Reasons for gain degradation with irradiation in LGADs

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Motivation

The key question is: What is the main reason for reduction of effective acceptors and by that of the gain in LGAD?

Options are:

- Introduction of deep traps which occupation probabilities are enhanced by larger hole concentration due to multiplication. These compensate the negative space charge of shallow acceptors.

  TCAD simulations based on “effective levels” predict the decrease of gain – moderation of the field by trapped holes

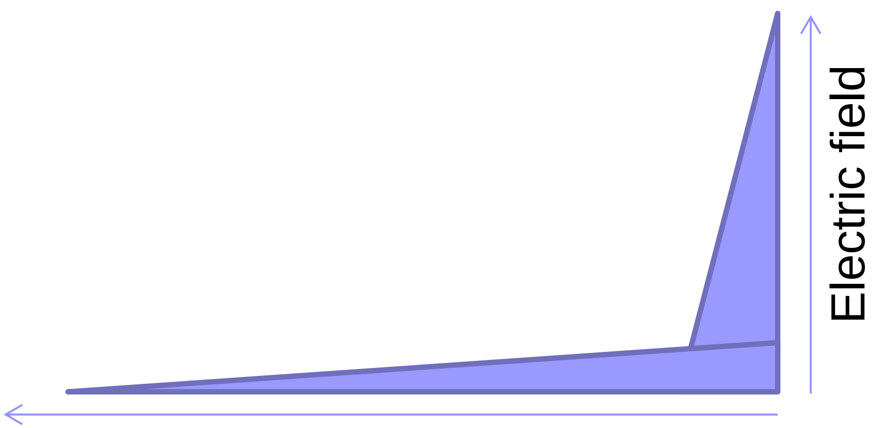
  - see F. Rogelio talk at 11th TRENTO workshop in Paris
  - see Ranjit talk at 2014 RD50 workshop at CERN

- Removal of initial acceptors (boron) from the p+ layer
  - TCT measurements of the “leg”
  - sharp drop/exponential of gain already at moderate fluences
  - HVCMOS measurements

Note: larger relative trapping effects in LGAD – holes need to drift over the entire depth (not only half on average), hence their trapping probability is larger.

Possible scenarios for gain reduction

Before irradiation → **After irradiation**

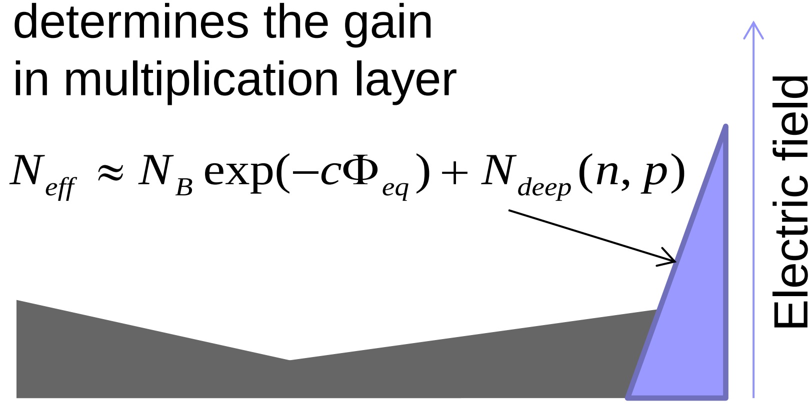


thickness (not to scale)

The voltage drop in the amplification layer is around V_{mr}=30 V ("foot"). The gain doesn't increase exponentially with voltage as after the depletion 300 V is required to increase E by 1V/um in the multiplication layer for 300 um thick sensor.

Effective dopant concentration determines the gain in multiplication layer

$$N_{eff} \approx N_B \exp(-c\Phi_{eq}) + N_{deep}(n,p)$$



The gain at very high voltages (V_{bias}>>V_{fd}) is reduced due to: initial acceptor (boron) removal or/and but also due to space charge from deep traps:

- Boron insensitive to concentration of free carriers in the bulk!
- **Deep traps sensitive to free hole and electron concentrations !**

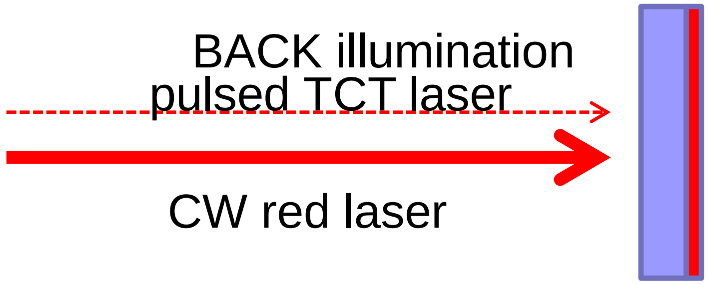
How to change free carrier concentrations?

1) The temperature variation of TCT signal, but the exponential term in occupation probability P_t (de-trapping) term changes at the same time as also free carrier concentration (generation current) – hard to analyse and see the difference (also ligth absorption is a function of T)

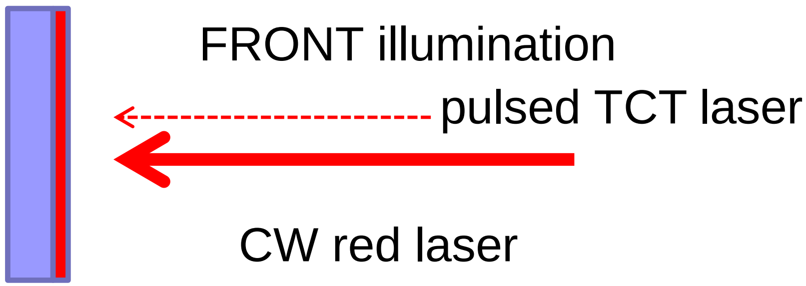
2) **Keep the detector at given temperature and vary the concentration of free carriers by continuous injection by DC light (CW laser) and probing the gain with TCT**

$$P_t = \left[\frac{c_p p + c_n n_i \exp(\frac{E_t - E_i}{k_B T})}{c_n n + c_p n_i \exp(\frac{E_i - E_t}{k_B T})} + 1 \right]^{-1} \quad , \quad N_{deep} = \sum_{donors} N_t (1 - P_t) - \sum_{acceptrors} N_t P_t$$

