Radiation damage studies in LGAD detectors from recent CNM and FBK runs

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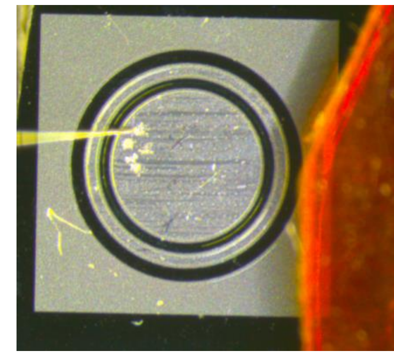
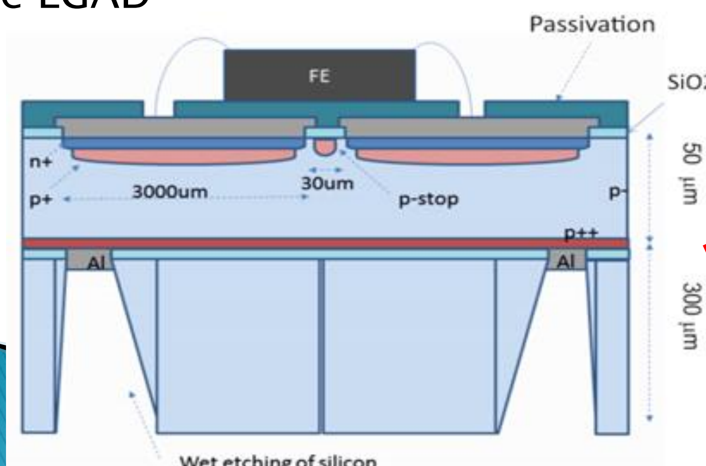
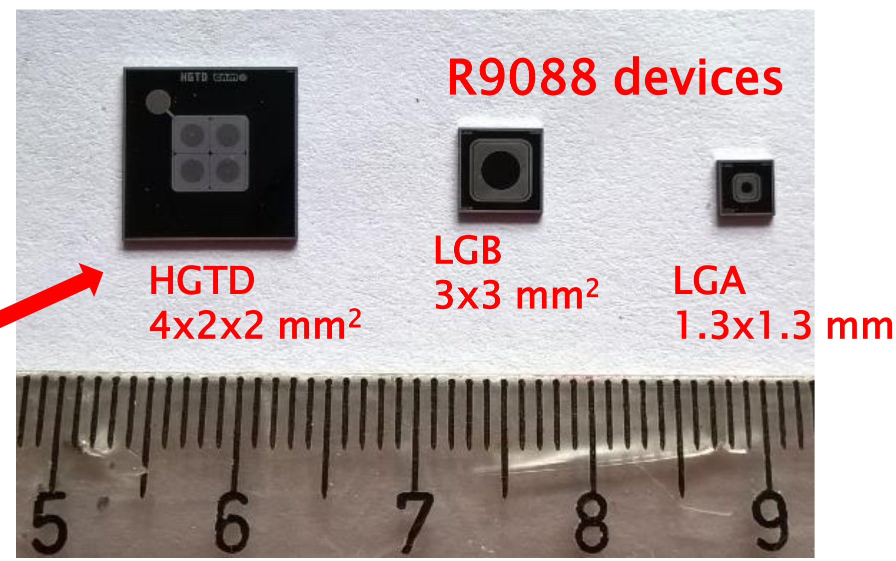
CNM devices under study

- **CNM Run** 6827 – 2 years old run (Epitaxial devices, 100 Ωcm, 50 μm thick)
  - LGAD samples of low boron concentration in multiplication layer – gain of 7 reached only at high bias voltages
  - Control PIN samples with no multiplication layer
  - Excellent high voltage tolerance
- **CNM Run** 9088 (SOI devices, high-resistivity, 45 μm thick)
  - Three different multiplication layer doping concentrations
    - W3 – Dose=1.8e13 cm^{-2}
    - W5 and W7– dose =1.9e13 cm^{-2} (most studied)
    - W11 – Dose=2.0e13 cm^{-2}
  - Three different device structures
  - Control PIN diodes produced along the LGAD



R6827 device





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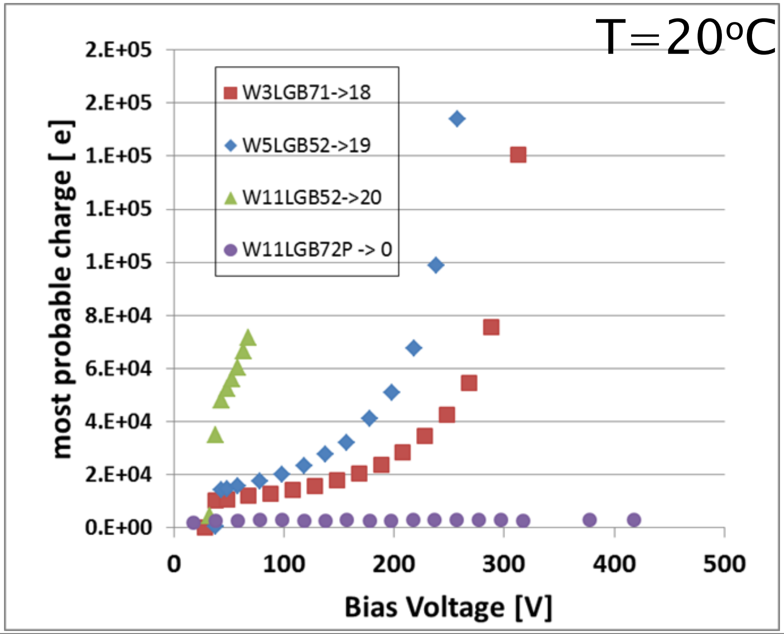
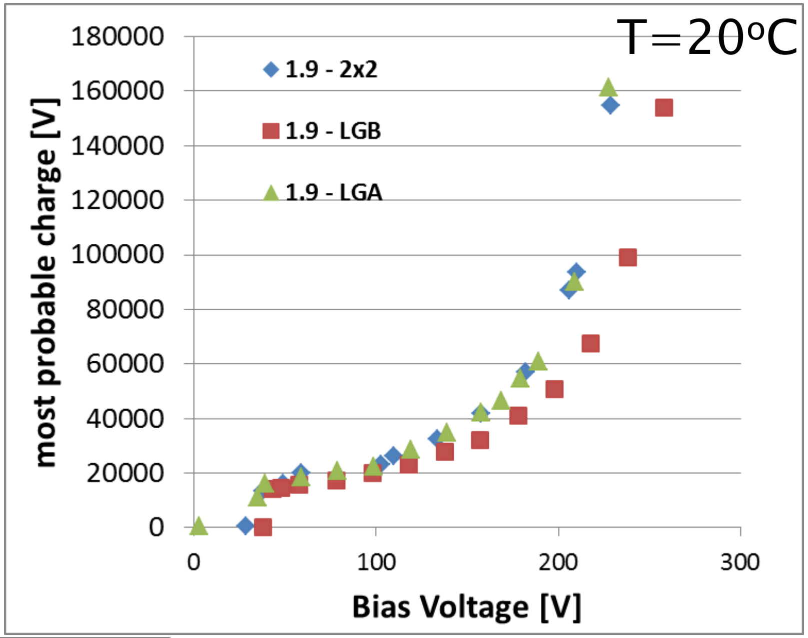
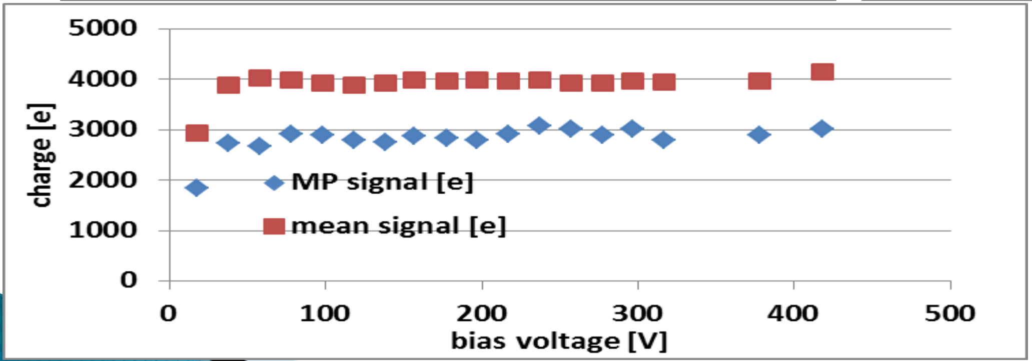
Non-irradiated devices CNM-R9088

