Annealing studies of HPK LGAD samples

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Motivation

- LGADs are planned for ATLAS High Granularity Timing Detector (HGTD)

- Lots of studies have been done, but a very large majority of those after 80min@60°C annealing

- Annealing studies are needed:
  - to predict long term operation and plan operation scenario
  - to know the limits/dangers of possible unplanned events/situations

- Annealing is important in detector operation
  - almost all detector bulk properties change with annealing (for LGADs these changes can be less important than for standard silicon detectors due to smaller thickness and high bias)
  - annealing could potentially influence initial acceptor removal

Annealing of LGADs

- We can expect significant decrease of generation current, but in LGADs the total current is the product of gain and I_{gen} so difficult to disentangle both
- Trapping will be less affected due to small thickness – improvements due to reduced electron trapping / occupied traps?

$$\begin{aligned} \Delta N_{eff} &= g_a \Phi_{eq} \exp\left(-\frac{t}{\tau_a}\right) + N_c + g_Y \Phi_{eq}\left(1 - \exp\left(-\frac{t}{\tau_{ra}}\right)\right) \\ N_c &= \pm N_{id}(1 - \eta(1 - \exp(-c \cdot \Phi_{eq}))) + g_c \Phi_{eq} \quad , \end{aligned}$$

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

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* depend on annealing (I,V reactions with B_s)?
- Are these equations still valid in the presence of enhanced hole concentration?
- Are they valid in very high electric fields?

What can we expect?

- Bulk will be affected : $g_Y \sim 0.05\ cm^{-1}$ around 2.5x larger than g_c:
  - at 8e14 cm^{-2} -> N_Y=4e13 cm^{-3} and N_C=1.6e13 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 should be small

- Gain layer – for c=5e-16 cm^2:
  - at 8e14 cm^{-2} -> 33% of acceptors are removed
  - at 3e15 cm^{-2} -> 78% of acceptors are removed

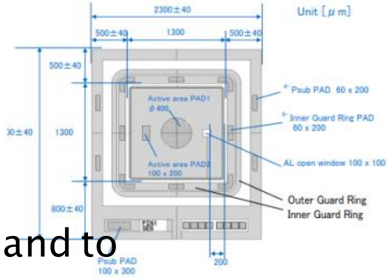
  N_B~1e16 cm^{-3} -> can not be much influenced by annealing

  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.

Samples, setup and procedures

- Samples were produced by HPK (LGAD run 4) – different gain layer doses for T3.2, T3.1
- 50 μm thick substrate,
- 1.3x1.3 mm^2 single pad devices
- V_{mr} ~55 V (very high initial gain, T3.2)
- V_{mr} ~40 V (moderate initial gain, T3.1)



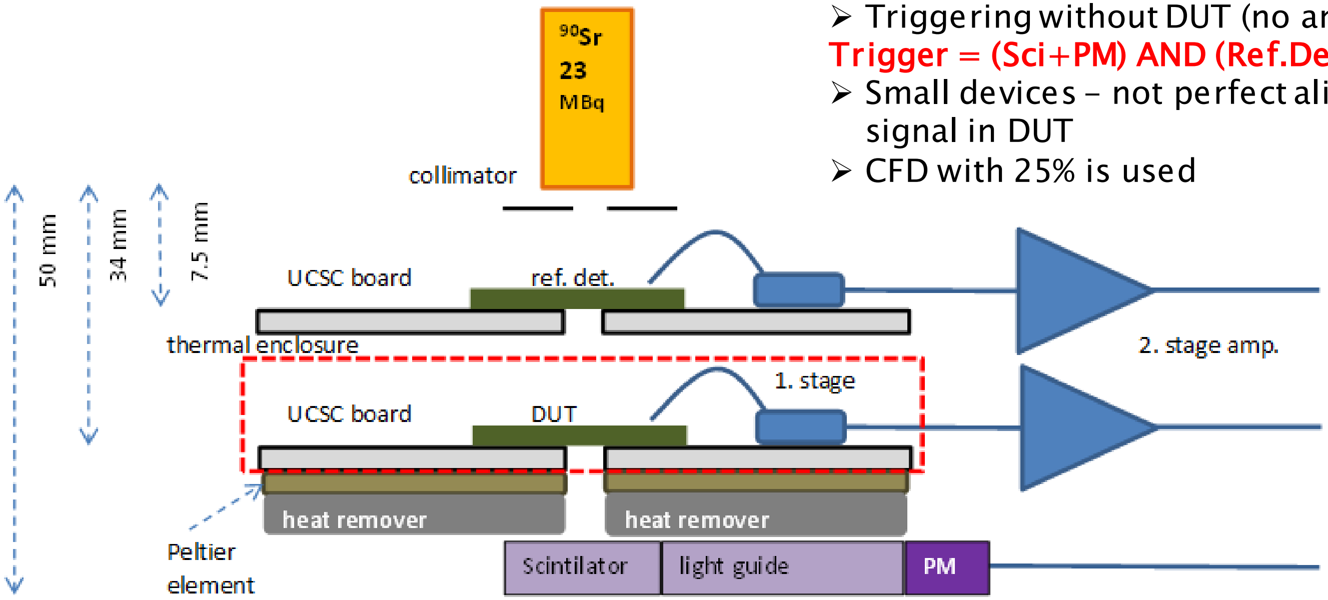
- ☐ T3.2 samples were irradiated to 4 ,8 ,15, 30, 60e14 cm^{-2} for annealing studies and to intermediate fluences for consistency (2.25,4,5e15 cm^{-2})
- ☐ T3.1 samples were irradiated to 15, 30e14 cm^{-2}

After irradiations the samples were annealed in steps to 2600 min @ 60C. Between the steps the timing/CCE performance of the system was measured at −30°C.