<u>ELECTRON INJECTION</u>

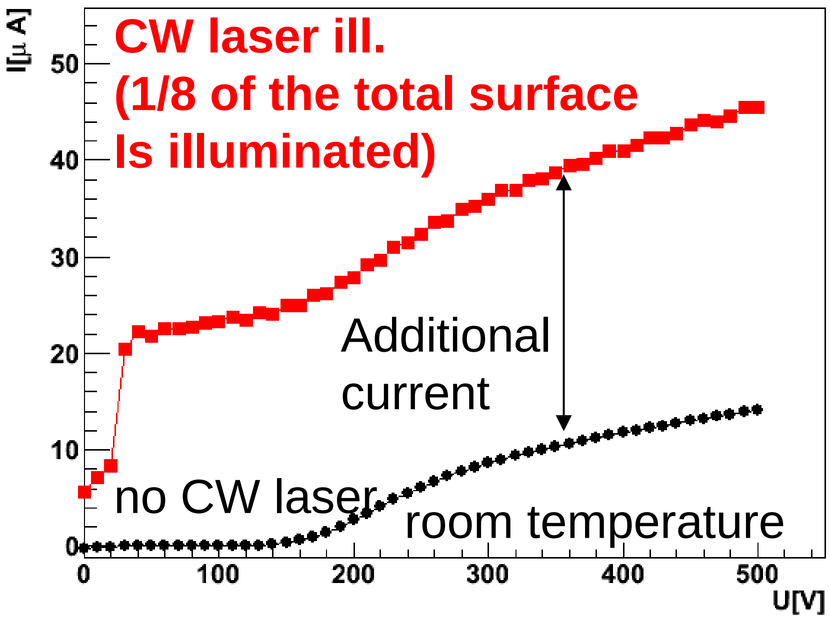


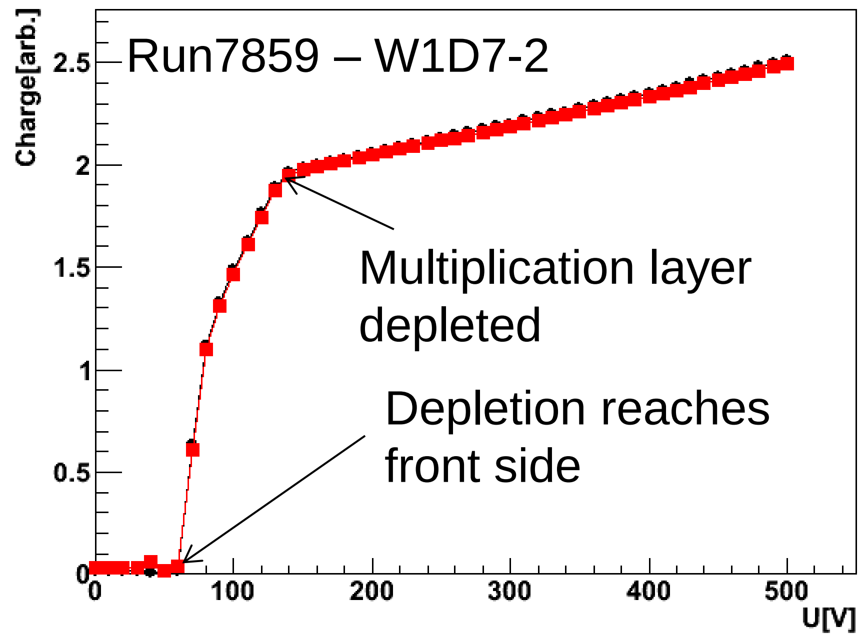
<u>HOLE INJECTION</u>

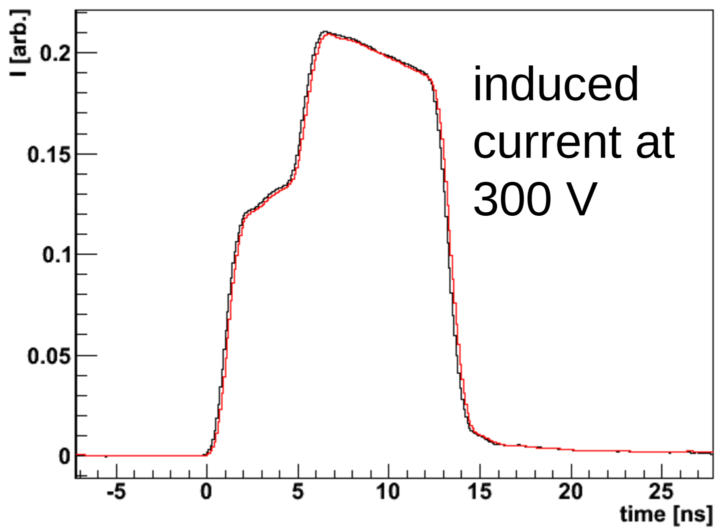


Non-irradiated detector (LGAD run 7859)

Back illumination (electron injection)