- Similar device performance regardless of the device type
- Typical break down in CCE measurements ~300 V (W3), ~260 V(W5) and 90V (W11)



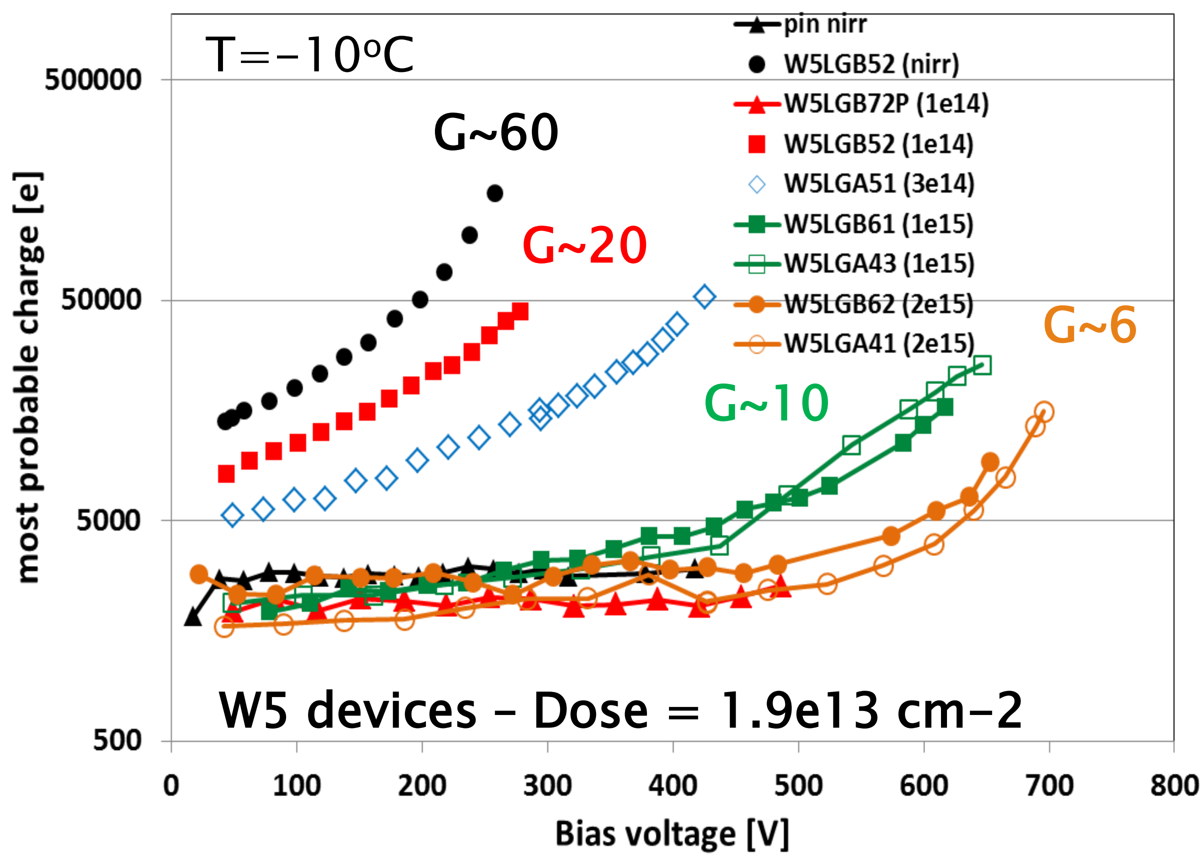




- Most probable signal ~2800 e for non-irradiated detector – 45 μm thick
- Ratio most probable/mean=0.7 – slightly less was expected.

Signal/gain after neutron irradiations(R9088)

- Gain degrades, but follows the expectations
- "Breakdown" of the device is shifting to higher bias voltages with irradiation for W5

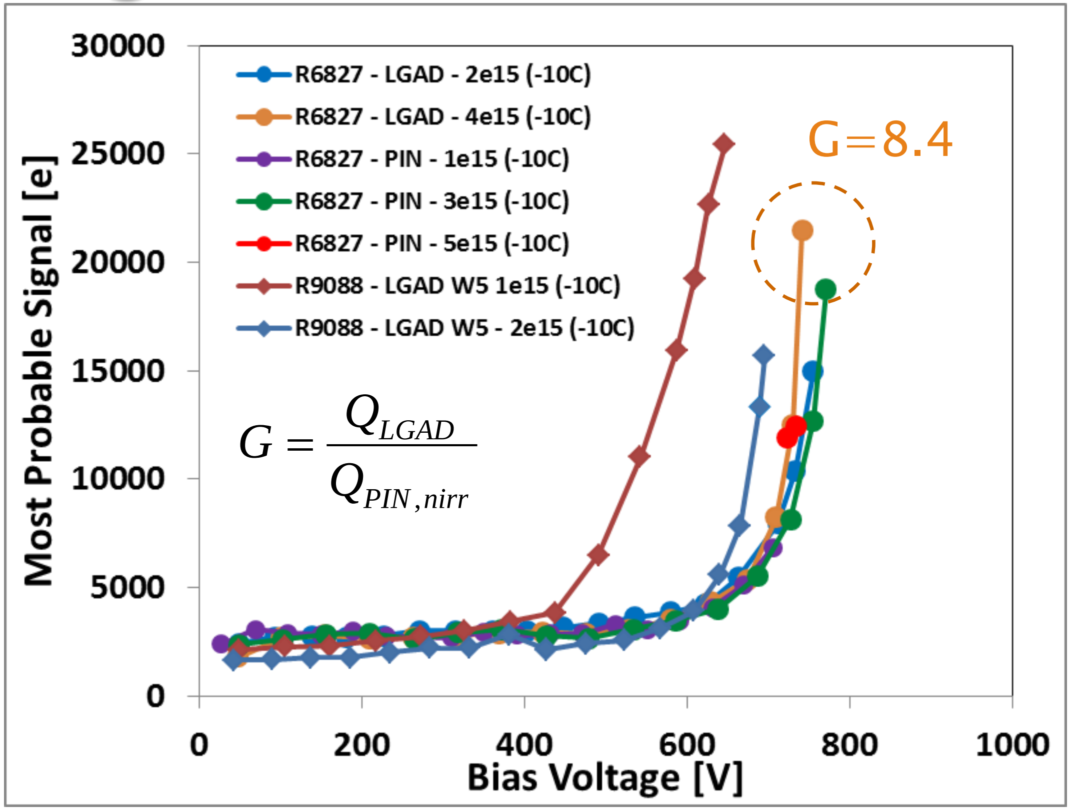


1.) for $\Phi_{eq} < 1e15\ cm^{-2}$ effective acceptor removal in multiplication layer reduces the gain, which appears as soon as the multiplication layer is depleted.

