Radiation hardness of thin LGAD detectors

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on behalf of RD50 project collaborators:
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SCIPP-UCSC Santa Cruz, Univ. Ljubljana and Jožef Stefan Institute

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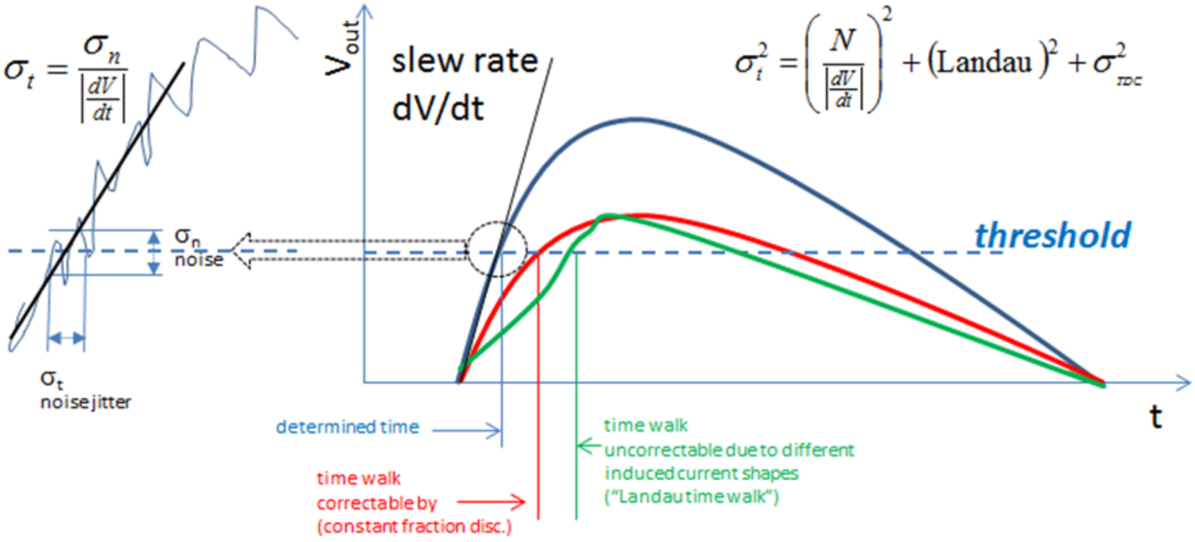
Motivation

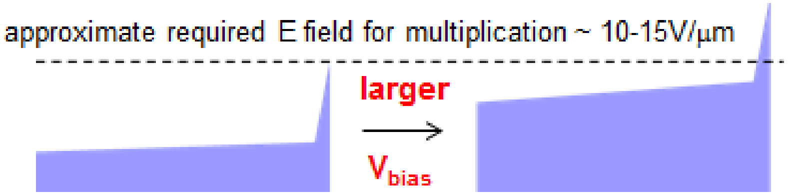
- ATLAS-High Granularity Timing Detector/CMS Totem-PPS- timing detectors
- Good timing devices require large gain and small thickness for several reasons:
    - “uncorrectable-Landau” time walk, due to energy loss fluctuations becomes a smaller problem
    - an additional advantage is short drift times 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 the ratio Gain/Thickness

(NIM A831(2016) p.18, N. Cartiglia 11th Trento Workshop)



Radiation damage

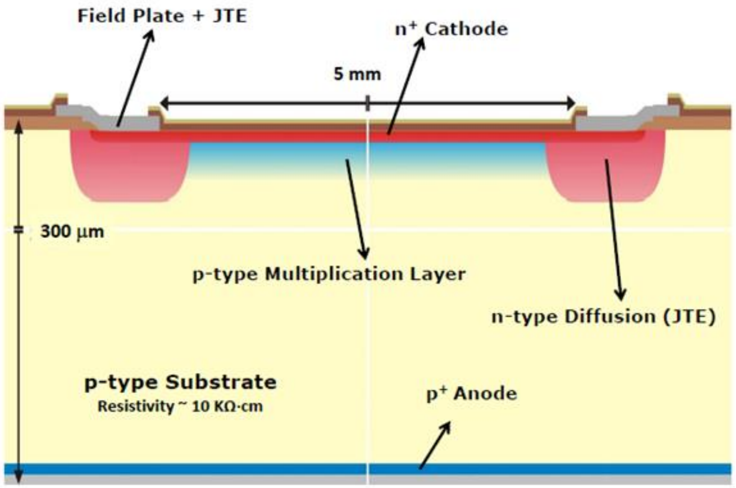
- Standard thickness LGADs have problems (JINST Vol. 10 (2015) P07006) with effective acceptor removal, which degrades gain fast – almost gone at 5e14 cm^{-2} for applicable voltages
- Why can thin sensors be potentially more radiation hard than standard even if the removal is the same:

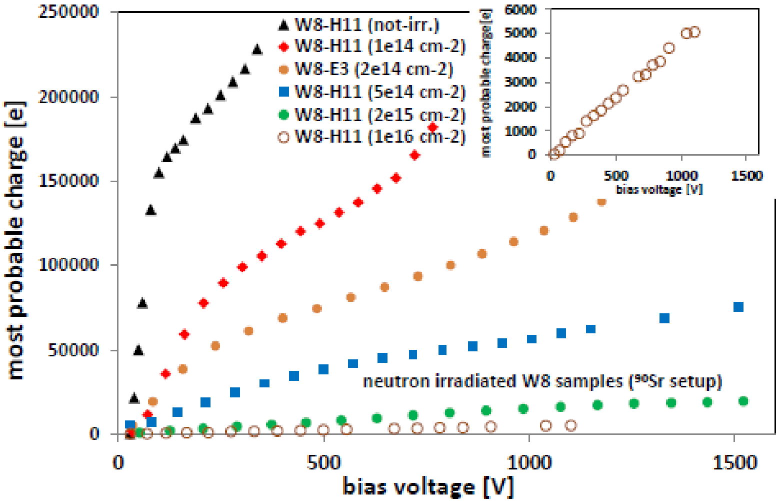


with over depletion ($V>V_{fd}$) the electric field in the multiplication layer grows as: $\Delta E=\Delta V/W$

Smaller electric field in the multiplication layer due to smaller N_{eff} can be much easily compensated with higher applied bias voltage.

Properties of the bulk material become more important.





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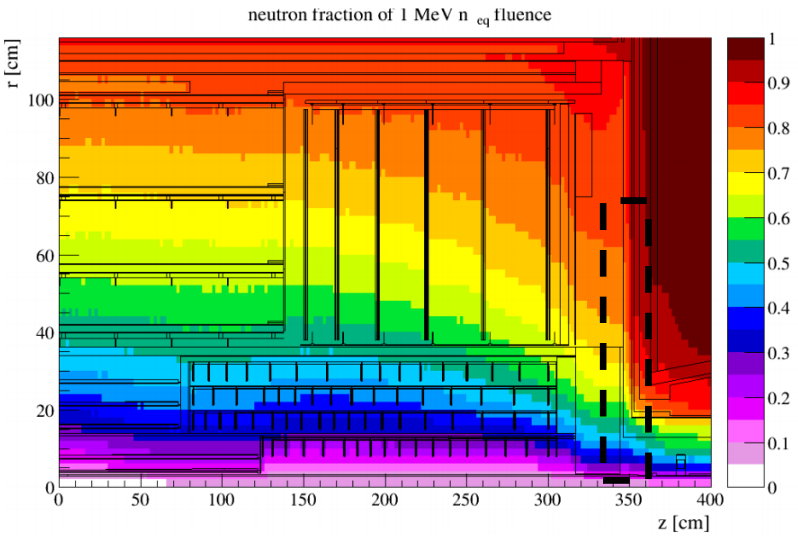
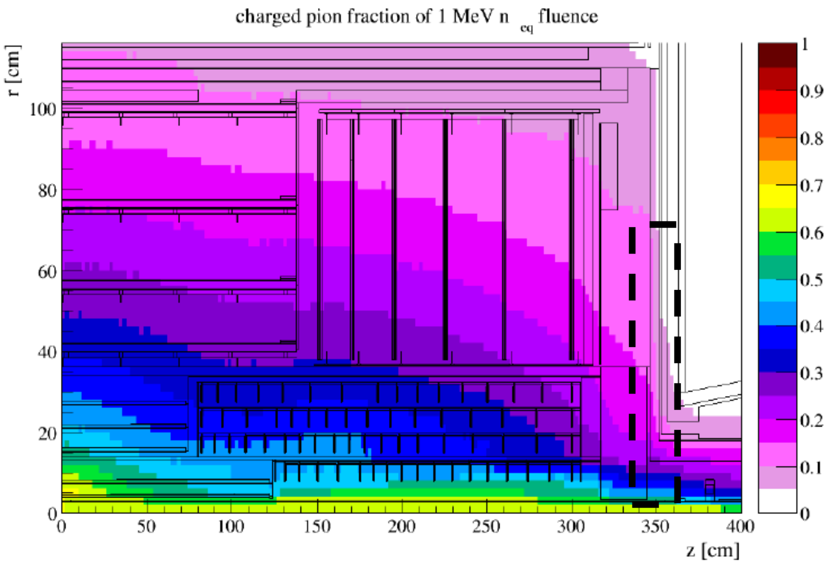
Radiation damage – particles

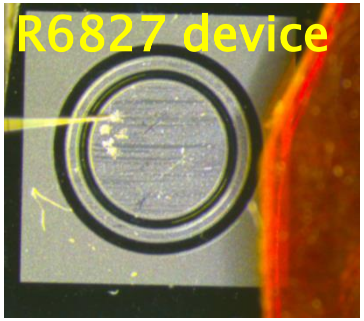

neutron fraction of 1 MeV n_{eq} fluence


charged pion fraction of 1 MeV n_{eq} fluence

- At r,z=(11 cm,350 cm) the share of charged hadrons/neutrons contribution to NIEL is ~0.5 in ATLAS
- Two potential differences wrt to neutron irradiated LGADs:
  - difference in effective acceptor removal (factor 2 observed in standard LGADs of small gain)
  - Difference in electric field profile in the bulk (more pronounced in thin sensors)
- **The key questions are:**
  - Can we operate e.g. ATLAS HGTD for the entire lifetime – Φ_{eq}~$4\cdot10^{15}$ cm^{-2} at adequate performance (~20 ke-> 55 ps per layer)?
  - Do we have to replace modules? If yes, how to do it?

