Performance of thin LGADs after long term annealing

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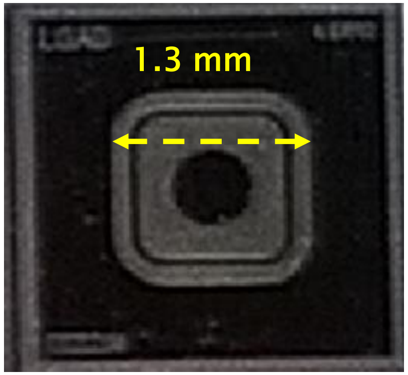
Motivation & Sensors used

- Annealing is important in detector operation
  - almost all detector properties change with annealing – **for LGADs these changes can be less important than for standard silicon detectors**
  - annealing can potentially influence initial acceptor removal
  - annealing studies are required to plan the operation scenario
  - required to predict operations in case of unplanned situations/events

- Most of the studies done so far with LGADs were either not-annealed (as irradiated whatever that means) or more often after 80 min annealing at 60°C.

- Samples from **CNM R10478** were measured with ^{90}Sr and TCT:
  - 1.3x1.3 mm^2 single pads (gain 1x1 mm^2)
  - 50 μm thick
  - W4 samples
  - samples irradiated 6e14 and 3e15 cm^{-2} of reactor neutrons



- Measurements were performed with triggered ^{90}Sr electrons (25 ns electronics)

Annealing of LGADs (N_{eff})

$$\Delta N_{eff} = g_a \Phi_{eq} \exp(-\frac{t}{\tau_a}) + N_c + g_Y \Phi_{eq} (1 - \exp(-\frac{t}{\tau_{ra}}))$$

$$N_c = \pm N_{id}(1 - \eta(1 - \exp(-c \cdot \Phi_{eq}))) + g_c \Phi_{eq} \quad ,$$

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

short term annealing

Stable damage
- removal
- deep acceptors

long term/"reverse" annealing

- What is the impact of short and long term annealing?
  - on bulk (low initial doping)
  - multiplication layer (large initial doping)
- Does *c* change in time (not "constant")? In principle it can (I,V reactions with B_s).
- If activation energy for reverse annealing is used E_a=1.31eV then multiplication t(60ºC)/t(20ºC)~510 -> 1day @ 20ºC ~ 3 min @ 60ºC

What can we expect?

- Bulk will be affected : g_Y~0.05 cm^{-1} around 2.5x larger than g_c:
  - at 6e14 cm^{-2} -> N_Y=3e13 cm^{-3} and N_C=1.2e13 cm^{-3}
  - at 3e15 cm^{-2} -> N_Y=1.5e14 cm^{-3} and N_C=6e13 cm^{-3}

  $V_{fd,max}$~370 V (for 3e15 cm^{-2}) << 600 V required for operation:
  - we expect fully active detector
  - saturated drift velocities
  - more bulk multiplication ??

  } bulk will be affected, but at operation point changes will be small

- Gain layer – for c=7e-16 cm^{-2}:
  - at 6e14 cm^{-2} -> 35% of acceptors are removed
  - at 3e15 cm^{-2} -> 87% of acceptors are removed

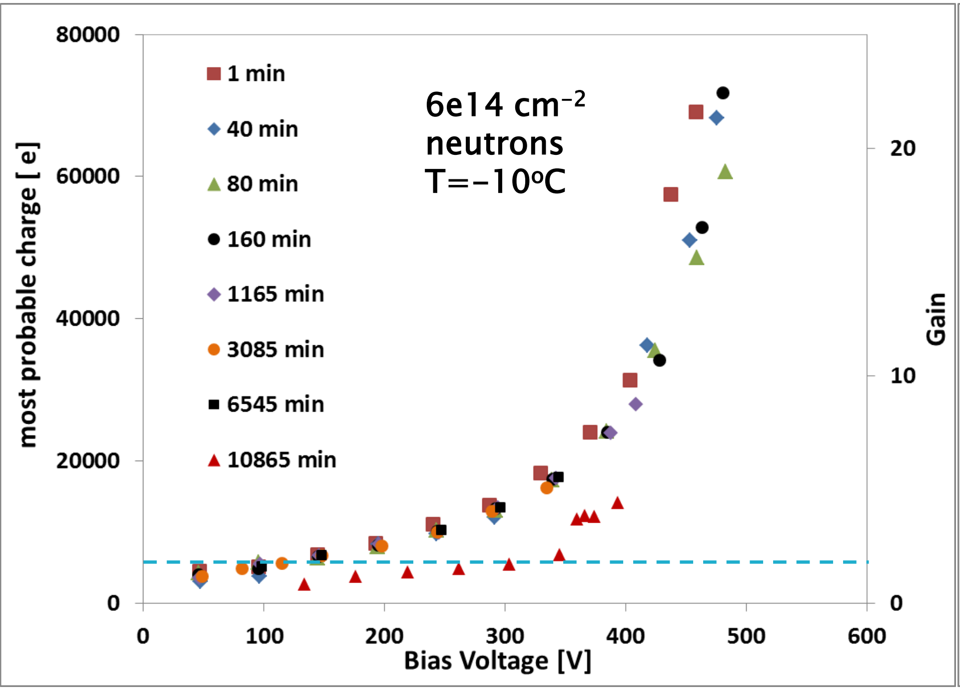
  N_B~1e16 cm^{-3} -> can not be much influenced by annealing

