A study on the stability of the charge collection in strongly biased silicon strip sensors showing charge multiplication

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Outline

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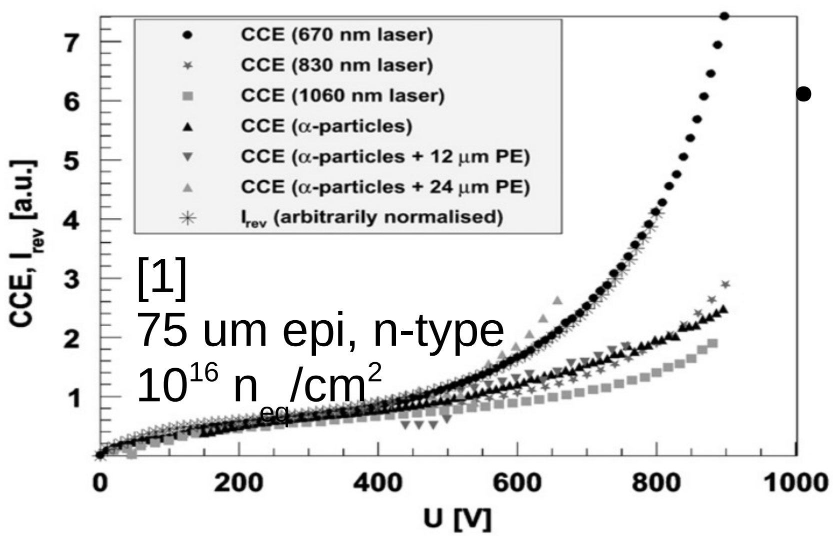
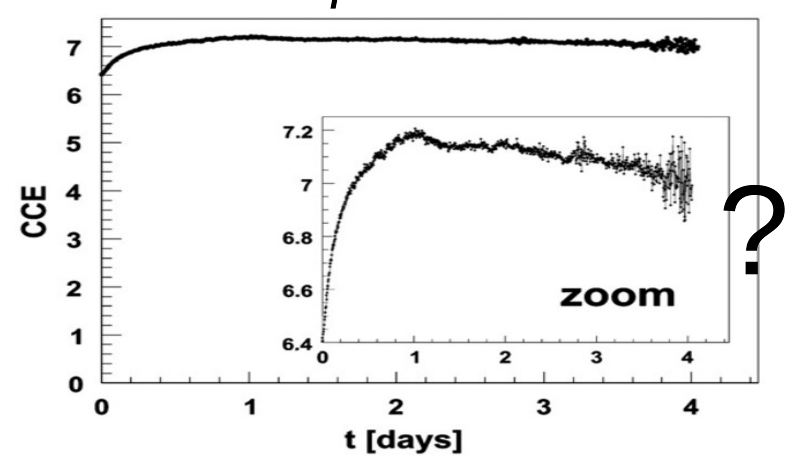
- Introduction:
  - charge multiplication and recent studies.
- Materials:
  - sensors;
  - set-up.
- Methods:
  - charge collection measurements;
  - procedure, for long term test;
  - monitoring.
- Experimental results:
  - starting point;
  - long term test:
    - first observation;
    - first (“failed”) tests;
    - last (“succesful”) tests: charge collections vs. voltage, monitoring, various.
- Discussion.
- Summary and outlook.

- Charge multiplication (CM):
  - *Observation:* charge collection higher than expected[1].
    (In (irradiated) Epitaxial, planar, 3D detectors.)
  - *Mechanism:* impact ionization taking place with high electric field, before breakdown.

  - Analytic description (charge distribution, dependence on voltage, temperature, etc.) still on going.
  - Sensors are at critical "stressing" point.



- *Is it a sustainable operative condition?*



[1] e.g. Casse, PoS, 2010; Lange et al., NIMA 622, 2010.

Materials

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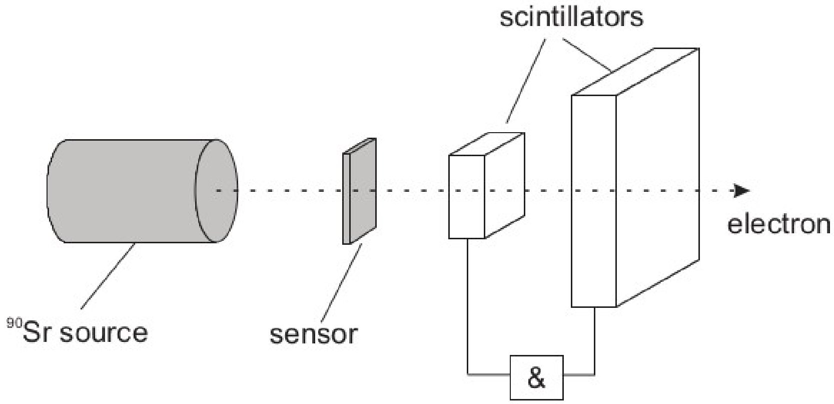
- Samples:
  - Micron, p-type, strip with (pitches, widths)=(100,10),(80,25) um.
  - Layouts: standard (some seem different); with double implantation energy.
  - Irradiation: neutrons, [1,5]*10^{15} n_{eq}/cm^2.
- Set-up:
  - Sr90 source, two scintillator in coincidence.
  - AliBaVa system (Beetle chip) (daughter board calibrated in temperature with a standard 296 um thick sensor).
  - Freezer + cold nitrogen vapour flow (down to -70 °C).
  - Software monitoring automatically temperature, current (and voltage); humidity monitored by the operator.
- Analysis:
  - Custom code in ROOT using the data extraction utilities of ALiBaVa.



Methods

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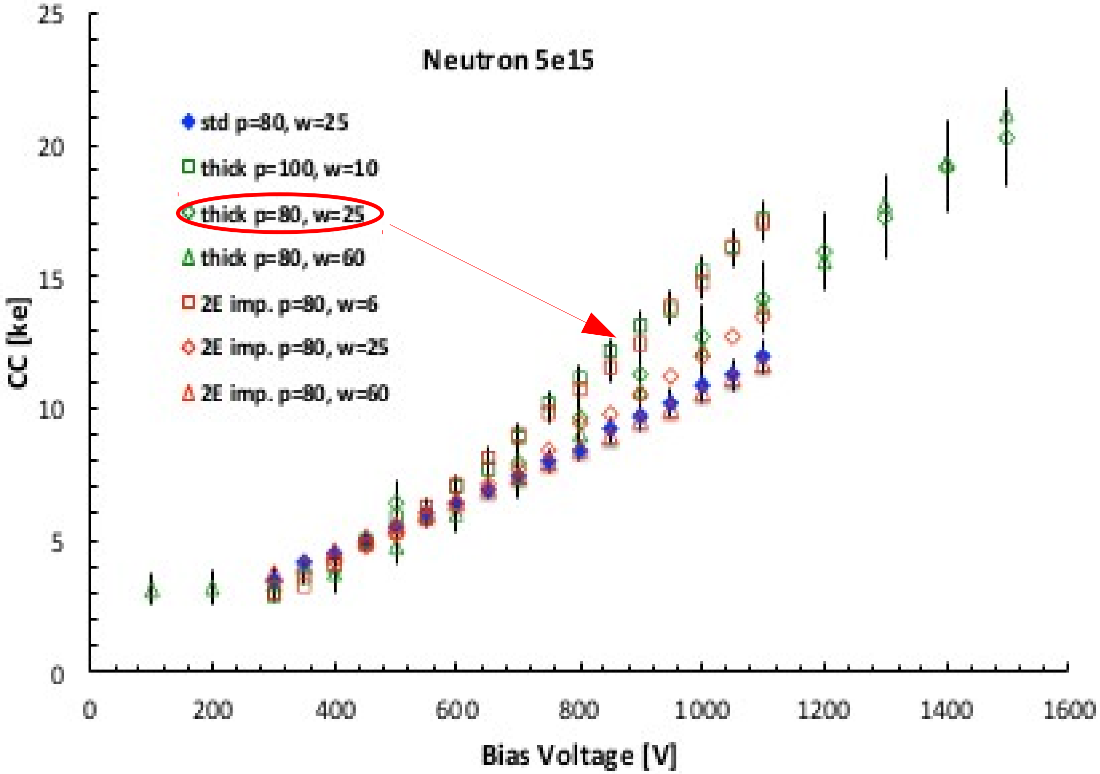
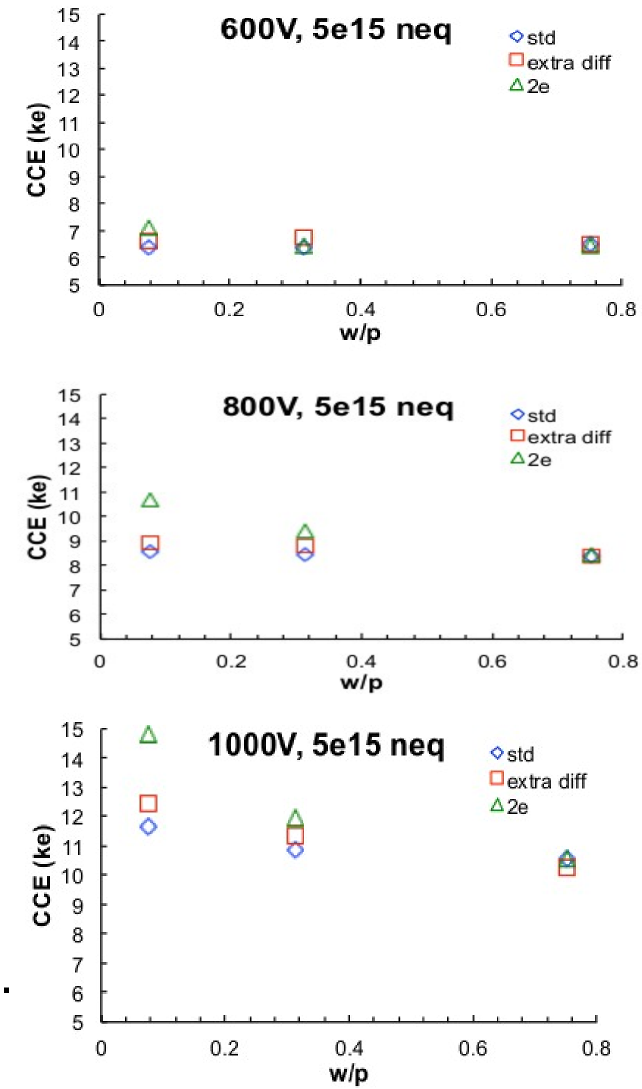
- Measurements:
  - Search for a the bias voltage at limit: before breakdown, short term stable current.
  - Preliminary evaluation of the charge collection at three bias voltages.
  - Monitored operative conditions:
    - temperature around -42 °C, deviations during N refilling;
    - relative humidity usually <5%;
    - compliance sometimes reduces the bias for ~1h/day during N refilling.

- Procedure: monitoring of the results and resulting actions:
  - Significant drop in charge collection?
    - Yes: remove the voltage for 1 h, then 24 h.
      - Recovered charge?
        - Yes: continue.
        - No: warm up for 24 h.
          - Recovered charge?...
  - I-V at every break.

- Charge collection dependence on layout[2]:



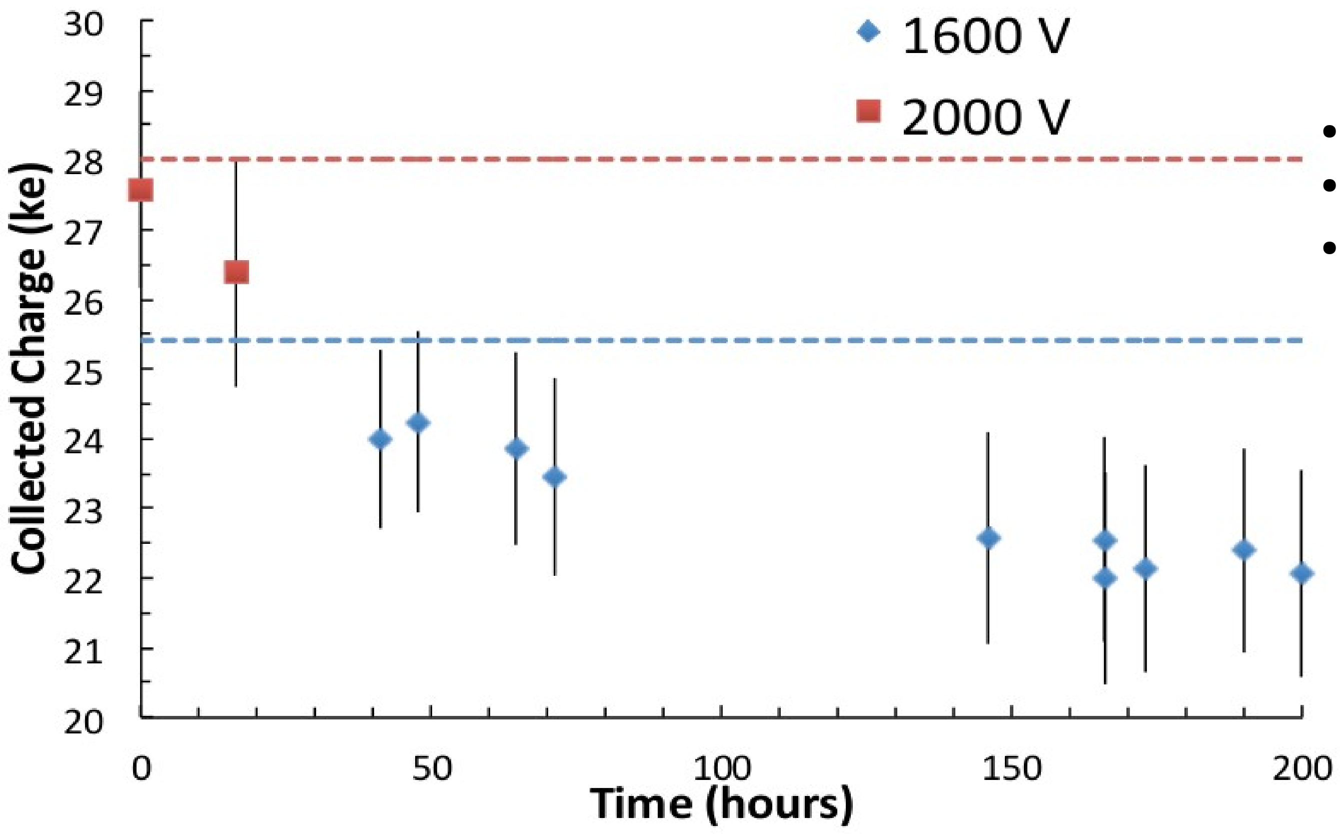


- Beneficial effect from decreasing pitch/width:
  - allow relatively larger high electric field regions.

