Technology and characterization results in 3D pixel detectors for future colliders

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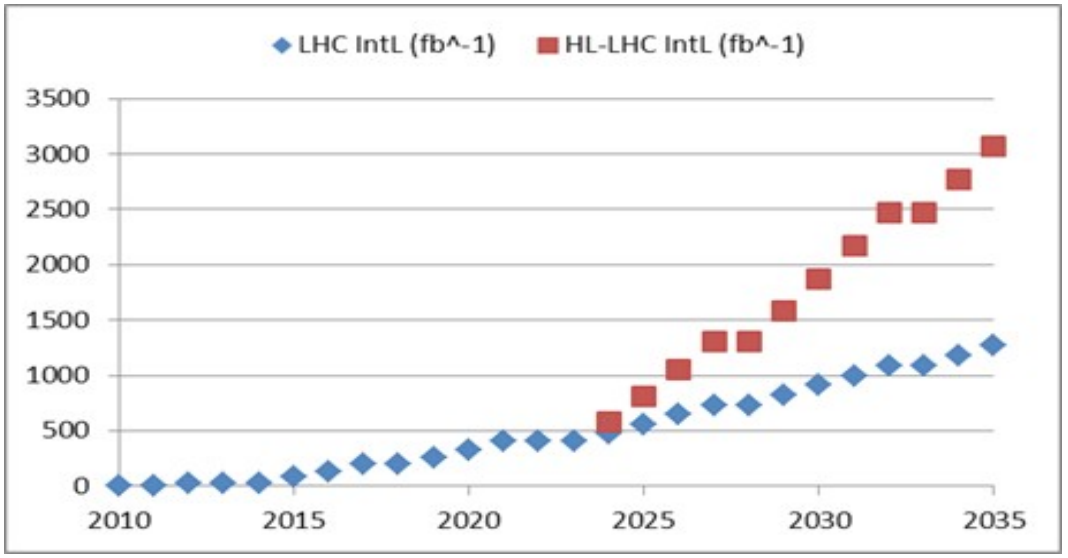
Outline

- Motivation
- 3D pixel technology and manufacturing
- Electrical characterization
- PSI46 Read Out Chip (ROC) and interconections
- Radiation resistance studies
- Summary

Motivation

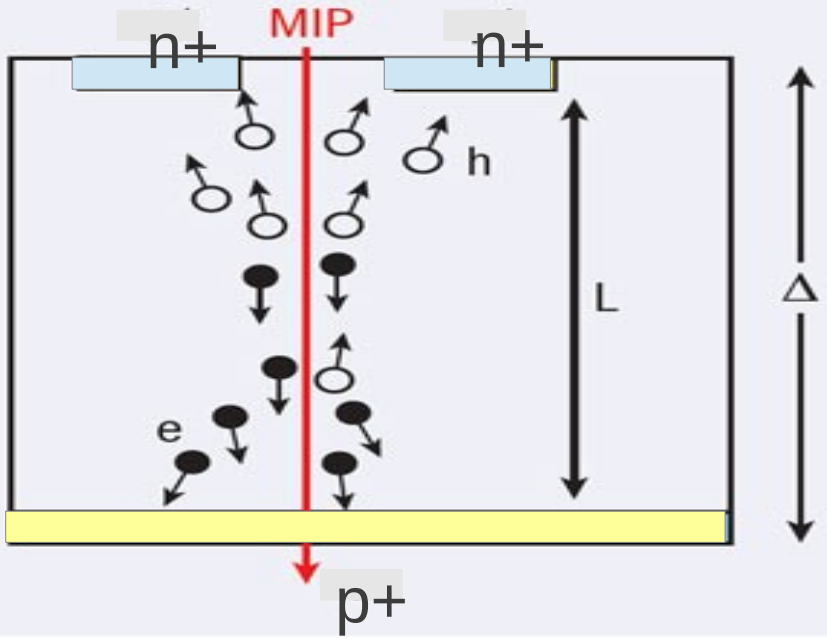
- LHC experiments are expected to undergo a constant increase of radiation levels, a possible HL-LHC scenario will get things tougher

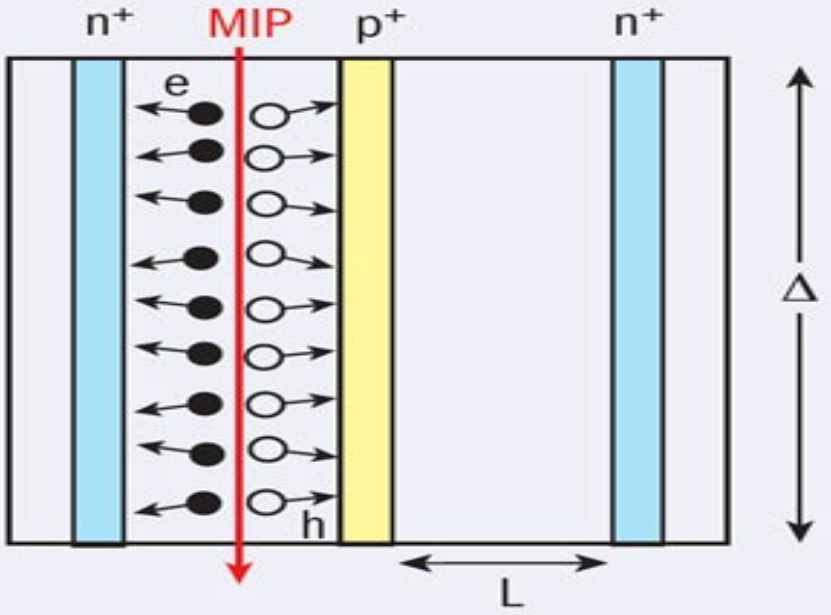


- New generation of vertex detectors must deal with fluences about $1*10^{16}$ neq/cm^2
- Here we are going to assess the radiation resistance of 3D double-sided pixel sensors in terms of:
  - Increase of the depletion voltage (Vfd)
  - Reduction of the CCE

Planar Pixel

3D Pixel





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

3D Detectors Advantages

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

3D- pixels timeline

- 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“

  …

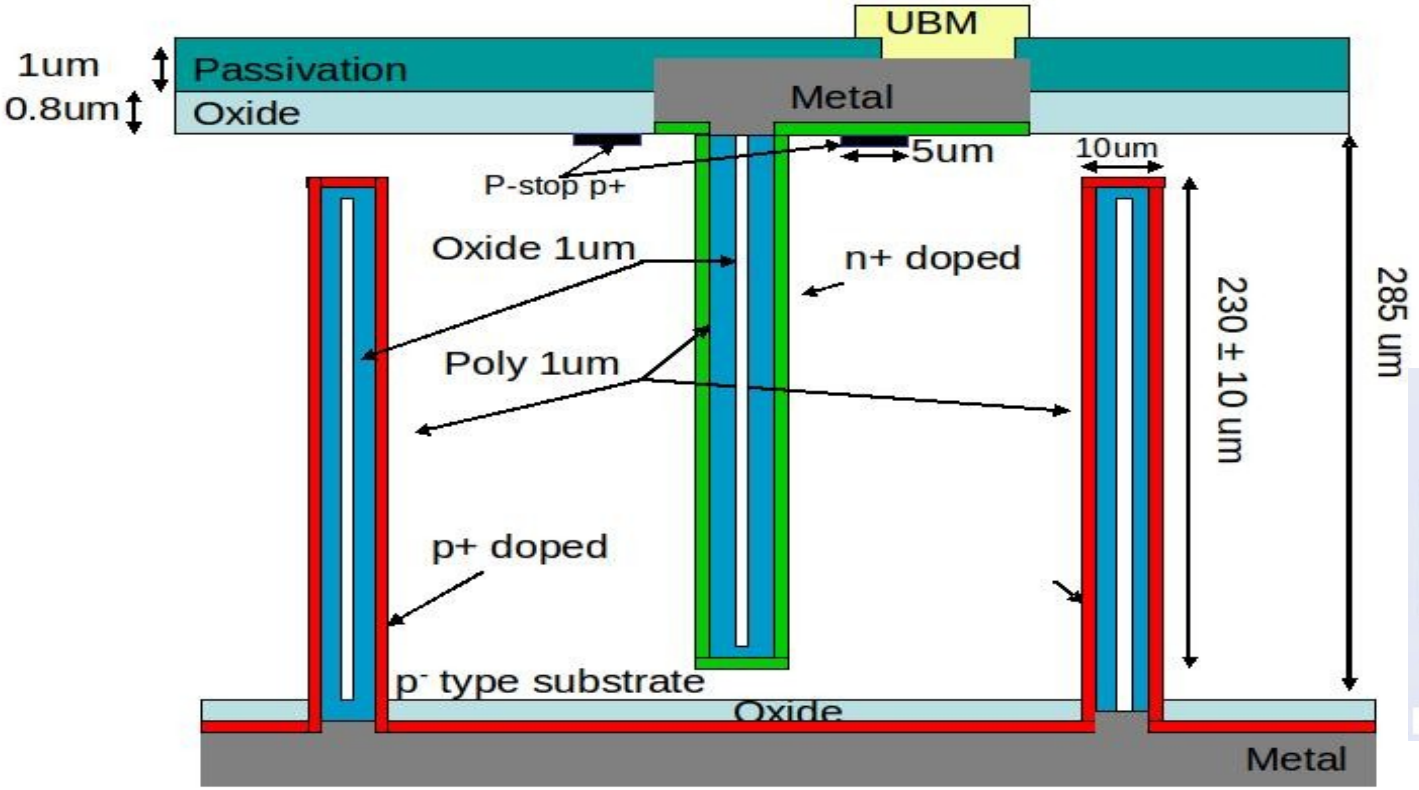
- 2010: 3D sensors become a technology for the ATLAS - IBL Upgrade

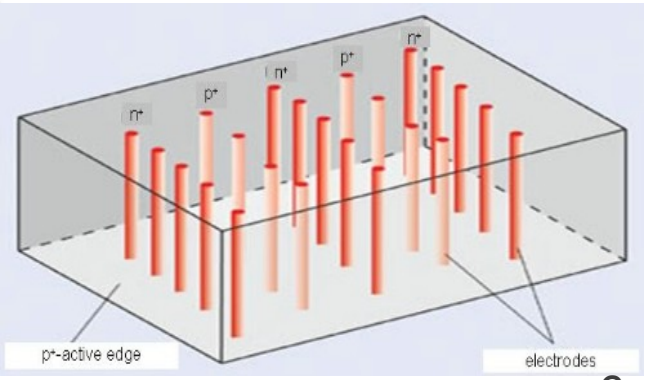
  The ATLAS Collaboration; “ATLAS Insertable B-Layer Technical Design Report”

Technology

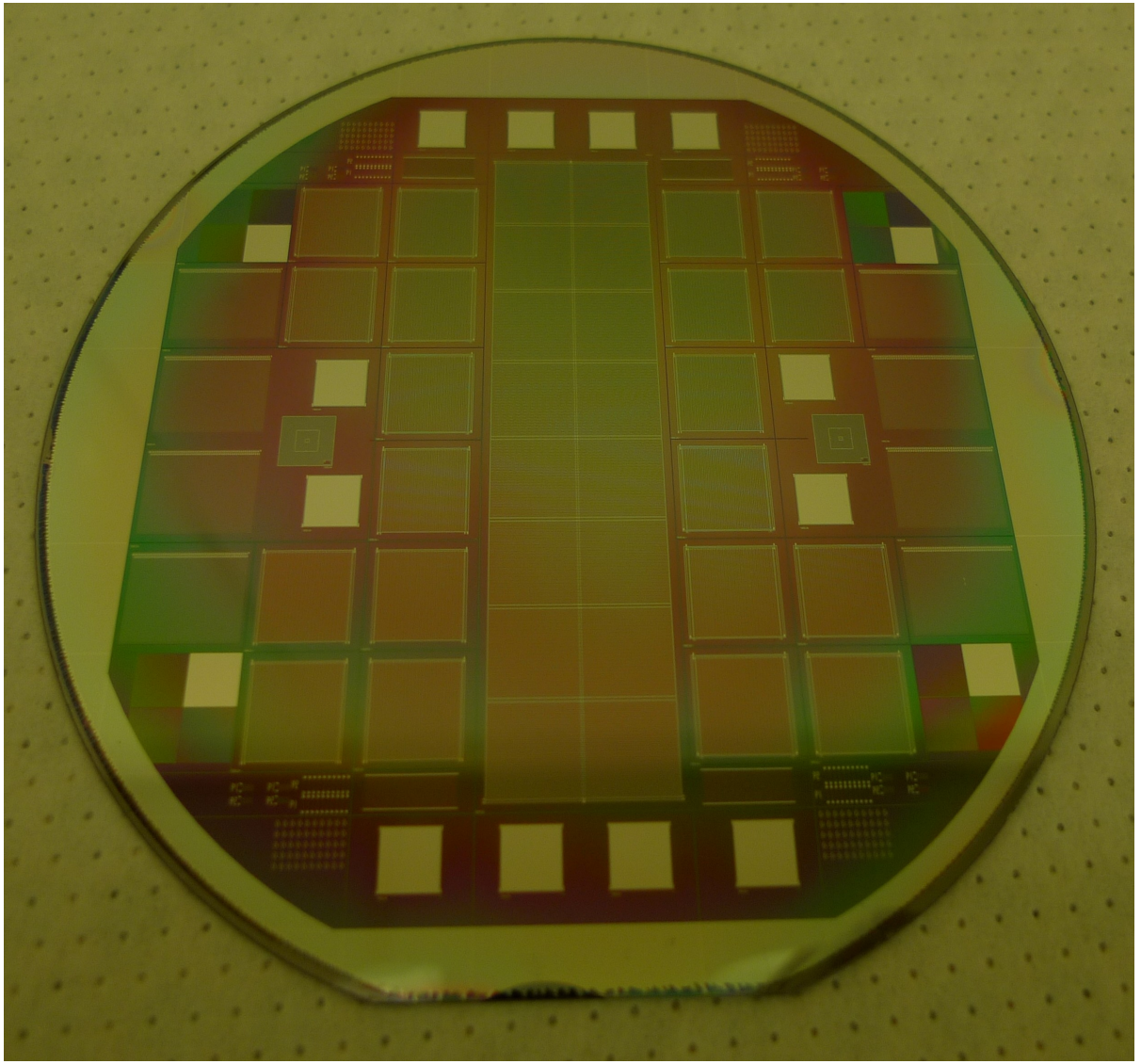
- Double-sided configuration (different doping type on each side)
- Safer fabrication process (reduced wafer stress)
- Photo-lithography to define electrode contacts is only necessary on top surface
- HV biasing on the back side by simple wire bonding

REF: G. Pellegrini at the Second Trento Workshop on Advanced Silicon Radiation Detectors, Trento,Italy, 2006





CNM Production and Description



6 wafers:
Wafers 5,6,7,8:
- **285 µm thickness**

Wafer 11:
- **230 µm thickness**

Wafer 3:
- **285 µm thickness**
- **Resistor bias grid**

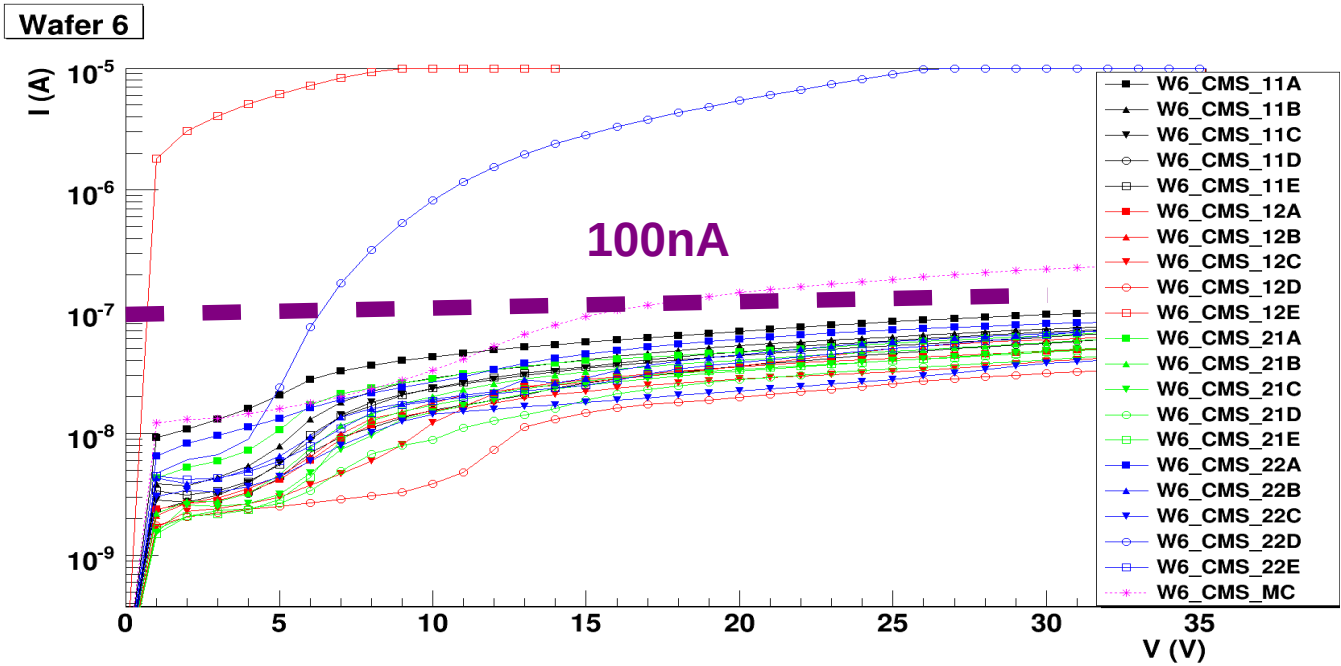
*** Each wafer includes:**

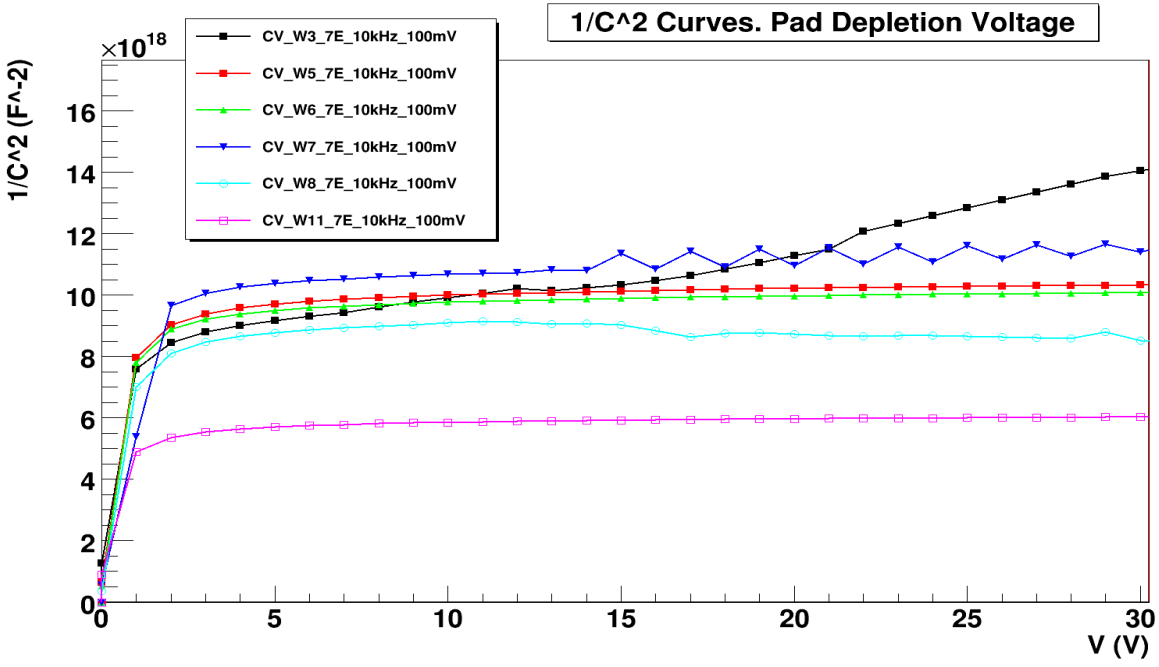
1 Full Module (8x2)
20 Single Chips
8 Strip sensors
12 Pads
Test structures