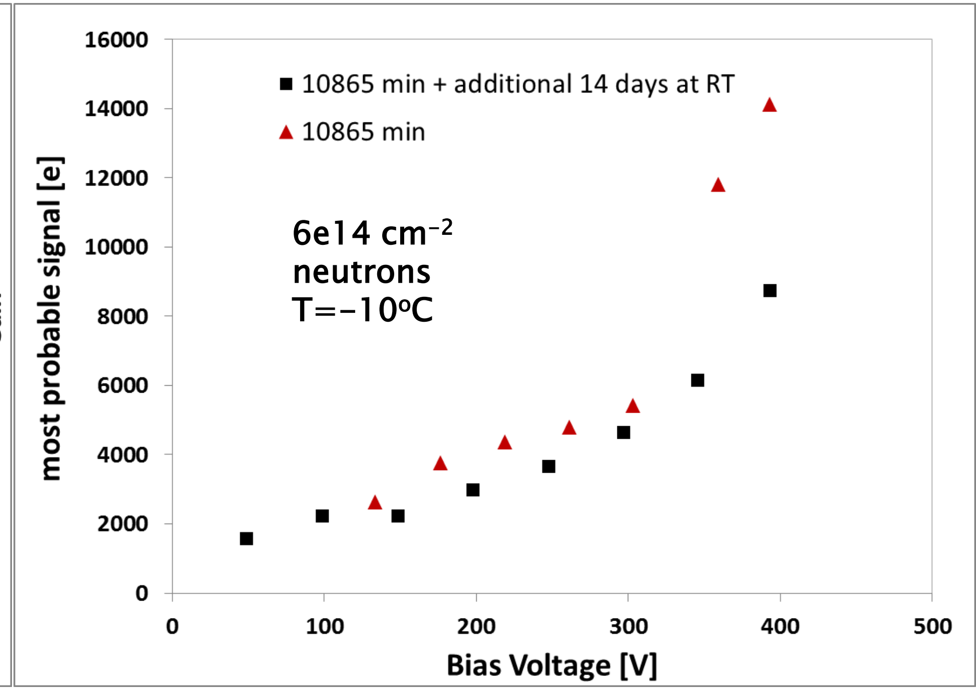
  } multiplication layer will not be affected significantly

- We should see a decrease of leakage current with annealing – there is no reverse annealing of leakage current. The leakage current should scale with $I = M_I \cdot I_{gen}$ in all stages.

- Annealing of trapping times should have a minor impact (if, then positive) on operation.

Gain measurements for 6e14 cm^{-2} (I)





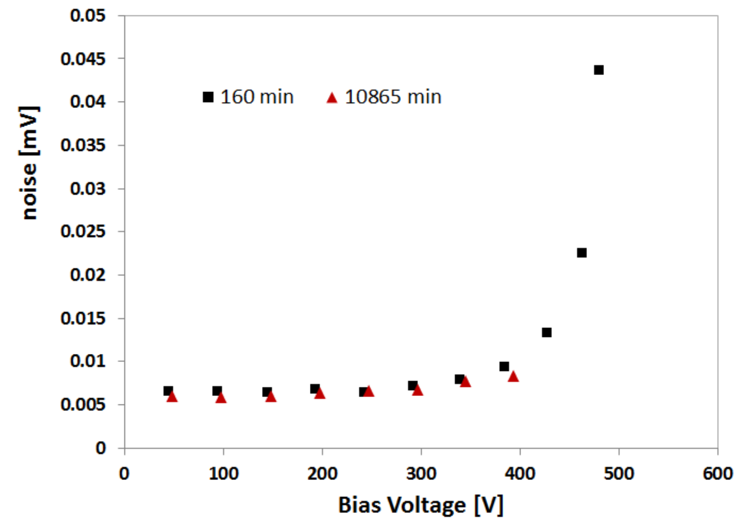
Several observations:

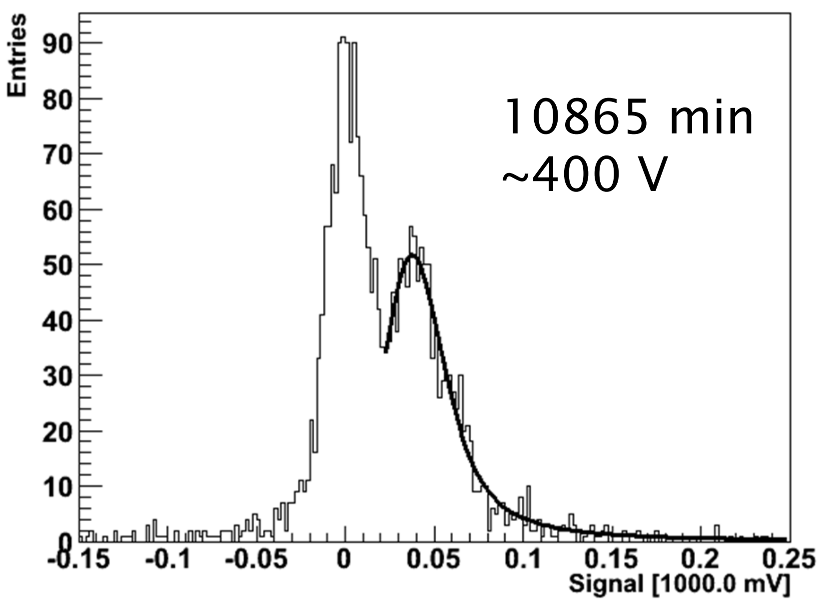
- annealing doesn't influence charge collection gain up to ~ 6000 min @ 60°C (as expected)
- after 10000 min the CC is significantly smaller – not clear how??
- at larger annealing times the spurious events ("micro-discharges") at rapid increase of gain reduce the reach of bias voltage:

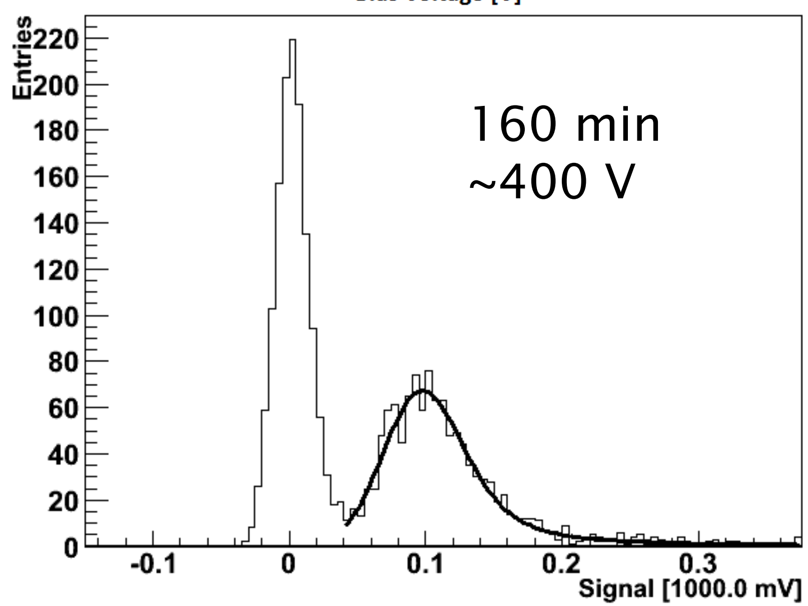
  ~500 V after 160 min @ 60C, ~430 V after 1165 min @ 60C ,
  ~340 V after 3085 min @ 60C, ~400 V after 10965 min @ 60C

Gain measurements for 6e14 cm^{-2} (II)

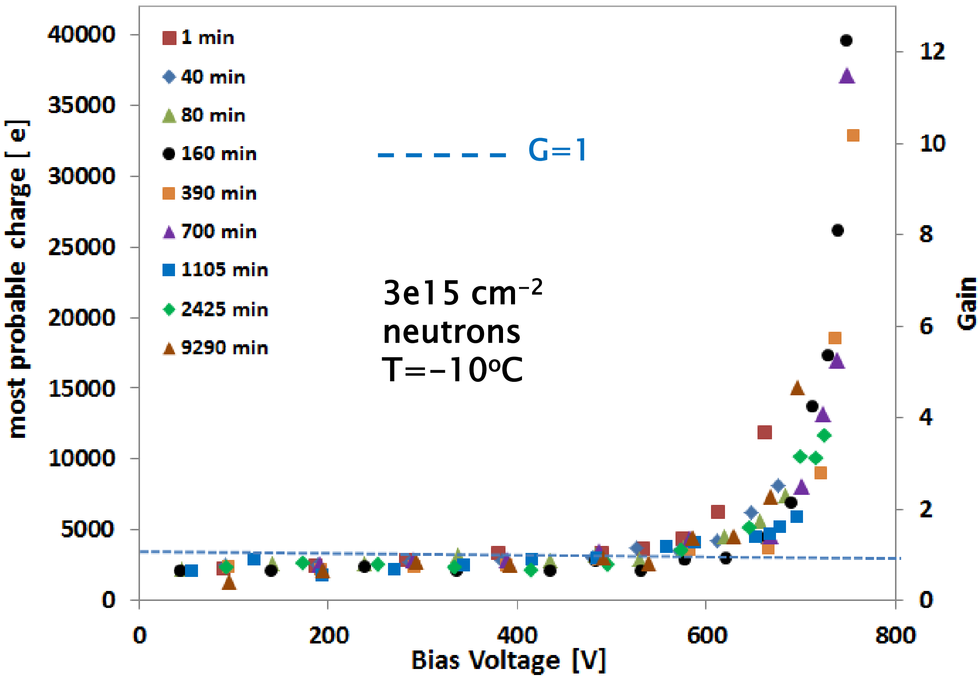
- A clear difference in signal spectrum at the same bias voltage
- Noise stays similar

