Charge Collection, Power, and Annealing Behaviour of Planar Silicon Detectors after Reactor Neutron, Pion and Proton Doses up to 1.6×10^{16} n_{eq} cm^{-2}

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

Miniature Silicon Micro-strip Sensors

Microstrips, ~1x1 cm^2, 100-128 strips, 75-80 μm pitch

Micron/RD50 (4" & 6" wafers) – 300 μm thick

- 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 – 300 μm thick

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

HPK/ATLAS06 and ATLAS07 – 300 μm thick

- n-in-p FZ (V_{FD} ~160V)

Micron/RD50 (4" & 6" wafers) – 140 μm thick

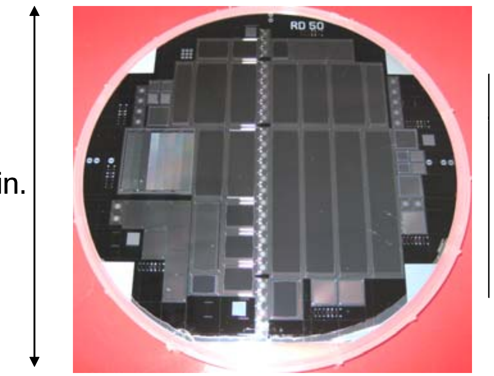
- n-in-p FZ (V_{FD} ~2-10 V)

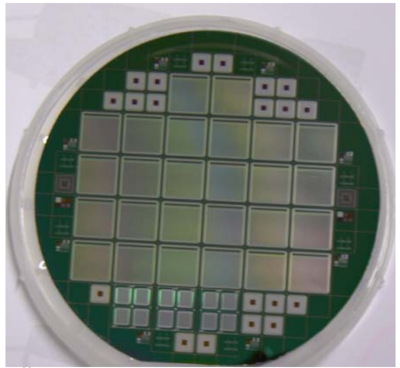
Micron/VELO test structures – 200 μm thick

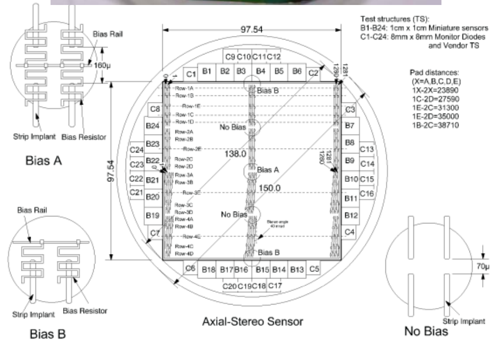
- n-in-n FZ (V_{FD} ~90V)

CNM/RD50 EPI – 150 μm thick active + carry-wafer

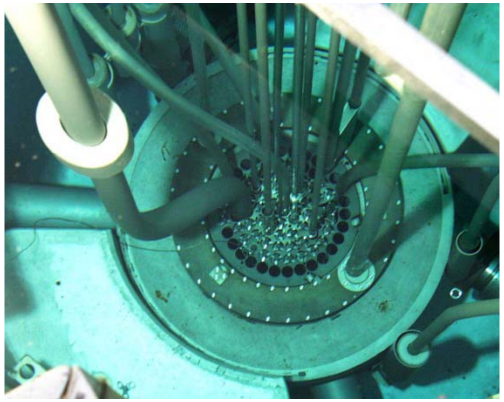
- n-in-p
- p-in-n

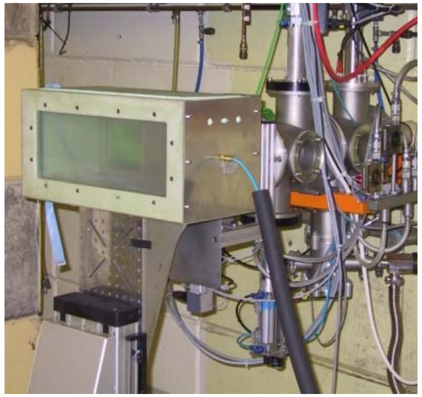






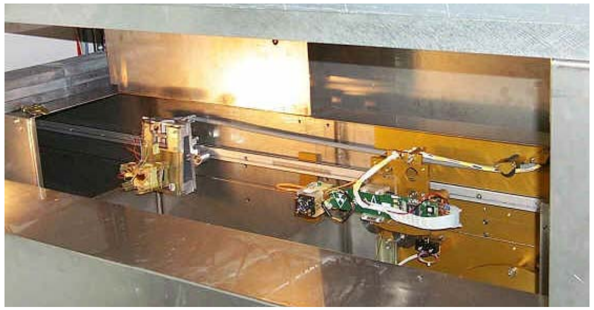
Irradiation Sources

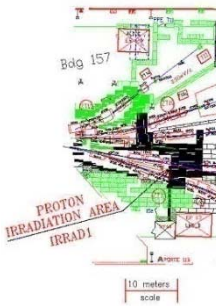


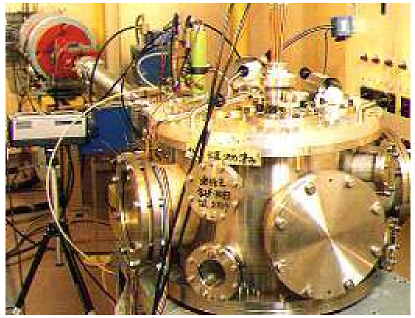


Irradiation and dosimetry (Neutrons):
Triga Reactor, Jozef Stefan Institute, Ljubljana, Slovenia: **V. Cindro, et. al.**

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





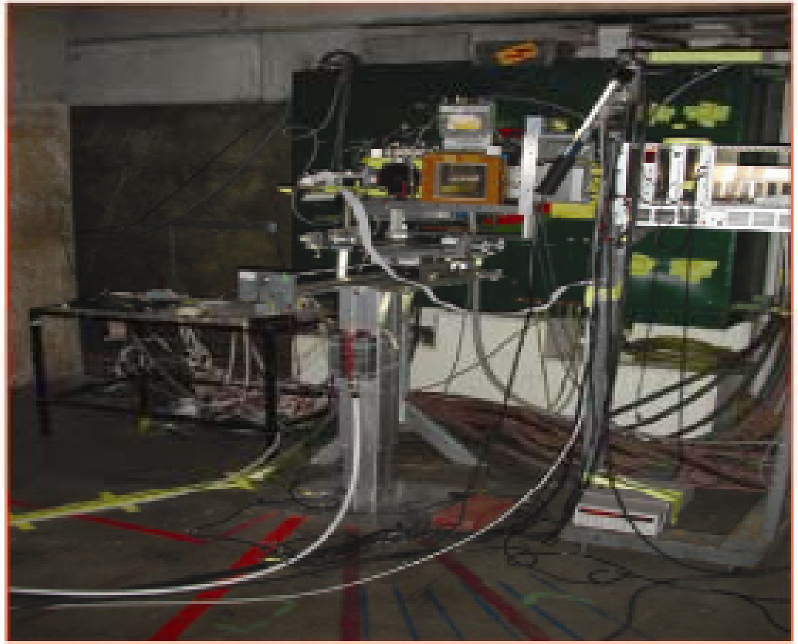


Irradiation and dosimetry (24 GeV Protons):
CERN PS Irrad1 facility, Geneva Switzerland:
M. Glaser, et. al.

Irradiation and dosimetry (70 MeV Protons):
AVF Cyclotron at CYRIC, Sendai, Japan:
Y. Unno, T. Shinozuka, et. al.

Pion Irradiations

- Radiation backgrounds at LHC/SLHC dominated by charged pions close to interaction point.



PSI Pion Beam

- 5cm along beam line
- Beam Energy : 191 MeV
- Beam Spot: 16mm × 13mm

Flux

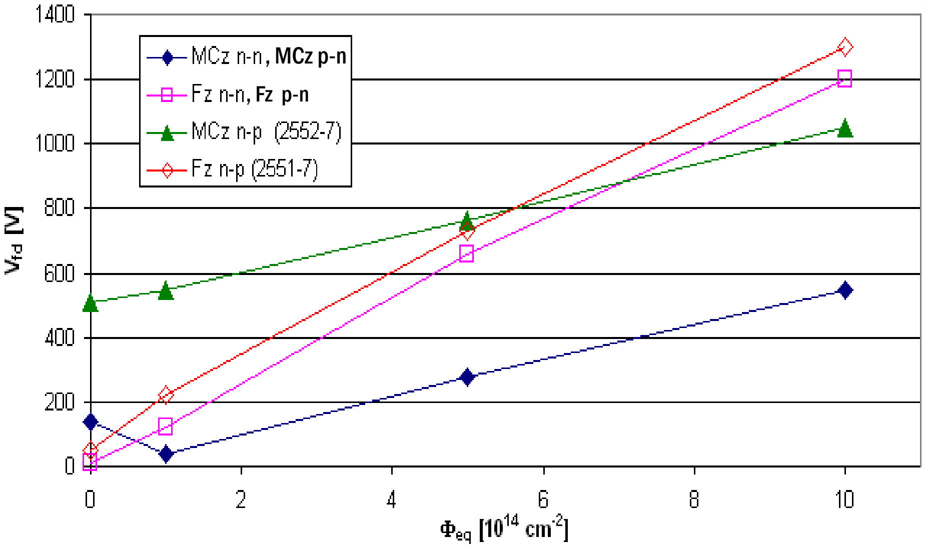
- 1.5×10^{14} pions cm^{-2} day^{-1}
- 7 days to reach 10^{15} pions cm^{-2}

