Charge collection and laser measurements on double-sided 3D strip sensors irradiated up to 2*10^{16} n_{eq}/cm^2

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Outline

- Introduction:
  - recent studies;
  - Motivations;
  - looking forward...
- Materials:
  - sensors;
  - set-ups.
- Methods:
  - calibration;
  - measurements: I-V, punch-through, β-source, laser;
  - analysis details.
- Experimental results and discussion:
  - I-V and punch-through;
  - β-source;
  - laser.
- Summary and outlook.

Introduction

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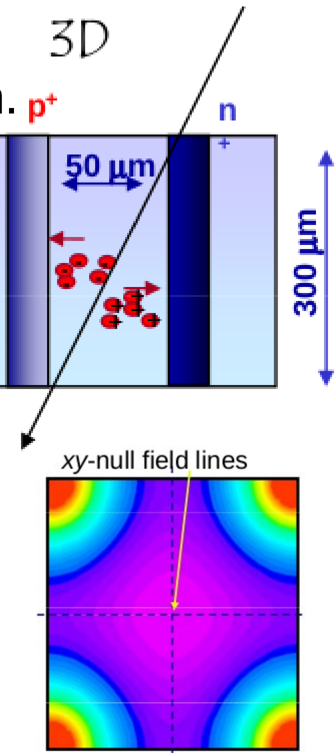
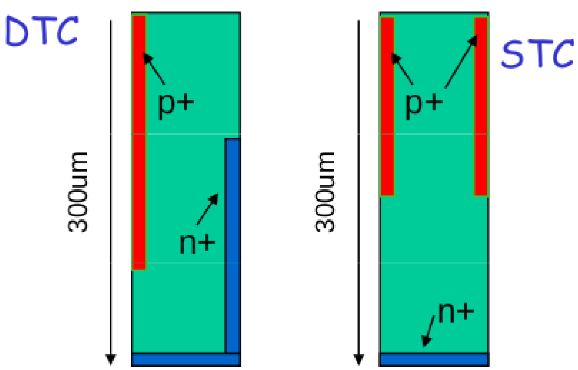
•Recent studies:

- 3D sensors main features:
  - Short "collection"-path, long "generation"-path => radiation-hard (up to $5*10^{15}$ n_{eq}/cm^2 and beyond[1]).
  - Dead zones between same type columns => non-uniform collection.
  - Narrow bulk => high capacitance => high noise.
  - Complex layout => challenging fabrication.
- Technologies:
  - Original 3D[2]:
    - Exploit of the advantages.
    - Complexity.
  - Single-type column (STC):
    - Much simpler.
    - Large dead zones.
  - Double-type columns (DTC):
    - Better performances than STC.
    - Simpler than the originals.
- Charge multiplication observed[3].
- First production of 3D pixels accomplished at FBK and CNM with DTC [4].





[1] The ATLAS IBL Coll., Jinst 7, 2012.

[2] Dalla Betta et al., PoS Vertex 2012, 2012.

[3] Köhler et al., NIMA 659, 2011.

[4] Da Via et al., NIMA 649, 2012.

Introduction

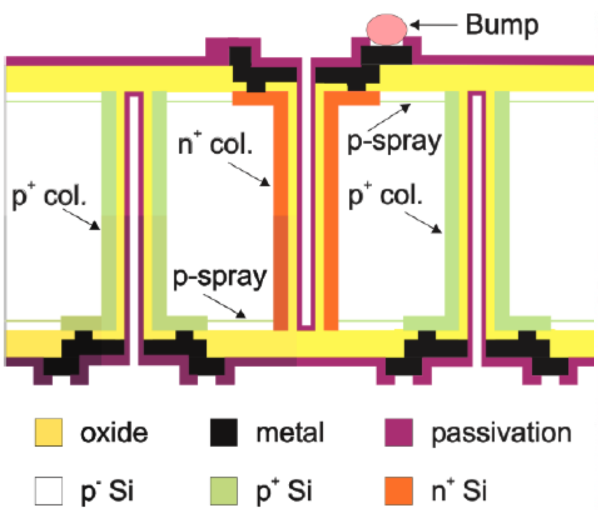
- Motivations:
  - Test radiation hardness up to higher fluences in view of the HL-LHC
    - => Samples highly irradiated.
    - Despite the higher noise, test the signal to noise ratio (at those fluences):
      - => β-source measurements.
    - Interest on the spatial uniformity with the improved technology:
      - => laser measurements.

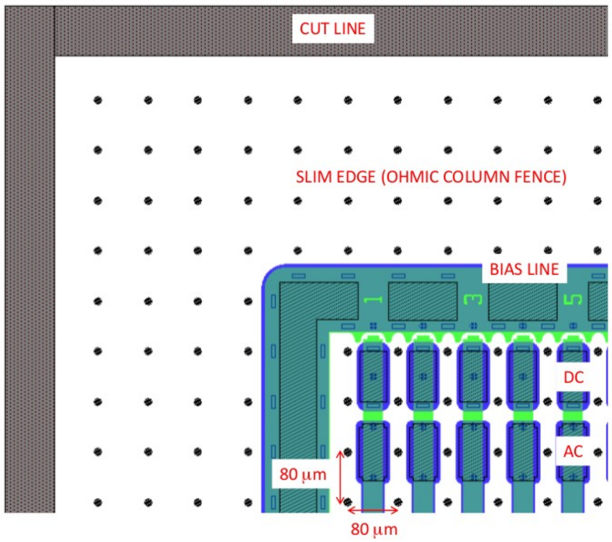
- Looking forward...
  - How to exploit the charge multiplication?
  - How important is the non-uniformity?
  - Is a new technology required?

Materials

- **Samples[1]:**
  - Double-sided 3D strip sensors (FBK ATLAS production wafers [2]).
    (Strips => easier testing with standard readout electronics.)
  - 4”, FZ, <100>, p-type, 230+/-20 um thickness, ~20 kΩ*cm.
  - 102 strips ~8 mm length, with 80 um pitch between same type columns and 40√2~56 um between different column types, slim edges.
  - Columns passing completely through the substrate, ~11 um diameter, not filled by polysilicon.
  - P-spray, front side strip connection by n+ diffusion (AC coupling, punch-trough biasing but readout with R-C fanins) or combination of metal and diffusion (DC coupling, readout by R-C fanins).
  - Irradiated at 25 MeV protons (NIEL hardness factor of 1.85) at the Karlsruhe Compact Cyclotron (annealing only due to holding during experiments).

Sensor ID	Fluence [n_eq/cm^2]	Coupl.
W19_SD2	2×10^15+/-10%	AC
W21_SD2	2×10^15+/-10%	AC
W24_SD1	5×10^15+/-10%	AC
W24_SD2	5×10^15+/-10%	AC
W19_SD3	2×10^16+/-10%	DC
W21_SD3	2×10^16+/-10%	DC





[1] M. Povoli et al., NIMA 730, 2013.
[2] Da Via et al., NIMA 649, 2012.

Materials

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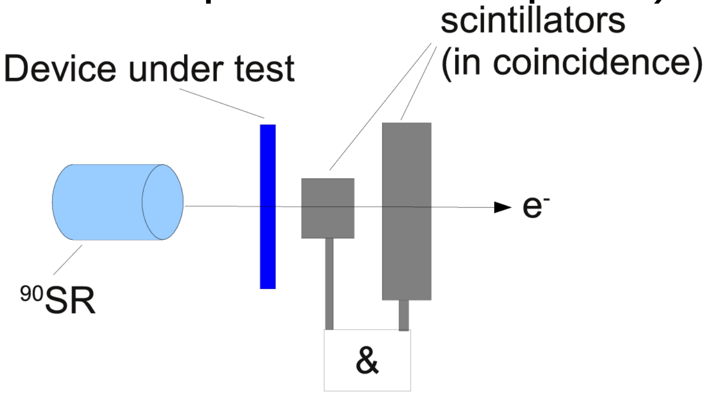
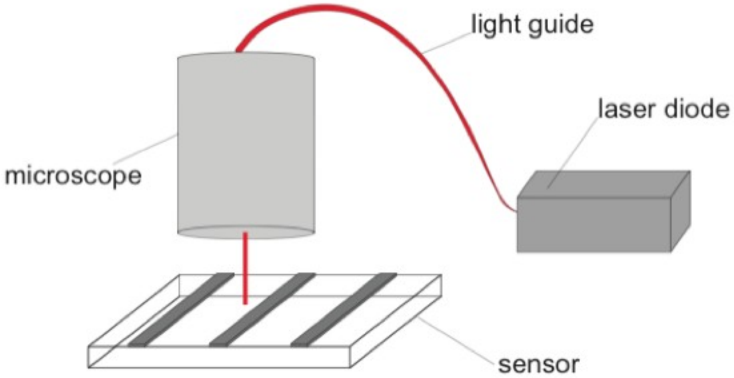
- Set-ups:
  - I-V:
    - Standard probe station, before, through AliBaVa, after irradiation.
  - Punch-through:
    - Stated the very high resistance before punch-trough, measurements made with a custom circuit (inverted amplifier with operational amplifier).
  - β-source:
    - AliBaVa (Beetle chip).
    - 37 Mbq ^{90}Sr source.
    - 2 scintillator in coincidence.
  - Laser:
    - AliBaVa.
    - 974 nm => ~90 um penetration depth, ~4.5 um FHWM.
    - Horizontal plane motorized stage.
  - Simulations:
    - TCAD with Synopsis Sentaurus, modified “Perugia” model [1].





[1] Pennicard et al., NIMA 592, 2008.

Methods

- Procedures:
  - β-source:
    - Calibration:
      - Sample: unirradiated sensor of known thickness.
      - Method: MPV vs. temperature; assumption of the generated charge (0.027ln(thick.)+0.176 [1]); linear fit of the gain vs. temperature.
    - Measurements:
      - AliBaVa “kazu” configuration (>25 ns peaking time); T∈[-41,-27] °C, RH<~10%.
      - Runs: pedestals+noise+source, at different voltages.
    - Analysis details:
      - Residual cut<~70 strips; time cut=10 ns around the peak; Clustering: seed cut also down to 2, neighbour cut also to 1.5 (maintaining clear signal).
  - Laser:
    - No calibration => relative measurements.
    - Measurements:
      - AliBaVa standard configuration (~25 ns peaking time); T<-35 °C, RH<~10%.
      - Runs: pedestals+noise+synch.+scan, at different voltages.
    - Analysis details:
      - Sometimes realignment/rebinning (bilinear interpolation, I-order).
      - Representation of the sum of two neighbour strips or a single strip.

[1] Meroli et al., Jinst 6 P06013, 2012.

