UNIVERSITY OF LIVERPOOL

Evidence of enhanced signal response at high bias voltages in Planar Silicon Detectors Irradiated up to 2.2x 10^{16} n_{eq}/cm^2.

G. Casse, A. Affolder, P.P. Allport,
H. Brown, I. McLeod, M. Wormald

OUTLINE

- Expectation of signal degradation with fluence
- Measurement of signal degradation with fluence (CC(V))
- Comparison of thin and thick sensors after neutron and proton irradiation
- Reverse current after severe irradiation
- Conclusions

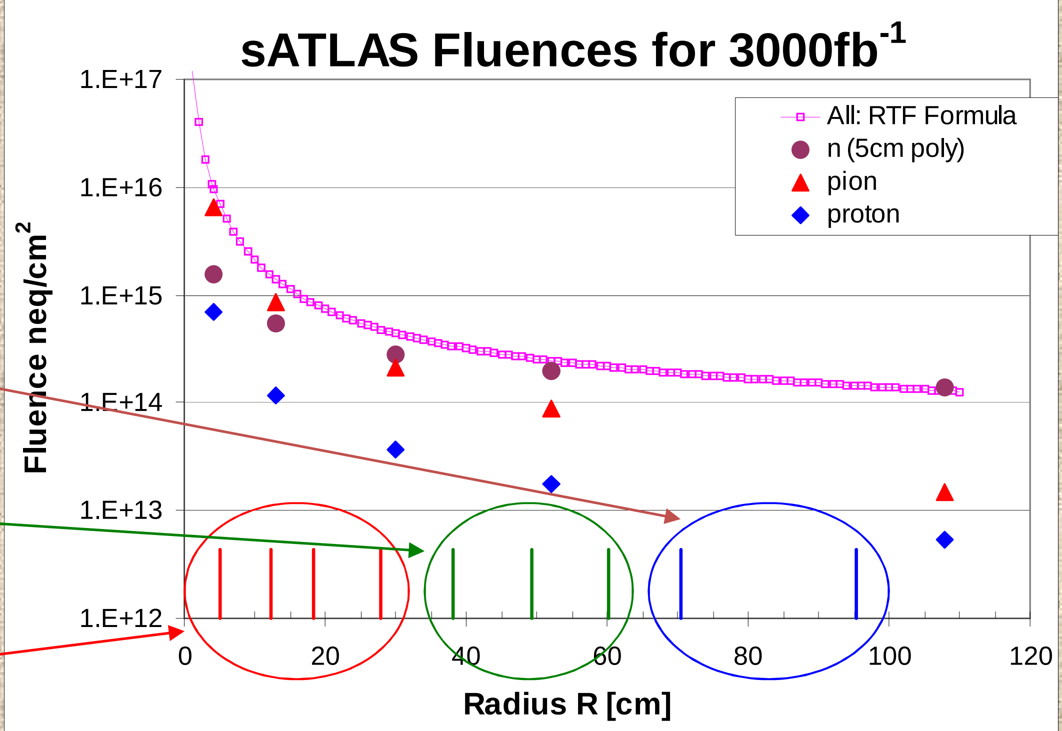
Fluence in Proposed sATLAS Tracker

Strip length and segmentation determined by occupancy< 2%

LongStrips

ShortStrips

Pixels



ATLAS Radiation Taskforce http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/RADIATION/RadiationTF_document.html

Mix of neutrons, protons, pions depending on radius R

Long and short strips damage largely due to neutrons

Pixels damage due to neutrons and pions

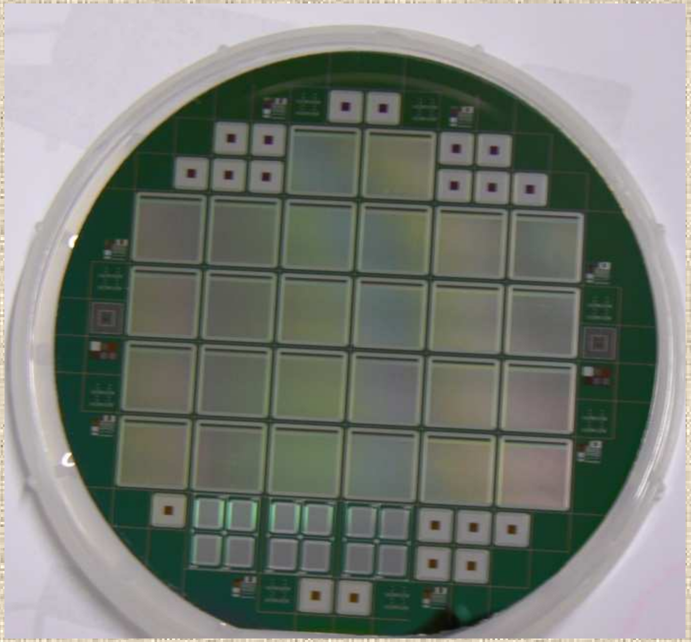
Design fluences for sensors (includes 2x safety factor) **:**

Innermost Pixel Layer:	1-1.6*10^{16} n_{eq}/cm^2 = 500 Mrad
Outer Pixel Layers:	3*10^{15} n_{eq}/cm^2 = 150 Mrad
Short strips:	1*10^{15} n_{eq}/cm^2 = 50 Mrad
Long strips:	4*10^{14} n_{eq}/cm^2 = 20 Mrad

Need to study response to both neutral (neutrons) and charged (proton) particle irradiations

Silicon miniature microstrip detectors and irradiation

RD50 mask set (see: http://rd50.web.cern.ch/rd50/)



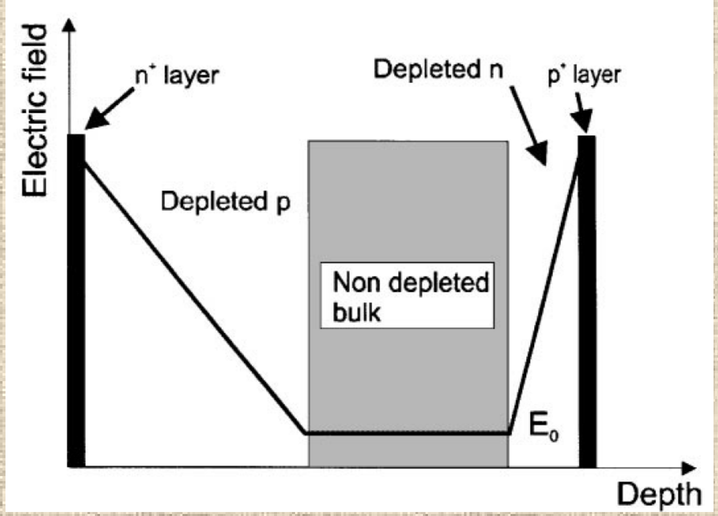
Miniature sensors, ~1x1 cm^2, 128 strips, 80 µm pitch, designed by Liverpool and produced by Micron on 300µm and 140µm thick wafers.

Irradiation and dosimetry:

Neutron:
TRIGA Mark II research reactor
Reactor Centre of the
Jozef Stefan Institute, Ljubljana, Slovenia, thanks to
V. Cindro

24GeV protons:
CERN-PS Irrad1, irradiated at area temperature (~30°C) and cold (<5°C). thanks to M. Glaser.
26 MeV protons:
Compact Cyclotron of the University of Karlsruhe, thanks to A. Dierlamm and W. de Boer.

N-side read-out can make planar segmented Si detectors suitable for tracking in extreme (SLHC levels: 1-2x10^{16} cm^{-2}) radiation environments.



Schematic changes of Electric field after irradiation

The “*main*” depletion region starts from the n^+ contact.

The high electric field under the n^+ contact also improve the charge collection.

$$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr}),\ 1/\tau_{tr} = \beta\Phi.$$

Collecting electrons provide a sensitive advantage with respect to holes due to a much shorter t_c. P-type detectors are the most natural solution for *e* collection on the segmented side.