2.) Smaller N_{eff} in multiplication layer leads to smaller slope of the Q-V plot.

3.) at fluences of 1e15-2e15 cm^{-2} the multiplication is visible only at higher bias voltages – up to few 100 V collected charge similar to pin diode – the difference between LGAD and PIN becomes small.

Signal after irradiation for thin LGADs



The last point is always taken just before the detector exhibits a "soft break down":

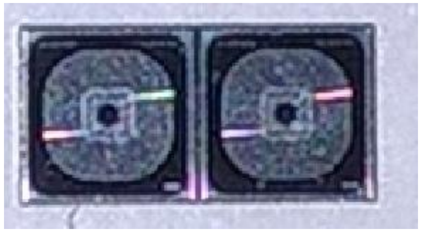
- Irradiation shifts the breakdown voltage to higher values.
- The rise of the charge is associated with the rise of the current and noise (system dependent) which could be kept under control by cooling and cell size
- Note that $\langle E \rangle \sim 15\ V/\mu m$

- LGAD are advantageous for high gain device up to 2e15 cm^{-2}
- At high fluences $\Phi > 2e15\ cm^{-2}$ the behavior is the same for all samples:
  - Regardless of initial doping concentration
  - Regardless of p^+ layer doping (acceptor removal is almost complete)
  - Regardless of annealing behavior (needs to be verified by several samples – so far PIN only).
  - It seems that at high enough fluences the performance doesn't degrade anymore – in accordance with predictions (talk at 28th RD workshop in Torino)

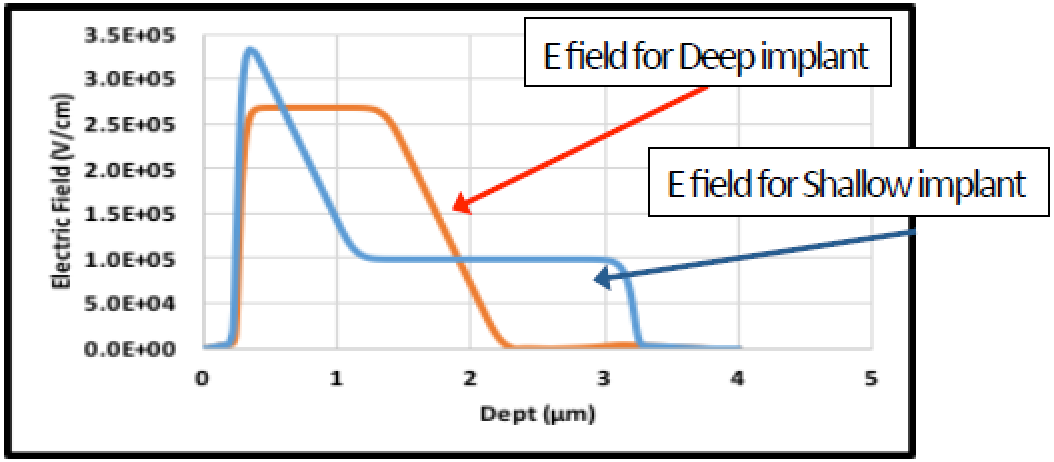
FBK sensors

see also talk from Roberto and Marco

- 1st FBK LGAD run
- Geometry
  - 300 μm thick detectors
  - Small 0.5 mm^2
  - Multi guard ring structure – high break down voltages achieved
  - Not all small diodes were diced (multiple samples)
- Several splits in p+ layer doping concentration
- Two wafers studies : W3 and W10
  - LGAD of different gains for W10 (Split 4), W3(Split 2)
  - No-gain diode for reference

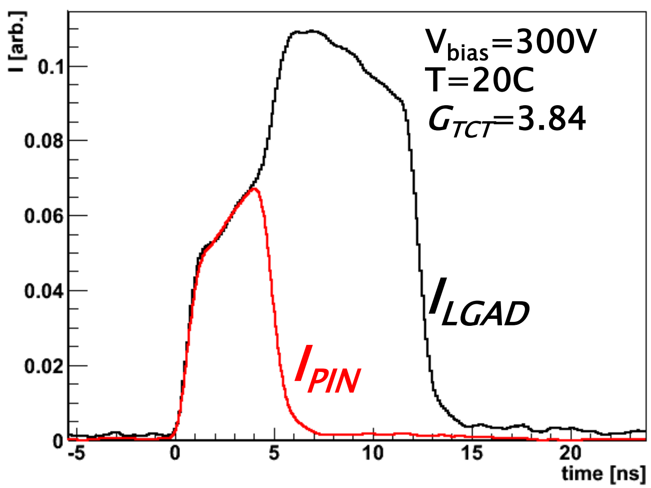


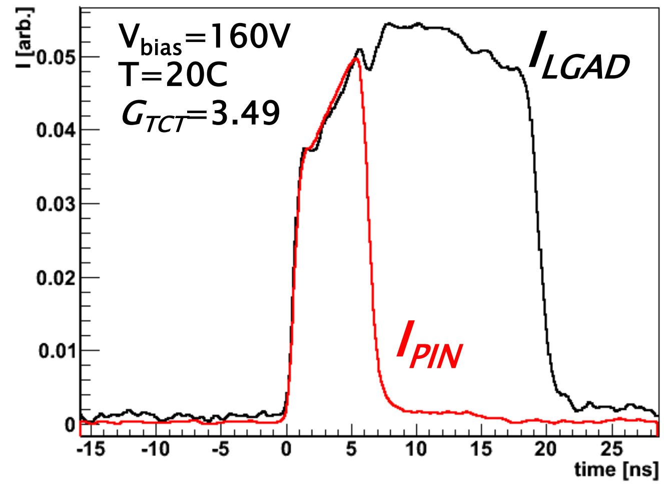
Is such profile more/less radiation hard?