Experimental results and discussion

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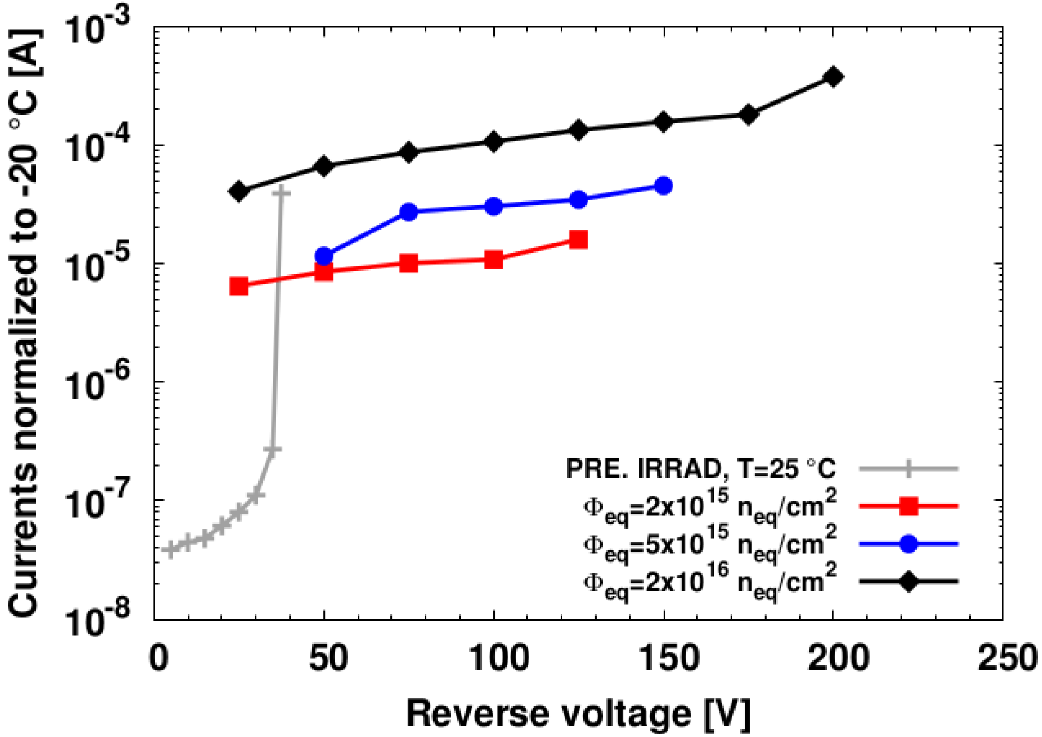
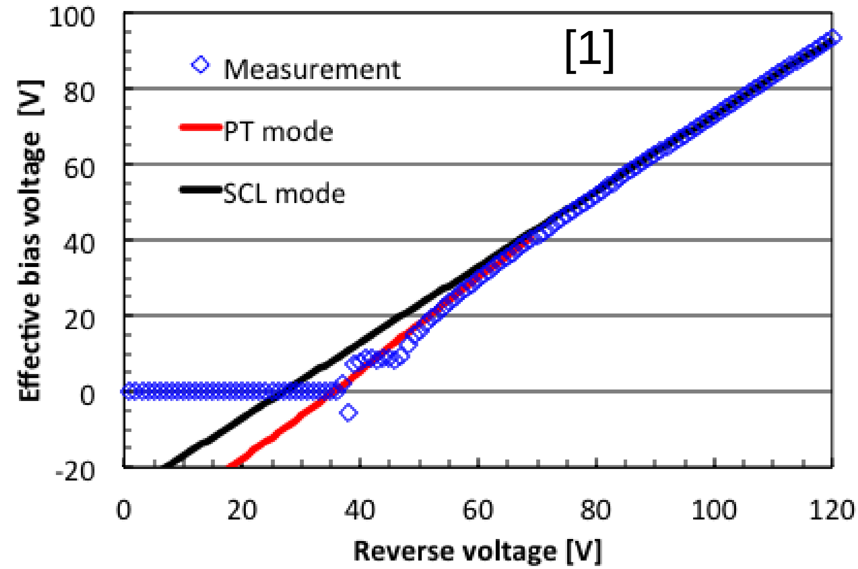
- I-V and punch-through:





- $\alpha = \Delta I/(V^*\Phi_{eq}) = 3.3 \div 3.7 \cdot 10^{-17}$ A/cm.
- $V_{BD} = 40 \rightarrow 125 \div 175$ V.
- $V_{PT} \sim 50$ V.

- Leakage current and break-down voltage increase with the fluence as expected.
- Punch-trough biasing still effective after irradiation.

[1] Betancourt et al., IEEE TNS 59(3), 2012.

Experimental results and discussion

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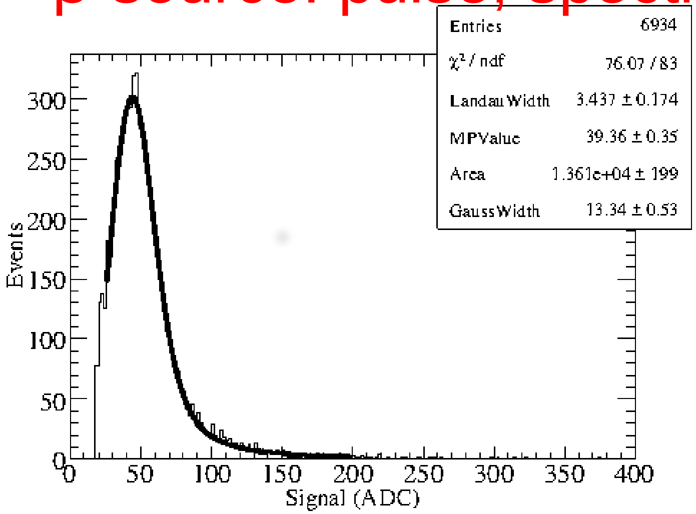
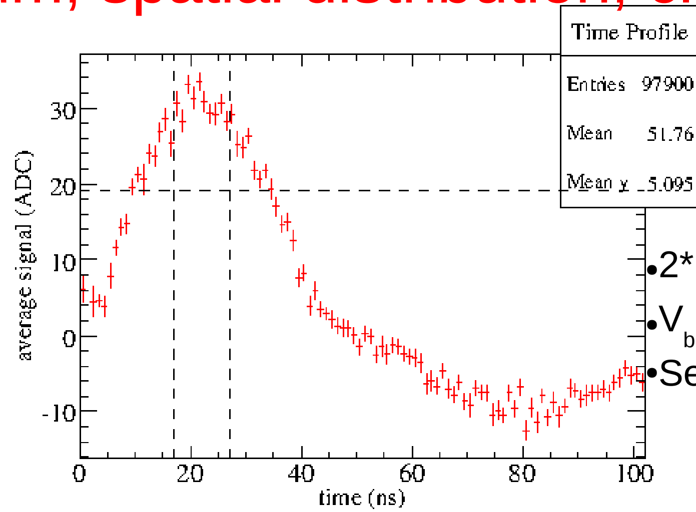
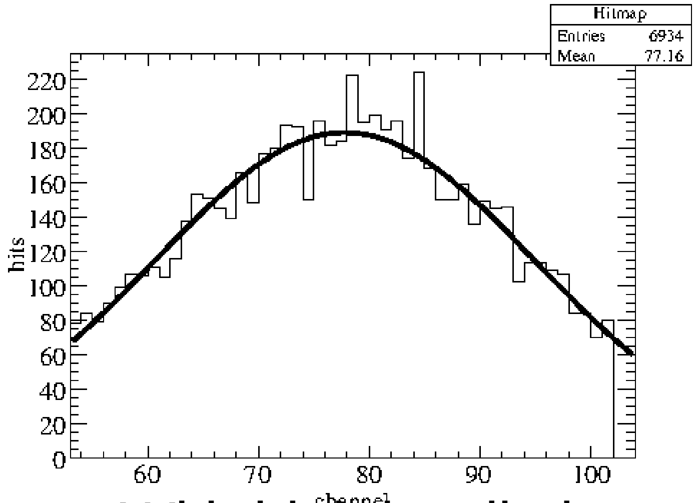
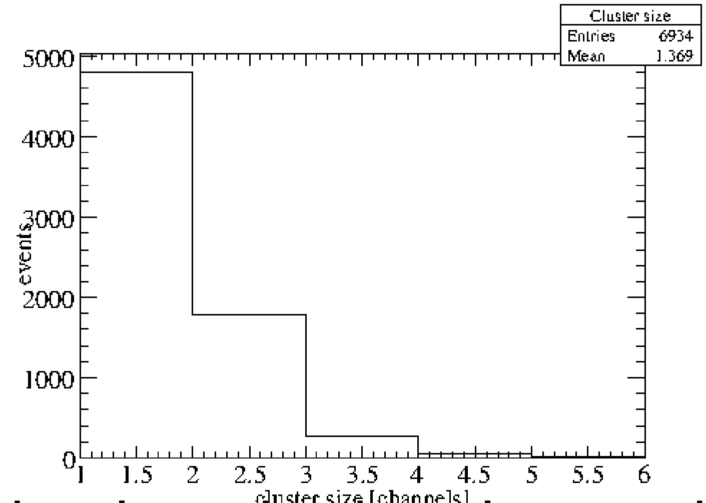
- β-source: pulse, spectrum, spatial distribution, clustering





- $2*10^{-16}$ n_{eq}/cm^2.
- V_{bias}=200 V; -30+/-1 °C.
- Seed cut=3.5, neighbour cut=3.





- With high irradiation, strict clustering but clear peak.
- Pretty large clusters at high voltage (narrow pitch).

