Beam test of thin epitaxial silicon strip sensors for the CMS phase II pixel upgrade

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on behalf of the CMS Tracker Collaboration

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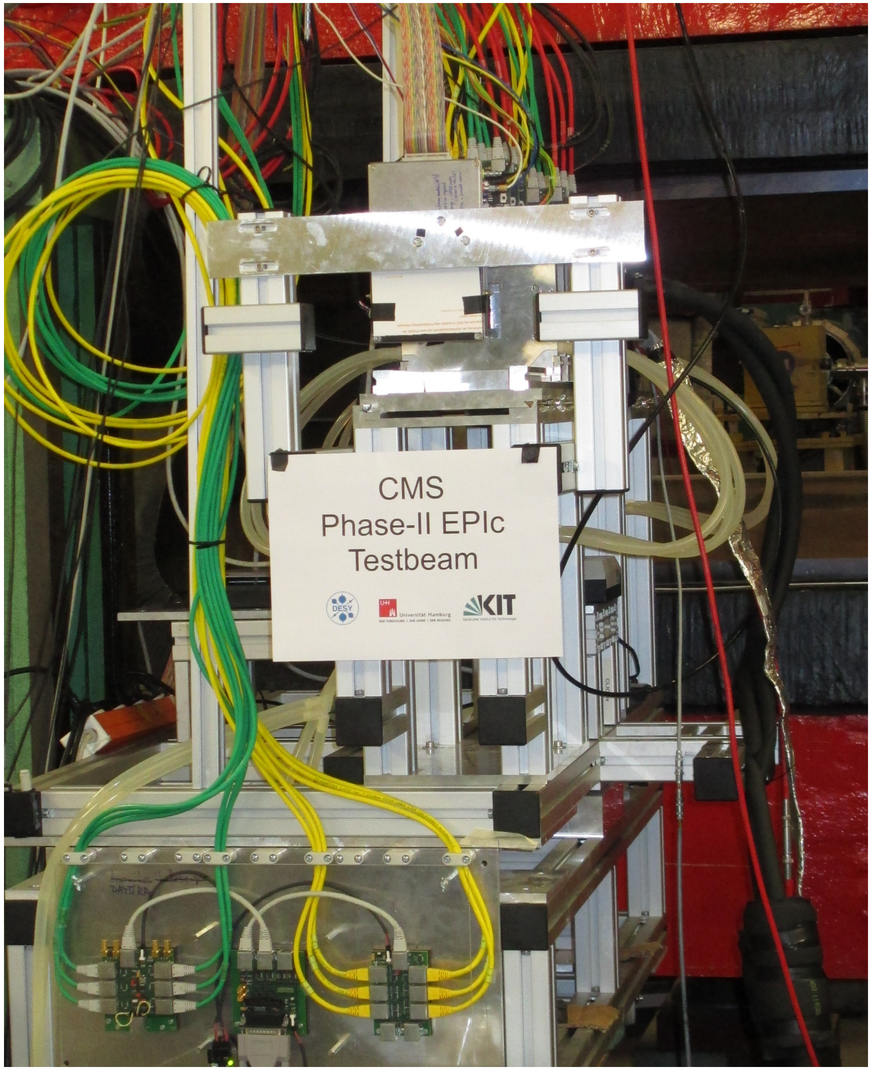
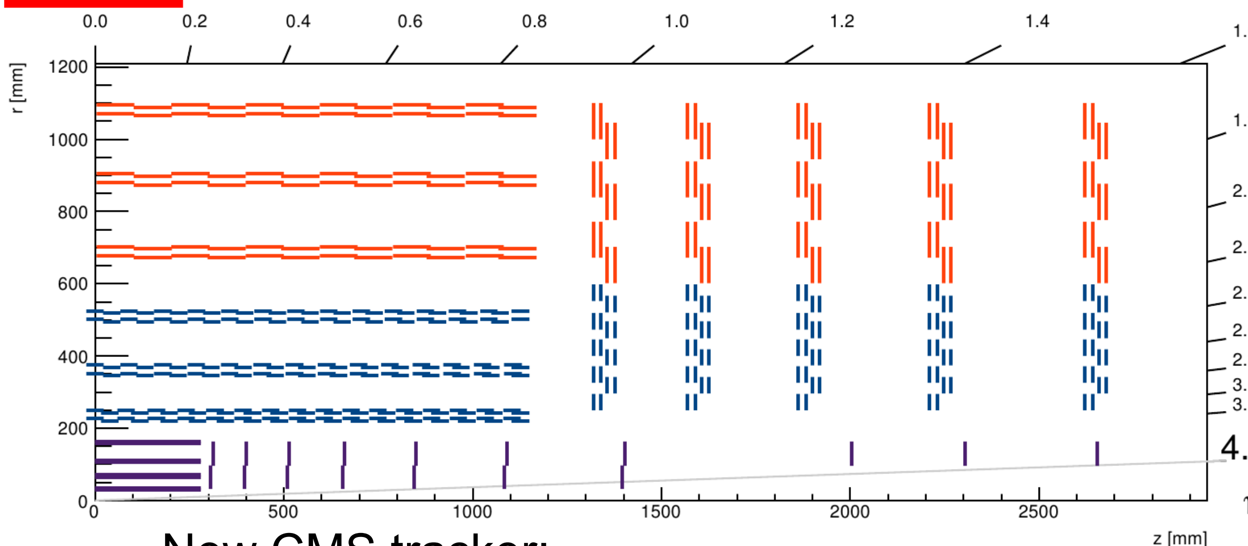
Content

- Motivation
- Test beam setup
- Analysis cuts and definitions
- Charge collection
- Noise
- Conclusions

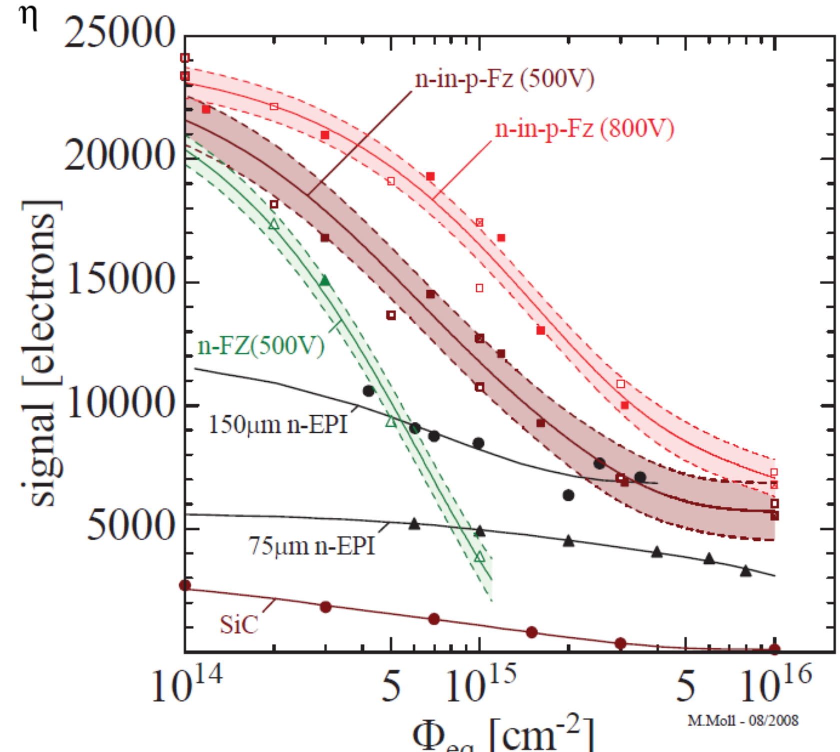


Motivation



2023: High Luminosity-LHC
- Luminosity of 5 x 10^{34} $cm^{-2}s^{-1}$
- Φ_{eq}~10^{16} cm^{-2} for the innermost layers of the pixel detector after 3000 fb^{-1}
- New material / design is required, is planar silicon a viable option?

New CMS tracker:
- **Momentum** information to L1 **trigger**
- 2S, PS and pixel modules



Thin sensors:
- Smaller signal degradation than thicker ones
- Small signal even before irradiation
  - → challenge for the readout electronics, low thresholds are required
  - → RD 53 collaboration for pixel ROC for the HL-LHC

→ **characterization with MIP-like signals required**

Test beam of thin epitaxial strip sensors to determine material characteristics

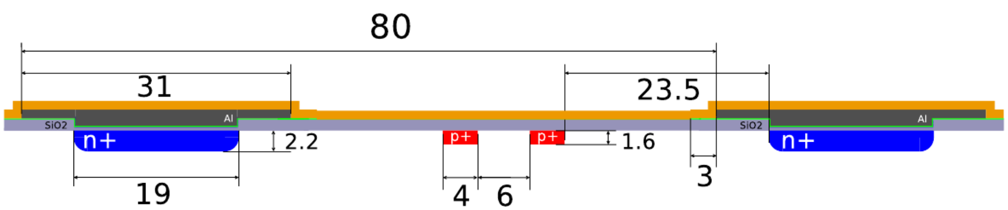
The EPIc test beam I

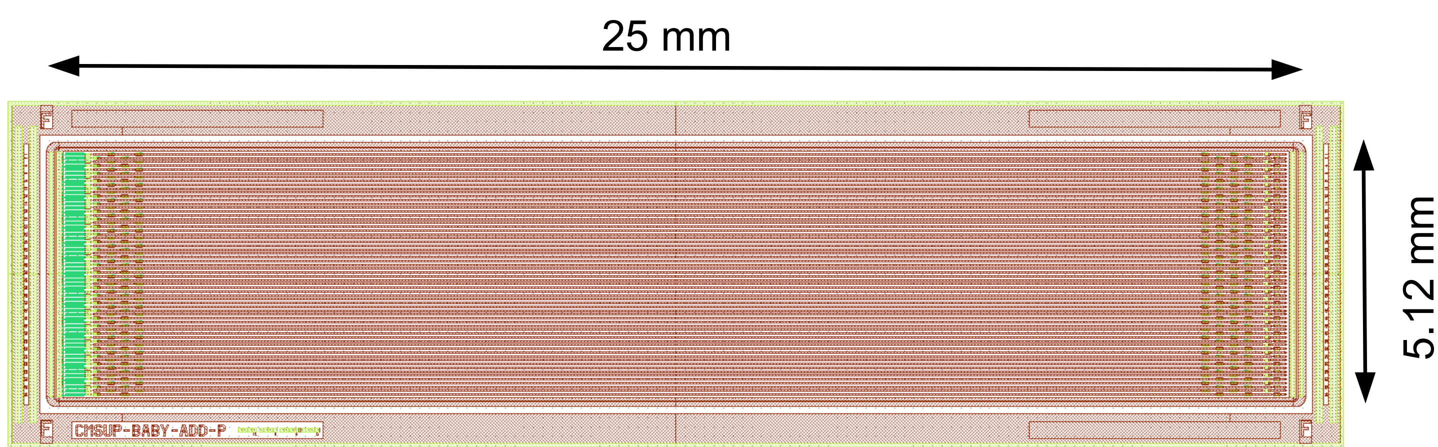
Sensors:
- Epitaxial silicon strips of n and p type (p-spray and p-stop isolation)
  - Baby additional from HPK campaign
- 100 µm thickness
- 80 µm pitch
- Irradiation with 800 MeV and 23 GeV protons
- Fluences up to 1.3 x 10^{16} n_{eq} cm^{-2}
- A few other sensors with 200 µm thickness

Strips detectors:
- Irradiation of sensor without readout electronics
- Higher noise → hit reconstruction using beam telescope

Fake rejection

Unbiased charge collection measurement
(no threshold involved)