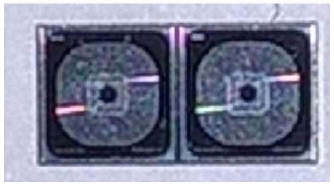


FBK TCT measurements – pulses & gain

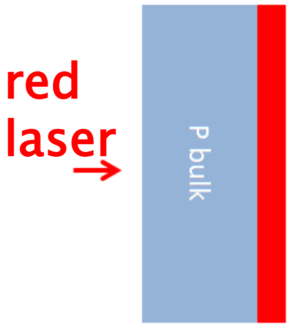
W3 – wafer



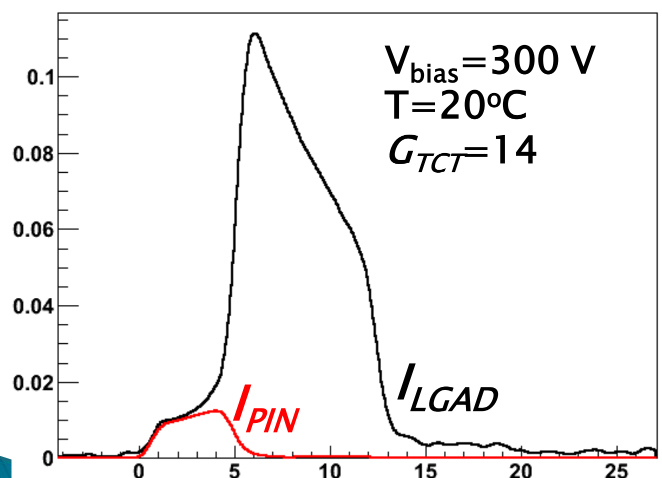


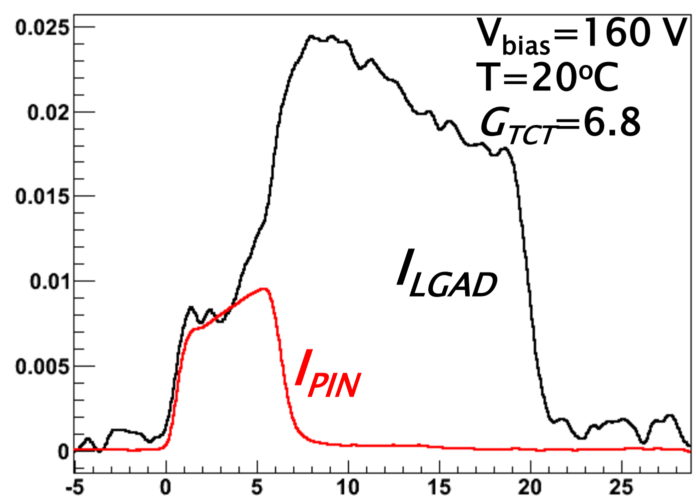


PIN diode

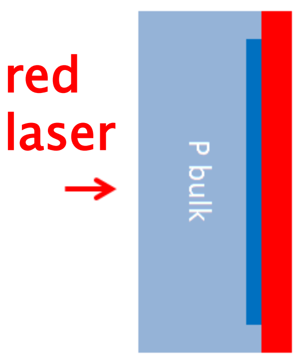


W10 – wafer





LGAD diode



$$G = Q_{LGAD} / Q_{PIN}$$

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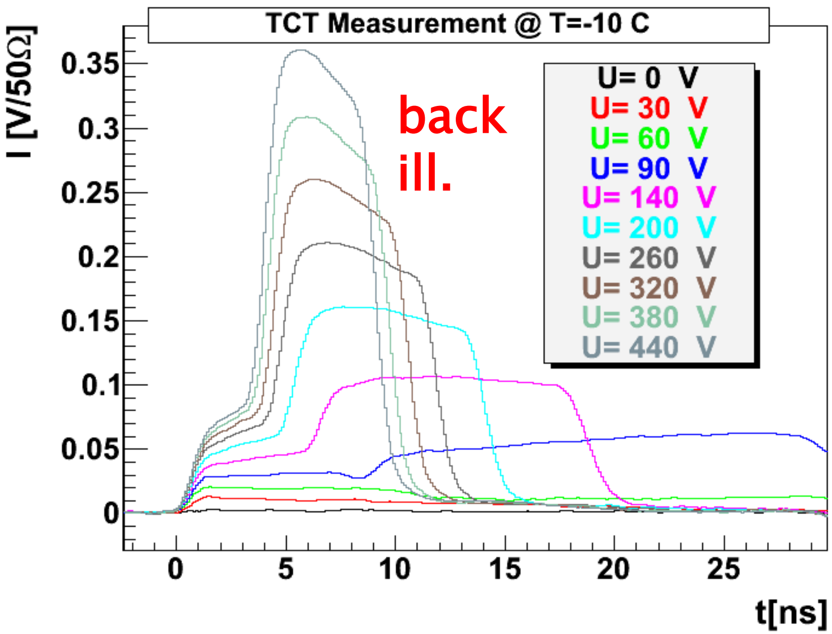
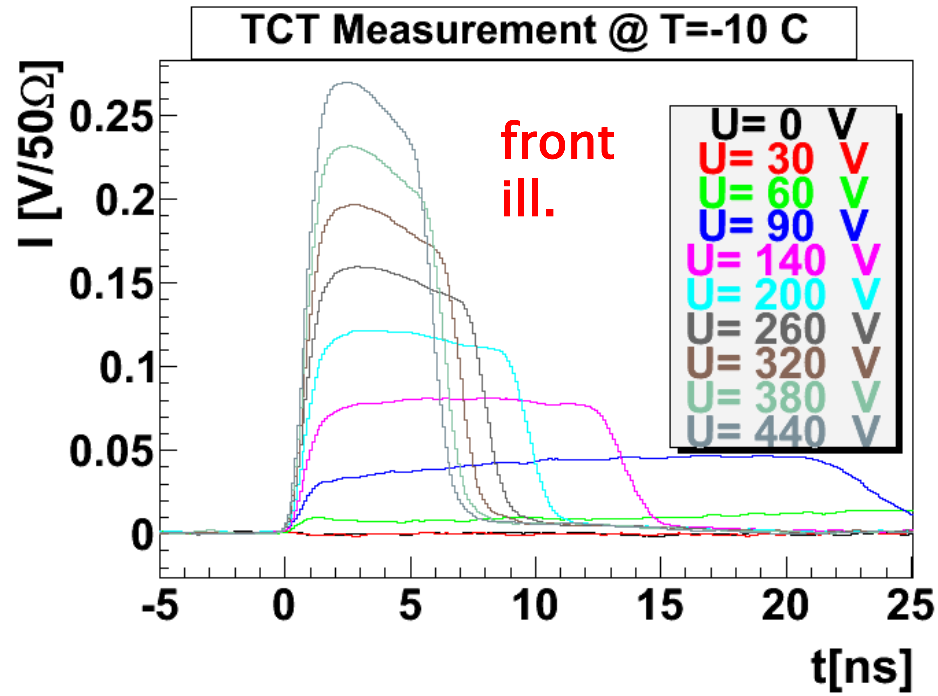
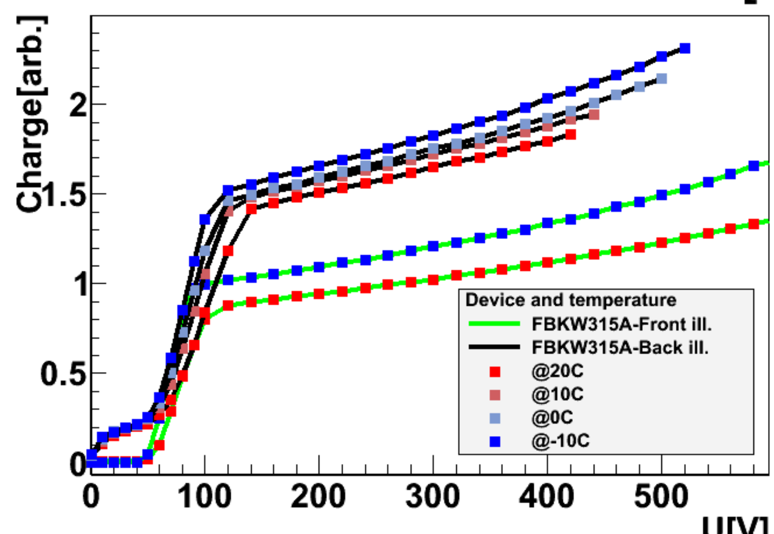
TCT (non-irradiated W3 samples)





- The space charge seems to change as a function of voltage
  - At lower voltages the space charge seems to **be positive** (see the slope of the charge)
  - At higher voltages the space charge seems to **be negative**
- Also seen in Q-V.