[2] C. Betancourt, RD50 workshop, 2013.11.

Results: long term, first observation

•Charge collection over time[3,2]:



•Standard.
•(p,w)=(80,60) um.
•$1*10^{15}$ n_{eq}/cm^2.

Thanks Sven!

- An indication of a possible drop after several (~6) days.

[3] Sven Wonsak, private communication.
[2] Chris Betancourt, RD50 workshop 2013.11.

Results: long term, first (failed) tests

- Long term biasing behaviour:
  - Standard, $1*10^{15}$ n_{eq}/cm^2: broke in less than a day at 1000 V.
  - Standard, $1*10^{15}$ n_{eq}/cm^2: broke after 3 stable days at 1100 V.
  - Standard, $1*10^{15}$ n_{eq}/cm^2: immediate breakdown, irreversible damage.
  - Standard, $5*10^{15}$ n_{eq}/cm^2: stable for 3 days at 1500 V; breakdown, permanent damage, moving to 1600 V.

- A relatively short term stability, does not imply long term stability.
  - *Really a critical operative condition...*

Results: long term, succesful test, initial

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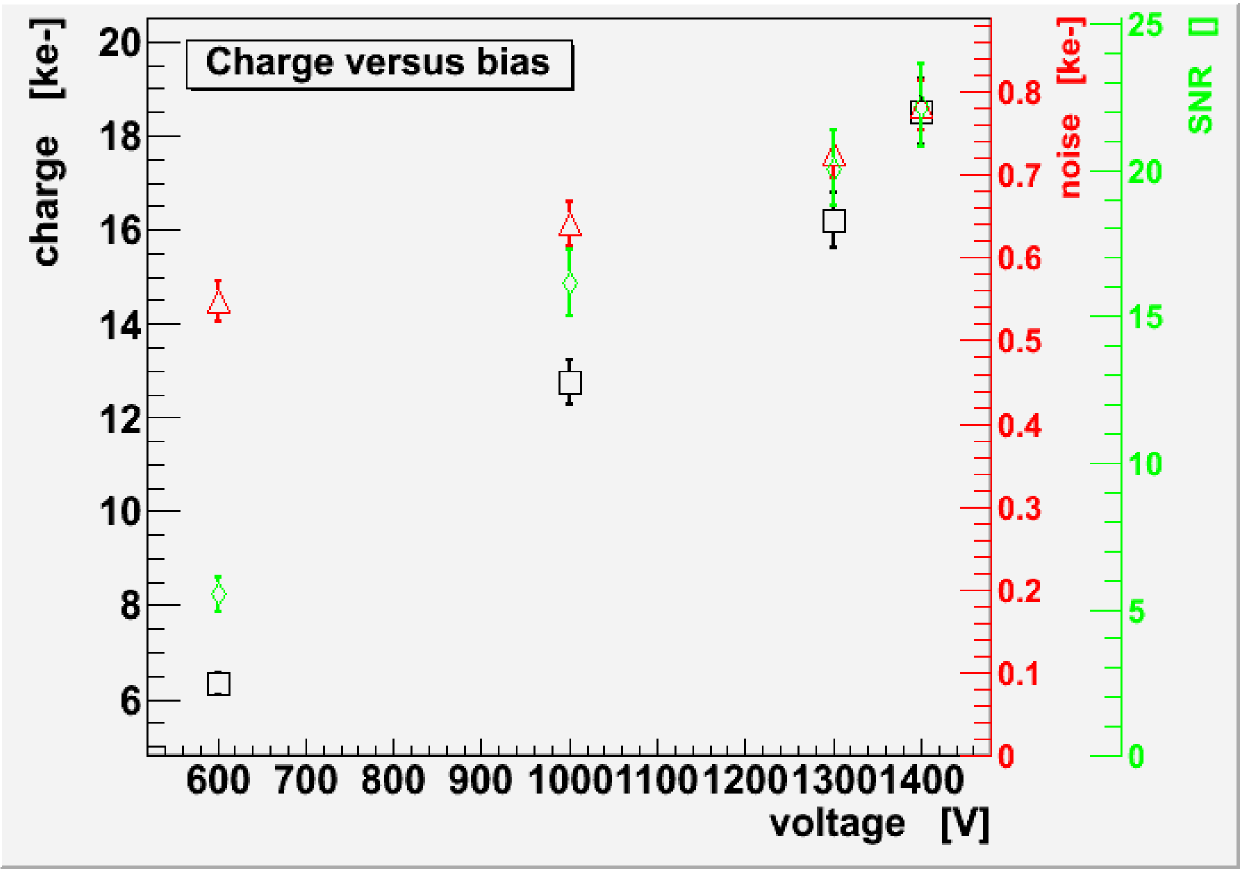
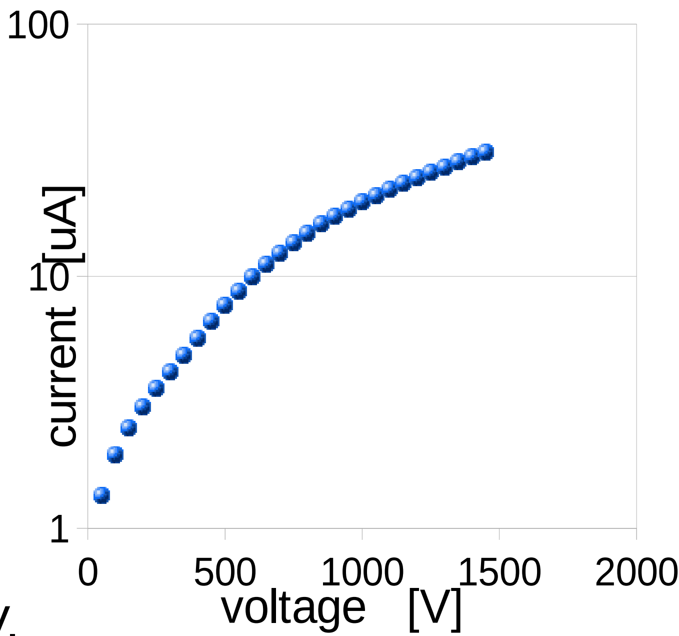
- First I-V, charge collection vs. bias::



- Standard.
- (p,w)=(100,10) um.
- $5*10^{15}$ n_{eq}/cm^2.

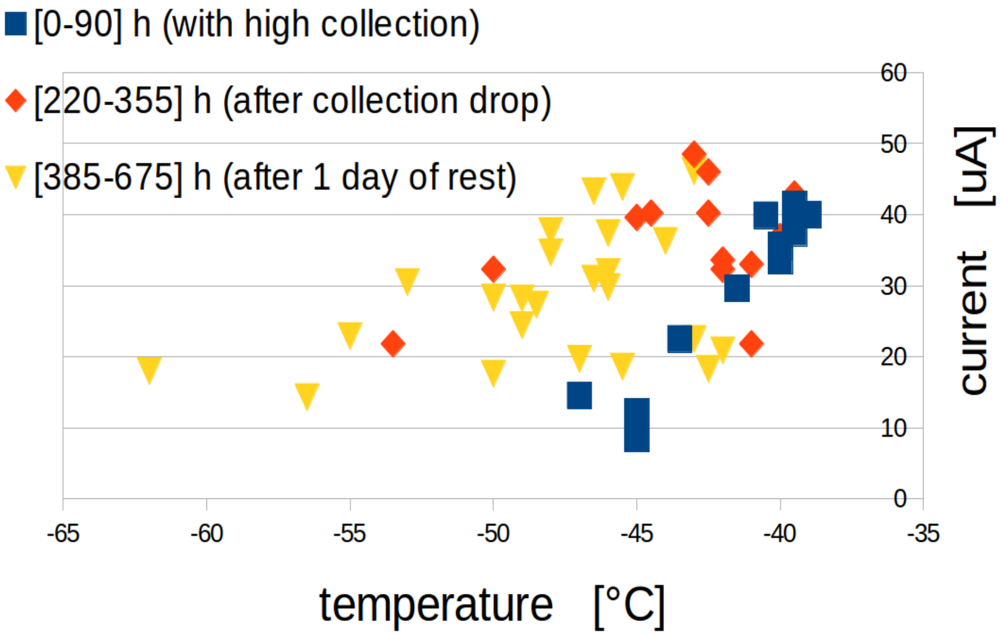
- Compliance=54 uA (too safe).



- Unstable behaviour at 1400 V => down to 1300 V.

Results: long term, succesful test, current

- Various: current in time



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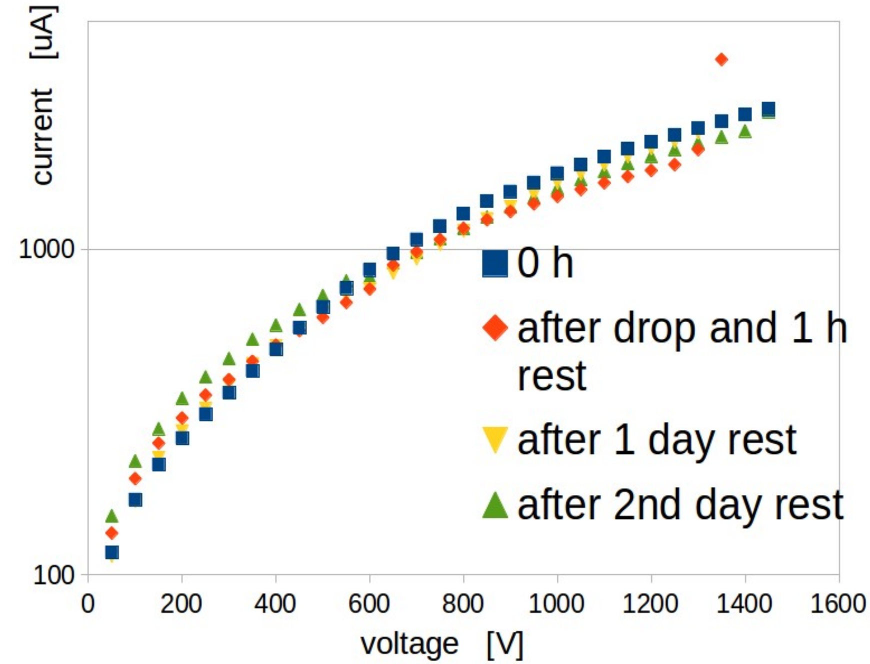
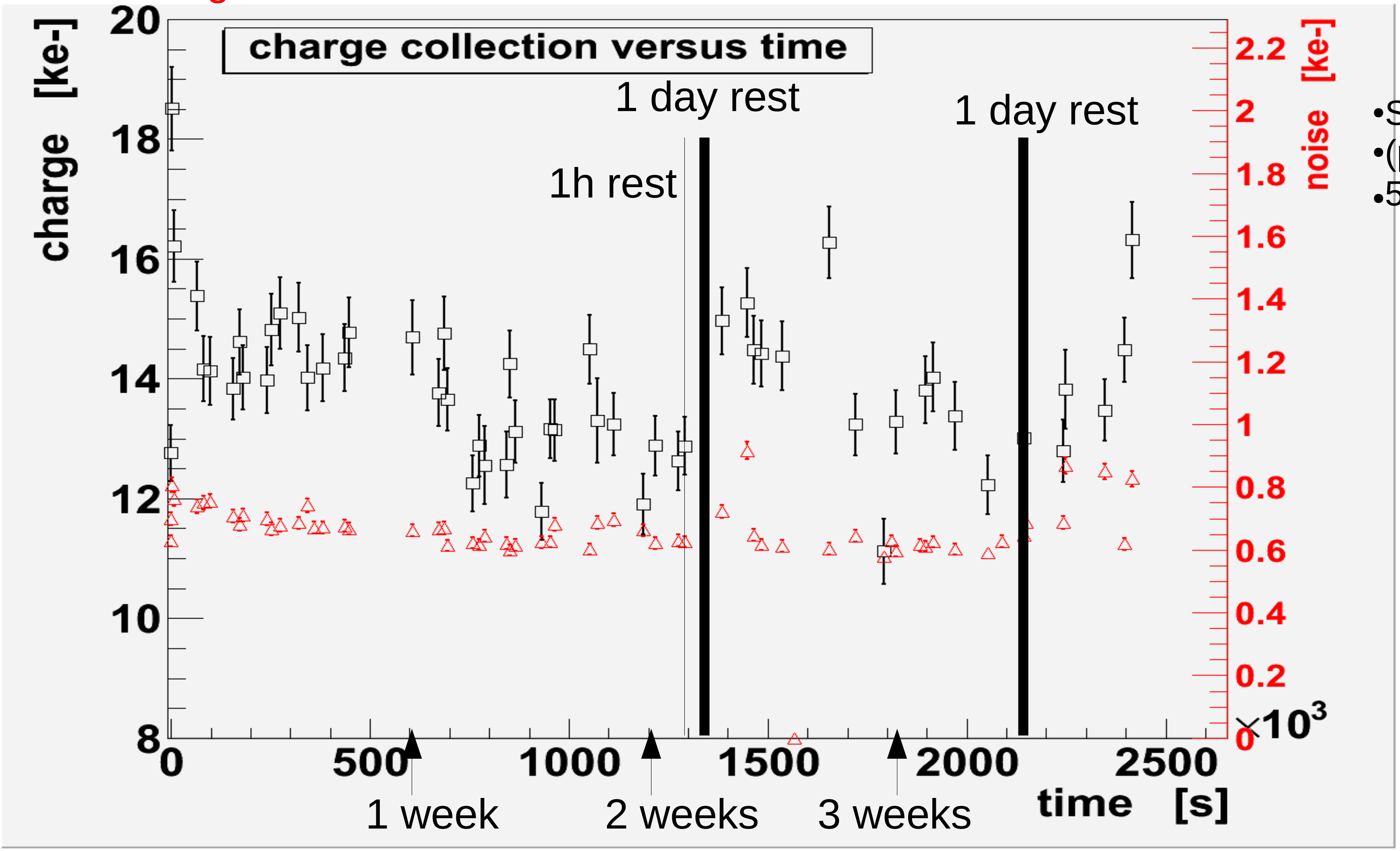


