Charge Collection Efficiencies of Planar Silicon Detectors after Reactor Neutron, Pion and Proton Doses up to $2.2\times10^{16}\ n_{eq}\ cm^{-2}$

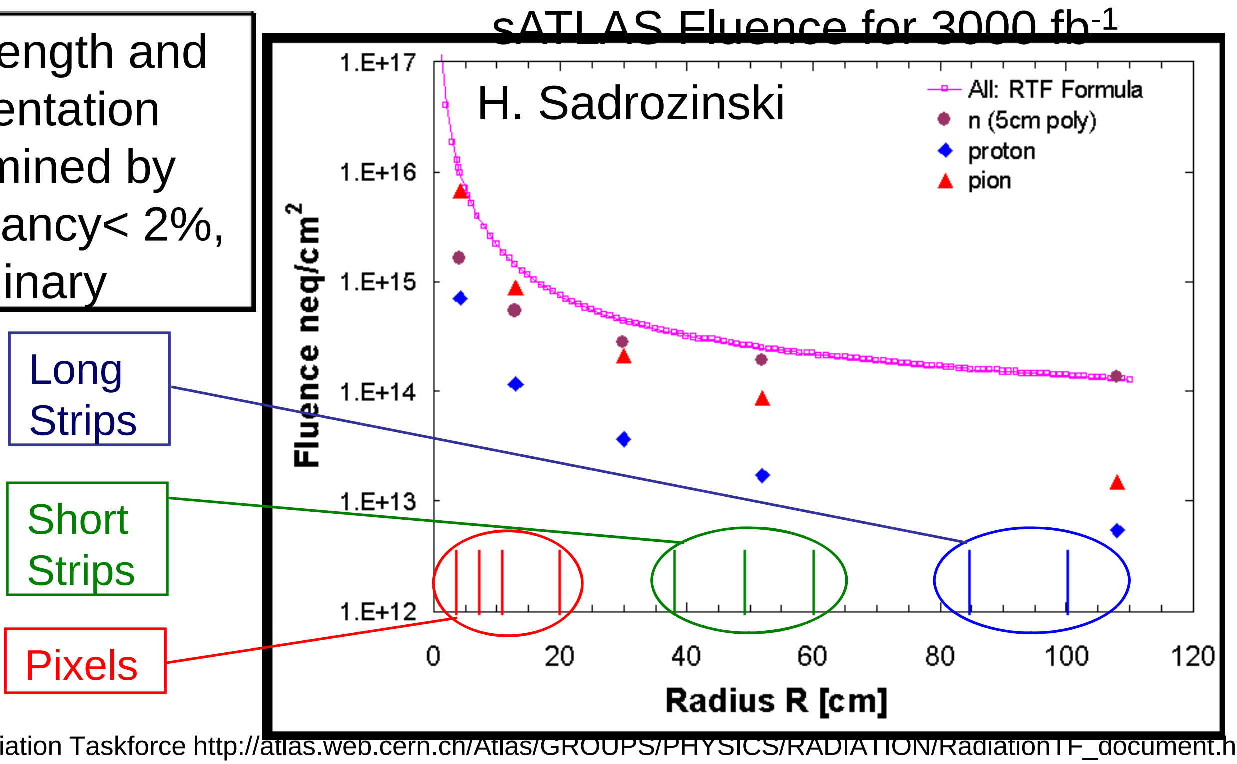
A. Affolder, P. Allport, G. Casse
University of Liverpool

Purpose of this Study

- Investigate the radiation hardness with respect to charge collection for the different implant configurations and silicon bulk materials available
  - FZ vs. MCz bulk
  - n-type vs. p-type bulk
  - n-strip vs. p-strip readout
- Determine which technology is best for the various regions of a SLHC upgrade
  - Using dominant damage source (charged/neutrals)
    - Charged irradiations from multiple sources needed to give the complete picture

Fluence in Proposed sATLAS Tracker

Strip length and segmentation determined by occupancy< 2%, preliminary



Long Strips

Short Strips

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

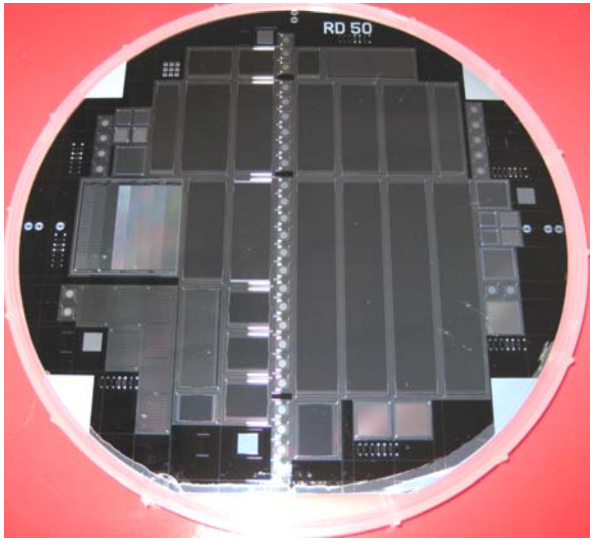
Pixels damage due to neutrons and pions

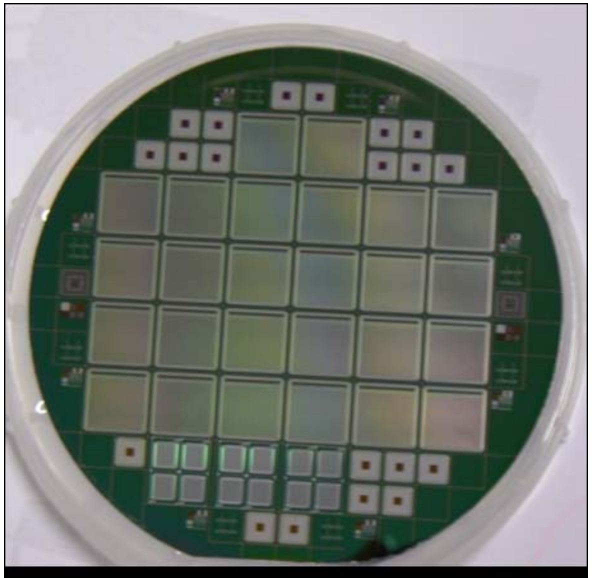
Design fluences for sensors (includes 2x safety factor) **:**

B-layer (R=3.7 cm):	2.5×10^{16} n_{eq}/cm^2 = 1140 Mrad
2nd Inner Pixel Layer (R=7 cm):	7.8×10^{15} n_{eq}/cm^2 = 420 Mrad
1st Outer Pixel Layer (R=11 cm):	3.6×10^{15} n_{eq}/cm^2 = 207 Mrad
Short strips (R=38 cm):	6.8×10^{14} n_{eq}/cm^2 = 30 Mrad
Long strips (R=85 cm):	3.2×10^{14} n_{eq}/cm^2 = 8.4 Mrad

Need to study response to <u>both</u> neutral (neutrons) and charged (proton) particle irradiations

Miniature Silicon Micro-strip Sensors





Microstrip, ~1x1 cm^2, 100-128 strips, 75-80 µm pitch, ~300µm thickness

Micron/RD50 (4” & 6” wafers)

Detector designed and produced within RD50 framework

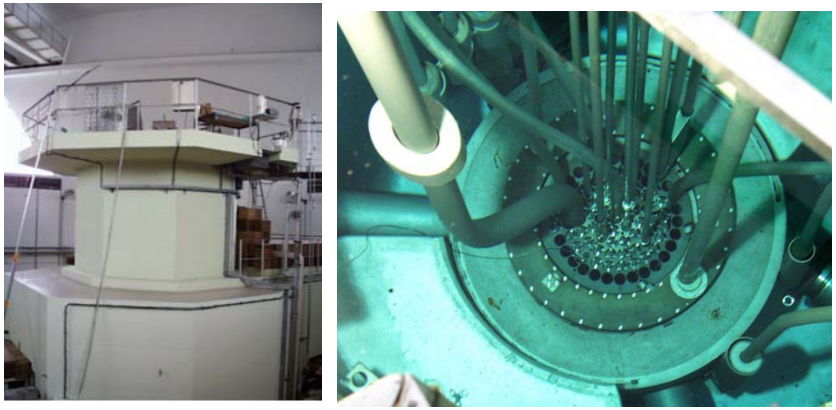
RD50 mask (see: http://rd50.web.cern.ch/rd50/)

- n-in-p FZ (V_{FD} ~15V/~70 V)
- n-in-n FZ (V_{FD}~10 V)
- p-in-n FZ (V_{FD} ~10V)
- n-in-p MCz (V_{FD}~550 V)
- n-in-n MCz (V_{FD}~170 V)
- p-in-n MCz (V_{FD} ~170 V)

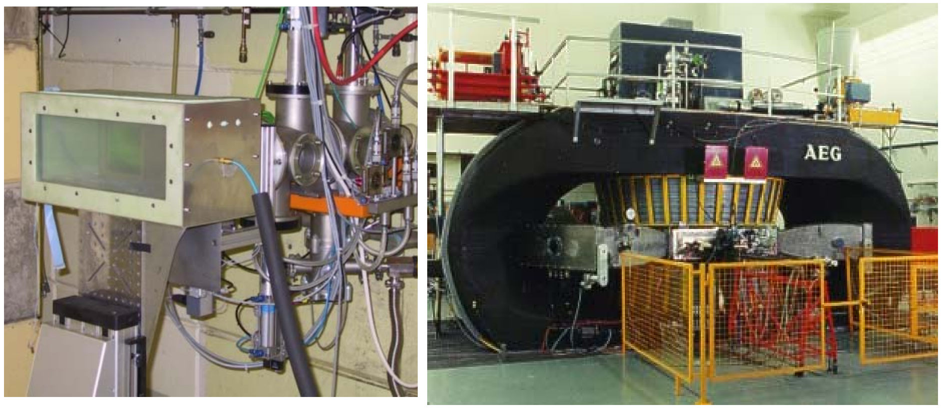
Micron/VELO test structures

- n-in-n FZ (V_{FD} ~70V)

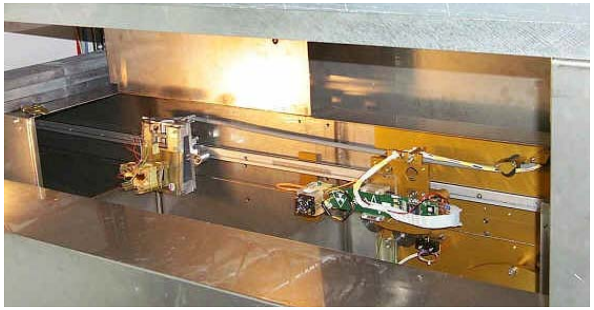
Irradiation Sources

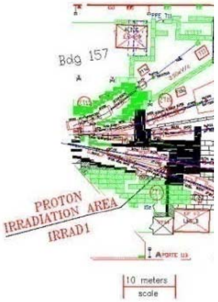


Irradiation and dosimetry (Neutrons):
Triga Reactor, Jozef Stefan Institute,
Ljubljana, Slovenia: **V. Cindro, et. al.**

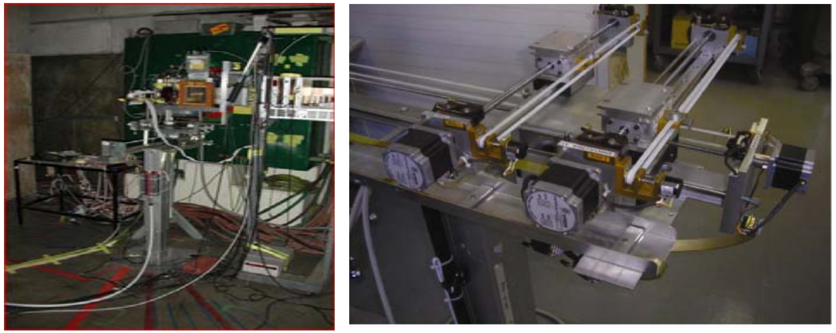


Irradiation and dosimetry (26 MeV Protons):
Compact Cyclotron, Karlsruhe, Germany:
W. de Boer, A. Dierlamm, et. al.





Irradiation and dosimetry (24 GeV Protons):
CERN PS Irrad1 facility, Geneva Switzerland:
M. Glaser, et. al.



Irradiation and dosimetry (280 MeV/c Pions):
Paul Scherrer Institut, Switzerland:
M. Glaser, T. Rohe, et. al.

Experimental Setup

- Charge collection efficiency (CCE) measured using an analogue electronics chip (SCT128) clocked at LHC speed (40MHz clock, 25ns shaping time).
  - Measurements performed in chest freezer at a temperature of ~-25 °C with N_2 flush

- ^{90}Sr fast electron source triggered with scintillators in coincidence used to generate signal.