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

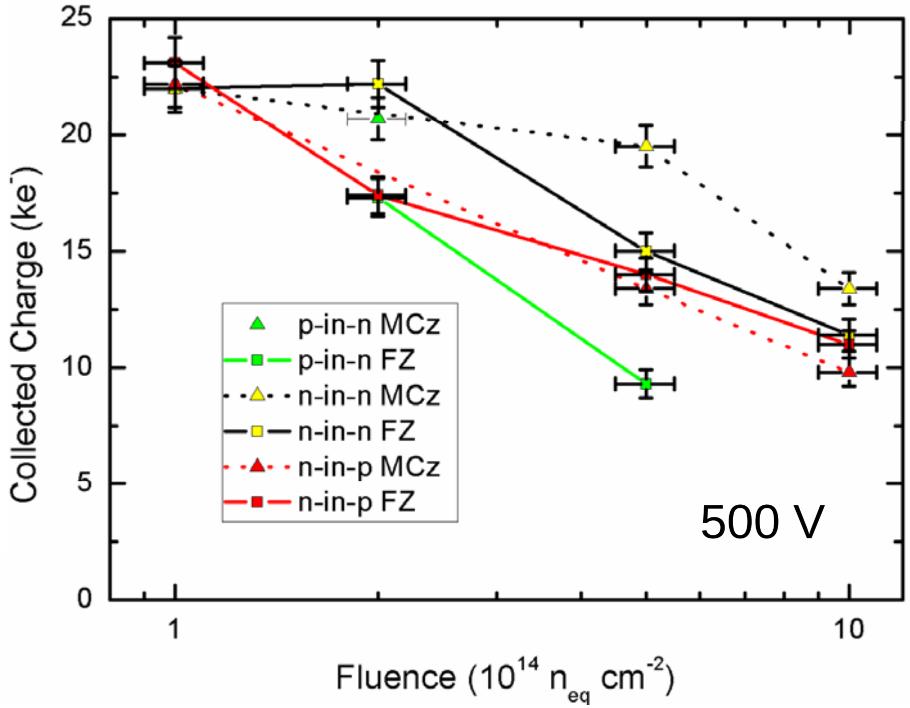
Experimental Setup

- 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 Summary



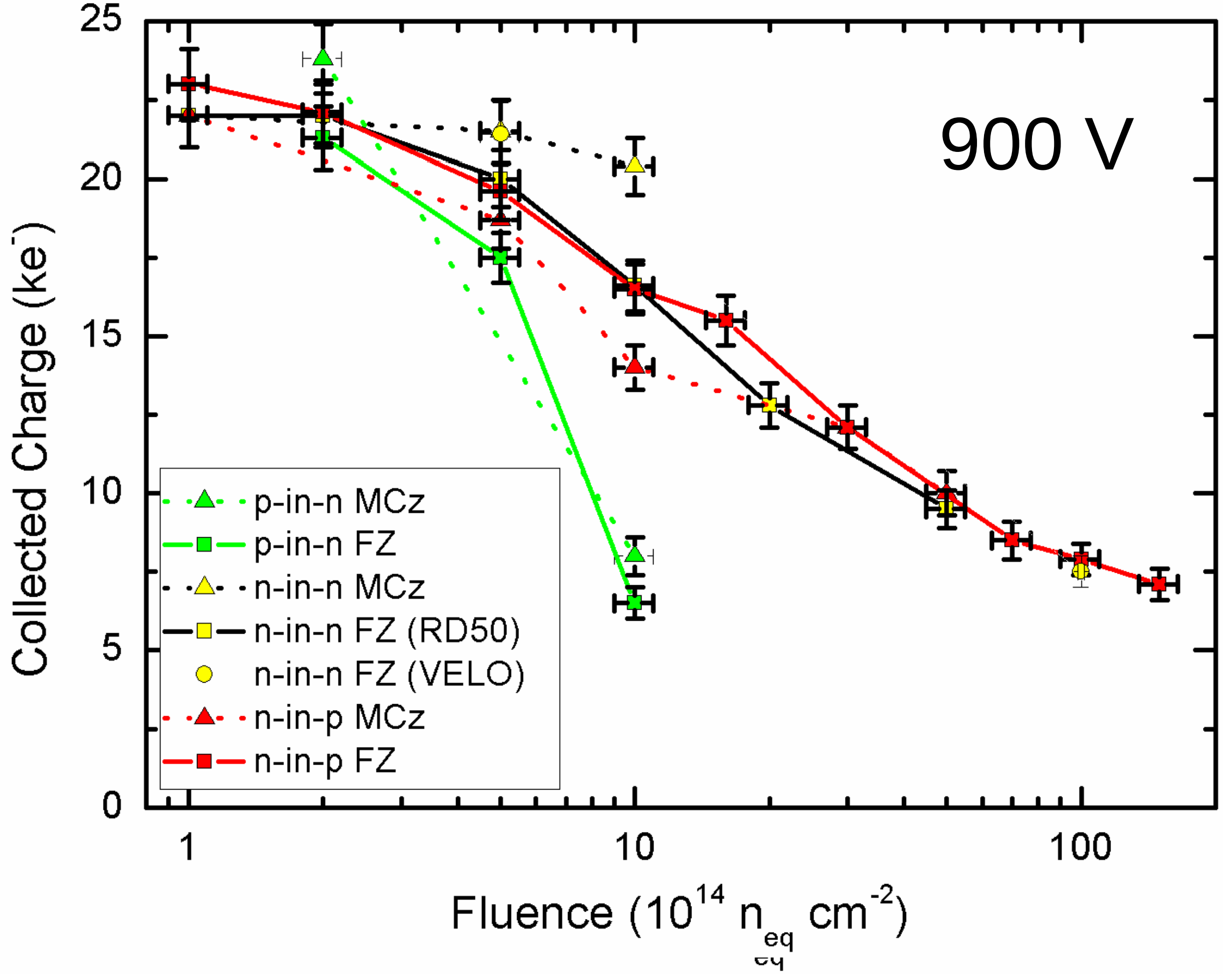
G. Kramberger, "Charge collection measurements on MICRON RD50 detectors", ATLAS Tracker Upgrade Workshop, Valencia 11-14 December 2007, http://ific.uv.es/slhc/ATLASUpgrade/



- Both p-in-n FZ and p-in-n MCz sensors show insufficient charge collection for short strip regions (>5×10^{14} n_{eq} cm^{-2})
- n-in-n FZ, n-in-p FZ, and n-in-p MCz have similar CCE at these doses
  - n-in-n FZ slightly better at doses < 5×10^{14} n_{eq} cm^{-2}
- n-in-n MCz shows the best performance as expected from CV measurements

Neutron Comparison

- 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

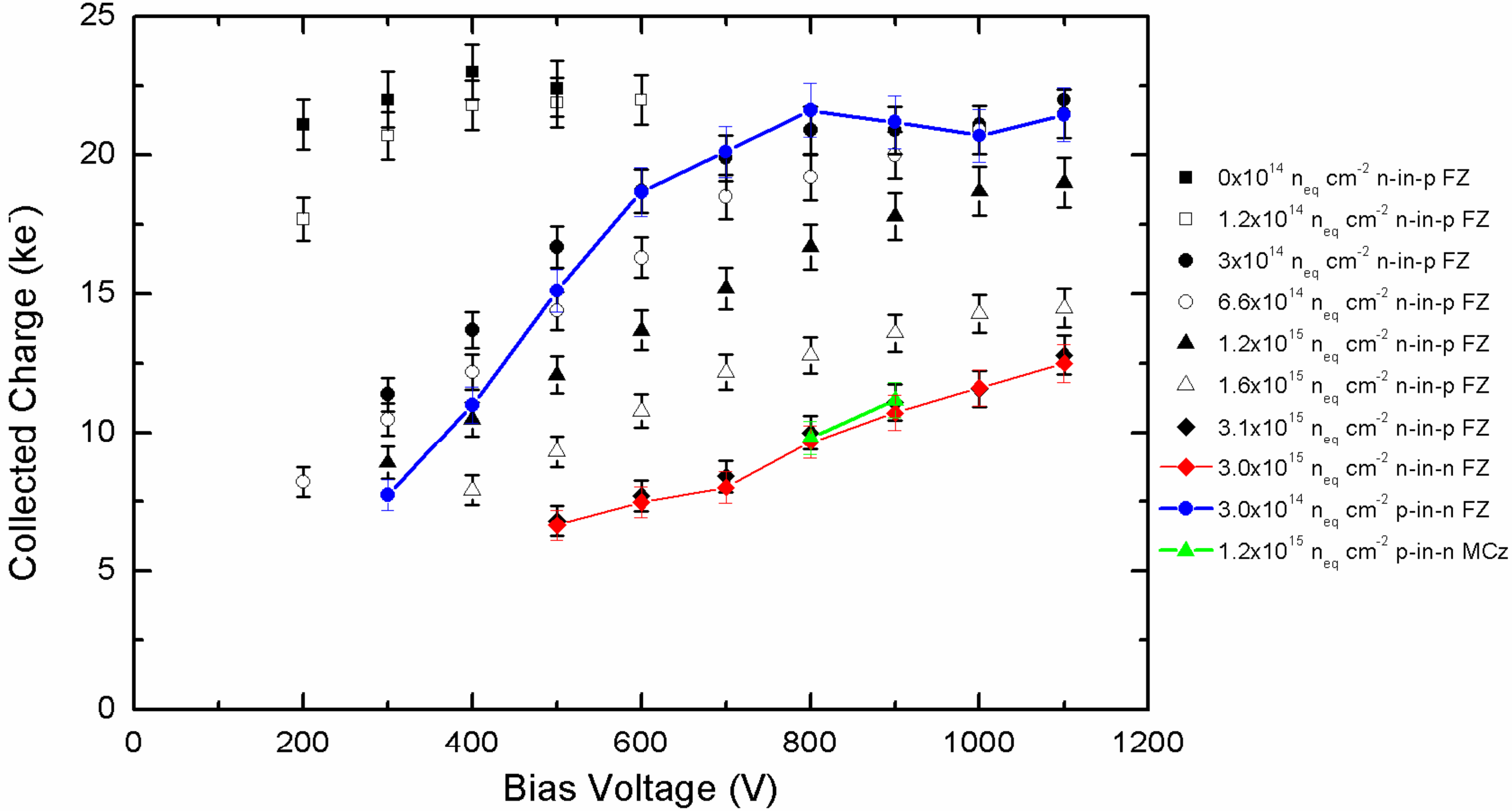


Appears once trapping dominates, all n-strip readout choices studied are the same after neutron irradiation

Charged Sources

- 24 GeV Protons
  - CERN PS
  - The “standard” so far
  - Long Irradiations
    - Flux: 1-2×10^{13} cm^{-2} h^{-1}
  - Limited periods during the year
  - Annealing during irradiation
    - Environment ~30 C°
    - Either include effects or cold irradiation
- 200 MeV Pions
  - PSI
  - Limited fluences
- 26 MeV Protons
  - Karlsruhe Compact Cyclotron
  - Easier access
  - Runs fairly often
  - High rates/short irradiations
    - Flux: 1-3×10^{15} cm^{-2} h^{-1}
      - No/little annealing during irradiation
  - Have to confirm hardness factor on IV/CCE
- 70 MeV Protons
  - CYRIC AVF Cyclotron
  - Similar advantages/issues as Karlsruhe
  - High rates/short irradiations
    - Flux: 1-6×10^{14} cm^{-2} h^{-1}

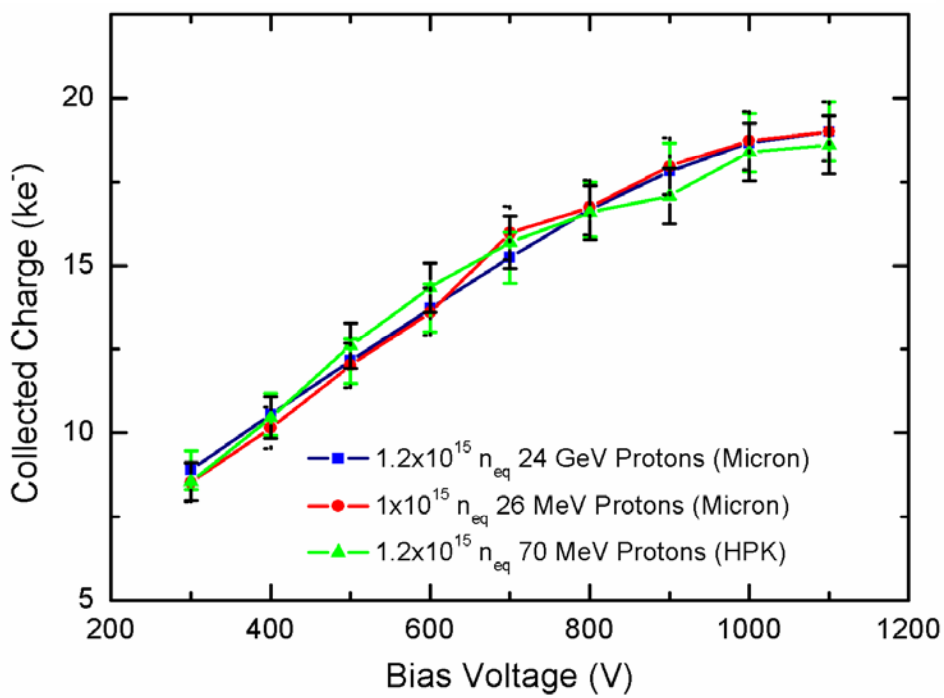
24 GeV Proton Irradiations

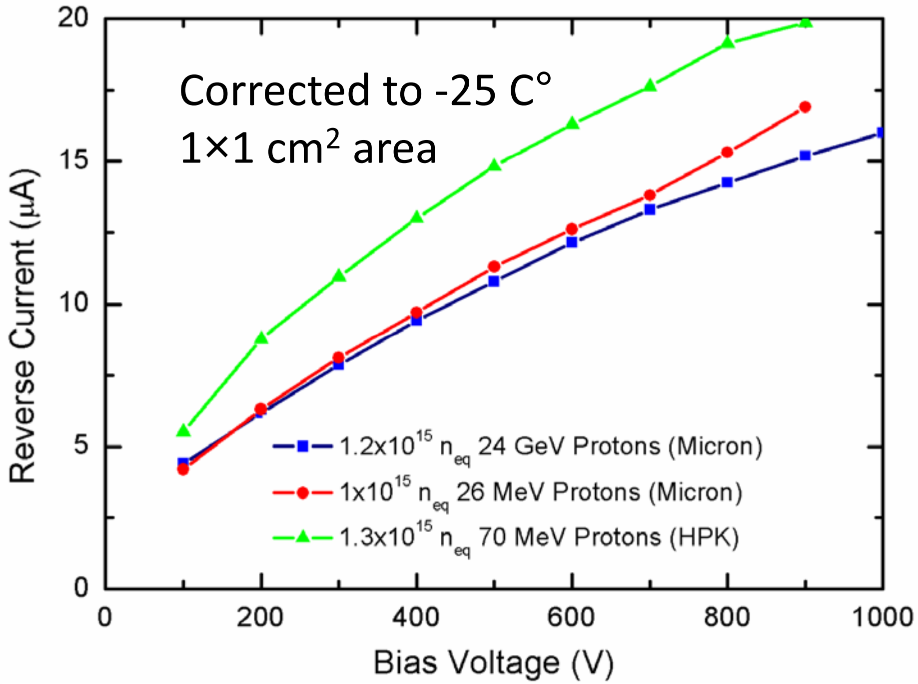


The current standard for proton irradiation studies.

Additional n-in-p FZ 6.2×10^{15} n_{eq} cm^{-2} and 1.0×10^{16} n_{eq} cm^{-2} pieces in hand.

