Systematic measurements of p and n type diodes irradiated with protons, pions and neutrons

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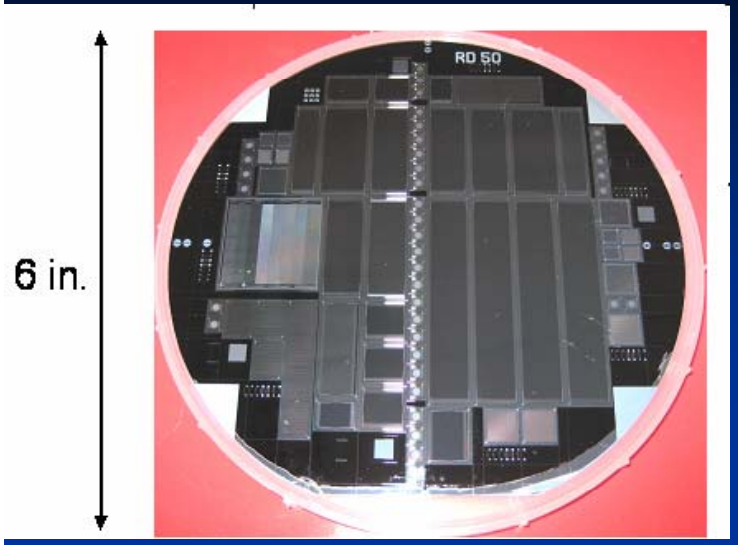
RD50 MICRON 6” project



- 36 processed wafers
- Fz (topsil) and MCz (okmetic) wafers of p&n type material
- n-on-n, n-on-p, p-on-n structures (pixels, strips, diodes)

Strips: ATLAS strips geometry 80 μm pitch (w/p~1/3)
Pads: 2.5 x 2.5 mm^2 , multiple guard rings

Material selected for the study – diodes only !

	MCz-p	MCz-n	Fz-p	Fz-n
Wafers	2552-6,7	2553-11; 2552-10,14	2551-1,3,4,6,7	2535-11; 2535-8,9
Resitivity	1.5 Ωcm	2 kΩcm	14 kΩcm	~20 kΩcm
Orientation	<100>	<100>	<100>	<100>

SSDs and diodes irradiated with neutrons and protons and pions; a collaboration of SCIPP, L’pool and Ljubjana!

The aim of this presentation is comparison of materials, n vs. p, MCz vs. Fz

Motivation

Answers to the following questions:

- What are properties (space charge) of investigated materials after irradiations?
  - Initial acceptor removal for p-type materials irradiated with different particles?
  - What is introduction rate of stable damage?
  - What is the effect of mixed irradiations?
- What are charge collection properties?
  - Are there any differences in charge collection for different materials?
  - Are there any differences in charge collection for different irradiation particles at given equivalent fluences?
  - Is V_{fd} from C-V correlated with the one determined from Q-V for all materials?

For neutron irradiated SSD and diodes we know (http://indico.cern.ch/conferenceProgram.py?confId=21398)

- Strips and pads has the same dependence of Q-V with some offset!
- The full depletion voltage from C-V coincides with the kink in Q-V plot!
- Collected charge is larger than expected from simulations

Samples & measurements

Single particle irradiations:

- **Reactor neutron irradiations:** for each material 3 fluences
  1, 5, $10 \cdot 10^{14}$ cm^{-2} – **12 diodes**
- **200 MeV pion irradiations:** for each material 3 fluences
  1.5, 3.2 (3.9), ~6.5(5.6)$\cdot 10^{14}$ cm^{-2} – **12 diodes**
- **24 GeV proton irradiations:** for each material 5 fluences
  1.85, 4.81,11,19.3,48.7$\cdot 10^{14}$ cm^{-2} – **20 diodes**

The fluences are in range of upgraded ATLAS - SCT

Mixed irradiations:

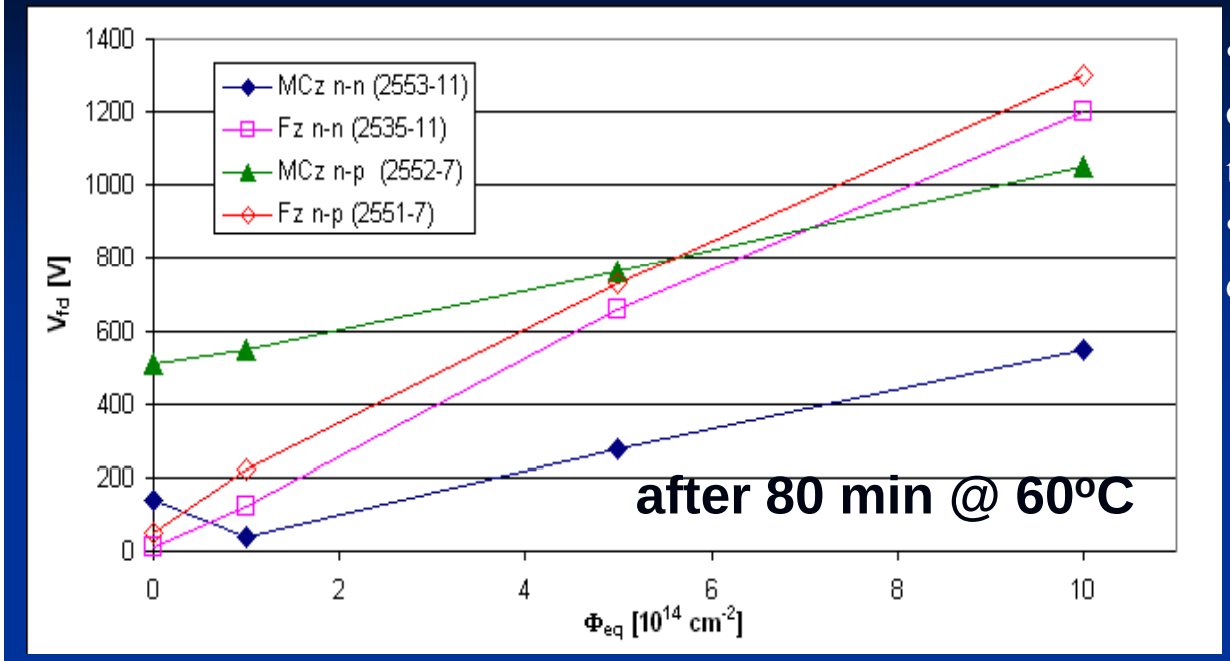
Pions+neutrons: for each material 1 sample – 4 diodes

Protons+neutrons: for each material 2 fluences – 8 diodes

Samples annealed in steps to 80 min@60°C (this is still ongoing study …):

- C-V / I-V performed during each step
- CCE measurements were performed at the end of the beneficial annealing at 80 min!
  - preamplifier + 25 ns shaping amplifier read-out of pulses on oscilloscope
  - scintillator used for triggering
  - measurements performed at T=-10C (Peltier cooling)

Neutron irradiated diodes



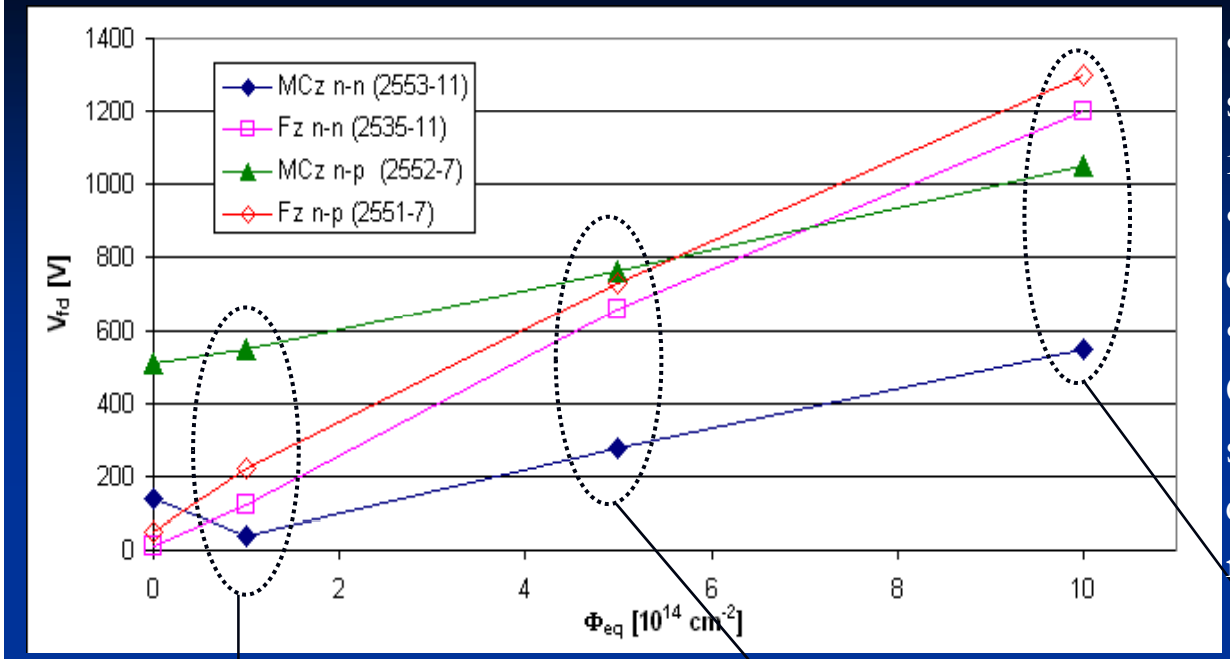
- all detectors have negative space charge (decrease of V_{fd} during short term annealing)
- Leakage current agrees with expectations ($\alpha \sim 3.5\text{-}5.5 \cdot 10^{-17}$ A/cm)