- Triggering without DUT (no analysis bias introduced by that):

Trigger = (Sci+PM) AND (Ref.Det)

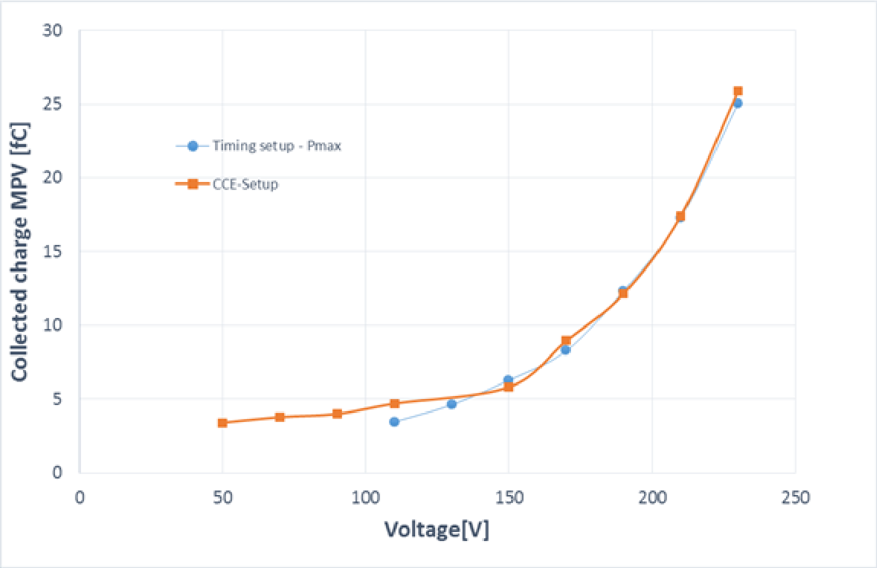
- Small devices – not perfect alignment (30-40% of trigger have signal in DUT
- CFD with 25% is used

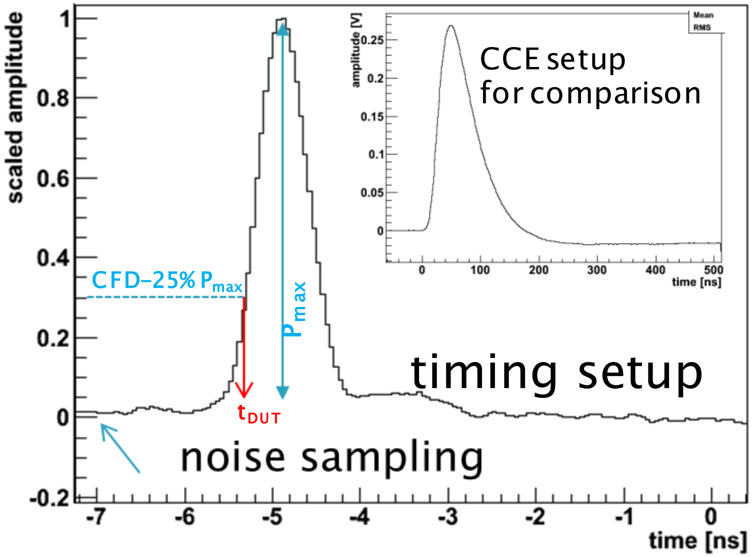


The humidity was monitored and the dew point was always well below the operation temperature (dry air ventilation)

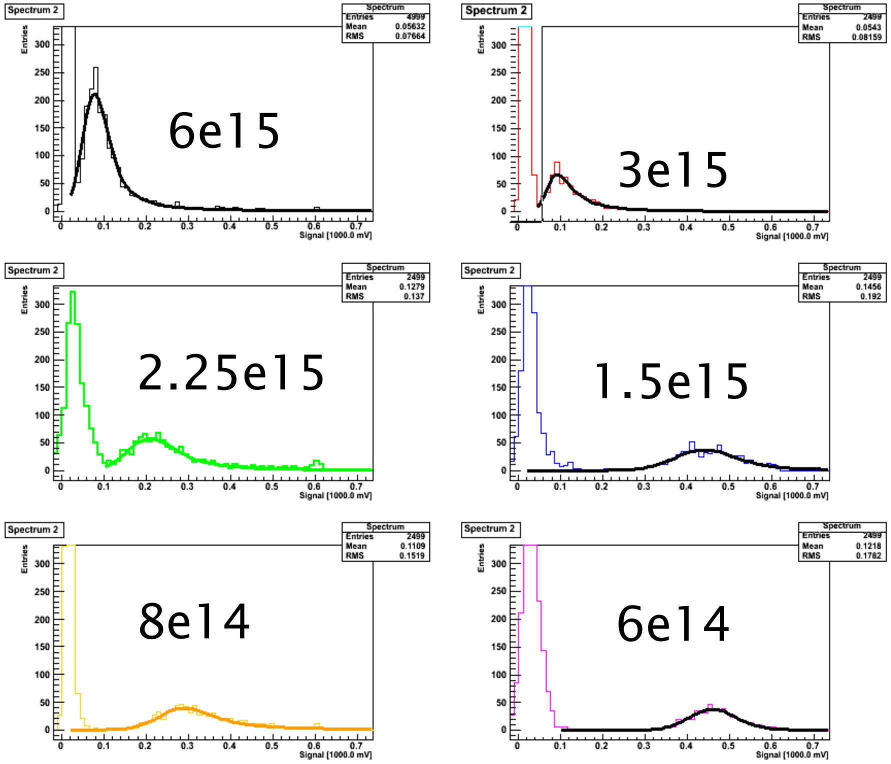
Calibration of the system

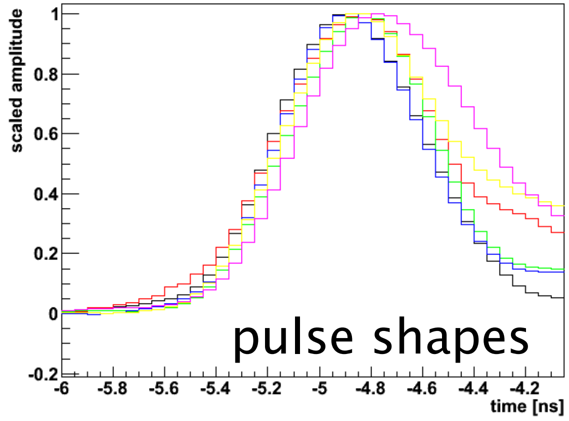
- The system was calibrated using a non-irradiated device of Type 3.1which was operable at room temperature
- Ljubljana CCE system (preamp+25 ns shaping circuit) was used which is precisely calibrated with standard silicon detector with ^{90}Sr and ^{241}Am 60 keV photons
- P_{max} scale was converted to fC using the calibration.
- The charge scale of the timing system was also verified using 3D detector, which was fast (P_{max} is proportional to the collected charge) and was thick enough so that S/N is good.
- most probable signal of ^{90}Sr electrons in 50 μm thick detector was ~3100 e which agrees well with expected 63 e-h/μm from literature



