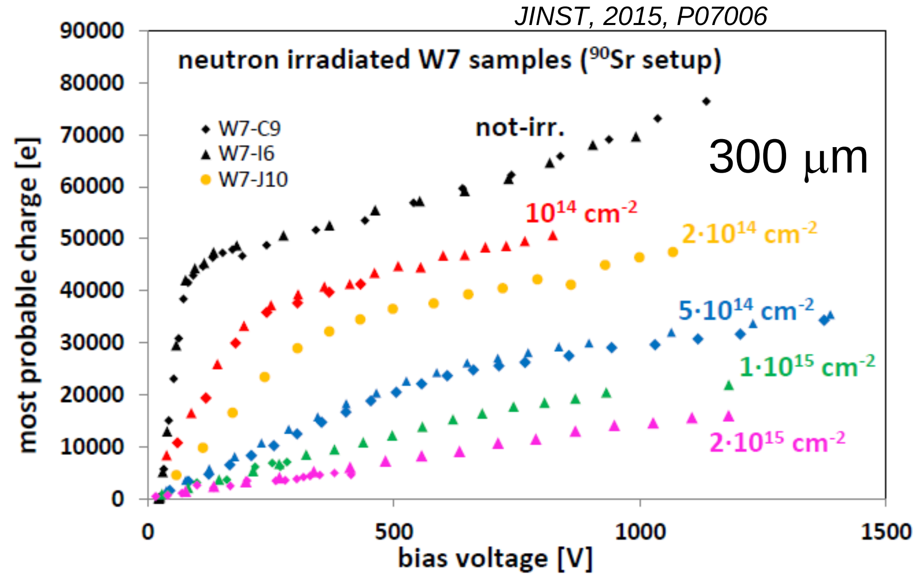
Performance of thin LGADs after irradiation

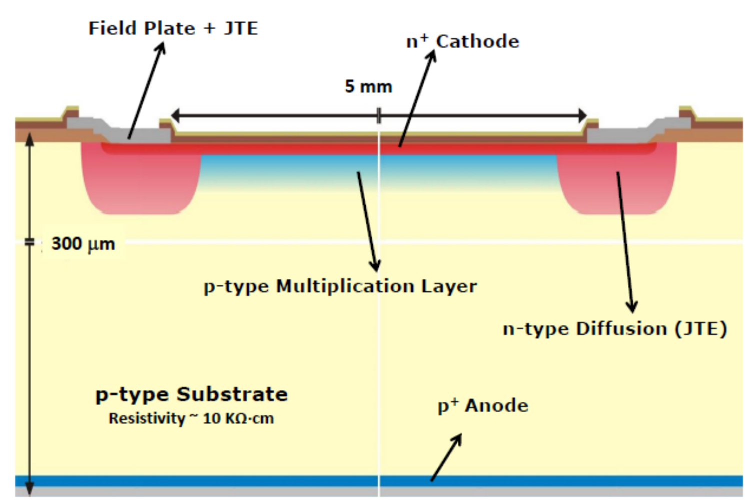
Gregor Kramberger
Jožef Stefan Institute, Ljubljana
in collaboration with
CNM Barcelona
UCSC Santa Cruz

Radiation hardness issues

- The gain of LGAD detectors decreases with irradiation – after few 10^{14} cm^{-2} the gain disappears.
- This is the main reason for degradation in timing (and efficiency) performance as the slew rate decreases
- The gain disappears:
  - mainly due to removal of effective acceptors in the multiplication region
  - to minor extent also due trapping of the multiplied holes therefore modifying the detector bulk
  - trapping of the drifting charge becomes more and more important
- **How to solve/mitigate the effect of radiation to gain loss?**