Experimental results and discussion

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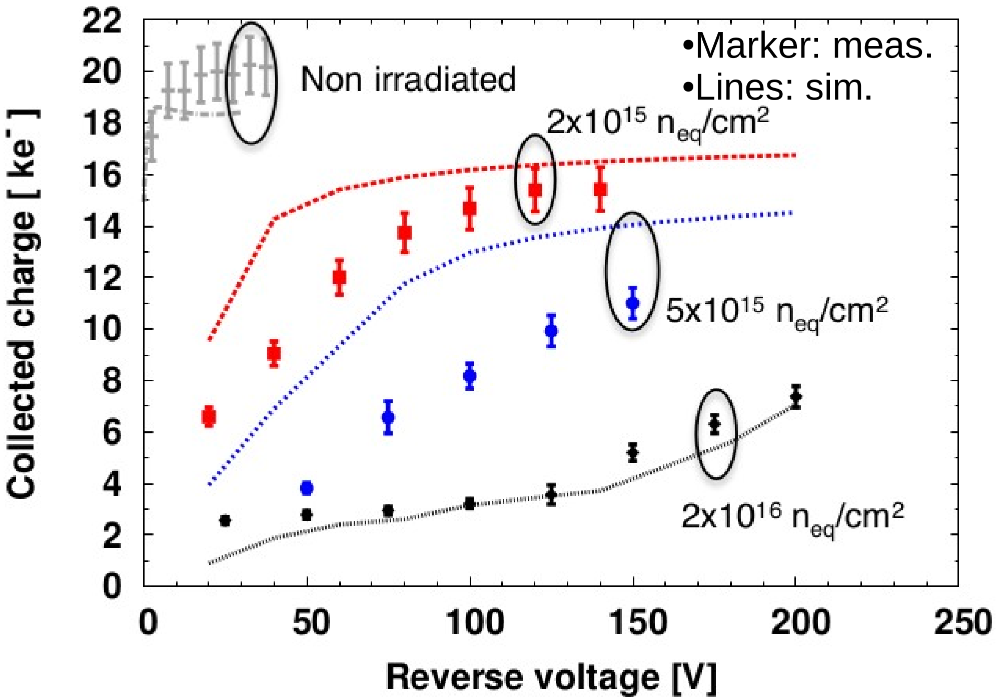
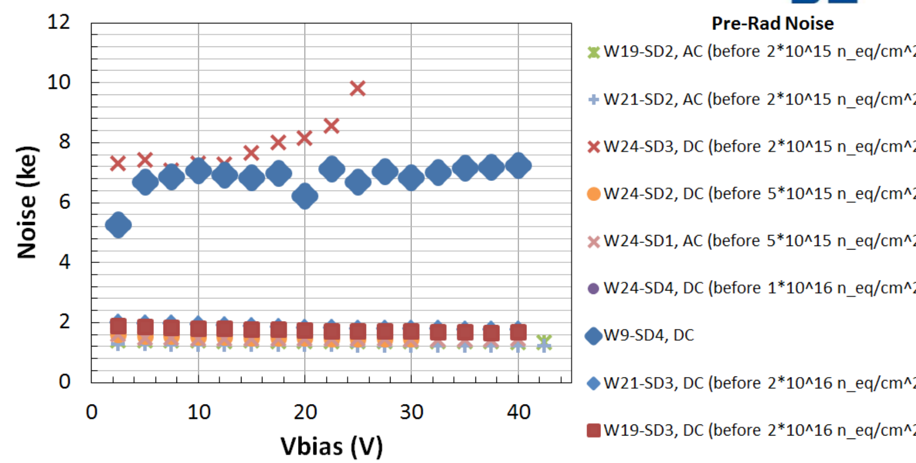
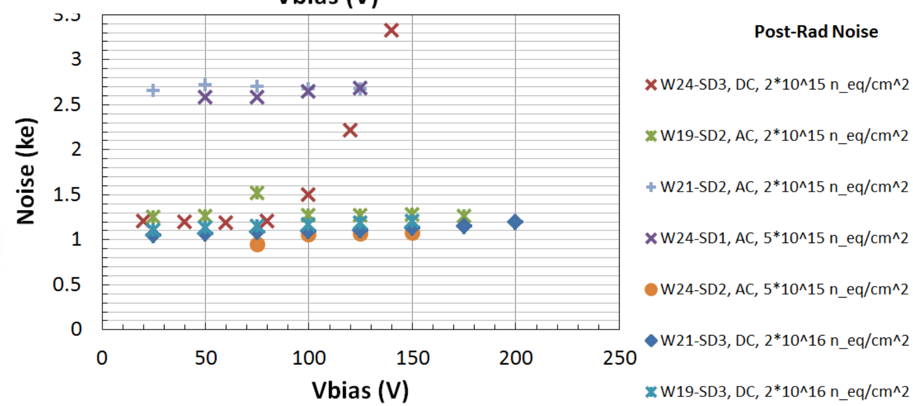
•β-source: charge collection versus bias



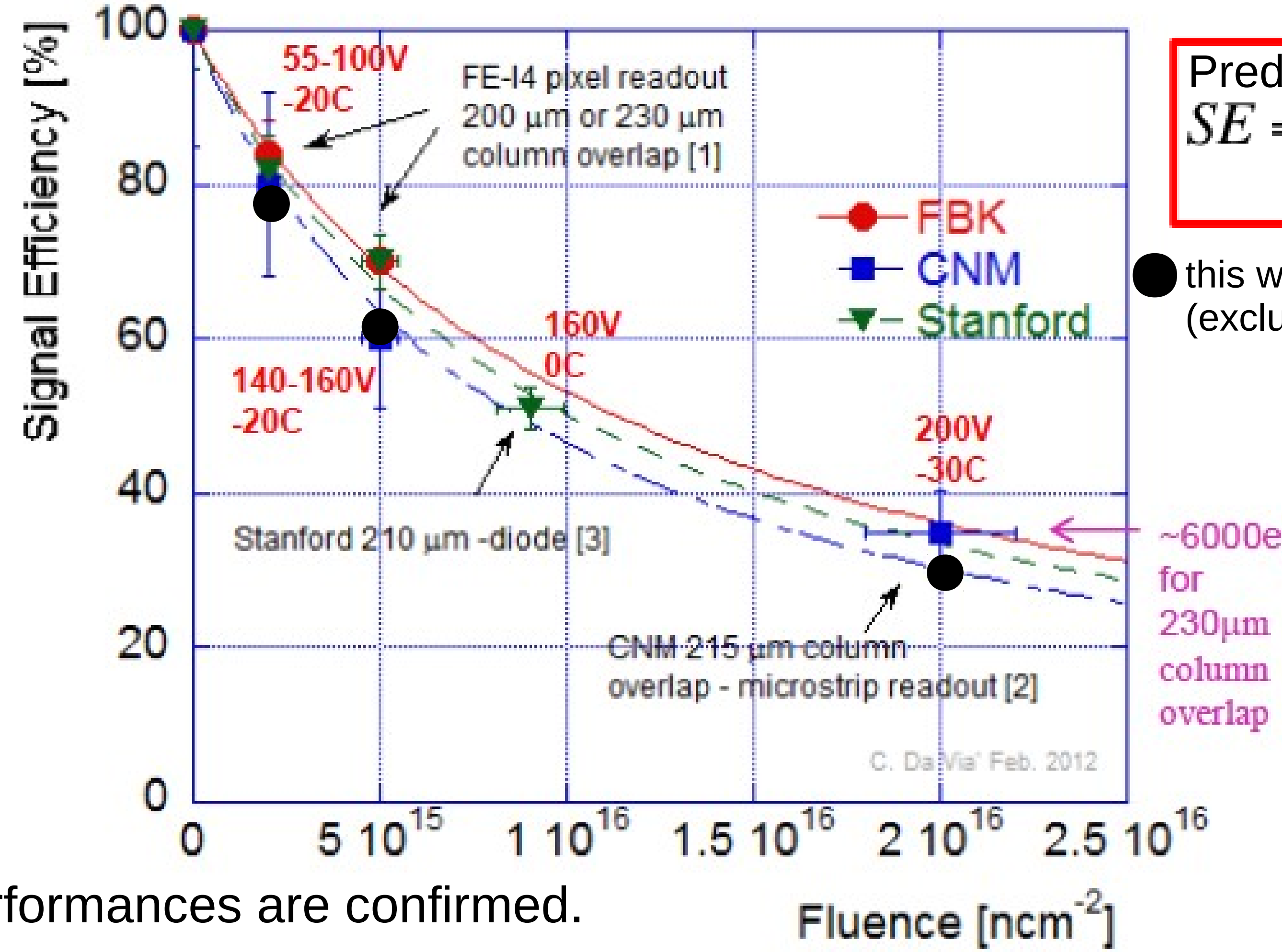




- Charge collection in agreement with simulations. Significant also at low voltages (see 20 V, $2*10^{15}$ n_{eq}/cm^2).
- No charge multiplication (maybe at $2*10^{16}$ n_{eq}/cm^2).
- Noise dominated by electronics, leakage current? (Interstrip/bulk capacitance<10%.)

Experimental results and discussion

- β-source: performances comparison



Prediction:

$$SE = \frac{1}{1 + K_C \cdot \Phi}$$

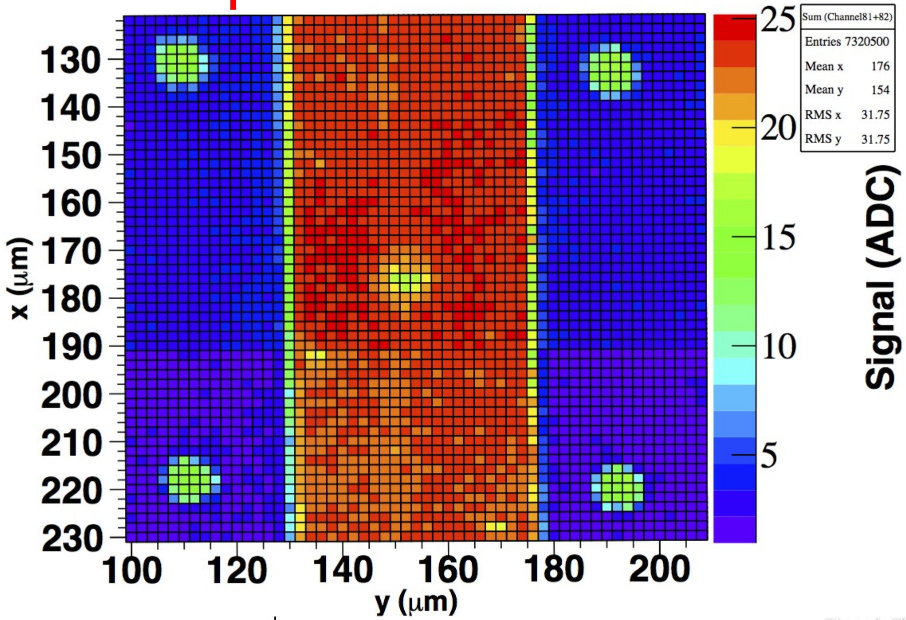
● this work (excluding the W19_SD2)

- Performances are confirmed.