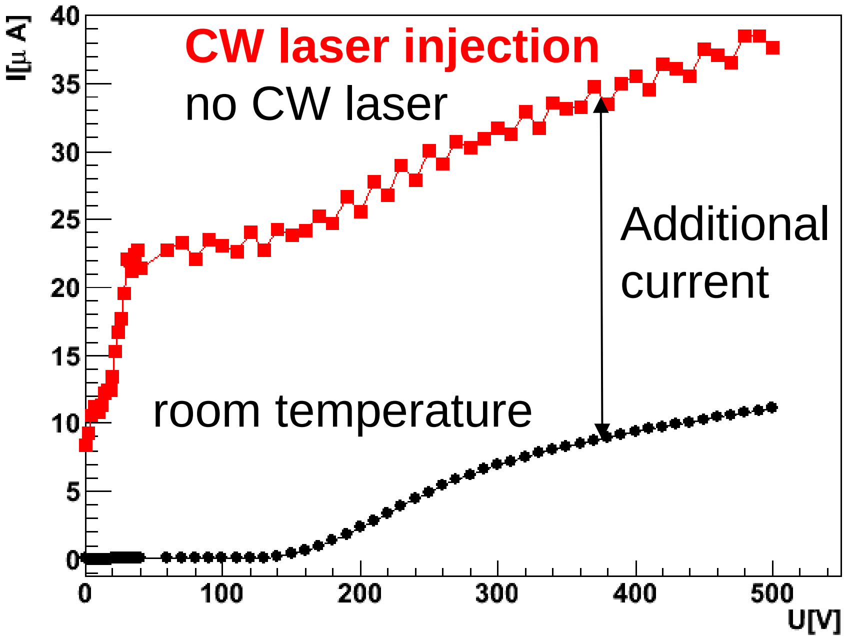


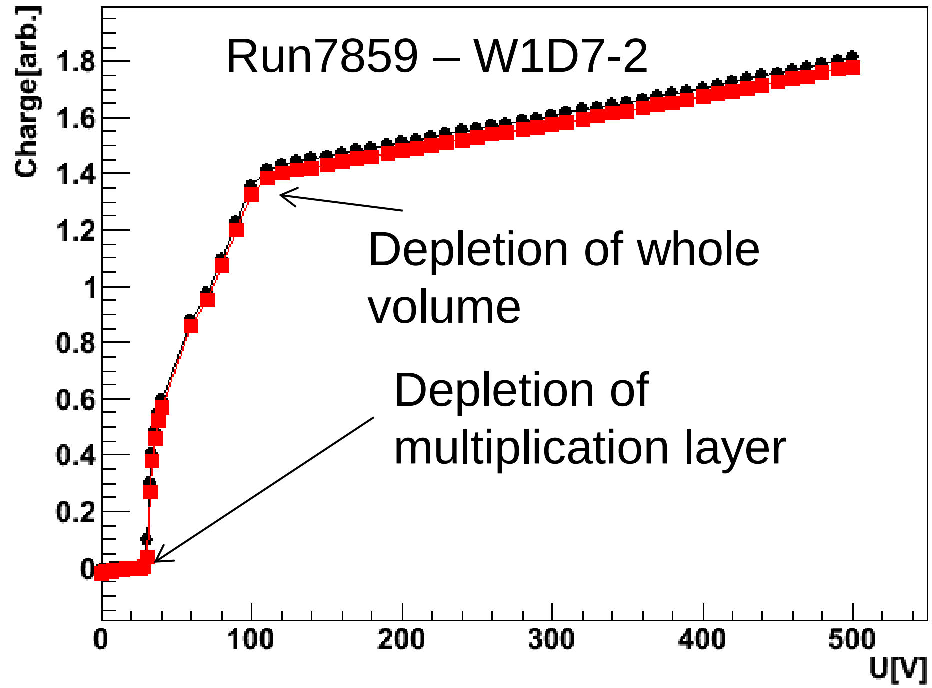
<u>**No change**</u> in both collected charge and electric field (deduced from the induced current shape) after large injection of electrons by DC light illumination!

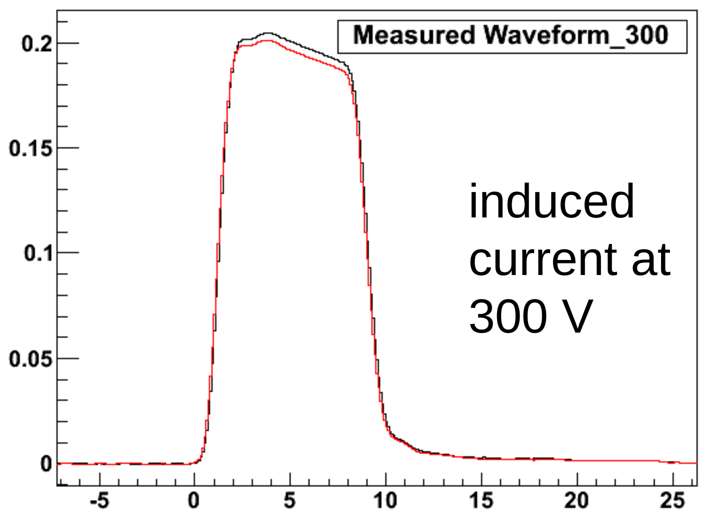
No deep ELECTRON traps present before irradiation!

Non-irradiated detector (LGAD run 7859)

Front illumination (hole injection)







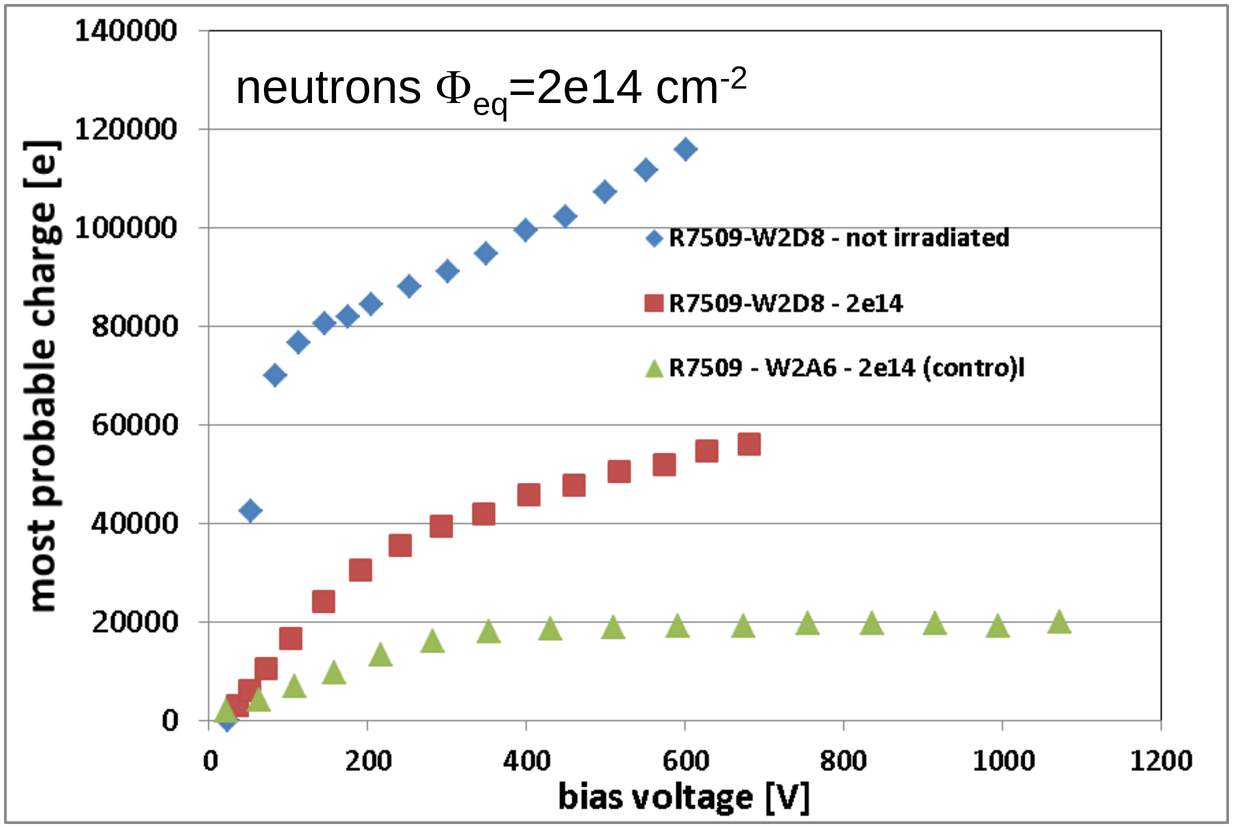
No change in both collected charge and electric field (induced current shape) after large injection of electrons by DC light illumination!

No deep HOLE traps present before irradiation!