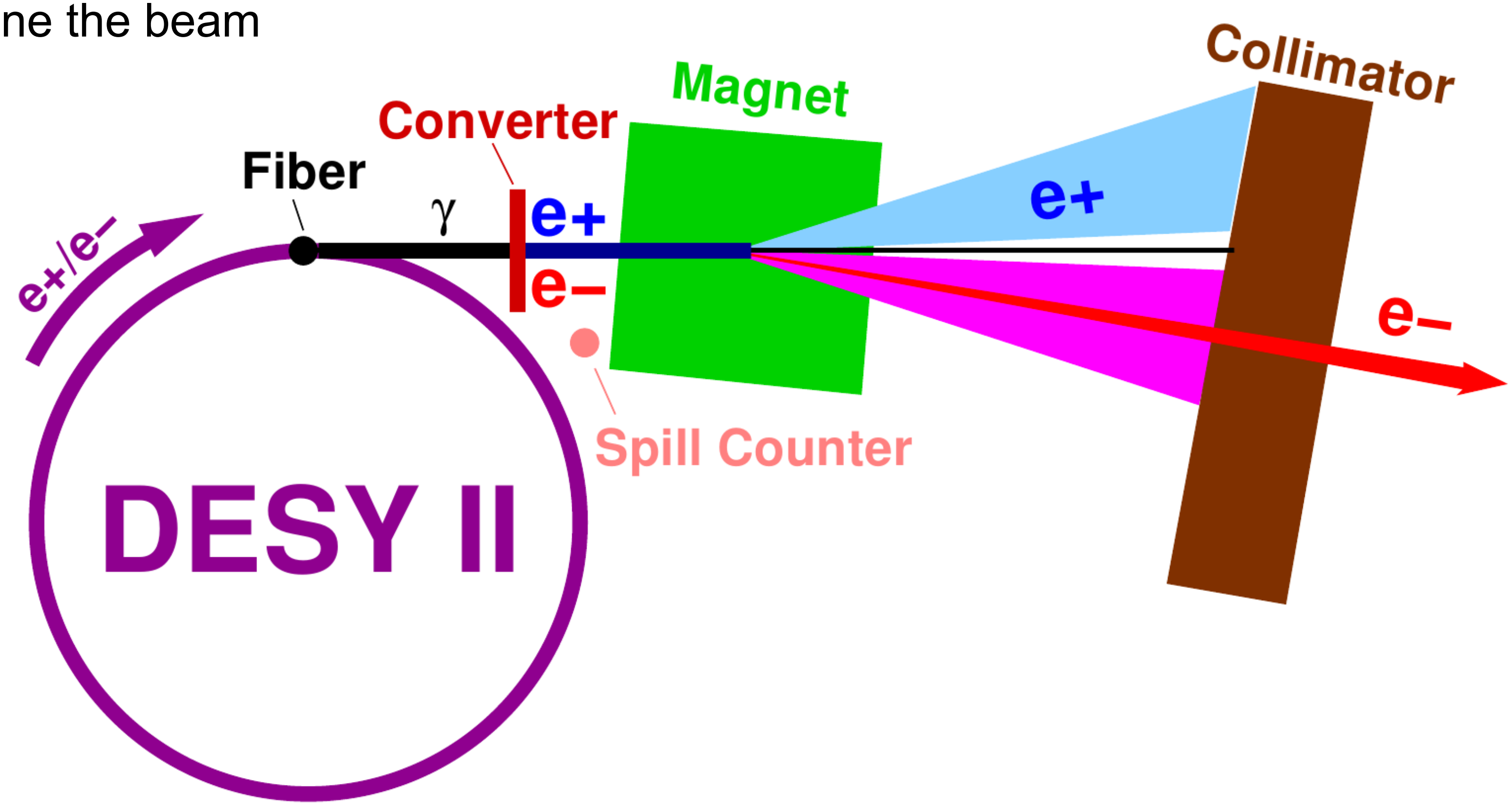




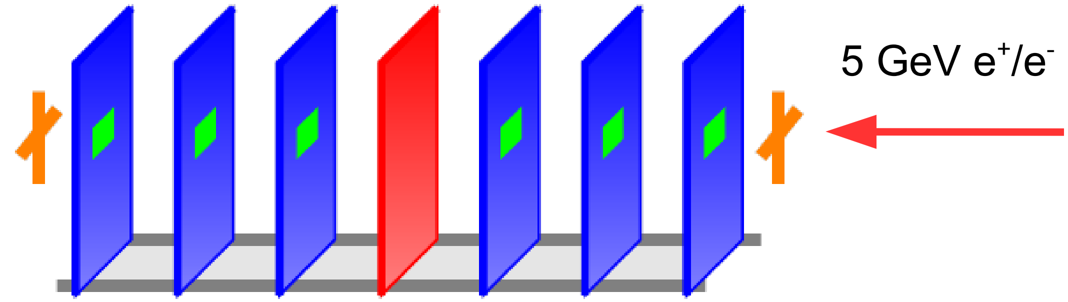
64 AC coupled strips

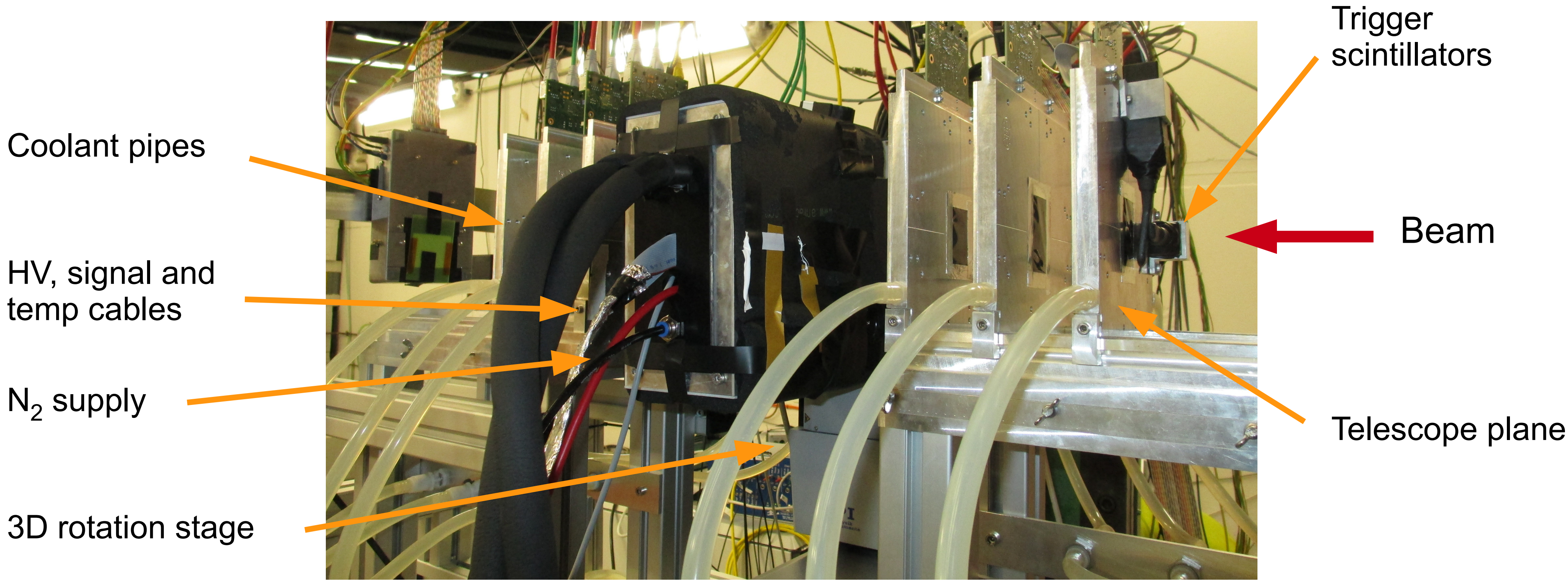
The EPIc test beam II

Beam generation at DESY test beam:
- Bremsstrahlung on C fiber
- Conversion in e^+e^- on a metal target
- Momentum selection using a magnet
- Collimator to define the beam



- Beam telescope to reconstruct tracks
  - DATURA and ACONITE
  - AIDA pixel telescopes
- Trigger scintillators to define events
- Cooling for irradiated samples down to -27 C
- Moving stage for different incidence angles
- Minimize material in the beam

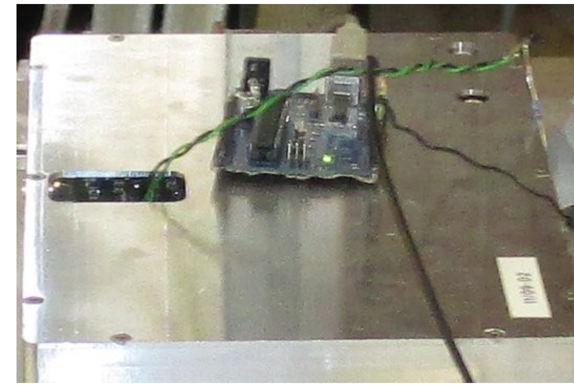




Setup II

Readout system:
- AliBaVa (A Liverpool Barcelona Valencia) readout system: mother + daughter boards
- Readout of positive and negative signals
- Based on LHCb strip readout chip
- Triggered readout
- Analog pulse height for 2 x 128 channels
- Maximum event rate ~150 Hz

