Laboratory and testbeam results for thin and epitaxial planar sensors for HL-LHC

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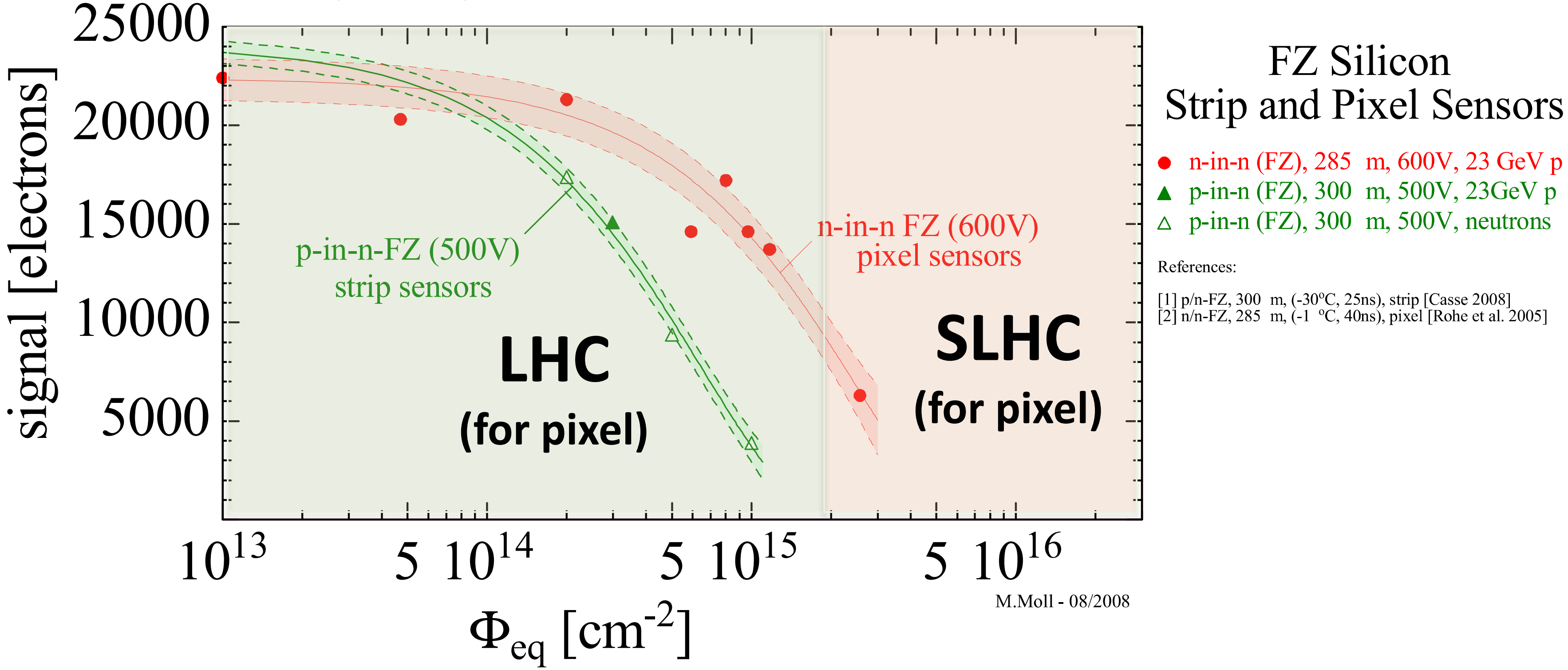
on behalf of HPK Tracker Campaign

CMS Pixel Sensor R&D

- Current CMS pixel detector can operate up to a fluence at least 6×10^{14} neq/cm^2.
- New rad-hard sensors must be developed for the HL-LHC
  - Peak luminosity $L = 5 \times 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ (factor of 50 above LHC nominal)
  - Dose of ~10^{16} neq/cm^2 @r=5cm
- CMS R&D currently focused on:
  - Thin planar: FZ, Epitaxial, FDB (Deep Diffusion)
  - 3D

Signal degradation for CMS silicon sensors



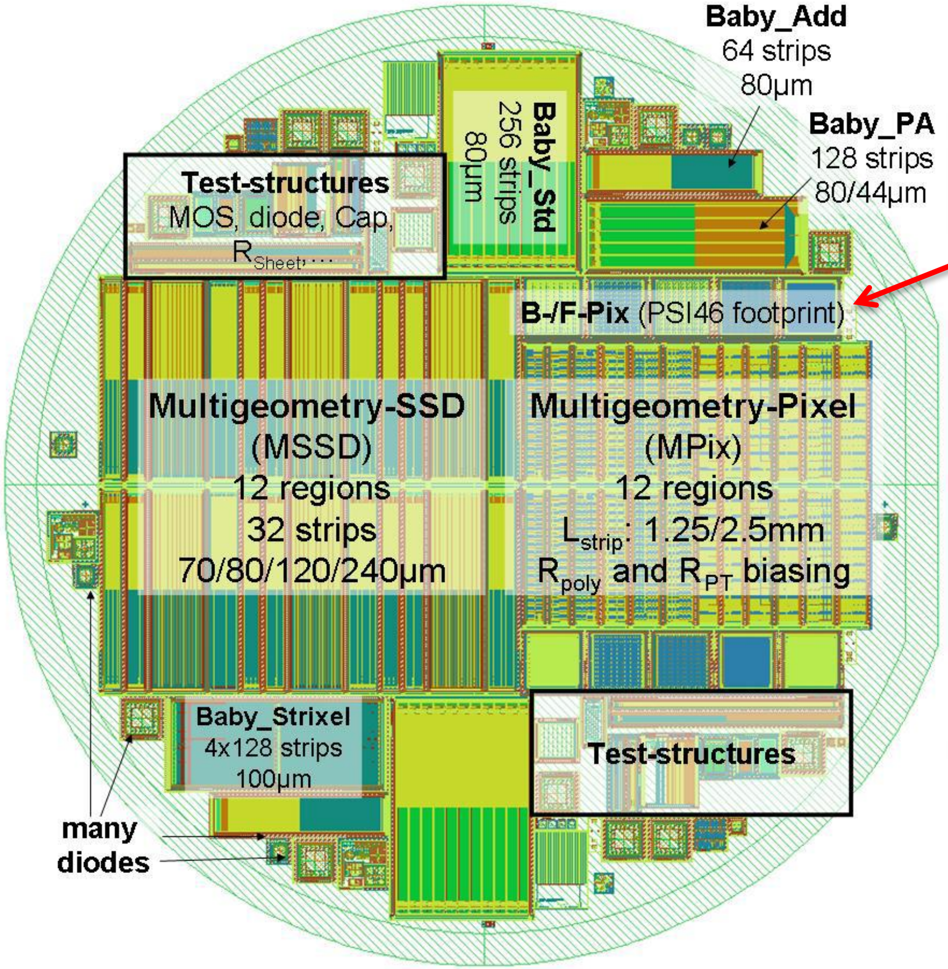
Outline of talk

- **The CMS HPK Tracker Campaign**
  - The main goal of this effort was the selection of the baseline material for the strip tracker.
  - Wafers also included pixel sensors of different layout
- **Laboratory measurement results**
  - Leakage and Capacitance measurements
  - Noise and Threshold measurements using analog and digital chips
  - Charge collection efficiency measurements using Sr90 source
  - Comparison of performance of different thickness and layouts
- **Testbeam measurements**
  - Pre-irradiation tracking efficiency
  - Comparison of different sensor layout results

HPK Tracker campaign

164 wafers:

- **Float zone**
  - 320um, 200um
  - 200um deep diff, 120um deep diff
- **Magnetic Czochralski**
  - 200um
- **Epitaxial Silicon**
  - 100um, 50um
- All as n-type and p-type (with p-stop and p-spray isolation)



Pixel region

P=p-type substrate with **p-stop** (mostly FPIX designs)

Y=p-type substrate with **p-spray** (mostly BPIX designs)

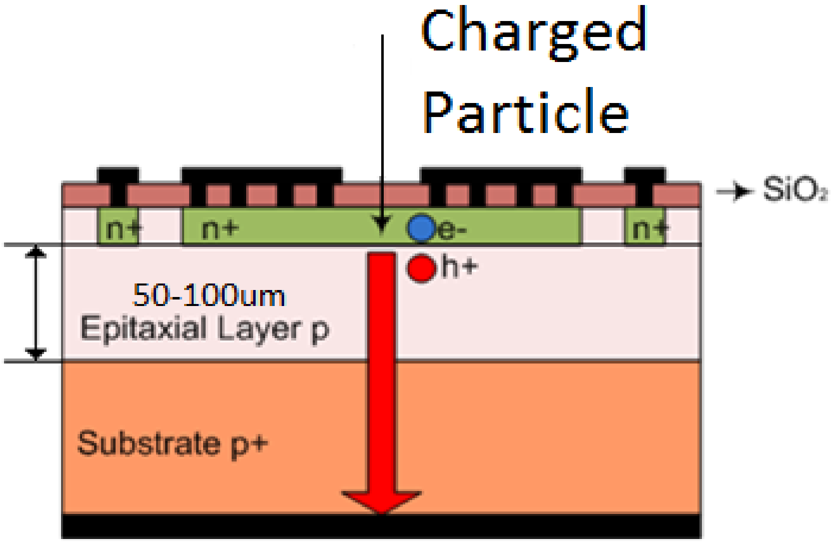
HPK Epitaxial Sensors

Reduction of Active thickness:

- **Smaller depletion voltage**
- **Charge collection length reduced by trapping in highly irradiated sensors**
  - **→ no gain in using thicker material.**
- **Epitaxial and Deep diffusion sensors allow reduction of active thickness which improves radiation hardness**
- **Using epitaxial, high electric fields can be created**
  - **→ charge multiplication after irradiation??**

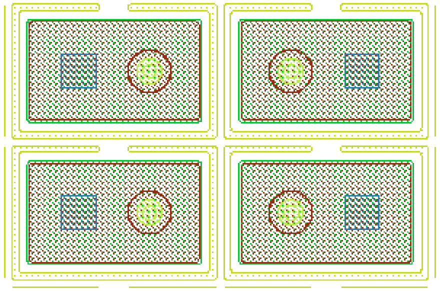
- **This talk presents laboratory and testbeam results for:**
  - **Epitaxial (50um, 100um)**
  - **FDB 120 um thick sensors.**

Material	Thinning	Active thickness	Total thickness	$O[10^{17}]$
FZ	Deep diffusion	120, 200, 300 um	320 um	0.2-5
FZ	Thinned	200 um	200 um	“
FZ	Handling wafer	120 um	320um	“
MCz	Thinned	200 um	200 um	3-6
Epi	Handling wafer	50, 100 um	320 um	0.3-2



Various FPIX and BPIX layouts

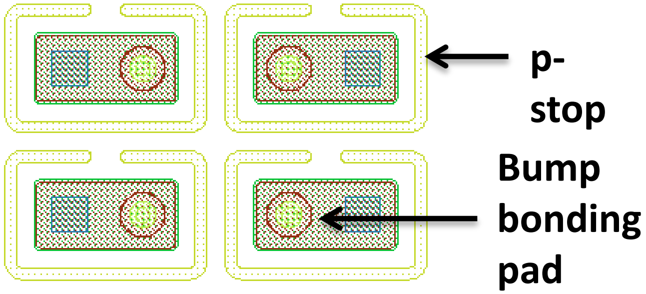
Layout FPIX-E



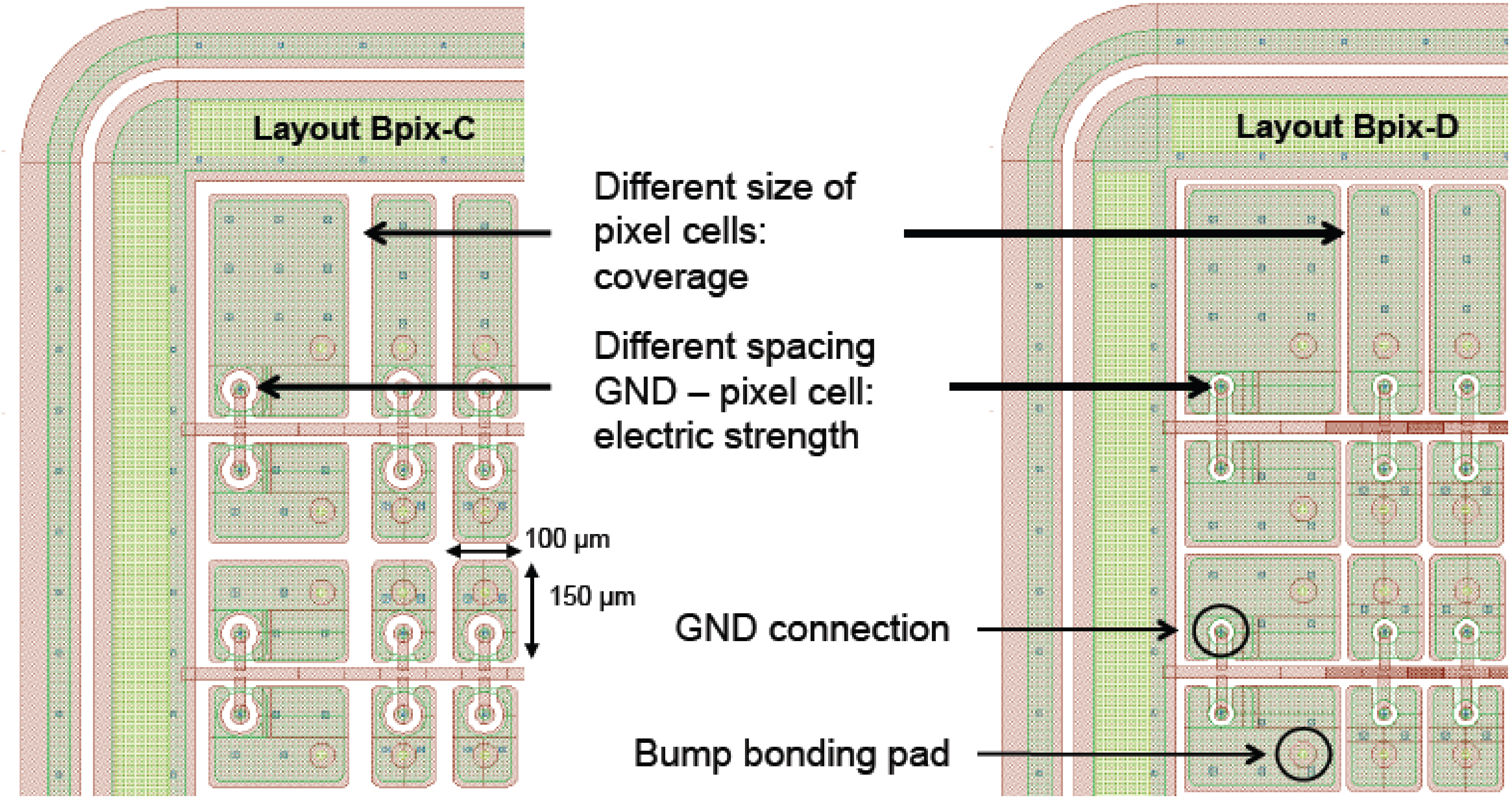
2 FPIX layouts:

- **Open p-stop**
- **Gap between p-stop and implant**
  - **30um for FPIXE**
  - **50um for FPIXF**

Layout FPIX-F



4 BPIX layouts (A-D): Gap in bias dot between 14 um and 22 um



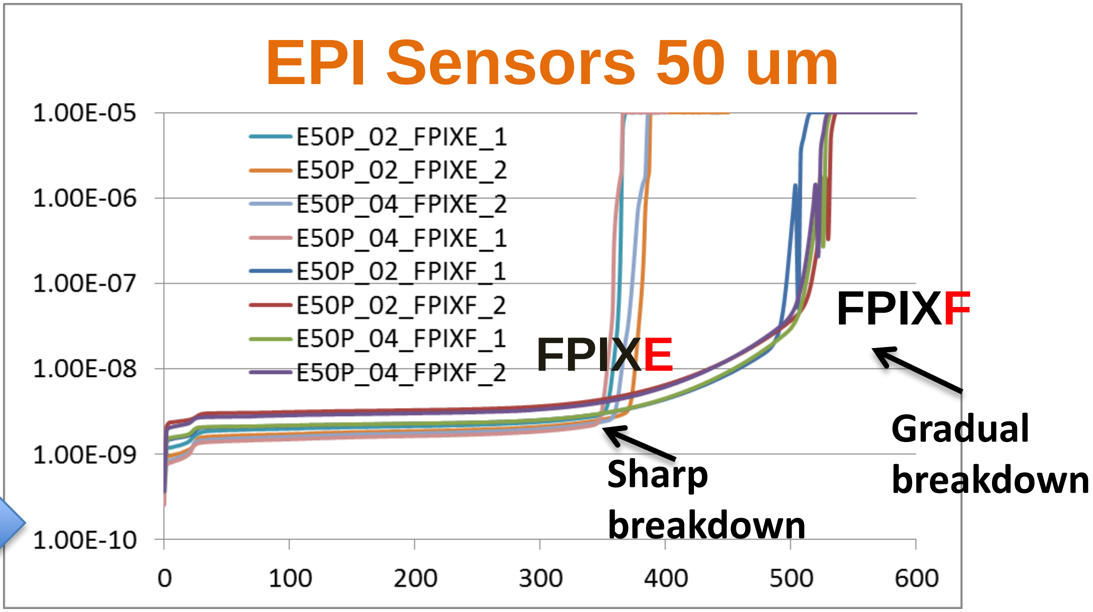
Leakage current – FPIX Epi sensors

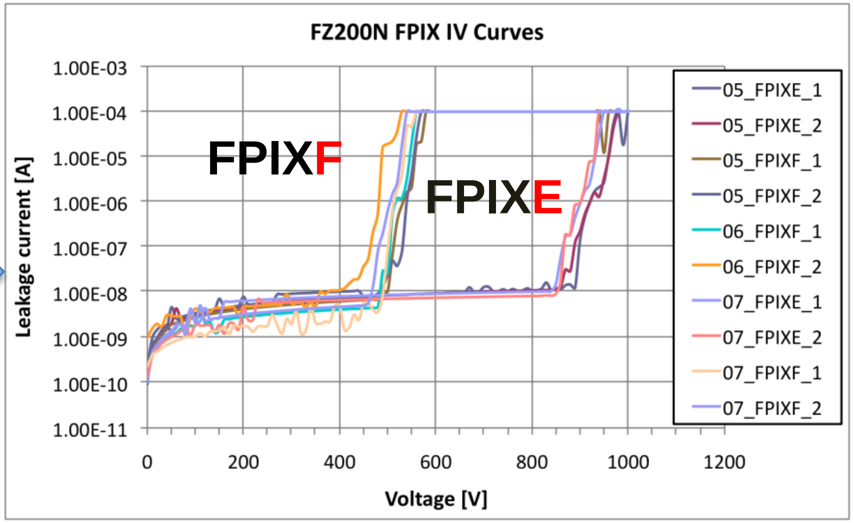
- **FPIX p-type Epitaxial 50um layouts with open p-stop (E50P)**

- **FPIX-F** sensors have 2X leakage after full depletion

- **FPIX-E** sensors with **larger implants and smaller gap** have **smaller breakdown** (350V- 380V) compared with larger gap pixel **FPIX-F** layouts (500V)
  - opposite trend from FZ n-bulk with same layout.