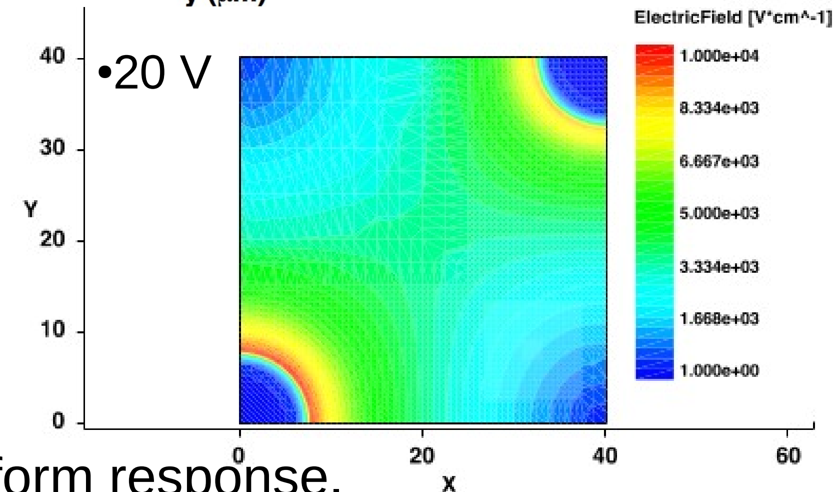
[1] ATLAS IBL Coll., Jinst 7, 2012.
[2] Köhler et al., NIMA 659, 2011.
[3] Da Via et al., NIMA 604, 2009.

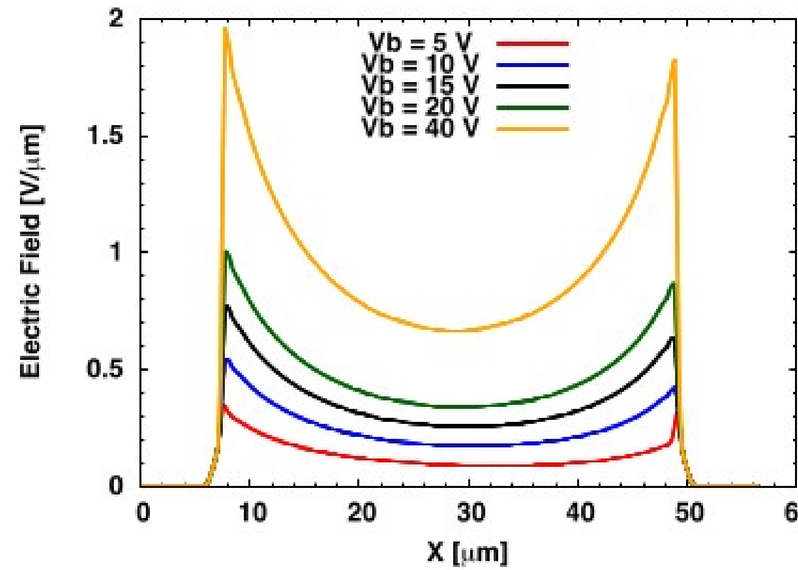
Experimental results and discussion

- Laser: pre-irradiation: results and simulations



- 20 V

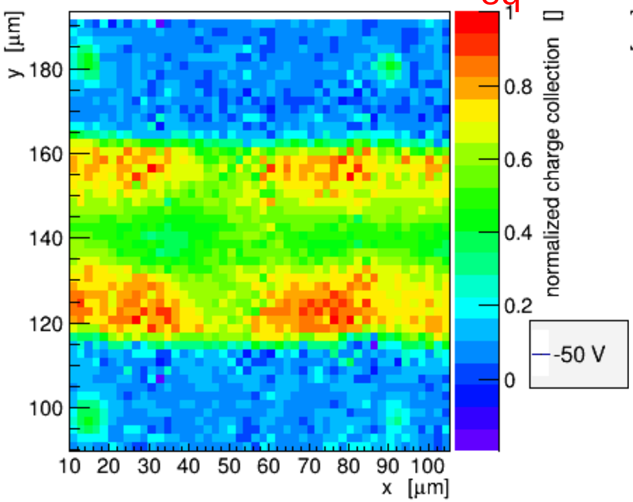


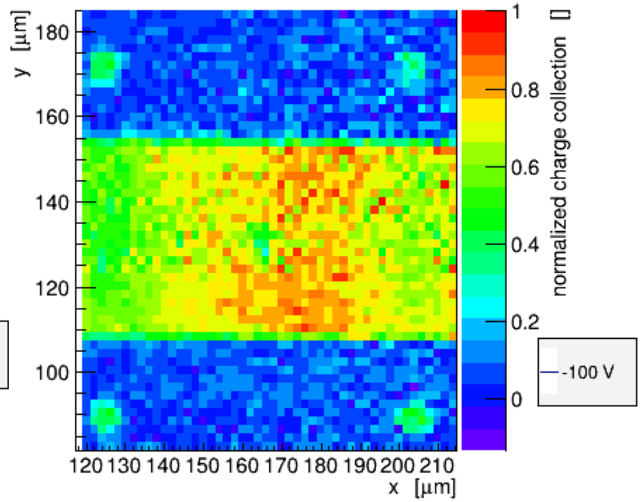


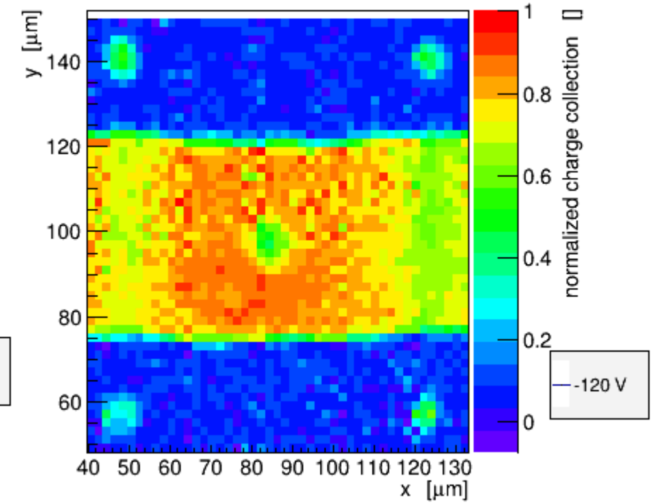
- Uniform response.

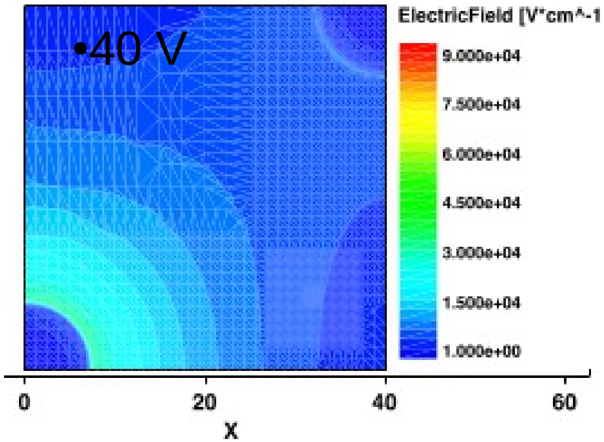
Experimental results and discussion

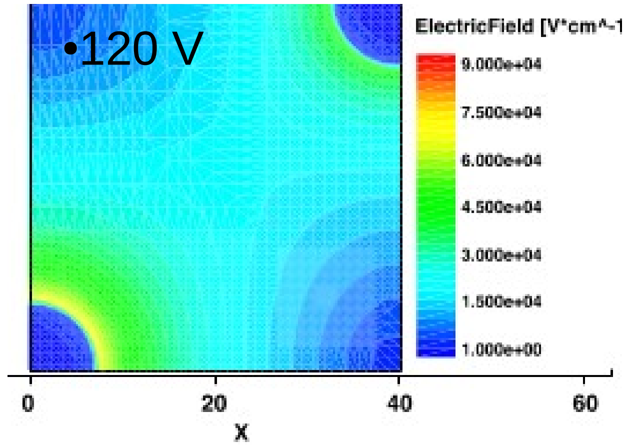
- Laser: $2{*}10^{15}\ n_{eq}/cm^2$: results and simulations







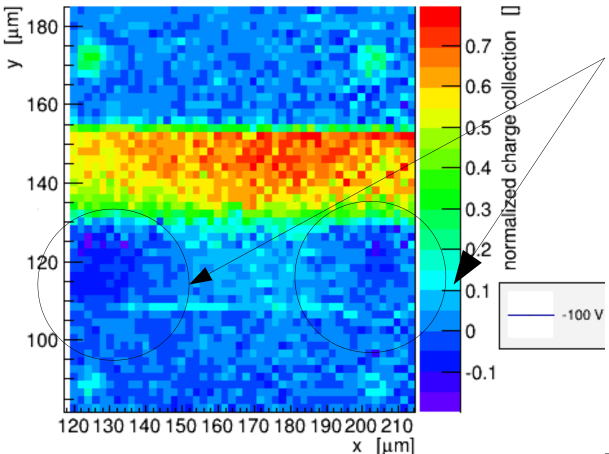




- Significant change with bias: collection from junction columns to in between those of the same strip => "compensation" effect: sum for same strip, subtraction for neighbours.

Experimental results and discussion

- Laser: $2*10^{15}$ n_{eq}/cm^2: discussion: “compensation” effect



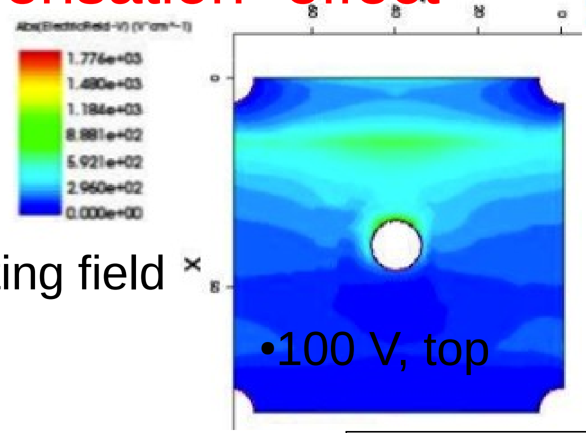
Large negative zones

From Ramo's Th.

