Radiation hardness of Low Gain Amplification Detectors (LGAD)

G. Kramberger, V. Cindro, I. Mandić, M. Mikuž[†], M. Zavrtanik
Jožef Stefan Institute, Ljubljana, Slovenia
[†] also University of Ljubljana, Faculty of Physics and Mathematics

G. Pellegrini, M. Baselga Bacardit, S. Hidalgo, P. Fernandez, D. Quirion
CNM Barcelona

V. Fadeyev, H. Sadrozinski
SCIPP , UC Santa Cruz

Motivation/Outline

The focus of this presentation will be on:

- **Gain (Pablos’s run R6474):**
  - its change with irradiation – neutrons and 800 MeV protons
  - reasons for degradation of gain
- **TCT measurements used to study properties of p$^+$ implant layer after irradiation**
- **Leakage current and noise after irradiation**

NEW

Diodes were irradiated with reactor neutrons in steps with 80 min annealing at 60^{o}C between irradiation fractions :

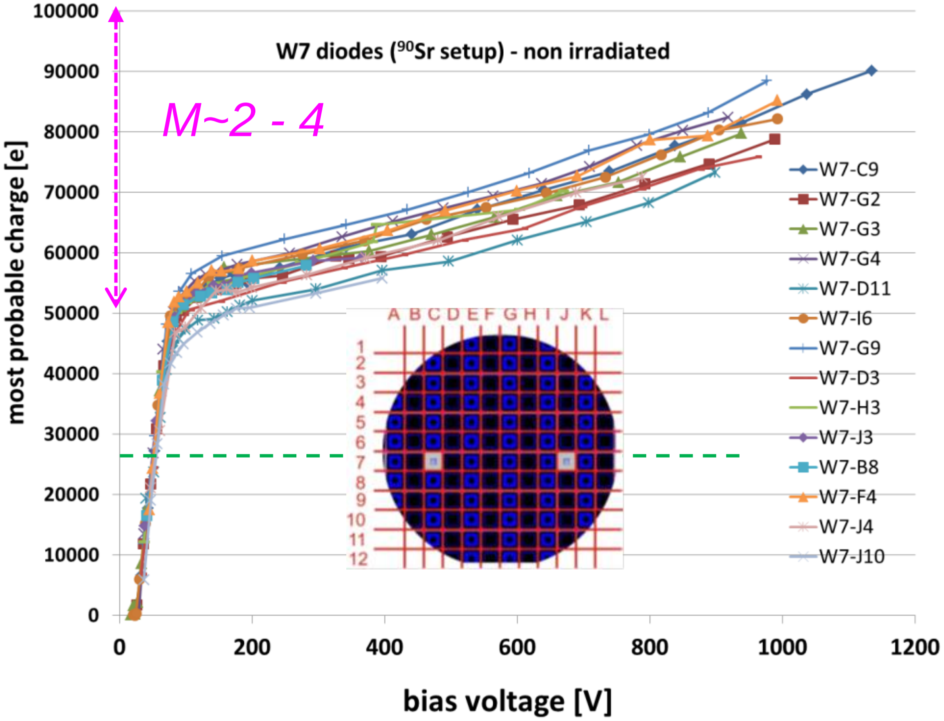
- W8 from 1,2,3,5,20,100·10^{14} cm^{-2}
- W7 from 1,2,3,5,10,20, 30·10^{14} cm^{-2}

Diode irradiated at Los Alamos with 800 MeV – were not intentionally annealed

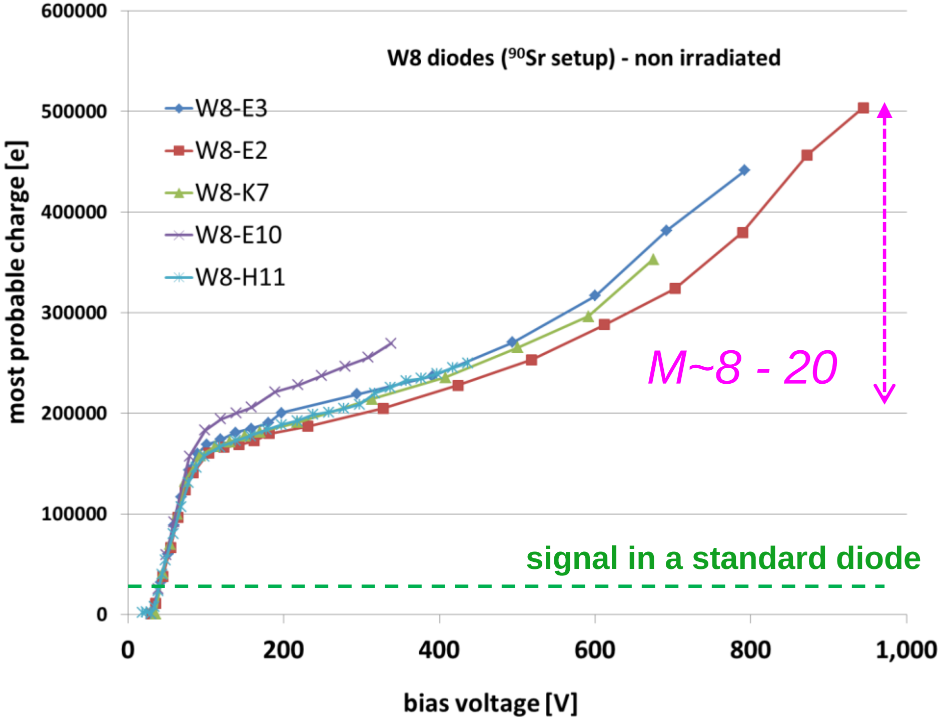
- W8 fluences ~5e12, 5e13, 5e14, 8e15 cm^{-2}
- W9 – control wafer (without amplification layer) - 5e12, 5e13, 5e14, 8e15 cm^{-2}

For setups and procedures please have a look at last workshops…

Charge collection of diodes from W7 and W8



M~2 - 4



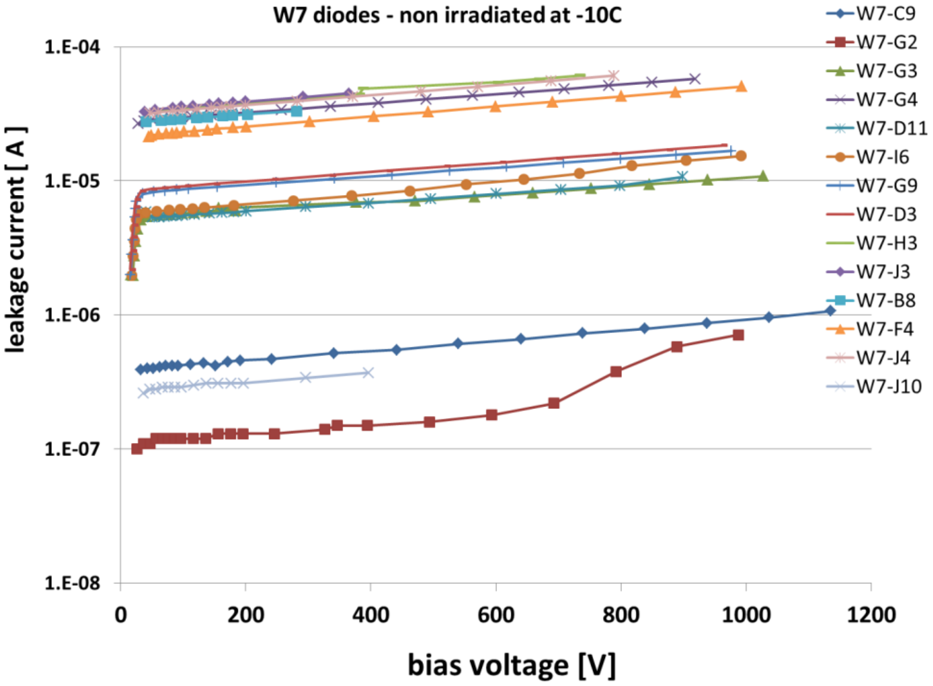
M~8 - 20

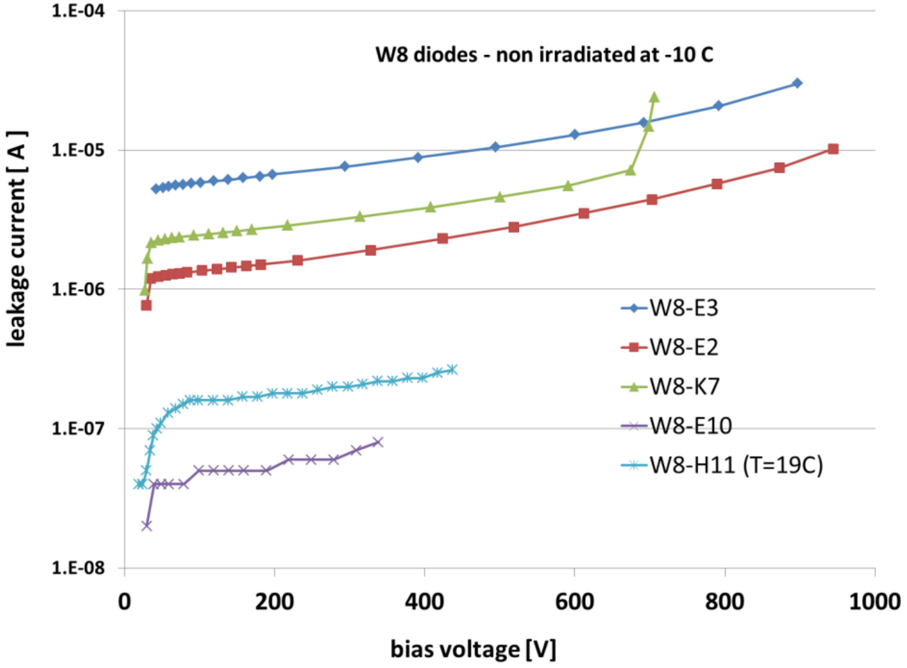
signal in a standard diode

Wafers have different gains:

- Good uniformity of gain over the wafer.
- Very good stability of some diodes up to >1000 V.
- For W8 samples the gain at >900 V is difficult to measure – amplifier saturates due to too large signals – note steeper increase of gain for U>500V.