- Breakdown sharp for FPIXE, gradual for FPIXF

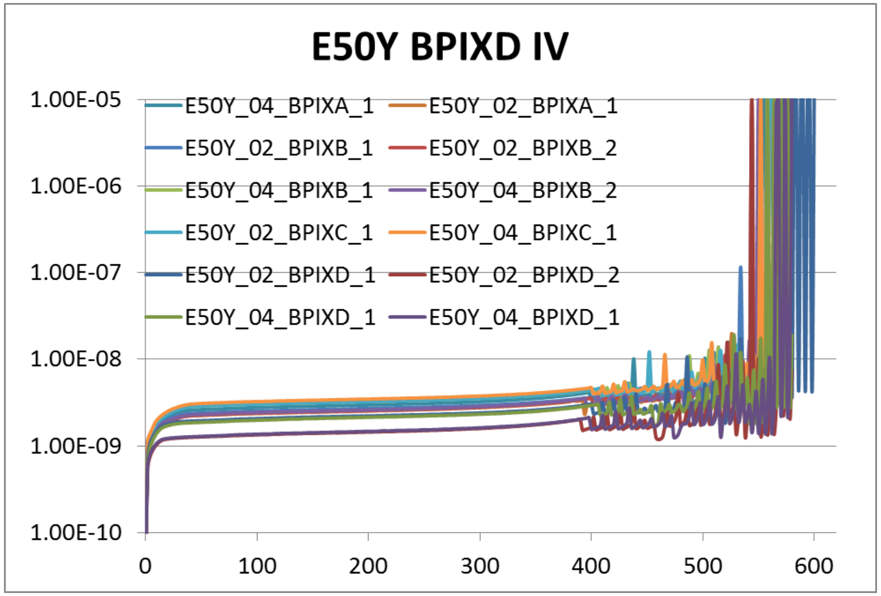




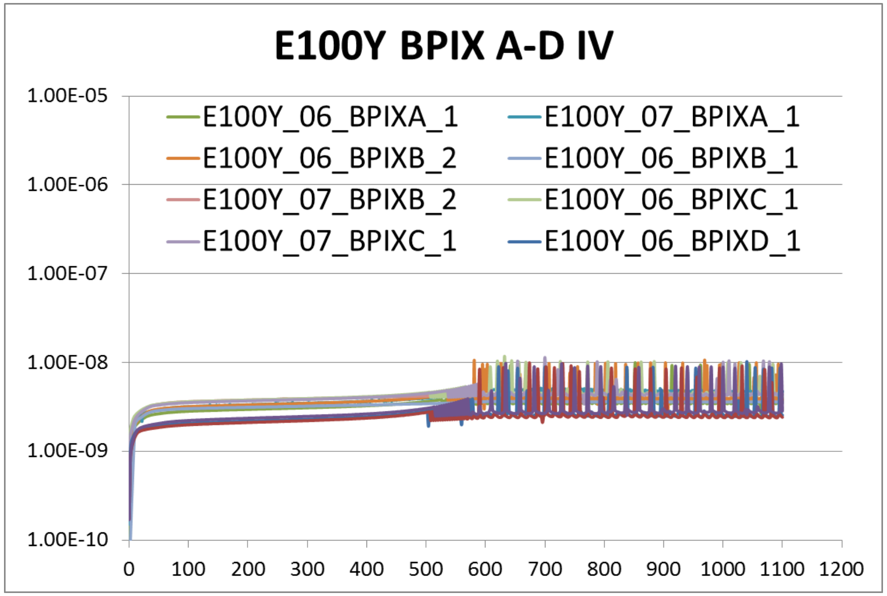
FZ 200um

FZ200N: V_{break} ~ 450V (**FPIXF**), 850V (**FPIXE**)

Leakage– Epi 50um, 100um BPIX sensors



Epi50um, BPIX with p-spray isolation: V_{break} ~ 550V for BPIXA-D

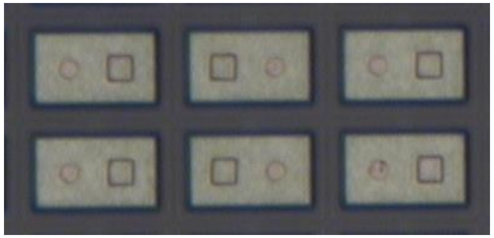


Epi100um, BPIX with p-spray isolation: V_{break} > 1100V for BPIXA-D

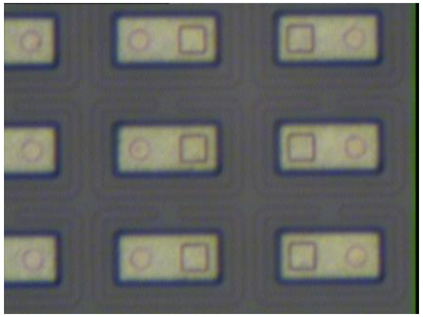
- **E100 BPIX** layouts with p-spray isolation and **different gap sizes** (**BPIXA** - **BPIXD**) have very high breakdown (1100V).
  - Bias-dot gap size does not matter
- **Leakage** of both E50 and E100 **BPIX sensors with p-spray** becomes **noisy** after 450V-500V
  - This effect can also be seen partially in E50P and E100P sensors with p-stop just before breakdown (450V-500V).

Capacitance – Epi 50um FPIX sensors

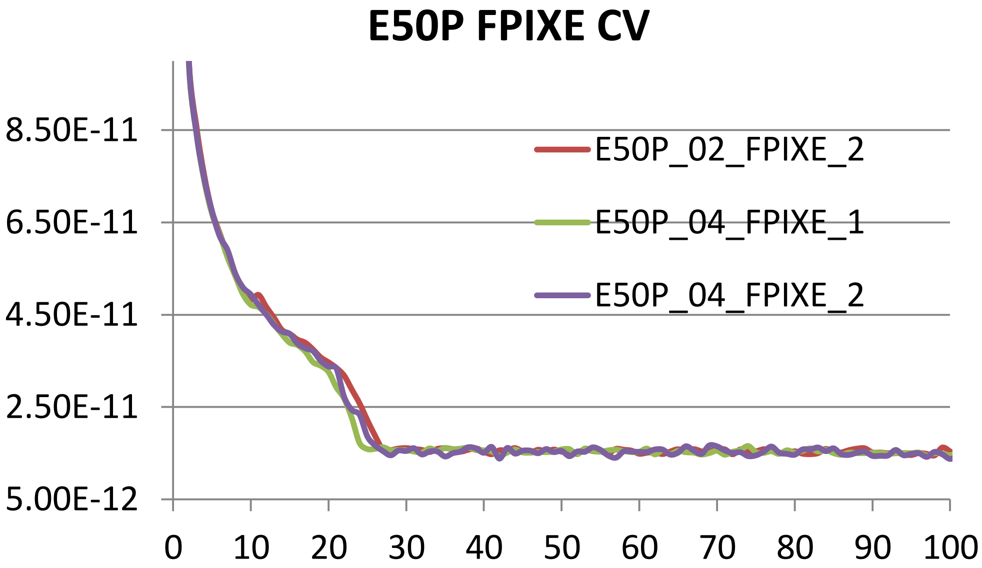
V_{dep}~ 25V for both FPIXE and FPIXF



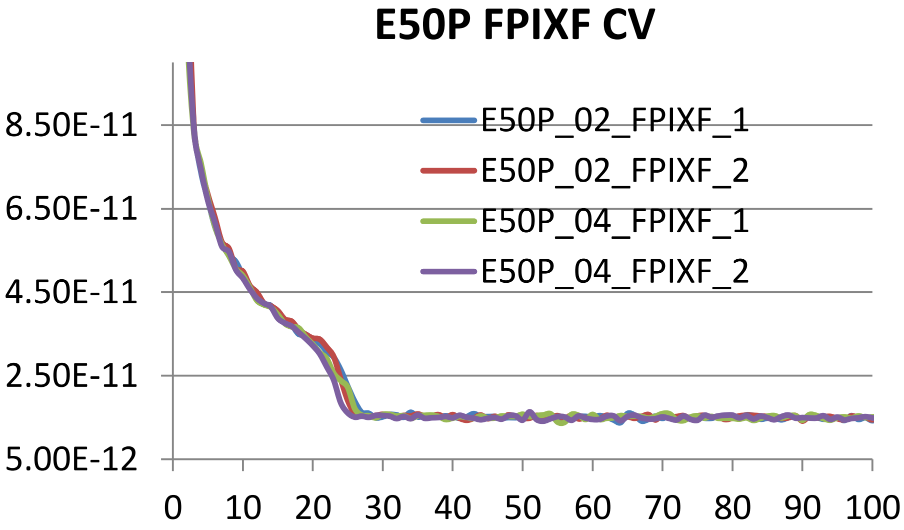
FPIX-E



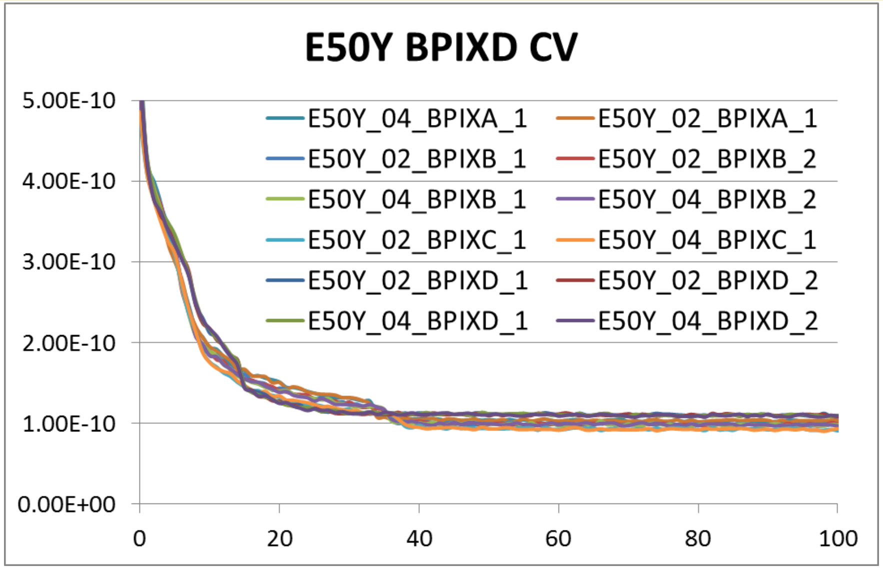
FPIX-F



- 1MHz, 50mV AC, 1V step.
- **FPIXE** and **FPIXF** layouts deplete around 24V.
- Depletion capacitance is similar for both FPIXE and FPIXF
  - **Expect similar noise for FPIX-E and FPIX-F**

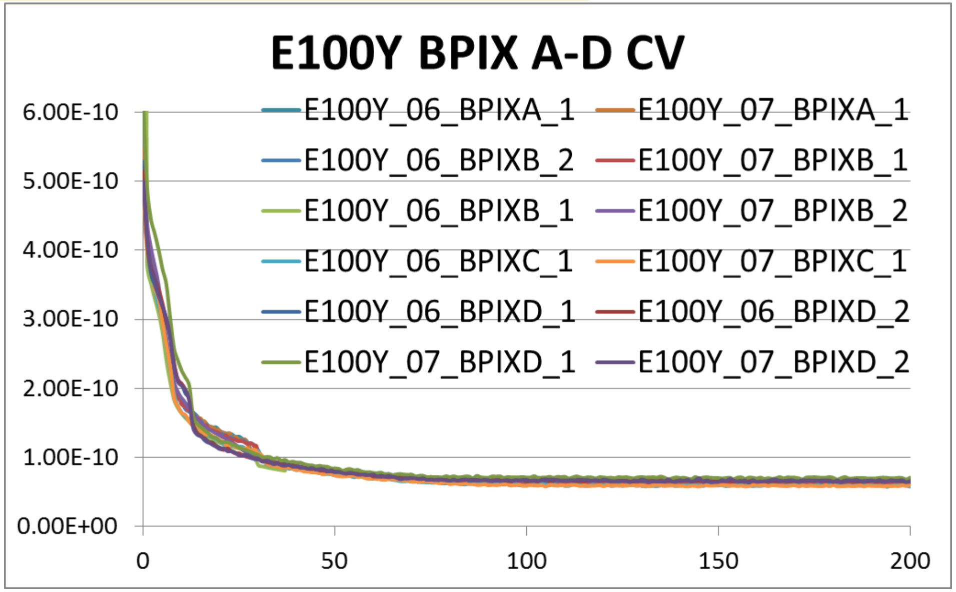


Capacitance – E50Y BPIX sensors



V_{dep}~ 35V-40V for BPIX A-C

V_{dep}~ 25V for BPIX-D

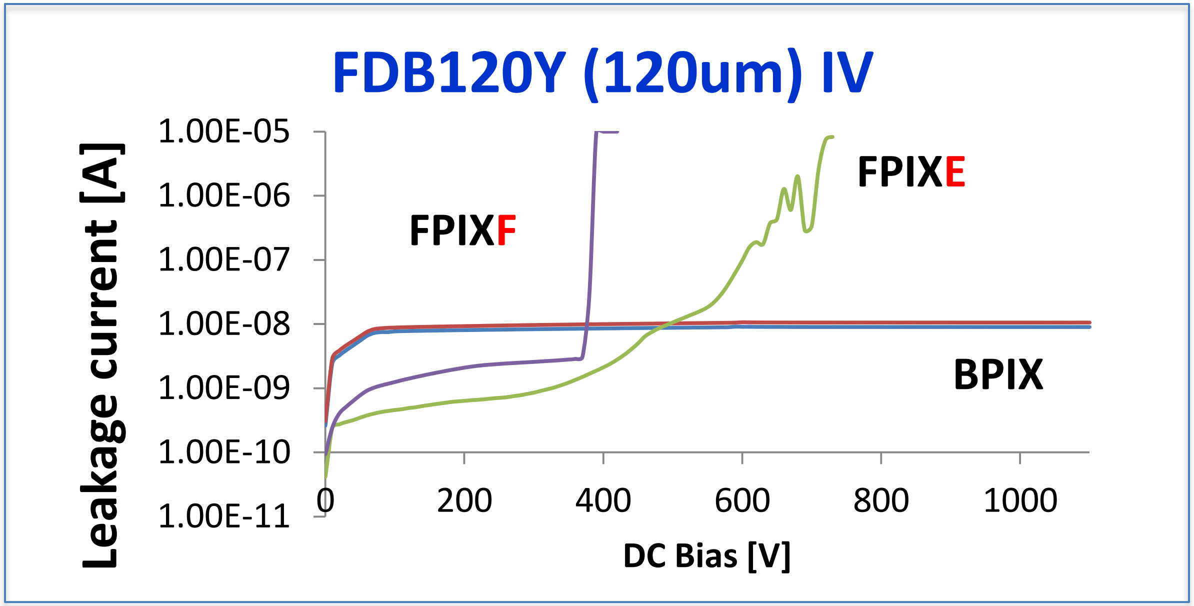


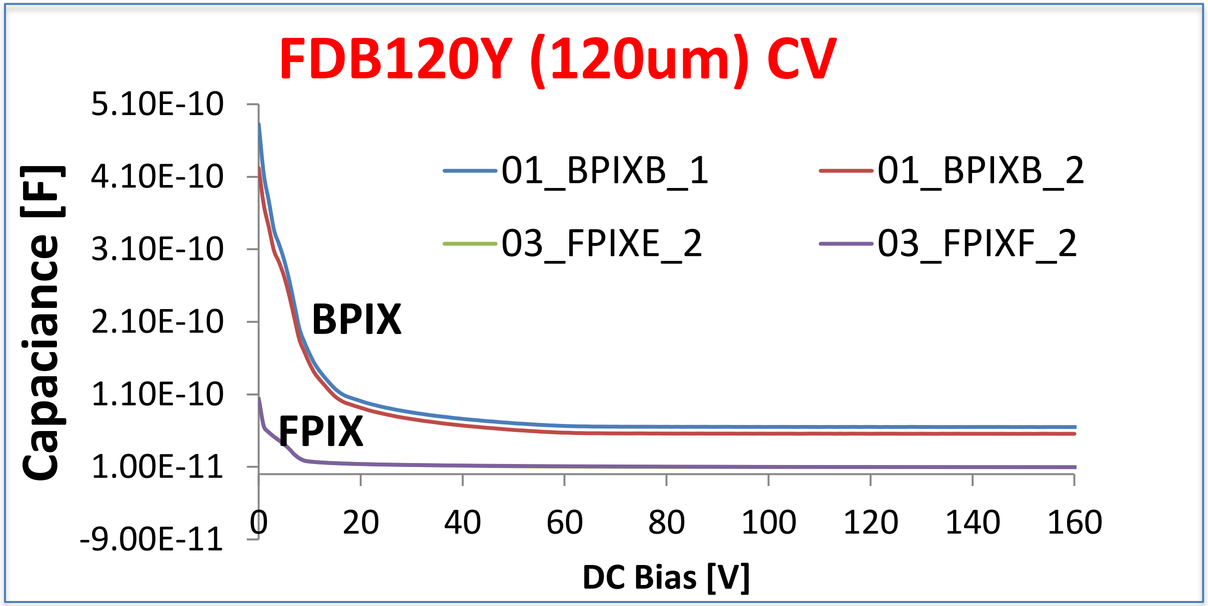
V_{dep}~ 35V-40V for BPIX A-C

V_{dep}~ 25V for BPIX-D

- Capacitance depends on pixel layout:
  - BPIXD depletes much earlier (~20V) compared to BPIX A-C (~40V).
  - E50Y BPIX sensors expected to be more noisy during operation
  - E50 FPIX with p-stop (E50P) layouts have smaller C (15pF) compared to E50 BPIX layouts with p-spray (100pF)
  - E50P FPIX sensors fully depletes around 24V, E50Y BPIX layouts ~38V.