Mother board



Daughter board

Signal cable connector

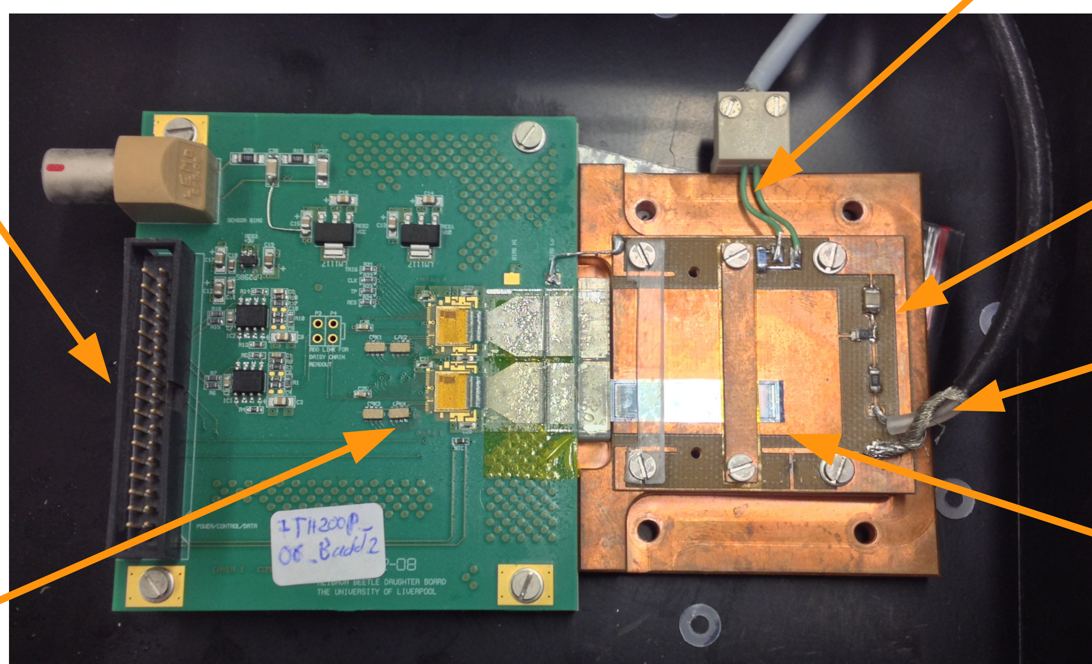
Pt100 temp read-out

Bias filter

Bias voltage

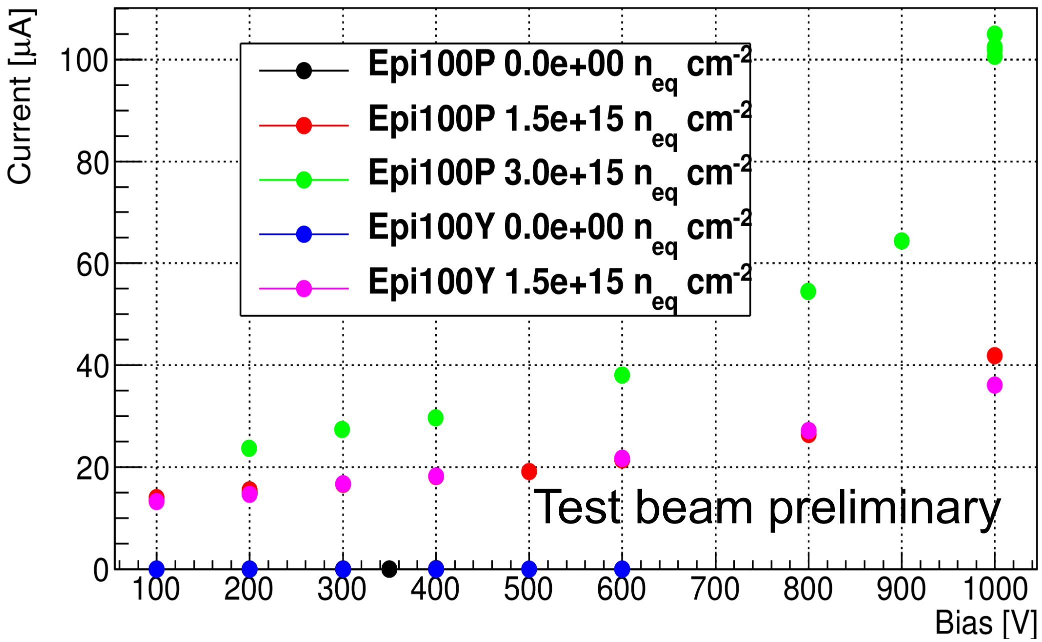
Strip sensor

Beetle readout chip



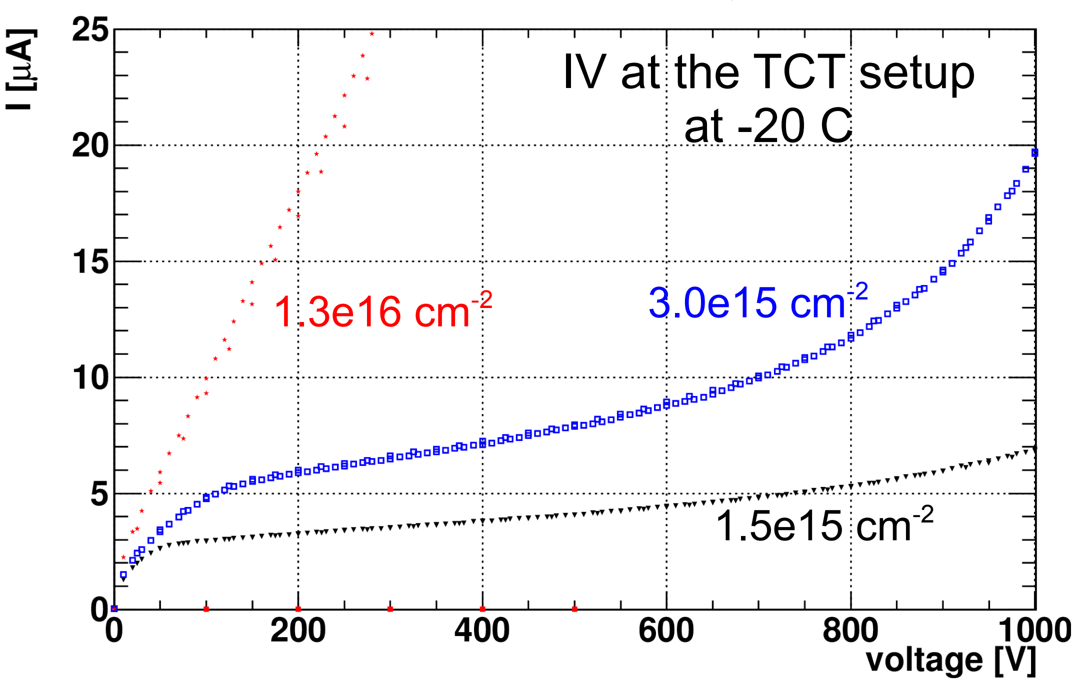
IV characteristic

IV of the sensors at the TB, scaled to -20 C

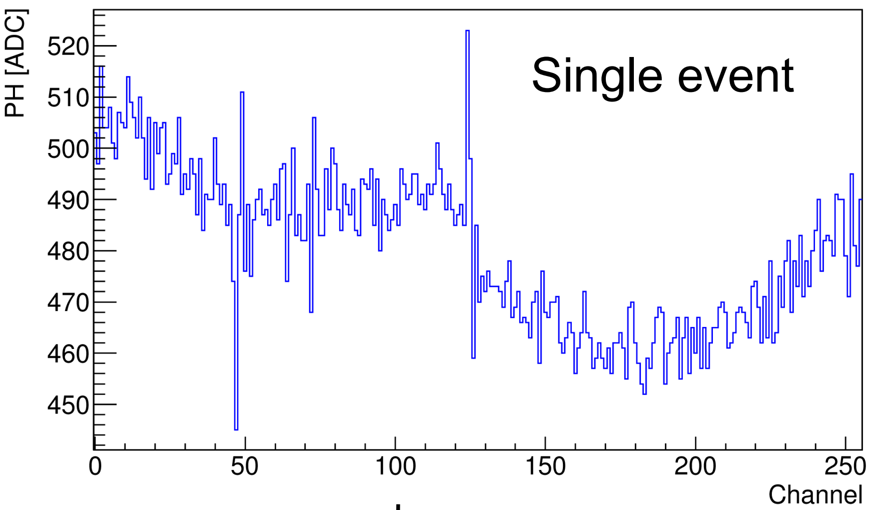


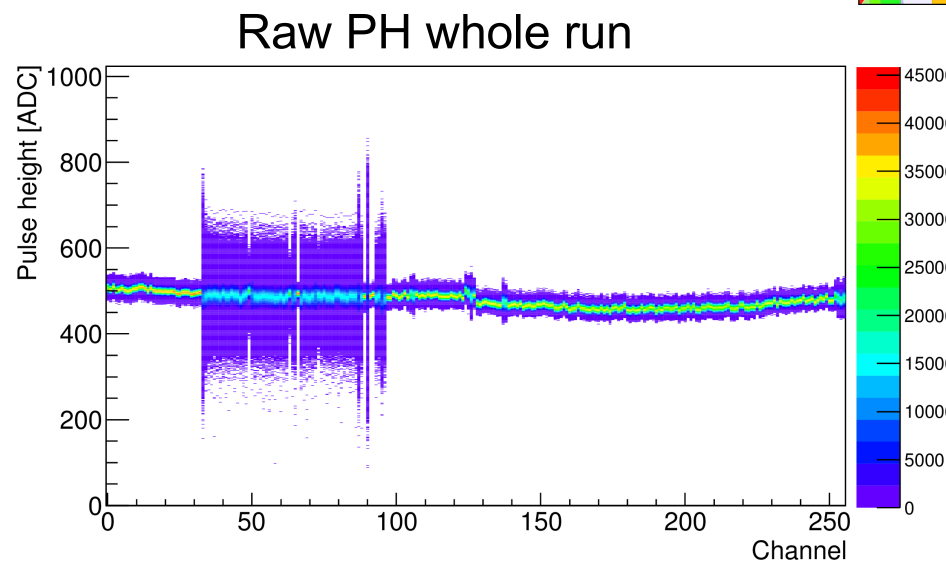
IV of both diodes and strips show a "soft breakdown"

P-bulk diodes with p spray insulation

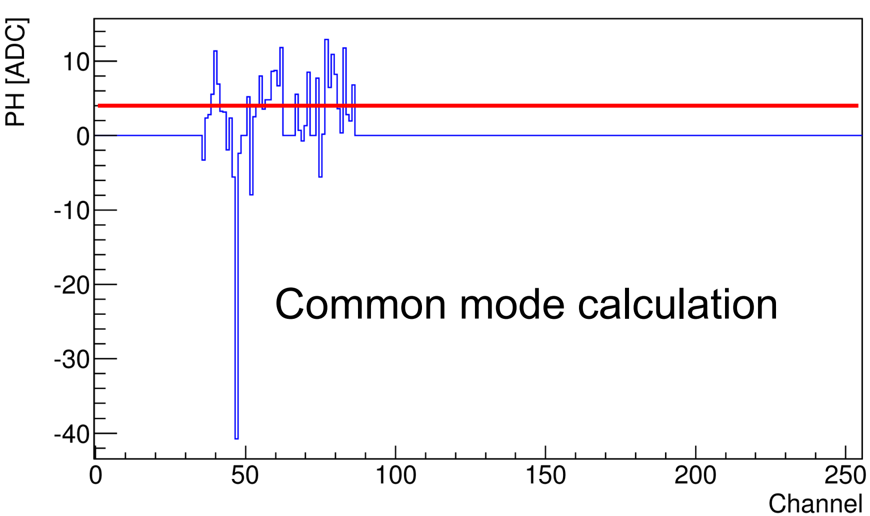


Signal definition

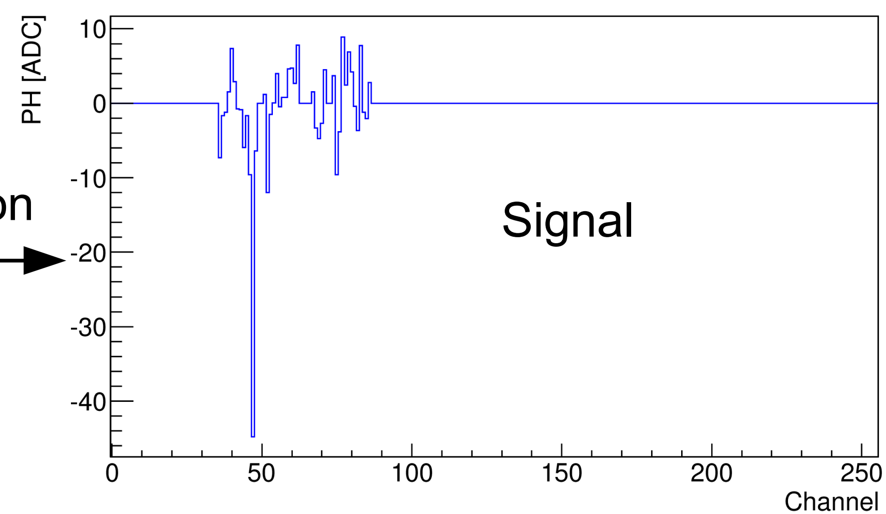




Pedestal subtraction
Channel selection

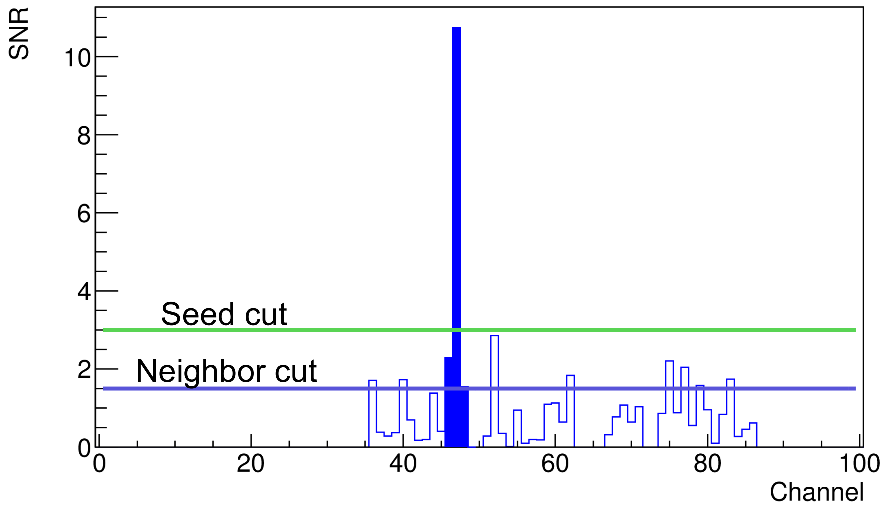


CM
subtraction



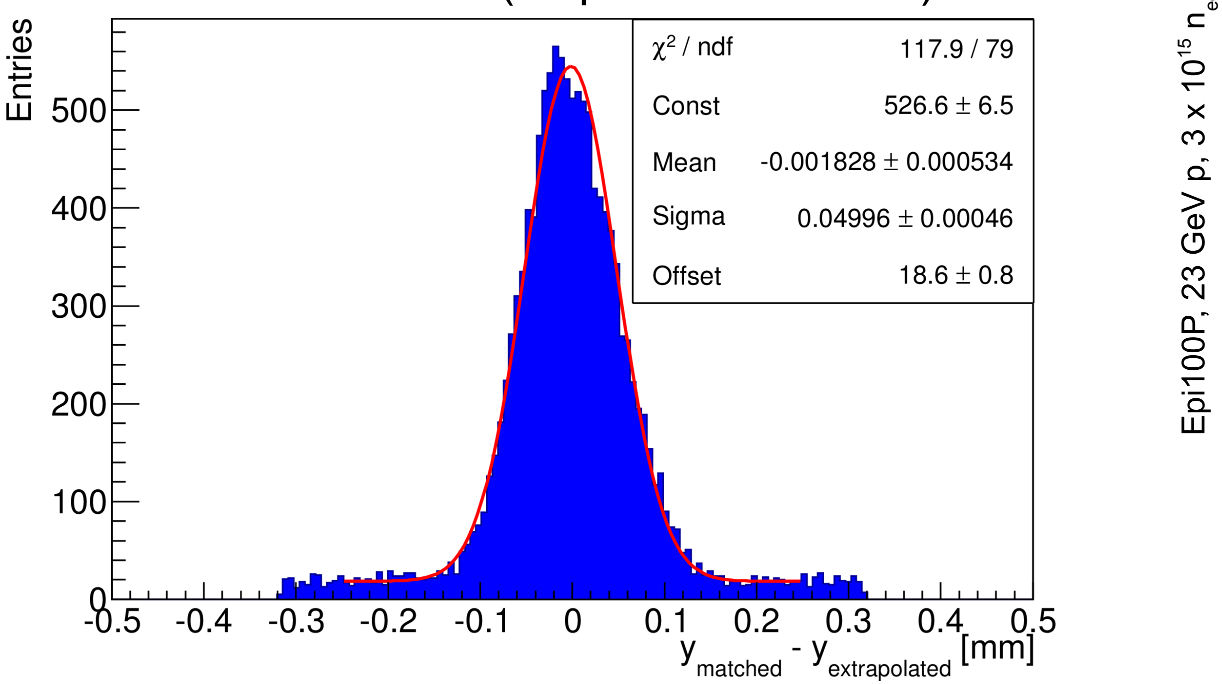
Epi100P, 23 GeV p, 3 x 10^{15} n_{eq} cm^{-2}, -800V, -20 C

