Studies of CNM diodes with gain

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work done in the framework of RD50 project

Fabrication of new p-type pixel detectors with enhanced multiplication effect in the n-type electrodes

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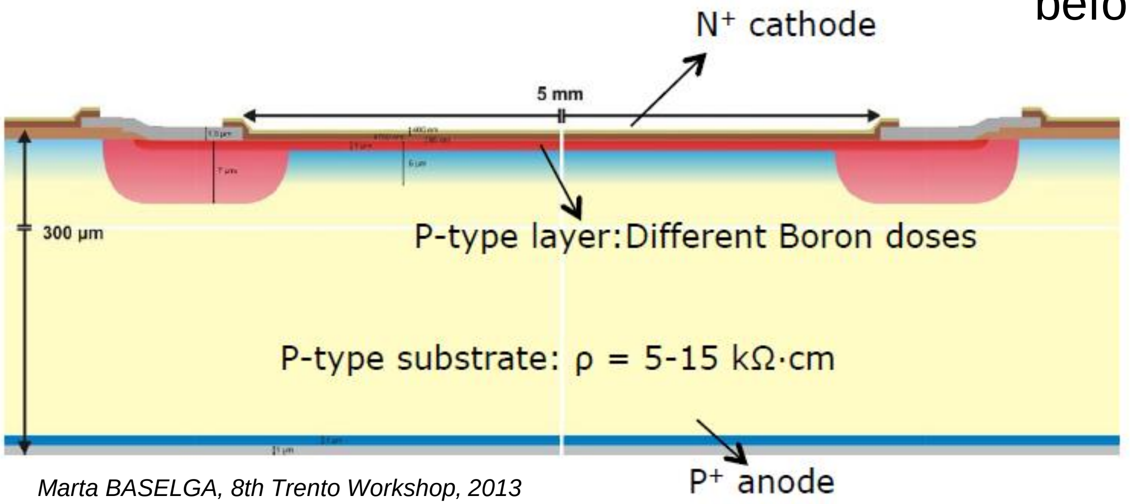
Outline

- Setups and samples
- Non-irradiated detectors
    - C-V
    - ^{90}Sr measurements
    - α –TCT measurements
- Tests of irradiated sensors
    - CCE/current dependence on fluence
    - α –TCT measurements
    - Noise
- Conclusions

Samples

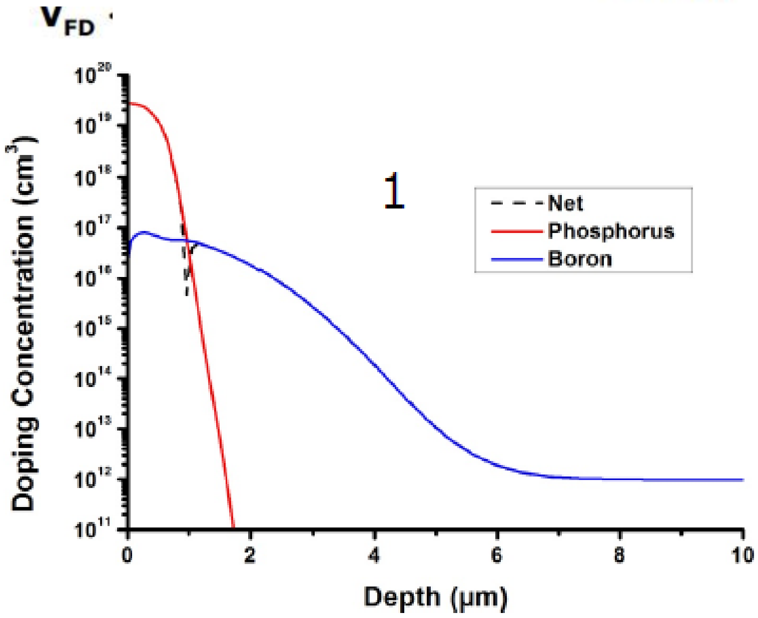


Marta BASELGA, 8th Trento Workshop, 2013

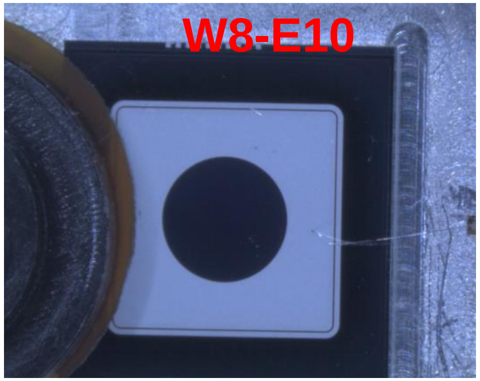
Avalanche multiplication already before irradiation – APD concept.

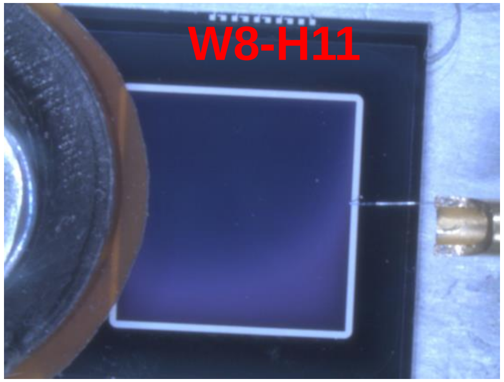
n^{++} - p^{+} - p – p^{+} stucture

$10^{16\text{-}17}$ cm^{-3} – much larger than in the bulk. Large N_{eff} provokes avalanche multiplication by impact ionization.



How do the diodes (pad detectors) behave before and after irradiation?





Setup – measurements technique

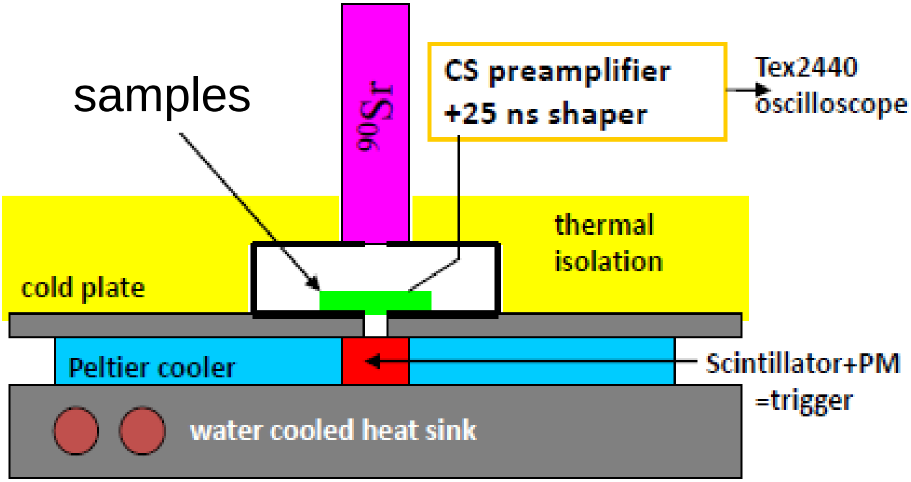
^{90}Sr Setup:

- Measuring absolute charge collection for MIP with LHC-type electronics
- Measuring noise performance

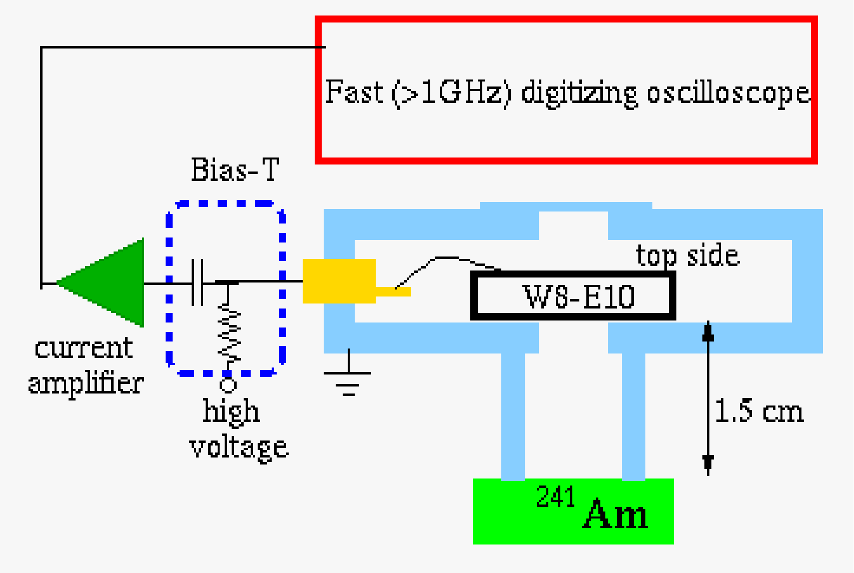
^{241}Am TCT Setup:

- Measures the induced current pulse shape and its time evolution
- Insight in the gain mechanism
- Homogeneity of response

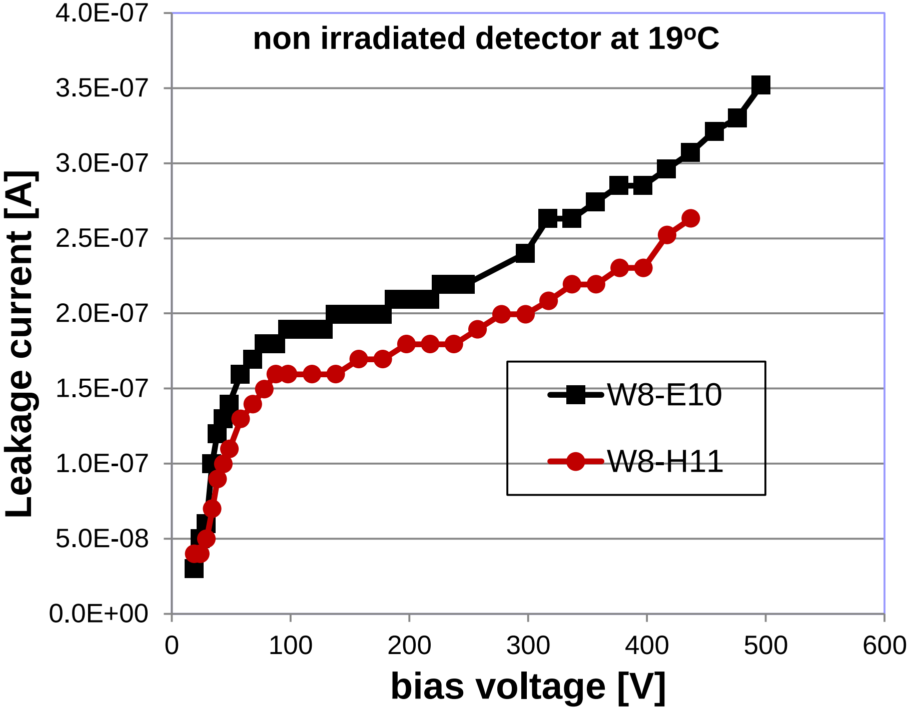
^{90}Sr CCE Setup

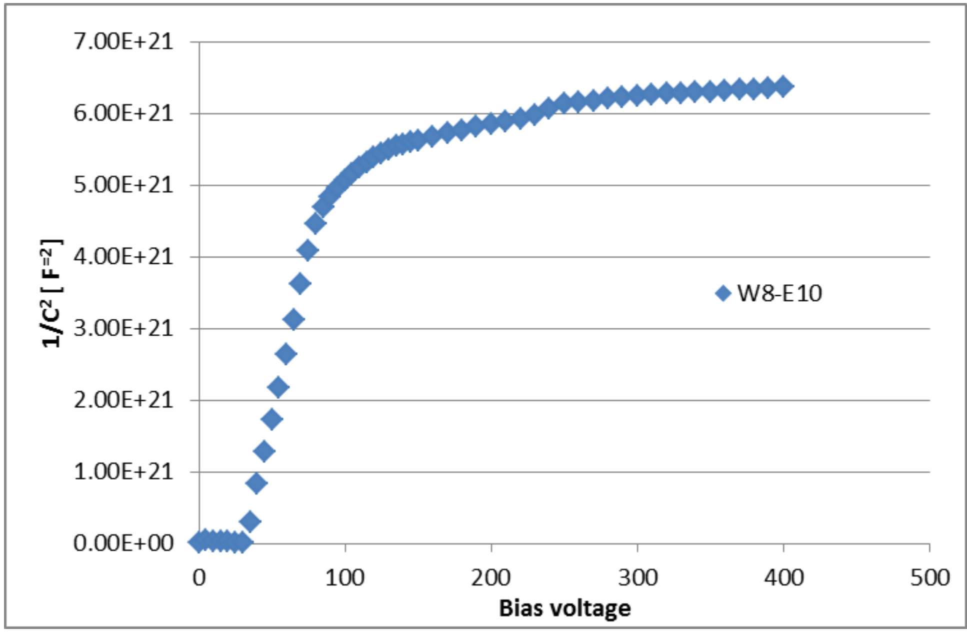


^{241}Am TCT Setup



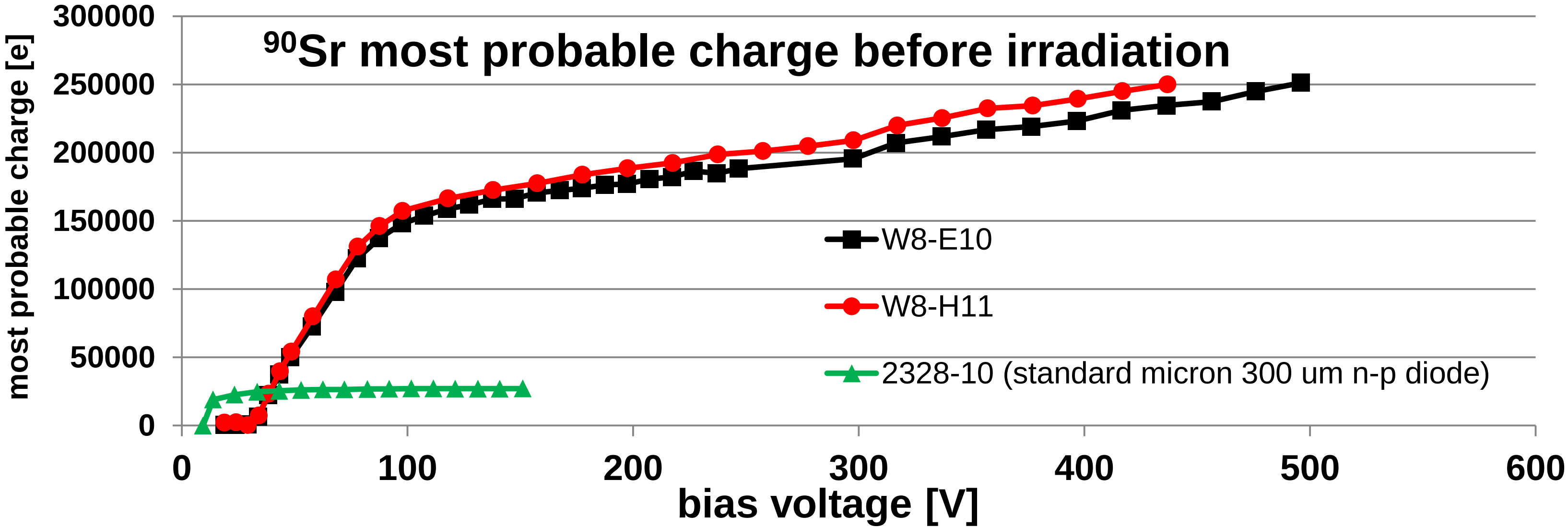
C-V and I-V before irradiations

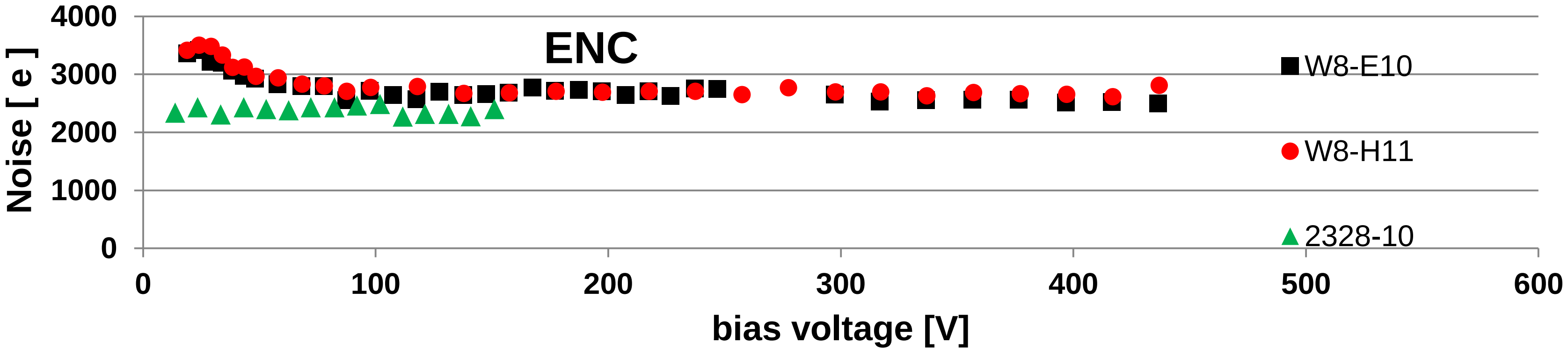




- Leakage current of order few 100 nA/cm^2 – high due to impact ionization.
- V_{fd} of ~90V. The geometric capacitance is in good agreement with measured one (12.5 pF).