- Increase of the current after long term stress and with temperature stress (during N refilling).
- Observed a lower current immediately after resting periods but still persistent higher current in long term (see how similar are the I-Vs!!!).

Results: long term, succesful test, charge in time

•Charge collection over time:



•Standard.
•(p,w)=(100,10) um.
•$5*10^{15}$ n_{eq}/cm^2.

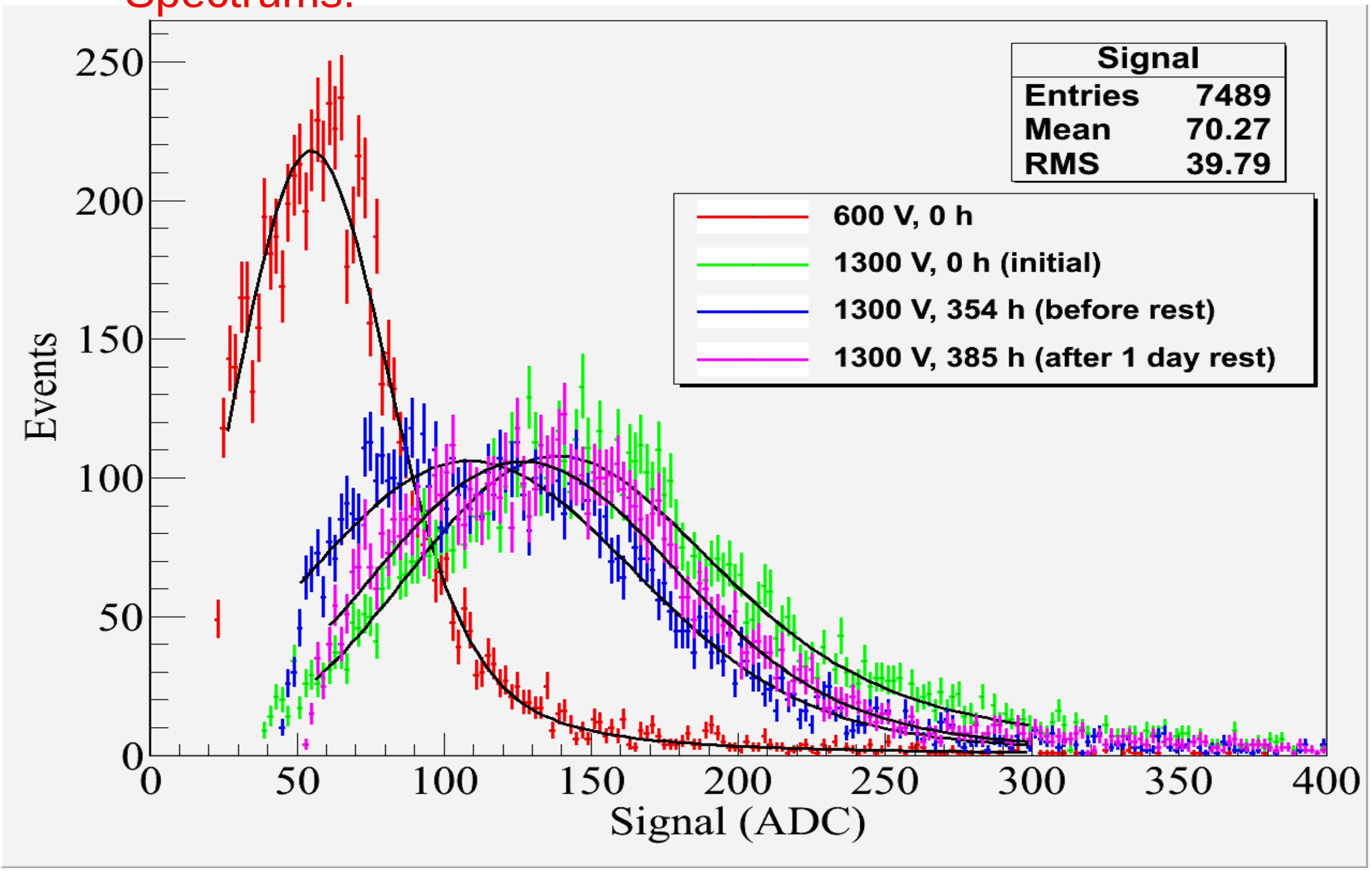
NOTE: outliers also due to much different (lower) temperatures (see backup). (AliBaVa work well down to -44°C[4].)

- Significant decrease after few days.
- Removing the voltage seem to (partially) recover the charge collection efficiency, but then drop again definitely.

[4] e.g. Löcher, Ph.D. thesis, 2006.

Results: long term, succesful test, distribution

•Spectrums:



•Standard.
•(p,w)=(100,10) um.
•$5*10^{15}$ n_{eq}/cm^2.

- Charge distribution change from 600 V and 1300 V (broader): statistical fluctuation and broader shot noise[1]:
  - charge multiplication take place.
- Drop in most probable charge reflect the change in the distribution: broad and lower.

[1] e.g. Lange et al., NIMA 622, 2010.

Summary and outlook

- **Summary:**
  - Charge multiplication is observed usually by “single-shot” measurements or in relatively short term tests[1], but a possible exploit need long term stability.
  - Results show:
    - Several sensor broken after significant time (several days): stress is long term related.
    - Drop after few days: long term change of sensor properties (electric field distribution).
    - Partial recover after a resting day: some change is reversible.
    - Current drift over time: further confirmation of long term properties change.

      - *So the big question: there is a change, but is it really permanent?*
- **Outlook:**
  - Long term measurements:
    - Confirmation by more samples.
    - Resting at higher temperature: after charge drop, 1 day of rest at 0 °C, then restart: is the heating helping in recovering the collection?
    - UV stimulation at low temperature for some time to see a possible effect of the oxide charge.
    - Different fluences: how the long term behaviour is dependent on the amount of defects?
    - Different structures: same measurements on as-grown samples showing CM before irradiation by special geometries (LGAD, etc...): to get information the difference between CM pre-rad and post-rad.
  - Other studies:
    - Charge multiplication versus temperature.
    - Annealing electric-field driven at low temperatures (e.g. by capacitance measurements).

[1] Lange et al., NIMA 622, 2010.

Open discussion

- First (and from discussions here) ideas about the charge collection drop:
  - No more charge multiplication
    - => electric field distribution change
      - Fixed charge distribution change:
        - Annealing induced by strong electric field also at such low temperatures??? Field has an effect...[5]
      - Trapped population (polarization) change:
        - But the so far described traps are “dynamic” (relaxing relatively quickly) above 200 K[6].
      - Effect of the oxide charge (thanks Gianluigi!).
- Information from the results:
  - Charge collection (partial) recover after removing the voltage.
  - Current increases with the stress, but restored after rest.
    - No permanent change in the crystalline structure
      - => Trapped population change and some bistable defects[5] seem to be more possible.
  - *From collateral observation*, temperature dependence of charge collection.
    - Lower the temperature, higher ionization coefficient is expected.

[5] Cindro et al., NIMA 498, 1998; Mikuz et al., NIMA 466, 2001.
[6] e.g. RD50 status reports.

Open discussion

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Thank you!

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[6] e.g. RD50 status reports.

Spares: results: long term, second (ongoing) test

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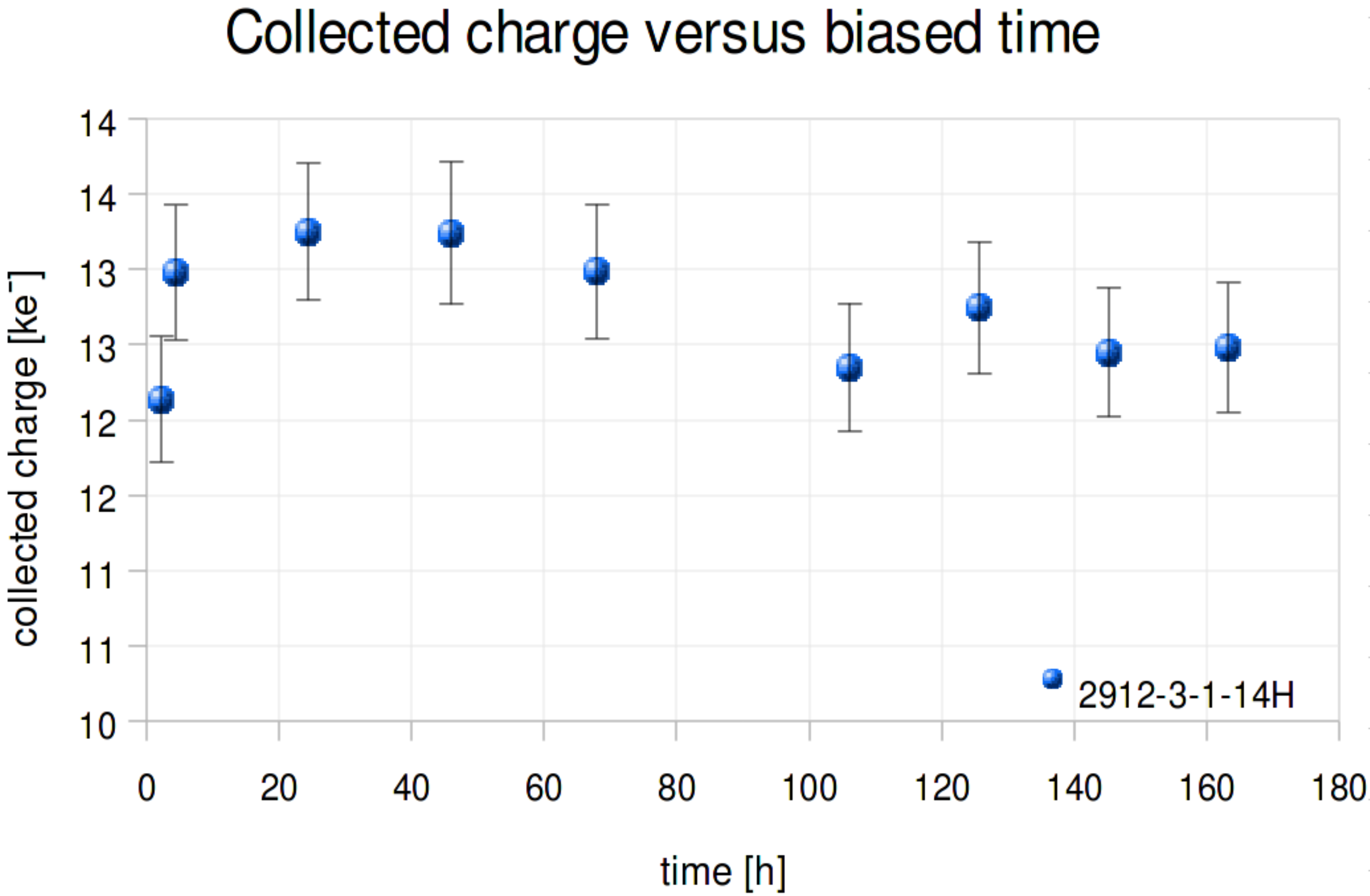
- Charge collection over time



- Standard.
- (p,w)=(80,25) um.
- $5*10^{15}\ n_{eq}/cm^2$.

