Characterization of CNM's 3D pixel sensors for the CMS Phase-2 upgrade

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Outline

- Motivation
- 3D pixel technology and manufacturing
- Electrical characterization
- PSI46 Read Out Chip (ROC) and interconnection process
- Radiation resistance studies
- Test Beam Results
- Conclusions

Motivation: LHC to HL-LH

- Luminosity: 10^{34} $cm^{-2}s^{-1}$.
- Fluence: $6x10^{14}n_{eq}cm^{-2}$.
- Inner Radius: 4.4 cm
- Planar n-on-n sensors

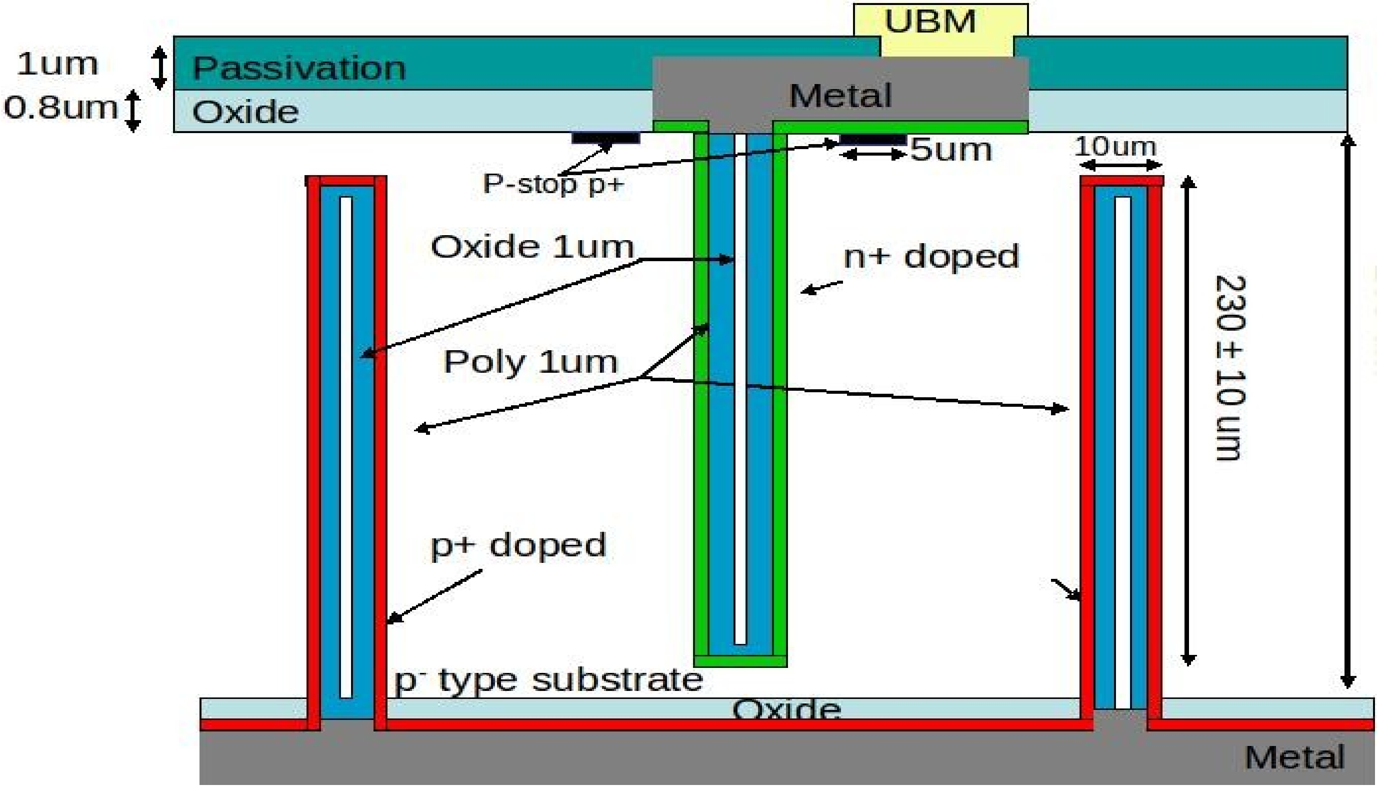
- Luminosity: 10^{35} $cm^{-2}s^{-1}$.
- Fluence: $2x10^{16}n_{eq}cm^{-2}$.
- Inner Radius: 3 cm
- 3D, thinned, n-on-p or diamond sensors?

Here we are going to assess the radiation resistance of 3D double-sided pixel sensors in terms of:

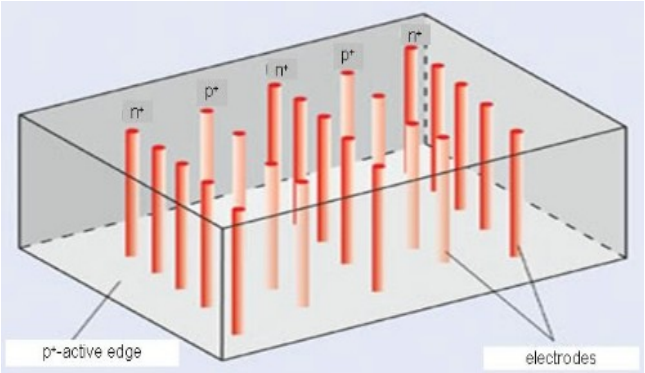
- **Increase of the depletion voltage (Vfd)**
- **Reduction of the CCE**
- **Tracking Performance and efficiency**

Technology

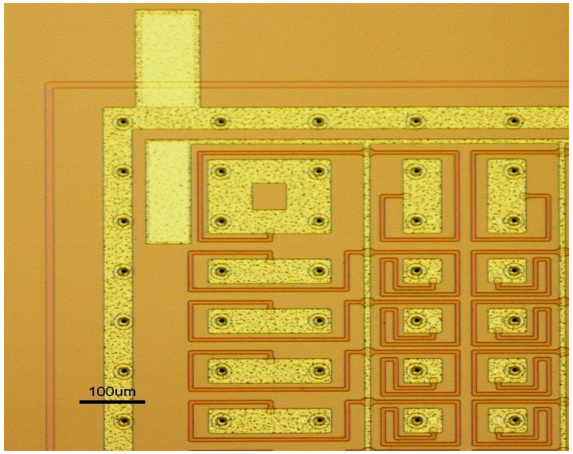
- Double-sided configuration (different doping type on each side)
- Simpler fabrication process
- Photo-lithography to define electrode contacts is only necessary on top surface
- HV biasing on the back side by simple wire bonding



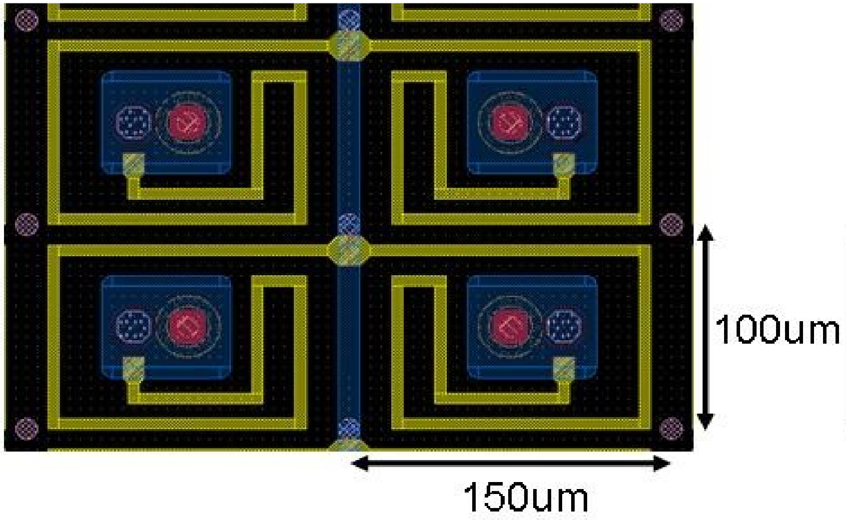
Proposed by G. Pellegrini (2006)



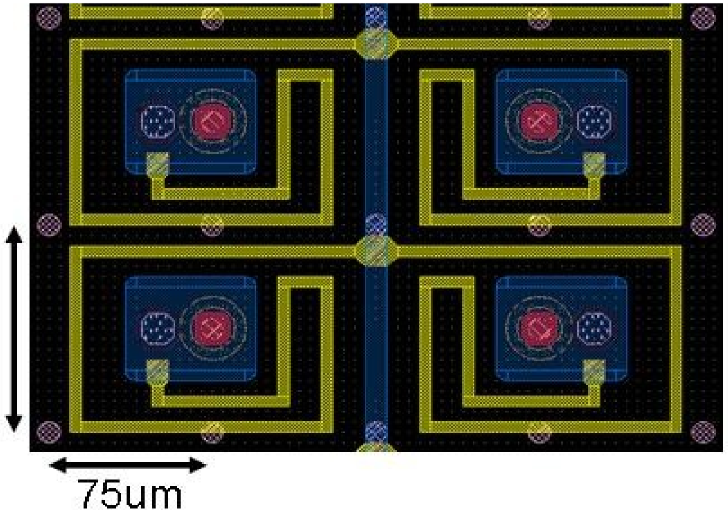
Sensor layout



* 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



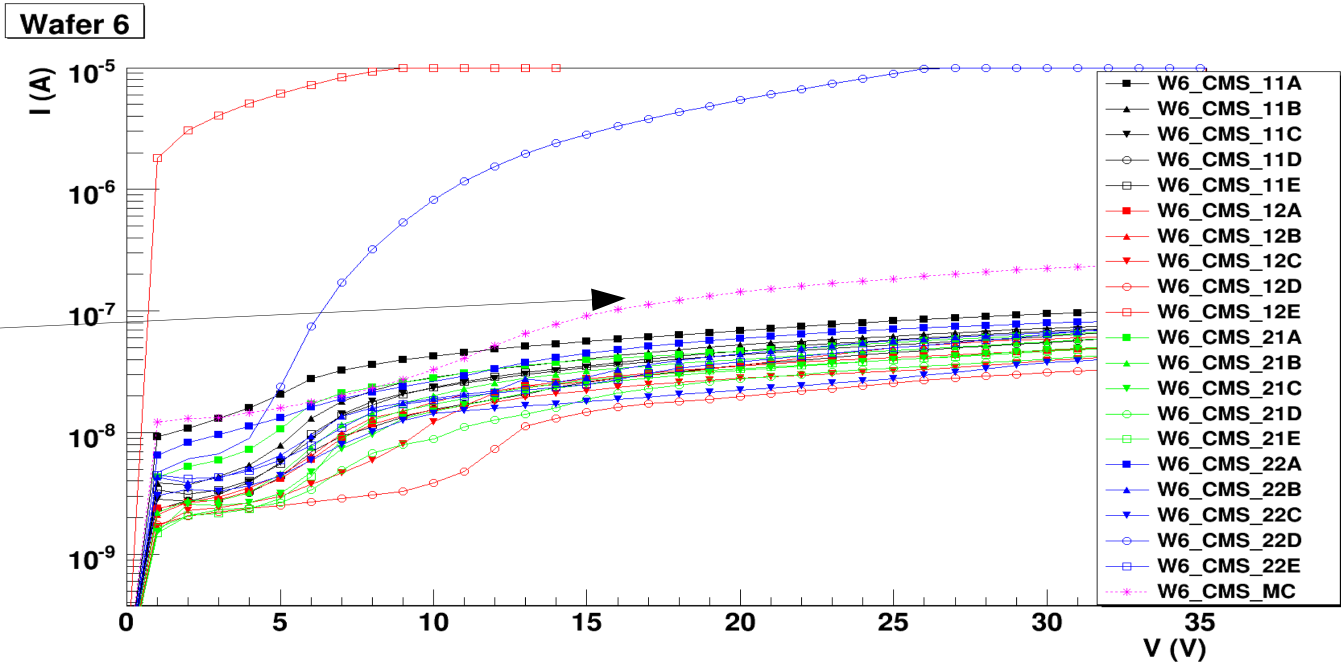
Dense pattern of holes P:
Rectangular matrix of 75x100um^2

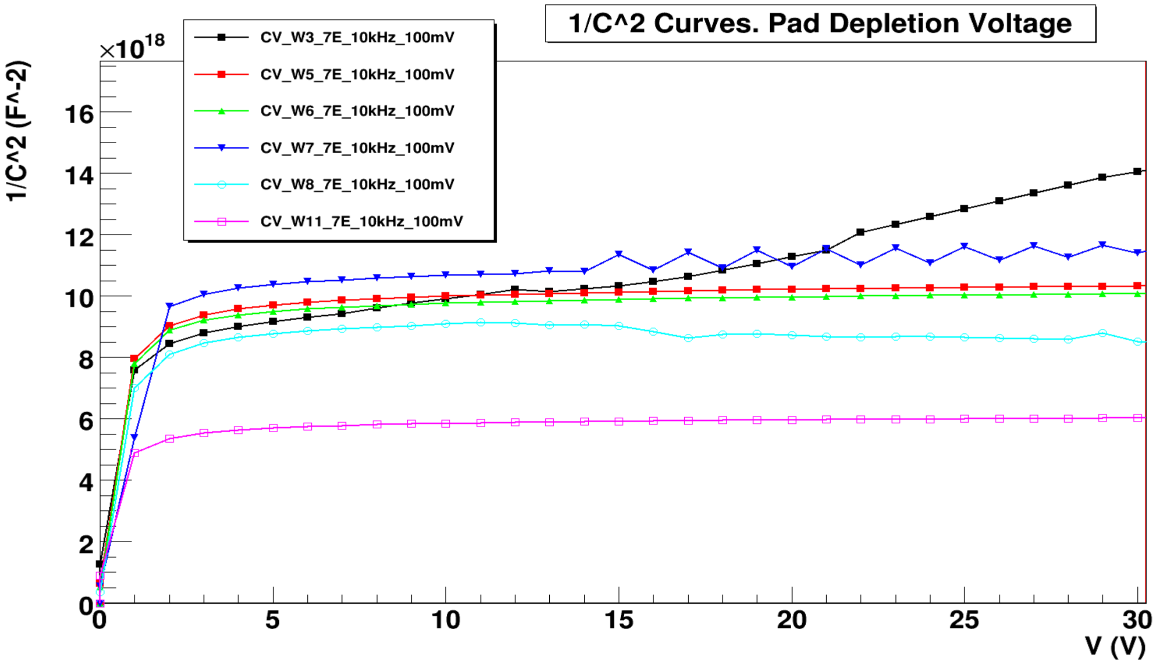
*** Wafer with a polysilicon resistor implemented for biasing without ROC**

Electrical characterization

IV Curves:
20 Single Chips with different Geometries.
1 CMS Full Module.

High homogeneity
And
Low current values



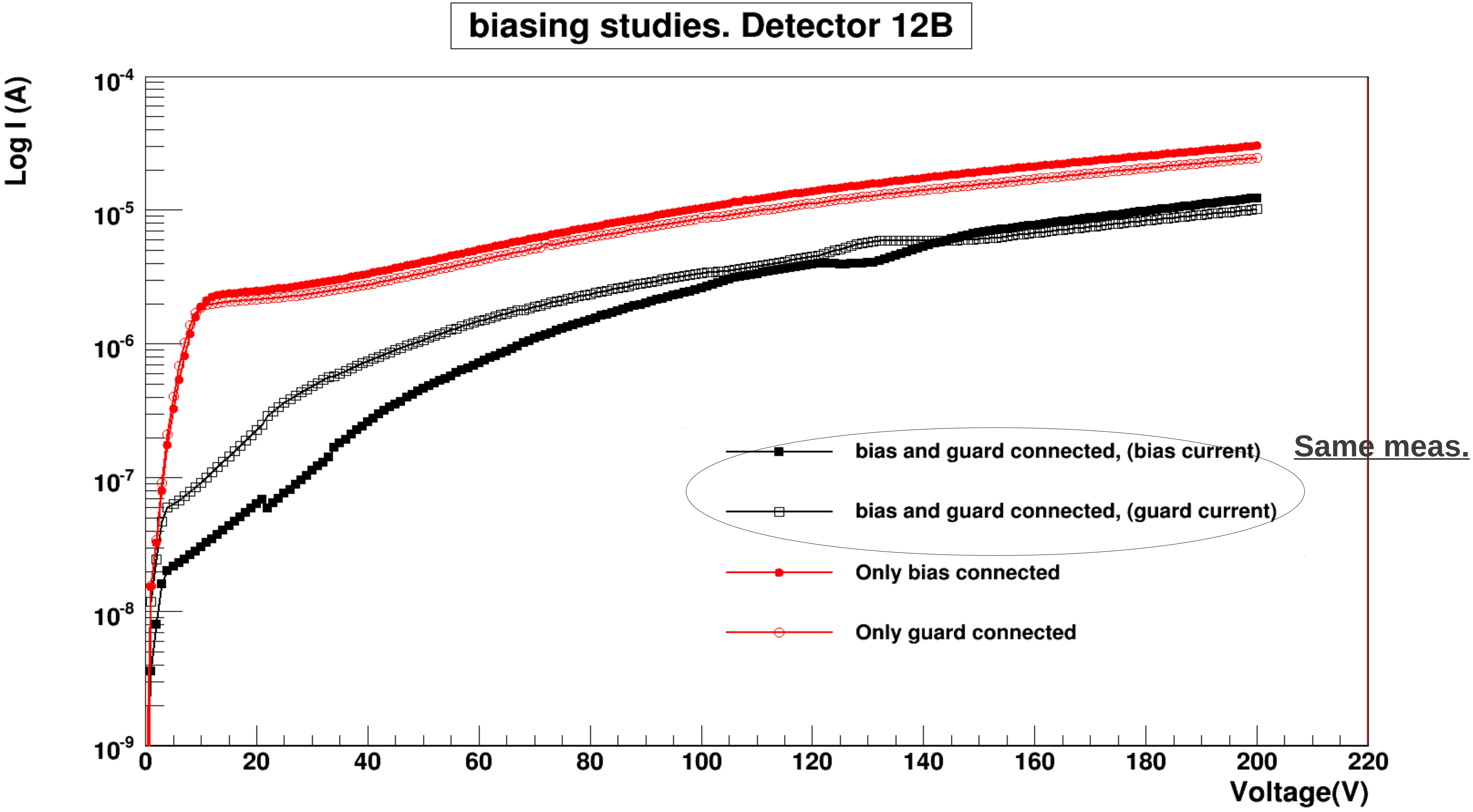


Vfd measured in dedicated TS.
Pads.