Proton Hardness Comparison

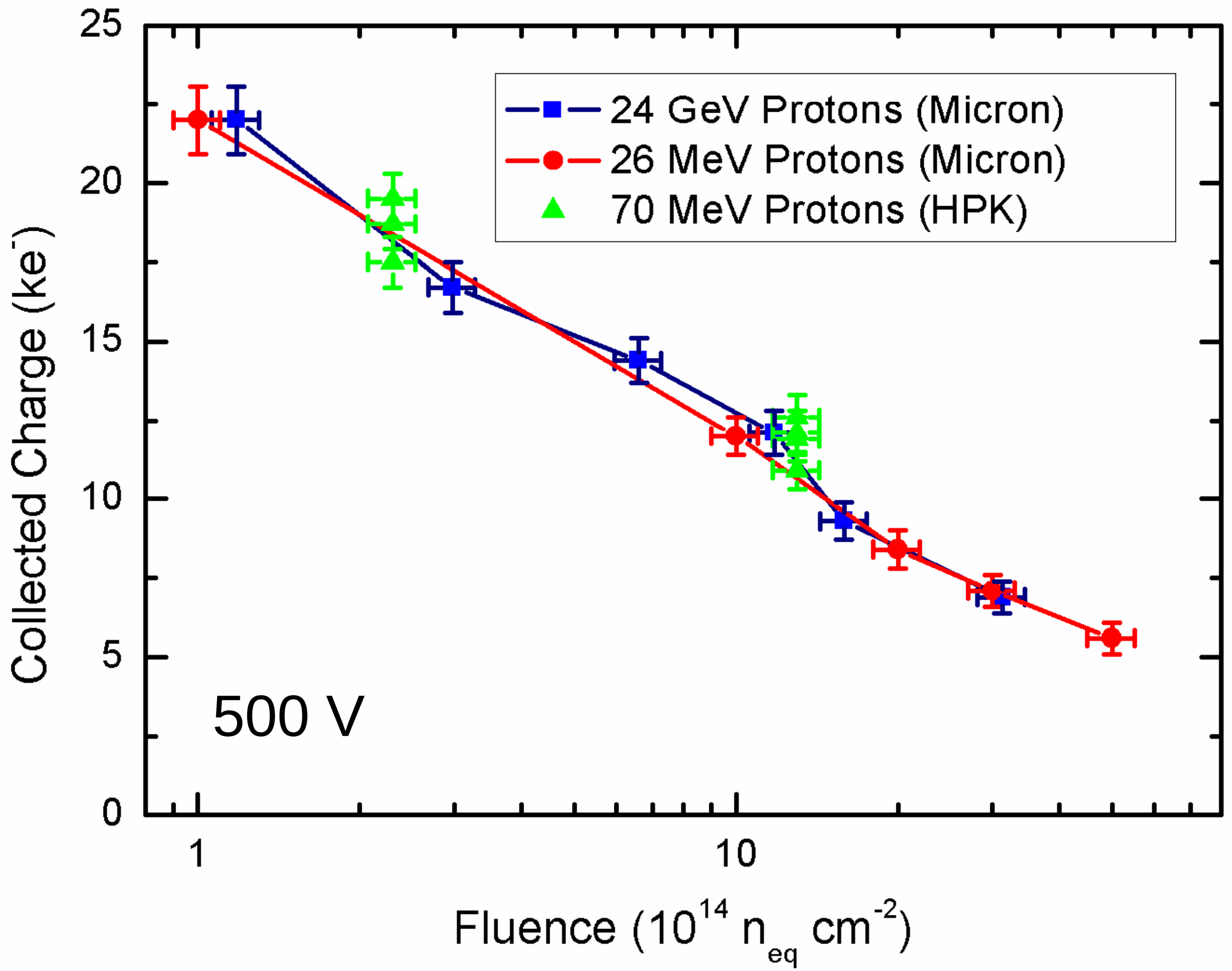




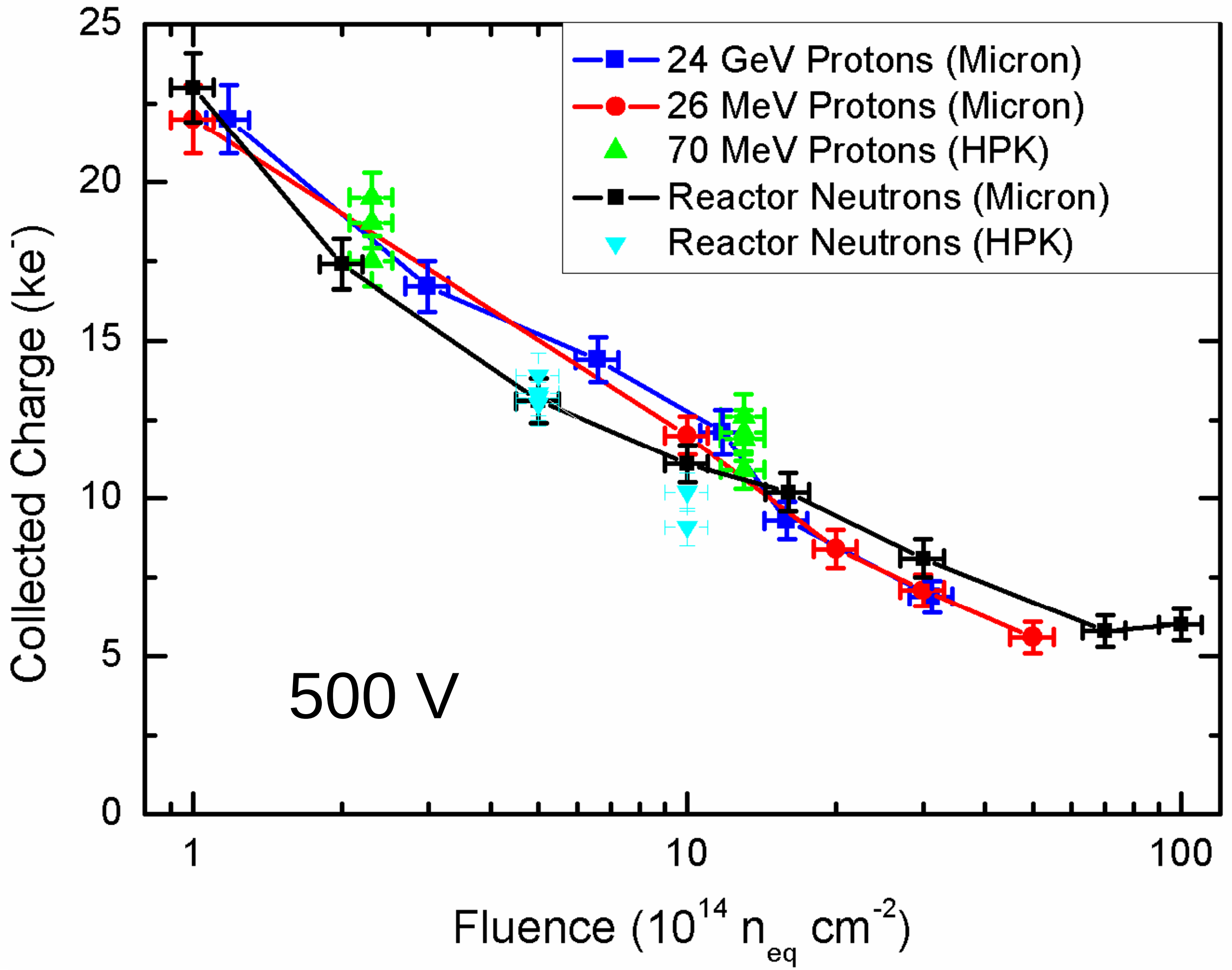
- After hardness correction, IV and CCE agree for all three proton sources studied with n-in-p FZ devices
  - Roughly ±10% error in fluence, ±0.5 C° error in temperature during measurement (Total ±15% error in current)
- Validates 70 MeV Protons from CYRIC for ATLAS sensor studies
  - 24 GeV Protons from CERN PS will also be used when available

n-in-p FZ Proton Comparisons

- For n-in-p FZ devices, CCE from all 3 proton sources look the same
  - Investigations for other geometries/ substrates ongoing



n-in-p FZ Irradiation Comparisons

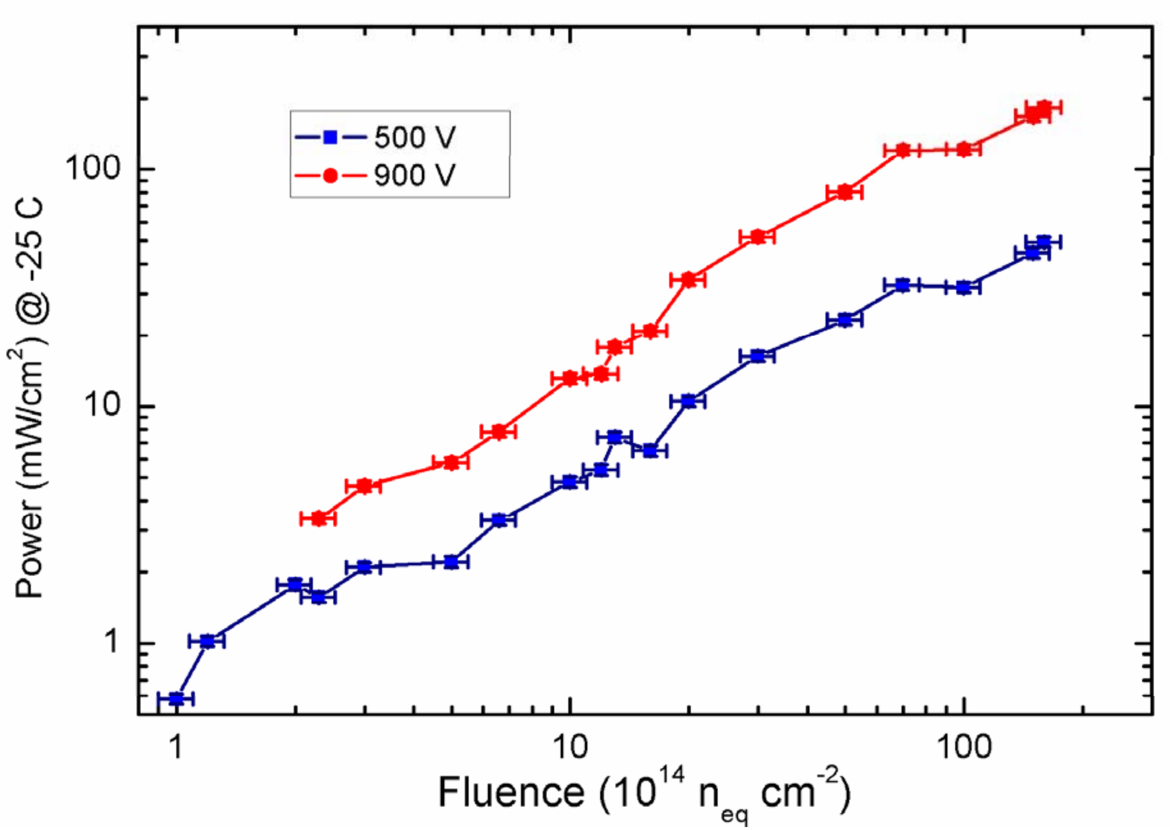


Neutrons and protons also very similar

- Might be signs that protons are slightly worse due to trapping at high fluences

Expected Sensor Power

- Sensor power/cm^2 @ -25 C° with **<u>no annealing</u>**
  - Averaged across diode geometries and substrate types
    - No significant difference seen above 5×10^{14} n cm^{-2}
- At radius of ~4 cm from beam, sensors would generate ~260 mW/cm^2
  - *<u>Significant challenge for cooling!!</u>*

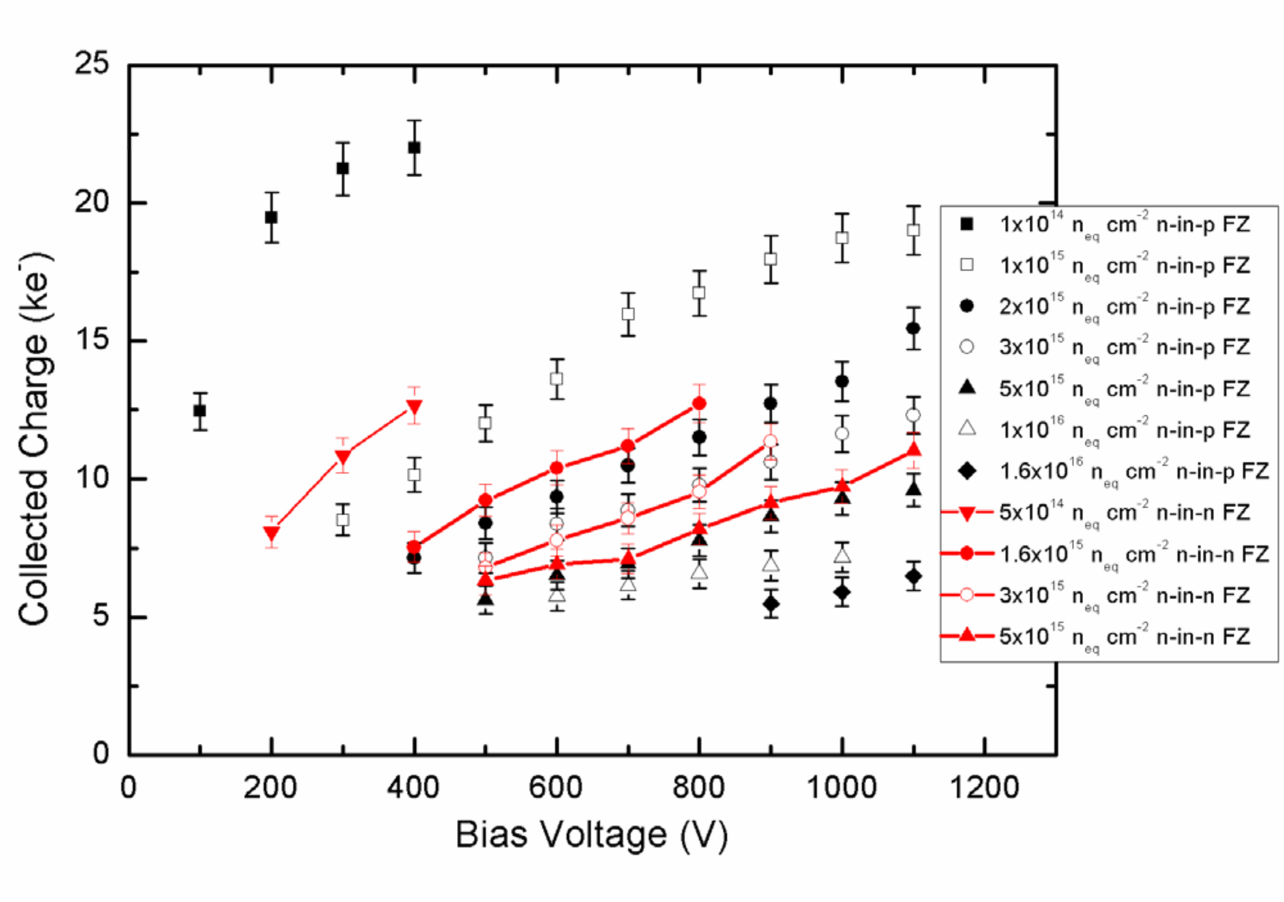


Average power vs. fluence, corrected to 1×1 cm^2 area at -25C°

±10% error in fluence, ±0.5 C° error in temperature (Total ±15% error in power)

