Long-term HV stability of the collected charge in charge multiplication sensors

25th RD50 Meeting, CERN

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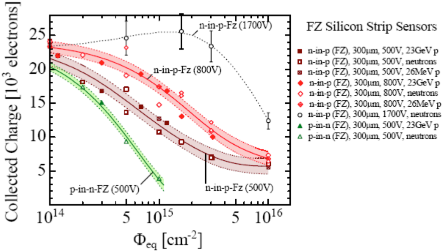
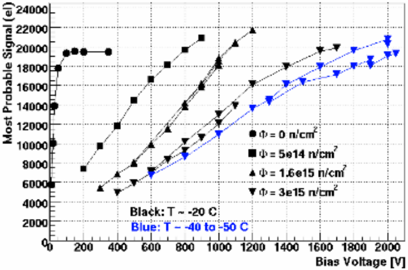
Motivation

- The HL-LHC will lead to a 10-fold increase in luminosity, exposing detectors to much higher levels of radiation
- At high fluences and bias voltages, charge multiplication of the signal in silicon detectors has been observed
- Signal is multiplied through the process of impact ionization, which typically begins in silicon when the field reaches 10-15 V/μm
- Charge multiplication can be beneficial for sensors, leading to higher signal
- Long-term stability of sensors operated in the charge multiplication mode needs to be investigated
- Recent studies* have shown a drop in the signal after being held at a large bias voltage for large time scales (days to weeks)

  *[S. Wonsak, Private Communications]

  *[M. Milovanovic et al., 21st RD50 Workshop, November 2012]



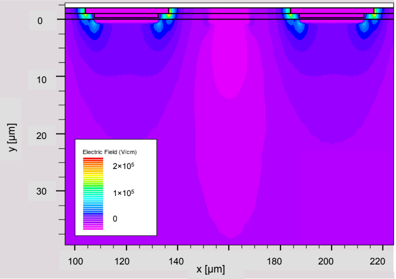


[I. Mandic, 12th RD50 workshop, 2008]

Devices under study

- CERN RD50 investigating rad-hard detector designs, with one option being charge multiplication detectors
- Multiplication of the signal is achieved by increasing the electric field near the strip edges
- Most sensors in this study are 1 cm^2 n-in-p FZ sensors produced by MICRON as part of a special charge multiplication run. Two sensors are irradiated HPK minis (ATLAS07, ATLAS12) which have been annealed out
  - Neutron irradiations - reactor neutrons at the Jozef Stefan Institute in Ljubljana from the TRIGA Mark II research reactor
  - Proton irradiation - 25 MeV protons from the Proton-Compact Cyclotron in Karlsruhe

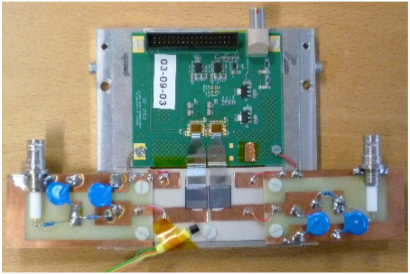
Type	Thickness [μm]	Resistivity [kΩcm]
Standard (std)	305$\pm$15	13
Double diffusion time (Extr. Diff)	305$\pm$15	13
Double implant enegery (2E imp)	300$\pm$15	10-13
Thick	675$\pm$30	8
Thin	150$\pm$10	10

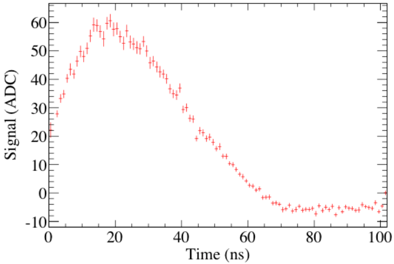


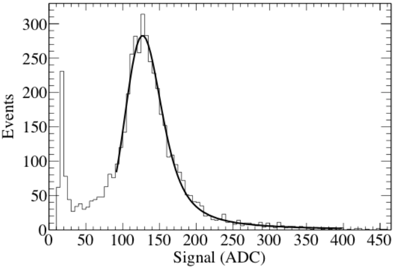
[L. Atlan, 20th RD50 workshop, 2012]

