Radiation Hardness of High Resistivity CZ Si Detectors after Gamma, Neutron and Proton Radiations

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OUTLINE

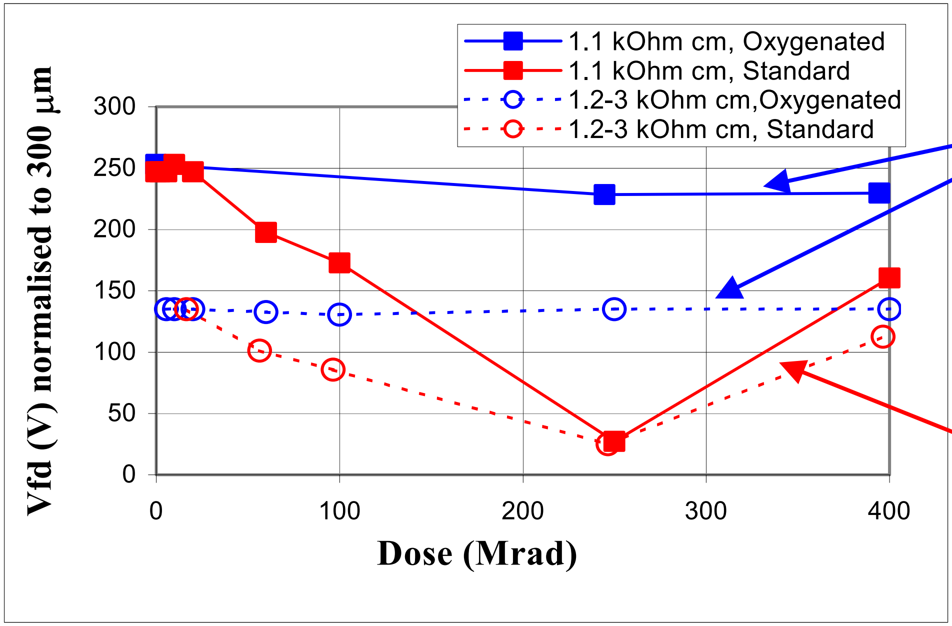
- **Introduction**
- **Review of gamma radiation results on STD and Oxy detectors**
- **Experimental**
  - **Samples**
  - **Radiation source**
  - **Measurements**
- **Preliminary results and discussions**
- **Summary**

Introduction

- **Oxygenated (HTLT and DOFZ) Si detectors are more rad hard to charged particles and gamma than STD FZ detectors**
- **[O] in oxygenated Si: in the 10^{17}'s /cm^3**
- **[O] in STD FZ Si: in the 10^{15}'s /cm^3**
- **[O] in CZ Si: in the 10^{18}'s /cm^3**
  - **Comes naturally from wafer manufacture process**
  - **Resistivity ≤100 Ω-cm**
  - **Thermal donor (TD) a problem**
- **Magnetic CZ technology now available:**
  - **High [O]**
  - **High resistivity ≥1000 Ω-cm : almost detector grade**
- **Is MCZ Si detector more radiation hard than Oxy Si?**
  - **Gamma radiation could offer a clear clue**
  - **How about to neutrons and protons?**

Review of gamma radiation results on STD and Oxy detectors

- **Oxygenated Si detectors have shown, as compared to STD ones (in terms of N_{eff}):**
  - **Partially rad-hardness improvement with charged particles radiation**
  - **Almost insensitive to gamma radiation**
  - **Little/no rad-hardness improvement with neutron radiation**



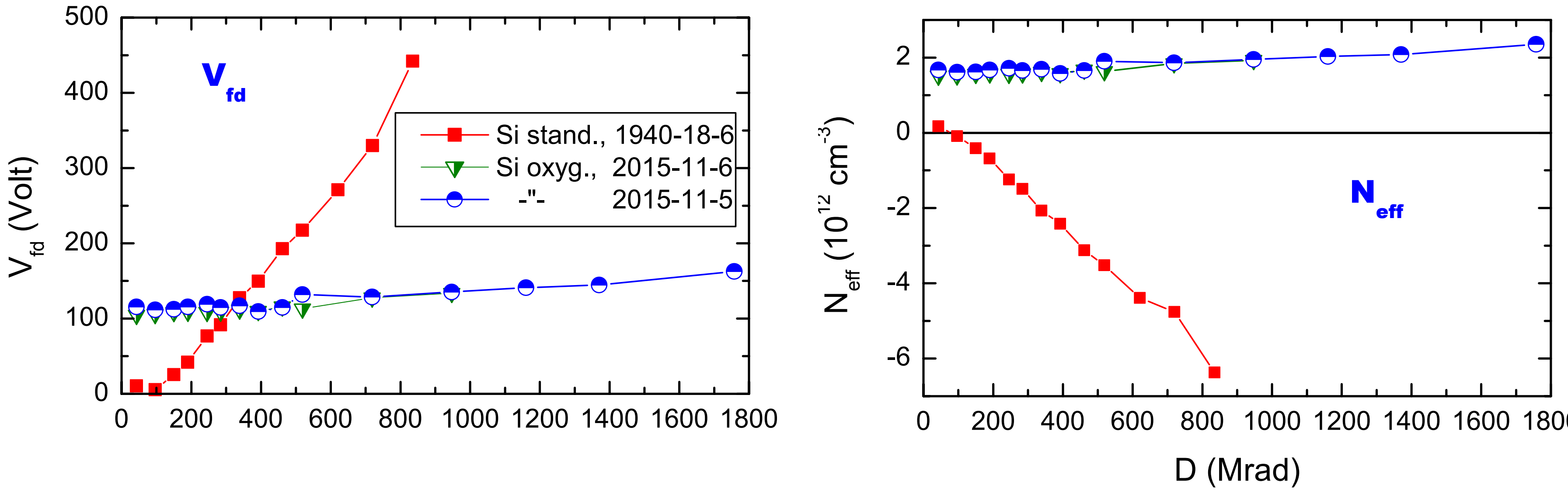
No SCSI observed by TCT (Oxy Si)

SCSI observed by TCT (STD Si)

B. Dezillie et al., IEEE TNS, Vol. 47 (2000) pp. 1892-1987

- **Recent results have shown in fact there is a slight increase in positive space charge in Oxy Si detectors with gamma dose:**
  - **NO SCSI in Oxy Si detectors**
  - **Positive space charge build-up may be due to the activation of thermal donors**

Z. Li et al., Presented on 4th Intern. Conf. on Rad. Effects on Semicond. Materials, Detectors and Devices, Firenze, Italy, July 10-12, 2002



For more details also from talks of E. Verbitskaya and E. Fretwurst on this Work shop.

Experimental

- **Samples**

  Control FZ (CFZ) samples and some MCZ samples processed together by Univ. of Helsinki, and some MCZ samples were processed by BNL

  Oxidation: 8+5 hours in O_2 at 1050 °C, all diodes are $p^+/n/n^+$ junctions

Wafer #	Type	Resistivity (Ω-cm)	Thickness (μm)
T15, 1	CFZ	3000	520
O6, 3	MCZ	1200	380

Various square diodes of 0.36 cm^2 each from each wafer were used

- **Radiation**

  60Co gamma: E = 1.25 MeV; Dose rate: 0.5 Mrad/hr; Dose range: 0-1.2 Grad

  Neutrons: <E>=1 MeV; fluence: 0 to 2.9×10^{14} n/cm^2

  Protons: 10 MeV and 20 MeV; fluence: 0 to 1.2×10^{14} p/cm^2

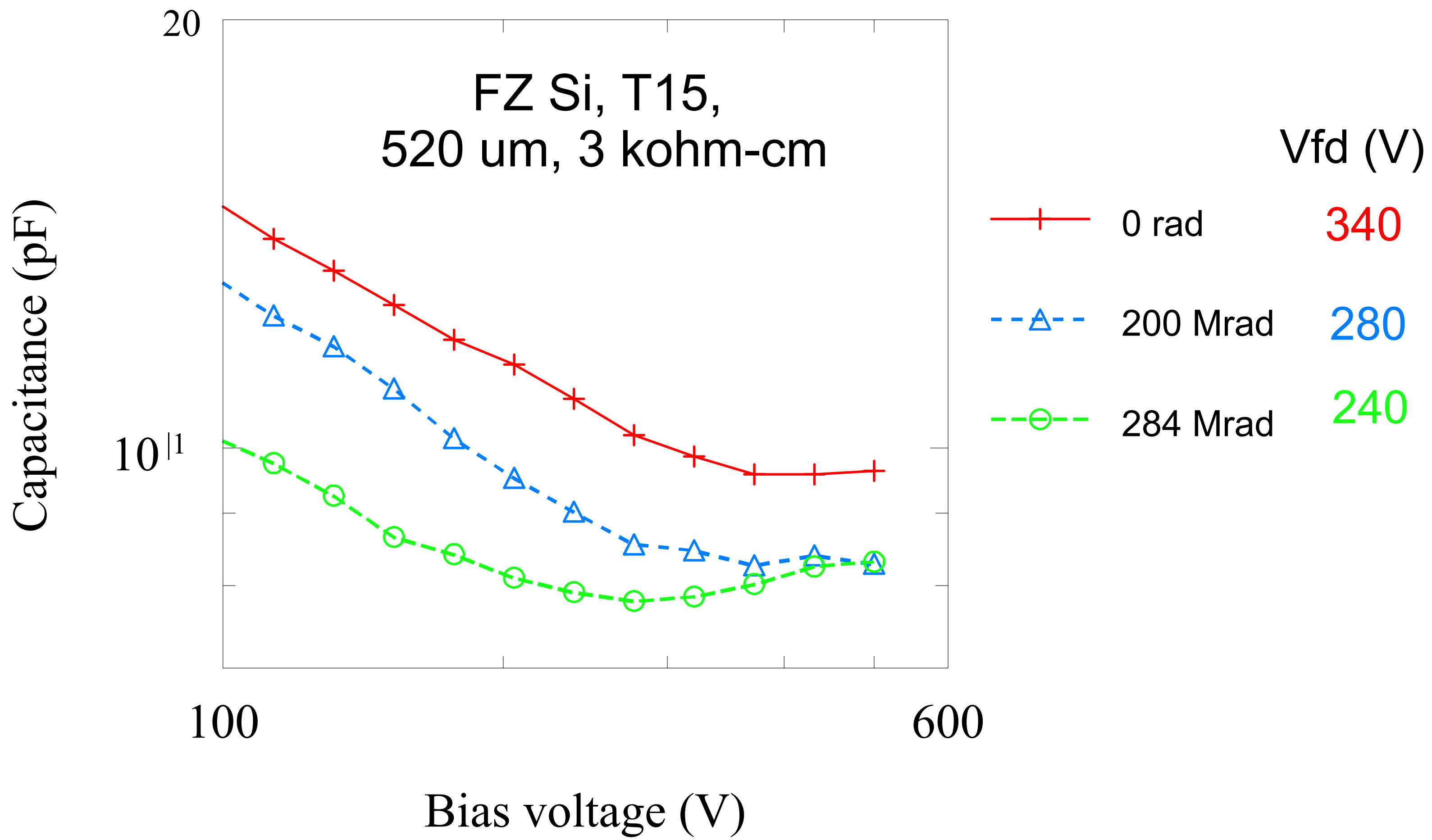
- **Measurements**

  C-V measurements at RT and 100 kHz

  TCT measurements using a red laser

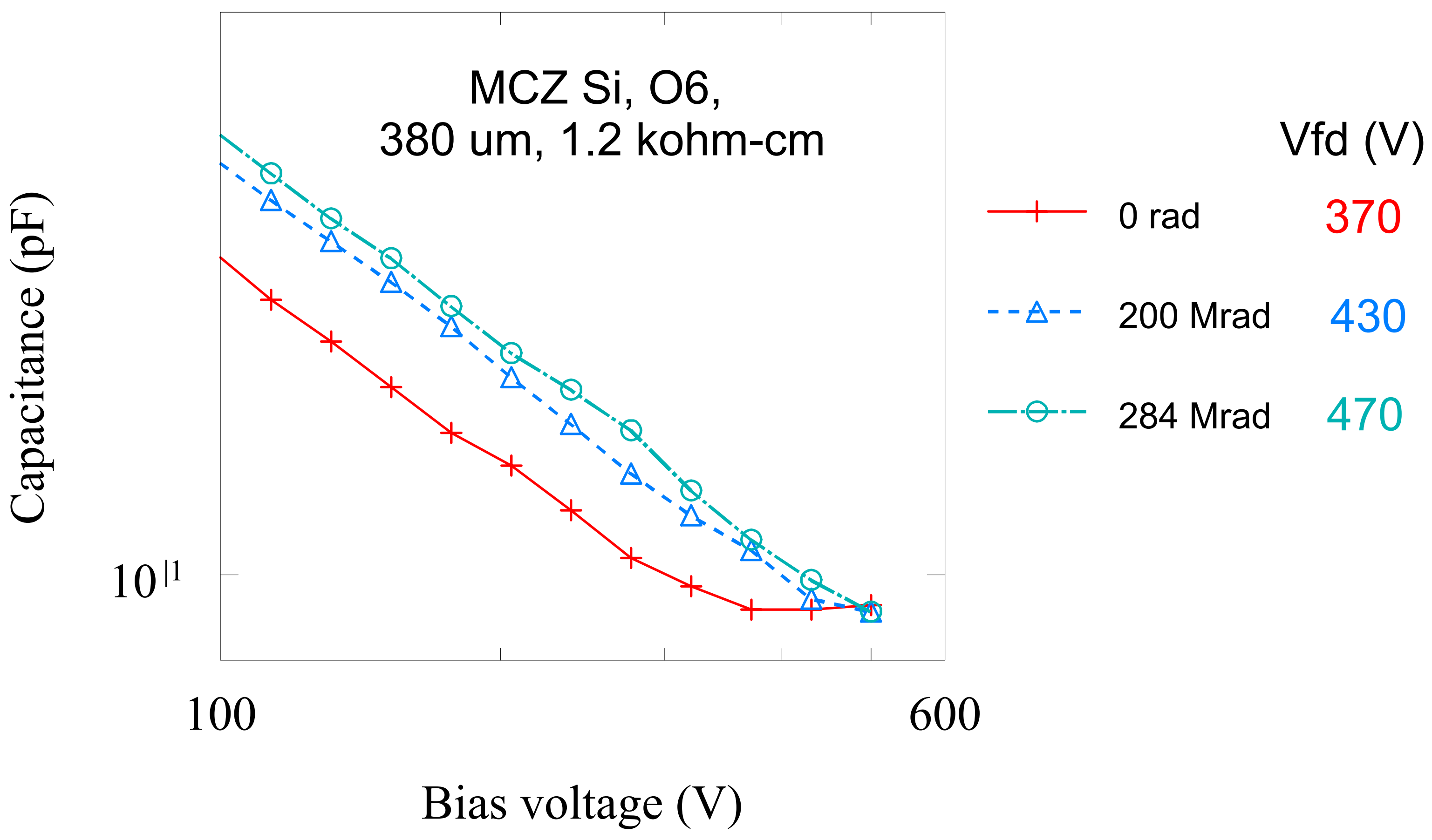
Results and Discussions

- **C-V measurements CFZ:**



For control FZ diodes, full depletion voltage decreases from 340 V to 280 V after 200 Mrad radiation.

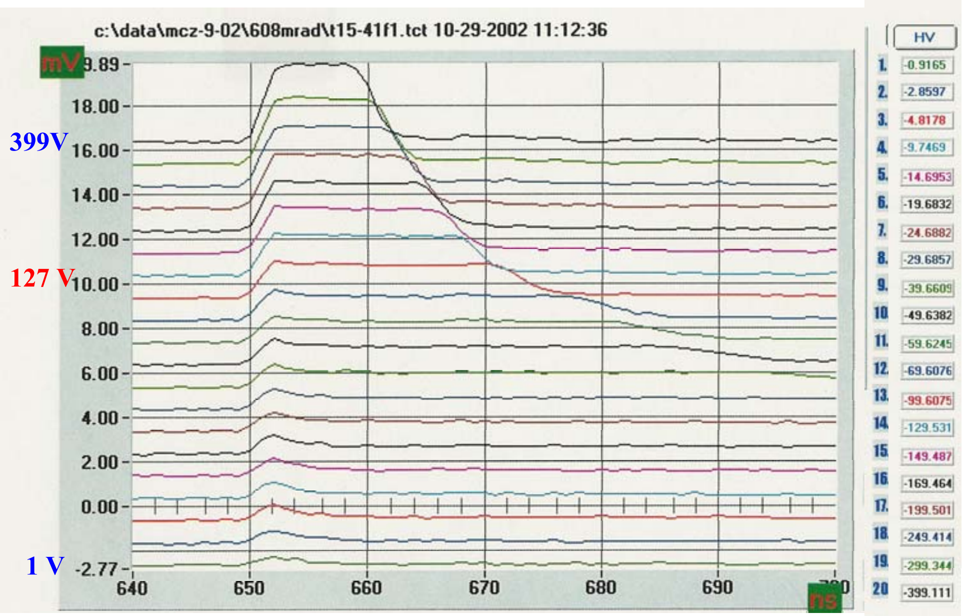
- **C-V measurements MCZ:**



For MCZ diodes, full depletion voltage increases from 370 V to 430 V after 200 Mrad radiation.