JINST, 2015, P07006

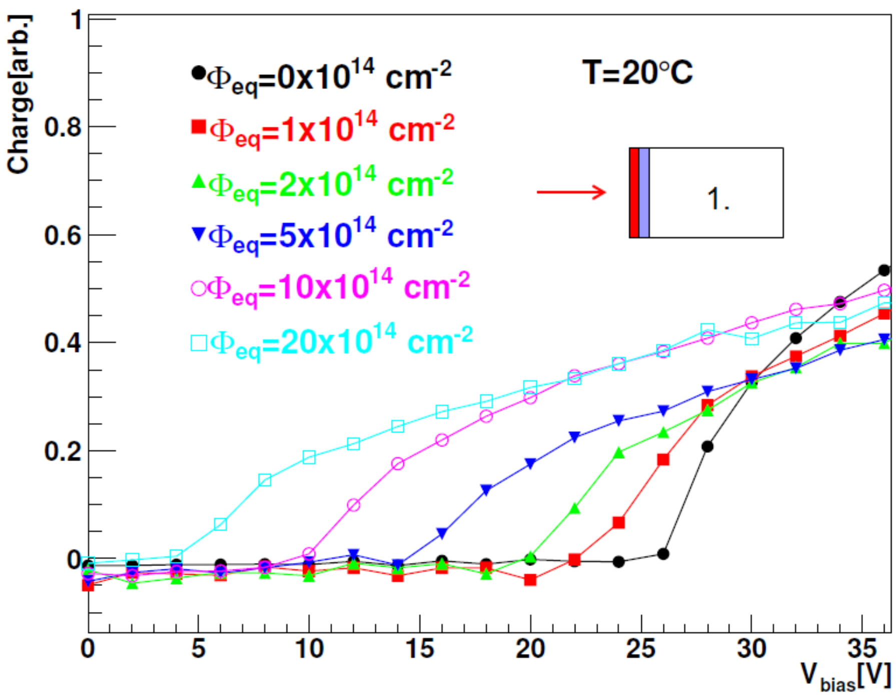


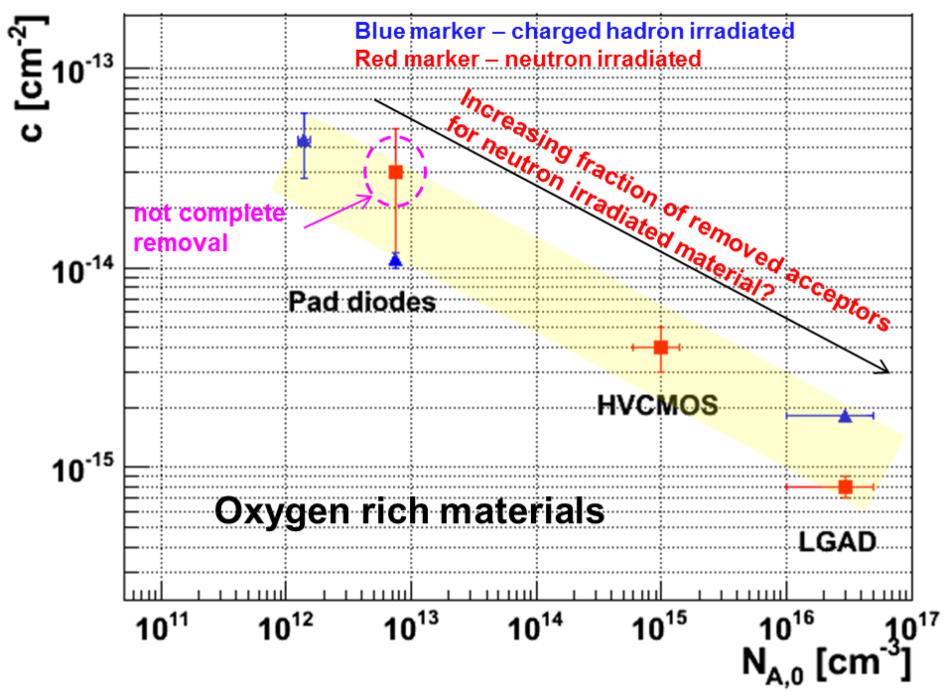


Changes in doping with irradiation

$$V_{fd} = \frac{e_0 N_{eff} W^2}{2\epsilon\epsilon_0}$$

$$|N_{eff}| = |N_{eff,0}| + g_{eff} \cdot \Phi_{eq} - N_{C0}\left[1 - \exp(-c \cdot \Phi_{eq})\right] + N_{BA} + N_{RA}$$





Gain degradation with fluence

- Gain degrades faster with charged hadrons than with neutrons at the same equivalent fluence (also in HVCMOS – see Igor's talk).
- Effective acceptor removal rate is a function of initial doping concentration – not all acceptors are removed for smaller concentrations (what is optimum doping).

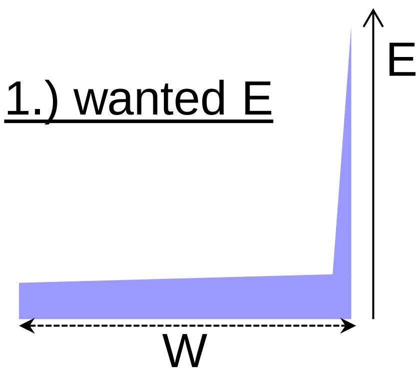
GO THIN

- Good timing devices are required to be thin for several reasons:
  - time walk, due to energy loss fluctuations becomes a smaller problem
  - an additional advantage is short drift times and consequently trapping effects (e.g. 50 μm thick device and the saturation velocity for holes yields drift time of 600 ps -> few 10^{15} cm^{-2} the trapping should not influence the performance dramatically
  - slew rate of the signal is proportional to ratio Gain/Thickness (weighting field effect)
- properties of the bulk becomes more important for gain than in standard detectors

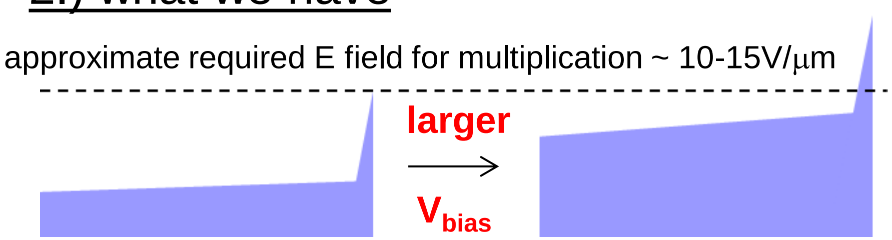
Thin epitaxial LGAD - device

- Run 6827 (CNM) – gain is smaller than expected from this run (too low boron concentration)
- They are functional devices which can stand very high voltages
- Small circular pads (2r=1 mm) – small capacitance