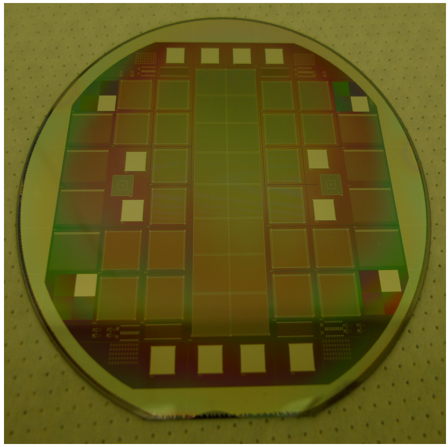
Vfd (3D-Detector) ~ 9 V

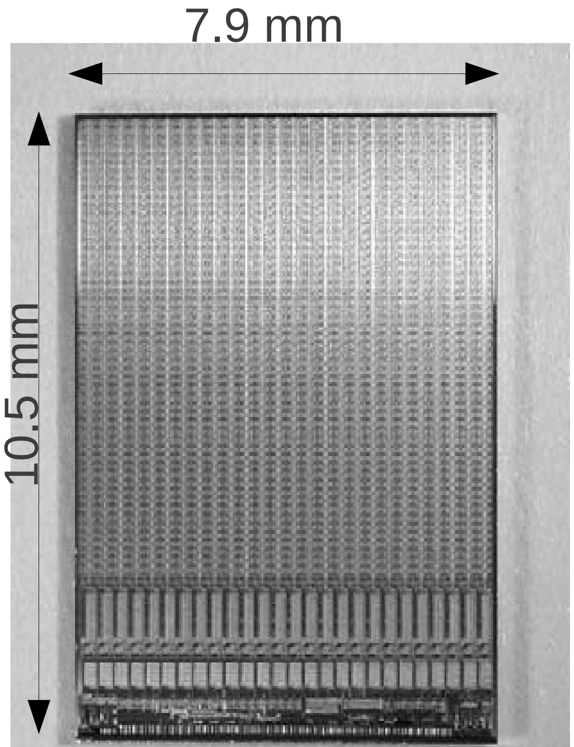
Biasing studies

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



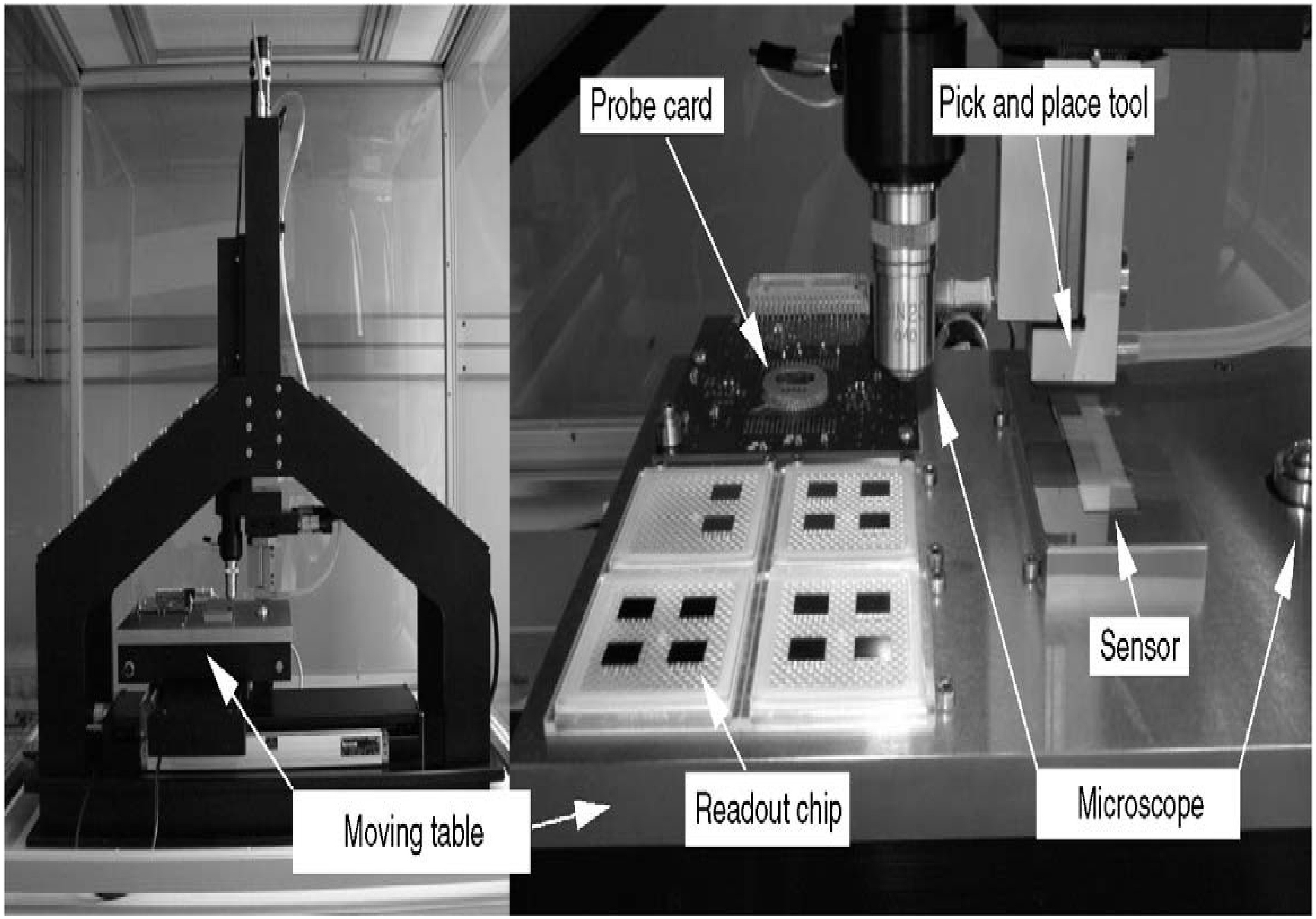
PSI46 ROC and interconnection proccess





(CMS pixel ROC)

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



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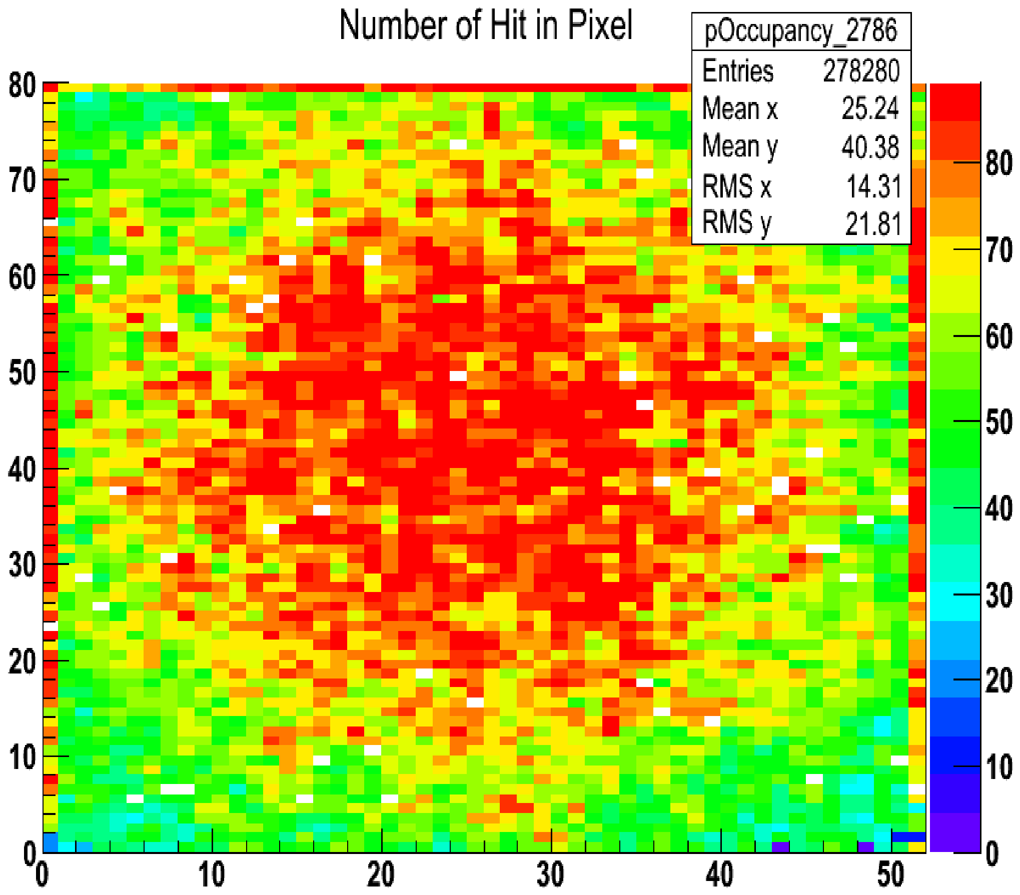
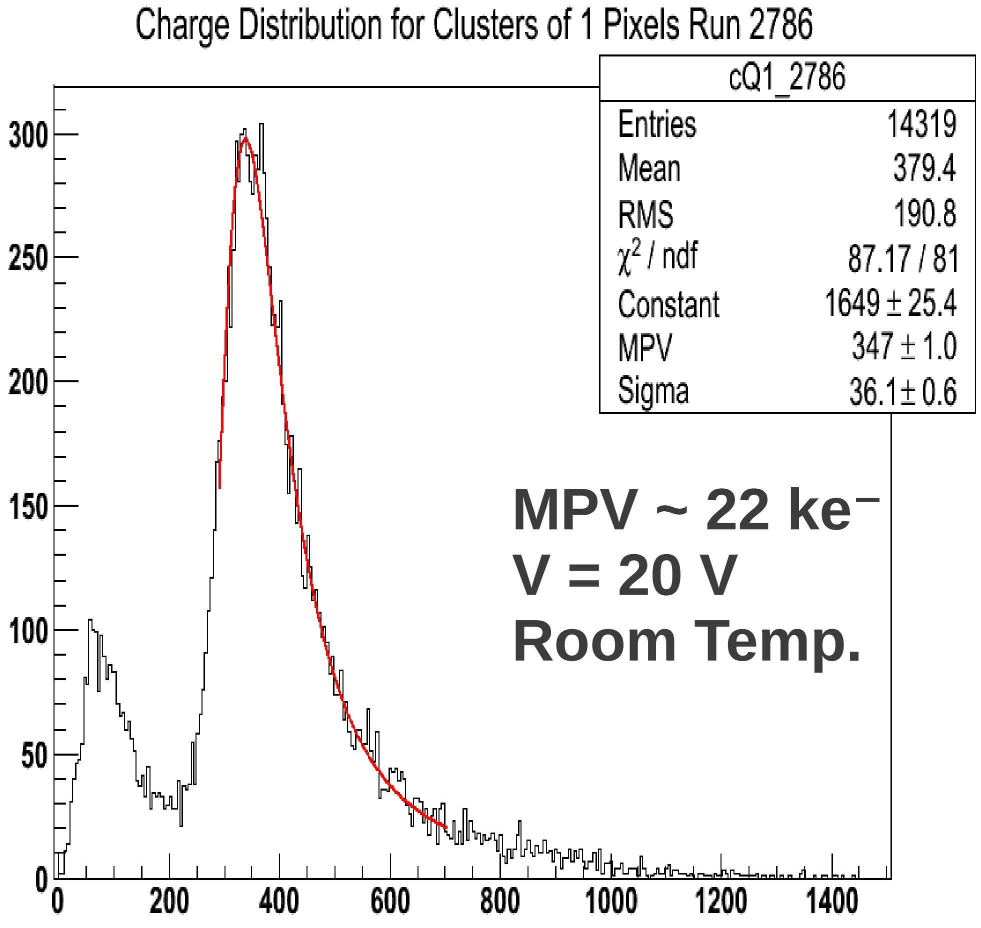
Nice Pixel map, and landau fit:





MPV ~ 22 ke$^-$
V = 20 V
Room Temp.

Irradiation Campaign:

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

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

$1 \times 10^{15}\ n_{eq}/cm^2$

$5 \times 10^{15}\ n_{eq}/cm^2$

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

$1 \times 10^{15}\ n_{eq}/cm^2$

$5 \times 10^{15}\ n_{eq}/cm^2$

$1 \times 10^{16}\ n_{eq}/cm^2$

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^{90}Sr Characterization

*** Charge Collection in irradiated samples**

*** Full Depletion Voltage:**

- Depletion Area grows in a 3D sensor horizontally

- A new variable:

$$\boxed{\mathbf{Er} = \frac{\textbf{Num. of hits}}{\textbf{Num. of triggers}}}$$

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

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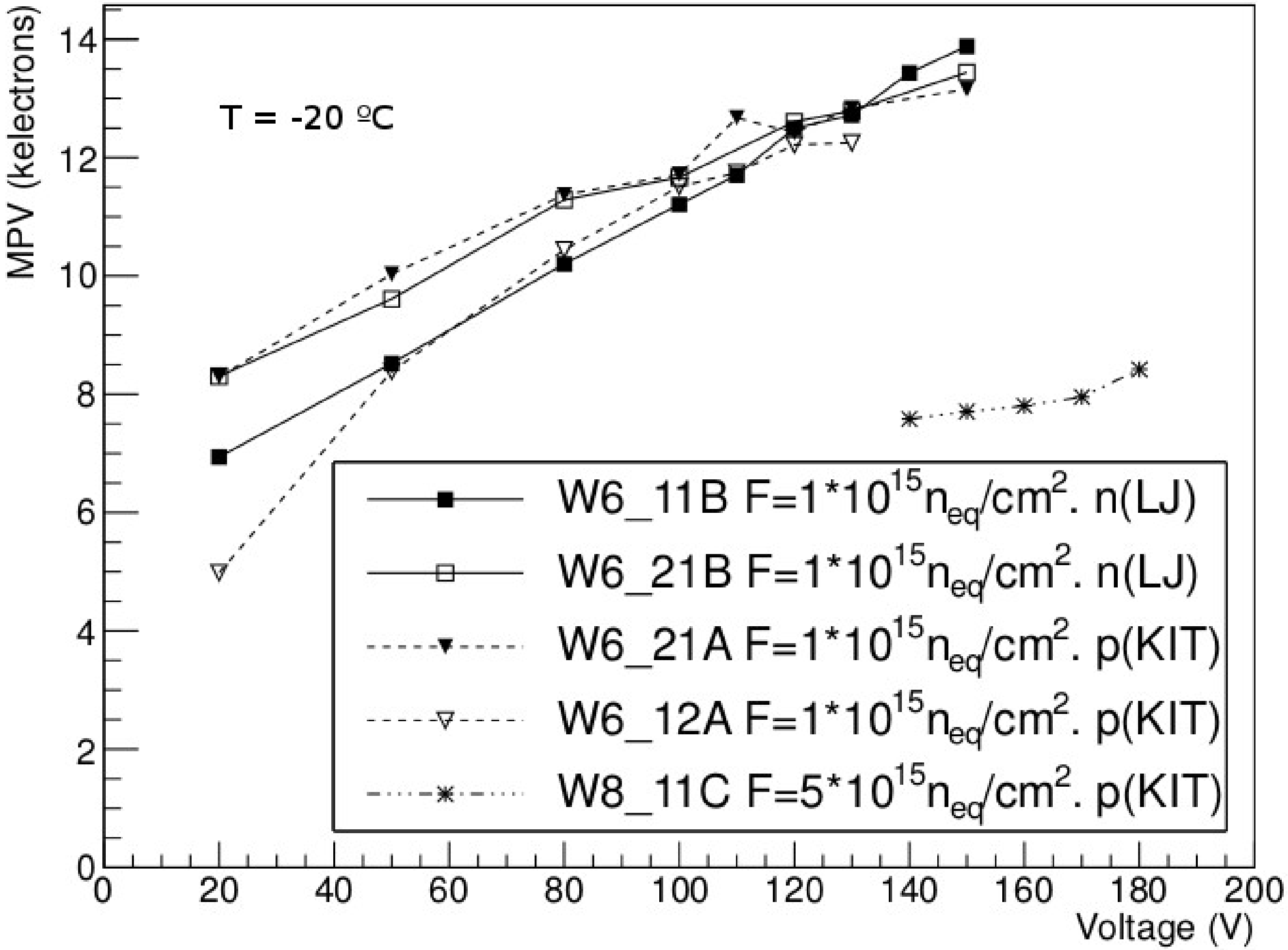
MPV vs bias Voltage in irradiated samples