Current of diodes from W7 and W8



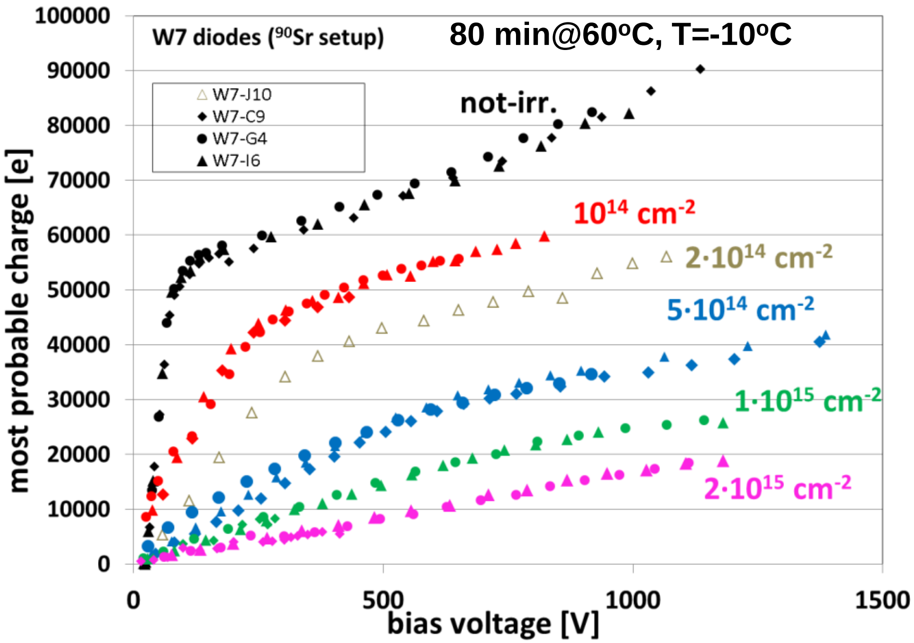


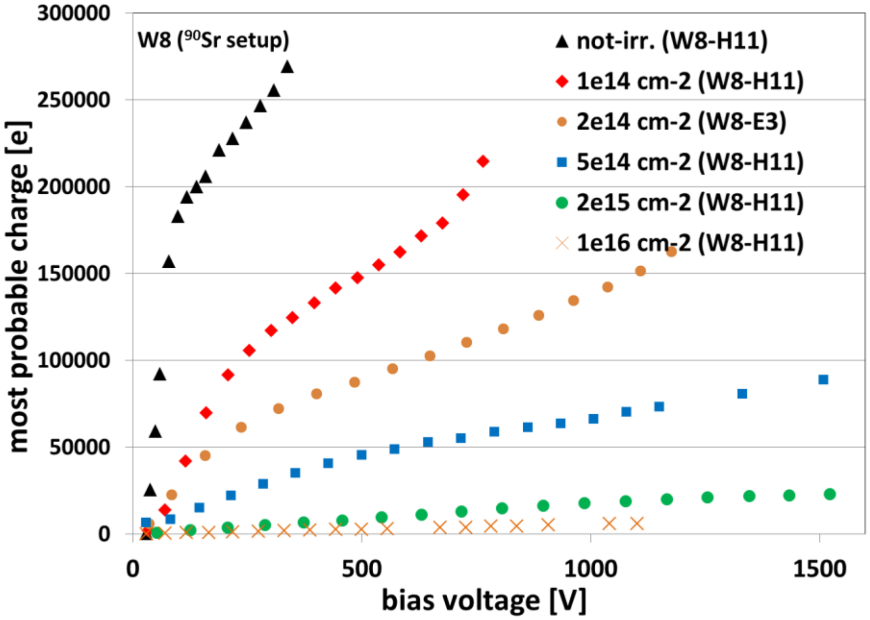
The current of the devices differ for almost 3 orders of magnitude for both wafers:

- It is not correlated with gain.
- The excess current for high current devices is not bulk related – almost no temperature dependence.
- It is probably homogenously distributed over the surface (IR images).

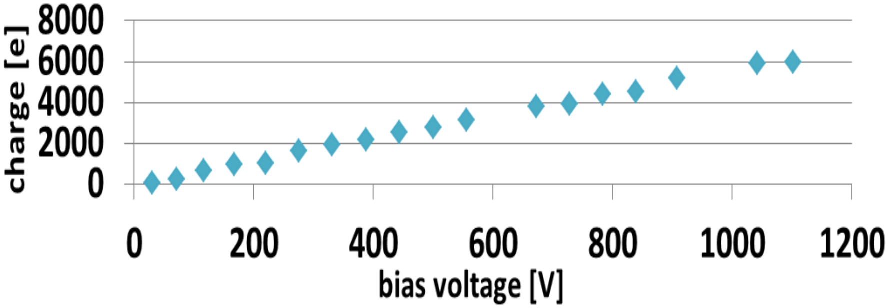
CCE of irradiated detectors (reactor neutrons)

- Selected detectors from wafers with different initial currents: W7-C9 (~1 μA), W7-I6 (~10 μA), W7-G4 (100 μA) and W8-H11 (< 1 μA), W8-E3 (<1 μA)

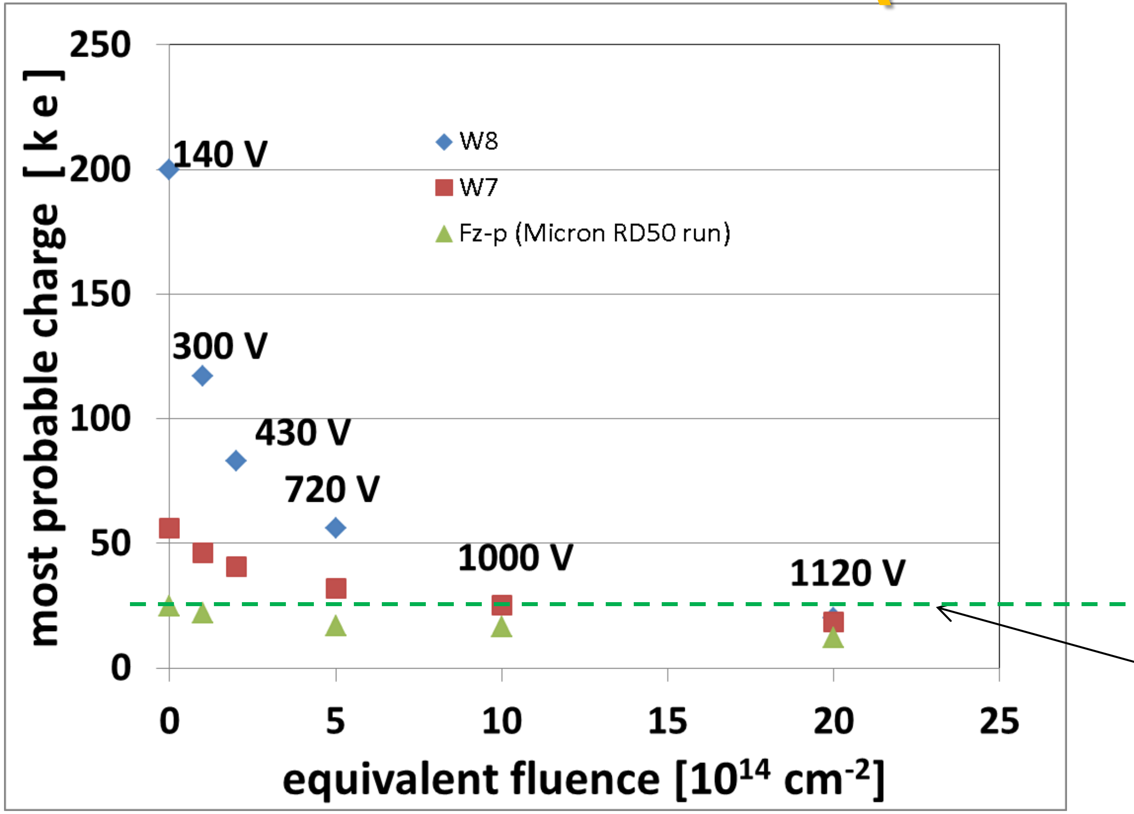




- W8 around 6000 e collected at 10^{16} cm^{-2} , which is roughly the same (or slightly more) as for standard diode
- There is almost no influence of CCE of devices on the initial current for W7– some difference at lower bias voltages at $5\cdot10^{14}$ cm^{-2}.