- Compliance~200 uA.

- Again unstable behaviour at 1400 V => down to 1300 V.
- Lower charge than the previous sensor.

Spares: introduction

- Charge multiplication:
  - What we know...:
    - Dependence on sensor mechanical properties: how to increase collection
    - Decreasing the pitch/(strip width) ratio allow to have relatively more high field regions.
    - Higher doping implantation energy increase locally the electric field, still in a limited region.
  - How to get it:
    - To get rid of the earlier breakdown:
      - “Ad-hoc” sensors: high enough electric field but in limited regions to avoid thermal breakdown.
      - Irradiated devices: trapping and recombination confine the phenomena (and increase the breakdown voltage) to obtain an impact ionization, avalanche, “under control”.

Spares: materials: calibration

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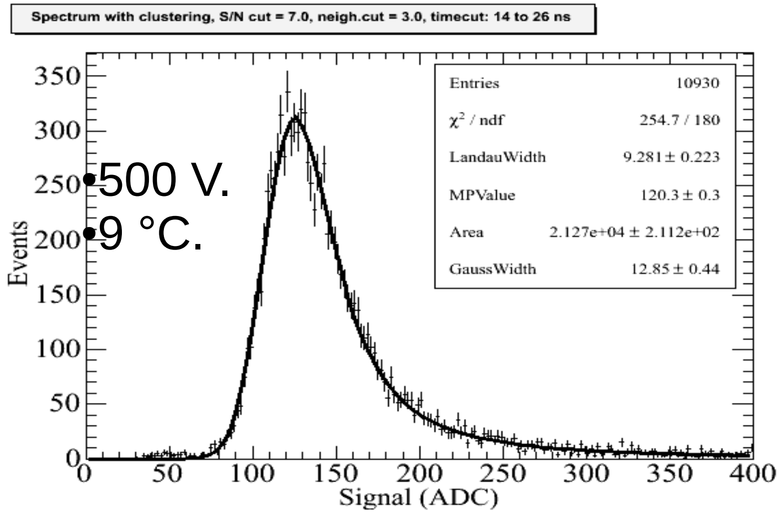
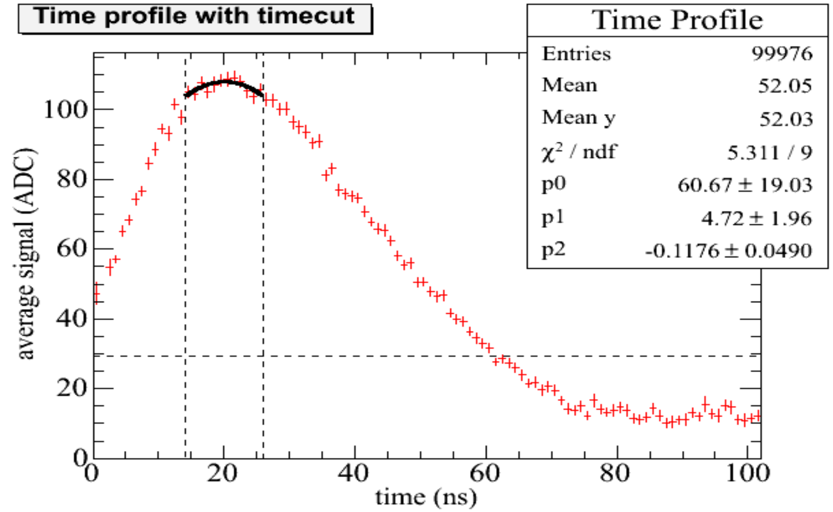
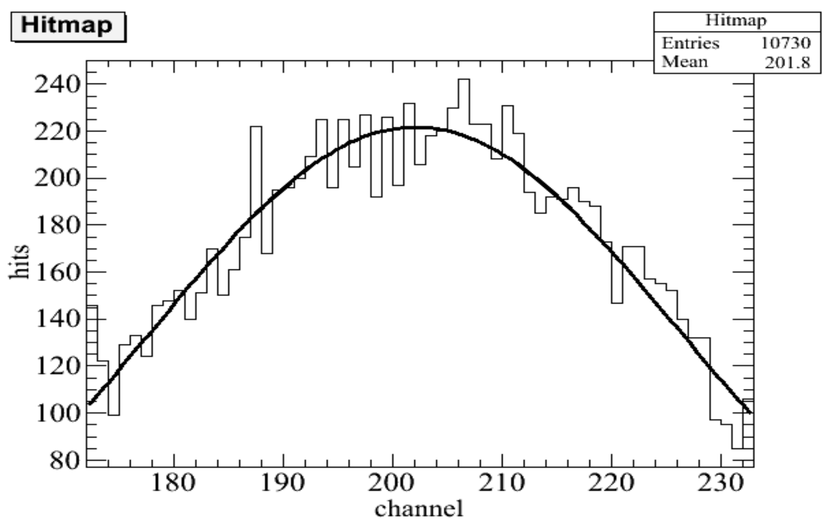
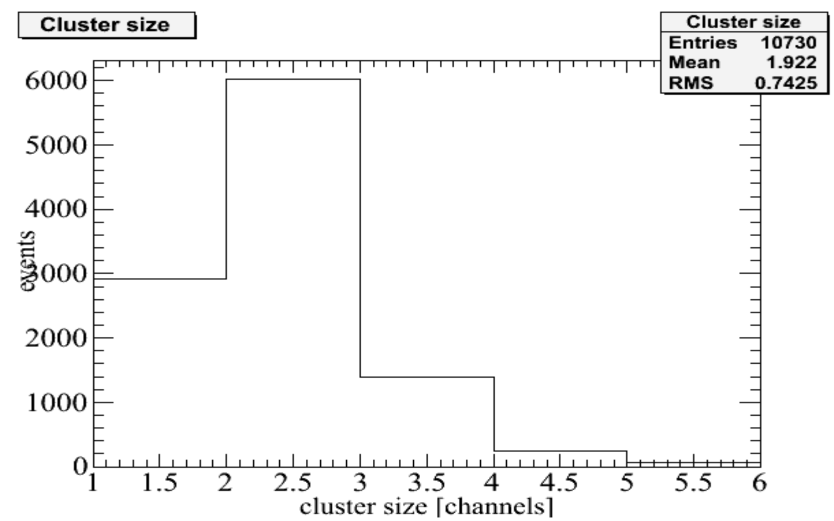
- Spectrum and calibration results:
- Micron, standard, p-type, 296 um.
- 500 V.
- 9 °C.









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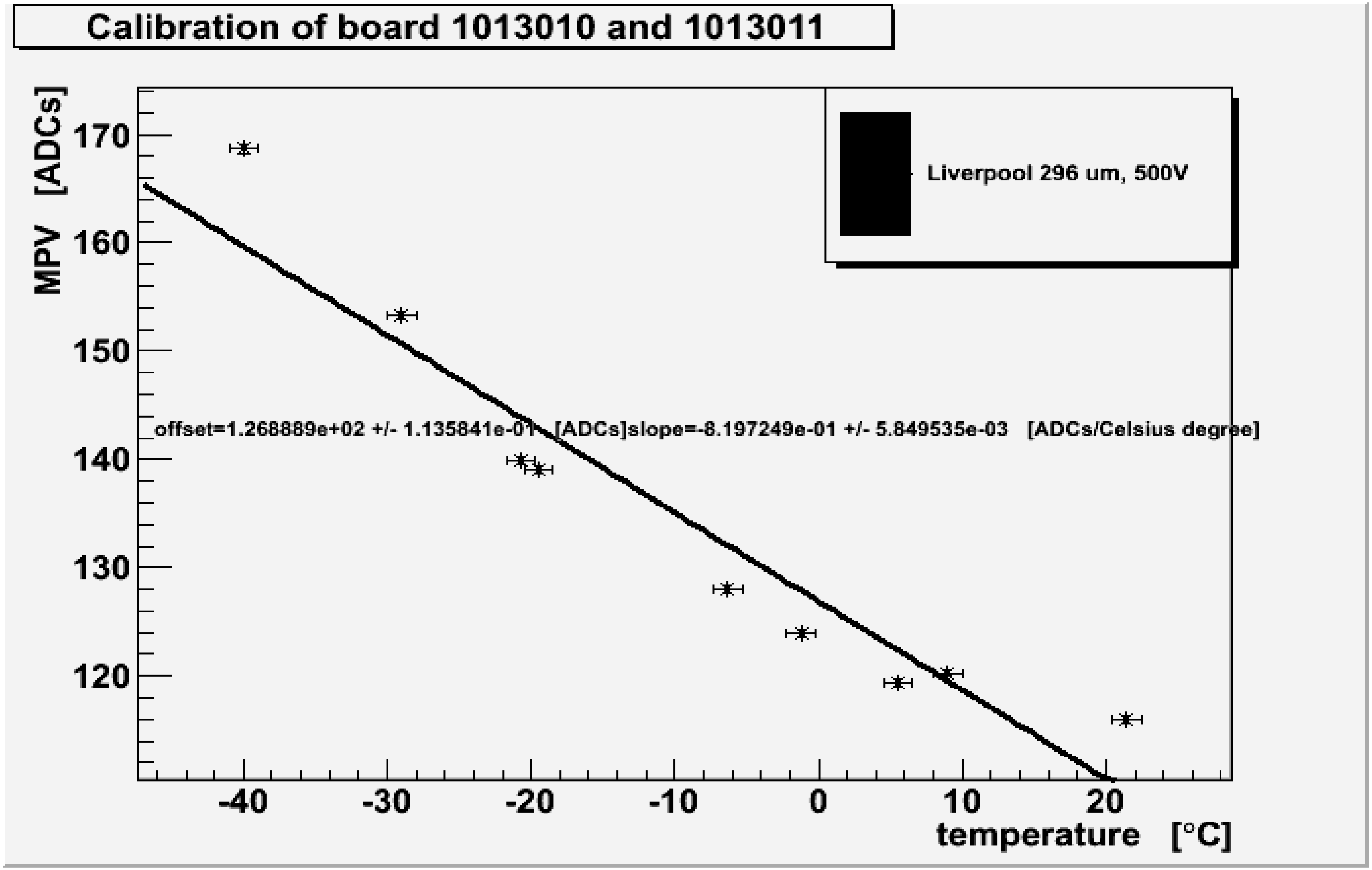


Spares: methods

- Measurements:
  - Search for a the bias voltage at limit: before breakdown, short term stable current.
  - Preliminary evaluation of the charge collection at three bias voltages.
  - Monitored operative conditions:
    - Temperature $\in$ [-62,-32] °C (usually around -42 °C, extremes touched during N refilling);
    - Relative humidity<12% (usually <5%);
    - Compliance sometimes reduce the bias for ~1h/day during N refilling.

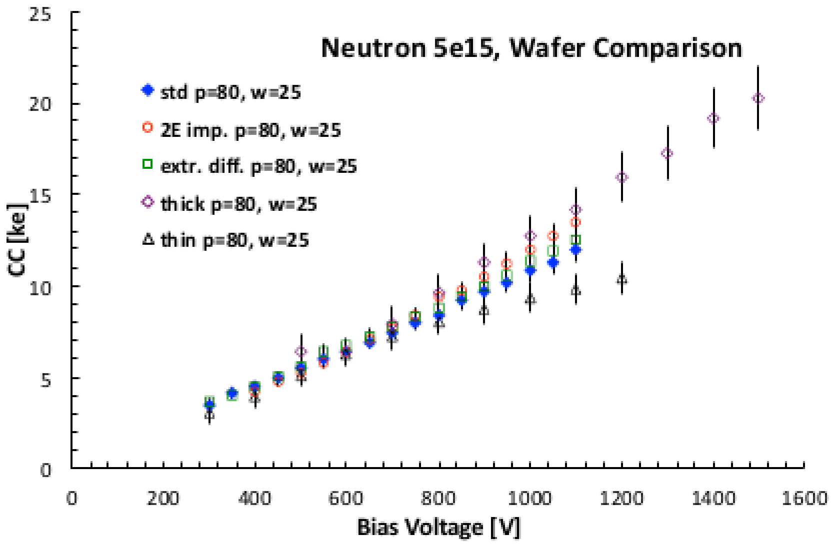
- Result monitoring:
  - Significant drop in charge collection?
    - Yes: remove the voltage for 1 h, then 24 h.
      - Recovered charge?
        - Yes: continue.
        - No: warm up for 24 h.
          - Recovered charge?...
  - I-V at every break.