Irradiated detectors

Requirements for good probing:

- fluence small enough to see a clear contribution from holes in TCT signal
- still a sizeable difference in gain to a non-irradiated detector
- measured also with ^{90}Sr to estimate the absolute charge



Investigated:

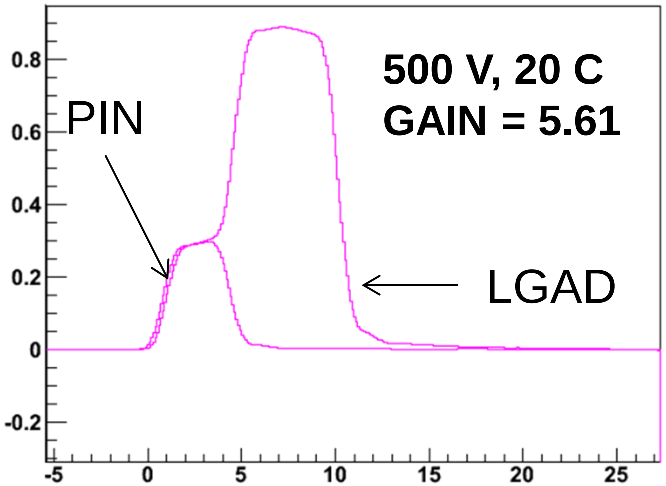
Run7509 – neutrons

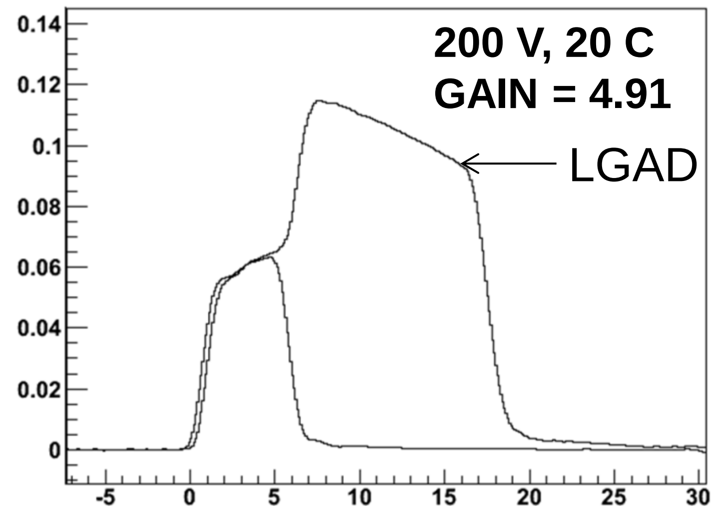
Run6474 – pions (not shown here)

$$G = \frac{Q_{LGAD}}{Q_{PIN}}$$

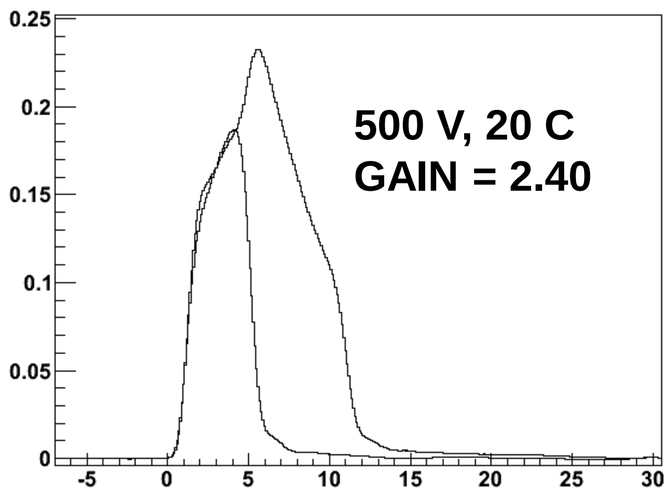
TCT – back illumination and loss of gain

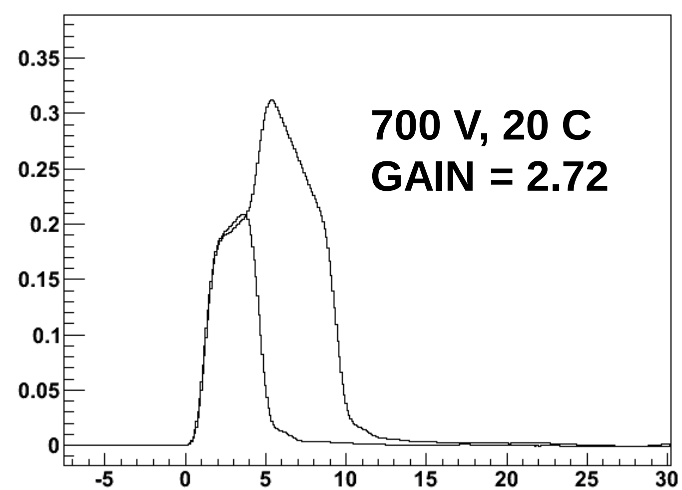
Non-irradiated PIN and LGAD induced currents