NIM A: http://www.sciencedirect.com/science/article/pii/S0168900213007328

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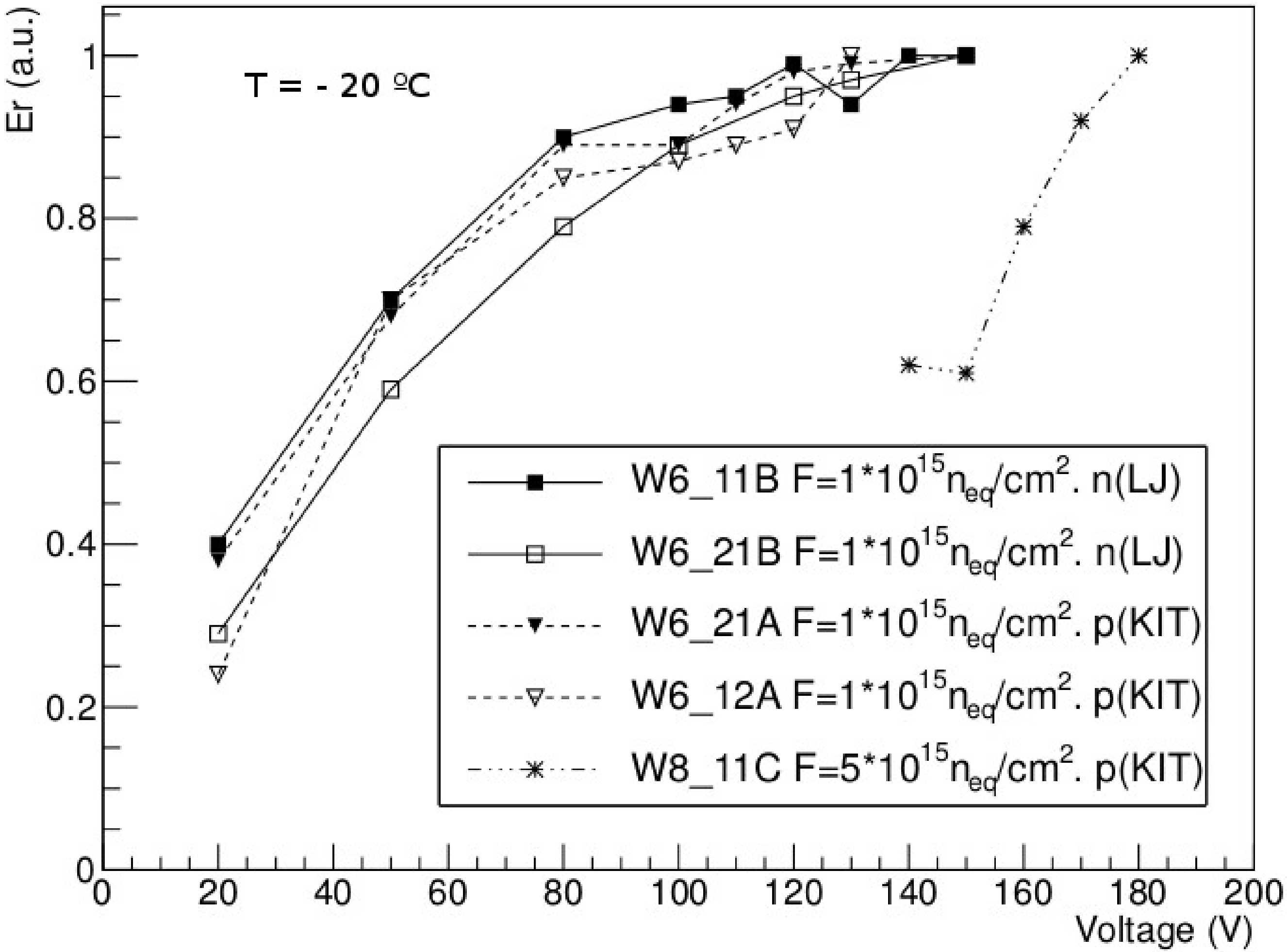
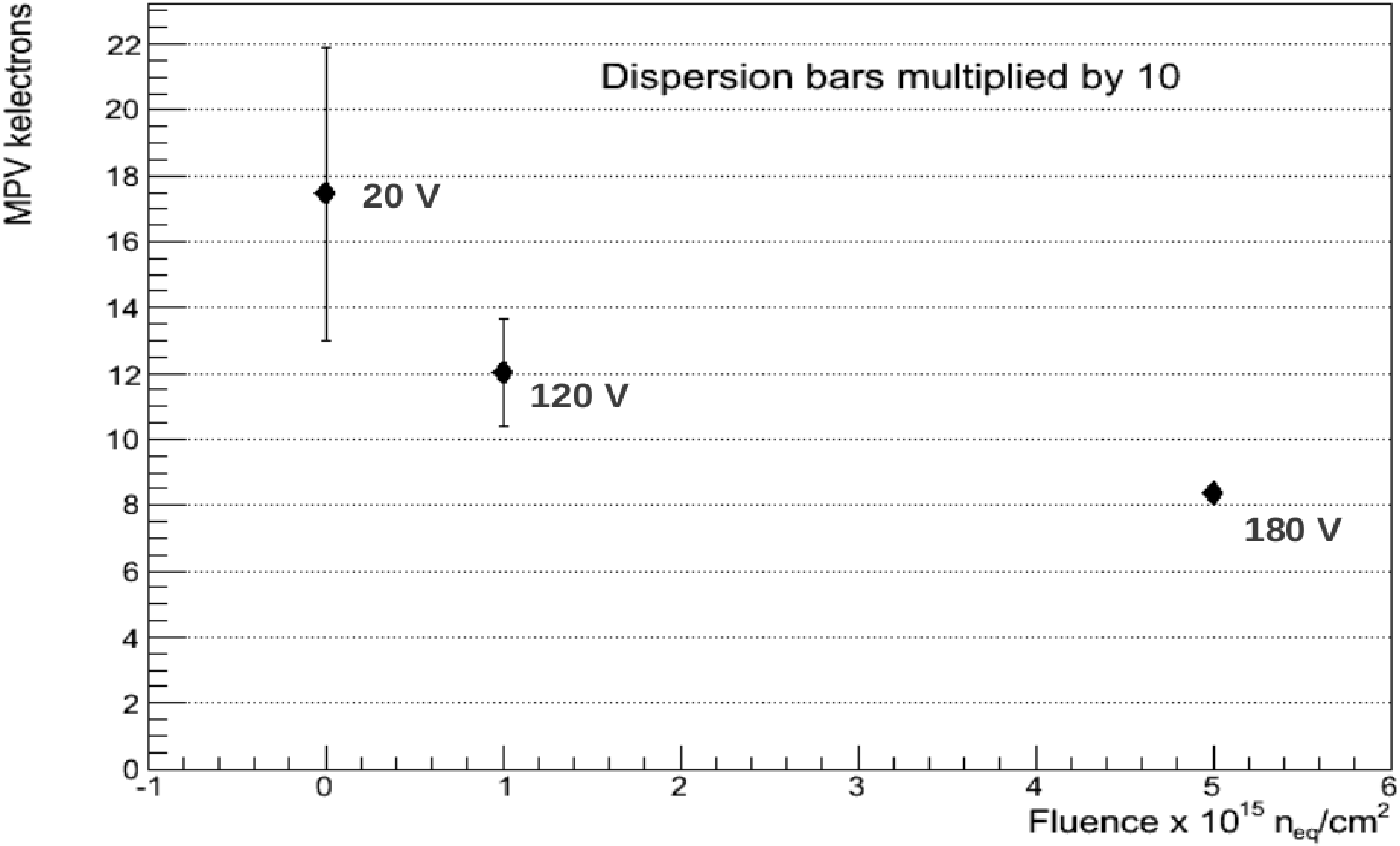
Er vs bias Voltage in irradiated samples

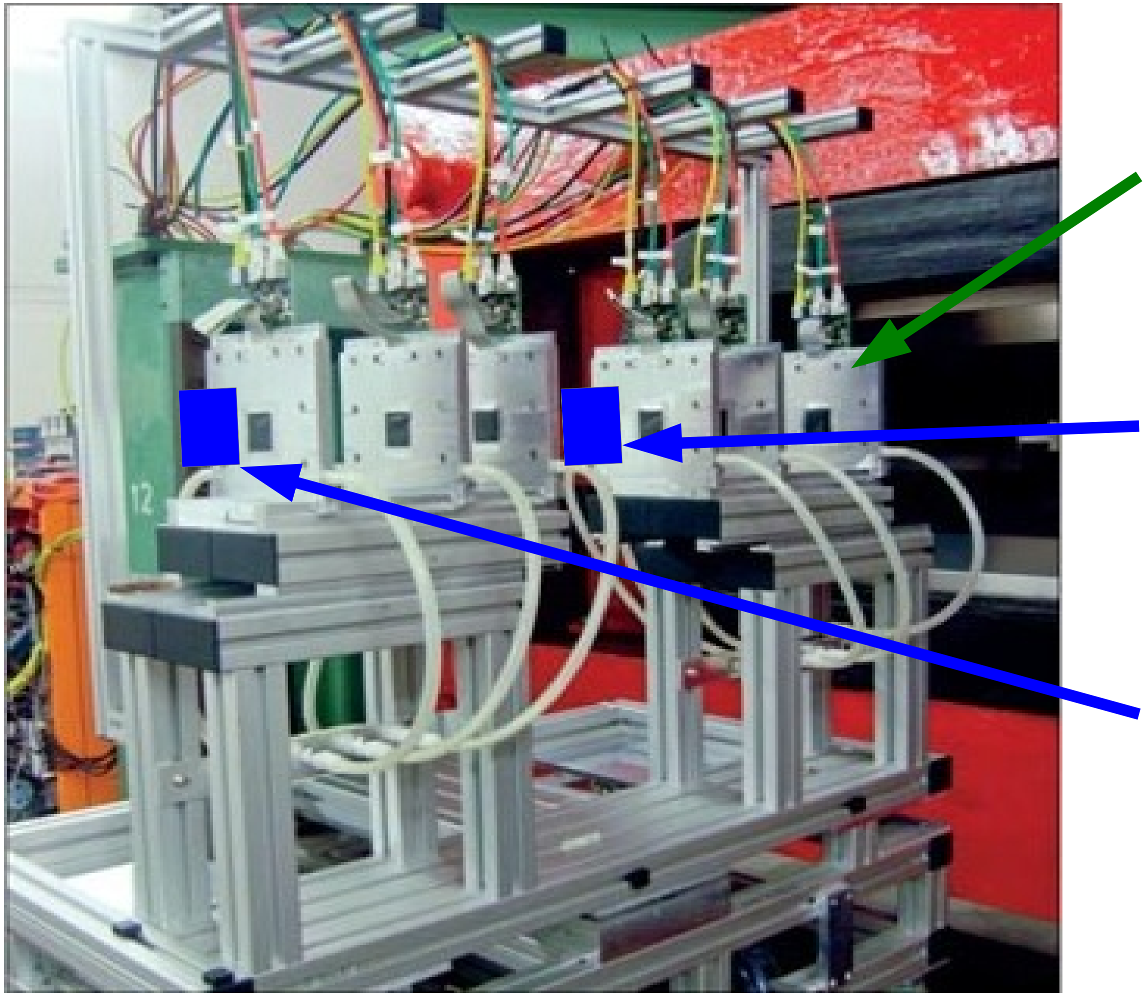


NIM A: http://www.sciencedirect.com/science/article/pii/S0168900213007328

Summary after ^{90}Sr characterization



DESY TEST BEAM.
e^+ beam (6 GeV)



DESY Experimental area 21:

DATURA TELESCOPE:
- 6 Mimosa26 monolithic active pixel sensors (Strasburg, 2009).

- Device under test (DUT). 3D pixel sensor. Normal incidence.

- Timing reference sensor. Planar CMS sensor, to correct telescope pile-up.

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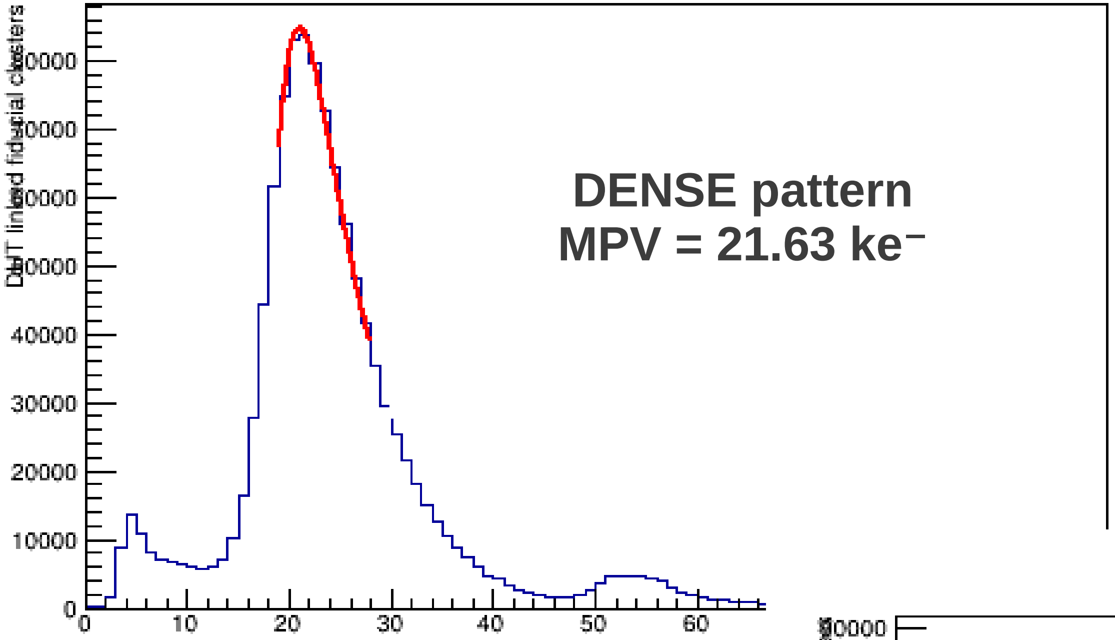
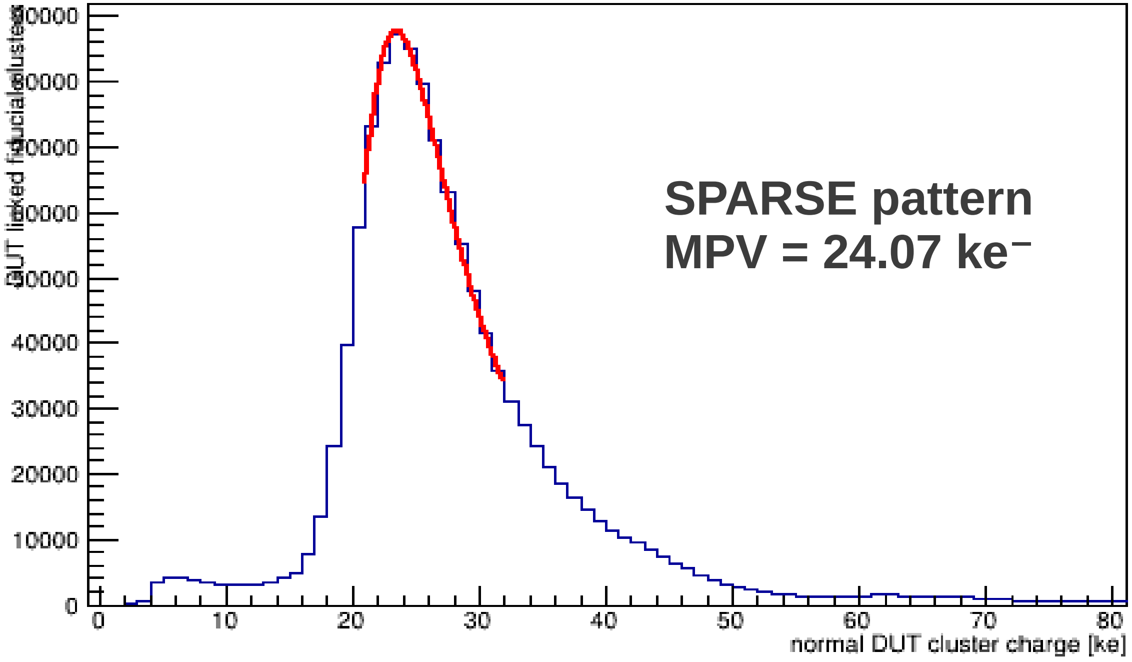
TEST BEAM RESULTS.
Unirradiated sensors.



DENSE pattern
MPV = 21.63 ke$^-$

Charge distribution differences
Can be due to:
ROC calibration uncertanties
that can be about 15 %.
Not necessary to the different
patterns

V_{bias} = 20 V
Room Temp.



SPARSE pattern
MPV = 24.07 ke$^-$

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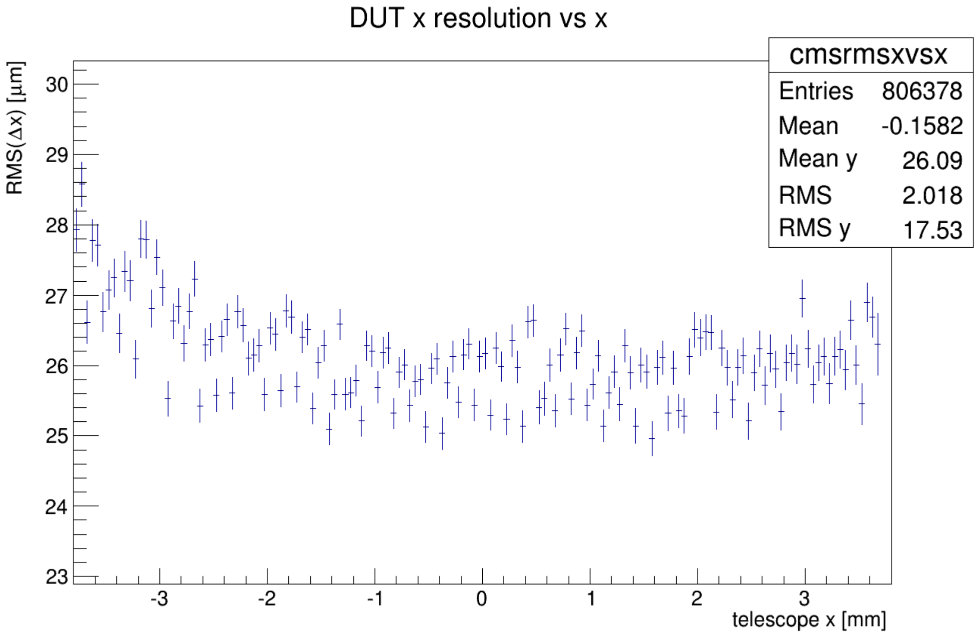
F