Electrical characterization

- Very Homogeneous Behavior

- Current Values in the expected range



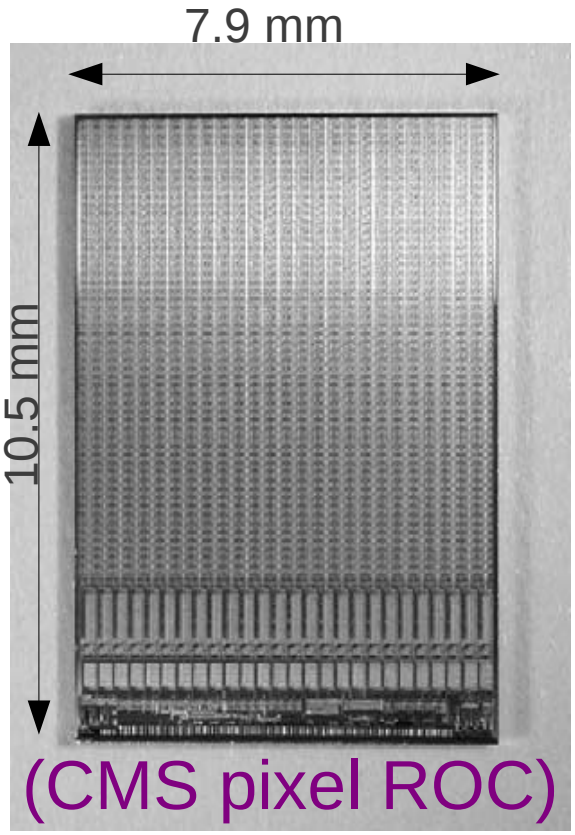


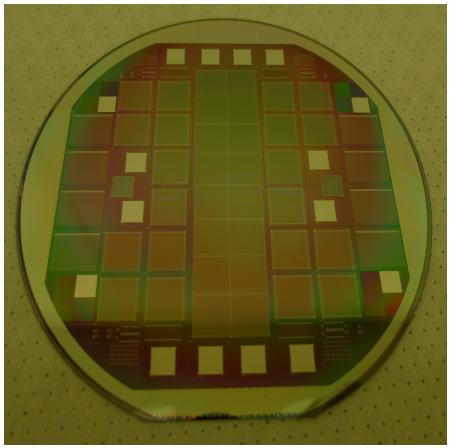
Measured Vfd (pad) ~ 1.5 V

Using Coaxial approximation, Extrapolating to sensor geom:

Vfd (3D-Detector) ~ 9 V

PSI46 ROC and interconnection process





52 x 80 pixel unit cells.
4160 units
150μm x 150μm

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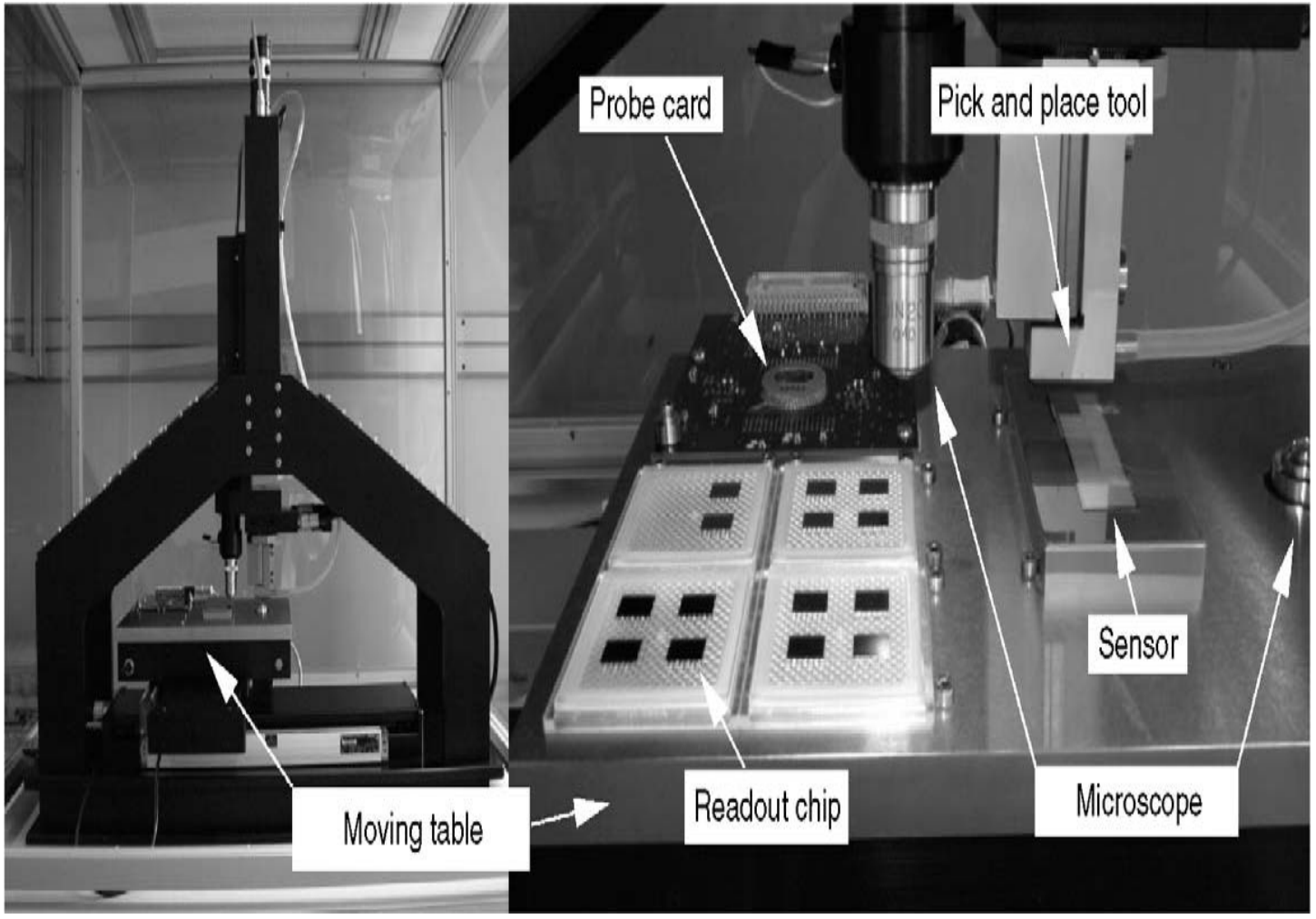
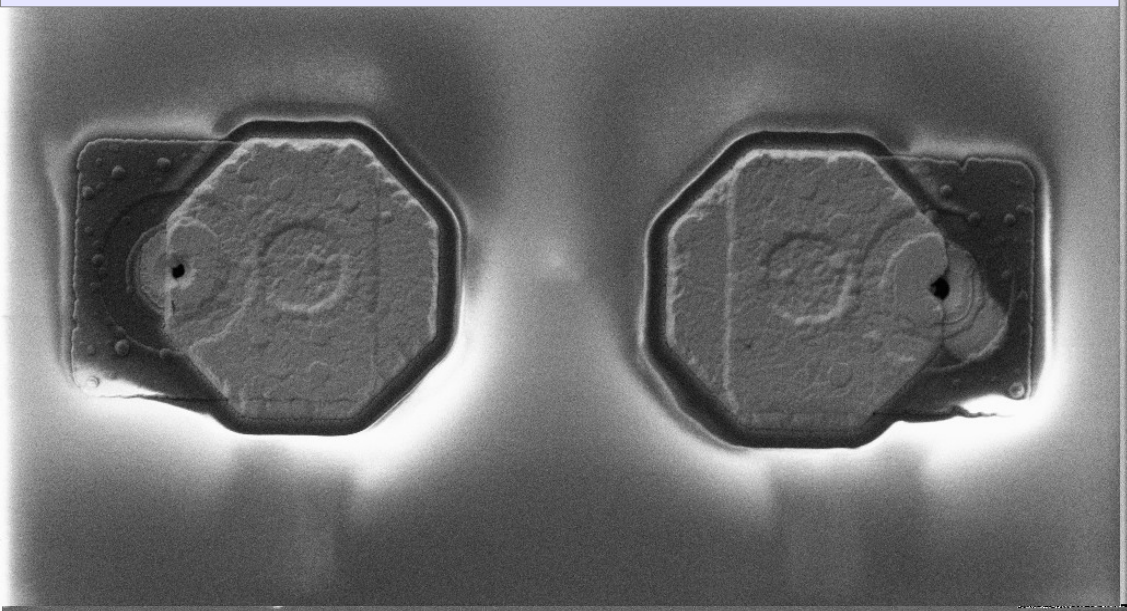
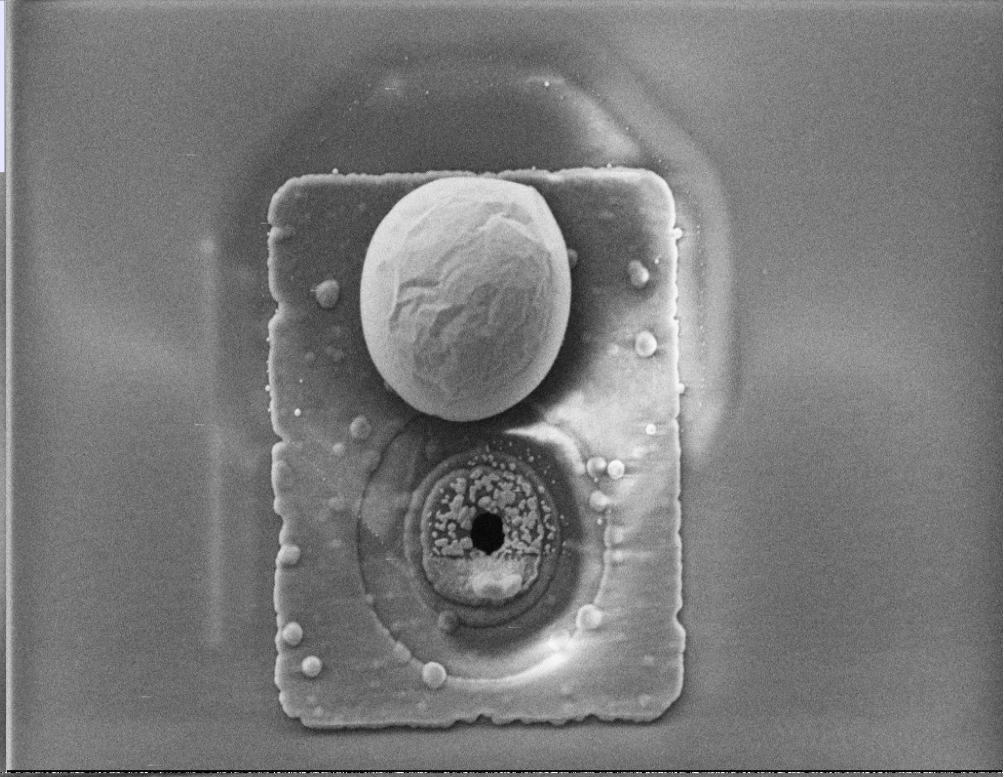
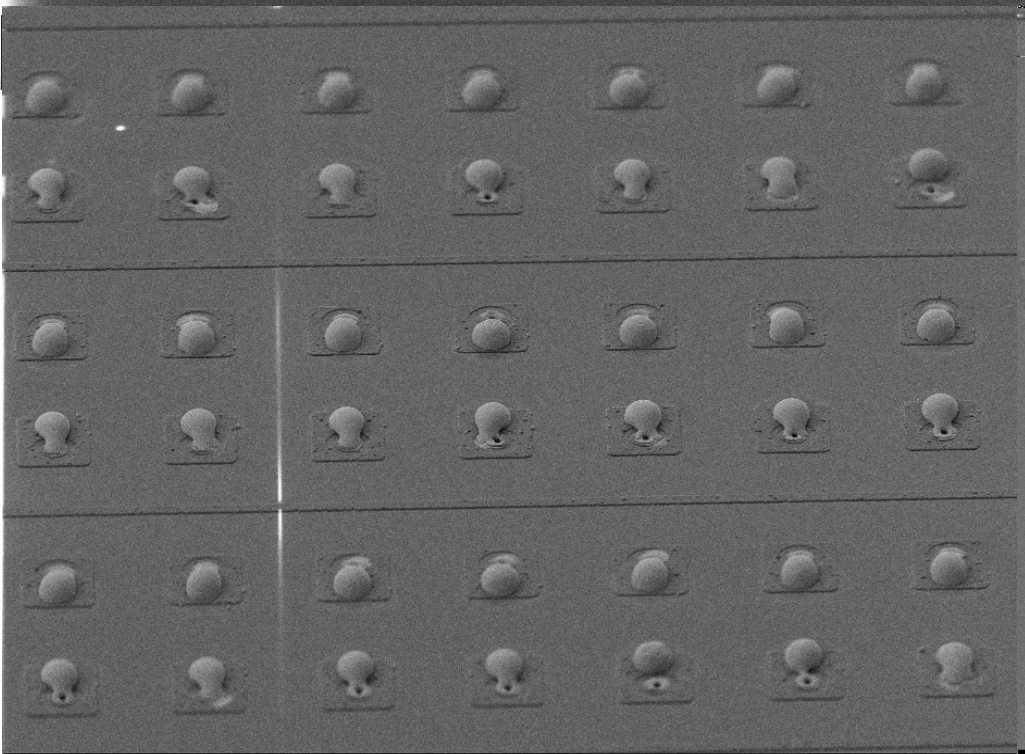
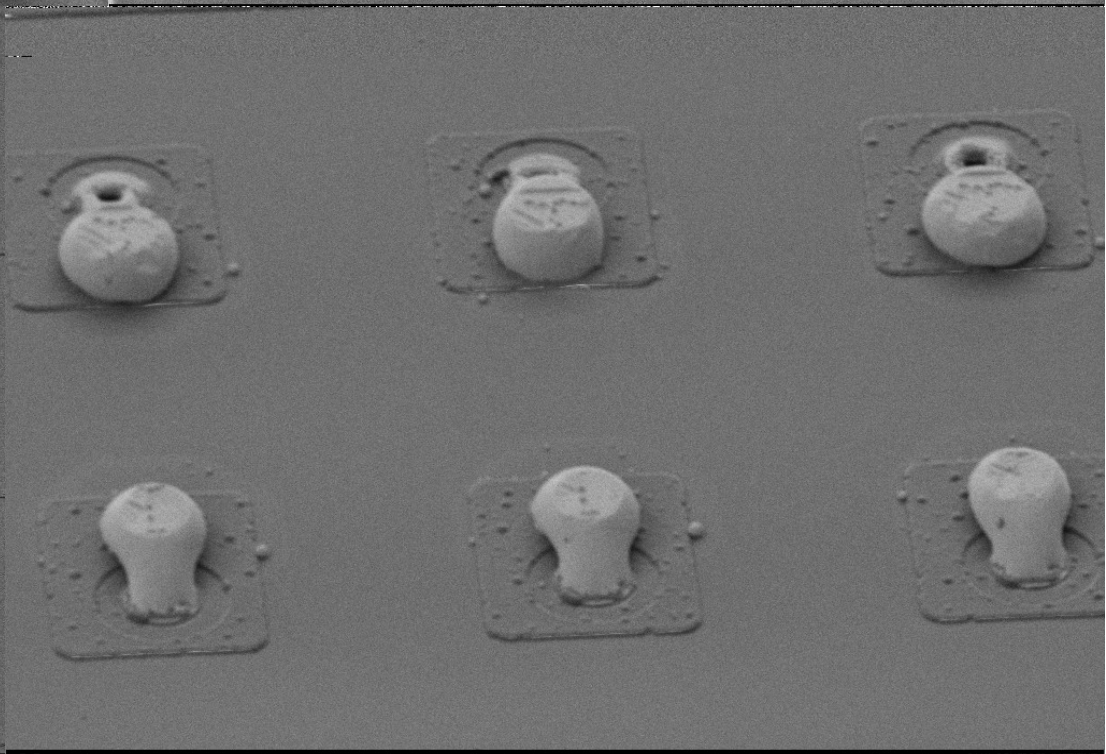