- E_w~<0
- E<<0
- $\overline{vel}$<0

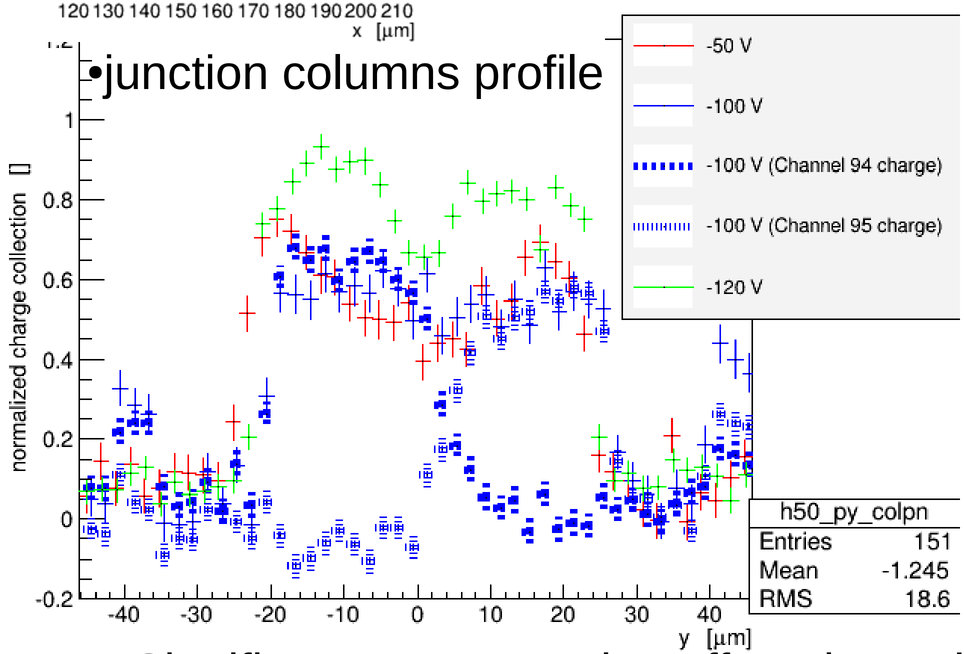
=> I(t:low)<0

- Weighting field

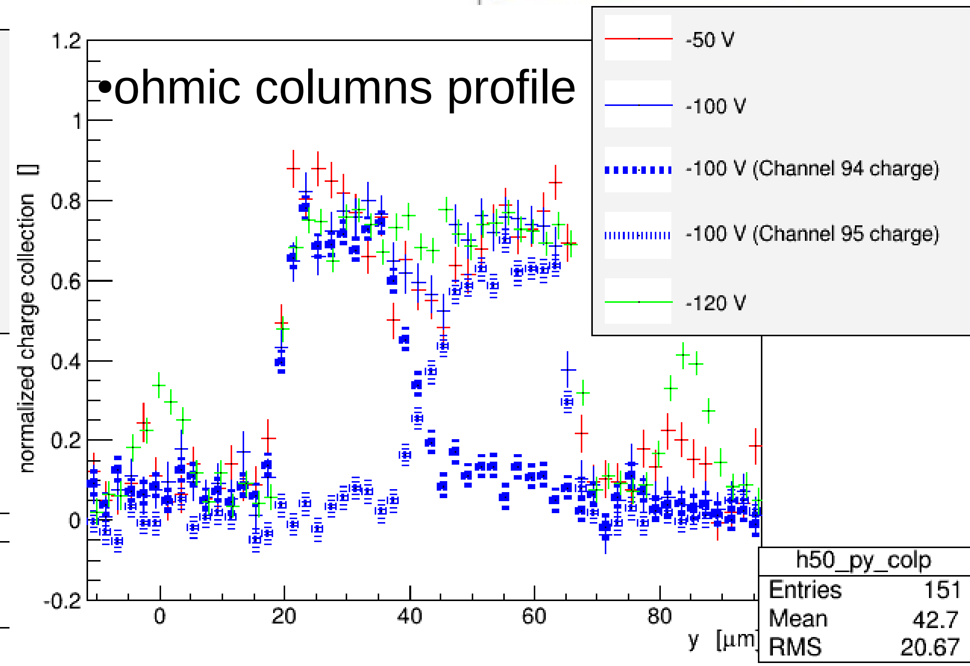


- 100 V, top

- junction columns profile



- ohmic columns profile



- Significant compensation effect due to limited integration time and hole deficit[1].

[1] Pöhlsen, RD50 workshop talk 2013.11.14, Experimental study of the Si-SiO2 interface region...

Experimental results and discussion

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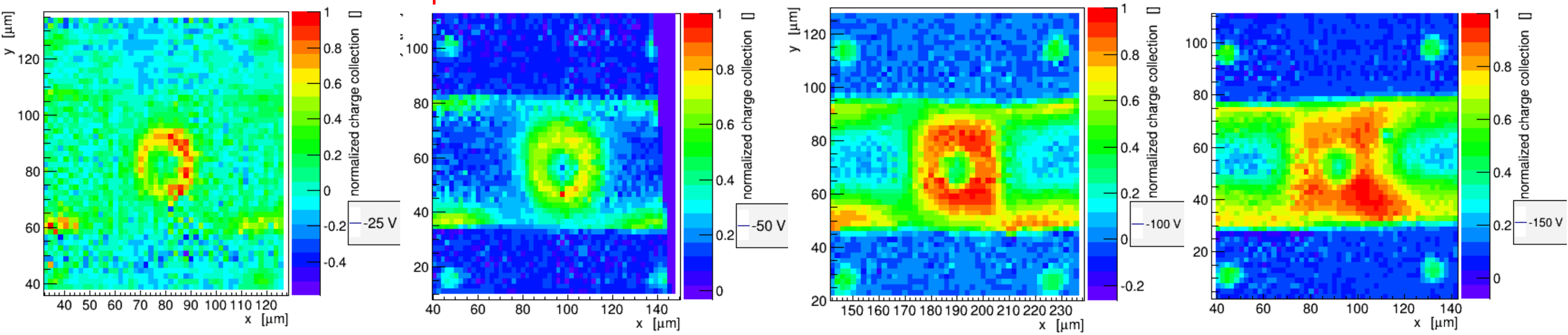
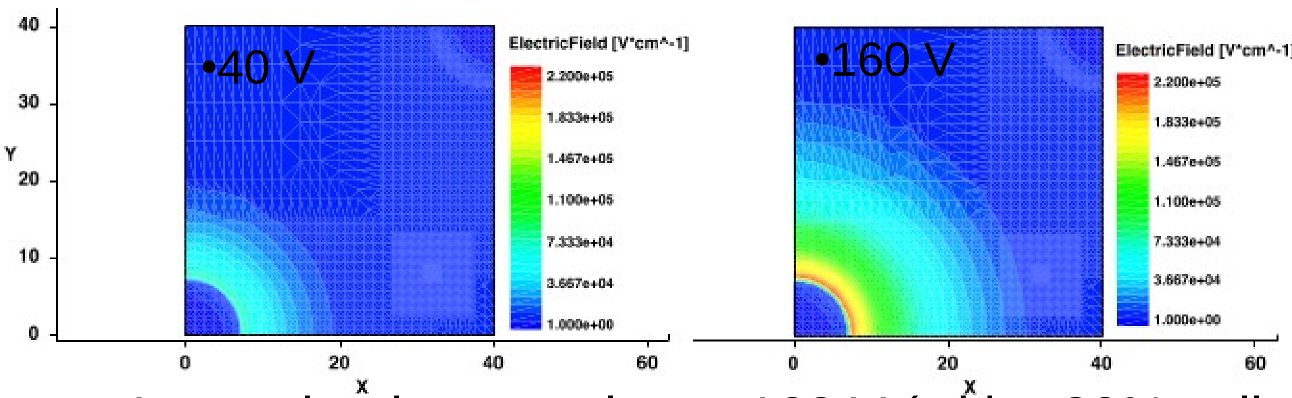
- Laser: $2 \times 10^{16}\ n_{eq}/cm^2$: results and simulations

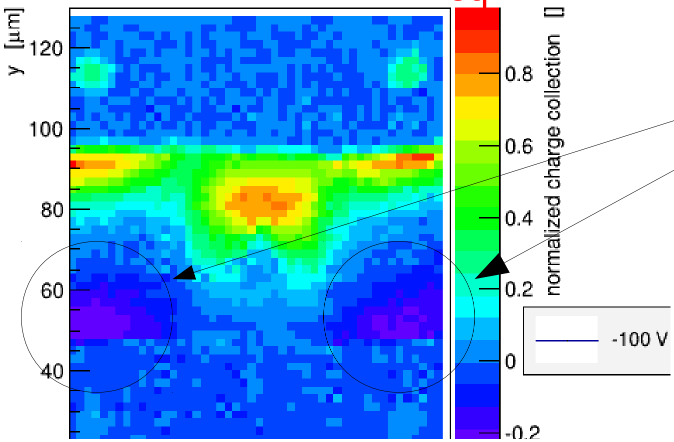




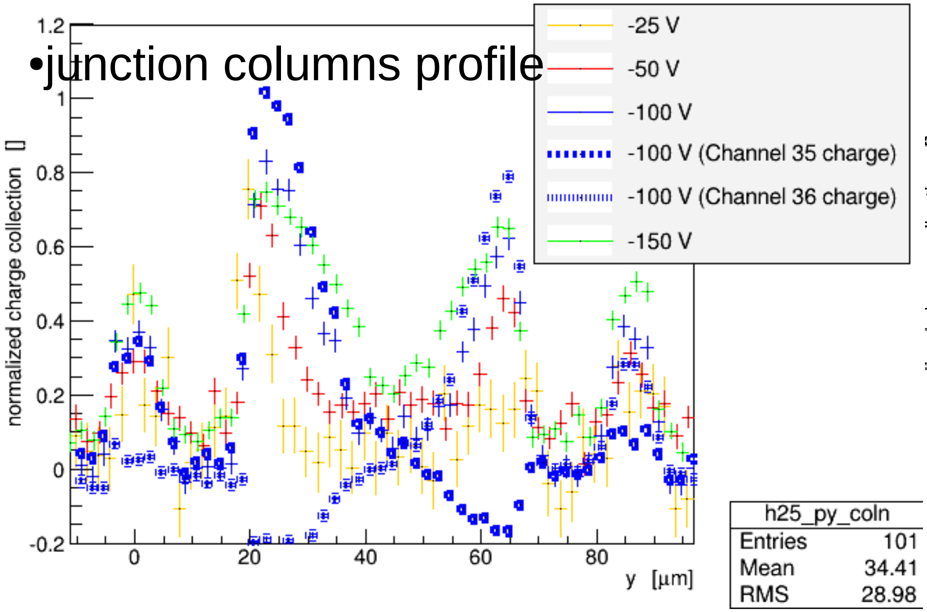
- Large dead zones also at 160 V (with ~20% collection).
  - NOTE: collecting 5 ke- at 150 V, an average unit cell collection of 50% means peaks collecting effectively 10 ke-!
- Significant collection at the ohmic columns also at low voltage. Double-junction on p-type??? Not predicted!