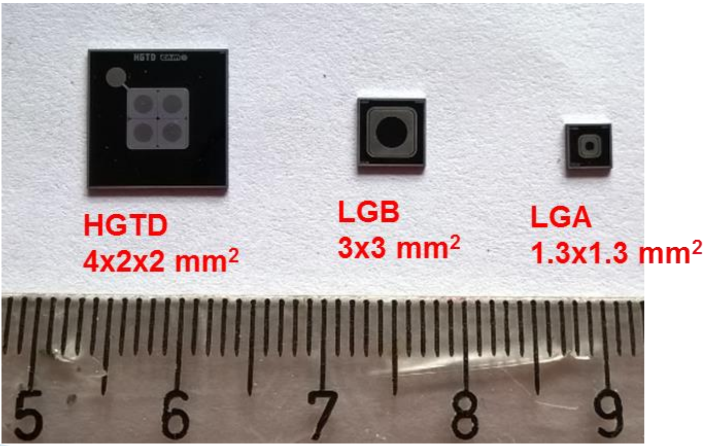
Devices and experimental technique

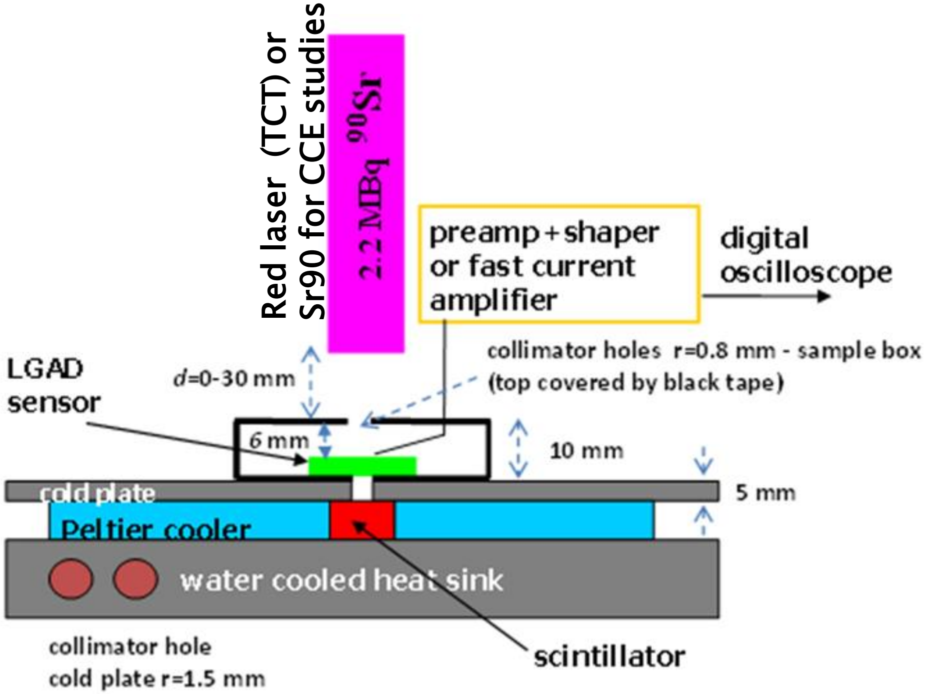
- **CNM Run** 6827 – (Epitaxial devices, 100 Ωcm, 50 μm thick)
  - LGAD samples of low boron concentration in multiplication layer – gain of 7 reached only at high bias voltages
  - Control PIN samples with no multiplication layer
  - Excellent high voltage tolerance



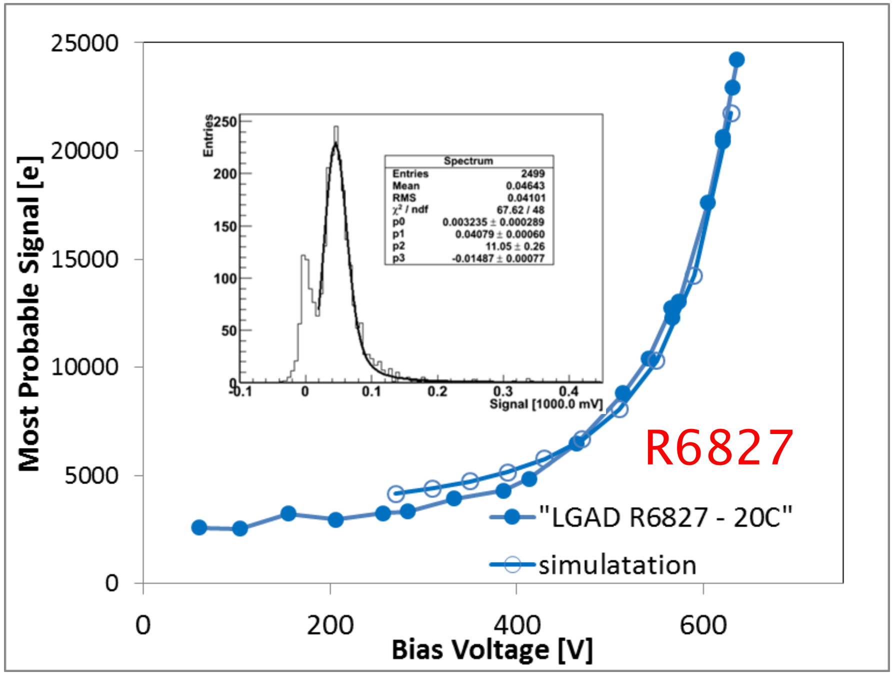
- **CNM Run** 9088 (SOI devices, high-resistivity, 45 μm thick)
  - Three different multiplication layer doping concentrations
    - W3 – Dose=1.8e13 cm^{-2}
    - W5 and W7- dose =1.9e13 cm^{-2} (most studied)
    - W11 – Dose=2.0e13 cm^{-2}
  - Three different device structures
  - Control PIN diodes produced along the LGAD

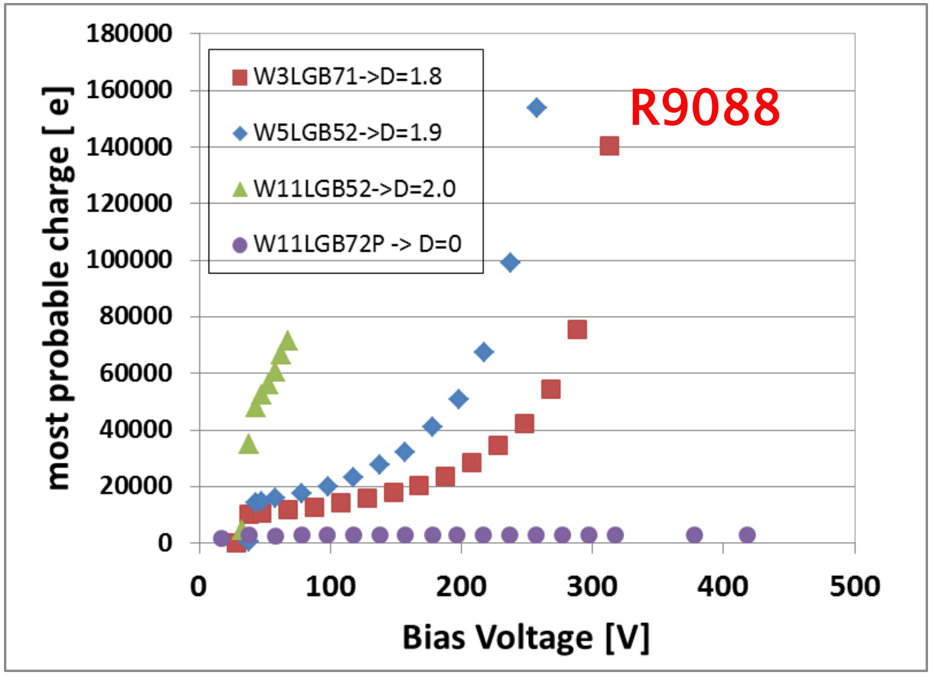
Excellent results with these R9088 devices – see:
Jörn Lange's talk and N. Cartiglia's paper arXiv:1608.08681