Scanning electron Microscope SEM



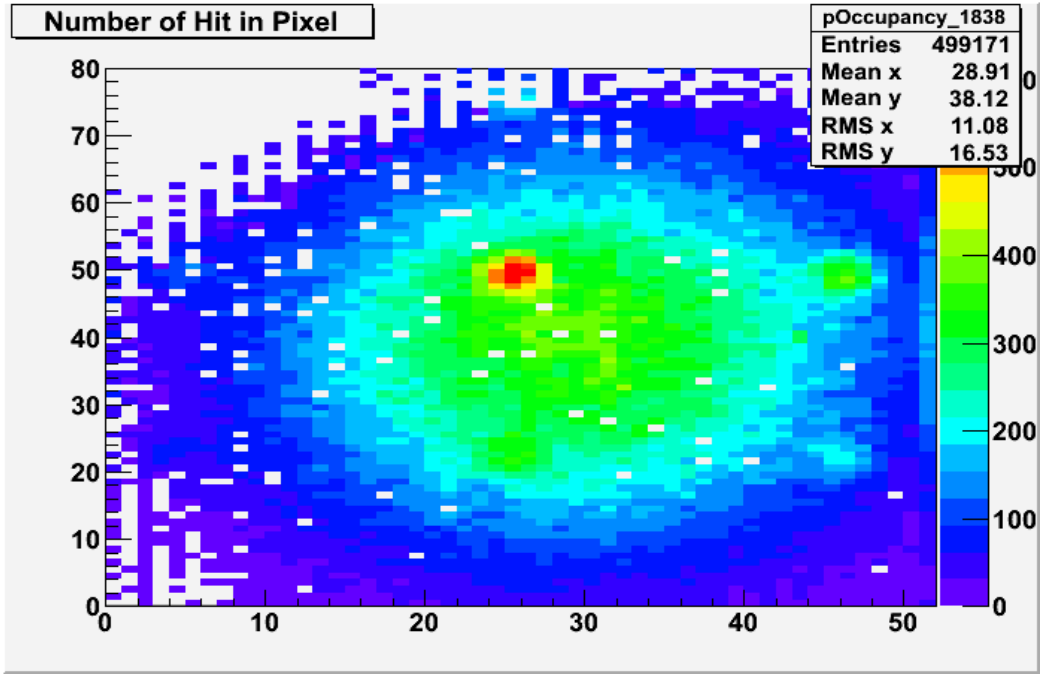






Bump bonding. Interconnection process

- Bum bonding yield test
- Using a ^{90}Sr radioactive source
- An uniform pattern has been observed. Including the holes on the PCB (between sensor and scintillator)



In other cases:

Reason:

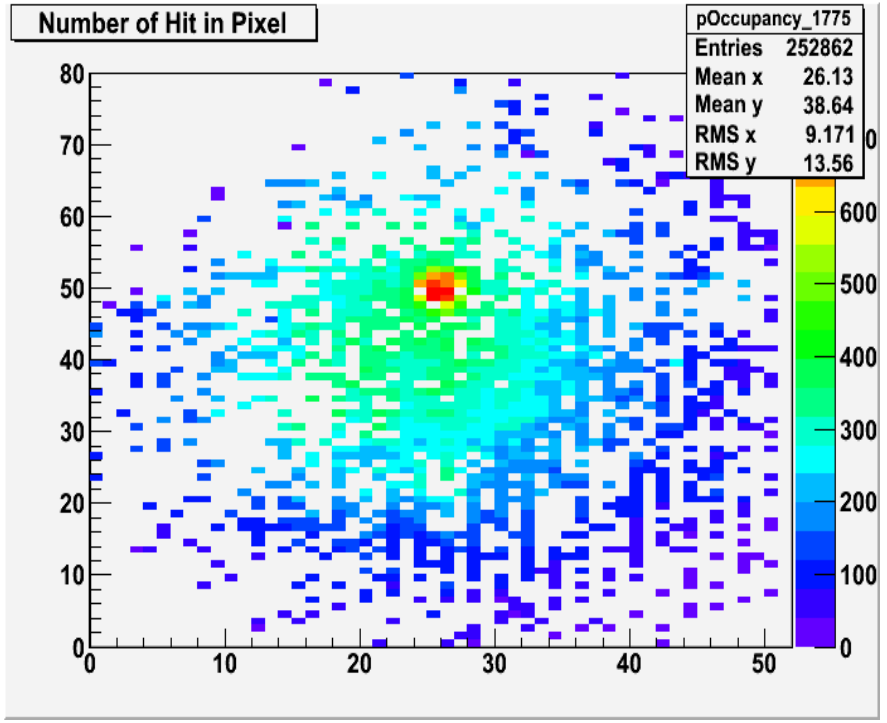
There are passivation layers only in one side of the wafer (overlooked during production)

Problem:

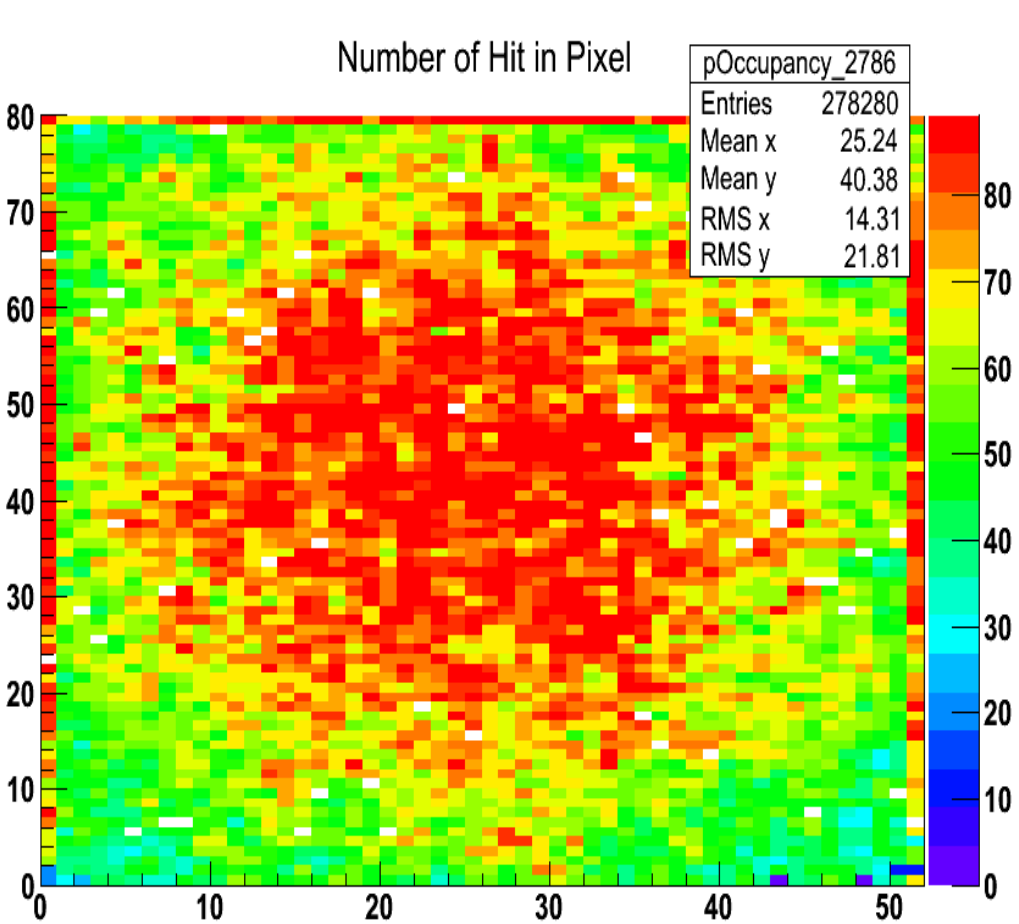
The stress during the second re-flow process, bows the Sensor breaking the bumps connections

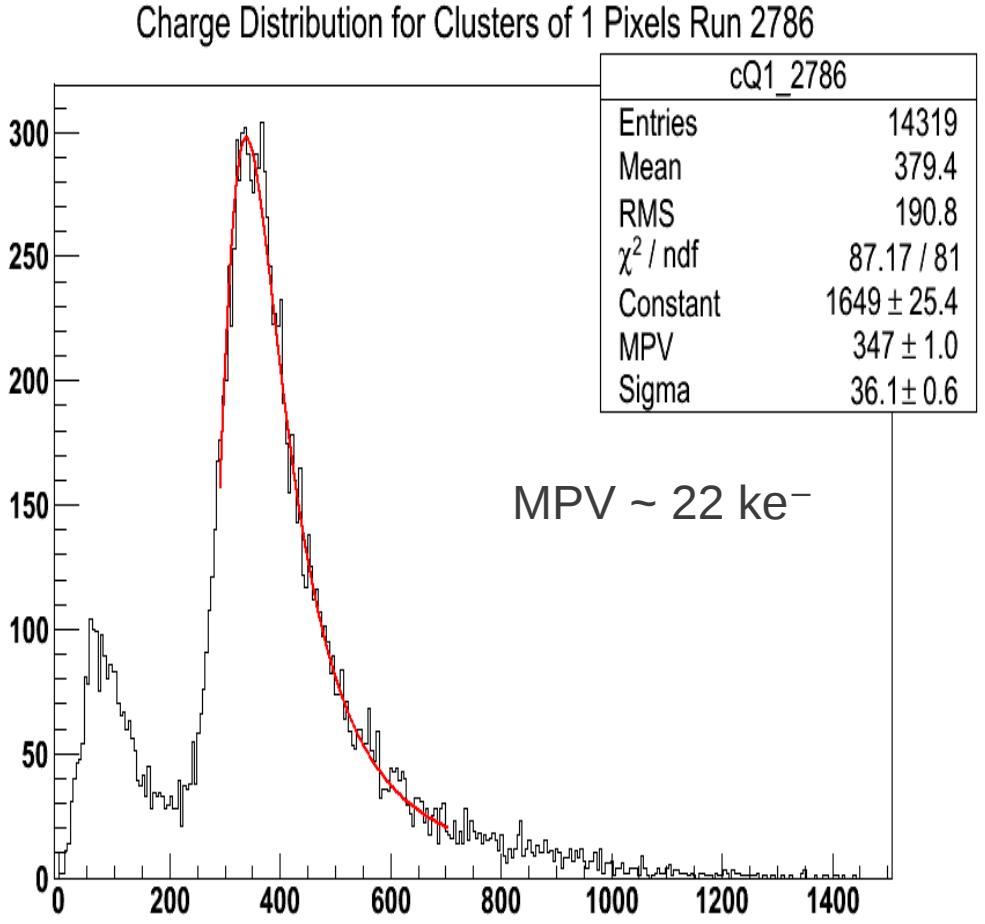
Provisional Solution:

To put some weight on top of the sensor-chip “sandwich” during 2nd reflow.



Nice Pixel map, and landau fit:





Irradiation Campaign:

4 pixel samples, 2 strips detectors and 2 pads up to each radiation fluence

- Proton Cyclotron @ KIT (Karlsruhe), 25MeV protons:

1×10^{15} n_{eq}/cm^2

5×10^{15} n_{eq}/cm^2

- Tigra Reactor @ JSI (Ljubljana), continuous spectrum neutrons:

1×10^{15} n_{eq}/cm^2

5×10^{15} n_{eq}/cm^2 (ongoing)

1×10^{16} n_{eq}/cm^2

^{90}Sr Characterization

*** Charge Collection in irradiated samples**

*** Full Depletion Voltage:**

- Depletion Area grows in a 3D sensor horizontally

- A new variable:

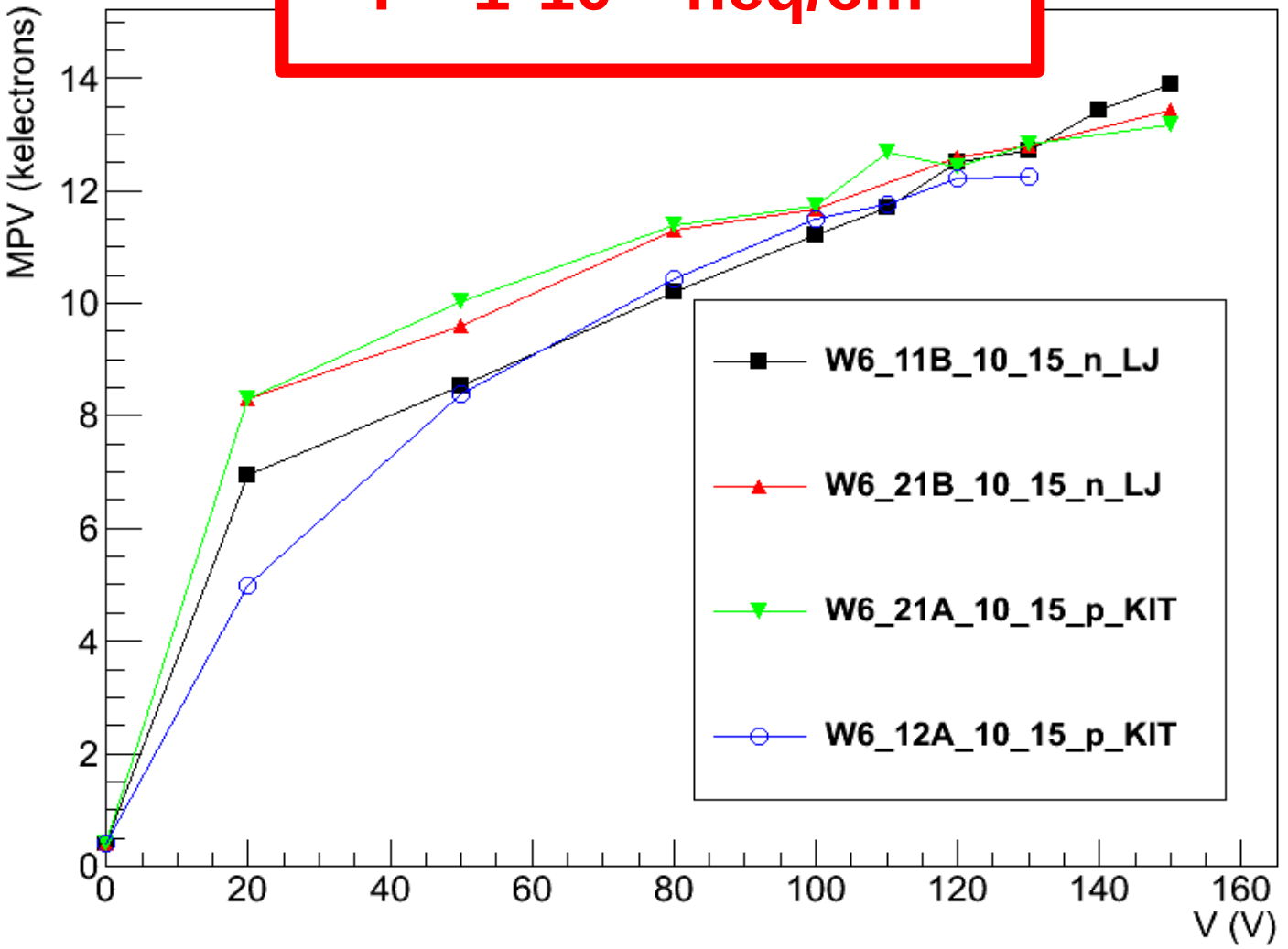
$$Er = \frac{\text{Num. of hits}}{\text{Num. of triggers}}$$

- When the Er saturates with bias voltage, we consider that we have depleted the maximum volume in the sensor