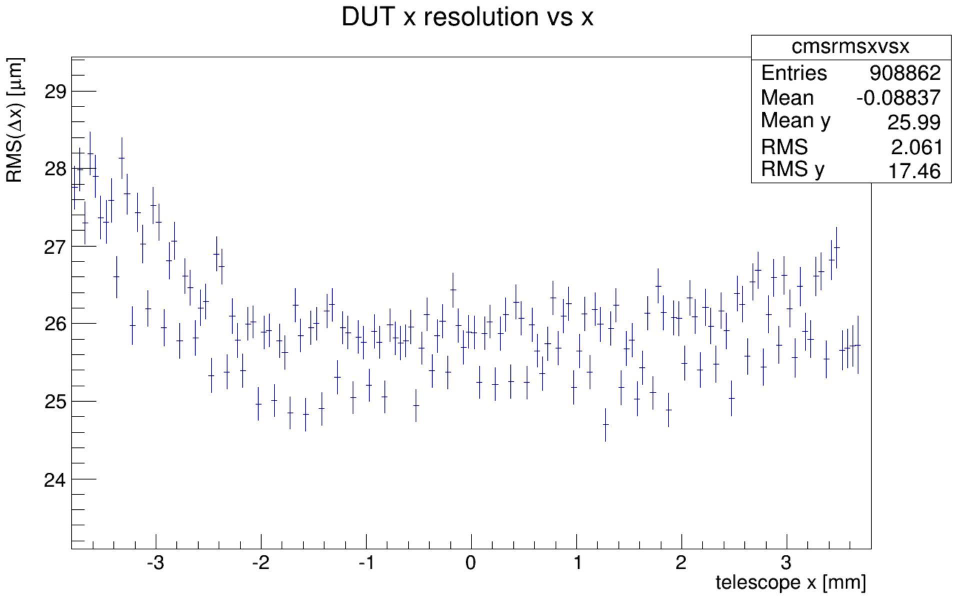
Resolution. Unirradiated Samples

Dense

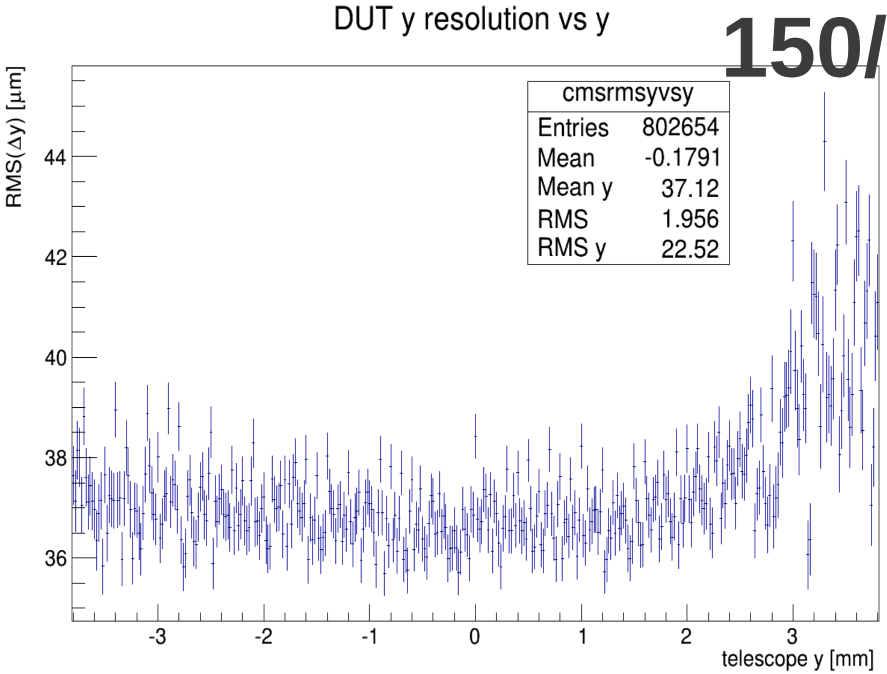
100/√12 = 28 um

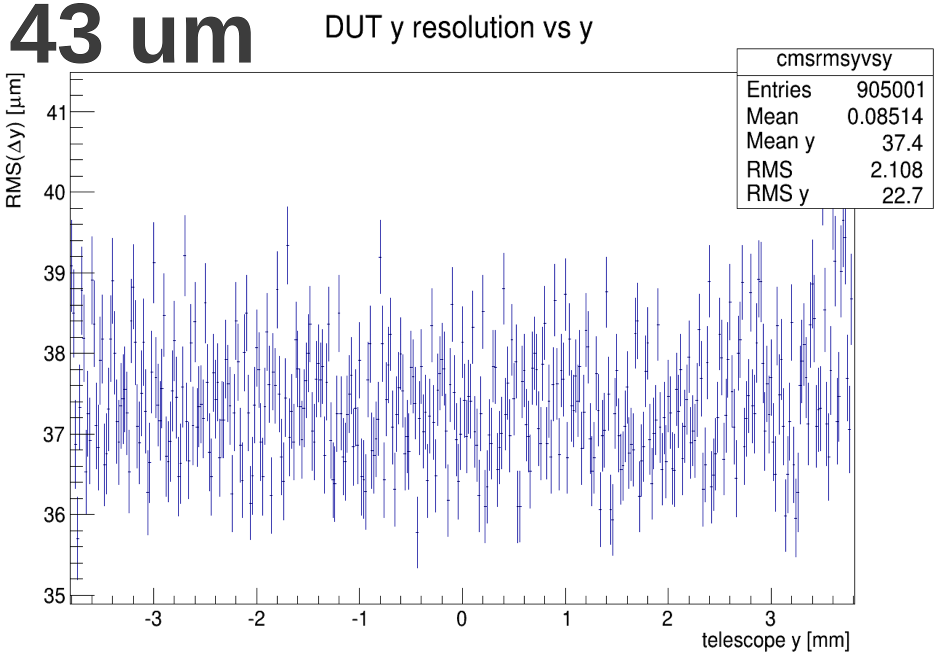
Sparse



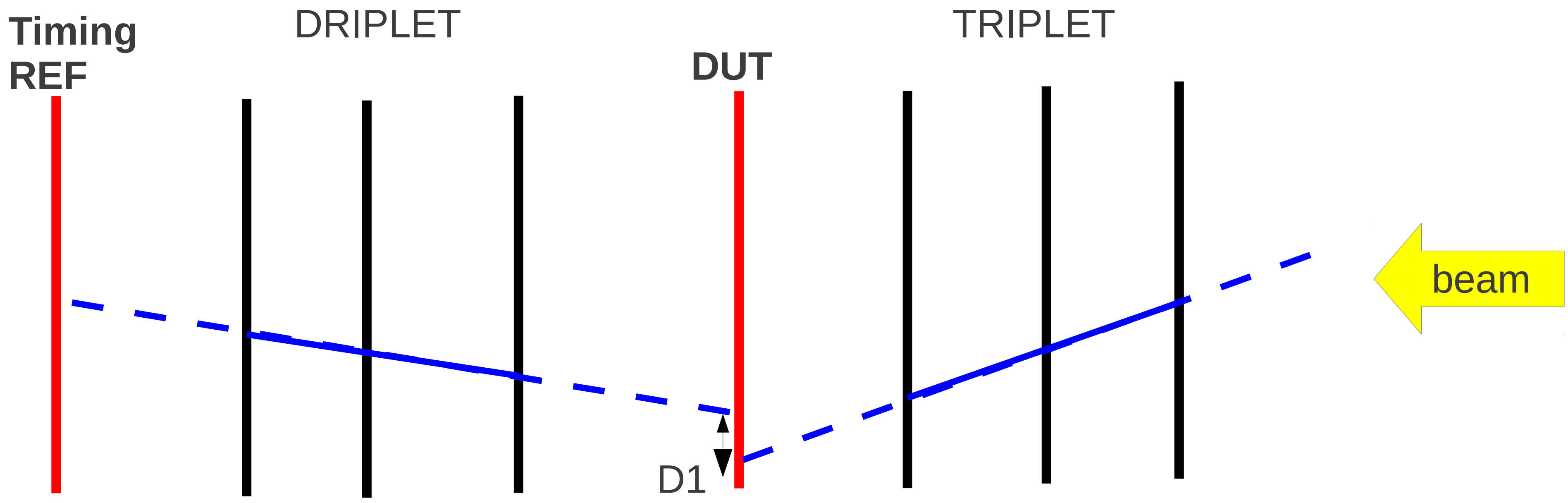


150/√12 = 43 um

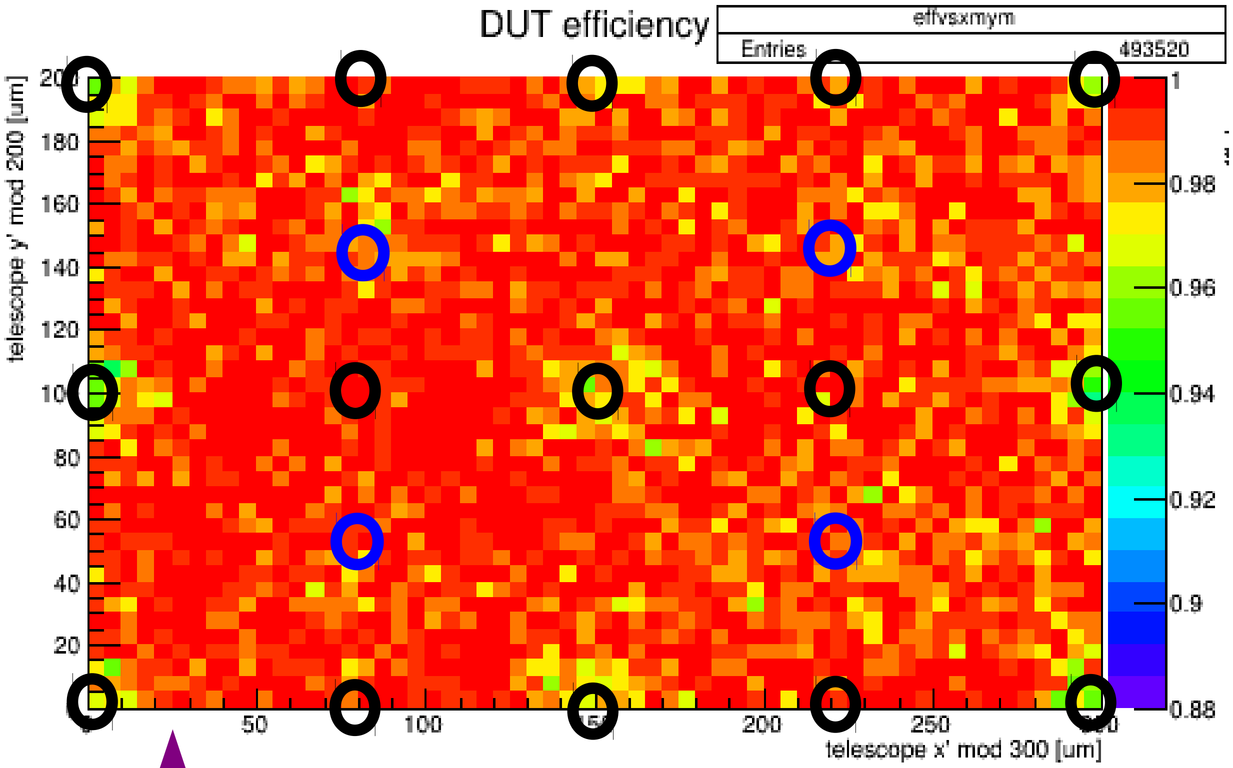




Efficiency Tracks selection



TRACKS: Driplet linked to REF and DUT
Triplet linked to DUT
D1 < 500um



RESULTS.
Unirradiated sensors.

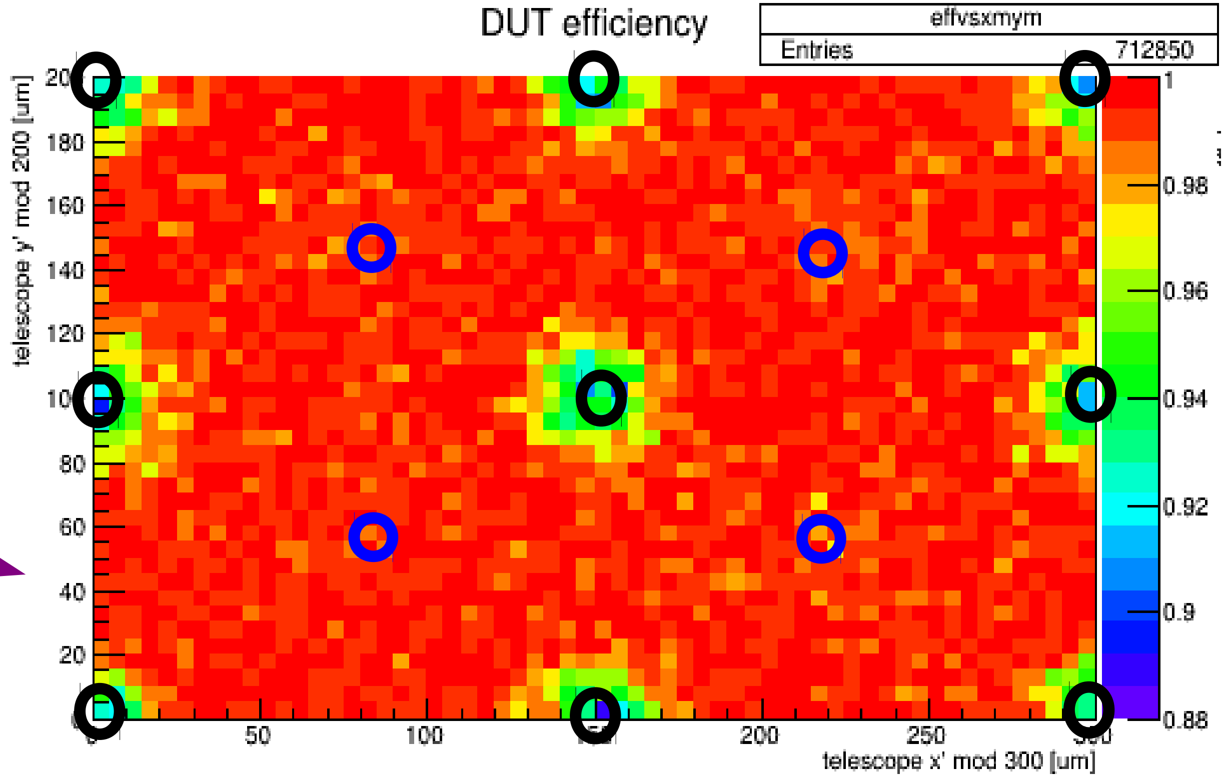
○ **Pn-junction column**

○ **Ohmic junction column**

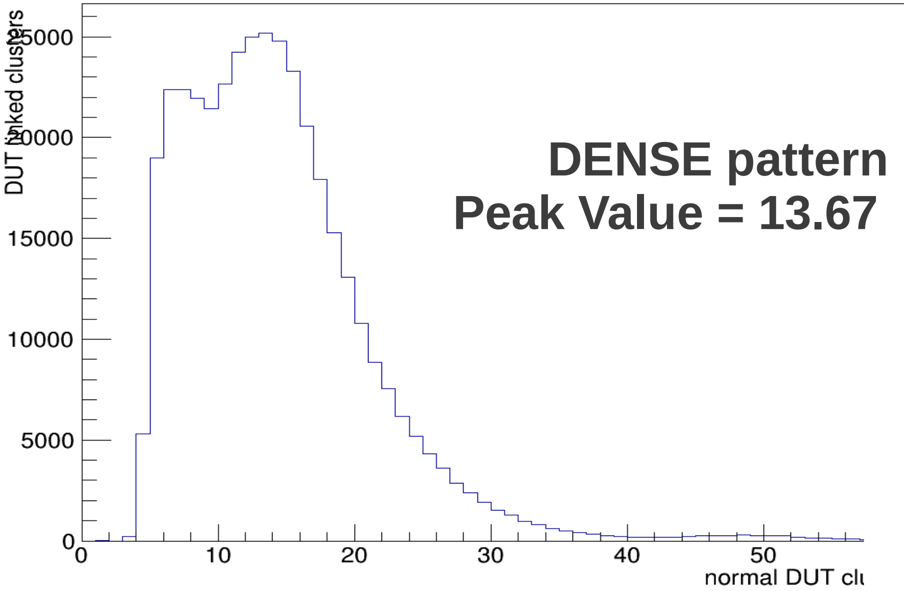
DENSE pattern sensor shows a more homogeneous Behavior In terms of efficiency then sensors With a SPARSE pattern

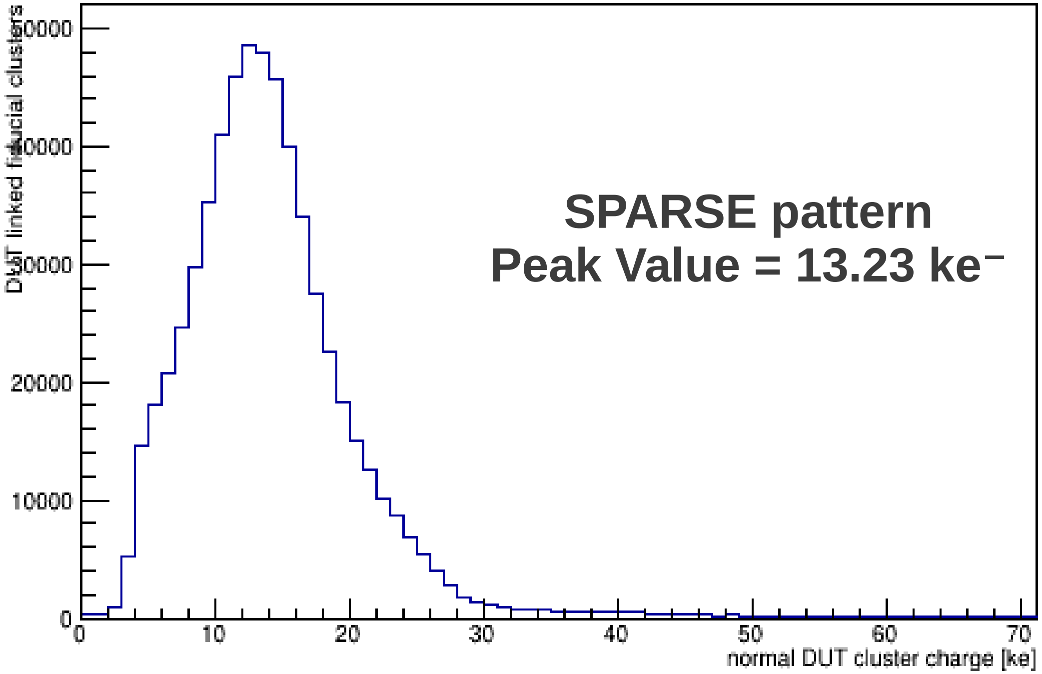
V_{bias} = 20 V
Room Temp.

Fran



TEST BEAM RESULTS.
n- Irradiated sensors (10^{15} n_{eq}/cm^2).



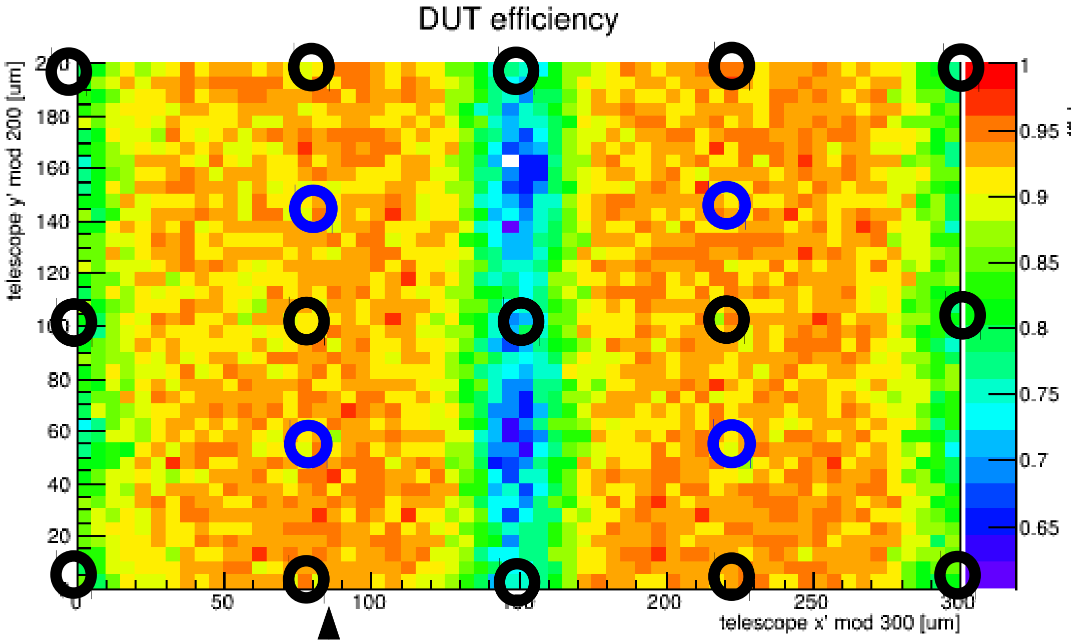


PRELIMINARY

V_{bias} = 120 V

T = -15 ºC

TEST BEAM RESULTS.
n- Irradiated sensors ($10^{15}\ n_{eq}/cm^2$).