Slope of V_{fd} increase with fluence

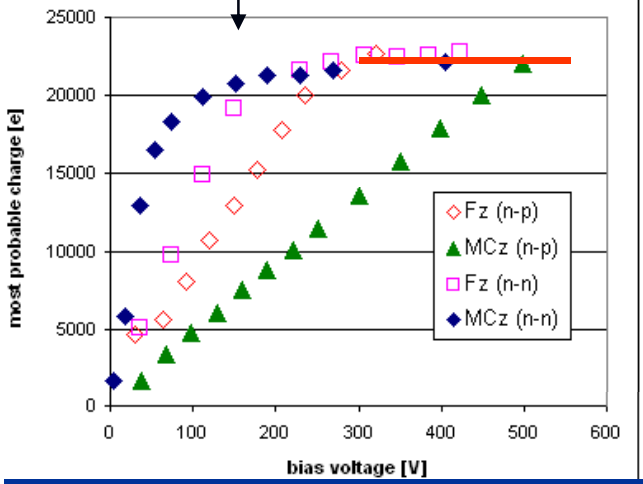
- MCz (p and n type): 55 V/10^{14} cm^{-2} ($g_c \sim 0.008$ cm^{-2}) – **lower stable damage than seen before ?**
- Fz (p and n type): 125 V/10^{14} cm^{-2} ($g_c \sim 0.018$ cm^{-2}) – in agreement with previous results

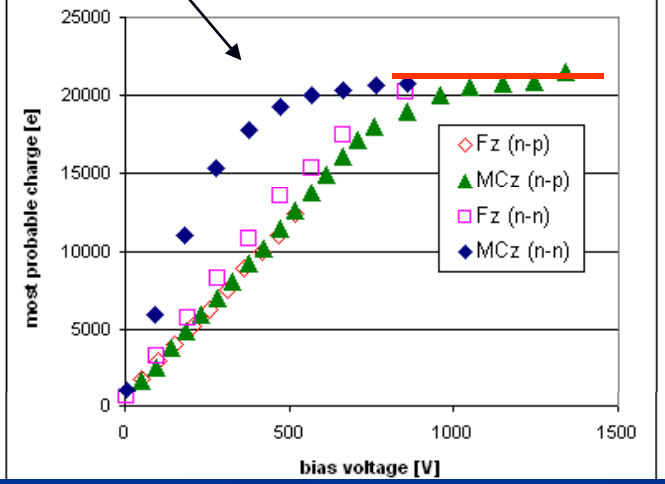
- There is no evidence of acceptor removal
- The difference in initial doping persists – MCz-n performs best of all!

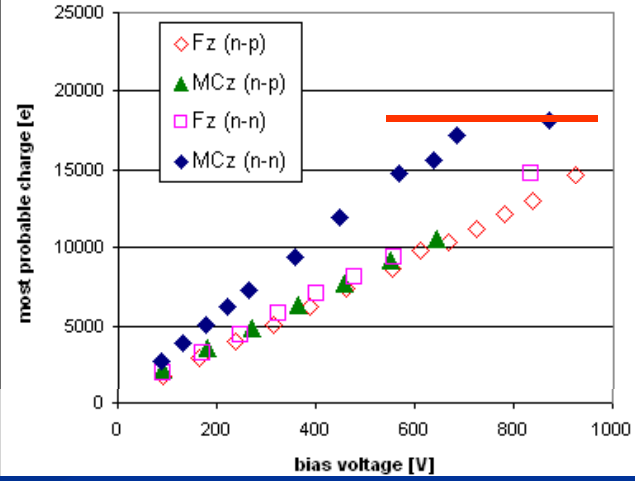
It seems that MCz should perform better – do we see this performance in CCE!



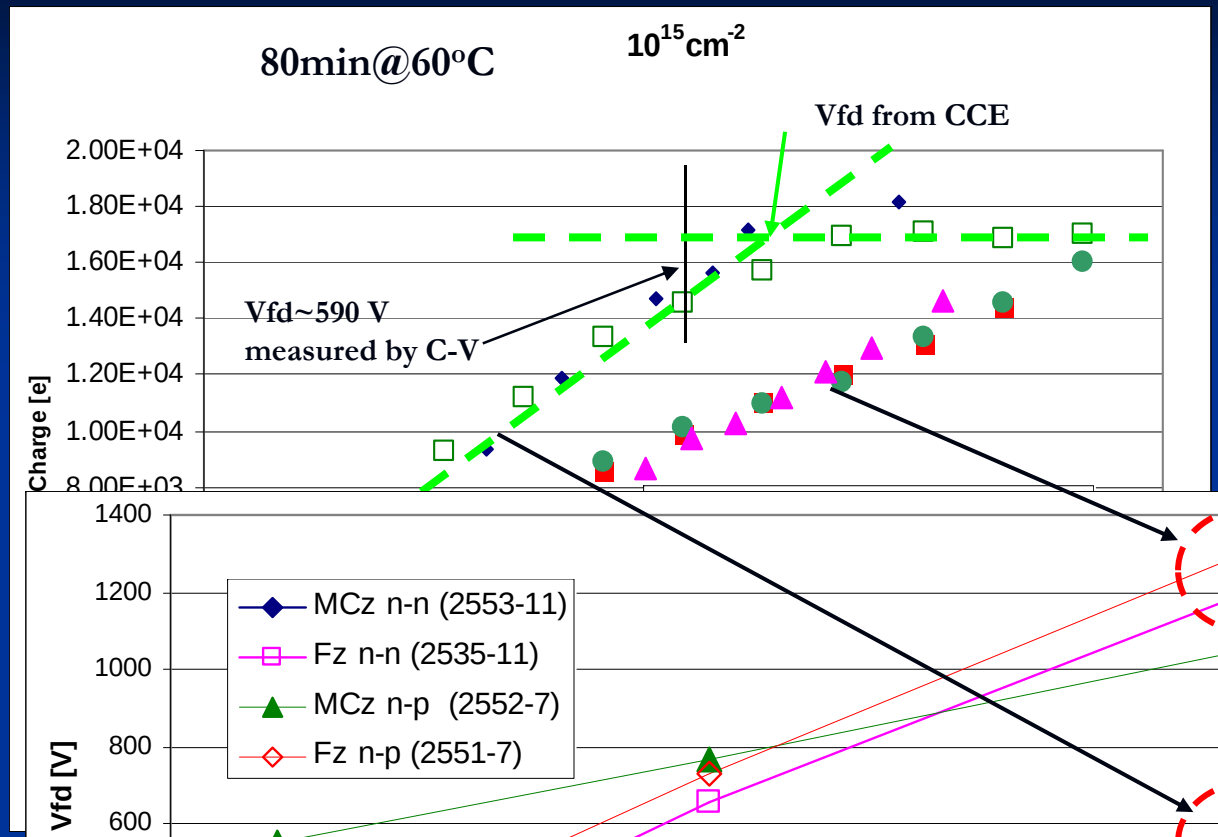
- The difference in V_{fd} can be clearly seen in charge collection at all fluences
- CCE for highly over-depleted diodes decreases with fluence
- Close to linear dependence of CCE on fluence -> with the initial slope dQ/dV and Q at over-depletion one can predict V_{fd} with reasonable accuracy