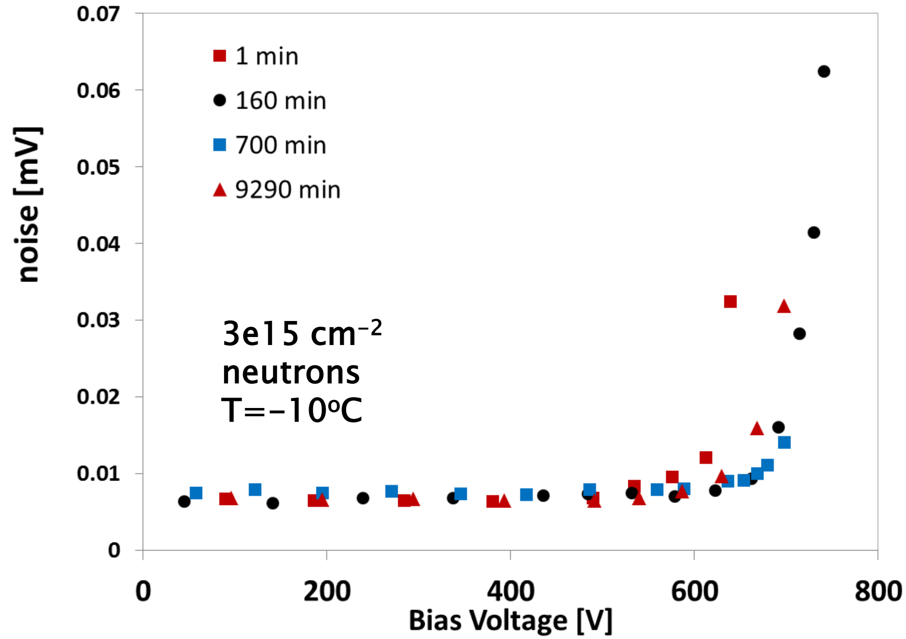






Gain measurements for 3e15 cm^{-2} (I)

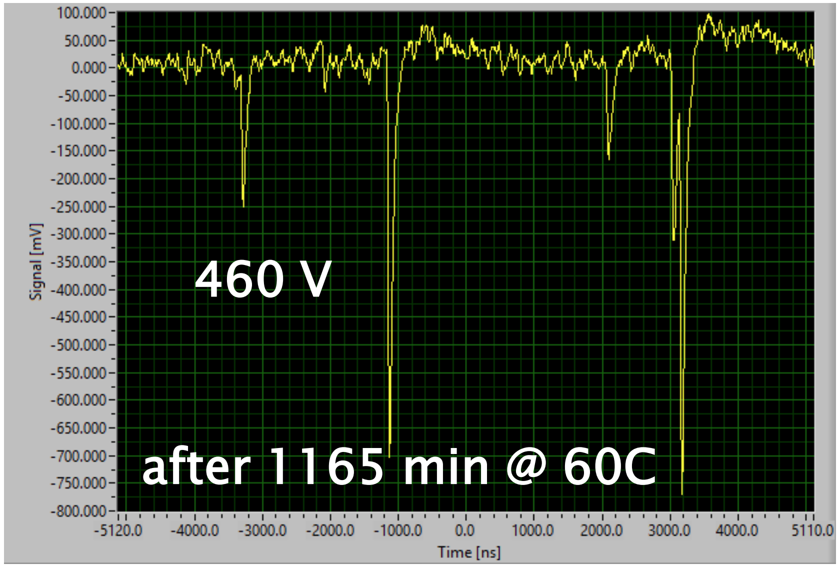




- The annealing doesn't influence much the collected charge – possibly somewhat better performance before annealing in terms of smaller voltage required for a given gain.
- Further steps are required to see more detailed impact of annealing.
- Noise depends on gain:
  - no the difference in noise between different annealing points with no gain and different leakage/generation current
  - large difference when gain appears.

