# Results with thin Si sensors, IV and CCE(V) annealing and implication for the operations

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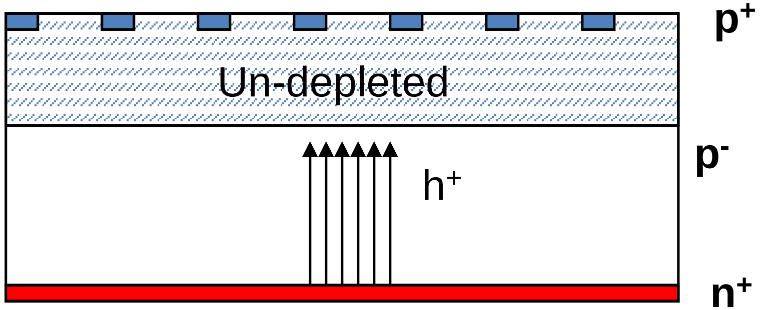
# P-strip vs N-strip Readout

Effect of trapping on the Charge Collection Efficiency (CCE)

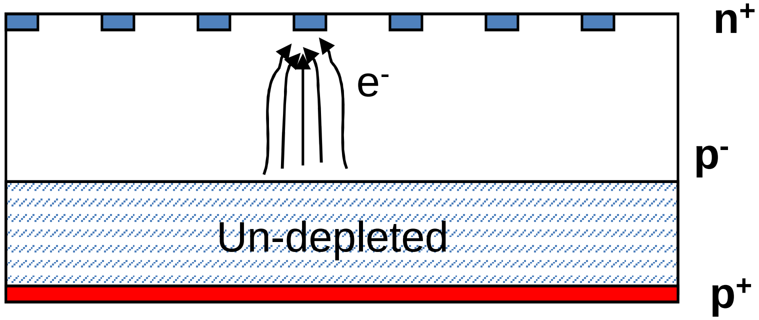
$$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr}),\ 1/\tau_{tr} = \beta\Phi.$$

$t_C$ is collection "time", $\tau_{tr}$ is effective trapping time

**"Standard" p-on-n after type inversion**




**"New" n-on-p before/after type inversion**




Type inversion turns lightly doped material to "p" type

- Holes collected
- Deposited charge cannot reach electrode
  - Charge spread over many strips
  - Lower signal

- Electron collected
  - Higher mobility and ~33% smaller trapping constant
- Deposited charge can reach electrode

# Effect of trapping on the Charge Collection Distance

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

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

After heavy irradiation thin detectors should have a similar (or better) CCE as thicker ones.

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

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

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

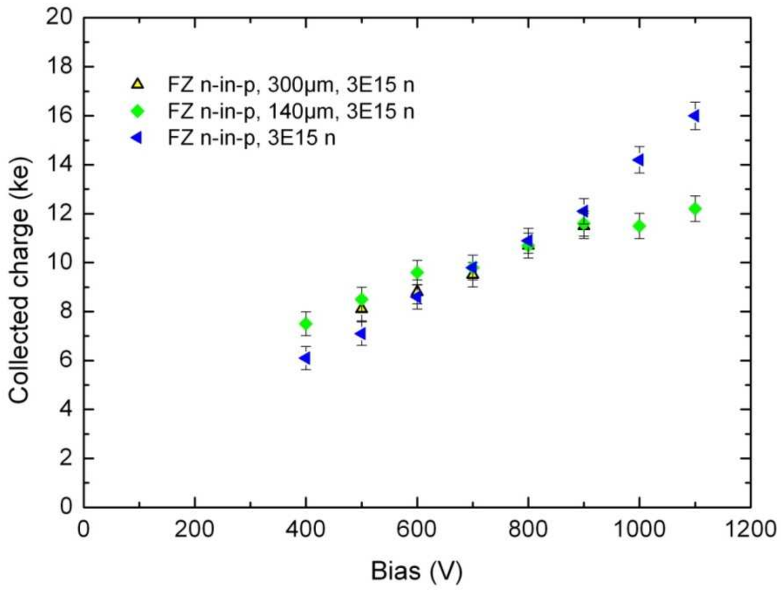
Is there any advantage in term of CCE and reverse current in going thin?

$$\lambda_{av}\ (\Phi\text{=}1e14) \cong 2400\mu m$$

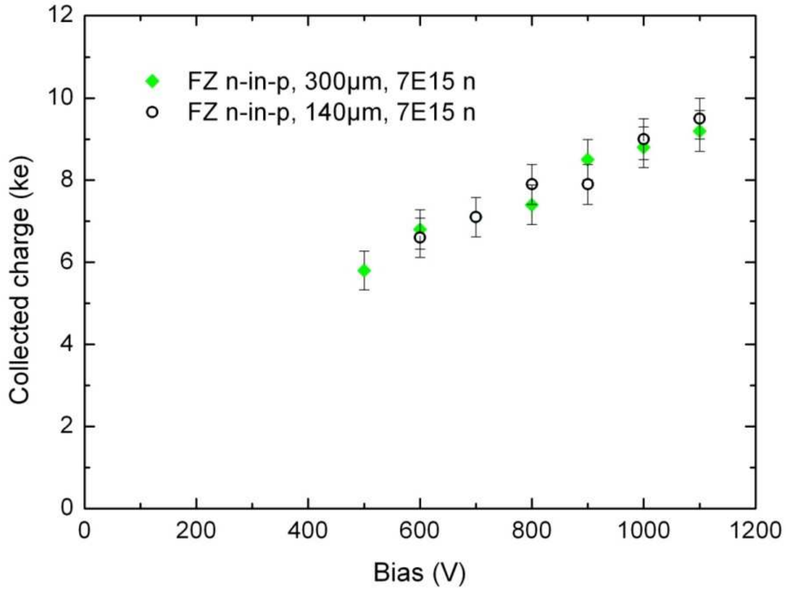
$$\lambda_{av}\ (\Phi\text{=}1e16) \cong 24\mu m$$

# Changes of the CCD: comparison of thin and thick detectors after 3 and 7.5x$10^{15}$ n cm$^{-2}$.

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




After 7.5x$10^{15}$ n cm$^{-2}$ the CCE of thin and thick sensors is the same up to 1100V.