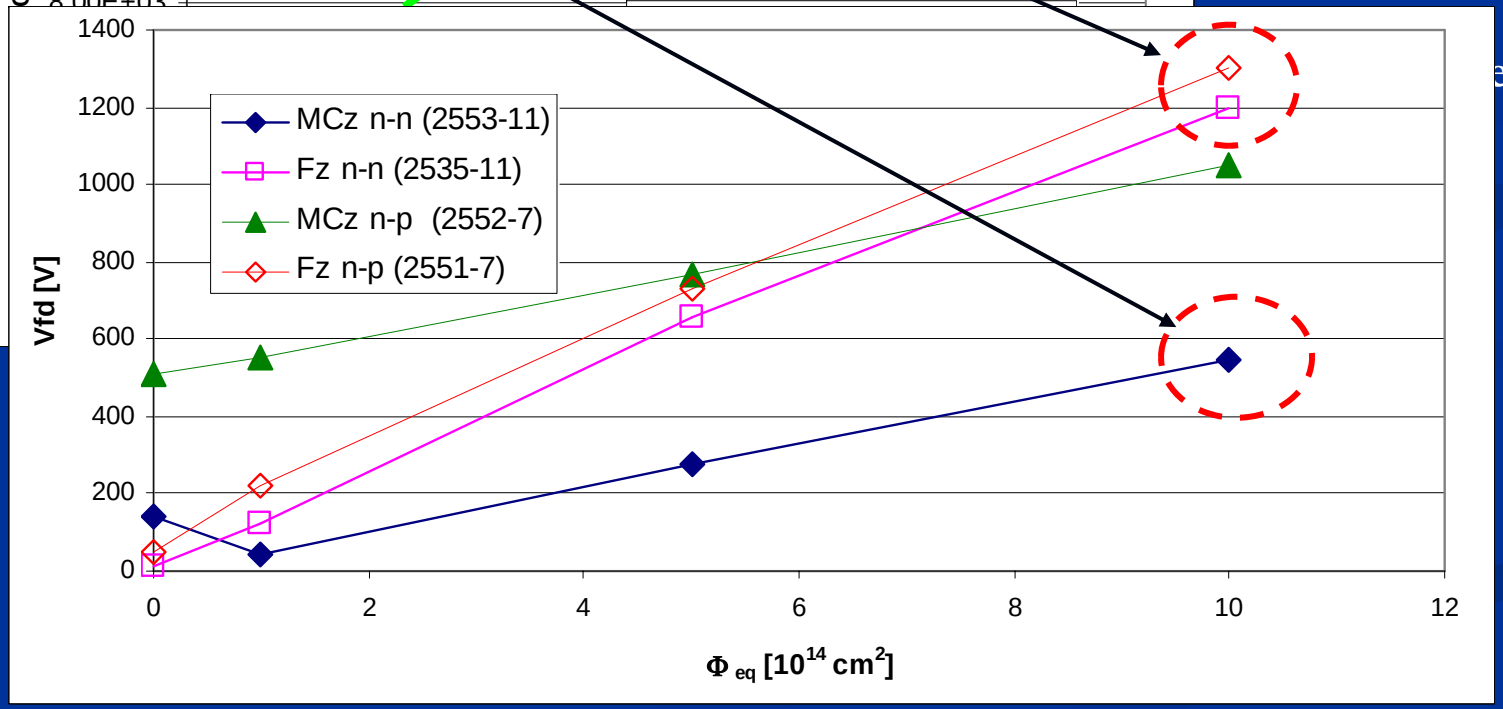






Fz-p vs. MCz-n and "V_{fd}" of strip detectors



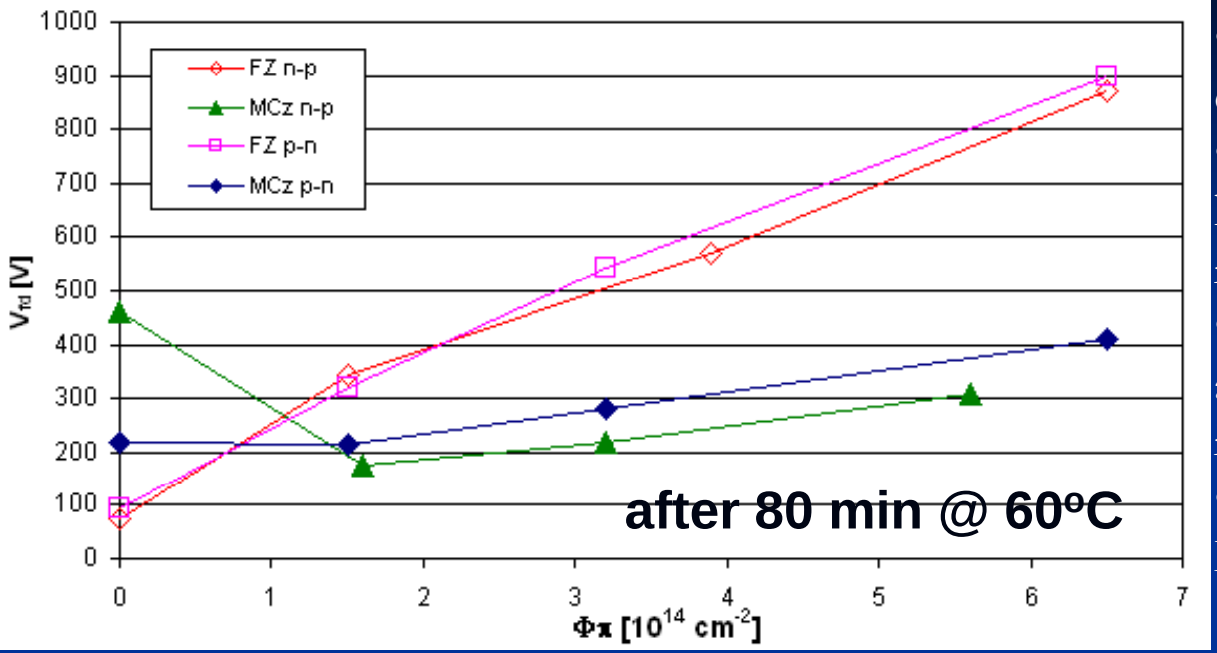


Big difference in the charge collection between MCz n-n and Fz n-p
~14000 e vs. ~8000 e at 500V!

Fully depleted detector – one can see kink in Q-V plot

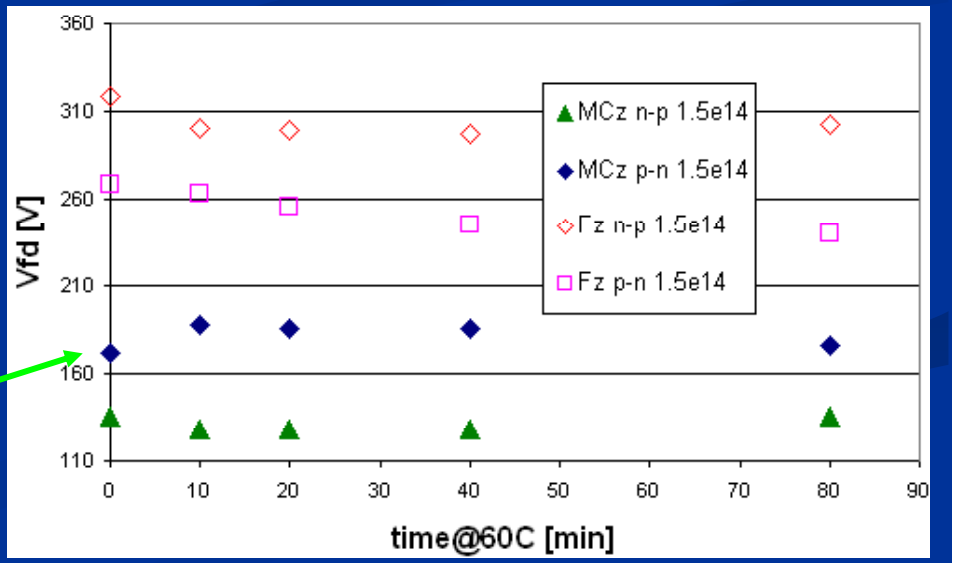
e in CCE is difference in

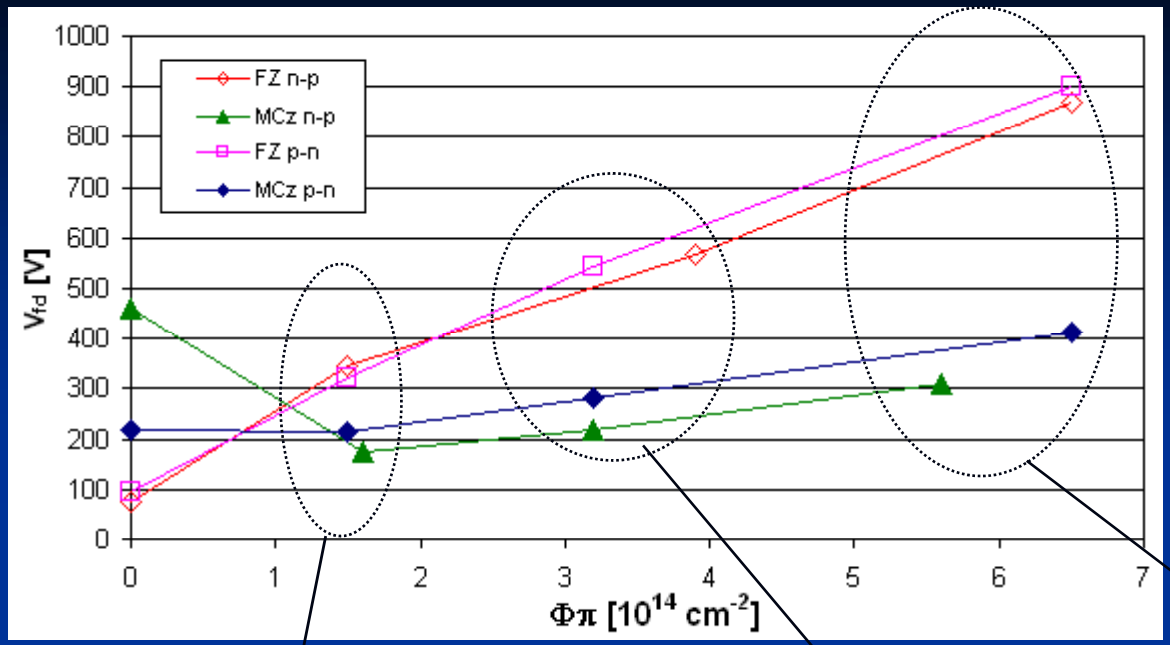
Pion irradiated diodes



- leakage current agrees with expectations
- all detectors but MCz-n seem to be have negative space charge after irradiations.
- a large part of initial annealing has already taken place during irradiations
- What is sign of space charge for MCz?

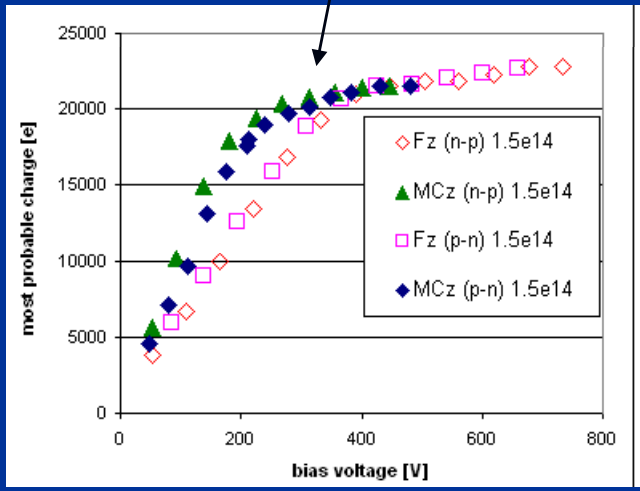
- Slope of V_{fd} increase with fluence
  - ✓ : MCz (p and n type): ~38 V/10^{14} cm^{-2} , $|g_c|$~0.0055 cm^{-2} ,using κ=1.14 (as expected)
  - ✓Fz (p and n type): ~110 V/10^{14} cm^{-2} g_c~0.014 cm^{-2} ,using κ=1.14 (as expected)
- There is a strong "effective acceptor removal" for MCz p type material!
  - It seems that that "effectively positive space charge is introduced for MCz-n
  - V_{fd} of MCz-p is lower than MCz-n!