Alignment



- **Track based alignment** (alignment and track reco in the telescope SW)
- Clustering using SNR and seed/neighbor threshold (5 and 2.5)
- Hit position on the strip sensor using CoG algorithm

Residuals Y (strips in X direction)



- Alignment only with translations (till now)
- **$\sigma_{res\ Y}$ ~ half of the strip pitch**
  - To be improved
  - Sufficient for charge collection analysis

Only results from normal incidence are presented

Hit selection

Problem:
- Telescope integration time: ~ 150 µs
- ALiBaVa integration time: 25 ns

} Many tracks on the telescope, (most probably) one on the strip sensor

Strategy:
The track with the highest charge deposit is the one that passed the strip at the right time
→ Geometry cuts to evaluate all the tracks in one event

Charge definition:
Sum of the signal over 5 strips, centered on the hit one

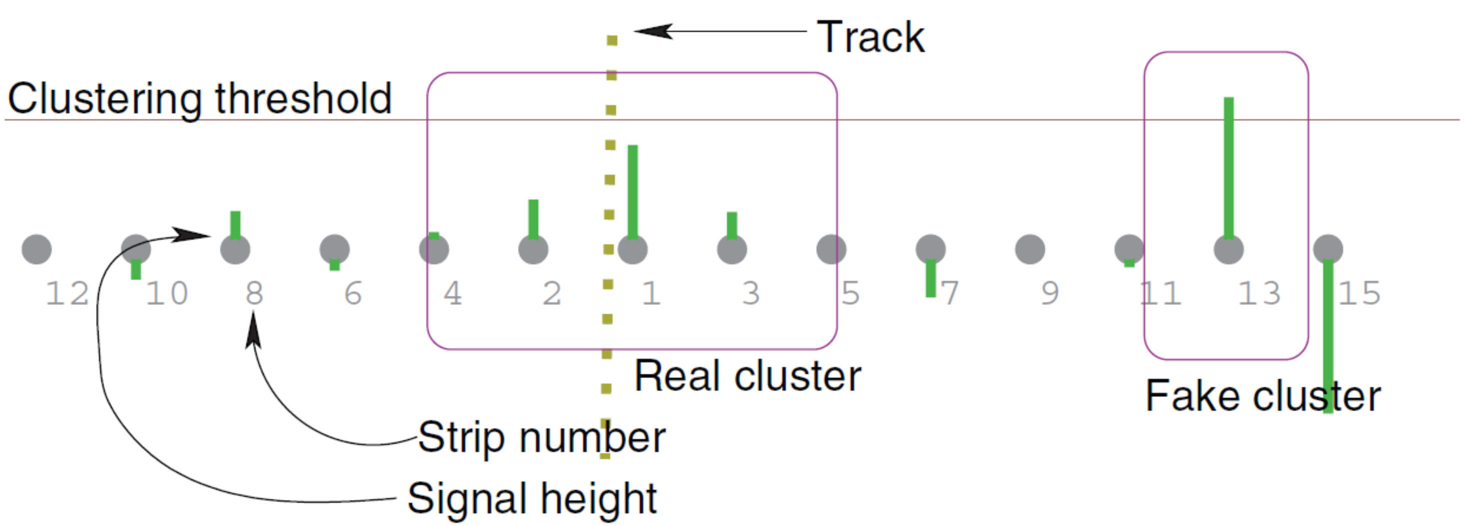
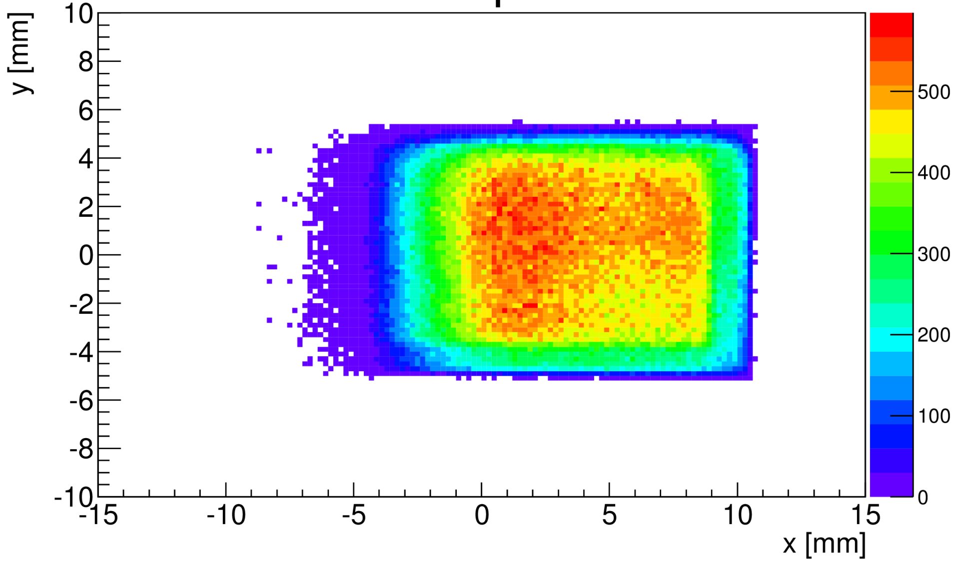


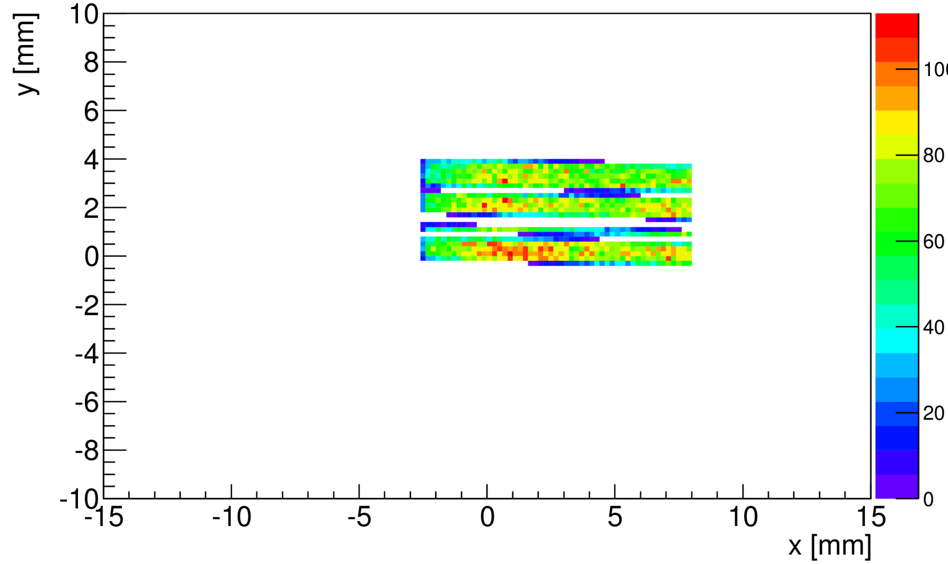
Fig. from T. Mäenpää et al, *Track-induced Clustering in Position Sensitive Detector Characterization* IEEE 2009

Geometry cuts

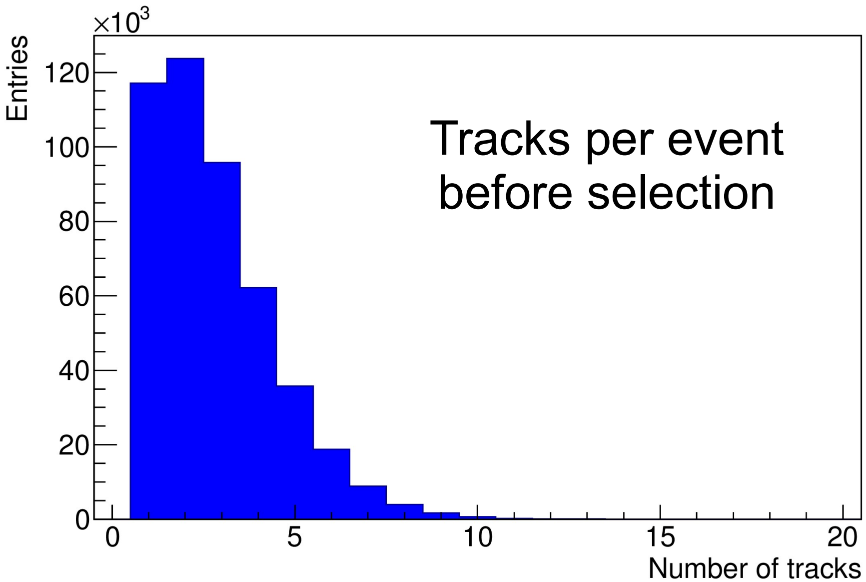
Beam spot

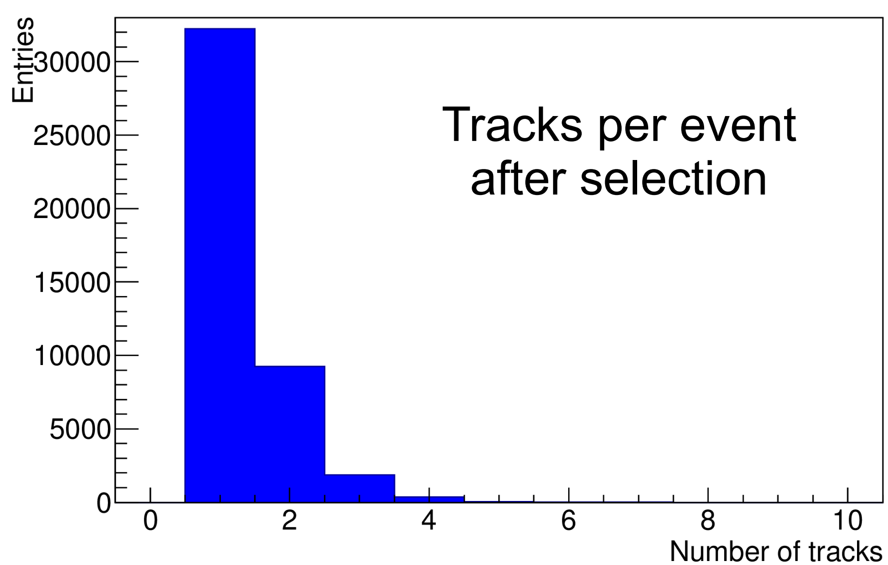


Selection



- Y cut: all the tracks of the event must pass through a bonded channel
- X cut: better volume definition