Spurious (“Self-trigger”) events (6e14 cm^{-2})

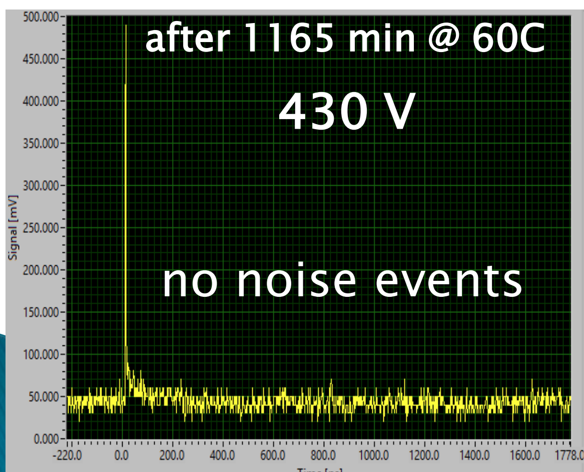
^{90}Sr setup with 25 ns shaping electronics

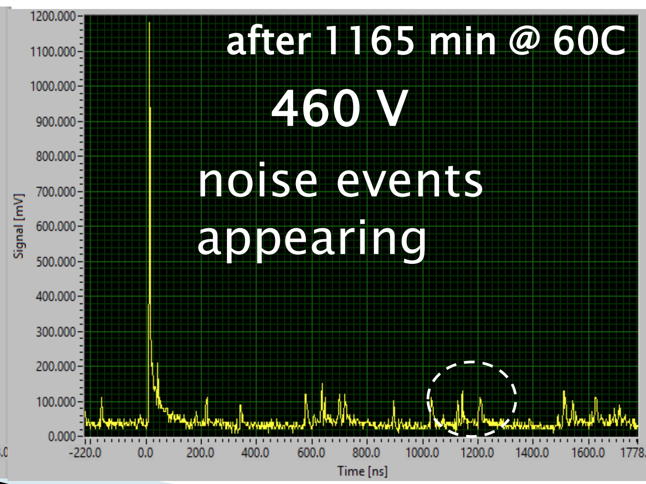


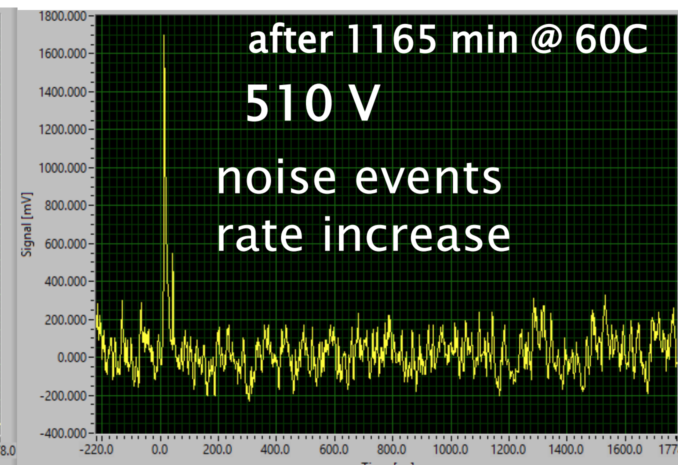
Occasional large signals – spurious events:

- the higher the voltage the larger the rate
- they look like regular hits – appear even without source (thermally triggered – SiPM like events?)
- appear in ^{90}Sr and TCT setups – not a feature of setup
- could be development of a hot spot with annealing around JTE or humidity related (not controlled in our setups) surface charge re-distributions or simply a much steeper rise of gain.