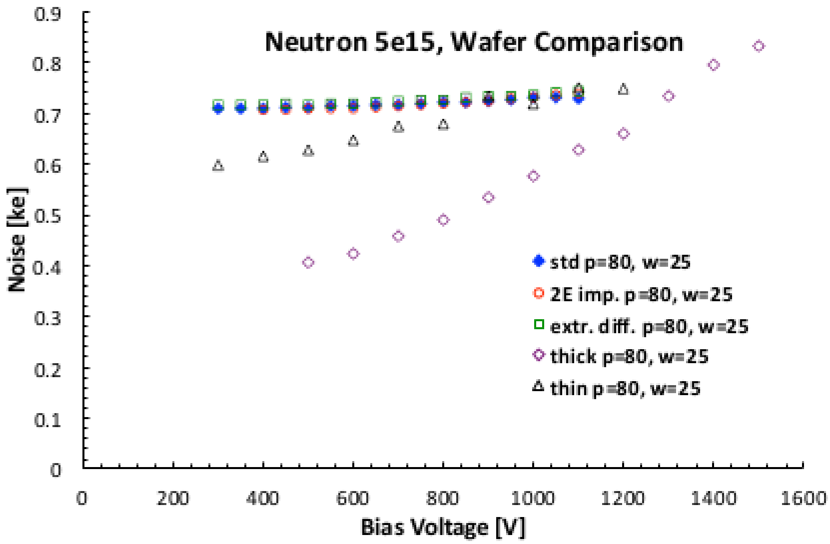
Spares: methods

- Measurements:
  - Charge collection: 300000 events for warming up, 100000 events source run, 10000 events pedestals run.
- Analysis:
  - Residual cut: ~70 channel around the hit map peak (considering the distances of the set-up).
  - Pedestals, common mode calculation: from pedestals and source runs (2 times iteration (to get rid of outliers influence)).
    - Noise calclulation.
  - Pedestals, common mode removal.
  - Time cut: 12 ns around peak, compensation (quadratic fit, factor=max/mean).
  - Clustering: seed cut $\in$[6,10], neigh cut $\in$[2.5,4].
  - Signal distribution fit: Landau$\otimes$Gaussian (also if very broad).

Spares: results: initial characteristics

• Charge collection dependence on wafer[2]:



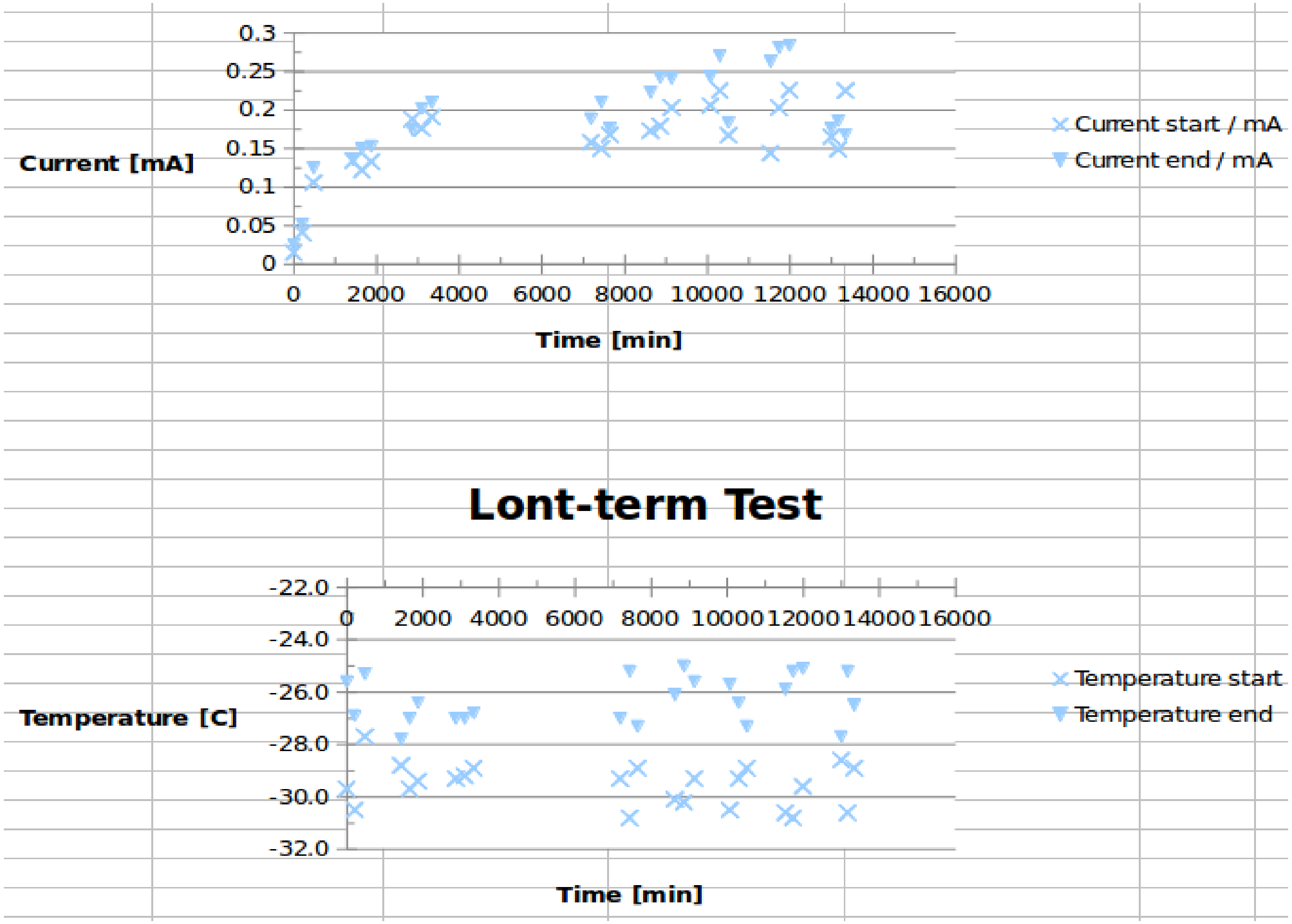


- Beneficial effects from extra diffusion, double implantation energy: increase locally the electric field, still in a limited region (no thermal breakdown).

[2] C. Betancourt, RD50 workshop, 2013.11..

Spares: discussion

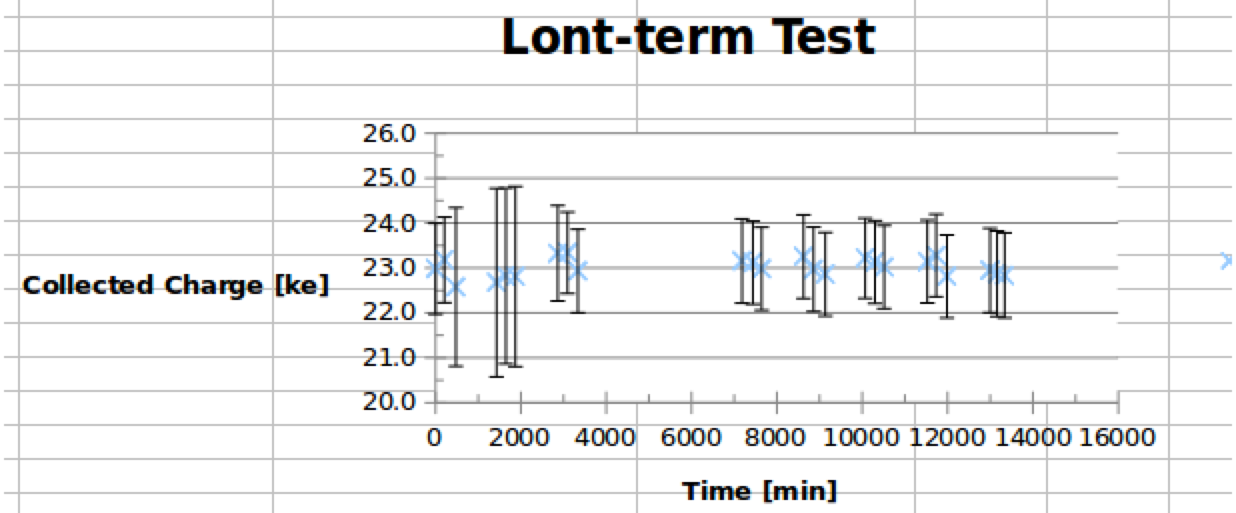
- Test ongoing [3]: current drift

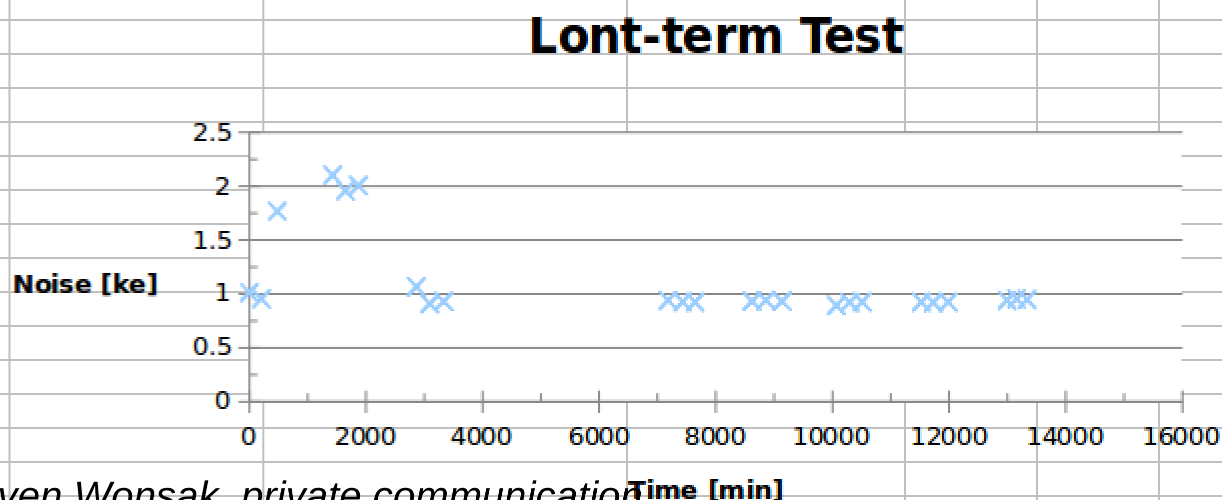


- Standard.
- (p,w)=(80,60) um.
- $1*10^{15}$ n_{eq}/cm^2.
- After test beam.

[3] Sven Wonsak, private communication.

•Test ongoing [3]: charge on time





- Standard.
- (p,w)=(80,60) um.
- $1*10^{15}$ n_{eq}/cm^2.
- After test beam.

[3] Sven Wonsak, private communication.

Spares: results: long term, first (failed) tests

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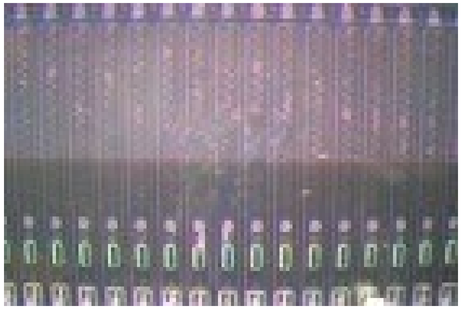
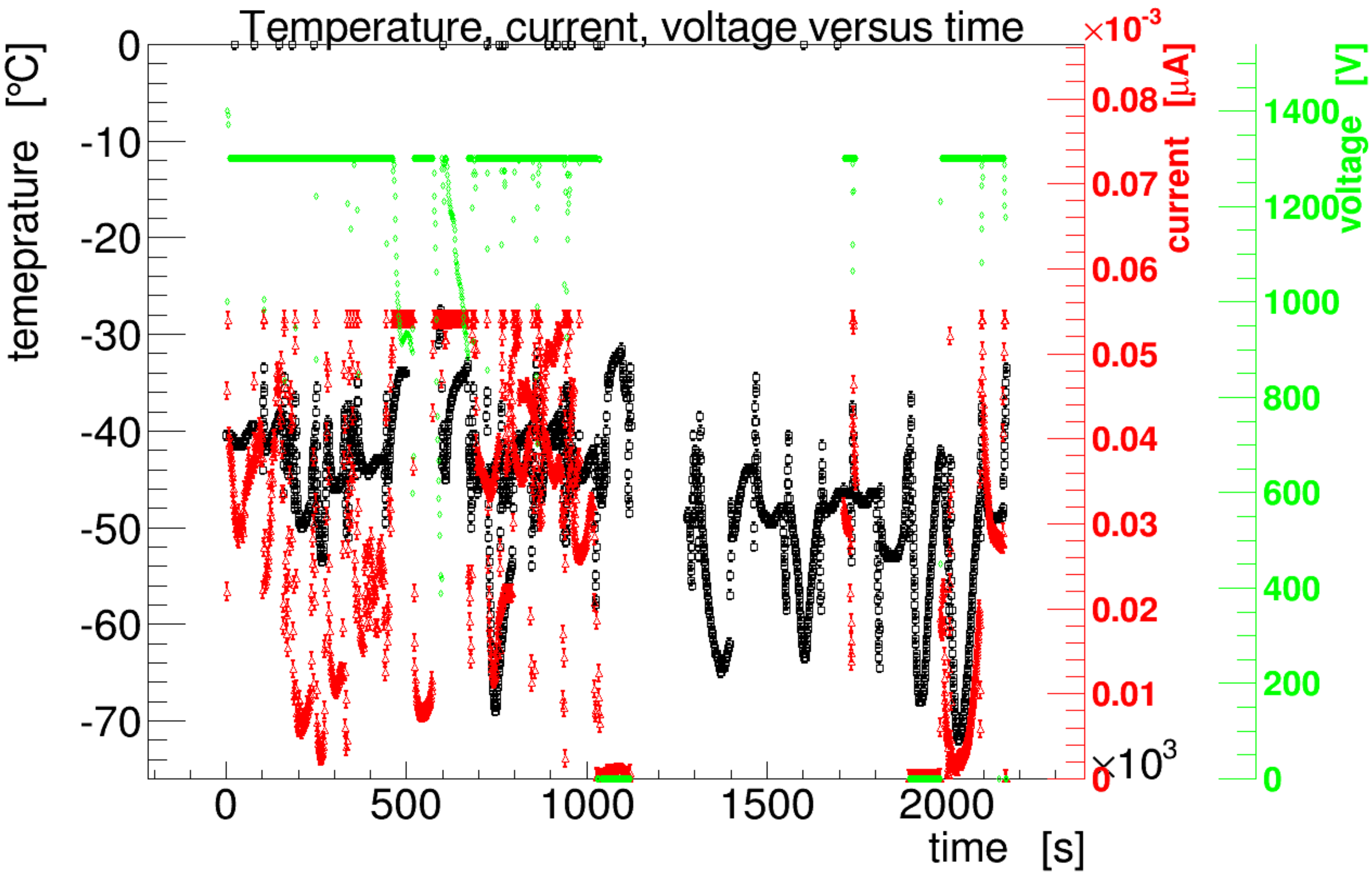
- 2935-8-1-14L: standard, (p,w)=(XXX,XXX), $1*10^{15}$ n_{eq}/cm^2:
  - ~-18 °C, 1000 V: ~124 uA.
    - Broke over night.
- 2935-8-1-13L: standard, (p,w)=(XXX,XXX), $1*10^{15}$ n_{eq}/cm^2:
  - ~-15.5 °C, 1100 V.
    - Broke after 3 stable days.
  - ~-40 °C.
    - Permanent high current (100 uA at 700 V).
- 2935-8-3-4L: standard, (p,w)=(XXX,XXX), $1*10^{15}$ n_{eq}/cm^2:
  - ~-17.5 °C.
    - Immediate breakdown at 1100 V.
  - ~-40 °C.
    - Persistent high current.
- XXXXXXXXX: standard, (p,w)=(XXX,XXX), $5*10^{15}$ n_{eq}/cm^2:
  - ~-40 °C, 1500 V.
    - Low charge collection over 3 days=> decided to increase the voltage.
  - 1600 V.
    - Breakdown, permanent damage.