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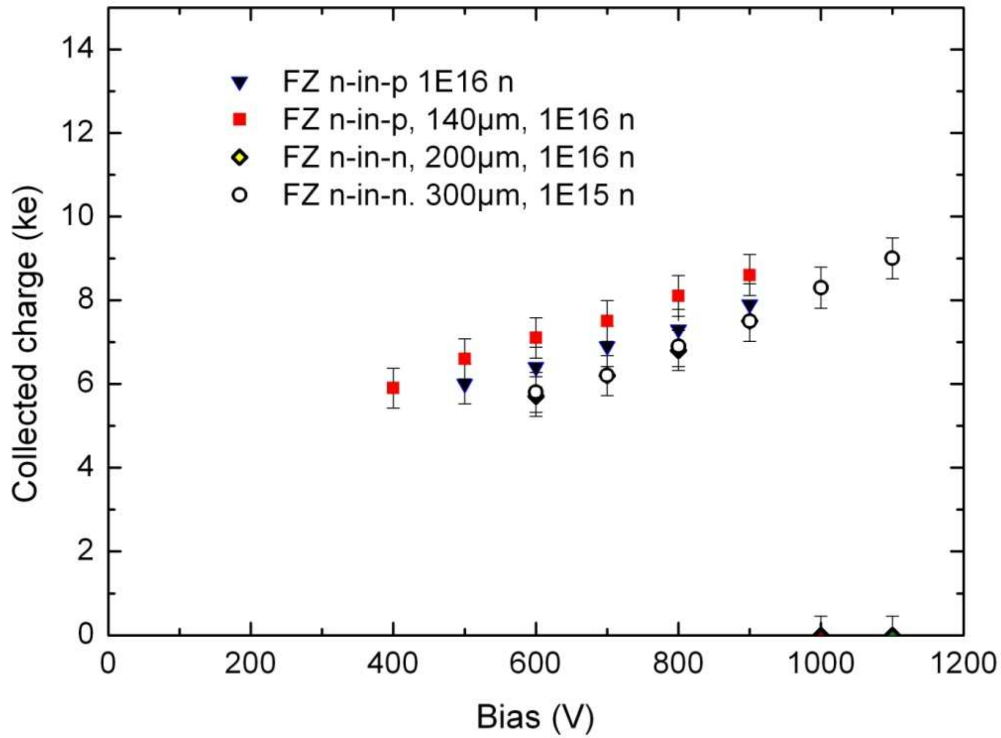
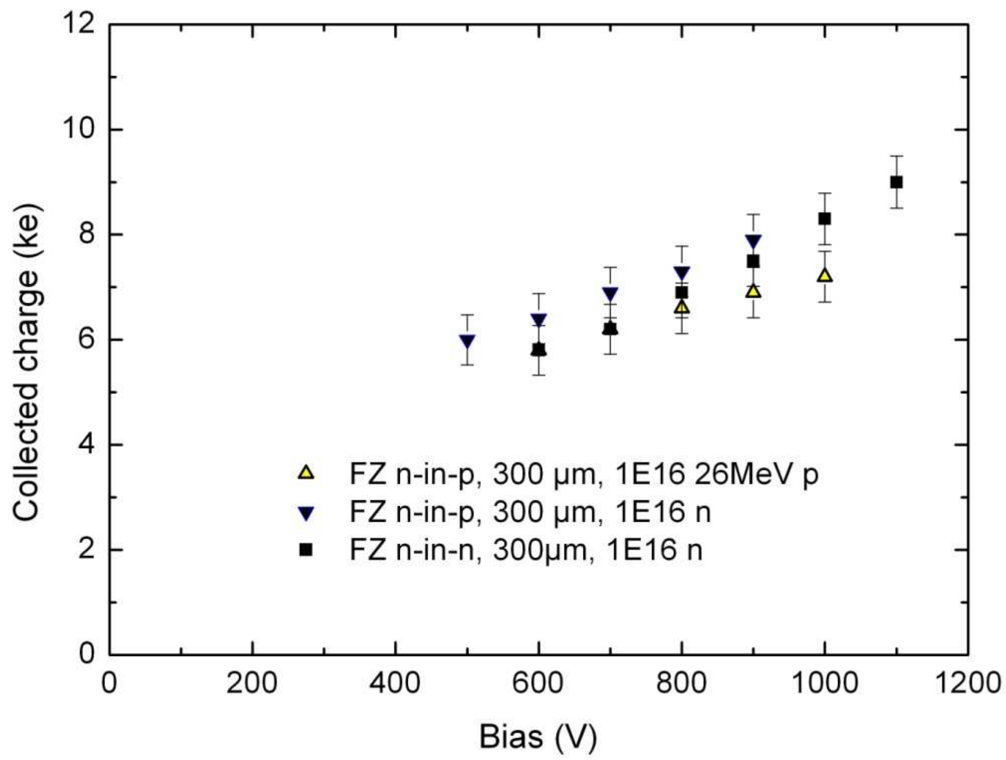
# 140, 200 and 300 μm thick detectors after ~$1x10^{16}$ n $cm^{-2}$!

About 10% higher CCE for the 140μm thick sensors (irradiated in the same session as the 300 μm thick one).



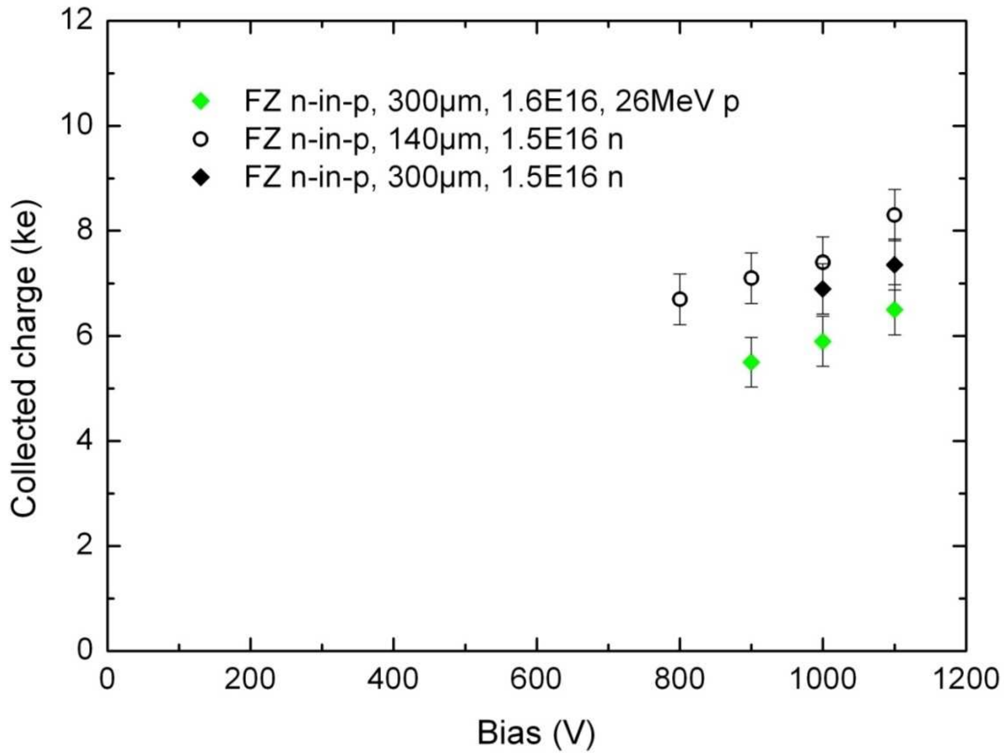
# 300 $\mu$m thick n-in-n and n-in-p detectors after ~1x10$^{16}$ n and 26MeV p cm$^{-2}$!