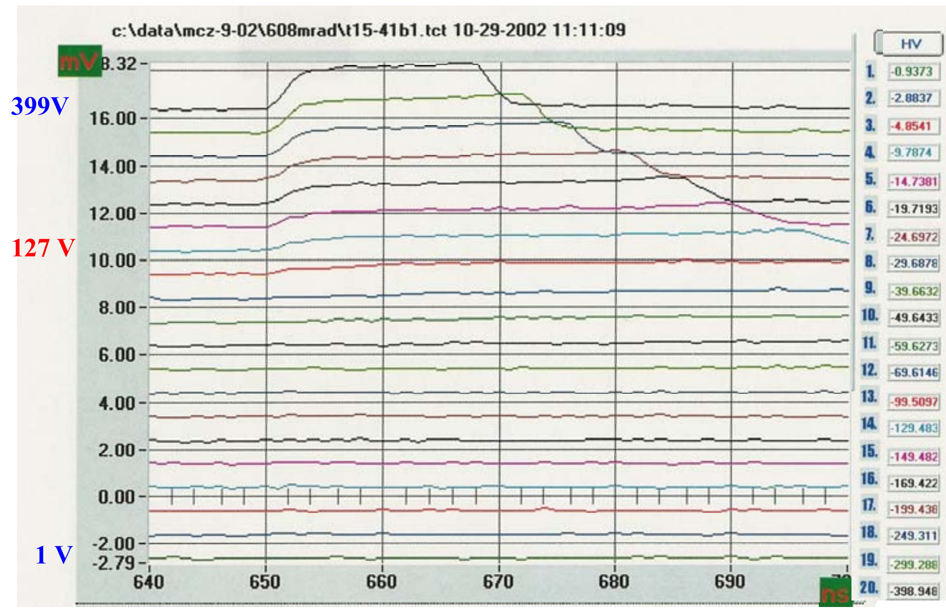
•TCT measurements (CFZ) 608 Mrad:

Laser on the p+ side (front side): + SC ~ 0



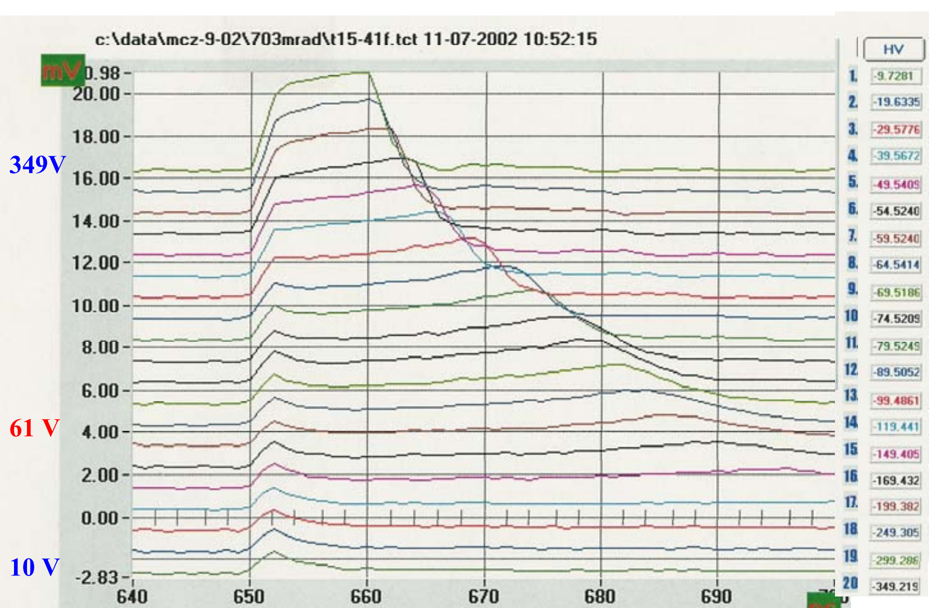
•TCT measurements (CFZ) 608 Mrad:

Laser on the n+ side (back side): + SC ~ 0



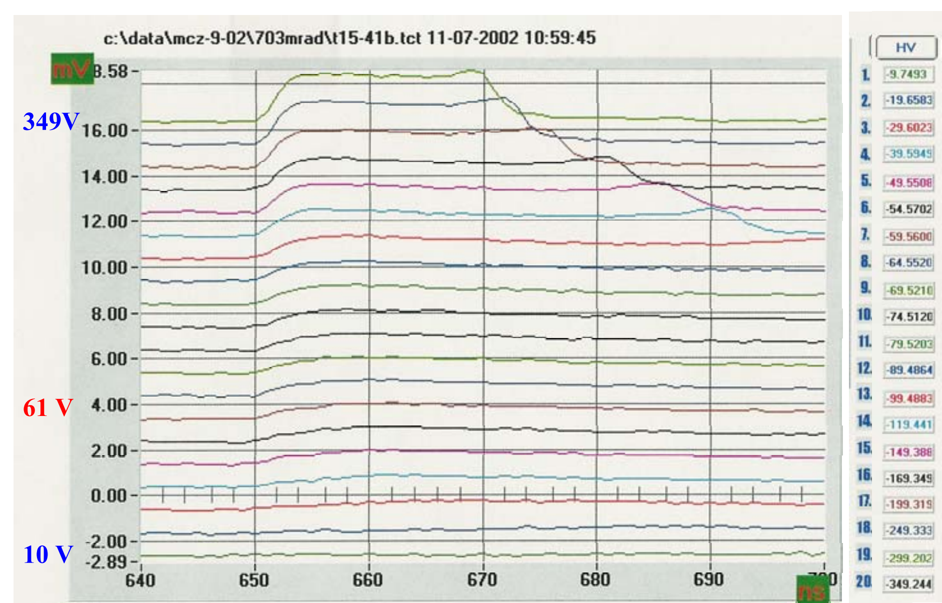
•TCT measurements (CFZ) 703 Mrad:

Laser on the p+ side (front side): - SC, Double peak/junction seen



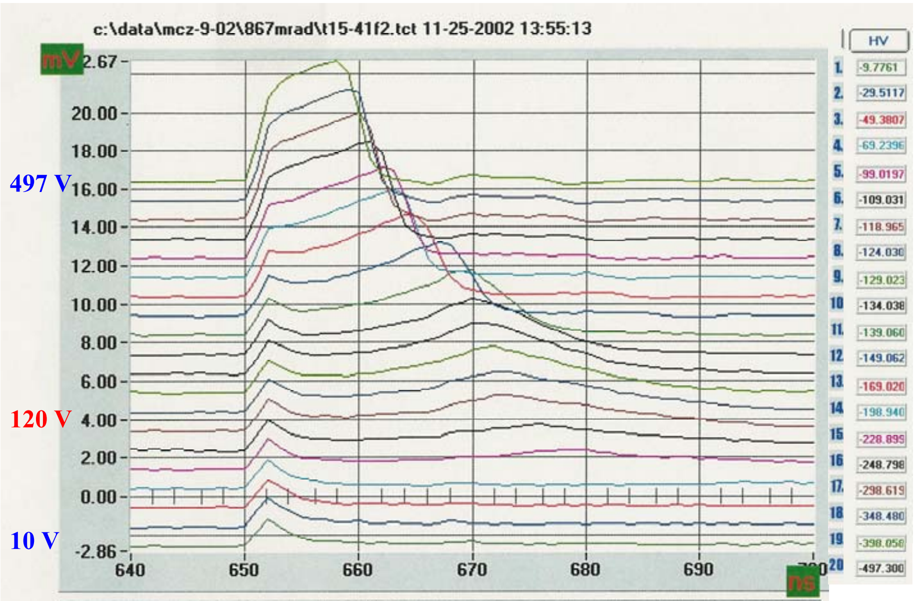
•TCT measurements (CFZ) 703 Mrad:

Laser on the n+ side (back side): - SC, Double peak/junction seen



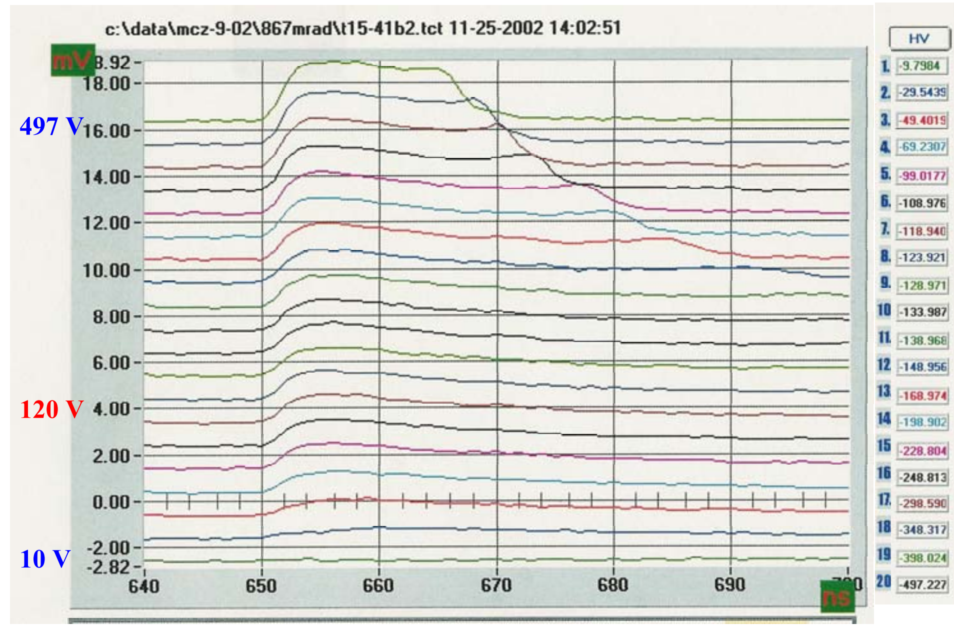
•TCT measurements (CFZ) 867 Mrad:

Laser on the p^+ side (front side): - SC, Double peak/junction seen



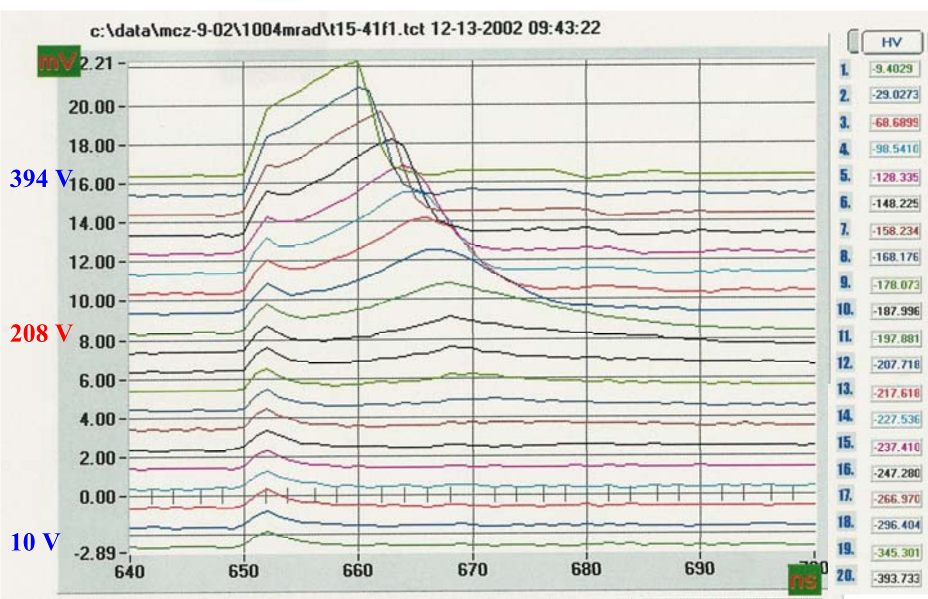
•TCT measurements (CFZ) 867 Mrad:

Laser on the n^+ side (back side): - SC, Double peak/junction seen



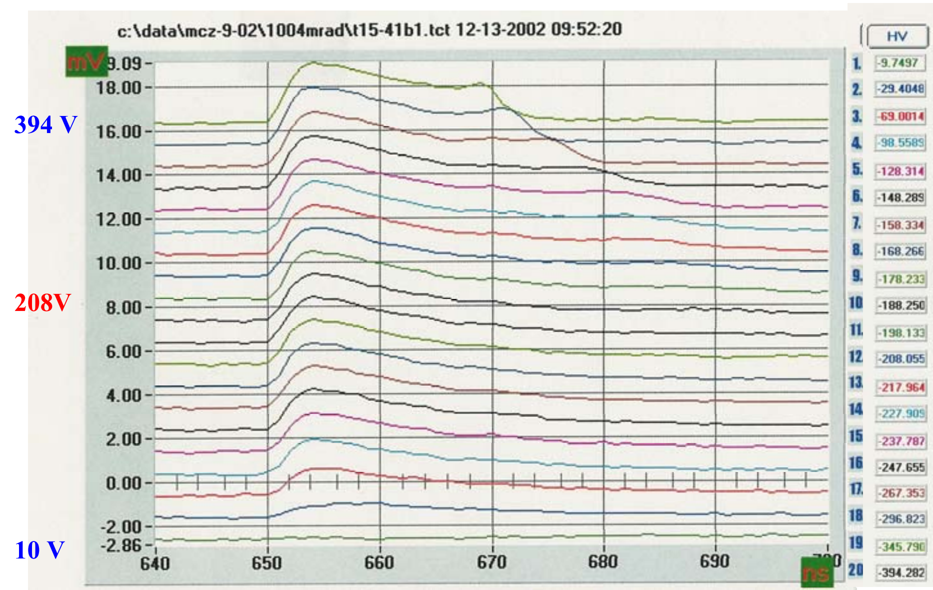
•TCT measurements (CFZ) 1004 Mrad:

Laser on the p^+ side (front side): - SC, Double peak/junction seen



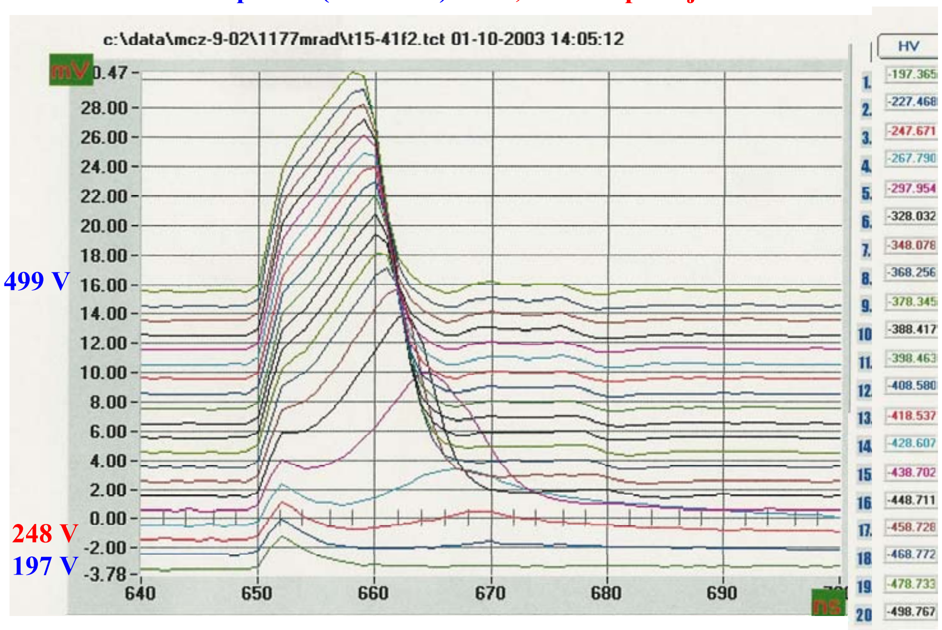
•TCT measurements (CFZ) 1004 Mrad:

Laser on the n^+ side (back side): - SC, Double peak/junction seen



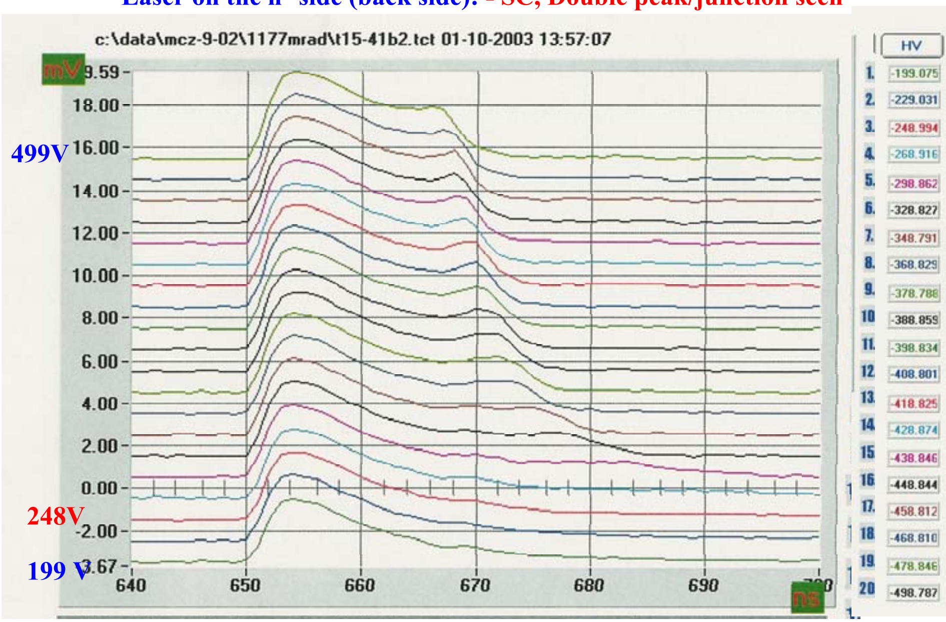
•TCT measurements (CFZ) 1177 Mrad:

Laser on the p^+ side (front side): - SC, Double peak/junction seen



•TCT measurements (CFZ) 1177 Mrad:

Laser on the n^+ side (back side): - SC, Double peak/junction seen

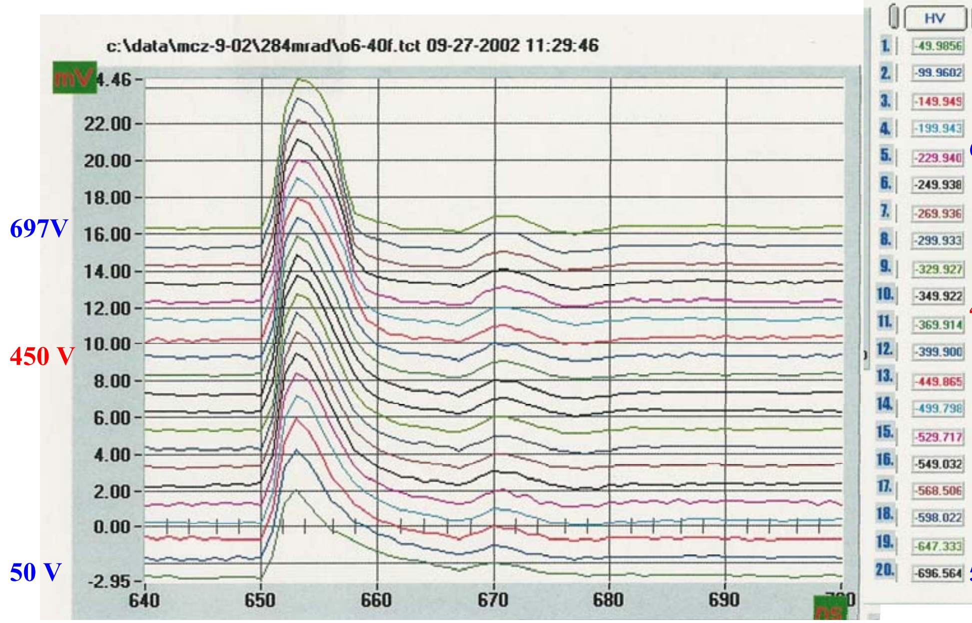


For CFZ diodes after gamma radiation:

- SCSI clearly observed ----- negative space charge build-up
- SCSI taking place between 600 to 700 Mrad
- DJ/DP clearly observed after SCSI

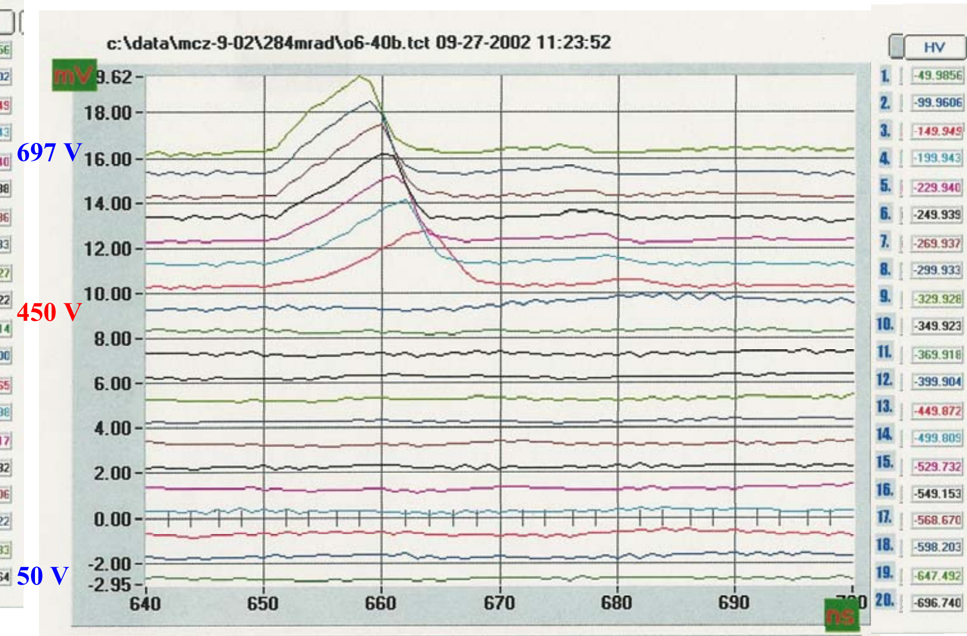
•TCT measurements (MCZ) 284 Mrad:

Laser on the p$^+$ side (front side): + SC



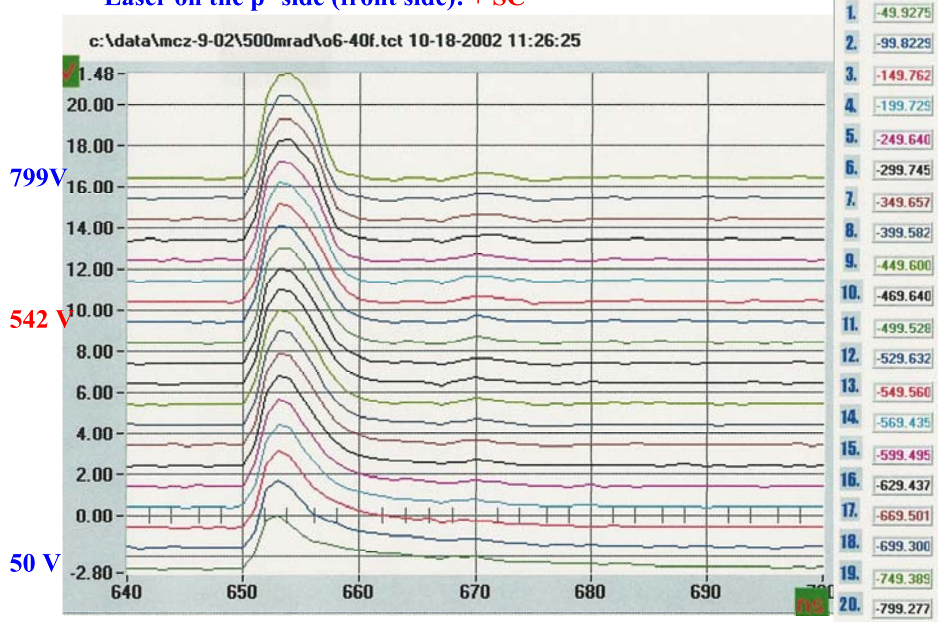
•TCT measurements (MCZ) 284 Mrad:

Laser on the n$^+$ side (back side): + SC



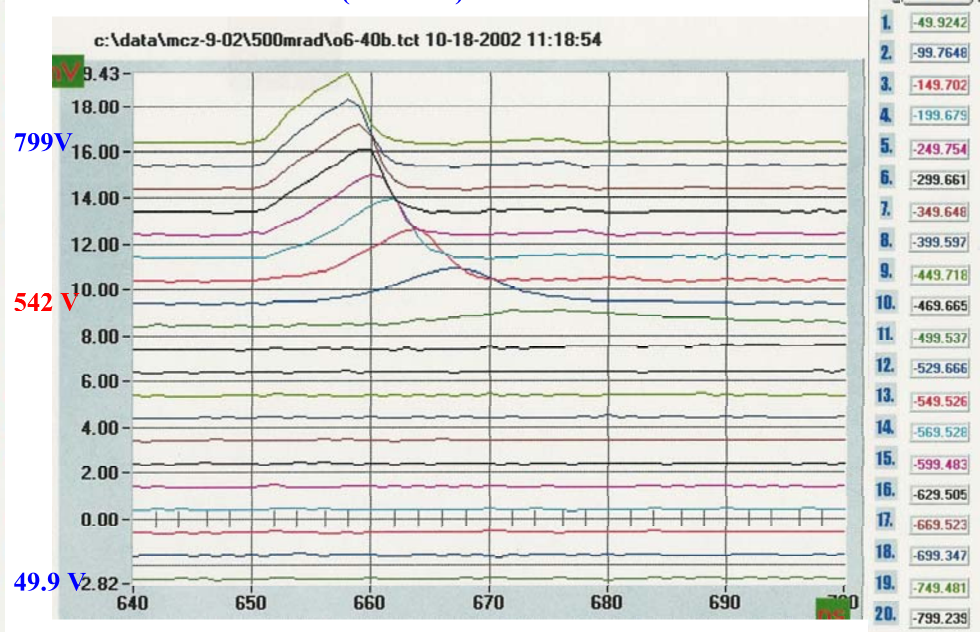
•TCT measurements (MCZ) 500 Mrad:

Laser on the p$^+$ side (front side): + SC



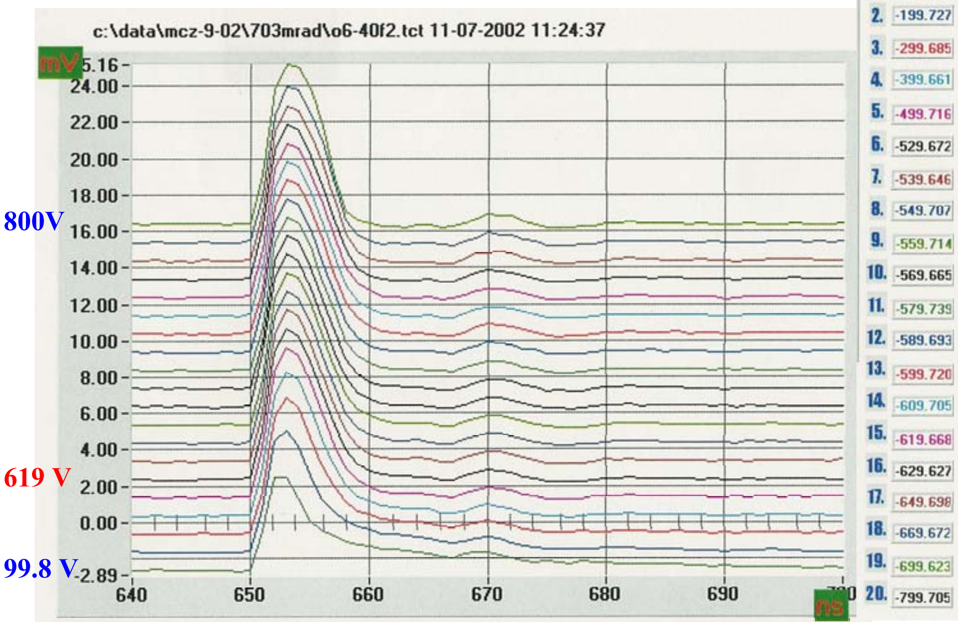
•TCT measurements (MCZ) 500 Mrad:

Laser on the n$^+$ side (back side): + SC



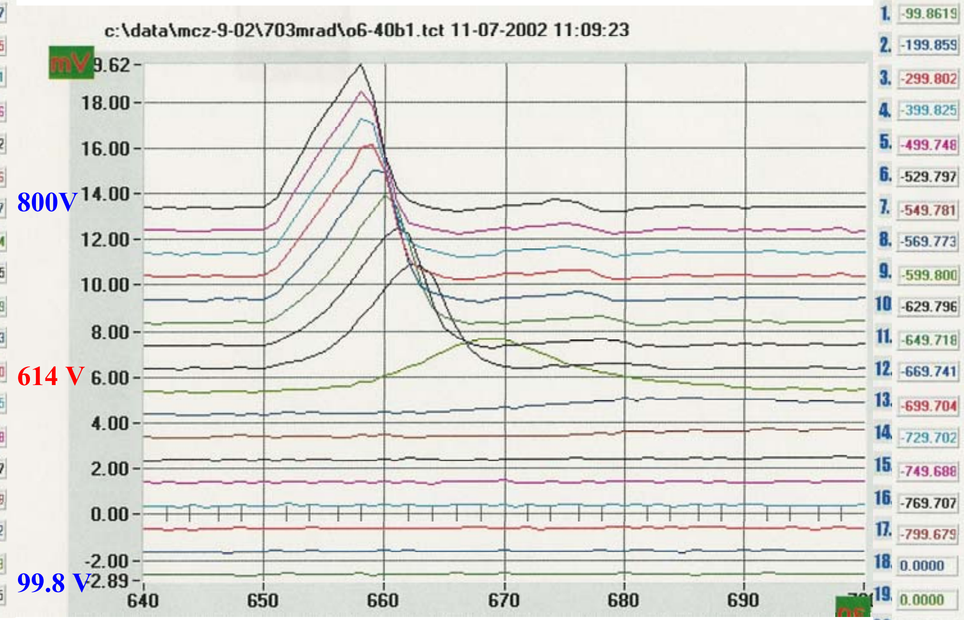
•TCT measurements (MCZ) 703 Mrad:

Laser on the p$^+$ side (front side): + SC



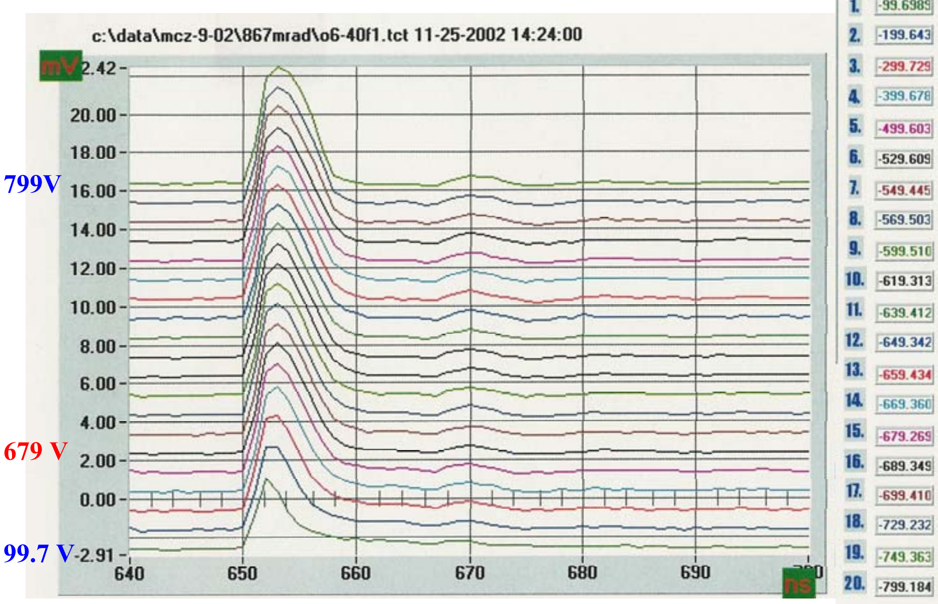
•TCT measurements (MCZ) 703 Mrad:

Laser on the n$^+$ side (back side): + SC



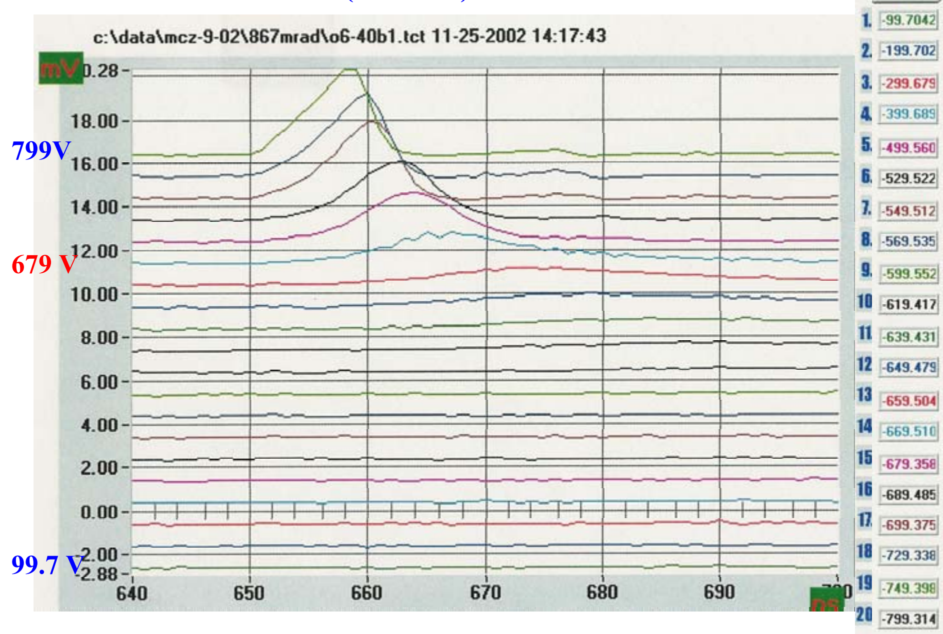
•TCT measurements (MCZ) 867 Mrad:

Laser on the p$^+$ side (front side): + SC



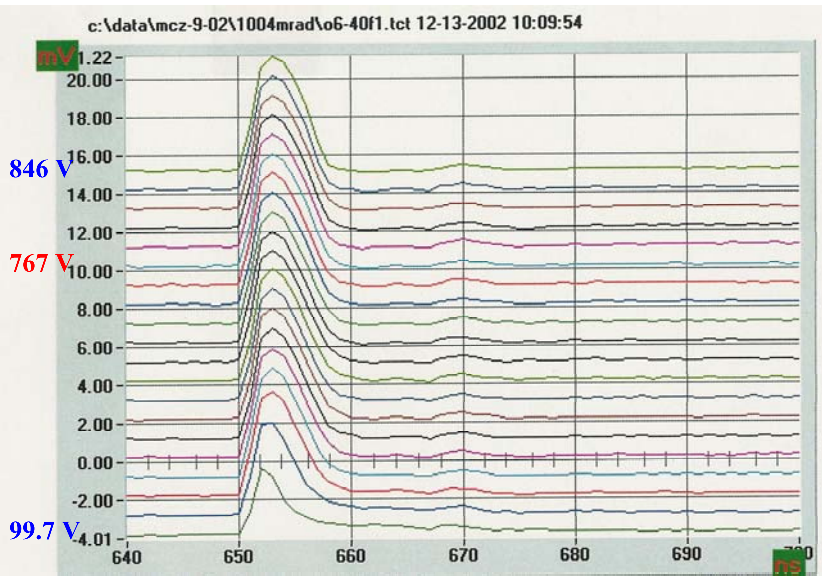
•TCT measurements (MCZ) 867 Mrad:

Laser on the n$^+$ side (back side): + SC



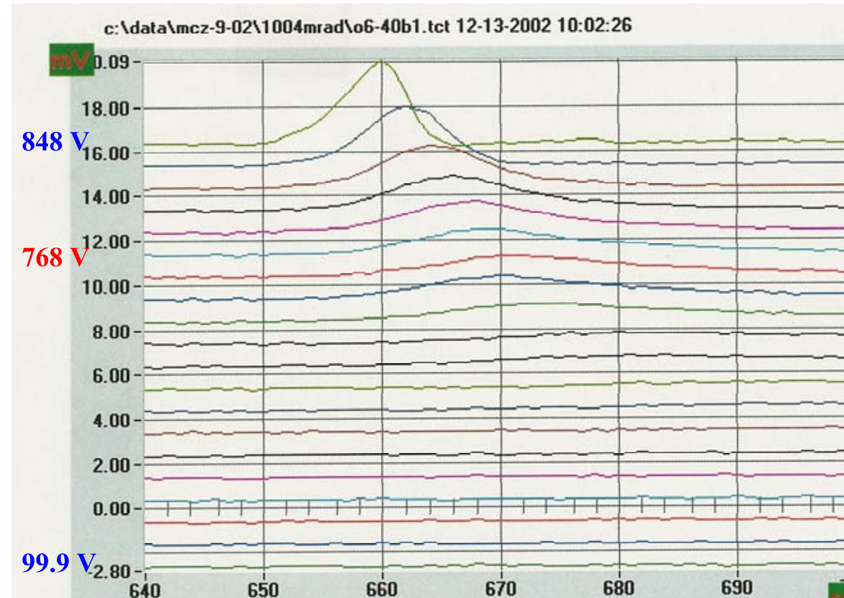
•TCT measurements (MCZ) 1004 Mrad:

Laser on the p$^+$ side (front side): + SC



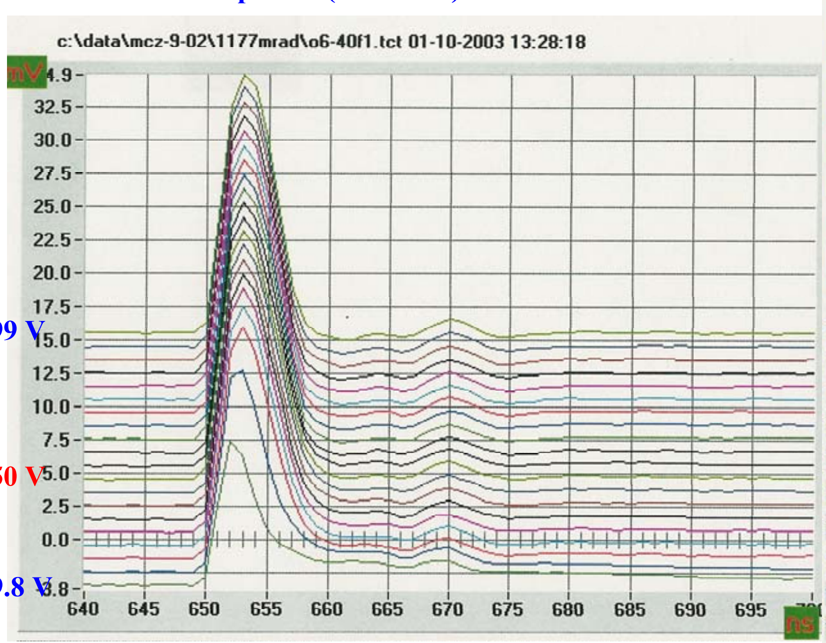
•TCT measurements (MCZ) 1004 Mrad:

Laser on the n$^+$ side (back side): + SC



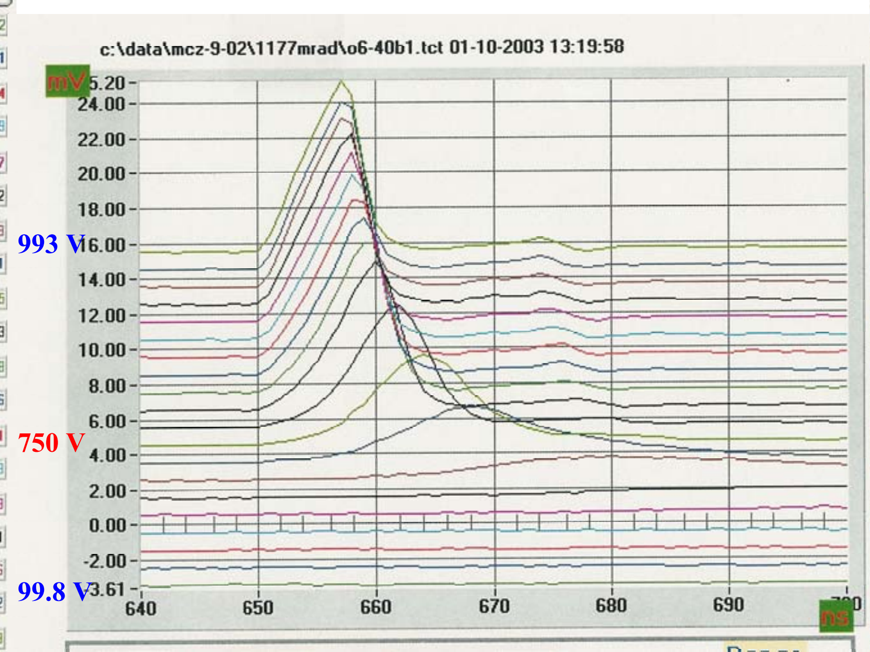
•TCT measurements (MCZ) 1177 Mrad:

Laser on the p$^+$ side (front side): + SC



•TCT measurements (MCZ) 1177 Mrad:

Laser on the n$^+$ side (back side): + SC



For MCZ diodes after gamma radiation:

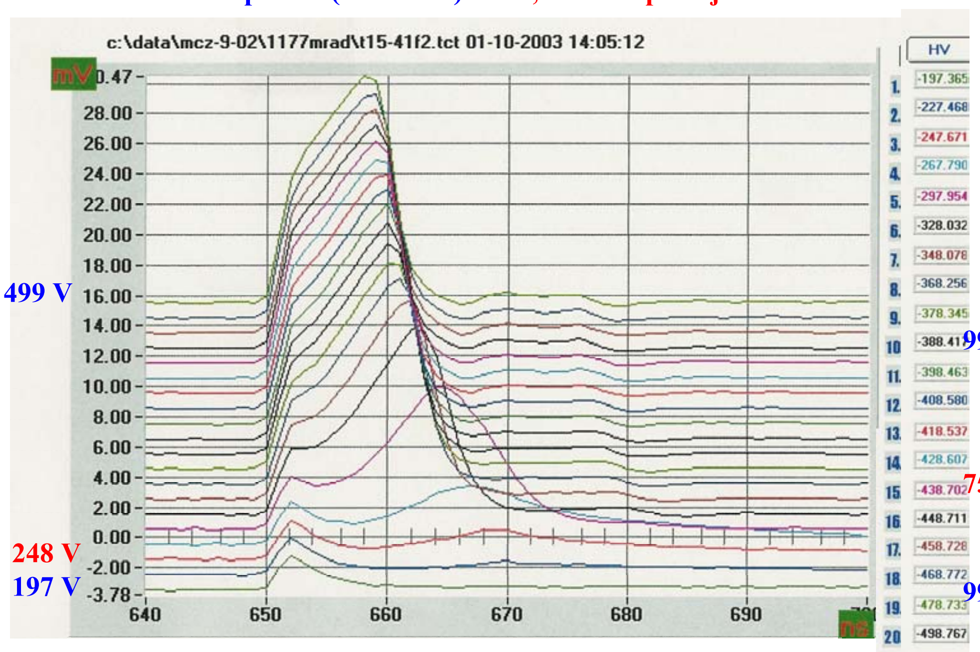
- No SCSI observed up to 1.2 Grad ----- no net negative space charge build-up
- V_{fd} increases with dose: net positive space charge build-up
- No DJ/DP observed up to 1.2 Grad

•Comparison of CFZ and MCZ detectors after gamma radiation to 1177 Mrad:

Laser on the p^+ side (front side), electron drift current

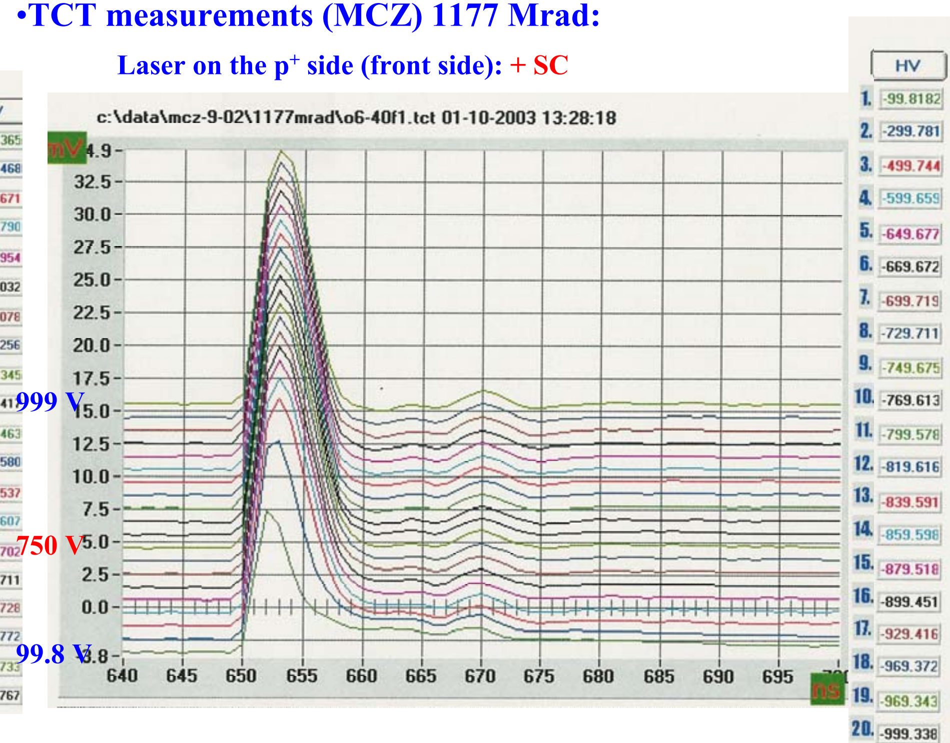
•TCT measurements (CFZ) 1177 Mrad:

Laser on the p^+ side (front side): - SC, Double peak/junction seen



•TCT measurements (MCZ) 1177 Mrad:

Laser on the p^+ side (front side): + SC

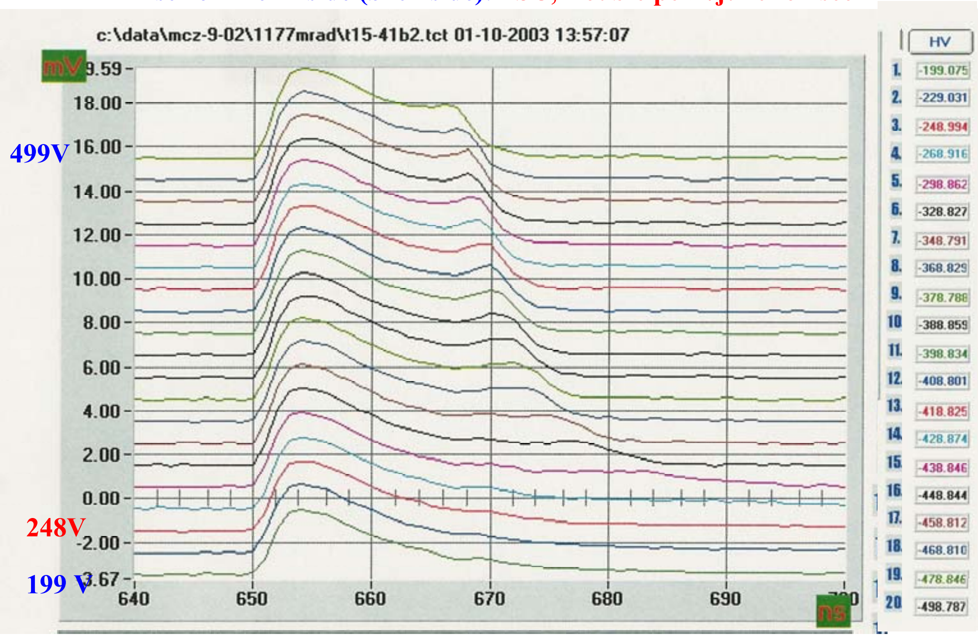


•Comparison of CFZ and MCZ detectors after gamma radiation to 1177 Mrad:

Laser on the n^+ side (back side), hole drift current

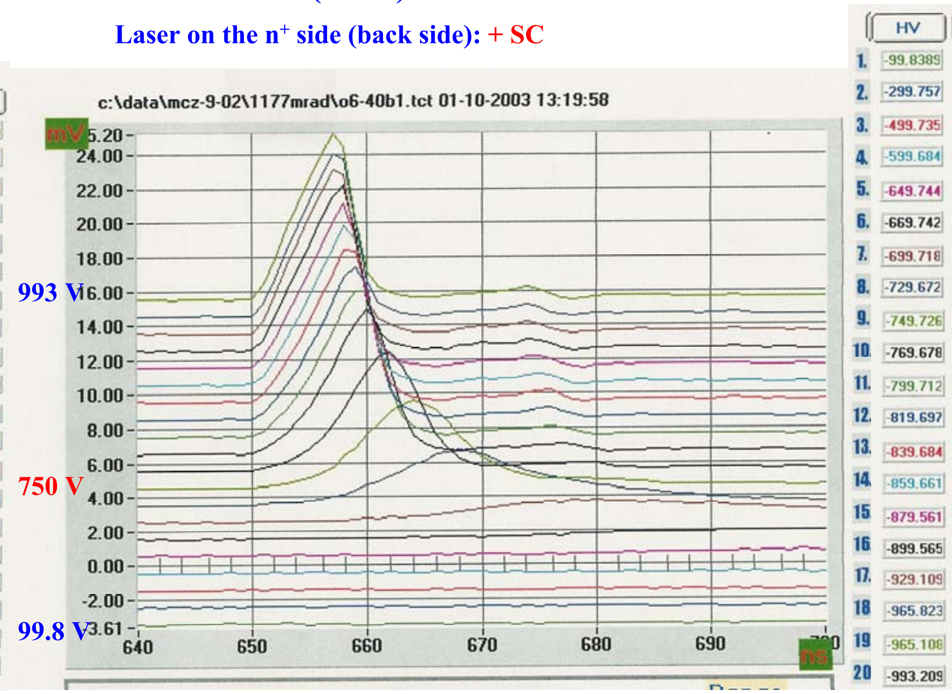
•TCT measurements (CFZ) 1177 Mrad:

Laser on the n^+ side (back side): - SC, Double peak/junction seen



•TCT measurements (MCZ) 1177 Mrad:

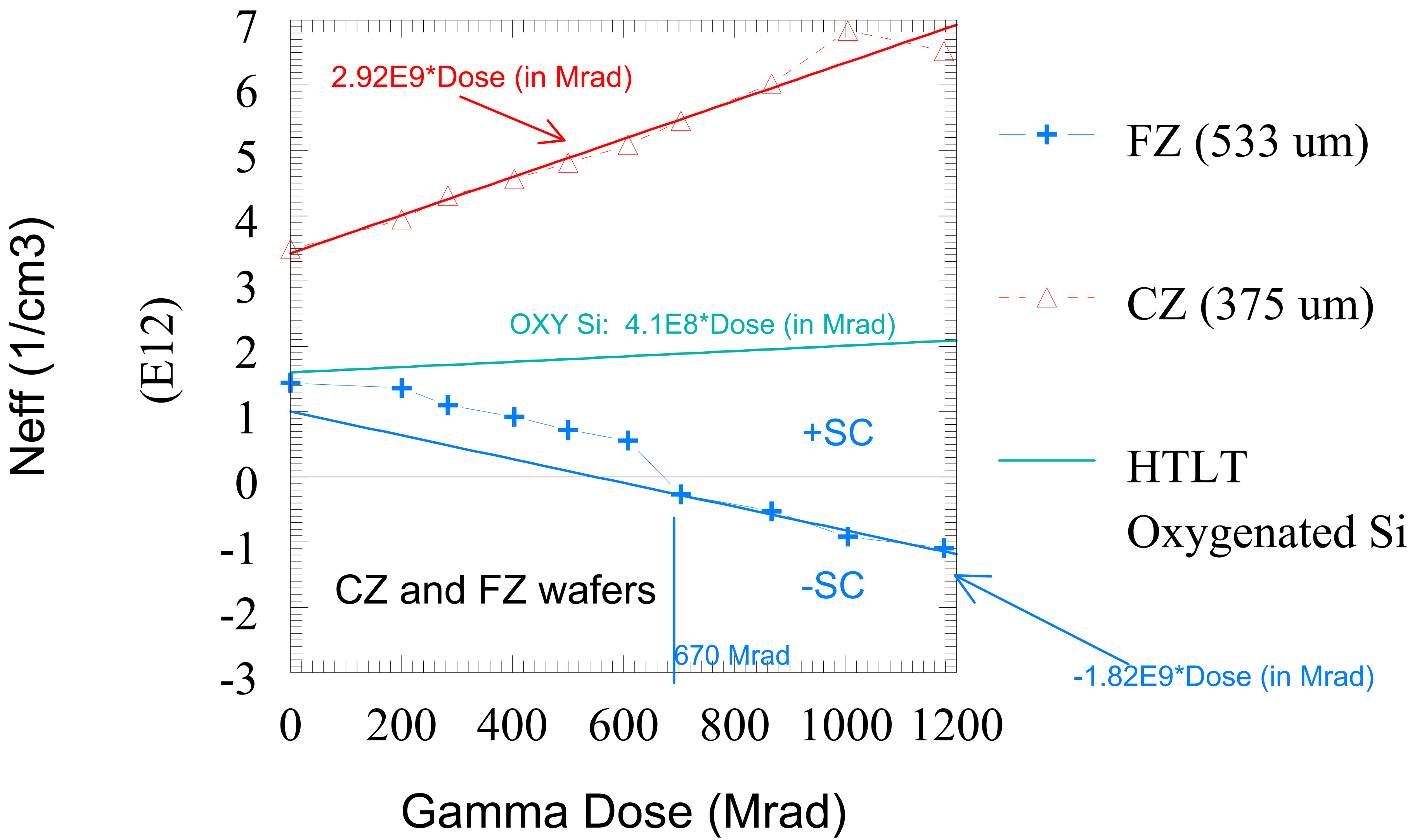
Laser on the n^+ side (back side): + SC



Negative SC build-up for control FZ Si detectors is: -1.82×10^9 x Dose

Positive SC build-up for Oxy Si detectors is: 4.1×10^8 Dose

Positive SC build-up for MCZ Si detectors is: 2.9×10^9 x Dose, about 8 times higher



The model:

$$N_{eff} = N^{0}_{eff} + \beta_{\gamma} \cdot \Phi_{\gamma}$$

where the introduction rate β_{γ} is:

$$\beta_{\gamma} = \kappa\{[O] - [O]_0\}$$

and $[O]$ is the oxygen concentration,

κ and $[O]_0$ are constants

The value of $[O]_0$ should be:

$$[O]_{CFZ} < [O]_0 < [O]_{Oxy} < [O]_{MCZ}$$

and in the order of high $10^{16}/cm^3$

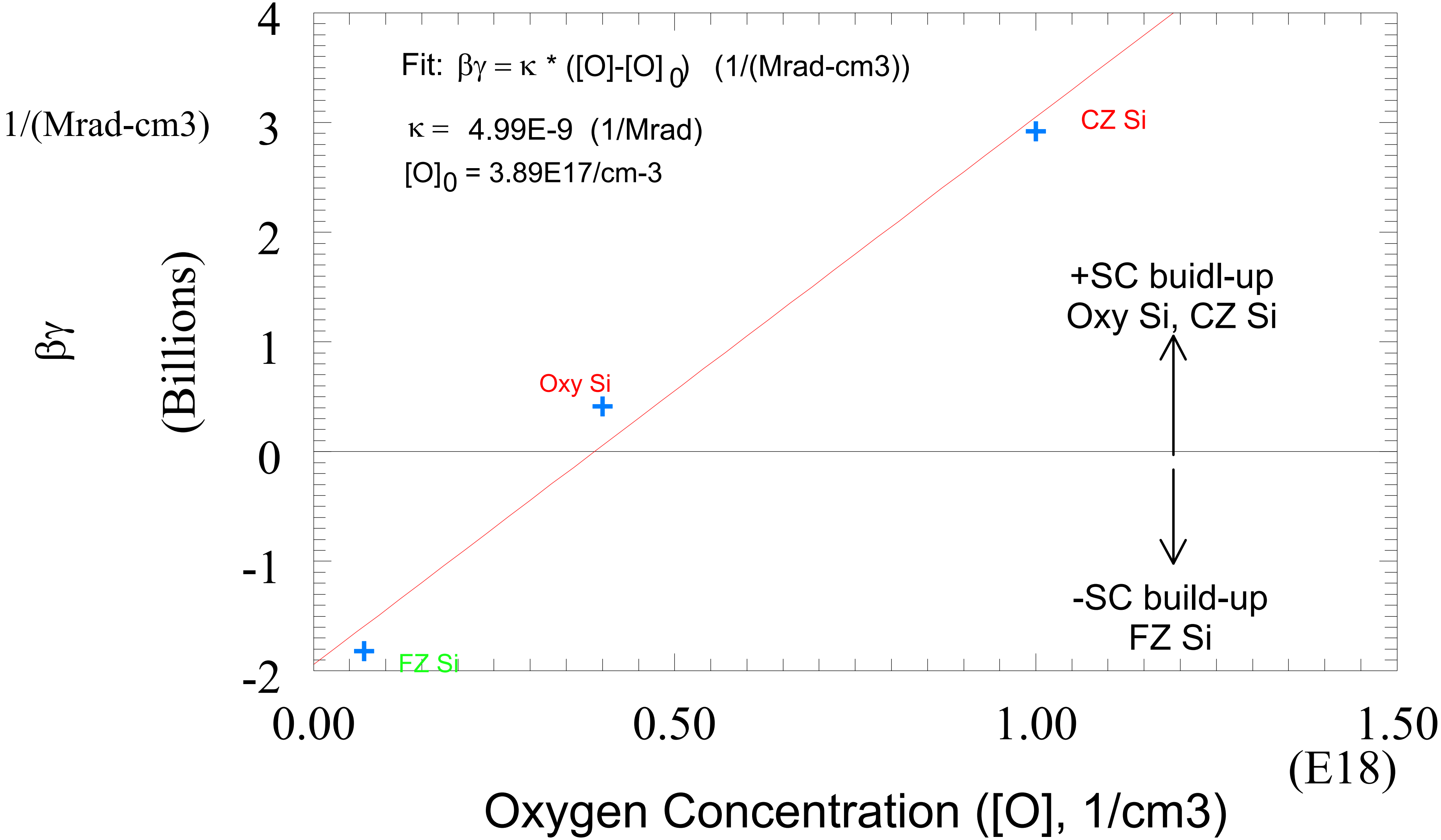
So the perfect oxygenated material is when $[O]_{Oxy} = [O]_0$

Then we have a beta zero material for gamma radiation

Determination of κ and $[O]_0$ from data fitting:

$\kappa = 4.99\times10^{-9}$ /Mrad

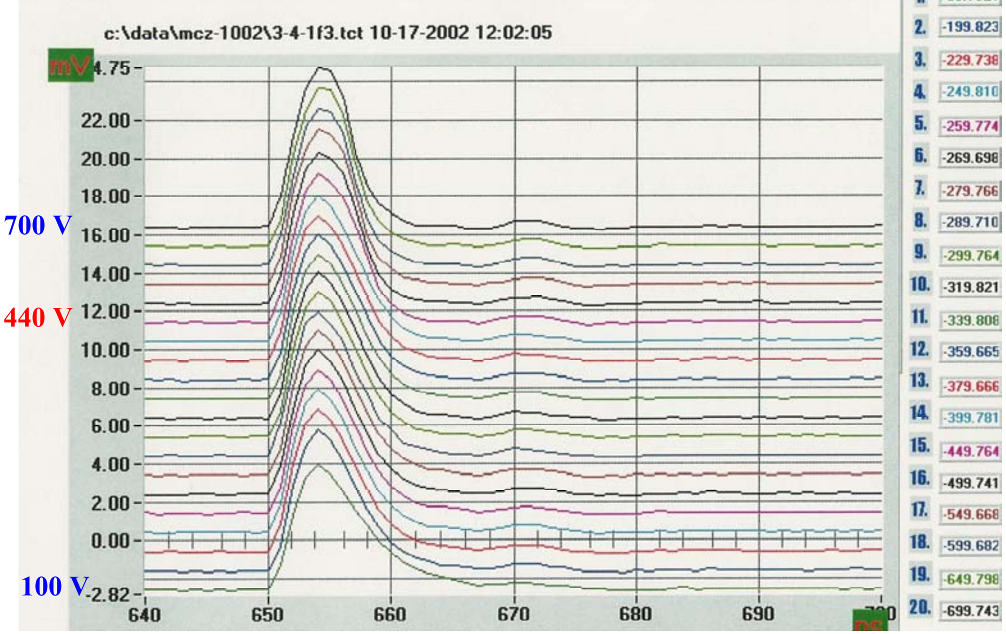
$[O]_0 = 3.89\times10^{17}$ /cm^3



Neutron Radiation

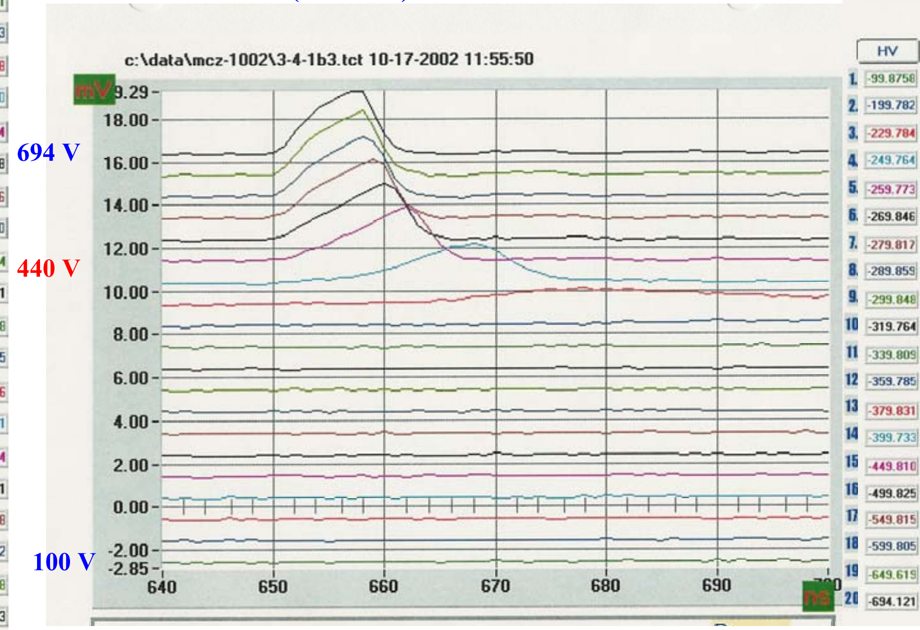
- **TCT measurements (MCZ):before radiation**