CCE of irradiated detectors (reactor neutrons)



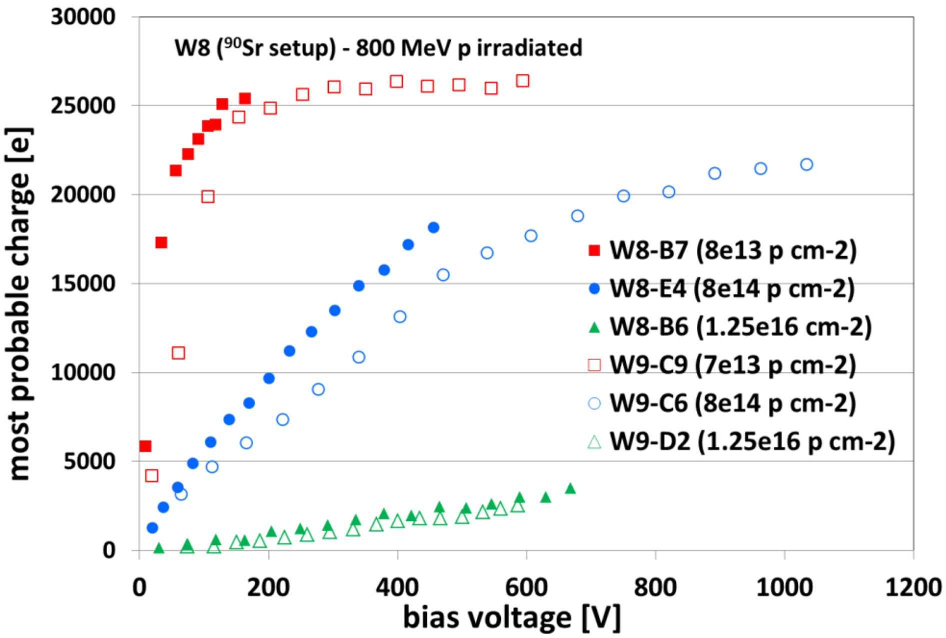
$$M_Q = \frac{Q_{W7,W8}}{Q_{st.diode}}$$

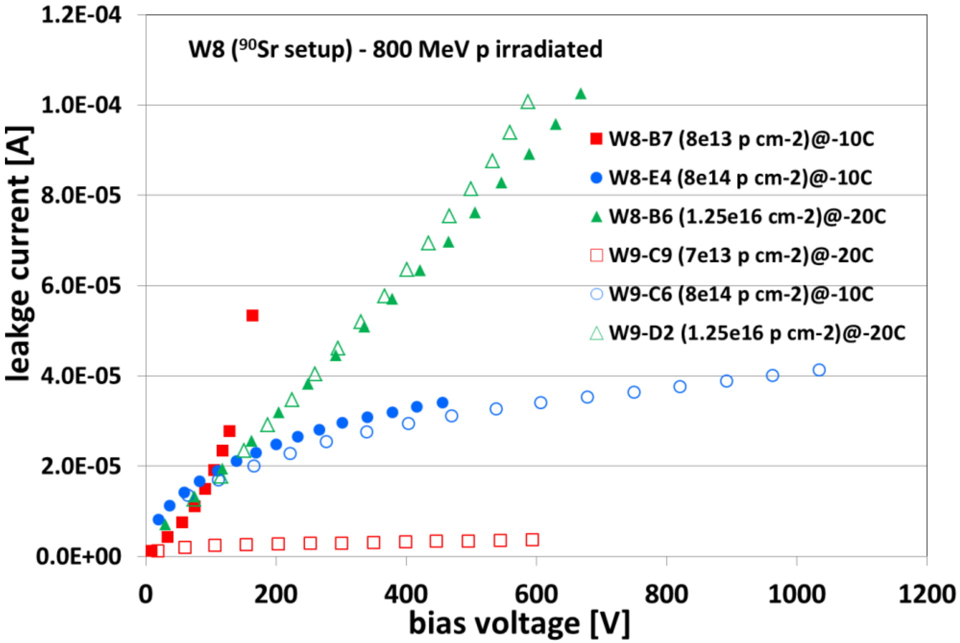
~25000 e
(st. nirr. diode)

M_Q~1.5

- Charge multiplication measured at ~V_{fd} (similar for W7 and W8) decreases with Φ_{eq}
- Decrease of charge collection:
  - Trapping (not severe enough at low fluences to explain decrease)
  - Decrease of multiplication?
    - initial acceptor removal
    - trapped holes reduce the field in the multiplication region

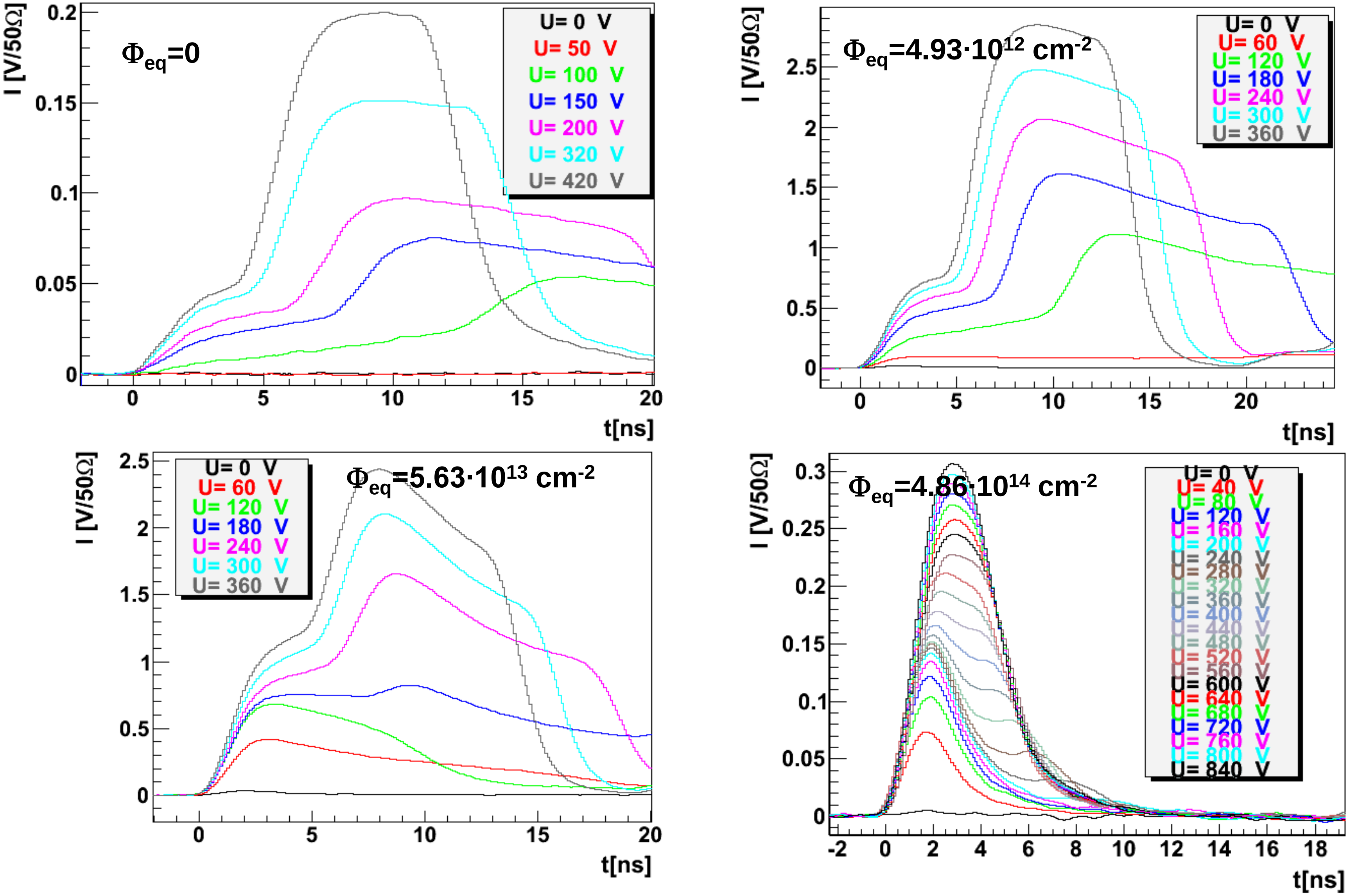
CCE of irradiated detectors (800 MeV p)





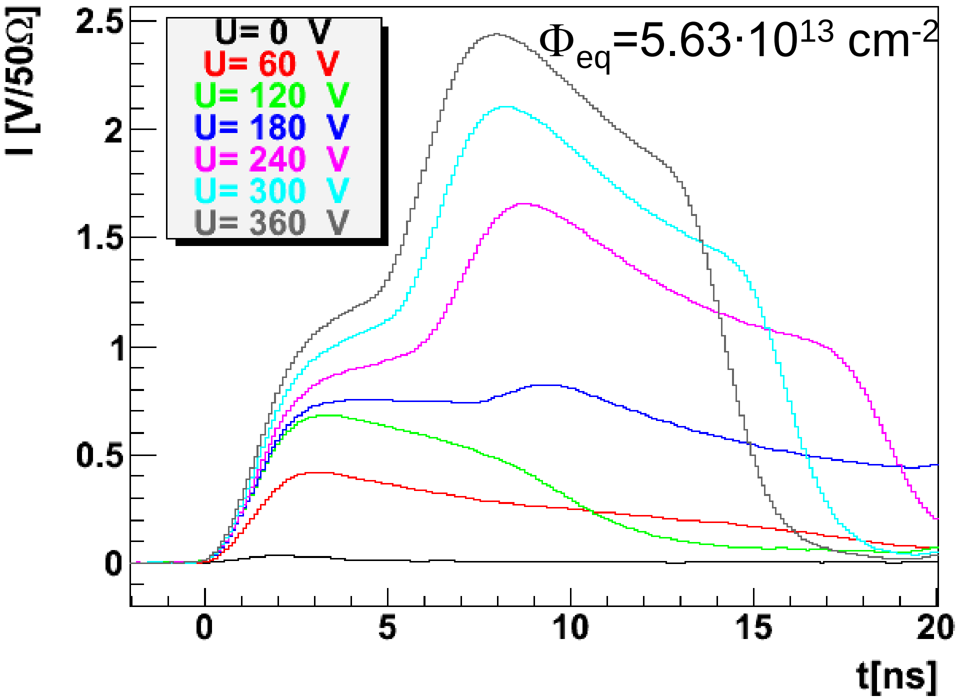
- As irradiated – no intentional annealing.
- **Stronger decrease of gain than with neutrons** – almost no gain at $8{\cdot}10^{13}$ p cm^{-2} (Φ_{eq}~$5{\cdot}10^{15}$ cm^{-2}).
- Measured current for control and LGAD devices are similar. For higher fluences there is almost no gain.
- Currents are very high for $8{\cdot}10^{13}$ p cm^{-2} (Φ_{eq}~$5{\cdot}10^{13}$ cm^{-2}) – also for Φ_{eq}~$5{\cdot}10^{12}$ cm^{-2} sensor ? W8-B7 shows gain at higher voltages!