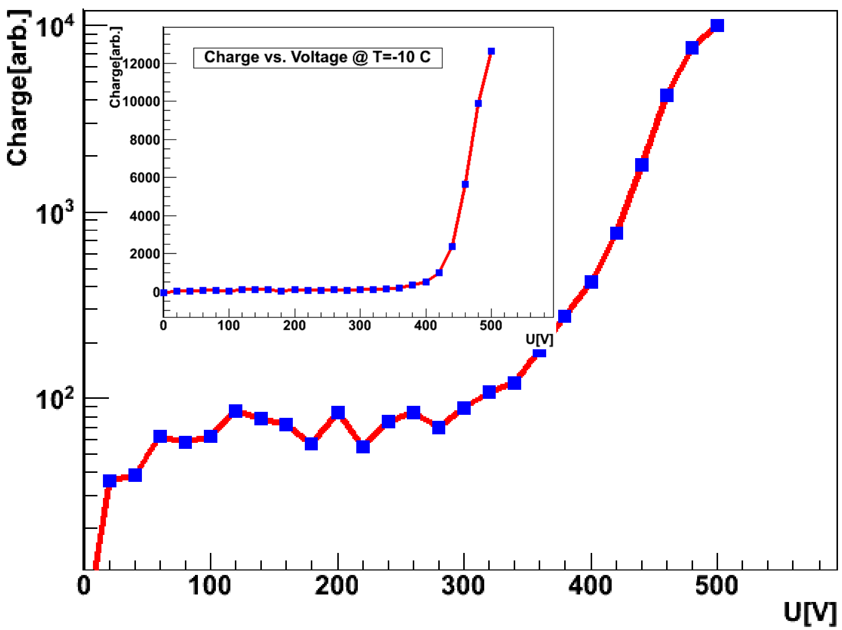
TCT measurements with red 660 nm laser

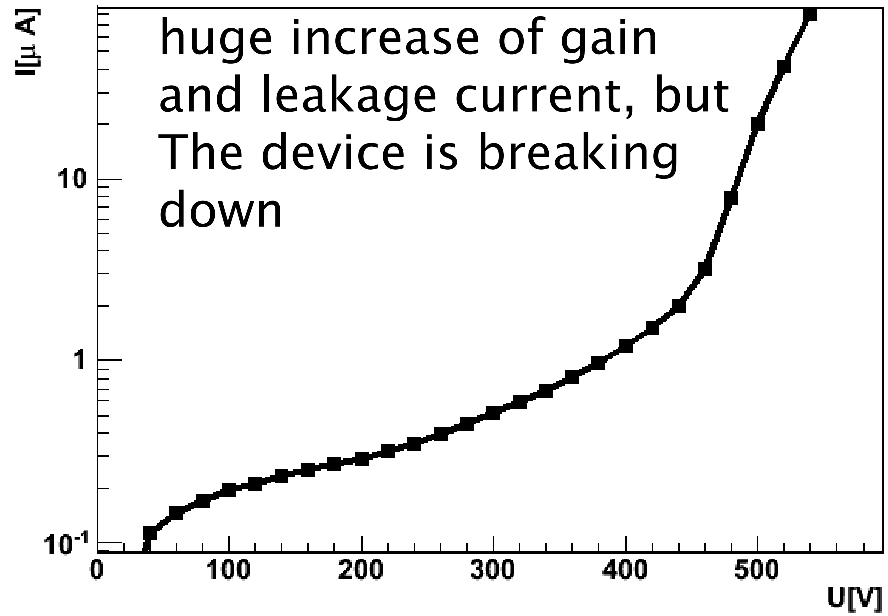






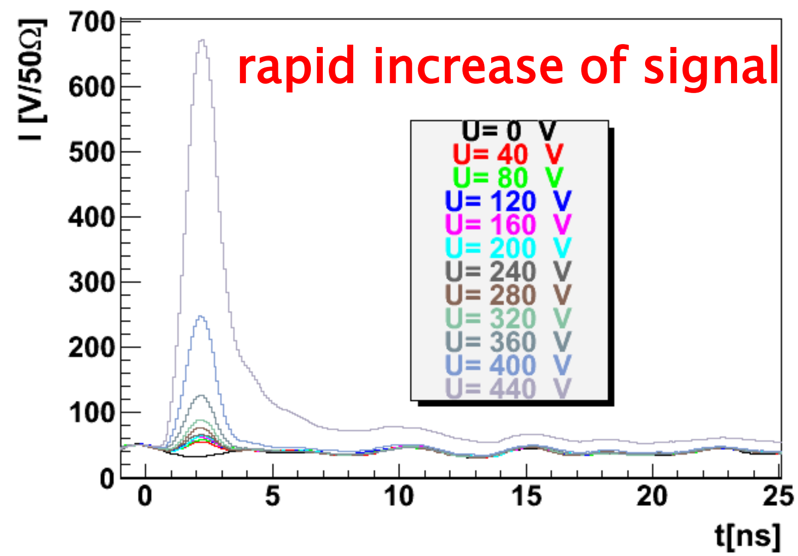
Spurious events with TCT (6e14 cm^{-2})