Spares: results: long term, succesful test, monitoring

- Temperature, current and voltage over time:



- Standard.
- (p,w)=(100,10) um.
- $5*10^{15}$ n_{eq}/cm^2.
- Compliance=54 uA (too safe).

- Voltage decreased during N refilling (~<1 h/day).

Spares: results: long term, succesful test

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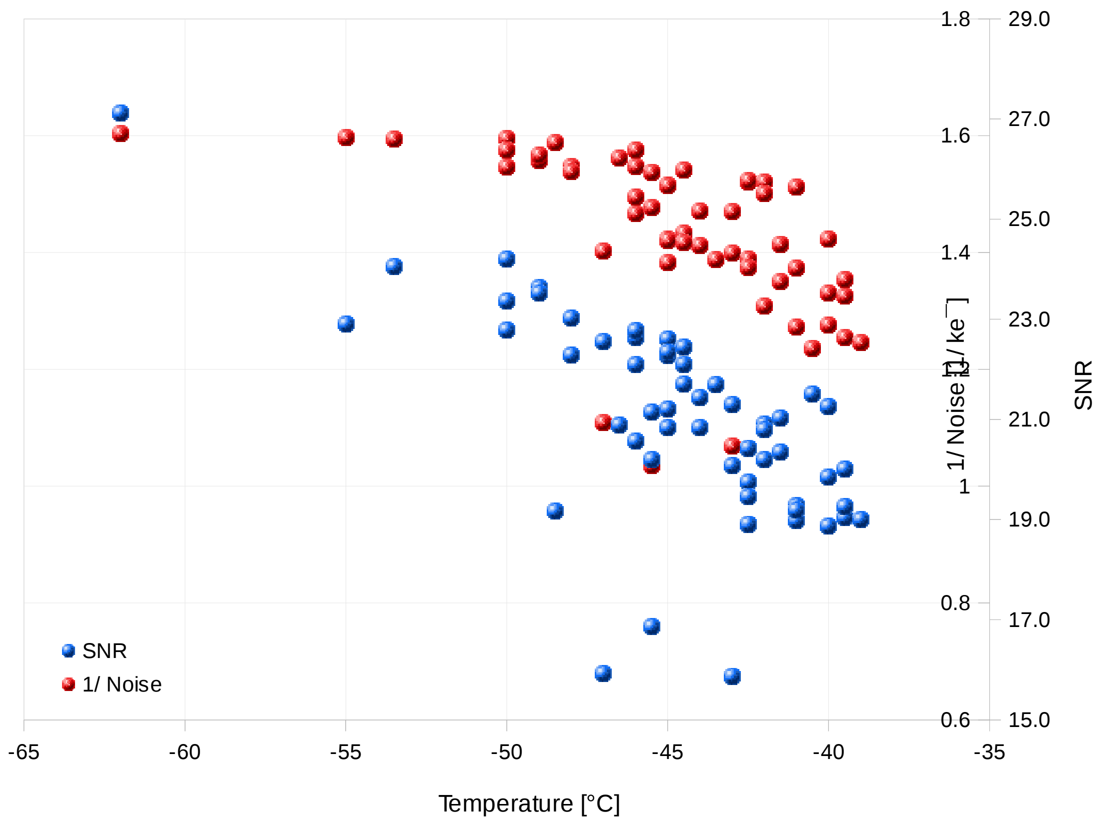
- Various: signal to noise ration versus temperature

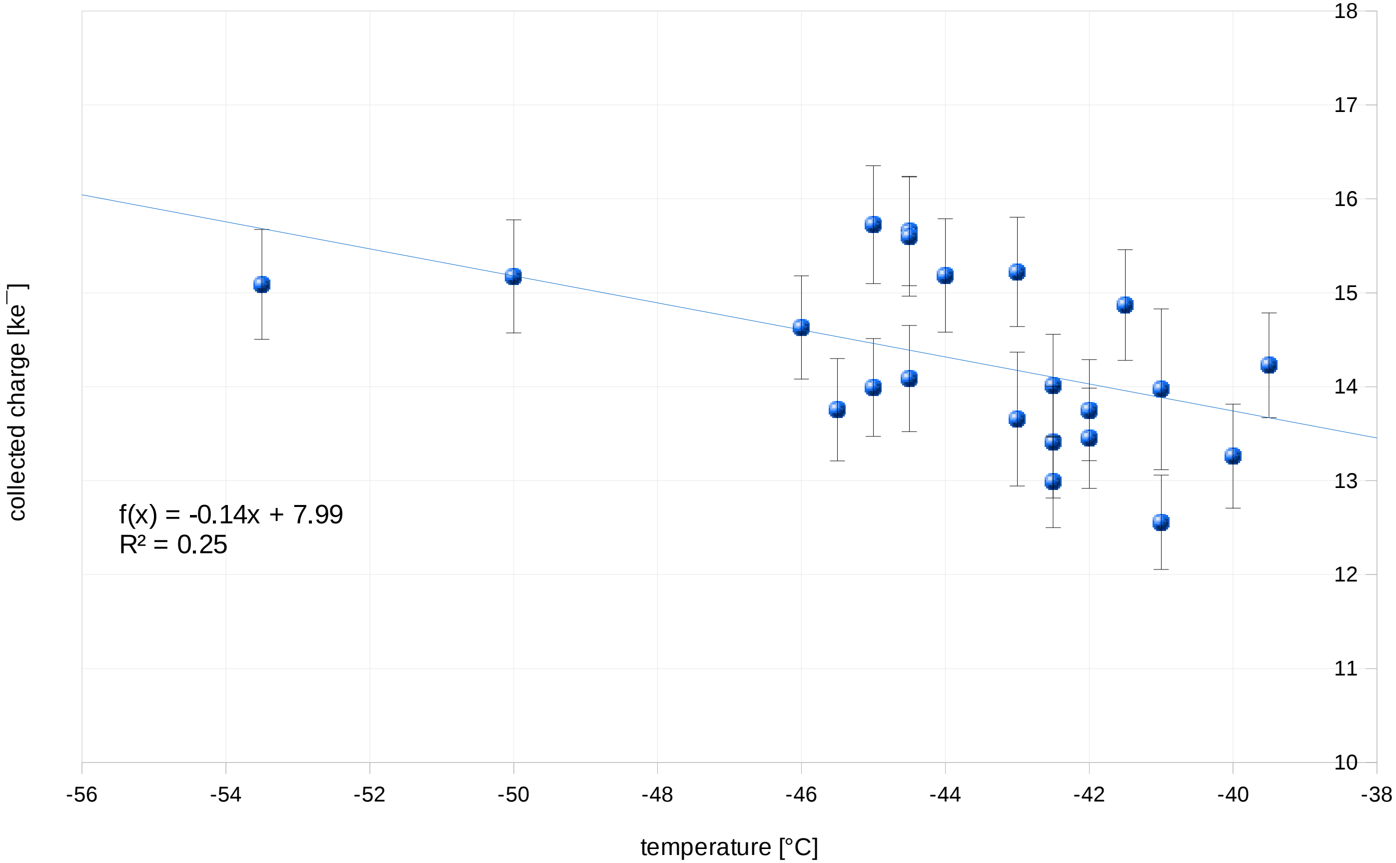


- Standard.
- (p,w)=(100,10) um.
- $5*10^{15}$ n_{eq}/cm^2.

- The signal to noise ratio, scaling as 1/noise, increases for lower temperatures.

Spares: results: various

- Various: charge collection versus temperature during stable (lower) performances



- Standard.
- (p,w)=(100,10) um.
- $5*10^{15}$ n_{eq}/cm^2.

- Compliance=54 uA
- (too safe).

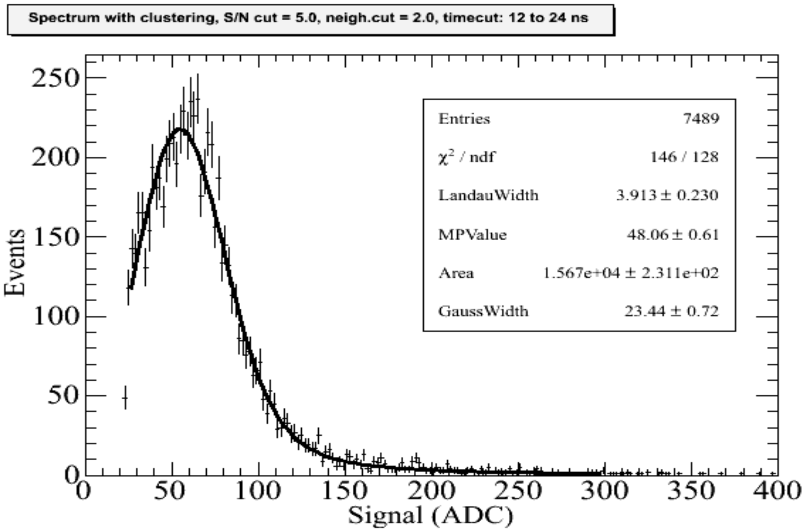
- [100-355] h.

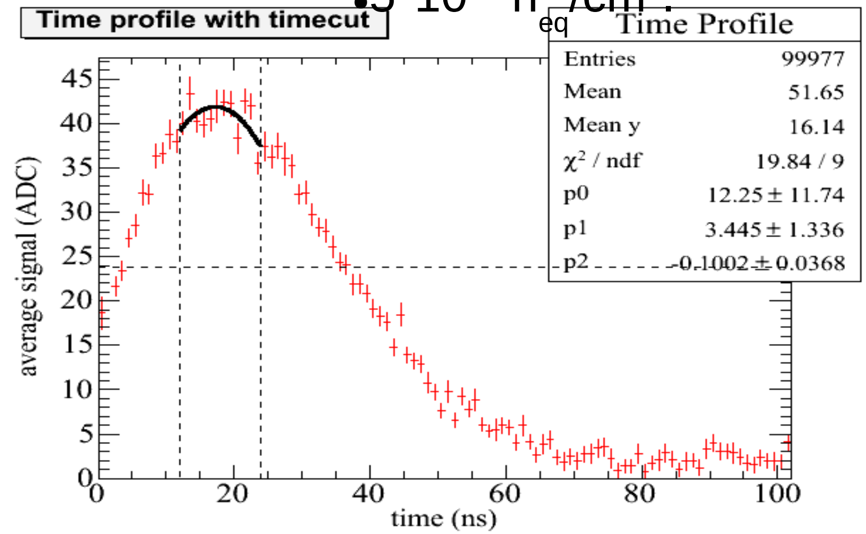
- Lower the temperature, higher the charge collection and the SNR are.
  - Expected higher ionization coefficient.