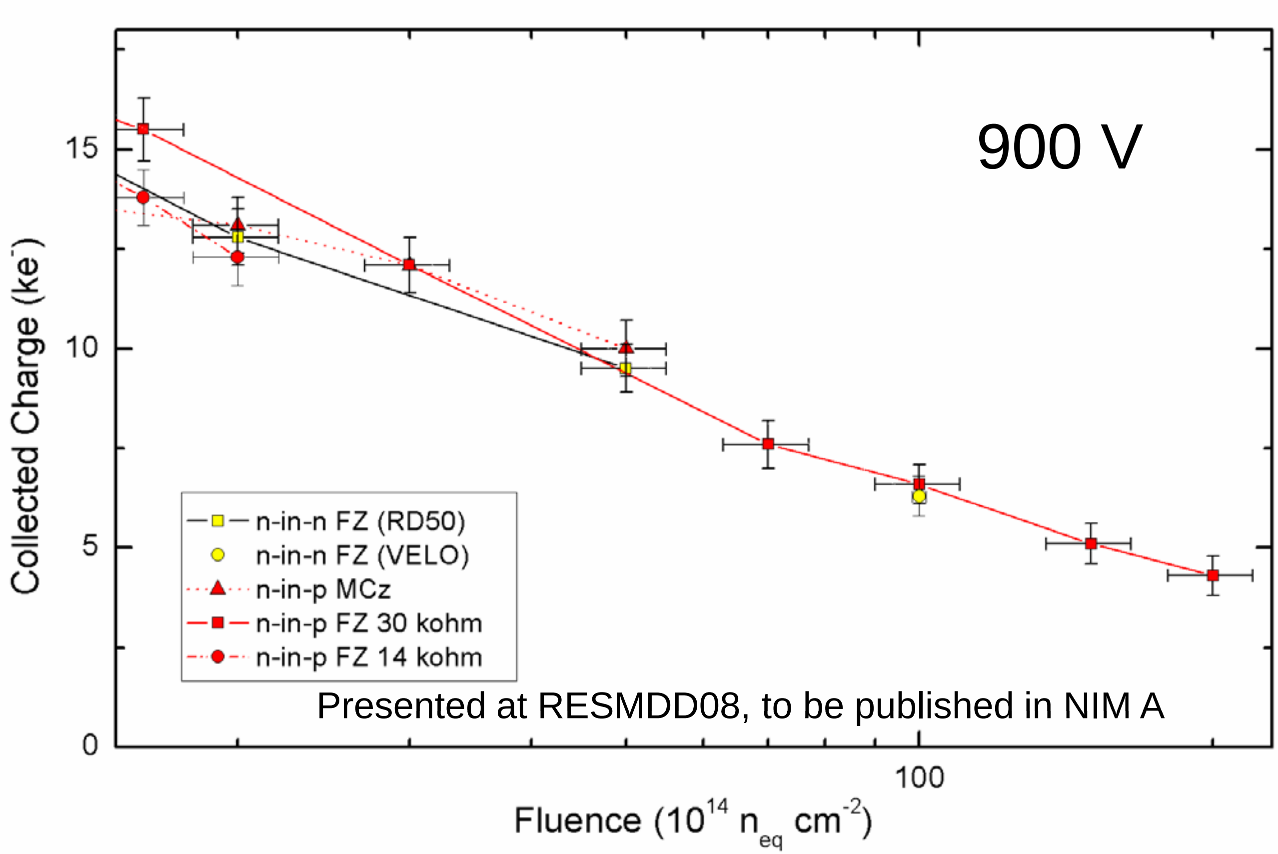
- The system is calibrated to the most probable value of the MIP energy loss in a non-irradiated 300µm thick detector (~23000 e^-).

Neutron Comparison

From previous studies we know:

- After ~5×10^{14} n cm^{-2}, n-in-n FZ, n-in-p FZ, n-in-p MCz very similar
- At higher voltage, n-in-n MCz superior up to maximum fluence (10^{15} n cm^{-2})
  - Need higher fluence data to determine if this continues
- p-in-n shows inferior performance as expected

Dominant source of damage at radii >30 cm



Presented at RESMDD08, to be published in NIM A

Appears once trapping dominates, all n-strip readout choices studied are the same after neutron irradiation

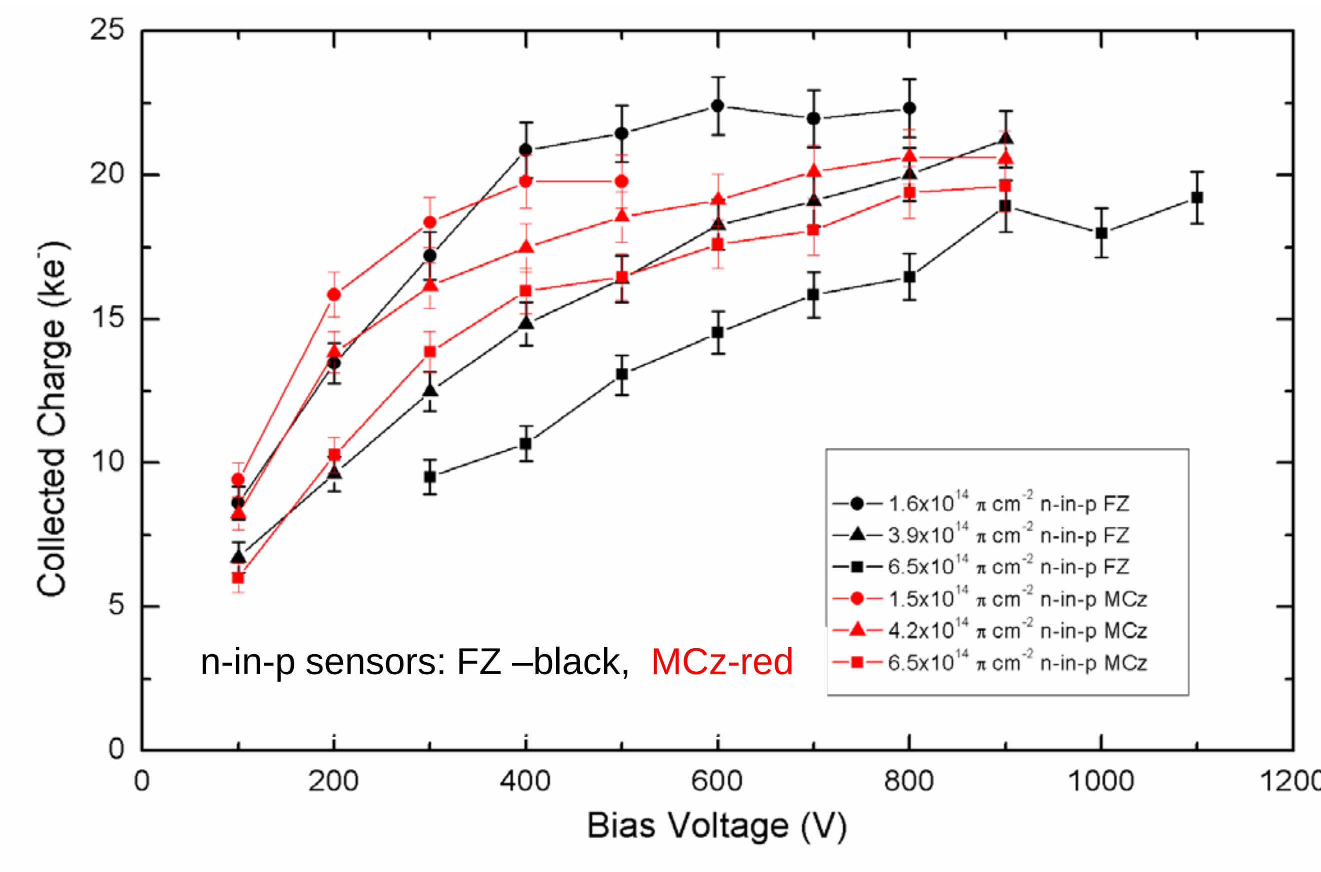
Charged Irradiation Sources

- 280 MeV Pions
  - ✓ Dominant source inside 20 cm
  - ✗ Low momenta
  - ✗ Low total dose (<1 10^{15} n_{eq} cm^{-2})
  - ✗ Annealing during irradiation
    Environment ~24 C
- 24 GeV Protons
  - ✗ Not the dominant source of damage
  - ✓ High energy charged particles
  - ✓ Higher flux, higher total dose
    - ✗ Long Irradiations
      - Flux: 1-2 10^{13} cm^{-2} h^{-1}
    - ✗ Limited periods during the year
  - ✗ Annealing during irradiation
    - Environment ~30 C
- 26 MeV Protons
  - ✗ Not the dominant source of damage
  - ✗ Low energy
  - ✓ Extremely high flux/total dose
    - Flux: 1-3 10^{15} cm^{-2} h^{-1}
  - ✓ Easy access
  - ✓ No/little annealing during irradiation

Need to combine information from all 3 sources. Confirm hardness factors at low fluence with pions and extend to highest fluences

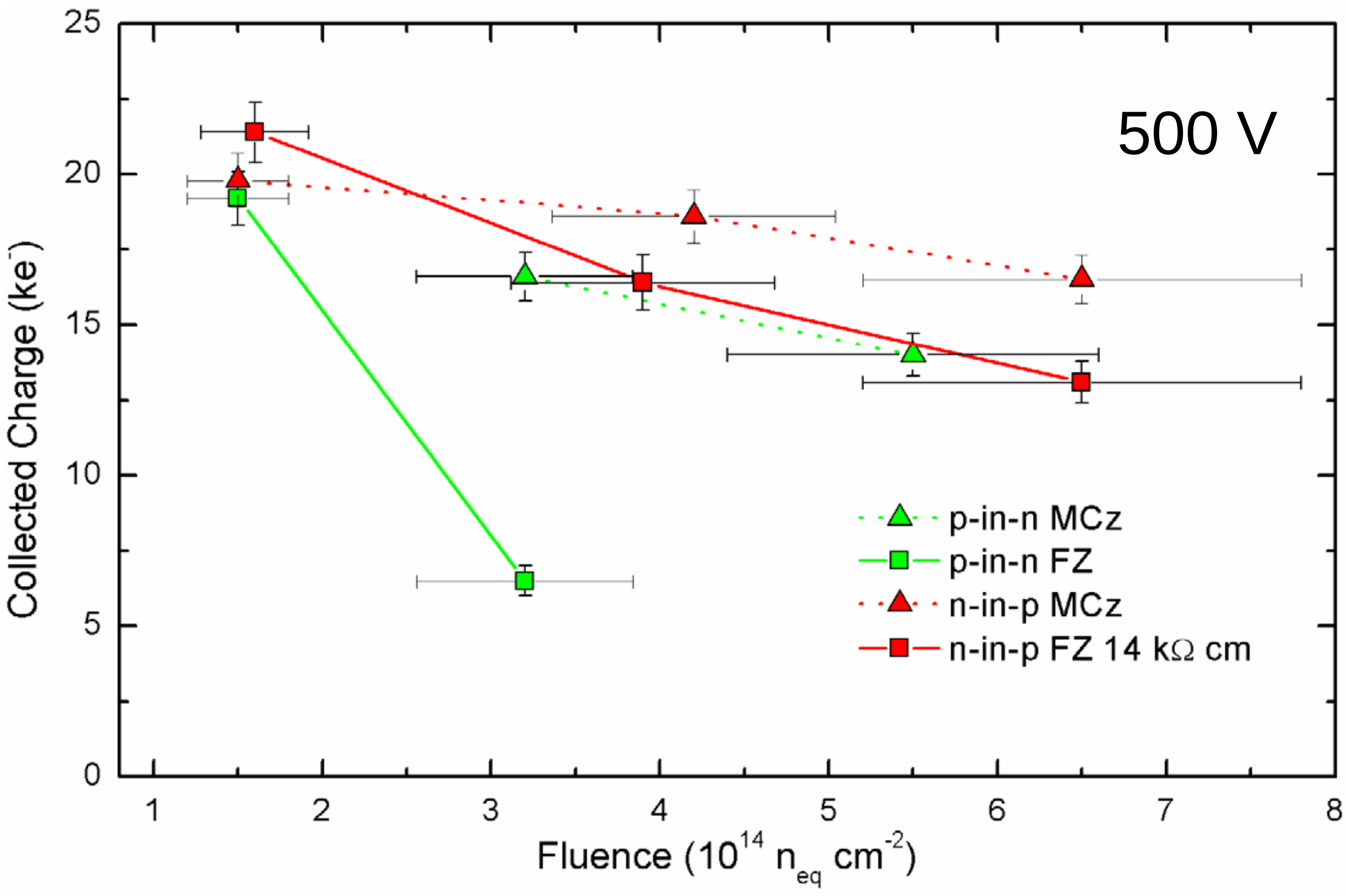
Pion Irradiations

- p-in-n
  - MCz significantly better than FZ
  - FZ insufficient CCE for tracking $>5\times10^{14}\ n_{eq}\ cm^{-2}$
- n-in-p
  - MCz better than FZ as expected