Indication that proton introduces more charge trapping than neutron irradiation for equivalent NIEL doses. Similar CCE vs Bias(V) for n-side read out n and p FZ substrates.



# 140 and 300 μm thick detectors after ~1.5x$10^{16}$ n and 26MeV p $cm^{-2}$!

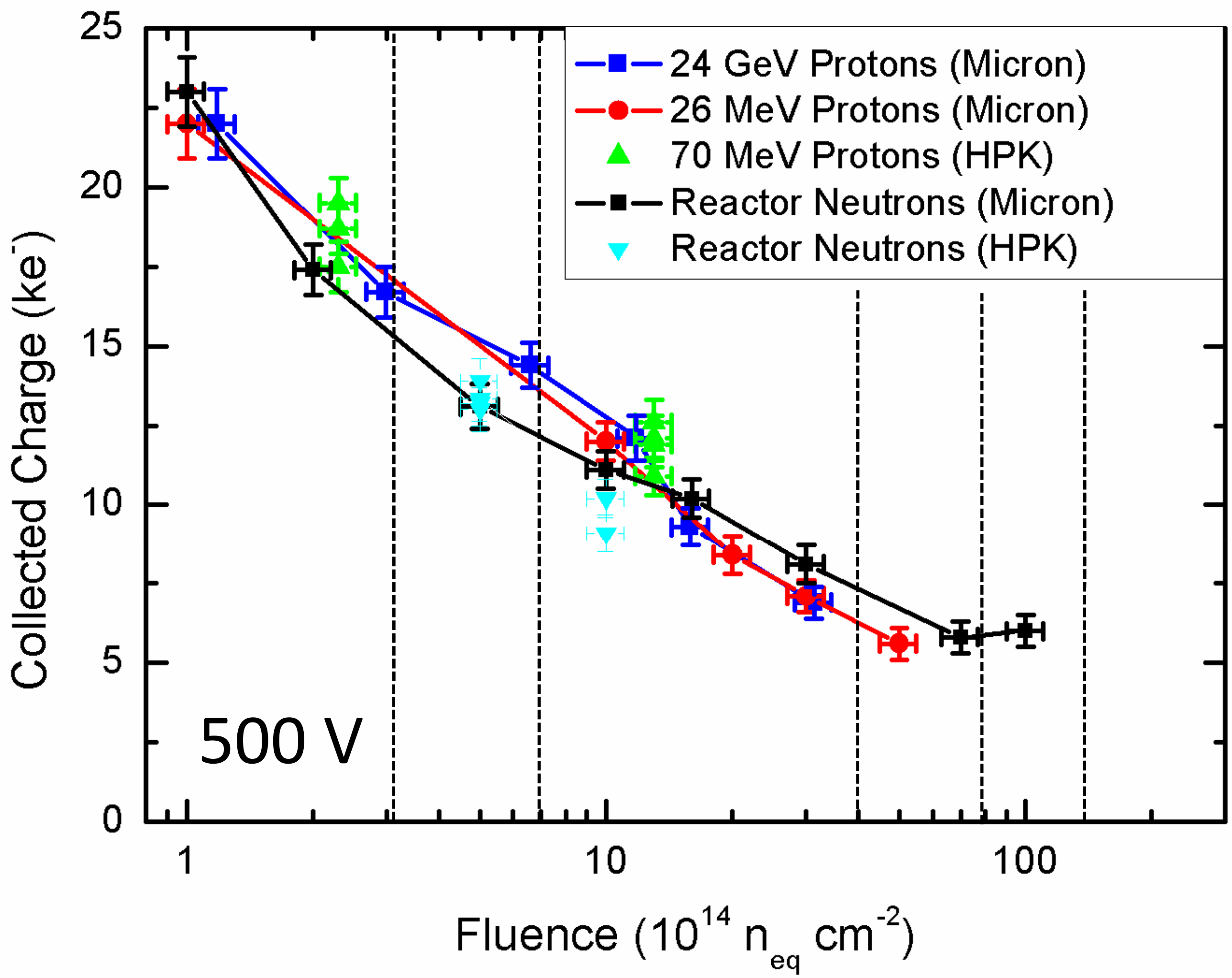
Evidence that proton introduces more charge trapping than neutron irradiation for equivalent NIEL doses.



# n-in-p FZ Irradiation Comparisons

CCE at expected fluences (2x)

- 1st Outer Pixel Layer
  - 500 V: 7 ke-
  - 900 V: 10 ke-
- 2nd Inner Pixel Layer
  - 500 V: 4 ke- (est.)
  - 900 V: 7.5 ke-
- 1st Inner Pixel Layer
  - 500 V: 2 ke- (est.)
  - 900 V: 5.5 ke-
- B-layer (estimated)
  - 500 V: 0.5 ke-
  - 900 V: 4 ke-




Efficient if Signal/Threshold > 2, Signal/Noise > 8

For planar silicon, need ~2 ke- threshold, ~500 electron noise for innermost pixel layers