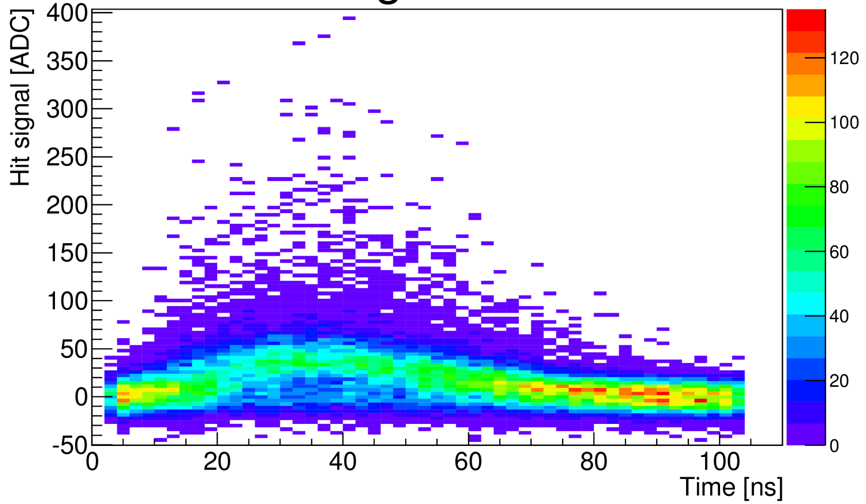




Epi100P, 23 GeV p, 3 x 10^{15} n_{eq} cm^{-2}, -800V, -20 C

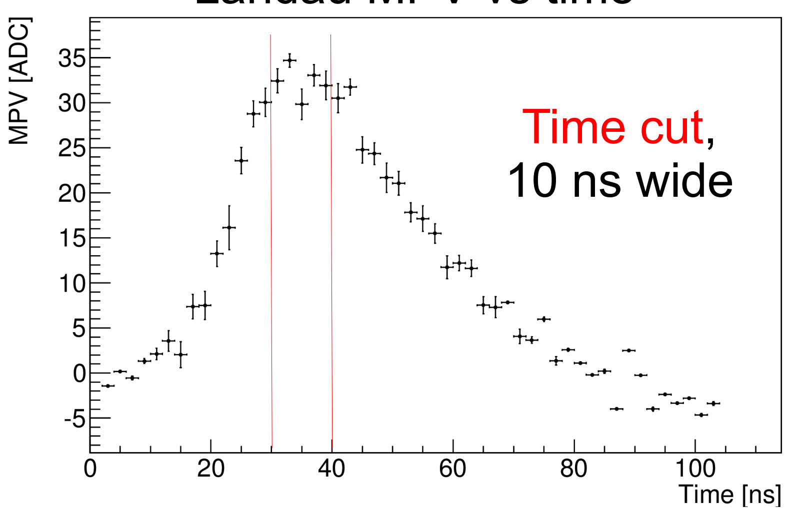
Time cut

Hit charge vs time



Landau-Gaussian convolution fit of each time slice

Landau MPV vs time



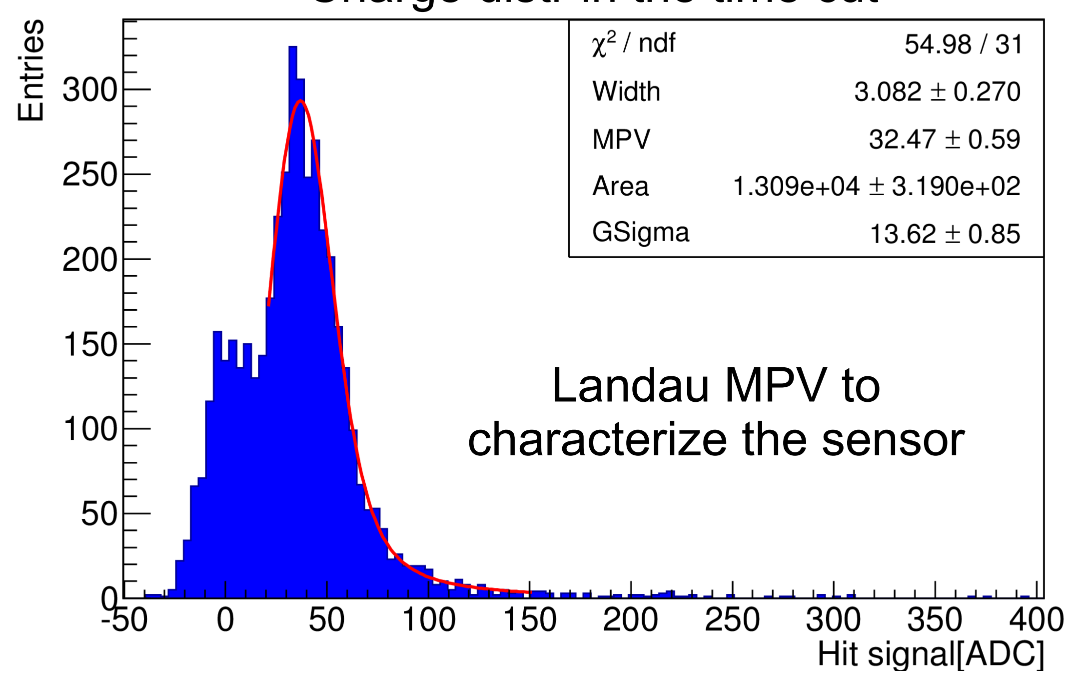
Time → phase between trigger and chip clock

Analog part of the chip → asynchronous
Sampling and buffering → clocked

PH depends on the sampling time

A selection in time is needed

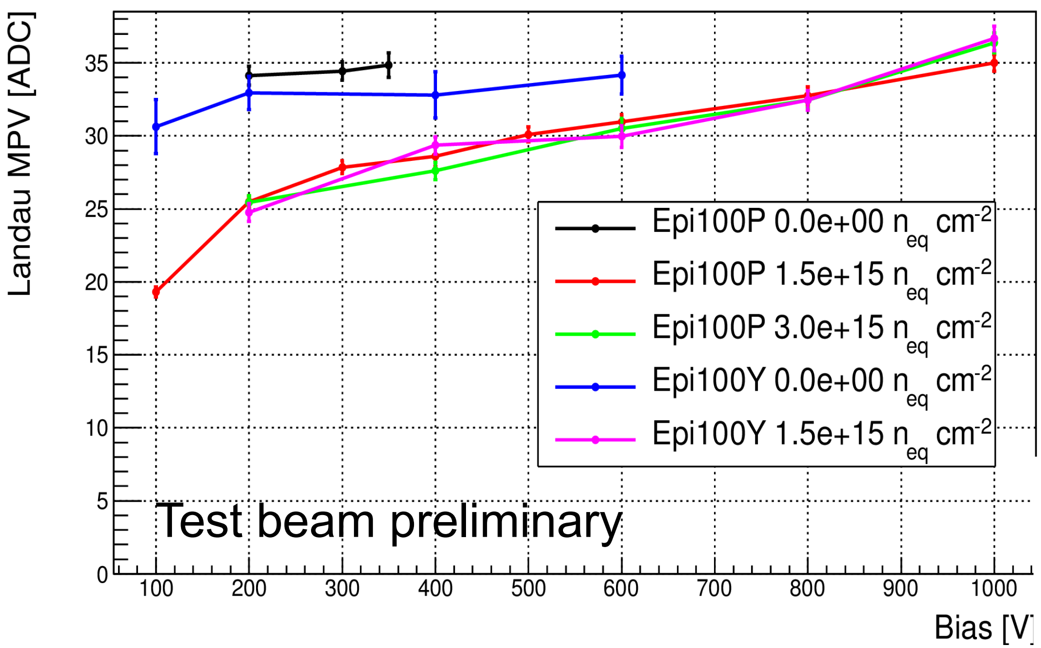
Charge distr in the time cut



Epi100P, 23 GeV p, 3 x 10^{15} n_{eq} cm^{-2}, -800V, -20 C

Charge collection

Fitted Landau MPV in the time cut



Note:

- Irradiated samples at -20 C (chip at ~ 9 C)
- Non-irradiated at 20 C (chip at ~ 24 C)

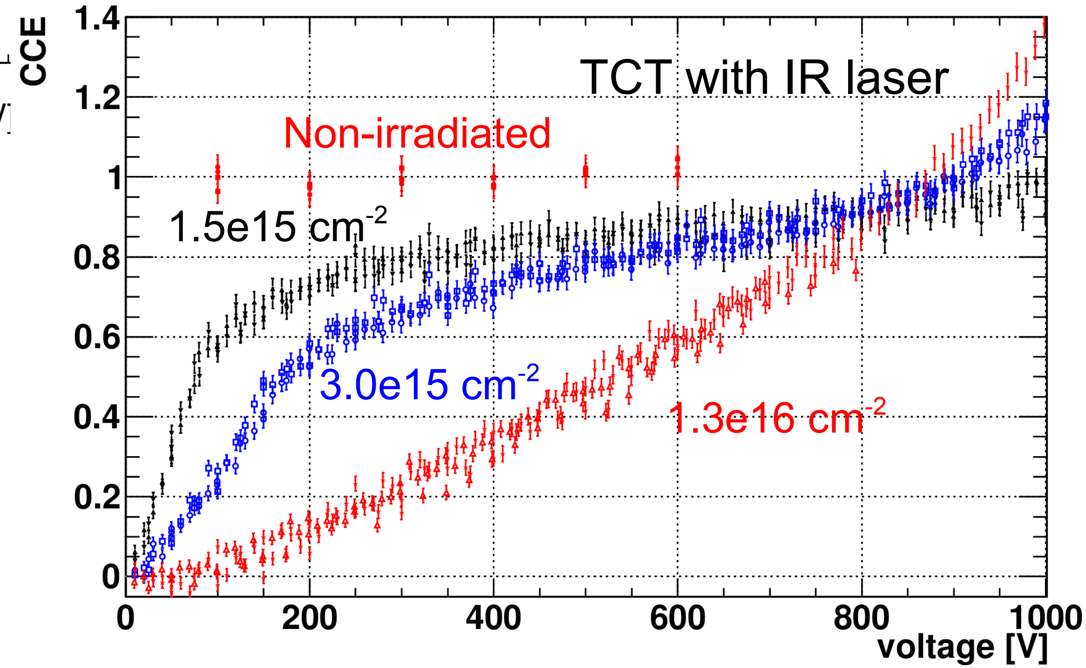
Test beam data are in agreement with TCT measurements of diodes

Both show charge multiplication

P-bulk strips:

- **Collected charge back to pre-irradiation levels at high bias**

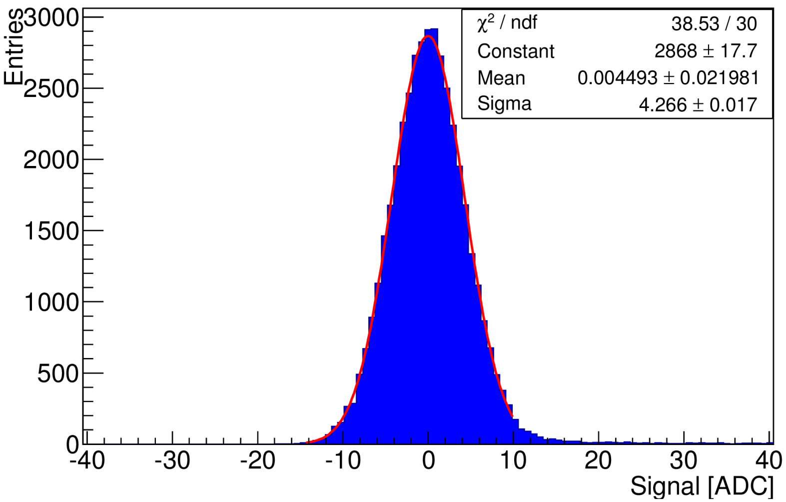
P-bulk diodes with p spray insulation

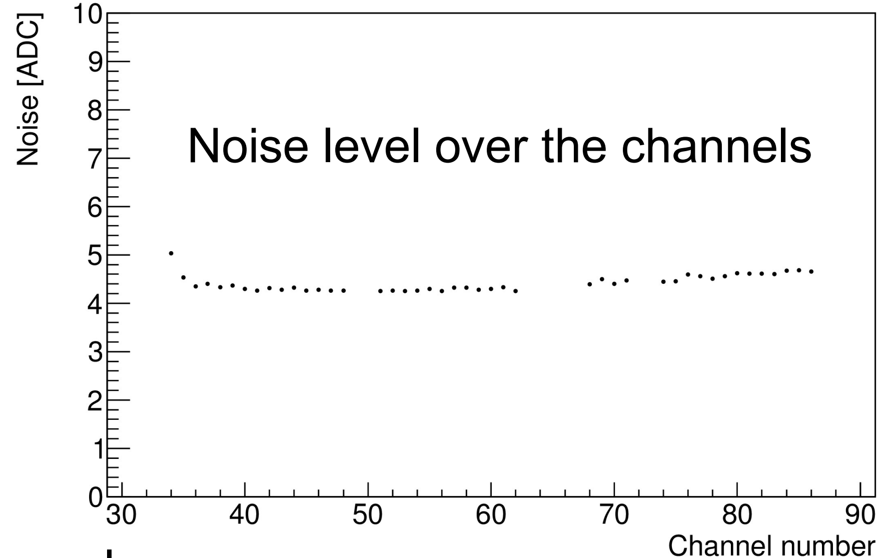


Noise

Signal not associated to a track

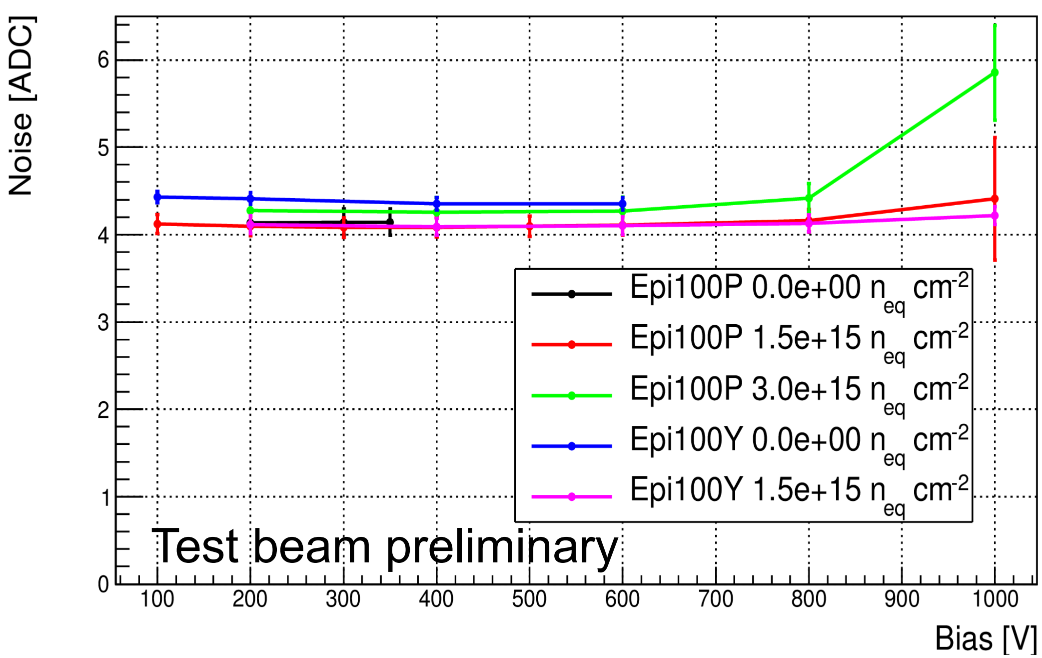
Noise distr for one channel





Epi100P, 23 GeV p, 3 x 10^{15} n_{eq} cm^{-2}, -800V, -20 C

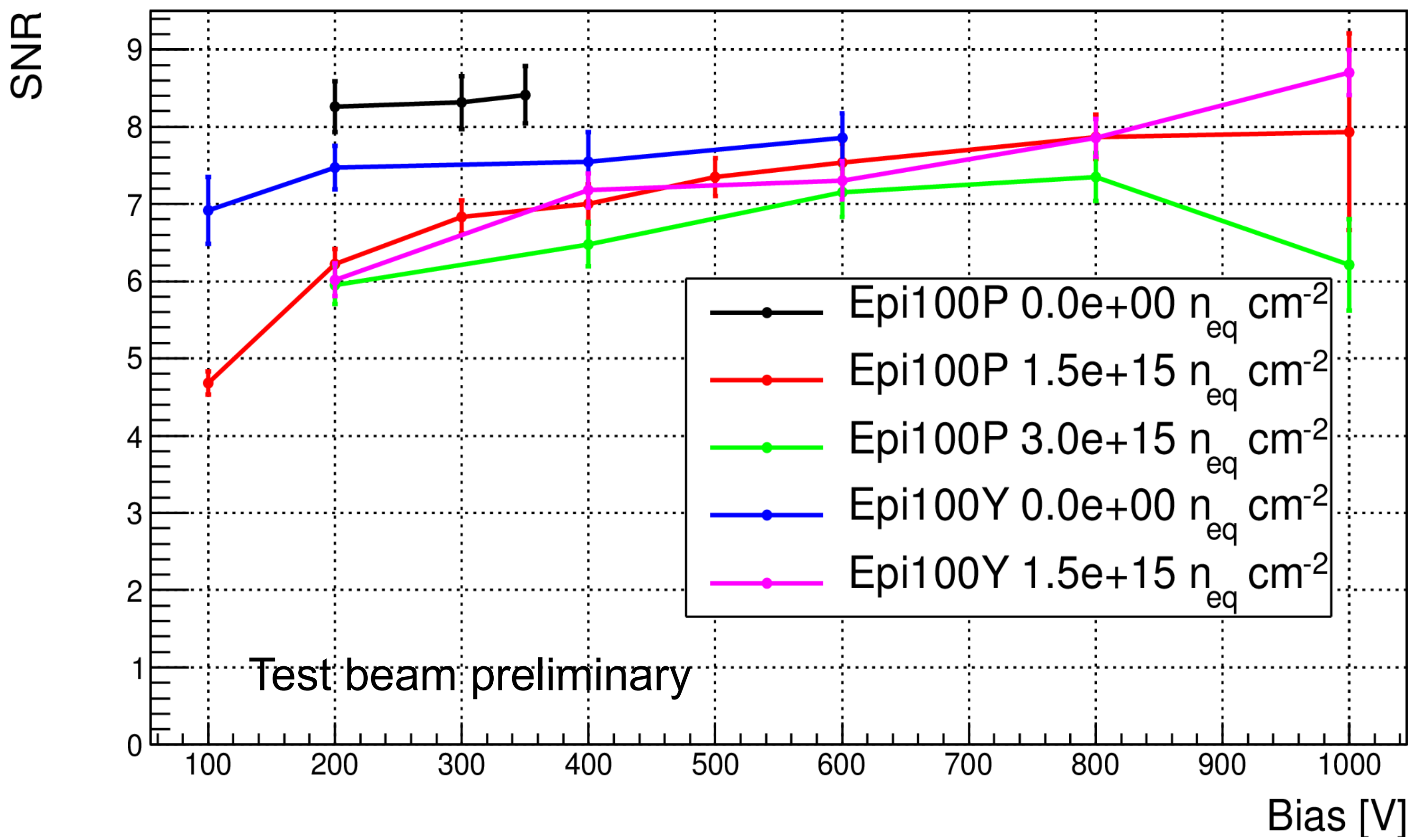
Mean and RMS of the noise over the channels



P-bulk strips:
- **Noise levels similar to pre-irradiation**
- Noise mean and RMS strongly increase at high bias

Signal-to-noise ratio

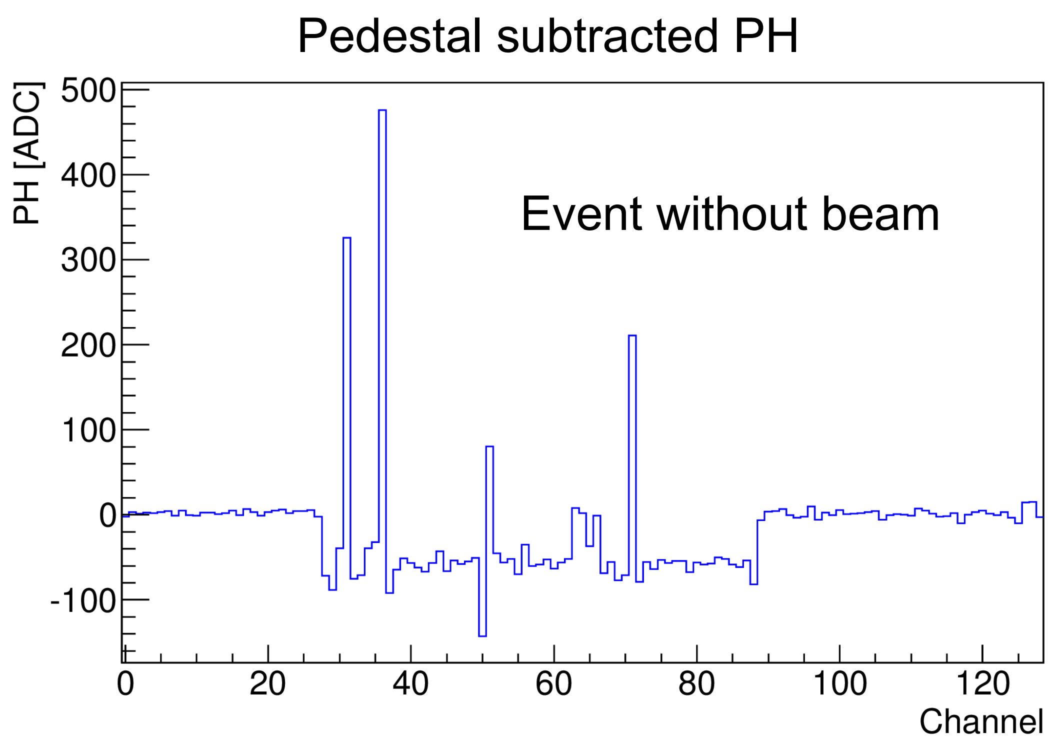
SNR → ratio of Landau MPV and noise level



P-bulk strips:
- **SNR close to pre-irradiation levels**

Micro discharges

Signal determination for **n-bulk** sensors is hard due to micro discharges
→ problems in the alignment (trustworthy hits to be defined)
→ difficult common mode estimation
→ more cuts can improve the situation



Epi100N, 23 GeV p, 1.5 x 10^{15} $n_{eq}cm^{-2}$, 400V, -20 C, no annealing

See talk from A. Nürnberg at the 23rd RD50 workshop

Conclusions and outlook

Conclusions:

- First test beam with highly irradiated epitaxial strip sensors
- Developed tools to analyze telescope and ALiBaVa data
- P-bulk
  - Small degradation of charge collection up to $\Phi_{eq} = 3 \times 10^{15}$ cm^{-2}
  - Noise compatible with non irradiated device
  - SNR close to pre-irradiation levels
- **Charge multiplication** confirmed by CCE measurement of diodes
- Irradiated n-bulk sensors show micro discharges

Outlook:

- Improve the alignment procedure
- Include the highest irradiation in the analysis
- Improve n-bulk sensors analysis
- Use the calibration runs to get rid of inhomogeneities / temperature effects

TB summary table

Taken data | Used in the talk

Angle	Sensor Voltage	0 P Beam 0 / 1	1.5e15 P Beam 1	1.5e15 N Beam 1	0 N (70um) Beam 1	3e15 P Beam 2	3e15 N Beam 2	1.5e15 Y Beam 2	1.3e16 P Beam 2	1.3e16 Y Beam 2 / 3	0 Y Beam 3	1e15 800M P Beam 4	1e15 800M N Beam 4	1e15 800M Y Beam 4	N70 Beam 4	1.3e16 N Beam 4	E16 Beam 5	FTH200Y E16 Beam 5	MCZ200N E16 Beam 5	MCZ200Y E16 Beam 5
0	1000	skipped	done	skipped	skipped	done	skipped	done	skipped	skipped	skipped	done	skipped	done	skipped	skipped	done	skipped	done (900)	done
0	800	skipped	done	skipped	skipped	skipped	skipped	done	done	done	skipped	done	done / 700V	done	skipped	done / 700V	done	skipped	done	done
0	600	skipped	done	skipped	skipped	done	done	done	done	done	done	done	done / 650V	done	skipped	done	done	done	done	done
0	500	skipped	done	done	skipped	skipped	done	skipped	skipped	skipped	skipped	skipped	done	skipped	skipped	skipped	skipped	skipped	skipped	skipped
0	400	done	done	done	done	done	done	done	done	done	done	done	done	done	skipped	done	done	done	done	done
0	300	done	done	done	done	skipped	done	skipped	skipped	skipped	skipped	skipped	skipped	skipped	skipped	done	skipped	skipped	skipped	skipped
0	200	done	done	done	skipped	done	done	done	done	done	done	done	done	done	done	done	skipped	skipped	skipped	skipped
0	100	done	done	done	done	skipped	done	done	done	skipped	done	skipped	skipped	skipped	done	done	skipped	skipped	skipped	skipped
25	1000	skipped	skipped	skipped	skipped	done	skipped	done	skipped	skipped	skipped	done	skipped	done	skipped	skipped	done	skipped	done (900)	done
25	800	skipped	skipped	skipped	skipped	done	skipped	done	done	done	skipped	done	skipped	done	skipped	skipped	done	skipped	done	done
25	600	skipped	skipped	skipped	skipped	done	done	done	done	done	skipped	done	skipped	done	skipped	done	done	done	done	done
25	400	skipped	skipped	skipped	skipped	skipped	skipped	skipped	skipped	skipped	done	skipped	done	skipped	skipped	skipped	done	done	done	done
25	300	done	done	done	done	done	done	done	done	skipped	skipped	done	done	done	skipped	done	skipped	skipped	skipped	skipped
25	200	skipped	skipped	skipped	skipped	skipped	skipped	skipped	skipped	skipped	skipped	skipped	done	skipped	done	skipped	skipped	skipped	skipped	skipped
51	100	done	done	done	done	skipped	done	skipped	skipped	skipped	skipped	skipped	skipped	skipped	done	done	-	-	skipped	skipped
51	1000	skipped	skipped	skipped	skipped	done	skipped	done	skipped	skipped	skipped	done	skipped	done	skipped	skipped	-	-	-	-
51	800	skipped	done	skipped	skipped	done	skipped	done	done	done	skipped	done	skipped	done	skipped	skipped	-	-	-	-
51	600	skipped	done	done	skipped	done	done	done	done	done	done	done	done / 650 V	done	skipped	done	-	-	-	-
51	500	skipped	skipped	skipped	done	skipped	skipped	skipped	skipped	skipped	skipped	skipped	skipped	skipped	skipped	skipped	-	-	-	-
51	400	done	done	done	skipped	done	done	done	done	done	done	done	done	done	skipped	done	-	-	-	-
51	300	done	done	done	done	skipped	done	skipped	skipped	skipped	skipped	skipped	done	skipped	skipped	skipped	-	-	-	-
51	200	done	skipped	skipped	skipped	done	done	done	done	skipped	done	done	done	done	done	done	-	-	-	-
51	100	done	done	done	done	skipped	done	done	skipped	skipped	done	skipped	skipped	skipped	done	done	-	-	-	-
31.7	1000	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	done	-	done (900)	done
31.7	800	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	done	-	done	done
31.7	600	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	done	done	done	done
31.7	400	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	done	done	done	done
36.8	1000	-	done	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
36.8	800	-	done	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
36.8	600	-	done	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
36.8	400	-	250000 Events	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