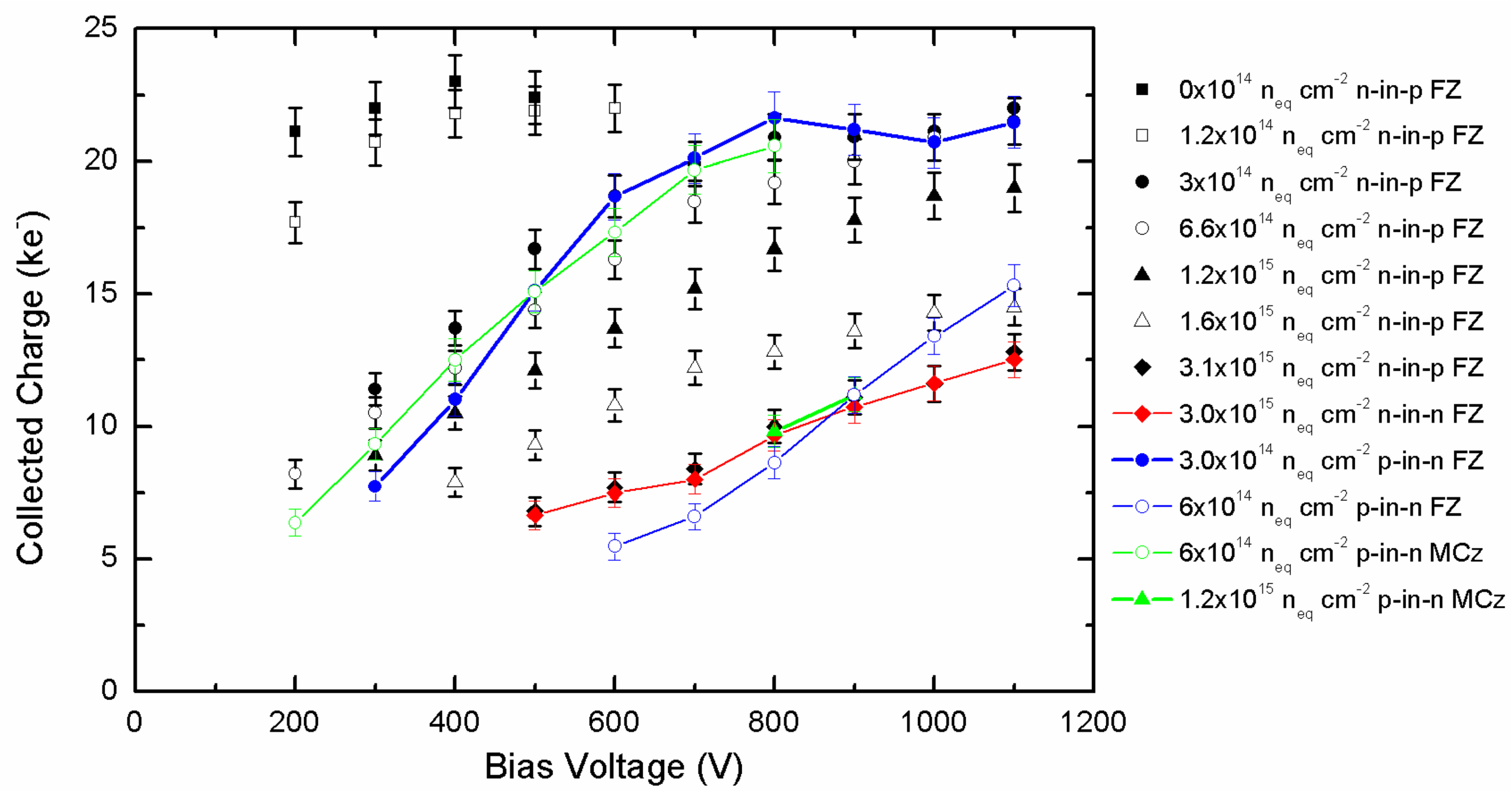
Significant annealing during irradiation
For highest doses, 13 days at 24 C°

Pion Summary



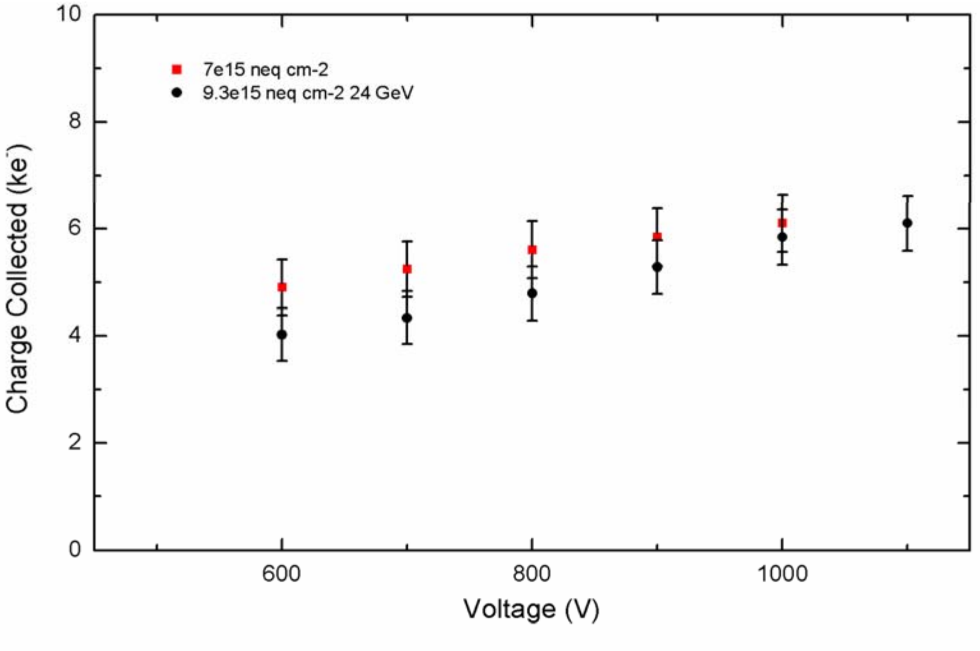
For the limited fluences achievable, p-in-n MCz similar to n-strip readout.
p-in-n FZ detectors would not be acceptable anywhere in the SLHC trackers

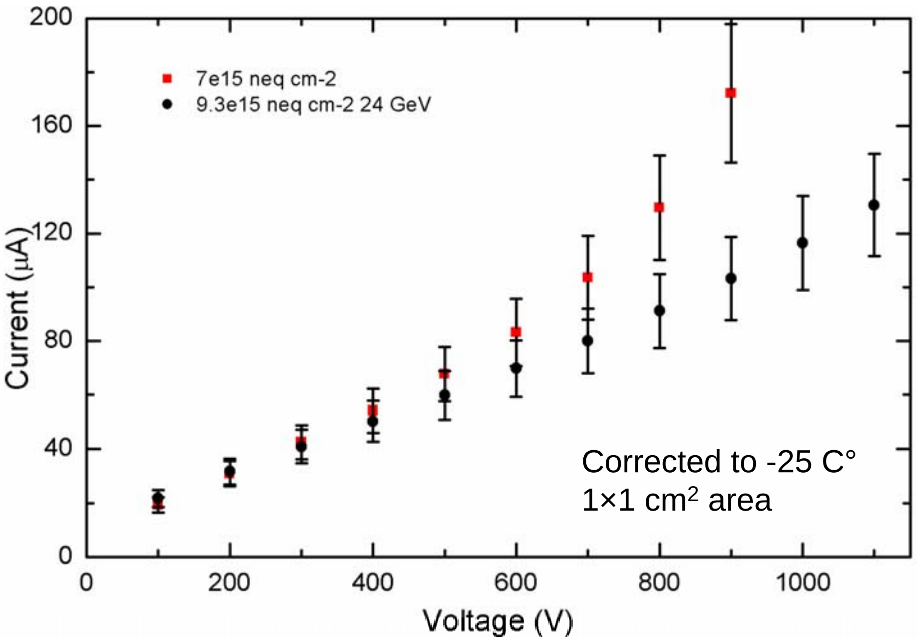
Warm 24 GeV Proton Irradiations



Limited number of devices studied for far

Proton Hardness Comparison





- After hardness correction, IV and CCE agree for both cooled irradiations sources (24 GeV CERN PS and 26 MeV Karlsruhe) with n-in-p FZ devices
  - Roughly ±10% error in fluence at CERN, ±20% error at Karlsruhe, ±0.5 C° error in temperature during measurement
- Gives indication the low energy protons can be used for radiation tolerance studies

26 MeV Proton Irradiations

p-in-n

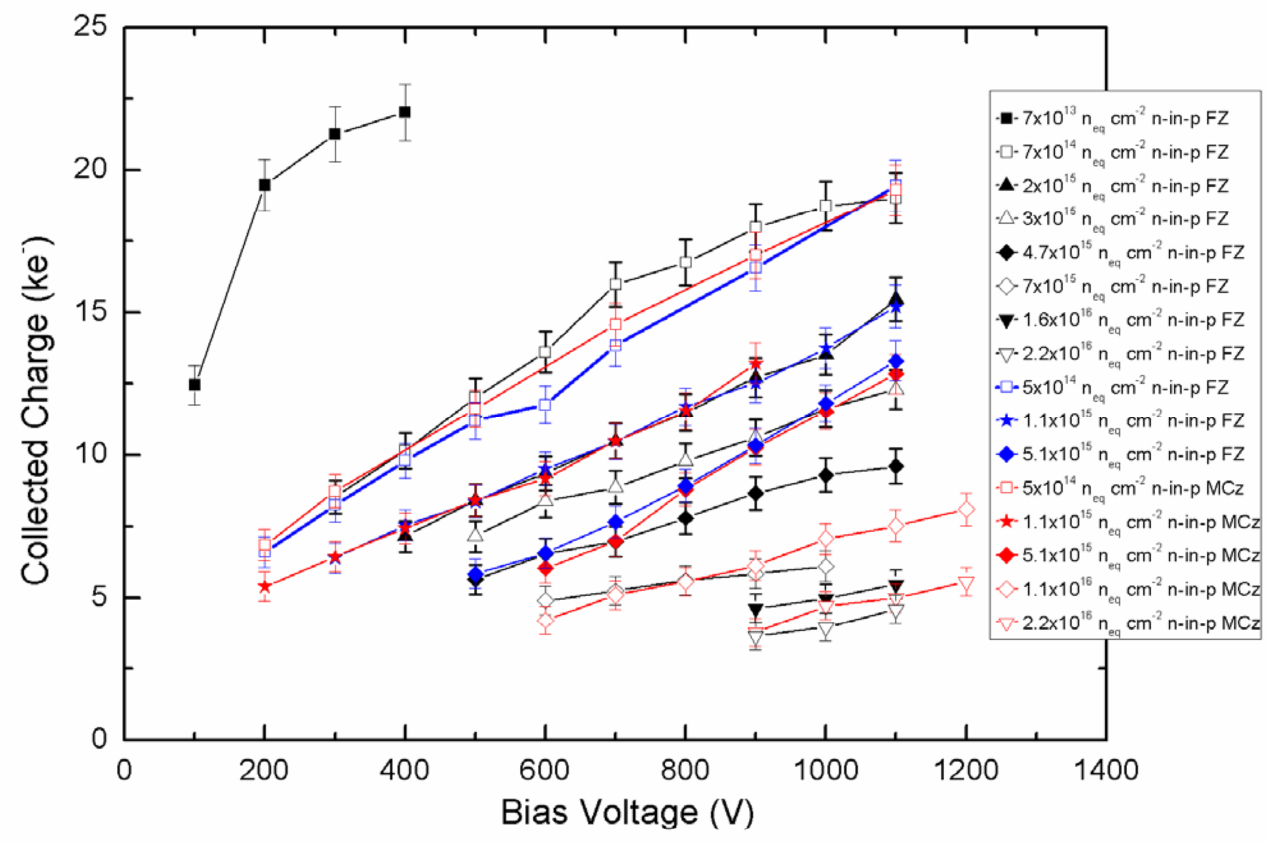
- MCz better than FZ
- Insufficient CCE for tracking $>10\times10^{14}$ n cm^{-2}

n-in-n

- MCz similar to FZ for piece measured
- *Charge seen after $2.2\times10^{16}\ n_{eq}\ cm^{-2}$*

n-in-p

- FZ and MCz similar response
- *Charge seen after $2.2\times10^{16}\ n_{eq}\ cm^{-2}$*



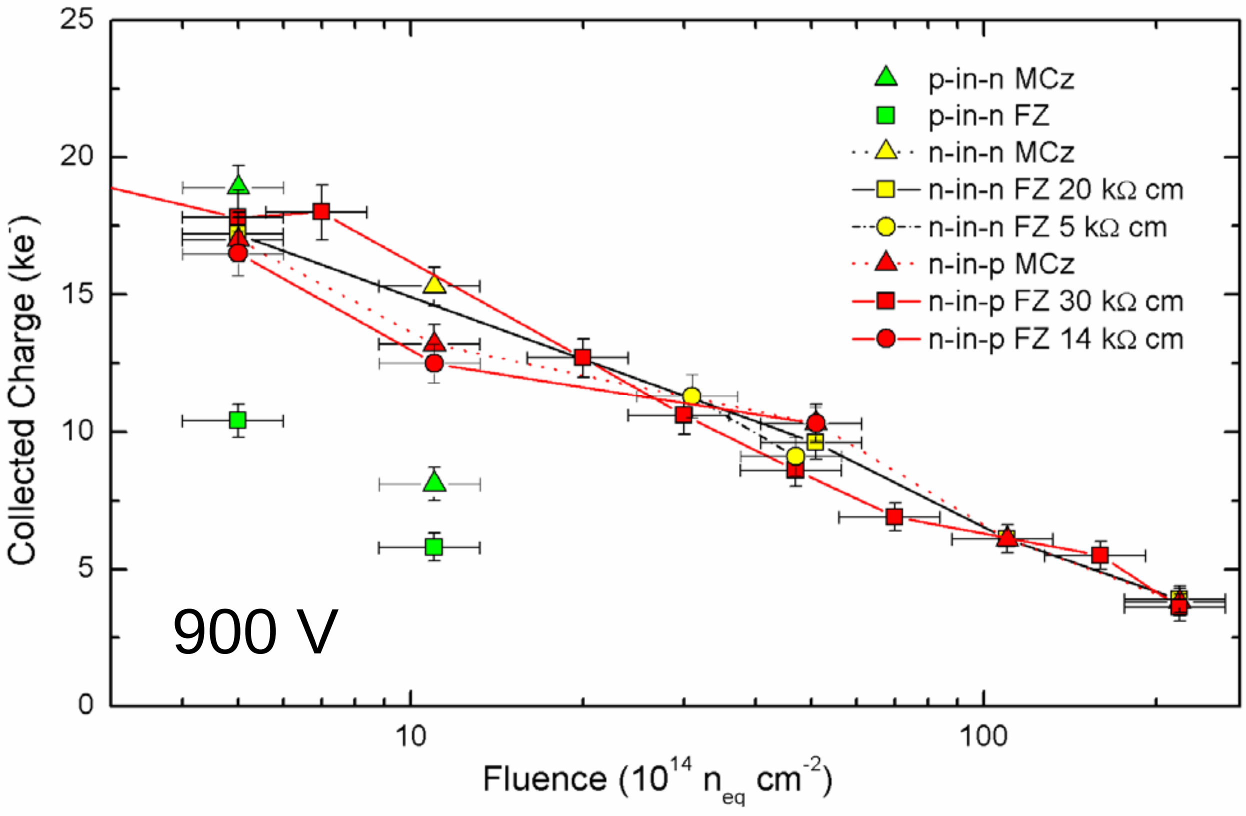
p-in-n sensors: FZ–black, MCz-red

Charge seen with n-strips after $2.5\times10^{16}\ n_{eq}\ cm^{-2}$

(expected maximum dose of innermost devices at SLHC)