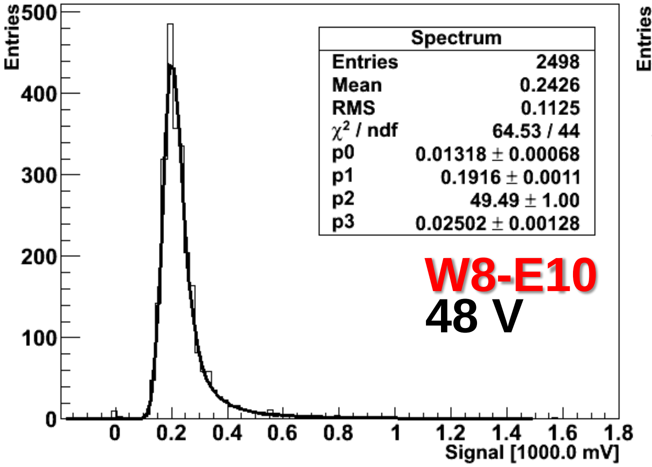
Most probable signal and noise

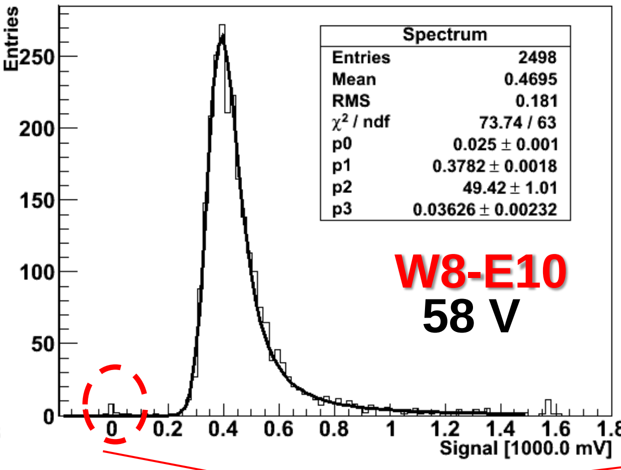


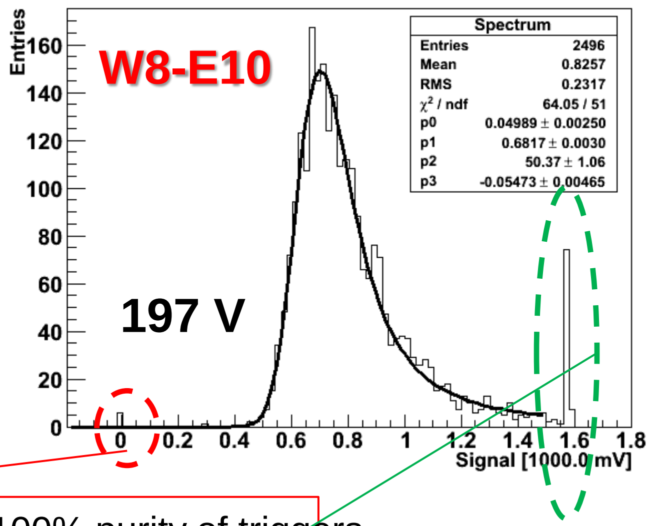


- Improvement of signal **for a factor 8 at 300** V before irradiation
- No significant increase of noise – dominated by series noise

^{90}Sr spectra



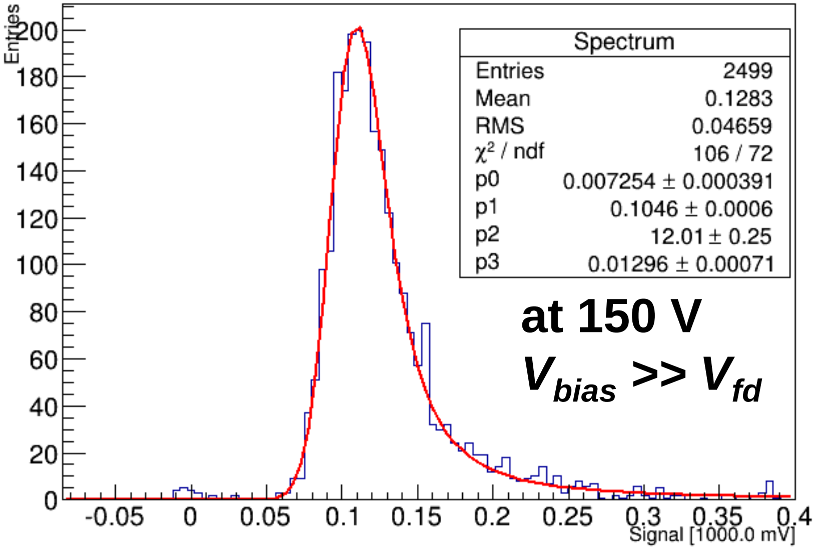




Almost no missed hits – almost 100% purity of triggers

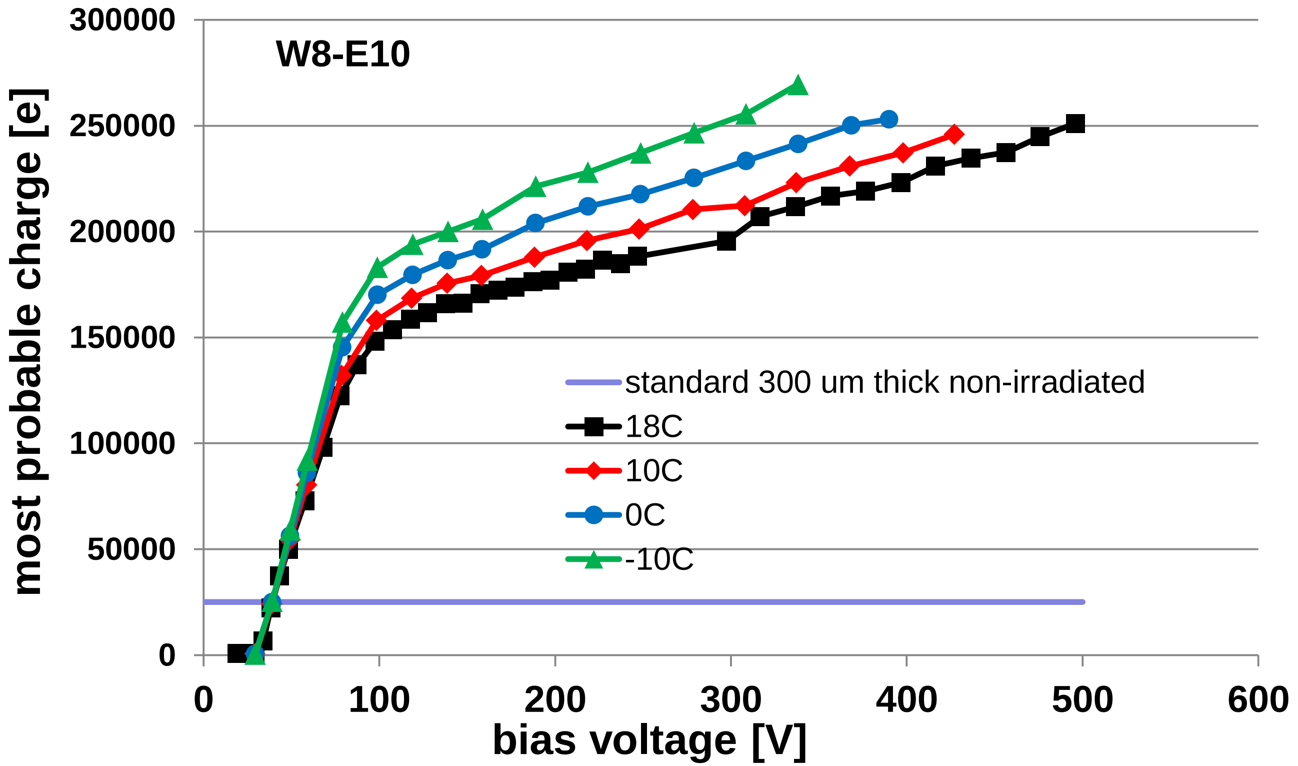
Some hits are outside dynamic range of the digital scope