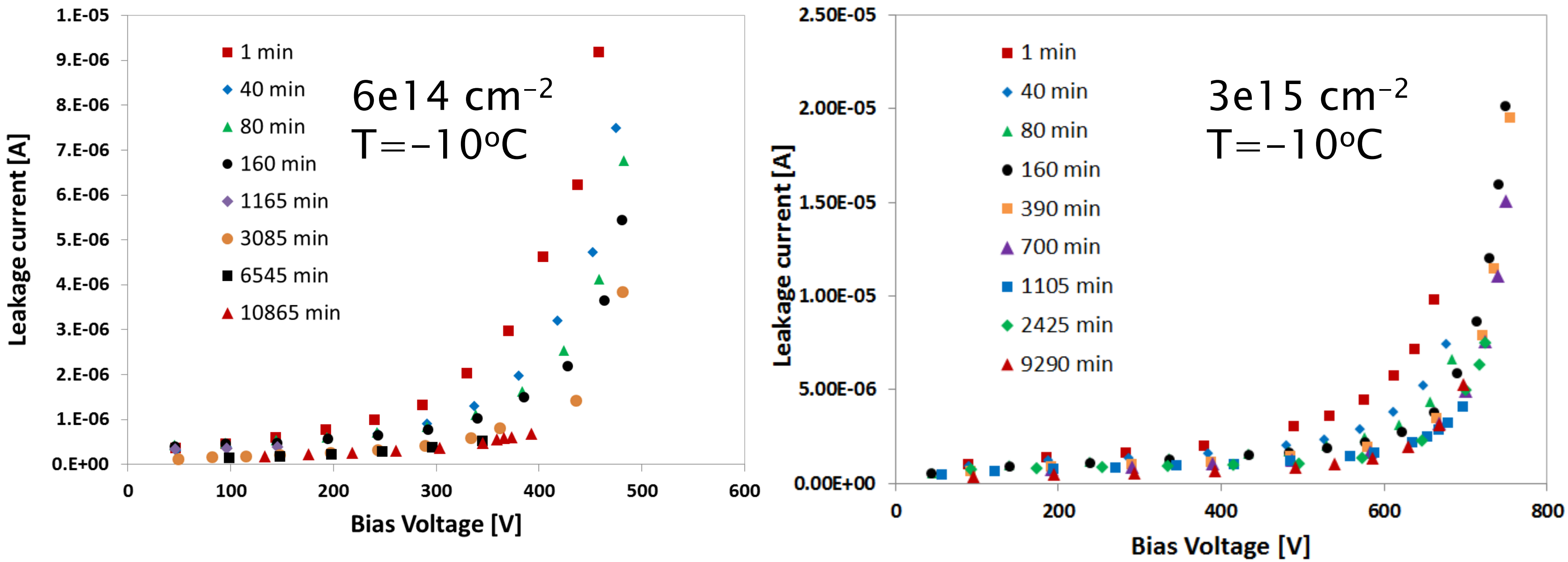


- Leakage current and induced current and charge show steep rise of the charge
- Device is breaking down – noise hits

after 1165 min @ 60C



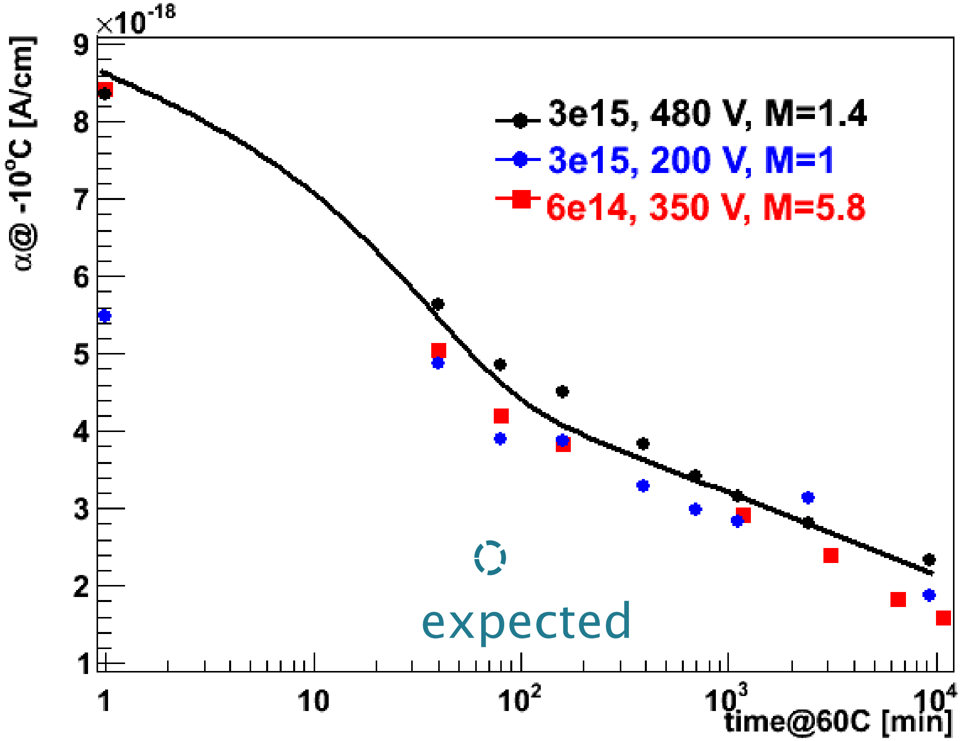
Leakage current



- Expected decrease of leakage current – larger for low fluence that for high fluence, due to larger multuplication factor
- Decrease of gain with fluence…

$$I = M_I \cdot I_{gen}$$

Annealing of leakage current



$$I = MI \cdot Ig_{en}$$

$$I_{gen} = \alpha \phi_{eq} \mathrm{Sd}$$

$$\alpha = \frac{I}{M_I \phi_{eq} \mathrm{Sd}}$$

$$\alpha(t) = \alpha_1 \exp\left(-\frac{t}{t_\alpha}\right) + \alpha_0 - \alpha_2 \ln(-\frac{t}{1min})$$

α_0 =(2.3±1)e-18 A/cm (5.4e-19)

α_1 = (6.3±0.8)e-18 A/cm (2.7e-18)

α_2 =(4.6±1.15)e-19A/cm (1.79e-19)