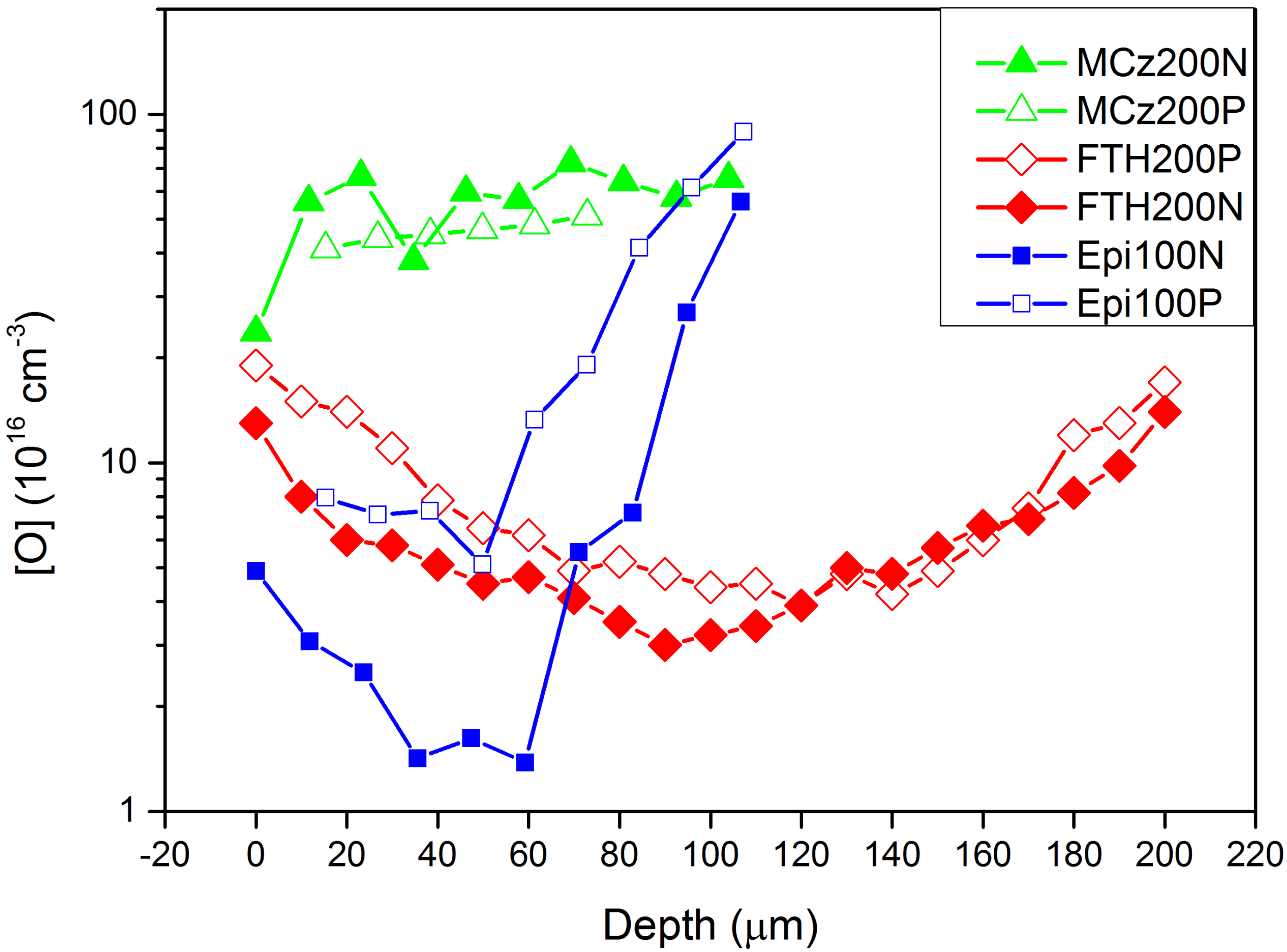
Much analysis to be done,
stay tuned!