N-side read out to keep lower t_c

Expected signal from depletion volume

The maximum collected charge should be about *$80e^{-}/\mu m \times w$* (w=depletion depth in µm). From the extrapolation of CV measurements at relatively low doses (less than 1×10^{15} n_{eq} cm^{-2}), the maximum charge collected at 1000V (excluding trapping) depends on the depleted volume:

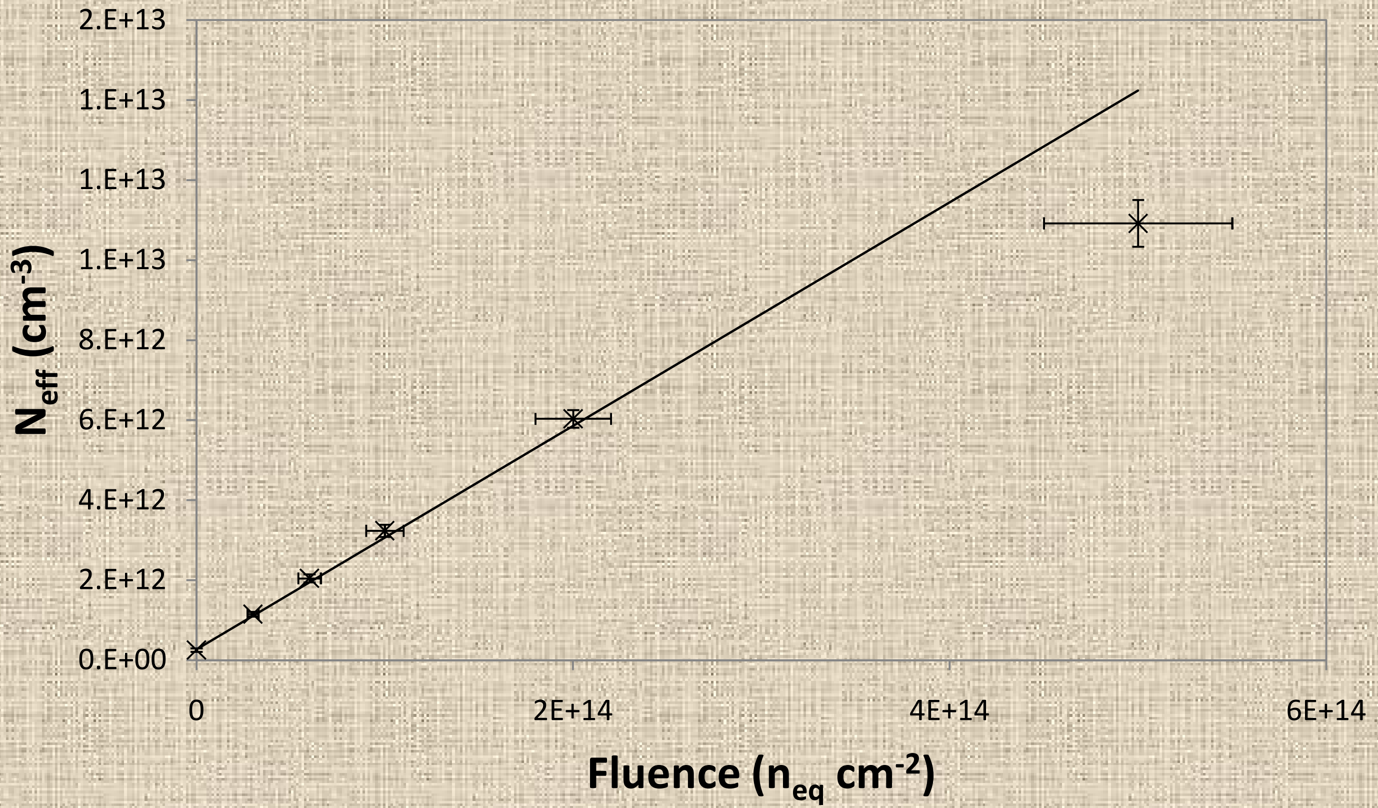
Extrapolation of the depleted volume at 1000V and Q_{max}:
300µm after 1×10^{15} n_{eq} cm^{-2} (ionised charge ~24ke).
170µm after 5×10^{15} n_{eq} cm^{-2} (ionised charge ~13ke).
120µm after 1×10^{16} n_{eq} cm^{-2} (ionised charge ~9.6ke).
85µm after 2×10^{16} n_{eq} cm^{-2} (ionised charge ~6.8ke)

Is the linear extrapolation from “low” doses correct?

N_{eff} vs ϕ measured with the CV characteristic of 300 μm n-in-p Micron sensors after 80 min 60^{o}C annealing time

$$N_{eff}=N_0(\exp(-c\phi)) - \beta\phi$$

$$\beta = 0.028 \pm 0.002 \text{ cm}^{-1}$$



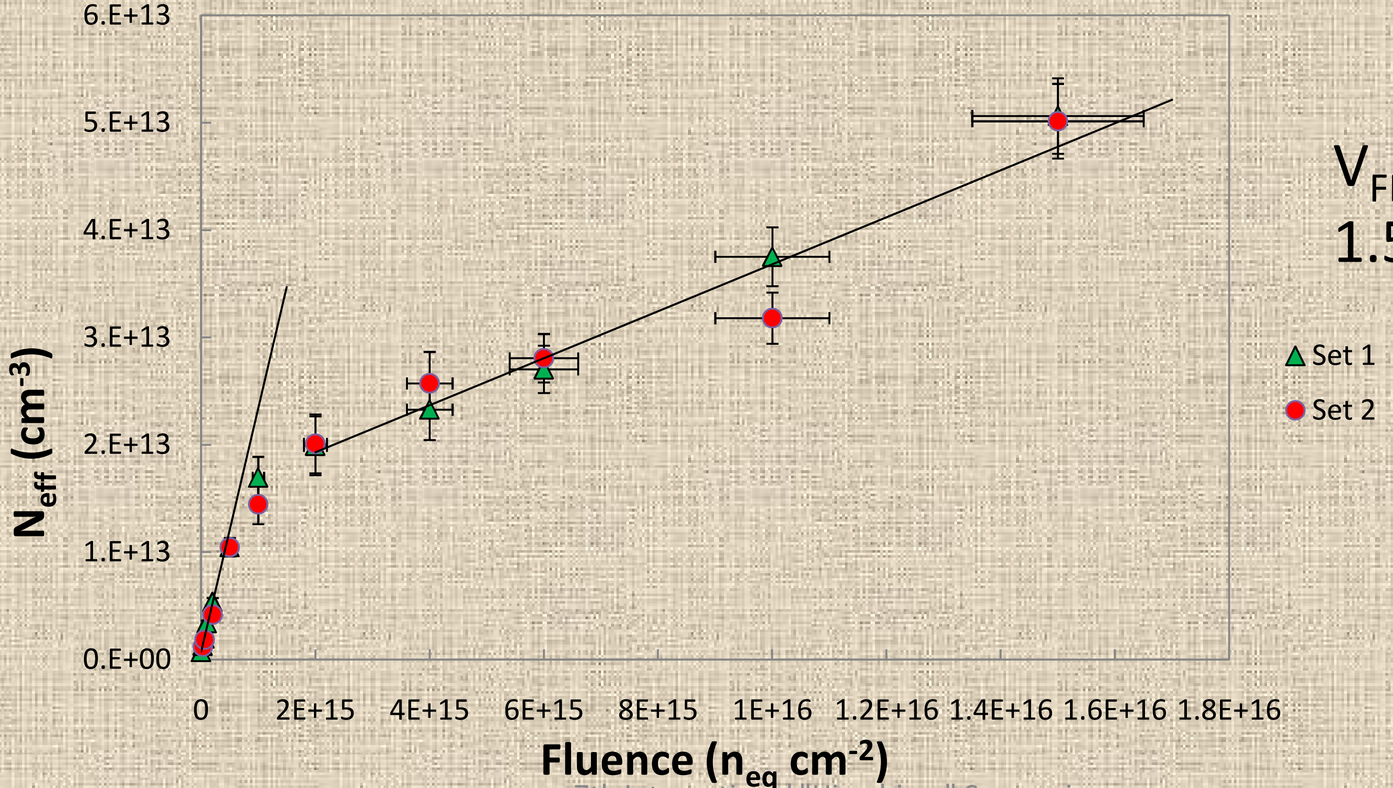
N_{eff} vs ϕ measured with the CV characteristic of 140 μm n-in-p Micron sensors after 80 min 60°C annealing time

β calculated for dose up to 5×10^{14} n_{eq} cm^{-2}

$\beta = 0.023 \pm 0.002$ cm^{-1}

β calculated for dose up to 5×10^{14} n_{eq} cm^{-2}

$\beta = 0.0022 \pm 0.0003$ cm^{-1}



$V_{FD} \cong 890$V after 1.5×10^{16} cm^{-2}

Expected signal from charge trapping

Effect of trapping on the Charge Collection Distance

After heavy irradiation it seems that the V_{FD} is lower than expected from extrapolation from lower doses. This could yield a larger signal. But, is depletion the limiting factor after heavy irradiation?

$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr})$, $1/\tau_{tr} = \beta\Phi$.

$v_{sat,e} \times \tau_{tr} = \lambda_{av}$

$\beta_e = 4.2\text{E}{-16}\ \text{cm}^{-2}/\text{ns}$

$\beta_h = 6.1\text{E}{-16}\ \text{cm}^{-2}/\text{ns}$

G. Kramberger et al., NIMA 476(2002), 645-651.

In fact, the charge trapping at radiation induced defect centres has a larger effect on the signal.

The collection distance at saturation velocity:

λ_{av} after $1\text{x}10^{15}$ n_{eq} cm^{-2}: 240µm (expected charge ~19ke).

λ_{av} after $5\text{x}10^{15}$ n_{eq} cm^{-2}: 50µm (expected charge <4ke).

λ_{av} after $1\text{x}10^{16}$ n_{eq} cm^{-2}: 25µm (expected charge <1.3ke).