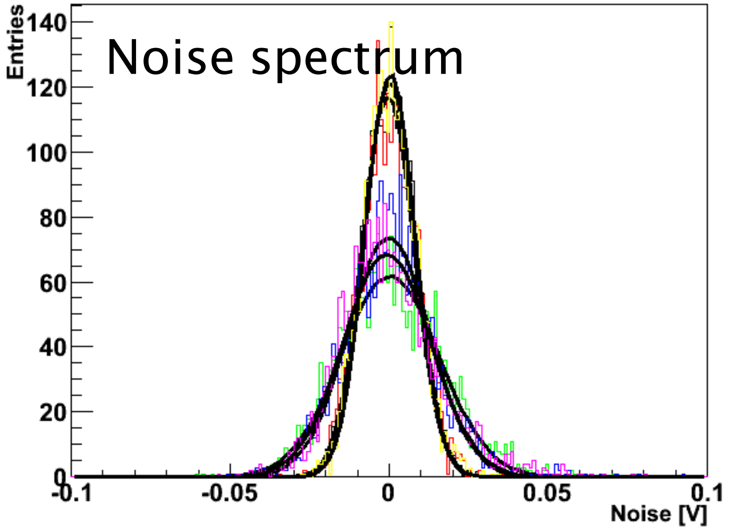


Analysis in short

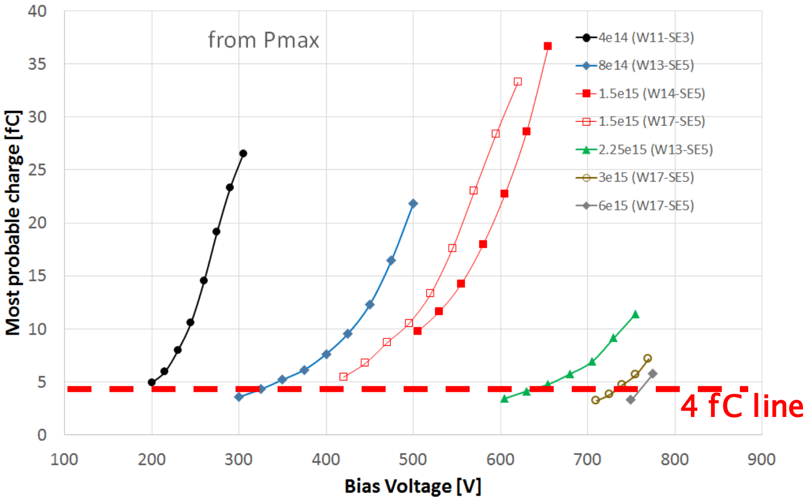


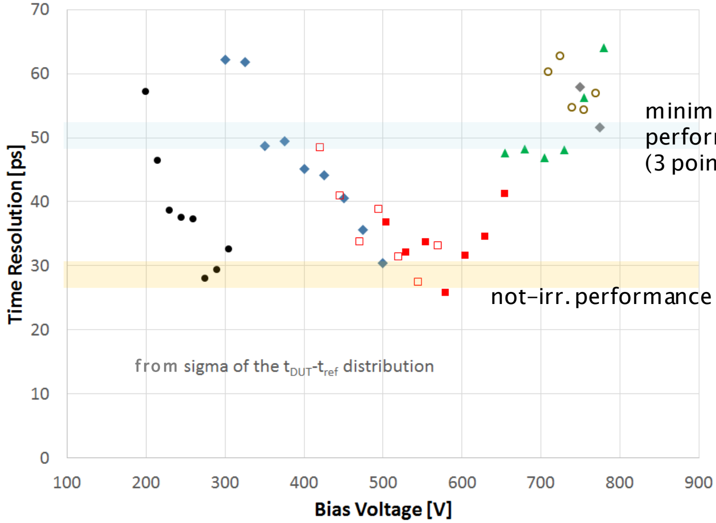


- Spectrum of P_{max} was recorded and fitted with convolution of Landau&Gauss (LG)
- MPV/timing was determined only for those measurements where it was clear peak separation.
- In addition it was required that the integral of LG (number of events) is approximately the same in the voltage scan (it depends only on the alignment)
- The trigger condition also removed all the possible “ghost” triggers
- Noise, rise time, jitter … were all monitored during the measurements



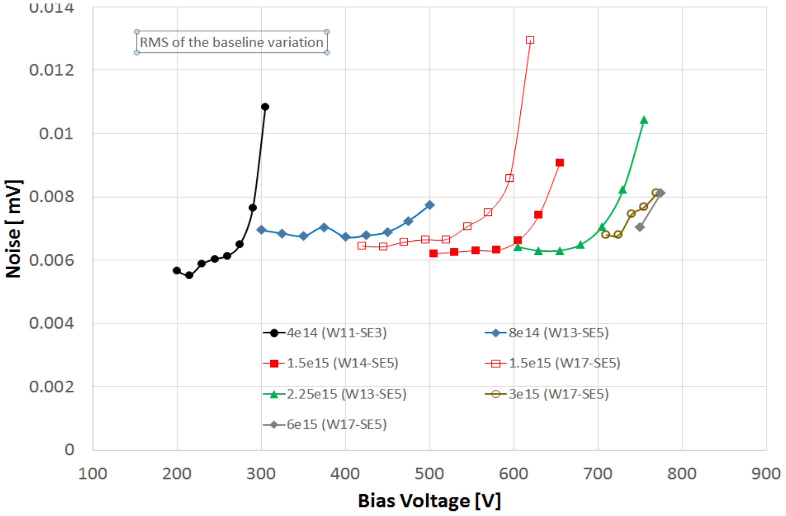
Results at standard annealing point (I)