Signal/Gain as the main parameter





- Signal/gain is directly correlated to timing resolution.
- Clear influence on implantation dose:

Smaller dose -> higher gain at given voltage, but earlier break down

- A good agreement with basic simulations

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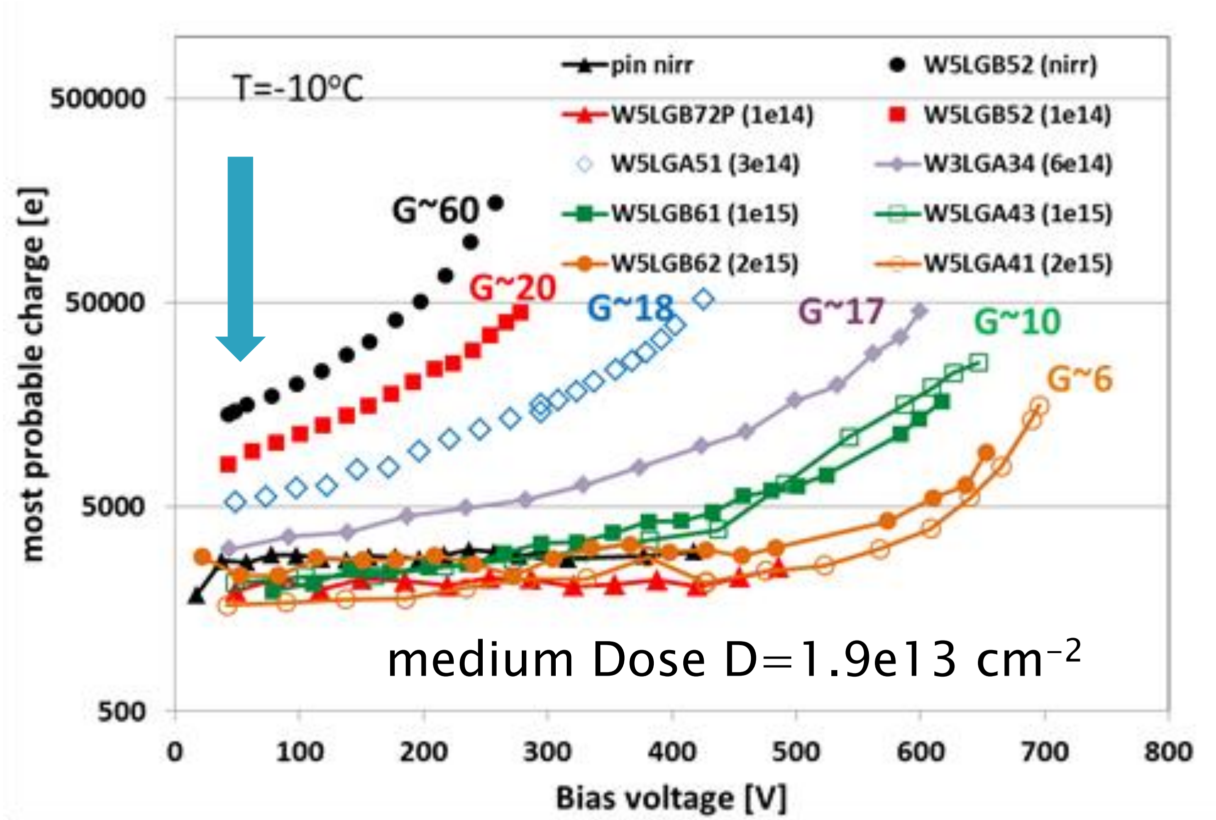
Signal after neutron irradiations (R9088)

- Gain degrades, but follows the expectations
- “Breakdown” voltage of the device is shifting to higher bias with irradiations



medium Dose D=1.9e13 cm^{-2}

1.) at fluences < 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 dependence.

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.

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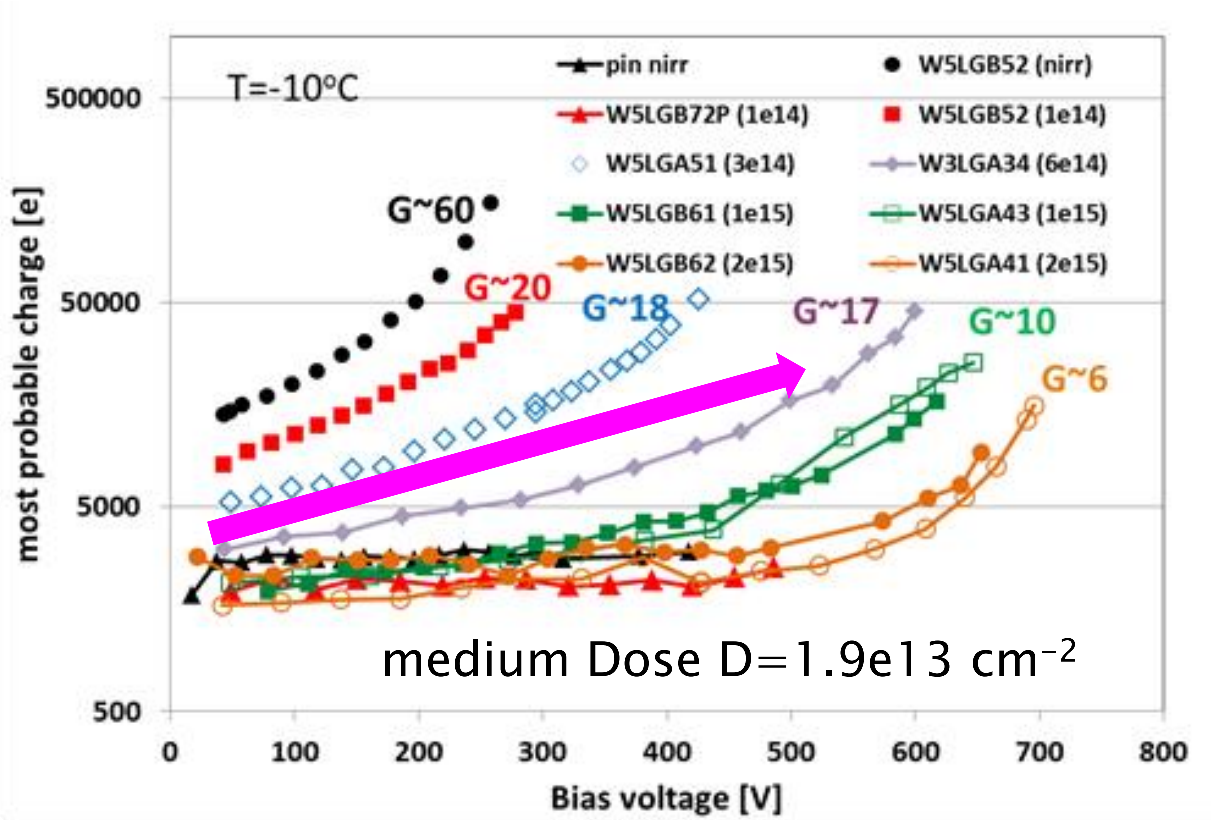

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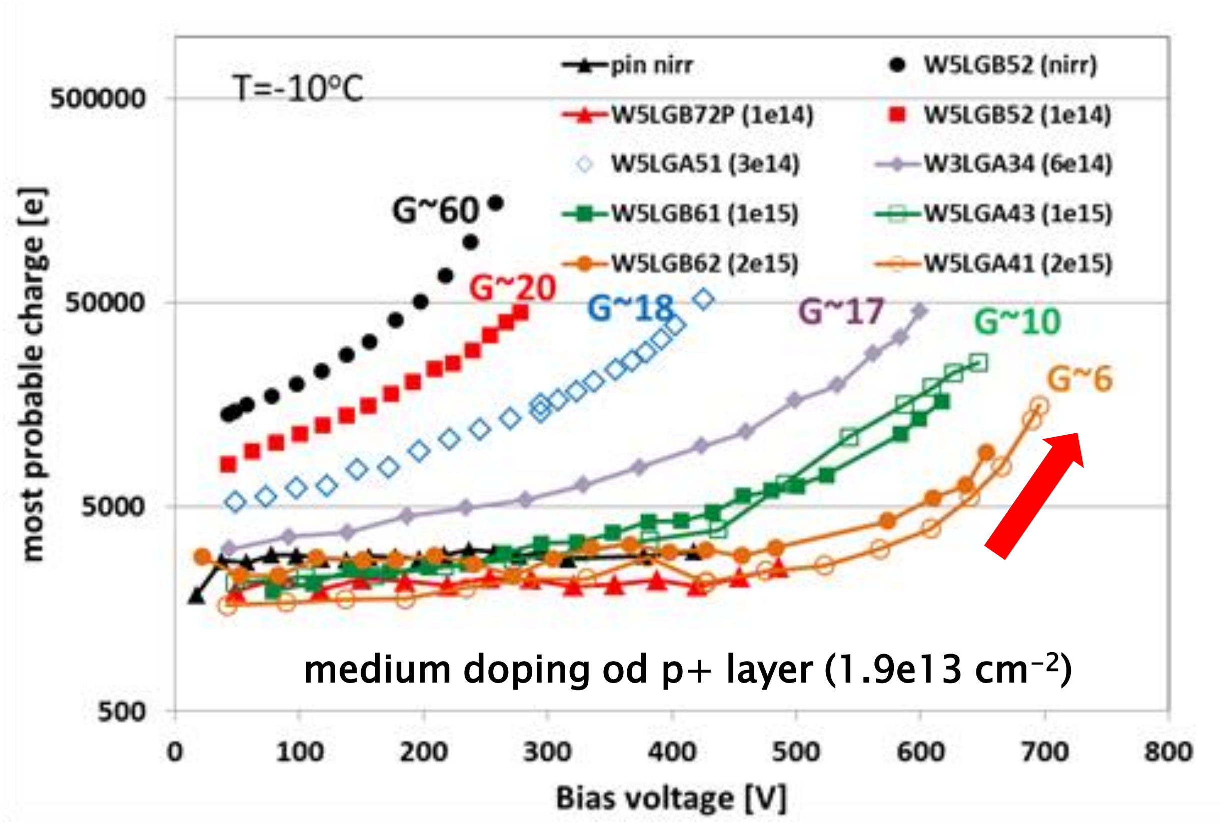

medium doping od p+ layer (1.9e13 cm^{-2})