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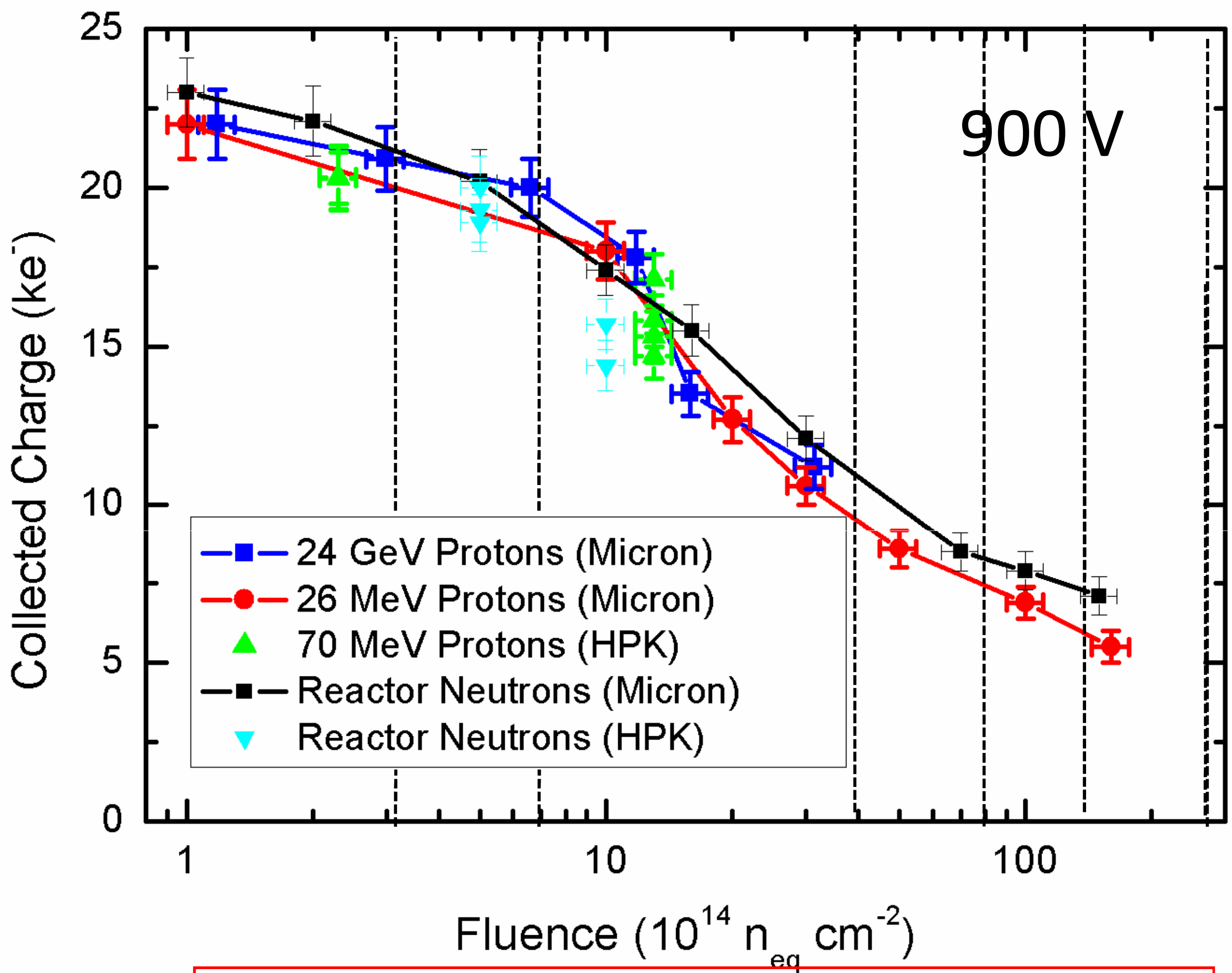


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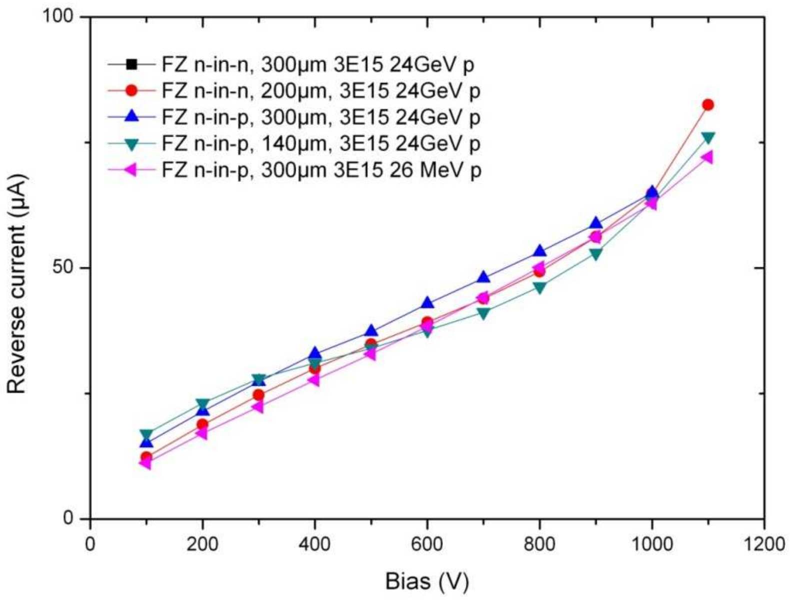
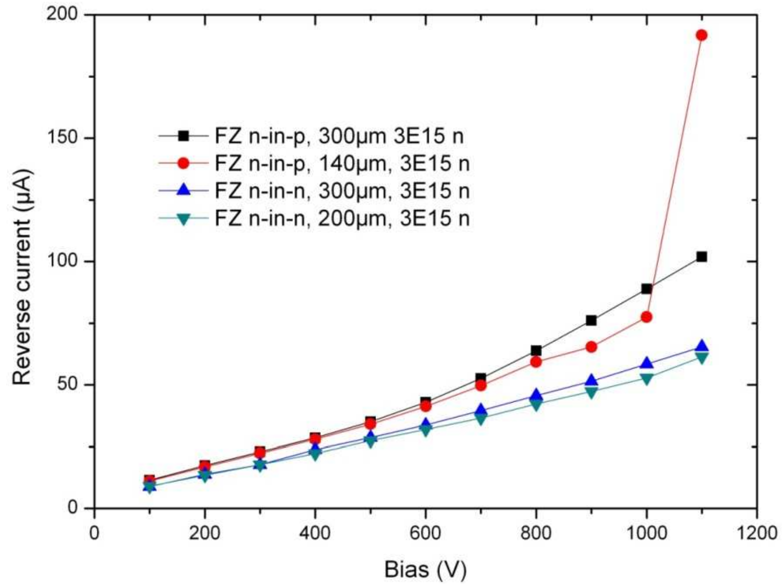
# IV thin vs standard, various irradiation