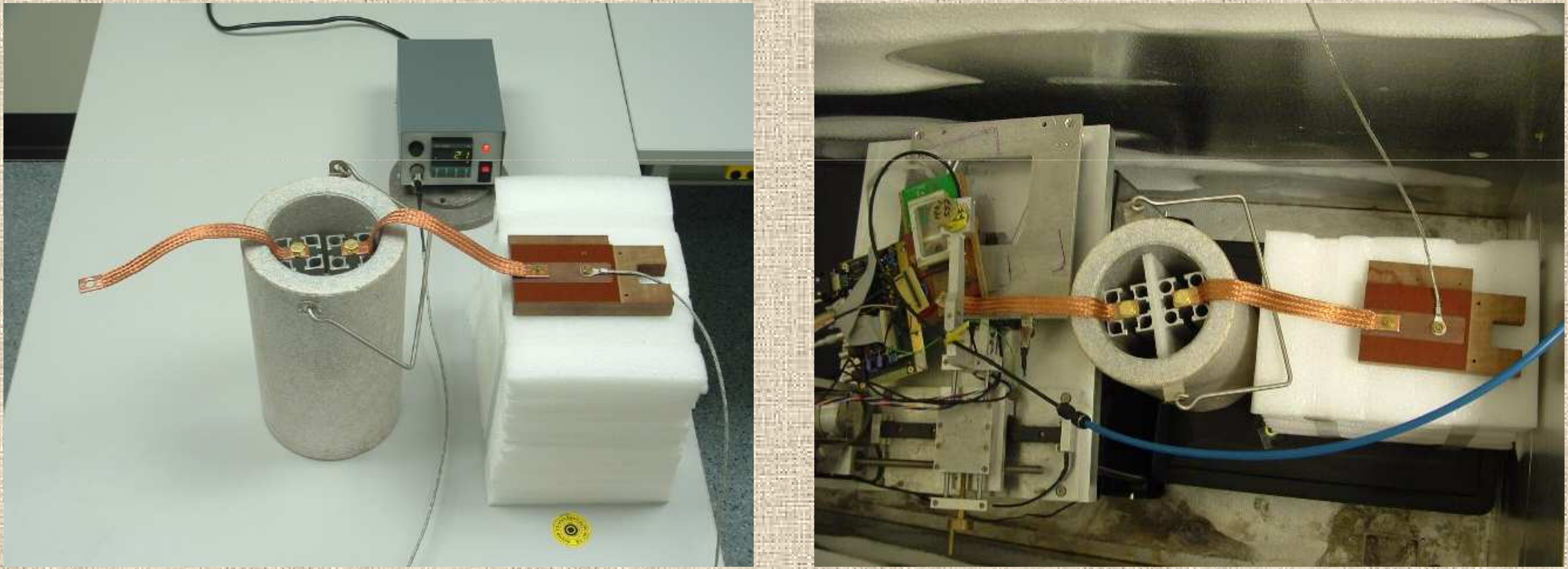
λ_{av} after $2\text{x}10^{16}$ n_{eq} cm^{-2}: 12µm (expected charge <1ke).

Is the linear extrapolation from "low" doses correct?

The trapping time has been measured at several relatively low doses, because the method requires "overdepletion" of the irradiated diode for carrying out the measurement. The linear extrapolation to high doses could still be not accurate.

MEASUREMENTS: at -25 and -45/50 °C.

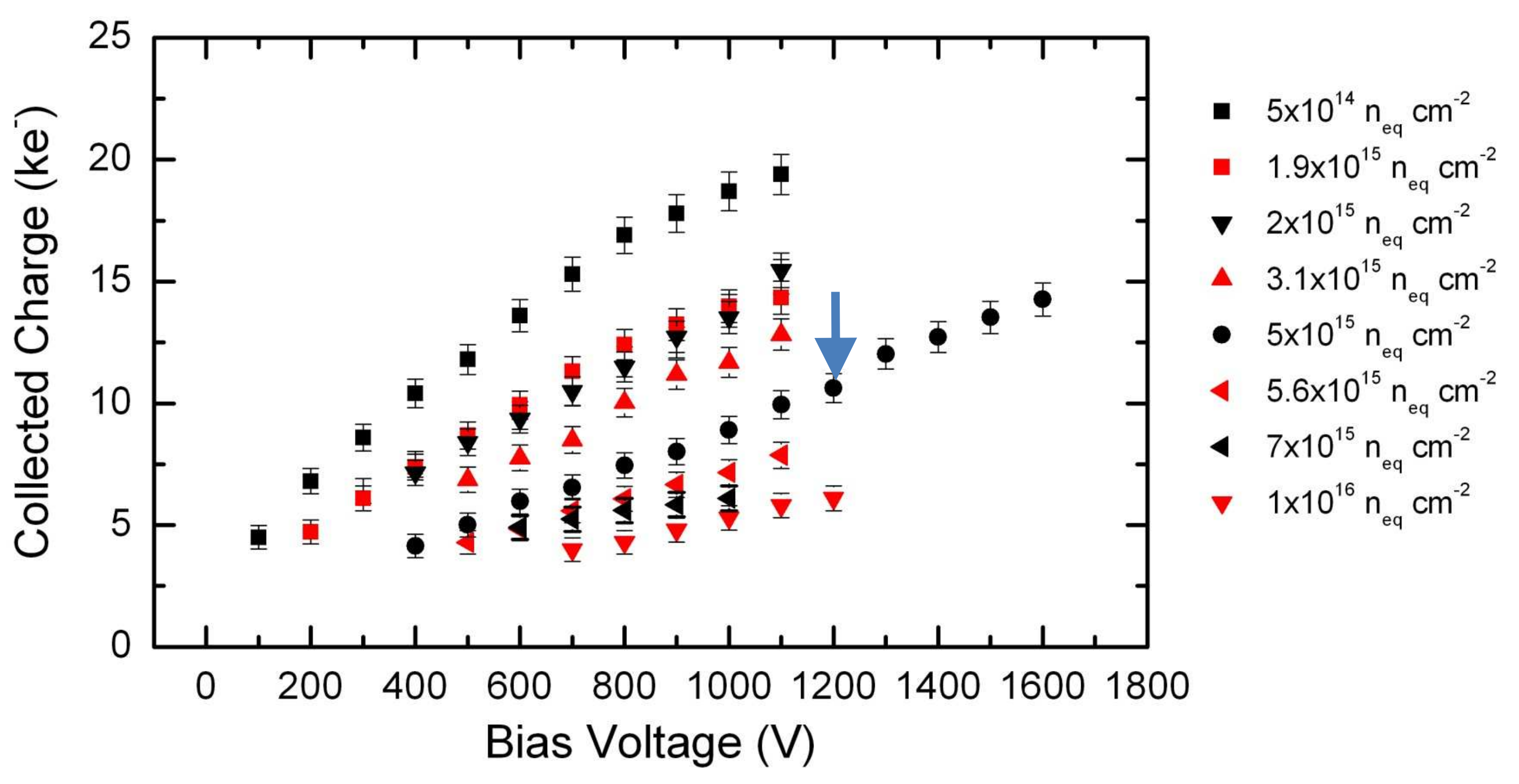
Cooling: “cold finger” system in liquid nitrogen bath. 40MHz analogue readout. ^{90}Sr with plastic scintillator trigger, with plastic filter to remove the lower energy electrons (mip’s). MP value is measured, calibration with a 300µm non irradiated sensor.



Results with proton irradiated 300 μm n-in-p Micron sensors (up to $1\times10^{16}\ n_{eq}\ cm^{-2}$)