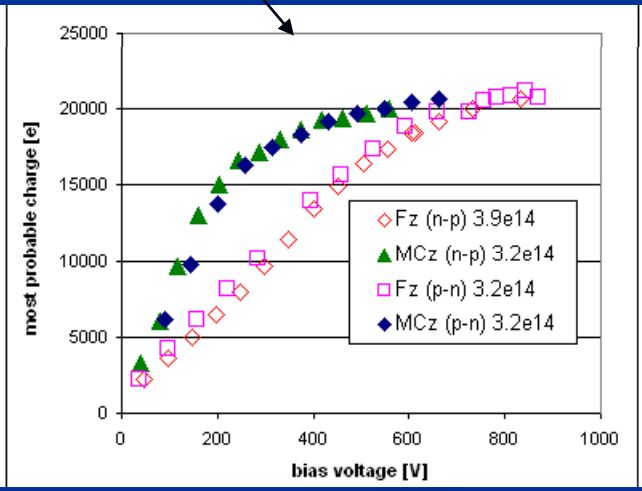


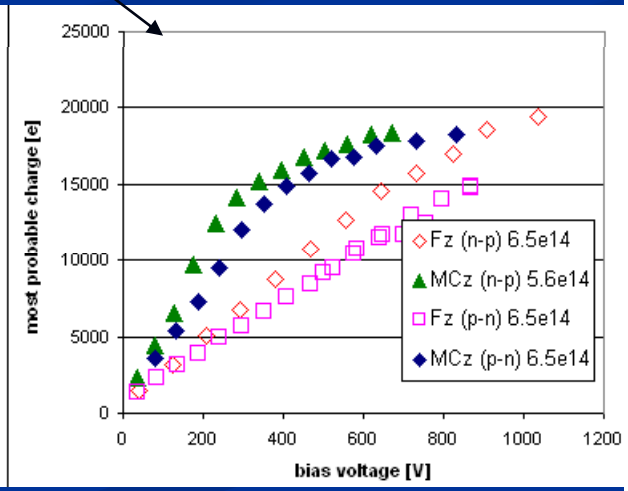


As in the case of neutron irradiated samples:

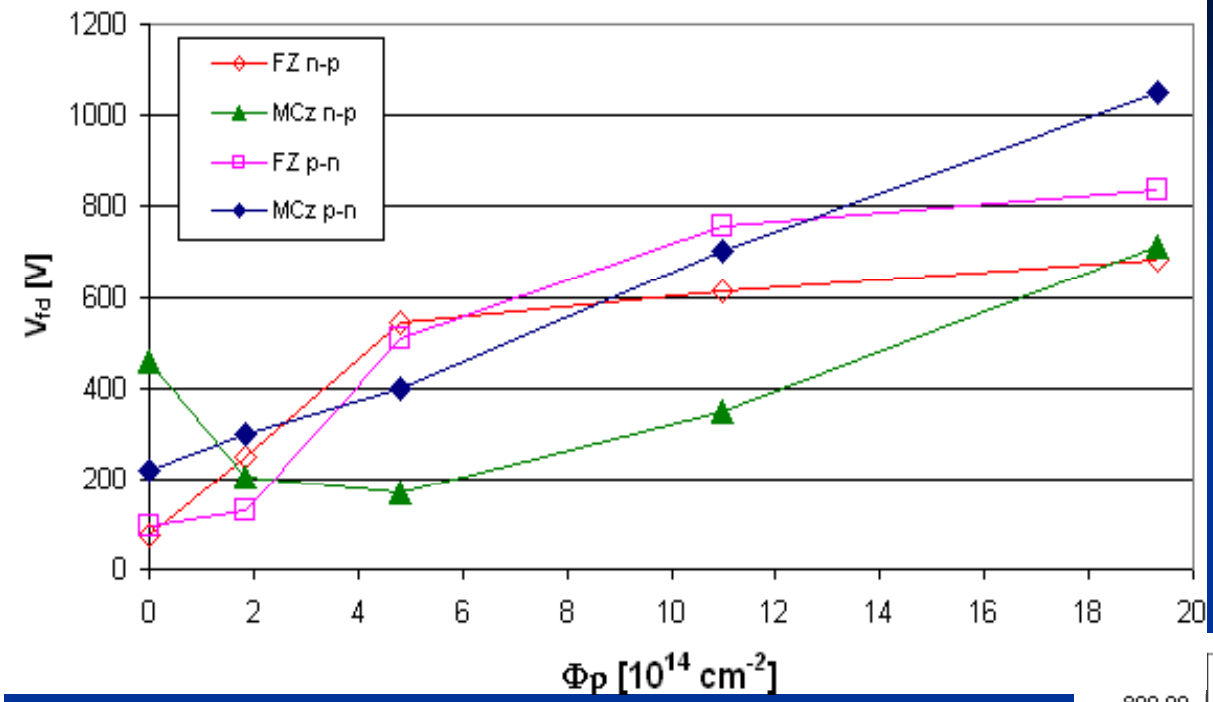
- the difference in V_{fd} can be clearly seen in CCE
- CCE for over-depleted samples is the same for all samples







Proton irradiated diodes



Annealing confirms the observation from pion irradiations; all have negative space charge except MCz-n shows annealing typical for positive space charge!

Leakage currents are as expected $\kappa_p/\kappa_\pi=0.543=0.62/1.14$ agrees perfectly with $\alpha_p/\alpha_\pi=0.553$

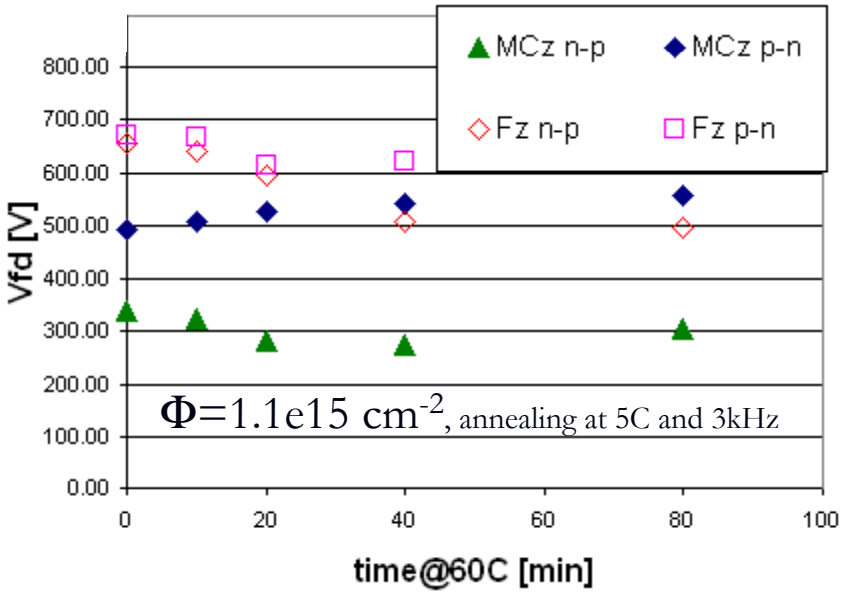
Slope of V_{fd} increase with fluence

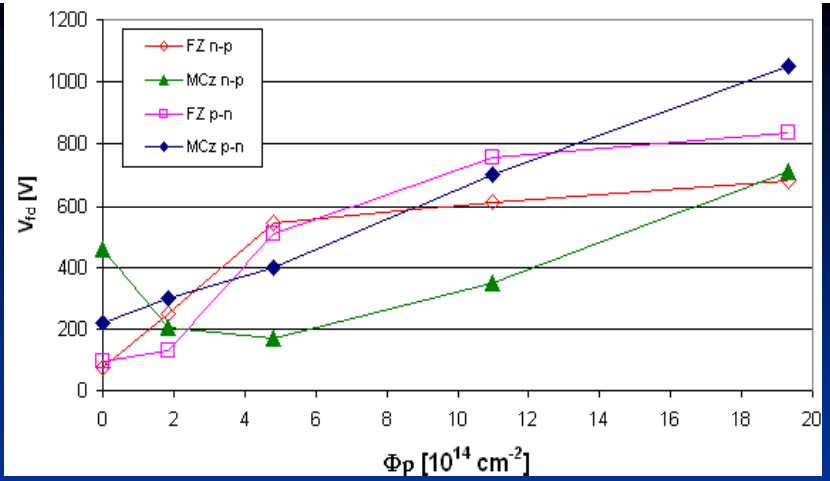
✓MCz (p and n type): 38 V/10^{14} cm^{-2}

$|g_c|$ **~0.007 cm^{-2}** ,using κ=0.62 (as expected)

✓ Fz (p and n type), **<u>at low fluences</u>**: ~150 V/10^{14} cm^{-2}

g_c~0.02 cm^{-2} ,using κ=0.62 (as expected). At higher fluences very low increase of V_{fd} for Fz materials?