Laser on the p^{+} side (front side): +SC



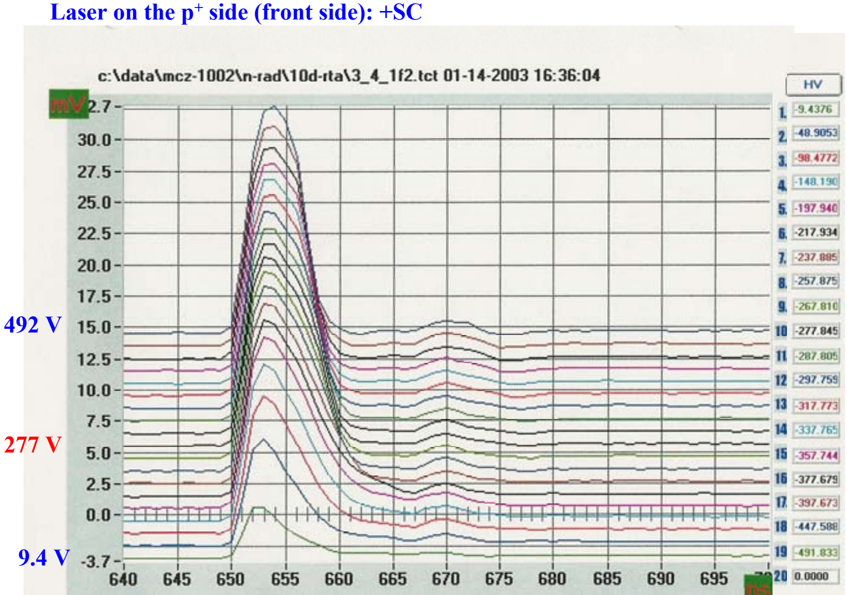
- **TCT measurements (MCZ):before radiation**

Laser on the n^{+} side (back side): +SC



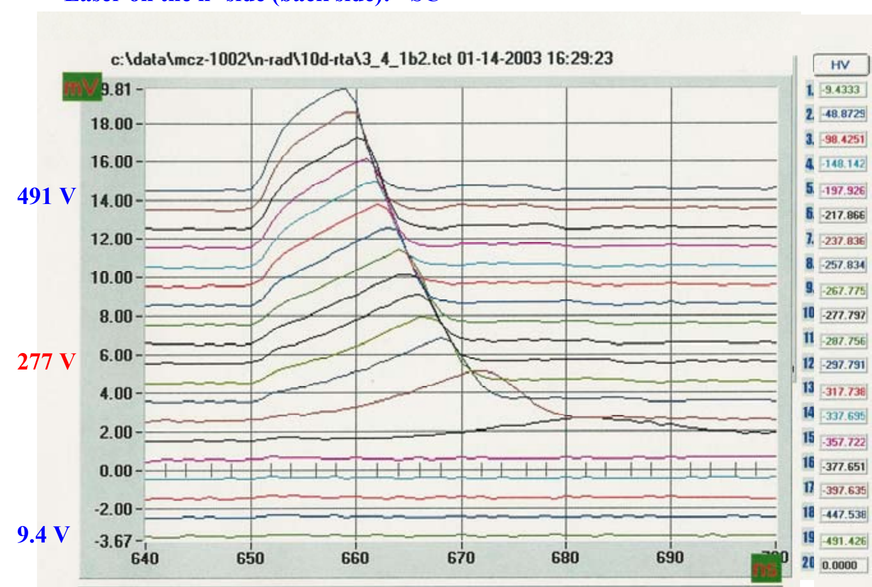
- **TCT measurements (MCZ):1.7x10^{13} n/cm^{2}**

Laser on the p^{+} side (front side): +SC

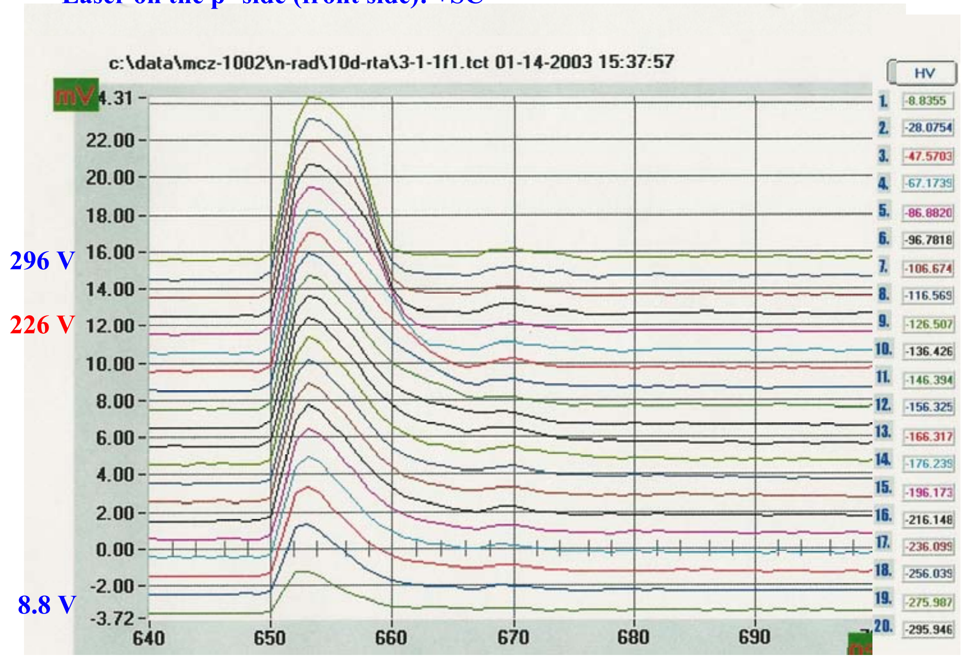


- **TCT measurements (MCZ):1.7x10^{13} n/cm^{2}**

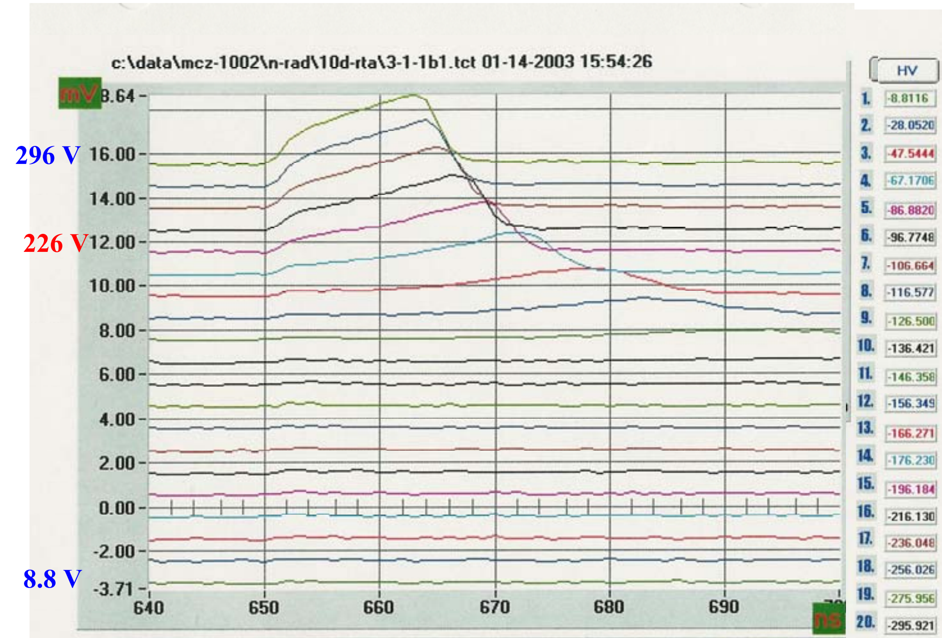
Laser on the n^{+} side (back side): +SC



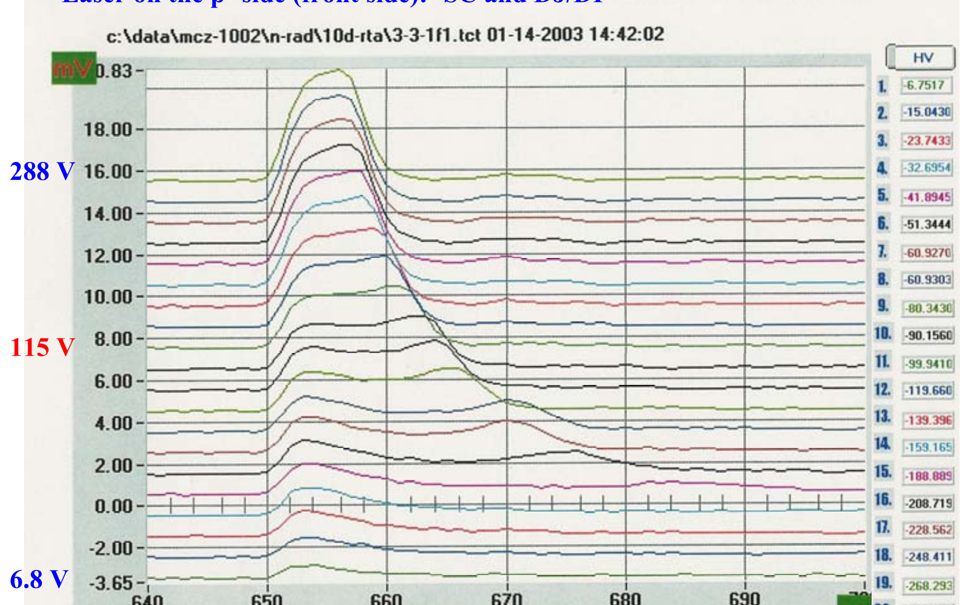
- **TCT measurements (MCZ):3.3x10^{13} n/cm^2**
  Laser on the p$^+$ side (front side): +SC



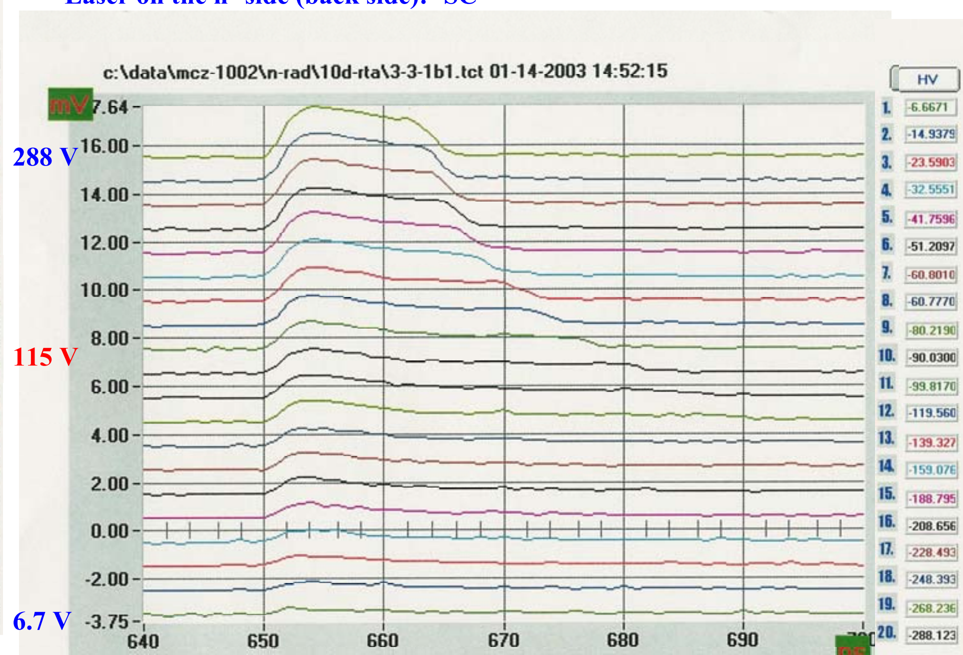
- **TCT measurements (MCZ):3.3x10^{13} n/cm^2**
  Laser on the n$^+$ side (back side): +SC



- **TCT measurements (MCZ): 8.2x10^{13} n/cm^2**
  Laser on the p$^+$ side (front side): -SC and DJ/DP

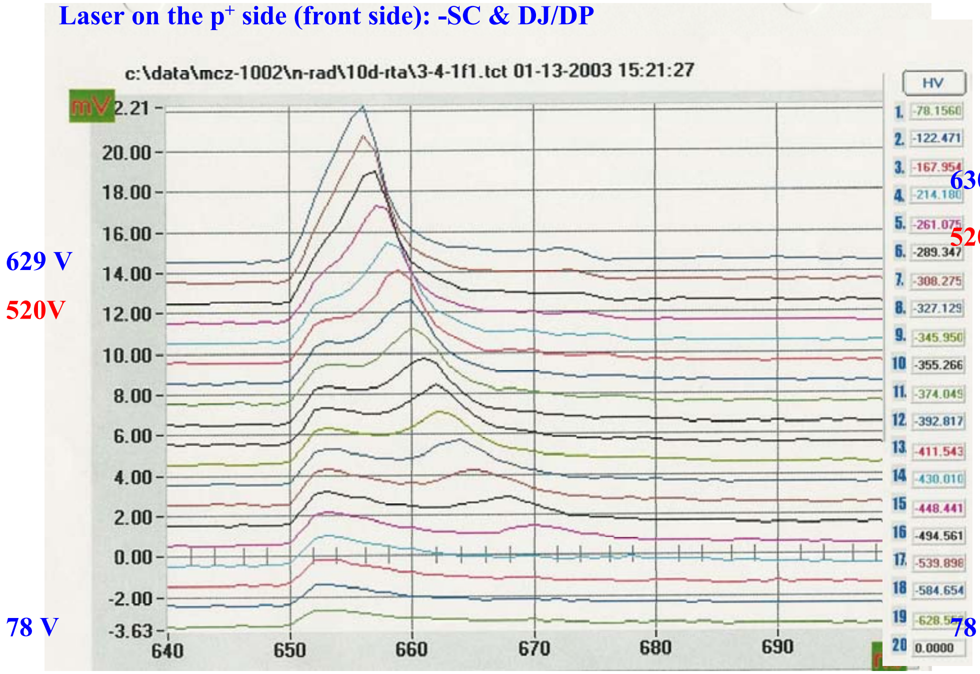


- **TCT measurements (MCZ):8.2x10^{13} n/cm^2**
  Laser on the n$^+$ side (back side): -SC



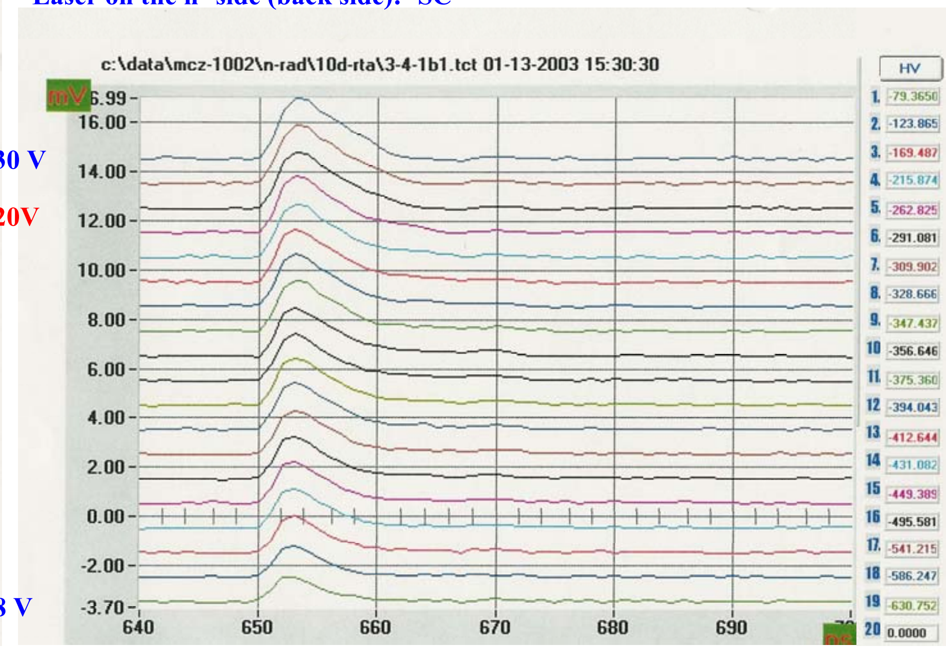
- TCT measurements (MCZ): 2.9×10^{14} n/cm^2

Laser on the p$^+$ side (front side): -SC & DJ/DP



- TCT measurements (MCZ): 2.9×10^{14} n/cm^2

Laser on the n$^+$ side (back side): -SC

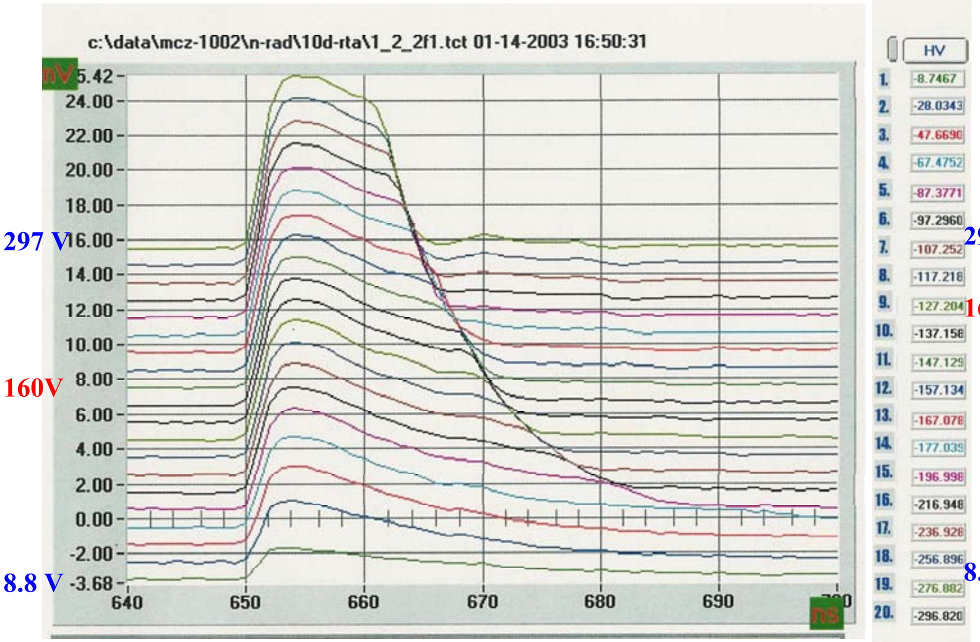


- **For MCZ Si detectors, SCSI takes place between 3.3×10^{13} n/cm^2 and 8.2×10^{13} n/cm^2 after 1 MeV neutron radiation.**