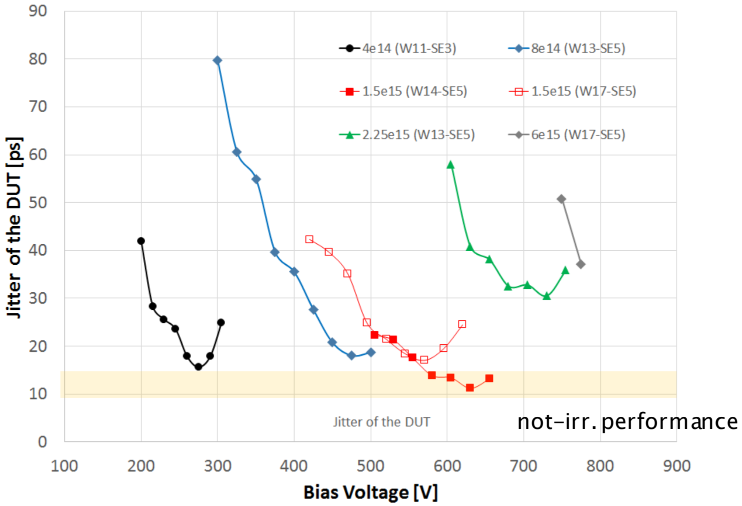




minimum required performance in ATLAS (3 points)

not-irr. performance



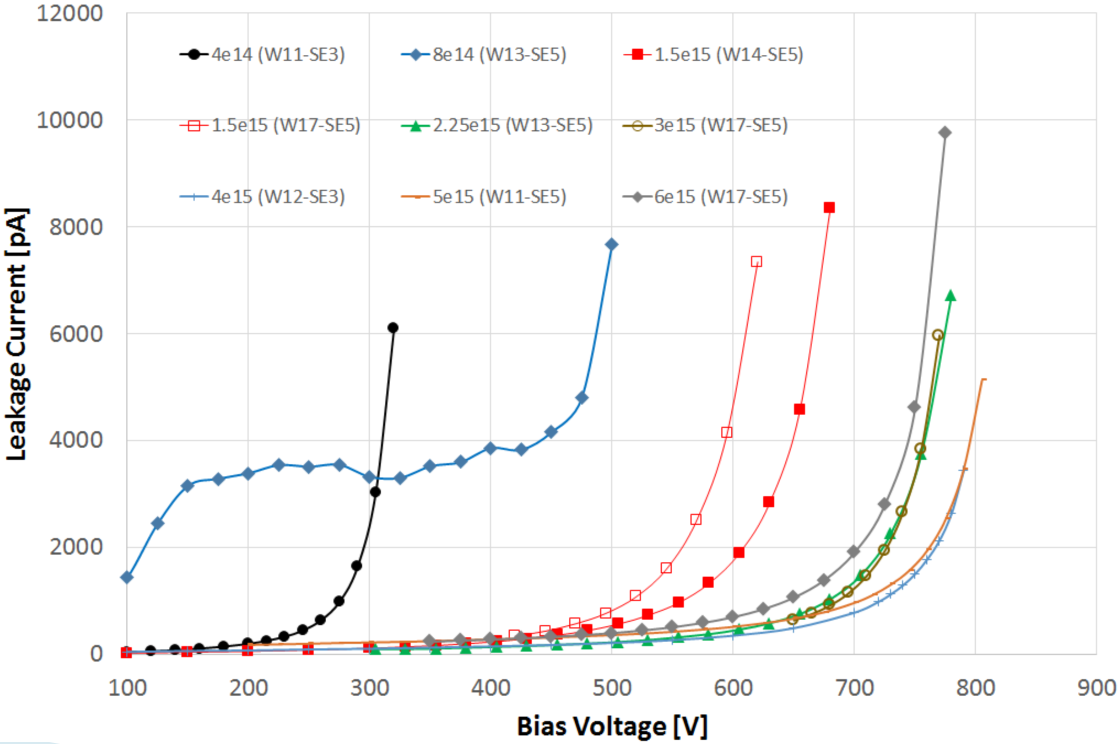


2.25e15 cm^{-2} after 80min@°60 all other after 120 min@60°C

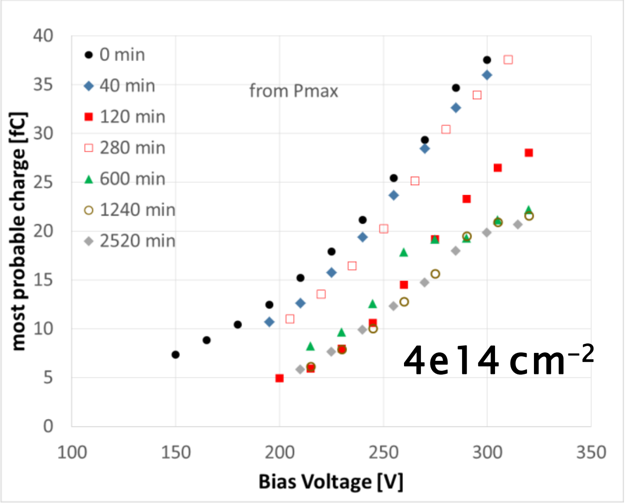
- Good performance of Type 3.2 sensors, but they can not be operated so close to break down (safety margin is required)
- Noise increases once the "break down"/large increase in gain appears and spoils resolution
- There is quite sizeable difference in performance of same detectors irradiated to same fluence (see 1.5e15 cm^{-2}), which can have various reasons: small fluence variation can play a role, humidity, long term biasing at high voltages – under investigation in ATLAS

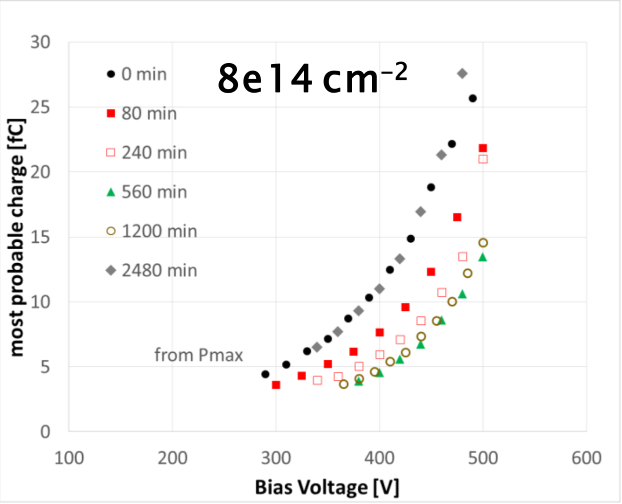
Results at "standard" annealing point (II)