Leakage and Capacitance: FDB120 sensors





- FDB120 FPIXE and FPIXF sensors break down in the range 380V-600V.
- FDB120 BPIX layouts do not break down until 1100V.
- Depletion voltage of **FDB120Y sensors** is around 55V-60V.
- BPIX layouts in general have higher depletion capacitance compared to FPIX layouts.

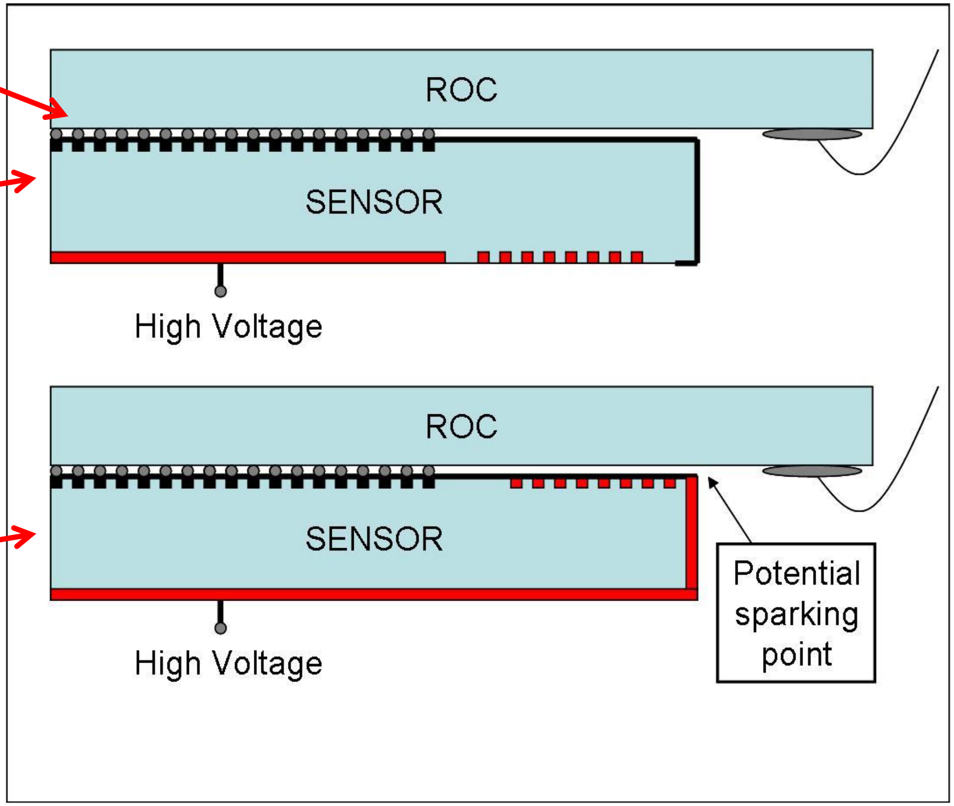
Bump bonding at Princeton University

- Processing at Princeton’s (Micro Nano Fabrication Facility) PRISM:
  - 5,000--square--foot clean room, class 100 for lithography, class 1000 for deposition and etch.
- Bump-bond solder material is Indium
- No reflowing applied, just mechanical pressure applied after solder deposition to ROC bump-bond pads
- UBM for silicon bump-bond pads
  - 100nm's of sputtered UBM TiW thin film deposition using e-beam thin film sputterer.
- Indium deposition using thermal evaporator
  - Solvent and light O2 plasma descum before bump bonding.
- Lithography possible on individually diced sensors.

Edwards E306A Thermal evaporator

Research Devices M8A Flip-chip bonder

Need for edge passivation after bump bonding


ROC at Ground

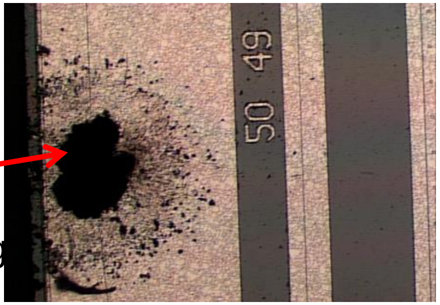
Double-sided, n-on-n module

Single-sided, n-on-p module

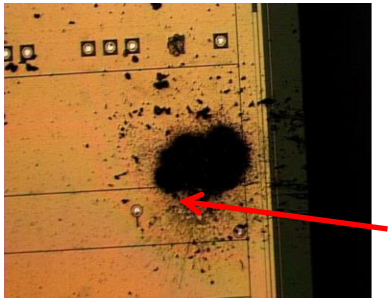
- A single-sided n-on-p bump bonded module compared to a double-sided n-on-n module
- Small air gap (<10um) between ROC and sensor due to soft Indium bumps, dielectric strength of air is only 3V/um
    - arcing through the sensor and ROC after applying >30V

Edge passivation using Parylene N at Birck

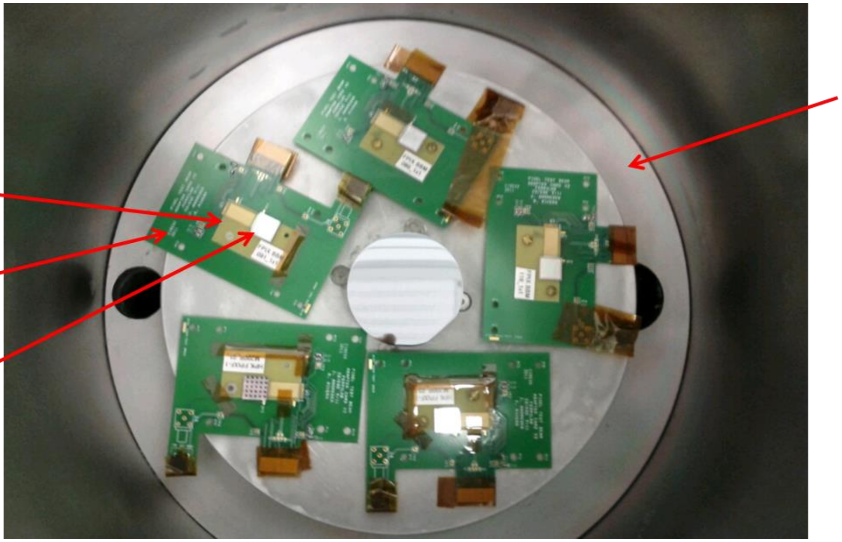
- Applying Parylene (N-type) at **Purdue Birck Nanotechnology Center**
  - 280 V/µm dielectric strength;
  - Good passivation, very conformal
  - Proven to be Radiation hard to 1E16 neq/cm^2
- Plan to apply BCB using photolithography at IZM, Gemany
  - higher dielectric strength (5300V/µm), easier to apply during fabrication



Sensor arced before coating



ROC arced before coating

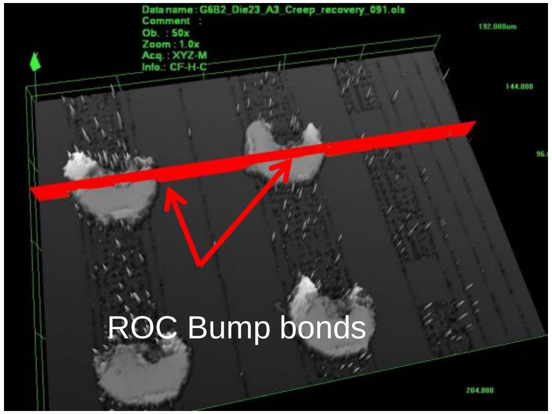


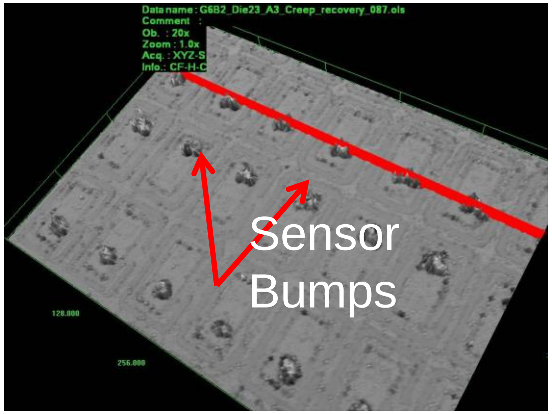
CVD chamber

Coating uniformity

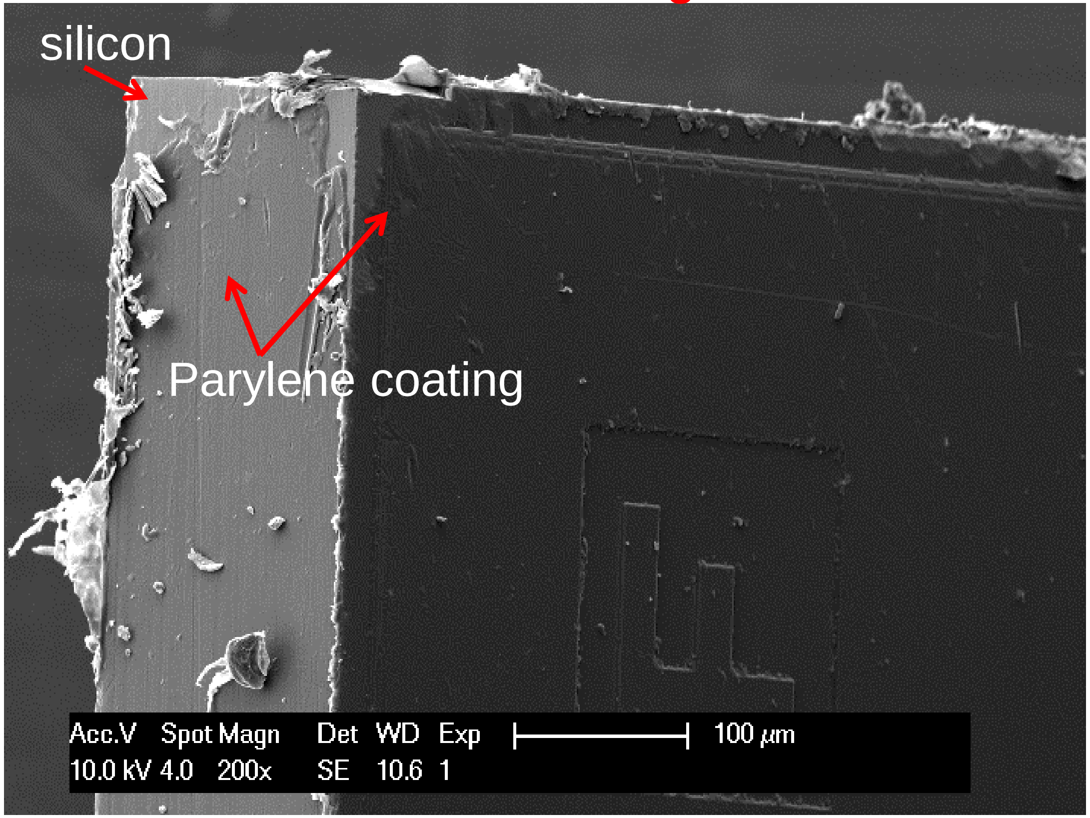
- SEM and Confocal microscope imaging done after coating:
  - A good coating uniformity observed
  - Coating distributed everywhere on the sensor
  - Verified with Alpha-step profilometer

Confocal microscope images

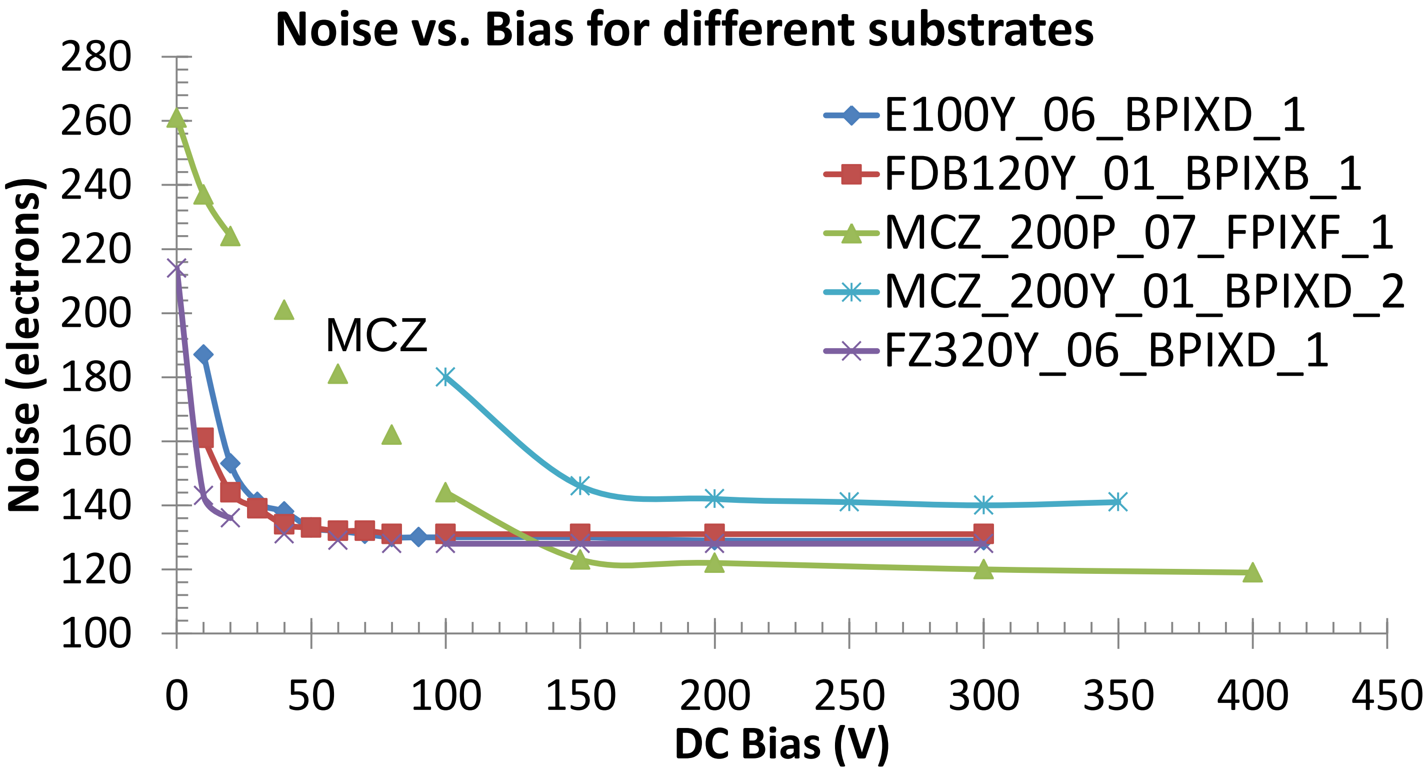




SEM Image

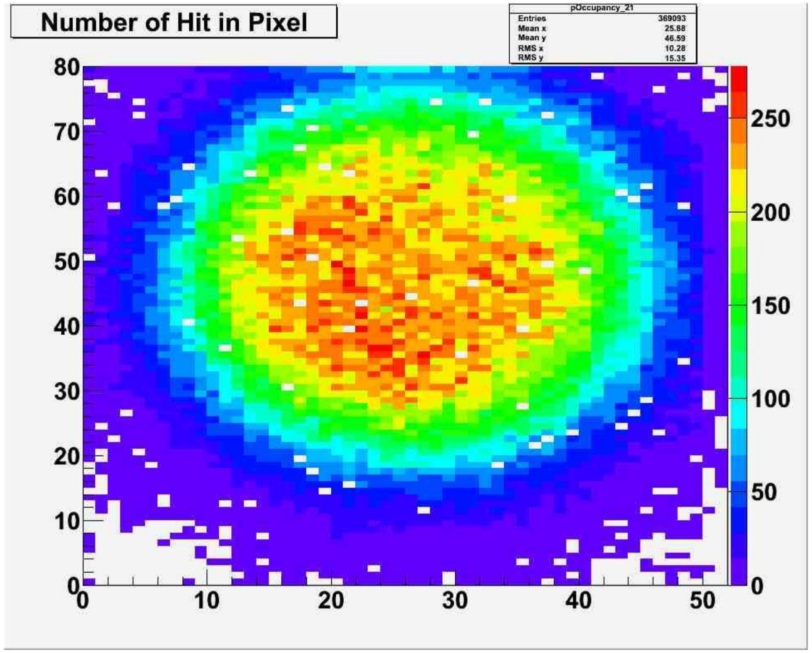


Lab tests: Noise vs. Bias



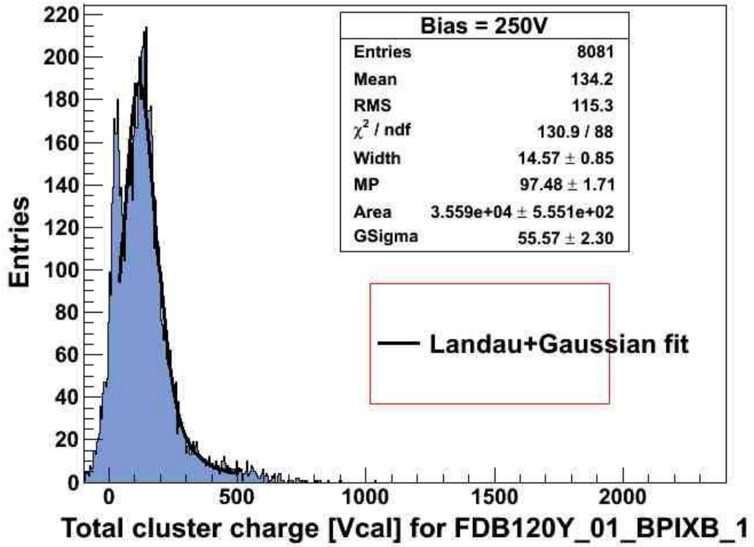
- **Noise for HPK sensors of different substrates saturates to 120e-140e after full depletion.**
- MCZ sensors have very high noise initially (280e) but saturates after full depletion.
- BPIX layouts (140e) are slightly higher noise than FPIX layouts (120e) for same substrate type
  - In agreement with CV results.