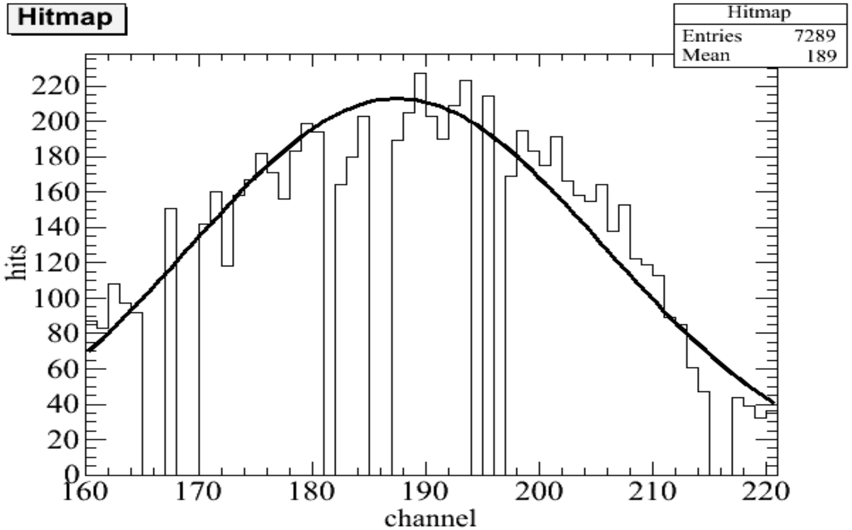
Spares: results: various

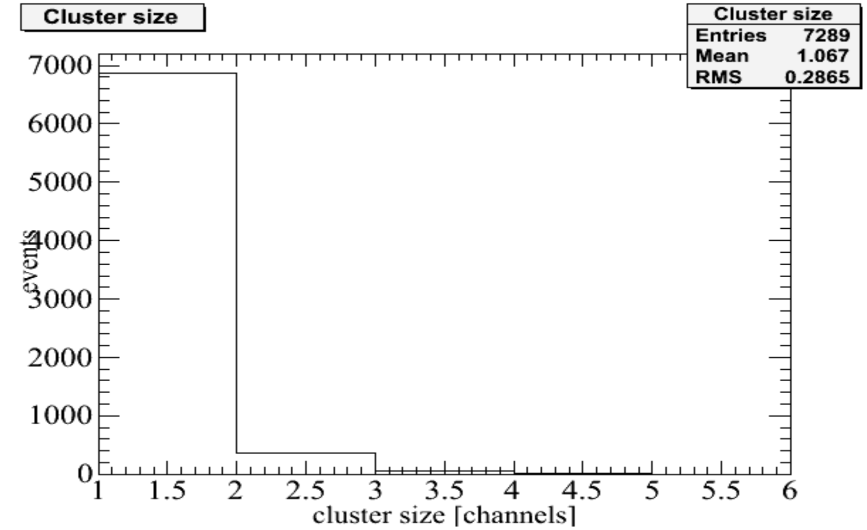
- Various: spectrum 600 V, 0 h

- Standard.
- (p,w)=(100,10) um.
- $5*10^{15}$ n_{eq}/cm^2.









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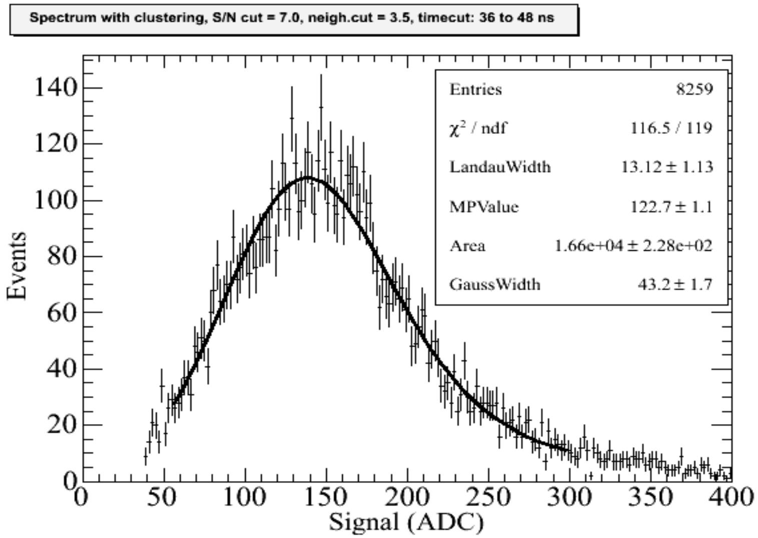
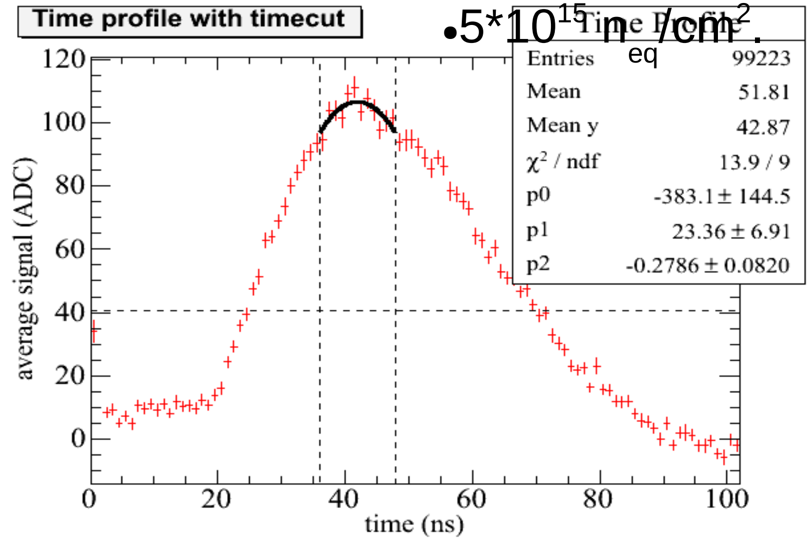
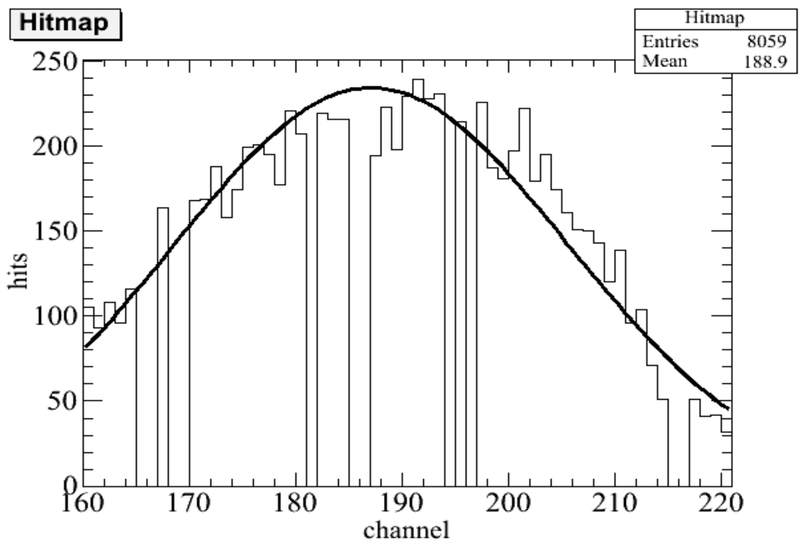
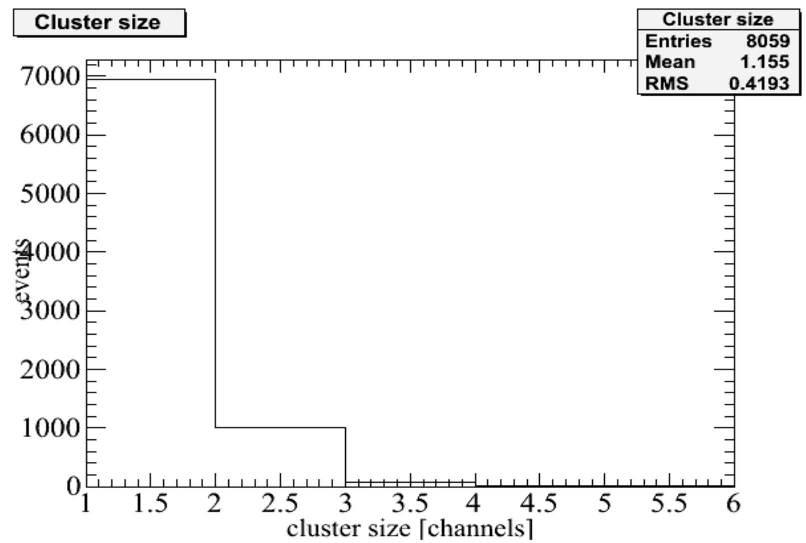
- (p,w)=(100,10) um.
- $5*10^{15}$ n_{eq} $/cm^2$.

- Various: spectrum 1300 V, 0 h









Spares: results: various

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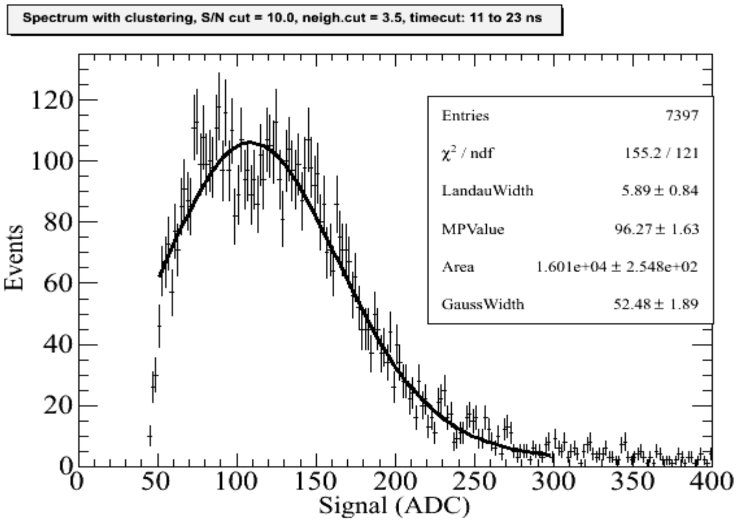
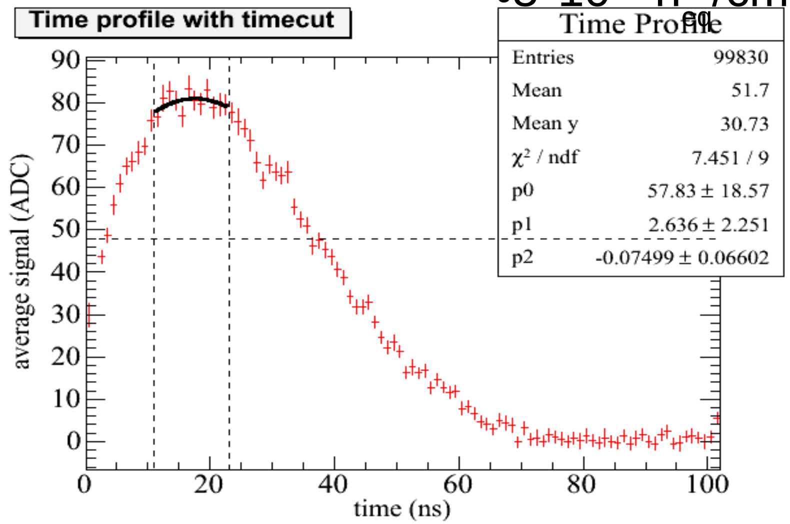
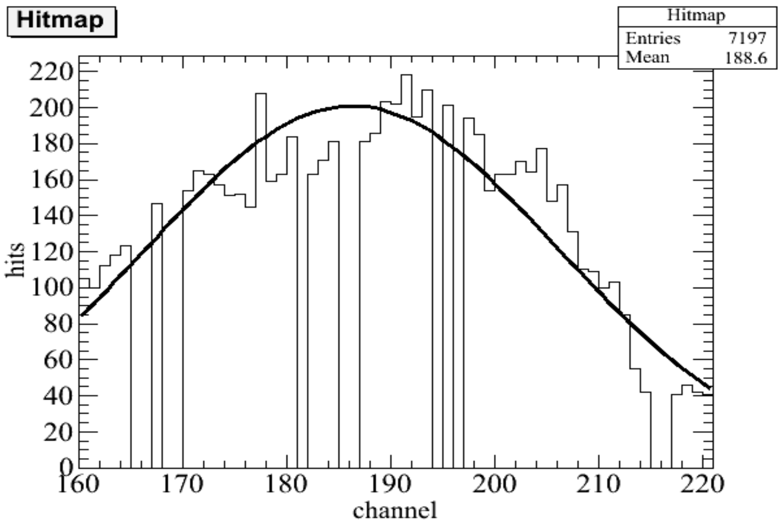
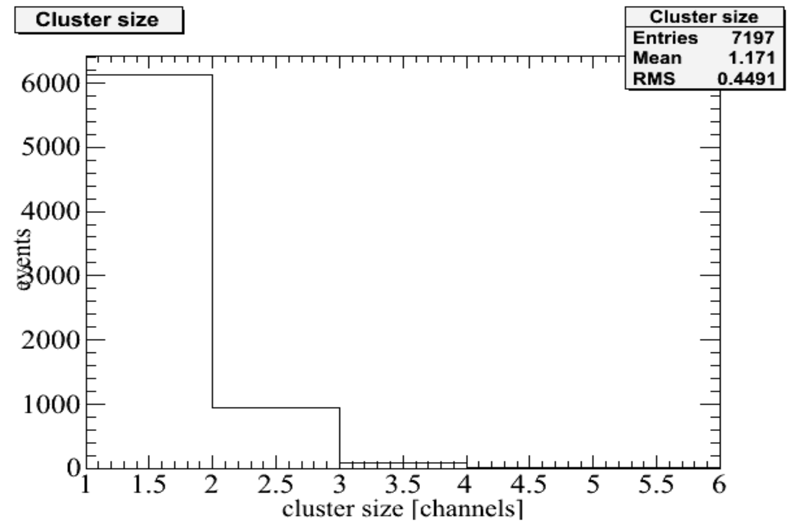
- Various: spectrum 1300 V, 354 h (after drop)

- Standard.
- (p,w)=(100,10) um.
- $5*10^{15}\ n_{eq}/cm^2$.