2328-10 – standard micron n-p diode



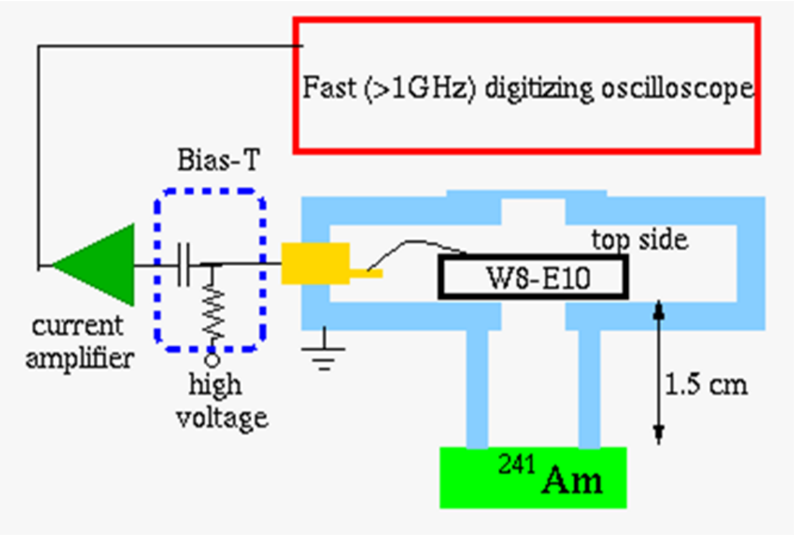
- Both W8-E10/W8-H11 perform very well
- Spectra are Landau – 100 mV corresponds to signal of 25ke
- For comparison the spectrum taken with standard micron n-p diode if 300 μm is shown. NOTE the difference!

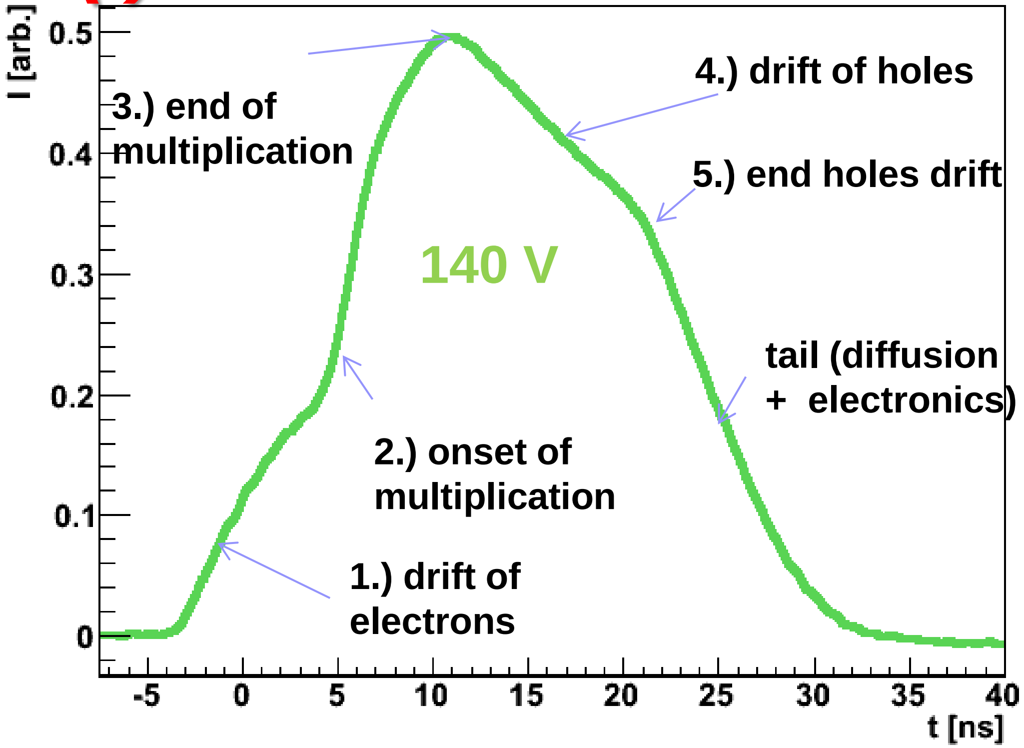
Temperature dependence of multiplication



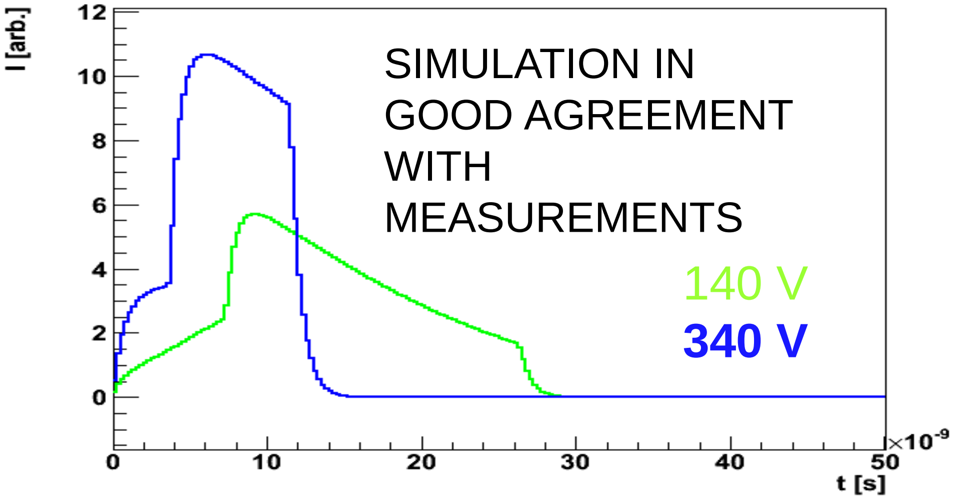
- It seems that there is a limit on multiplication of around a factor of 10. **At lower temperatures break down is reached at lower voltages.**
- Increase of multiplication at lower temperatures is expected – larger impact ionization coefficients.

α-TCT Measurements (I)



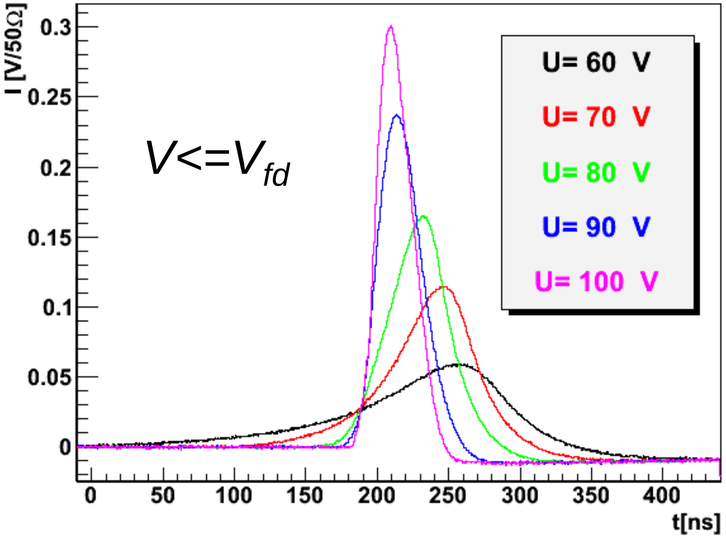


- Exposing the back of the detector to α particles = electron injection. Penetration depth in silicon is less that 20 μm (backside is fully metallized).
- The shape of induced current has the shape which clearly shows the field in the detector. This even more clearly shown at other voltages.