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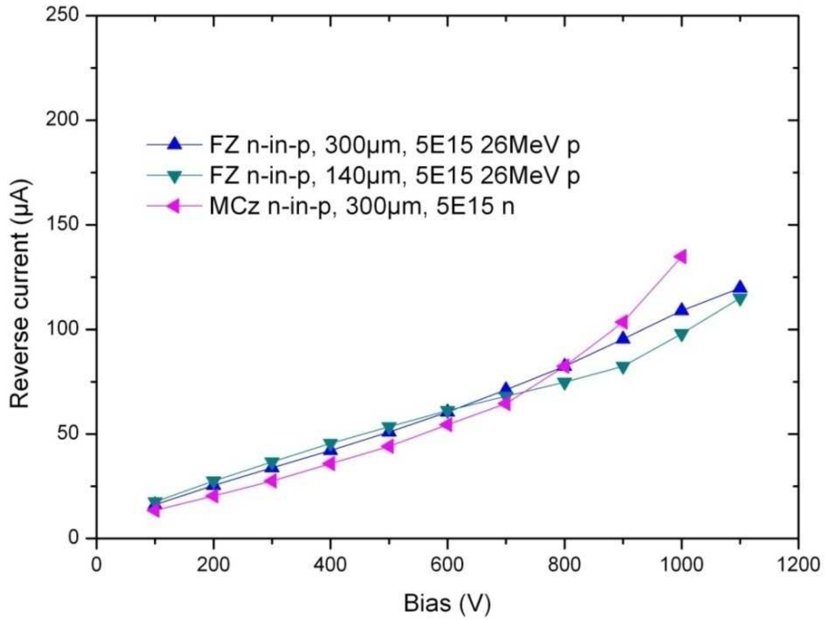
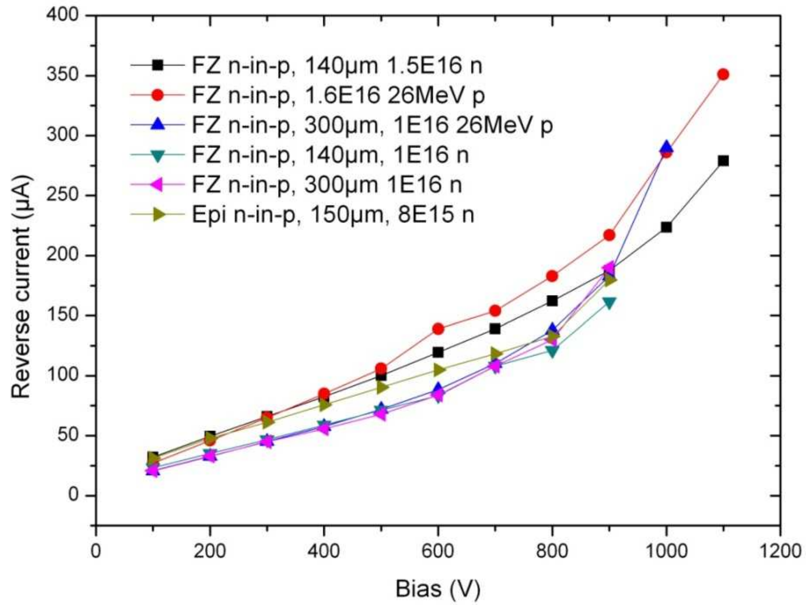


# How to control the reverse current?

The $I_R$ introduces significant power consumption (same level as the estimate on the chip after 1E16 $cm^{-2}$, about 100mW/$cm^2$), risk of runaway and increase of shot noise (not relevant for pixel sensors). Need cooling (-25$^o$C) to keep it low. Is there a way to reduce $I_R$, besides temperature? Thin sensors do not help in this respect, so …….

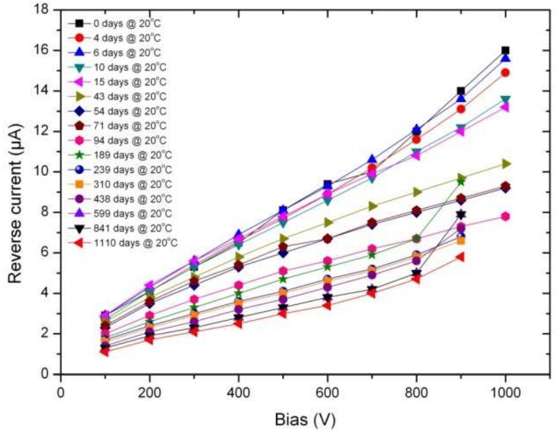
$$I(T_{ref}) = \left(\frac{T_{ref}}{T}\right)^2 \exp\left(-\frac{E}{2k_B}\left[\frac{1}{T_{ref}} - \frac{1}{T}\right]\right) \times I(T)$$

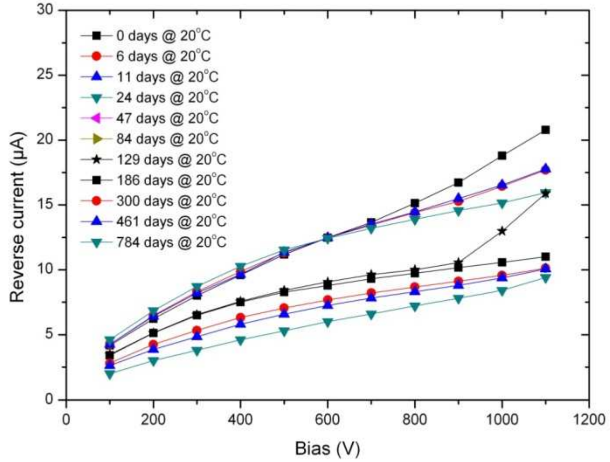
To scale from -25 C°, multiply by:

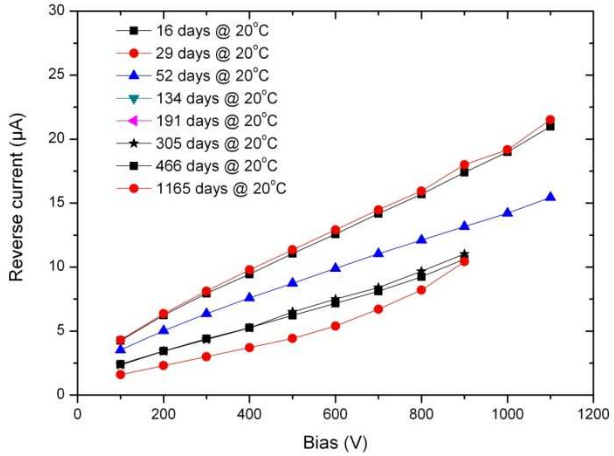
0.54 for -30 C° at sensor
1.8 for -20 C° at sensor
3.1 for -15 C° at sensor