Irradiated (2e14 cm^{-2}) PIN and LGAD induced currents

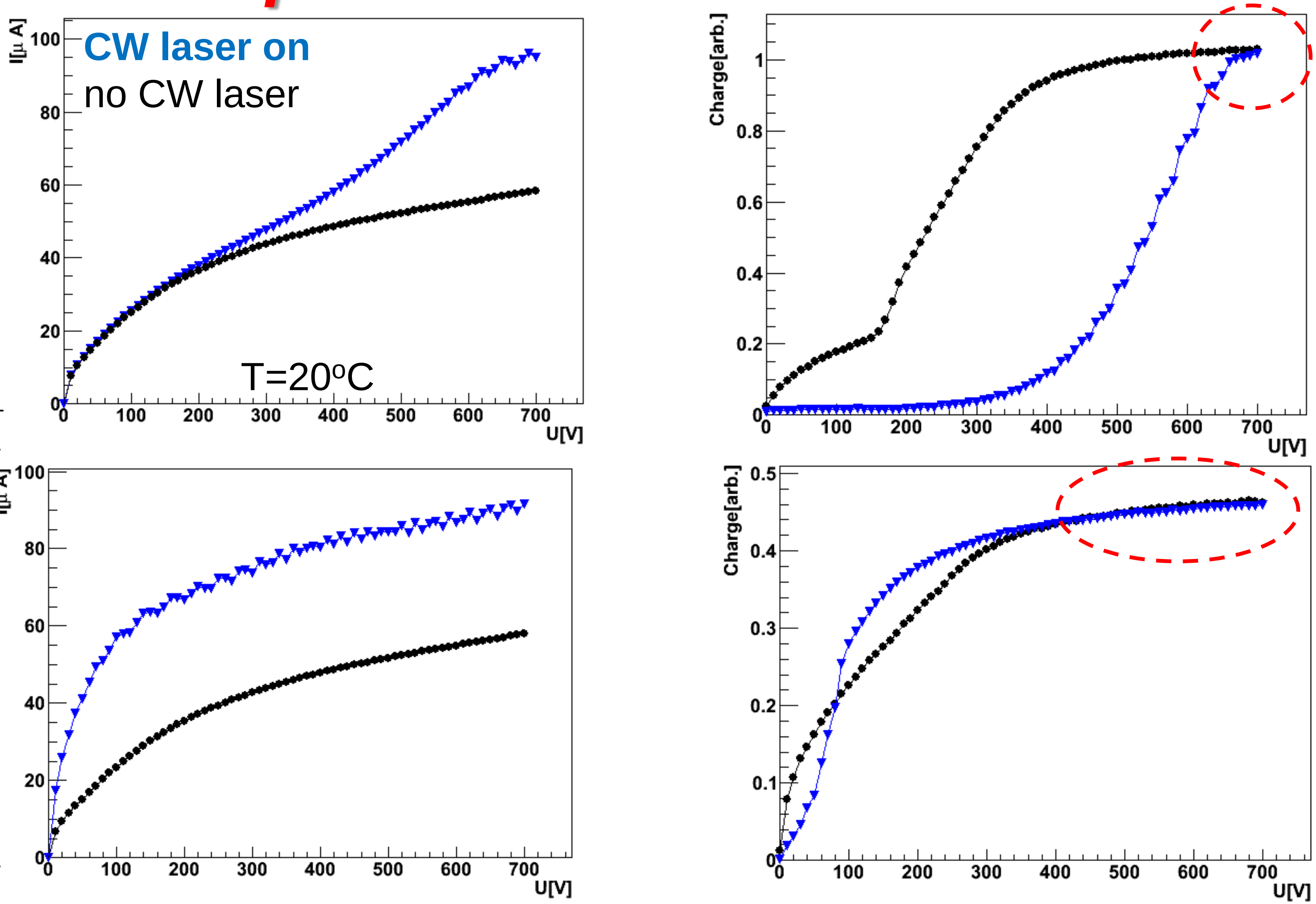




Control sample irradiated to 2e14 cm^{-2}

Electron injection (back illumination)

Hole injection (front illumination)

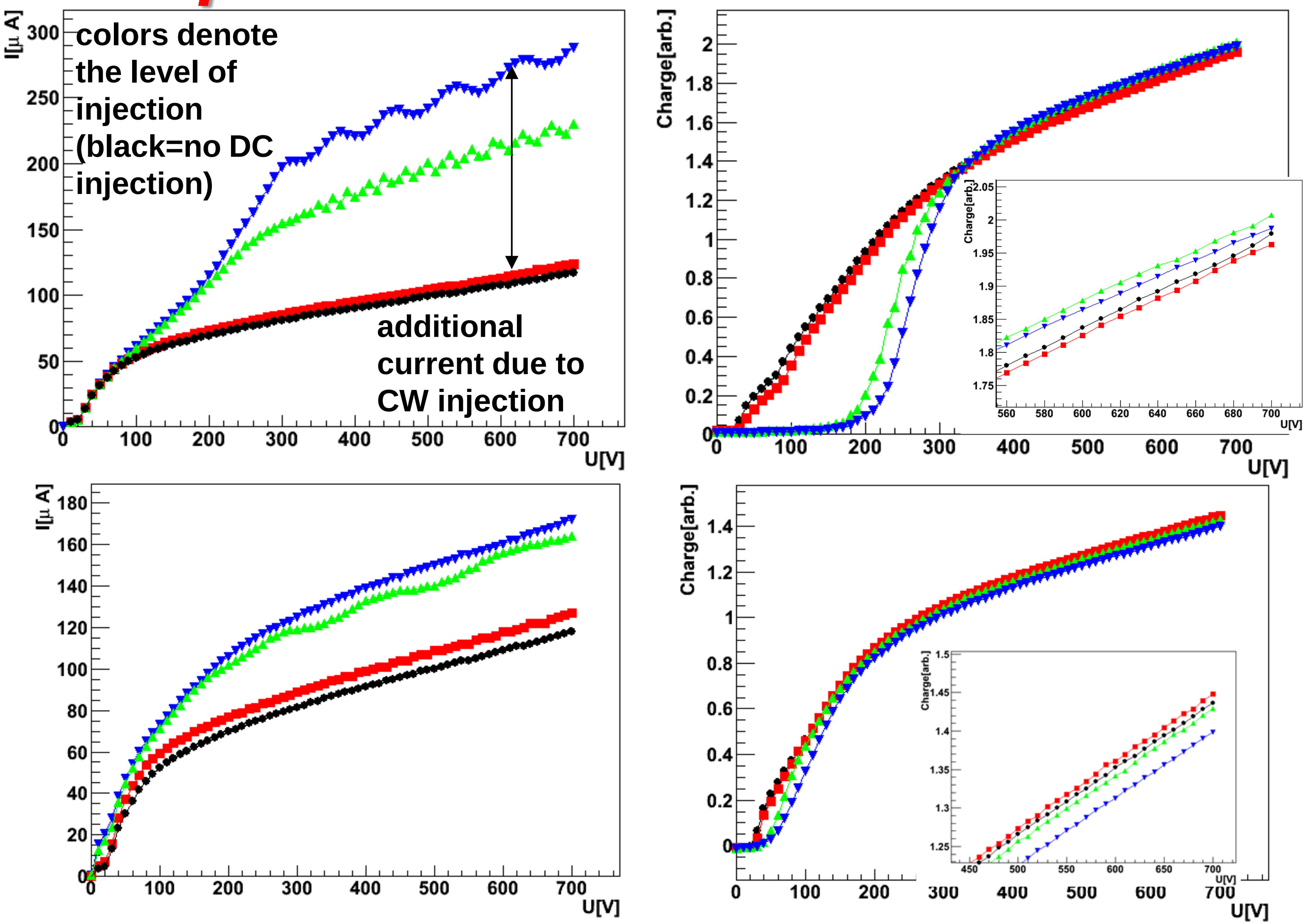


Electric field changes, but not the charge at high V_{bias}!

LGAD sample irradiated to 2e14 cm^{-2}

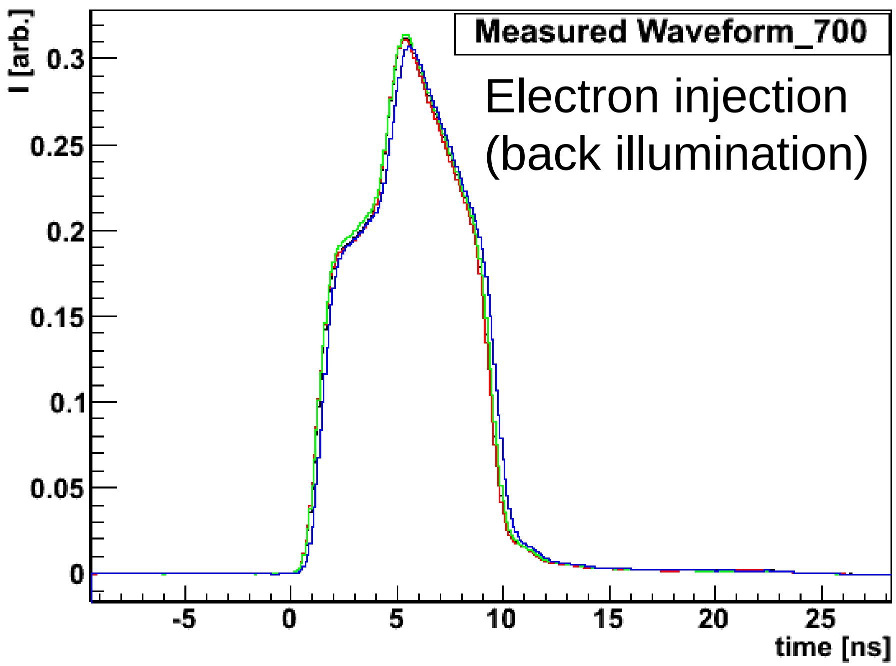
Electron injection (back illumination)