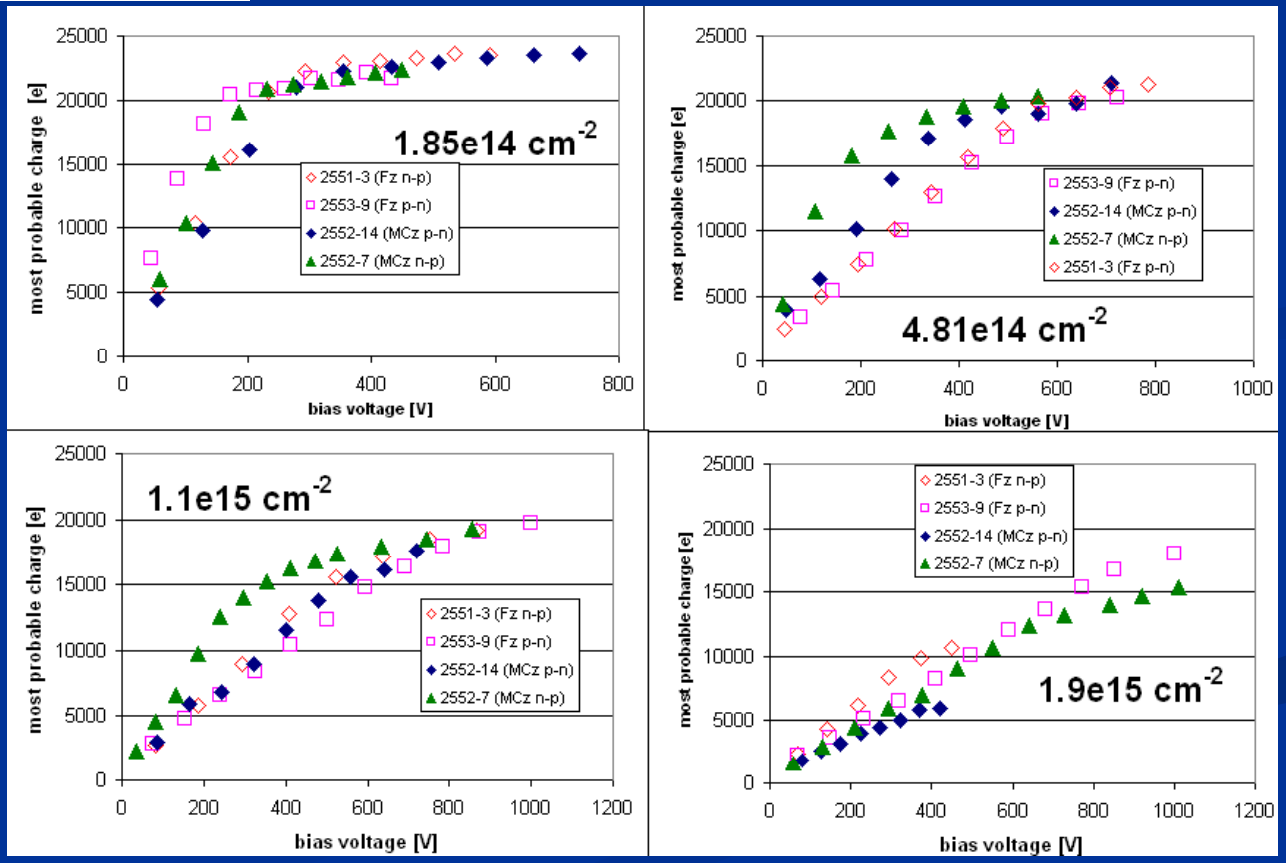


As in the case of neutron and pion irradiated samples:

- the difference in V_{fd} can be clearly seen in CCE
- CCE for over-depleted samples is the same for all samples

For Φ_p=1.93e15 cm^{-2} only two detectors could be over-depleted before the onset of micro discharges.

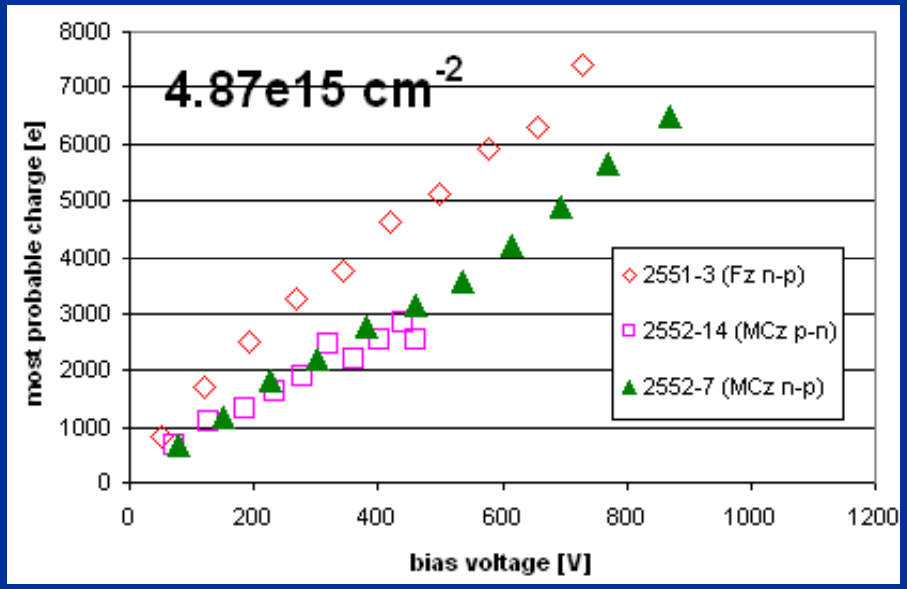
Remember: MCz-n is at the maximum of V_{fd} – for positive space charge the reverse annealing "should" be beneficial.

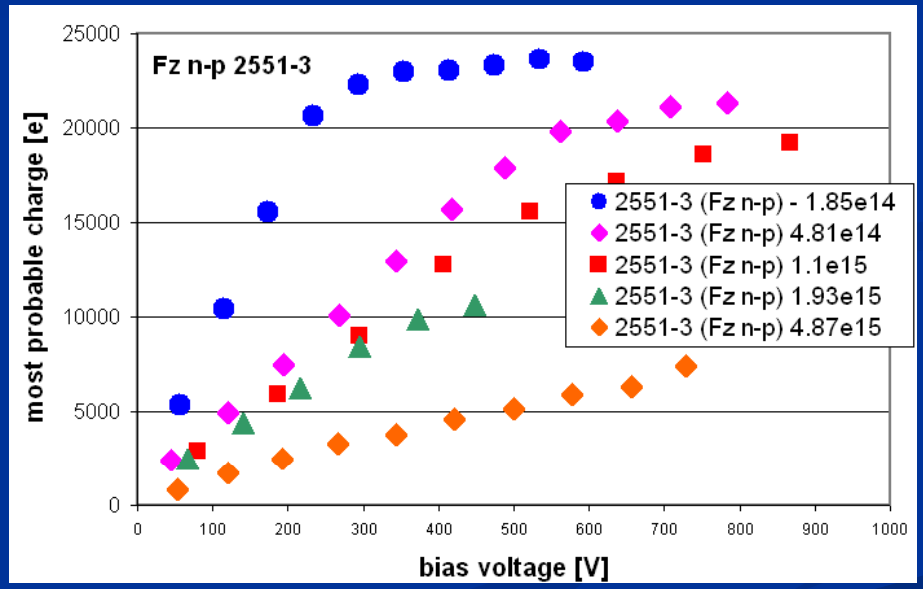


The Fz n-p performs best of all at the highest fluence. Around 5100 e at 500V, which should be considerably more for SSD!

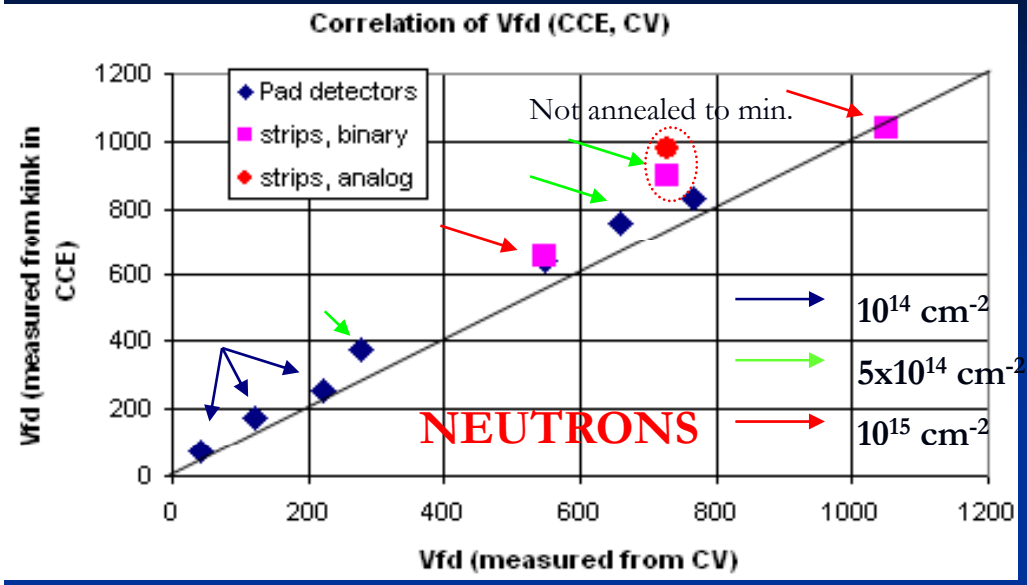
The estimated V_{fd} from the slope of the Q-V plot and assuming "saturated" charge of 16000e would give V_{fd} of around 1500V (far less than for "normal" Fz)

It seems "double peak" becomes visible at high fluences!



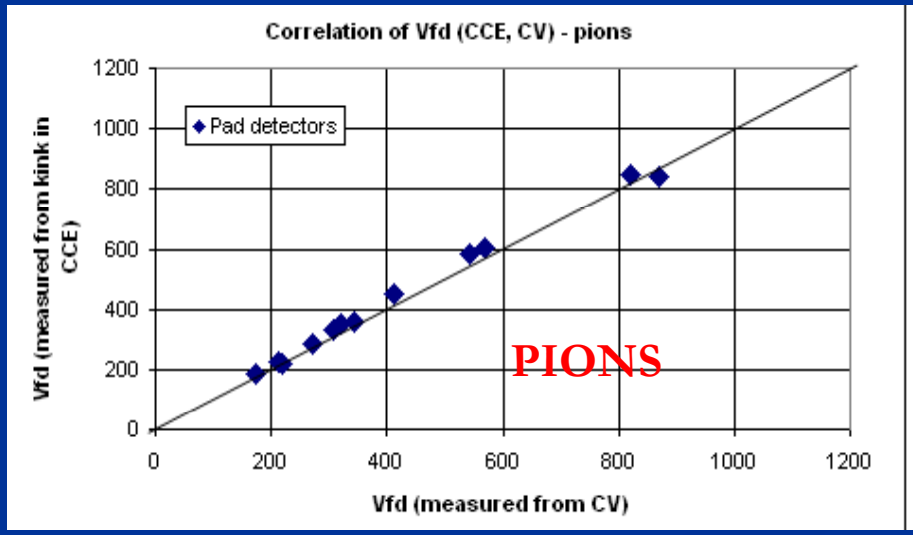


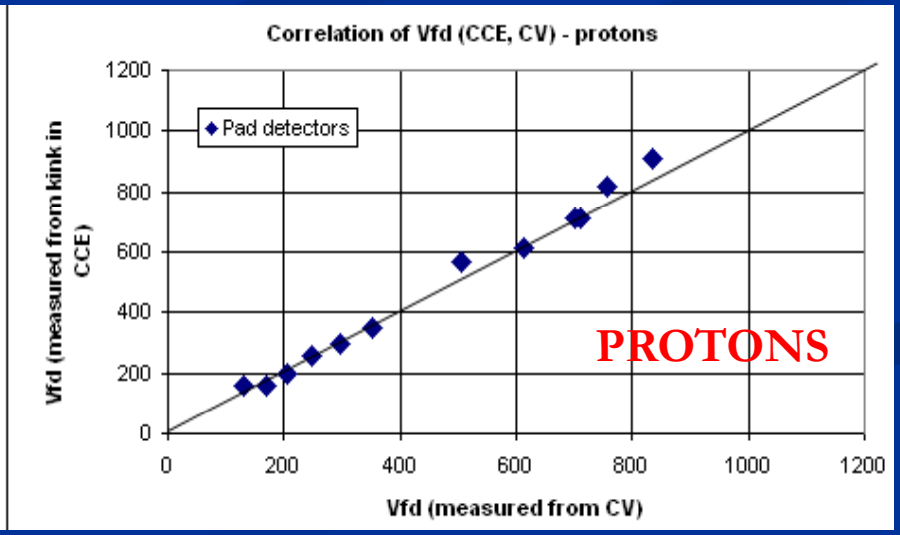
V_{fd} from C-V vs. V_{fd} from Q-V (pads, strips)