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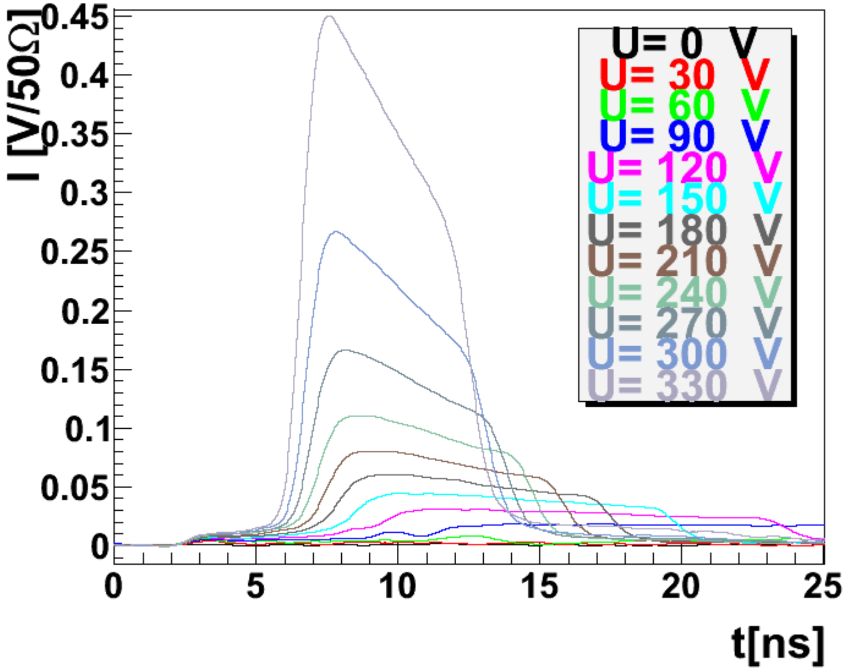
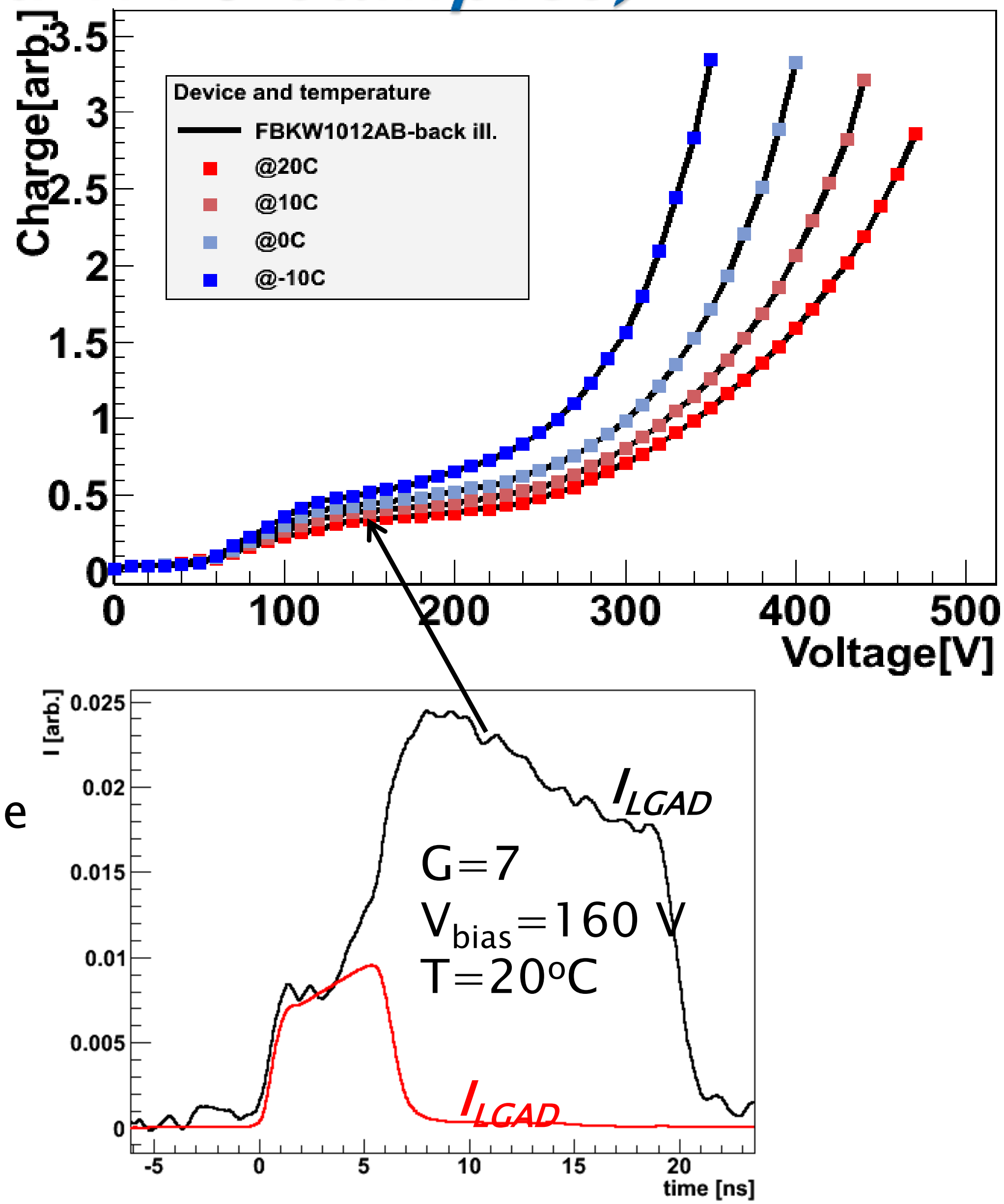
TCT (non-irradiated W10 samples)





- Huge gain for W10; G>100
- Same observation of space charge changing with bias voltage
- large gain -> large temperature dependence