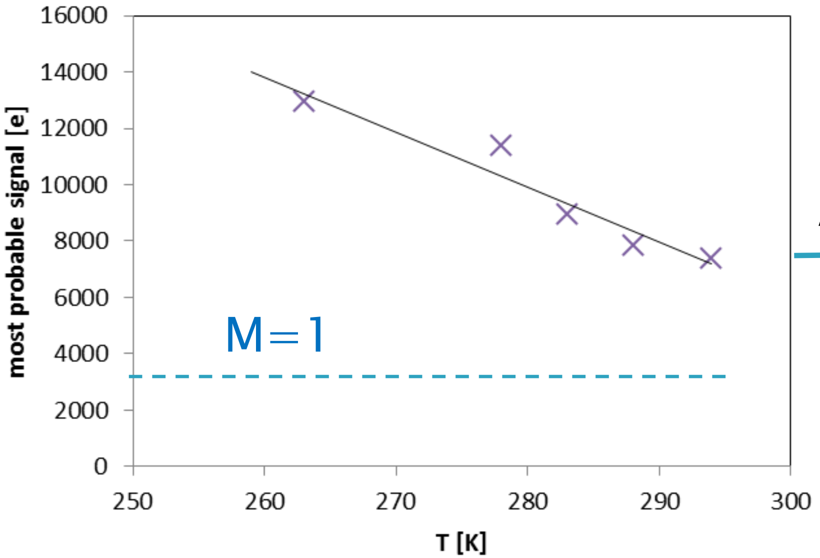
t_α =37±28 min (93 min)

From NIM A 426 (1999) 87.
and scaled to -10C

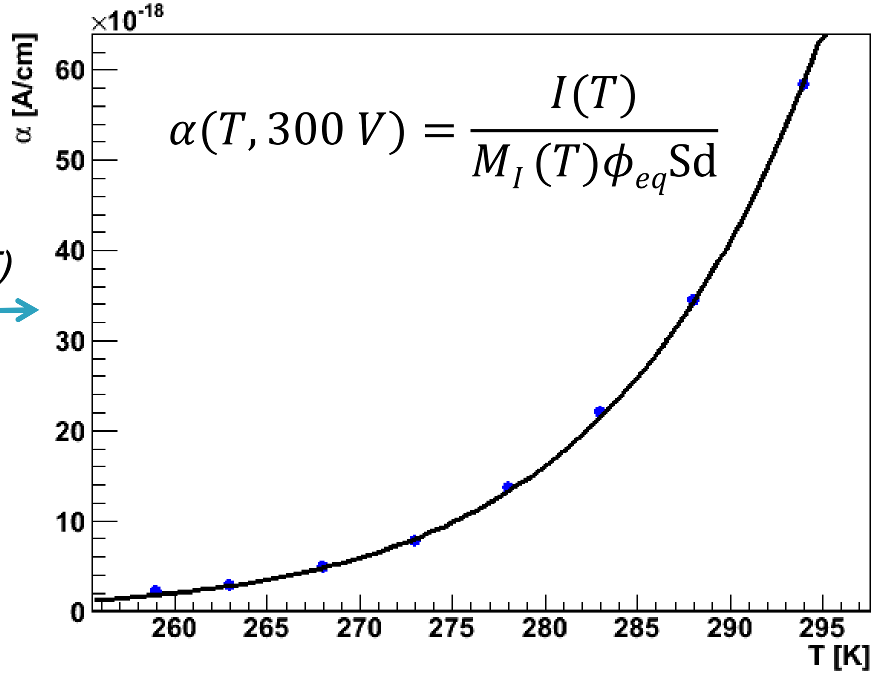
- Leakage current damage constant around a factor of two higher than calculated: guard current, systematic shift in T, $M_I \neq M_Q$?
- The annealing function works well
- If multiplication is accounted for the agreement at different bias points is acceptable.
- Clearly much more studies are needed to get/confirm the parametrization – important for both ATLAS and CMS

Temperature dependence of I_{gen}

after 3085 min annealing at 60°C
for 6e14 cm^{-2} sample



$M_I(T)$



$\alpha \propto T^2 \exp(-E_a/2k_BT)$

Leakage current scales as expected with T – determined by $M_I(T)$ and $I_{gen}(T)$.

There is no reason that wouldn't hold at all annealing stages.

E_a=1.21 eV – compatible with previous measurements!

Conclusions

- Annealing has little effect on operation of LGADs apart from beneficial large decrease of current (as expected) up to around 6000 min at 60ºC
- There is an indication that short term annealing pushes the operation point (at given gain) to somewhat higher voltages
- After long term annealing we noticed:
  - "spurious events" – observed both in TCT and ^{90}Sr measurements
    - appear close to break down of the device
    - look like regular hits (thermally generated carriers?)
    - should be further studied!
  - drop in charge collection after ~10000 min@60ºC for detector irradiated to low fluence
- Leakage current
  - behaves as expected during long term annealing, but model parameters should be confirmed
  - scales with temperature if E_a=1.21eV