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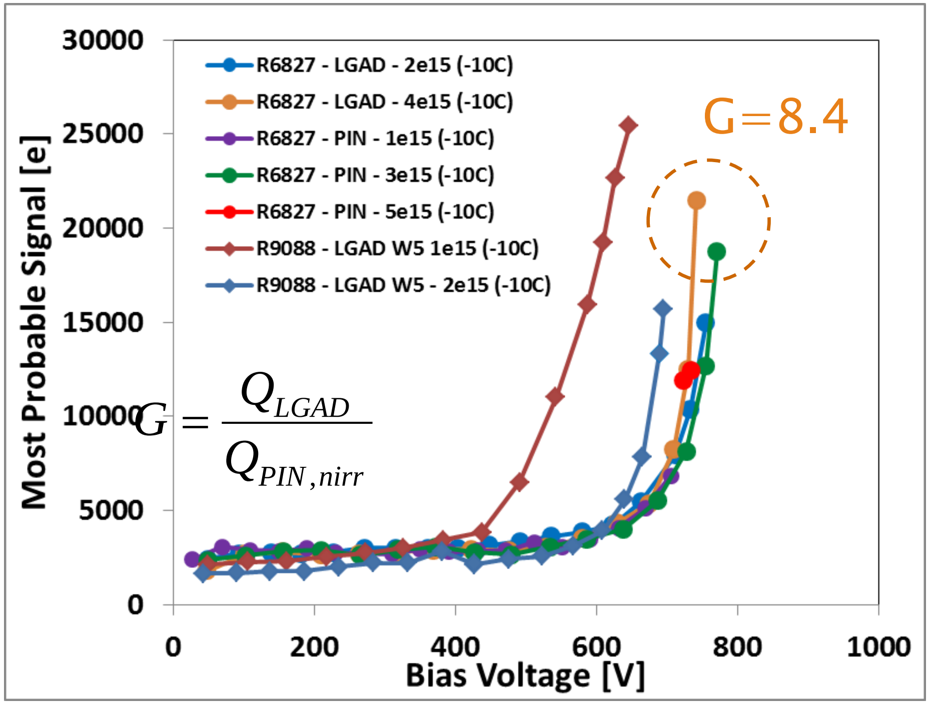
Signal after irradiation for thin LGADs at high Φ_{eq}

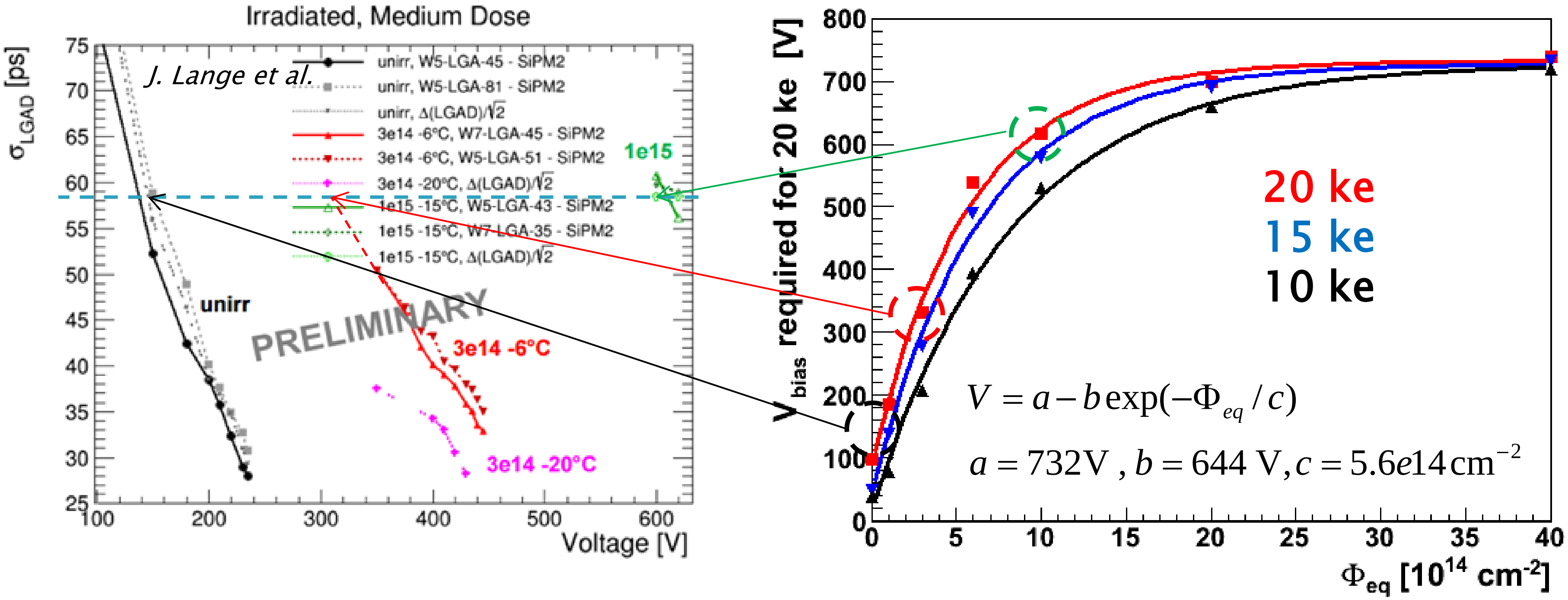


The last point is always taken just before the detector exhibits a “soft break down”:

- 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 average E > 12 V/μm for voltages above 600 V.

- LGAD are advantageous for high gain device up to 2e15 cm^{-2}
- At high fluences $\Phi_{eq}>2\cdot10^{15}$ cm^{-2} the behavior is the same for all samples:
  - regardless of initial doping concentration (to confirmed by more statistics)
  - 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 (see G. Kramberger et al talk at 28th RD 50 Workshop in Torino)

Correlation of charge with time resolution



- Two factors are important for good timing resolution:
  - Gain
  - saturated drift velocity (high gain at low bias voltage is not sufficient)
- With irradiations the required bias voltage for gain increases (above <E>=3 V/μm the velocity is almost saturated) and the gain becomes directly related with time resolution
- Is there a a sensor design that allows with all the required geometry constraints operation at extreme voltages?

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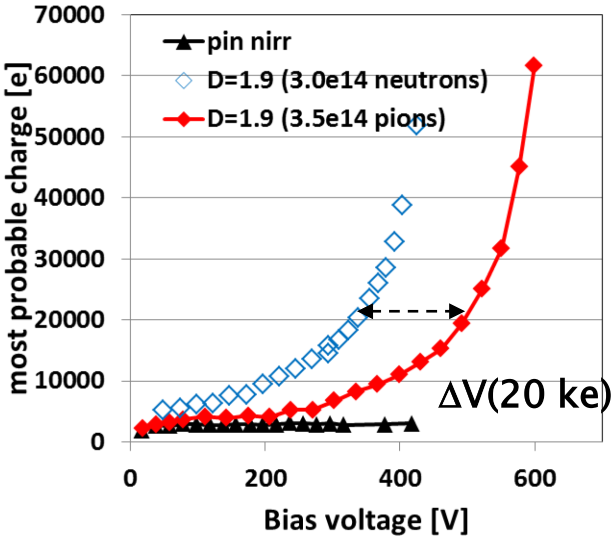
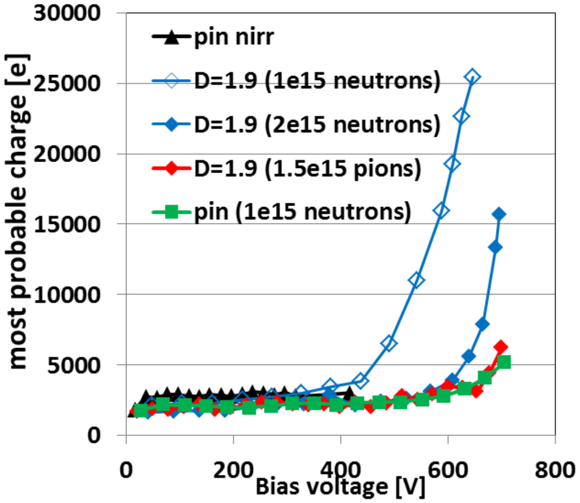
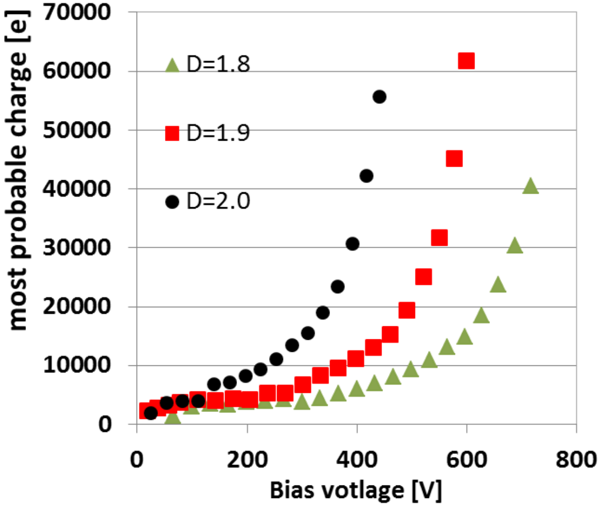
Comparison of reactor neutrons and 200 MeV pion irradiations