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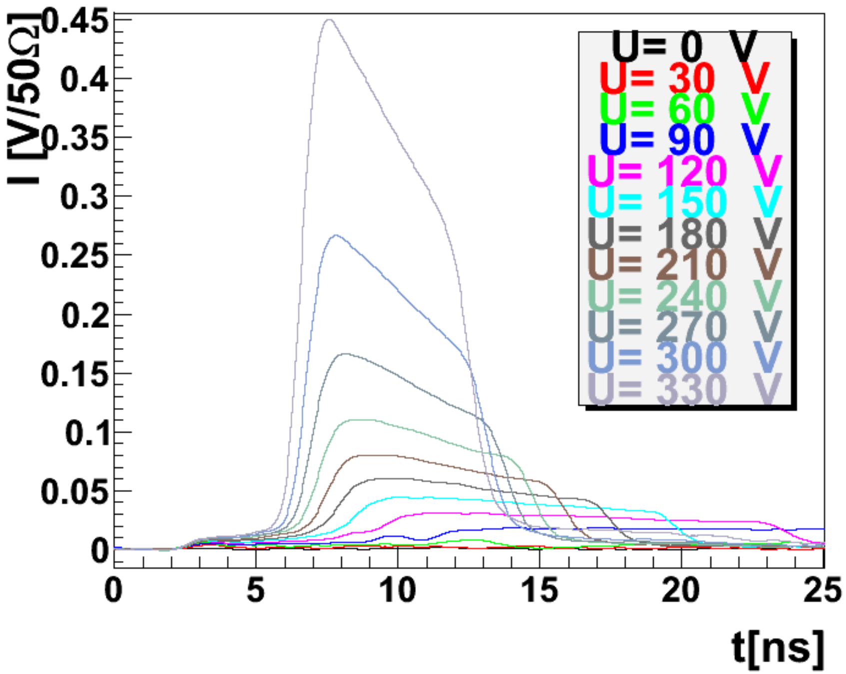
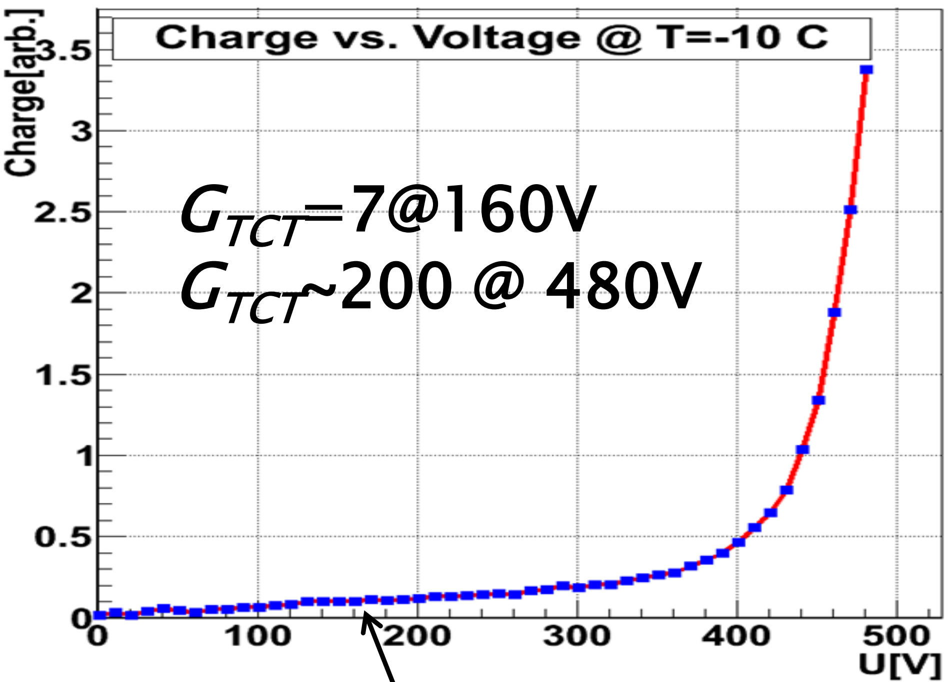
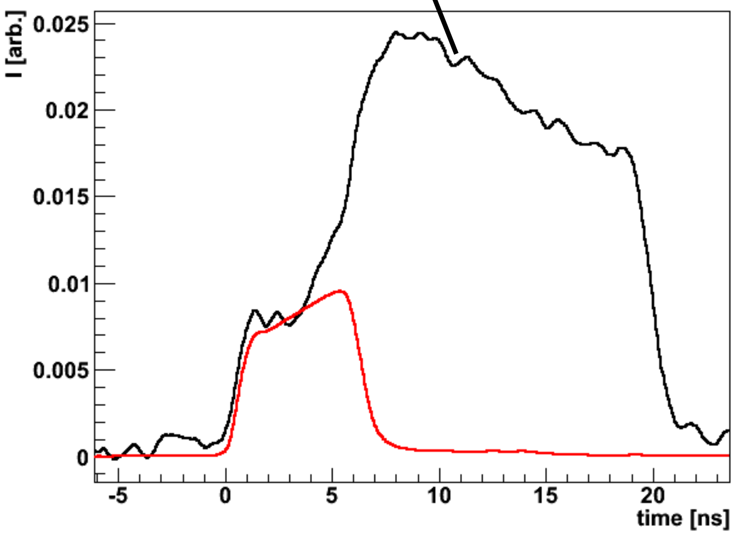
TCT (non-irradiated W10 samples)







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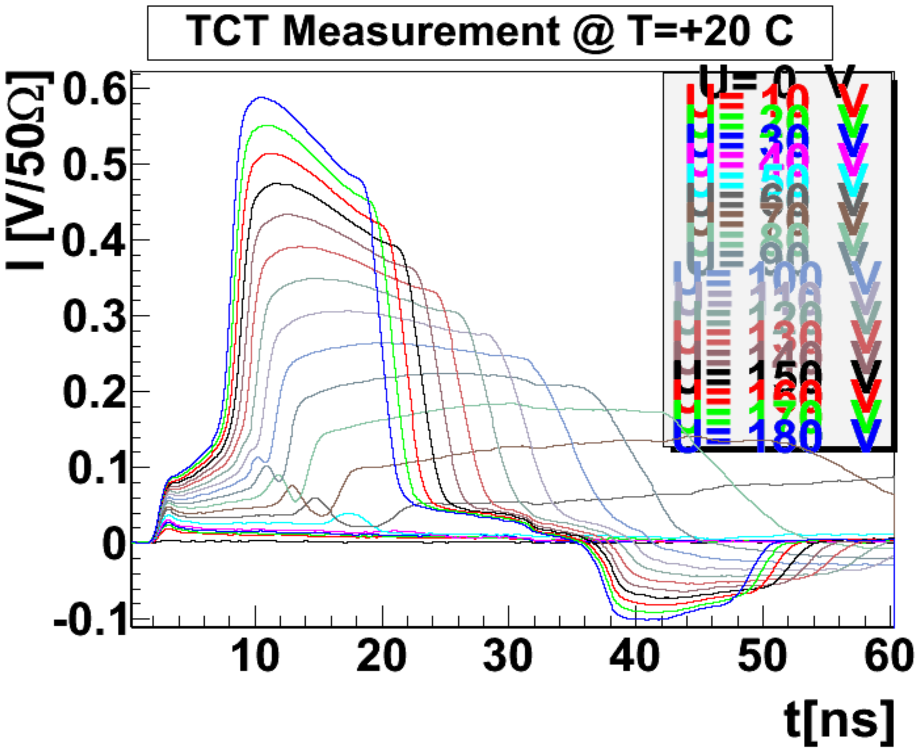
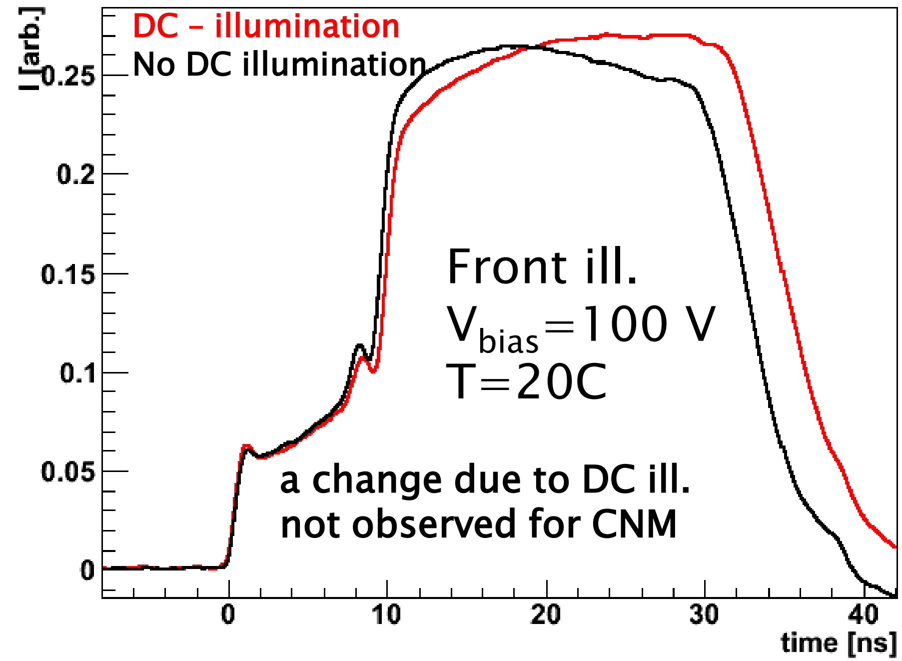
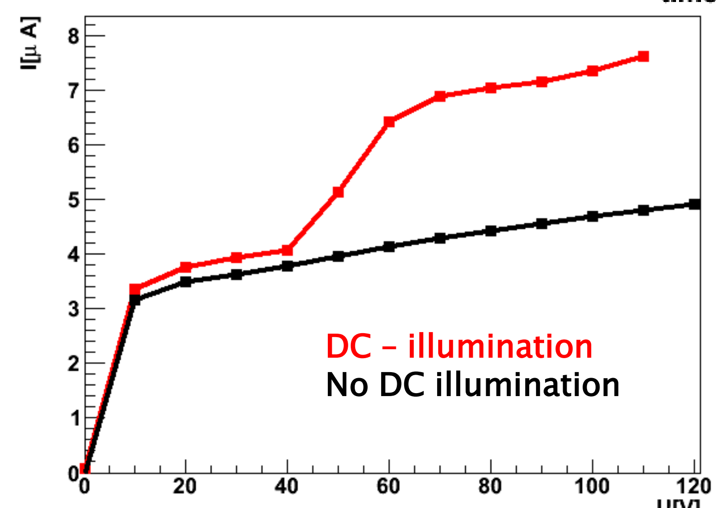
TCT for W10 – changes in space charge