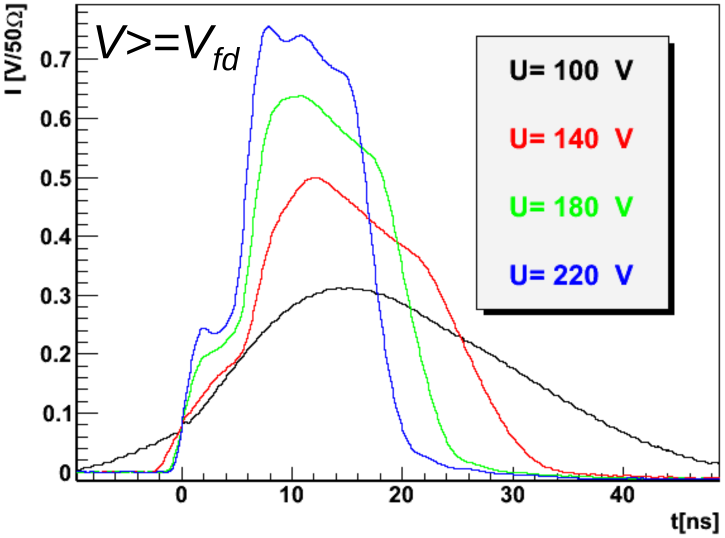
SIMULATION IN GOOD AGREEMENT WITH MEASUREMENTS

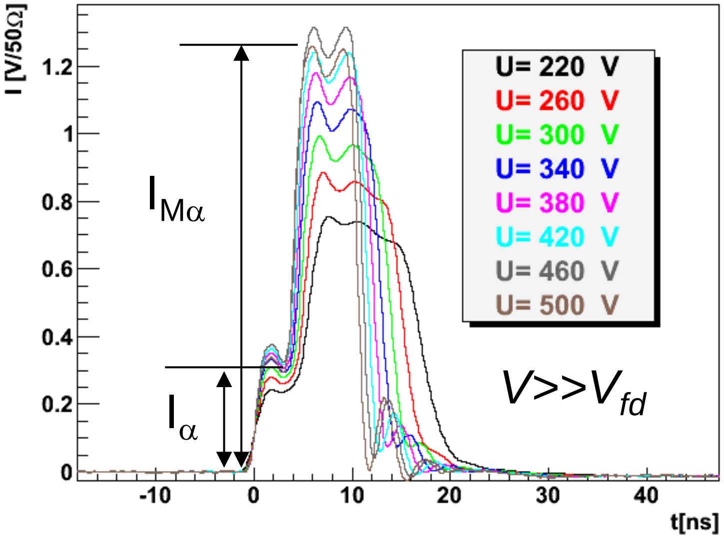
α-TCT Measurements (II)



$I_{M\alpha}$= due to drift of multiplied holes
I_α = due to drift of electrons

$9>I_{M\alpha}/ I_\alpha>3$ –> we get $I_{M\alpha}/ I_\alpha$~4-5

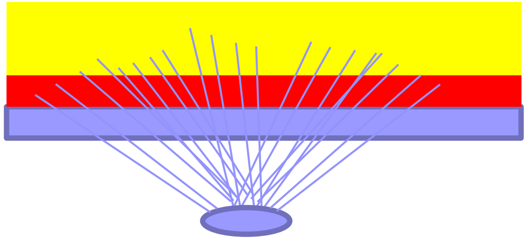




α-TCT Measurements (III)

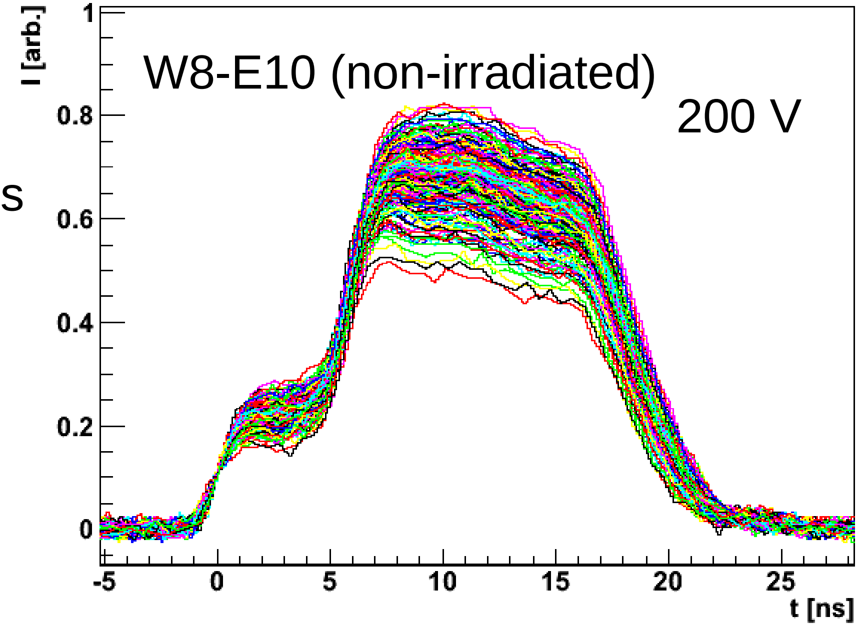
Homogeneity of response – is multiplication uniform over the surface?

A TCT different as conventional TCT (light pulse -> each pulse recorded and not averaged on the oscilloscope.



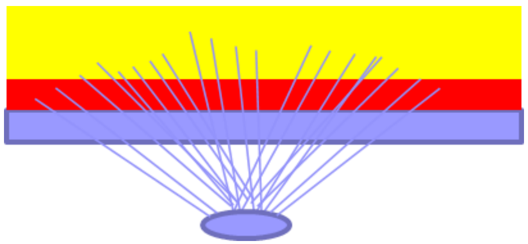
α hit different part of the surface and variation of the multiplication should be seen in the induced current:

- the shape is almost the same for all 300 hits
- amplitude varies by 30%, which may be explained by inclined tracks depositing e-h pairs in the non-active part

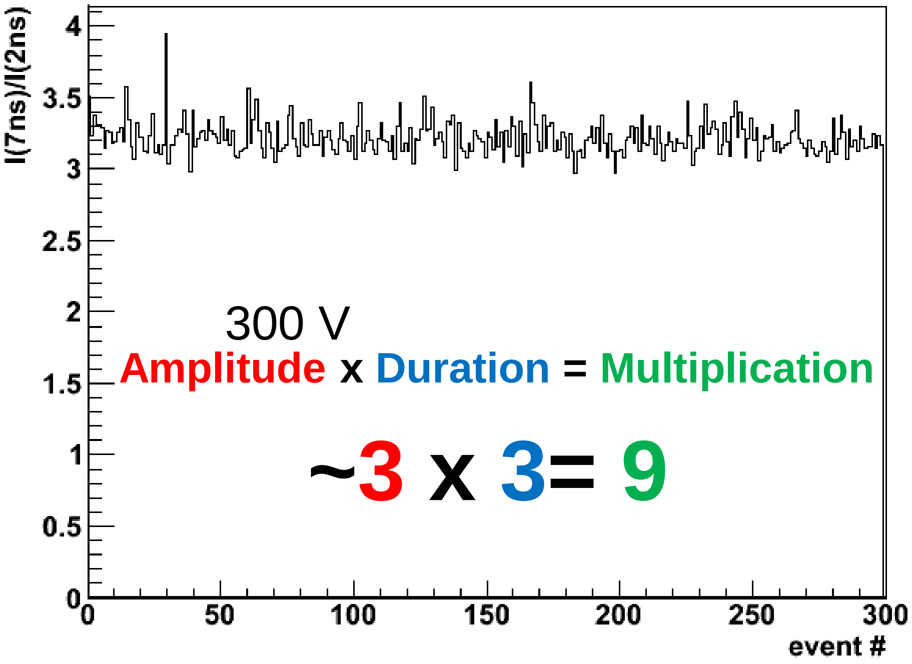


α-TCT Measurements (IV)