- Shift of required bias voltage to larger values: ΔV_{bias}(20 ke, ~3e14 cm−2)~160 V
- Smaller collected charge for 1.5e15 cm^{-2} wrt to neutron irradiated samples – the same performance as for pin sample – the beneficial effect of LGAD has gone
- The effect of initial doping remains visible after low fluence irradiation, while it is gone at the Φ_{eq}=1.5e15 cm^{-2} pions.

Charged hadrons are more damaging than neutrons!

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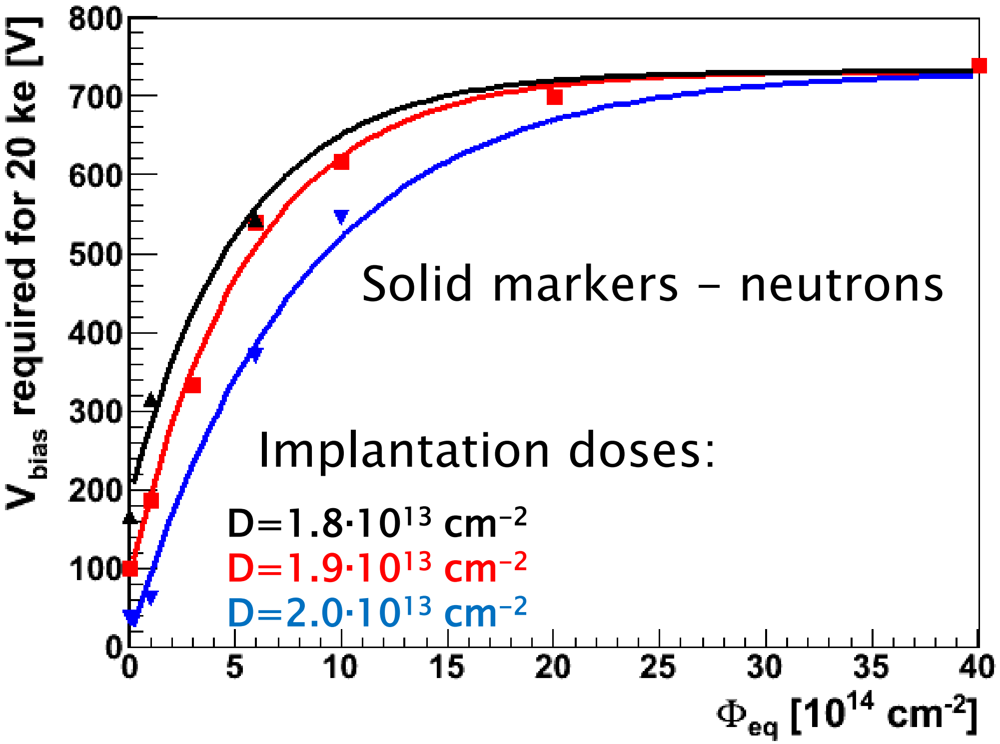
What is the best initial gain/dose?



- High implantation dose – very high initial gain, but early break down
- Low implantation dose – lower initial gain, but high voltages can be applied
- The difference in doping is seen as difference in V_{bias}(20 ke) up to Φ_{eq}~$2\cdot10^{15}$ cm^{-2}?

Is it worth risking some of the initial performance in timing for lower e.g. V(20 ke) in the high fluence region? Already at $\Phi_{eq}=1\cdot10^{14}$ cm^{-2} high implantation dose devices can be biased to >150V!

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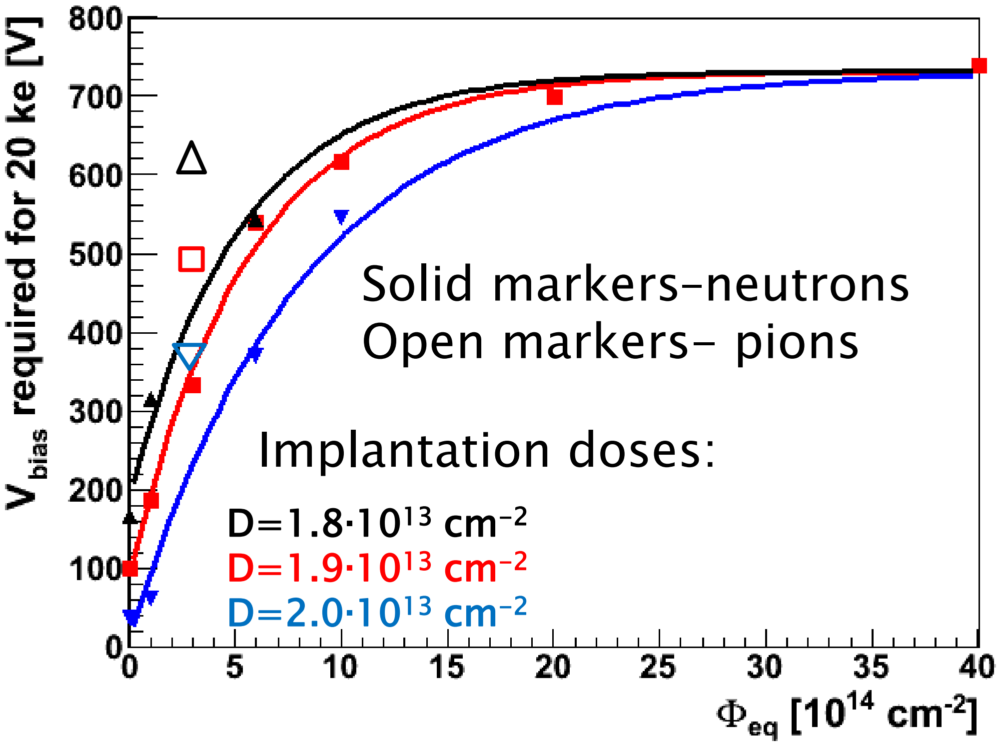

- High implantation dose – very high initial gain, but early break down
- Low implantation dose – lower initial gain, but high voltages can be applied
- The difference in doping is seen as difference in V_{bias}(20ke) up to Φ_{eq}~$2\cdot10^{15}$ cm^{-2}?

Option of risking some of the initial performance in timing for lower required bias in the high fluence region? In particular as already at $\Phi_{eq}=1\cdot10^{14}$ cm^{-2} high implantation dose devices can be biased to >150V.

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Leakage current

- Leakage current follows the equation : $I=M_I \cdot I_{gen}$
- Leakage current affects thermal performance (requires powerful cooling to avoid thermal runaway and keep the noise low)

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

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

For S/N to increase in multiplication mode

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

Clear benefits for thin sensors:

- smaller I_{gen} due to smaller cell size
- Integration time ($\tau \sim 1$ ns) can be very small due to short drift, hence small parallel noise contribution
- $M_Q \sim M_I$

A drawback is higher capacitance, which however makes is slightly easier to fulfil the above condition