MPV vs bias Voltage in irradiated samples

2 samples with protons
2 samples with neutrons

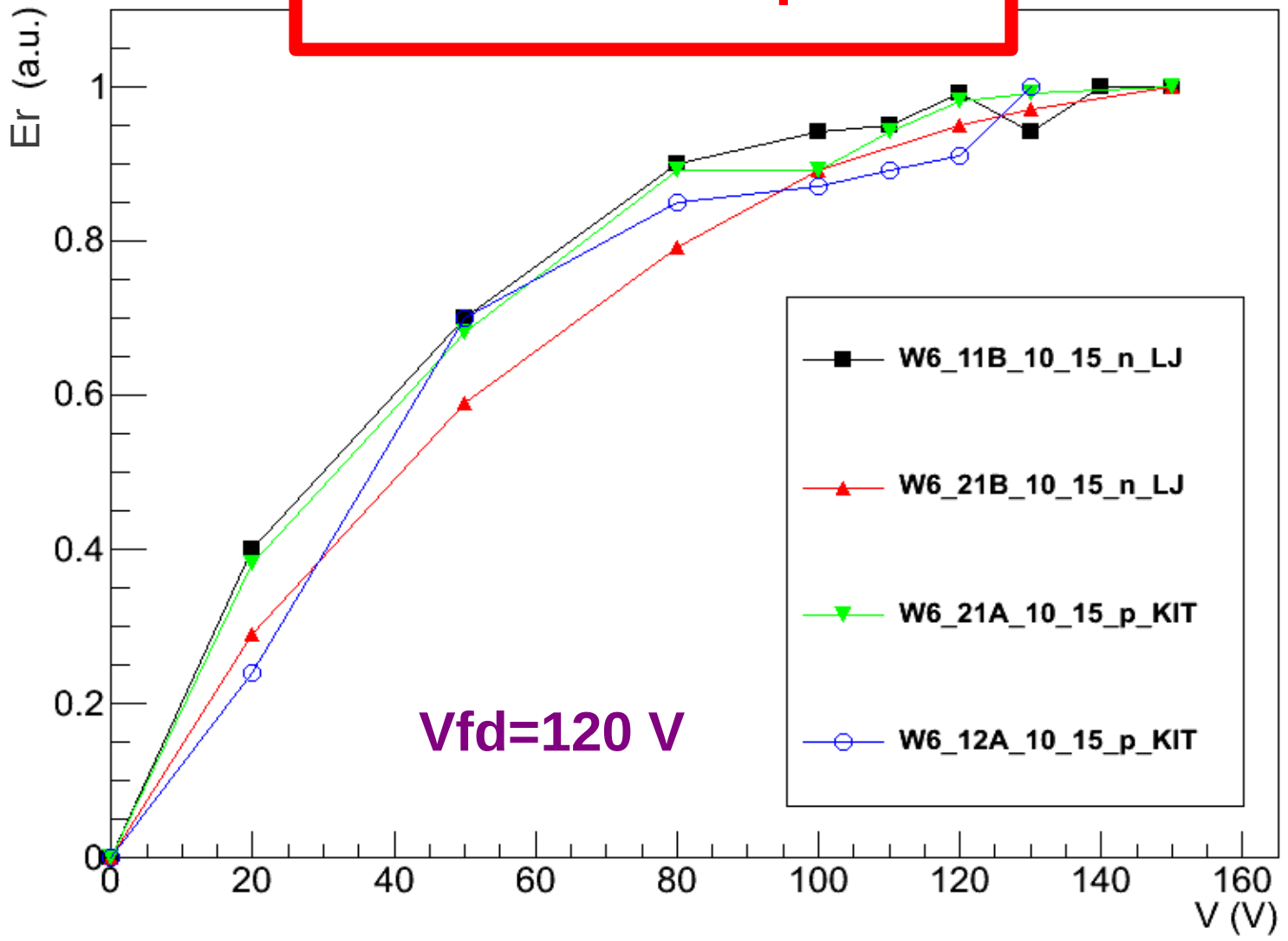
F= 1*10¹⁵ neq/cm²



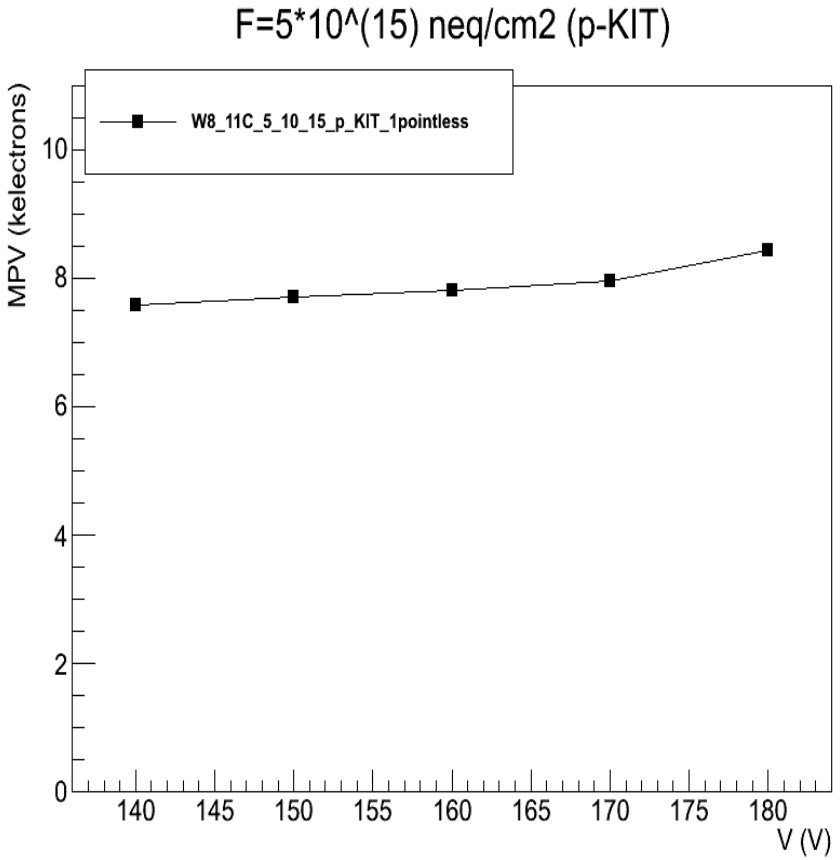
Er vs bias Voltage in irradiated samples

2 samples with protons
2 samples with neutrons

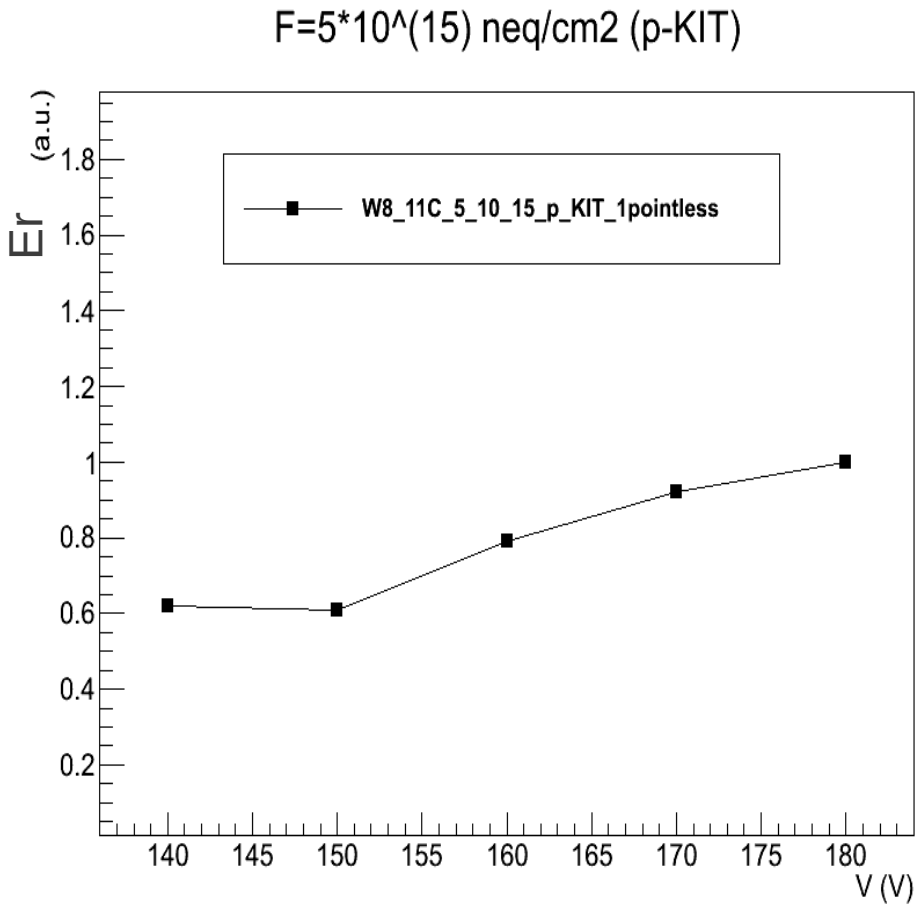
F= 1*10¹⁵ neq/cm²



MPV and Er vs bias Voltage in irradiated samples

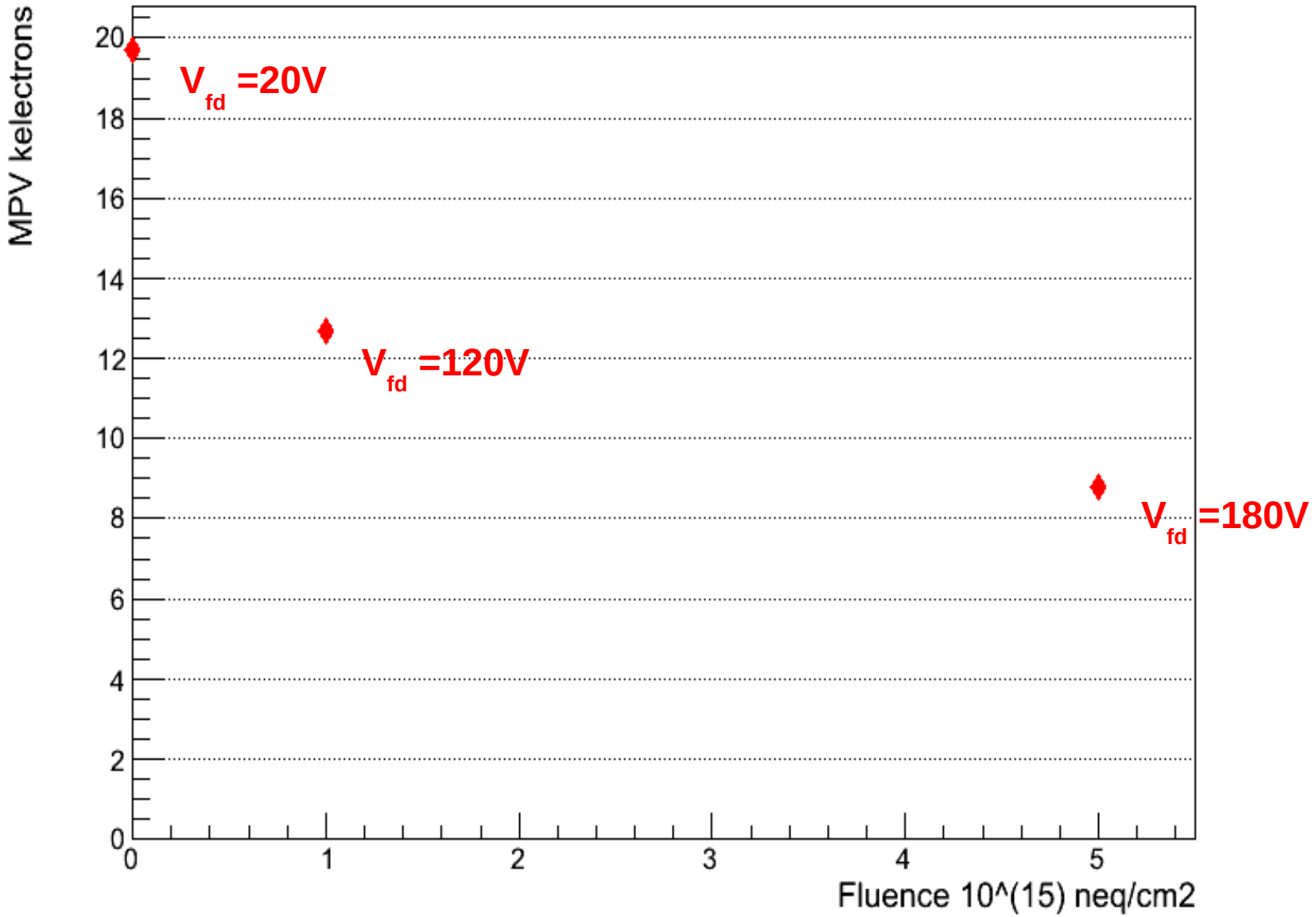


F= 5*10¹⁵ neq/cm² protons



Vfd=180 V

MPV vs Fluence



FUTURE WORK:

- Studies on the ROC performance after $1*10^{16}$ neq/cm^2
- Test Beam @ DESY in March (Tracking Eff.)
- Capacitance meas. In the two different patterns

CONCLUSIONS:

- Sensors show a good performance up to $5*10^{15}$ neq/cm^2

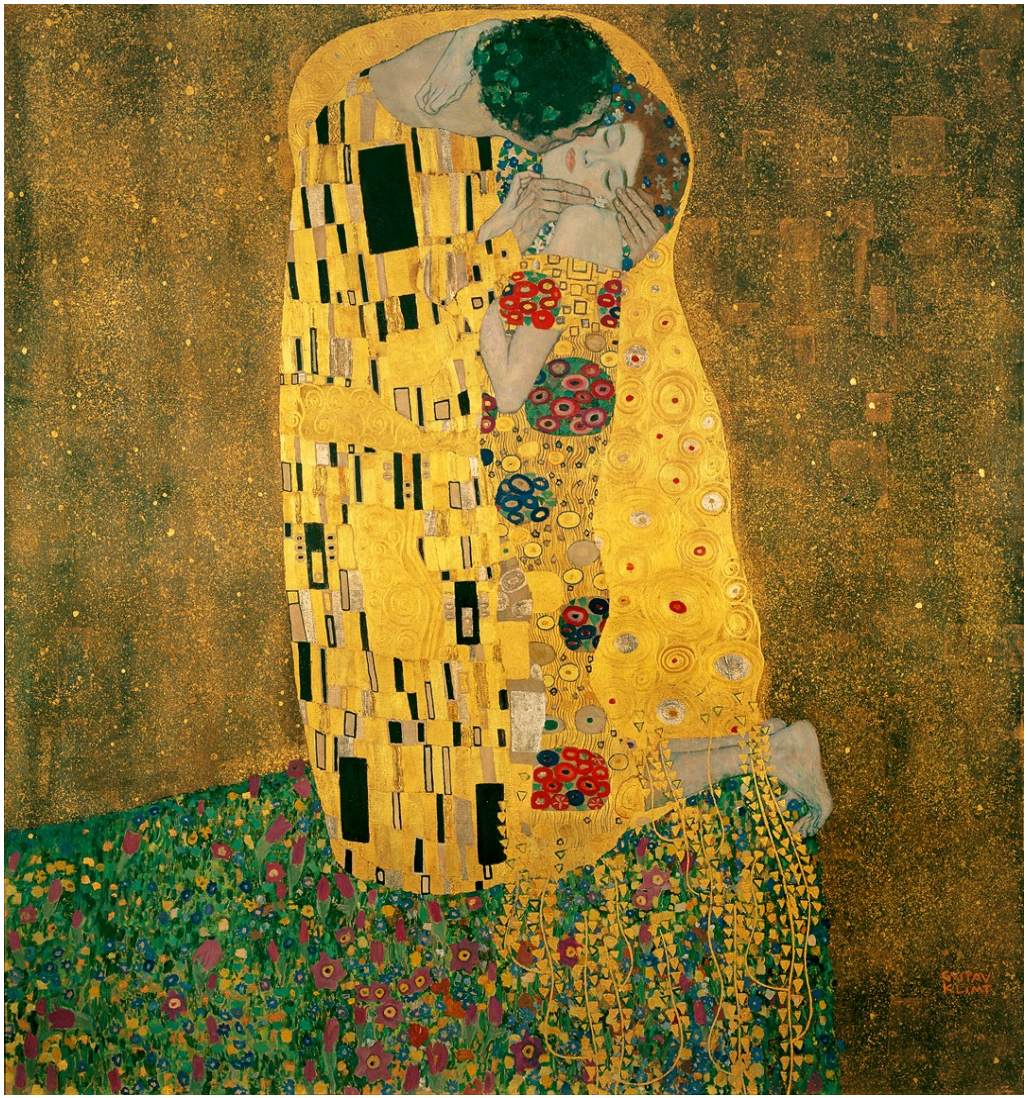
- Mechanical stress reduces the bump-bonding yield.
  A problem to fix in a future production

- Still plenty of work ahead testing samples

Acknowledgements:

- PSI and ETH – CMS pixel team
- Specially
    - Hans Christian kaetsli
    - Andrey Starodumov
    - Dmitry Hits
    - Silvane Streuli
- KIT & KJ irradiation facilities
- AIDA project

THANK YOU FOR YOUR ATTENTION!