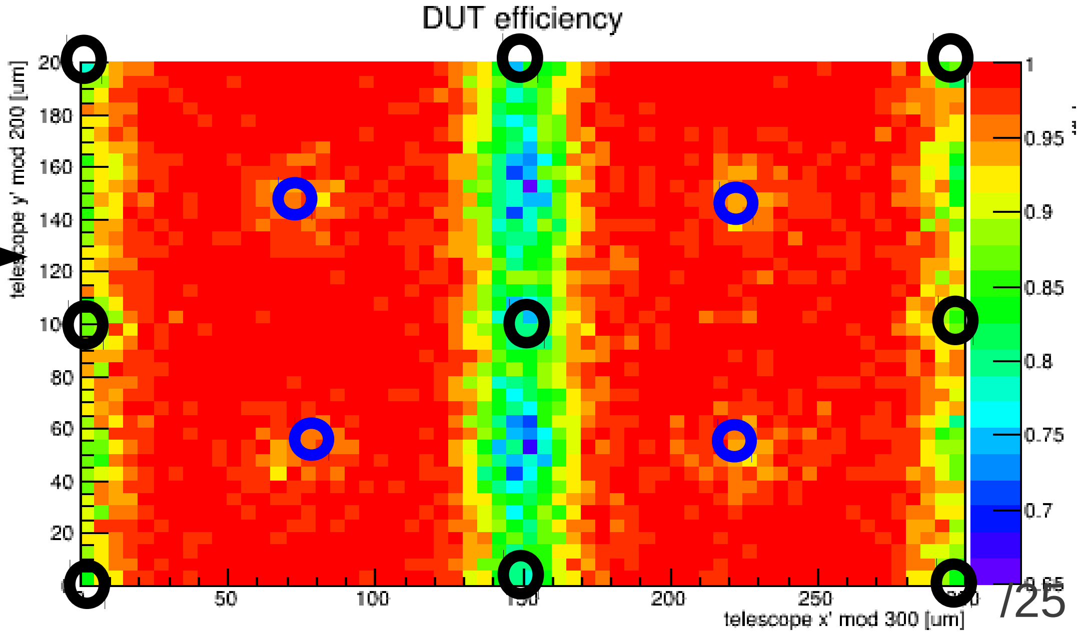
PRELIMINARY

$V_{bias} = 120$ V

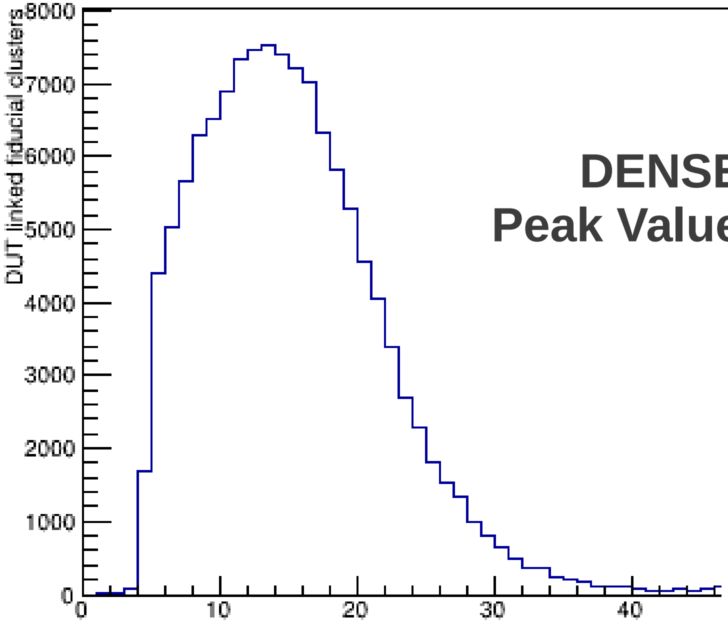
T = - 15 ºC

DENSE

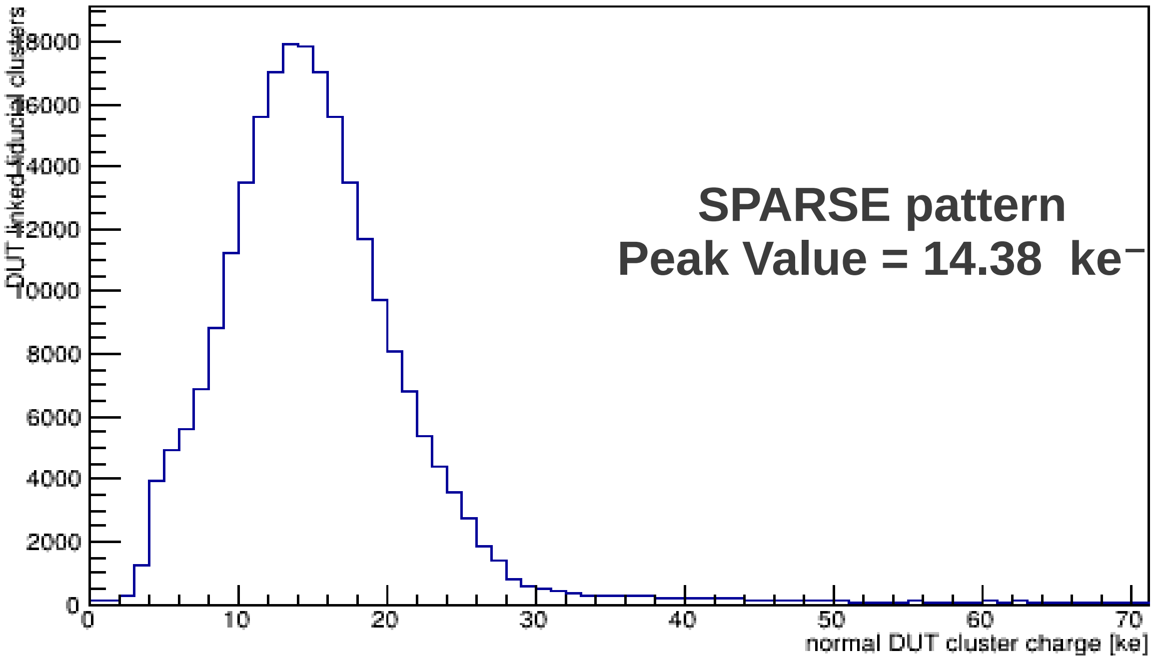
SPARSE



TEST BEAM RESULTS.
n- Irradiated sensors (10^{15} n_{eq}/cm²).



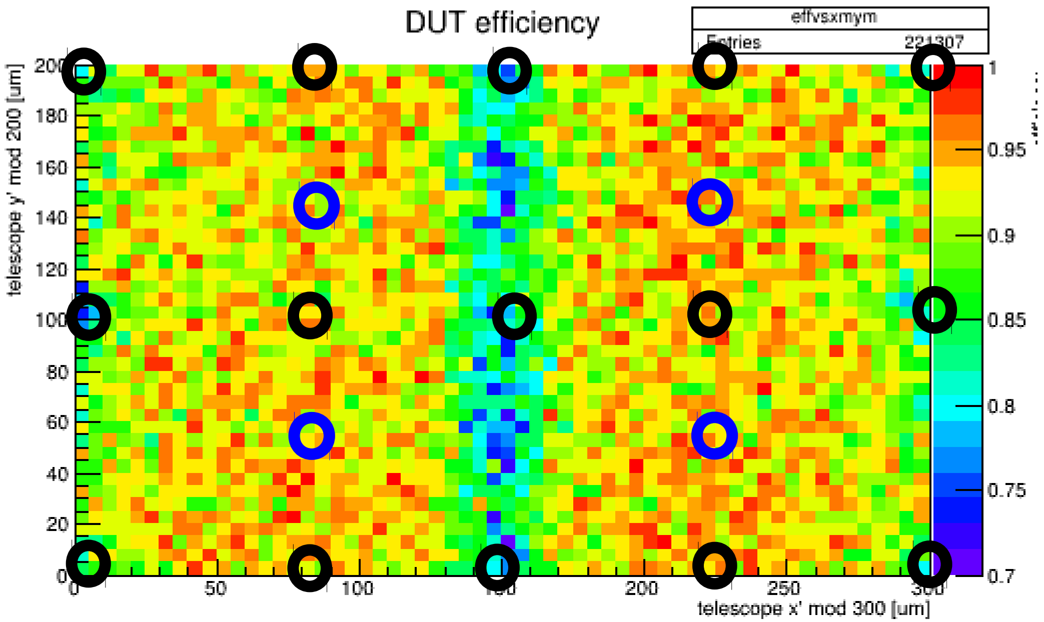
DENSE pattern
Peak Value = 13.87 ke⁻



SPARSE pattern
Peak Value = 14.38 ke⁻

PRELIMINARY
V_{bias} = 140 V
T = - 15 ºC

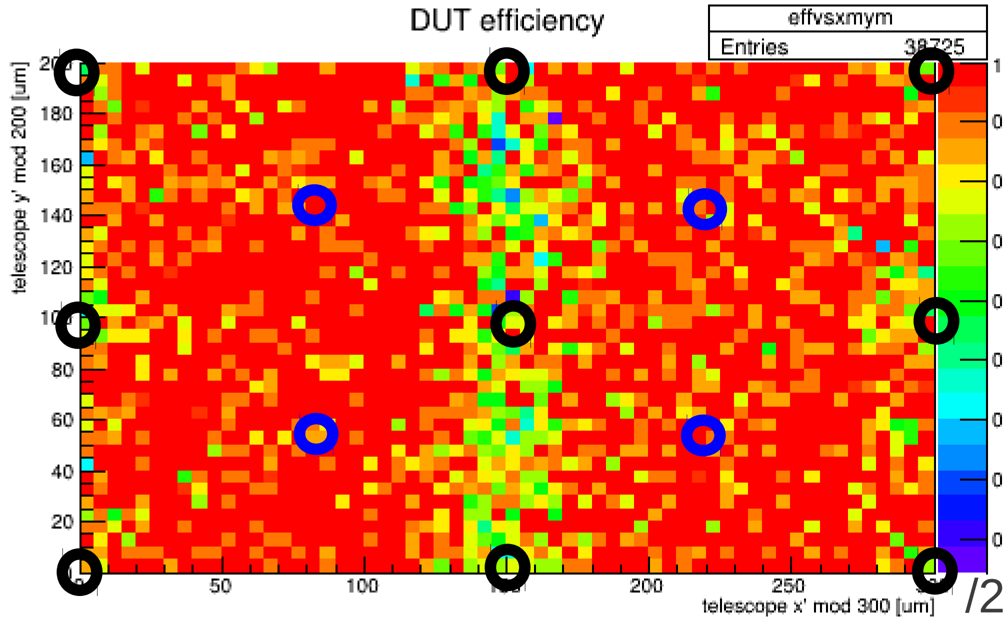
TEST BEAM RESULTS.
Irradiated sensors (10^{15} n_{eq}/cm^2).



DENSE

PRELIMINARY
140 V
T = - 15 ºC

SPARSE



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CONCLUSIONS:

* Electrical characterization

Sensor biasing through the bias ring and by Punch through are in a good agreement

* ^{90}Sr Characterization

- Sensors show a good performance up to 5*10^{15} neq/cm^2
- Operation voltage below 200V
- These results are compatible with those from IBL (ATLAS)

* Test Beam

- Unirradiated Dense pattern show a more homogeneous performance in terms of efficiency.
- Irradiated samples charge distributions under study. Pulse High Calibration performance.
- Efficiency maps in irradiated samples. V_{FD}?

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THANK YOU FOR YOUR ATTENTION!

Acknowledgements:

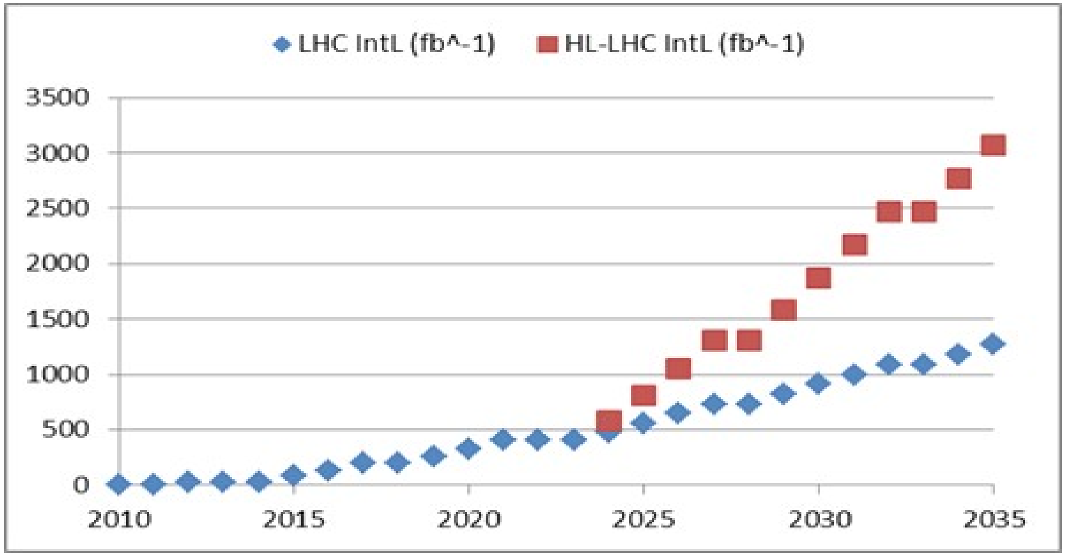
- PSI, ETH and DESY – CMS pixel teams
- Specially
  - Hans Christian kaetsli
  - Silvane Streuli
  - Andrey Starodumov

- KIT & LJ irradiation facilities
- AIDA telescope crew

Backup

Motivation

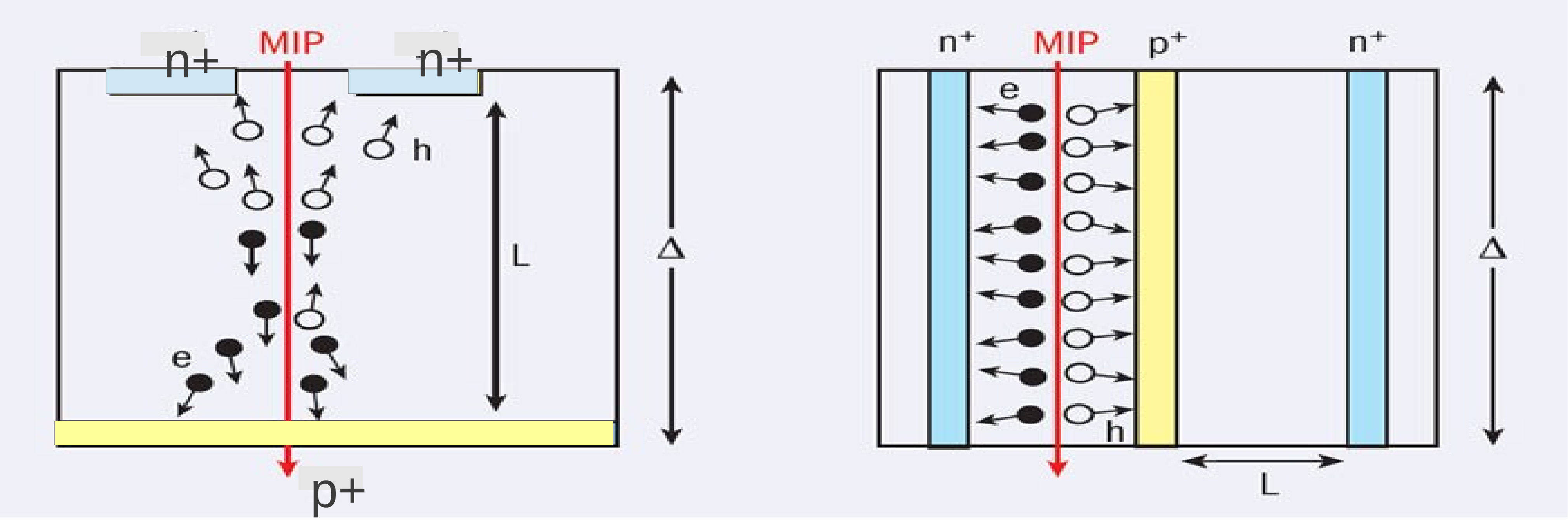
- LHC experiments are expected to undergo a constant increase of radiation levels, a possible HL-LHC scenario will get things tougher



- **LHC Phase II vertex detectors must deal with fluences about $2*10^{16}$ 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**
  - **Tracking Performance and efficiency**

Planar Pixel

3D Pixel



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

3D Detectors Advantages

- Operational. Full depletion of the detector requires lower voltages

- Intrinsic. Shorter collection distances

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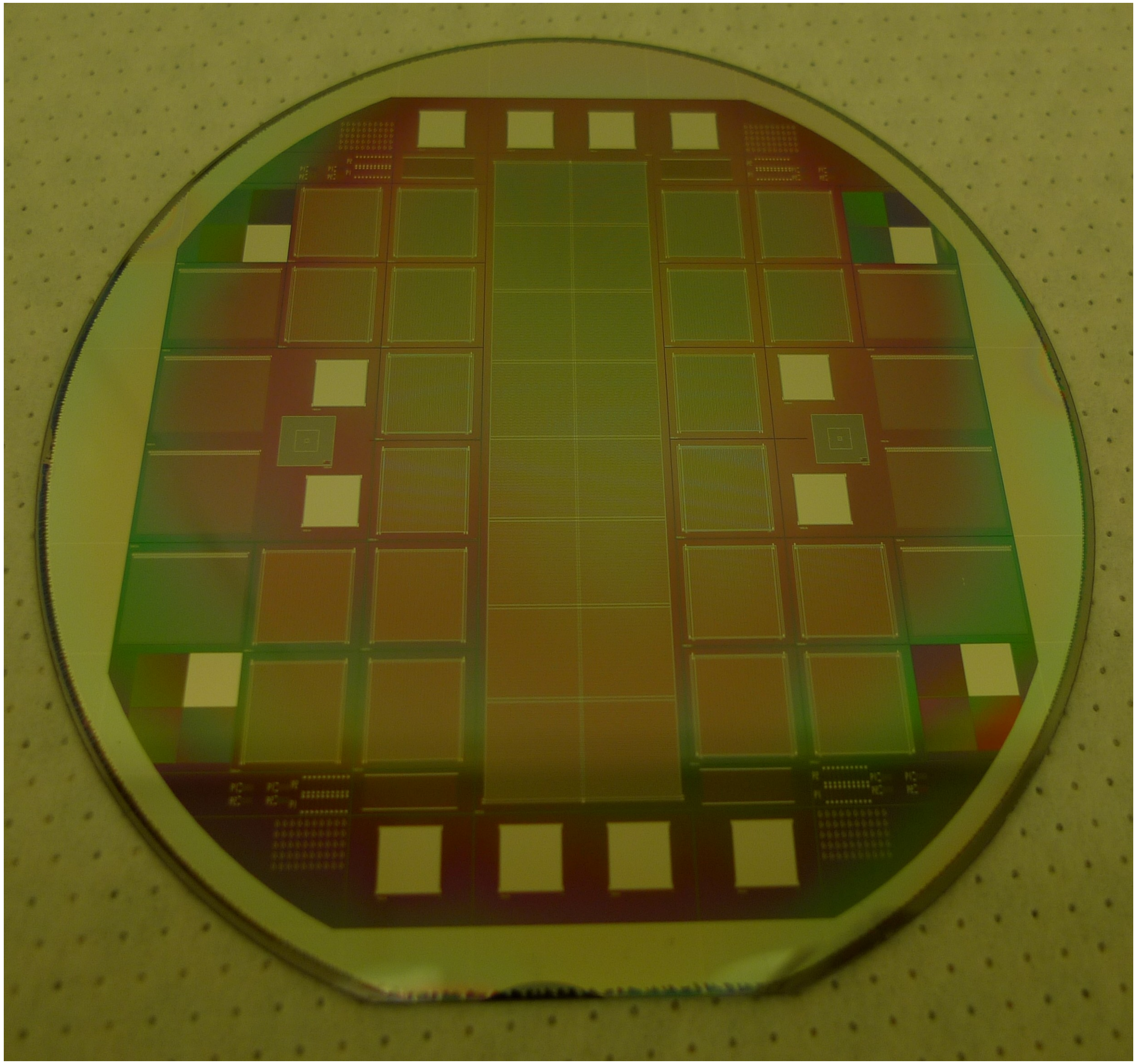
Depletion Area in 3D-Pixels