Experimental set-up

- MIPs from a ^{90}Sr source are used to perform charge collection measurements
- Charge collection measurements are done through the ALIBAVA readout system
- Time between trigger signal and edge of a 10 MHz clock is measured by the ALIBAVA TDC
- Only events around a 10 ns time window are considered, and resulting spectrum is fitted with a convolution of a landau and a gaussian to determine MPV of the charge





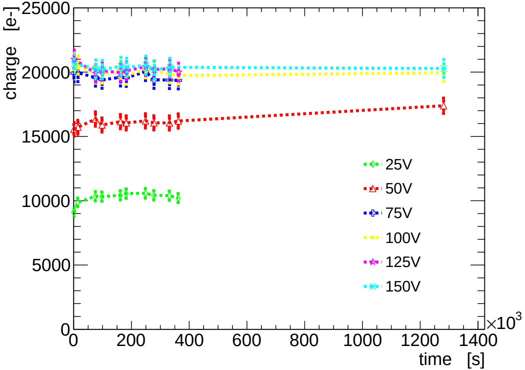


Types of measurements performed

- The effect of the beta source was investigated, with one pre-rad sensor having the source placed in front of it for 1 week without a HV source. The signal was periodically measured at several voltages
- All irradiated sensors were housed in a freezer with the temperature ranging between -20 and -40° C, depending on the fluence. Nitrogen gas was used to keep the humidity $\approx$ 5%
- Sensors were biased to large voltages over time scales spanning days to weeks
- The collected charge was measured a few times a day, and the current measured every 10 min
- After a drop of signal was observed, a few methods for recovering the lost charge were tested:
  - Removing the HV for a period spanning a few hours to several months
  - Forward biasing the sensor for a period of time
  - Shining UV light over the sensor (no HV) for a period of time, in an attempt to reset surface charges

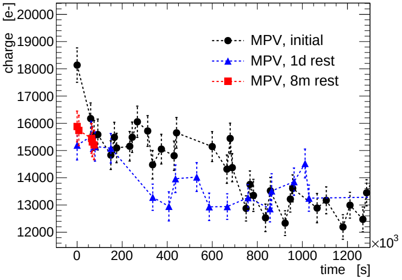
2E imp., w=25 μm, p=100 μm, Non-irradiated, Source effect

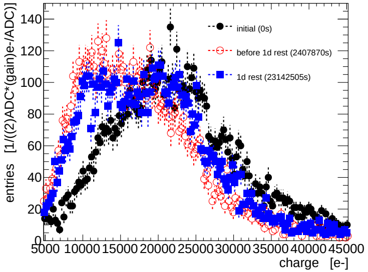
- Previous studies have shown a drop of signal due to the beta source changing the oxide charge (p-stop detectors)
- Sr^{90} source was held in front of the sensor without HV
- Measurements were made periodically between 25 - 125 V
- No drop in the signal was observed, presumably due to the better protection of the p-spray across the entire sensor



thick, w=10 μm, p=100 μm, Φ =$5\times10^{15} n_{eq}/cm^2$ (Neutrons), V_{bias}=1300V

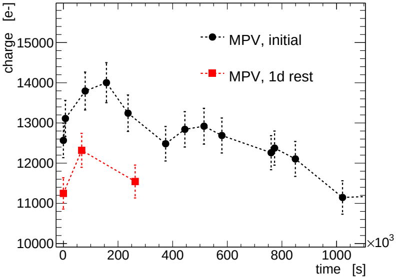
- Sensor is in the CM mode at t=0, showing a large excess of charge compared to a standard sensor of the same fluence and geometry
- Significant drop of about 2-3 ke$^-$ is seen in the signal after about 1-2 days, with a further decrease happening after 1-2 weeks
- A partial recovery of the signal is seen after removing the HV for a period of time, although the initial charge is never recovered, even after resting for 8 months
- Significant change in the landau spectrum of the signal seen before and after the drop of charge