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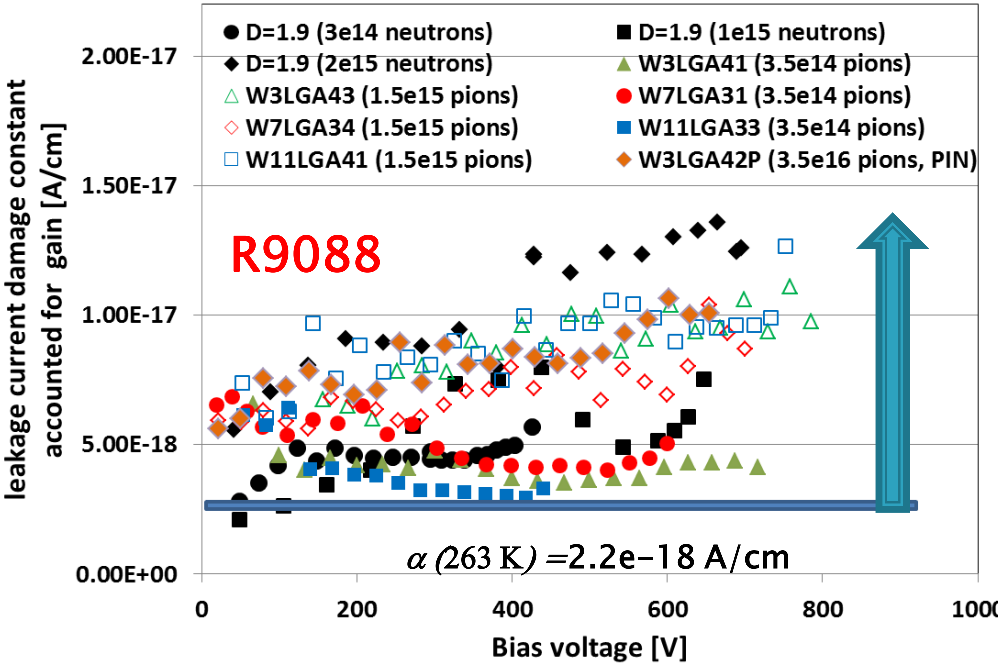
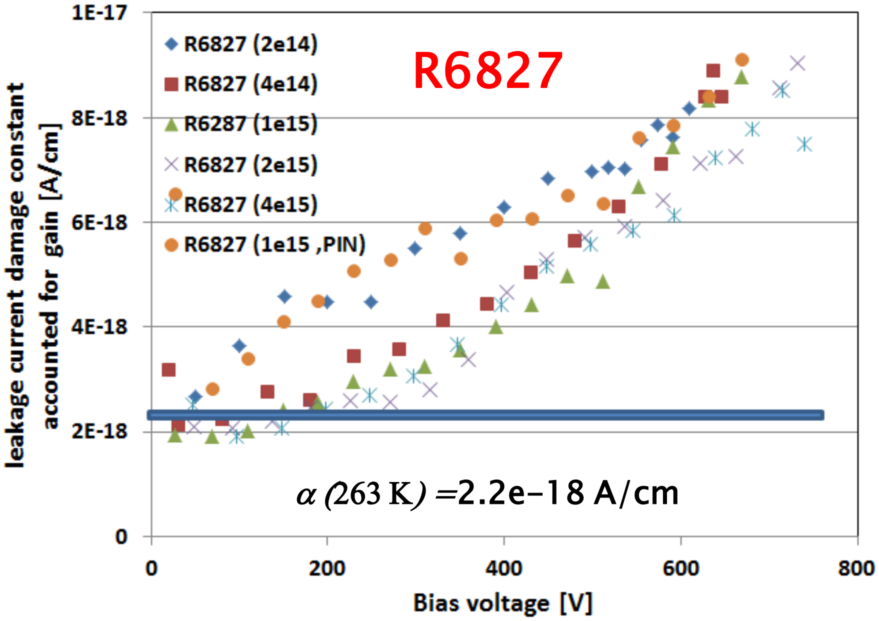
Leakage current

$$\alpha = \frac{I_{gen}}{S \cdot d} = \frac{I}{S \cdot d \cdot M_I} = \frac{I}{S \cdot d} \cdot \frac{Q_{no,gain}}{Q_{LGAD}}$$





- Leakage current measurements are nicely correlated with gain measurements.
- Measured leakage currents are higher than expected for factor 2-4
  - possibly larger temperature than measured (T is not measured on the sensor)
  - leakage current gain can be larger than that for the charge collection
  - surface current contribution is not separated in these measurements
  - we still don't understand fully the origin of the dark current before irradiation

Probably not related to multiplication mechanism as control samples show same behavior

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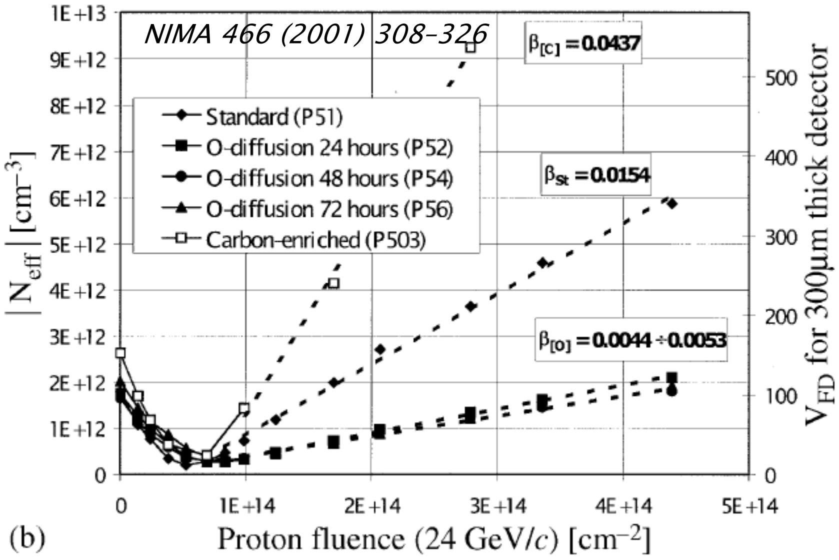
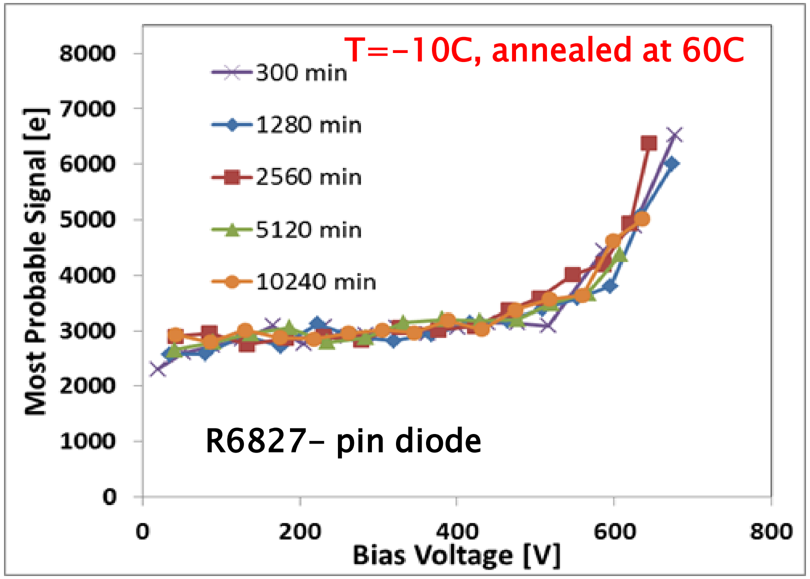
Ways to improve gain after irradiation

The paradigm has changed from that in the past – we want as high N_{eff} as possible for peaked fields which result in gain:

- Long term "reverse" annealing has been shown to increase multiplication in standard FZ strip devices (JINST 7 P06007 ,) – no such effect seen in thin control samples at $\Phi_{eq}=10^{15}$ cm^{-2}.
- 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 -> answer at 13th Trento workshop… first samples coming in few moths





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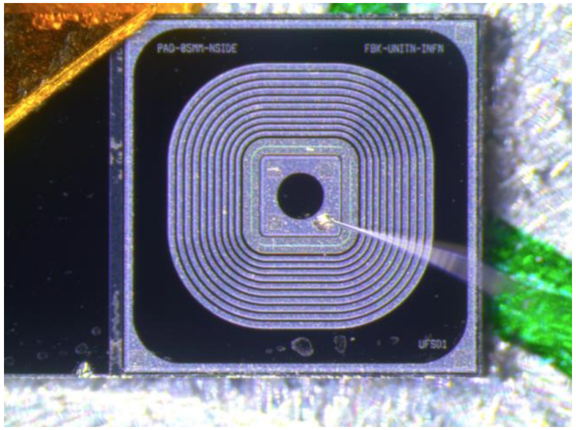
FBK samples – radiation hardness by different gain layer design

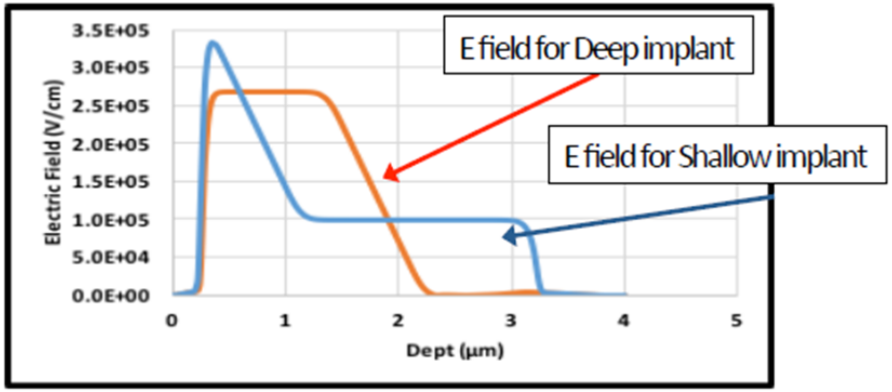
FBK Run samples-300 μm, 10 kΩcm,

- 0.5 mm^2 active region (source of difficulties)
- two different implant doses (**W3**, **W10**)
- pin control sample
- **A deeper doping profile – is it more than CNM standard one?**
- Samples irradiated to equivalent fluences of



0,1,2,5·10^{14} cm^{-2} – fluence range selected to maximize effects that could be determined by measurements