- 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)

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

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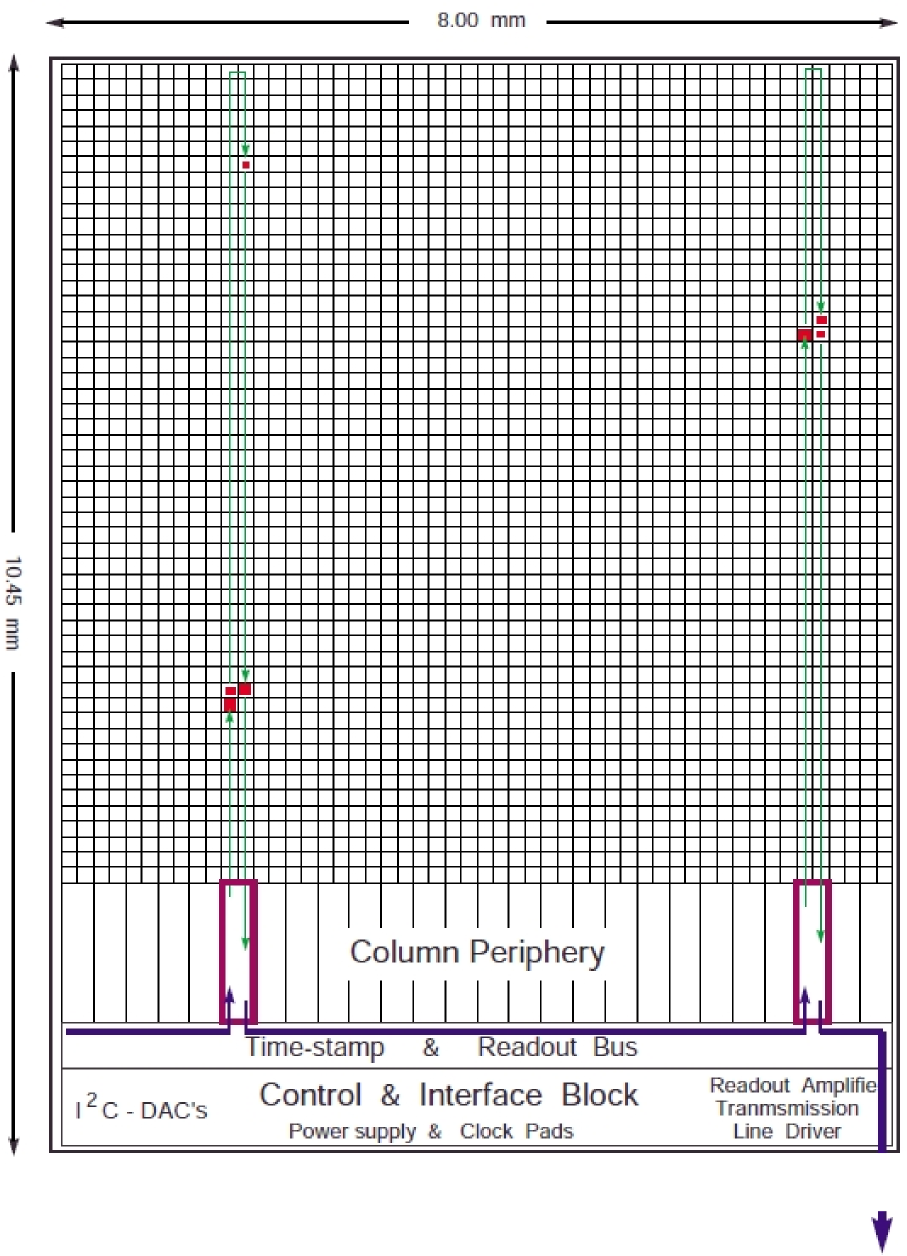
Readout Chip



- 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

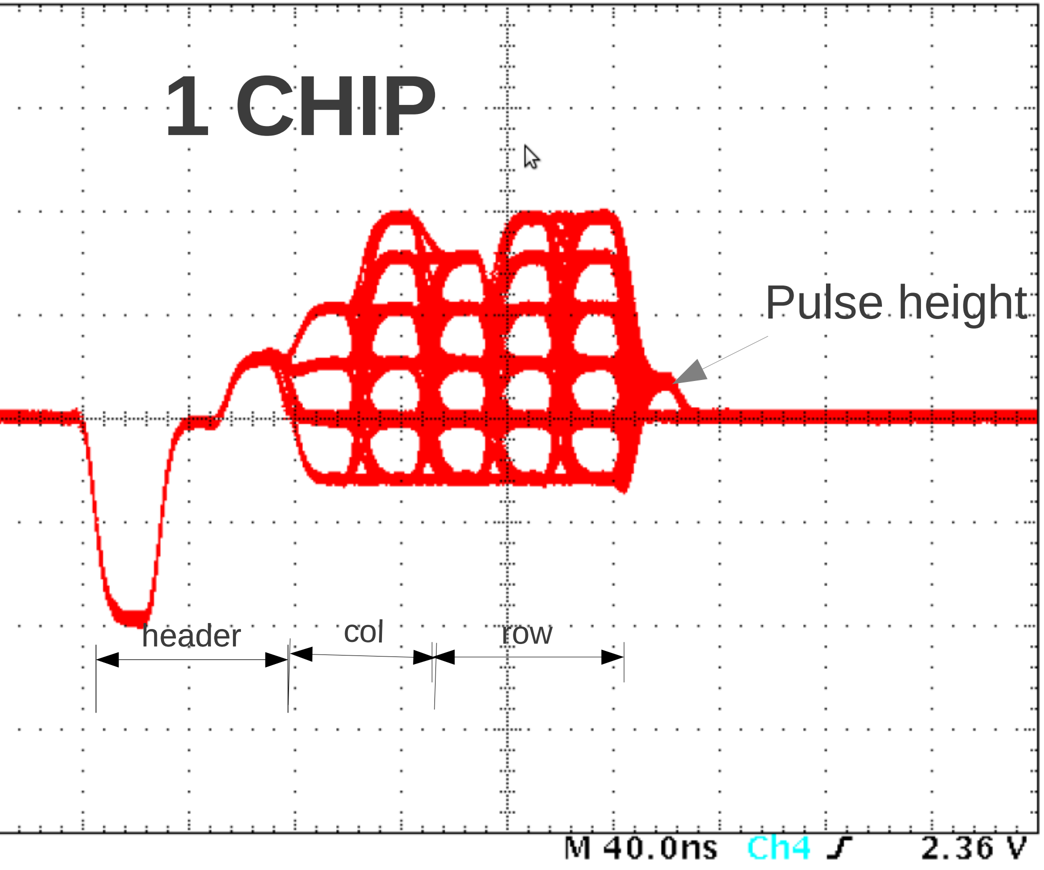
- Other double columns without hits for this Trigger are not affected and continue data acquisition

Readout format

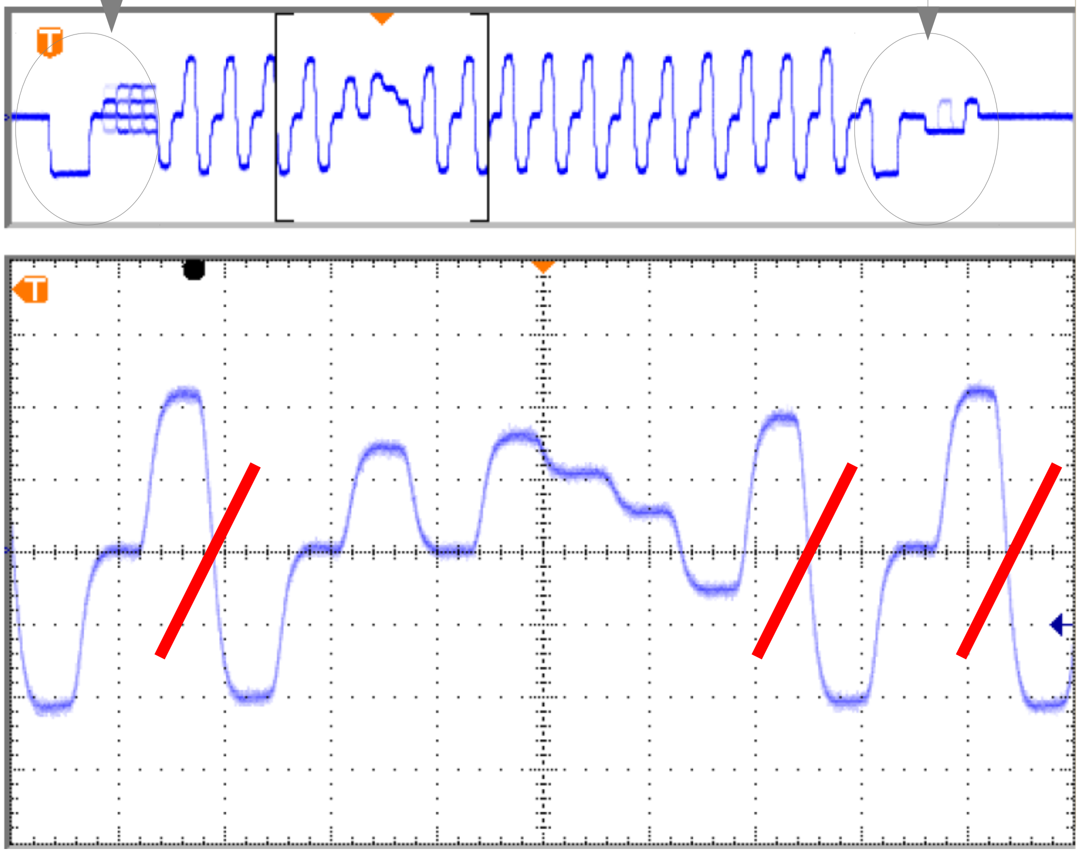
TBM header within an event counter

TBM trailer

1 CHIP



16 CHIPS



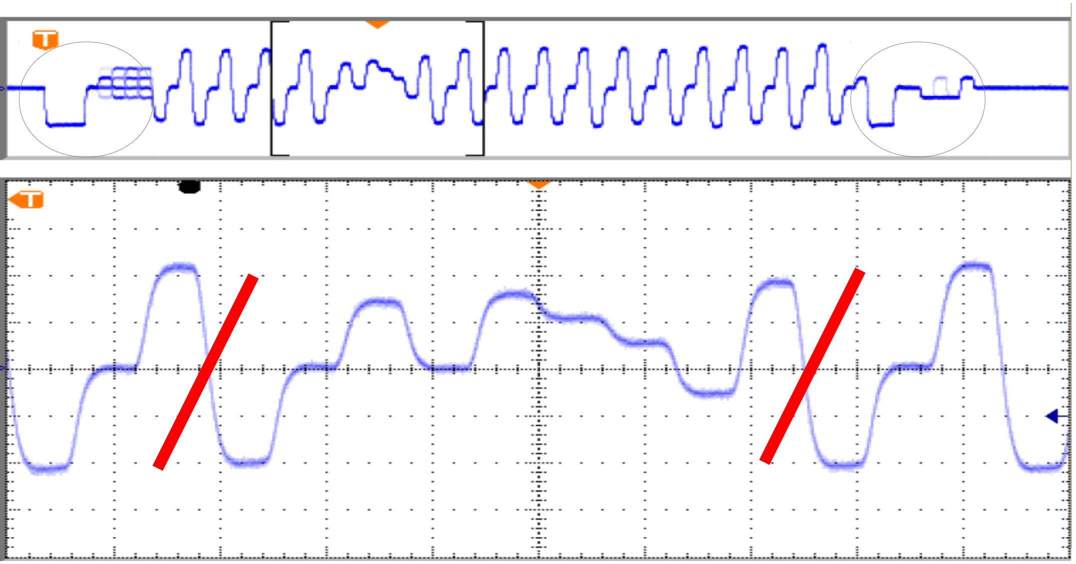
TOKEN-BIT-MANAGER

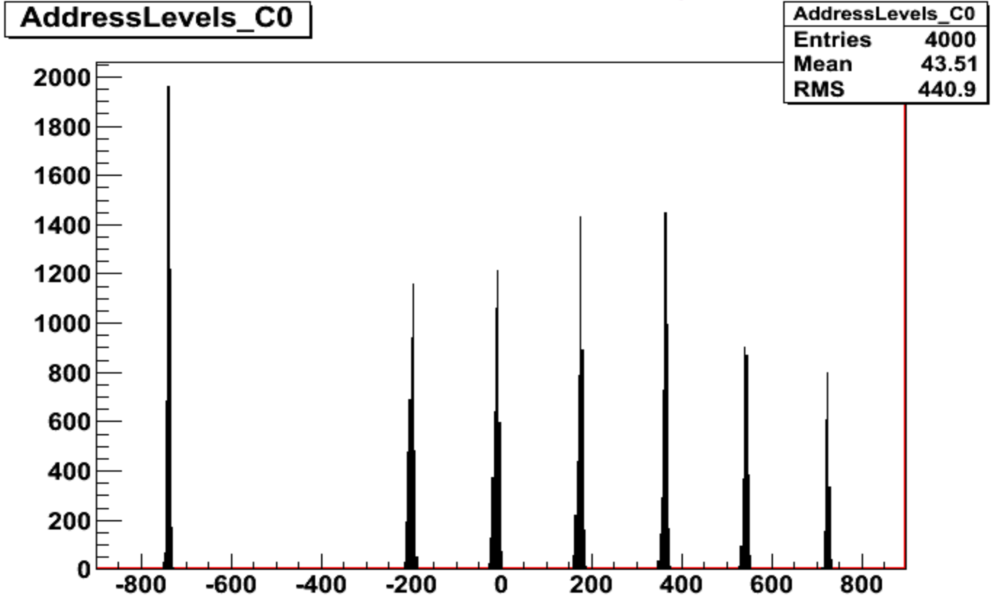
Chip 1,2,3,4--> no data
Chip 5--> 1 data
Chip 6--> no data
...