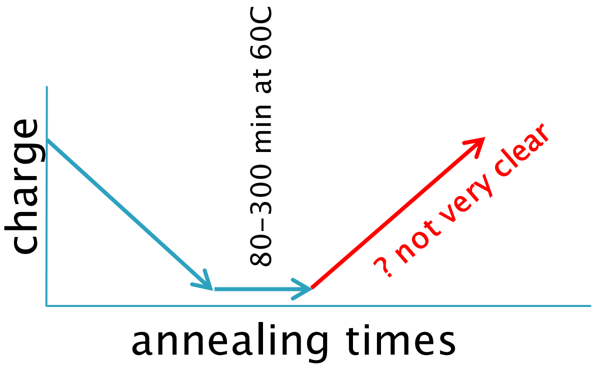
- The shape of the IV for 8e14 cm^{-2} is not clear, but we mount/unmount and it remains (probably related to guard rings)
- The 4e15 and 5e15 cm^{-2} were also measured, but we couldn't see the Landau peak – hence not analyzed – there must be a correlation between low current/low gain seen in this plot
- At 6e15 cm^{-2} we measured only at 40 min annealing as the device broke down at 80 min due to very high voltage applied.
- The IV curves get steeper at larger fluences and are shifted to high bias voltages -> that leaves less voltage headroom

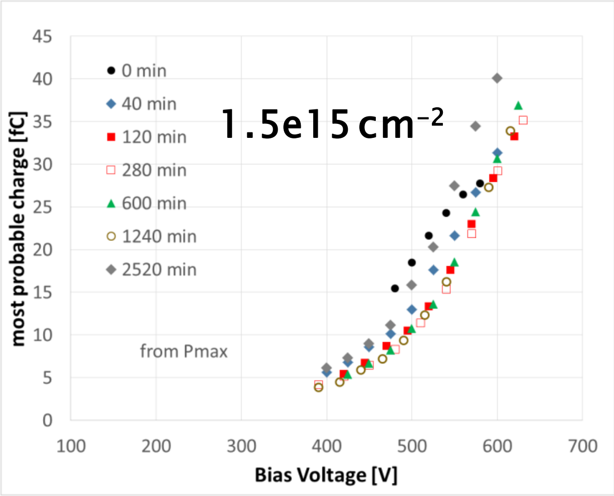


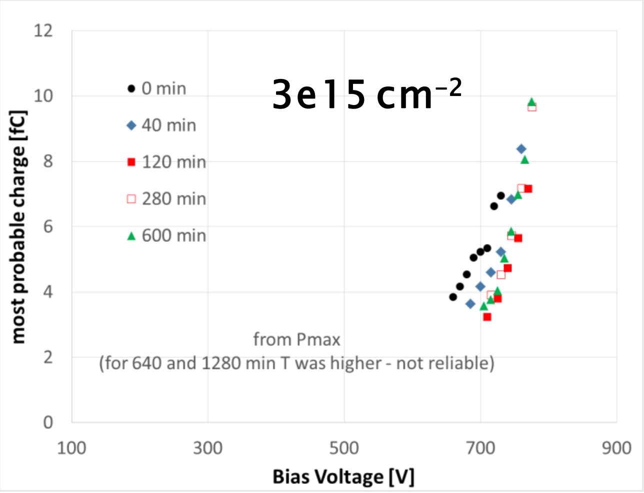
Annealing effects for Type 3.2 (charge)









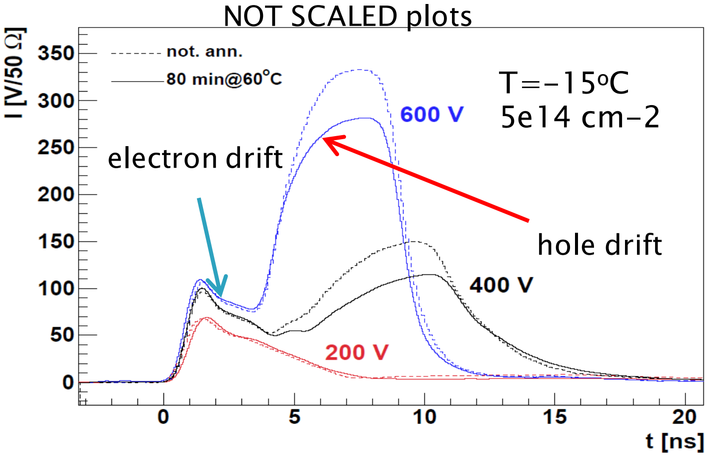


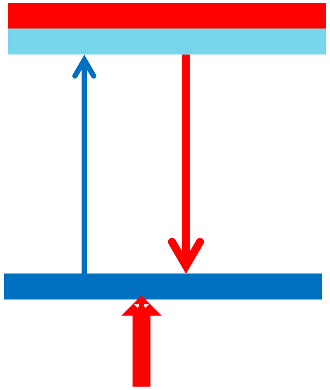
- Annealing effects are not very large (expected)
- The slope of the QV is even more important than mere charge, which can be translated to larger voltage required
- Most of the measurements done so far actually present the "worst case scenario" -> 80min @ 60°C
- Similar behavior – with less detectors studied was also observed for CNM detectors
- Type 3.2 sensors have very "fluctuating behavior"

Is the decrease of CC with short term annealing due to:
- reduction of the bulk N_{eff} and related smaller field?
- acceptor removal "reverse" annealing in gain layer?

Reasons for CC annealing behavior

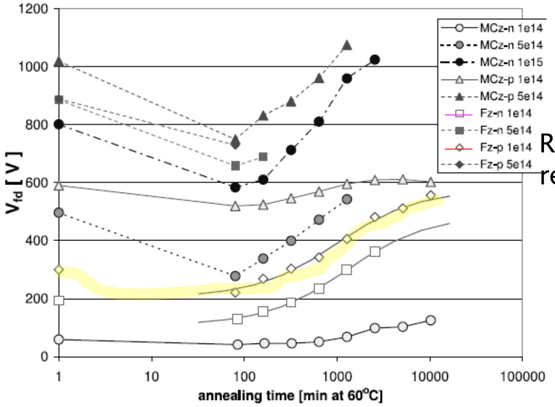
An example of gain layer – acceptor removal annealing on 300 μm thick Ga LGADs samples from CNM irradiated with neutrons (NIM A 898 (2018) 53-59)