- annealed for 80min@60°C



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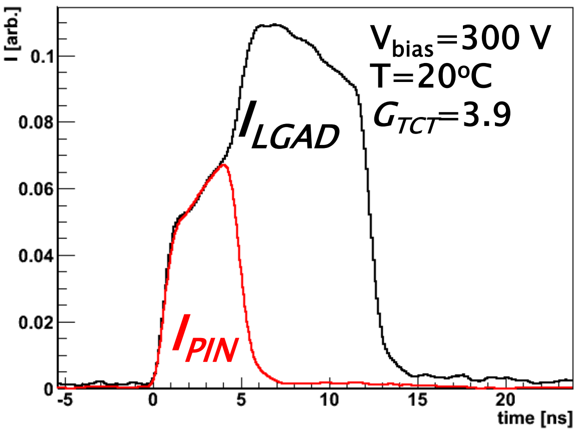
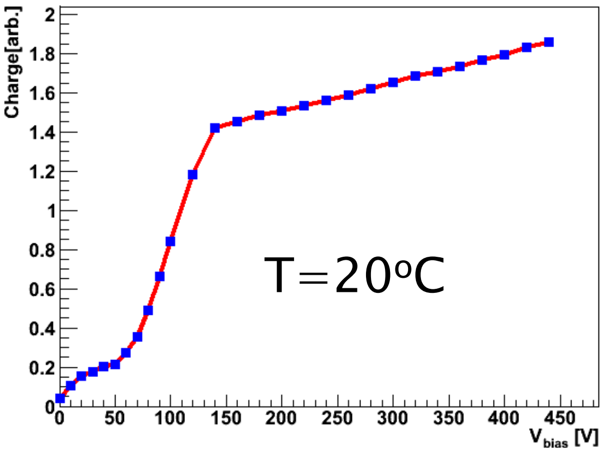
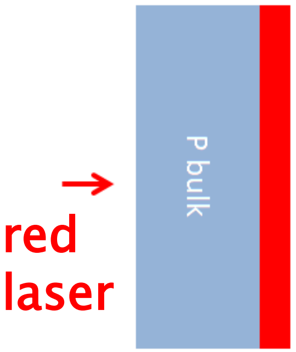
Determination of the gain – back ill. TCT

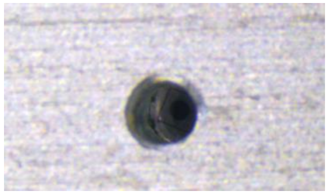
W3 – wafer





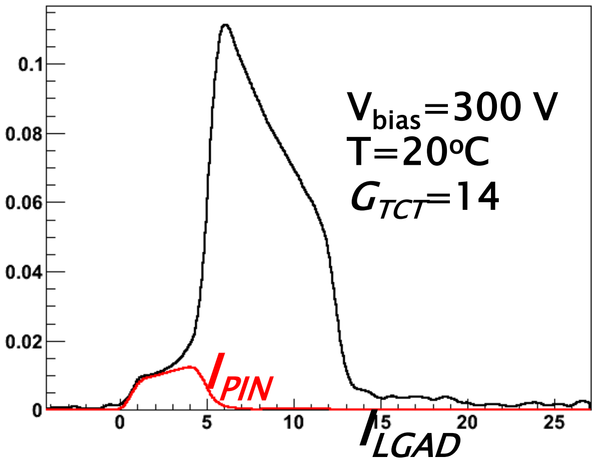
PIN diode

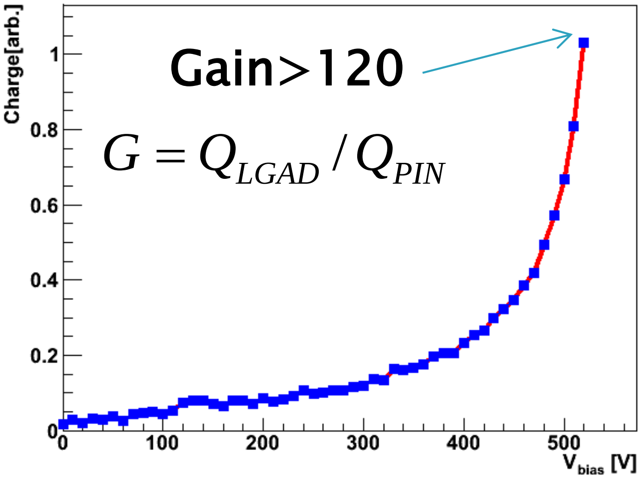


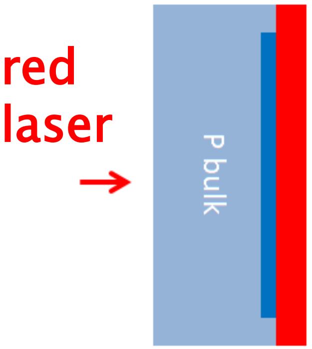


LGAD diode

W10 – wafer







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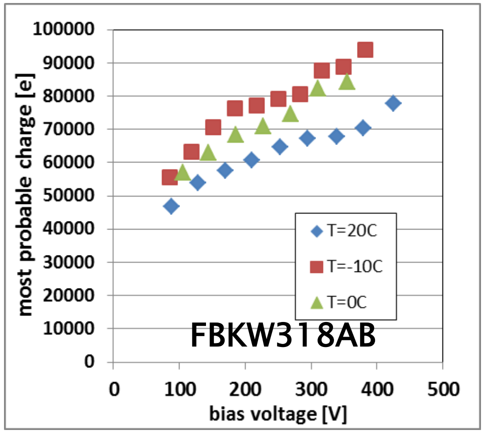
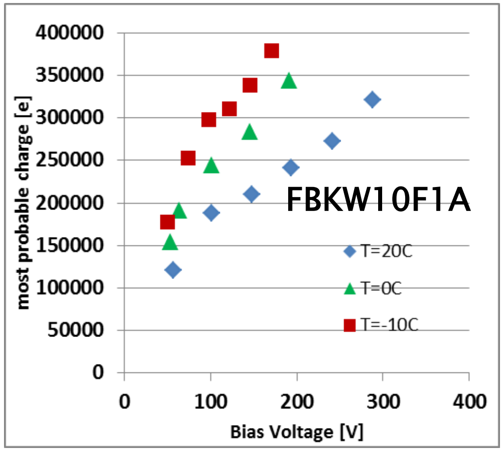
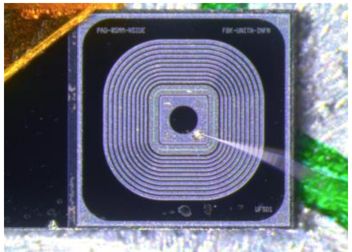
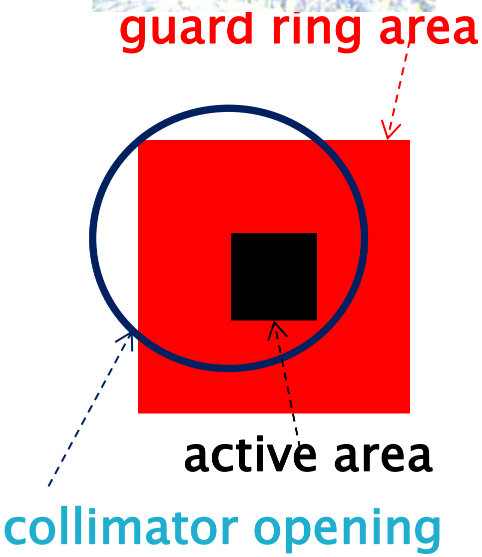
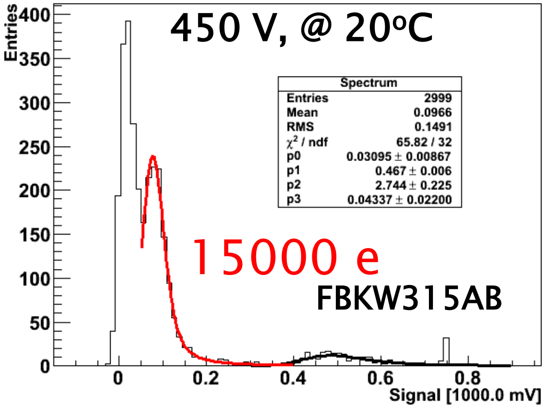
FBK ^{90}Sr measurements – charge collection