RED: irradiated with 24GeV/c protons
Other: 26MeV protons

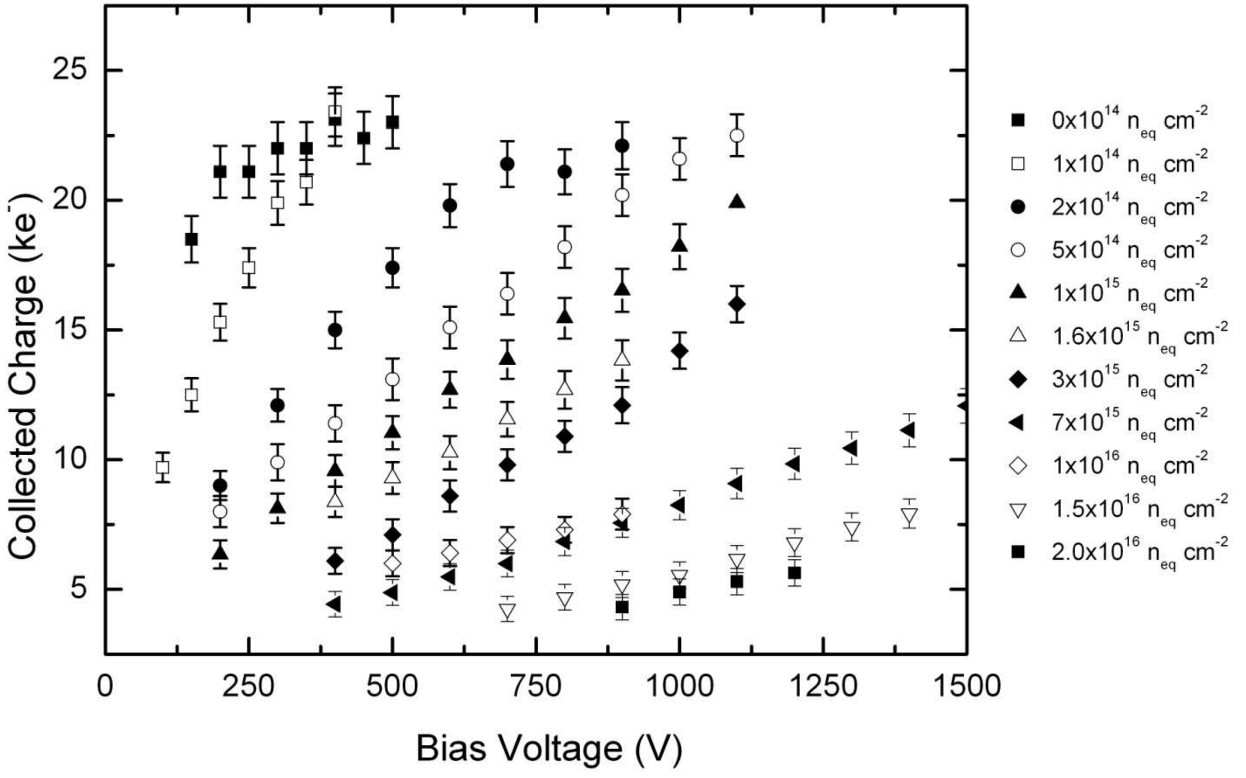
24GeV/c protons irradiated COLD, all but the 3.1E15 cm^{-2} series, which had ~ 10 days @ 33°C



Results with neutron irradiated 300 μm n-in-p Micron sensors (up to 2x10^{16} n$_{eq}$ cm^{-2})

Short irradiation time, practically no annealing

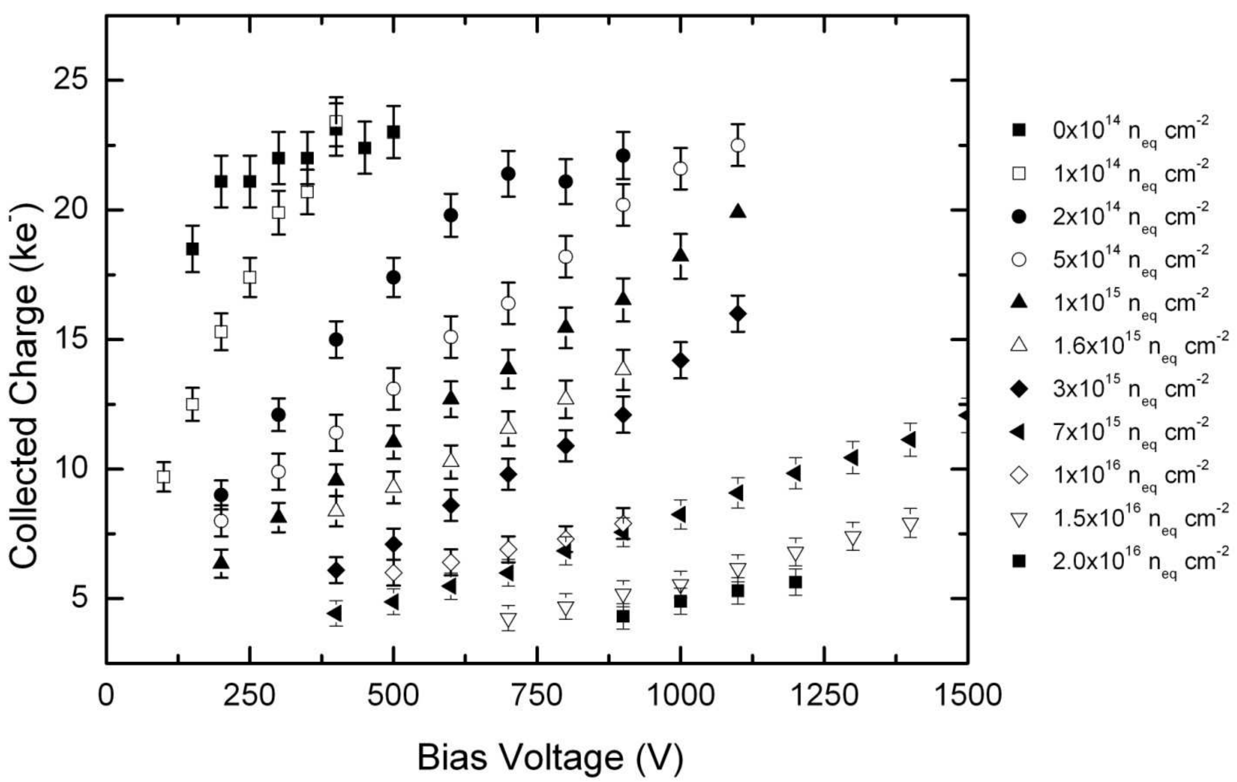
After both p and n irradiations, the collected charge is much higher than expected from charge trapping measurements (<1300e after 1x10^{16} cm^{-2}).



Results with neutron irradiated 300 μm n-in-p Micron sensors (up to $2\text{x}10^{16}$ n_{eq} cm^{-2})

Short irradiation time, practically no annealing

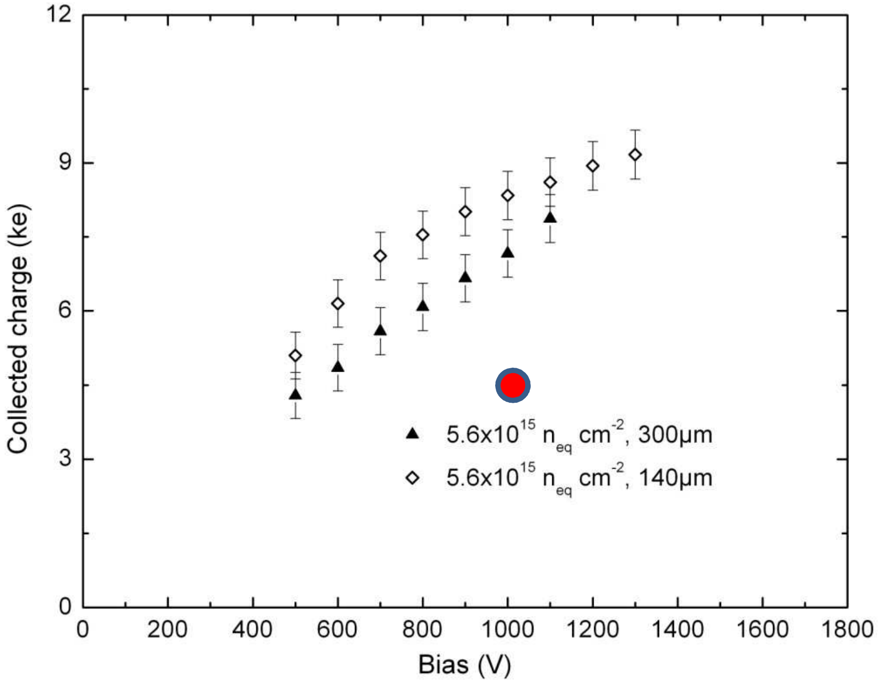
Is there a mechanism to explain this enhanced signal, at high bias voltages and after heavy irradiation?

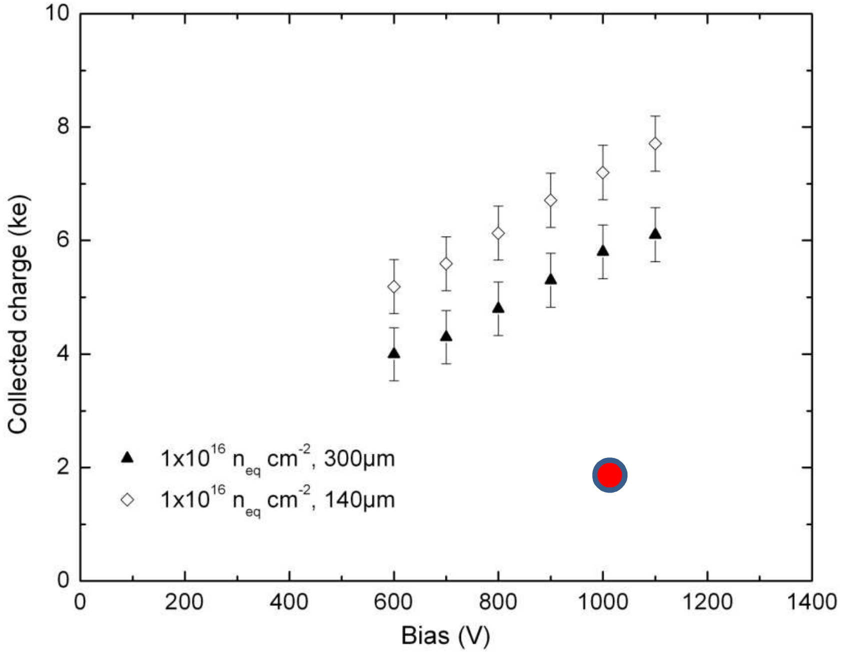


This was achieved with 300μm thick sensors (High Energy Physics standard). The collected charge after extreme doses is much higher than expected from the dependence of τ_{tr} with fluence. Moreover, can thin devices be even better (from the charge trapping measurement, the effective thickness of a sensors falls under 300μm after less than $1x10^{15}$ n_{eq} cm^{-2}, at a V_{bias} of 1000V). ?