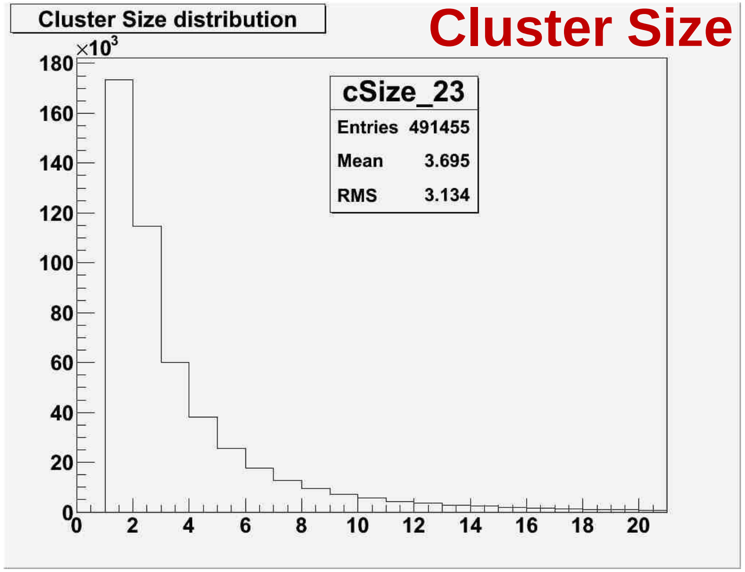
Source test with Sr90 – FDB120um BPIXB



- Sr90 source directly on top of sensor
- V_{bias} = 250V
- Threshold trimmed 2600e-
- Extra peak in Landau distribution observed
    - Large number of 2 pixel clusters contribute to extra peak in Landau.

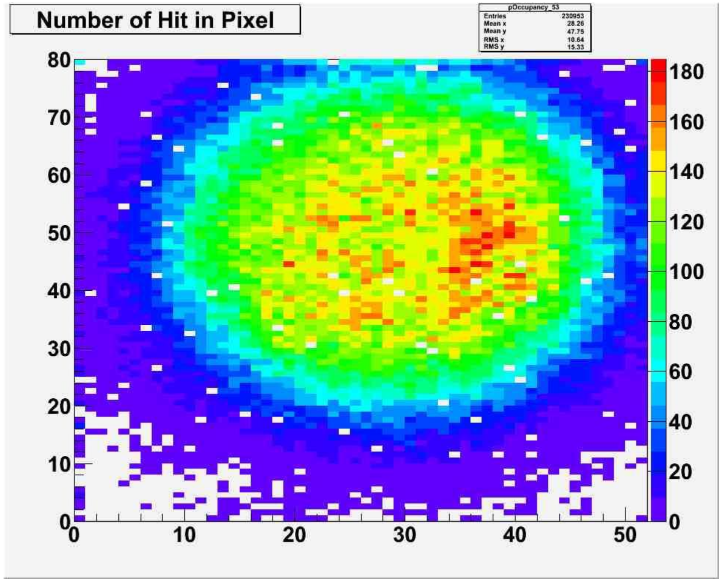
Charge collection



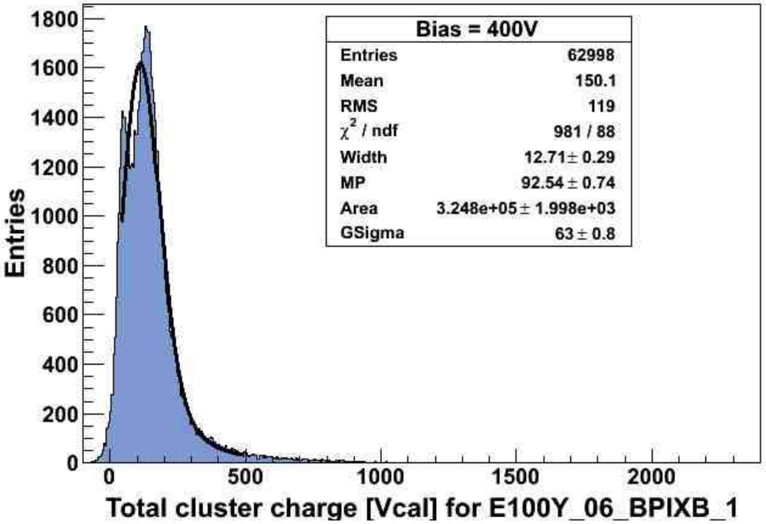


Cluster Size

Source test – E100um BPIXB with p-spray

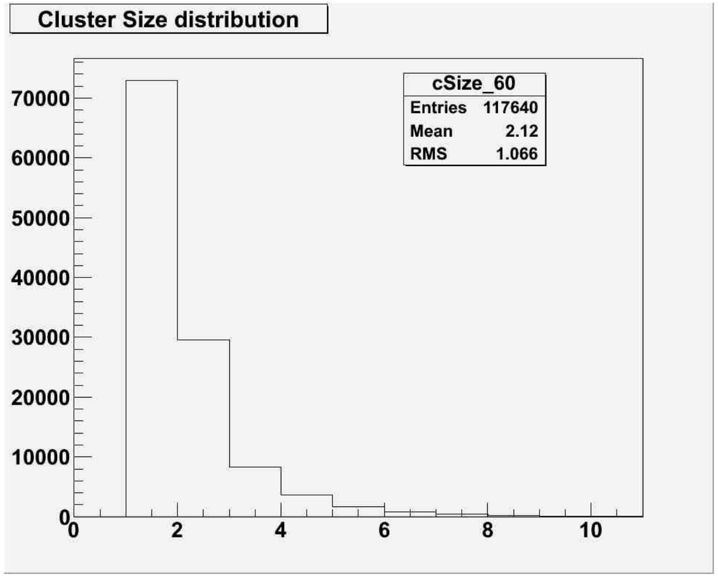


Charge collection



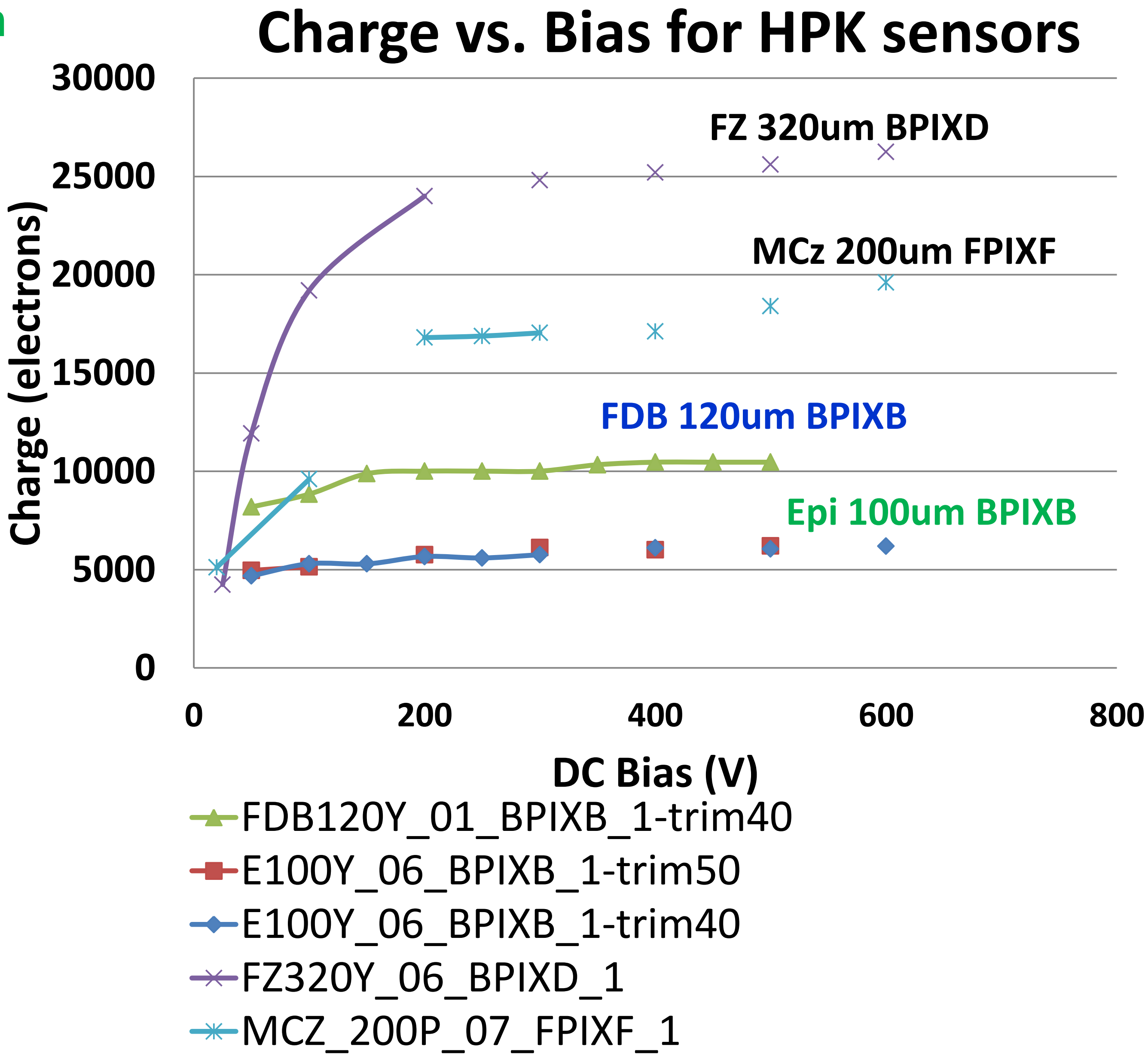
- **V_{bias} = 400V**
- **Needed to increase threshold (3300e) to reduce noisy pixels**
- **Average signal (6ke) lower than expected (8ke)**
- **Large number of 2-pixel clusters**

Cluster size distribution

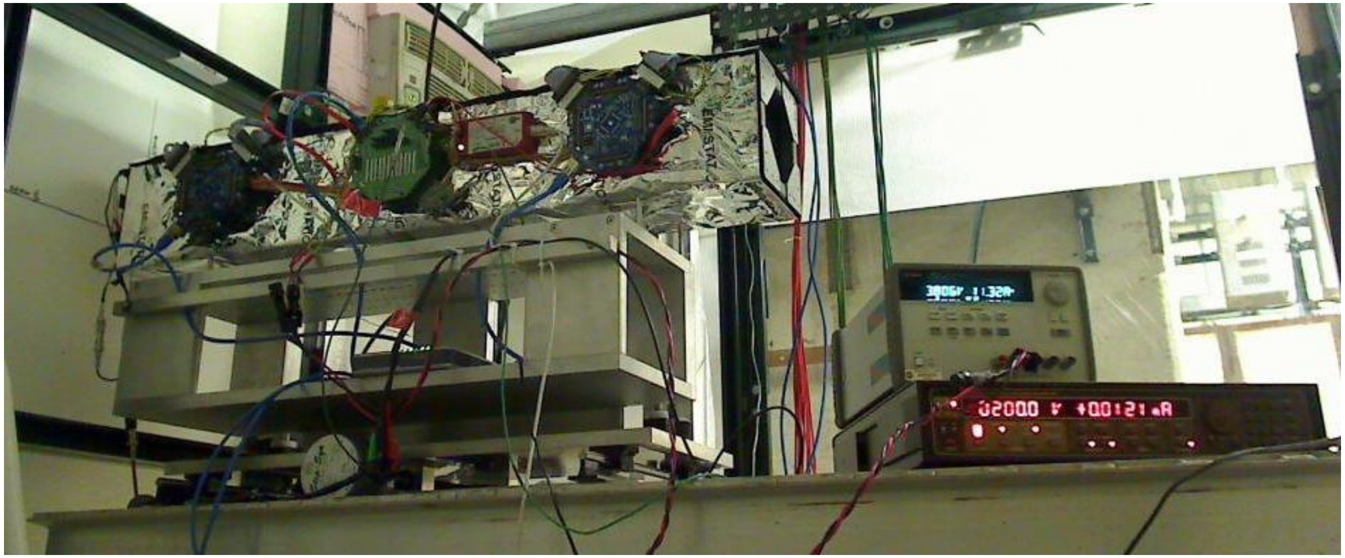


Charge vs. Bias for HPK sensors

- For **Epitaxial 100um** sensors, average charge collected (6ke) is less than expected (100*80)=8ke at trim of Vcal=40.
- For **FDB 120um sensors**, charge collected (10.4 ke) is slightly higher than expected value (120*80)= 9.6ke
  - **Need to trim threshold better.**



Testbeam at Fermilab Meson Test facility

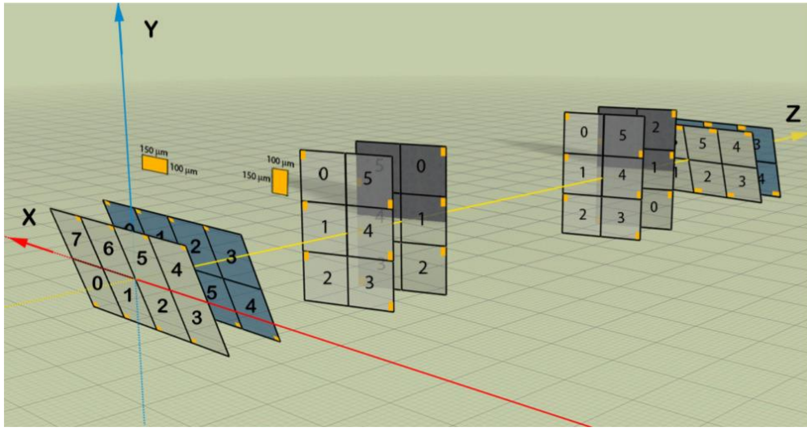


- 120 GeV proton beam.

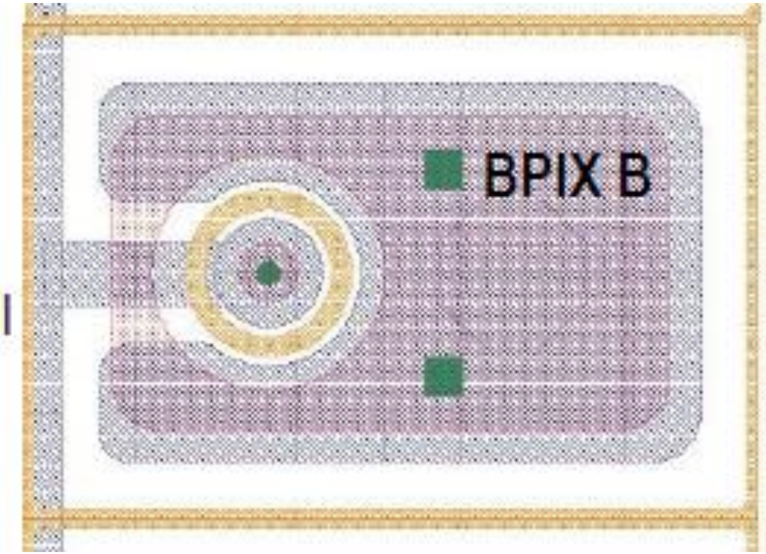
- 8 telescope planes of CMS pixel modules (pixel size 100x150 μm^2), 4 upstream and 4 downstream with respect to the DUTs.

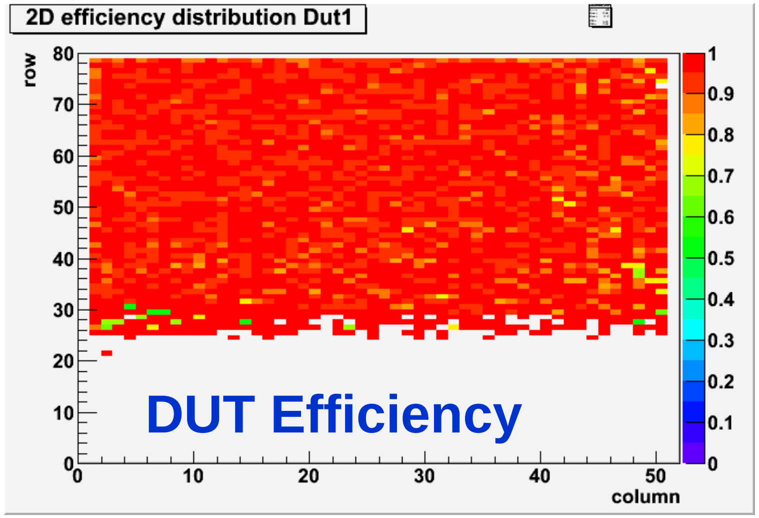
- Rotation on 100 μm pixel pitch direction for improving telescope resolution (8 μm).

- Various institutes involved in data taking and analysis: Fermi National Lab, INFN Milano, INFN Torino, Purdue etc.