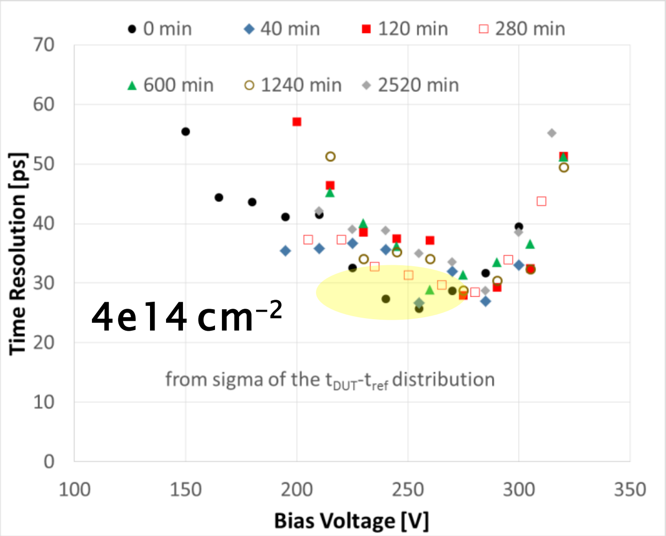
Equal signal after electron drift and reduced gain is a strong indication that "reverse" annealing of acceptor removal is the main reason, **but these measurements should be repeated!**

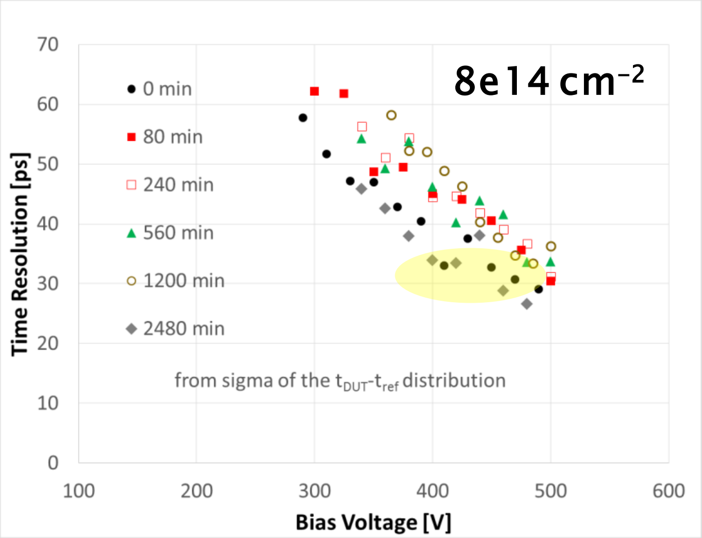
- Bulk N_{eff} after ~2500 min should be much larger than that after irradiation – so if the bulk would be the main reason we should see larger gain after annealing than before annealing
- That bulk is not dominant can be seen at 4e14 where reverse annealing of Neff is not enough to produce back the initial gain – gain remains low at 2520 min
- Gain increase after long term annealing clearly seen in ATLAS strip detectors (JSI, Freiburg)

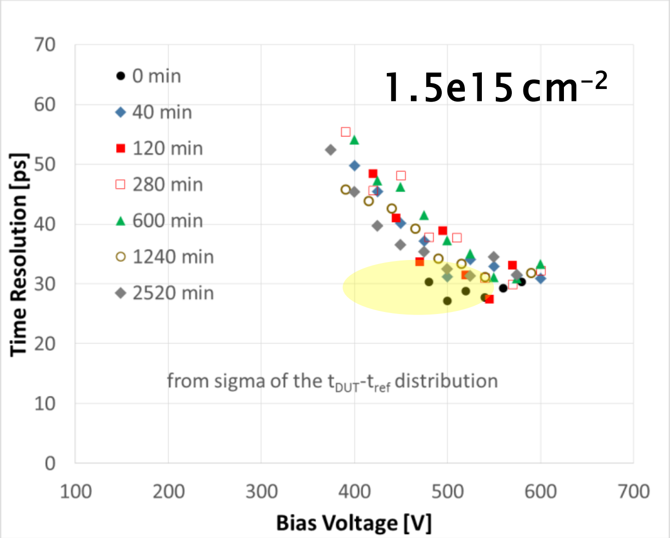


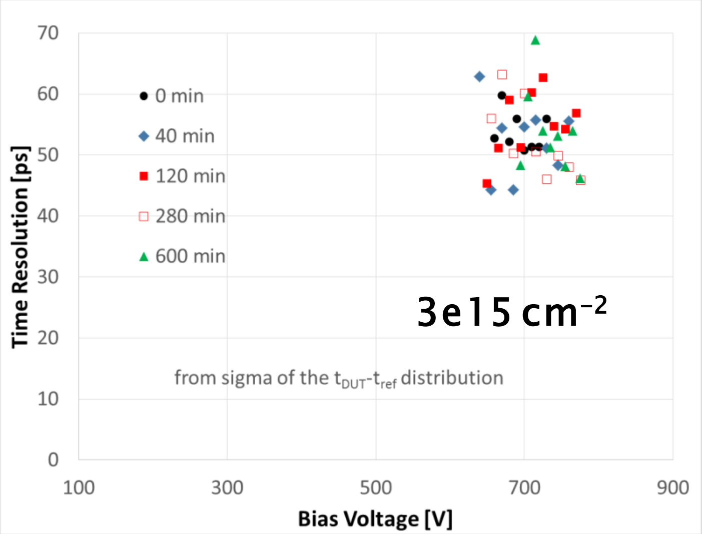
RD50 micron project results from 2008/9

Annealing effects for Type 3.2 (time resolution)