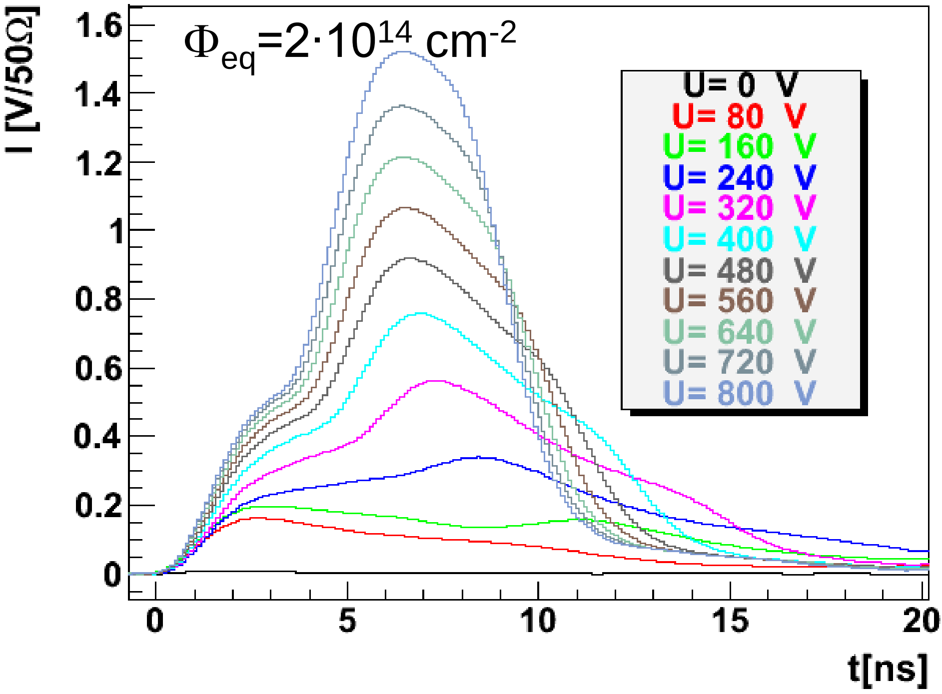
TCT signals – back injection (I)



Significant decrease of amplification with fluence.

TCT signals – back injection (II)

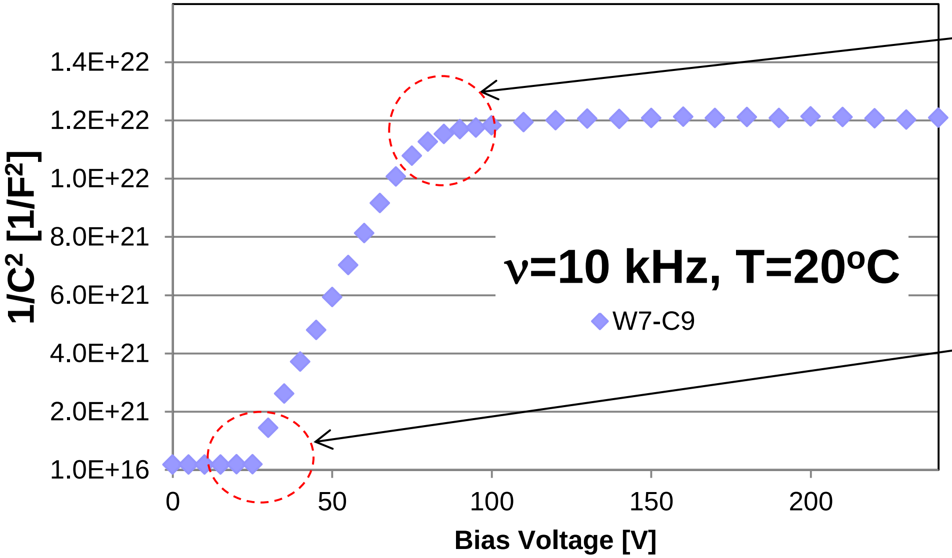




Similar TCT signals, but the difference in fluence is a factor of 4.

How to probe the field ?

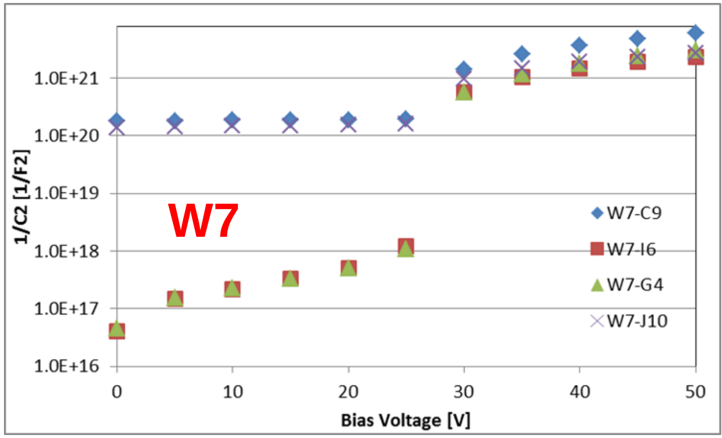
C-V offers a way to profile N_{eff} (unfortunately not reliable after irradiation)

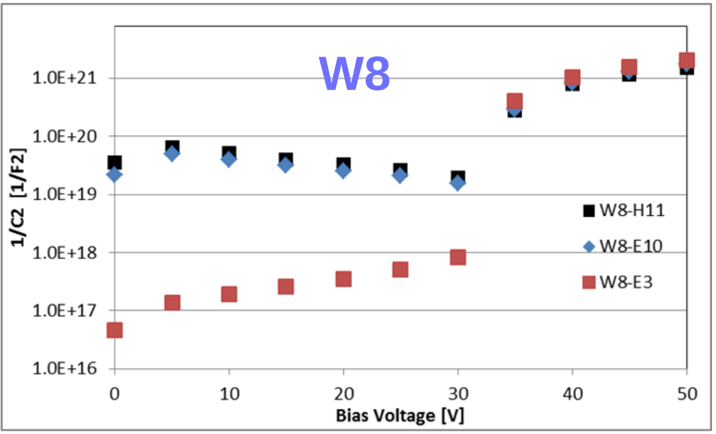


depletion of the p-bulk (**V_{fd}~80 V**)

depletion of p^+ layer (**V_{mr}~30 V**)

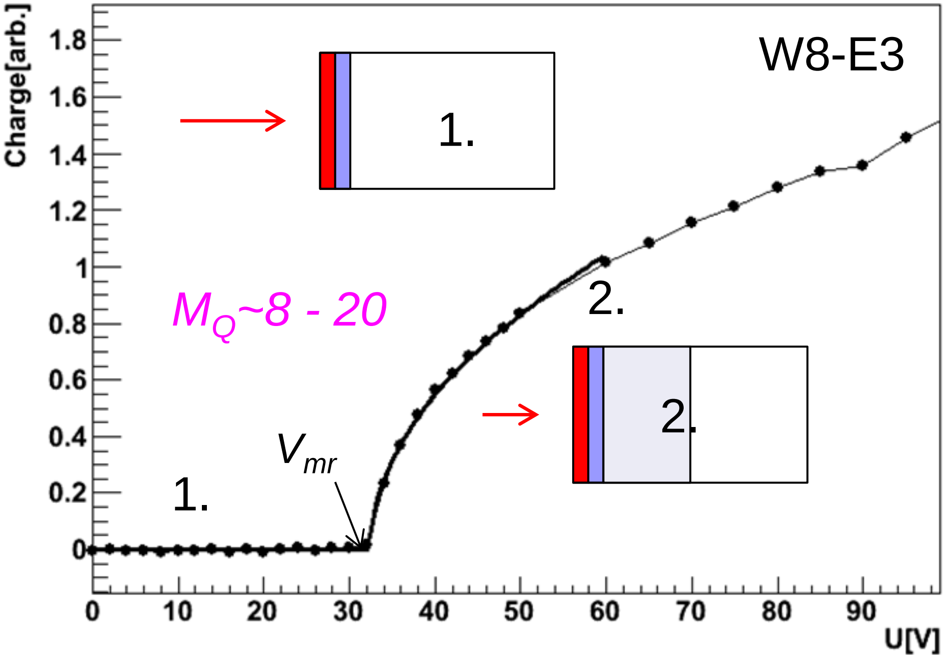
V_{mr} determines approximately the gain that can be achieved

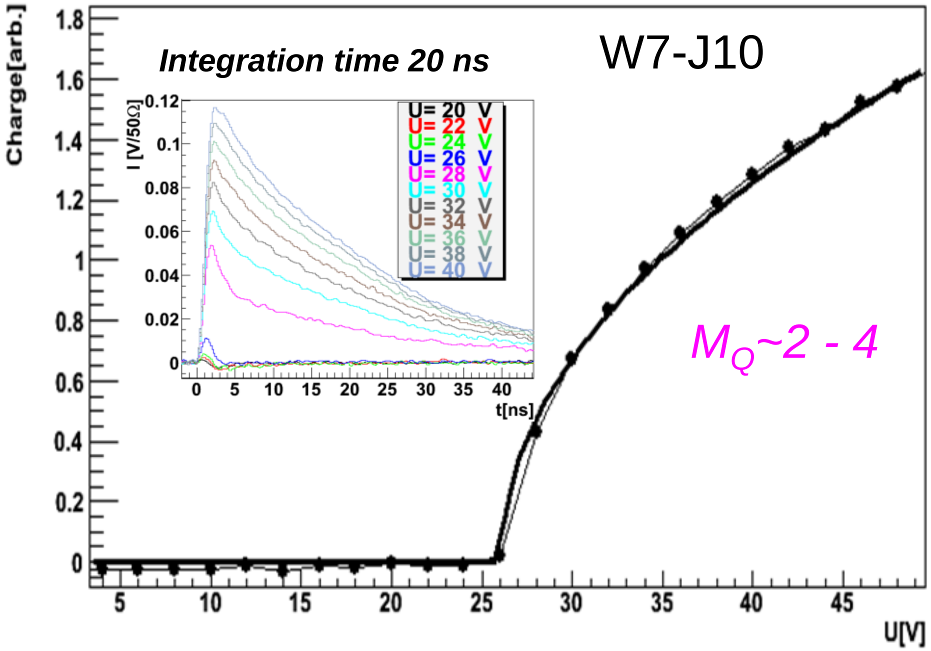




Probing multiplication layer with TCT

In similar way as C-V one can determine the V_{mr} from the signal.
Front illumination with red light is exploited – illumination of n^{++}-p^{+} contact