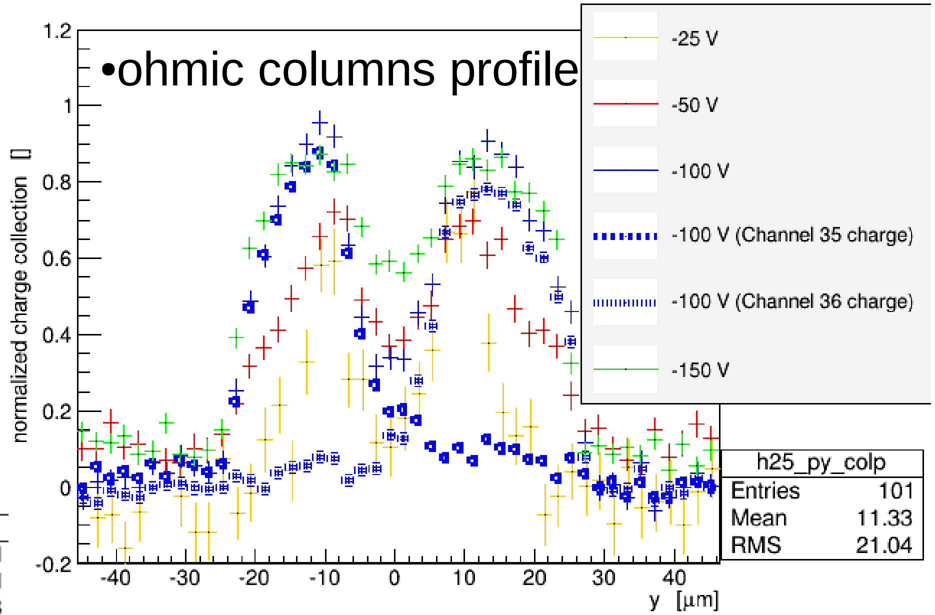
Experimental results and discussion

- Laser: 2×10^{16} n_{eq}/cm^2: discussion: “compensation” effect



Very large and very negative zones





- Larger than at lower fluence: relatively higher field distributed closer to the junction columns.

Experimental results and discussion

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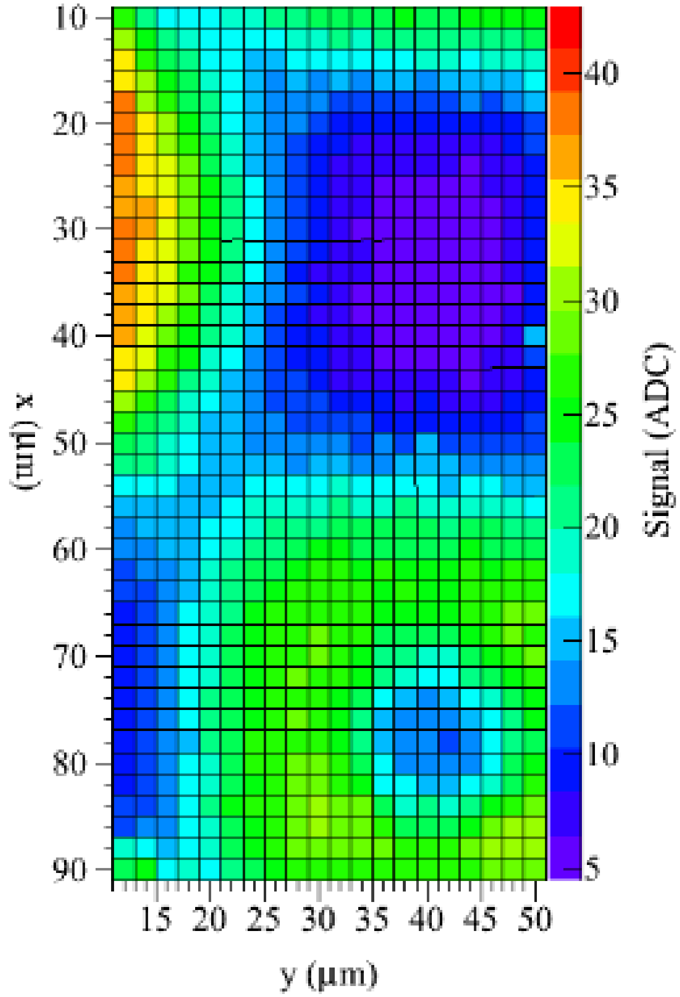
- Laser: $2*10^{16}\ n_{eq}/cm^2$: comparison with CNM sensors

  - 3D irradiated at KIT.
  - ~285 um thickness, ~215 um columns overlapping.
  - ~56 um column pitch
  - Same set-up.

  - $2*10^{16}\ n_{eq}/cm^2$.
  - 100 V.

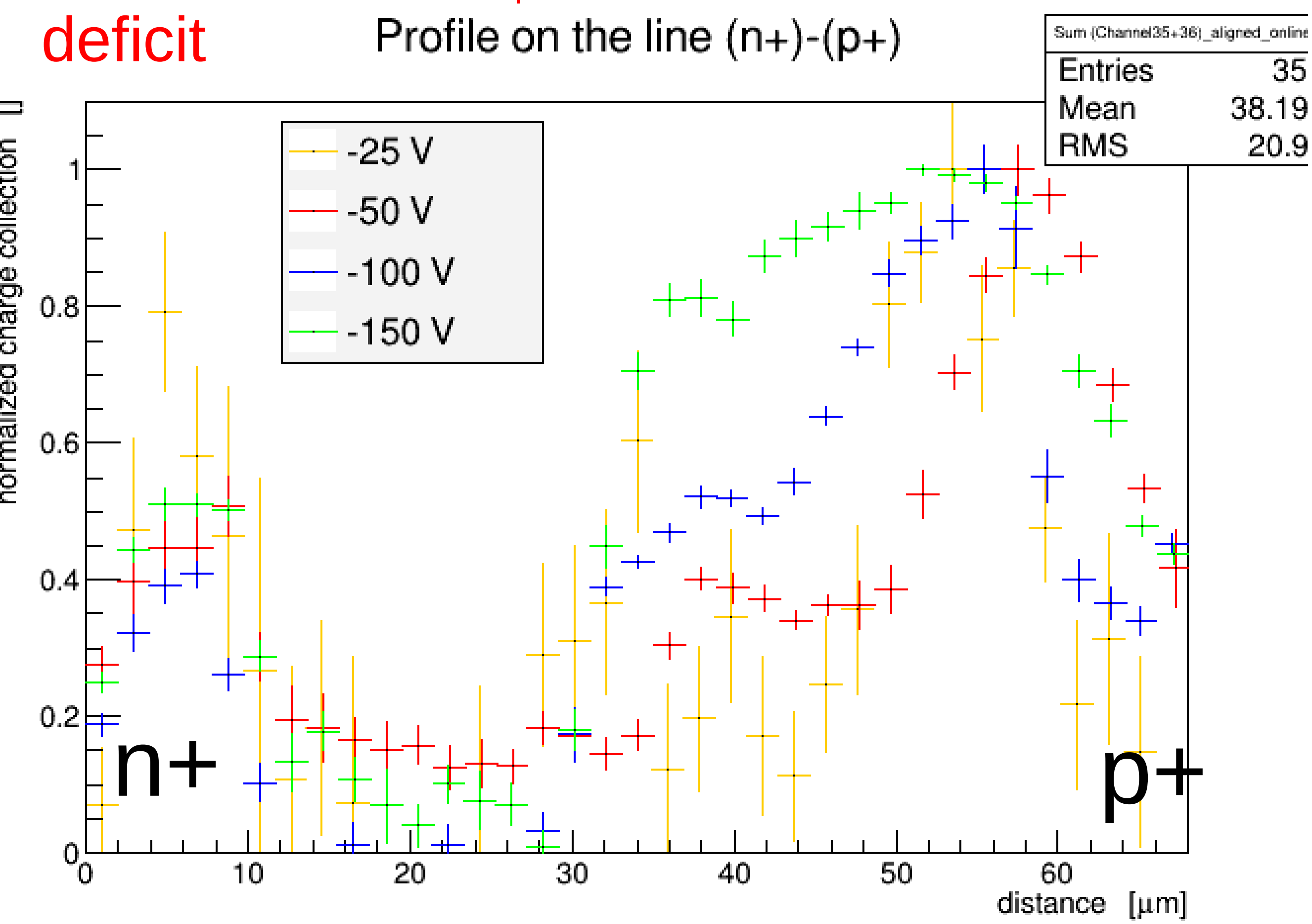


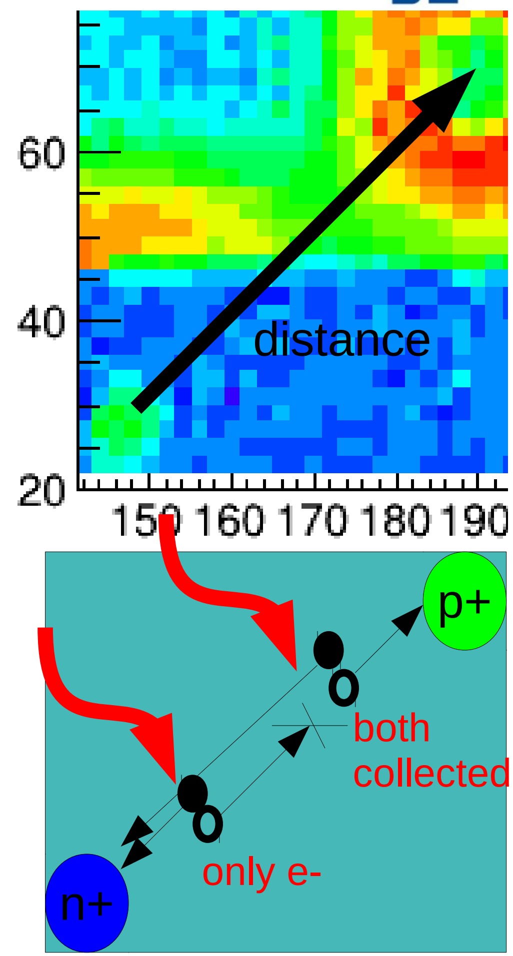
- (Measured charge multiplication.)
- Similarly high collection at the ohmic columns.

[1] Köhler et al., NIMA 659, 2011.

Experimental results and discussion

- Laser: $2*10^{16}\ n_{eq}/cm^2$: discussion: hole trapping and ballistic deficit





- With the low field, the slower holes are not integrated and are more prone to recombine. Increasing the bias, the effect is reduced.