Spares: results: various

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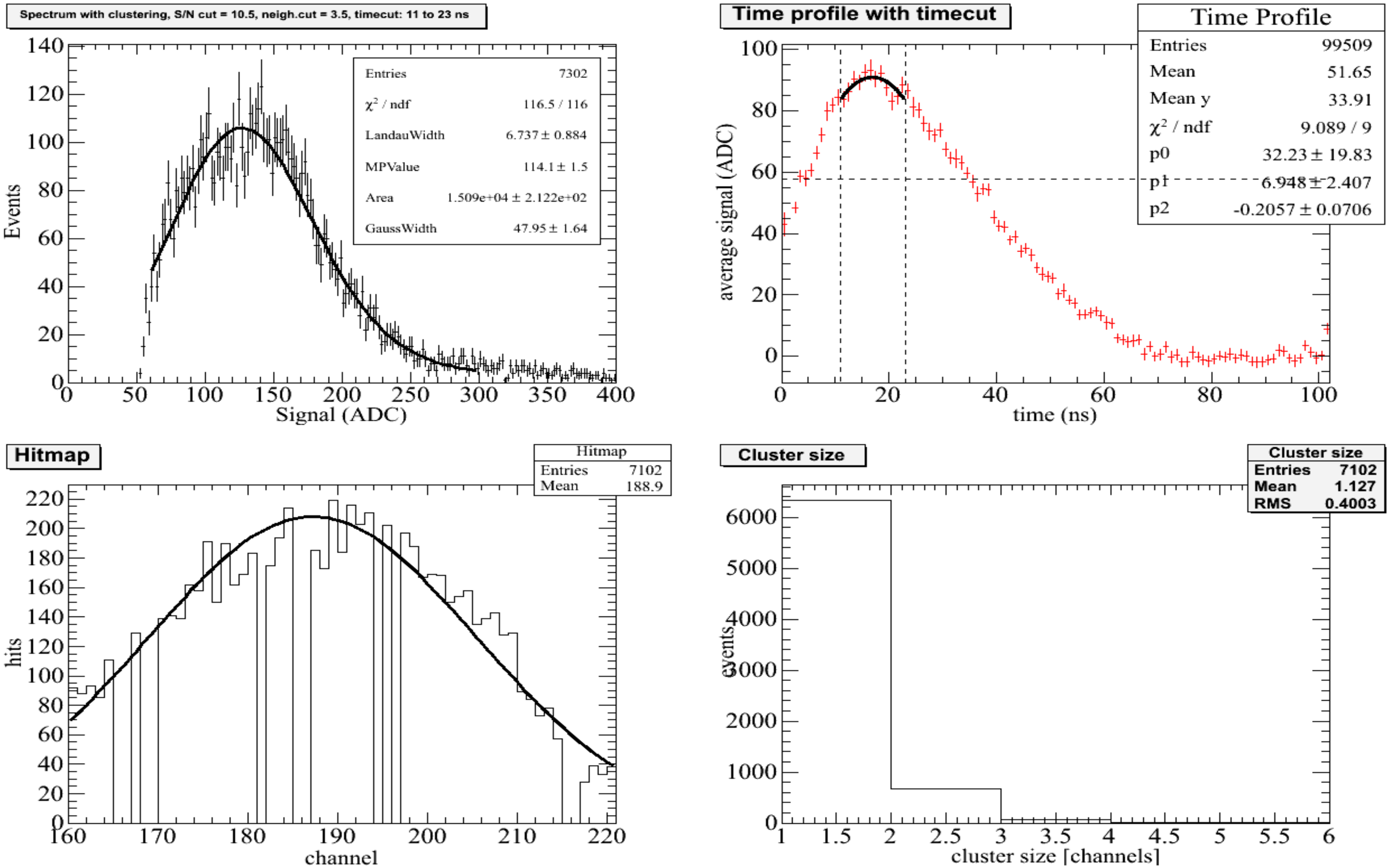
- Various: spectrum 1300 V, 385 h (after 1 day rest)



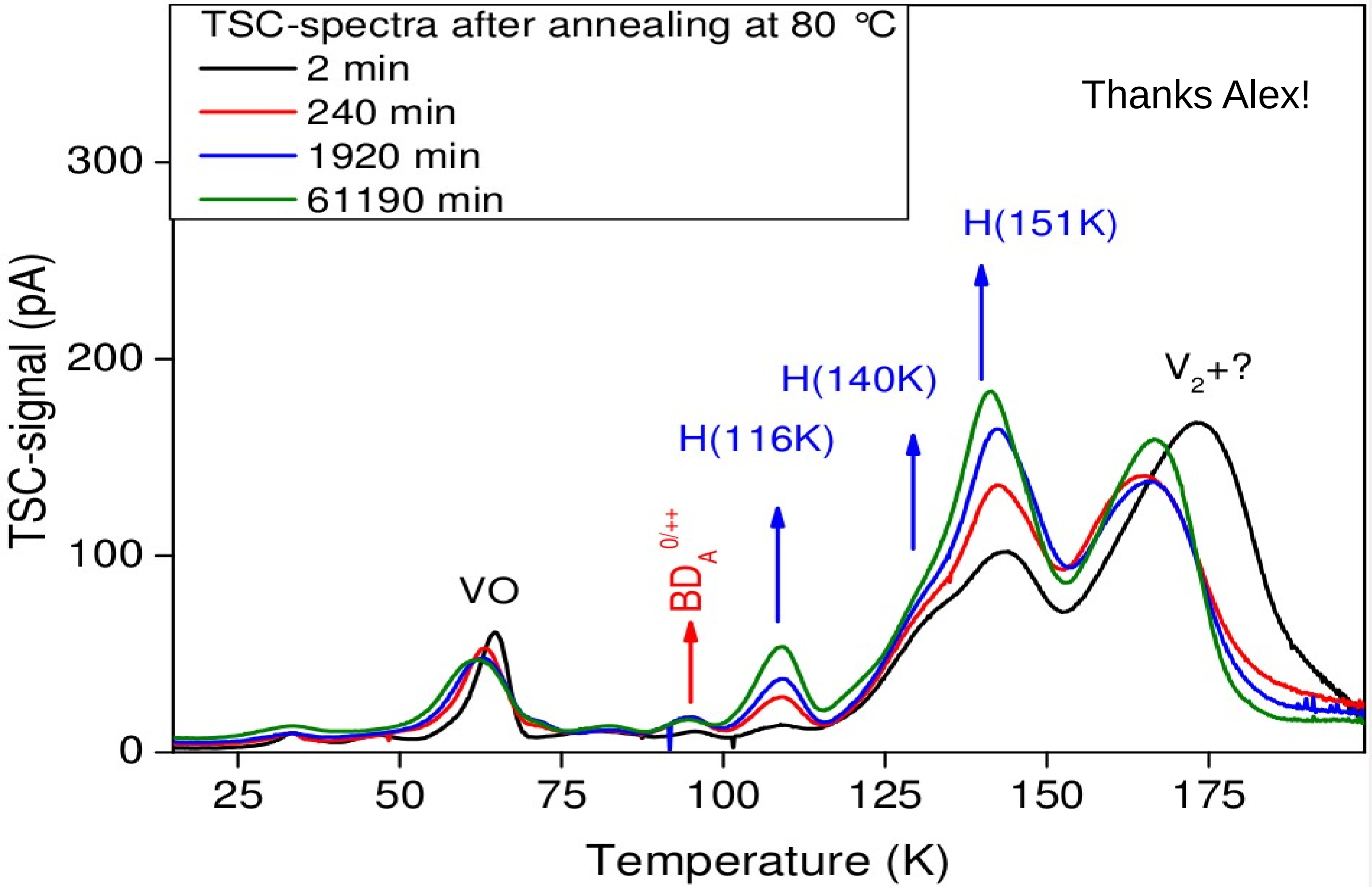
.0) um.
^{2}.

Spares: summary and outlook

- Summary:
  - Charge multiplication is observed by “single-shot” measurements, but a possible exploit need stability.
  - Results show:
    - Several sensor broken after significant time (several days): stress is long term related.
    - Drop after few days: long term change of sensor properties (electric field distribution): annealing (seem to be not the case) or polarization change.
    - Recover after resting day: polarization change seem more probable.
    - Current drift over time: further confirmation of long term properties change.
    - Charge collection strongly dependent on temperature: further studies, descriptions, are required.
- Outlook:
  - Long term measurements:
    - Confirmation by more samples.
    - Resting at higher temperature: after charge drop, 1 day of rest at 0 °C, then restart: is the heating helping in recovering the collection?
    - Different fluences: how the long term behaviour is dependent on the amount of defects?
    - Different structures: same measurements on as-grown samples showing CM before irradiation by special geometries (LGAD, etc...).
  - Other studies:
    - Charge multiplication versus temperature.
    - Annealing electric-field driven at low temperatures (e.g. by capacitance measurements).

Spares: discussion

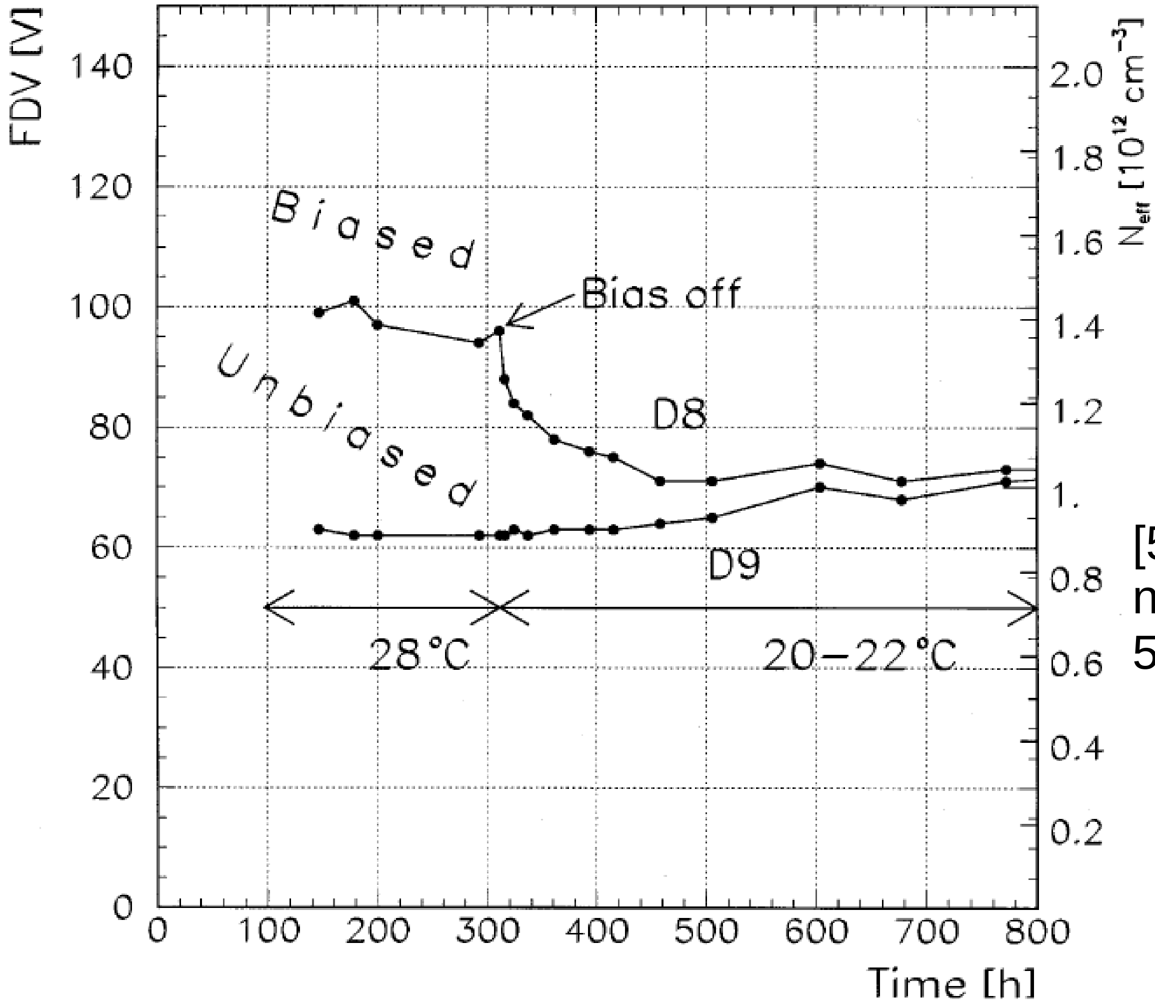
- Deep defects [7]:



[7] A. Junkes, private communication.

Spares: discussion

•Annealing with electric field[5]:



[5]
n-type
$5*10^{13}$ n_{eq}/cm^2

[5] Cindro et al., NIMA 498, 1998; Mikuz et al., NIMA 466, 2001.