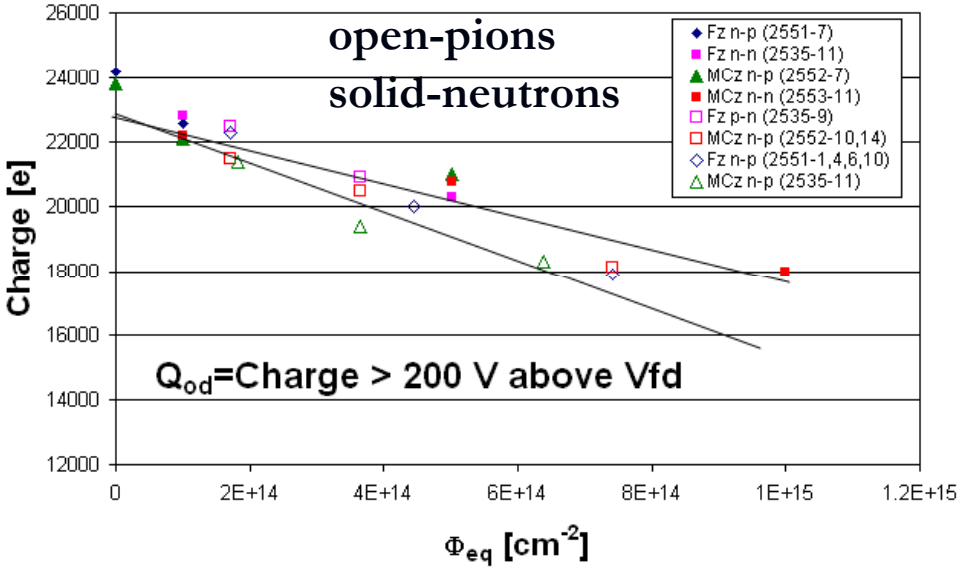
V_{fd} from C-V is determined for pad detectors (80min @ 60°C – end of beneficial annealing)

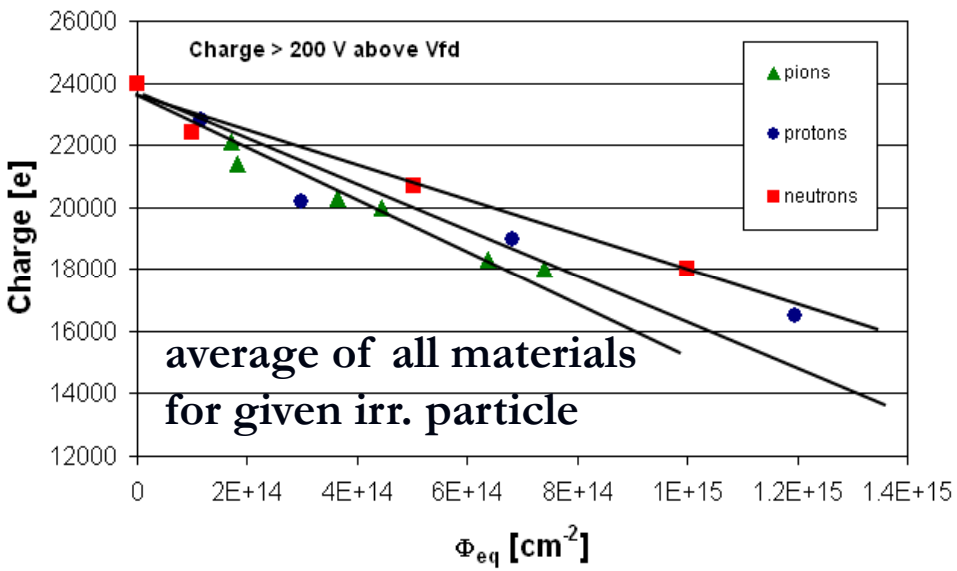
- V_{fd} from CV underestimates the onset of saturation in CCE by max. 100-150 V
- It seems that correlation is even better for protons and pions (electric field?)
- after V_{fd} the collected charge continues to increase due to shorter drift





Charge collection efficiency (CCE)





At the same equivalent fluence, charge hadrons seem to be more damaging

thus confirming the $\tau_{au,eff}$ measurements:

$dQ_{od}/d\Phi_{eq}$~600 e/1e14 cm^{-2} for neutrons

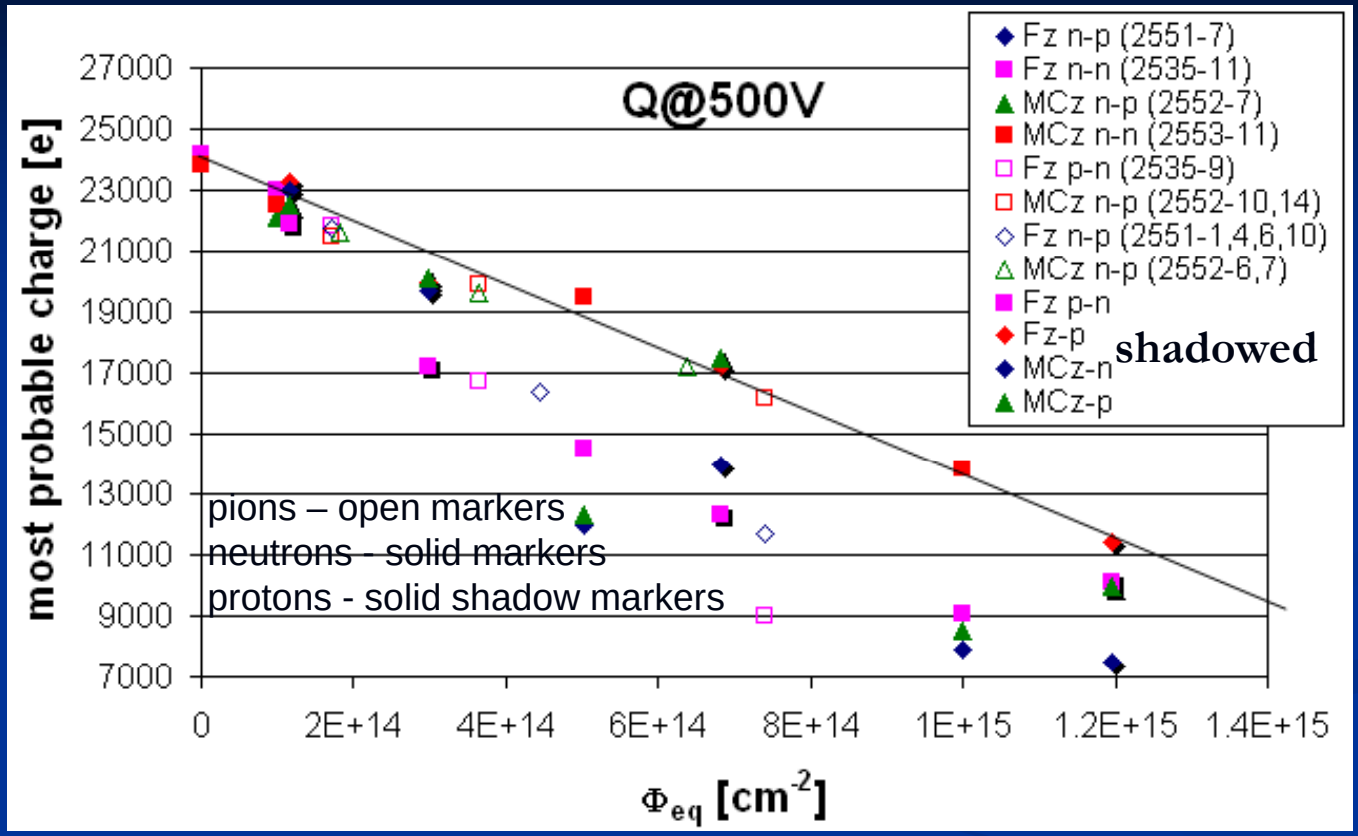
$dQ_{od}/d\Phi_{eq}$~850 e/1e14 cm^{-2} for pions

$dQ_{od}/d\Phi_{eq}$~800 e/1e14 cm^{-2} for protons

The measured trapping probabilities from TCT are around 40% too large to give the agreement with measured charge!

There is no dependence of Q_{od} on material!