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Backup

Depletion Area in 3D-Pixels

- Coaxial Symmetry
- r1 is the electrode radius
- r2 is the distance between columns(38µm|pad,90µm|sensor)
- 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)

Vfd Calculation

- Measured Value has to be extrapolated to the device structure dimensions (electrodes distances were not the same in pad and detector)
- Coaxial formula instead planar one:

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

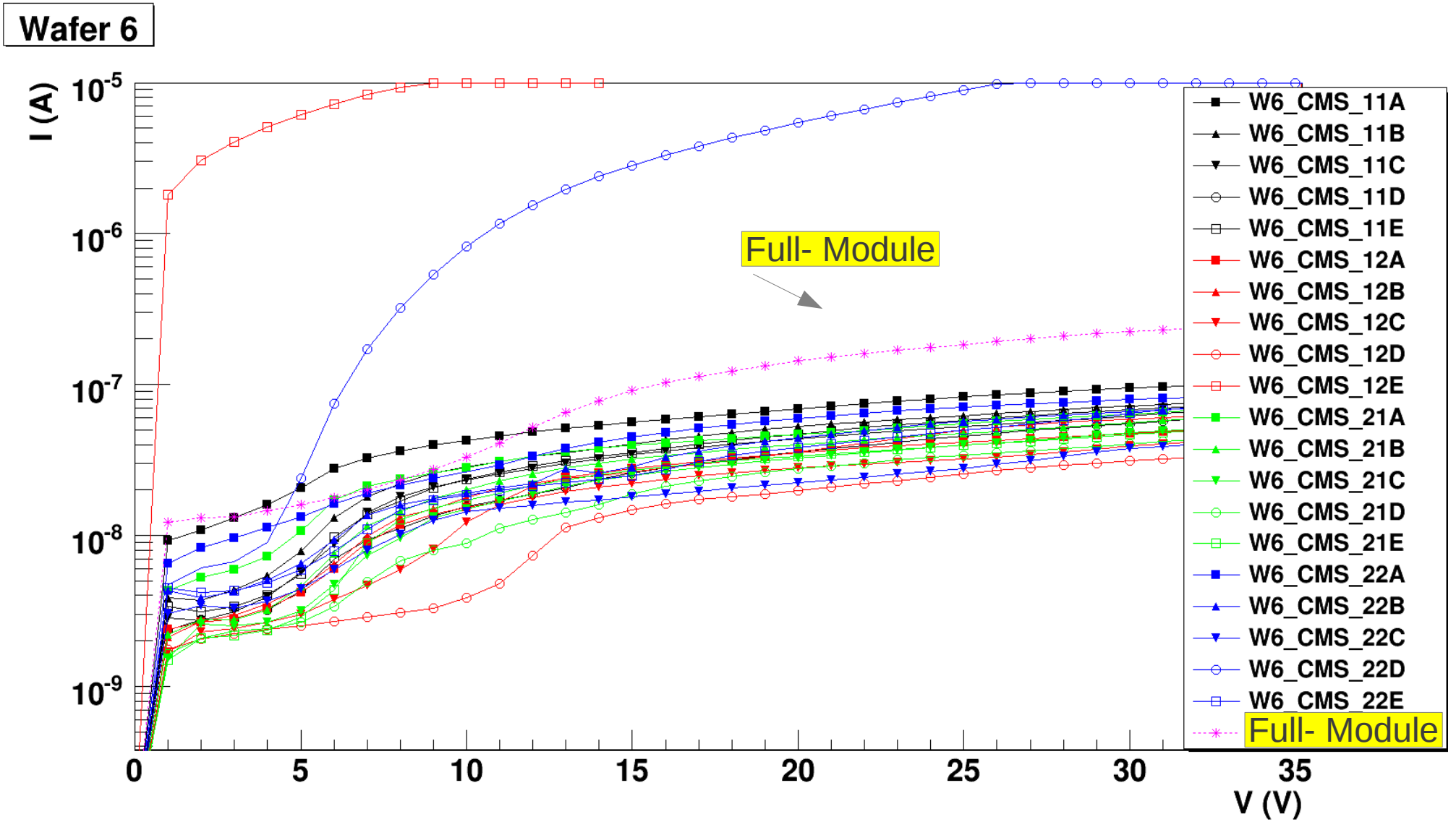
- $r_{2,detector} = 2.4 * r_{2,pad}$
- $Vfd_{detector} = 6 * Vfd_{pad}$

Vfd (detector) ~ 9V **Coax.**

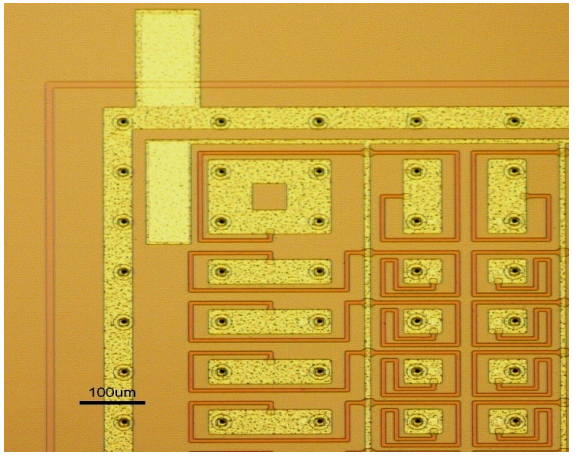
$Vfd_{detector} = 6.6 * Vfd_{pad}$ Planar Formula

Electrical Characterization. IV Curves

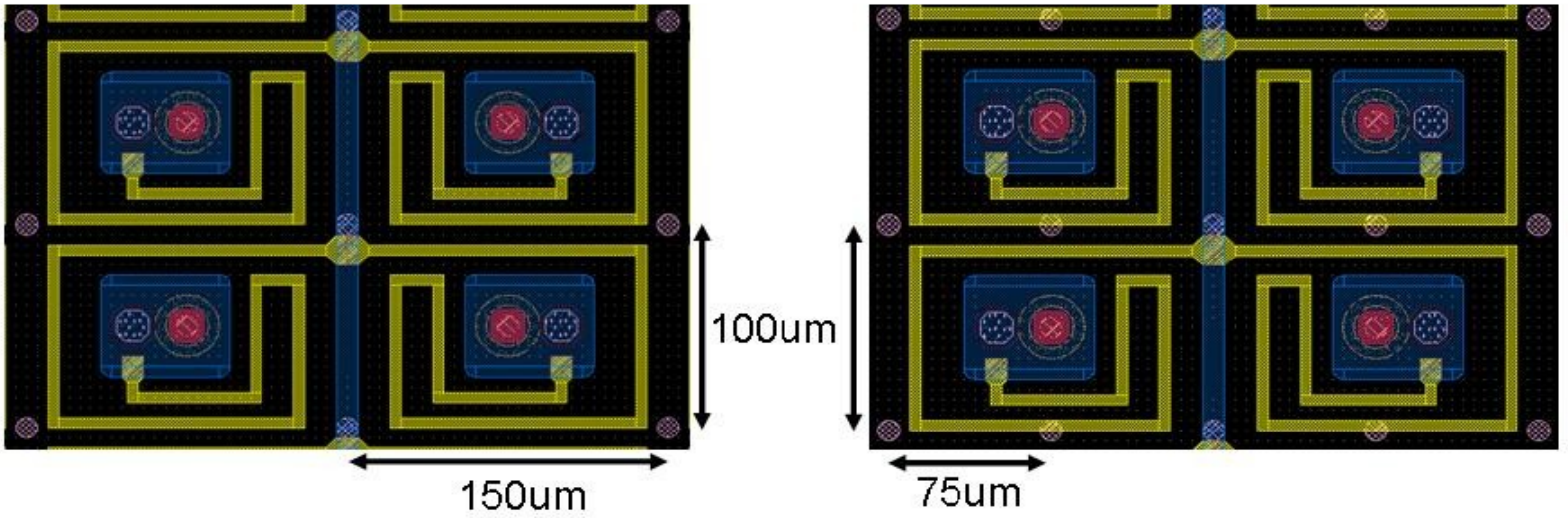
* Homogeneous behavior and acceptable current values



Wafer layout



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



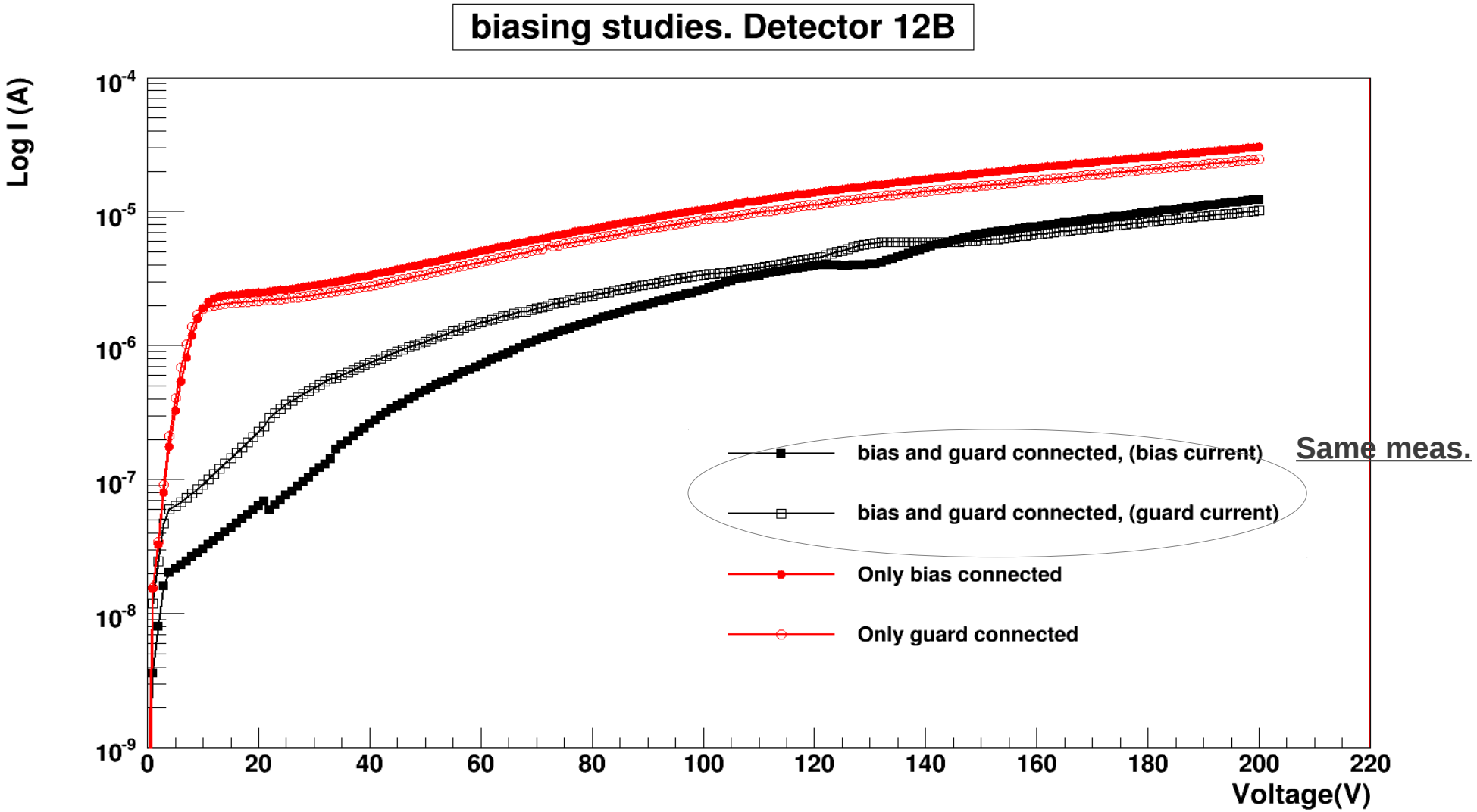
Sparse pattern of holes P:
Rectangular matrix of 150x100um^2

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

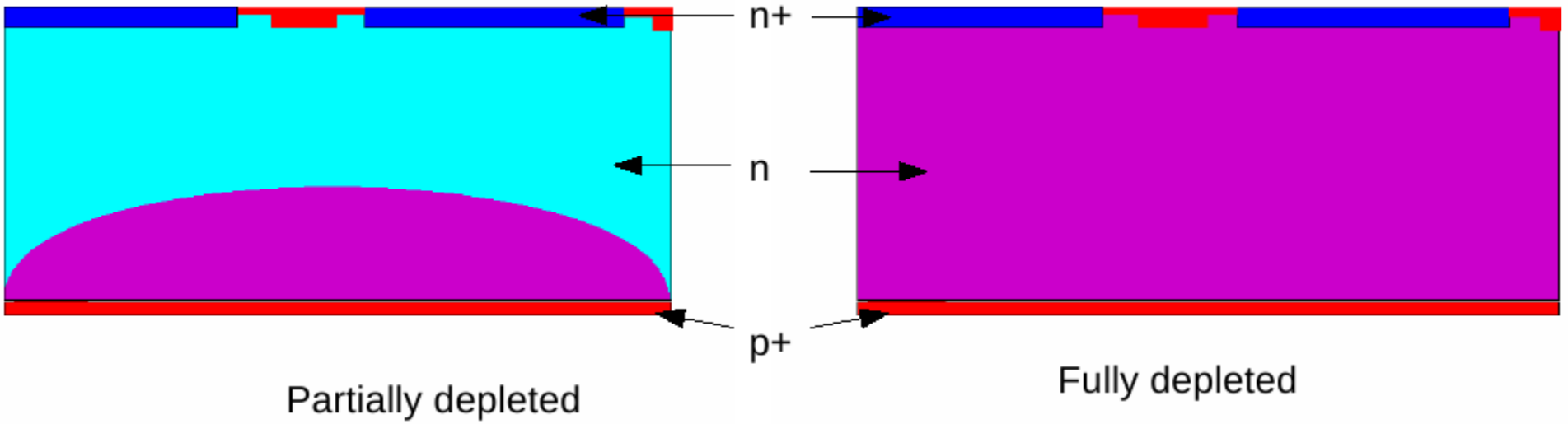
Biasing studies. Wafer 3

Only guard connected → “punch through” polarization
Only bias connected → pixel by pixel polarization



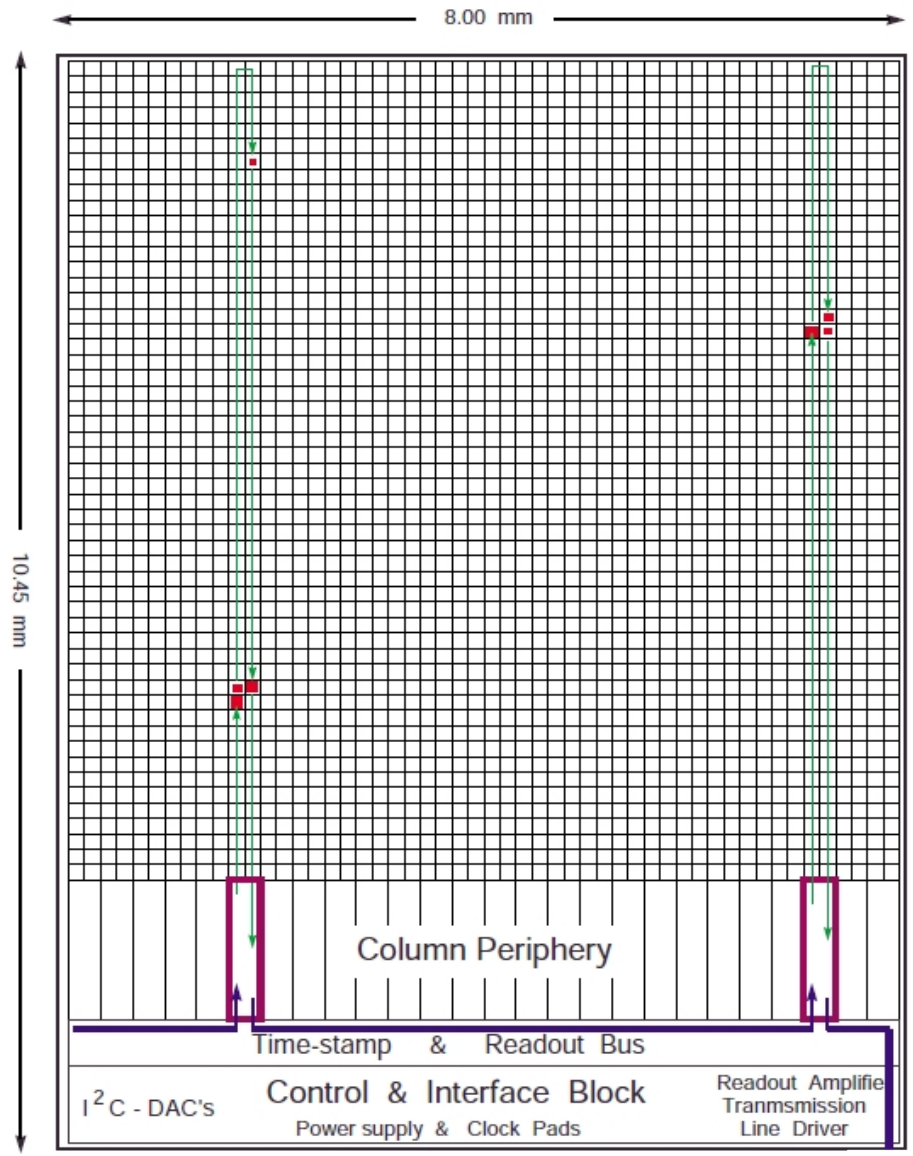
Same meas.