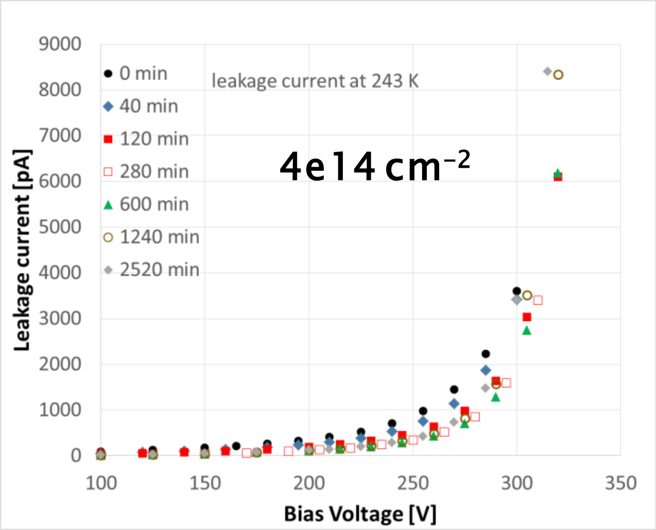


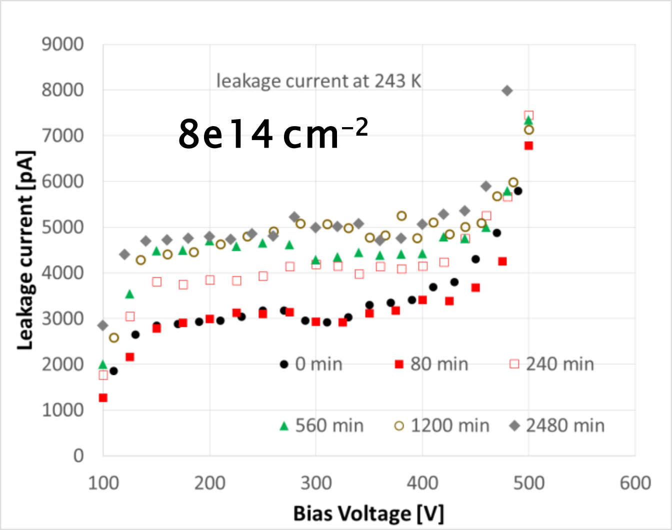


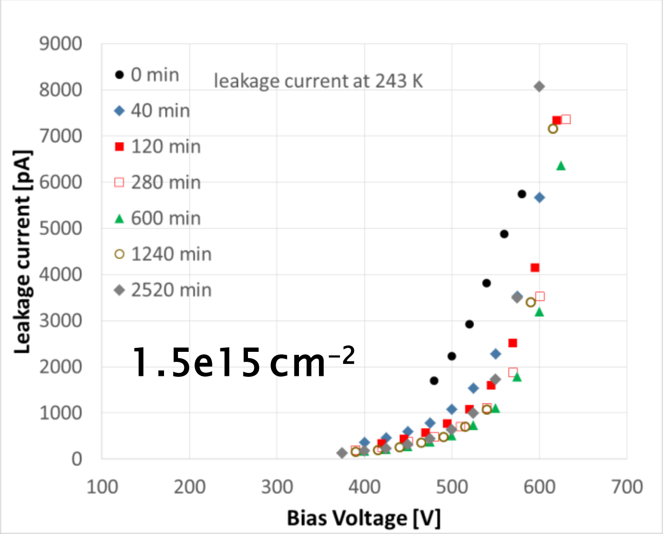


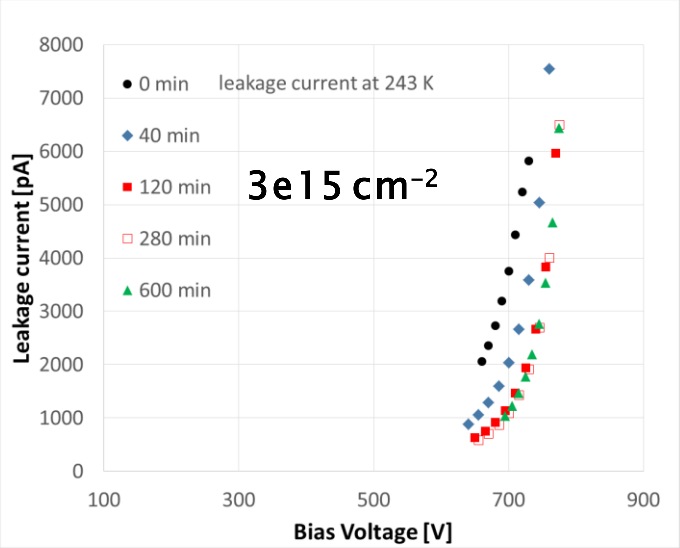
- The annealing of the charge collection is loosely translated to the time resolution
- 30 ps can be reached sooner in terms of voltage for lower fluences
- for 3e15 cm^{-2} it wasn't possible to clearly separate peaks in the spectrum – data are missing. Reason is probably that we couldn't cool the detectors below −22C.

Annealing effects for Type 3.2 (leakage current)