26 MeV Proton Summary

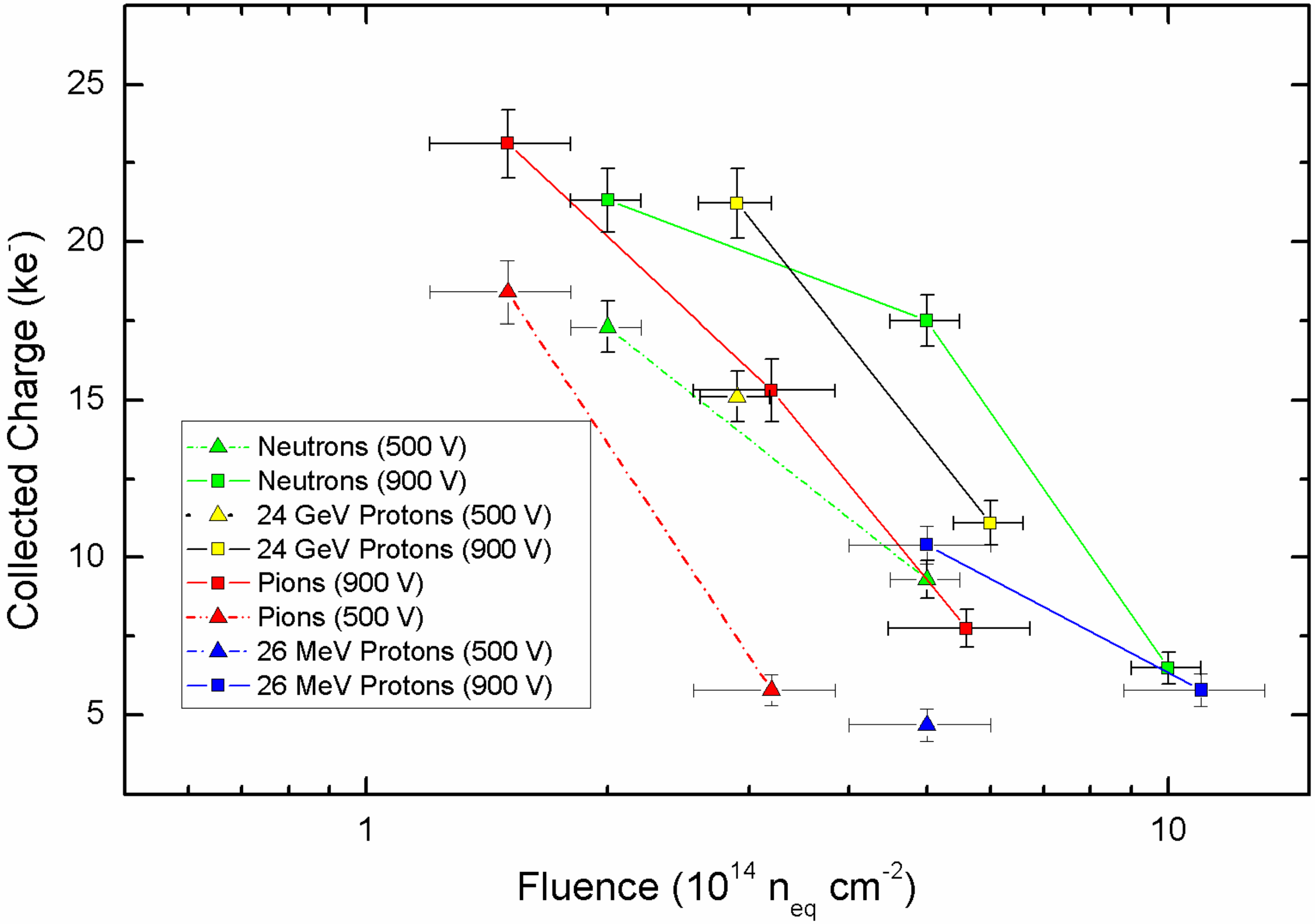
- All n-strip readout devices give similar results
  - Need low fluence data to see if V_{FD} effects significant
- p-in-n shows inferior performance as expected



Appears once trapping dominates, all n-strip readout choices studied are the same after 26 MeV protons irradiation as well

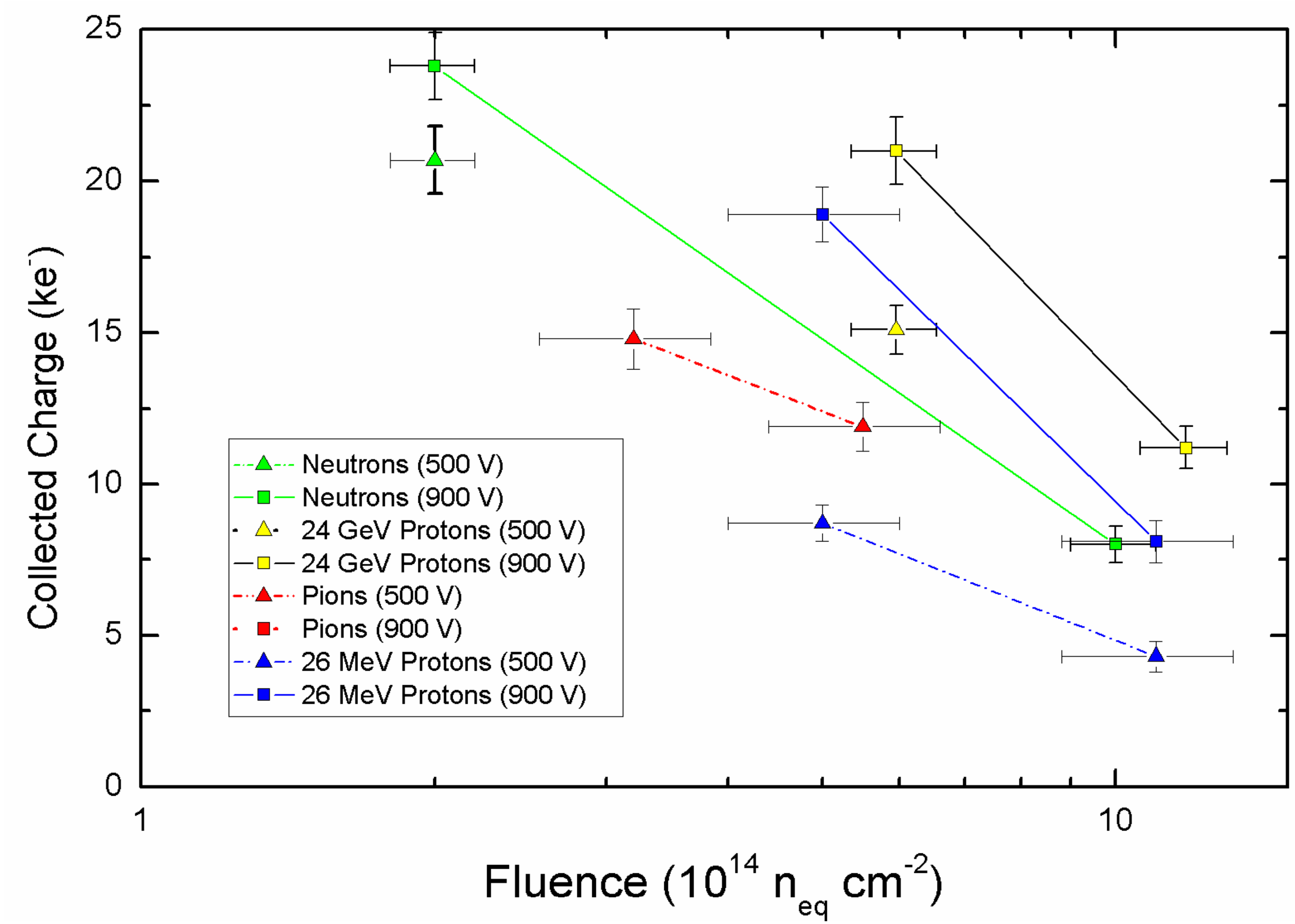
p-in-n FZ Irradiation Summary

p-in-n FZ has significant decrease in CCE $>5\times10^{14}$ n_{eq} cm^{-2}



p-in-n MCz Irradiation Summary

More radiation hard than p-in-n FZ, but still fails at $>10^{15}\ n_{eq}\ cm^{-2}$