If the variation is a consequence of smaller deposited energy by α particle than the ration of $I_{M\alpha}/ I_{\alpha}=I(7ns)/I(2ns)$ should be the same



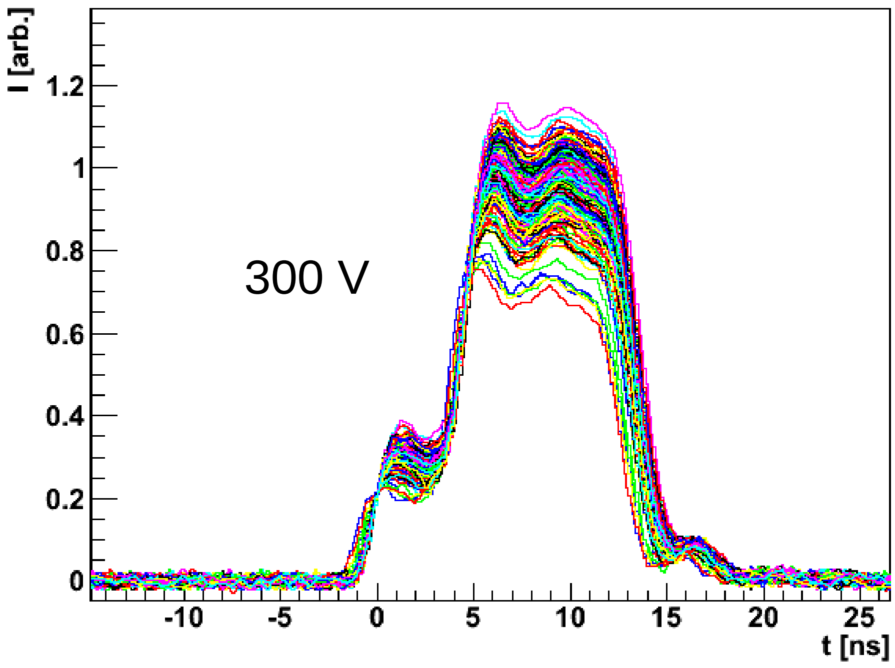
The variation of multiplication over the surface seem not to be significant.



300 V

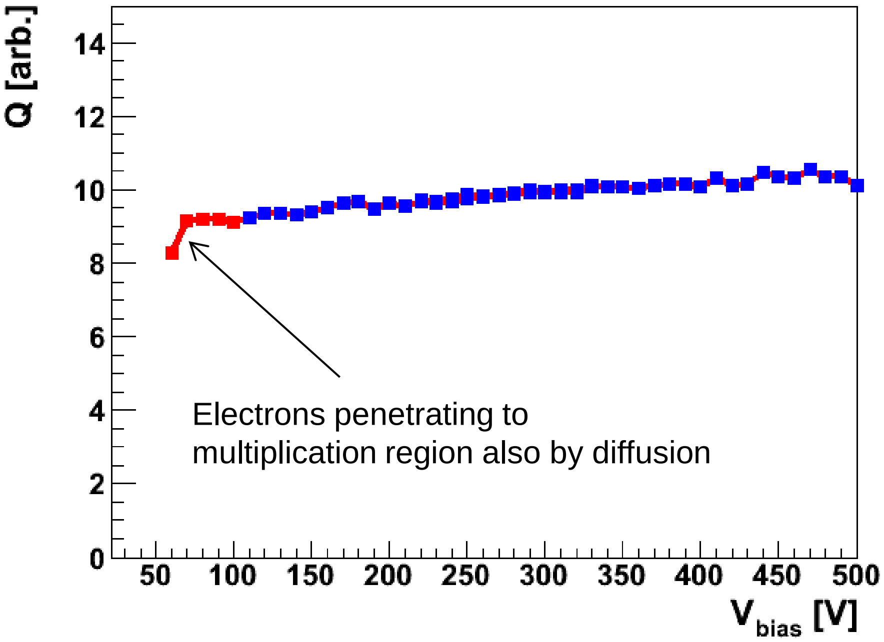
Amplitude x **Duration** = **Multiplication**

~3 x 3= 9

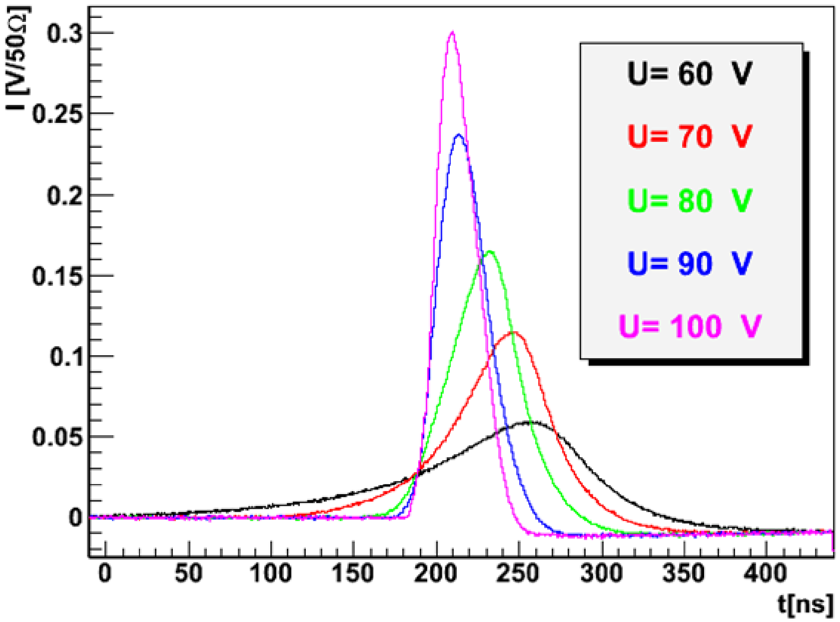


α-TCT Measurements (V)

- If you integrate over the whole time scale of 500 ns – there is very little variation of the charge after all the electrons reach the front electrode – constant multiplication
- For ^{90}Sr electrons with 25 ns electronics there is large ballistic deficit at smaller voltages (note that electrons from the back should get to the front and multiplied holes should drift to the back again = almost double the time of the drift), hence the collected charge e.g. from 80-300 V is bigger for TCT
- Once the multiplication region is depleted additional voltage increases only moderately the gain



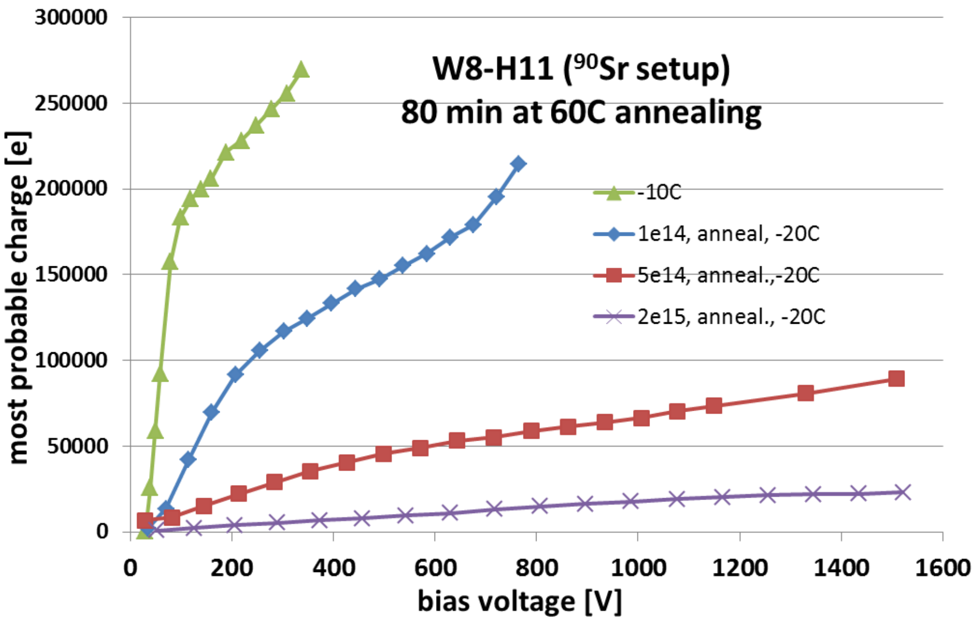
Electrons penetrating to multiplication region also by diffusion