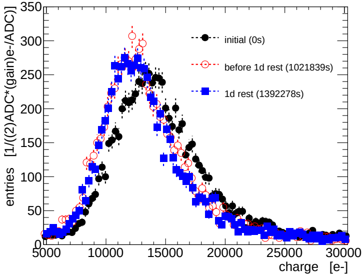




2E imp., w=25 μm, p=80 μm, Φ =5$\times 10^{15} n_{eq}/cm^2$ (Neutrons), V_{bias}=1300V

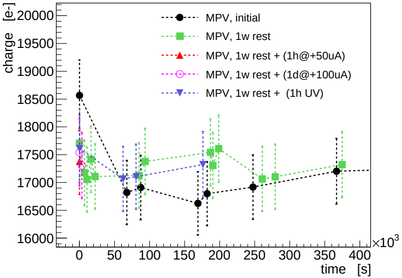
- Although sensor was not in the CM mode (excess of signal compared to a standard process sensor), a decrease of charge is again evident
- A small anomolous increase in signal is seen at small times, although at later times the signal always decreases
- Partial recovery of the signal is seen after 1 day of rest, but again the original signal is never recovered

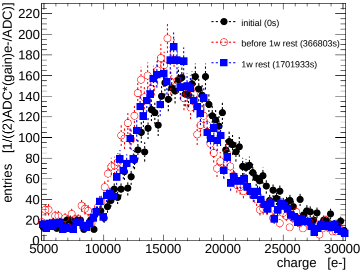




2E imp., w=10 μm, p=100 μm, $\Phi = 1\times10^{15} n_{eq}/cm^2$ (Protons), V_{bias}=1300V

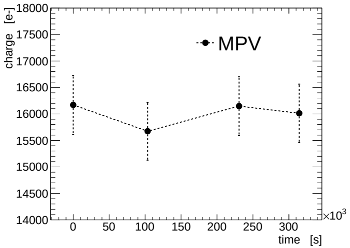
- Drop in signal is also observed after proton irradiation
- The timescale for the signal degredation is smaller than for neutron irradiated sensors
- Several attempts were made to "reset" the signal
  - Turning HV off for 1 week
  - Forward biasing at 50μA for 1 hour
  - Forward biasing at 100μA for 1 day
  - Illuminating sensor with UV light for 1 hour
- Although some small (within erros) recovery is seen, the drop in signal seems to be permanent



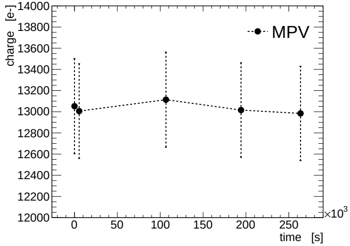


Sensors without signal degradation

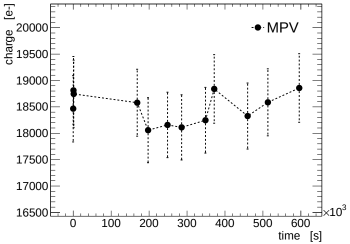
- Drop is not universal, with many sensors showing no degradation
- The drop seems to be bias dependent, which has only been observed at 1300V so far



std, w=25 μm, p=80 μm, $\Phi = 1\times10^{15} n_{eq}/cm^2$ (Protons), V_{bias}=820V



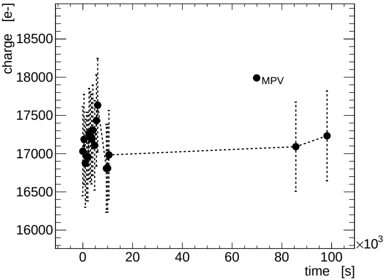
std, w=15 μm, p=40 μm, f15 μm, $\Phi = 1\times10^{15} n_{eq}/cm^2$ (Neutrons), V_{bias}=700V



2E imp, w=6 μm, p=80 μm, $\Phi = 1\times10^{15} n_{eq}/cm^2$ (Protons), V_{bias}=1000V

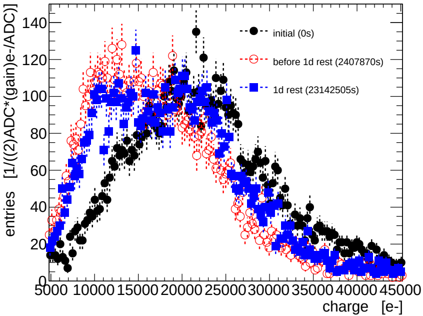
ATLAS12A HPK mini, w=16 μm, p=75.4 μm, $\Phi = 2\times10^{15} n_{eq}/cm^2$ (Protons), V_{bias}=1100V, Annealed for 80 min at 60° C