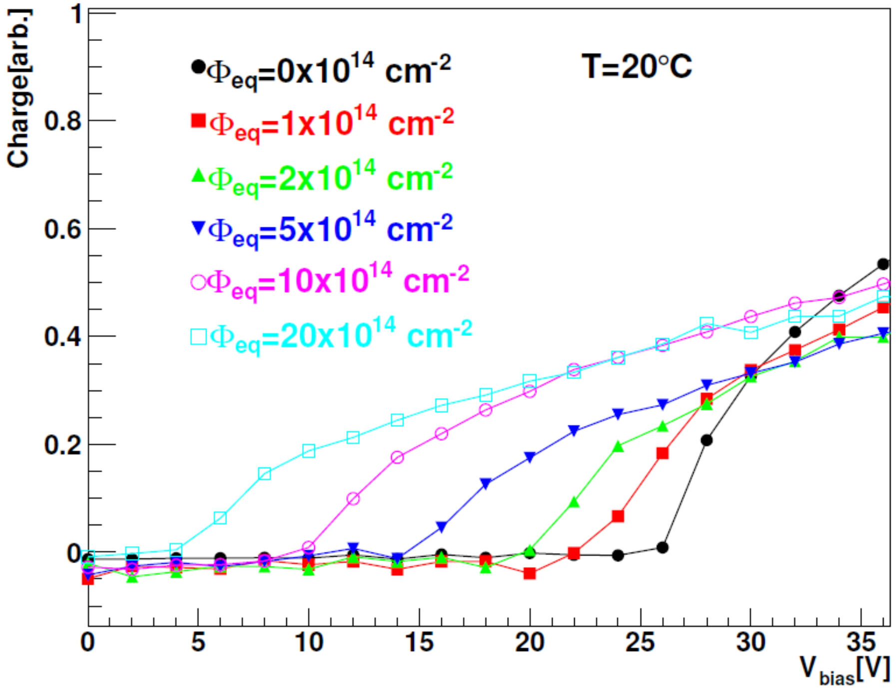


- Clear onset of depletion region growth in p bulk – coincides well with CV
- Strong dependence of multiplication on $N_{eff,p+}$ (~7 V in V_{mr} difference between W7 and W8)

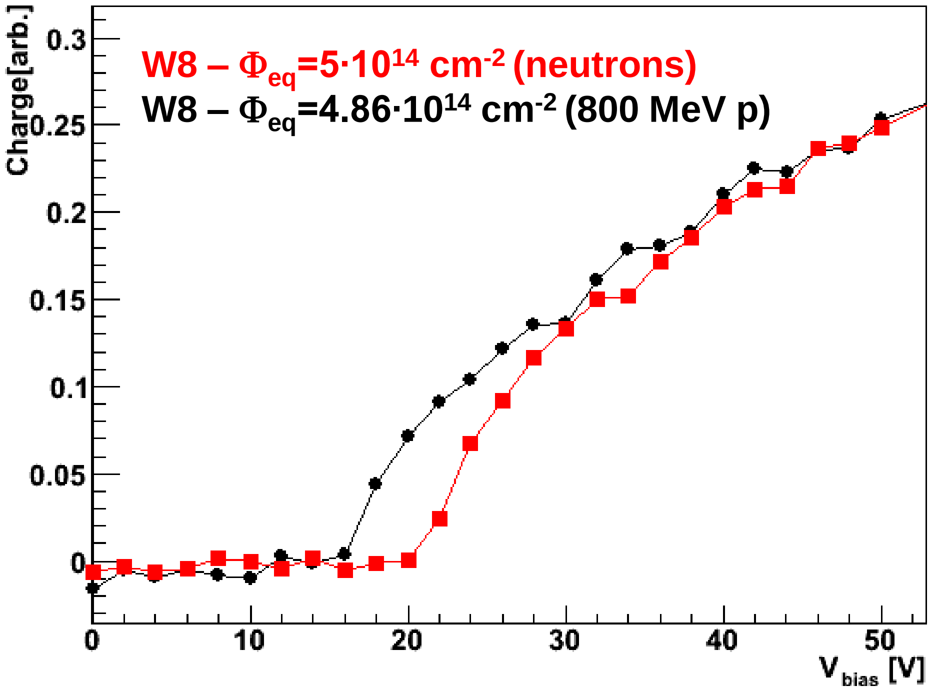
$$V_{mr} \propto N_{eff,p+}$$

TCT probing of V_{mr}

W7 wafer irradiated with neutrons

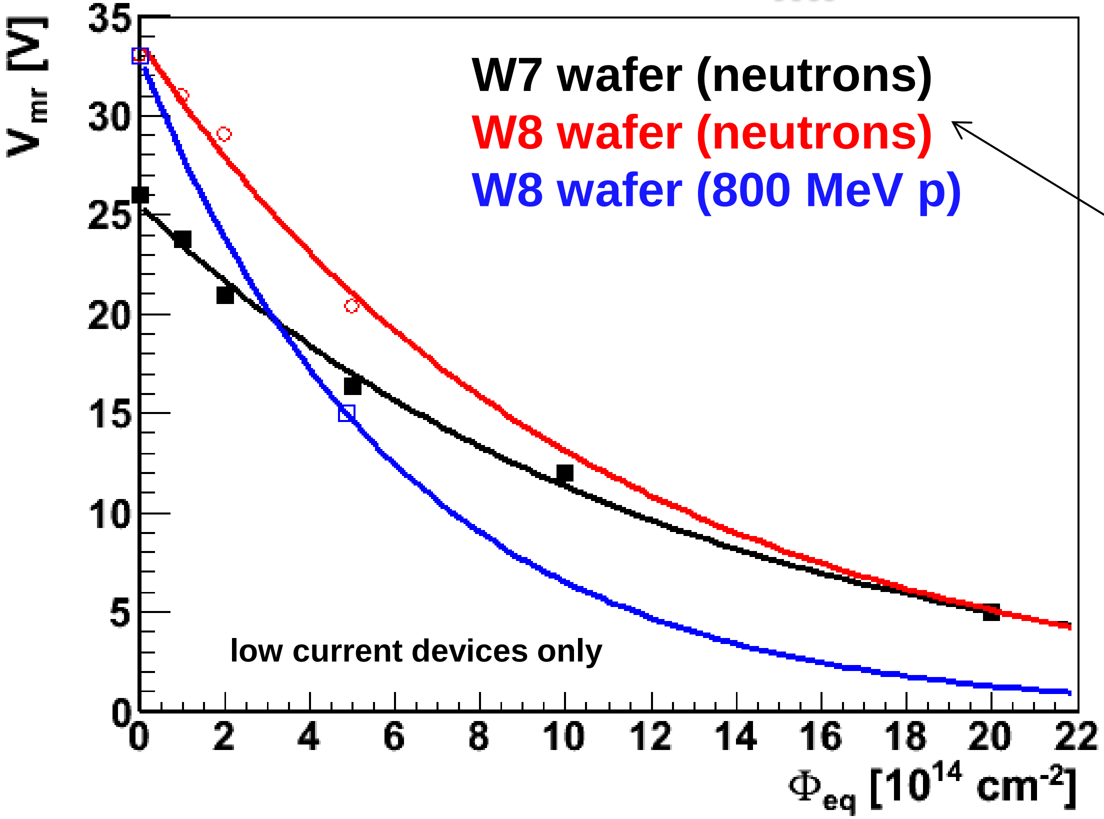


Difference: neutrons/800 MeV p



- V_{mr} decreases with fluence
- V_{mr} decreases more for 800 MeV protons than reactor neutrons

Dependence of V_{mr} on fluence



$$V_{mr} = V_{mr,0} \cdot \exp(-c \cdot \Phi_{eq})$$

$c_{W8} = 9.4 \cdot 10^{-16}\ \mathrm{cm}^2$

$c_{W7} = 8.1 \cdot 10^{-16}\,\mathrm{cm}^2$

$c_{W8} = 1.6 \cdot 10^{-15}\ \mathrm{cm}^2$

Assuming linear relation between V_{mr} and $N_{eff,p+}$ one can compare *c* to old data on high res Si

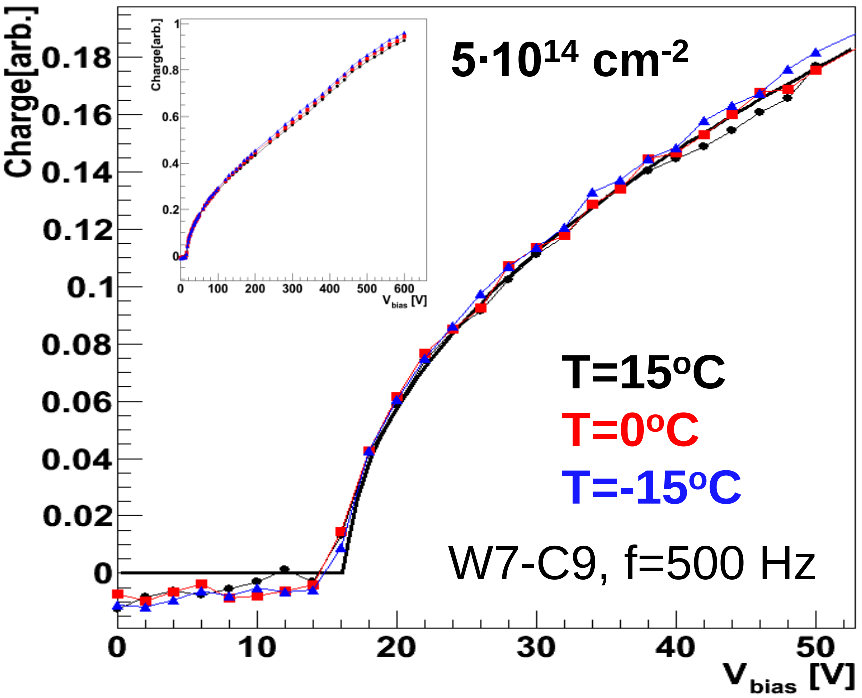
(R. Wunstorf, NIMA 377 (1996) 228.))