140 and 300 μm n-in-p Micron sensors after 5.6 and $1x10^{16}$ n_{eq} 24GeV/c p

Cold(0-5 ^{o}C) irradiation

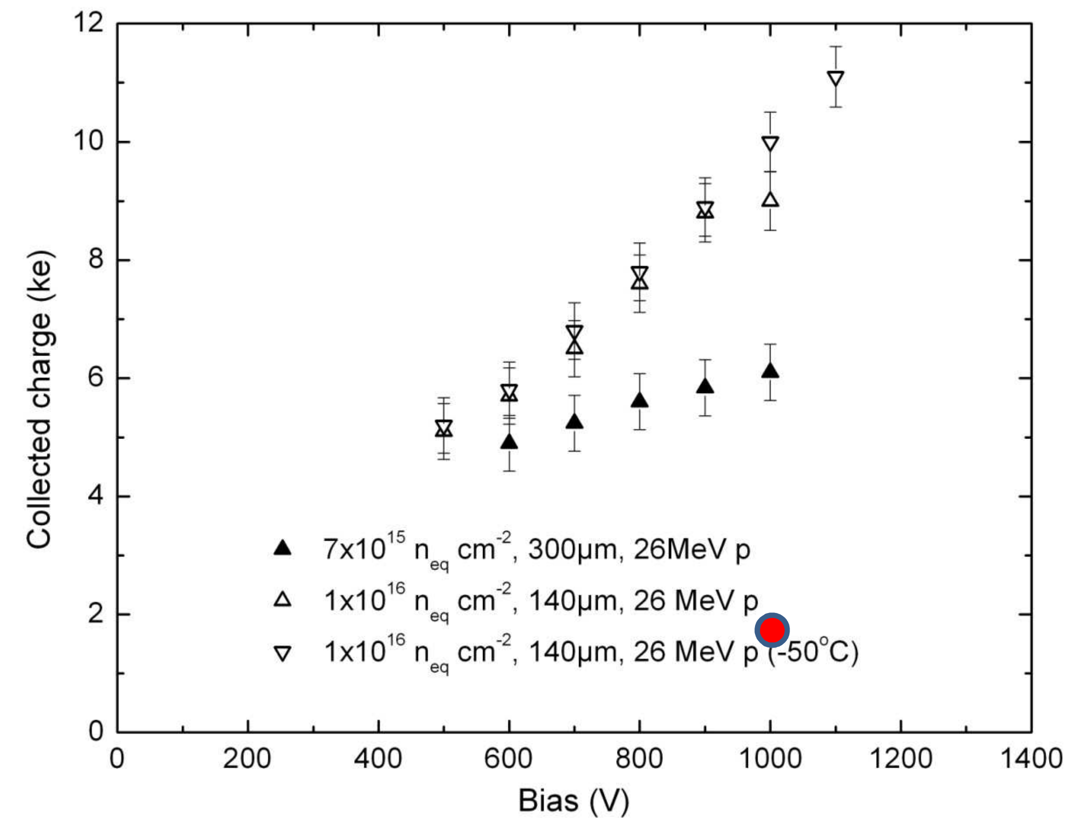




● Maximum expected charge collection from trapping.

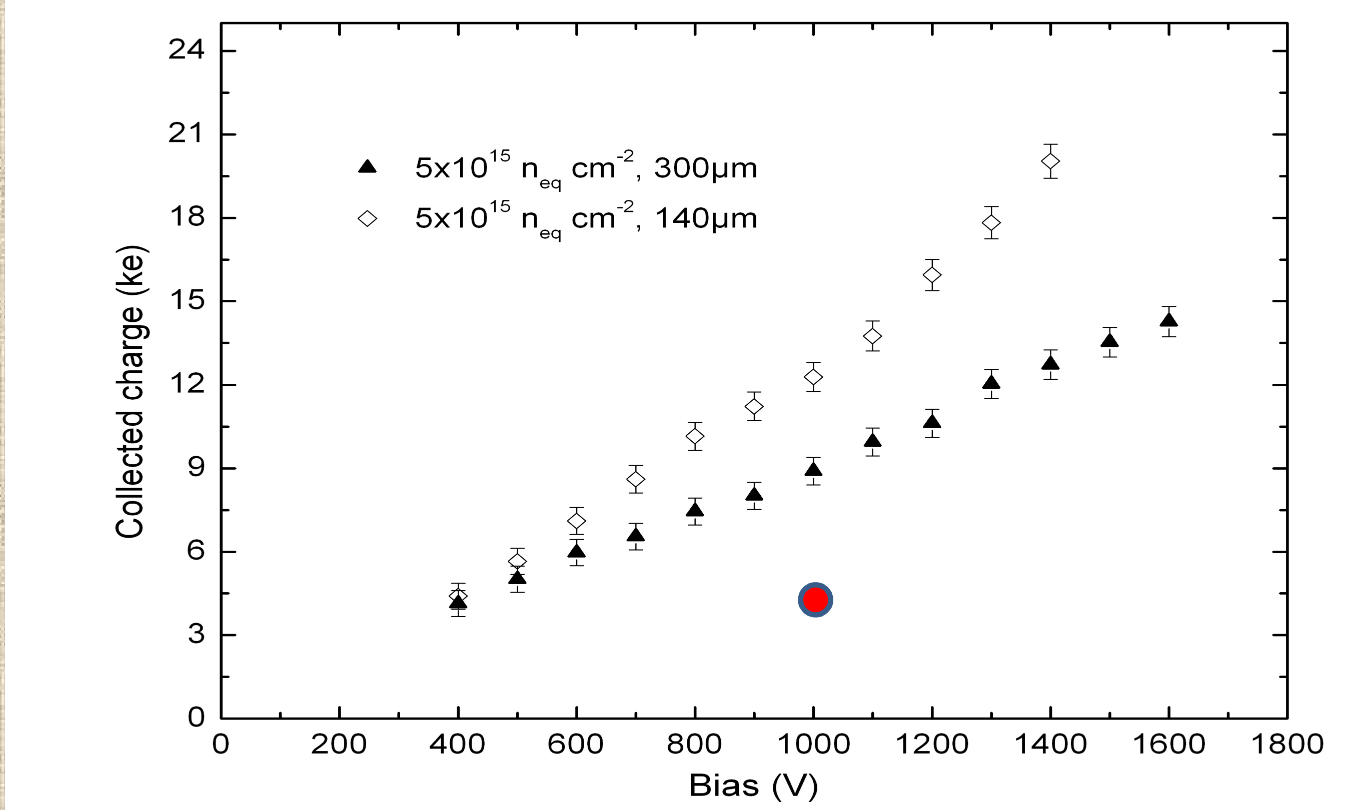
140 and 300 μm n-in-p Micron sensors after $1x10^{16}$ n_{eq} 26MeV p

Even after heavy irradiation it is possible to recover the whole ionised charge (the 140μm thick sensors collects here ~12000e).