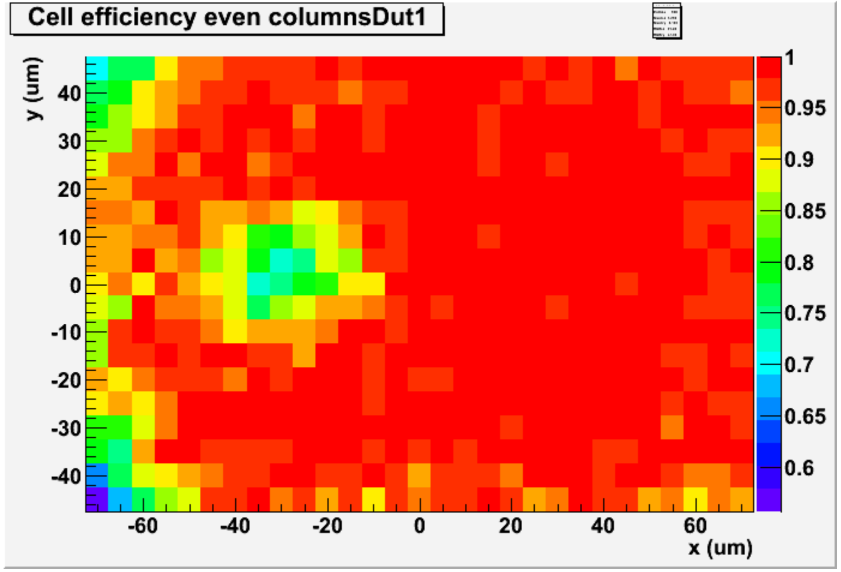


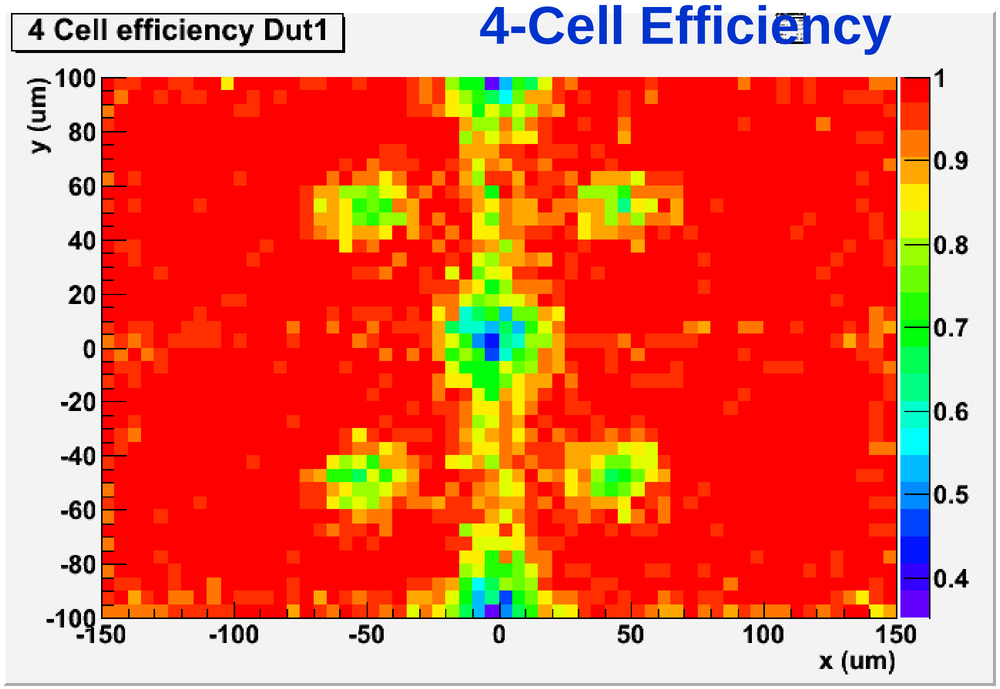
Beam test at Fermilab: E100um BPIX-B p-spray





DUT Efficiency



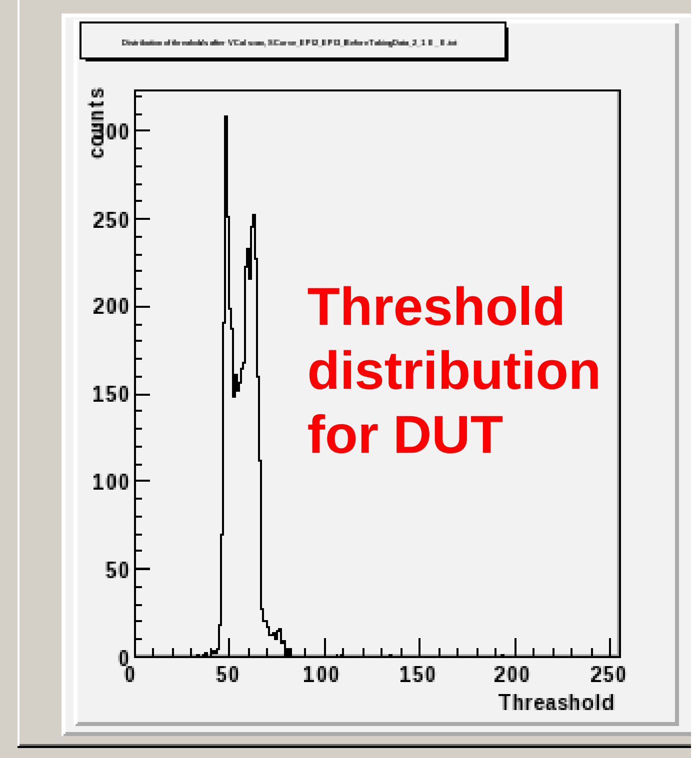


4-Cell Efficiency

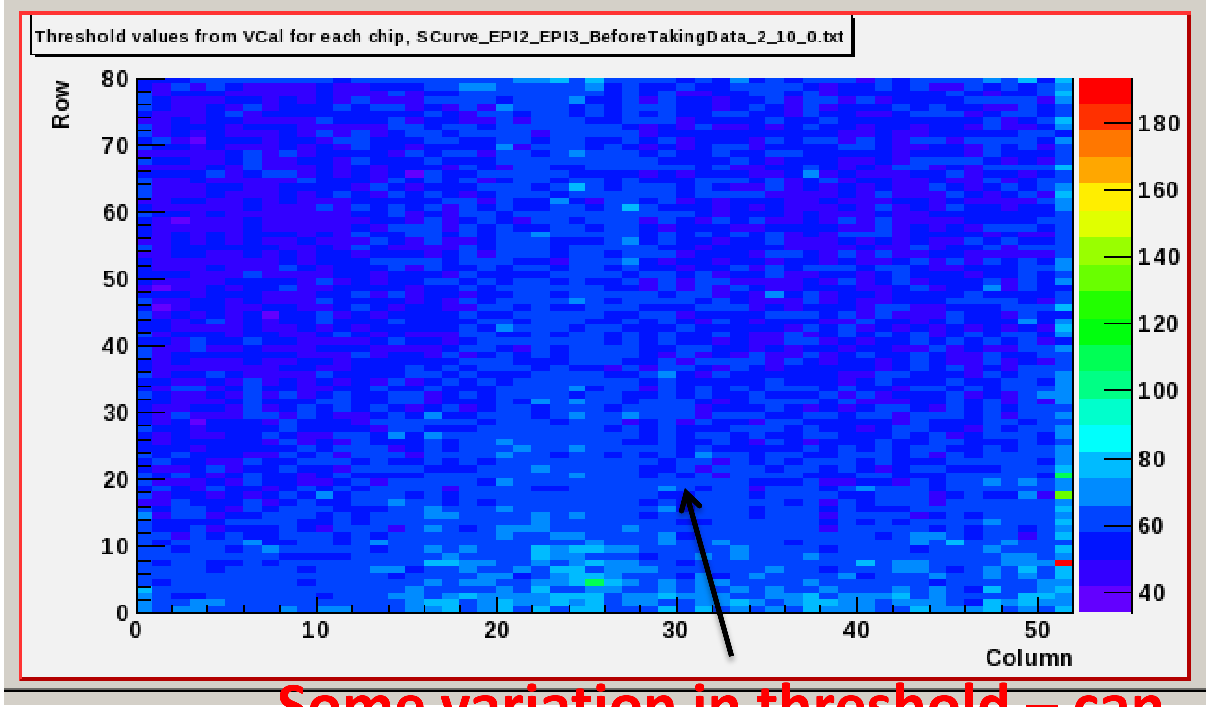
Applied voltage: 300V

Cell efficiency: 95.4%

Epi 100um BPIXB: Threshold distribution



Threshold distribution for DUT

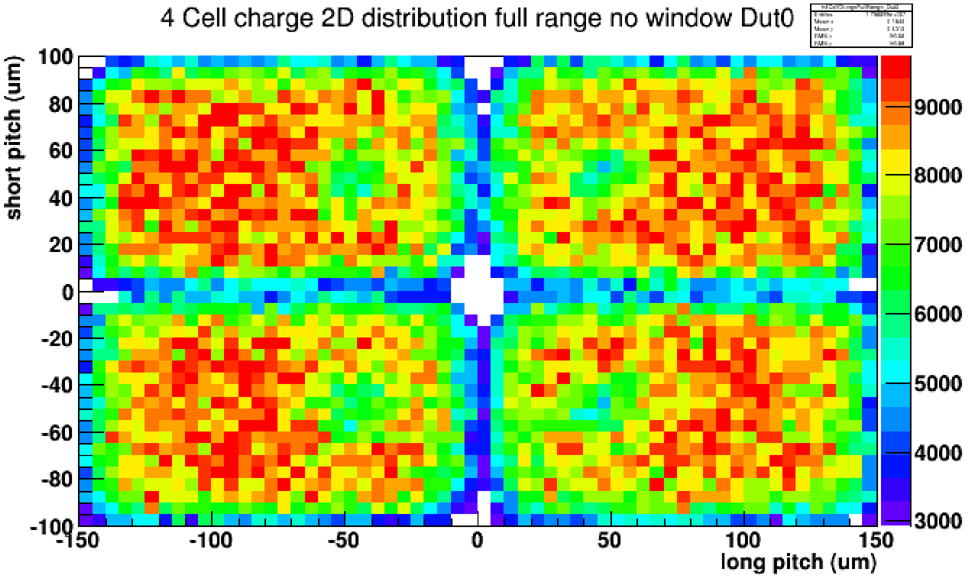


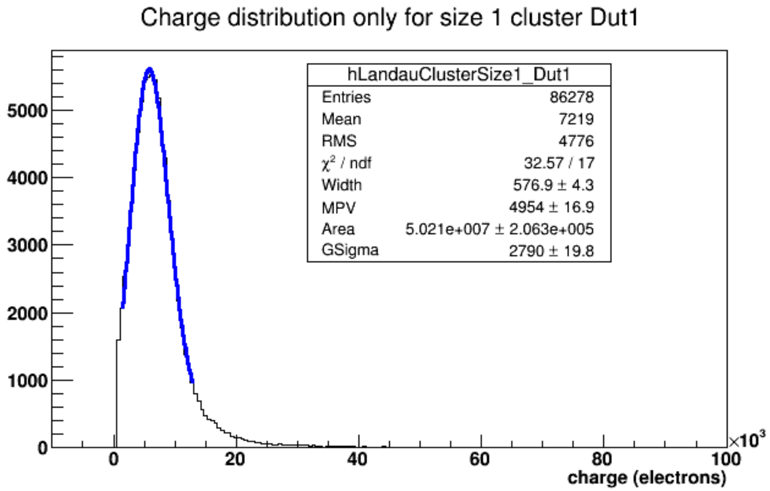
Some variation in threshold – can be improved with trimming

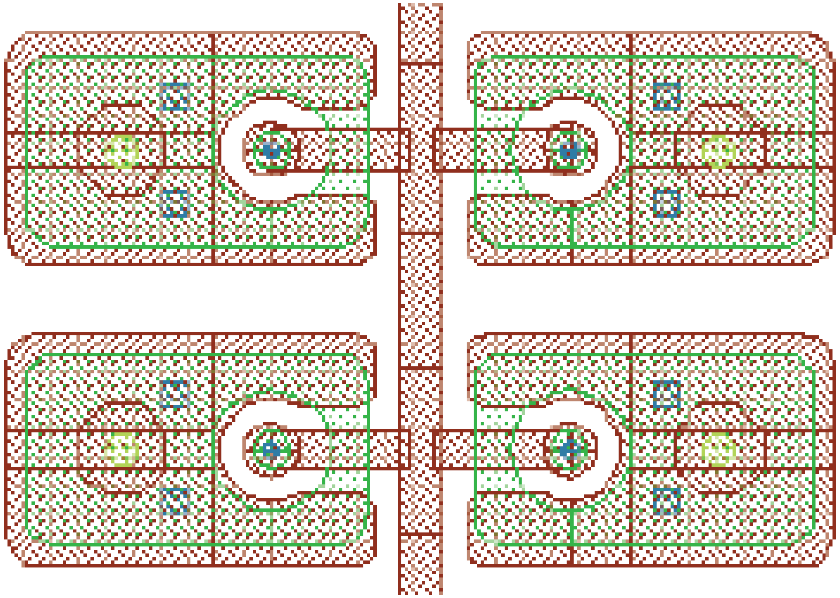
- Result for Analog chips
- Threshold distribution for 4160 pixels (without trimming) calculated using S-Curves.
- Average threshold: ~60 ADC

  = 60*65e/ADC= ~3900e

E100Y_BPIXB: Charge collection

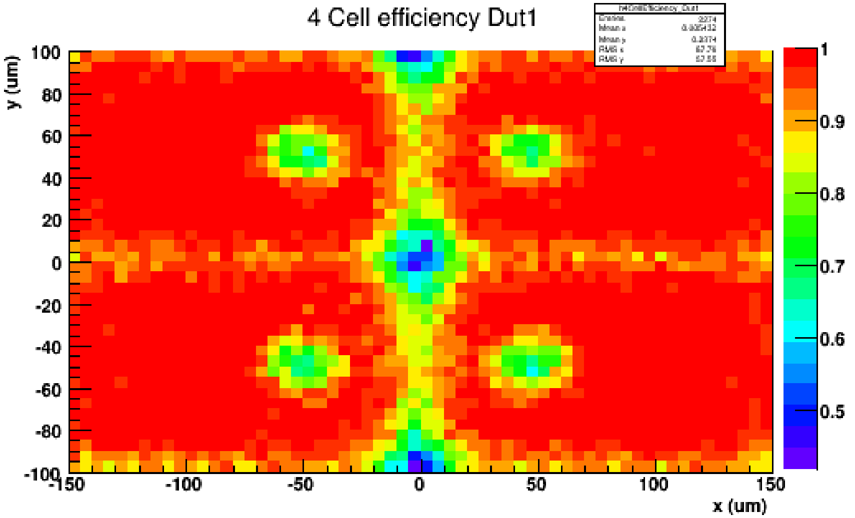




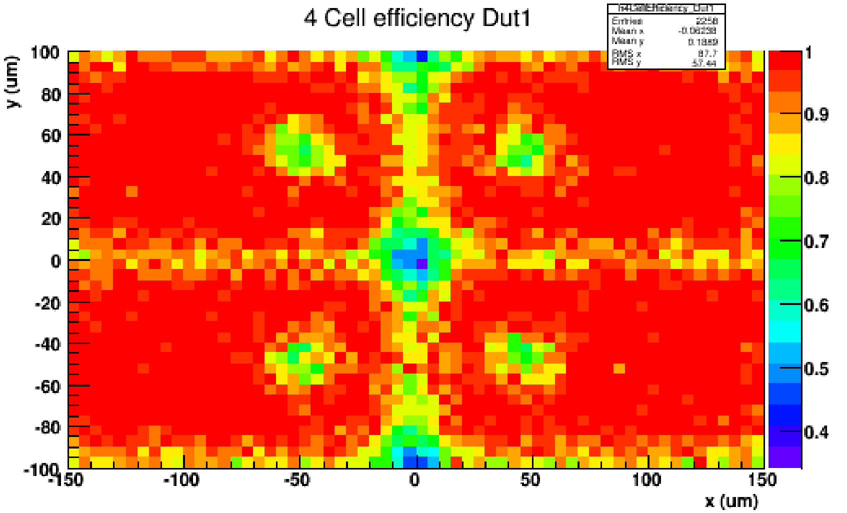


- **100um thickness**
- **Threshold: 3.9ke**
- **Charge (MPV): 5ke, much less than expected (8ke).**
- **Need to understand charge and efficiency results.**