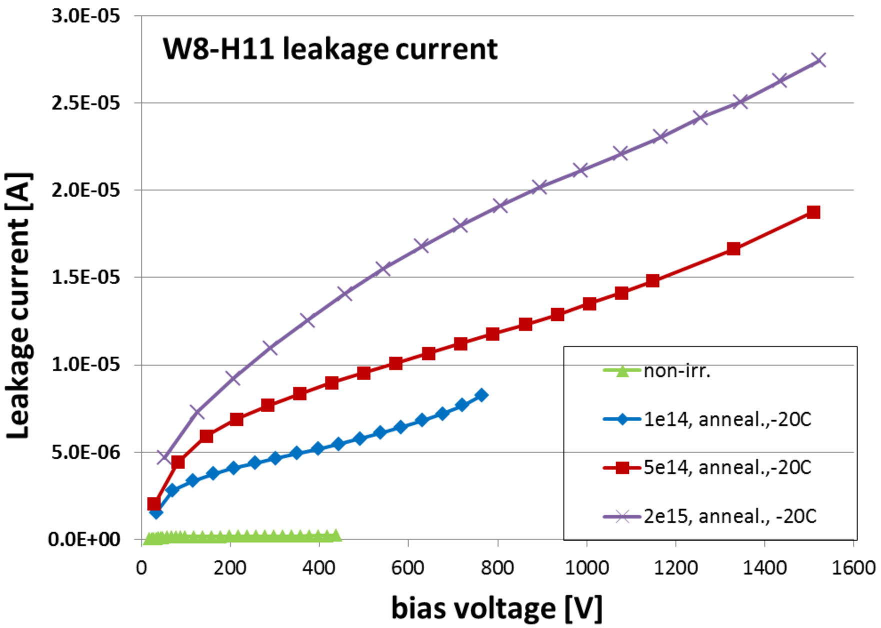


Irradiation results

- W8-H11 was selected for irradiation campaign
- The sample was irradiated in steps to total fluence of 1,5,20e14 cm^{-2}
- Between the steps the samples were annealed for 80 min@60°C
- Basically the measurements were repeated

CCE and leakage current

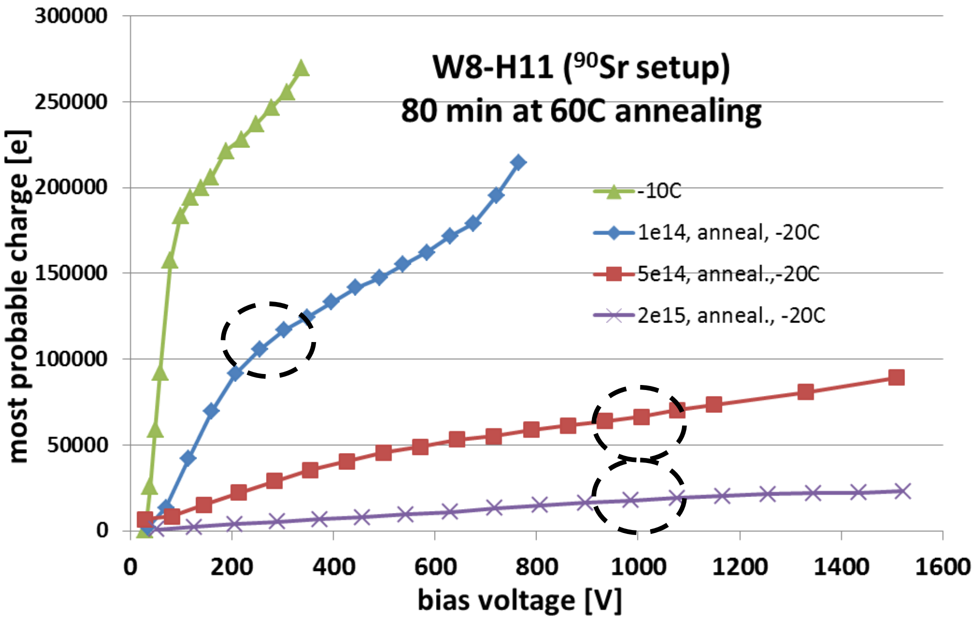


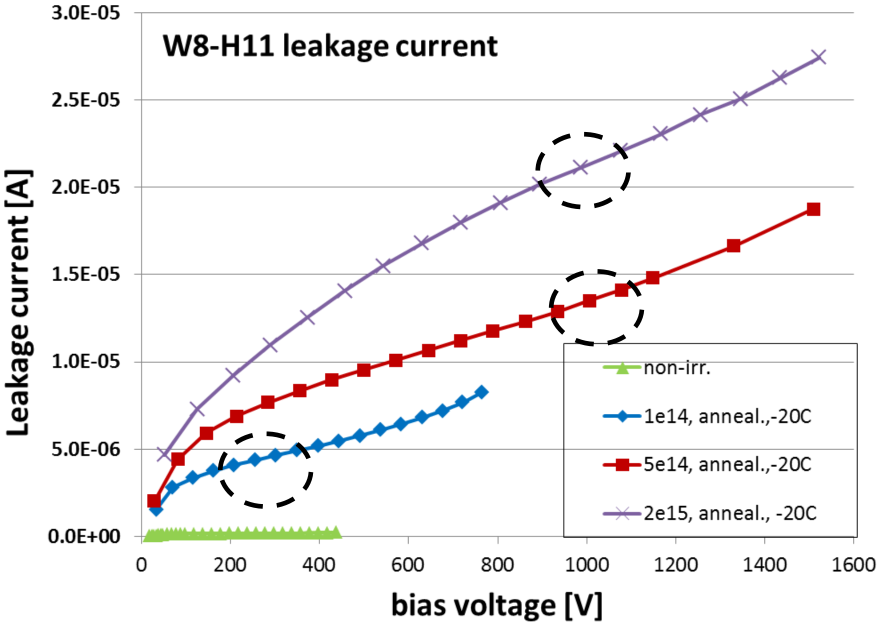


- **Multiplication decreases significantly with irradiation**
- Break-down performance is excellent
- Leakage current increase is not linear with fluence – increase with fluence in smaller due to degradation of multiplication

$$I_{leak} = M_I \cdot I_{gen} = \underset{\downarrow}{M_I} \cdot \alpha \cdot \underset{\uparrow}{\Phi}$$

CCE and leakage current





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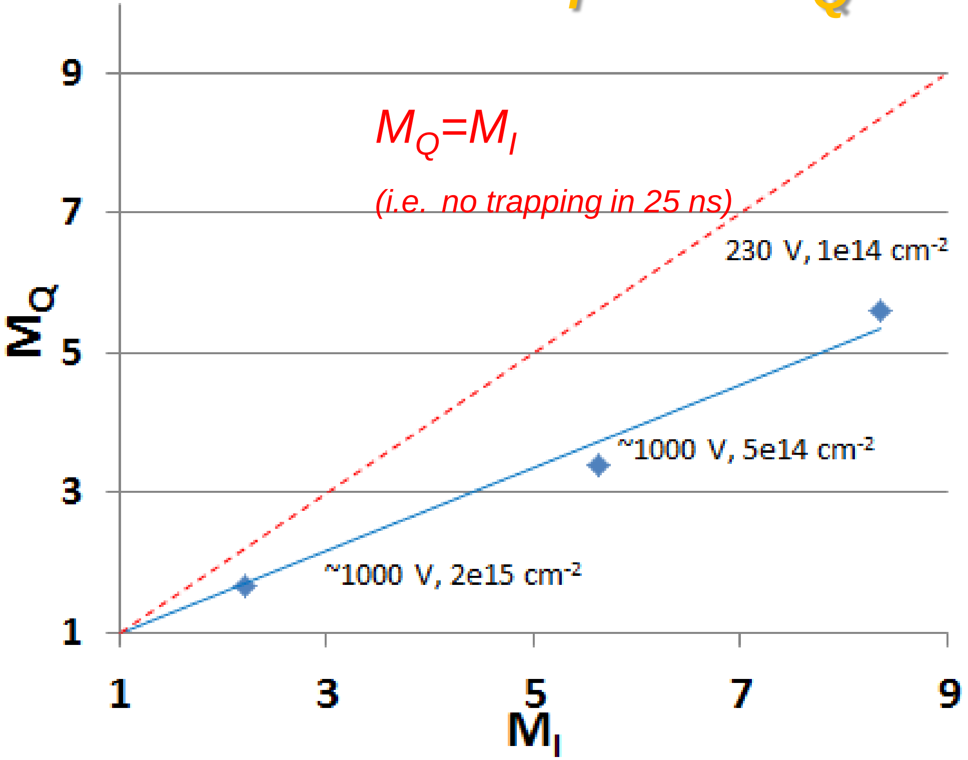
Multiplication factors M_I and M_Q