The over depletion is more important at lower V_{fd} and less at high V_{fd} as the <E> is already very high and drift velocities close to saturated in large part of the detector

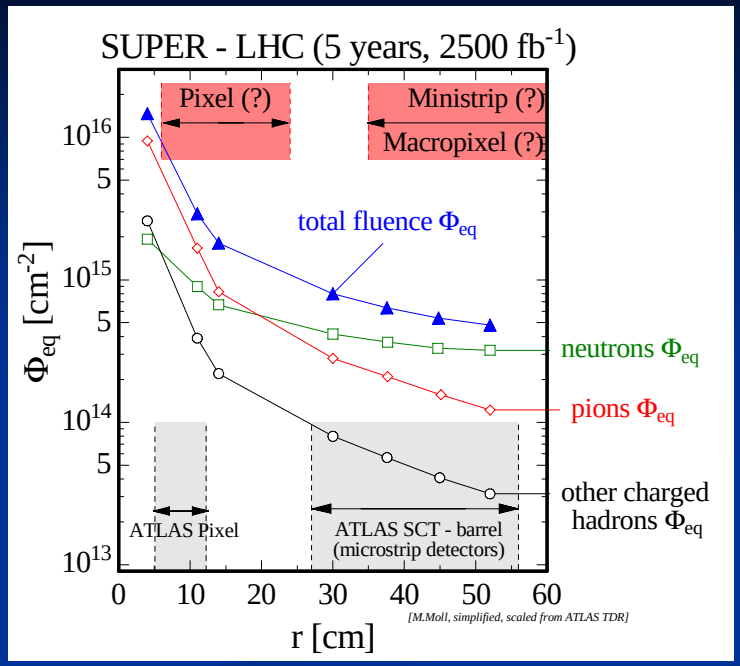


Except the Fz-p (irradiated with protons) all diodes lying on the "ideal line" are MCz. With SSD you should get more…

Mixed irradiations (I) - preliminary

The detectors at experiments will be exposed to both charged hadrons and neutrons!

- Are damages additive, both for I and V_{fd}?
- Do we see V_{fd} of MCz-n detectors go down after neutron irradiations (indication of positive space charge sign)?



The following detectors were exposed to additional $2 \cdot 10^{14}$ cm^{-2} neutrons:

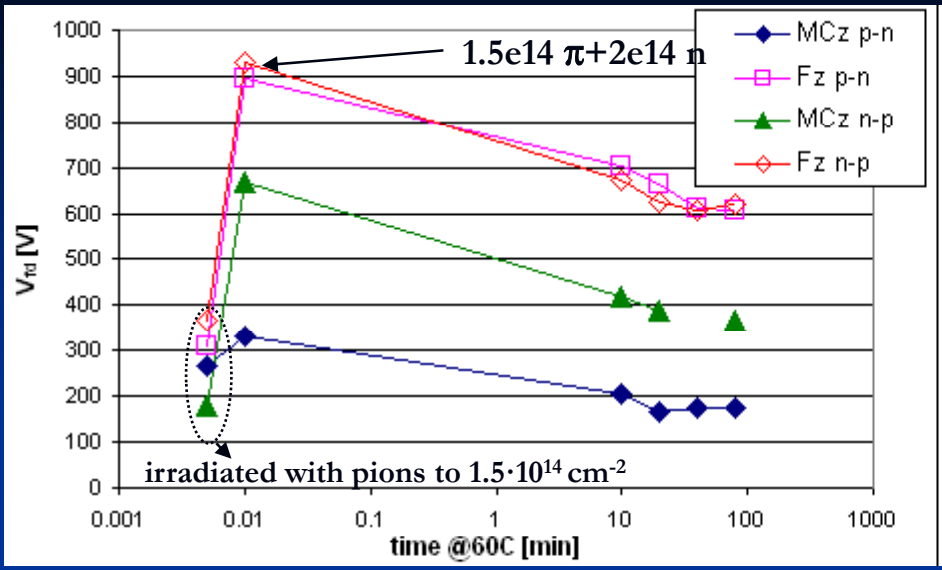
- Fz n-p: 1.85, 4.81 p; 1.5 π [10^{14} cm^{-2}]
- Fz p-n: 1.85,4.81 p; 1.5 π [10^{14} cm^{-2}]
- MCz n-p: 1.85, 4.81,11 p; 1.5 p [10^{14} cm^{-2}]
- MCz p-n: 1.85, 4.81,11 p; 1.5 p [10^{14} cm^{-2}]

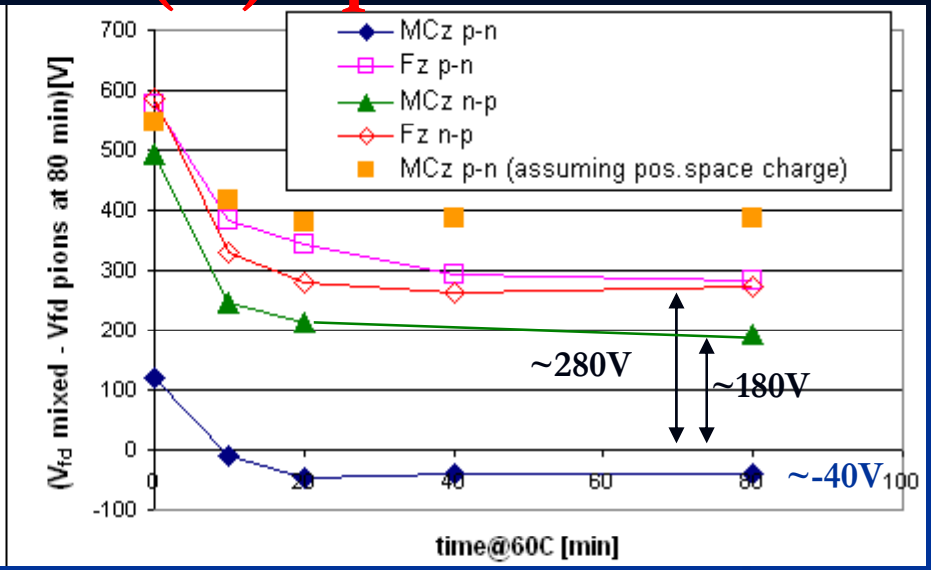
Each of these detectors has a counterpart without neutrons!

Proton irradiated detectors were annealed prior to neutron irradiations for 10 min@60°C.

Unfortunately we couldn't do CCE due to bonding machine problems last week!!

Mixed irradiations (II) - pions





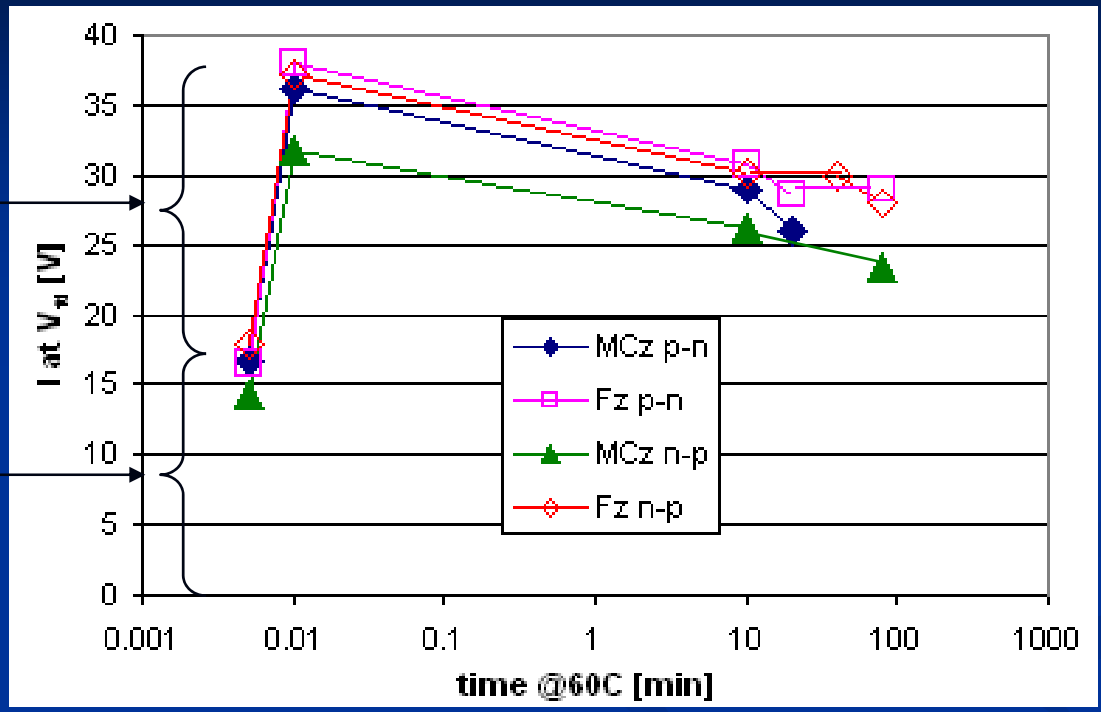
Observations from annealing plots:

- short term annealing indicate negative space charge for all (reduction of acceptors)
- initial jump in ΔV_{fd}~550 V is similar for Fz and MCz-p, almost no increase of V_{fd} for MCz-n!
- large introduction rates of short term annealing can be of short irradiation and immediate storage at low T
- the difference $V_{fd,mixed}$-$V_{fd,pions}$ corresponds to expectations **(additive damage)**
  - ~180 V for MCz-p (expected: 110 V = 2 x 55 V)
  - ~280 V for Fz (expected: 250 V=2 x 125 V)
  - **negative difference for MCz-n can be explained by the SCSI from positive after pion irradiation to negative due to additional neutron irradiation (orange squares)!**
  - V_{fd} at equivalent fluence of ~4e14 cm^{-2} < 200 V!