- An ATLAS12A sensor irradiated with protons and annealed for 80 min at 60° showed no multiplication and no drop in charge
- Tests were performed first at 600V, and then again at 1100V

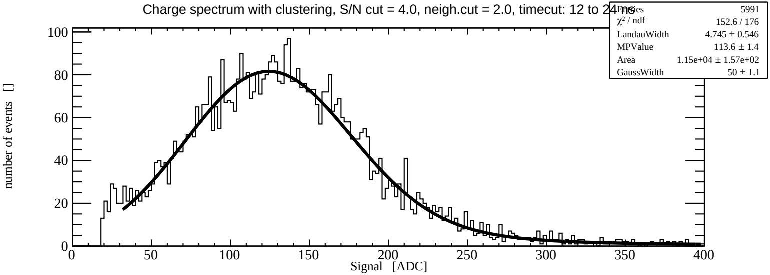


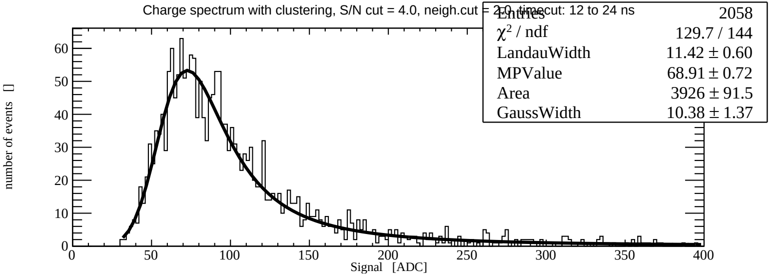
Charge multiplication and the signal spectrums

- Sensors exhibiting excess charge also exhibit peculiar Landau spectrums
- Double peak Landau or broadening of the spectrum is seen in the charge multiplication mode
- Could be a result of some signal going through high-field regions (causing CM) and lower-field regions
- The double peak/broadening is seen from arising from 2 overlaping Landau signals: one peak comes from 1-hit clusters, the other from 2 or more hit clusters

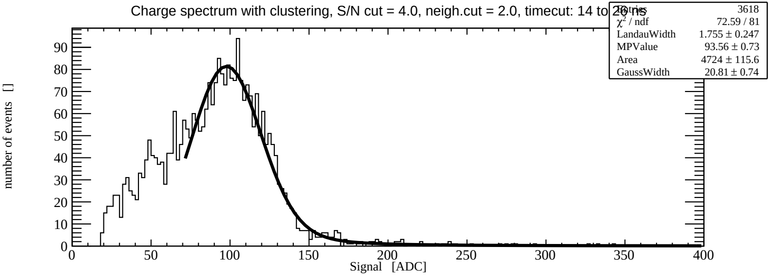


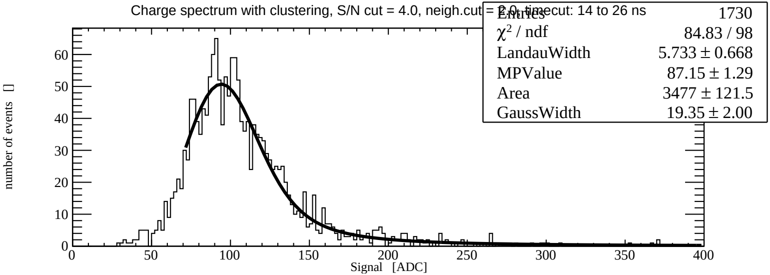
1 vs 2 hit clusters: thick, w=10 μm, p=100 μm, $\Phi = 5\times10^{15} n_{eq}/cm^2$ (Neutrons), V_{bias}=1300V