140 and 300 μm n-in-p Micron sensors after $5x10^{15}$ n_{eq} 26MeV p

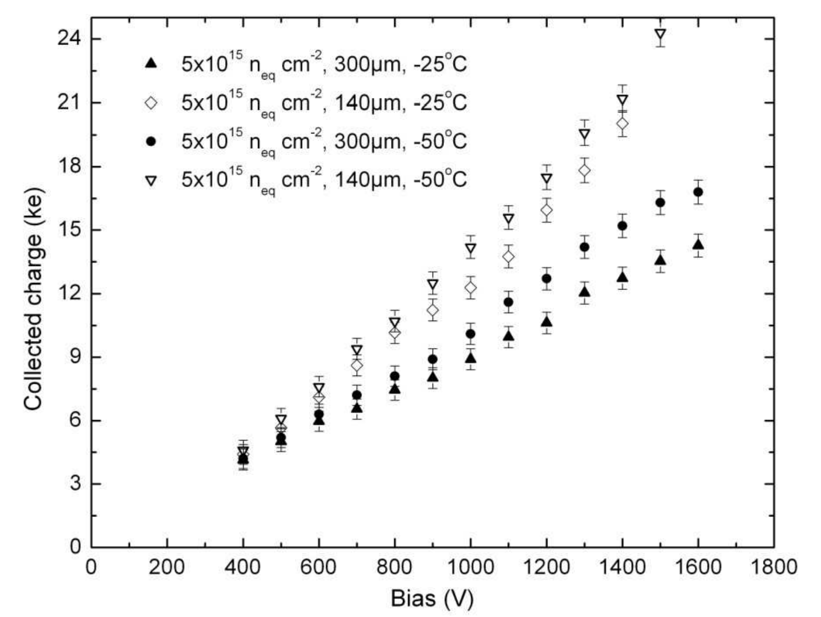
Evidence of a charge multiplication effect: not only the whole charge is recovered, but increased by f = 1.75

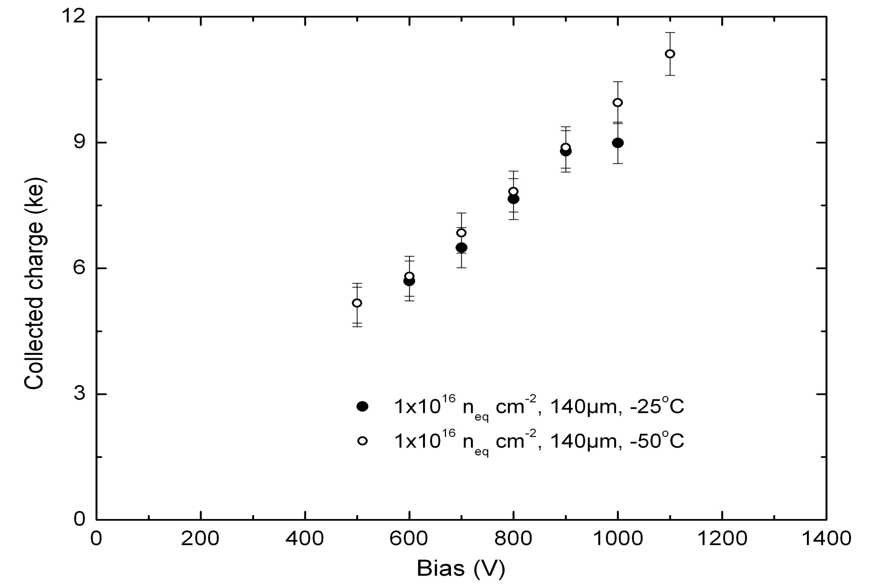


140 and 300 μm n-in-p Micron sensors after 5 (26MeV p) and 10x10^{15} n_{eq} (24GeV/c p) at low (-50°C) T.

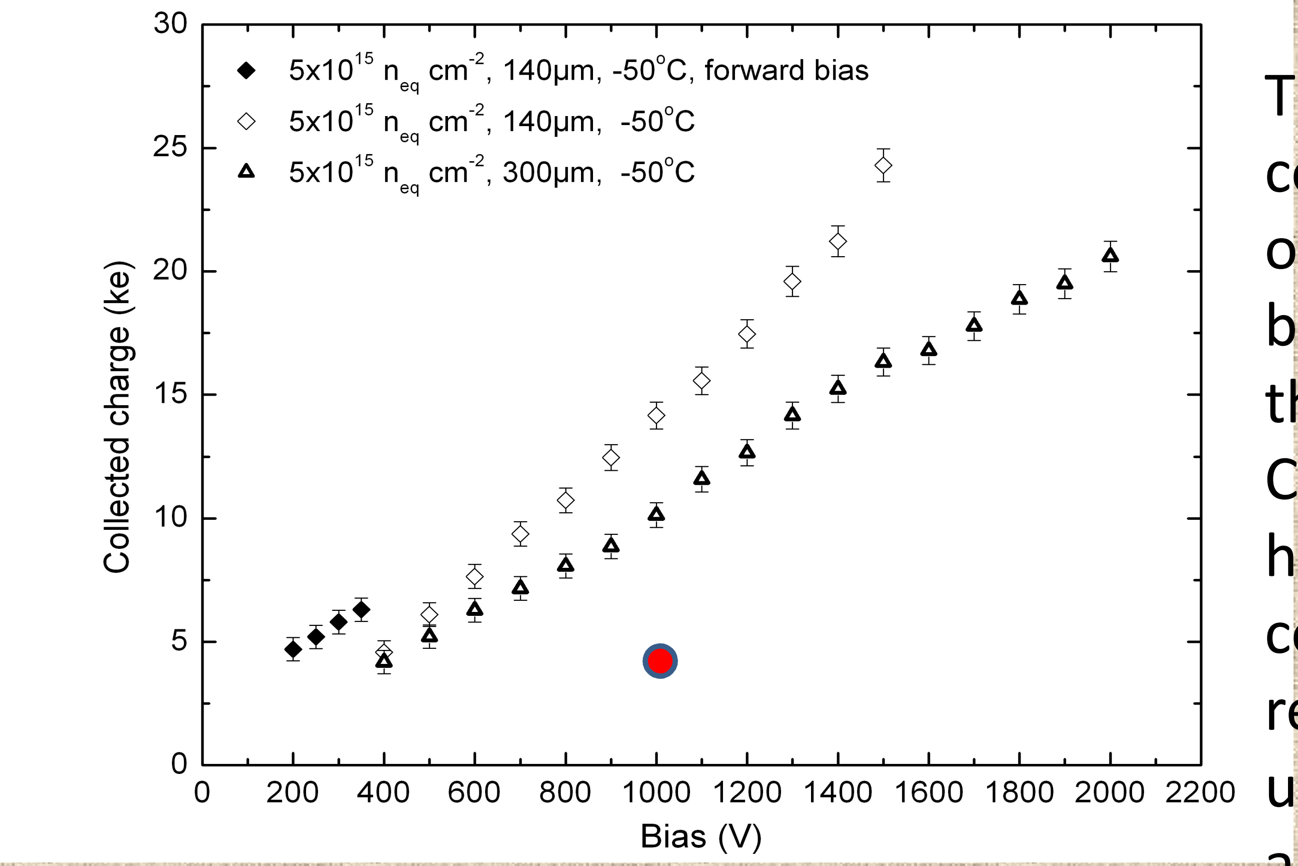
F = 2.1 at -50°C!

Pre-irradiation charge recovered after 1x10^{16} n_{eq}.