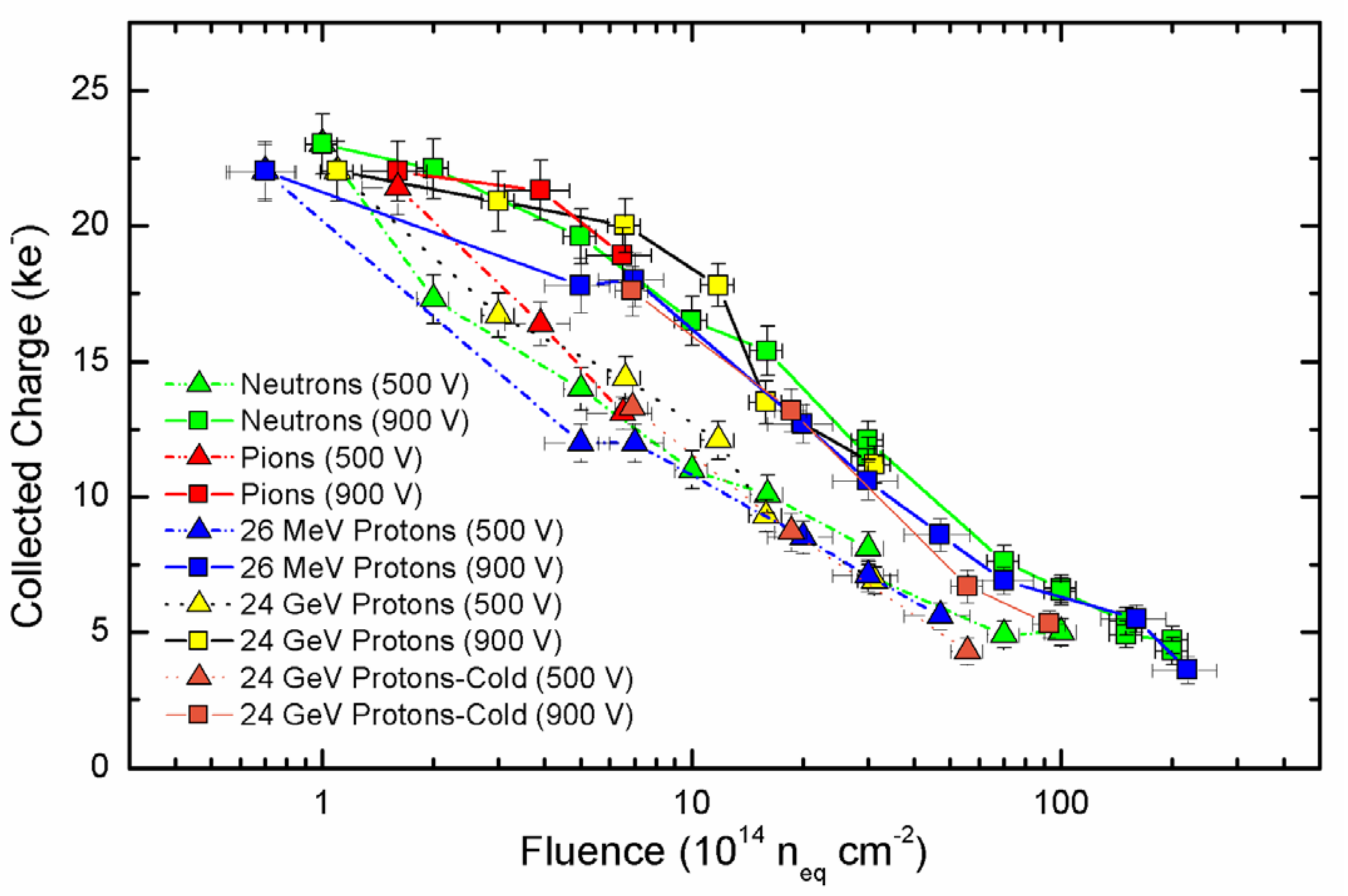


n-in-p FZ Irradiation Summary

Results after neutron, pion, and proton irradiations are very similar

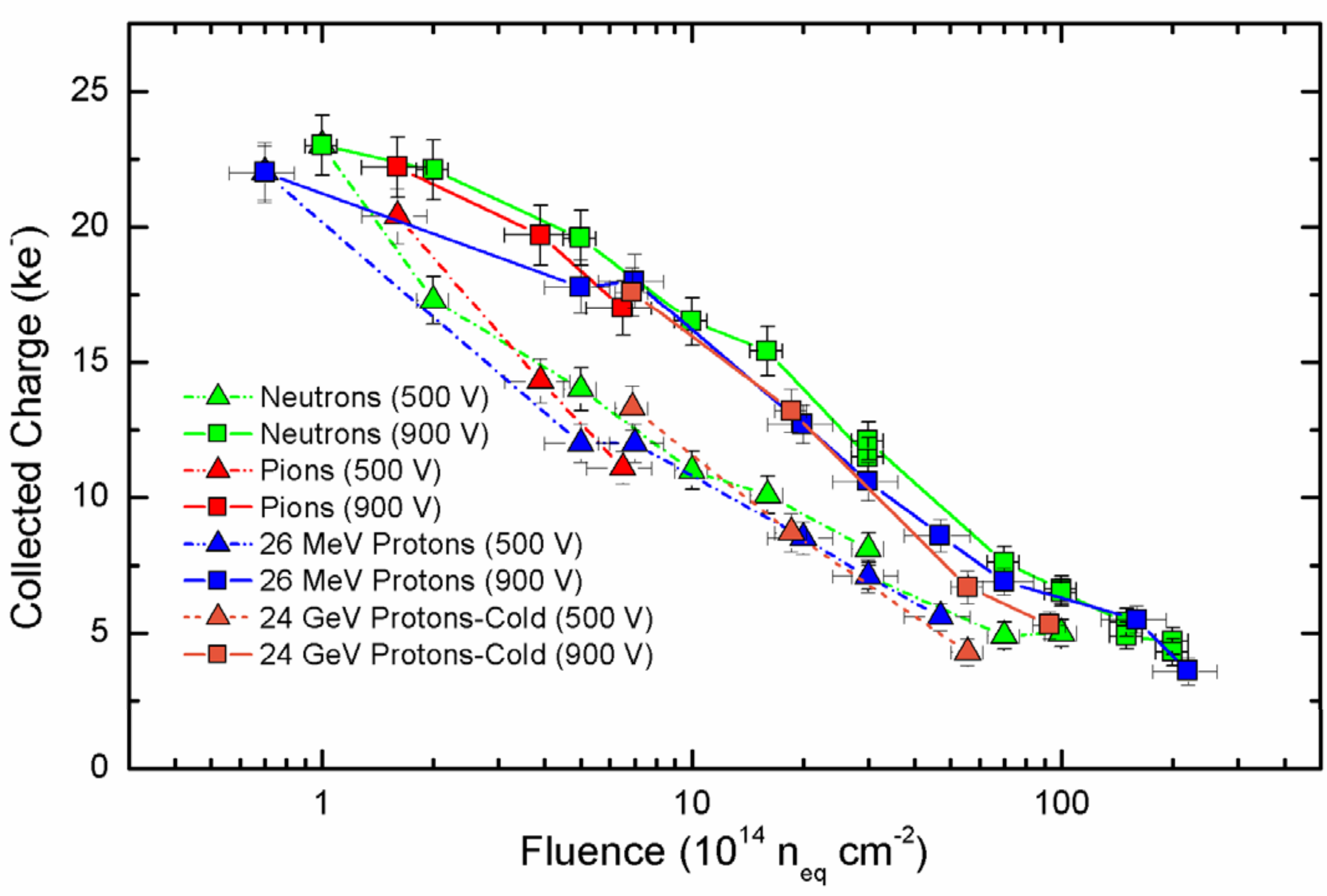
- Pions and 24 GeV protons have significant annealing

Charge collected may be sufficient at inner-most layer of SLHC upgrades



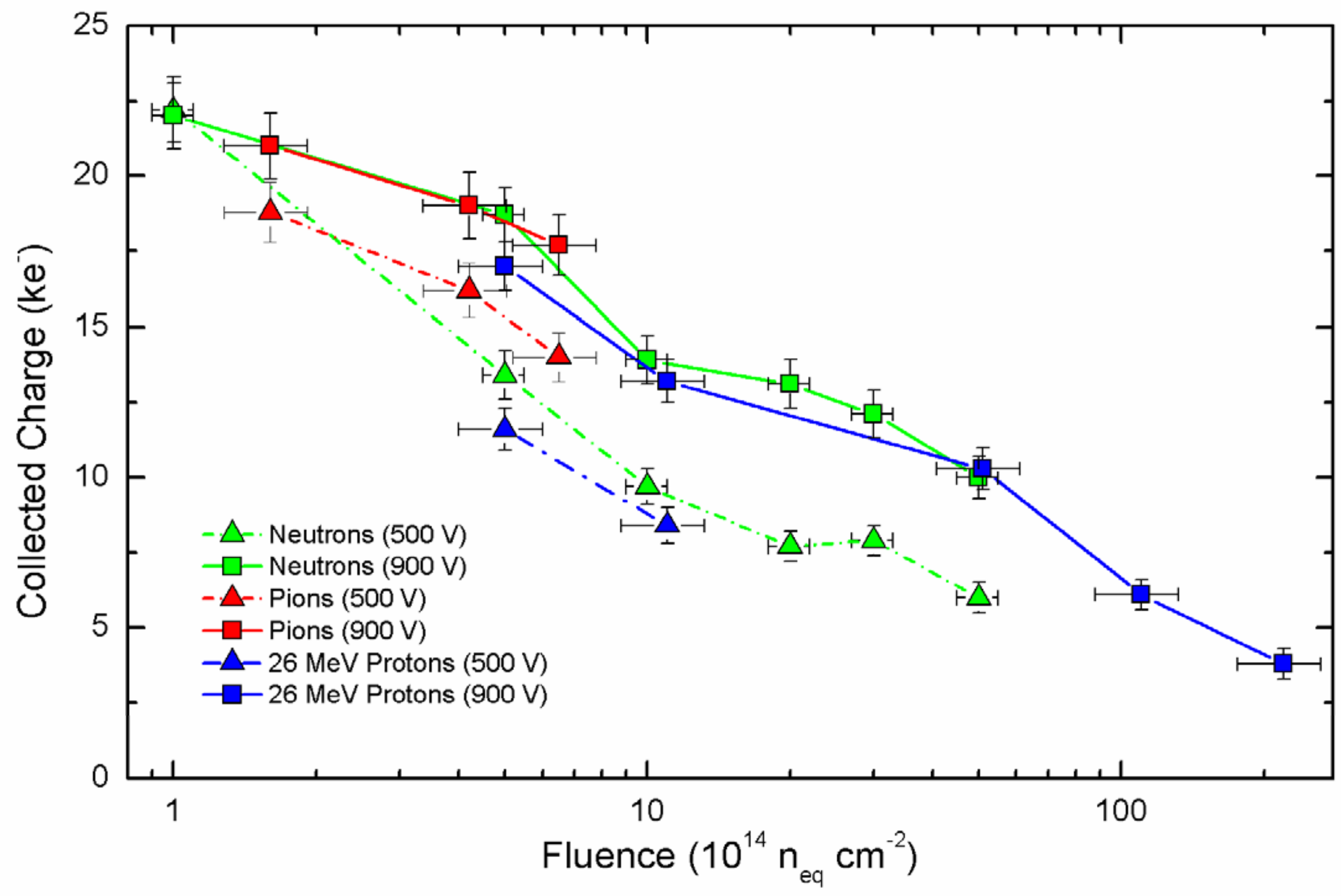
n-in-p FZ Irradiation Summary (II)

After reducing the pion CCE by estimated annealing factor, all sources give consistent CCE vs. fluence within uncertainties



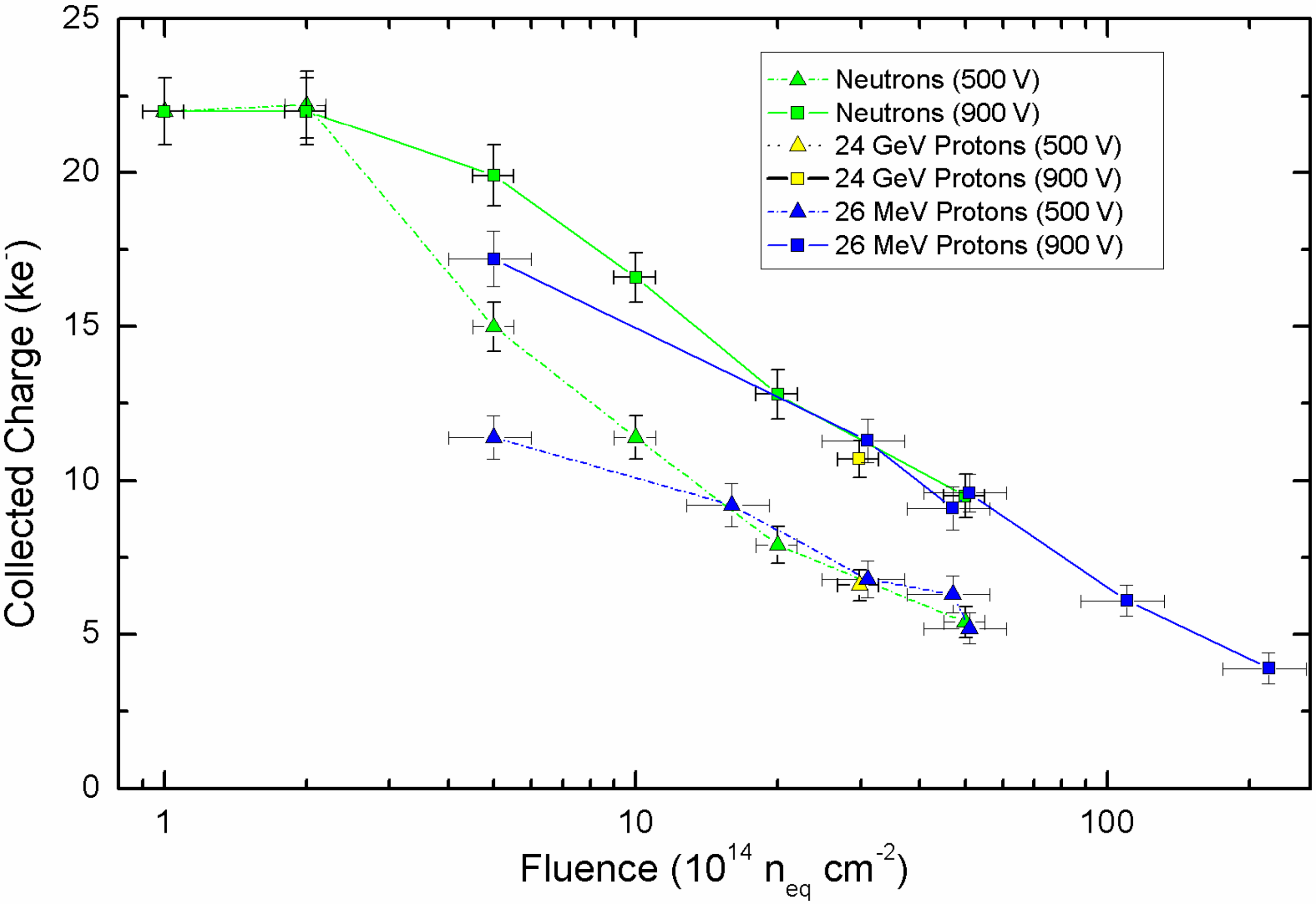
n-in-p MCz Irradiation Summary

Collected charge after charged irradiations are similar, after corrected pion CCE for annealing