Mixed irradiations (III) - pions

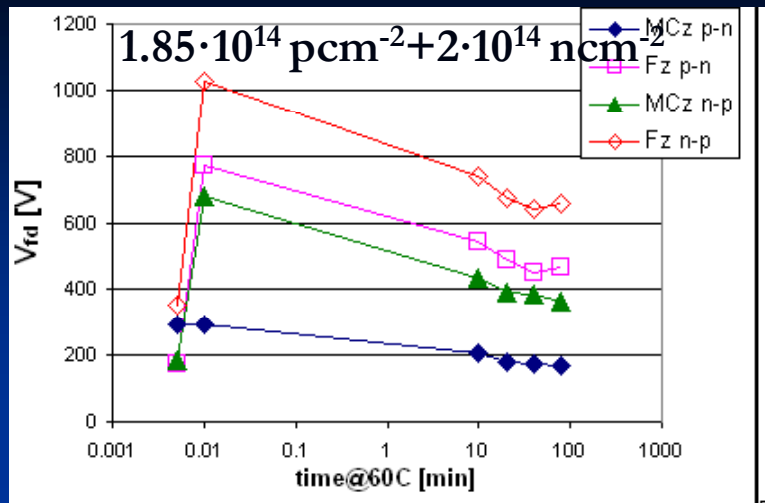
after neutrons

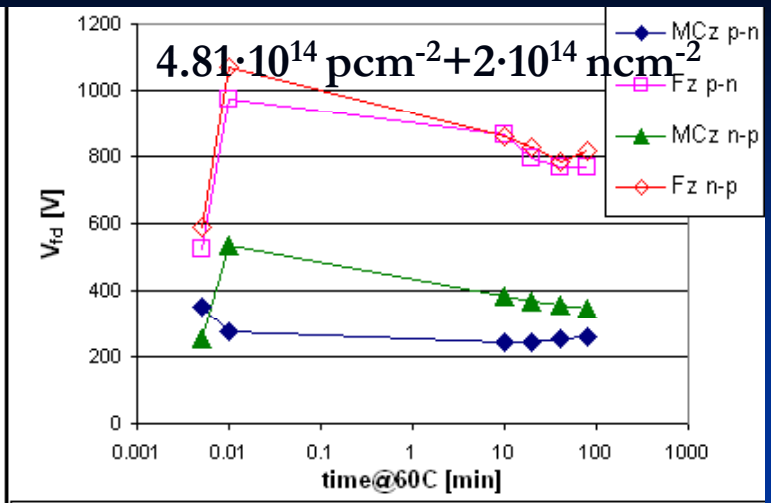
after pions

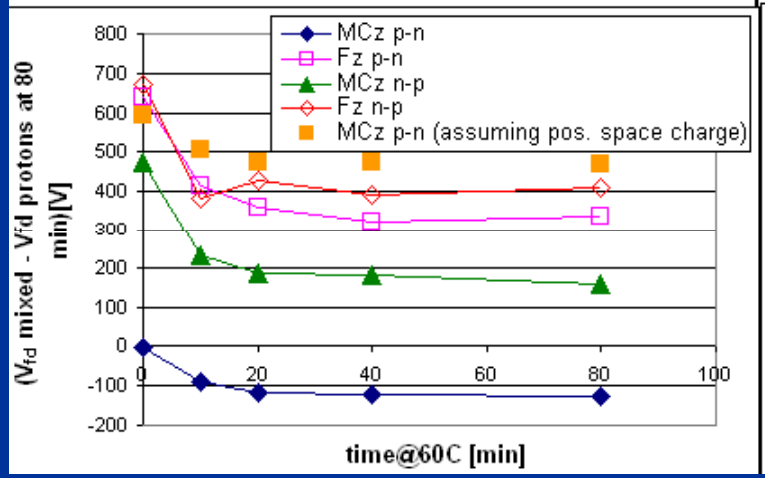


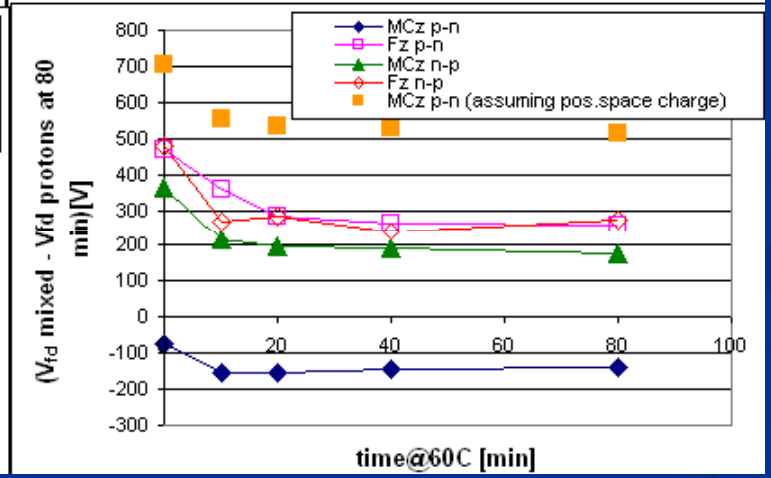
The current increase after neutron irradiation is the same for all!
The contribution from the pion and neutron irradiation are additive.
Annealing is the same as for single particle irradiation.

Mixed irradiations (IV) - protons







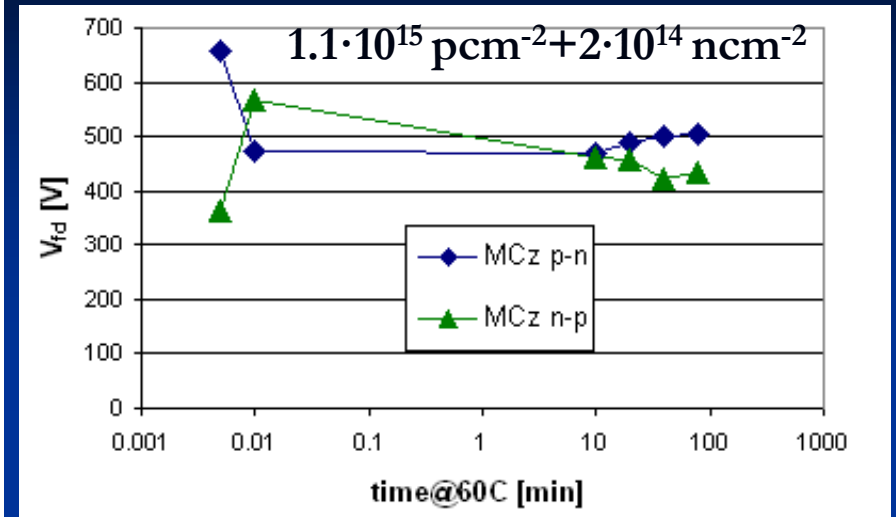


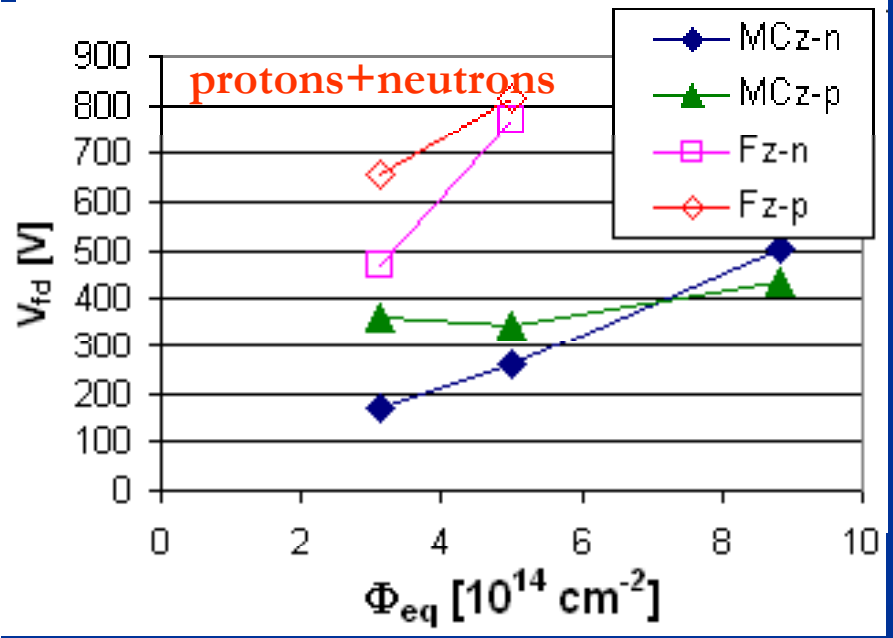
As for pions there are no surprises in leakage current- it is additive!

Similar observations are valid as for pion+neutron irradiated samples:

- After adding neutrons the Vfd decreases for MCz-n substantially
- MCz-p has a smaller initial rise after n irradiations than Fz materials for high fluence irradiation
- the difference $V_{fd,mixed}$-$V_{fd,protons}$ corresponds to expectations for MCz-p and Fz,
- For MCz-n the difference could be due to **change in the space charge sign**.

Mixed irradiations (V) - protons





It is clear that:

•MCz-n -> positive space charge (N_{eff} before neutron irradiation is large enough not to be overcompensated). The V_{fd} is reduced by ~200 V after additional neutron irradiation.

•MCz-p -> neagative space charge, but increase of V_{fd} after additional neutrons is just 80V !

After almost Φ_{eq}=1e15 cm^{-2} the V_{fd} of MCz detectors is around 500V. Even if initial resisitivity of MCz-p is low the "acceptor removal" will help to get the V_{fd} down.

For MCz-p the Vfd is lower than the initial V_{fd} of 460 V!

Conclusions

- On V_{fd} :
  - Vfd from CV and CCE are highly correlated
  - gc sadas
  - "effective acceptor removal" is very strong for MCz-p
- On CCE:
  - charged hadrons are more damaging than neutrons at the same equivalent fluence (in accordance with τ_{eff} measurements around 30-40%)
  - the CCE values point to ~40% longer trapping times than measured
  - there is no difference between different materials!
  - at 500 V the we can expect 18ke for 5e14 cm^{-2} and 13ke for 1e15 cm^{-2}
- On mixed irradiations:
  - the damage for Fz is additive in V_{fd}, MCz-p and leakage current! The additional neutron irradiation increases the V_{fd} (negative space charge)
  - for MCz-n charged hadrons introduce positive space charge. The V_{fd} after beneficial annealing is lower than for charged hadron only irradiated detector.
  - after Φ_{eq}=9e14 cm^{-2} (22% neutrons, 78% charged hadrons) the V_{fd} for MCz material is below 500V. It will interesting to see is also in CCE…

Leakage currents and hardness factor