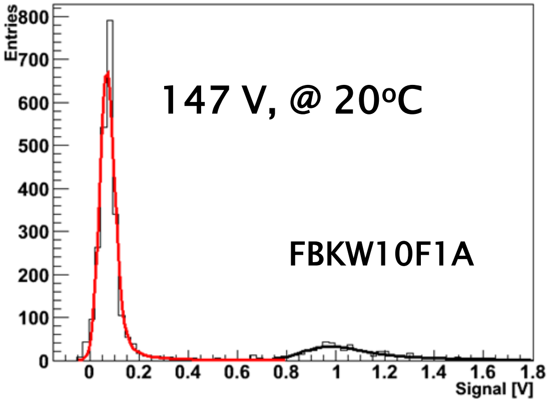










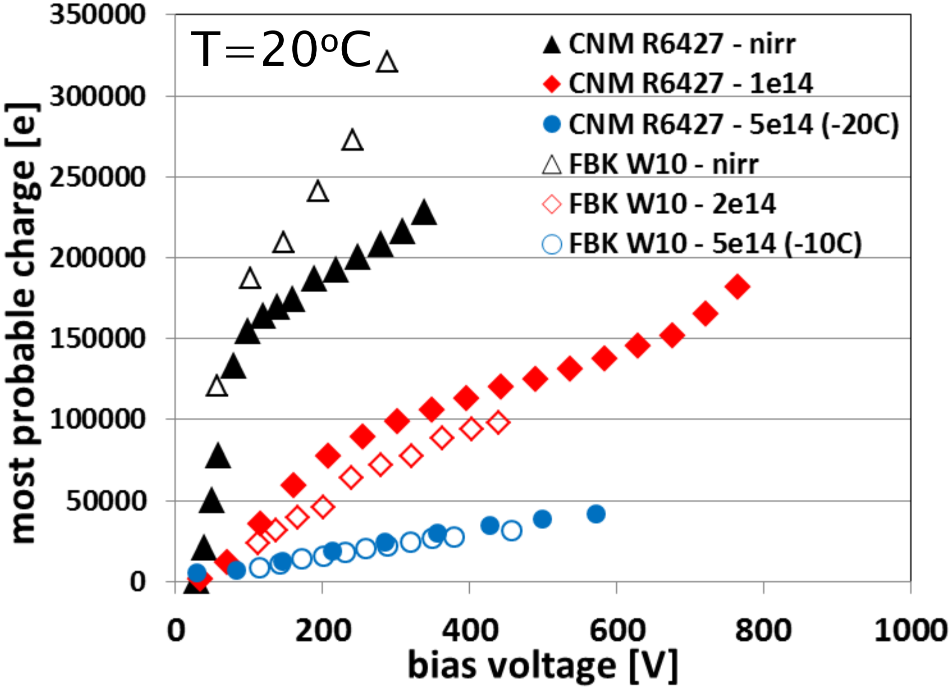


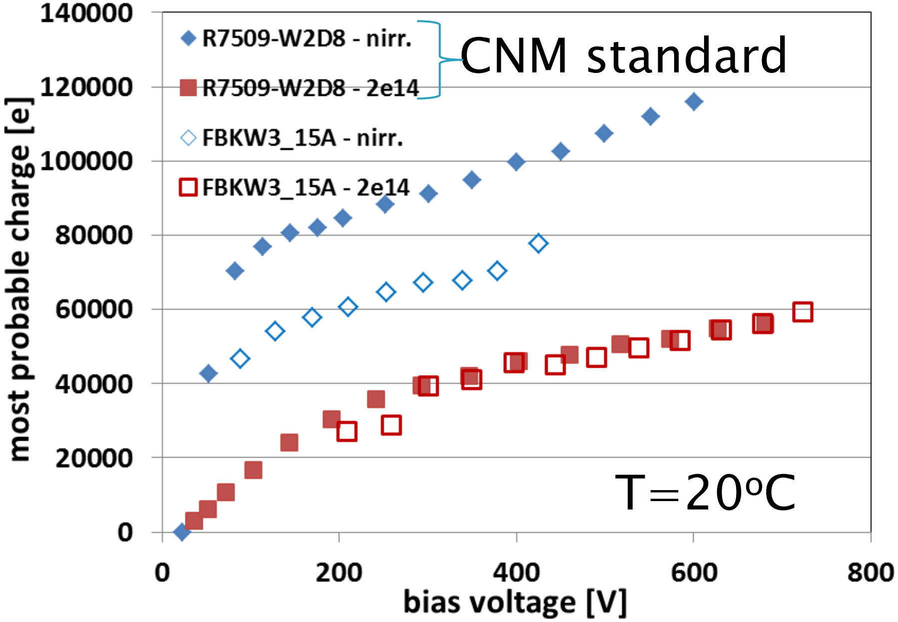
Small sample size is a problem as trigger purity is affected:

- Noise peak – events missing the sensor
- Guard ring collection – capacitvely transferred charge to the connected electrode
- Active area – multiplication

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

FBK – CCE with ^{90}Sr after irradiation

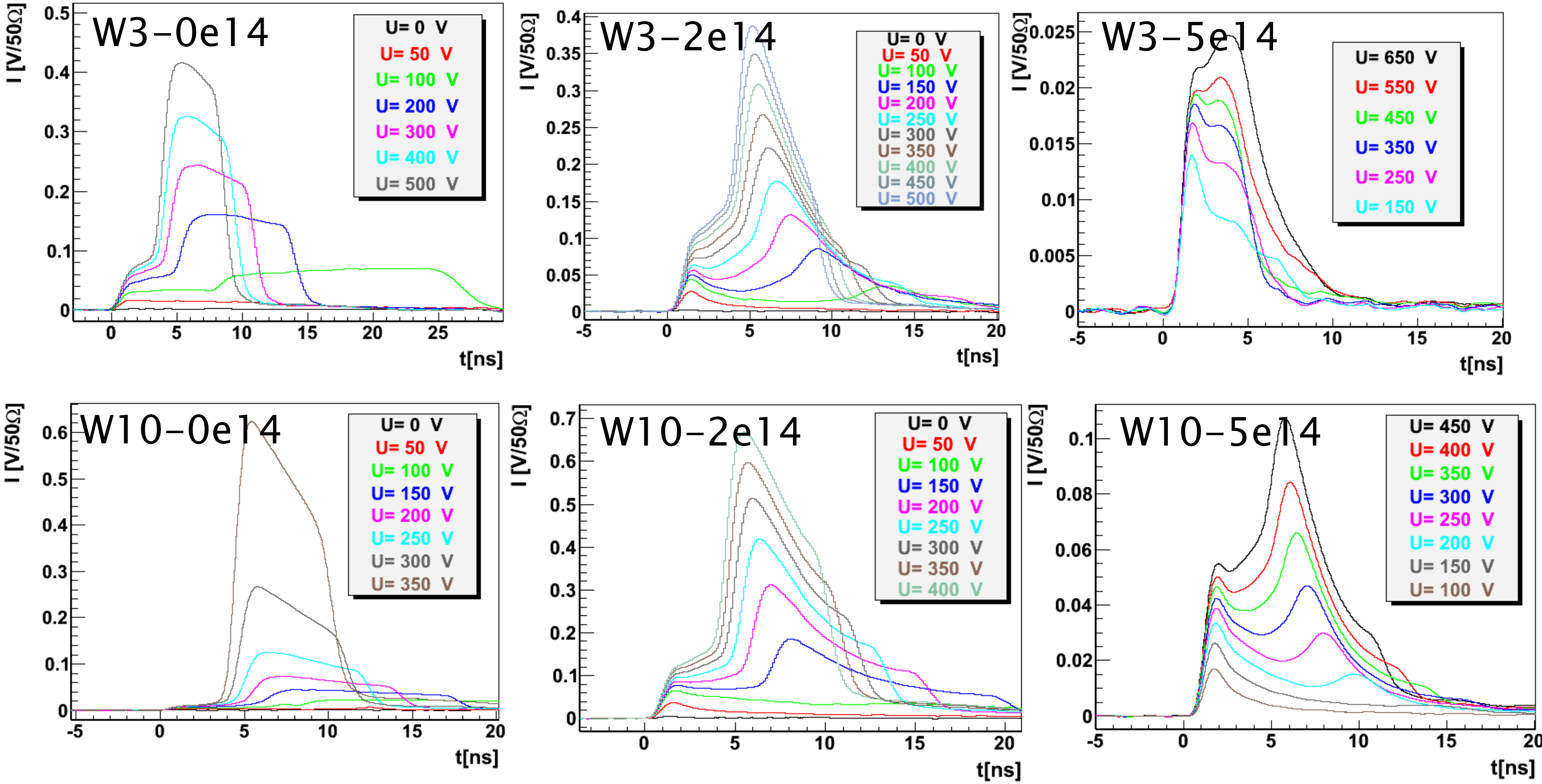




- Impure trigger complicates the analysis; even more at smaller gain (difficult separation of peaks – analysis not possible for W3 at high fluences).
- Evaluation of FBK detectors performance in terms of gain after irradiation seems to be comparable to CNM detectors – still ongoing study.

G. Kramberger et al.,"Radiation hardness of thin LGAD detectors", 12th Trento Workshop, Trento

FBK – TCT after irradiations



- Clear and significant decrease of gain seen in TCT signals – almost gone at 5e14 cm-2
- Gain somewhat larger than measured in CCE
- Some ununderstood features in the signal – change of SC for non-irradiated samples

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Conclusions

- Thin LGAD sensors perform better than that of standard thickness and retain the beneficial effect on collected charge up to 1–2· 10^{15} cm^{-2}.
- at fleunces >2· 10^{15} cm^{-2} the LGAD and control samples performs similarly even at very high V_{bias} where there is gain
- The Gain(V) depends on fluence and implant dose – the larger the doping (implant dose) the higher the fluence up to which LGADs perform beneficially.
- Pions are more damaging than neutrons in terms of gain.
- Time resolution is correlated with gain -> V(Q) can be mapped to σ_t(V) once the voltage is high enough to saturare drift velocity

How to overcome the loss of multiplication layer?

Several approaches of how to mitigate the loss of multiplication layer are under investigation?

- Ga doping (more difficult to displace than B)
- C enrichment (less deactivation of B); both diffusion and implantation
- Prolonged annealing (works on strips, not seen in pads so far)
- Different doping profiles – benefit on different acceptor removal rate for different concentrations (FBK run) – preliminary studies show small effect!