- **Double junction and double peak (DJ/DP) have been observed after SCSI**

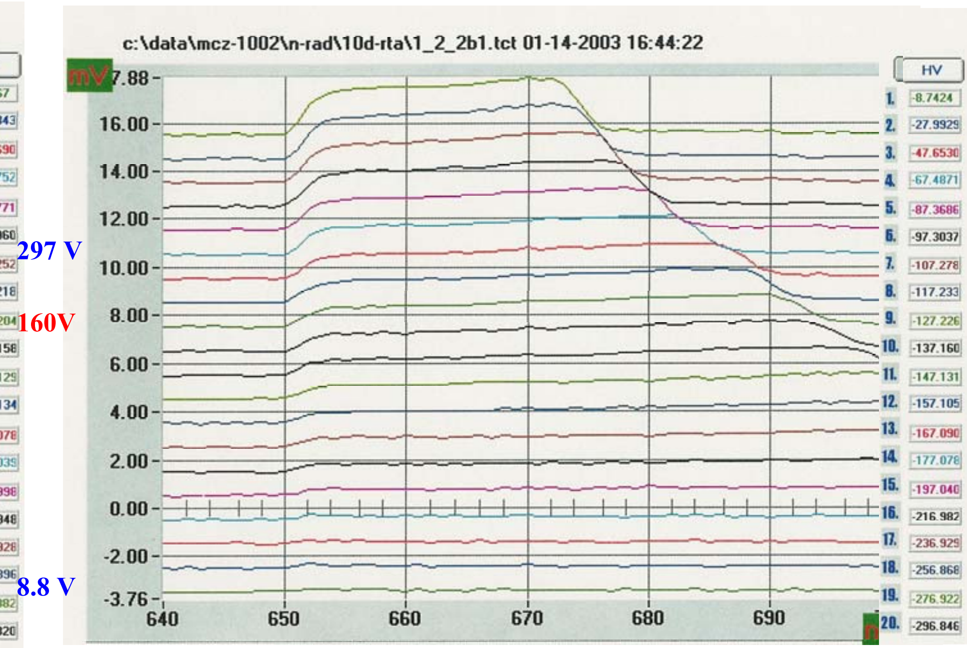
- **TCT measurements (CFZ): 1.7x10^{13} n/cm^2**

  Laser on the p$^+$ side (front side): +SC



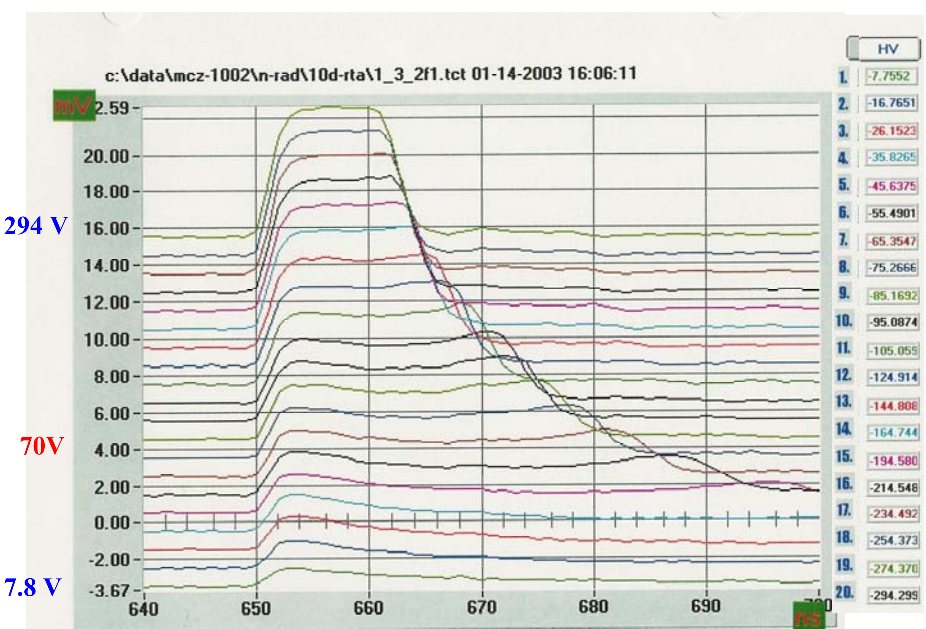
- **TCT measurements (CFZ): 1.7x10^{13} n/cm^2**

  Laser on the n$^+$ side (back side): +SC



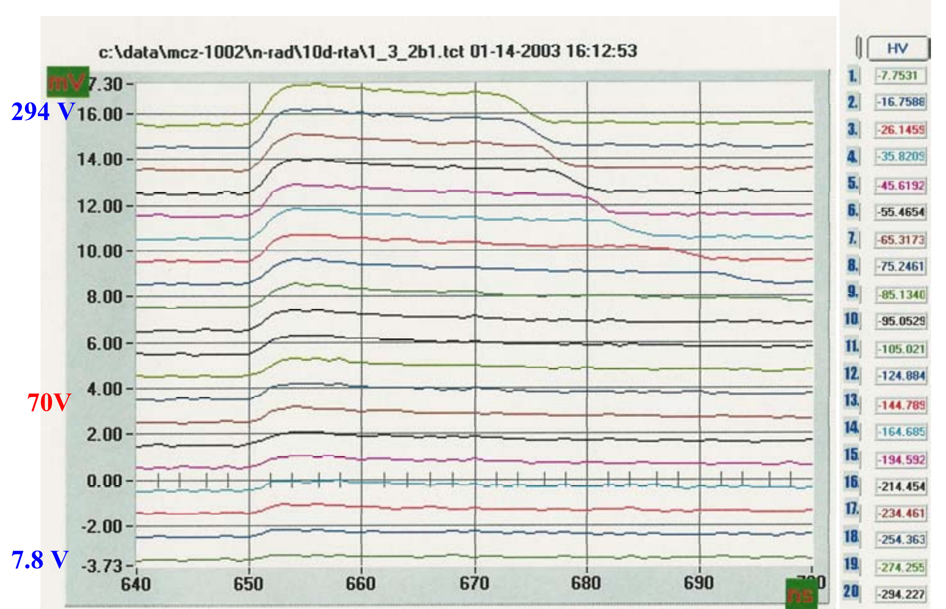
- **TCT measurements (CFZ): 3.3x10^{13} n/cm^2**

  Laser on the p$^+$ side (front side): -SC and DJ/DP



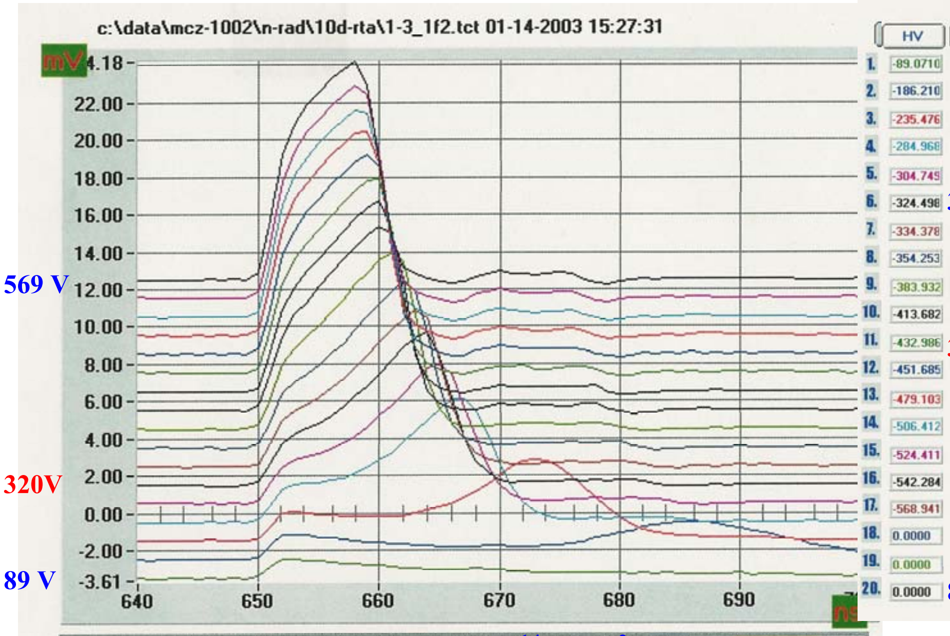
- **TCT measurements (CFZ): 3.3x10^{13} n/cm^2**

  Laser on the n$^+$ side (back side): -SC



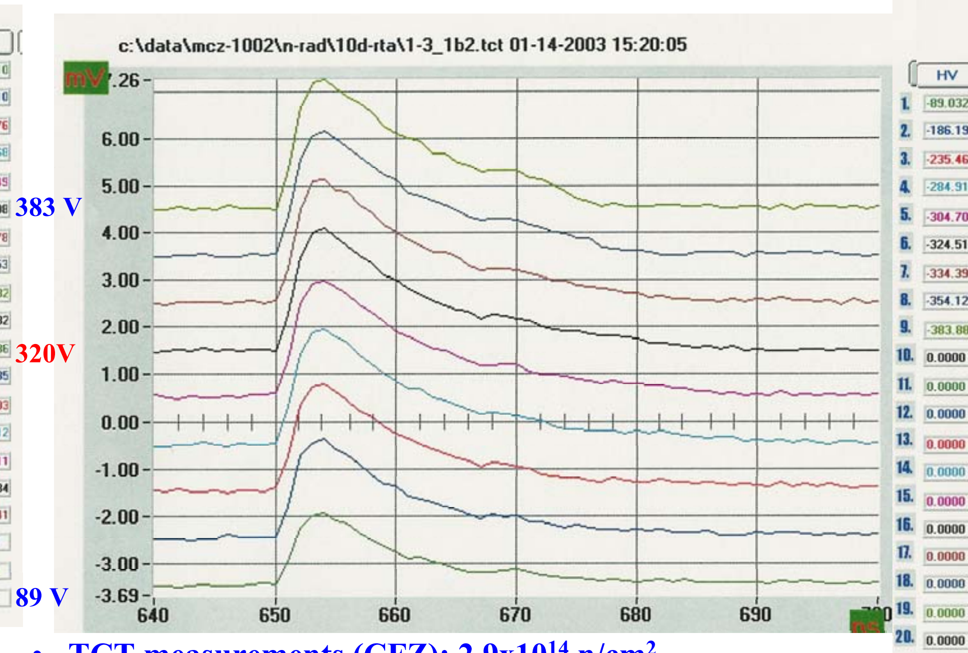
- **TCT measurements (CFZ): 8.2x10^{13} n/cm^2**

  Laser on the p$^+$ side (front side): -SC and DJ/DP



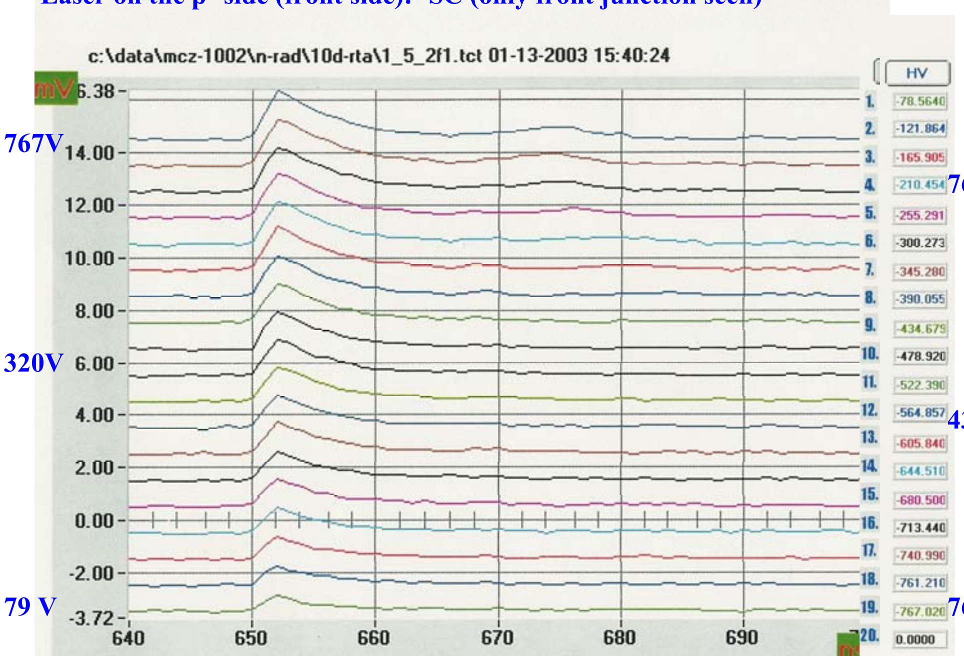
- **TCT measurements (CFZ): 8.2x10^{13} n/cm^2**

  Laser on the n$^+$ side (back side): -SC



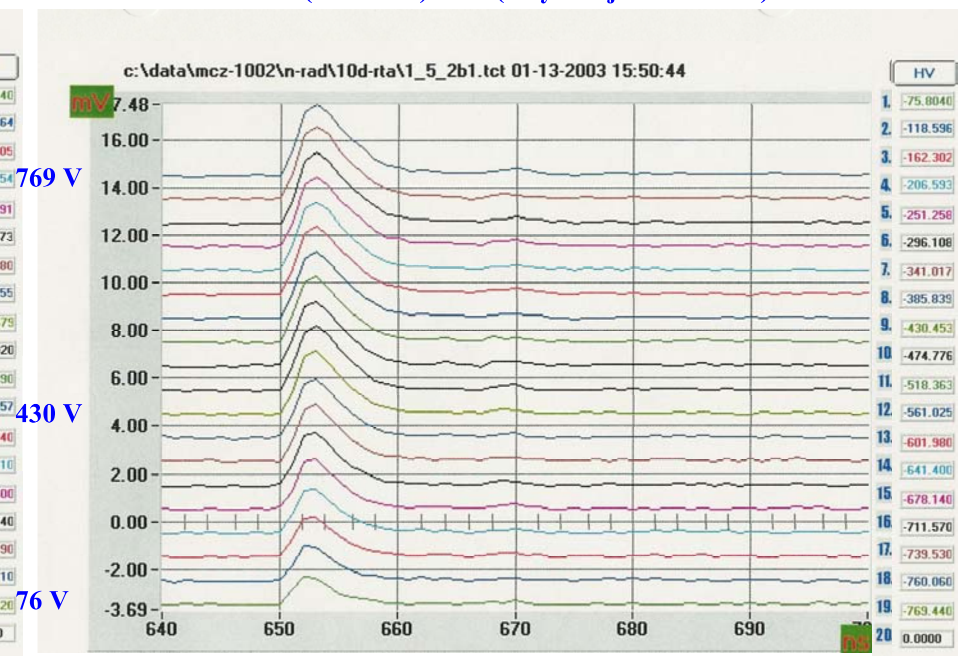
- **TCT measurements (CFZ): 2.9x10^{14} n/cm^2**

  Laser on the p$^+$ side (front side): -SC (only front junction seen)



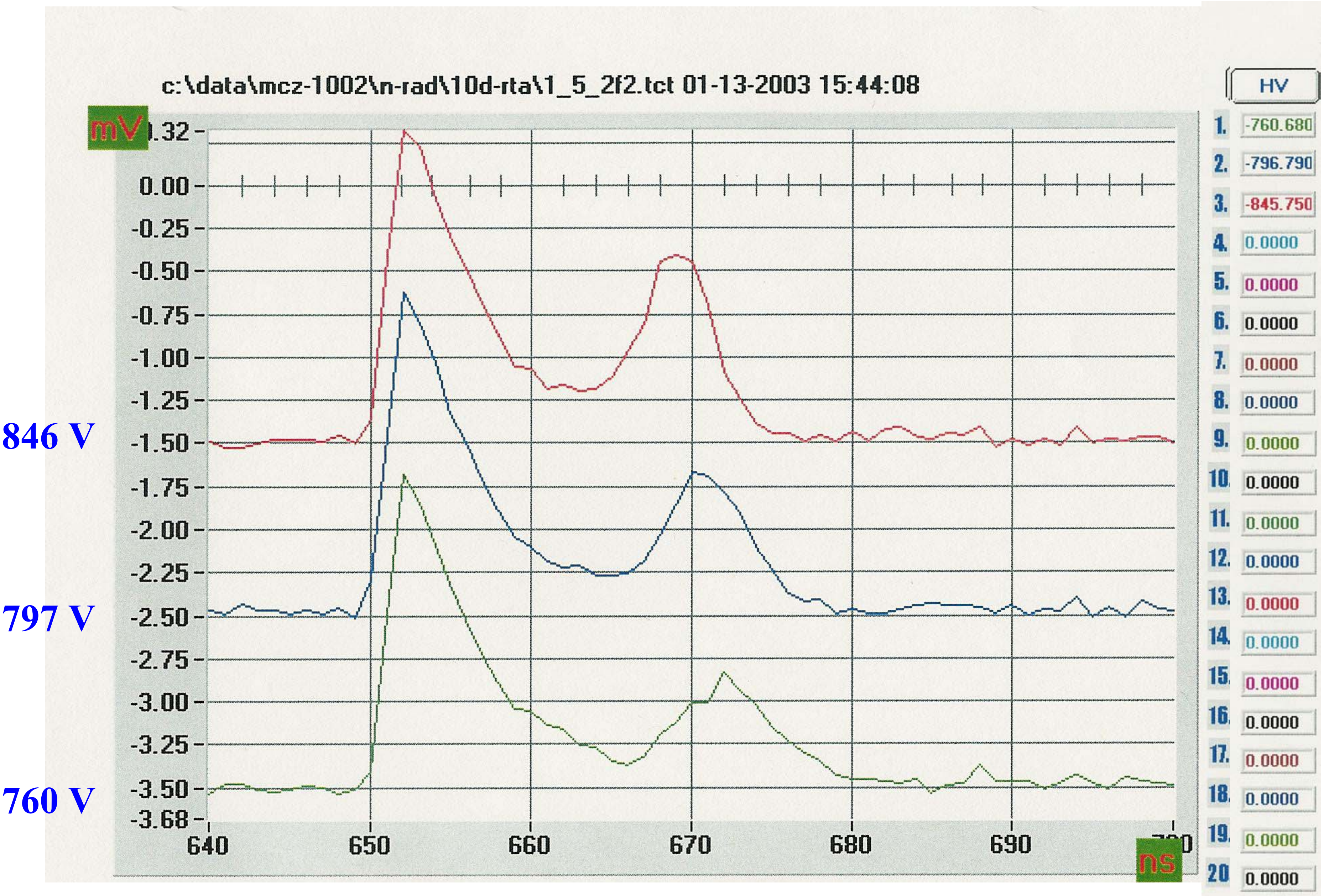
- **TCT measurements (CFZ): 2.9x10^{14} n/cm^2**

  Laser on the n$^+$ side (back side): -SC (only one junction seen)