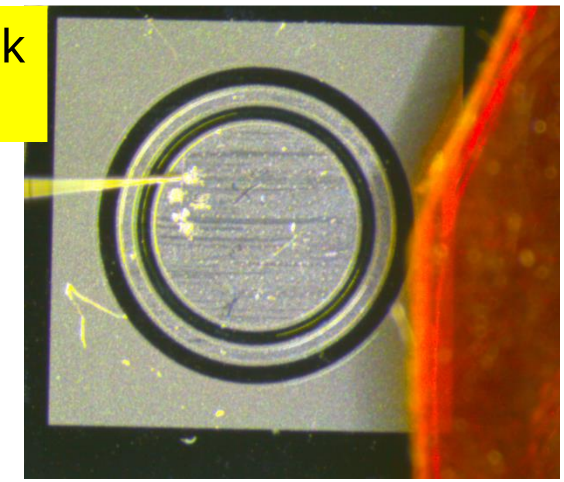
1.) wanted E



2.) what we have



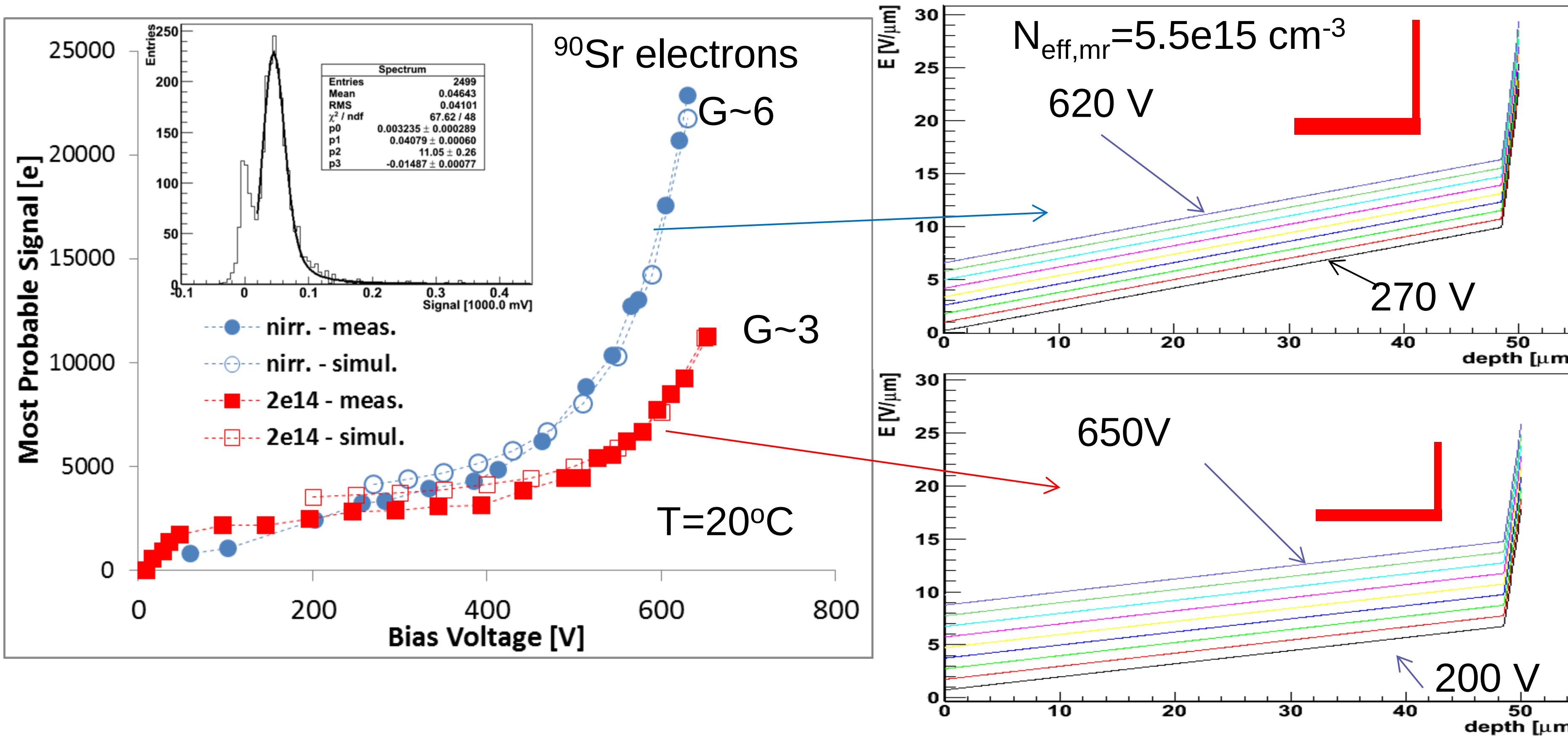
Epi 50 μm thick
100 Ωcm



with over depletion ($V>V_{fd}$) the electric field in the multiplication layer grows as: **$\Delta E = \Delta V / W$**

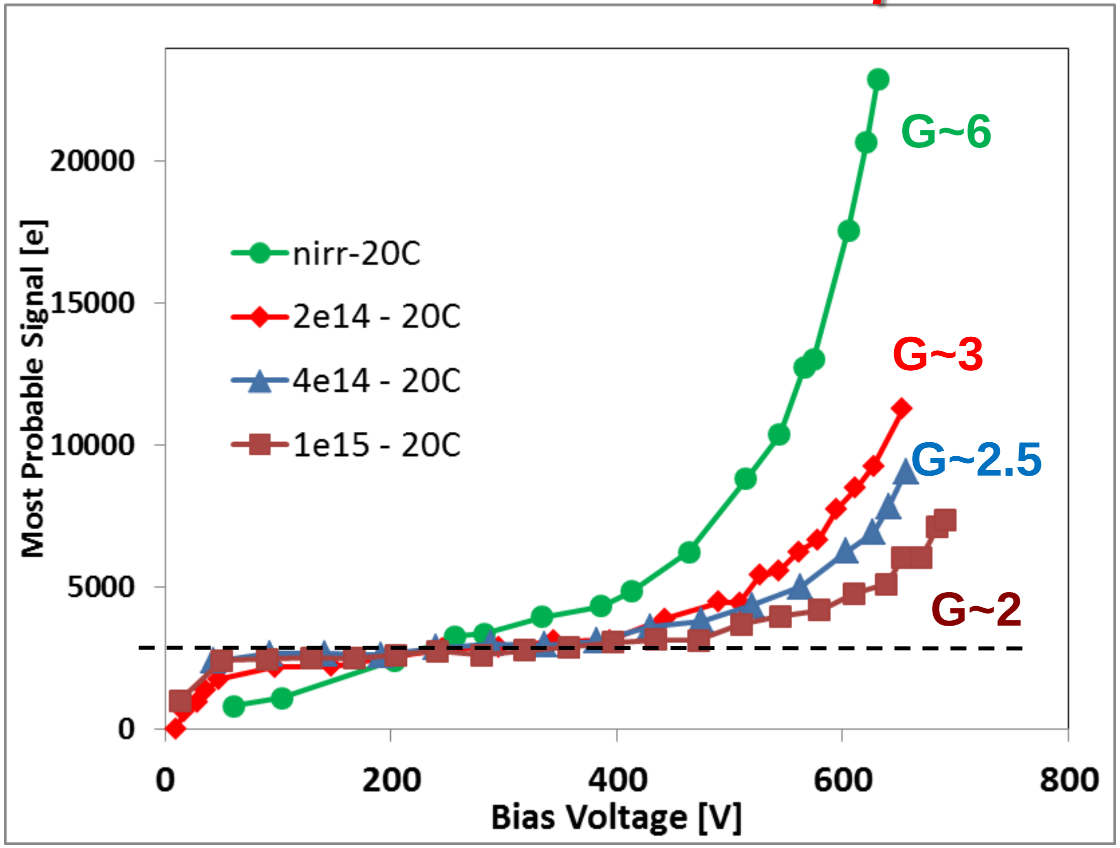
Smaller electric field in the multiplication layer can be much easily compensated with higher applied bias voltage.