n-in-n FZ Irradiation Summary

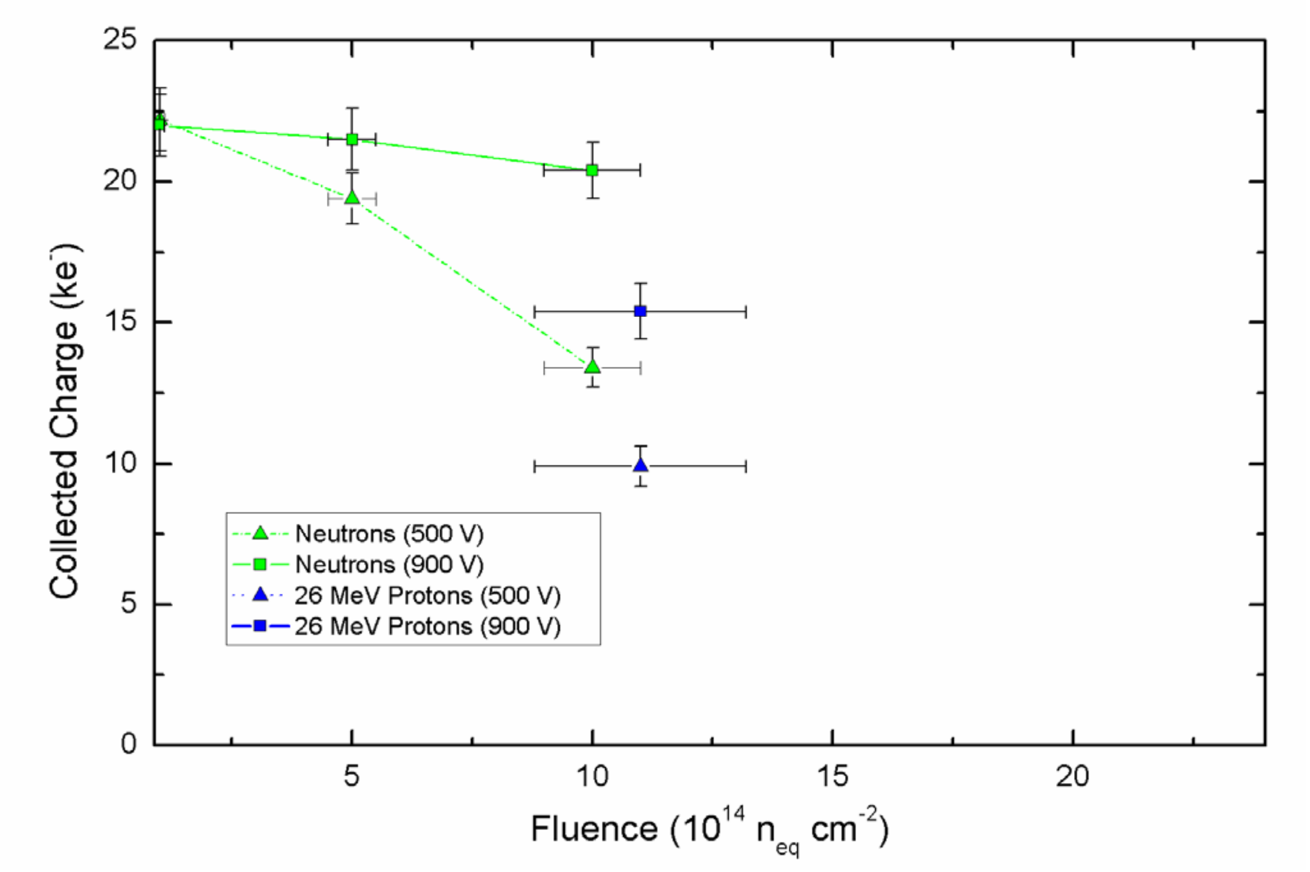
Results after neutron and proton irradiations are again very similar



n-in-n MCz Irradiation Summary

Study limited by part availability

There are signs that it might be the most radiation hard material, especially after mixed irradiations. Much more study is needed.



Radiation Hardness Measurements

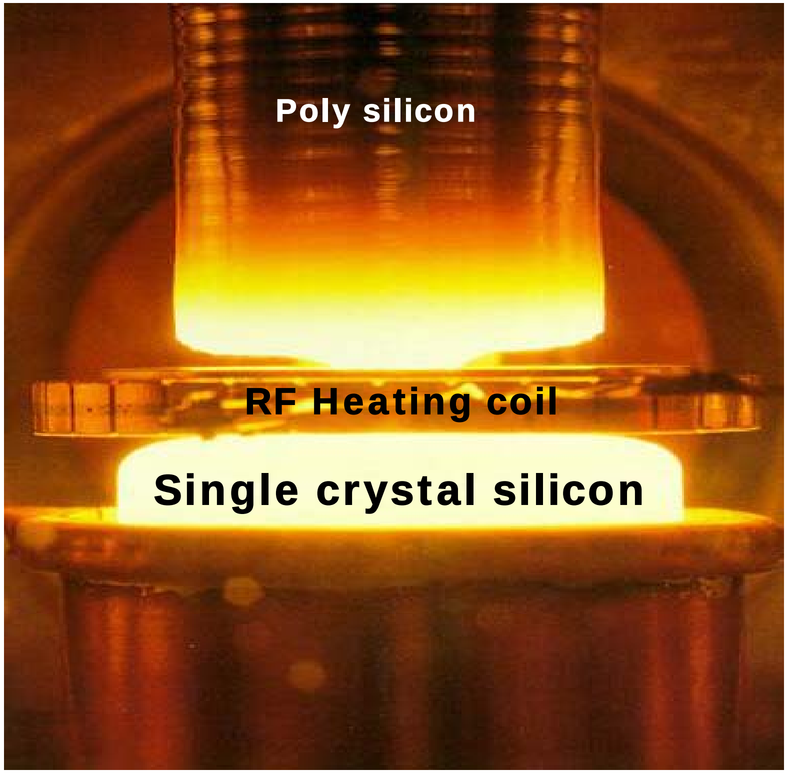
- To complete these irradiation comparisons, a new round of radiation hardness measurements need to be made
  - – Diodes at each site with careful measurement of environmental conditions
    - PT100 in diodes during measurements
  - – Annealing to a standard time correcting for annealing that occurred during irradiation
    - 80 minutes at 60 C??

Conclusions

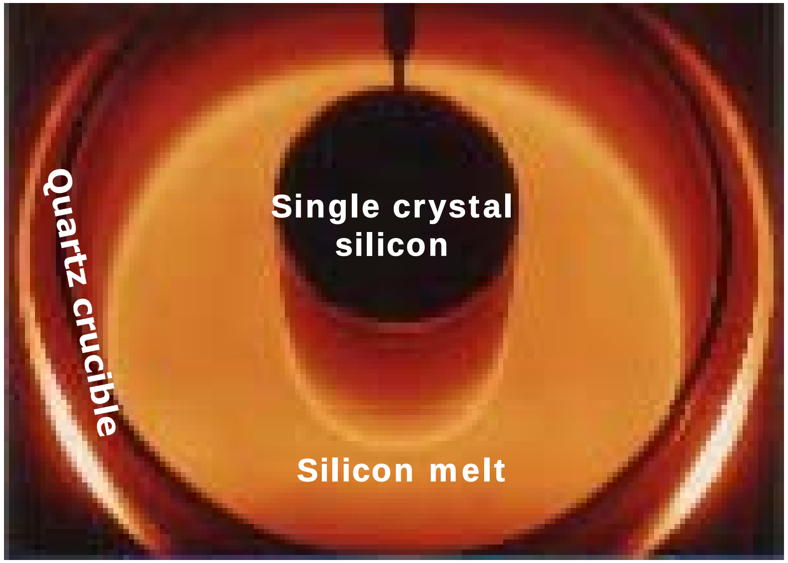
- Various detector configurations and bulk material types have been studied after neutron, pion, and proton irradiations
- p-in-n FZ/MCz devices are not radiation tolerant enough for the inner regions of the SLHC
- After neutron, pion, and proton irradiations, n-in-n FZ, n-in-p FZ, and n-in-p MCz are very similar at high fluences
  - There are indications that n-in-n MCz might be better but needs further study
- All n-strip readout devices have sufficient CCE for even the inner-most SLHC layers
  - *Higher bias voltages, better cooling & lower threshold electronics are needed!!*
- Studies of annealing properties and mixed irradiations are next.

Backup Slides

Wafer Technology Choices



- Float Zone (FZ)
  - Most experience
  - Relatively low initial V_{FD} (20-150V)

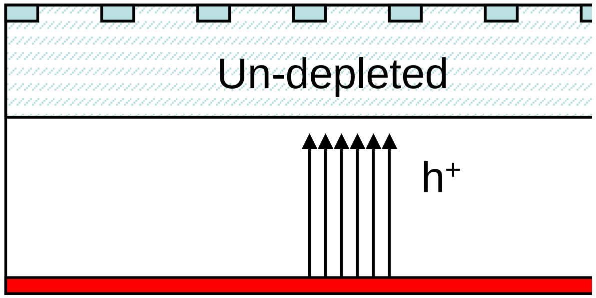


- Magnetic Czochralski (MCz)
  - More oxygen
    - More rad. hard??
  - Less uniformity in resistivity within wafer??
  - Less expensive??
  - Higher initial V_{FD} (150-700 V)

P-strip vs. N-strip Readout

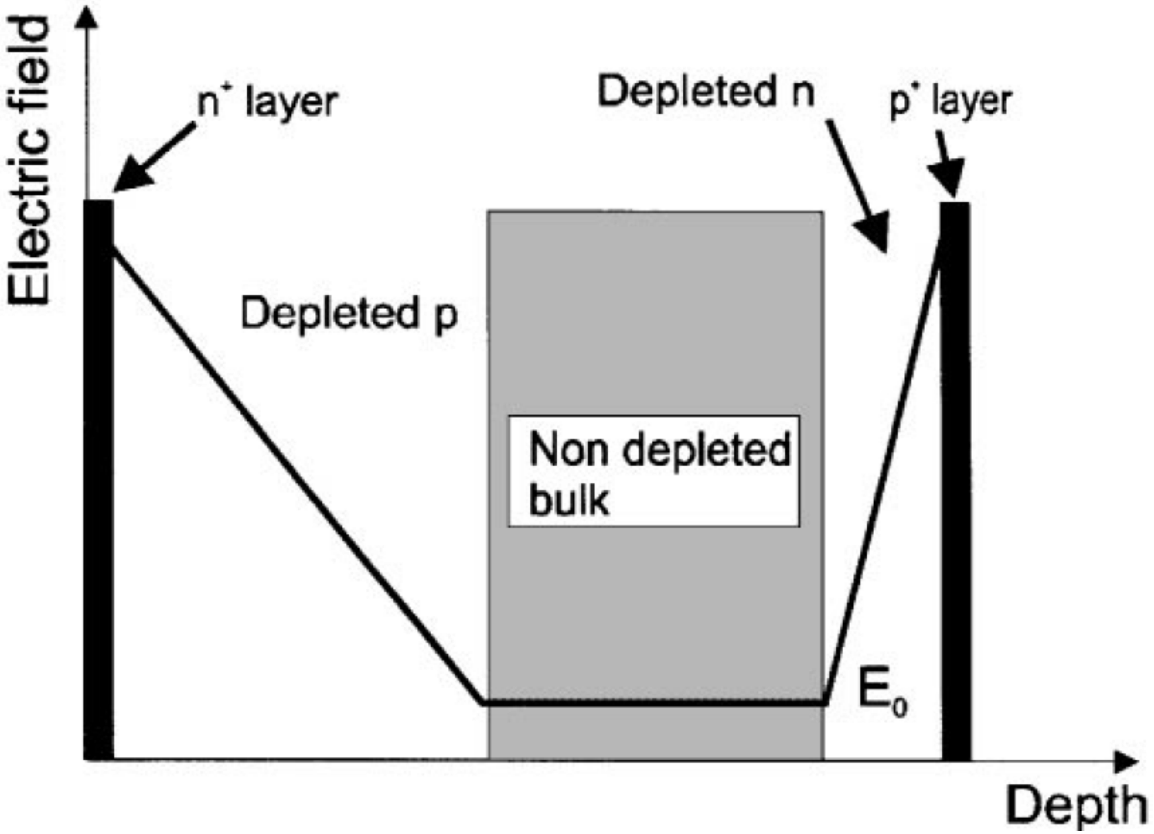
Effect of trapping on the C
Collection Efficiency (C

**“Standard” p-in-n geometr
(after type inversion)**



Type inversion t

- Holes collected
- Deposited charge can reach electrode
  - Charge spread over r strips
  - Lower signal