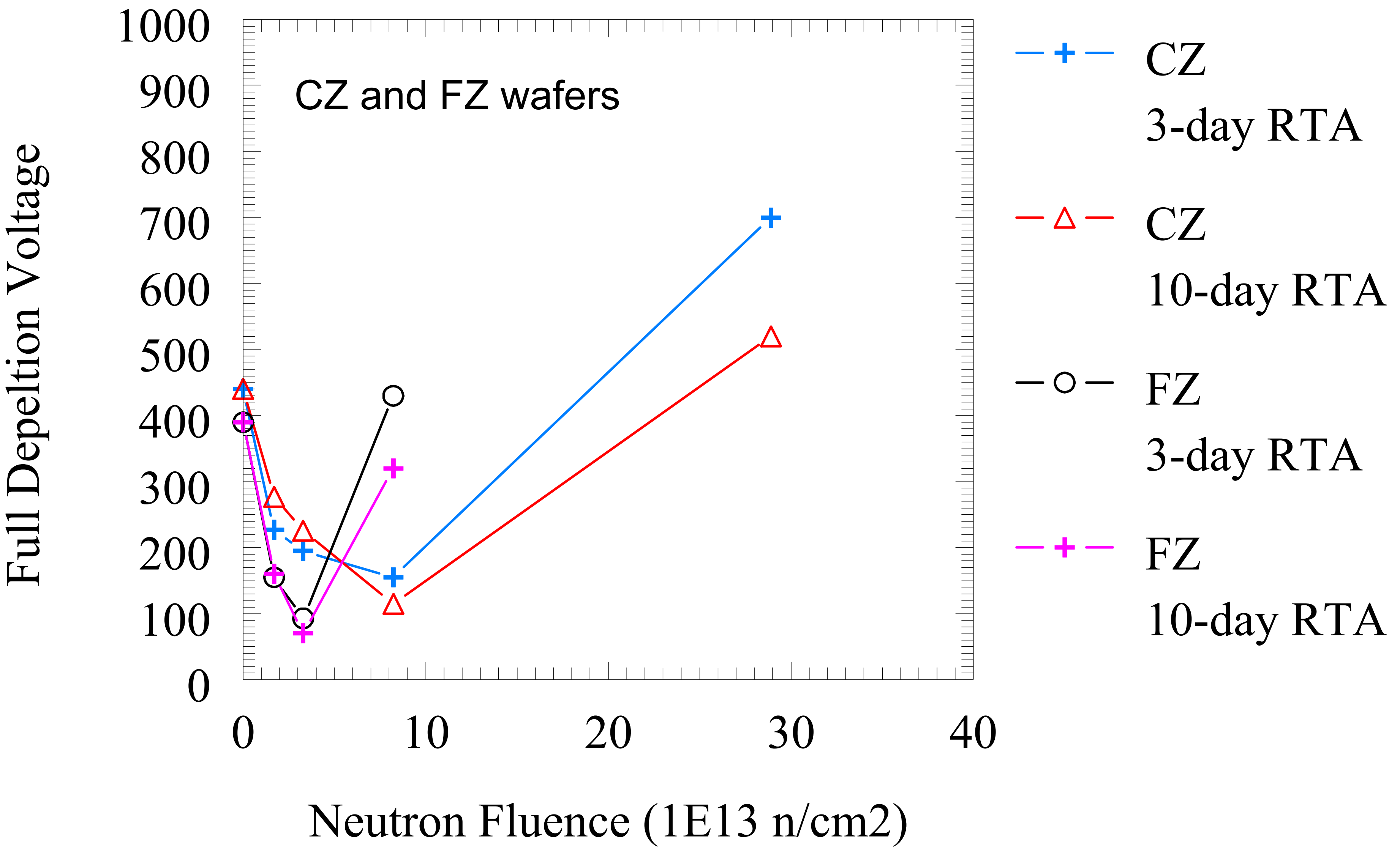


- **TCT measurements (CFZ): 2.9×10^{14} n/cm^2**

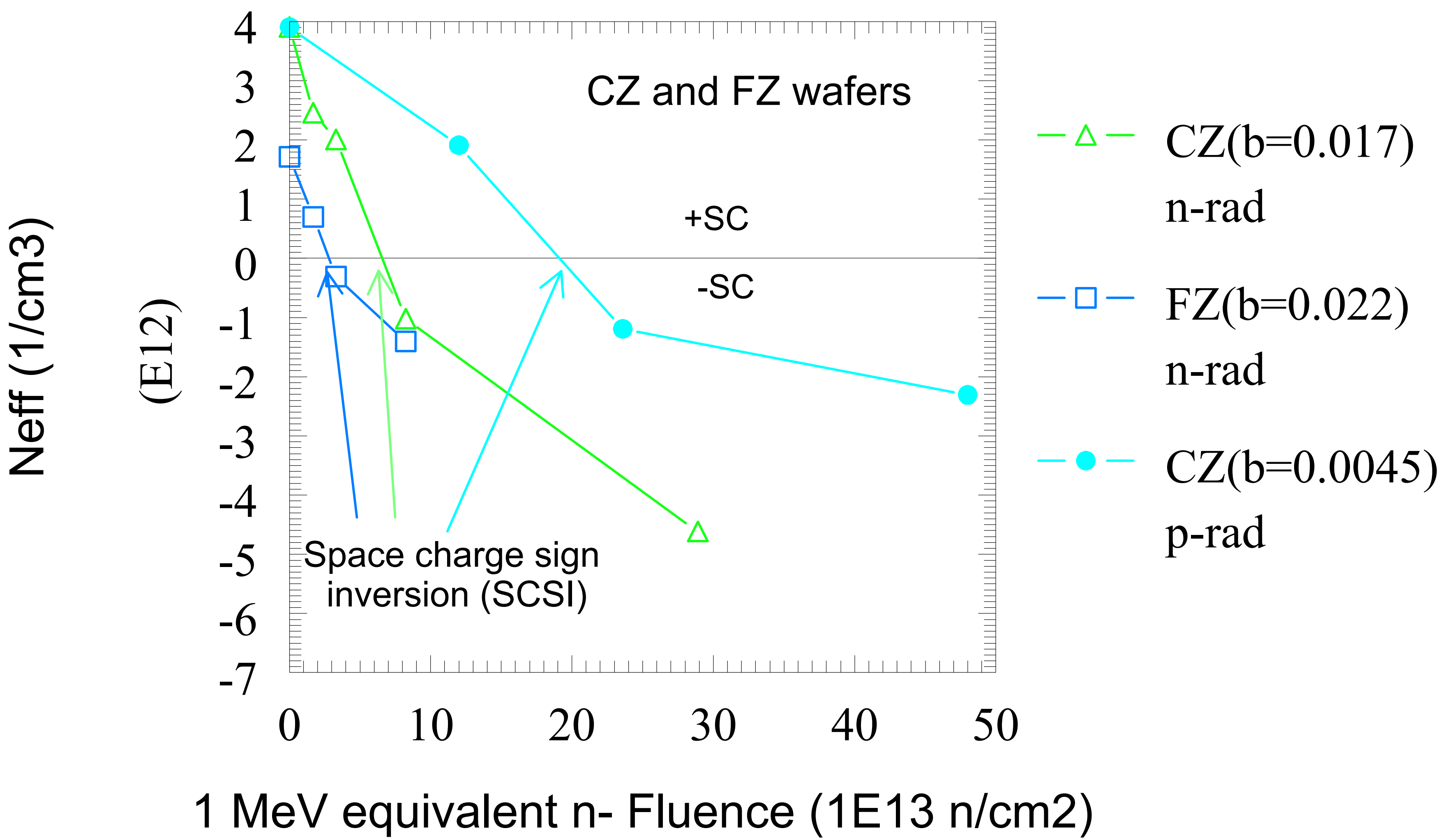
Laser on the p$^+$ side (front side): -SC and DJ/DP



Full depletion voltage vs. n-fluence

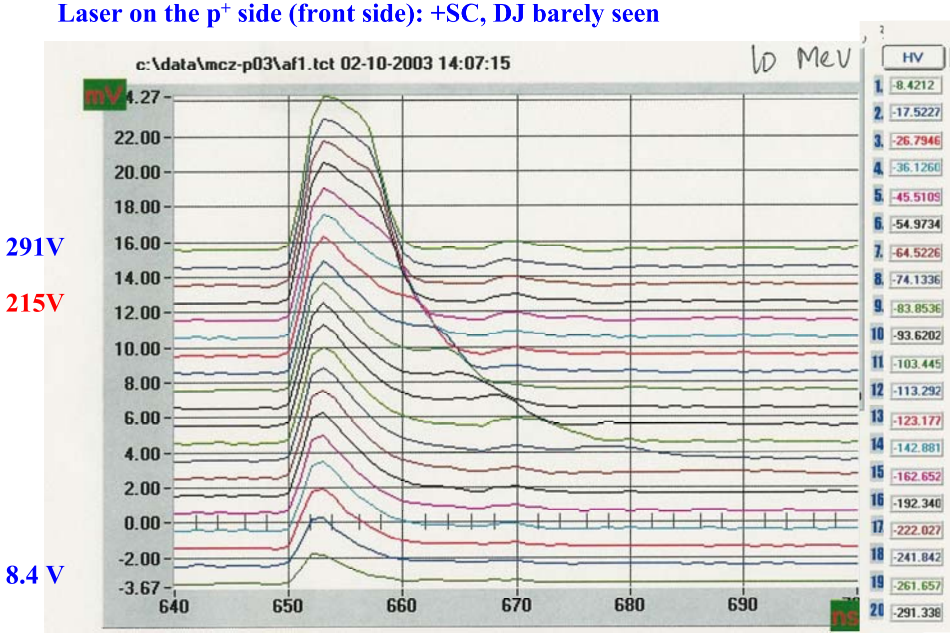


N_{eff} vs. n-fluence

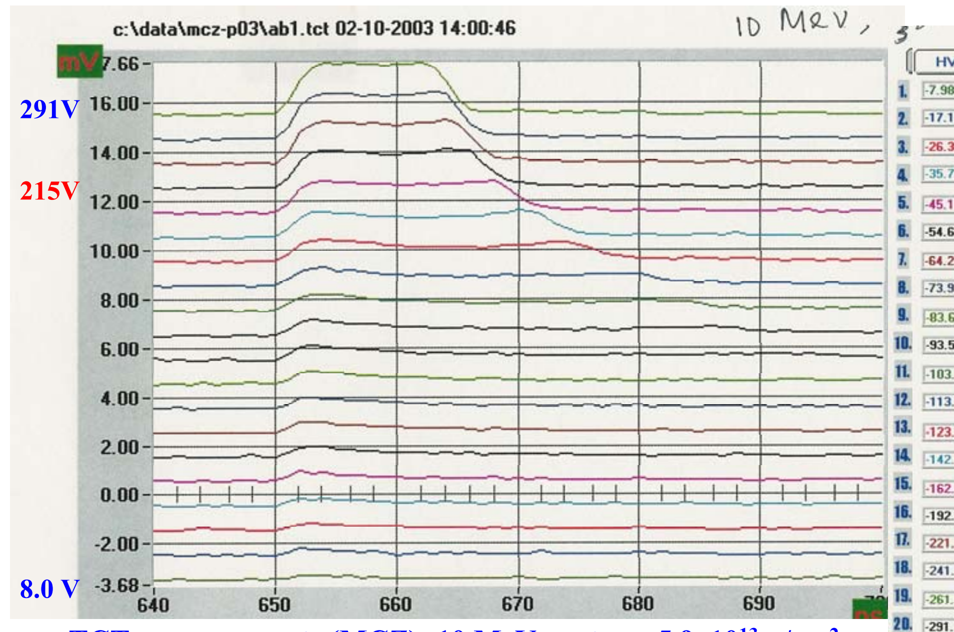


Proton Radiation

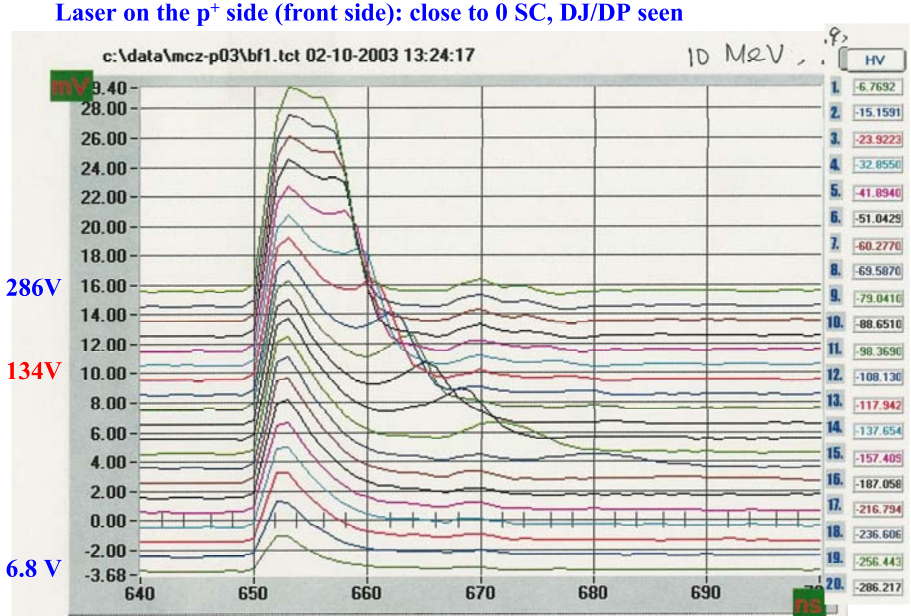
- **TCT measurements (MCZ): 10 MeV protons, 3.0x10^{13} p/cm^2**
  Laser on the p$^+$ side (front side): +SC, DJ barely seen



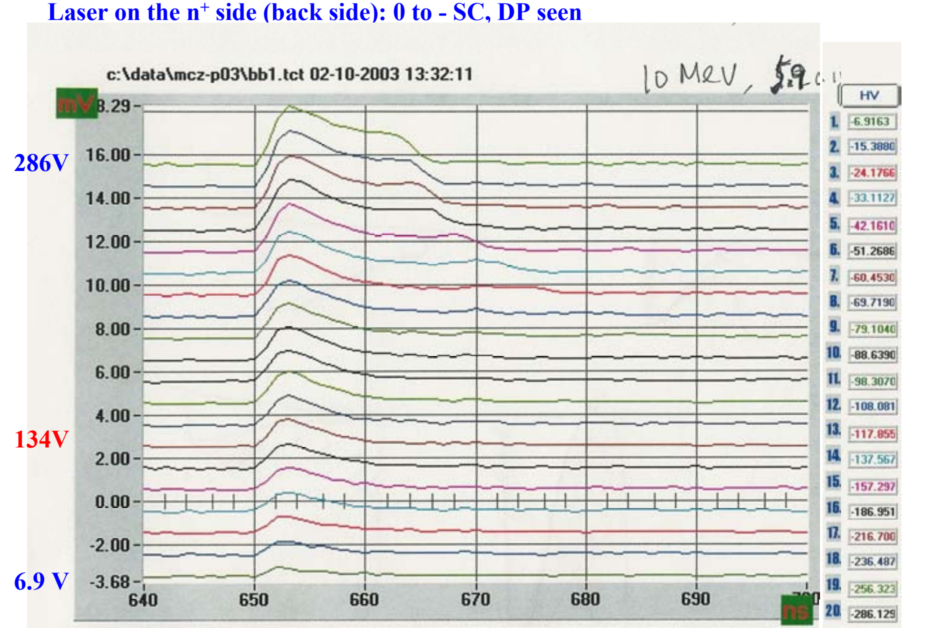
- **TCT measurements (MCZ): 10 MeV protons, 3.0x10^{13} p/cm^2**
  Laser on the n$^+$ side (back side): +SC, DJ barely seen



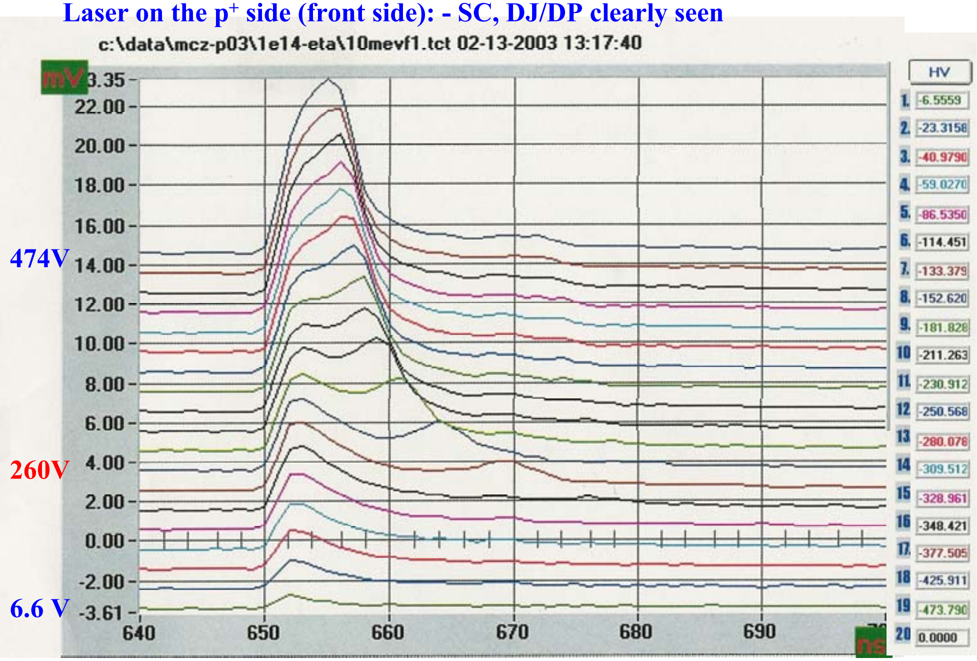
- **TCT measurements (MCZ): 10 MeV protons, 5.9x10^{13} p/cm^2**
  Laser on the p$^+$ side (front side): close to 0 SC, DJ/DP seen



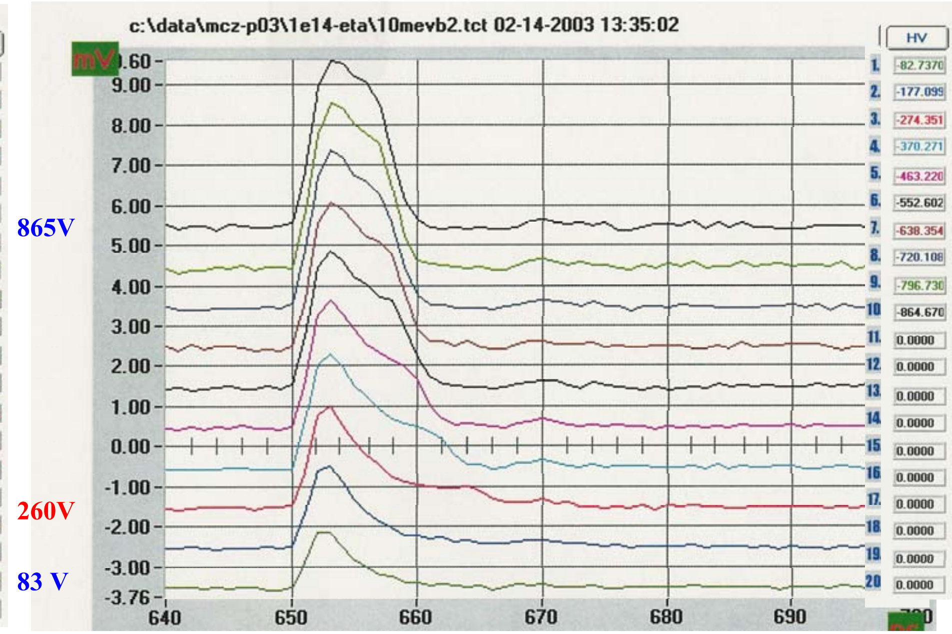
- **TCT measurements (MCZ): 10 MeV protons, 5.9x10^{13} p/cm^2**
  Laser on the n$^+$ side (back side): 0 to - SC, DP seen



- **TCT measurements (MCZ): 10 MeV protons, 1.2x10^{14} p/cm^2**
  Laser on the p^+ side (front side): - SC, DJ/DP clearly seen



- **TCT measurements (MCZ): 10 MeV protons, 1.2x10^{14} p/cm^2**
  Laser on the n^+ side (back side): - SC, DP seen

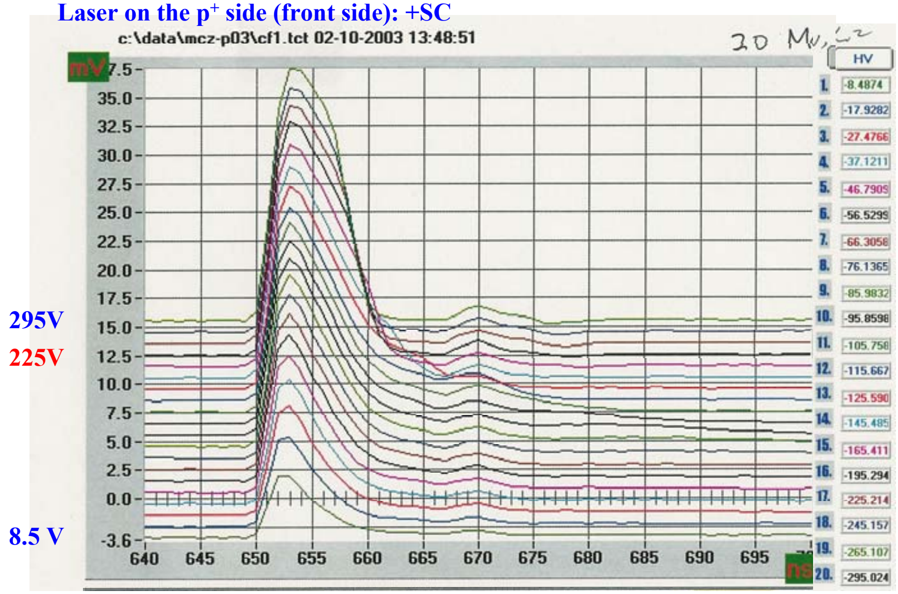


- **For MCZ Si detectors, SCSI takes place around 5.9x10^{13} p/cm^2 after 10 MeV proton radiation.**