Charge collection and simulation



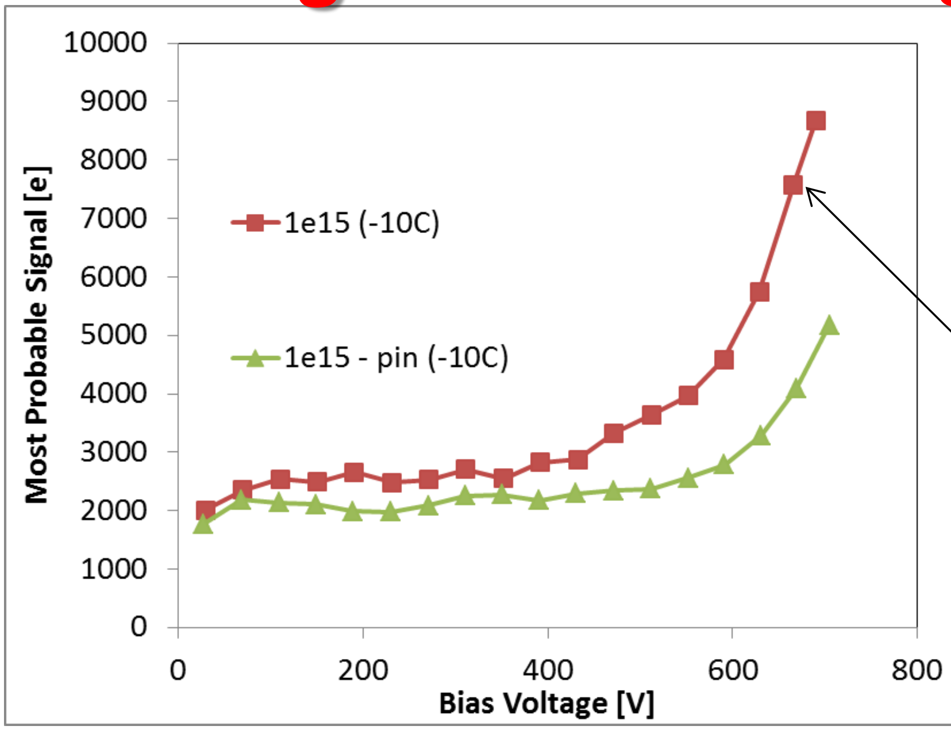
- At high voltages the simulation describes quite well the measurements
- Effect of deep traps is small due to small thickness and high bias voltage
- Acceptor removal and deep acceptor generation was assumed with data known from LGAD and HVCMOS measurements.

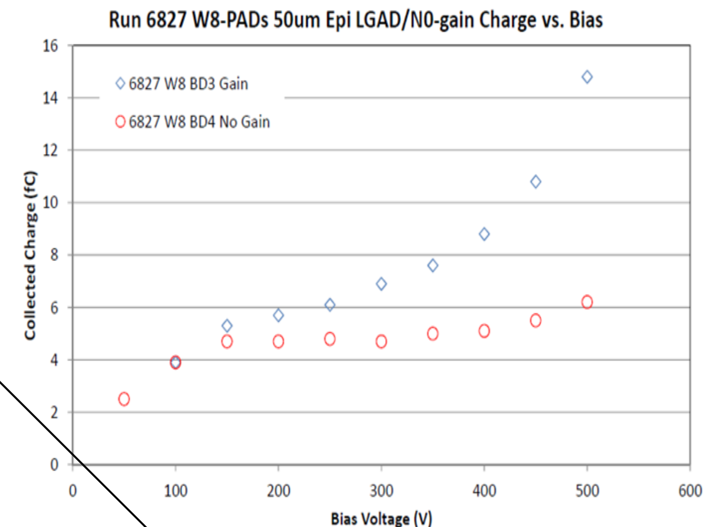
Charge collection – Q-V(Φ_{eq})

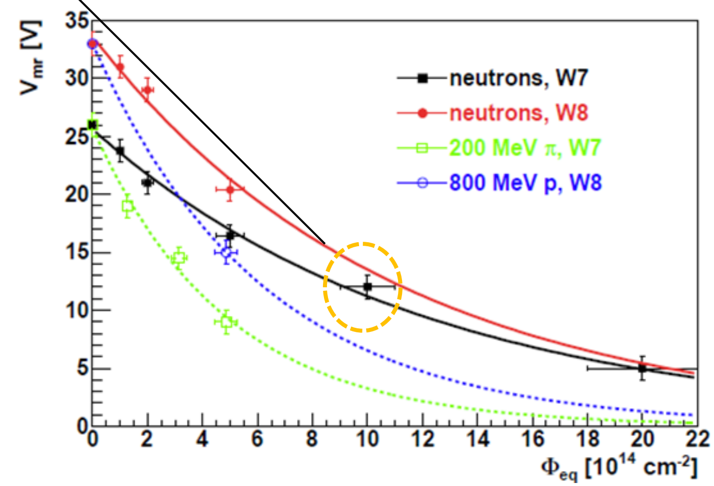


- Gain decreases with irradiation in expected way.
- Almost no trapping of the drifting charge.
- Significant reduction of full depletion voltage – acceptor removal in the bulk.

