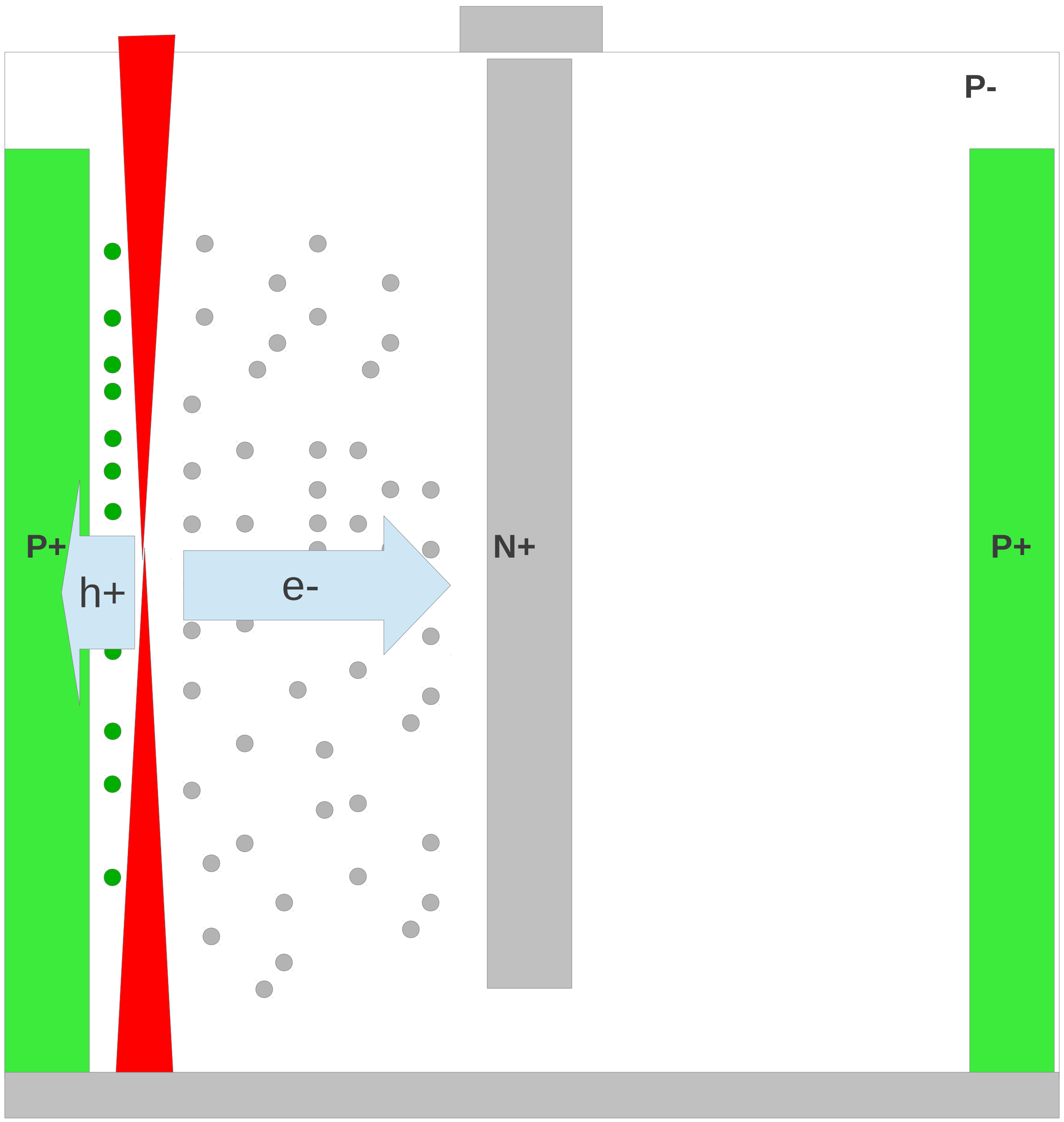
3 Different cases:

- Electrons injection

- Holes injection

- Both contributions

Electrons injection



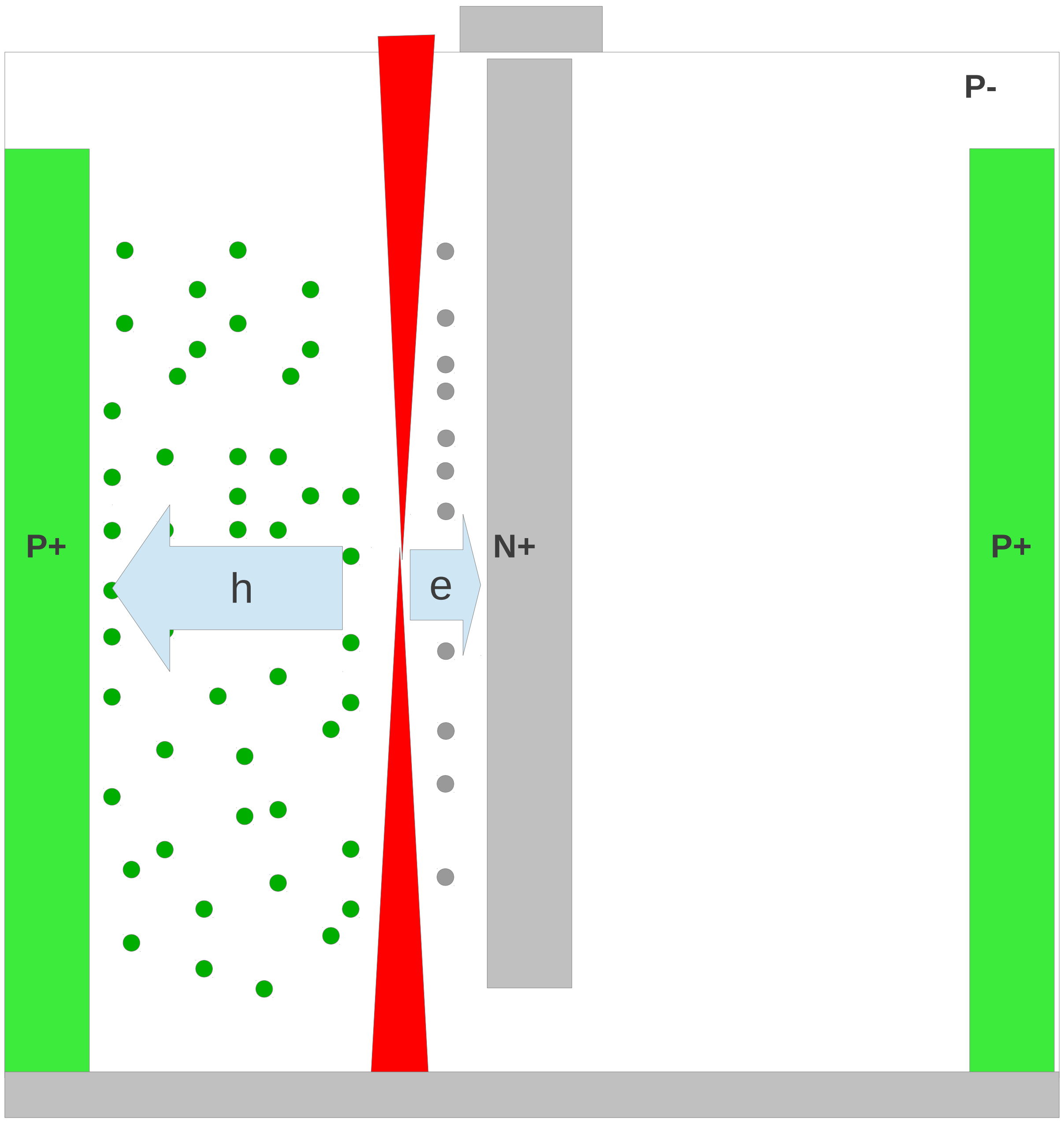
Holes are collected very fast,

We see mostly signal due to

Electrons movement.

Ramo's theorem!!!