26 MeV Proton Irradiations

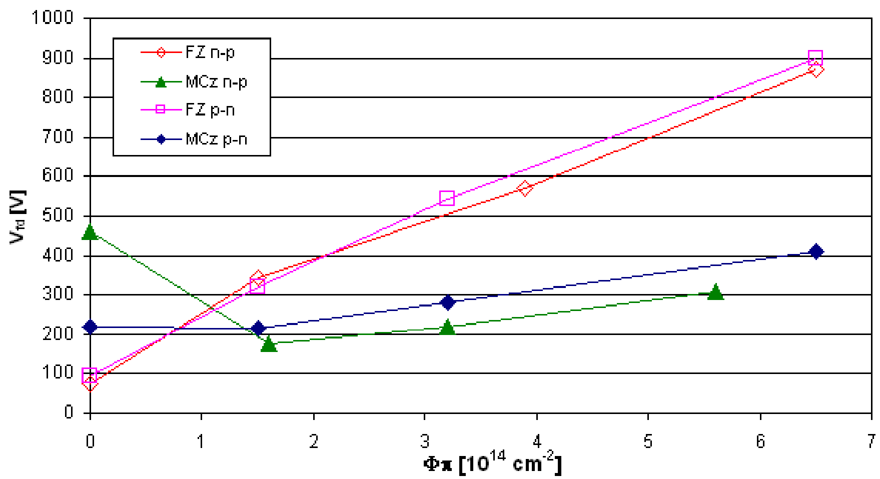
- n-in-n FZ and n-in-p FZ look the same for proton doses studied so far
  - Study limited by part availability
    - More parts sent to Karlsruhe
  - More wafers under process at Micron



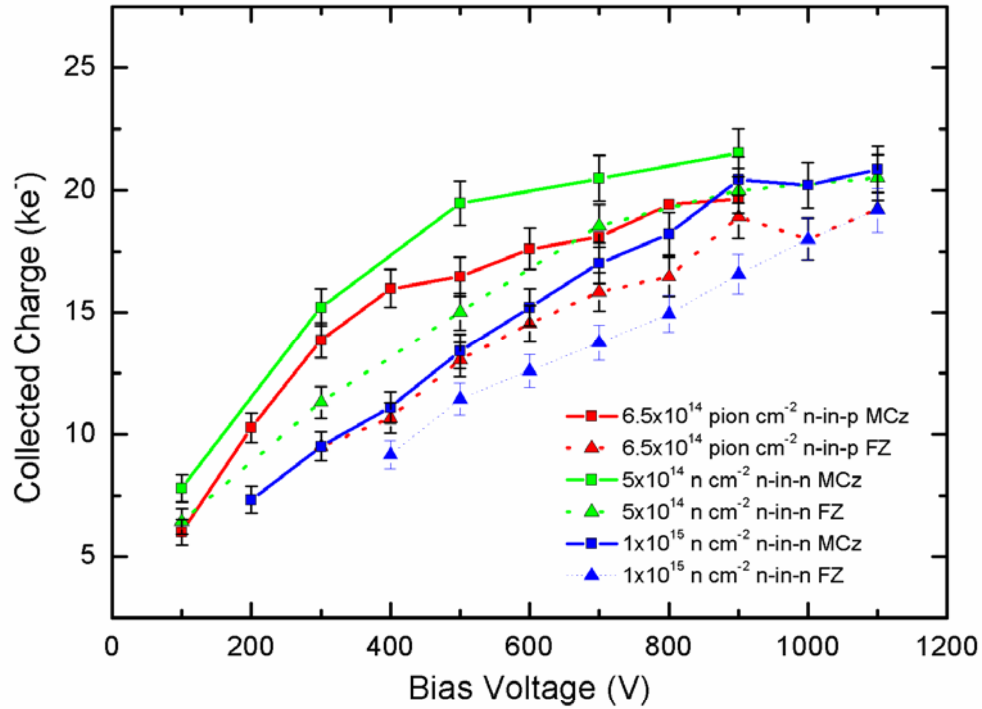
Charge seen with n-in-p FZ after 1.6×10^{16} n_{eq} cm^{-2}

(expected maximum dose of innermost devices at SLHC)

Pion Irradiations

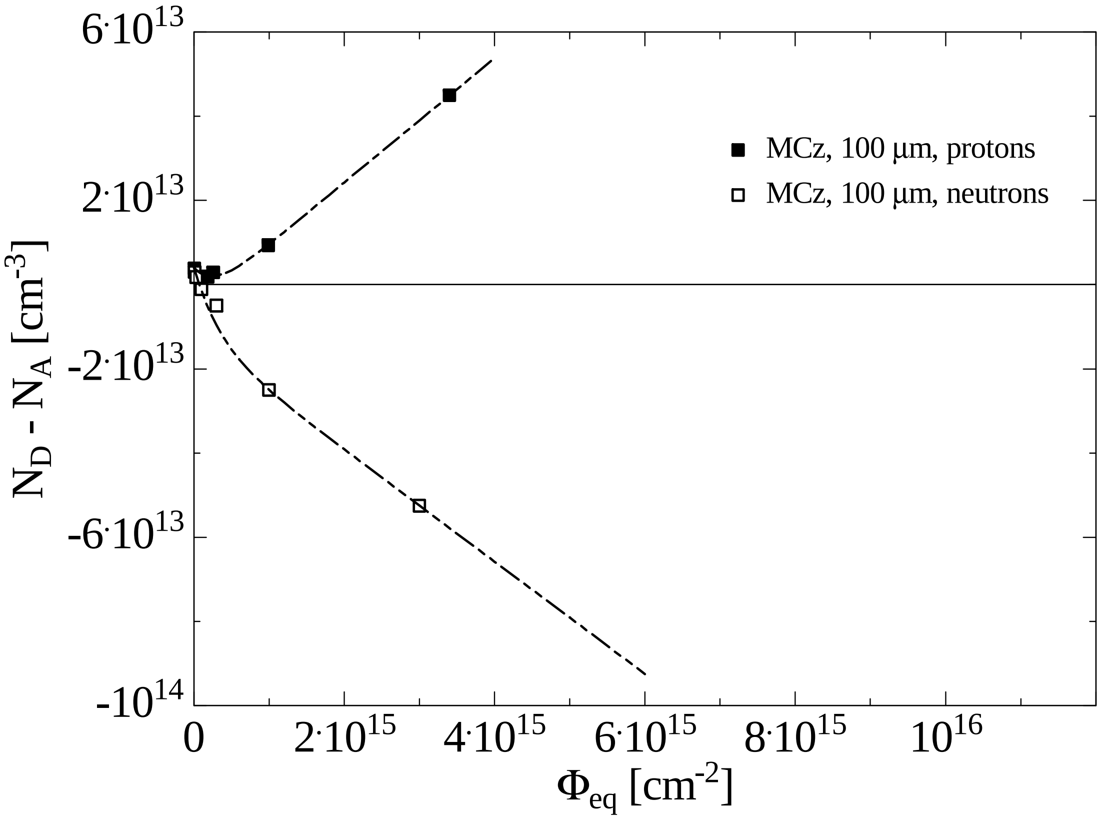


G. Kramberger, et.al., 3rd Workshop on Advanced Silicon Radiation Detectors (3D and P-type Technologies), Barcelona 14-16 April 2008
http://indico.cern.ch/conferenceDisplay.py?confId=28165



- n-in-p MCz superior to n-in-p FZ after pion irradiation, as expected from diode CV measurements
  - Acts like n-in-n MCz after neutron irradiation
- Plan on confirmed charge particle behaviour of n-in-p MCz with 26 MeV protons from Karlsruhe
  - Under irradiation currently

Mixed Irradiations (MCz)



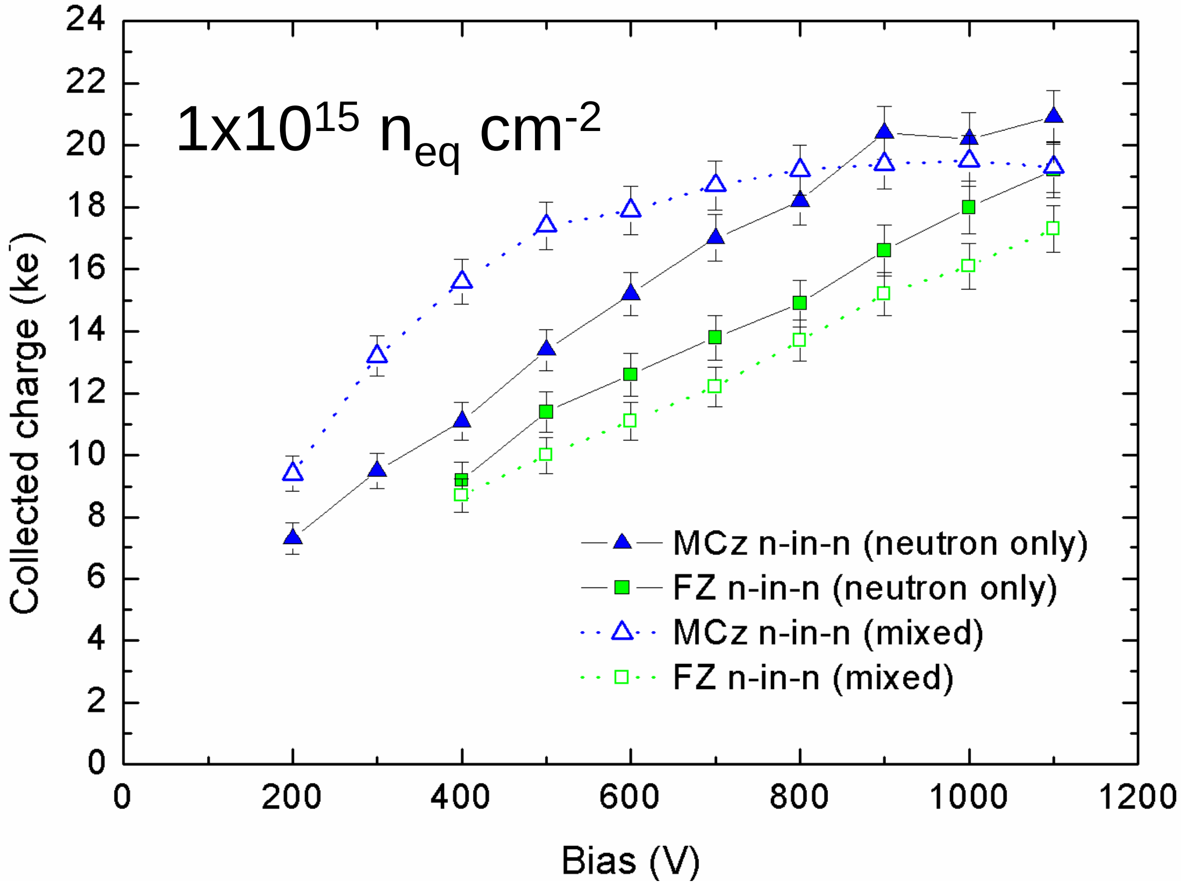
E. Fretwurst et al., 11th RD50 workshop

Practical outcome: possible partial compensation of N_{eff}, therefore **better CCE at low voltages**?