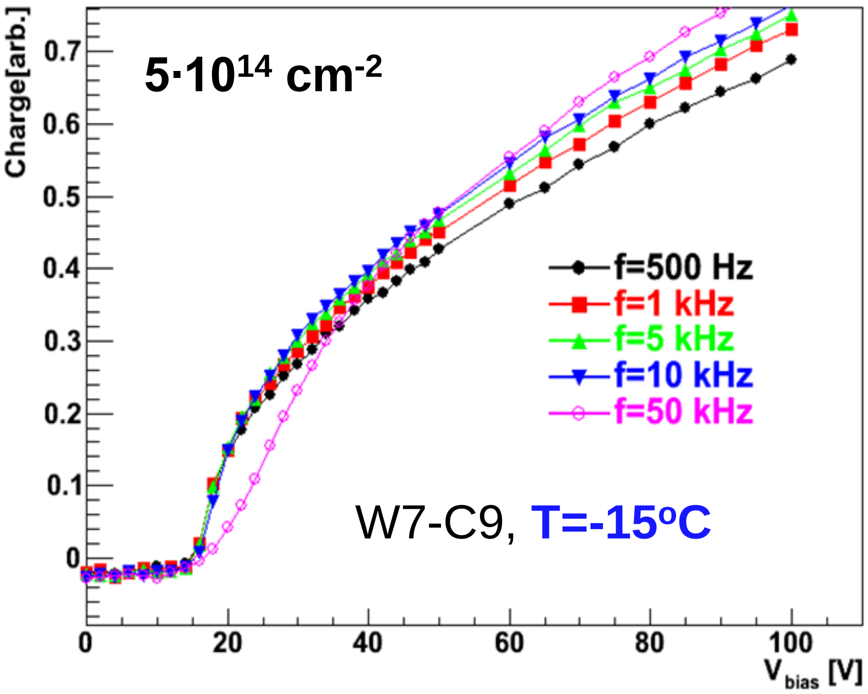
$c = 2 \cdot 10^{-13}\ \mathrm{cm}^2$

- After removal of 50 % of effective acceptors the gain in signal due to amplification is of the order of M_Q~1.2 (for W7)
- For the W8 samples at 1e14 cm^{-2} the removal is only marginal ~10% (32 V – 30 V) which is in accordance with reduction of M_Q=8 to M_Q=5 .
- **Removal constant is much smaller than one would expect from high resistivity measurements.**
- **Removal constant for 800 MeV p is much larger (note: a single point)**

What is the reason for reduction of V_{mr}?

- Decrease of shallow acceptors concentration (B)->
  - no temperature dependence (in the investigated range)
  - weak dependence of $N_{eff,p+}$ on enhanced free carrier concentration (achieved by higher frequency of pulses)
- Moderation of field by trapped holes -> G-R processes can lead to dependence of V_{mr} on temperature and free carrier concentration

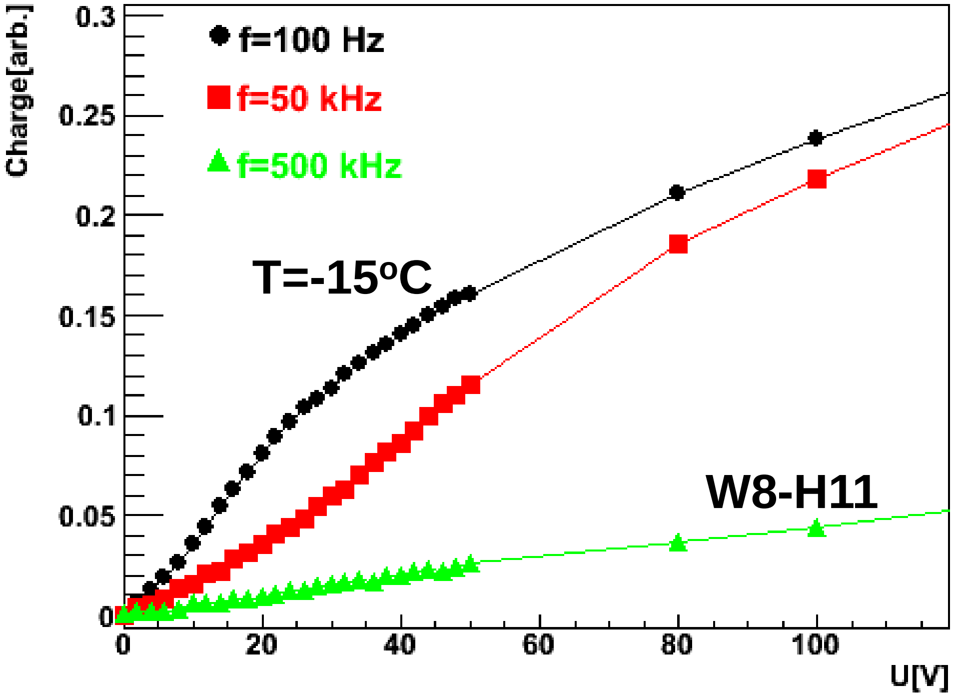


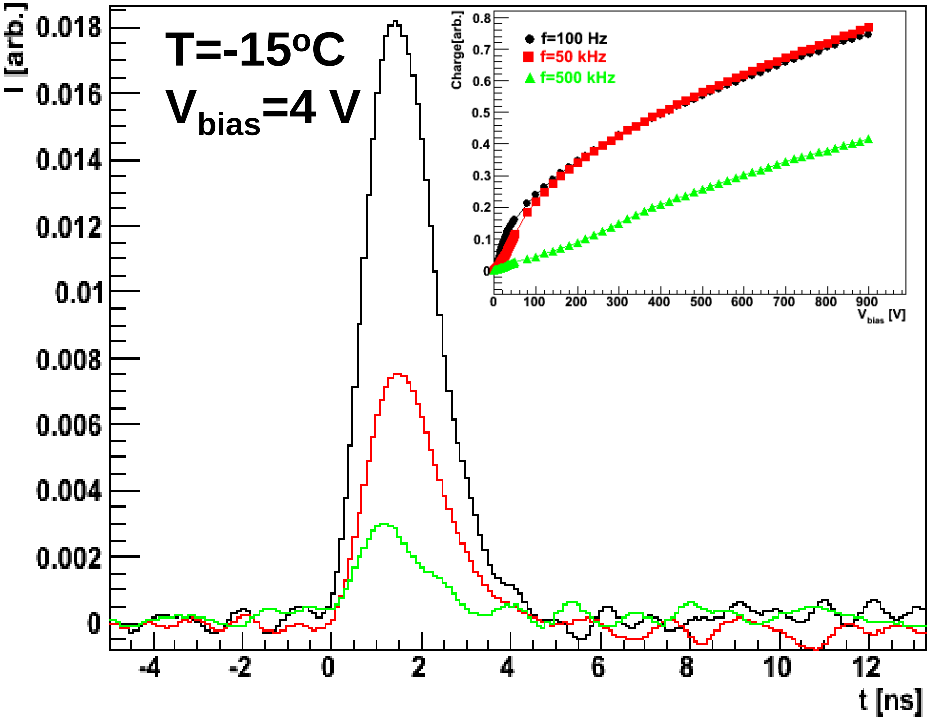


It seems that removal of shallow acceptors is responsible for gain degradation.