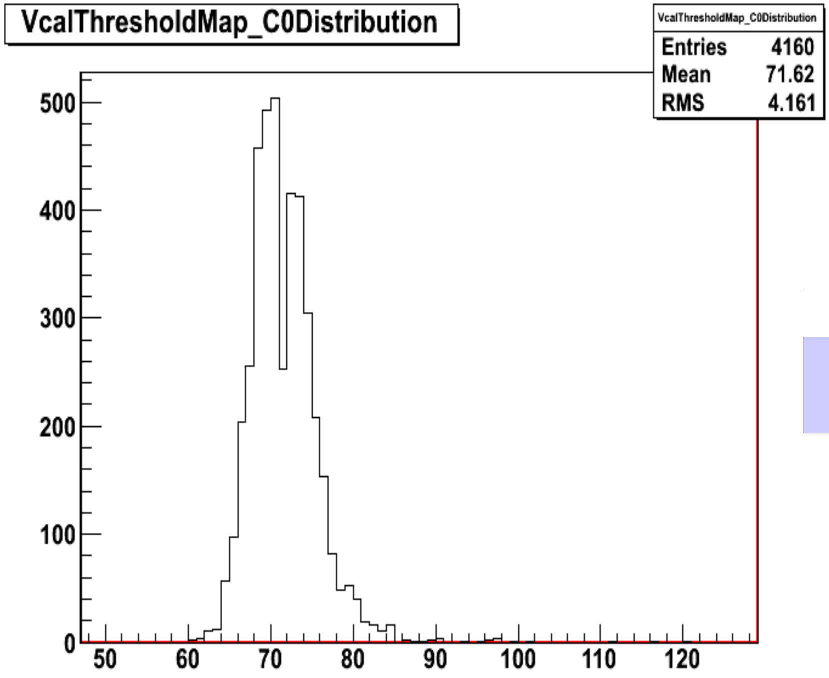
ROC QUALIFICATION

- **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

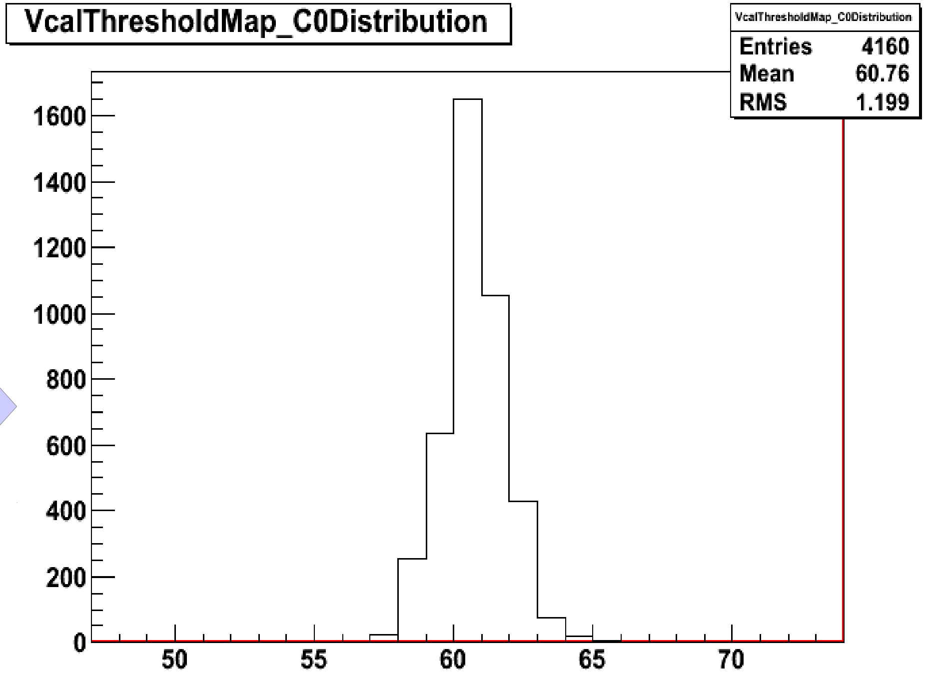
Address levels and trimming



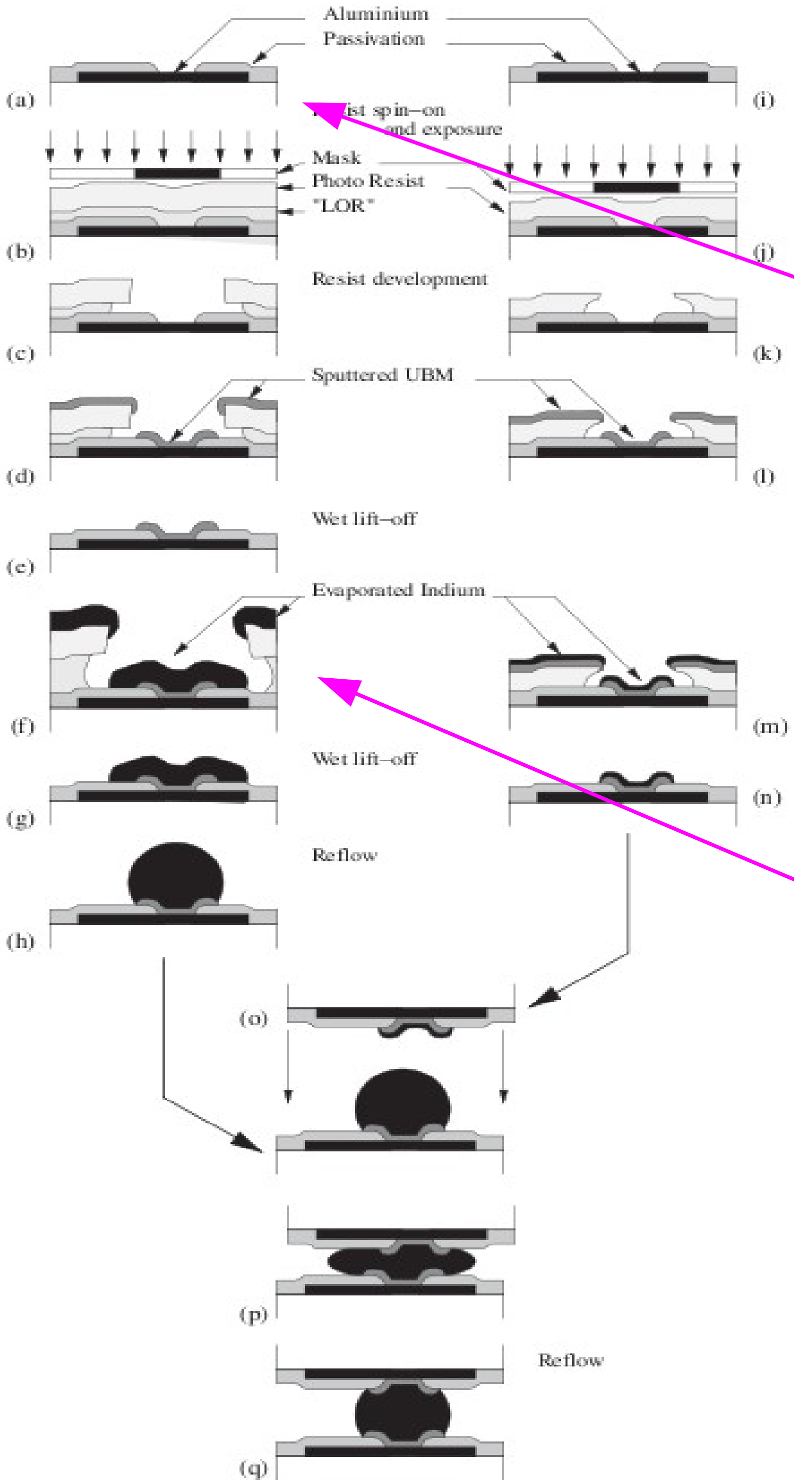


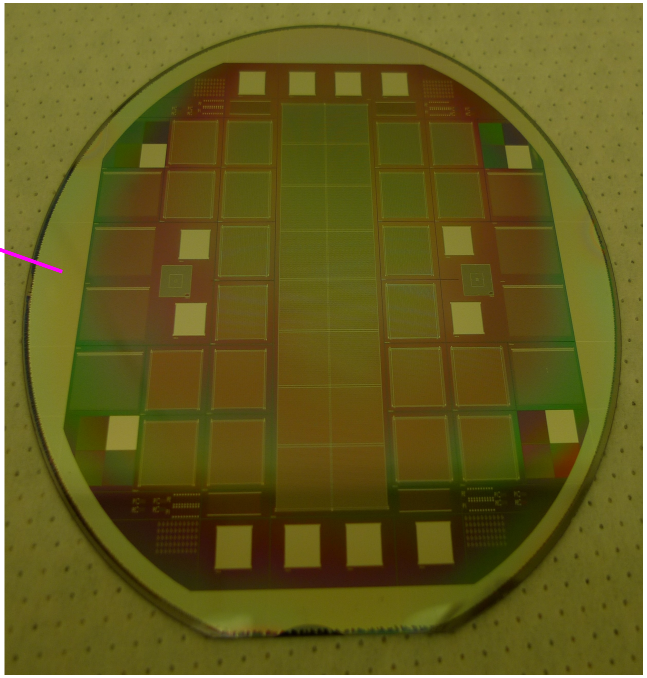


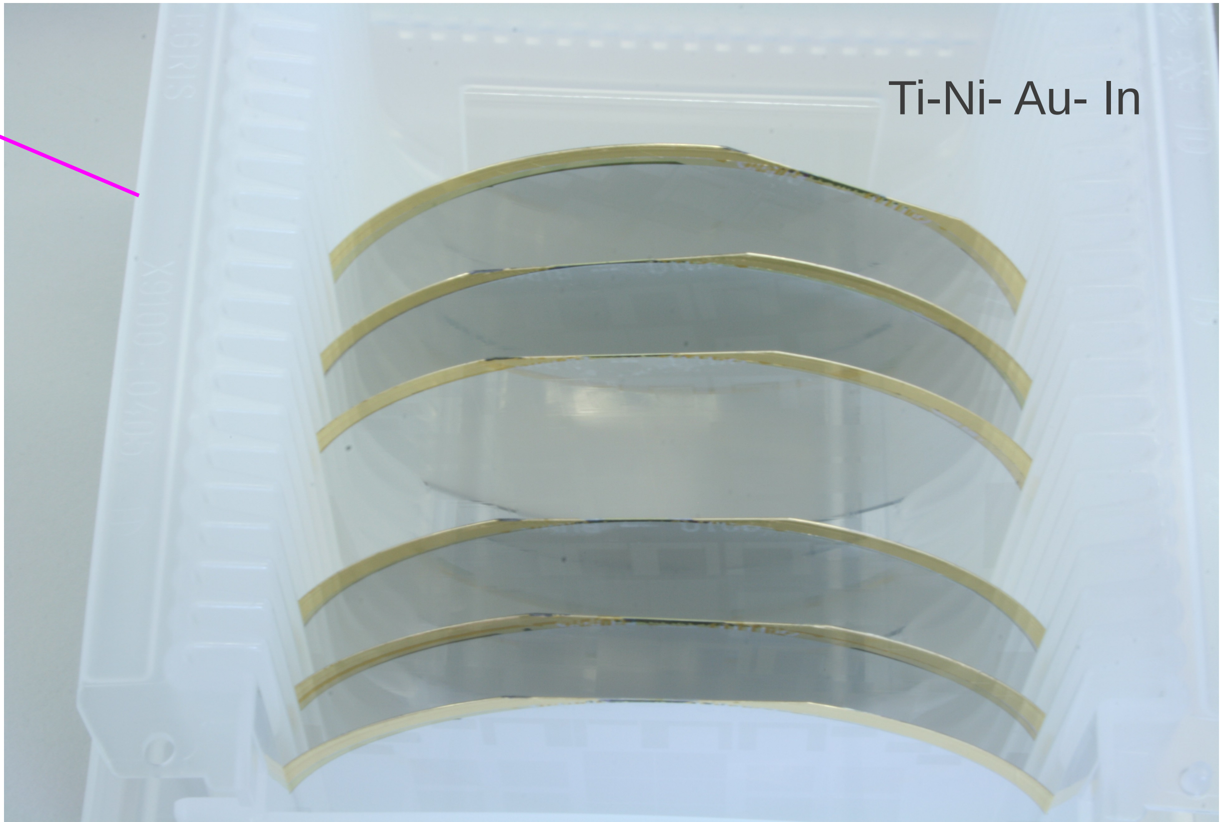
Trimming



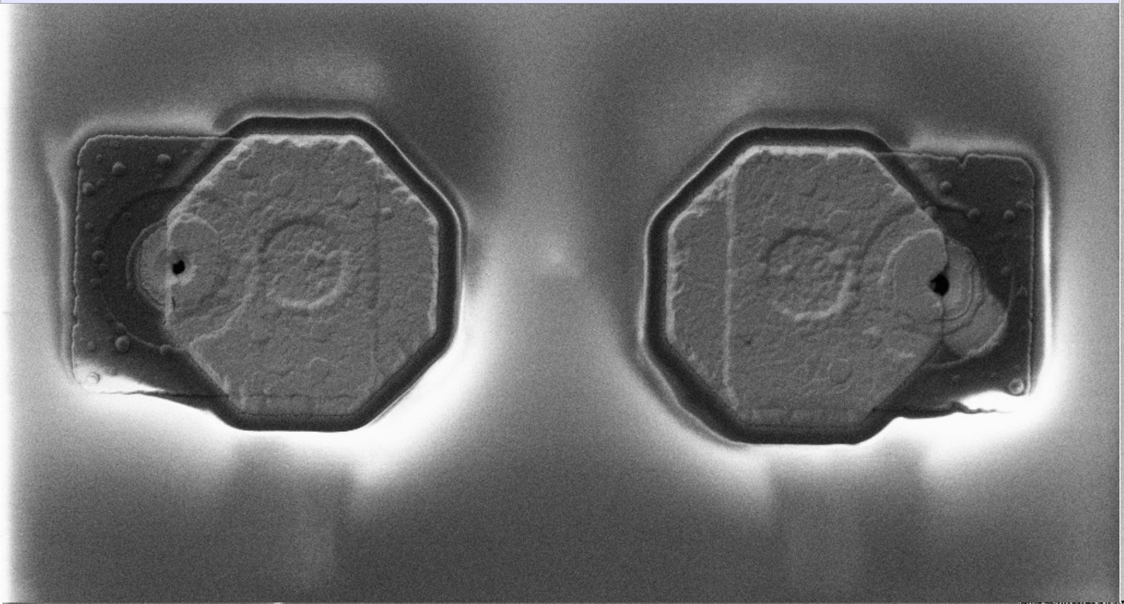
Bump bonding

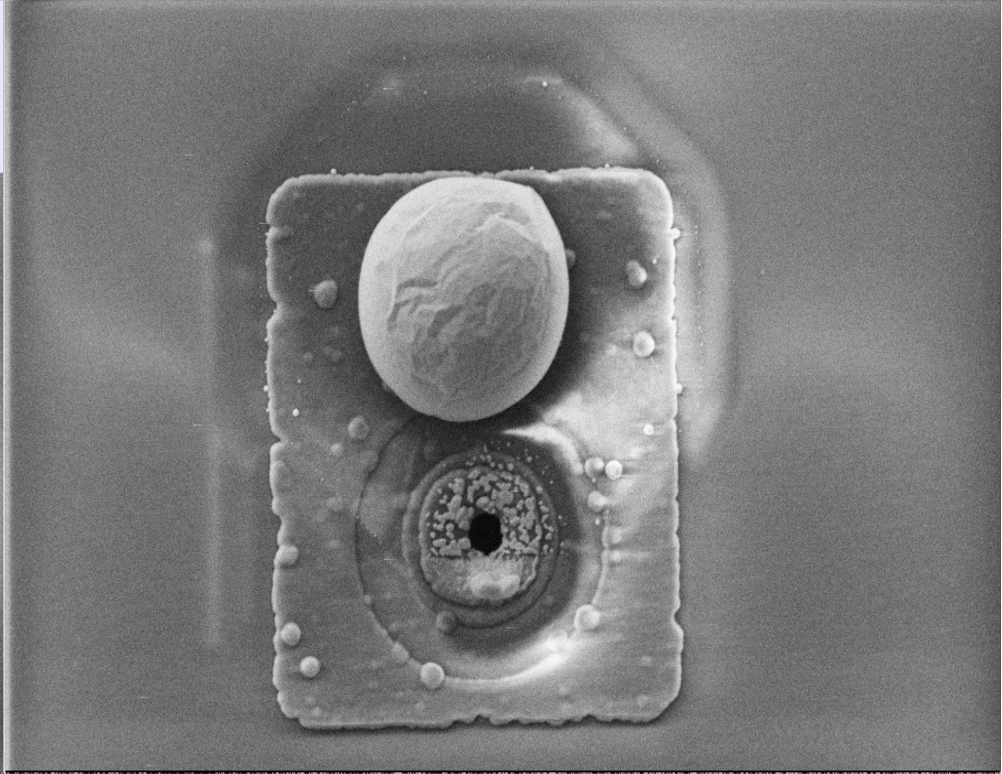


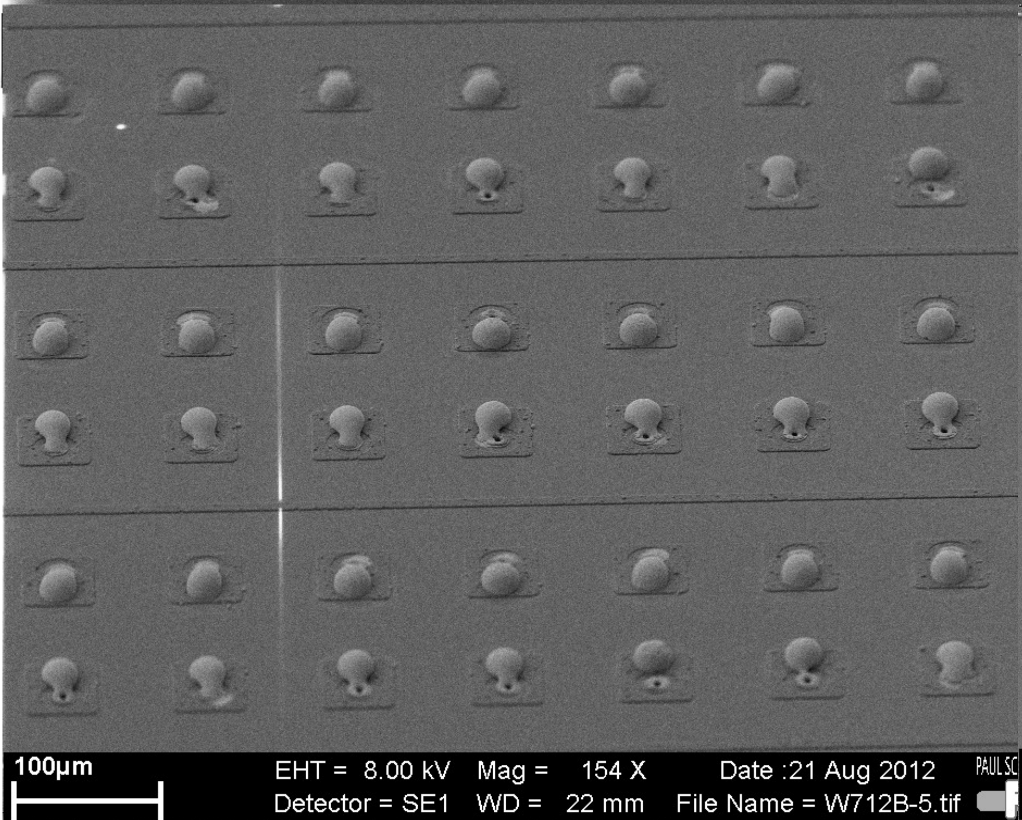


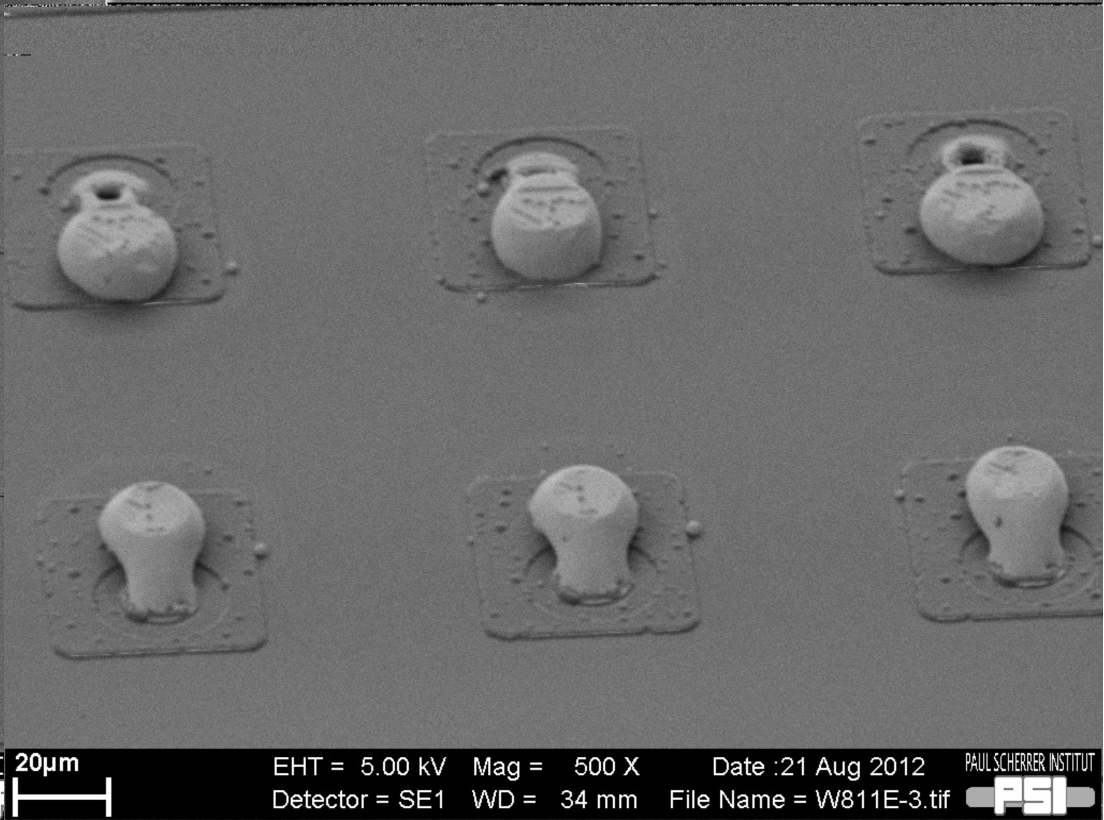


Scanning electron Microscope SEM









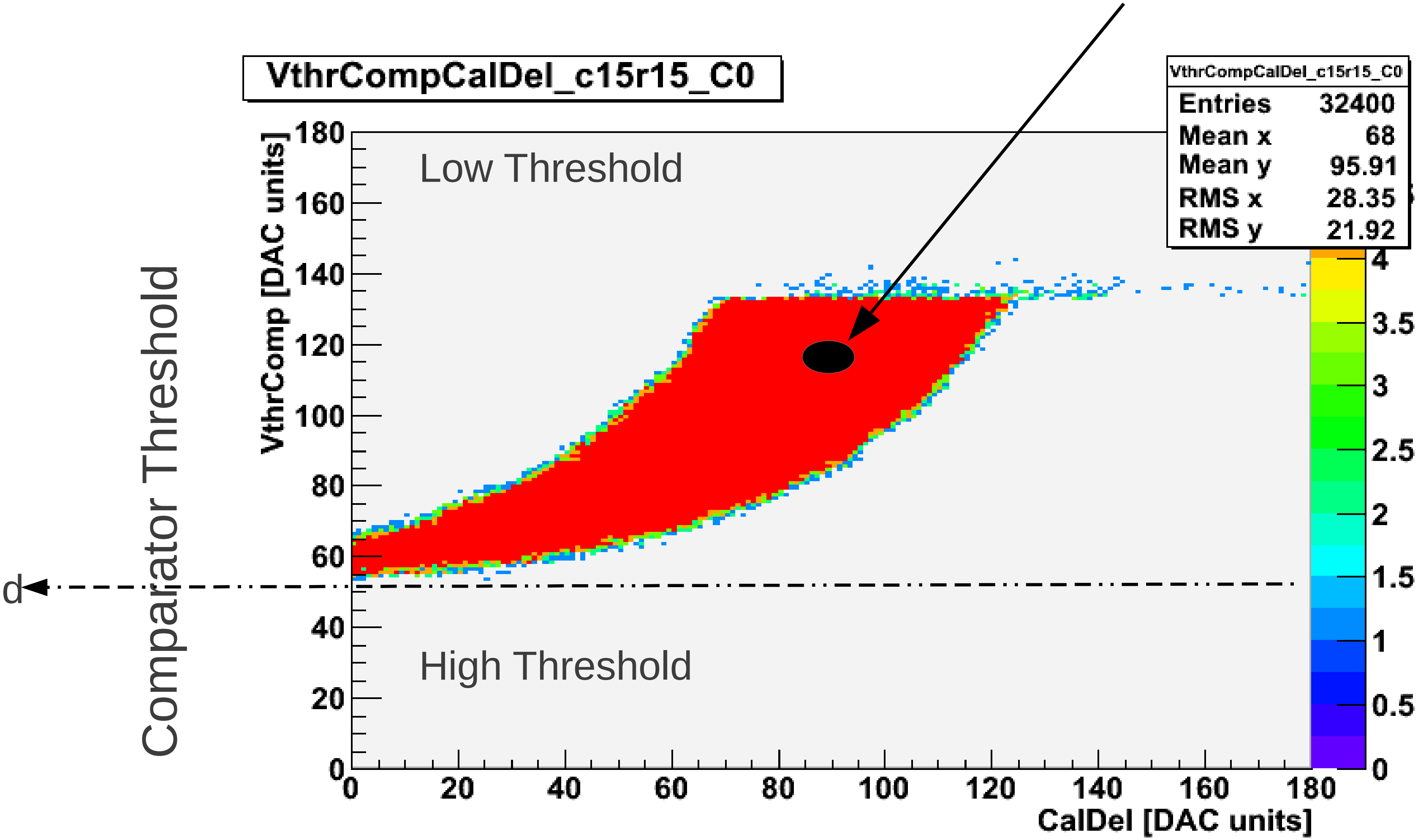
VthrComp vs CalDel

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

Working area

Threshold

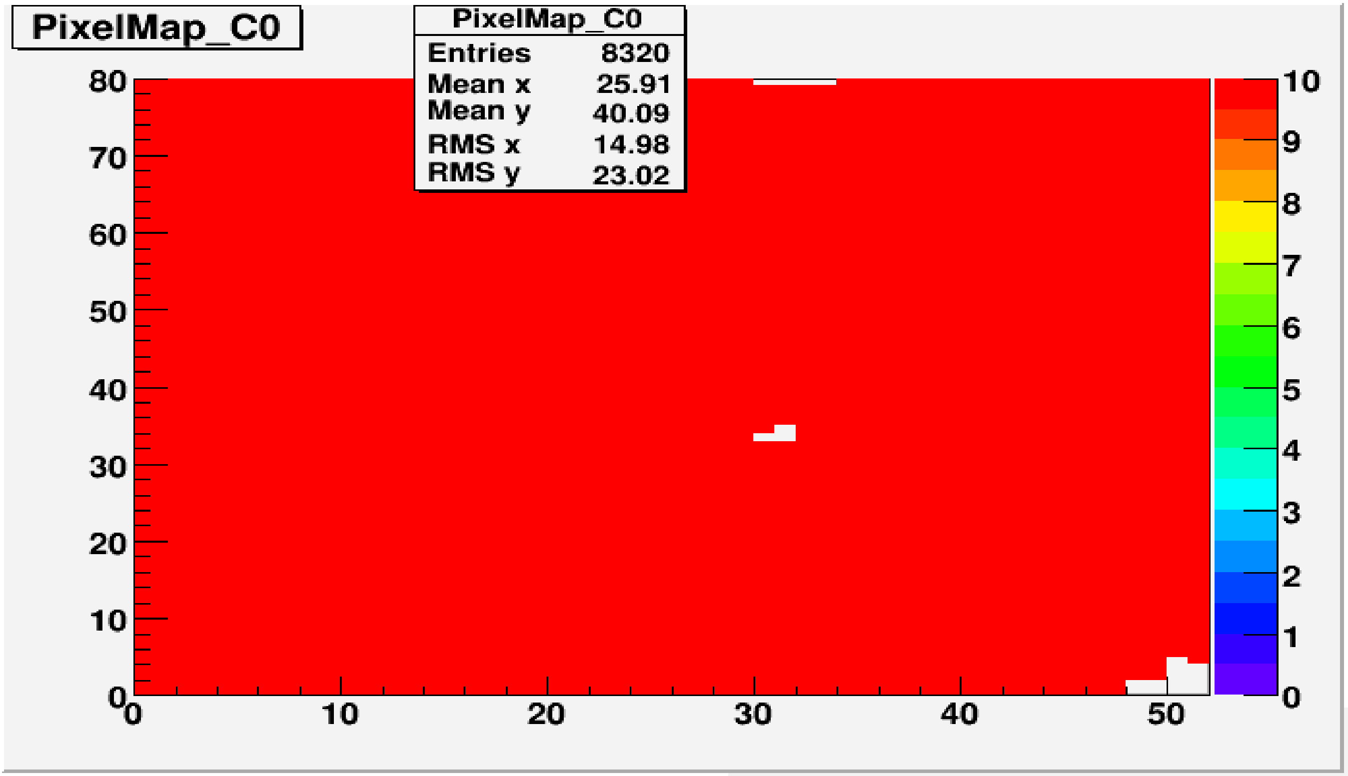


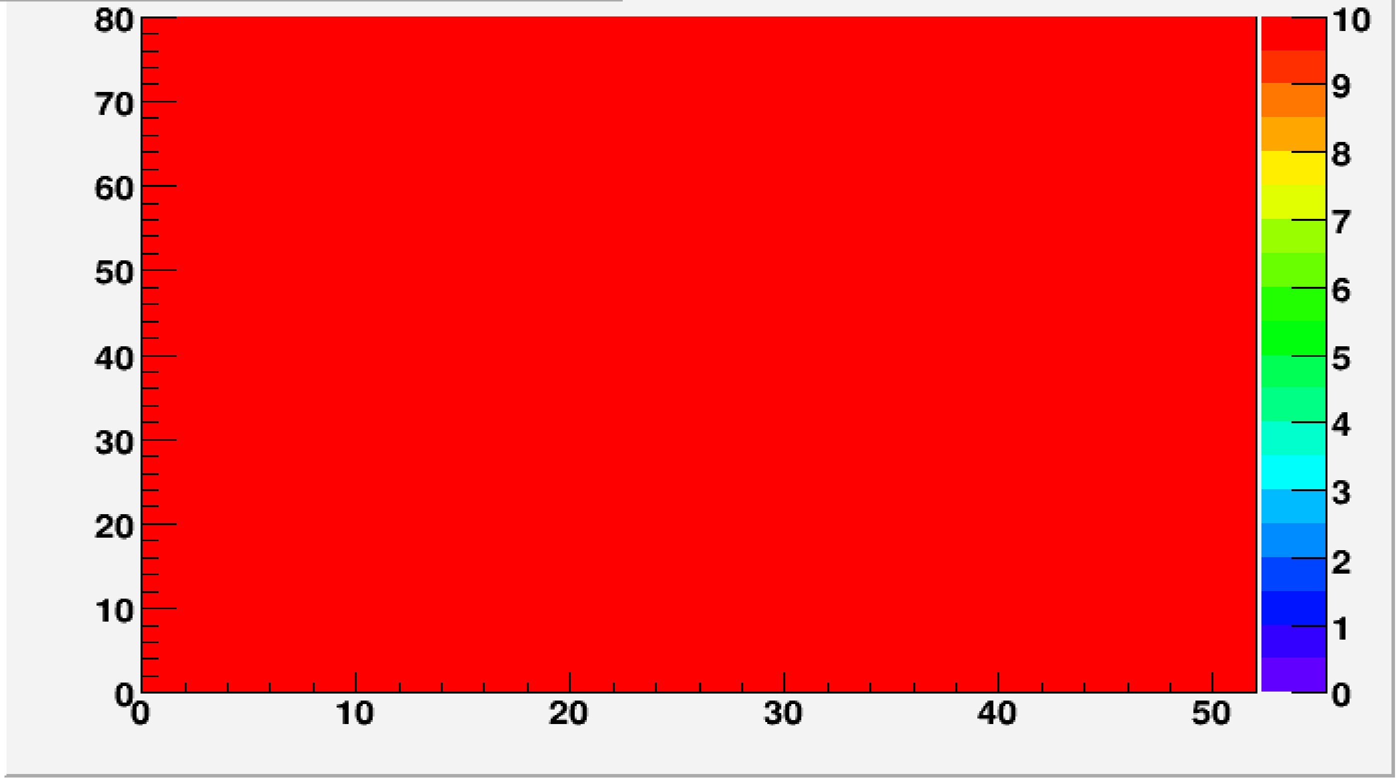
Low Threshold

High Threshold

Comparator Threshold

Pixel test





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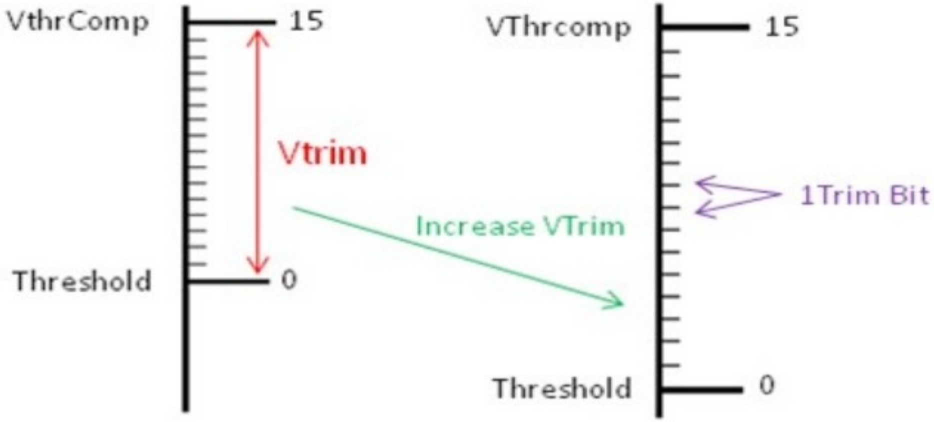
VthrComp, Vtrim and the Trim Bits

- 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

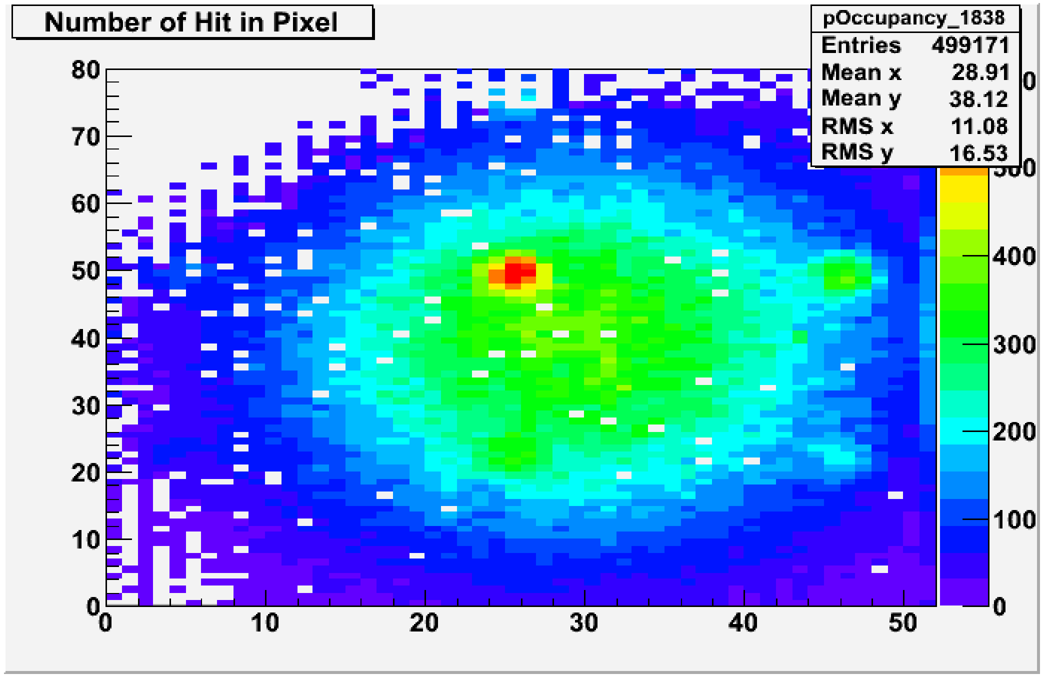