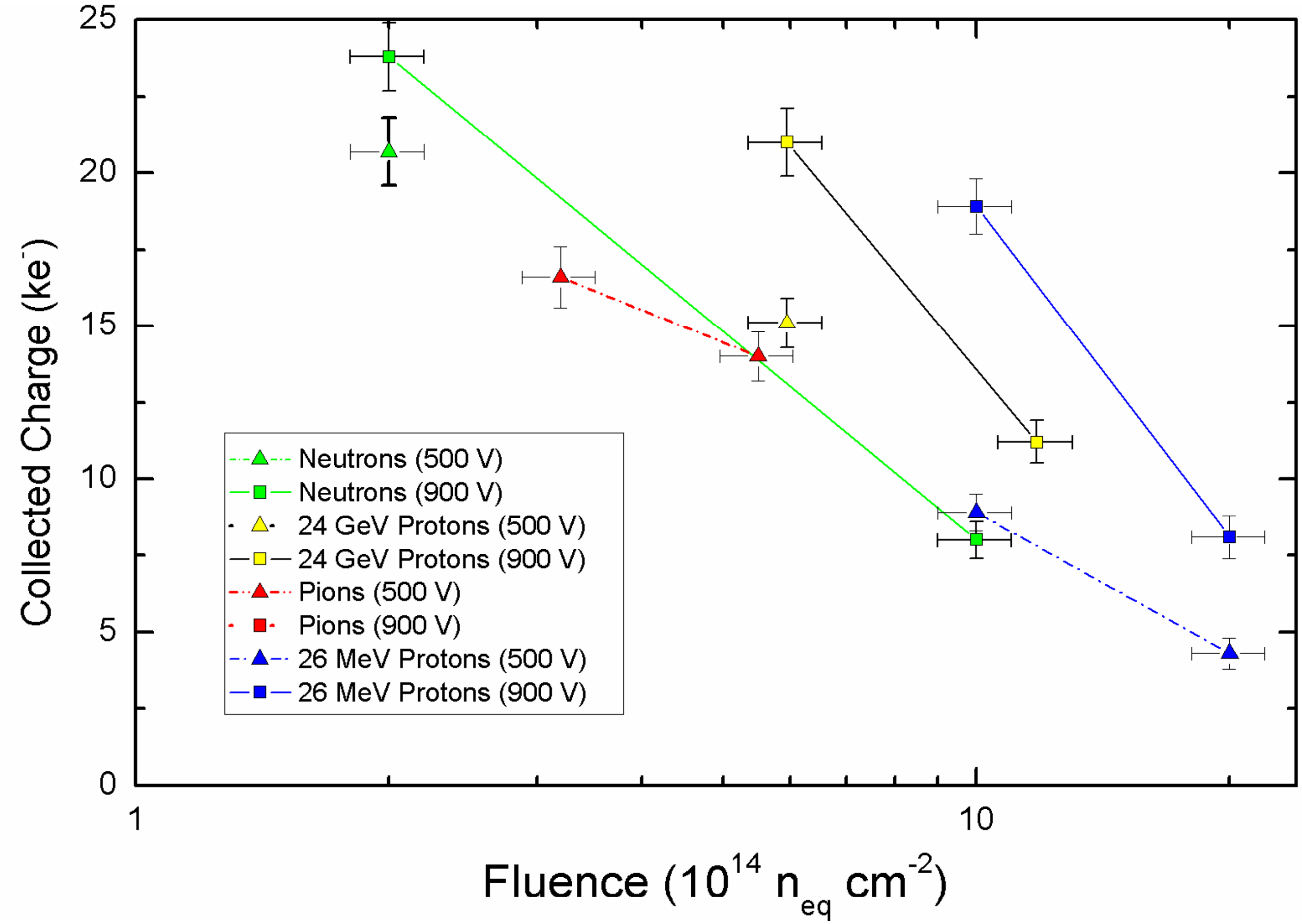


Reality is more complex, but dominant junction is located near n^+ implant

p-in-n MCz Irradiation Summary

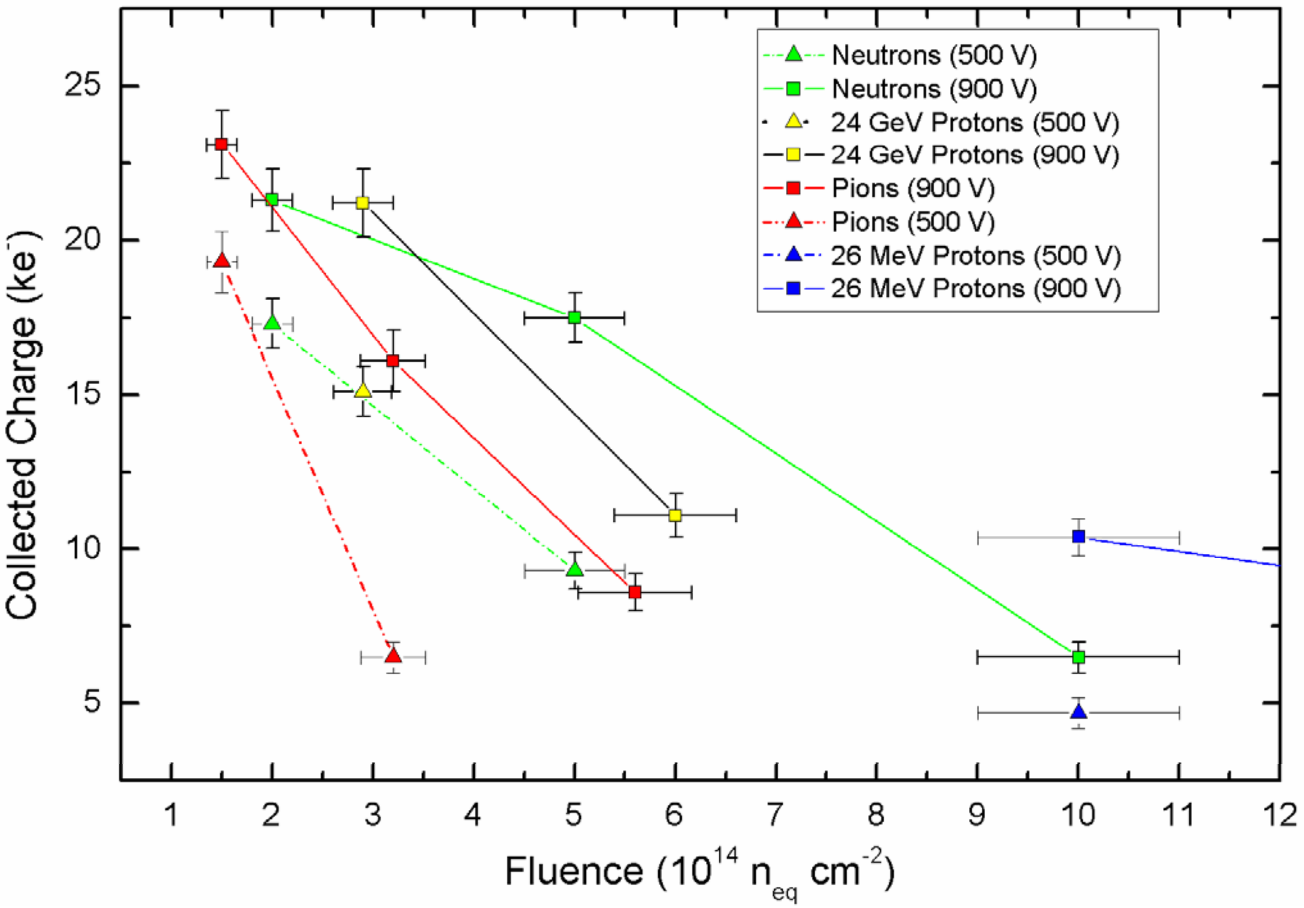
P-in-n MCz is significantly better than p-in-n FZ.

When it can’t be fully depleted, p-in-n MCz is much worse than all n-strip readout options studied

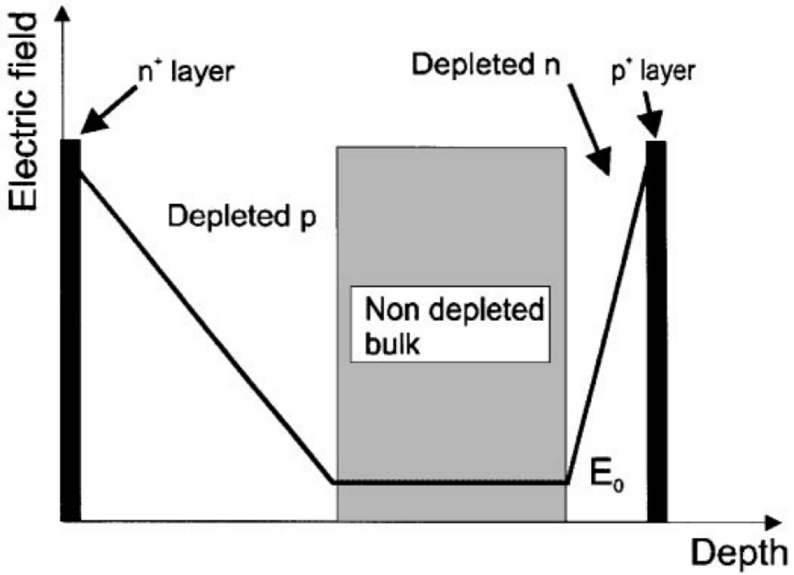


p-in-n FZ Irradiation Summary

p-in-n FZ is poor as expected. Differences between sources not understood

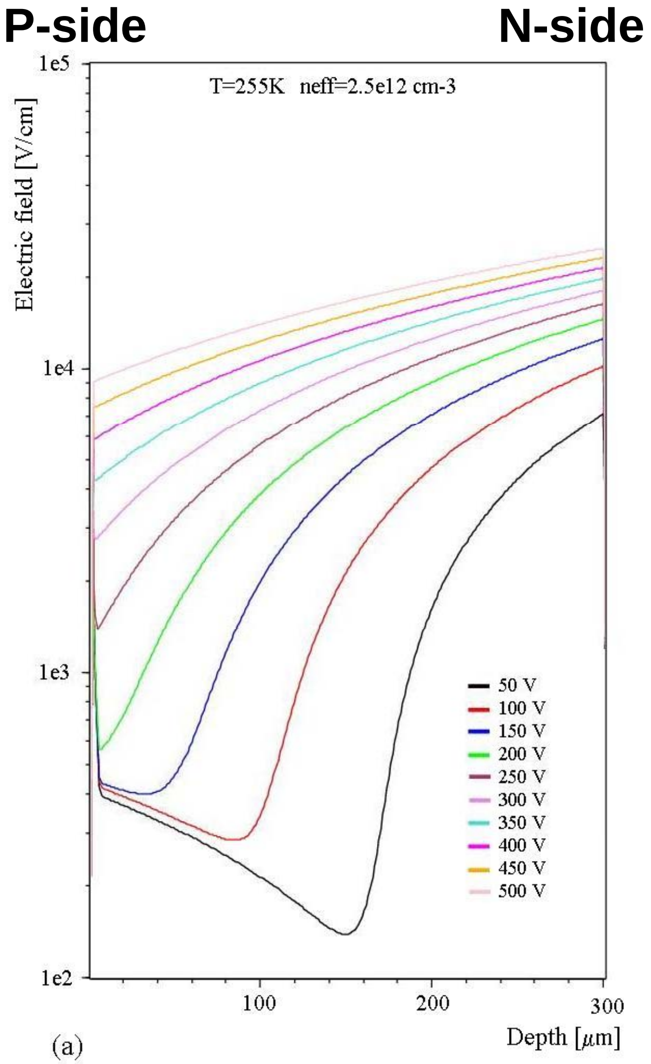


Double Junction



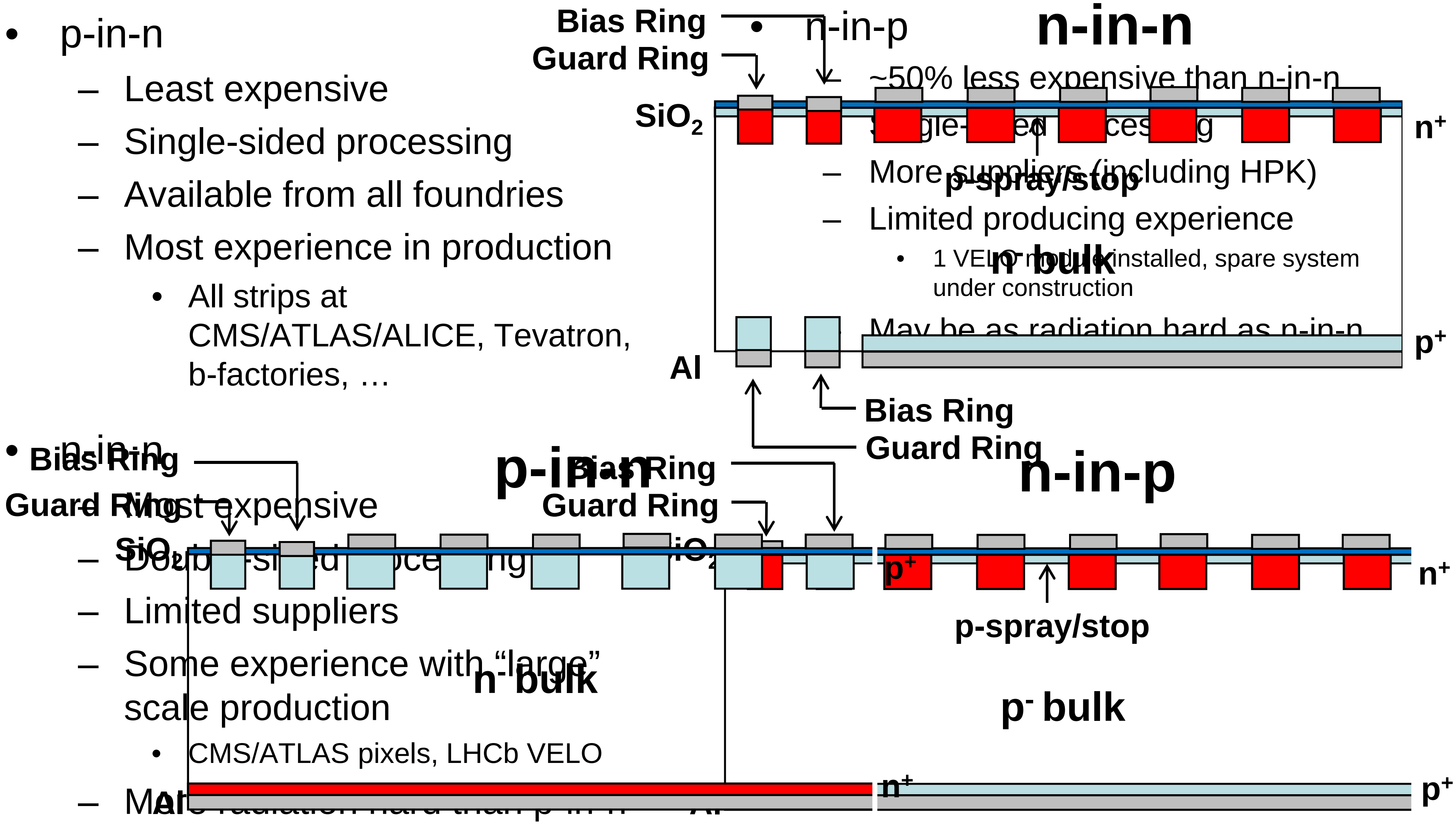
In reality, after irradiation electric fields show a double junction structure with a non-depleted bulk in the middle of the sensor below the full depletion voltage