- **β > 0 (dominant donor creation) for protons (more point defects than clusters)**
- **β < 0 (dominant acceptor creation) for neutrons (more clusters than point defects)**

Mixed Irradiations (Neutrons+Protons)

- Both FZ and MCz show "predicted" behaviour with mixed irradiation
  - FZ doses add
    - $|N_{eff}|$ increases
  - MCz doses compensate
    - $|N_{eff}|$ decreases

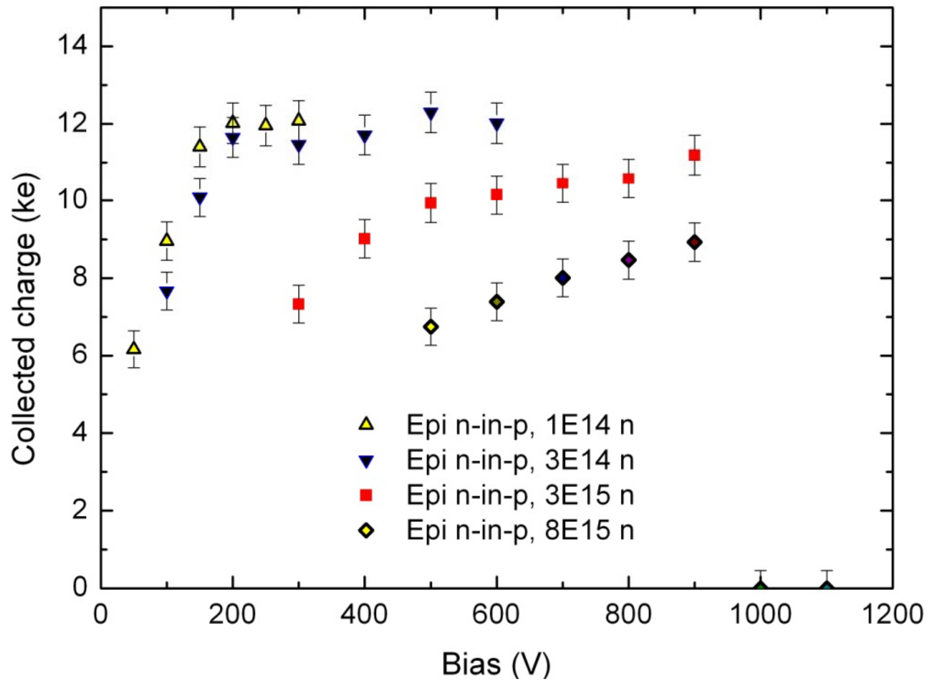


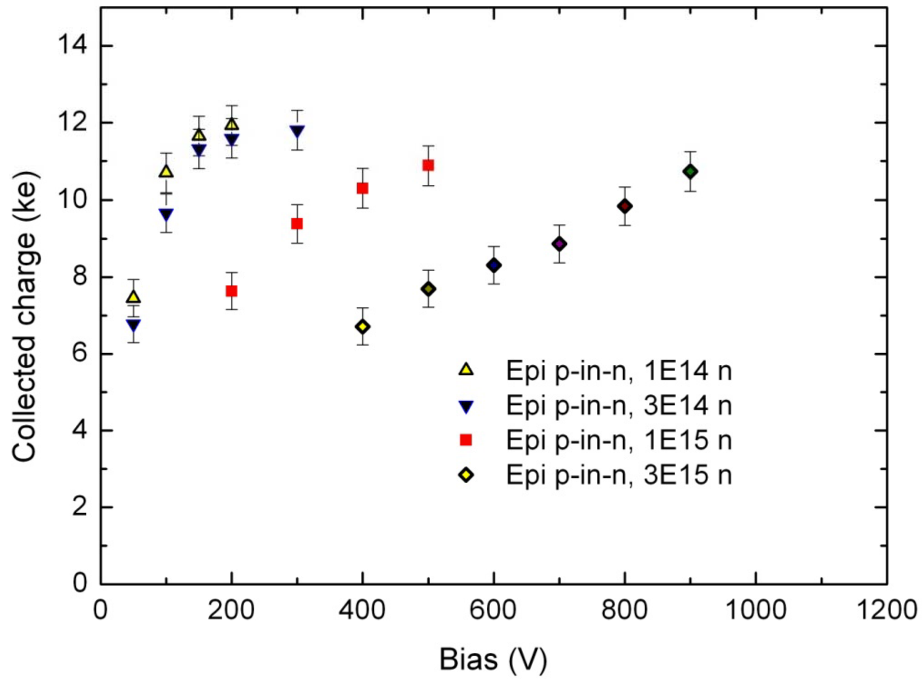
Needs further study with both nMCz and pMCz substrates and differing mixed doses

Thin Sensors

150 µm EPI - Neutrons

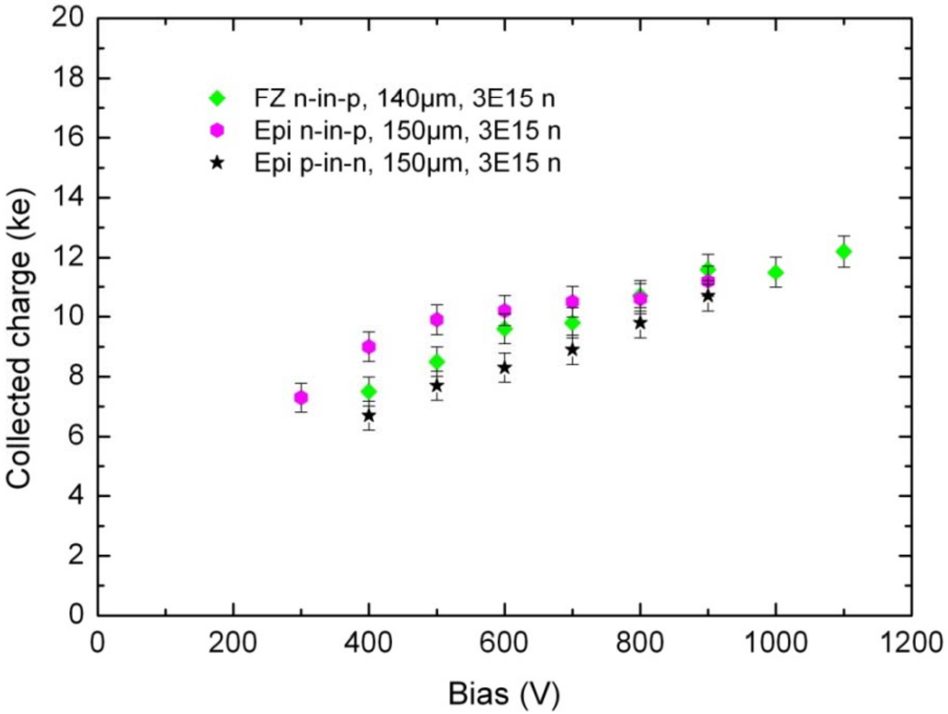
Produced by CNM Barcelona

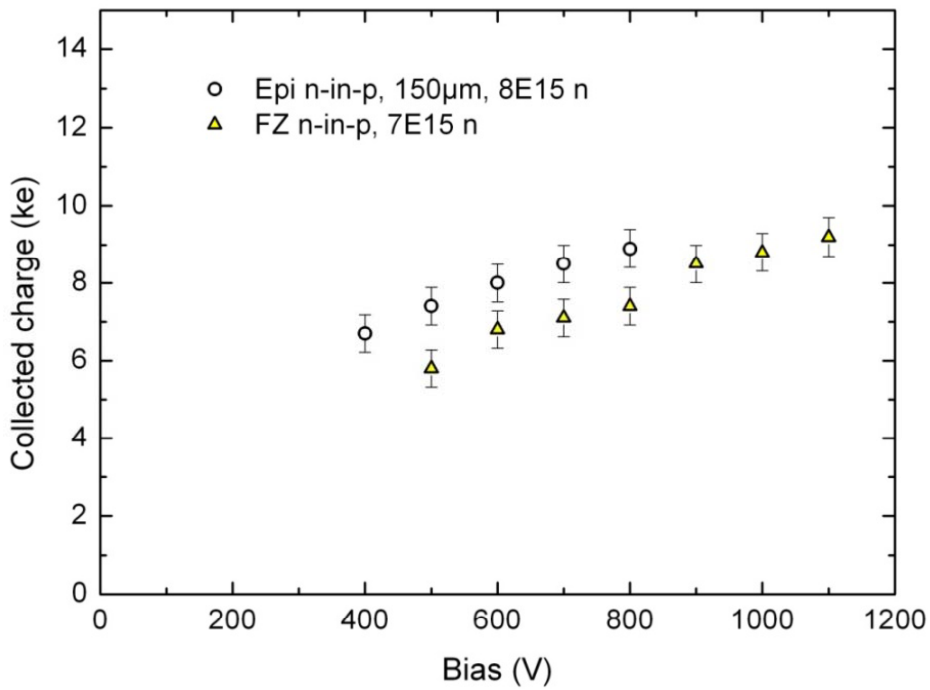




Significant charge (6.7 ke$^-$) measured after 8×10^{15} n cm^{-2}

EPI vs thin n-in-p FZ

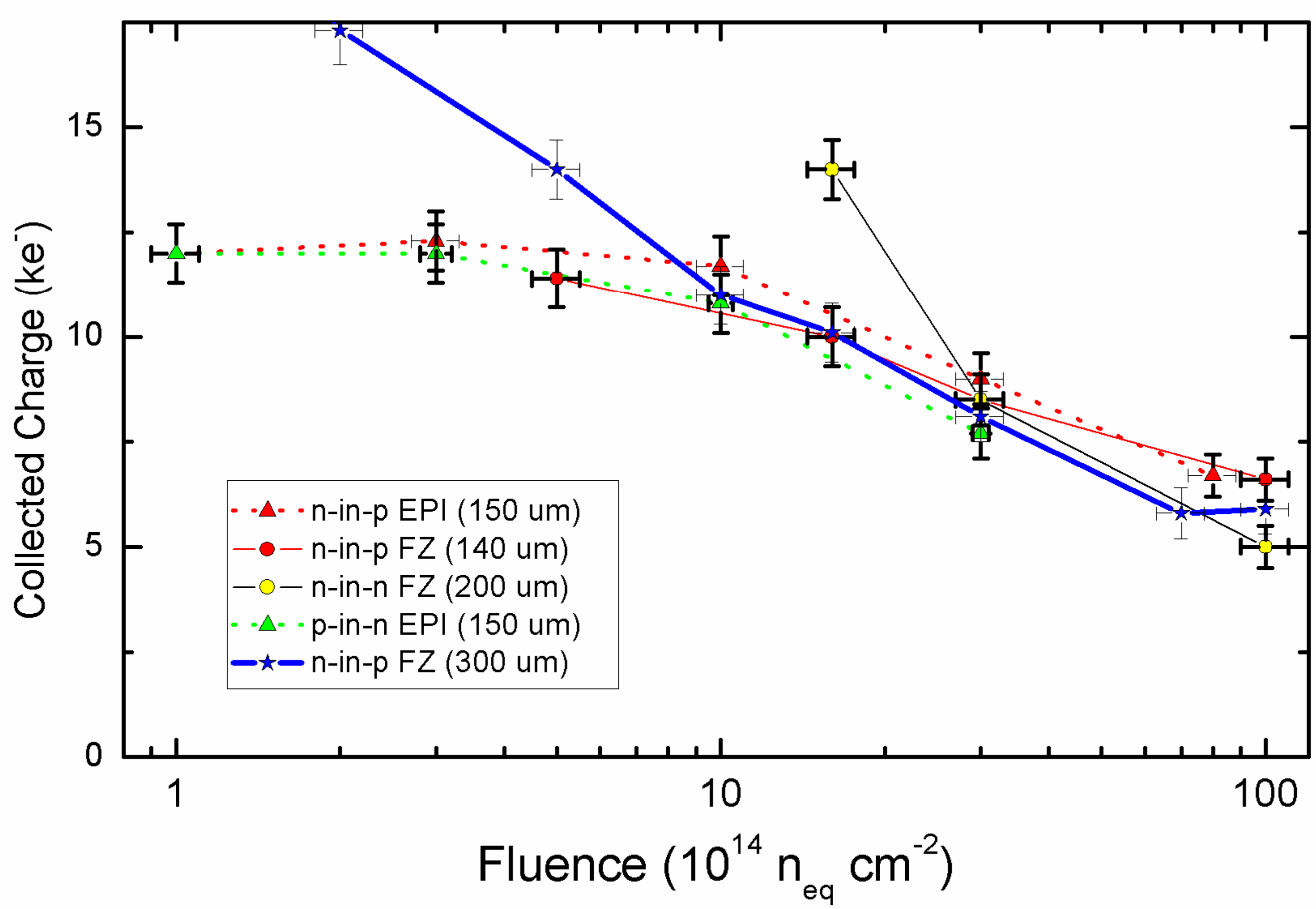




Good CCE results with Epi!

Drawbacks: difficult to process, expensive, limited sources of thick Epi (150µm), possible variability of performances!