Charge collection – Q-V(Φ_{eq})

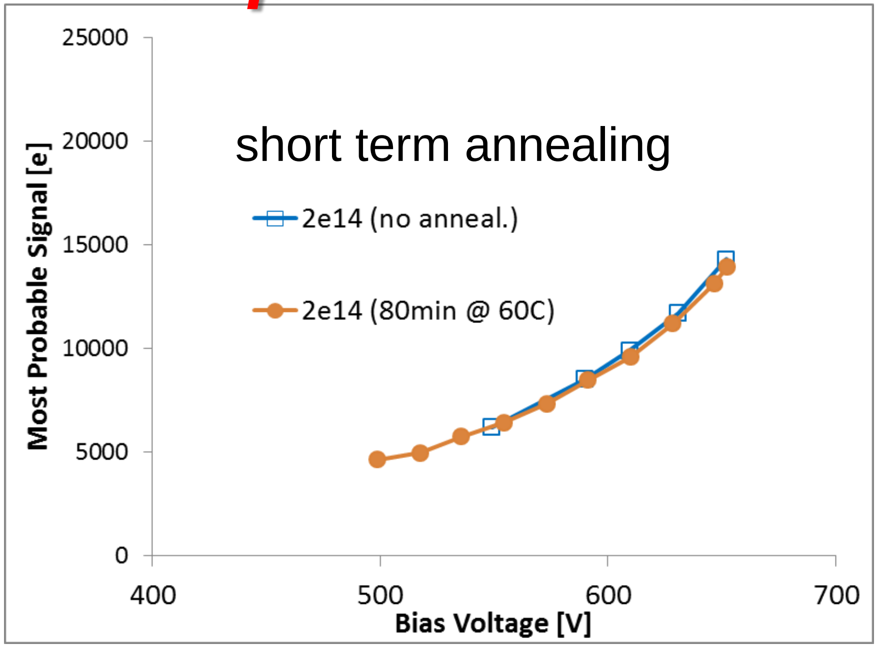


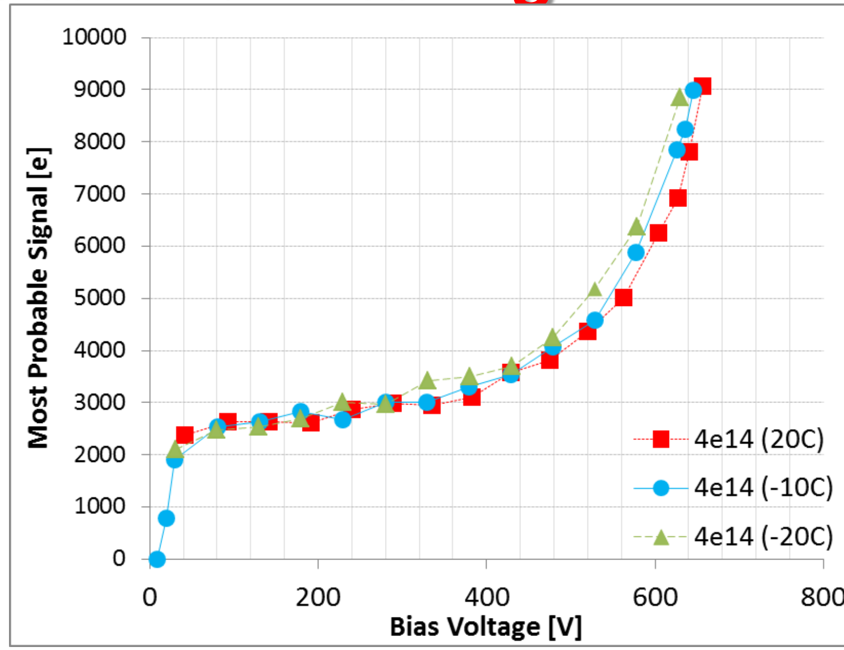




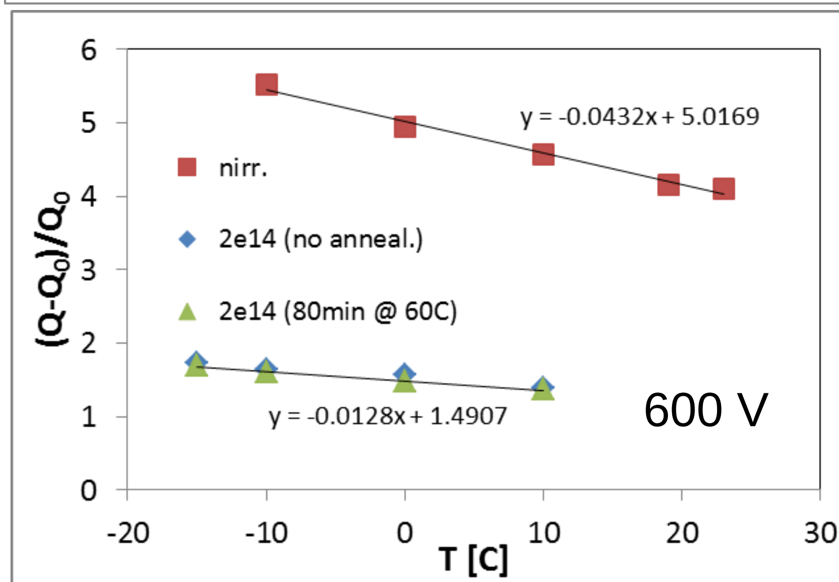
- A significant difference between LGAD and PIN sample after 1e15 cm^{-2}
- Can we shift that to lower values? We should see in the new run from CNM…