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



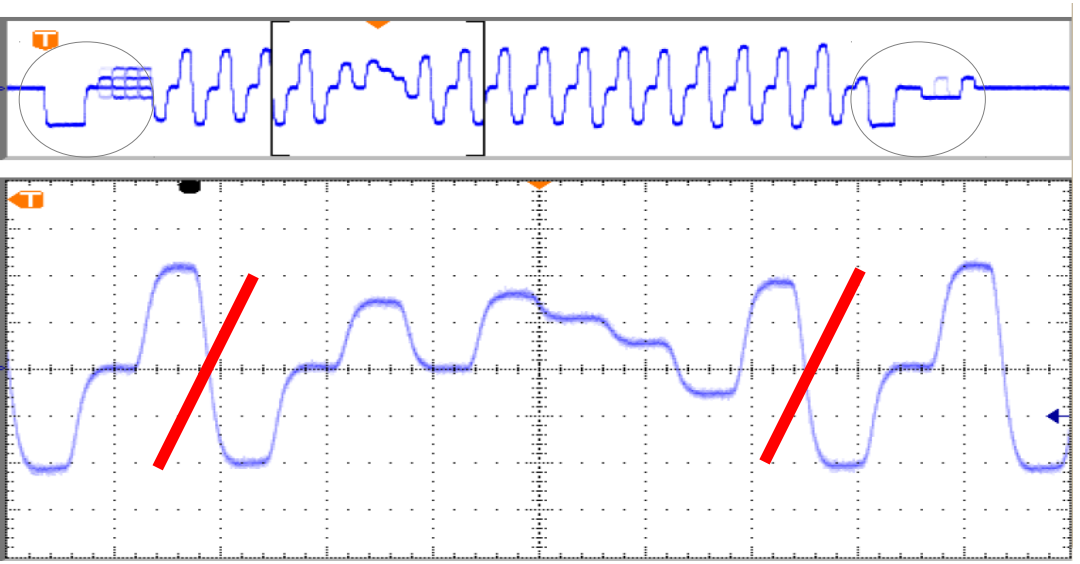
- Paths of column token through double-column (green)
- Paths of the readout Token through the double- column peripheries

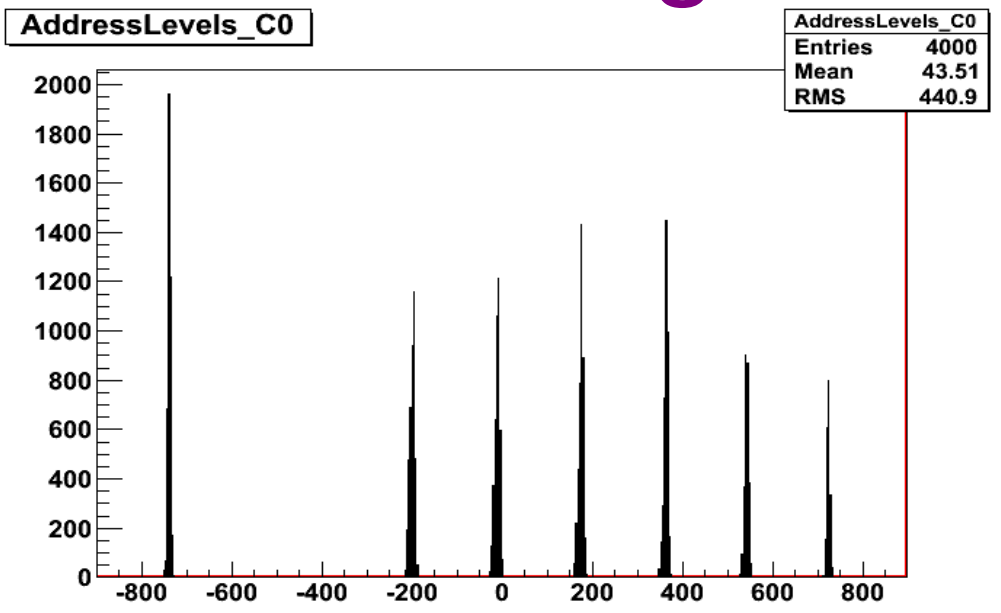
- When the column token stops at a pixel with hits. All hit information (pulse height, address...) is transferred To the column periphery where it is Stored in data buffer

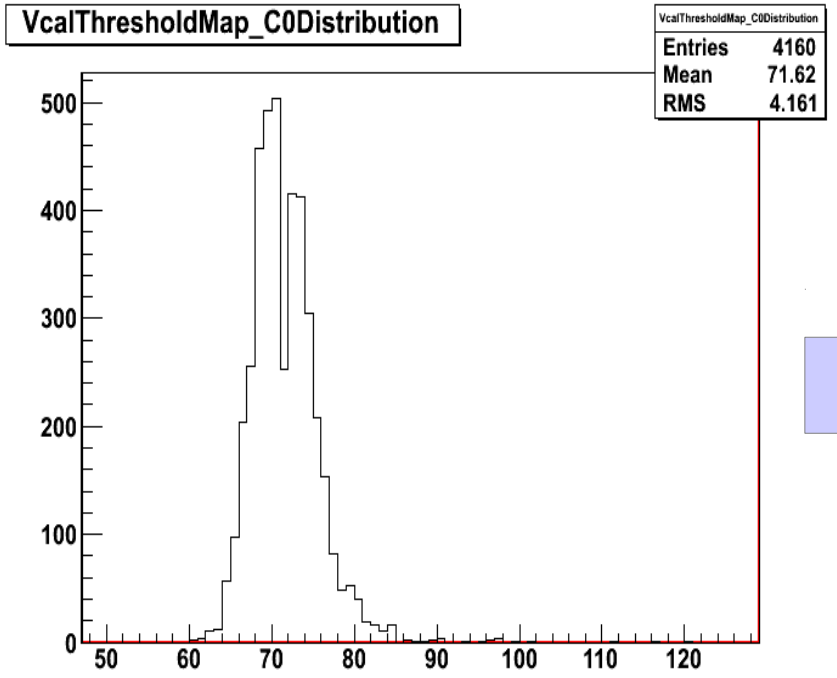
- Pixels without hits are skipped by the token

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

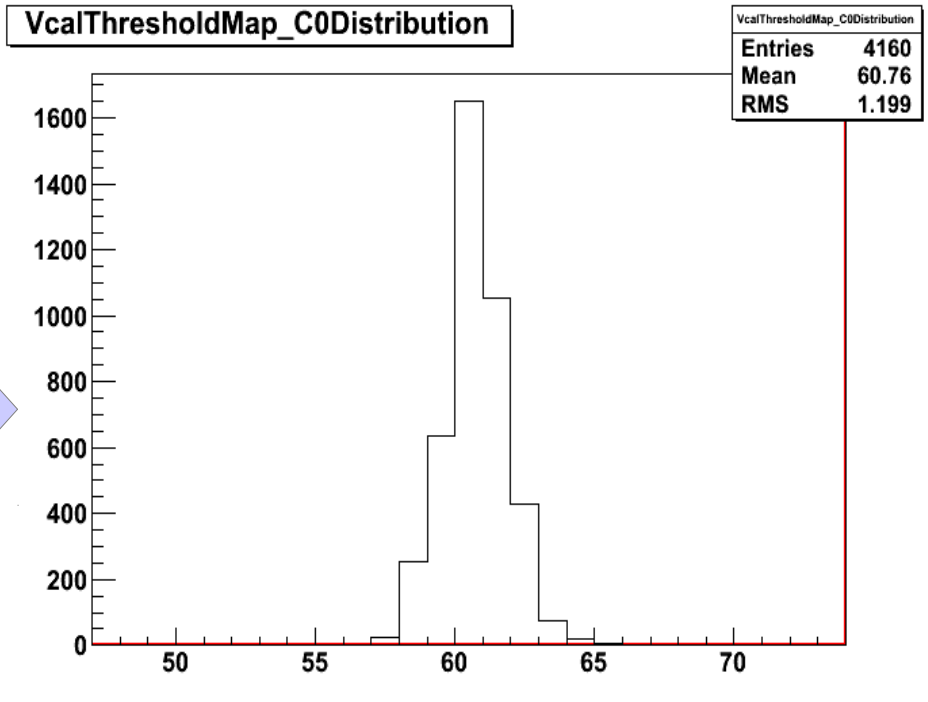
Address levels and trimming







Trimming



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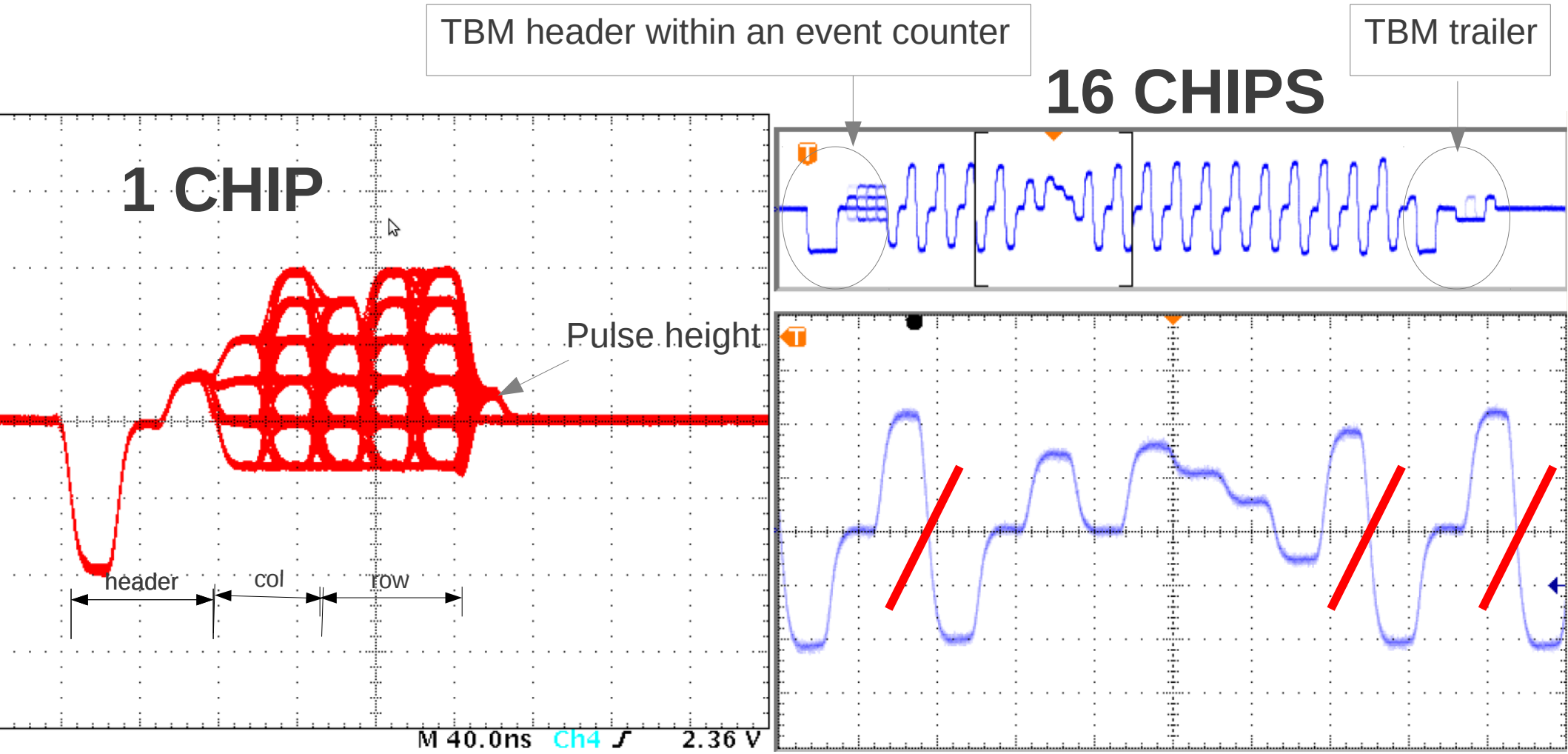
Readout format



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

ROC QUALIFICATION

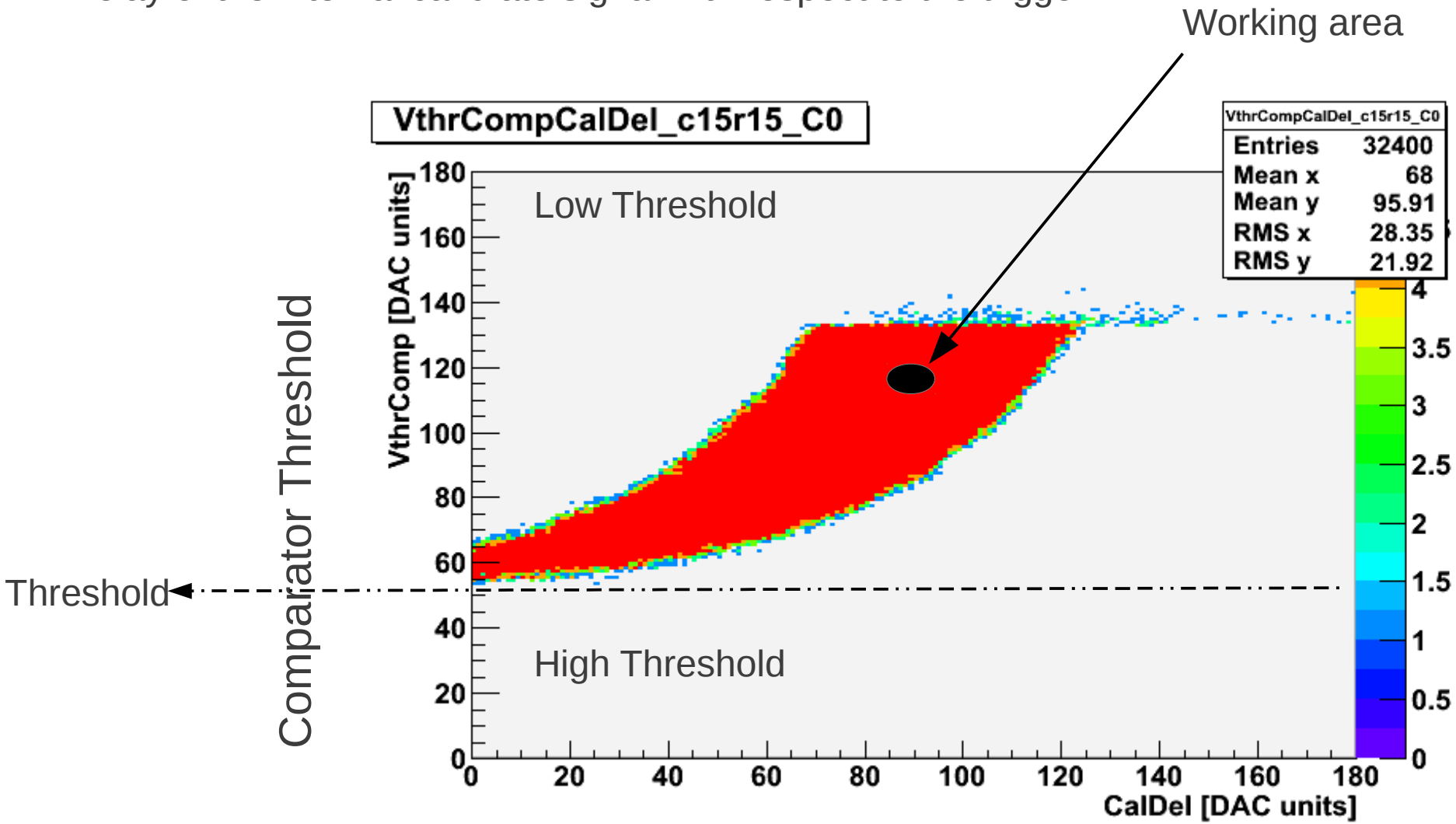
- **Calibrate Signal inputs**
  - Vcal
  - Vana
  - Vthrc
  - CalDel
- **Pixel readout circuits**
  - Pixel
  - Trim bit
  - Bump-Bonding
  - Pixel Address

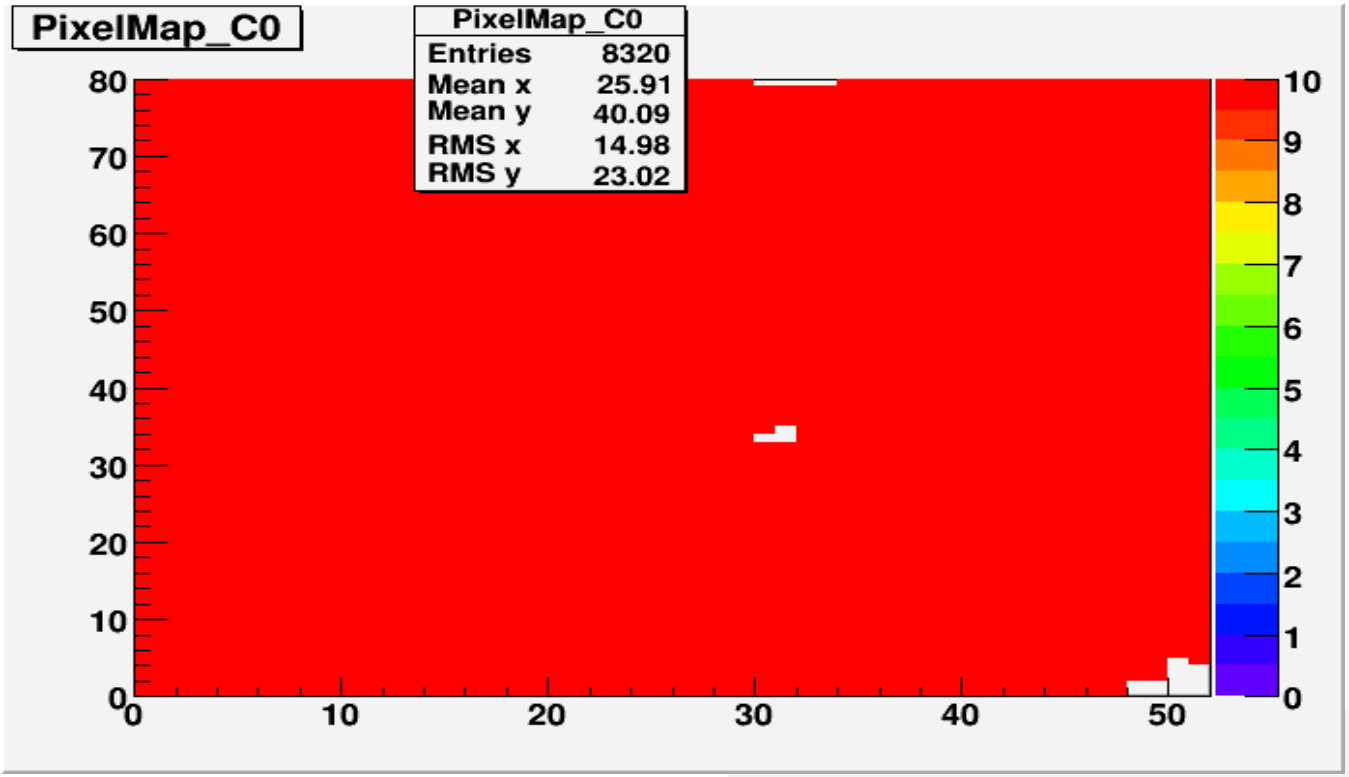
- **Functionality of the module**
  - Noise
  - Trimming
  - Gain and Pedestal
  - IV
  - Thermal Cycle