5.6 for -10 C° at sensor
15.8 for 0 C° at sensor
104 for 20 C° at sensor

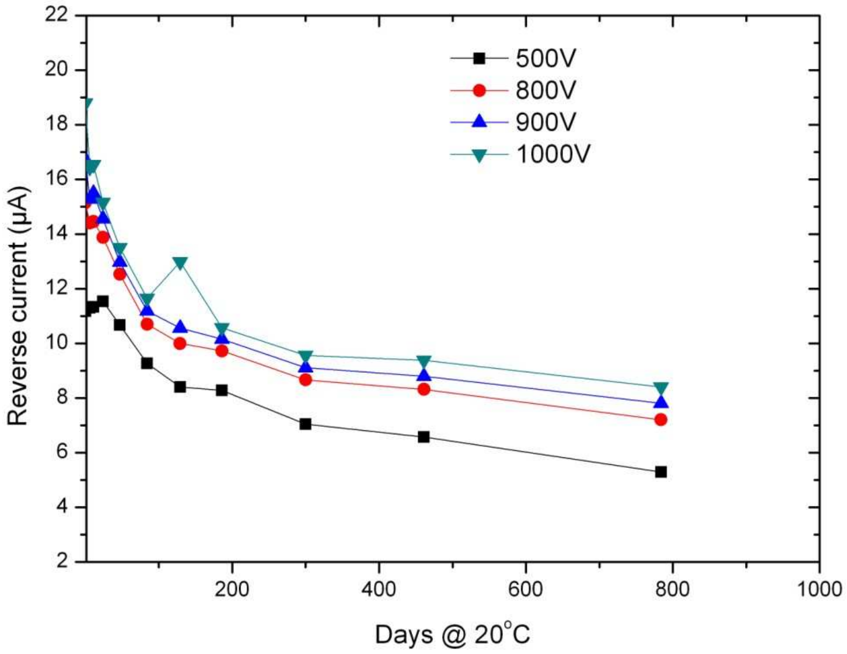
# “Fine step” Annealing of the reverse current, Micron FZ n-in-p, 1E15 n $cm^{-2}$ (26MeV p irradiation), Micron FZ n-in-n, 1.5E15 n $cm^{-2}$

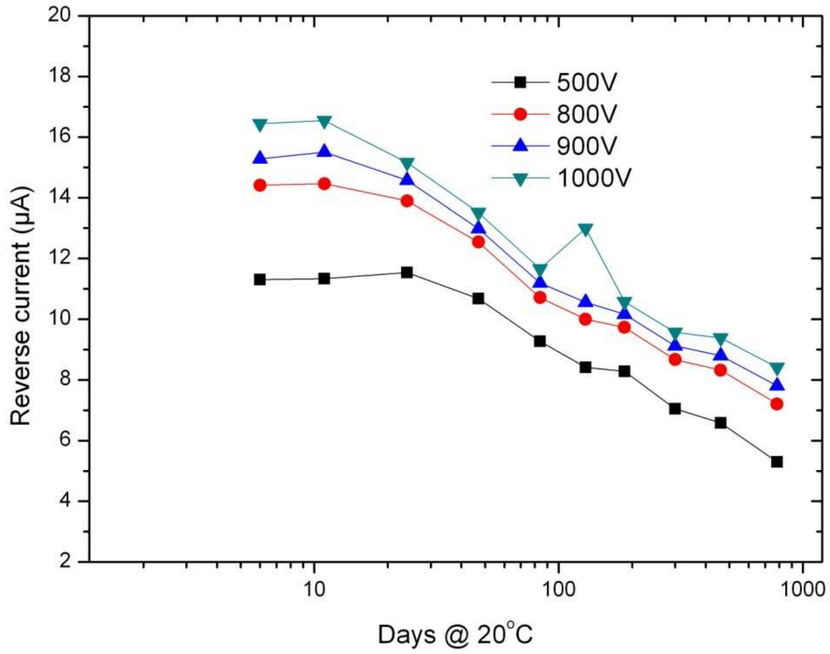


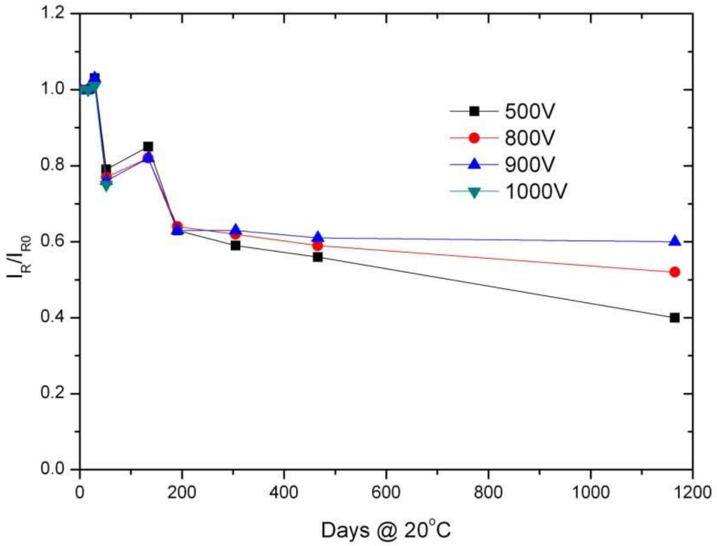



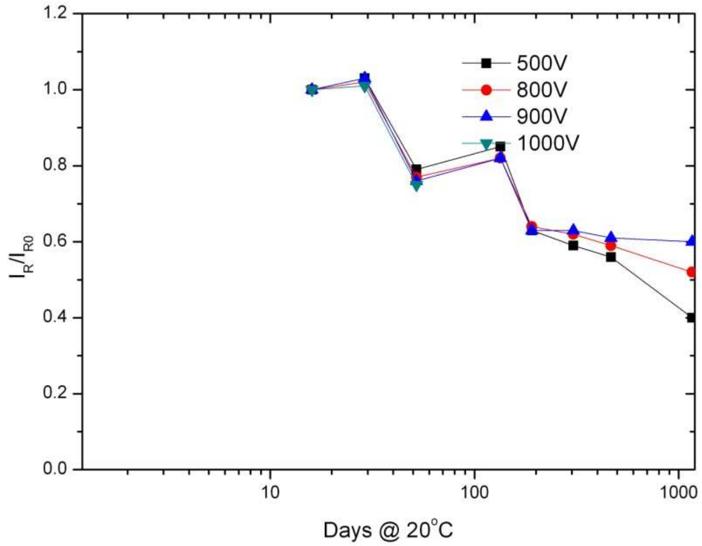
# "Fine step" Annealing of the reverse current, Micron FZ n-in-p, 1E15 n cm$^{-2}$ (26MeV p irradiation)



# “Fine step” Annealing of the reverse current, Micron FZ n-in-n, 1.5E15 n $cm^{-2}$



# “Old” assumption:

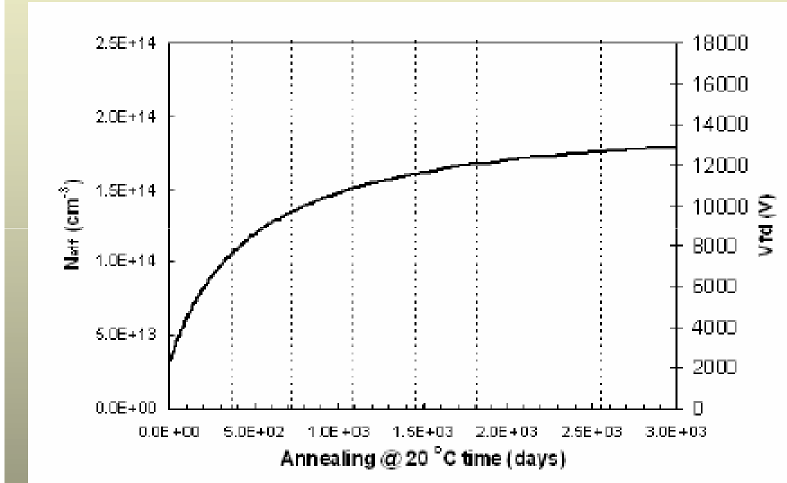
Avoid to warm the irradiated detectors above 0°C, even during beam down and reduce maintenance at room temperature to minimum.