Temperature and short term annealing

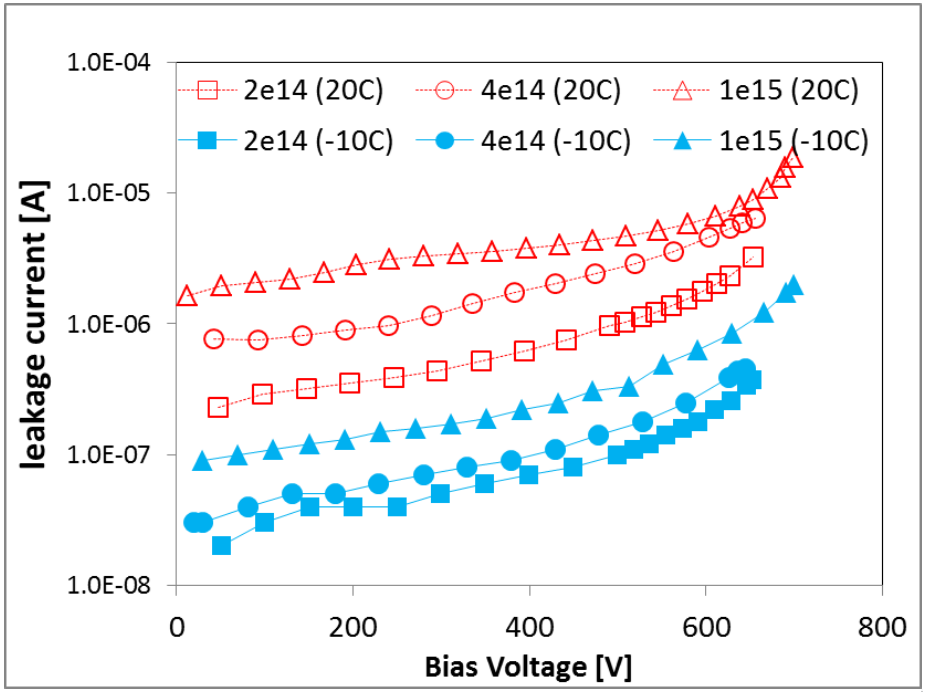


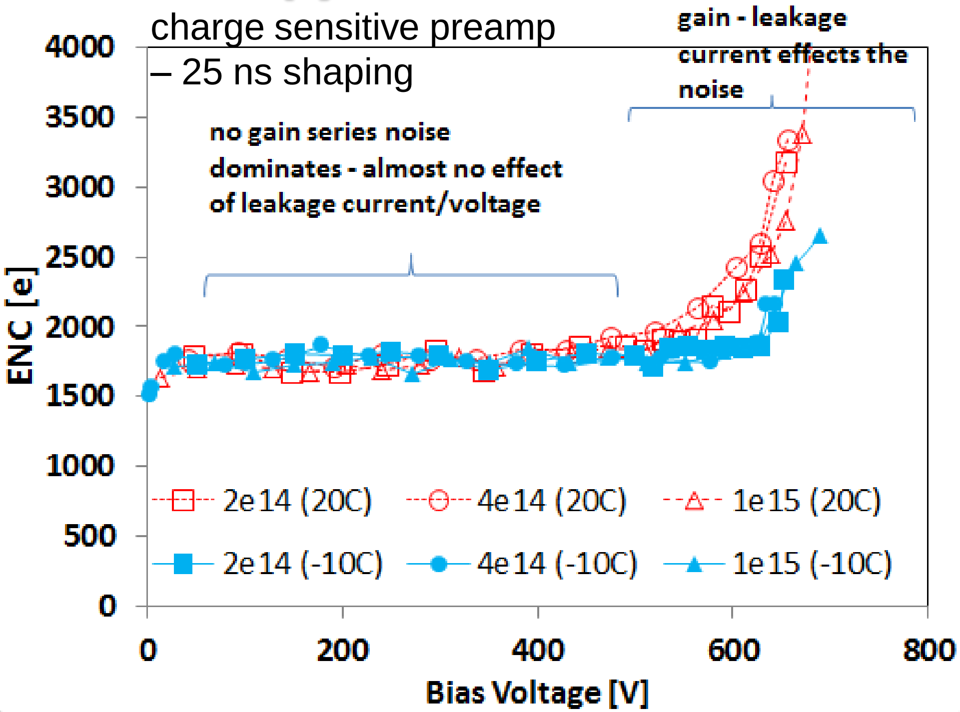


- No influence of short term annealing (changes of N_{eff} to small in comparison with doping)
- The gain depends on temperature roughly ~1%/K
- Going to lower temperatures improves substantially the signal



Leakage current and Noise (I)





How to influence/control the noise:

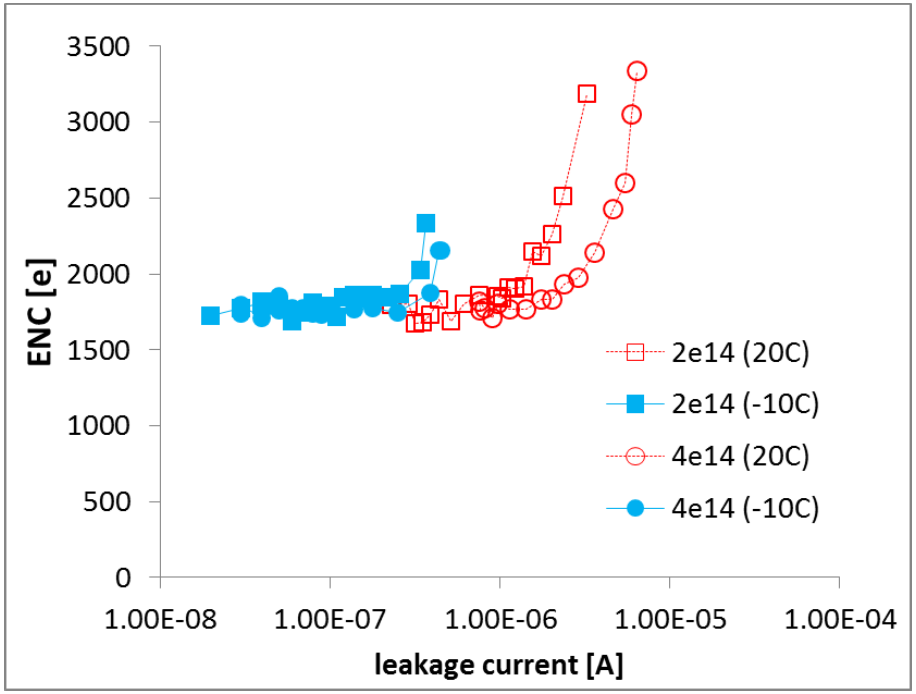
- keep generation current I_{gen} small
  - cool down the detectors
  - thin detectors
  - annealing of the current
- go fast – small τ
- optimize shaping k_f