Summary and outlook

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- Motivations:
  - Test radiation hardness up to $2*10^{16}$ n_{eq}/cm^2: charge collection, spatial uniformity.
- Results:
  - New sensors DTC: reasonable increase in the breakdown voltage before and after irradiation achieved.
  - Punch-through effective at $2*10^{15}$ n_{eq}/cm^2.
  - Charge collection as expected. Significant also at low voltages (6 ke- @ 20 V, $2*10^{15}$ n_{eq}/cm^2). No charge multiplication observed.
  - Collection still far to be uniform at high irradiation fluences:
    - Compensation effect due to limited integration time and holes deficit.
    - For $2*10^{15}$ n_{eq}/cm^2 increasing the bias the highest collection moves from around the junction columns to in between them; still due to compensation.
    - High collection close to the ohmic columns: determined by the amount of the holes contribution to the overall signal (how big deficit).
- Outlook:
  - Smaller inter-electrode spacing to have more uniform collection at lower voltages. Higher break-down voltage needed (encouraging results in new FBK samples[1]).
  - Changing integration time to investigate the compensation effect and the hole deficit.
  - Test beam or X-rays!!!

[1] Dalla Betta et al., IEEE NSS N41-1, 2013.

Summary and outlook

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Thank you!!!

[1] Dalla Betta et al., IEEE NSS N41-1, 2013.

Spares

- Sensor details.
- Clustering effect.
- Hole deficit for $2*10^{15}$ n_{eq}/cm^2.
- Tilted cell.

Spares: sensors details

- Coupling details:
  - AC: biased by punch-through from the bias line and have integrated coupling capacitors
  - DC: can be used via an external R-C fan-in (R= 1 MΩ, C=275 pF).

- Methods details:
  - Results were qualitatively similar, but in the AC configuration, the non-optimized thickness of the coupling oxide layer (which is about 1 μm due to other process constraints) caused the coupling capacitance (~8 pF) to be insufficient, and higher signal and signal/noise values were obtained by using R-C chips. Thus, although the punch-through bias was proved to properly work also after irradiation, all functional tests discussed here were carried out by using external R-C chips.

Spares: clustering effect (1)

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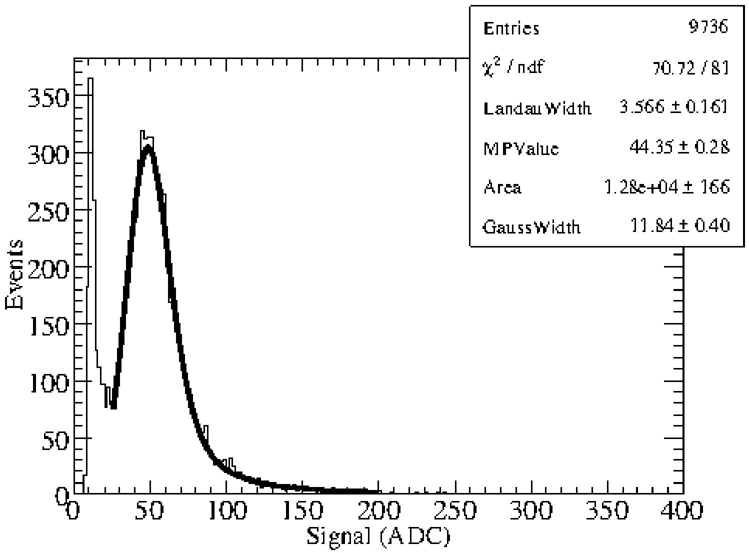
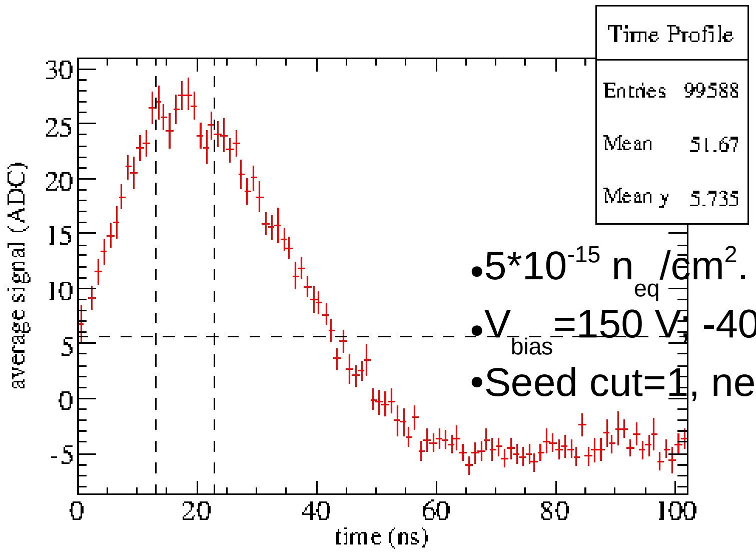
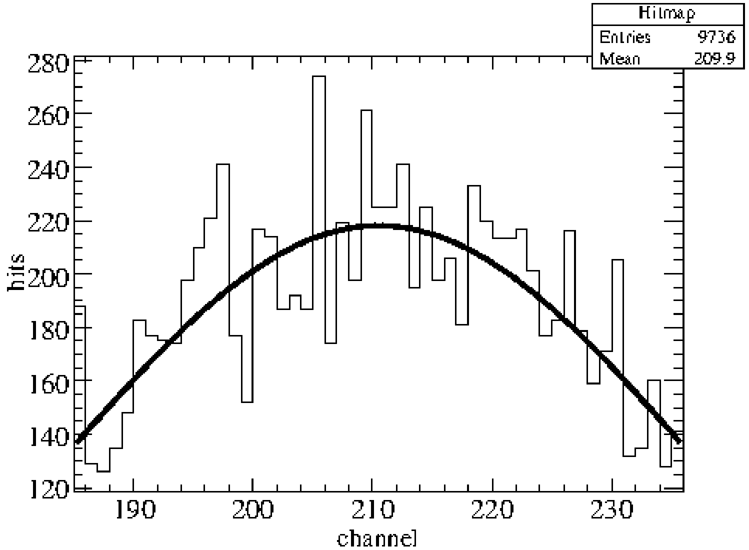
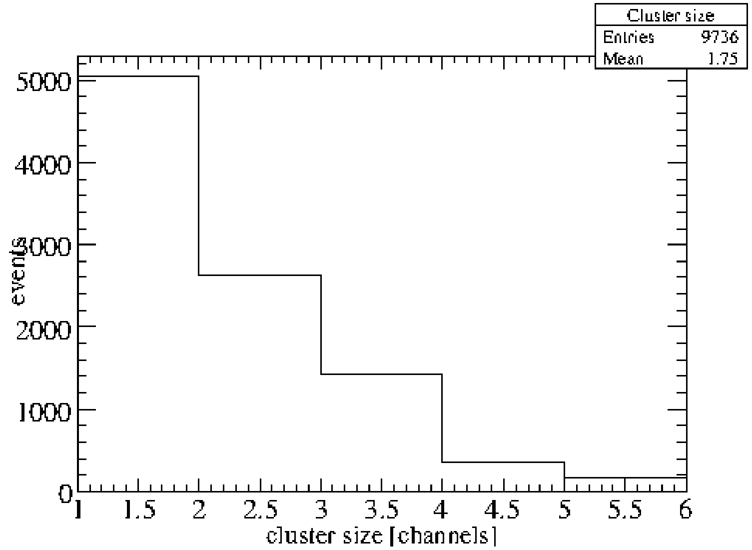
- β-source: pulse, spectrum, spatial distribution, clustering





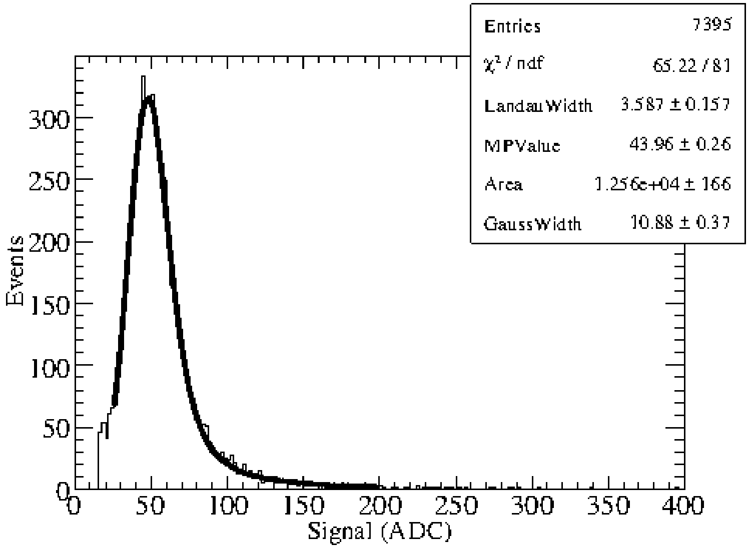
- $5*10^{-15}$ n_{eq}/cm^2.
- V_{bias}=150 V; -40+/-2 °C.
- Seed cut=1, neighbour cut=1.

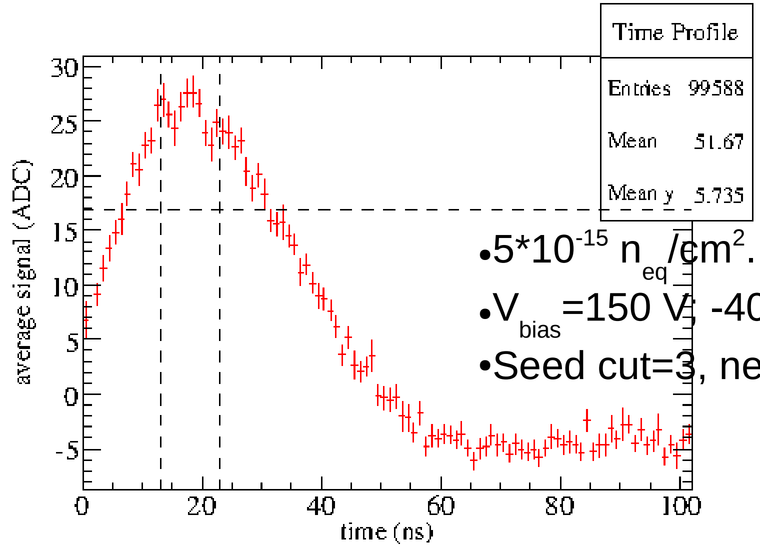




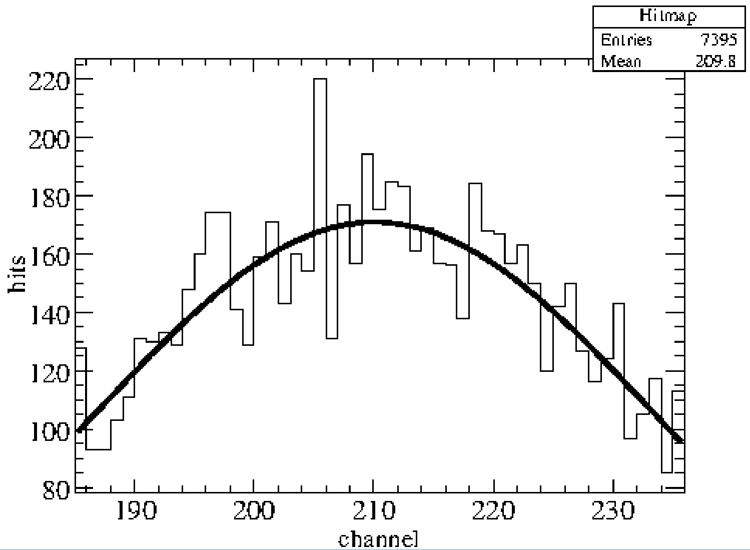
Spares: clustering effect (2)