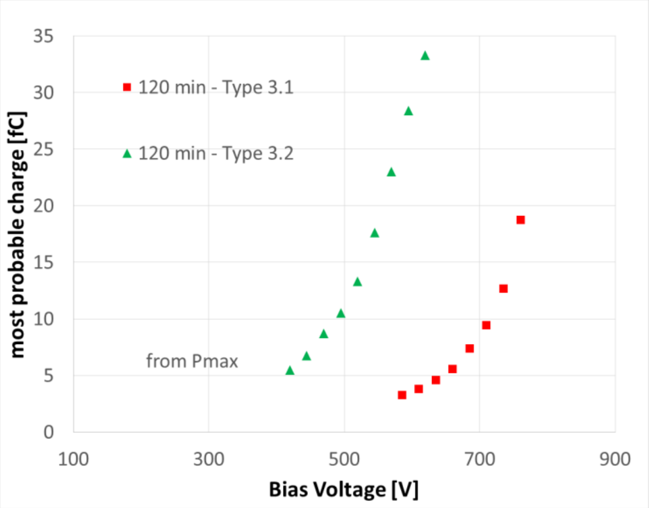


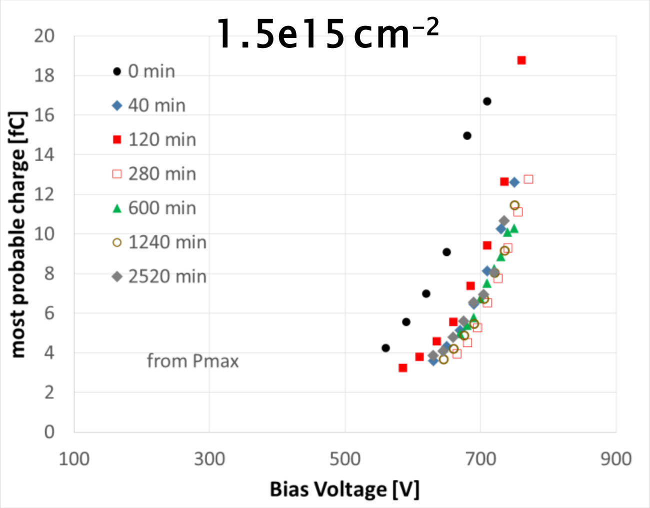


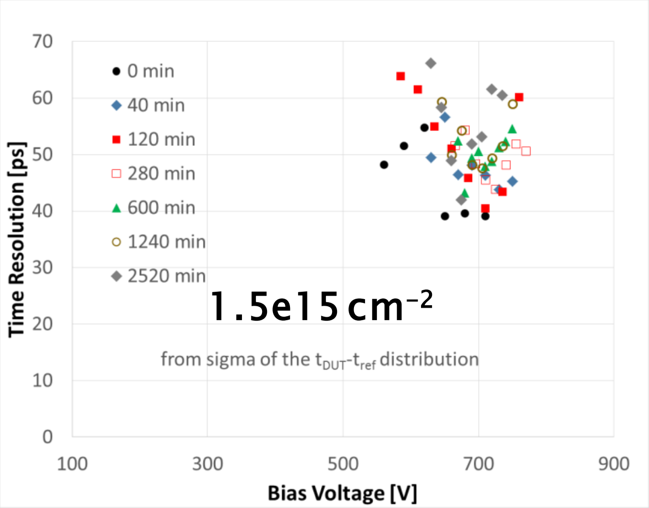


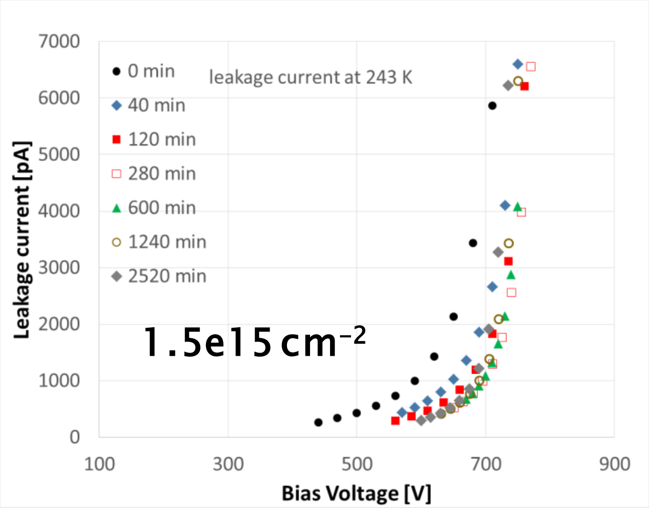
- The shape of the IV for 8e14 cm^{-2} is not clear, but it seems some kind of GR effect – increase of the current with annealing
- As expected the leakage current decreases with annealing, due to annealing of generation current– most notable for the first annealing step.

Annealing effects for Type 3.1 (1.5e15 cm^{-2})



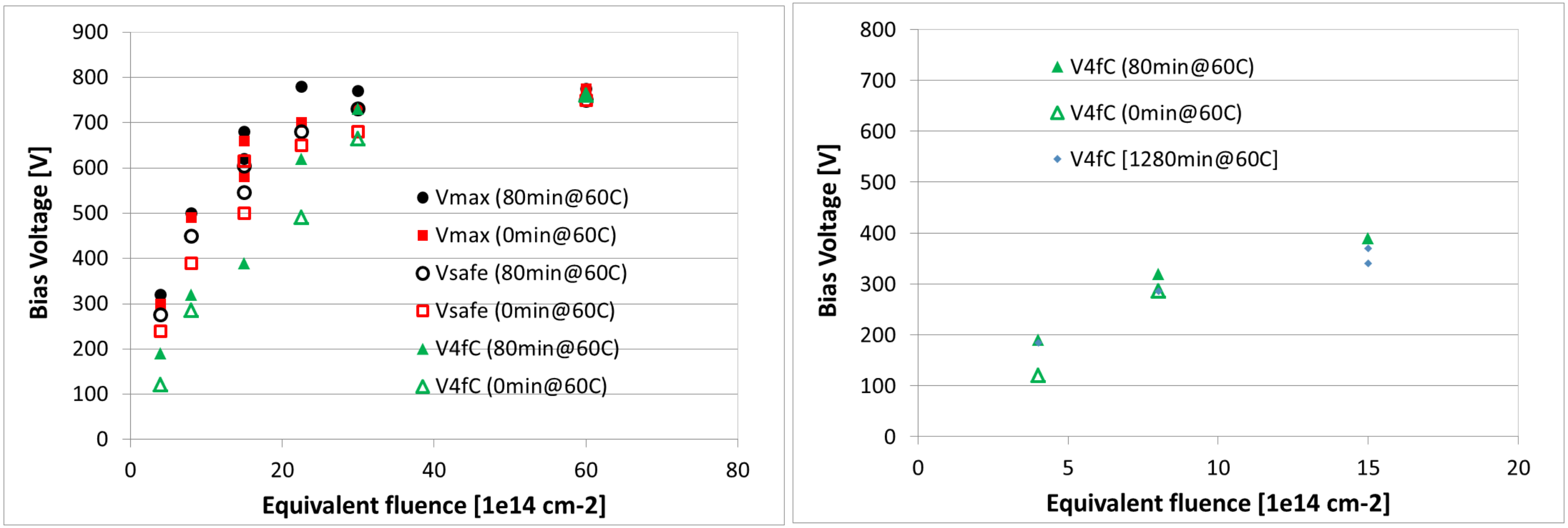






- Type 3.1 have smaller gain at larger fluences than Type 3.2 as the initial gain layer doping is smaller
- The worse performance is reflected also in time resolution
- As for Type 3.2 better performance before annealing

Summary



- up to ~2.5e15 cm^{-2} the operation seems to be safe – far enough from break down
- for >3e15 cm^{-2} the QV becomes very steep and all "voltages" are very close together – unsafe
- "Standard annealing" actually shows worst case for V4fC (voltage at 4 fC) – in terms CC and bias voltage required except at lower fluences where the depletion of the detector bulk requires significant voltage drop.
- **annealing of gain layer has to be better understood –> separate TCT measurements are needed for that** (NIM A 898 (2018) 53-59)

Conclusions

Annealing of HPK Type 3.2/3.1 diodes (narrow and highly doped gain layer) were studied

- The impact of annealing on timing and charge collection is not very strong in the range of our interest (0-2600 min @ 60^{o}C)
- QV plots are shifted to lower bias voltages immediately after annealing and maybe also at very long annealing times (worse at ~100 min @ 60^{o}C)
  - short term annealing is associated with less initial dopants (needs to be studied by TCT to confirm that)
  - long term annealing improvement is associated with more bulk gain
- Annealing current anneals as expected and improves the power consumption -> in that sense longer annealing would be beneficial for operation at HL-LHC