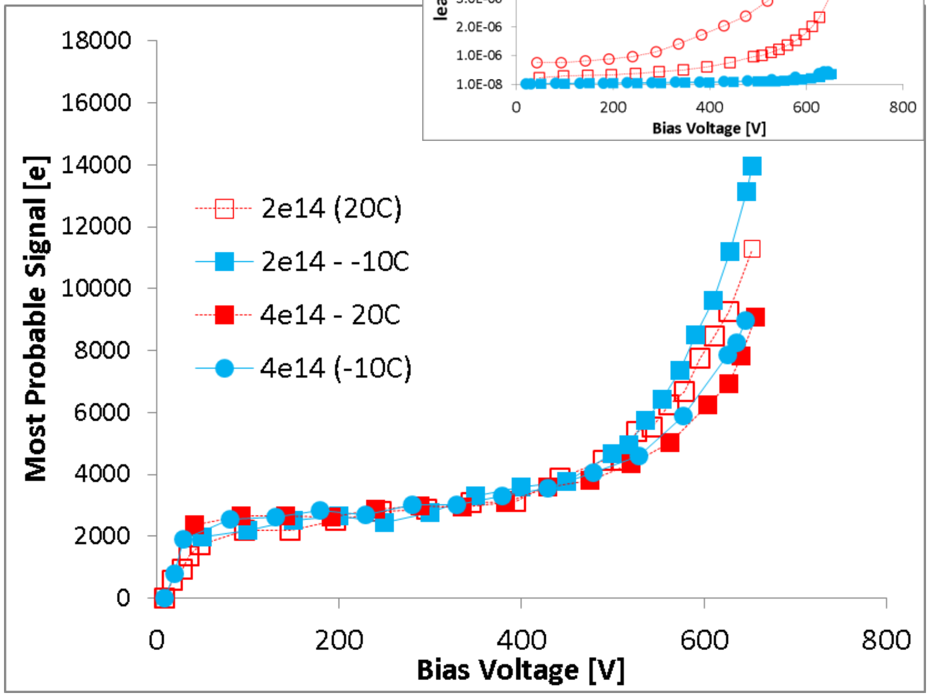
$$\frac{S}{N} = \frac{M_Q Q}{\sqrt{ENC_S^2 + k_f\, F\, M_I^2\, e_0 I_{gen}\, \tau}}$$

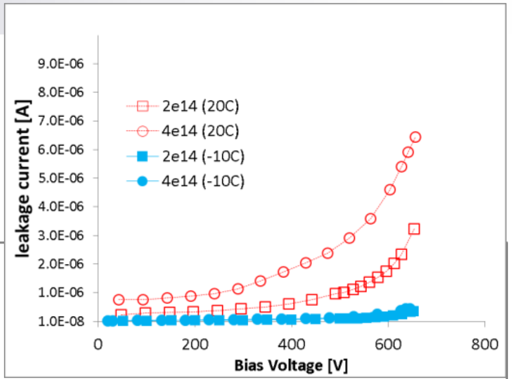
$$ENC_S^2 \gg k_f\, F\, M_I^2\, e_0 I_{gen}\, \tau$$

- $M_I \sim M_Q$ (for thin) - gain
- $F = 2$ for $M \gg 1$, $F=1$ for $M \sim 1$
- k_f - factor depending on shaping
- τ –shaping time

Leakage current and Noise (II)