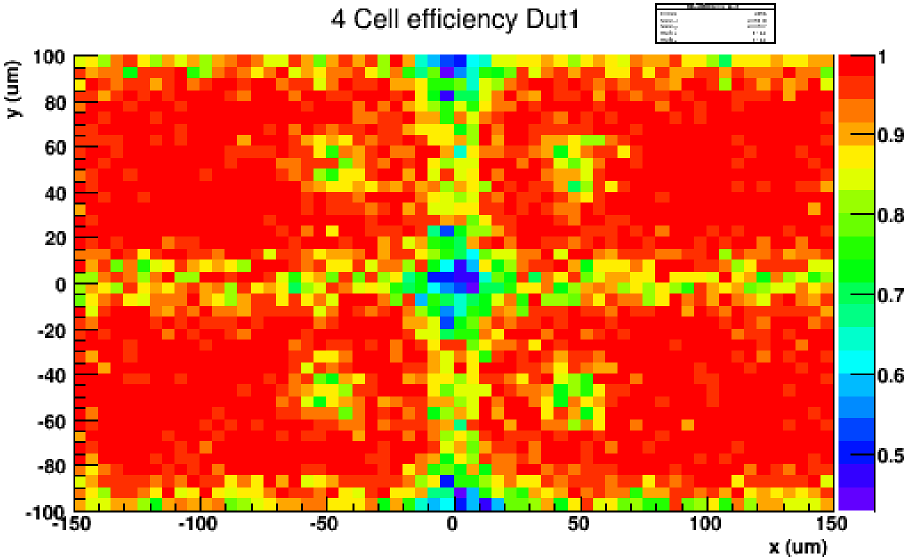
E100Y_BPIXB: Angle Scans



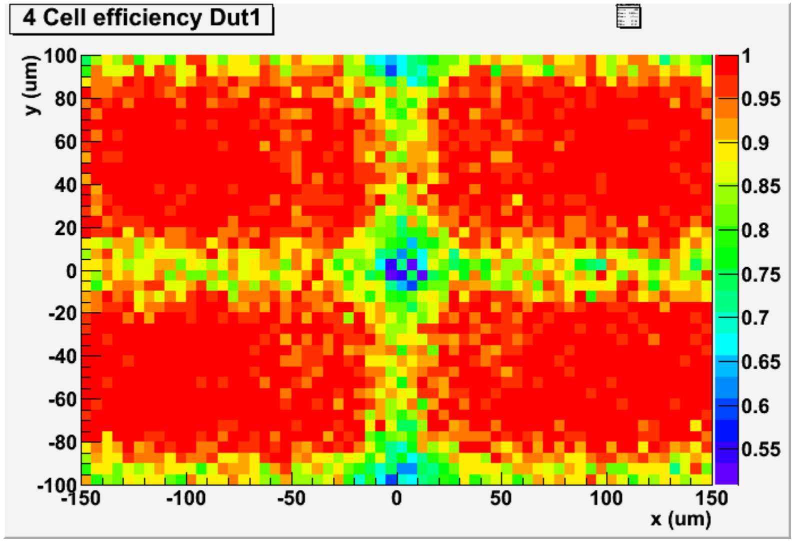
5° Cell efficiency: 94.5%



10° Cell efficiency: 94.1%

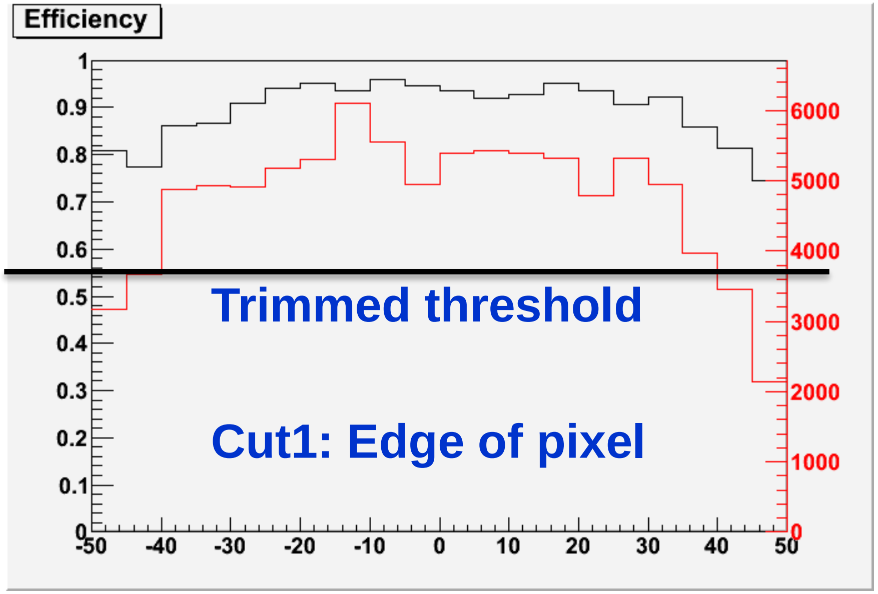


15° Cell efficiency: 94%



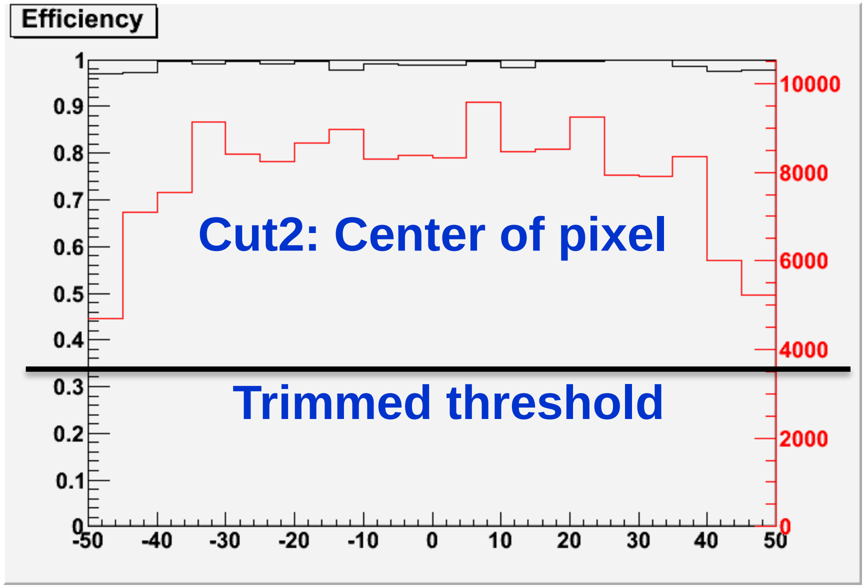
25° Cell efficiency: 95%

Mismatch between Efficiency and Charge



Trimmed threshold

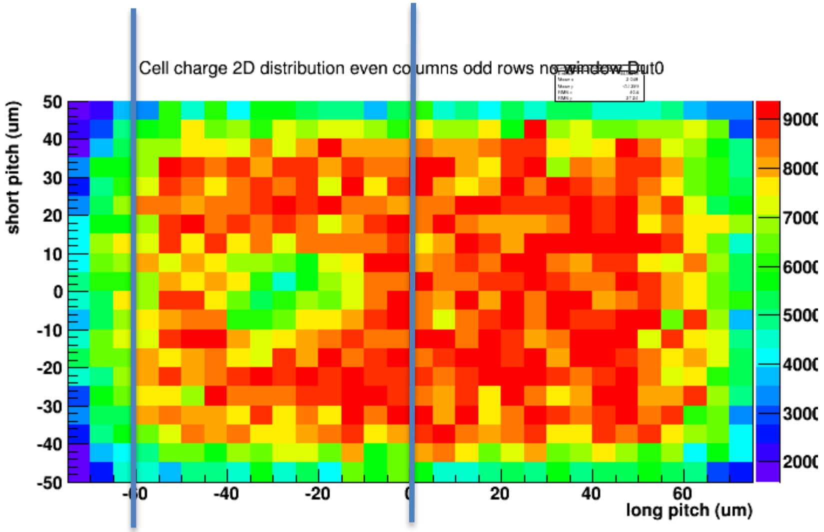
Cut1: Edge of pixel



Cut2: Center of pixel

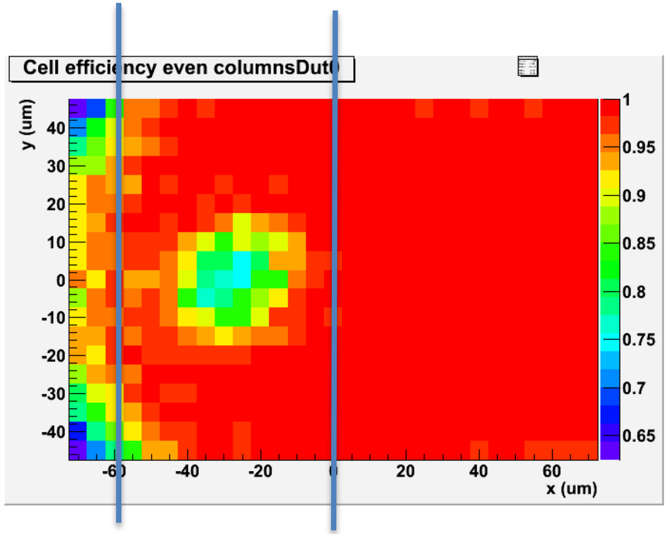
Trimmed threshold

Charge vs. Efficiency at different cuts of pixel along short pitch



Cut1

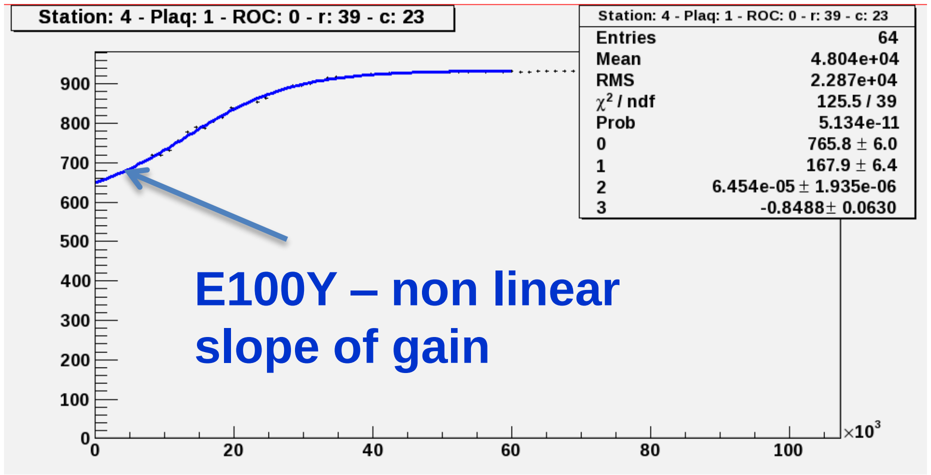
Cut2



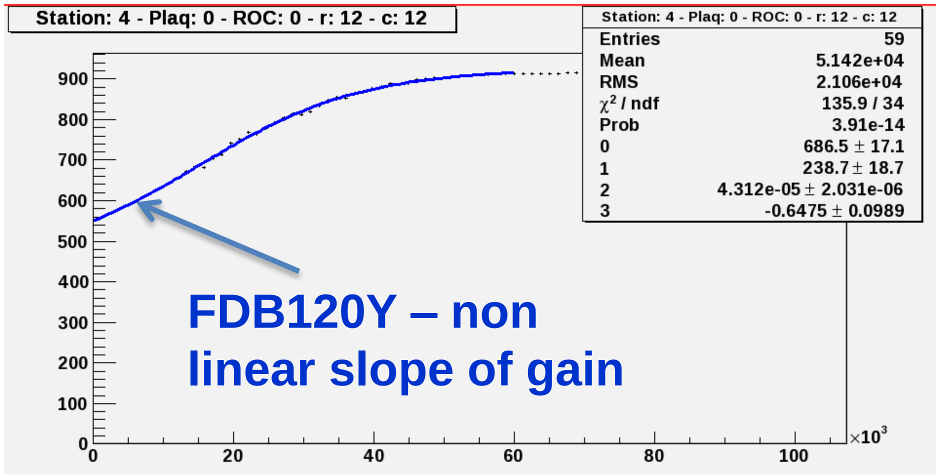
Cut1

Cut2

Reason for Lower Charge collection

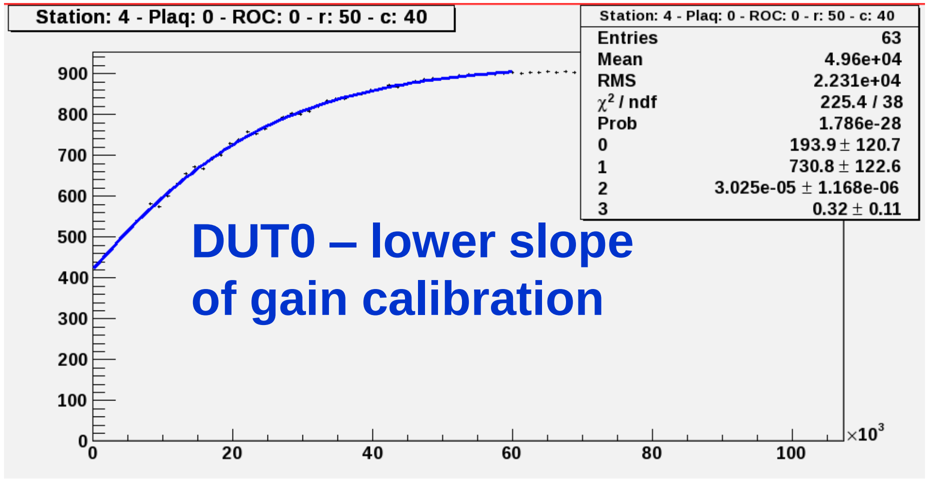


E100Y – non linear slope of gain

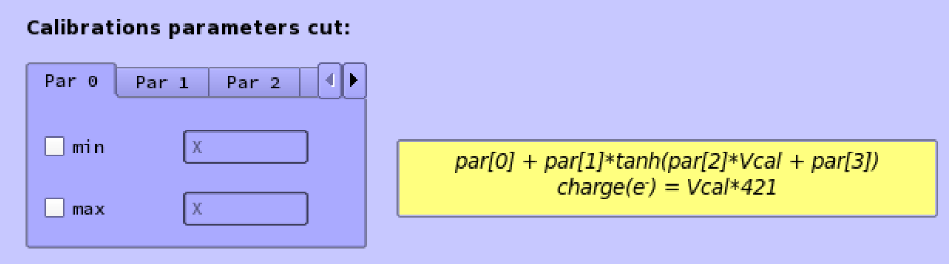


FDB120Y – non linear slope of gain

Non-linear gain calibration in low charge region



DUT0 – lower slope of gain calibration

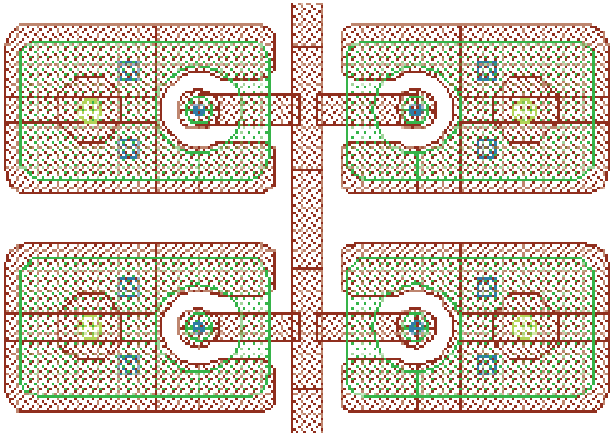


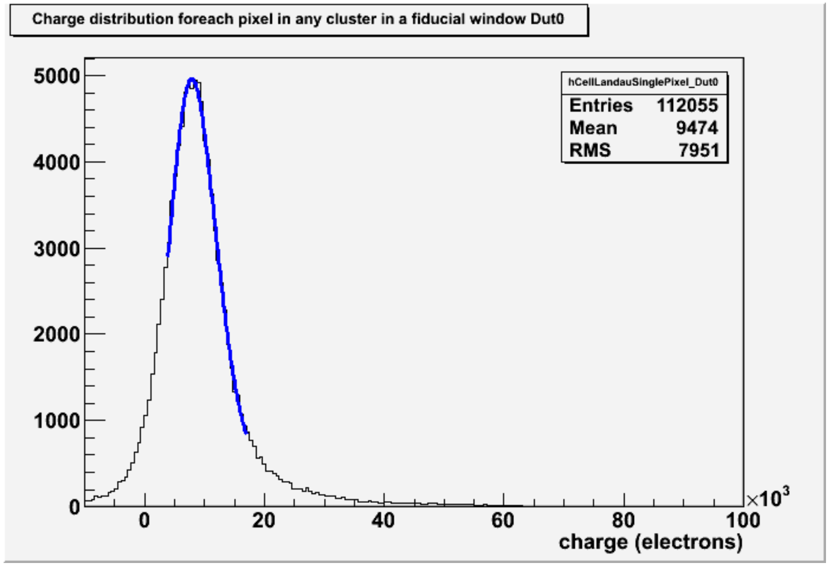
*par[0] + par[1]*tanh(par[2]*Vcal + par[3])*
*charge(e⁻) = Vcal*421*

Different values of gain for different pixels: lower gain means lower charge collected

- **Tried to use Weibull gain calibration fitting function in low charge region to better estimate charge collected**
  - **Did not converge**