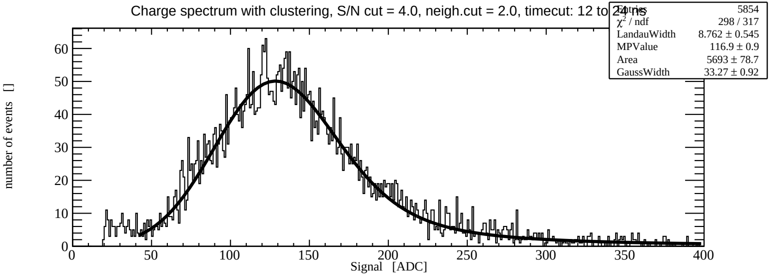


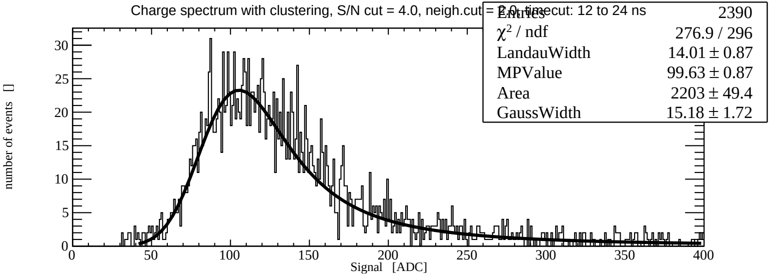
1 vs 2 hit clusters: std, w=25 μm, p=80 μm, $\Phi = 1\times10^{15} n_{eq}/cm^2$ (Protons), V_{bias}=1000V





1 vs 2 hit clusters: ATLAS07 HPK mini, w=16 μm, p=75.4 μm, $\Phi = 2\times10^{15} n_{eq}/cm^2$ (mixed irr.), V_{bias}=1100V, Annealed for 4200 min at RT





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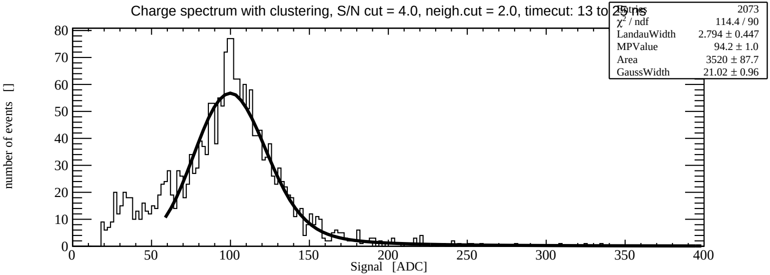
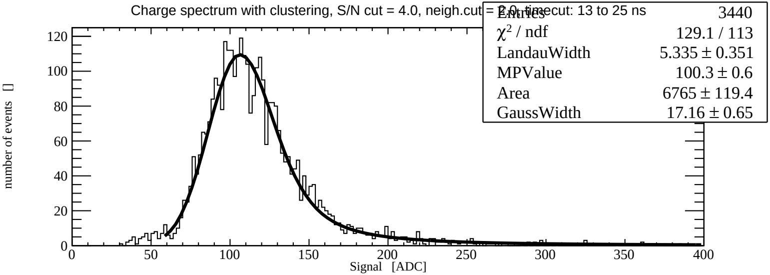




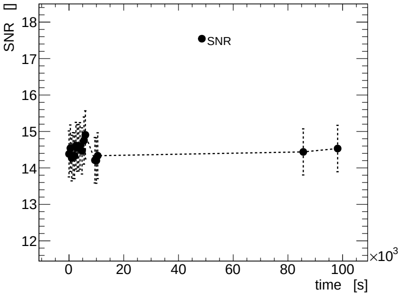
Possible mechanisms

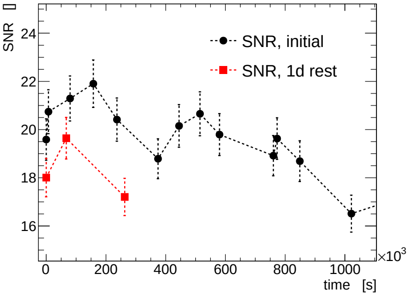
- Beta source changes the SiO_2, leading to lower fields near the surface
  - Ruled out by source test, p-spray acts as good protection against this
  - Irradiated sensors should already have their oxide charge saturated
- Polarization effect: Defects with large lifetimes change N_{eff}, causing a reduction in depletion width
  - Has been observed not only in very large band gap materials like diamond, but also e.g. in CdTe (1.47eV) at relatively high temperatures
  - Should be reversible by turning off HV
  - Should happen at lower voltages as well
  - Capture cross-sections for these time scales are extremely small, on the order of 10^{-21} to 10^{-22} m^2
- Annealing due to the Electric field: changes spatial distribution of defects leading to a modification of the space charge
  - Permanent effect
  - Should depend on the strength of the electric field, and thus the voltage applied
  - Not as well documented as other mechanisms