$V_{FD}$ undergoes reverse annealing and

becomes progressively higher if the detectors are kept above 0°C.

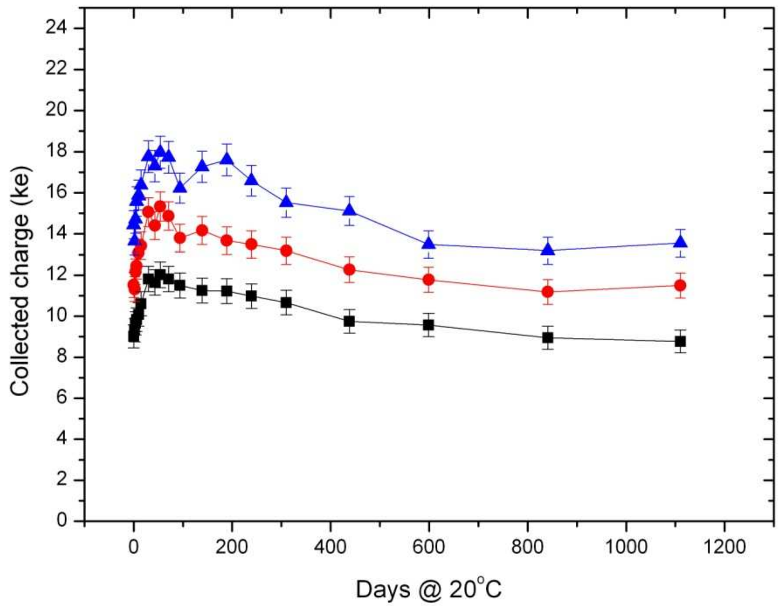
But what happens to the reverse current and the CCE of n-side readout detectors?

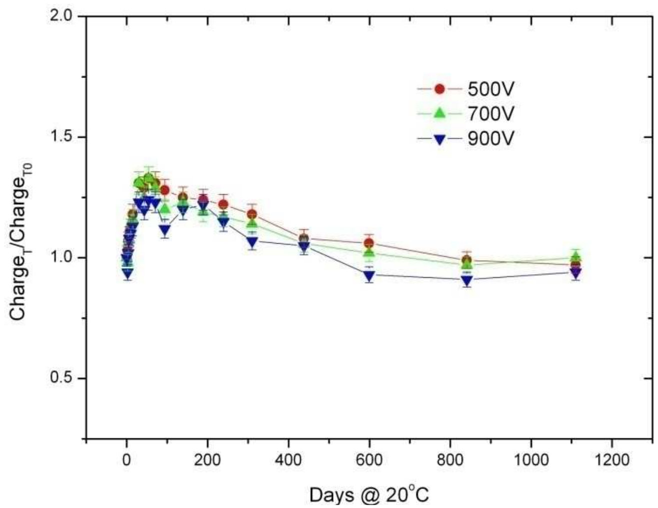
Initial $V_{FD}$ ~ 2800V

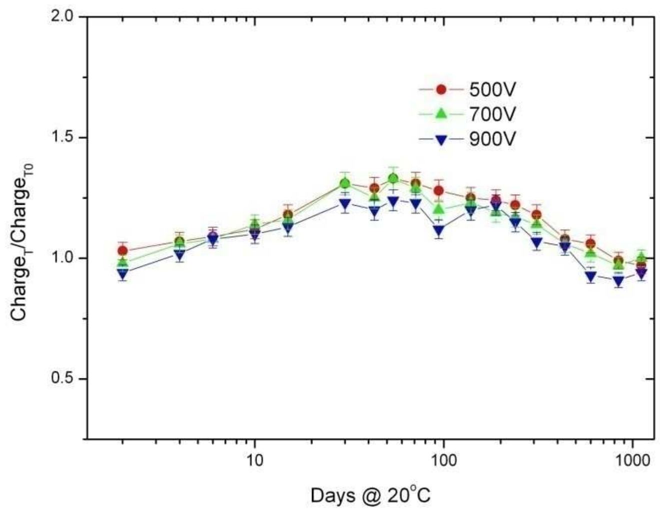



Predictions from RD48 parameters for Oxygen enriched devices (best scenario: after 7 RT annealing years the $V_{fd}$ goes from ~2800V to ~12000 V!

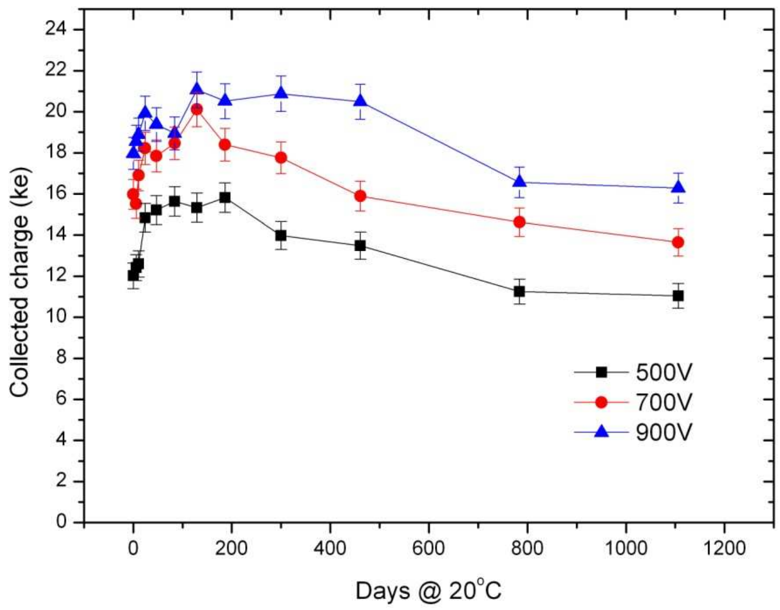
# “Fine step” Annealing of the collected charge, HPK FZ n-in-p, 1E15 n cm$^{-2}$