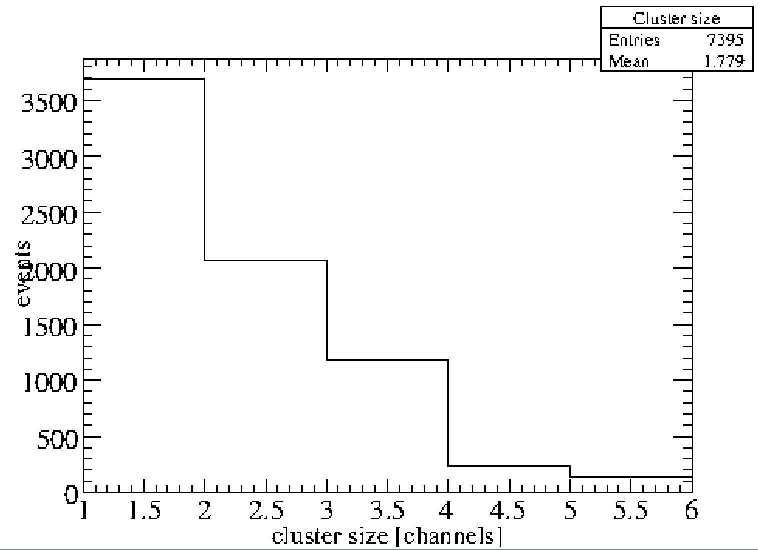
- β-source: pulse, spectrum, spatial distribution, clustering





- $5*10^{-15}$ n_{eq}/cm^2.
- V_{bias}=150 V, -40+/-2 °C.
- Seed cut=3, neighbour cut=1.2.





Spares: hole deficit at 2*10^15 n_eq/cm^2

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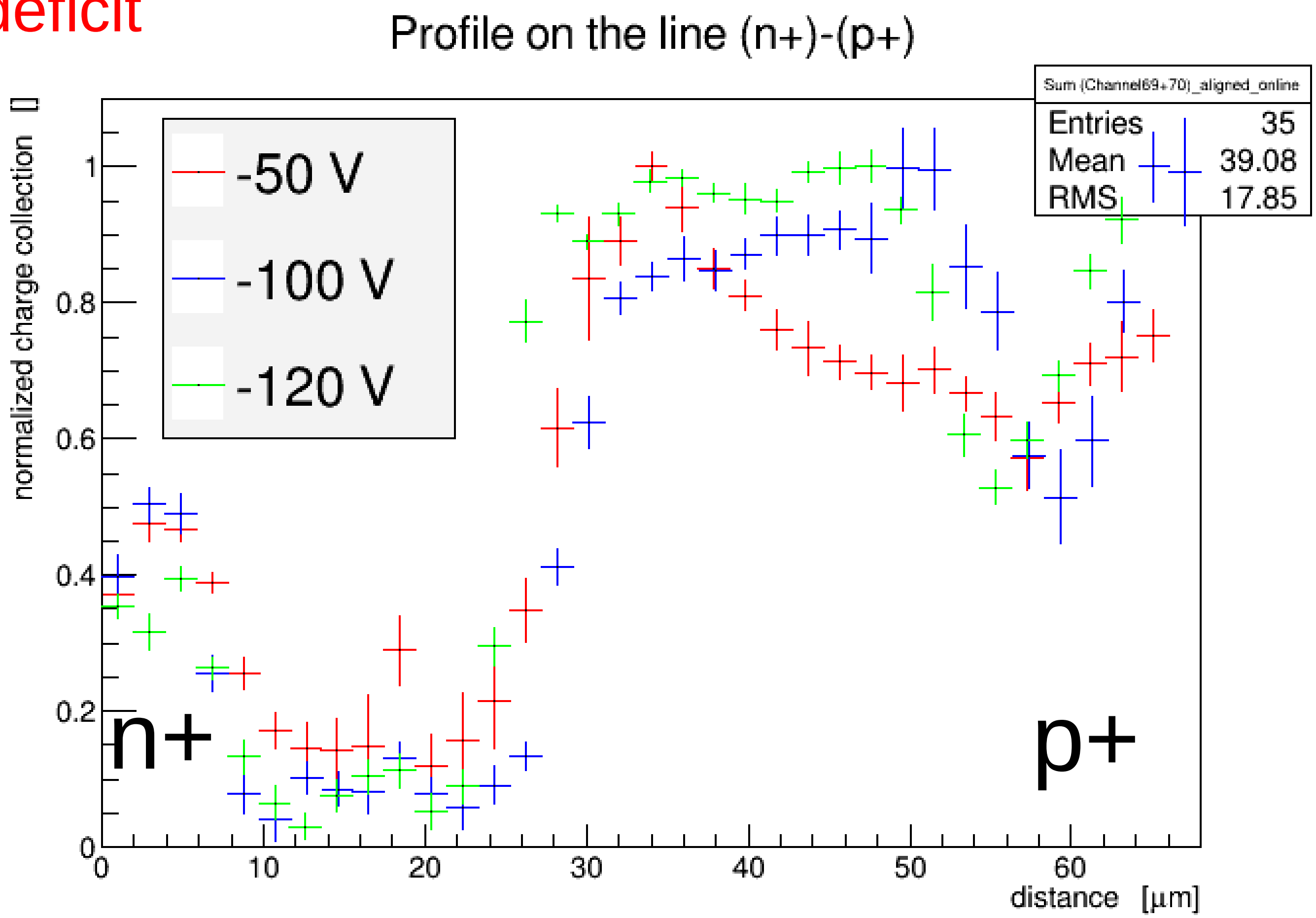
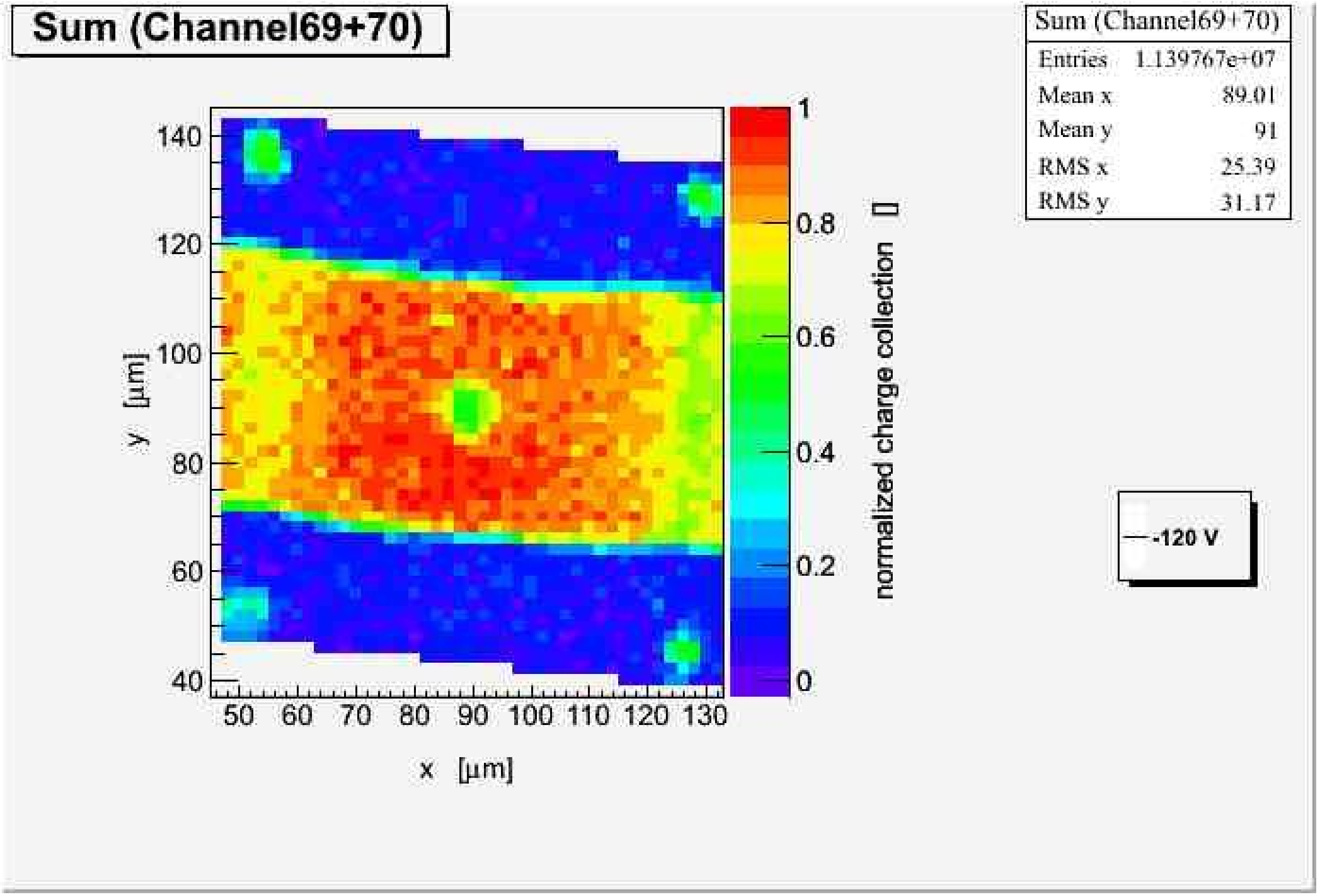
- Laser: $2 \cdot 10^{15}$ n_{eq}/cm^2: discussion: hole trapping and ballistic deficit



- Before depletion, holes still collected and/or much lower electron contribution close to the ohmic columns (relative collection!!!).

Spares: tilted cell



- $2*10^{15}\ n_{eq}/cm^2$