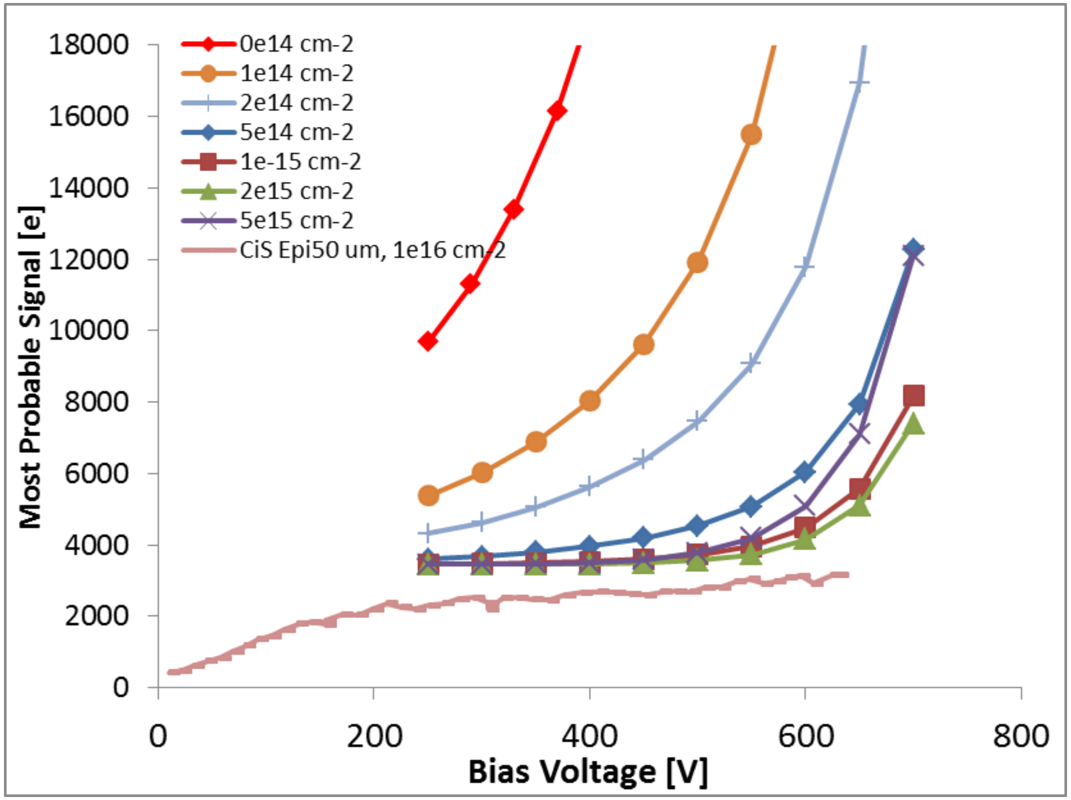


- Leakage current increases linearly with gain – so does the noise
- At low temperatures the increase of noise is smaller with bigger gain.

OPERATION AT LOW TEMPERATURES IS ESSENTIAL.

What can we expect?

Same material is assumed as simulated before, with double N_{eff} in multiplication zone (~1e16 cm^{-3}), other parameters as known from literature



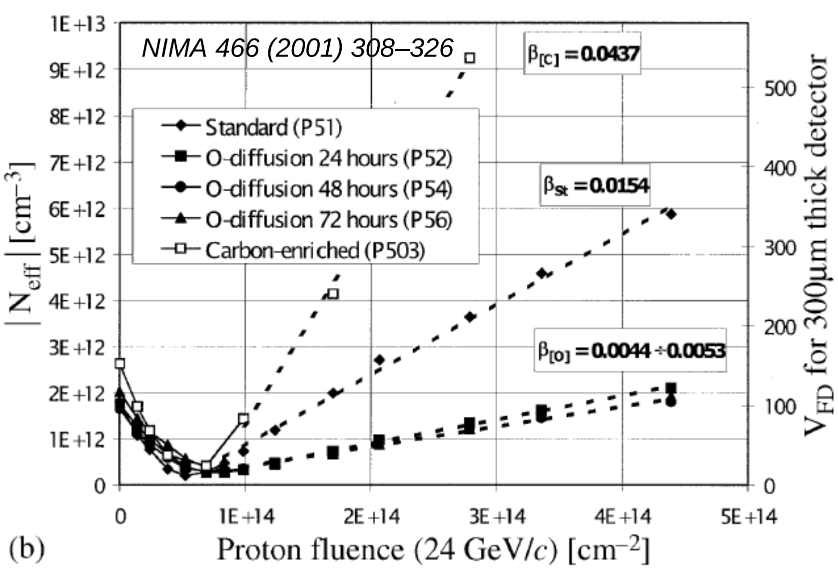
- Trapping of drifting charge ignored – effect nicely seen for irradiated sample
- Irradiation should affect multiplication in the similar way as it does mobility >5e15 cm-2 - one of our tasks is to measure $\alpha_{e,h}(\Phi_{eq})$
- There will be moderation n of the field (due to trapped holes) at extreme fluences

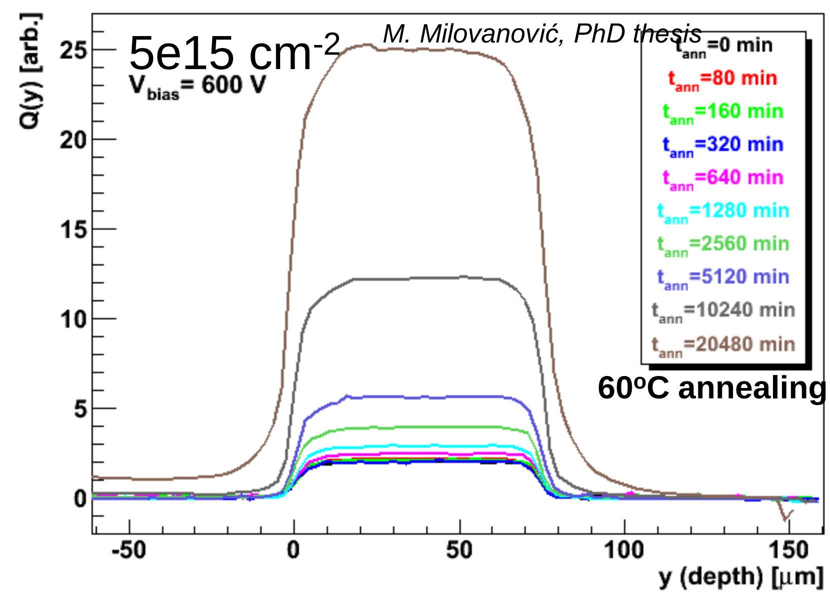
A better detector is needed for e.g. HGTD.

Ways to improve gain after irradiation

The paradigm has changed - we want as high N_{eff} as possible for peaked fields:

- ✓ Long term annealing has been shown to significantly increase multiplication (soon to be tested on LGAD devices)?
- See if impurities such as C (carbon enriched Si) help to keep N_{eff} high:
  - reduces the amount of removed initial acceptors
  - larger introduction of deep acceptors
- Is maybe Ga less prone to effective acceptor removal?





Conclusions

- Radiation hardness is a major challenge for LGAD: fast degradation of the gain with fluence
- Thin sensors that can sustain large bias voltage show better performance than standard detectors – less sensitive to acceptor removal in multiplication layer
- A significant difference of LGAD and PIN diode at 1e15 cm^{-2}
- Different ways to improve gain loss are sought:
  - prolonged annealing
  - carbon enrichment of silicon
  - gallium doping

A new CNM and FBK run with much larger gain at lower voltages opens a lot of possibilities….