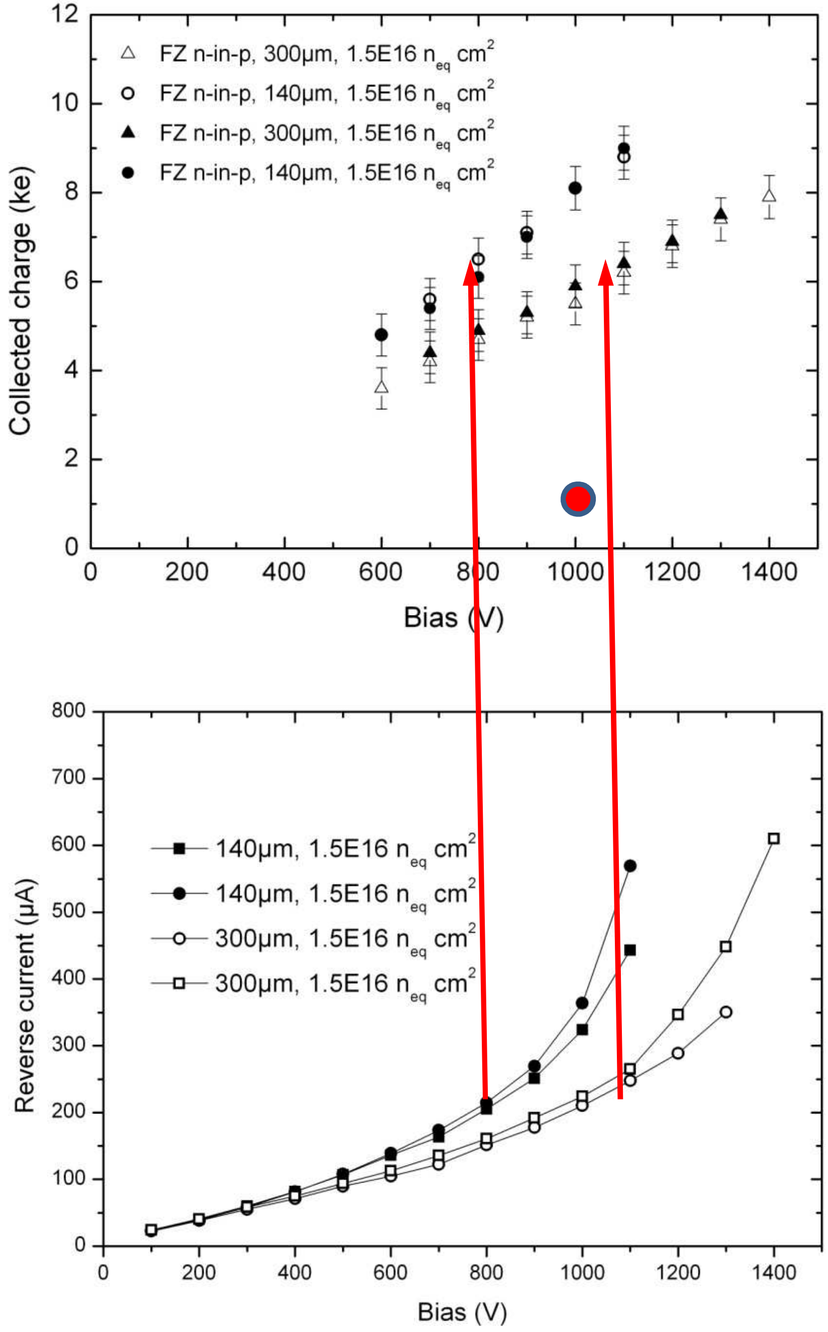


Special effects: forward bias

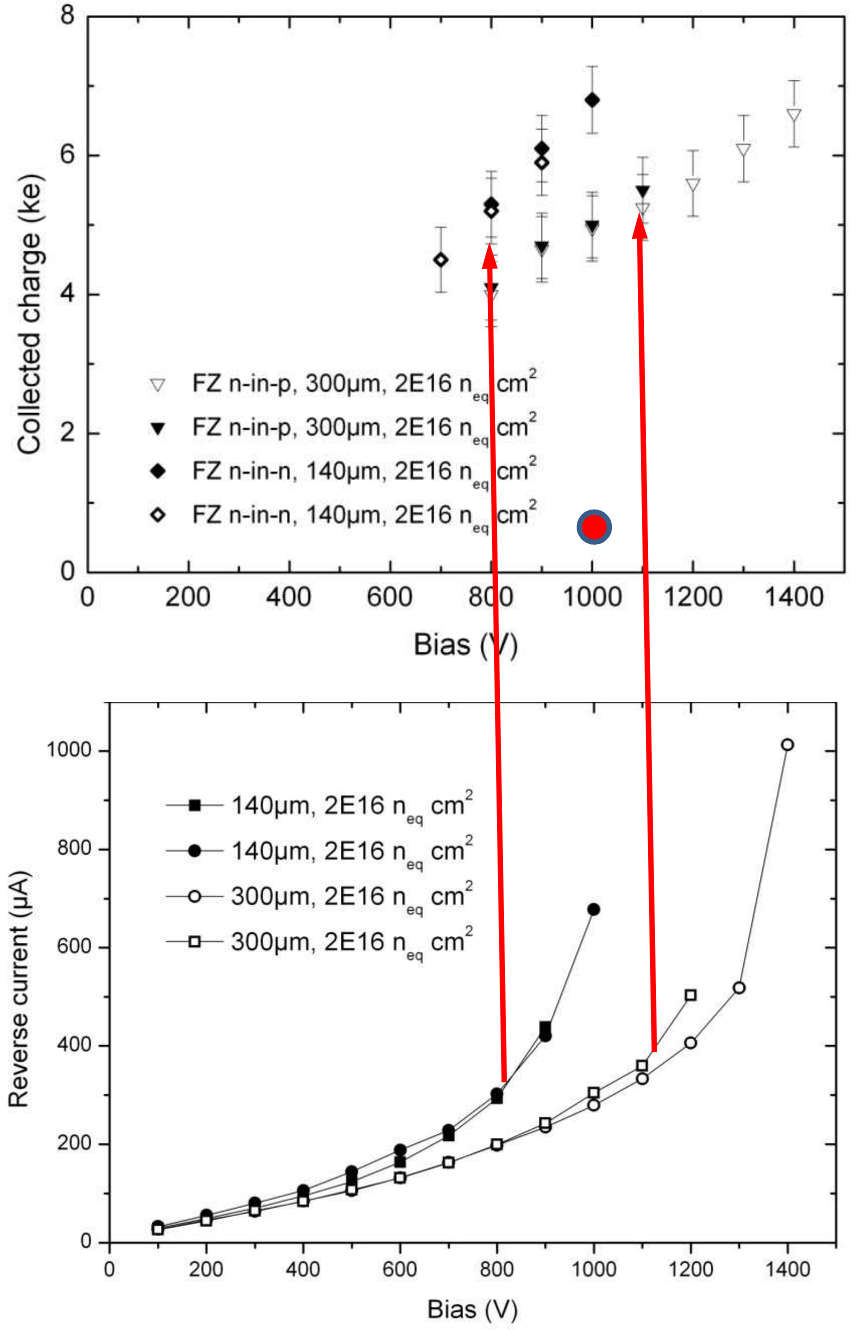


The 140µm detectors could also be operated in forward bias (unlike the thicker devices). The CCE was surprisingly higher than at the corresponding reverse bias voltage, up to the maximum applicable bias before thermal runaway.

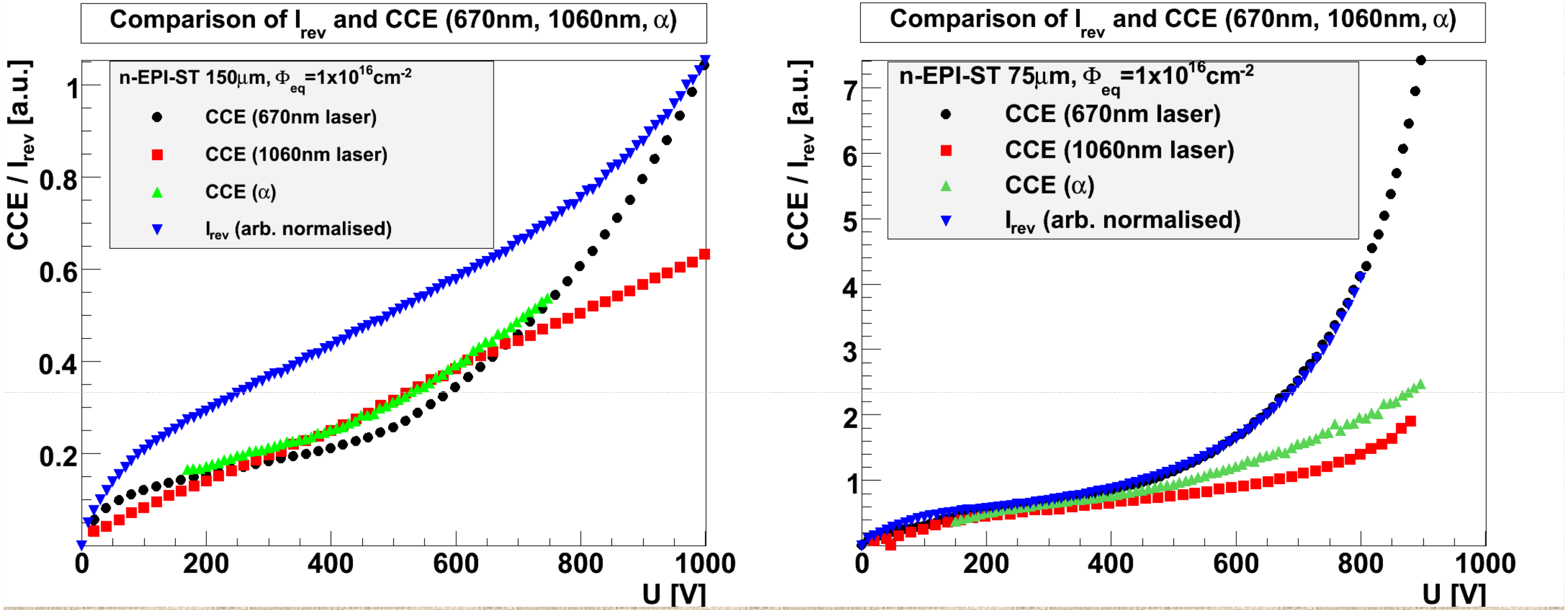
CC(V) and currents after neutron irradiations to $1.5\times10^{16}\ n_{eq}\ cm^{-2}$



CC(V) and currents after neutron irradiations to $2\times10^{16}\ n_{eq}\ cm^{-2}$