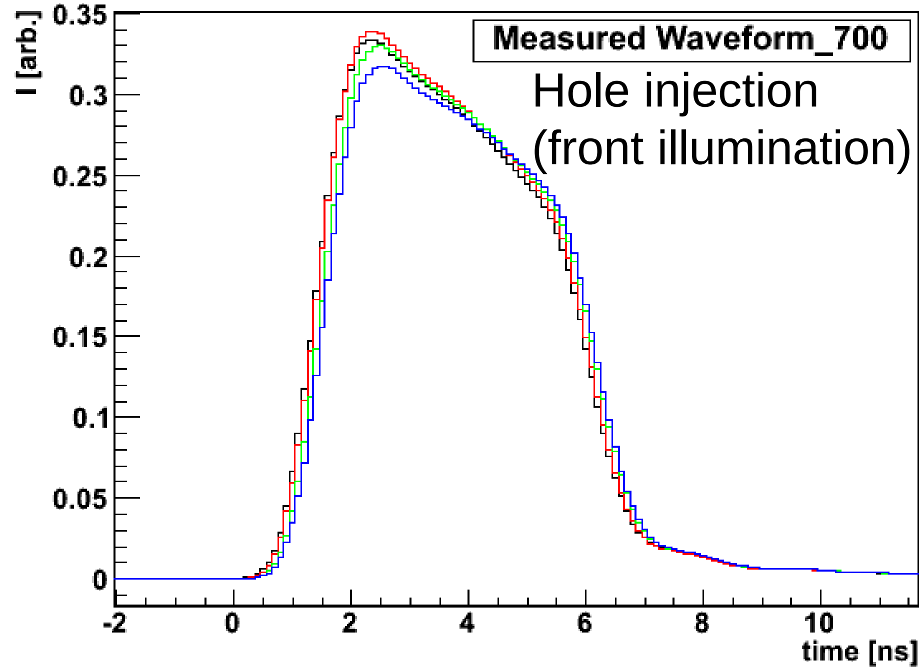
Hole injection (front illumination)



- **Once the sensor is depleted -> gain reflects the difference in** $N_{deep}(p,n)+N_B$ **.**
- **At high bias voltages the charge changes with light intensity by max few percent.**

TCT – induced currents for LGAD (2e14 cm^{-2})



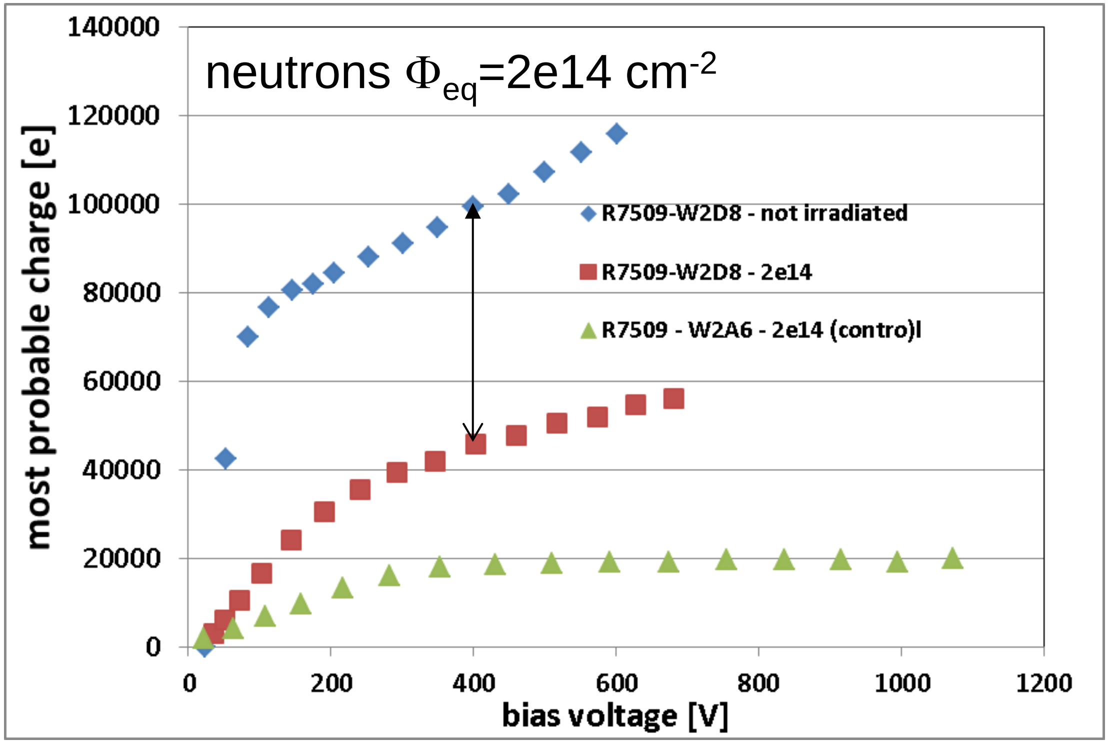


- No difference in induced current pulse shapes at high bias voltages for different DC illumination levels for electron injection
- Small difference in induced current for hole injection at the highest intensity – trapped holes moderate the bulk, but have little effect on doping concentration of p$^+$ layer
- Similar conclusions for pion irradiated samples (not shown)

How does that compute?