Beam test Fermilab: FDB120um BPIXB p-spray





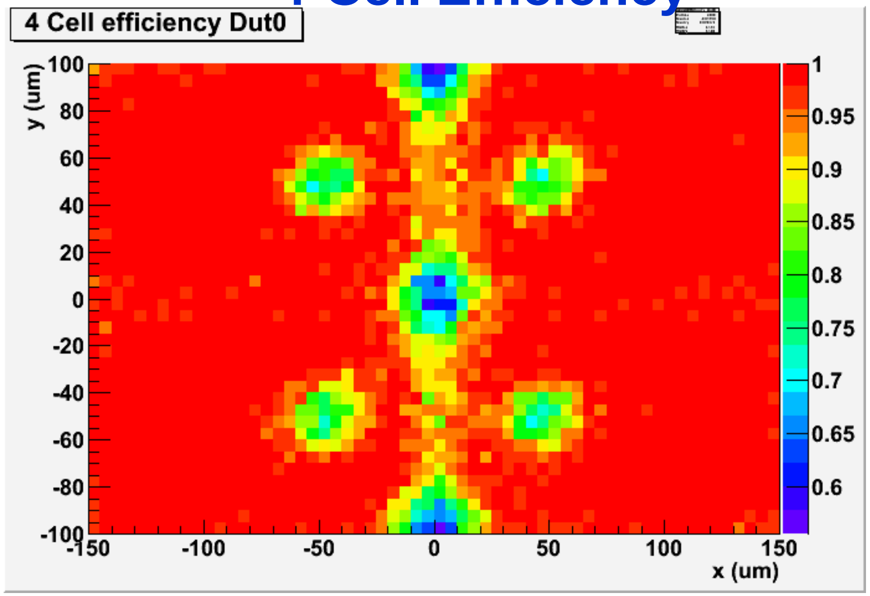
Applied voltage: 300V

Depletion voltage: 55V

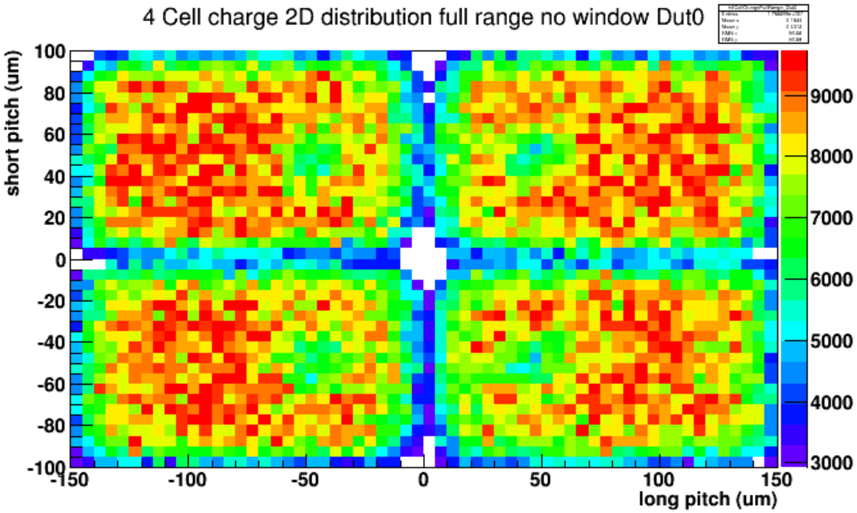
Cell efficiency: 96.8%

Charge collected: 9.5 ke

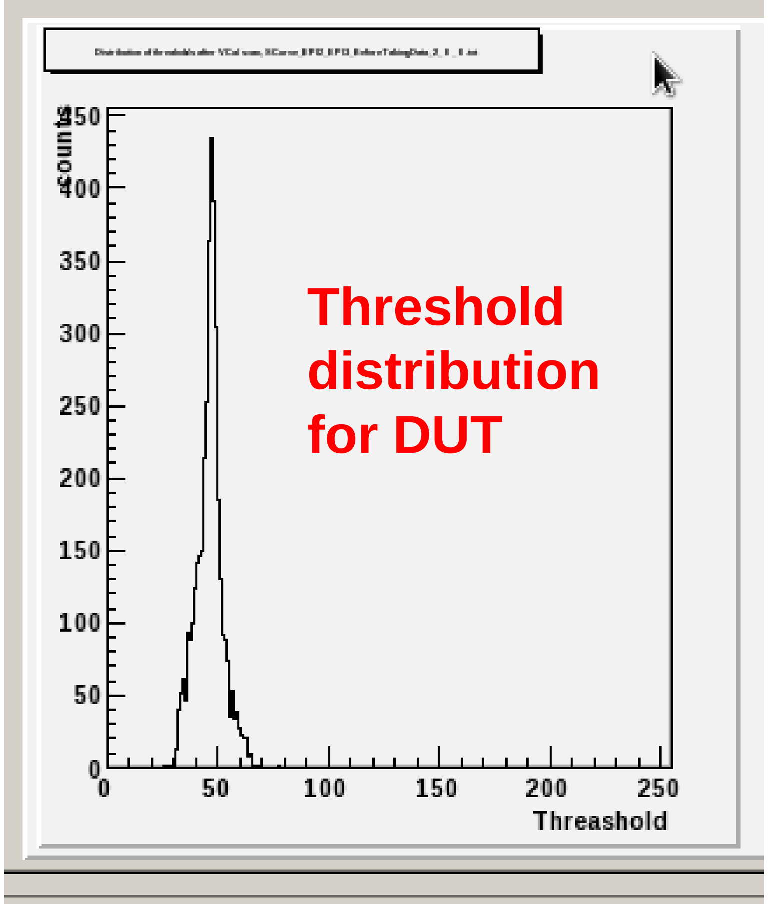
4-Cell Efficiency



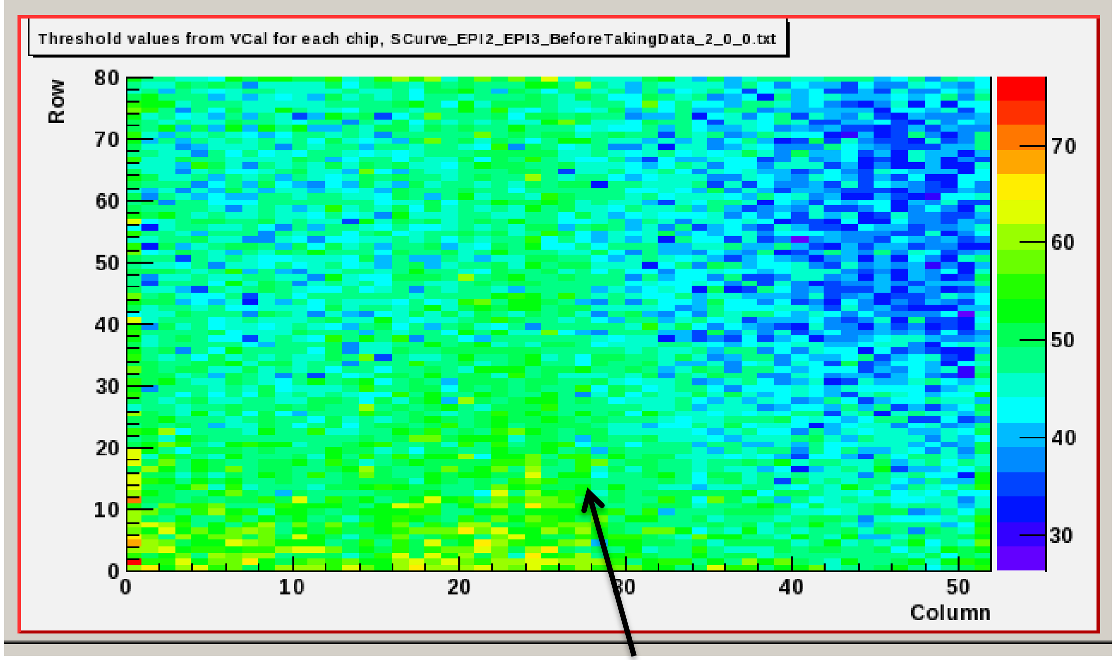
Charge distribution



FDB120Y_BPIXB: Threshold distribution



Threshold distribution for DUT

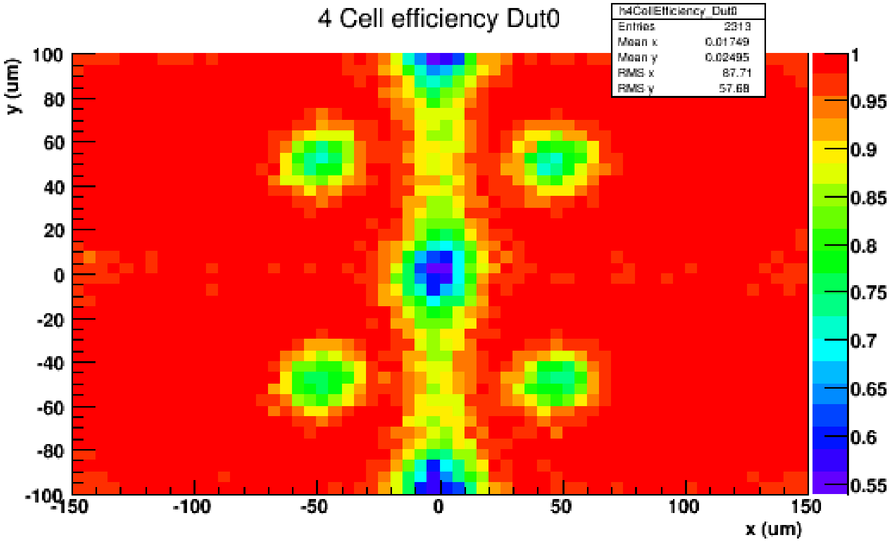


Wide variation in threshold – can be improved with trimming

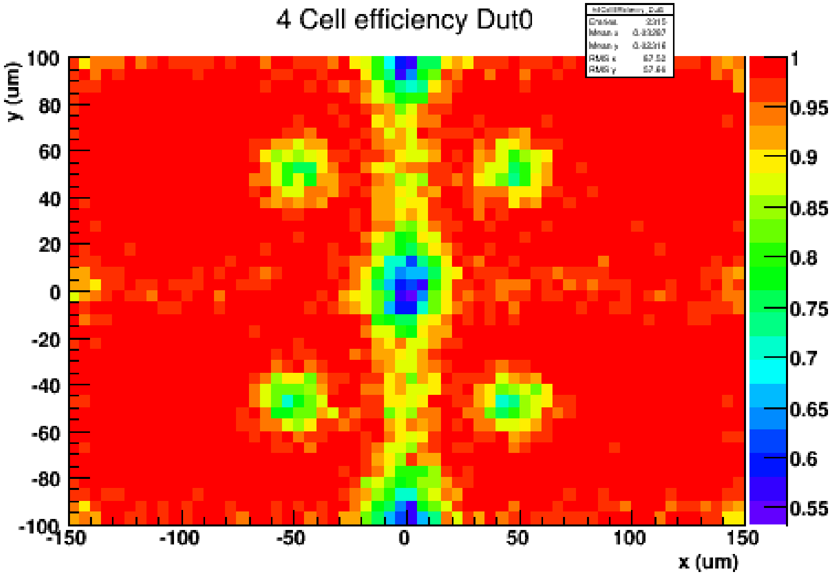
- Result for Analog chips
- Threshold distribution for 4160 pixels (without trimming) calculated using S-Curves.
- Average threshold: ~45-50 ADC

  = 50*65e/ADC= ~3250e

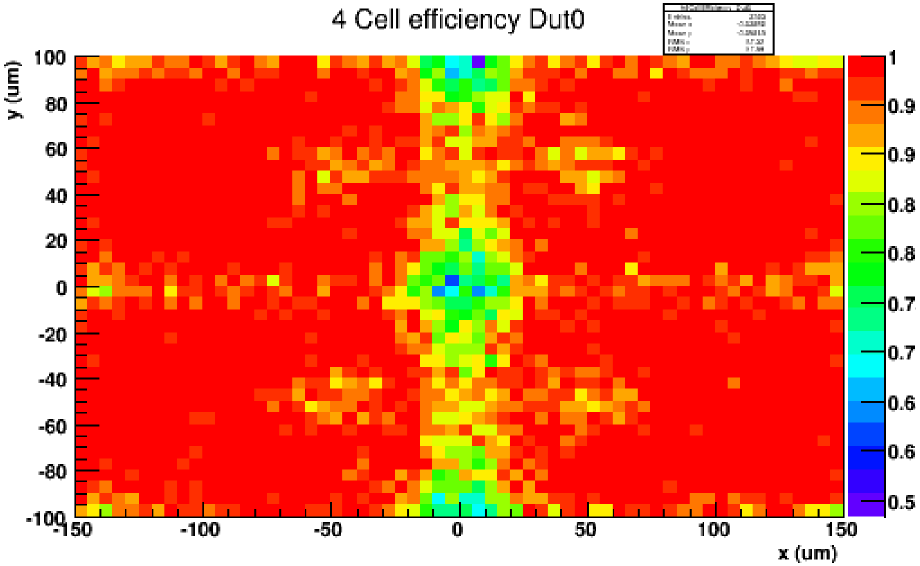
FDB120Y_BPIXB: Angle Scans



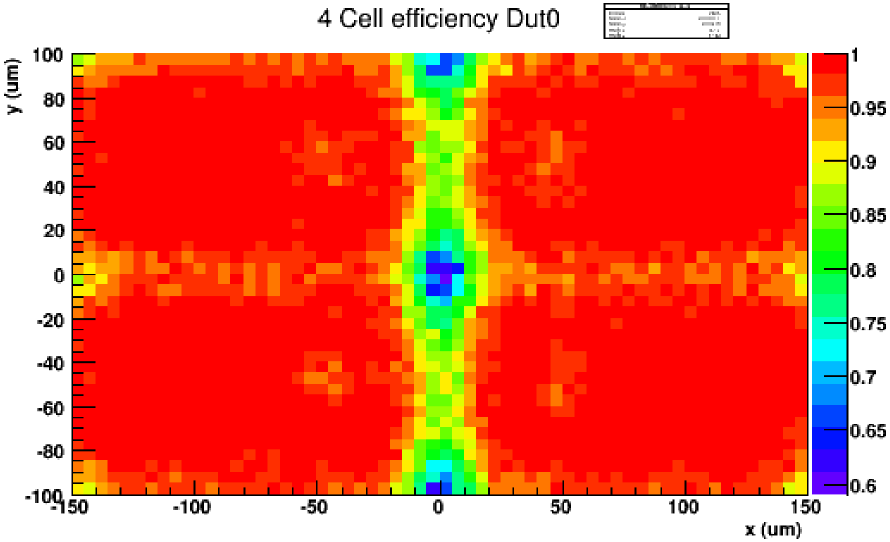
At 5° Efficiency: 96.3%



At 10° Efficiency: 96.5%

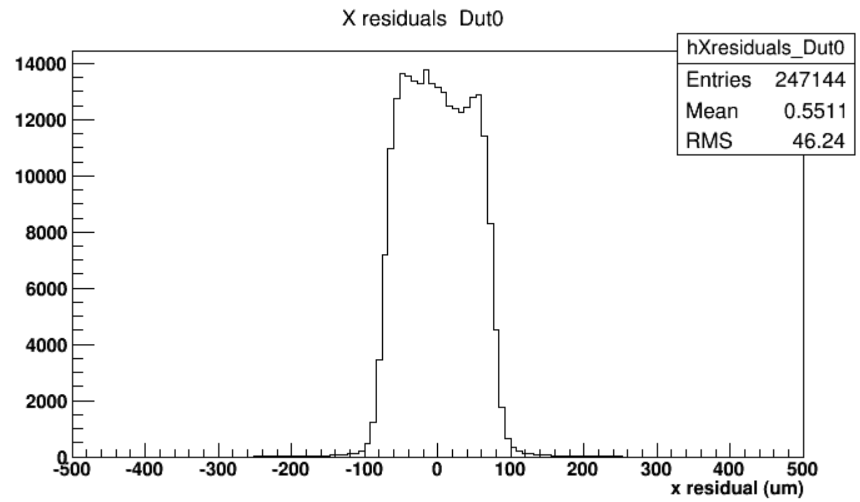


At 15° Efficiency: 97.7%



At 20° Efficiency: 98.5%

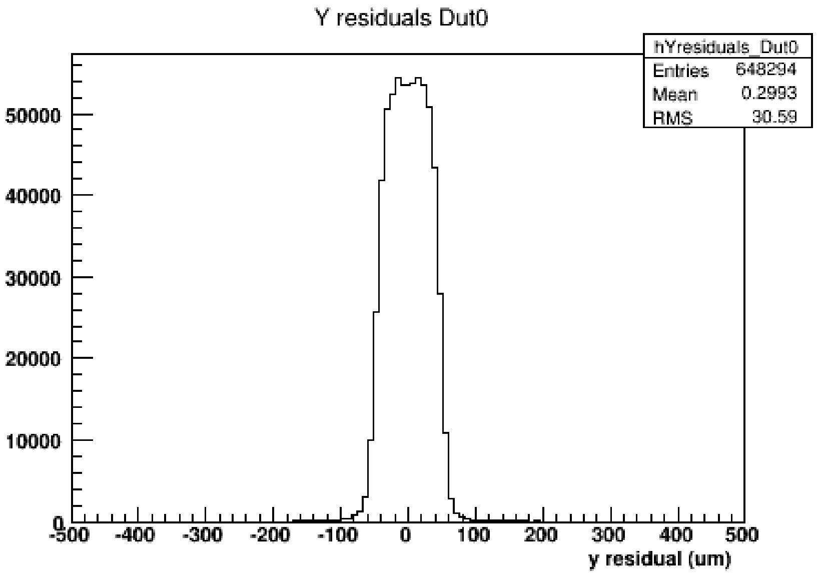
FDB120Y_BPIXB: Resolution (0 degree)



Cluster size 1&2

X-residual: σ_X=46.2um

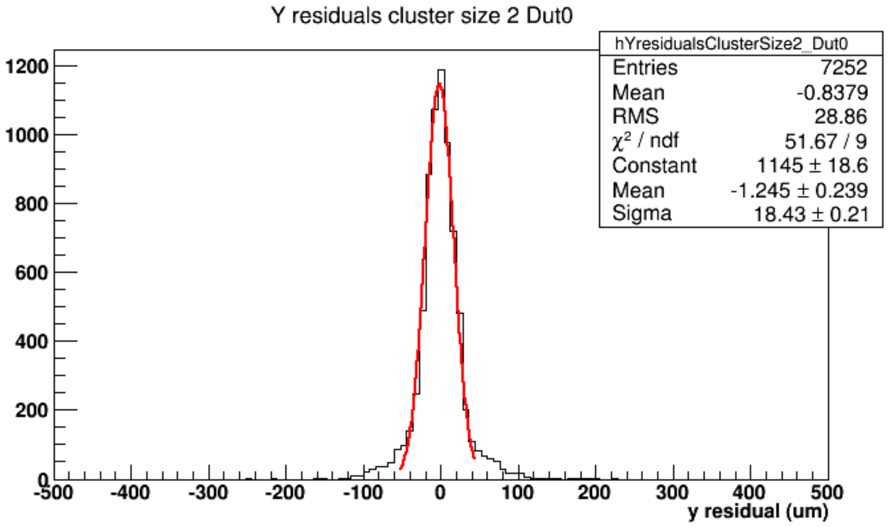
Pitch(150)/√12=43um



Cluster size 1 and 2

Y-residual: σ_Y=31um

Pitch(100)/√12=29um



Best DUT resolution: 18.4um

Analysis ongoing- expect improved results

Conclusion and Future Plans

- Epitaxial and FDB sensors show good efficiency before irradiation.
- Threshold needs to be lowered to get full charge collection
    - Use digital ROCs with threshold of 2ke.
- Detailed lab measurement (Sr90, laser) of epitaxial sensors undergoing.
- Sensors will be sent for irradiation to 5E15 and 1E16 1 MeV neq/cm^2 after testbeam/lab measurements are complete.
- Plan to study “charge multiplication effects” after heavy irradiation in epitaxial sensors.