VthrComp vs CalDel

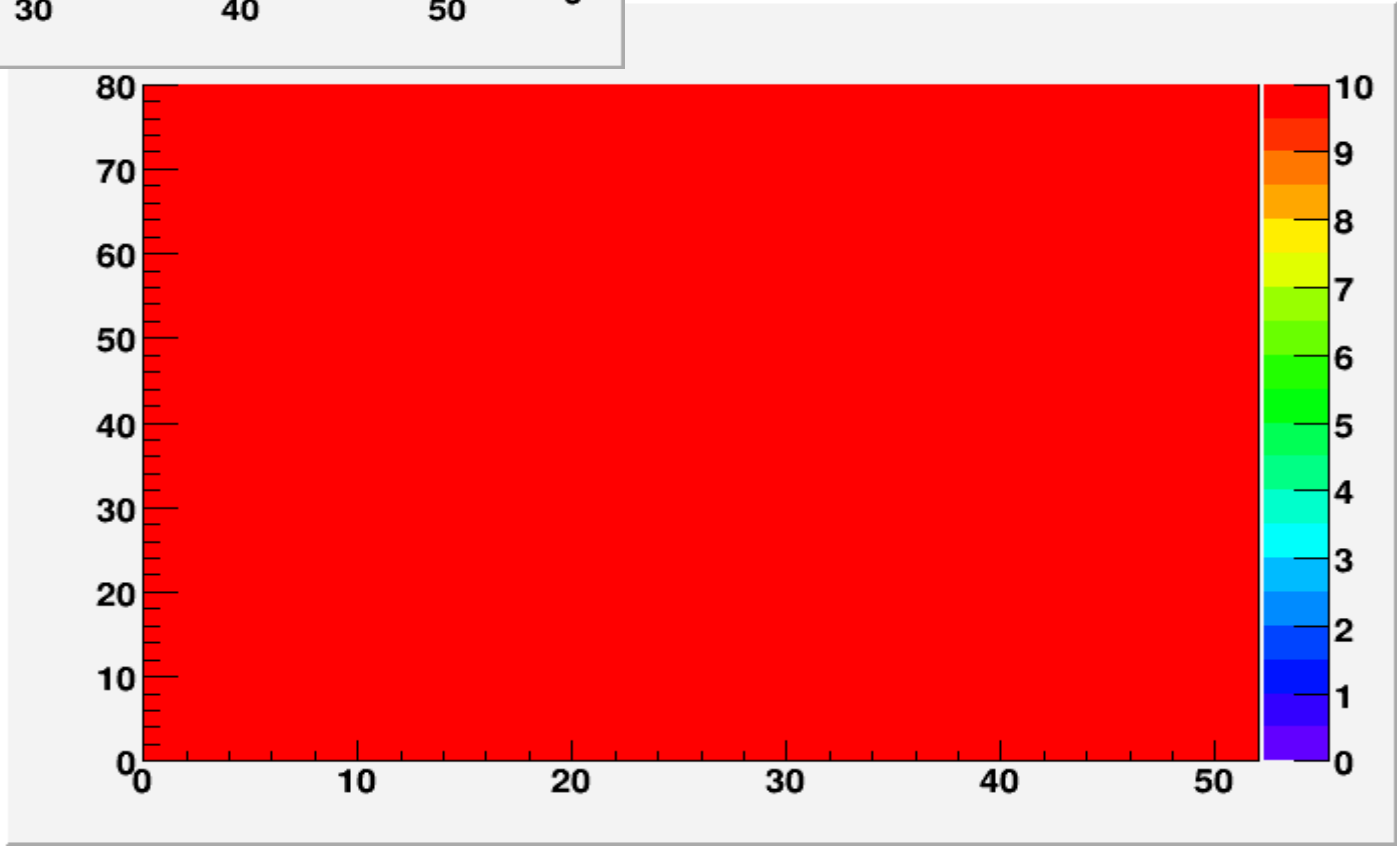
VthrComp → Injecting a signal with fixed amplitude (Vcal), finding the value at the comparator at which this signal is above threshold

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





Pixel test



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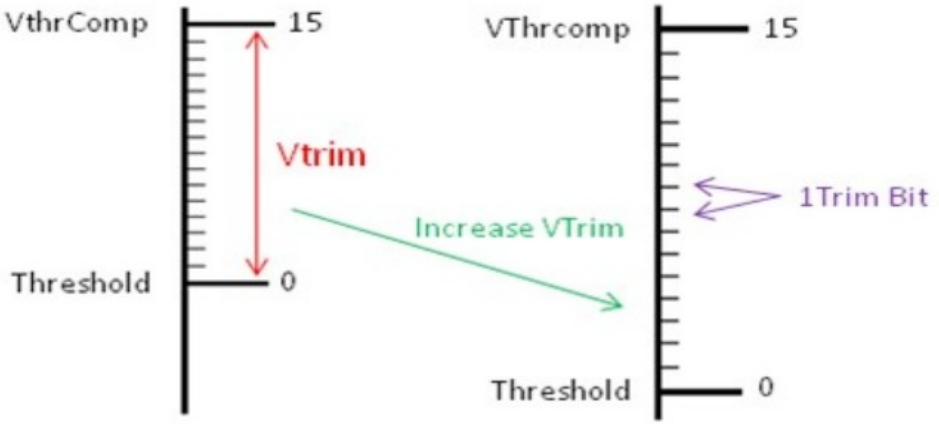
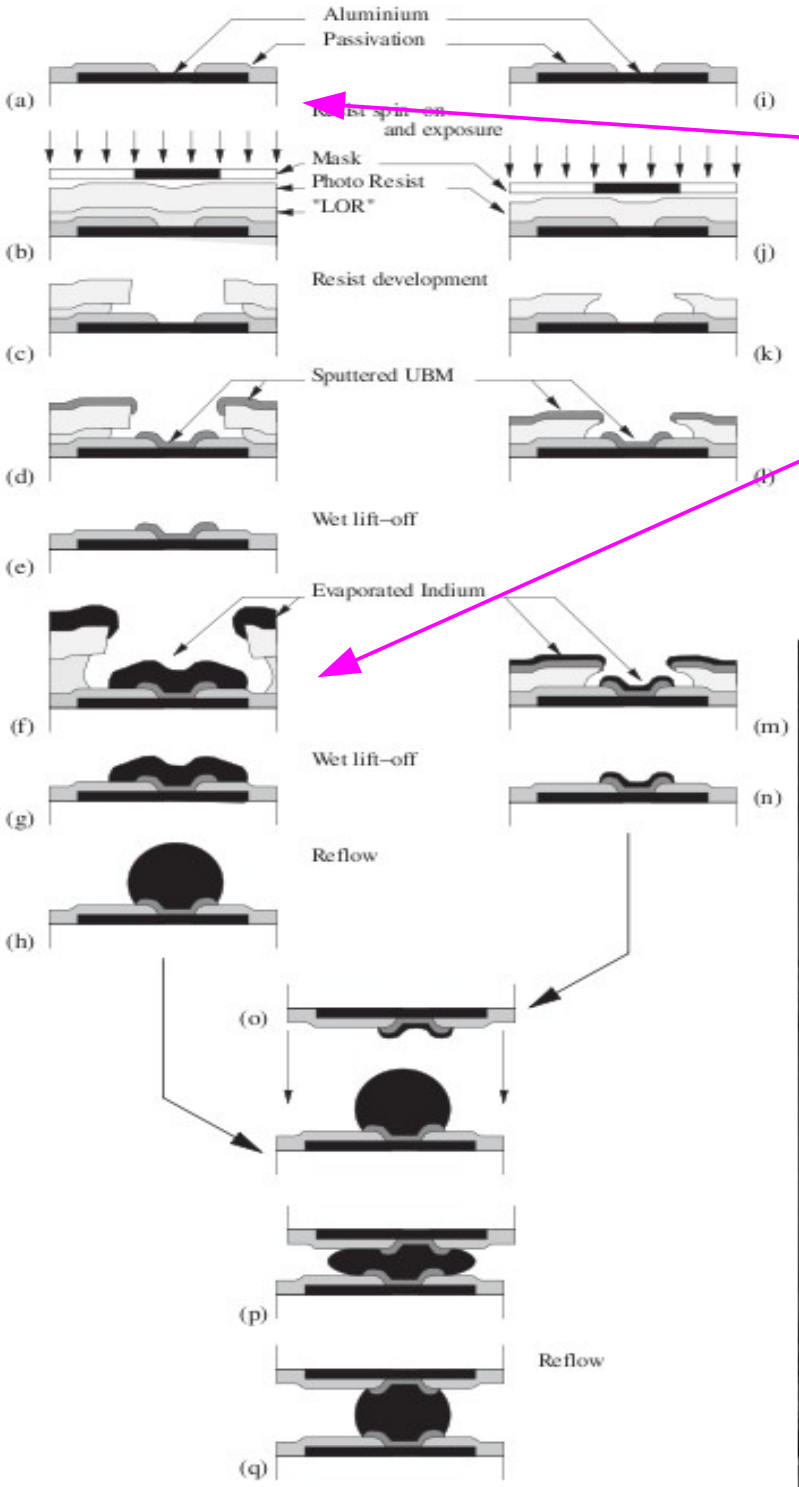
VthrComp, Vtrim and the Trim Bits

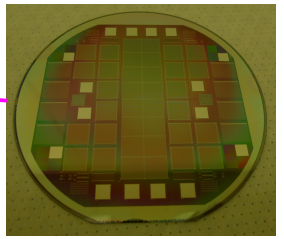
- These are the DAC's used to adjust the thresholds of the comparators of the PUC
- VthrComp adjusts the threshold for every pixel on the ROC
- Vtrim sets range of thresholds the trim bits can be used to program the PUC to have
- Higher VthrComp and Vtrim translates into lower thresholds
- Trim Bits 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

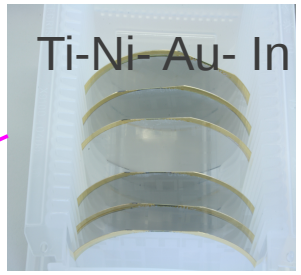
- The goal of setting Vtrim and the trim bits is to make up for the small differences in transistors due to limitations of IBM process used to manufacture the ROC
- These differences vary from pixel to pixel, and it is important to have the same threshold across the entire ROC



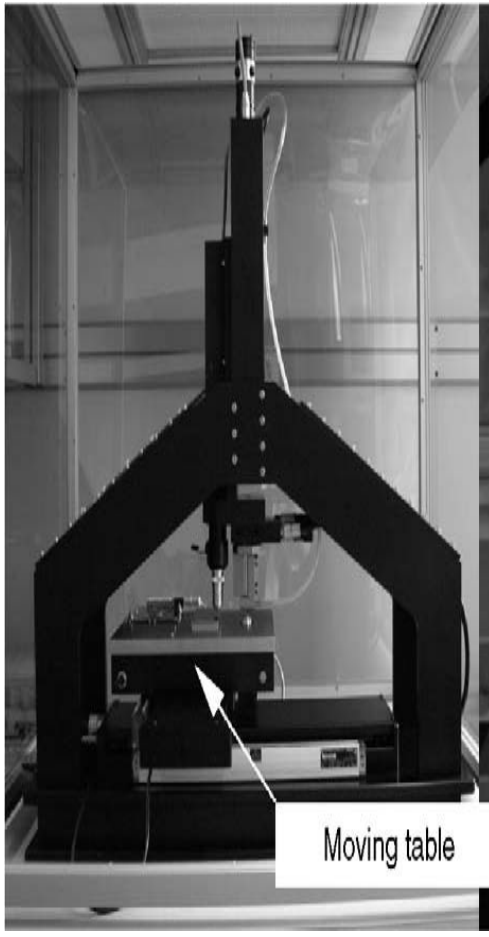
Source: Cameron Bravo's Talk, PIRE program Student PSI, Summer 2012

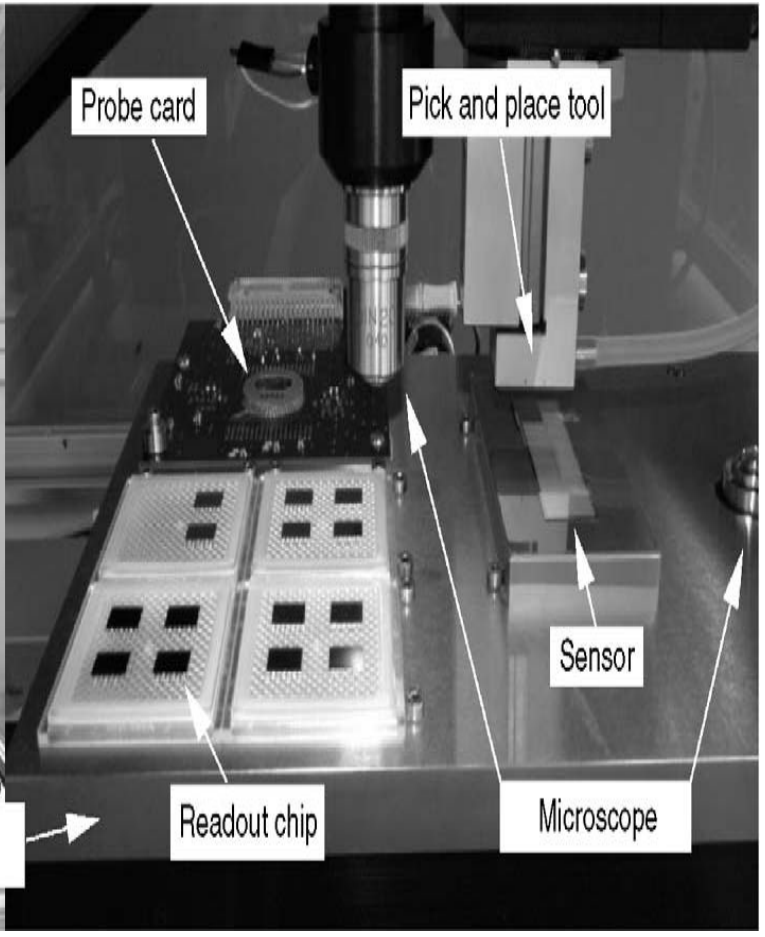






Bump bonding. Interconnection process





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

TEST BEAM in 2012:
@ PS Facilities. 1-15 Aug
@ SPS Facilities.18-30 Nov

PS Test-beam
* 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

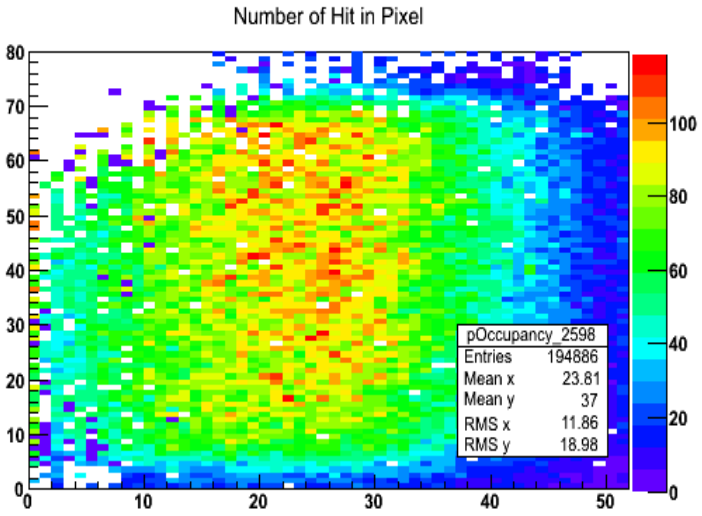
SPS Test-beam
* Not much beam time, and in parasitic mode
* Bump connections reduced after irradiation (mechanical stress)

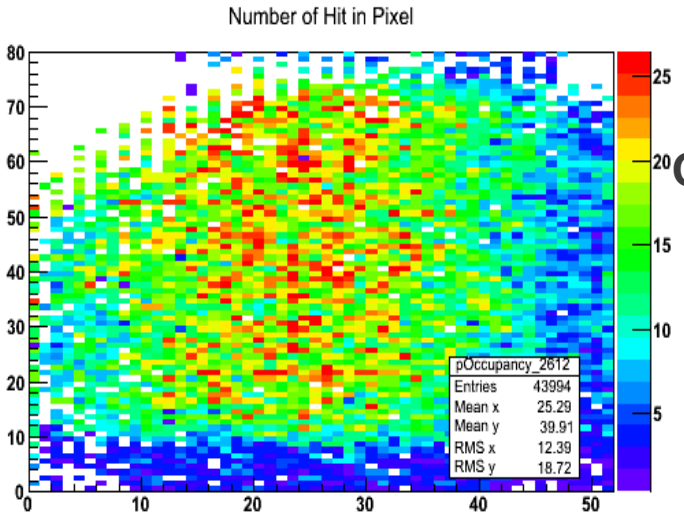
TEST BEAM @ PS

An unirradiated sensor has been measured at two different angles

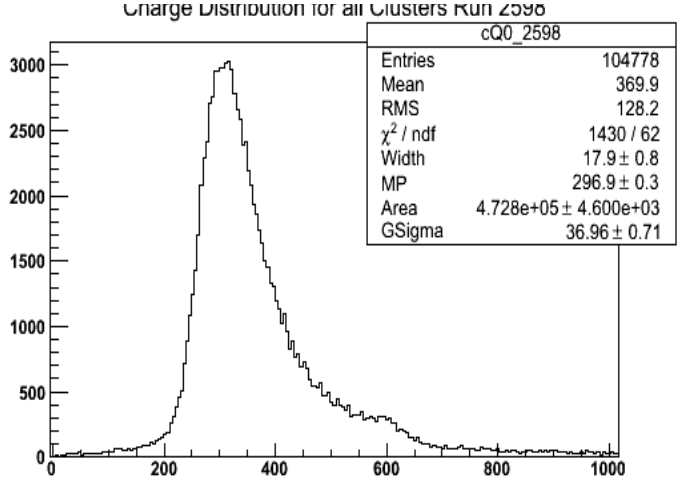
SENSOR 12B: $MPV_{(0^o)} = MPV_{(\alpha)} * \cos(\alpha)$