Thin Summary-Neutrons



n-in-p EPI (150 um) slightly superior at higher neutron fluences

Thin Sensors (CCE)-Neutrons

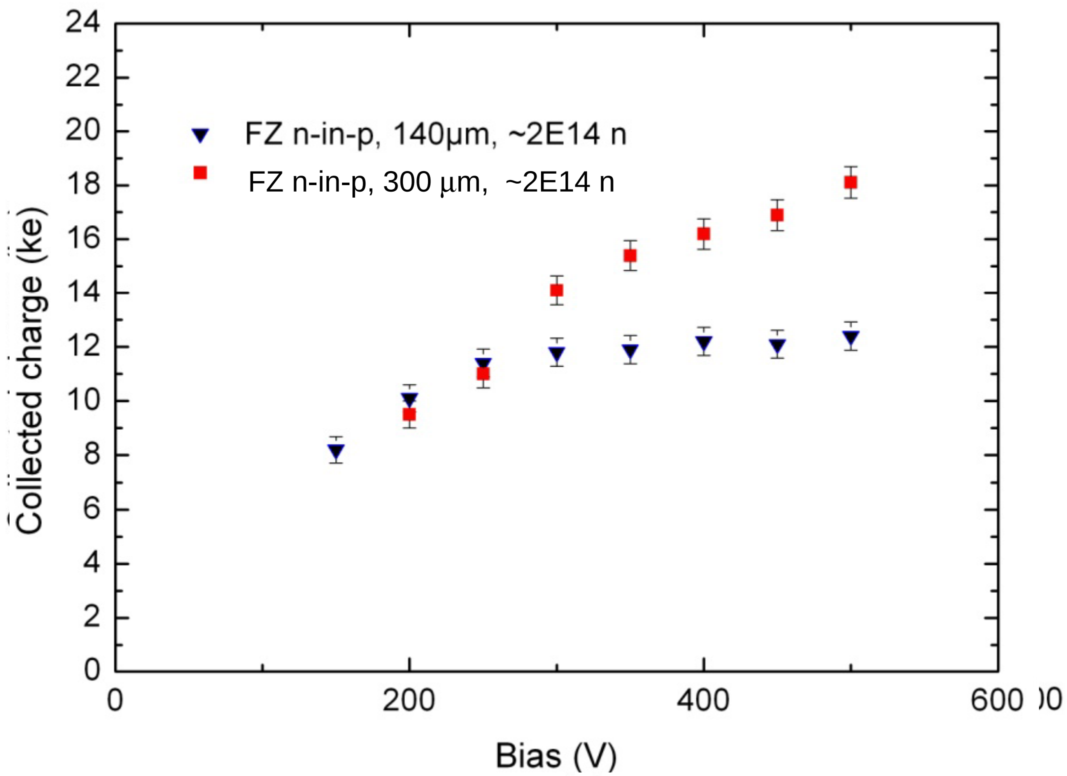
After 2×10^{14} n cm^{-2}, same CCE at low voltages and than saturation for the thin sensor (~250V).

After 5×10^{14} n cm^{-2}, same CCE at low voltages and than saturation for the thin sensor (~400V).

After 1.6×10^{15} n cm^{-2}, saturation for the thin sensor (~600V).

After 3×10^{15} n cm^{-2} the CCE of the 300µm thick devices becomes higher above 900V.

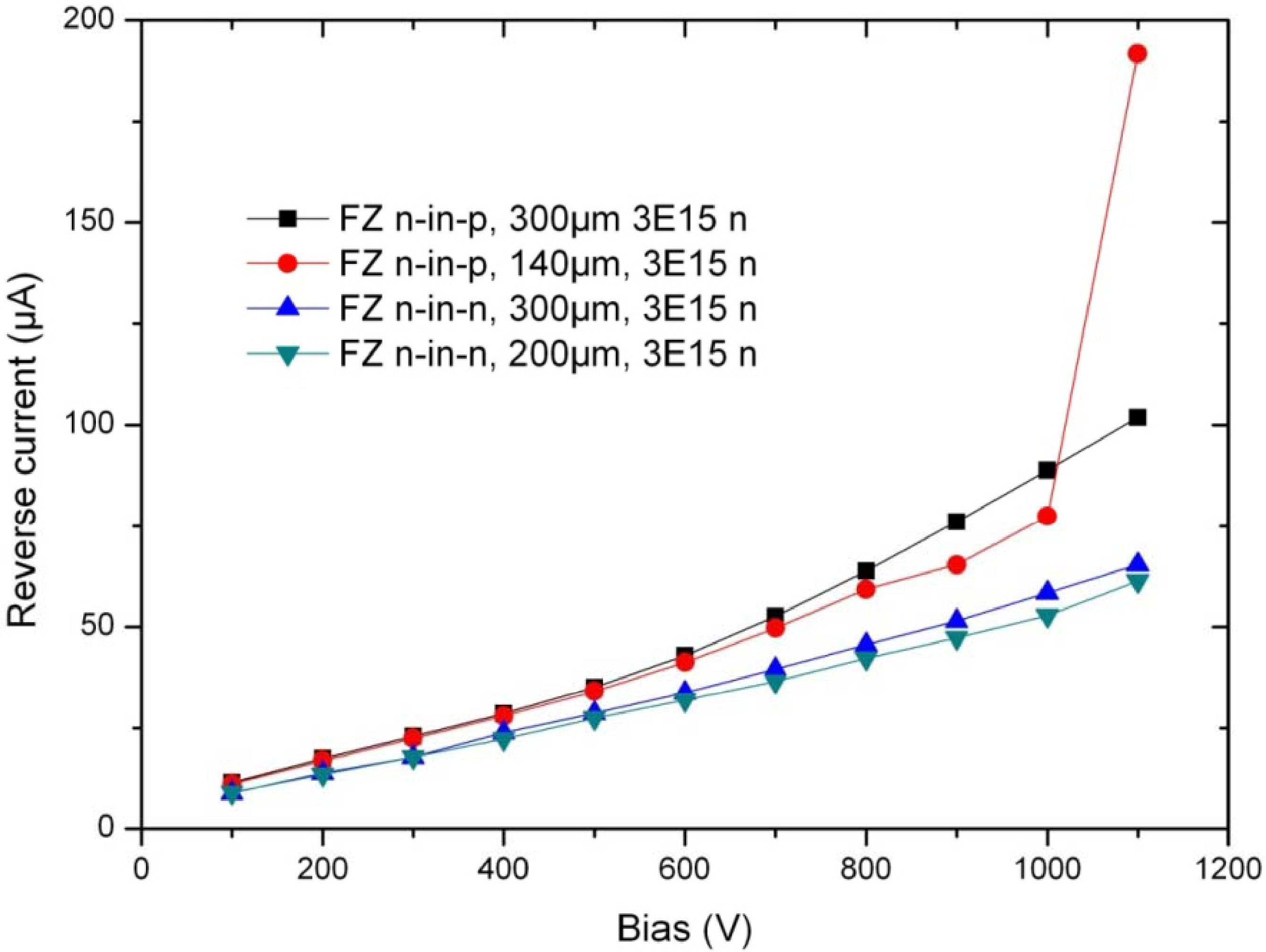
After 7×10^{15} n cm^{-2} the CCE of thin and thick sensors is the same up to 1100V.



Above 7×10^{15} n cm^{-2} , ~10% higher CCE for the 140µm thick sensors, but within uncertainties

Thick/Thin Reverse Currents

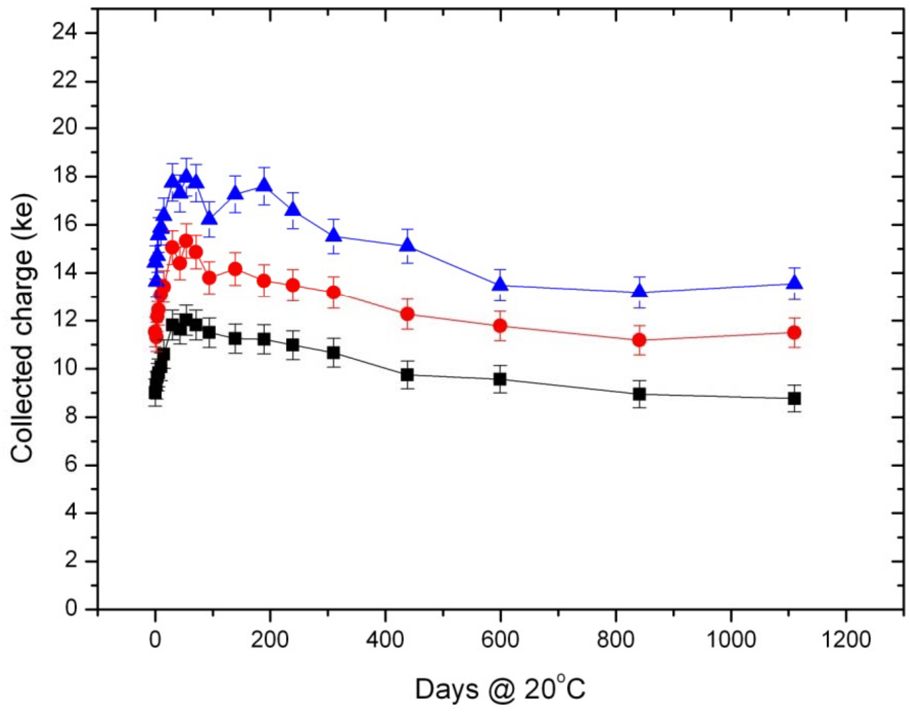
$>3\times10^{15}\ n_{eq}\ cm^{-2}$, no significant gains in current (power) with thinner sensors

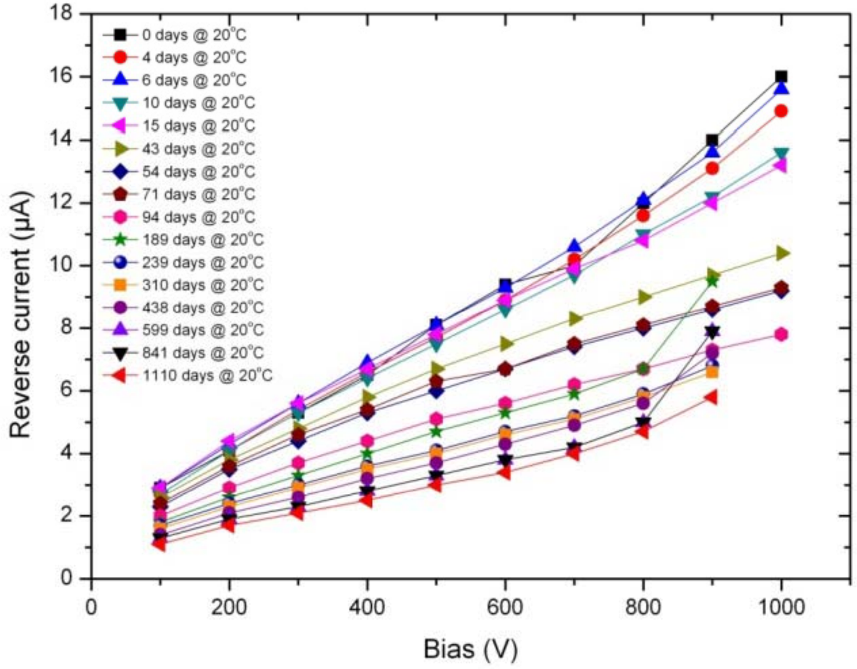


Annealing

n-in-p FZ Neutrons (1E15)

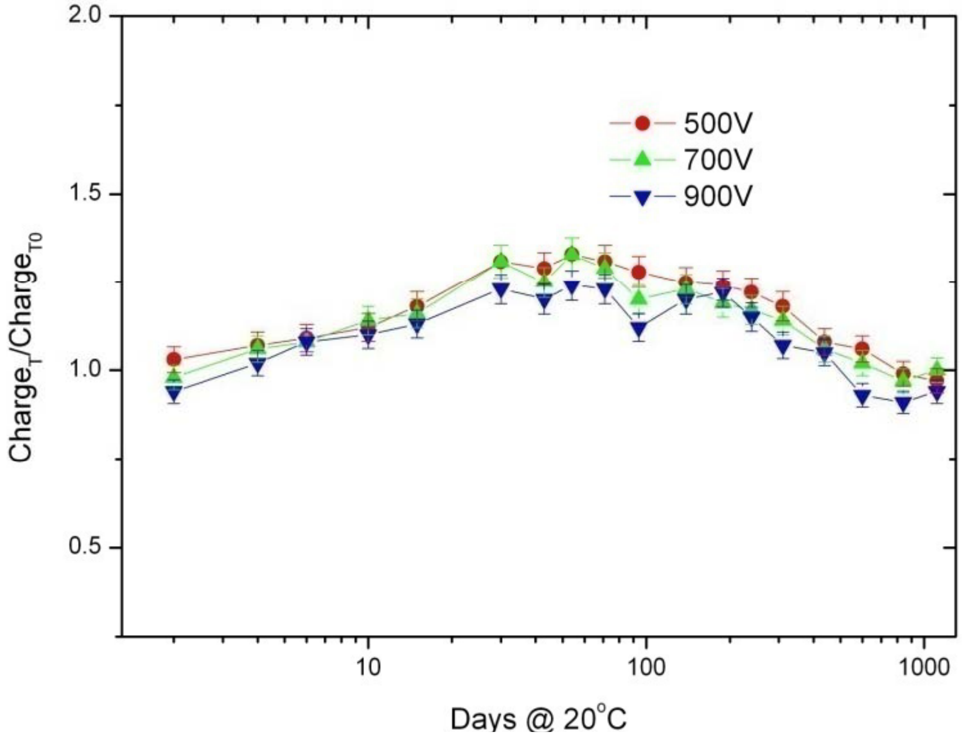
“Fine step” Annealing of the collected charge,
HPK FZ n-in-p, 1E15 n cm^{-2}