Special thanks to:
- Test beam shifters
- HIWI students for the TCT measurements

Thank you for your attention

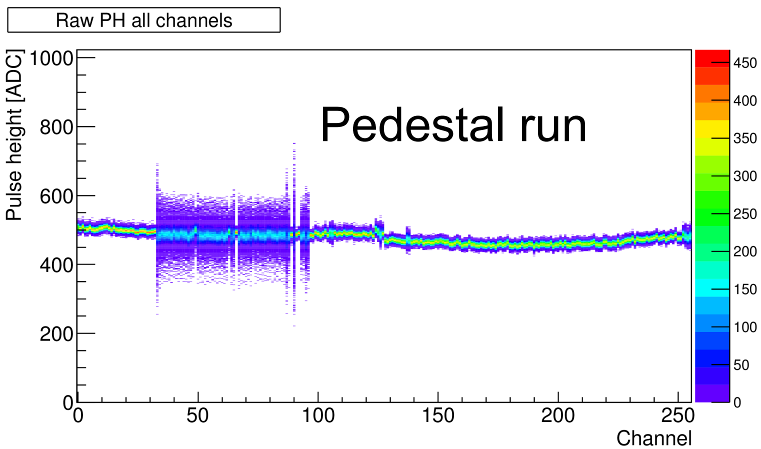
Backup

Oxygen content

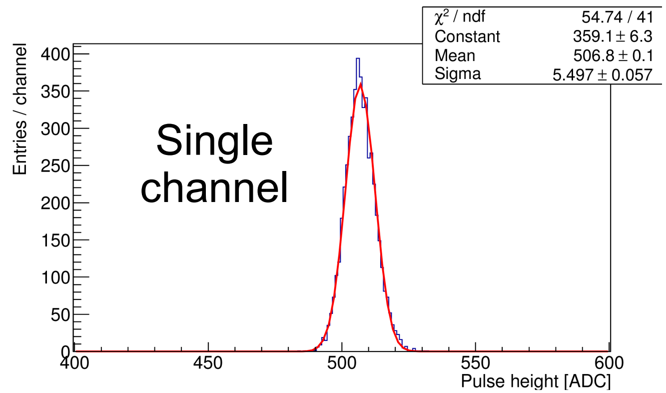


Pedestal run analysis I

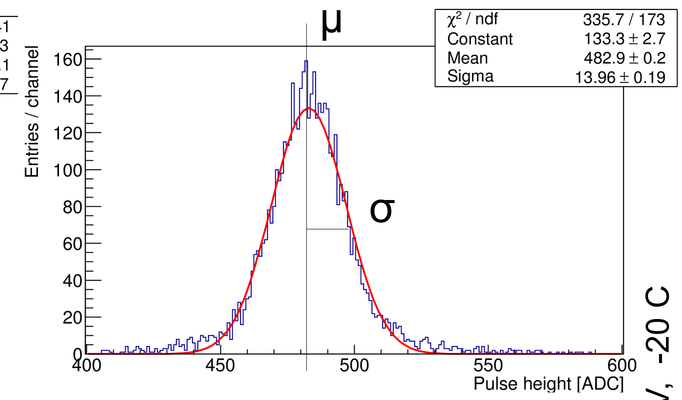
All entries



Gaussian fit

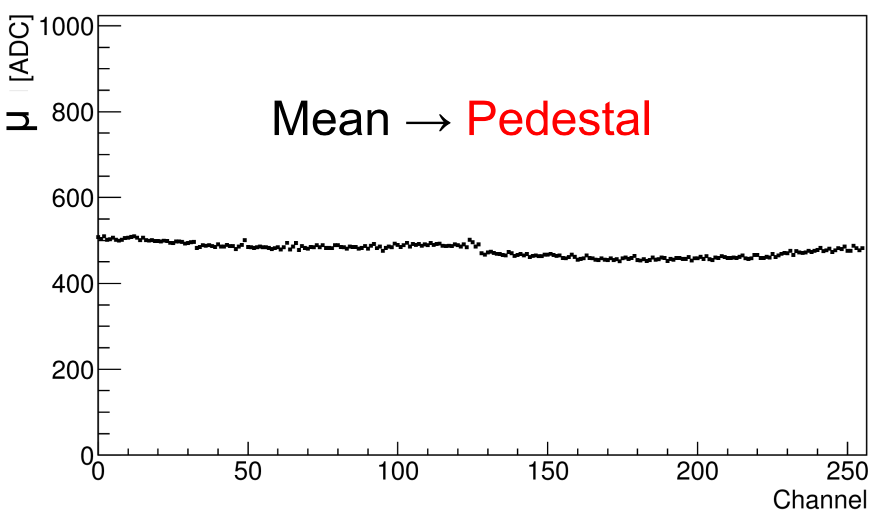


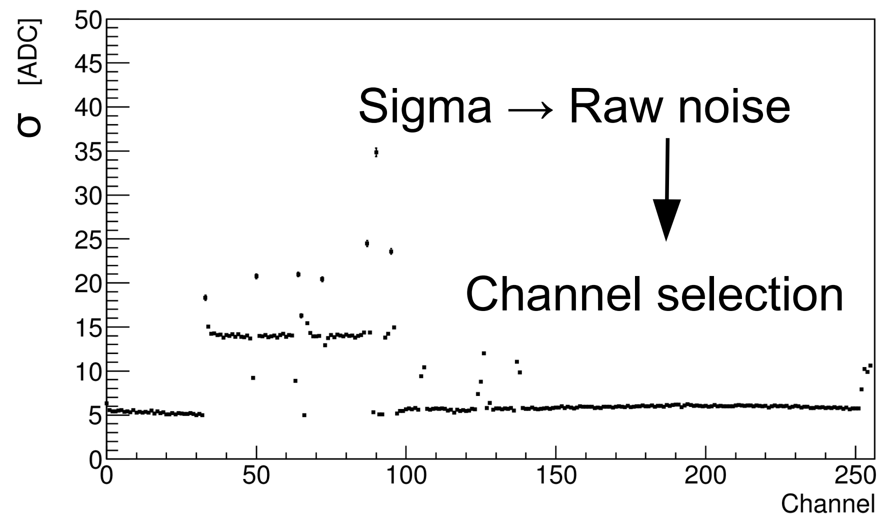
Not bonded



Bonded

Difference: common mode and sensor capacitance

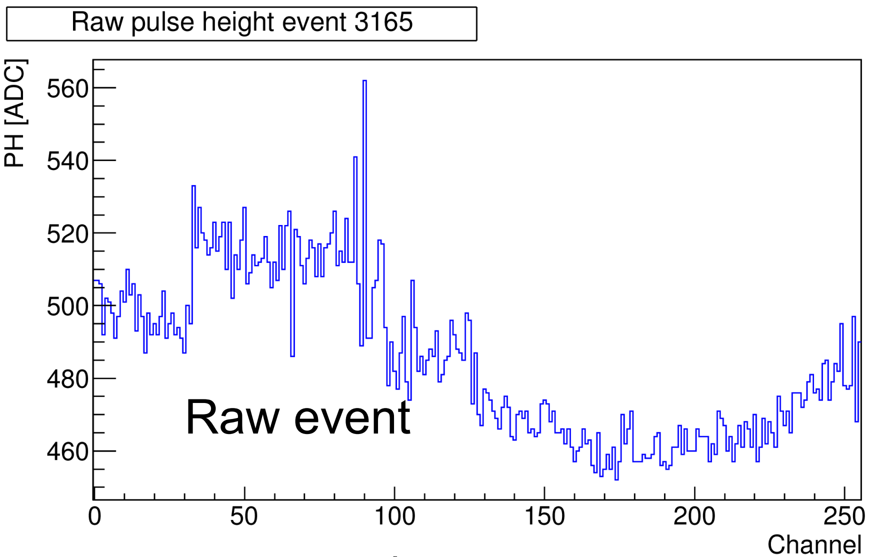




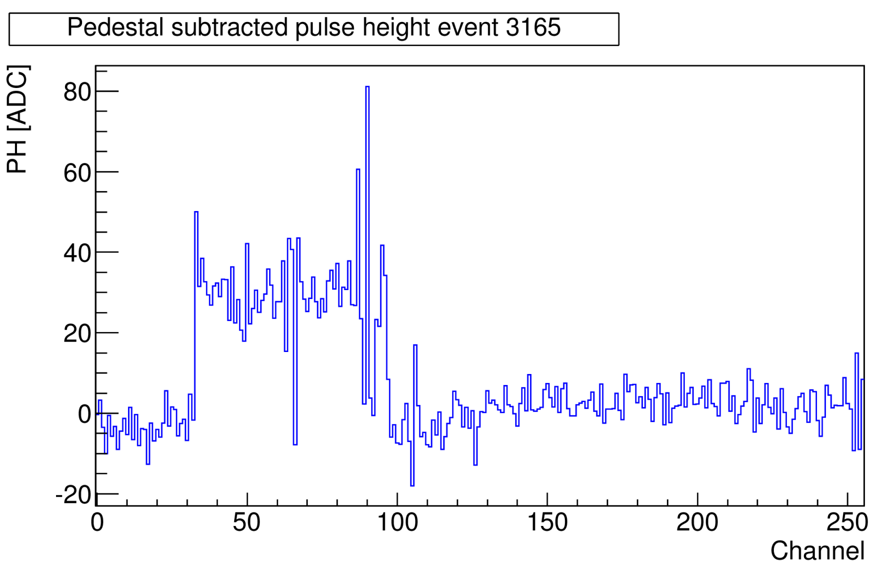
Epi100P, 23 GeV p, 3 10^{15} n_{eq} cm^{-2}, -800V, -20 C

Pedestal run analysis II

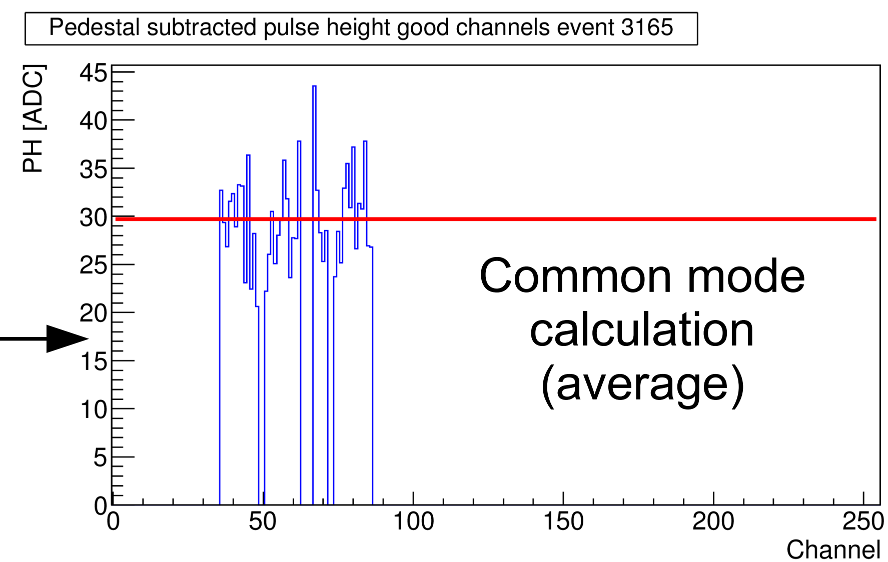
Common mode → all channels are shifted from their base line (event-wise)



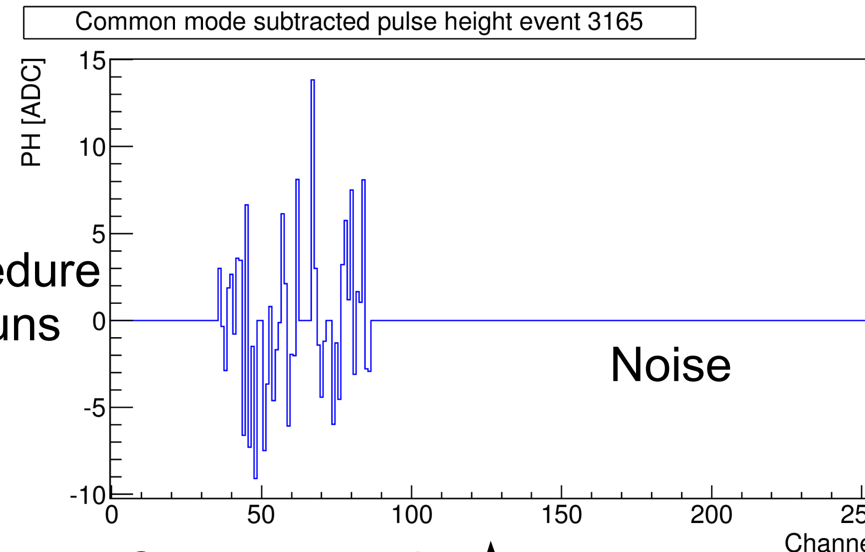
Pedestal subtraction



Channel selection



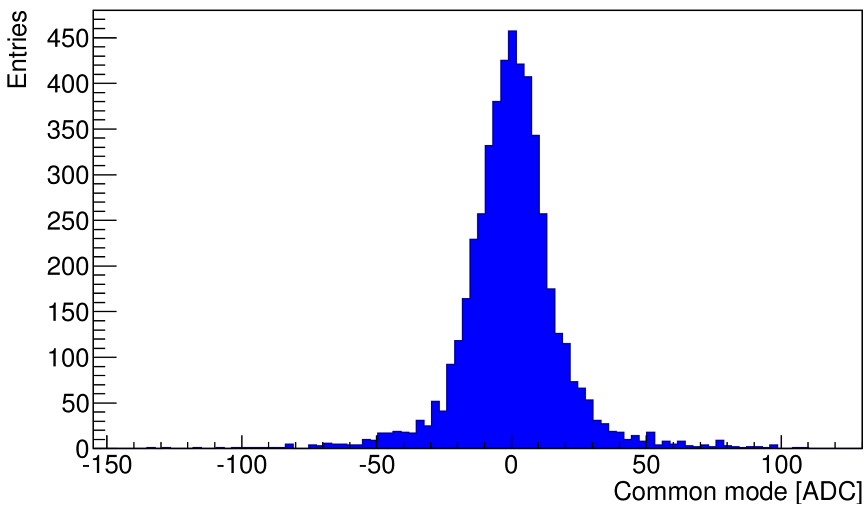
Common mode subtraction



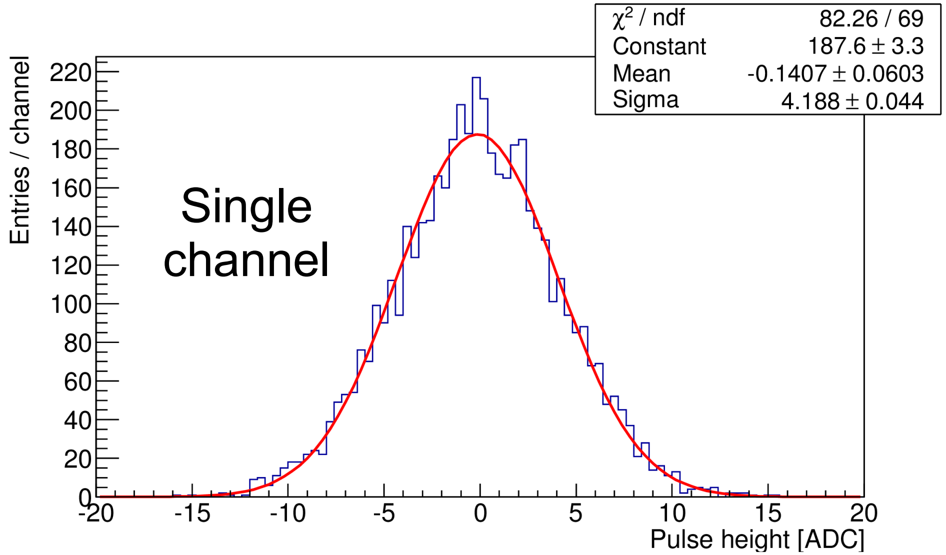
Similar procedure for beam runs

Epi100P, 23 GeV p, 3 10^{15} n_{eq} cm^{-2}, -800V, -20 C

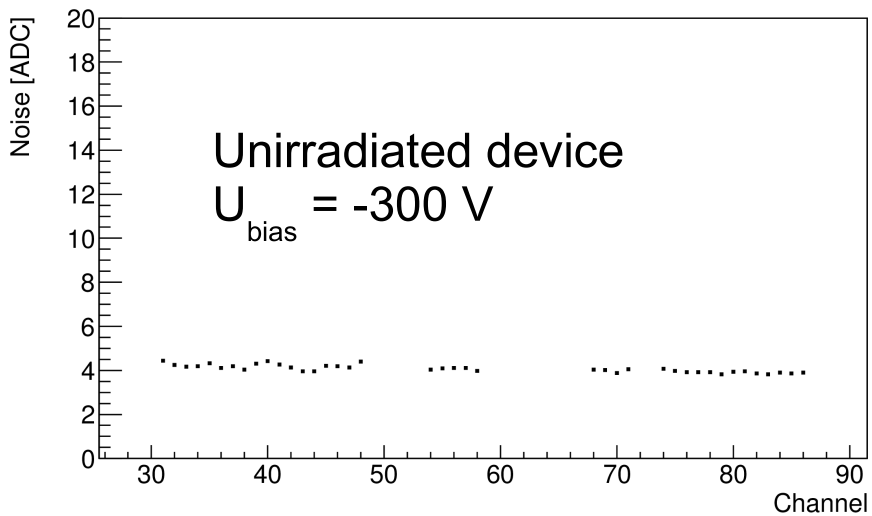
Pedestal run analysis III

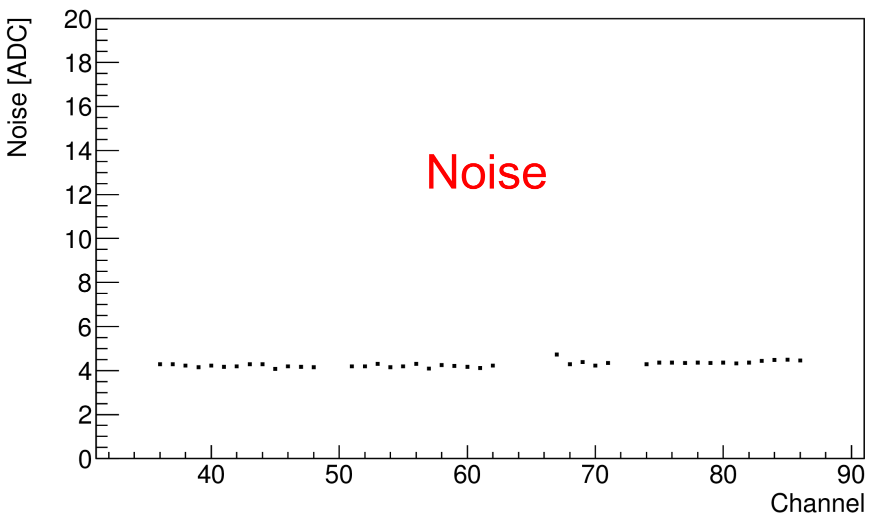


Common mode distribution



Noise distribution





Epi100P, 23 GeV p, 3 10^{15} n_{eq} cm^{-2}, -800V, -20 C

For this bias, **pedestal** and **noise** levels **similar to unirradiated sensor**