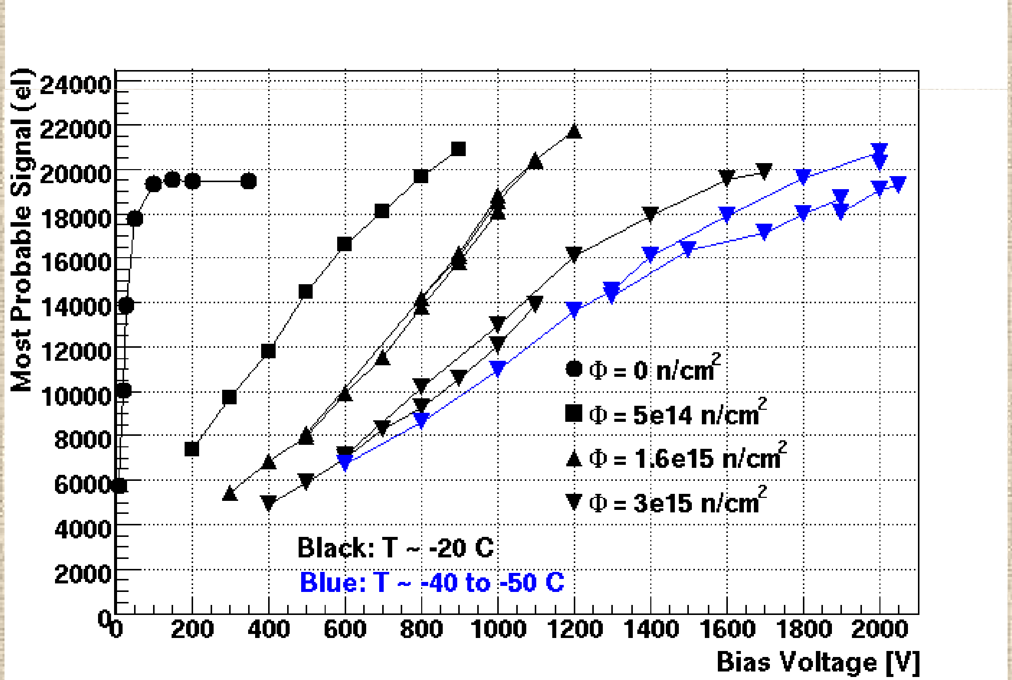


Results with diodes
Comparison CCE (670nm, 1060nm laser, α)



- Smaller penetration depth → stronger charge multiplication (more charge deposited in high-field region; more e instead of h)
- CCE(670nm)- and IV-curves almost identical at high voltages (for 75µm, 10^{16}cm^{-2})

Comment: this multiplication concept took time to sink-in, but it has been a while since the CCE results puzzled us for being much better than expected from the anticipation of trapping. Just remind another direct result of this, from I. Mandic at the 12th RD50 workshop.



CONCLUSIONS

A much enhanced CCE is measured with proton and neutron irradiated diodes (Hamburg) and microstrip sensors (Liverpool and Ljubljana) after extreme doses (equivalent to the anticipated doses for the innermost pixel layers of SLHC).

Even considering a non-linear dependence on fluence of the so called V_{FD}, and under the hypothesis of reduced trapping (non linear dependence on fluence? Field enhanced fast de-trapping?) the charge collected exceed the expectations. A signal with more charge than the ionised amount (x2) in a non irradiated detector has been measured.

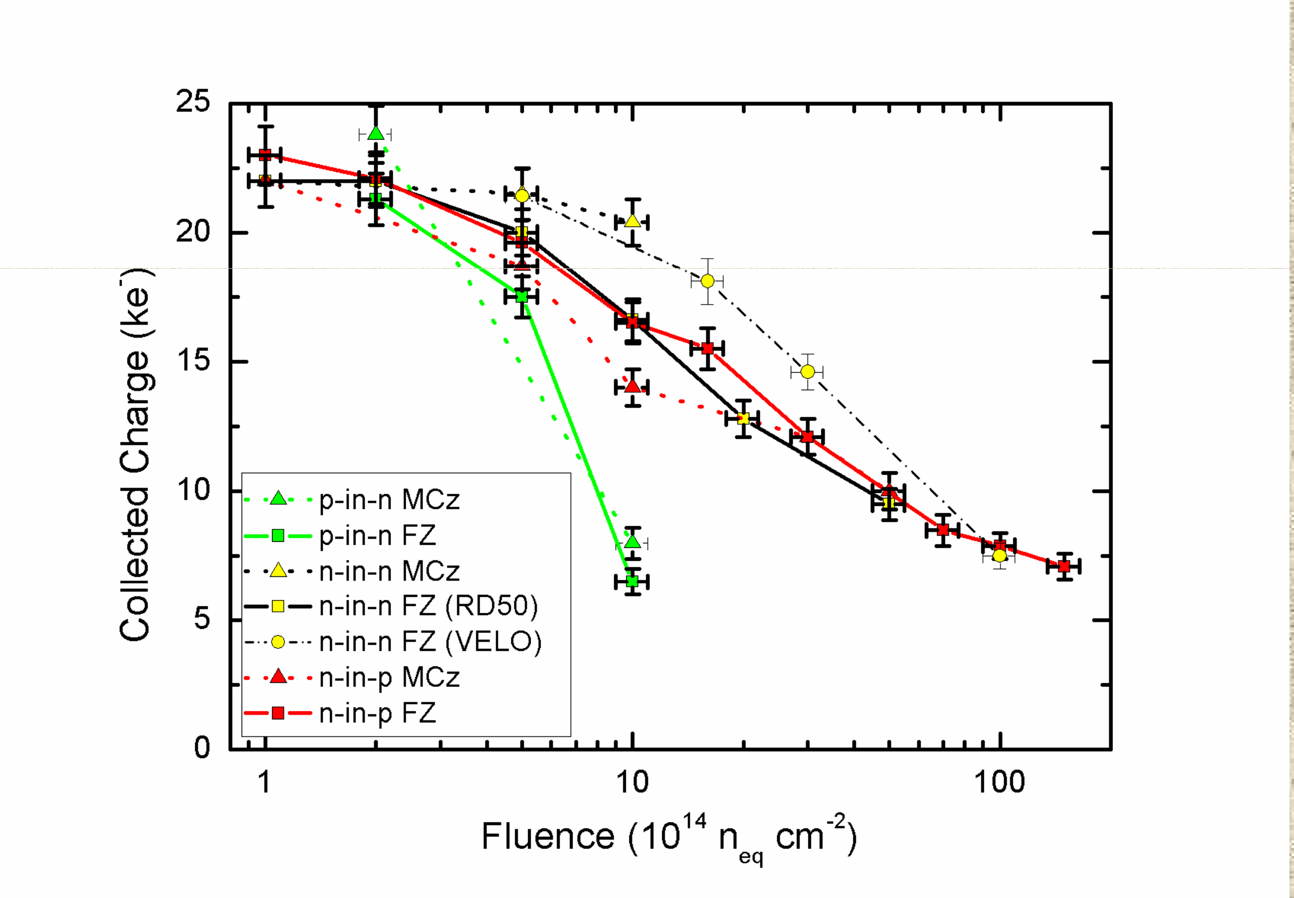
A controlled multiplication is taking place with irradiated microstrip detectors. This opens the possibility of engineering the geometrical parameters of the detectors to increase the radiation tolerance of segmented detectors for applications where extreme hadron radiation damage is expected.

Future work

The similar behaviour of the reverse current and the signal indicate that a stable multiplication process is taking place in irradiated sensors, at high electric fields near the junction. It might be possible to “shape” the electric field by mean of junction engineering (e.g. dose, profile and width of the implants). A dedicated R&D project will be launched within the RD50 collaboration to investigate the possible exploitation of the CM mechanism.

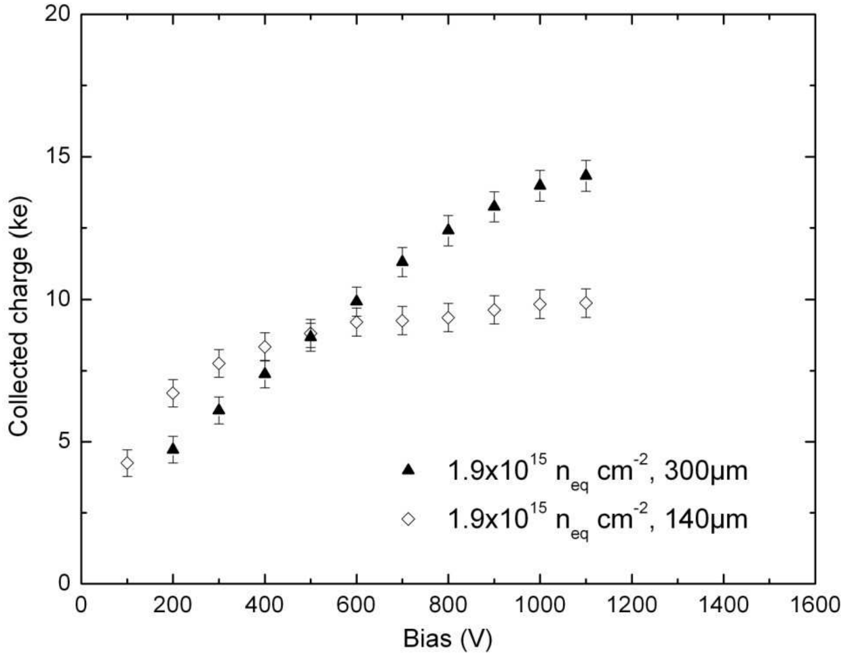
Spare slides

Degradation of the signal as a function of the neutron fluence (measured at 900V) for various type of microstrip sensors up to $2x10^{16}$ n_{eq} cm^{-2}.



140 and 300 μm n-in-p Micron sensors after 1.9 and $3.1\text{x}10^{15}$ n_{eq} 24GeV/c p

Cold(0-5 °C) irradiation



Room T (29-31 °C) irradiation