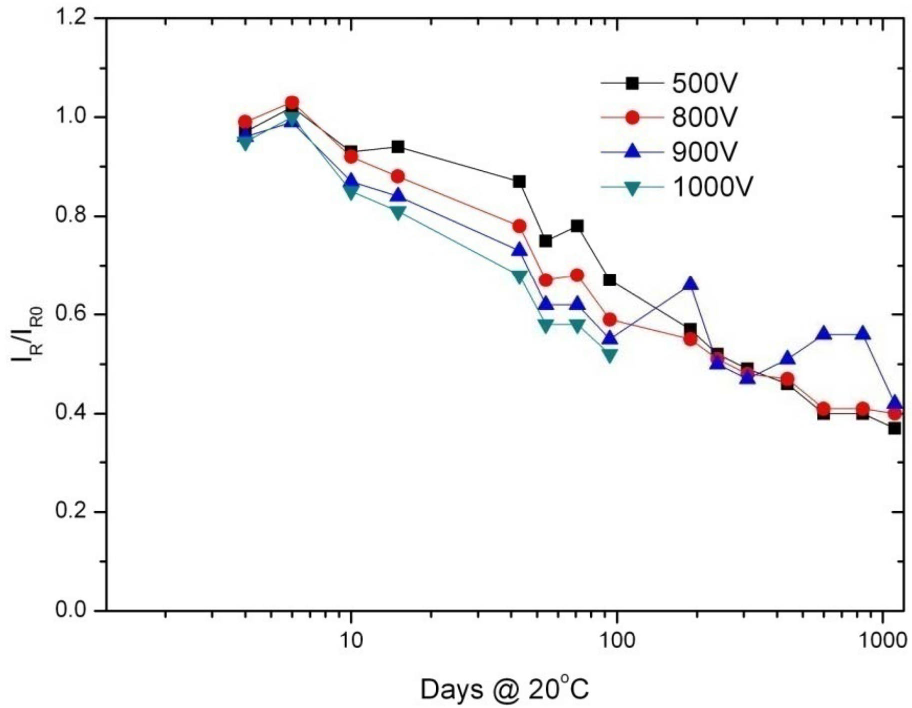




n-in-p FZ Neutrons (1E15)

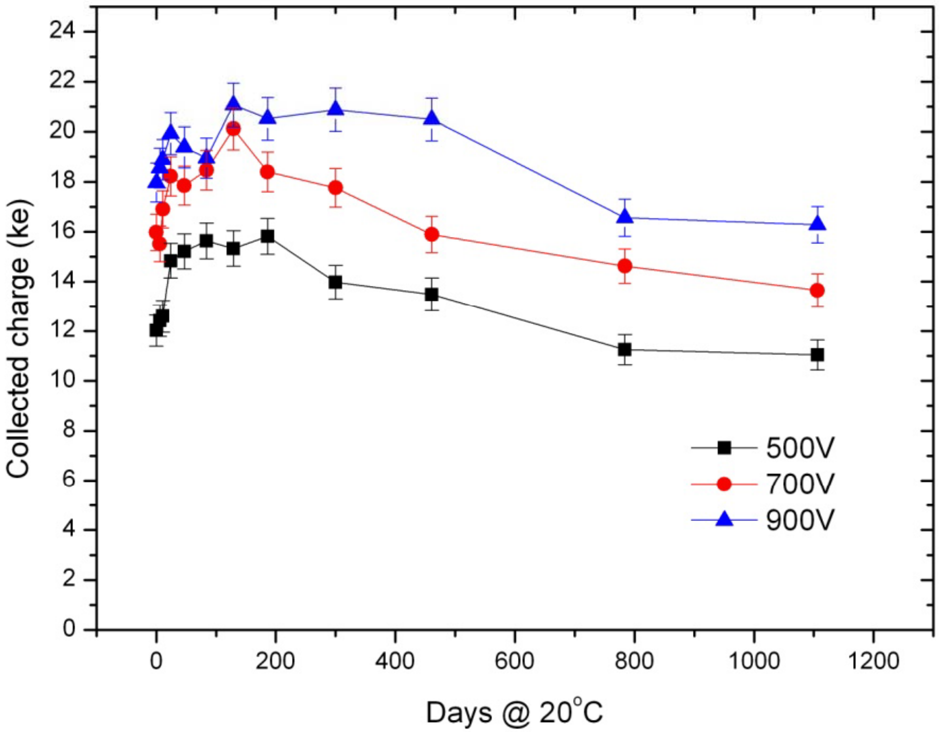
“Fine step” Annealing of the collected charge,
HPK FZ n-in-p, 1E15 n cm^{-2}

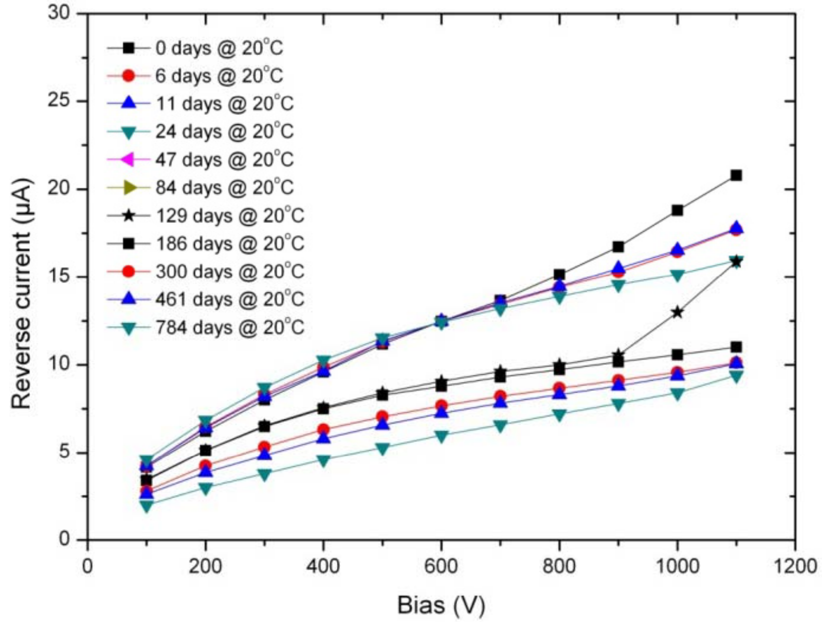




n-in-p FZ 26 MeV Protons (1E15)

"Fine step" Annealing of the collected charge, Micron FZ n-in-p, 1E15 n cm^{-2} (26MeV p irradiation)





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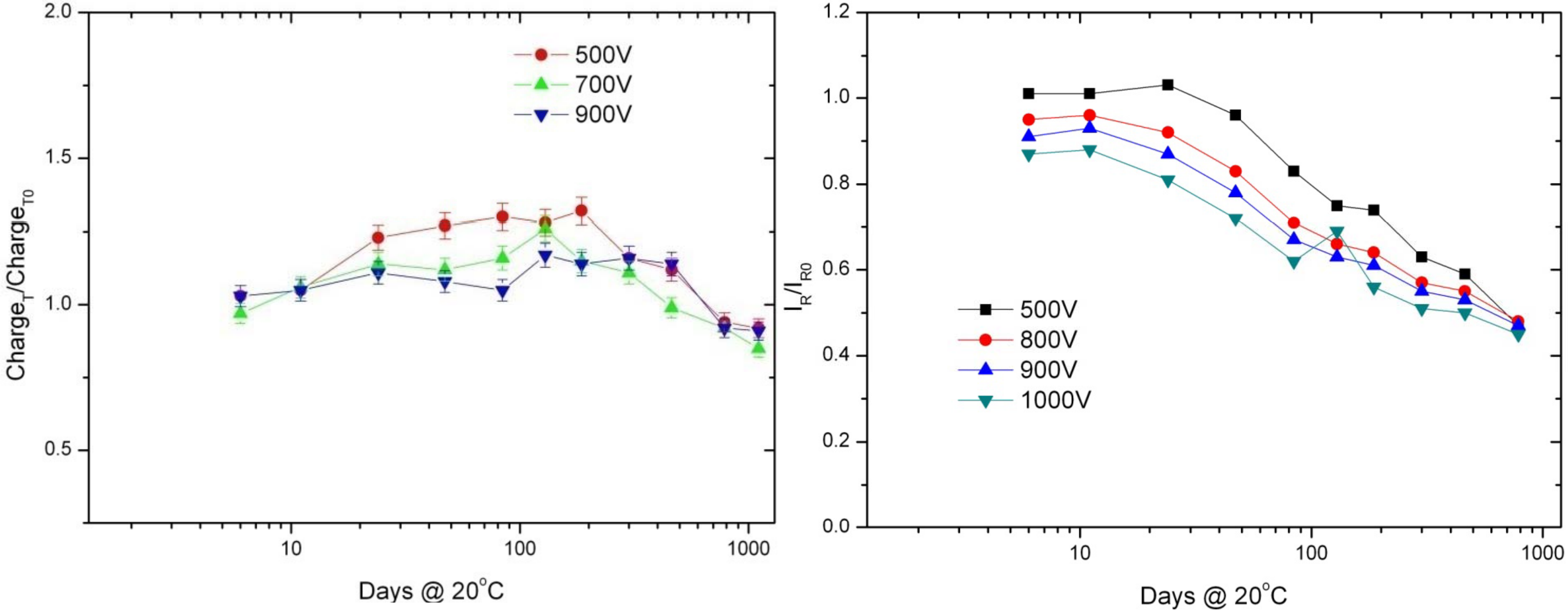
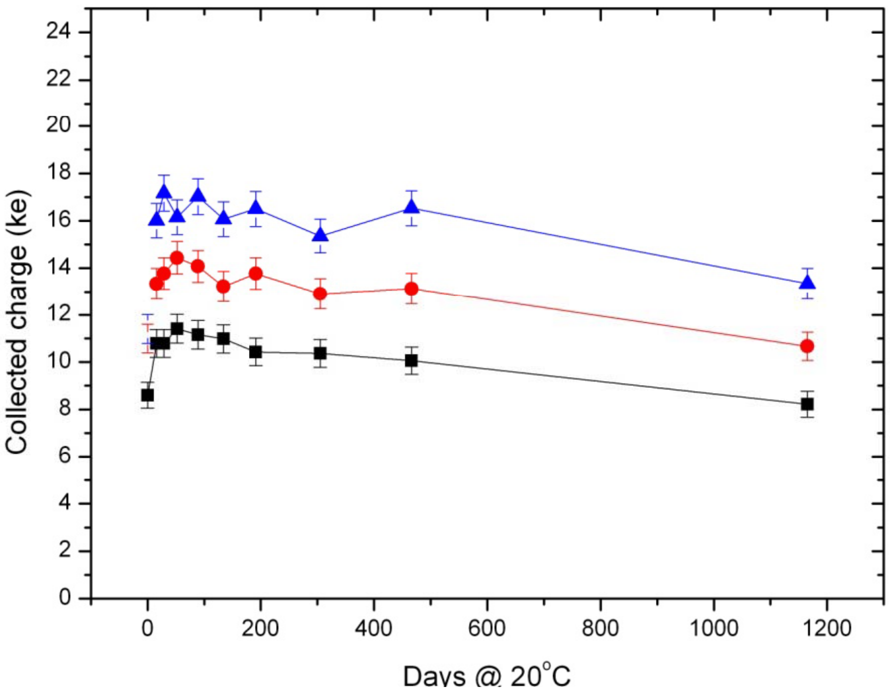
n-in-p FZ 26 MeV Protons (1E15)

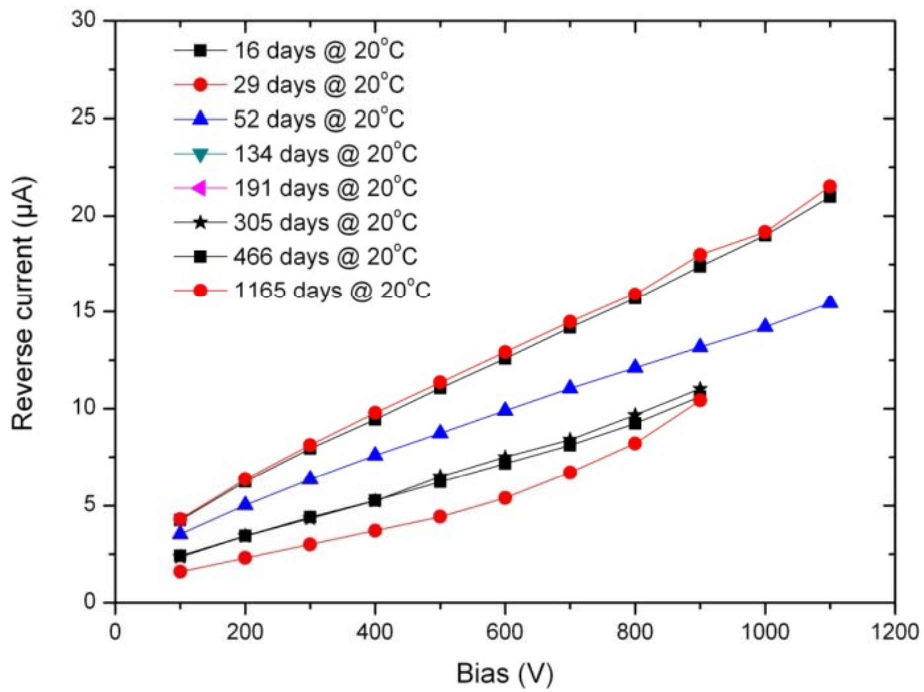
"Fine step" Annealing of the collected charge, Micron FZ n-in-p, 1E15 n cm^{-2} (26MeV p irradiation)



n-in-n FZ Neutrons (1.5e15)