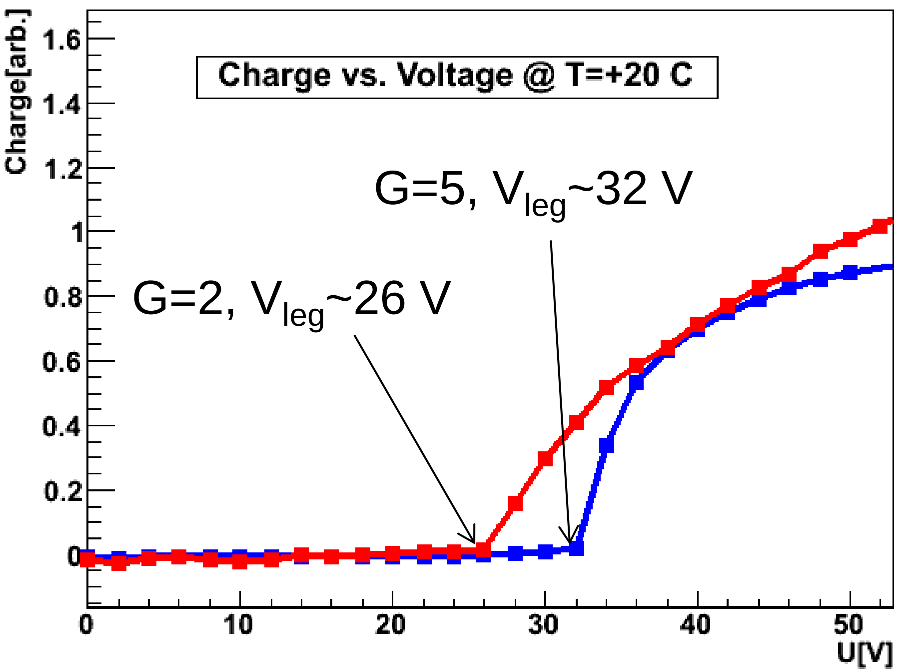
- The contribution of multiplied charge (holes) decreases therefore from around 80000 e to around 26000 e (see below)
- Estimated trapping time of holes is around 10 ns which at duration of current pulse of 5 ns gives a deficit of <15%
- The variation of n,p concentrations in large range makes a difference of of gain max 5%

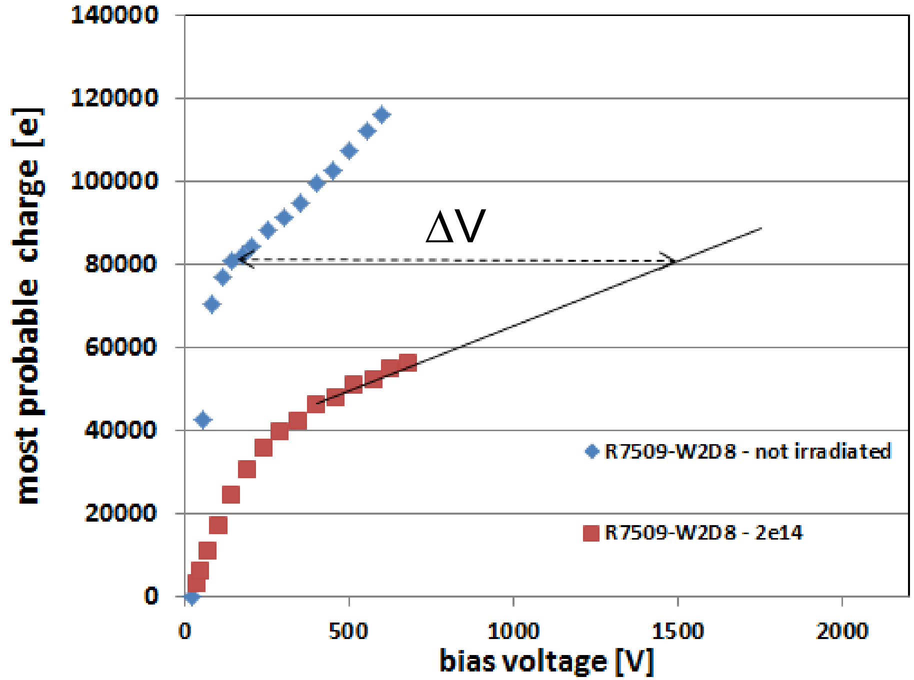
Reduction of signal by ~55%
reduction of gain of holes ~ 70%



The difference of gain can not be explained by deep traps moderating the field or trapping only. Removal of initial boron is required!

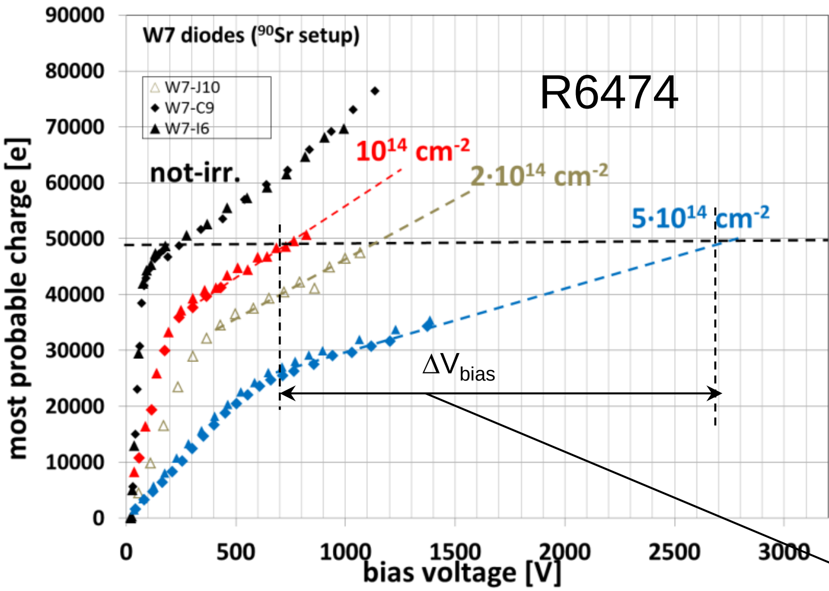
How does the "leg" shift correlate with gain?