- The goal of setting Vtrim and the trim bits is to make up for the small differences in transistors due to limitations of IBM process used to manufacture the ROC
- These differences vary from pixel to pixel, and it is important to have the same threshold across the entire ROC



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

Bump bonding. Interconnection process

- 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)



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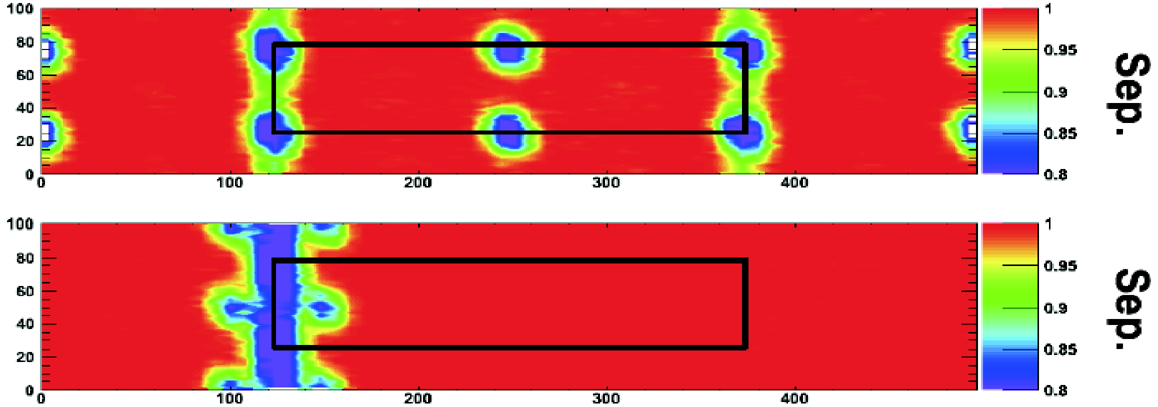
Latest results. IBL-ATLAS

Test-beam Results: planar and 3D

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

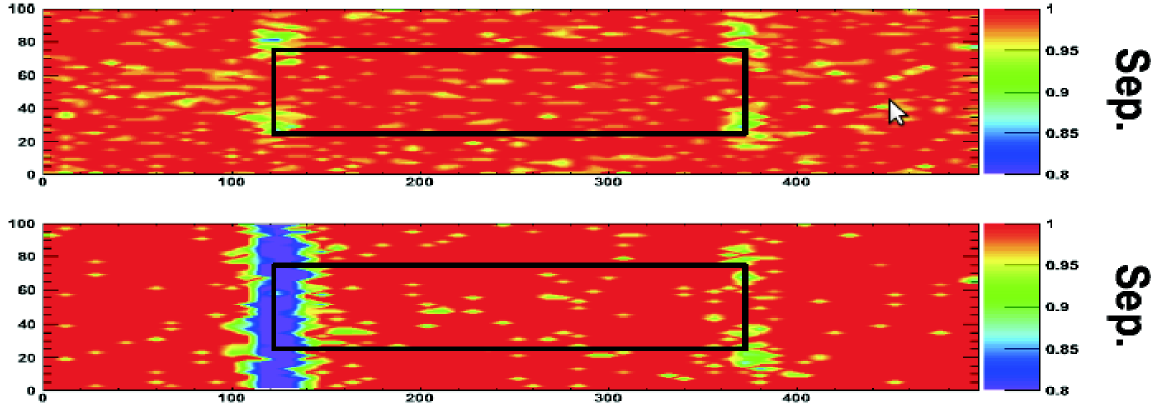
LUB4 (Planar), HV=1000V
$5*10^{15}$ n-irrad, Eff=97.90



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

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

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



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

S. Grinstein - IFAE Review

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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