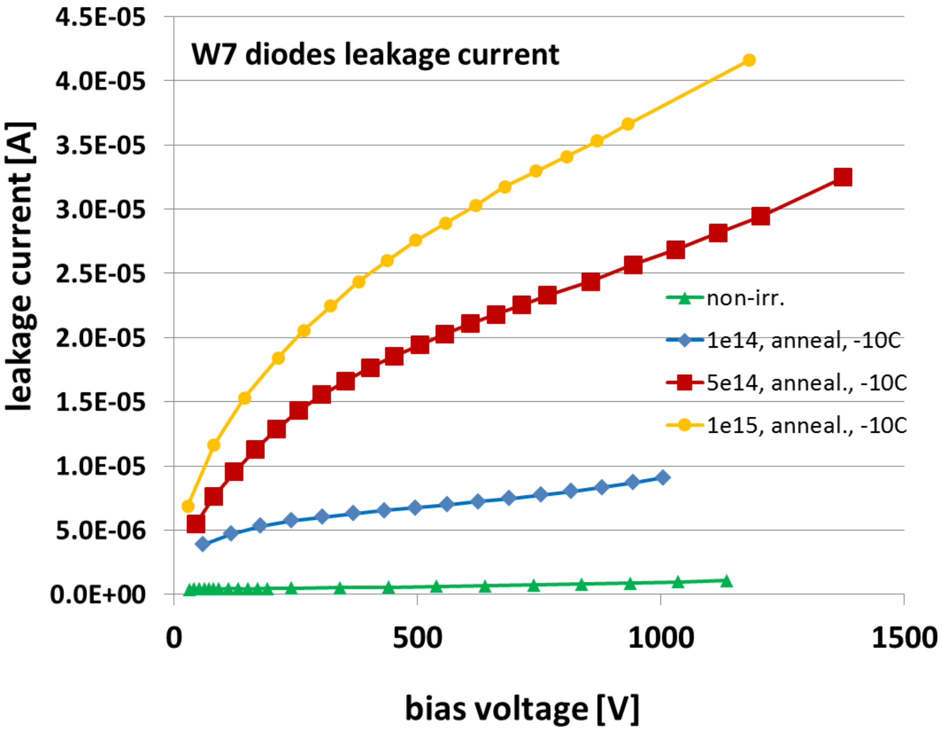
Amplification after 10^{16} cm^{-2}

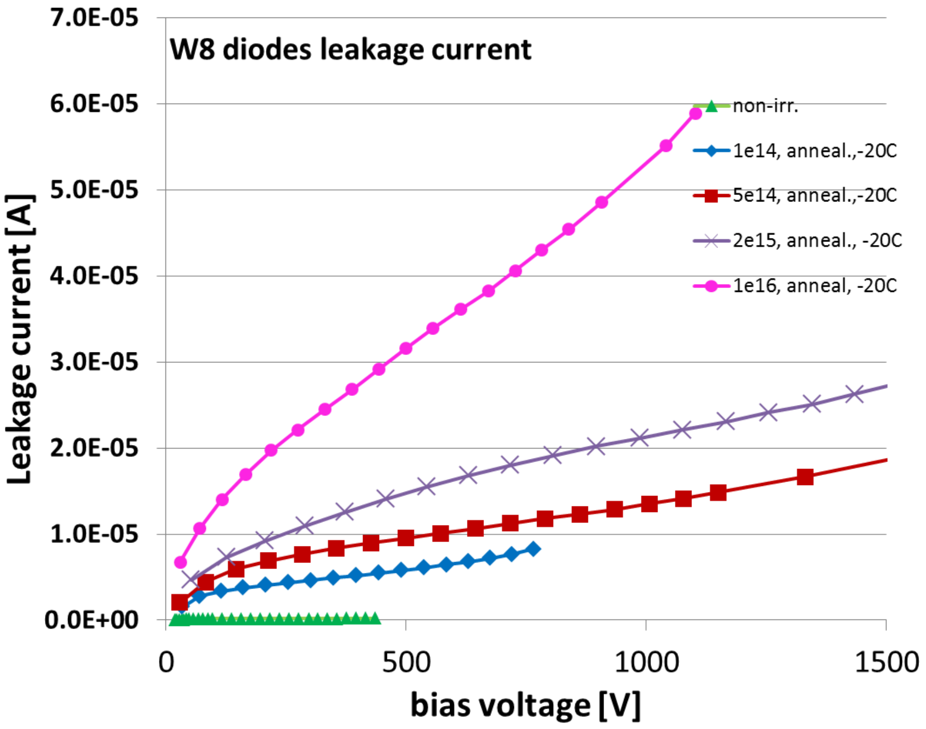
No visible V_{mr} – indicates that “highly doped” p^{+} layer has vanished. This is in accordance with observation of almost no difference between standard and LGAD diode





Leakage current after irradiation





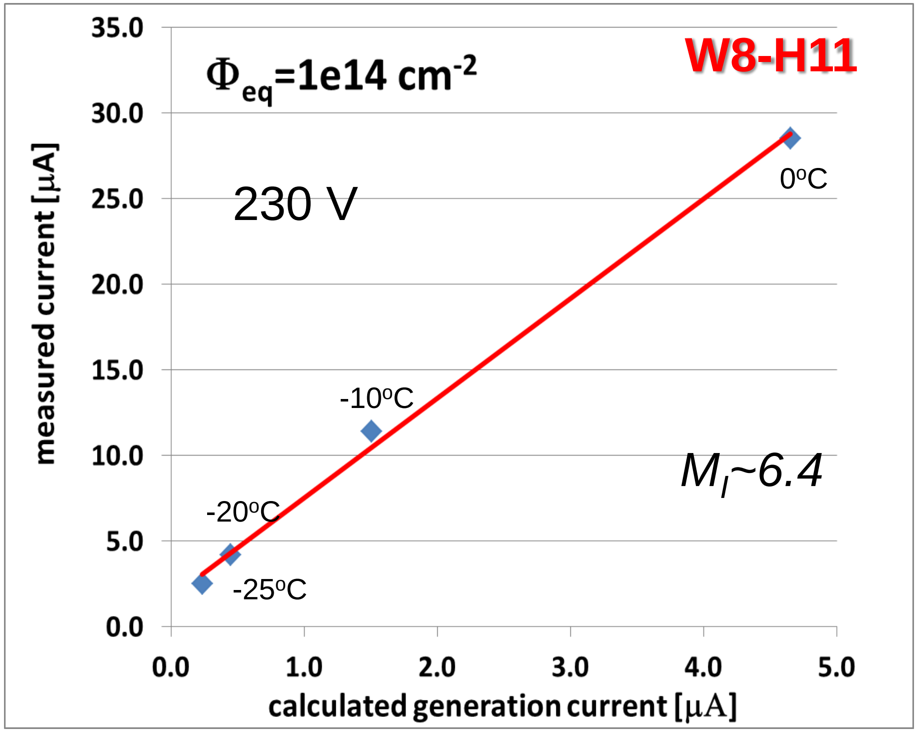
Leakage current increase is not linear with fluence.

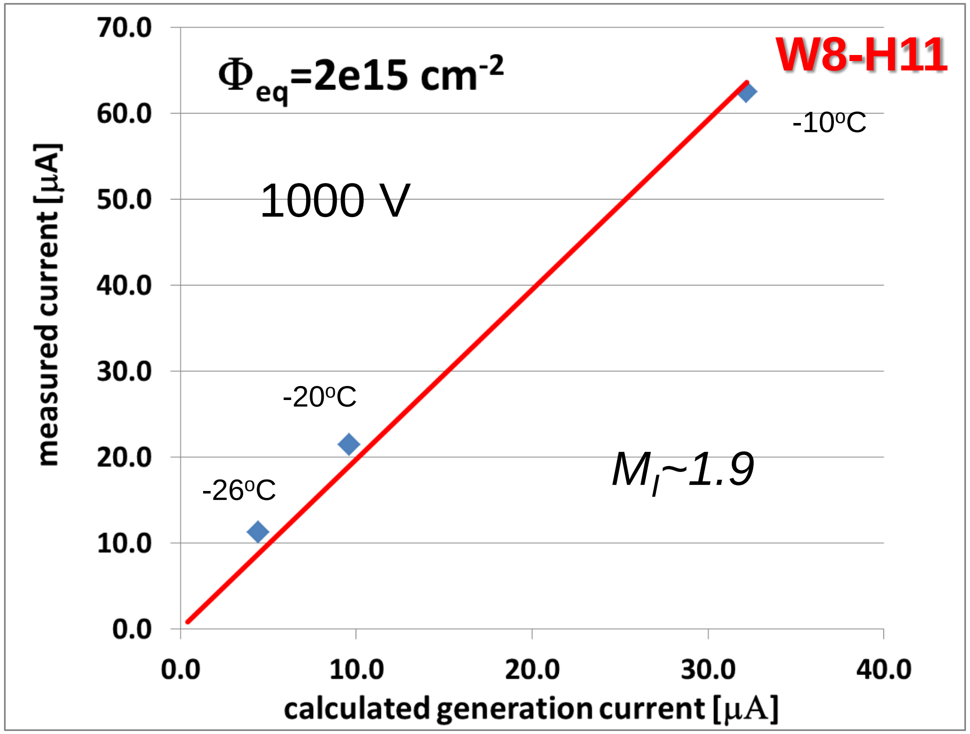
Increase with fluence in **smaller** due to degradation of multiplication

$$I_{leak} = M_I \cdot I_{gen} = M_I \cdot \alpha \cdot \Phi$$

decreases with irradiation **increases with irradiation**

Multiplication factors M_I





$$M_I = \frac{I_{leak}}{I_{gen}} = \frac{I_{leak}}{\alpha \cdot \Phi}$$

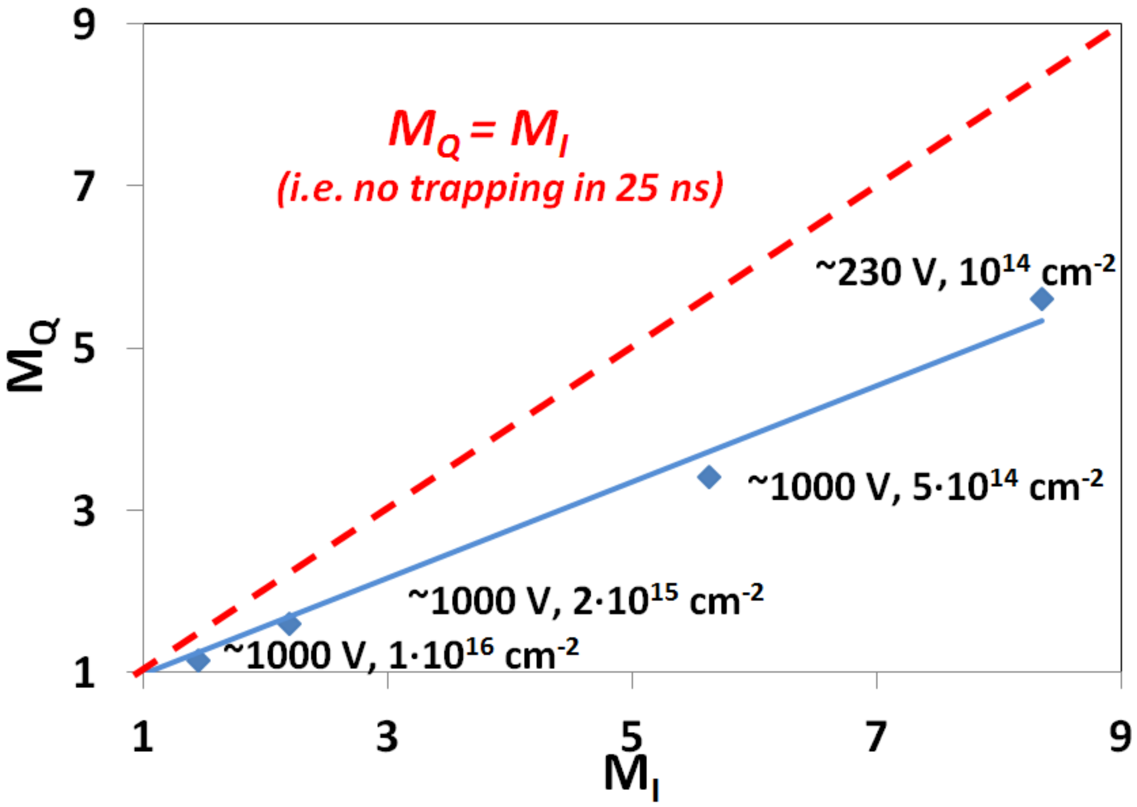
$\alpha(-20^{o}C)$=5.1e-19 A cm^{-1}

Temperature dependence:

- generation current – strong
- multiplication - weak

Multiplication factors M_I and M_Q

T=-20°C



$$M_Q = \frac{Q_{W8-H11}}{Q_{st.diode}}$$

whole bulk active (1000V at high Φ)

$$M_I = \frac{I}{I_{gen}} = \frac{I}{\alpha\cdot\Phi}$$

$\alpha(-20^{o}\mathrm{C}) = 5.1e\text{-}19$ A cm^{-1}

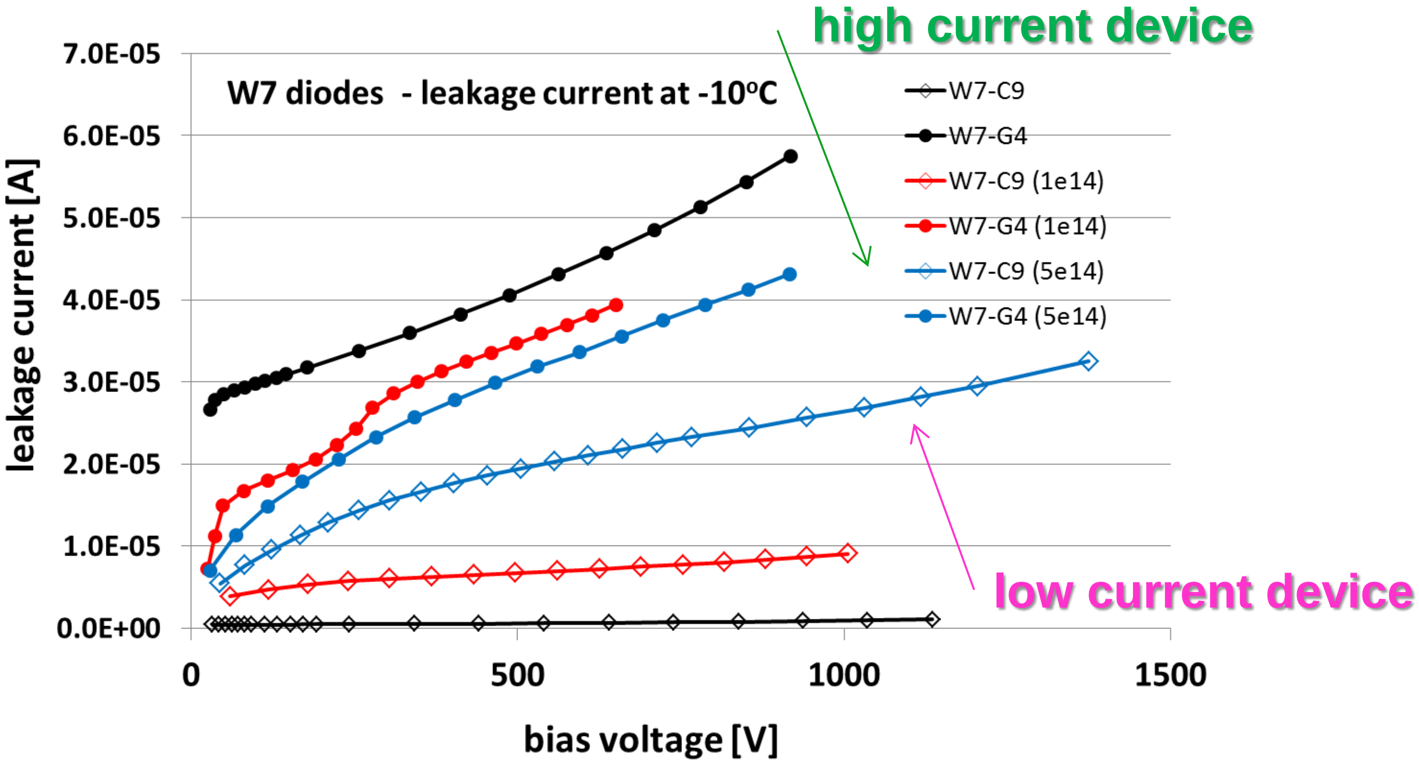
$Q_{st.diode}$ from:

G.Kramberger et al.,21st RD50 workshop, CERN 2012

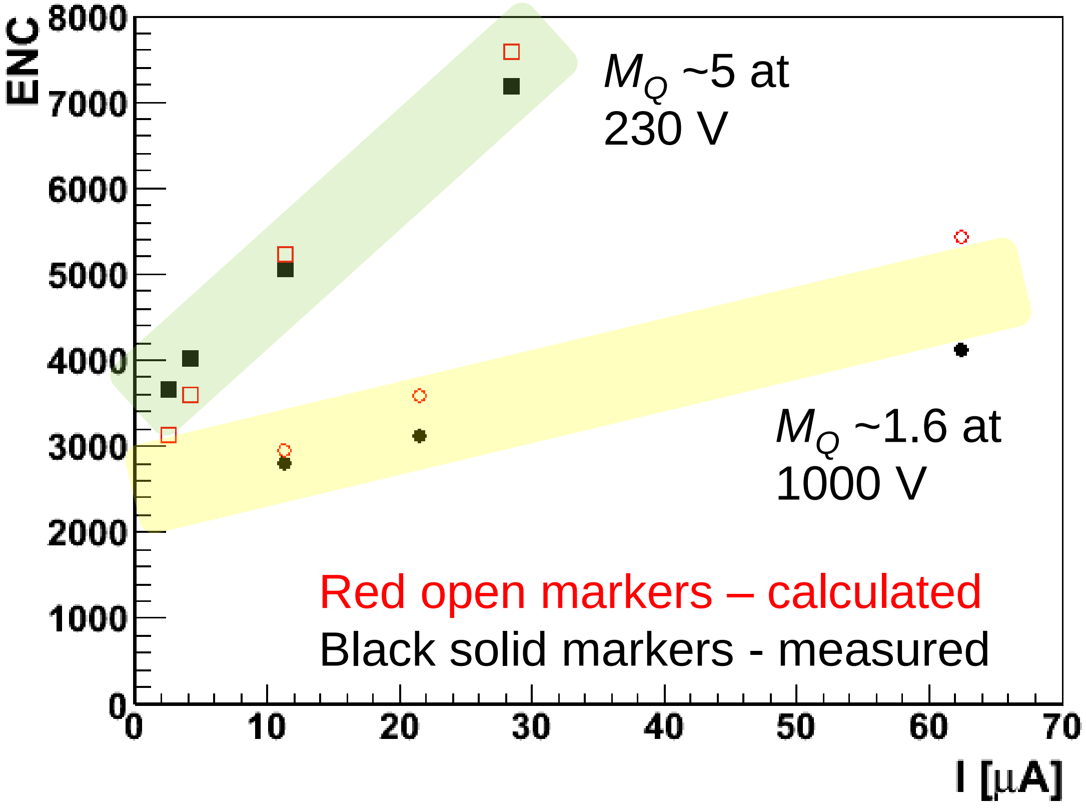
G.Kramberger et al., NIMA 612(2010) 288.

Leakage current of irradiated W7 detectors

- The leakage current increases as expected (reduction of M_I and increase of I_{gen}) for W7-C9 device
- For the “high current” devices the **leakage current decreases at moderate fluences**:
  - reduction of M_I
  - deactivation/decrease of injection centers ???



Calculation of the noise



M_Q ~5 at 230 V

M_Q ~1.6 at 1000 V

Red open markers – calculated

Black solid markers - measured

$$\boxed{ENC^2 = ENC_{MI}{}^2 + ENC_S{}^2}$$

ENC_S=2300 e – series noise

$$\boxed{ENC_{M_I} = M_I \cdot \sqrt{F} \cdot ENC_I}$$

$$ENC_I = e/2 \cdot \sqrt{I_{gen} e_0 \tau}$$

ENC_I –noise due to generation current without amplification – short noise (CR-RC shaping)

$F = 2$ for $M \gg 1$, $F=1$ for $M \sim 1$

$\tau = 25$ ns

$I_{gen} = \alpha \cdot \Phi_{eq}$ $M_I \sim M_Q$

Good agreement between measured and calculated noise.

$$\boxed{\frac{S}{N} = \frac{M_Q Q}{\sqrt{ENC_S{}^2 + M_I{}^2 I_{gen} \frac{e^2 F e_0 \tau}{4}}}}$$

S/N improves with multiplication if:

$$\boxed{ENC_S{}^2 \gg M^2 I_{gen} \frac{e^2 F e_0 \tau}{4}}$$

Conclusions

- Diodes with gain perform formidably before the irradiation with gain of up to ~20 for ^{90}Sr electrons

- Gain decreases significantly with neutron irradiation and even more with 800 MeV p irradiations
  - Effective acceptor removal in the p^+ layer is responsible for gain degradation
  - TCT was used to determine the rate of effective acceptor removal
  - It seems that removal of initial acceptor dominates over changing the occupancy of deep traps

- Leakage current:
  - behaves accordance with expectations for “low current” devices
  - decreases with irradiation for “high current” devices

- Noise agrees well with calculation taking into account multiplication factors