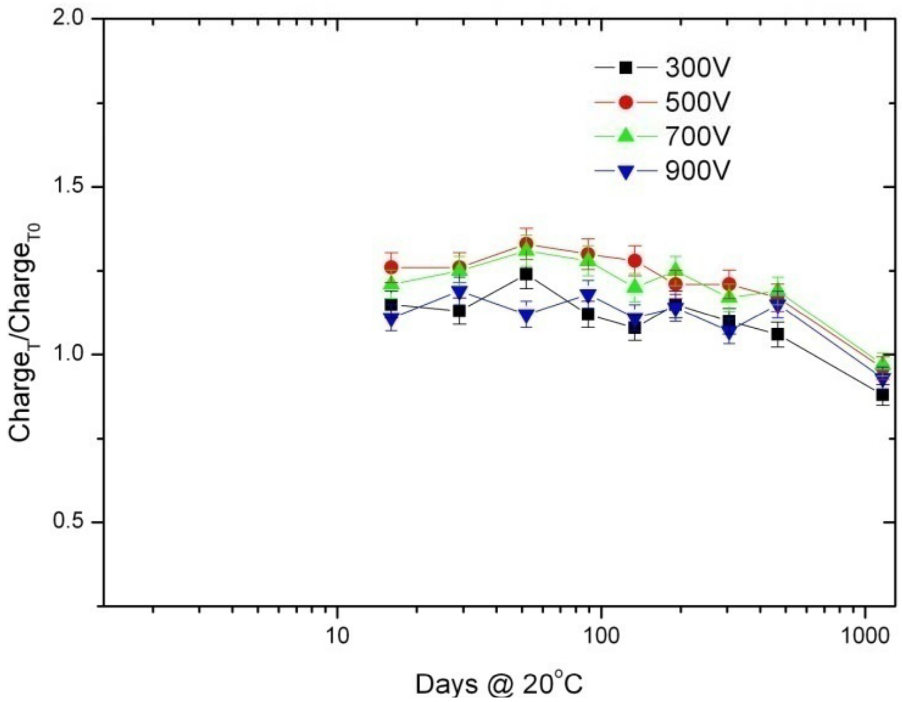
"Fine step" Annealing of the collected charge, Micron FZ n-in-n, 1.5E15 n cm^{-2}

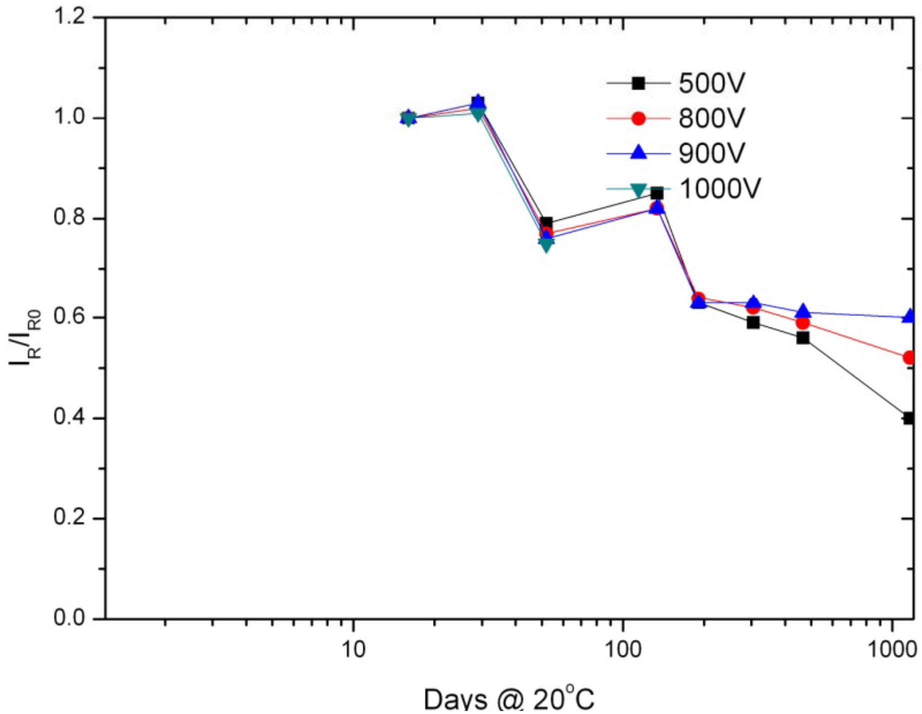




n-in-n FZ Neutrons (1.5e15)

“Fine step” Annealing of the collected charge,
Micron FZ n-in-n, 1.5E15 n cm^{-2}





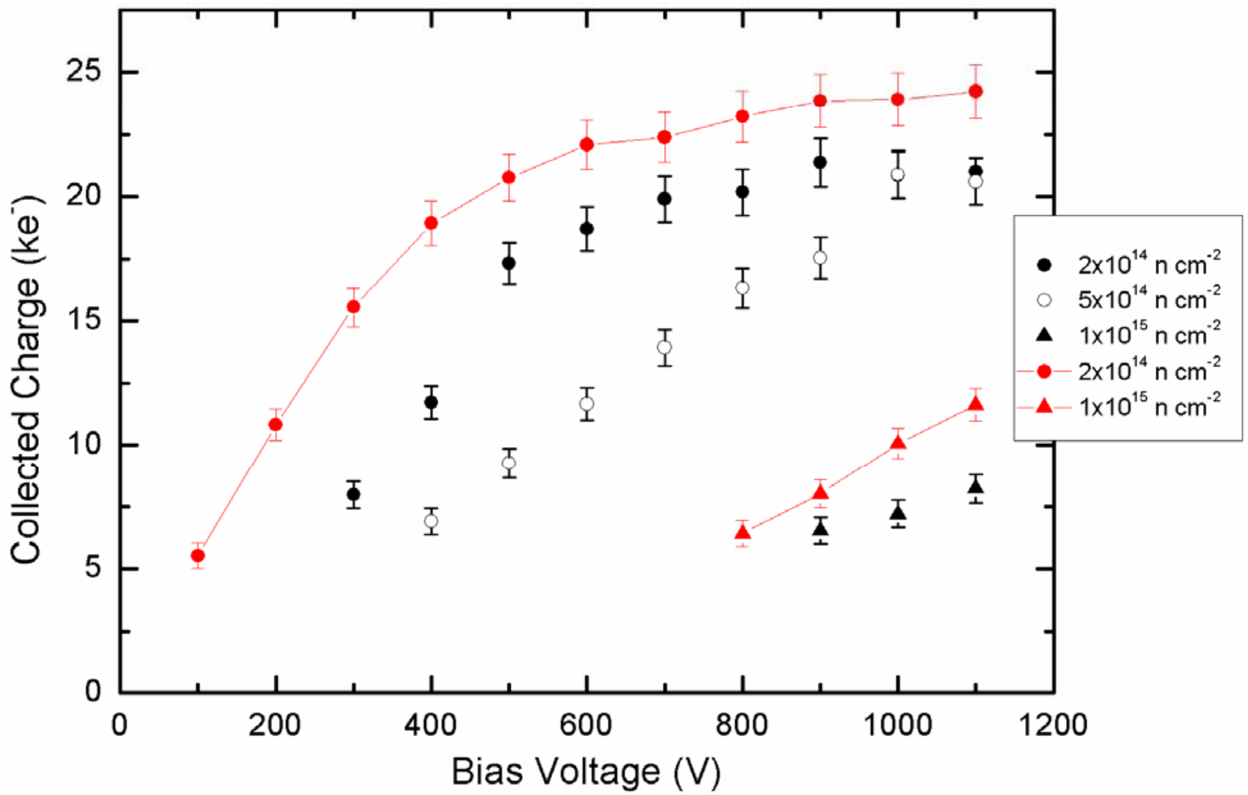
Conclusions

- Planar, n-strip detector detectors have shown sufficient collected charge for innermost layers at SLHC assuming that:
  - Low threshold (2ke$^-$), low noise (500 enc) electronics achievable
  - Cooling can handle ~260 mW/cm^2 sensor power with -25 C° at sensor
- n-in-n MCz shows promise after neutral irradiation
- n-in-p MCz shows promise after charged irradiation
  - Need mixed, high dose irradiations
- n-in-p EPI shows some benefit relative to thin FZ after neutron irradiation
  - Power might be an issue
- Fine annealing performed after neutron/proton irradiations for n-in-p/n-in-n FZ
  - +30% CCE and -40% Power after 100 days annealing at 20 C

Backup

Neutron Irradiations

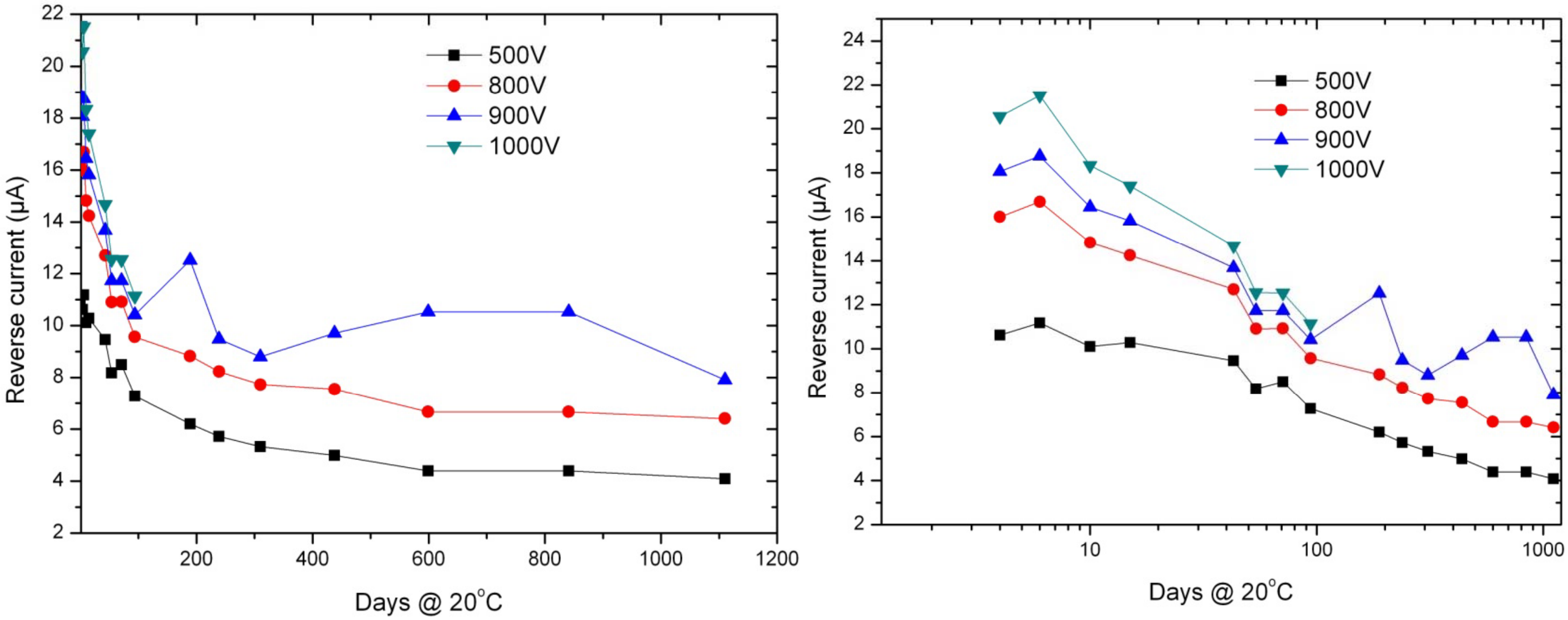
- p-in-n
  - MCz slightly better than FZ
  - Insufficient CCE for tracking >5-10×10^{14} n cm^{-2}
- n-in-n
  - MCz much better than FZ
  - Higher dose MCz data needed
- n-in-p
  - FZ/MCz similar response
  - *Charge seen after 1.5×10^{16} n cm^{-2}*



p-in-n sensors: FZ–black, MCz-red

Annealing Reverse Current

"Fine step" Annealing of the reverse current,
HPK FZ n-in-p, 1E15 n cm^{-2}



Material comparison: EPI n vs p, reactor neutrons