Holes injection



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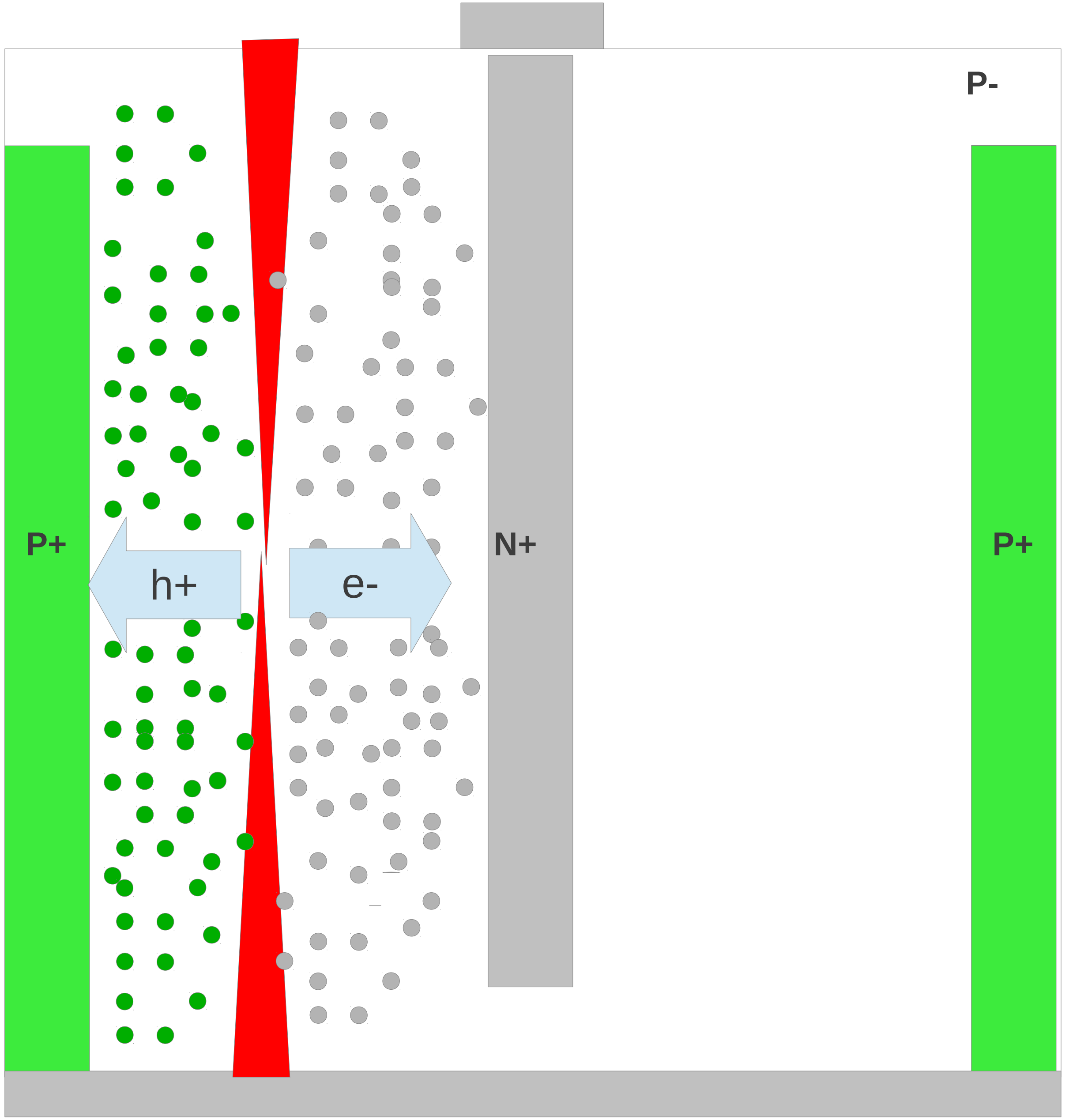
Both contributions



Both contributions are expected

A faster peak for electrons and

A slower peak for holes

Devices

Name	Qty	Description
CMS_MC	1	Large module, matrix 8x2 detectors, sparse pattern of P columns and single guard ring
CMS_SC_11	5	Single chip detector with sparse pattern of P columns and single guard ring
CMS_SC_12	5	Single chip detector with sparse pattern of P columns and double guard ring
CMS_SC_21	5	Single chip detector with dense pattern of P columns and single guard ring
CMS_SC_22	5	Single chip detector with dense pattern of P columns and double guard ring
3D-Strip detector (6)	8	3D-strip detectors with 128 strips of 80 μm pitch,15μm strip width and single guard ring
3D-Pad detector (7)	12	3D-pad detector with single guard ring
Test structures	-	Layer deposition test, polysilicon resistance test, hole alignment test