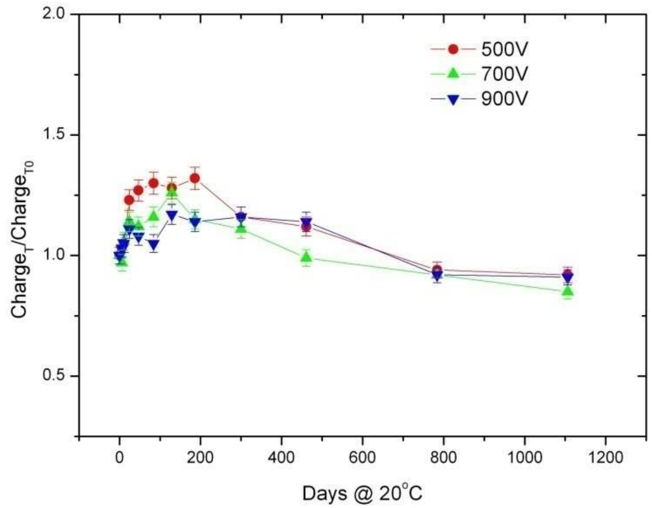


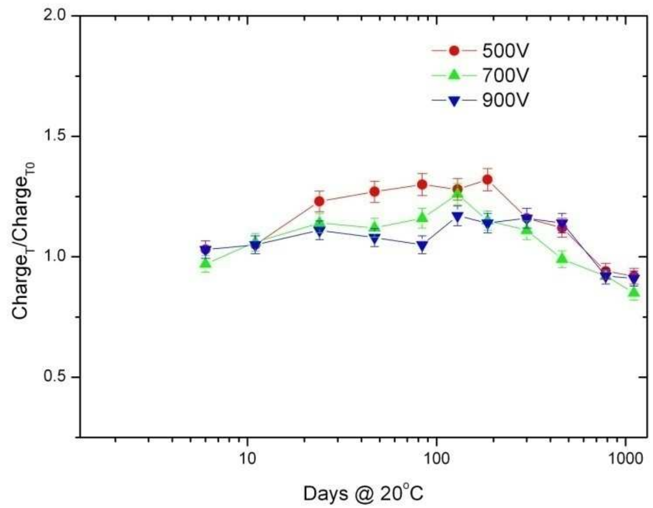



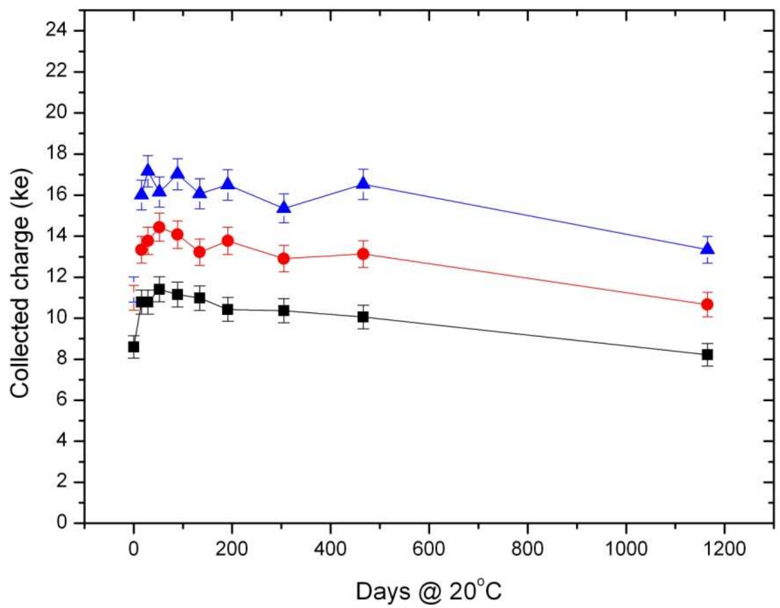
# "Fine step" Annealing of the collected charge, Micron FZ n-in-p, 1E15 n cm$^{-2}$ (26MeV p irradiation)

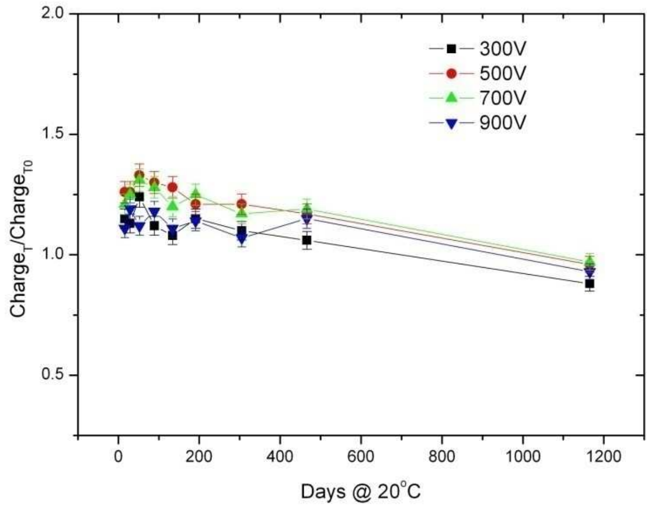


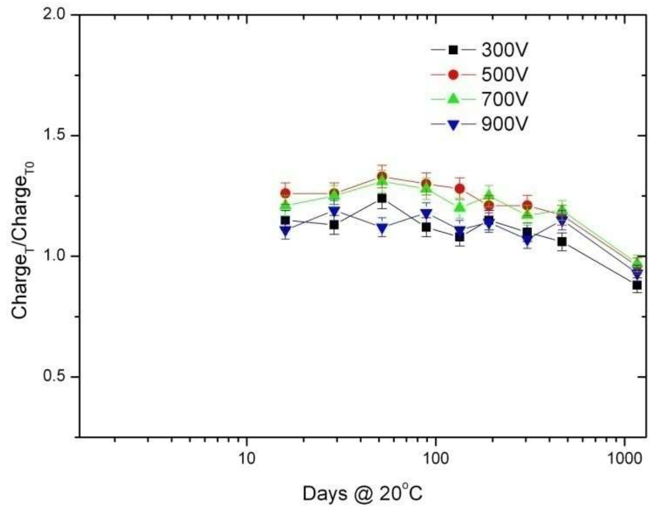



# “Fine step” Annealing of the collected charge, Micron FZ n-in-n, 1.5E15 n $cm^{-2}$



# CONCLUSIONS

CCE of planar detectors could yield ~4ke after the final fluence at the innermost pixel layer radius, with a bias voltage of 900V.

Thin and thick devices do not appear to have a significant difference in performances both in $I_R$ and CCE. The choice of thickness can be left to other considerations, like material budget ….

Controlled annealing (at $20^0$C) could increase this value (up to 20%?). Annealing studies after heavy irradiations is foreseen to confirm this concept.

Annealing is also a very useful tool to reduce power dissipation and recover fraction of S/N in heavily irradiated silicon detectors. Optimum annealing time is between 100-300 days for CCE (while no restriction is found with reverse current recovery).

By the way, once confirmed with high doses, the effect of the annealing can be used also on the present pixel detectors!