Several features not really understood:

- Sensitivity to DC illumination (not seen in CNM samples) – indication of deep defects?
- Deep defects would also explain changes of space charge with voltage
- Unknown features in the signal for W10 – unclear if real physics (e.g. illumination of guard rings) or "feature of setup"



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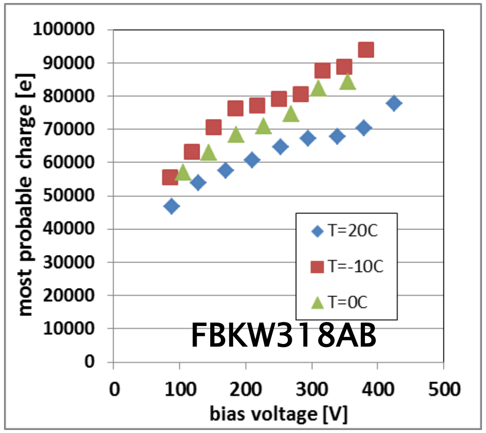
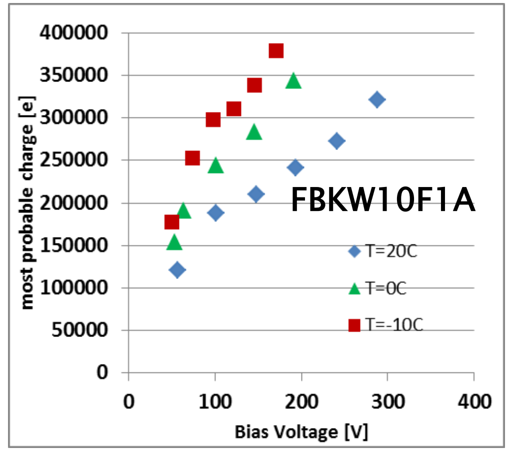
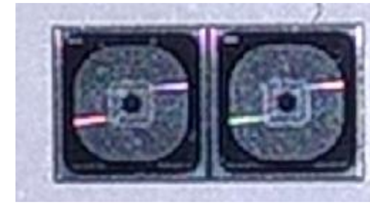
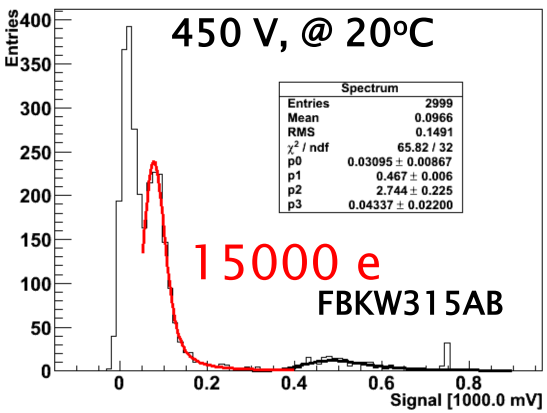
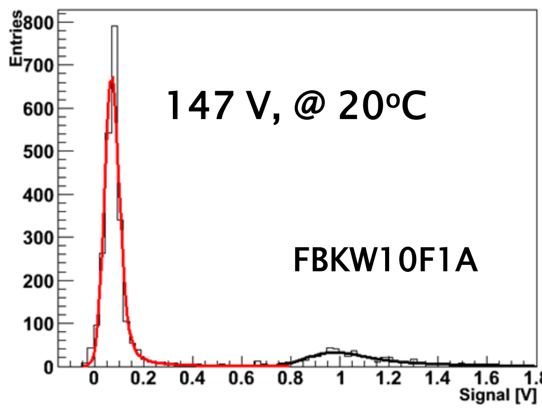
FBK ^{90}Sr measurements (non-irradiated)

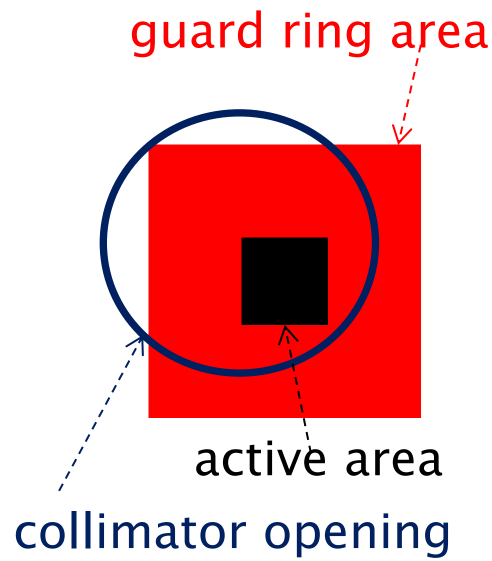












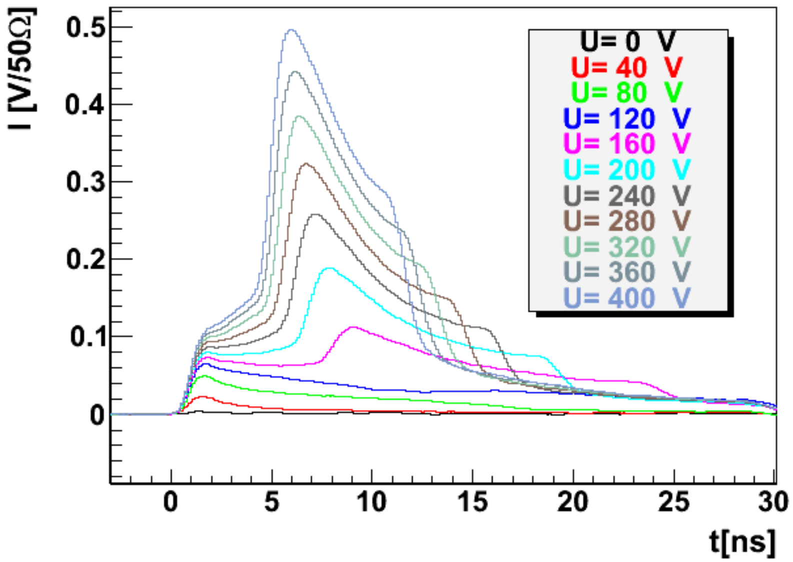
Small sample size is a problem as trigger purity is affected:

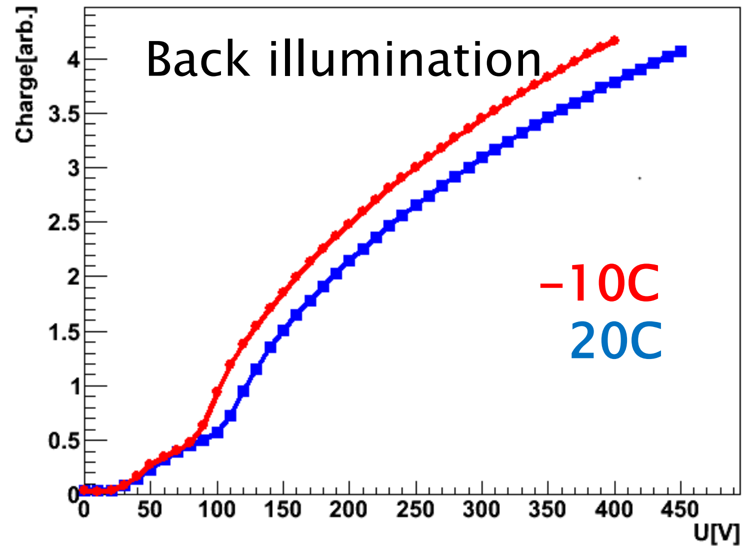
- events missing the sensor (Noise peak)
- guard ring collection ? (capacitevly transferred charge to the collecting electrode)
- active area collection (multiplied signal)

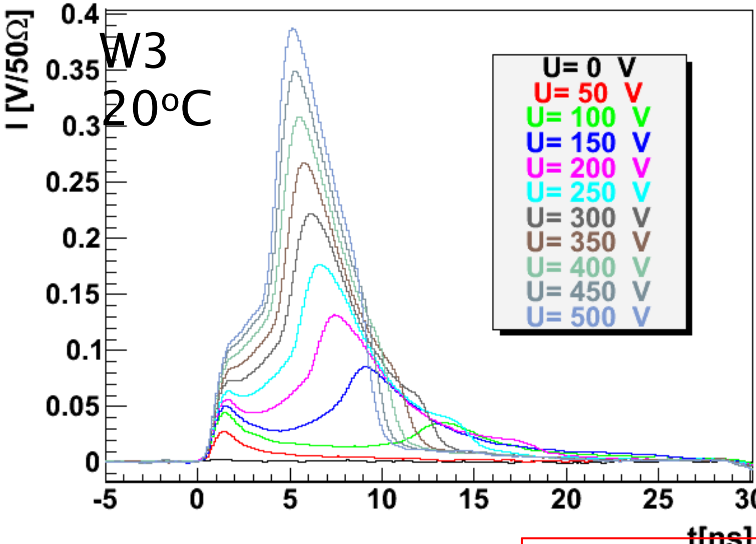
Huge signals saturate the amplifier for W10 – break down ~500-600V

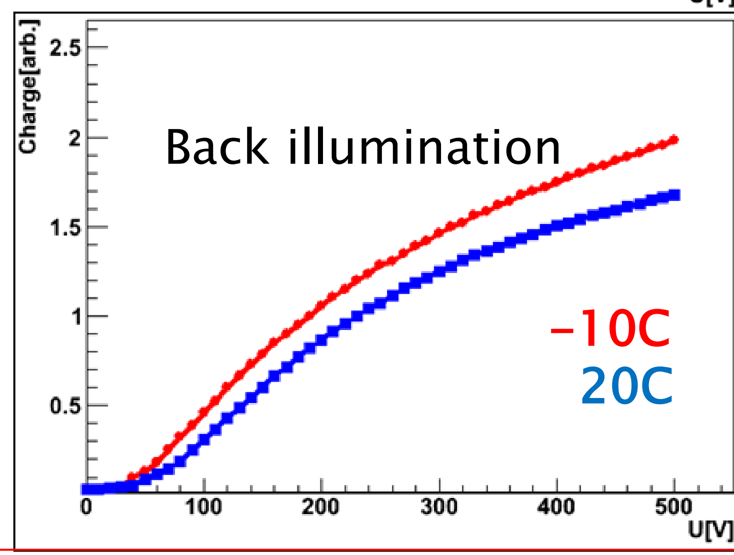
some discrepancy between G_{TCT} and G_{MIP}

TCT – W10 (2e14 cm^{-2})



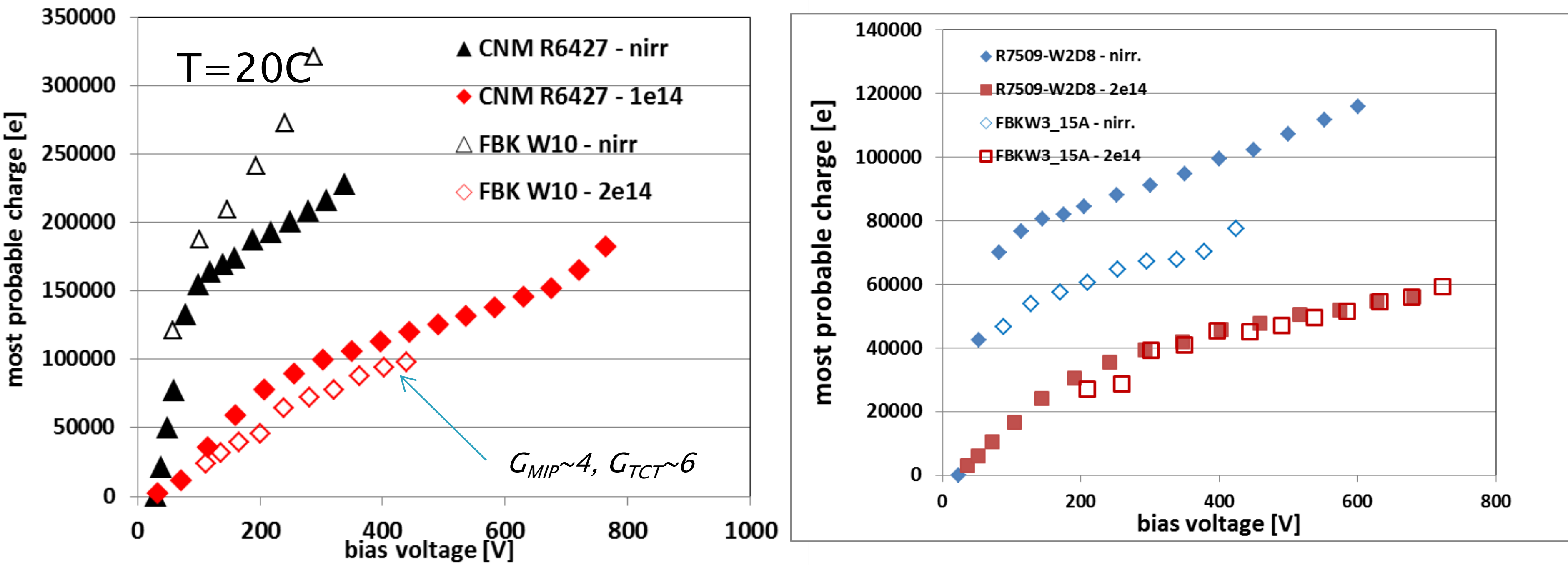






- More negative space charge for W3 (expected)
- Q-V plot is not understood – why smaller slope at high bias
- Much smaller temperature dependence as before irradiation

FBK – CCE with ^{90}Sr after 2e14 cm^{-2}



- Larger gain loss measured with G_{MIP} wrt. *to* G_{TCT} – under investigation
- Impure trigger complicated the analysis even more at smaller gain (difficult separation of peaks)

Preliminary evaluation of FBK detectors performance in terms of gain seems to be comparable to CNM detectors.

Conclusions

- The gain degrades in CNM thin LGADs in accordance with expectations, but high bias voltage tolerance and residual acceptors in p+ layer may allow for successful timing applications.
- For fluences >2e15 cm-2 the effects of p+ gain layer are not visible anymore (however the gain is still there)
- First FBK production of LGADs demonstrated working devices
- TCT and CCE measurements showed very high multiplication and excellent break down performance before irradiation.
- After irradiation loss of gain is comparable to CNM devices – a more systematic study is ongoing.