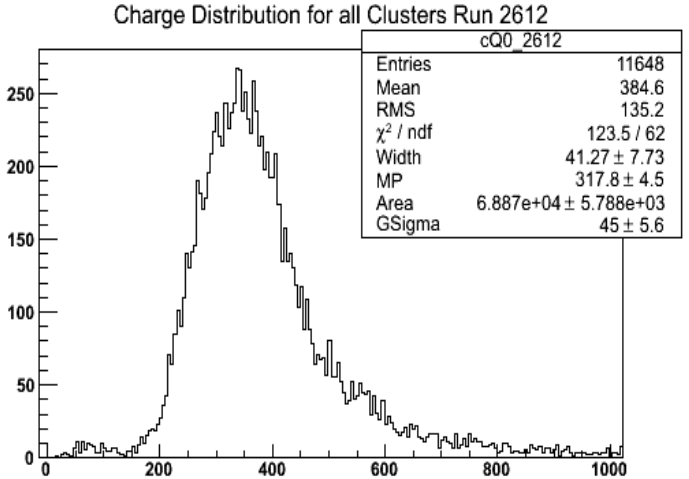
$296.9 = 317.8 * \cos(\alpha)$ -----> $\alpha = 21^o$





Occupancy Maps for the two Different angles





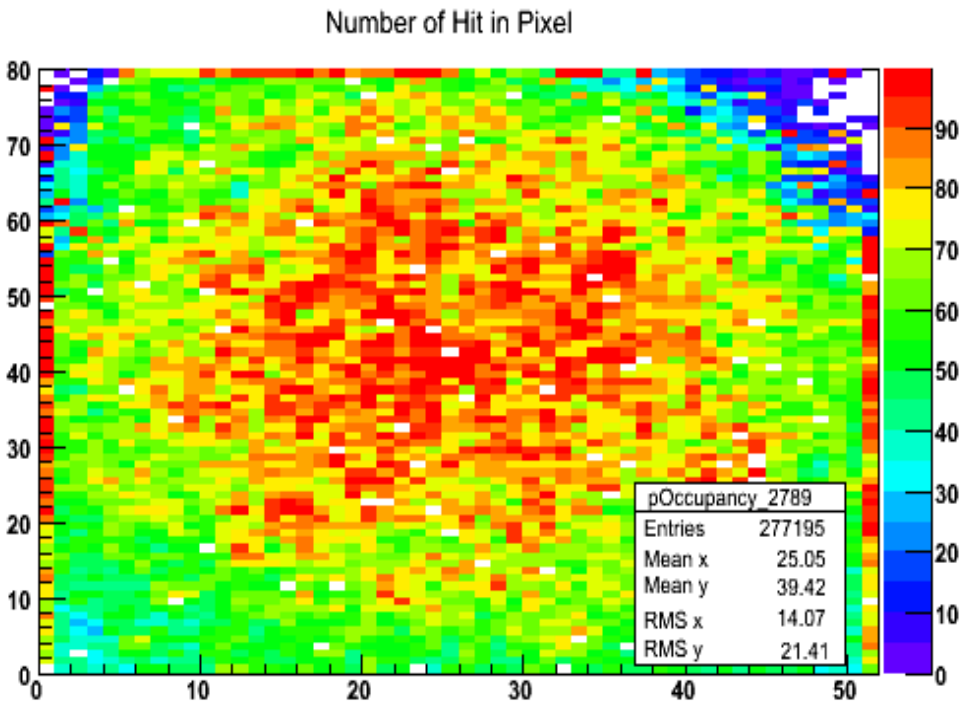
Landau distributions

TEST BEAM @ SPS

Bump connections reduction after irradiation due to the mechanical stress

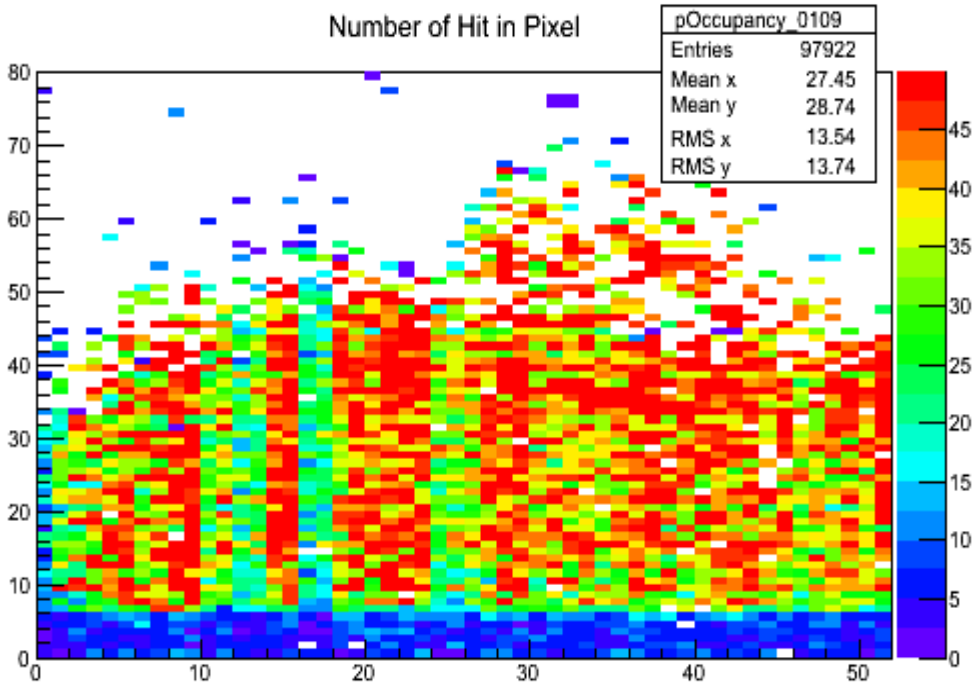
Occupancy map before irradiation in

PSI laboratory



Occupancy map after irradiation in

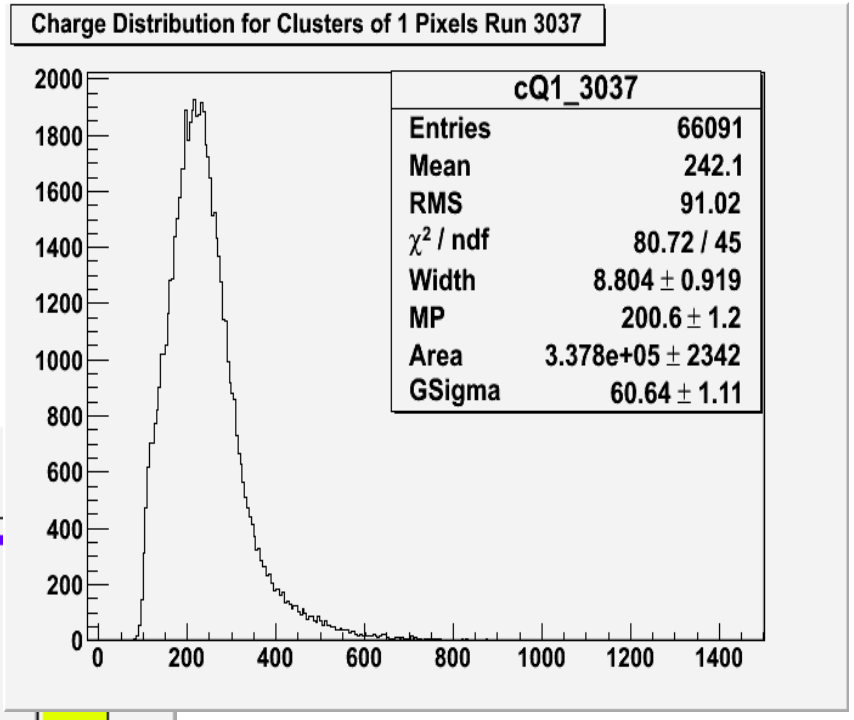
SPS Test Beam

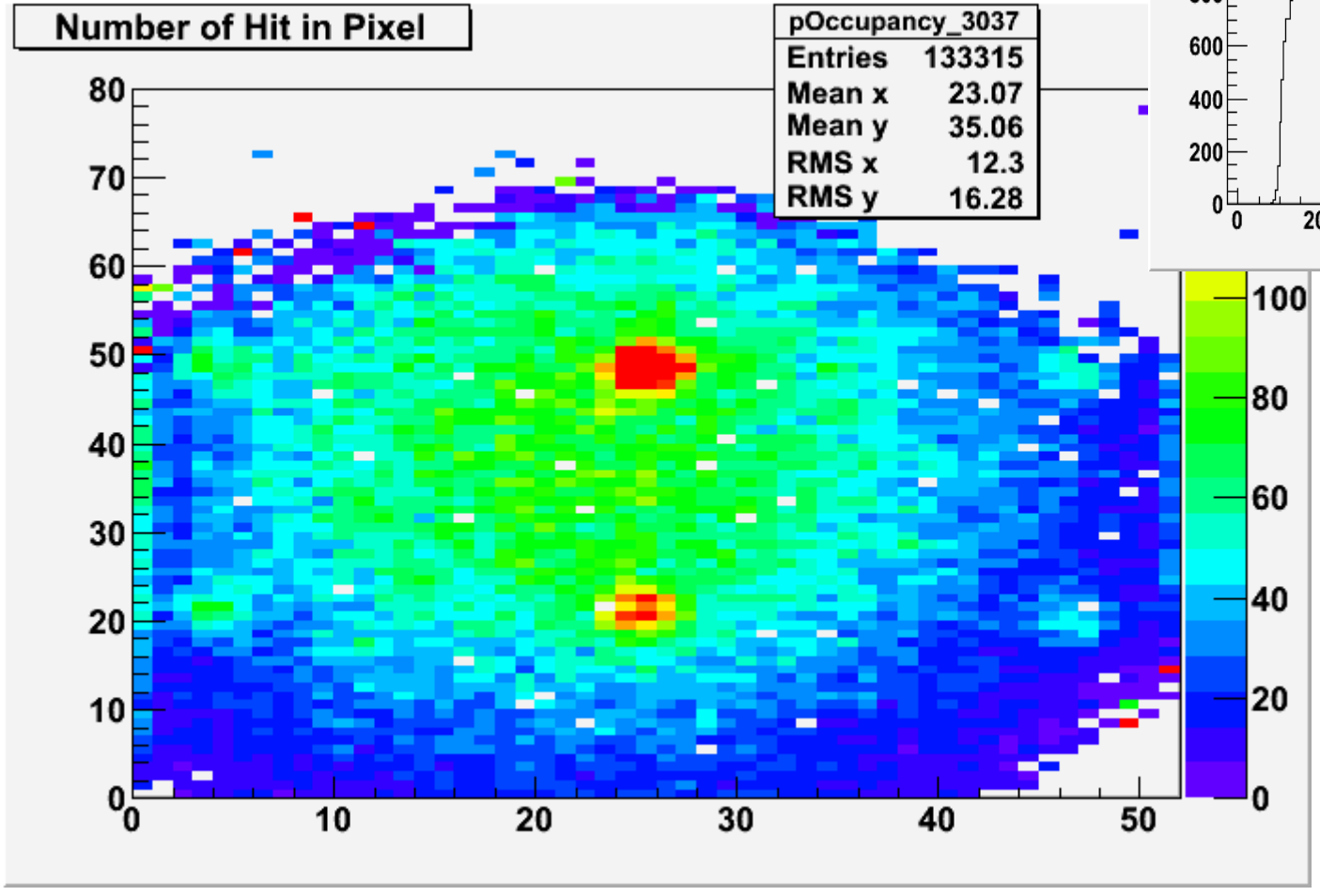


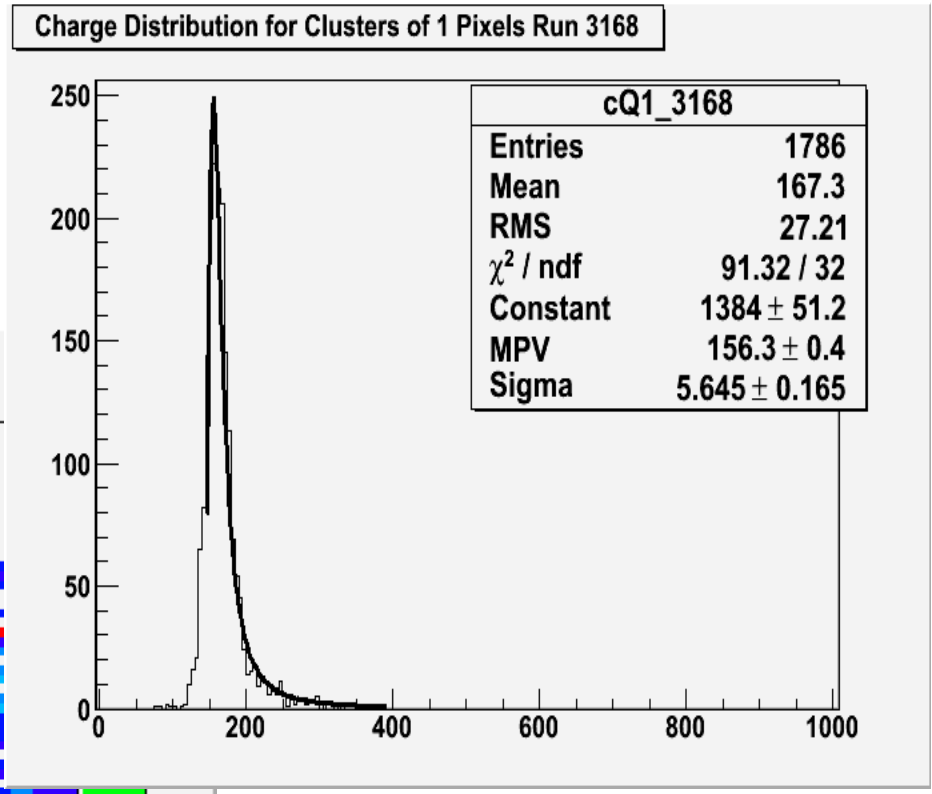
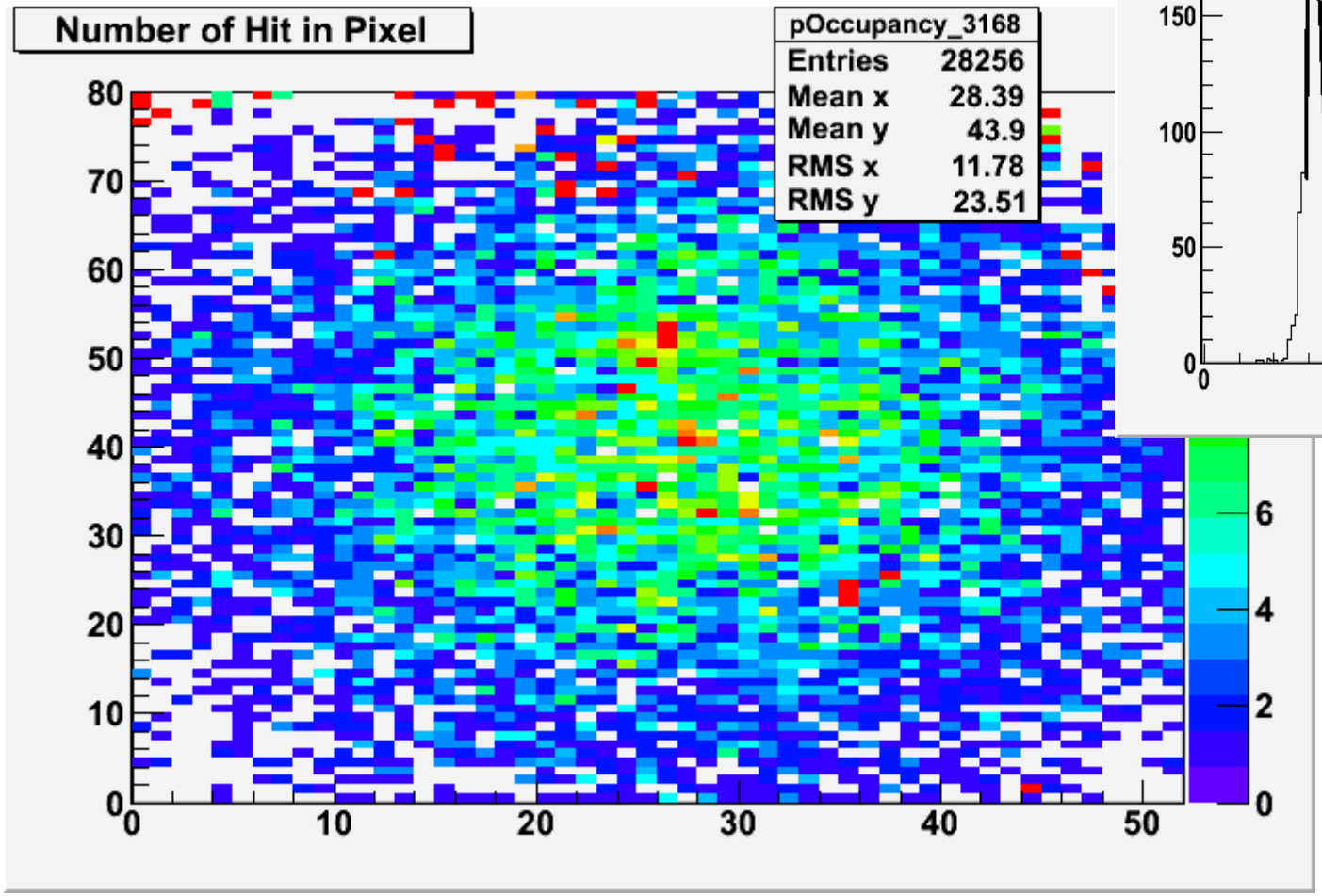
Irradiated up to $1*10^{15}$ neq/cm²

W6_21B @ 150V
T=-20ºC

NEUTRONS





Irradiated up to 5*10^{15}neq/cm^2 Protons

V= 180V @ -20ºC