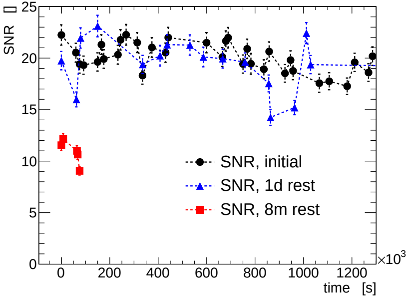
Summary and Outlook

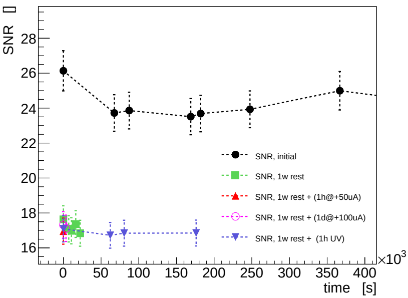
- Recent measurements have called into question the viability of charge multiplication detectors for use under high-bias conditions
- At high voltages (1300 V), a siginificat drop in the collected charge is seen on both neutron and proton irradiated sensors
- Drop in charge is semi-permanent: some partial recovery is seen, although the initial charge is never fully recovered
- Drop in the signal is not seen at lower bias voltages where multiplication is not observed
- The degredation is not due to the beta source used to do measurements
- Possible explanations might include the polarization effect, which is reversable, or annealing of the sensor due to the electric field, which would be permanent
- Need to see if this is a purely radiation induced effect, or due to operating in the CM mode - Tests on Low-Gain Avalanche Diodes (LGADs) could be used to investigate this before irradiation
- Landau spectrums provide insight to determining if sensors are in CM or not
- Further tests on irradiated HPK sensors showing CM is ongoing
- More tests needed to investigate the origin of the charge drop!

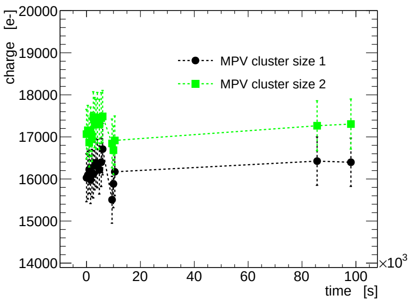
BACKUP

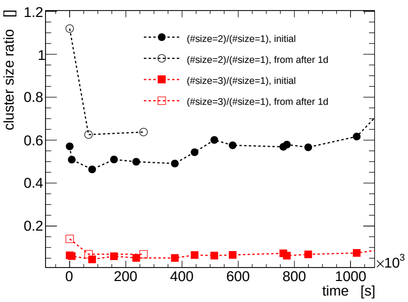

SNR
SNR
time [s]
×10³


SNR
SNR, initial
SNR, 1d rest
time [s]
×10³


SNR
SNR, initial
SNR, 1d rest
SNR, 8m rest
time [s]
×10³


SNR
SNR, initial
SNR, 1w rest
SNR, 1w rest + (1h@+50uA)
SNR, 1w rest + (1d@+100uA)
SNR, 1w rest + (1h UV)
time [s]
×10³


MPV cluster size 1
MPV cluster size 2
charge [e-]
time [s]
×10^3


(#size=2)/(#size=1), initial
(#size=2)/(#size=1), from after 1d
(#size=3)/(#size=1), initial
(#size=3)/(#size=1), from after 1d
cluster size ratio []
time [s]
×10^3

Annealing behavior of ATLAS07 HPK mini, w=16 μm, p=75.4 μm, $\Phi = 1\times10^{15} n_{eq}/cm^2$ (mixed irr.), V_{bias}=1100V