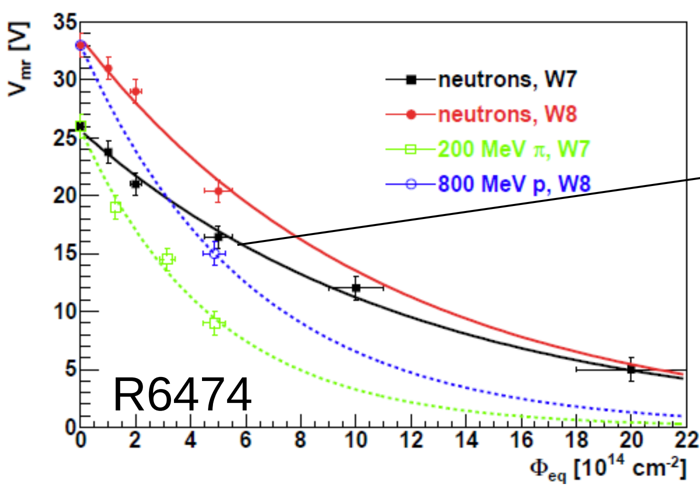


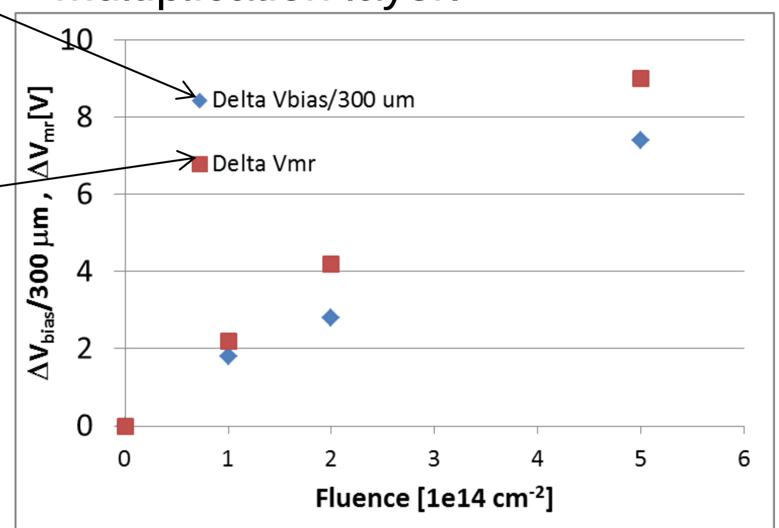
- V_{leg}=26 V is also for R6428 W7 wafer before irradiation!
- ~6 V lower voltage is required for depletion of multiplication region
- Assuming a fully depleted device and ~1 μm wide multiplication region, then one can calculate required over depletion for achieving the same gain as before irradiation. To establish the same field one needs $\Delta V=E*300\ \mu m$

Gain and over depletion

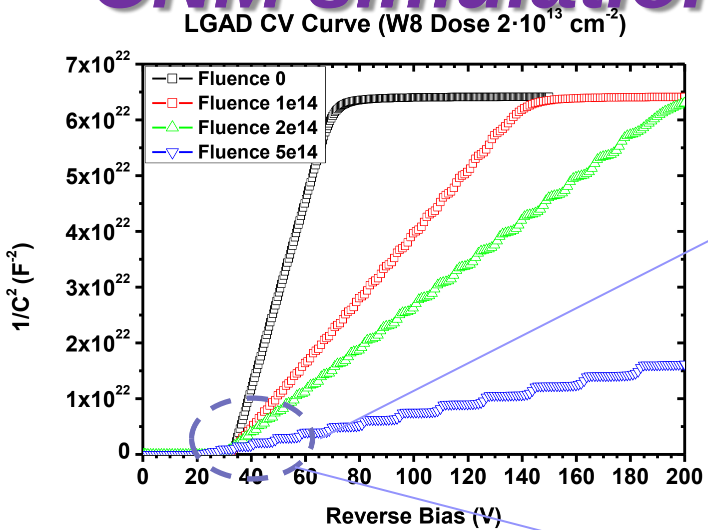


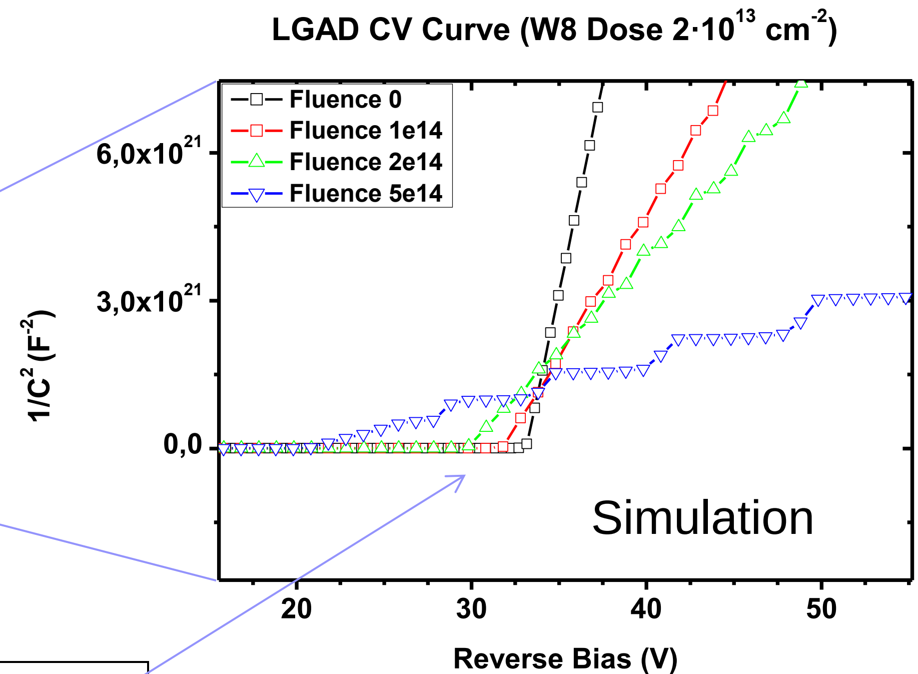
- After full depletion an additional 300 V means increase of electric field in multiplication region by 1 V/μm.
- If the deficit in charge after irradiation is attributed to reduction of the field, due to smaller N_{eff}, then the extrapolated over-depletion required to achieve pre-irradiation charge should match ΔV_{mr} (voltage required to deplete multiplication layer) assuming 1 μm thick multiplication layer.

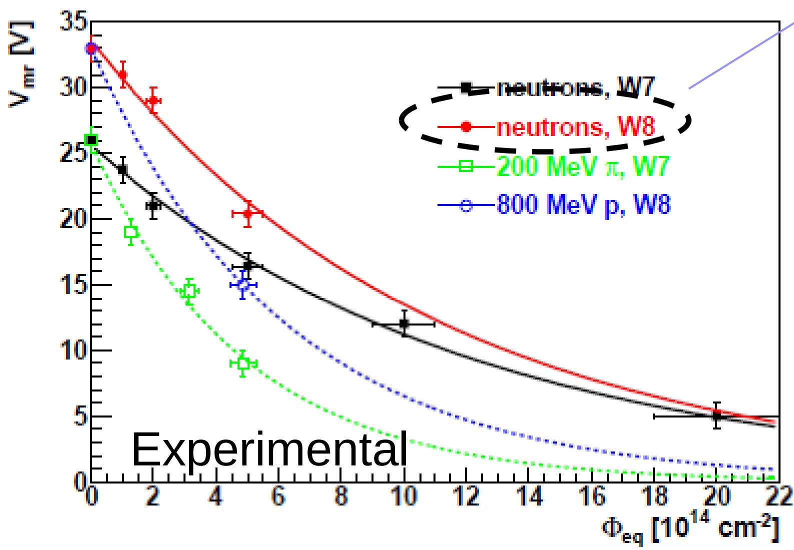




CNM simulations (thanks to Giulio)







The idea is to modify the doping profile and the substrate according to neutron fluence and try to fit the experimental "depletion Voltage ". From this we calculate the expected gain after irradiation

Conclusions

- The origin of effective loss of acceptors in the multiplication layer of LGAD was examined.

- Red DC light was used to change occupation probabilities of traps to separate contribution from shallow and deep acceptors:
  - Large effect on bulk electric field
  - Little effect on collected charge at very high voltages

- Deep traps do not influence much the gain of LGAD at very high voltages – deactivation of shallow acceptors should be responsible.

- The decrease of the “leg voltage” roughly agrees with the over depletion need to achieve the same electric field in the multiplication layer