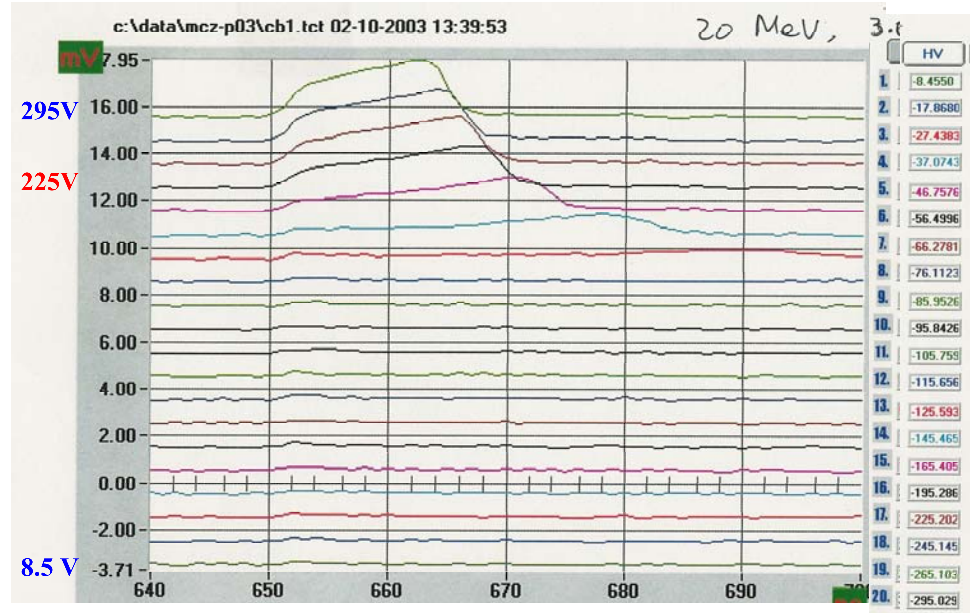
- **Double junction and double peak (DJ/DP) have been observed after SCSI**

Proton Radiation (20 MeV)

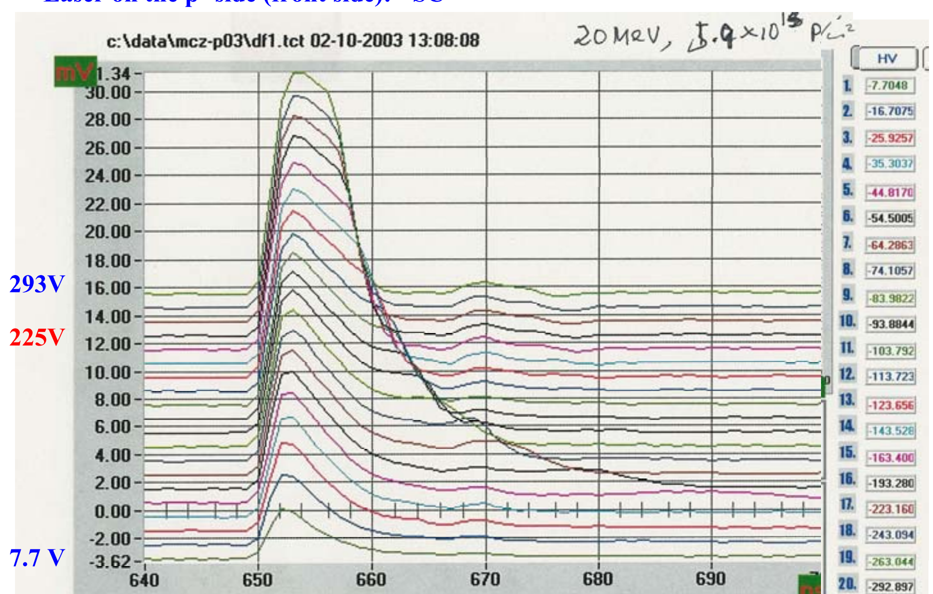
- **TCT measurements (MCZ): 20 MeV protons, 3.0×10^{13} p/cm^2**
  Laser on the p$^+$ side (front side): +SC



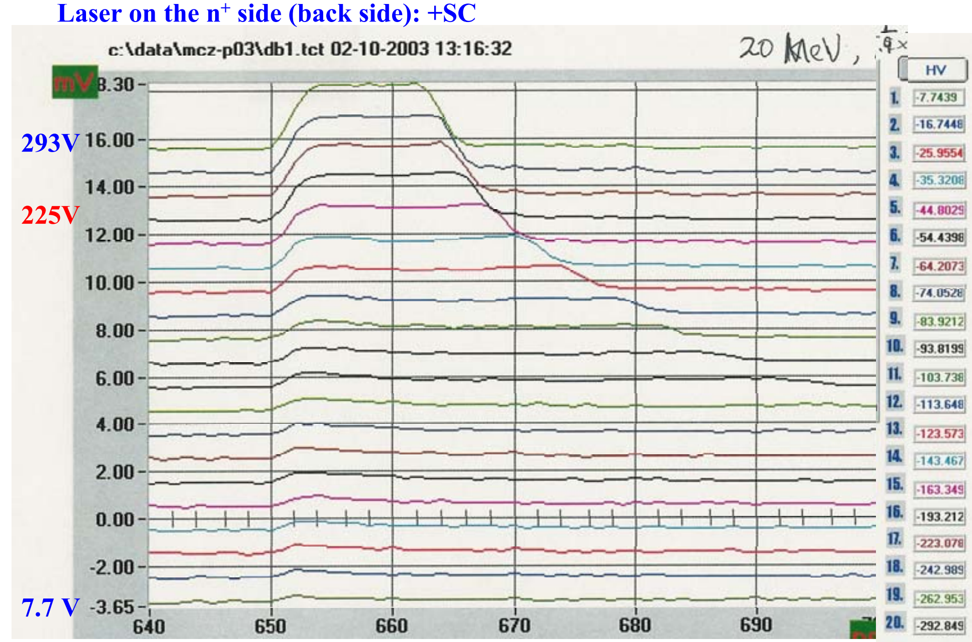
- **TCT measurements (MCZ): 20 MeV protons, 3.0×10^{13} p/cm^2**
  Laser on the n$^+$ side (back side): +SC



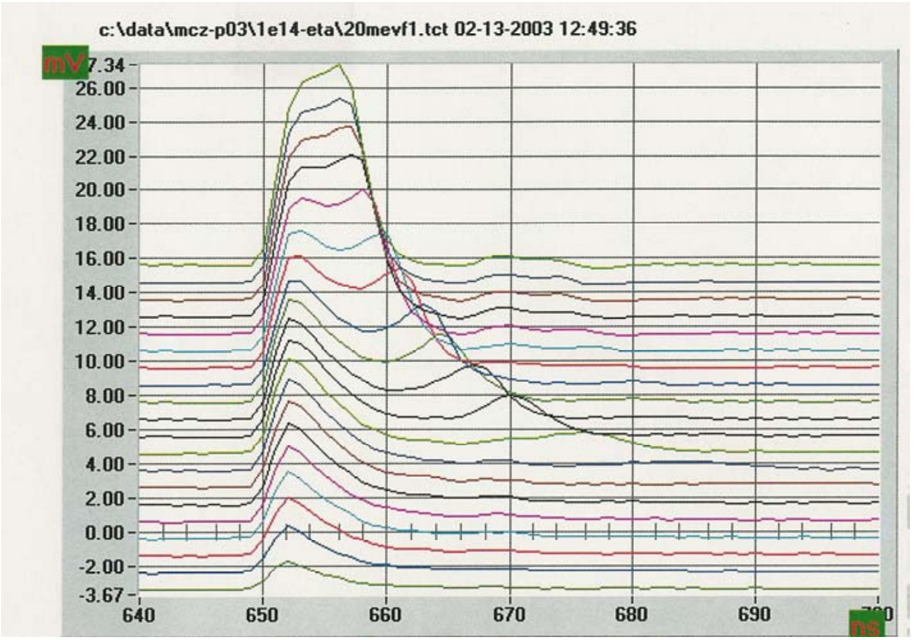
- **TCT measurements (MCZ): 20 MeV protons, 5.9×10^{13} p/cm^2**
  Laser on the p$^+$ side (front side): +SC

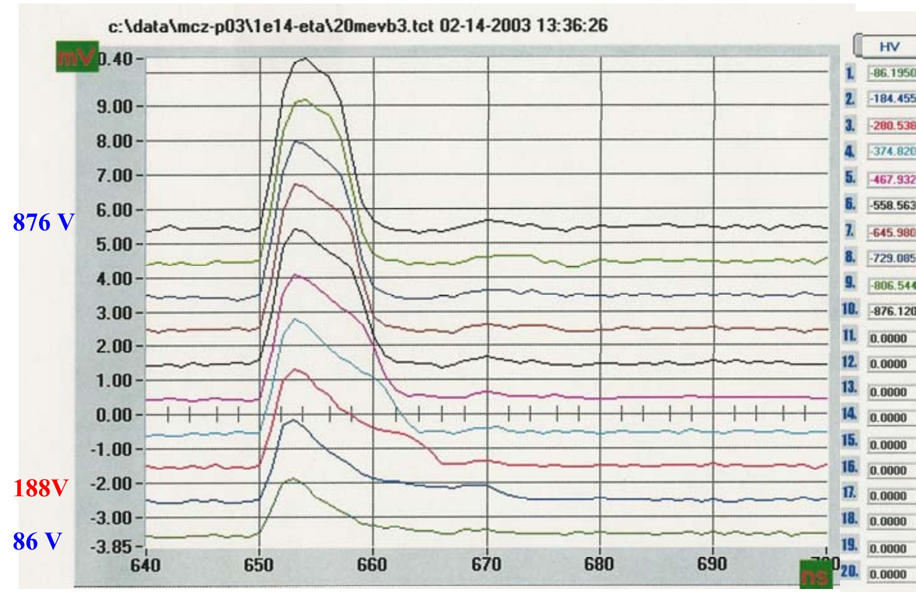


- **TCT measurements (MCZ): 20 MeV protons, 5.9×10^{13} p/cm^2**
  Laser on the n$^+$ side (back side): +SC



- **TCT measurements (MCZ): 20 MeV protons, 1.2×10^{14} p/cm^2**
  Laser on the n^+ side (back side): -SC

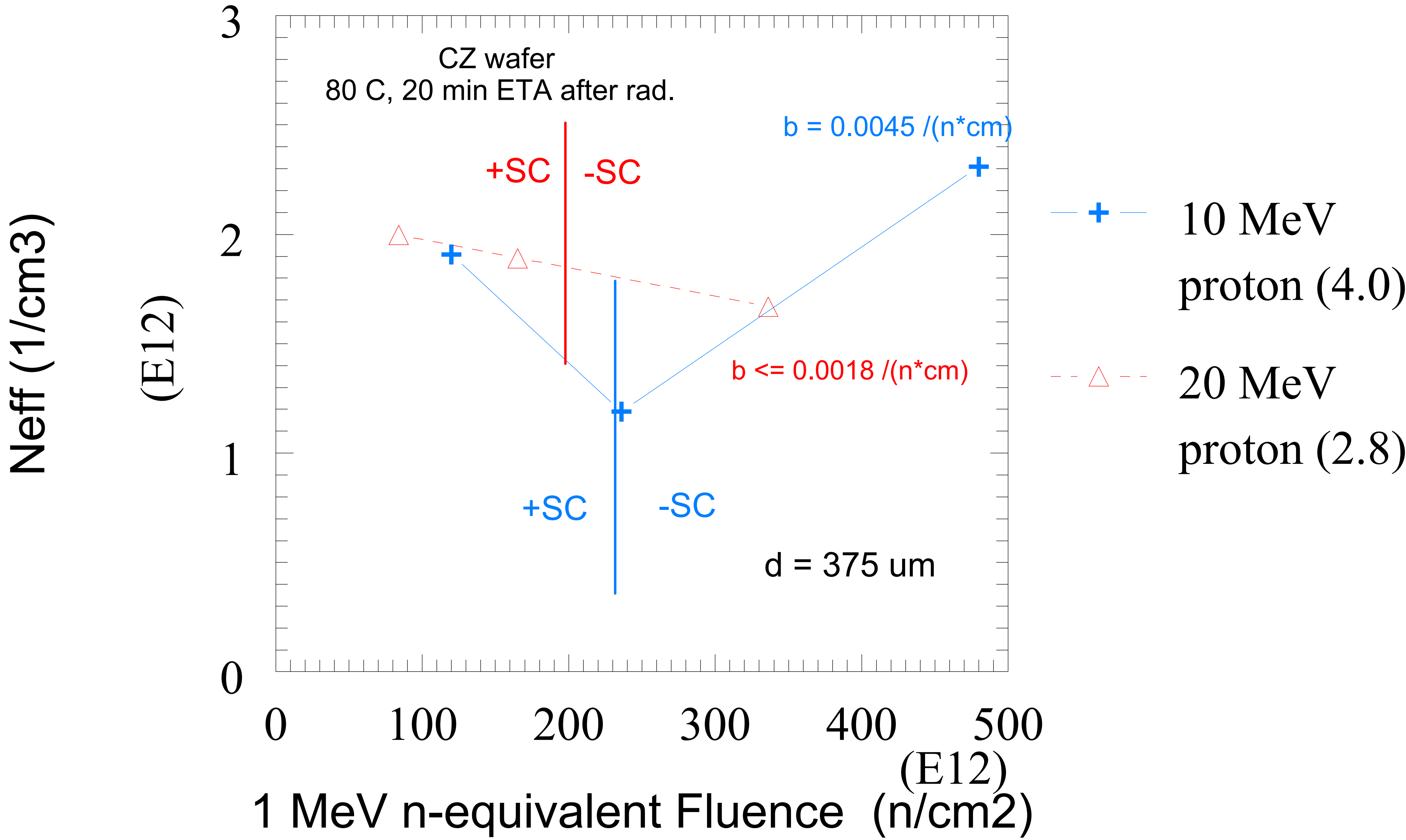




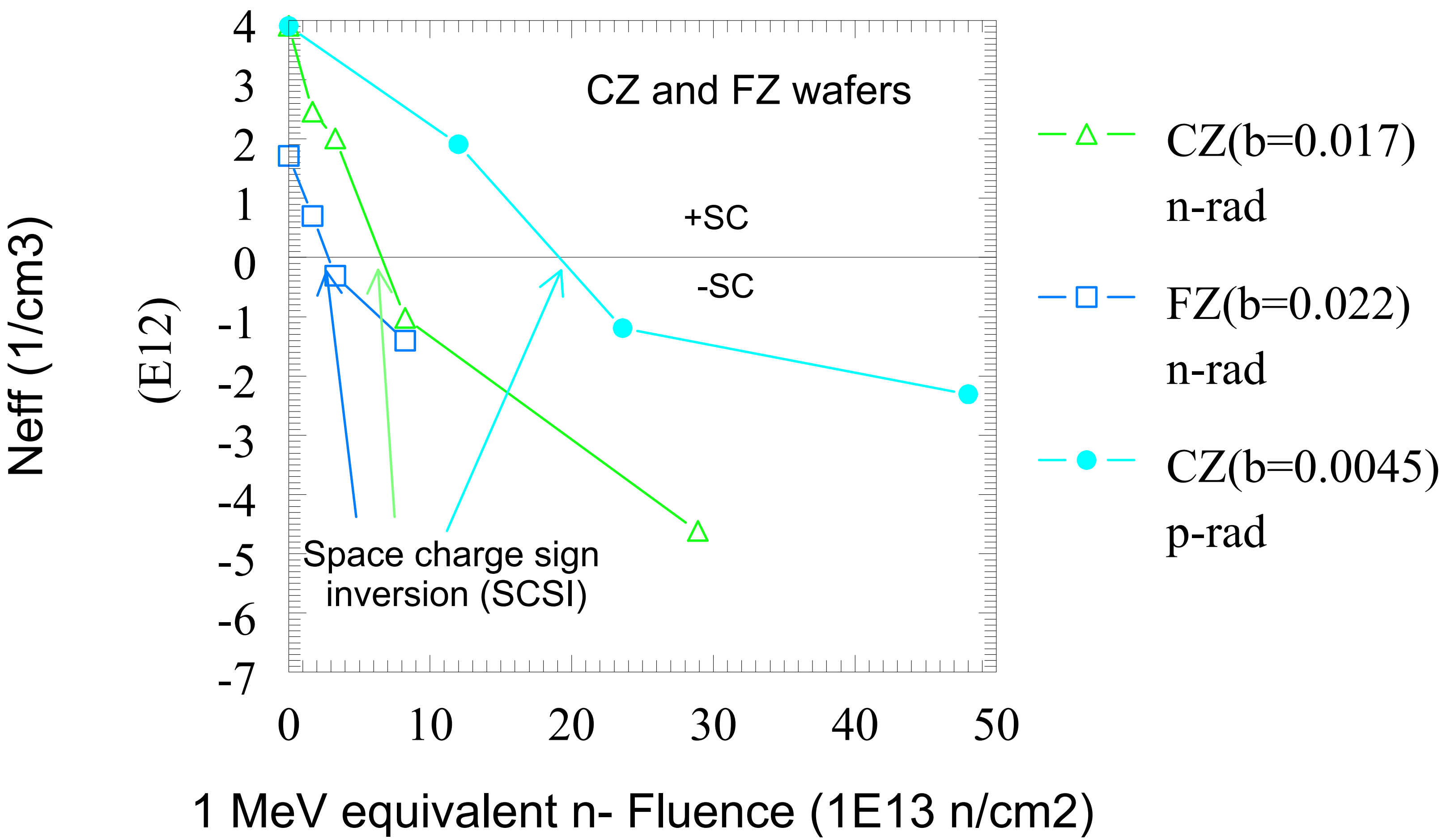
- **For MCZ Si detectors, SCSI takes place between 5.9×10^{13} p/cm^2 to 1.2×10^{14} p/cm^2 after 20 MeV proton radiation.**

- **Double junction and double peak (DJ/DP) have been observed after SCSI**

N_{eff} vs. 1 MeV equivalent n-fluence



Comparison of N_{eff} vs. 1 MeV equivalent n-fluence between neutron and proton radiations



- CZ Si detectors are slightly more rad-hard than FZ ones with n-rad
  - β_{CZ} (b in the figure) is about 23% less than β_{FZ}
- CZ Si detectors are much more rad-hard than FZ ones with p-rad
  - β_{CZ} is about 1/5 of β_{FZ} and is about ½ of β_{OXY}
  - SCSI fluence is 3 time higher than that of FZ

- **With higher [O], MCZ Si has more un-activated TD's**
  - **Produced during the TD killing process**

- **Gamma radiation activates those un-activated TD's, giving rise to the higher positive SC build-up rate**

- **This positive SC build-up may also happen in charged particle irradiated MCZ Si detectors, giving possibility of compensating regular negative SC ---- improvement of rad-hardness**

- **The degree of this improvement in rad-hardness may depend type of particle radiation**

Summary

o Experimental results indicates that, upon gamma radiation, the MCZ Si detectors behave similarly to oxygenated Si detectors

- Positive SC build-up
- No SCSI

o The build-up rate positive SC in gamma irradiated Si detectors is higher than that in oxygenated Si detectors, and is proportional to [O]

- Much higher [O] in MCZ
- Even higher concentration of un-activated TD

o Gamma-induced activation of TD's may be responsible

o MCZ Si detectors are also partially rad-hard to charge particles (protons in our case) and are more rad-hard than oxygenated Si detectors, and may be slightly radiation hard to neutrons than CFZ Si detectors.