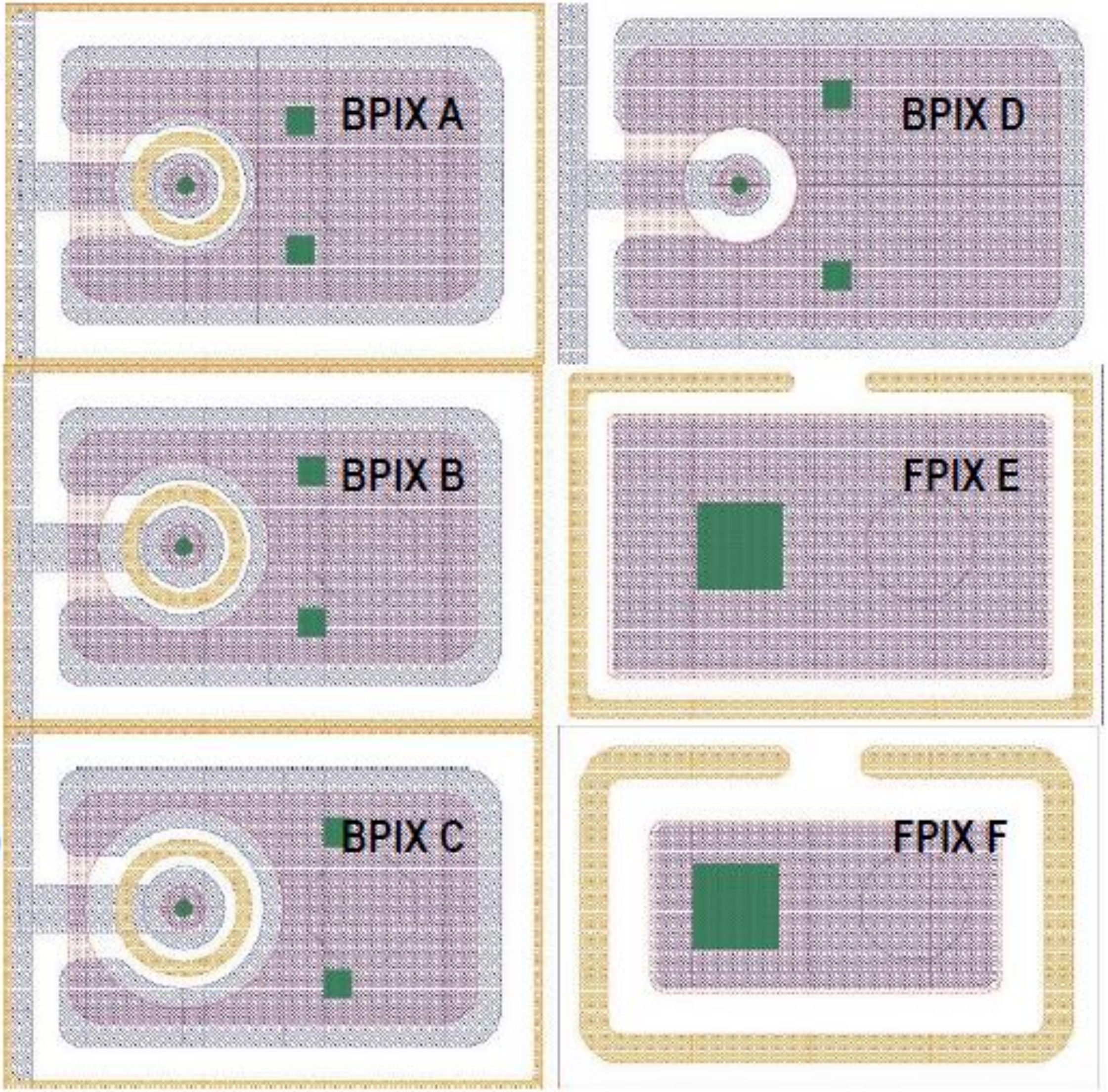
Pixel Devices from recent HPK Production

HPK wafer contains 6 different layouts

- **BPIX A-C**: Gap in the bias structure between 14 µm (~8% affected area) and 22 µm (16% of the area affected), gap between pixels: 36 µm contain p-stop mask and (in principle) work with p-stop isolation also.
- **BPIX D**: No p-stops, small bias structure (10 µm gap, ~5% affected area), gap between pixels: 22 µm (all measures are close – but not identical – to the present BPIX sensor)
- **FPIX E+F**
  - Open p–stop
  - Different gap size (~30 and 50 µm)

Available substrates (all n- and p-type)

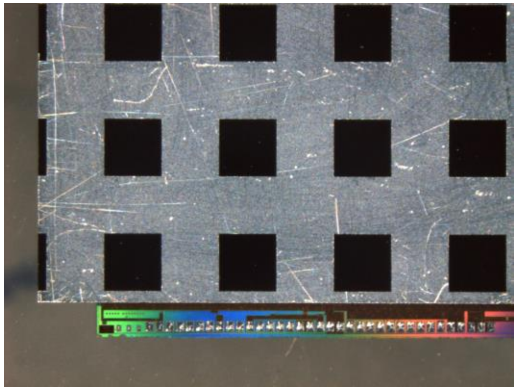
- FZ 320, 200, (120) µm
- mCz 200 µm
- Epi 100 (70), 50 µm
- FZ 200 µm, 2 metal layers (still to come)



- Slide from Tilman Rohe et. al, 11.05.2011

Bump bonding to analog chips

- 6 epitaxial sensors bump bonded to PSI46 analog ROCs:
  - 2x E100P, 1x E100Y, 1x FDB120Y, 2x E50Y
  - Solvent and light O2 plasma descum before processing.
  - In order to ensure large gaps between sensor and ROC, bilayer lithography process used with an extra spacer (3-5 um) – clearance improved to 5-6 um
  - 15 kgf applied to break through native Indium oxide on the sensors
  - Coated with 4.2um thick parylene at Purdue’s Birck nanotechnology center
  - Yield: 2 good, 2 partially good (67% and 24% efficiency), 2 bad ROCs.
  - 4 sensors tested in the beam at Fermilab in November 2013 and January 2014.



Bump bonding to digital chips

- Bump bonded to digital ROC v2.1 received from PSI in April 2014:
  - PSI has digital chips (with Ti-W as UBM and 2um of Indium).
- 6 sensors bump bonded in April (2x E100P, 1x E100Y, 2x E50Y, 1x FDB120Y)
  - 1 out of 6 ROCs alive after bump bonding (~10% pixels alive after bump bonding in good module)
  - Shorts in the digital power rails, large increase in digital current of ROC after bump bonding (~500mA)
  - ROC surface got punctured due to dust/debris, too large compressive force (15 kgf).
- 4 more sensors bump bonded in July 2014 (2x E100Y, 2x FDB120Y)
  - reduced the compression force to 8 kgf,
  - short HCl clean to remove Indium oxide on ROCs.
  - Yield was better: 2 out of 4 ROCs working after bump bonding

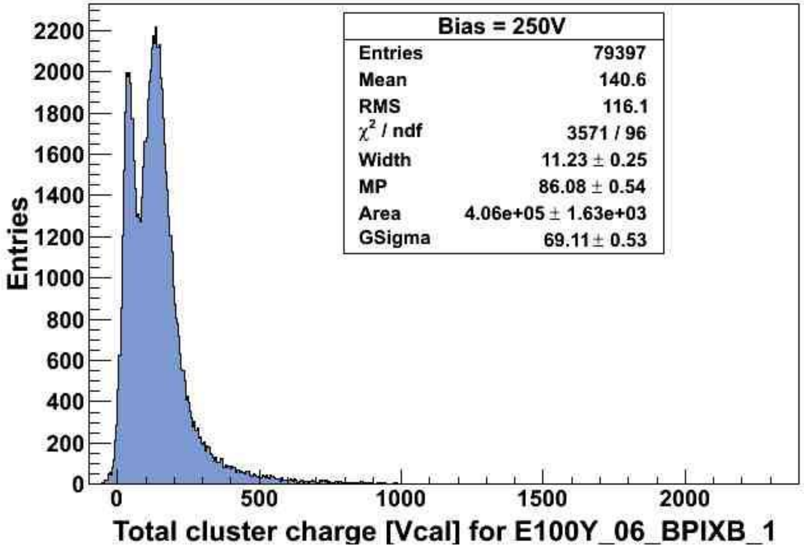
- Currently bump bonding 6 more epitaxial sensors (2x E50P, 4x E50Y):
  - Checked all ROCs before bump bonding – less than 6 dead pixels in all of 6 ROCs
  - Usual cleaning procedure, extra careful with handling

Status of Epitaxial sensor testing at Purdue

SENSOR	E100P	E100Y	E50P	E50Y	FDB120Y	Total
FPIXE	2		4	2	2	34
FPIXF	2	2	4			
BPIXA		2		2	2	34
BPIXB		4		4		
BPIXC		2		2		
BPIXD		4		4		
Probe test-IV	√	√	√	√	√	68
Probe test-CV	√	√	√	√	√	12
Bump bonding (analog chip)	2	1		2	1	12
Bump bonding (digital chip)	2	3		2	3	

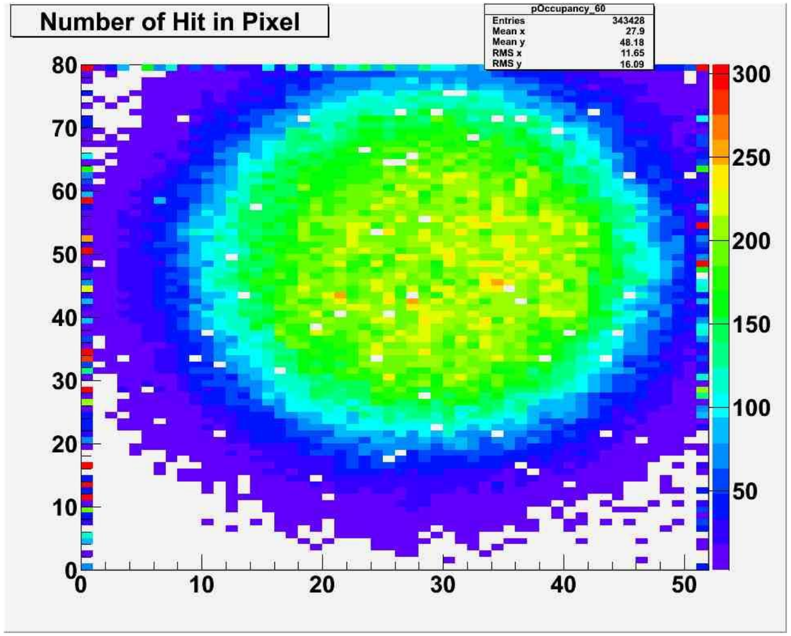
Source test – E100Y_06_BPIXB_1

trim40



Bias = 250V

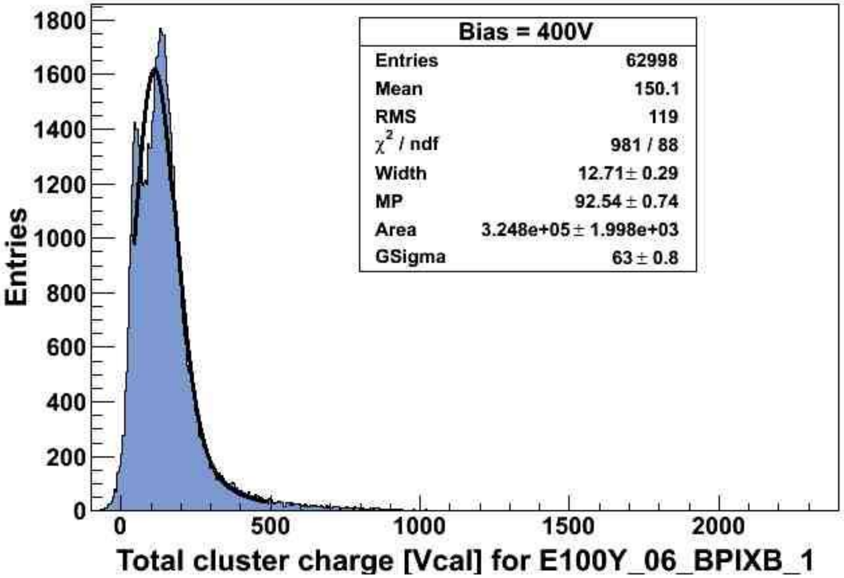
Entries	79397
Mean	140.6
RMS	116.1
χ^2 / ndf	3571 / 96
Width	11.23 ± 0.25
MP	86.08 ± 0.54
Area	4.06e+05 ± 1.63e+03
GSigma	69.11 ± 0.53



pOccupancy_60

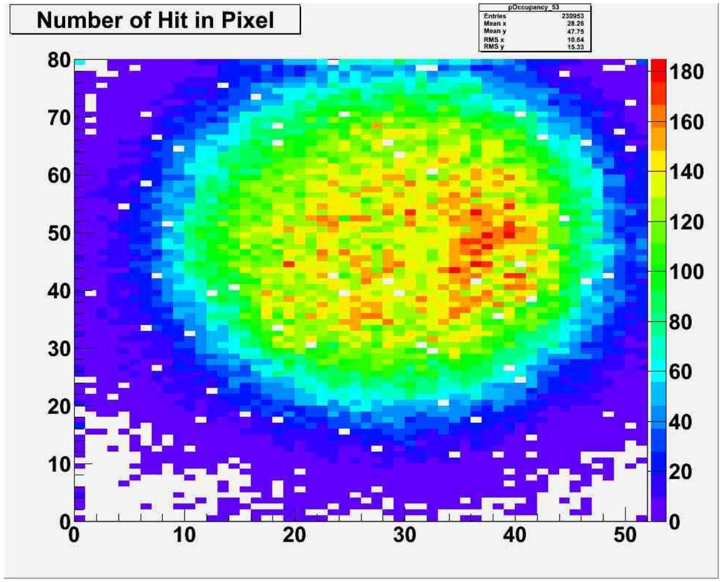
Entries	343428
Mean x	27.9
Mean y	48.18
RMS x	11.65
RMS y	16.09

trim50



Bias = 400V

Entries	62998
Mean	150.1
RMS	119
χ^2 / ndf	981 / 88
Width	12.71 ± 0.29
MP	92.54 ± 0.74
Area	3.248e+05 ± 1.998e+03
GSigma	63 ± 0.8

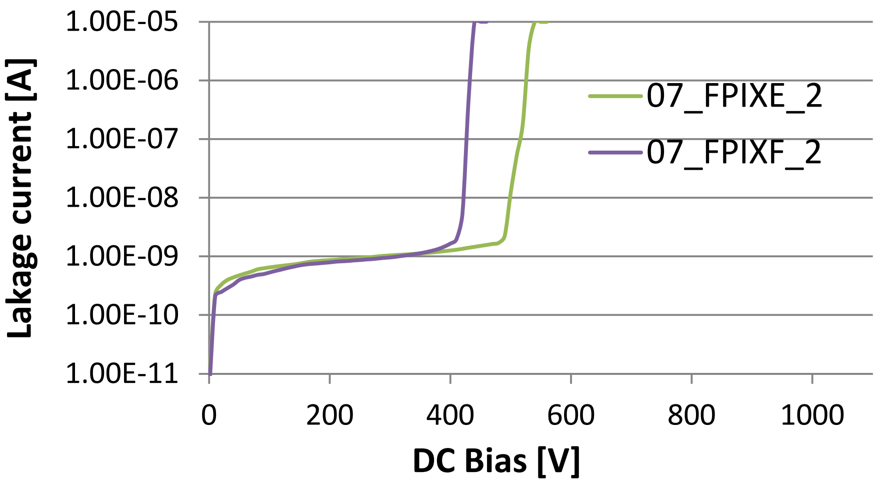


pOccupancy_53

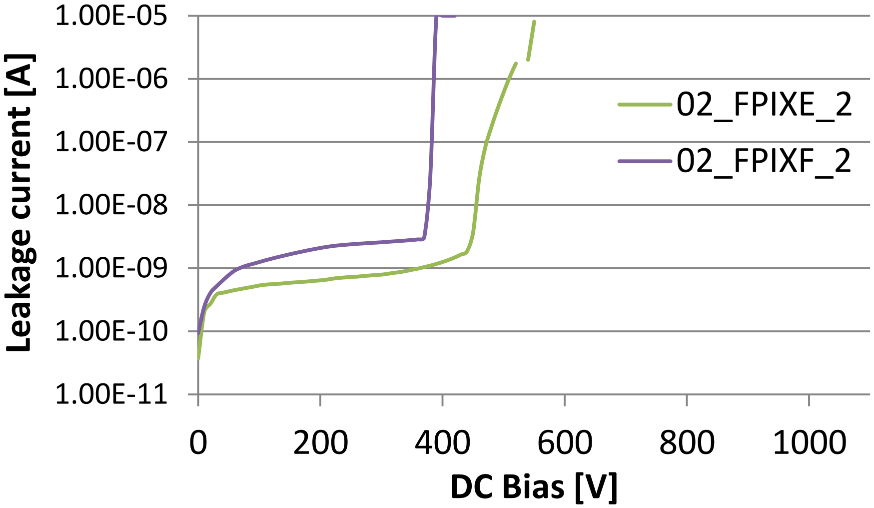
Entries	230953
Mean x	28.26
Mean y	47.75
RMS x	10.64
RMS y	15.33

Probe Station IV/CV of Epitaxial sensors

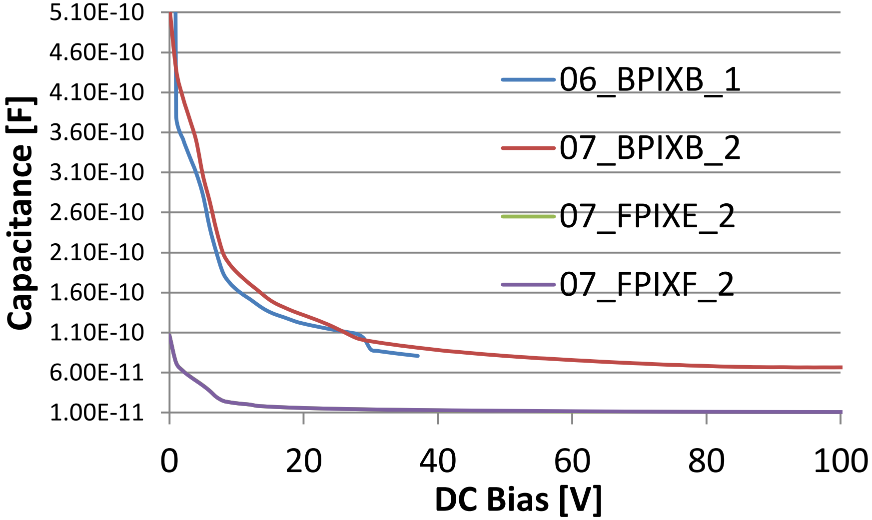
E100Y IV



E50Y IV



E100Y CV



E50Y CV