See G. Casse, et. al., NIMA **426** (1999) 140-146 and G. Kramberger, et. al., NIMA **579** (2007) 762-765 for details



ISE-TCAD simulation after 6×10^{14} p cm^{-2}

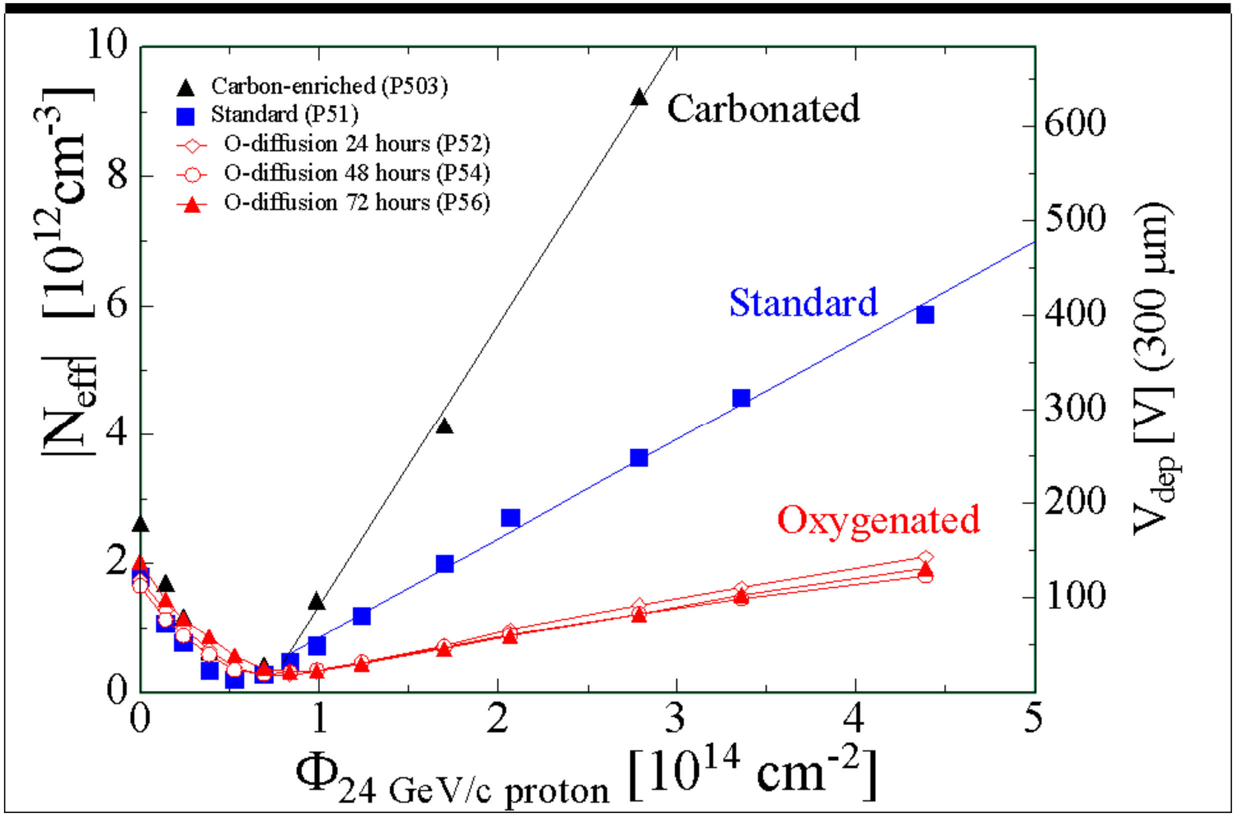
Geometry Choices



- p-in-n
  - Least expensive
  - Single-sided processing
  - Available from all foundries
  - Most experience in production
    - All strips at CMS/ATLAS/ALICE, Tevatron, b-factories, …
- n-in-p
  - ~50% less expensive than n-in-n
  - Single-sided processing
  - More suppliers (including HPK)
  - Limited producing experience
    - 1 VELO module installed, spare system under construction
  - May be as radiation hard as n-in-n
- n-in-n
  - Most expensive
  - Double-sided processing
  - Limited suppliers
  - Some experience with “large” scale production
    - CMS/ATLAS pixels, LHCb VELO
  - More radiation hard than p-in-n

Oxygenation RD48

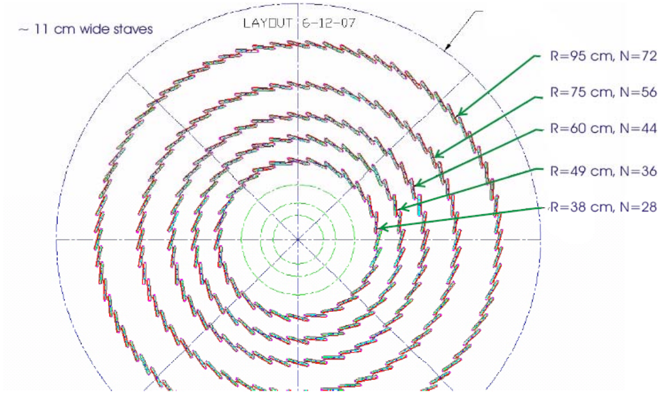
- Oxygenation shown to reduce damage due to protons
  - No improvement seen to the increase in |Neff| with neutron irradiations

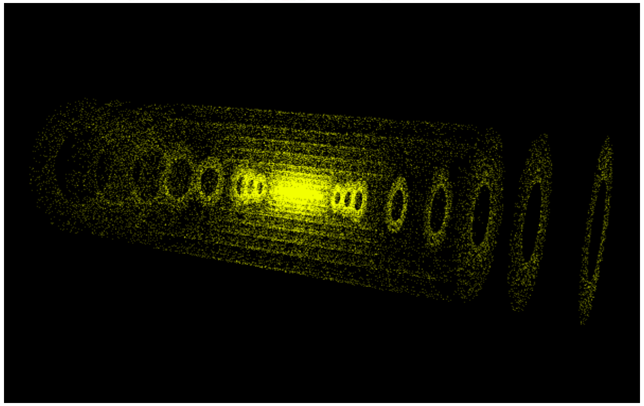


Motivates looking at naturally high oxygen content bulk materials (Cz, MCz, EPI)

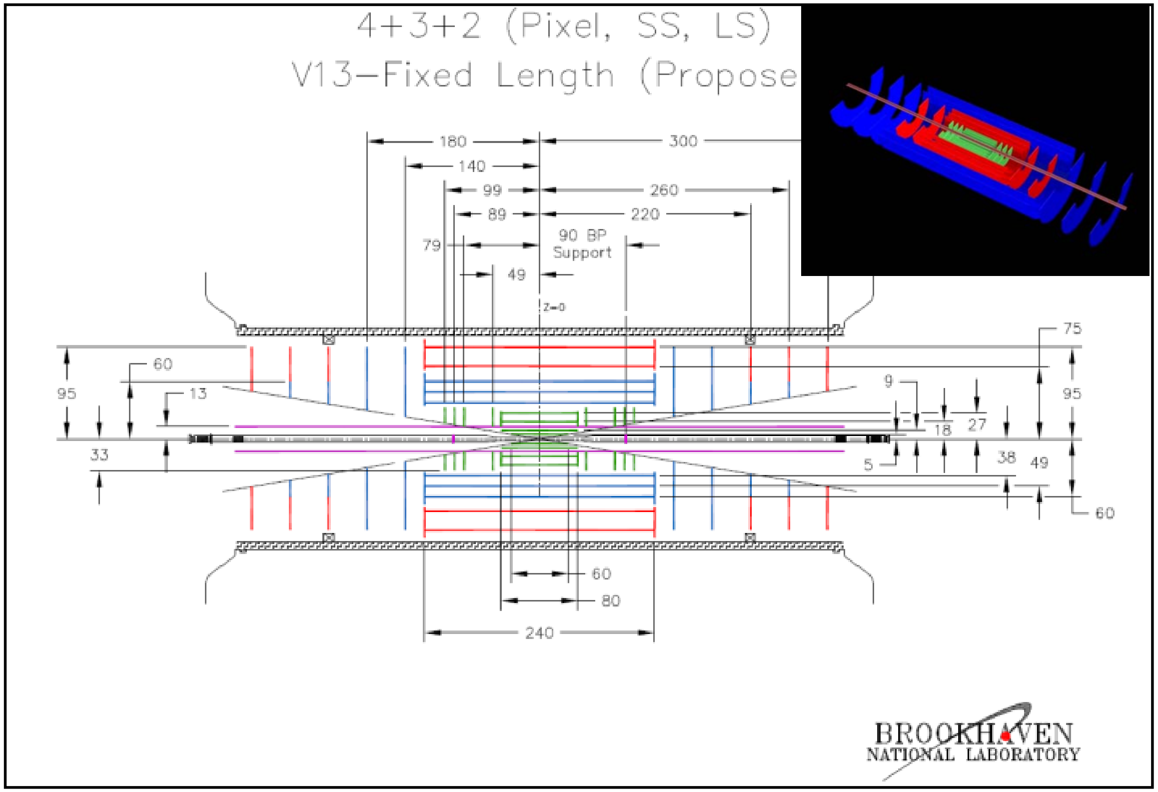
Current SLHC ATLAS Layout

Barrel Pixel Tracker Layers:	r = 3.7cm, 7.5cm, 16cm, 20cm
Short Strip (2.4 cm) μ-strips (stereo layers):	r = 38cm, 49cm, 60cm
Long Strip (9.6 cm) μ-strips (stereo layers):	r = 75cm, 95cm



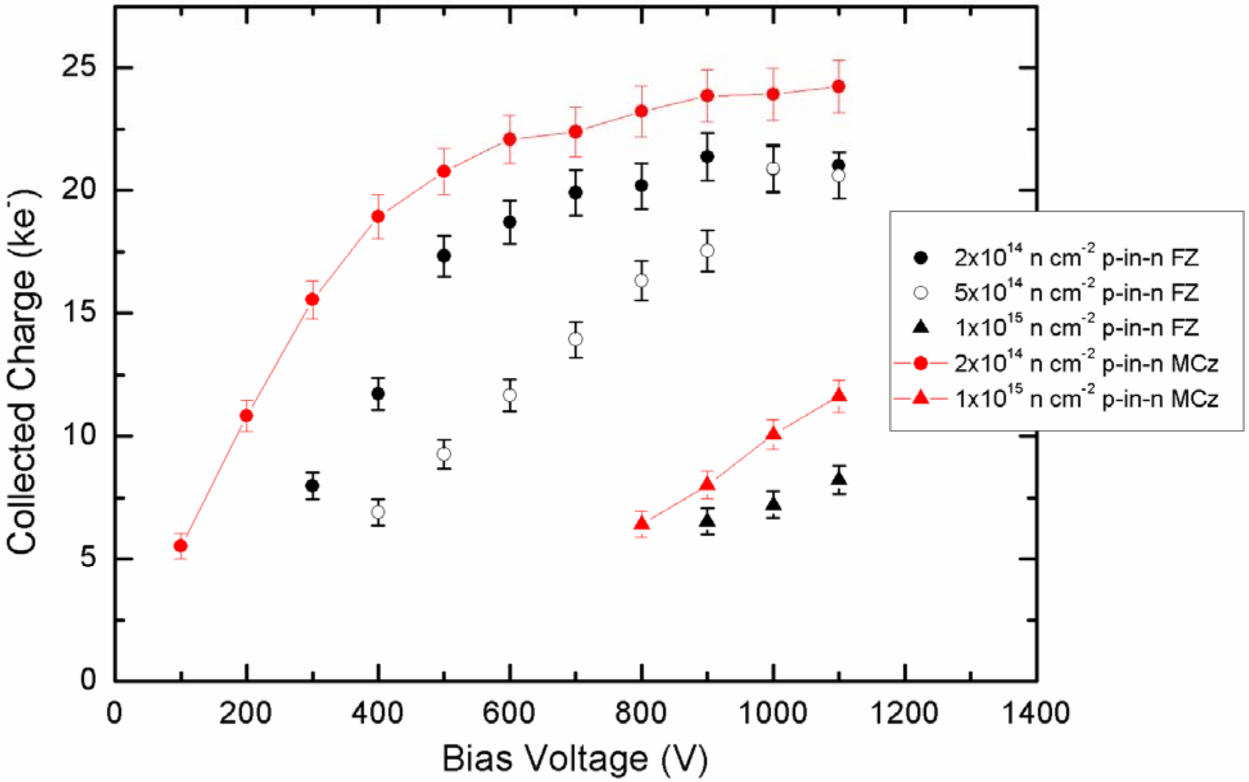


(400 collisions per beam crossing)



Neutron Irradiations

- p-in-n
  - MCz slightly better than FZ
  - Insufficient CCE for tracking >5-10×10^{14} n cm^{-2}
- n-in-n
  - MCz much better than FZ
  - Higher dose MCz data needed
- n-in-p
  - FZ/MCz similar response
  - *Charge seen after 1.5×10^{16} n cm^{-2}*



p-in-n sensors: FZ–black, MCz-red