$$M_Q = \frac{Q_{W8-H11}}{Q_{st.diode}}$$

Qst.diode from:

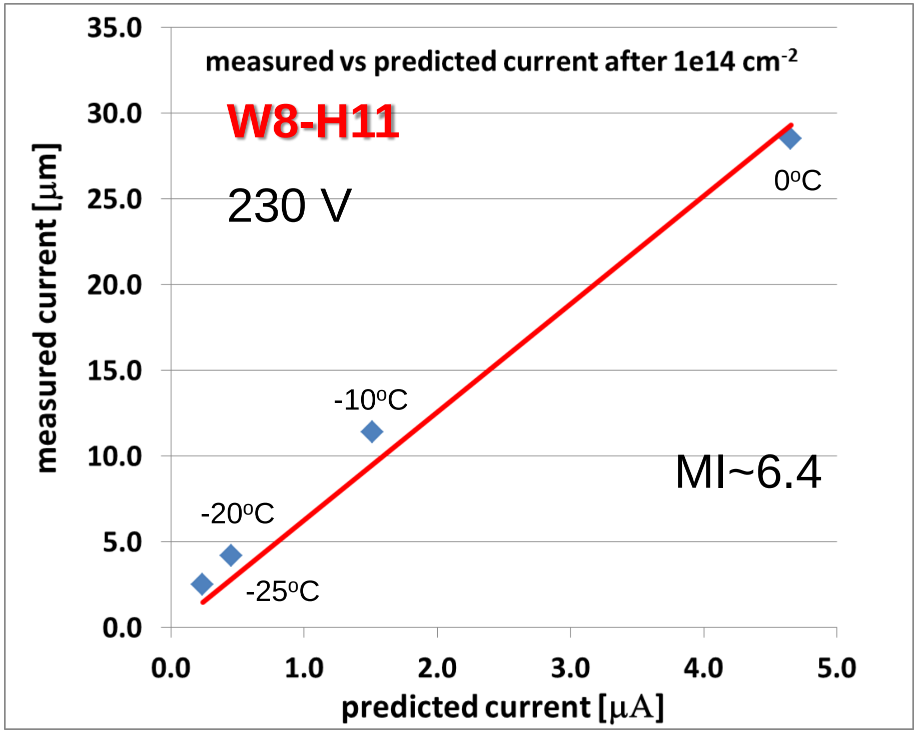
G.Kramberger et al.,21st RD50 workshop, CERN 2012
G.Kramberger et al., NIMA 612(2010) 288.

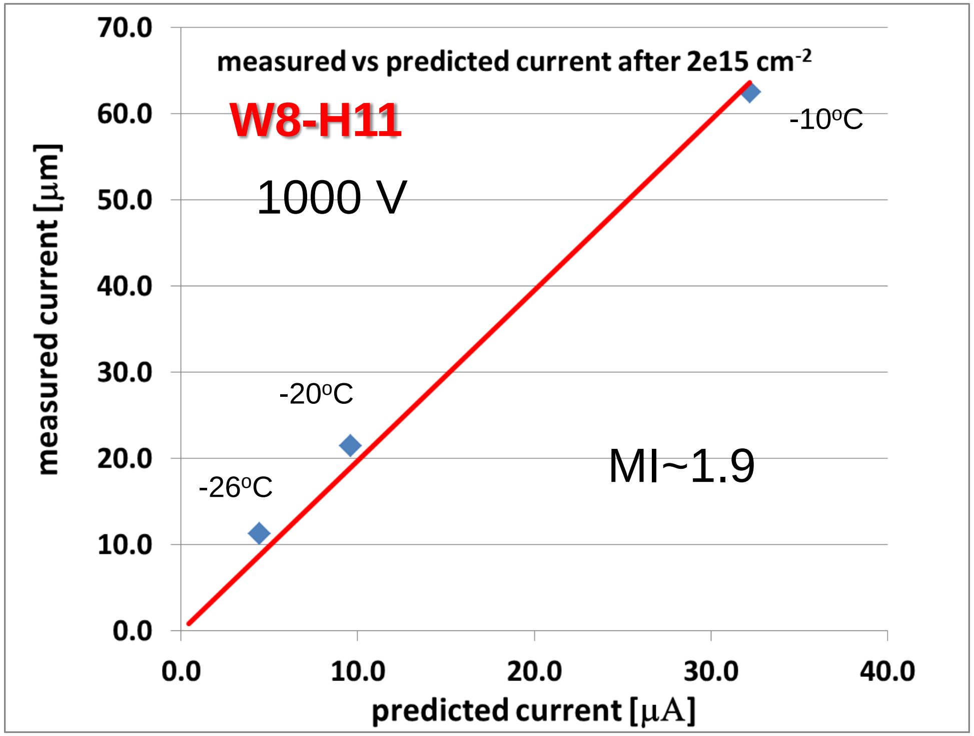
whole bulk active (1000V at high Φ)

$$M_I = \frac{I}{I_{gen}} = \frac{I}{\alpha \cdot \Phi}$$

$\alpha(-20^{o}\mathrm{C})=5.1e\text{-}19$ A cm^{-1}

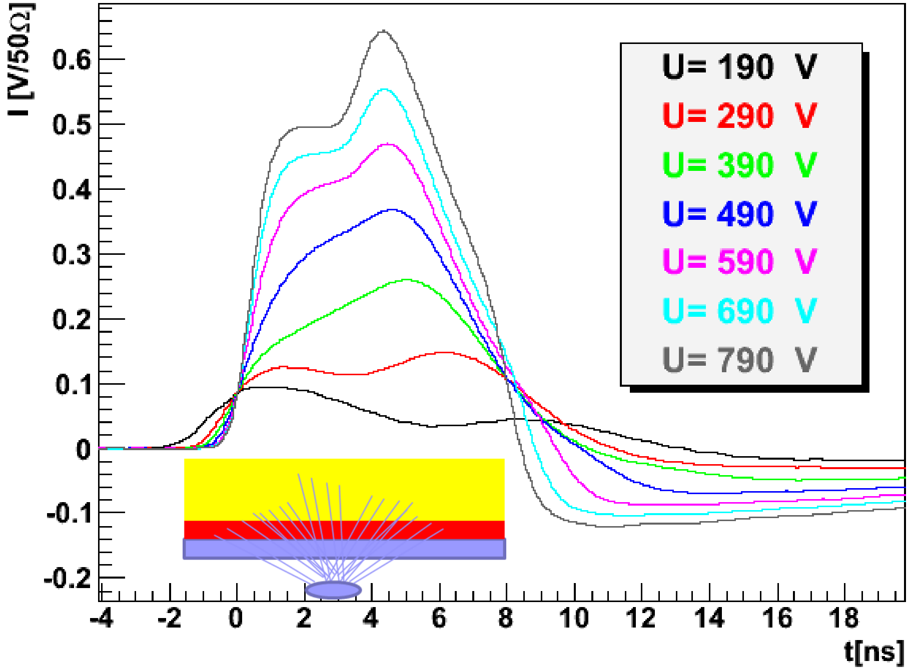
Multiplication factors M_I

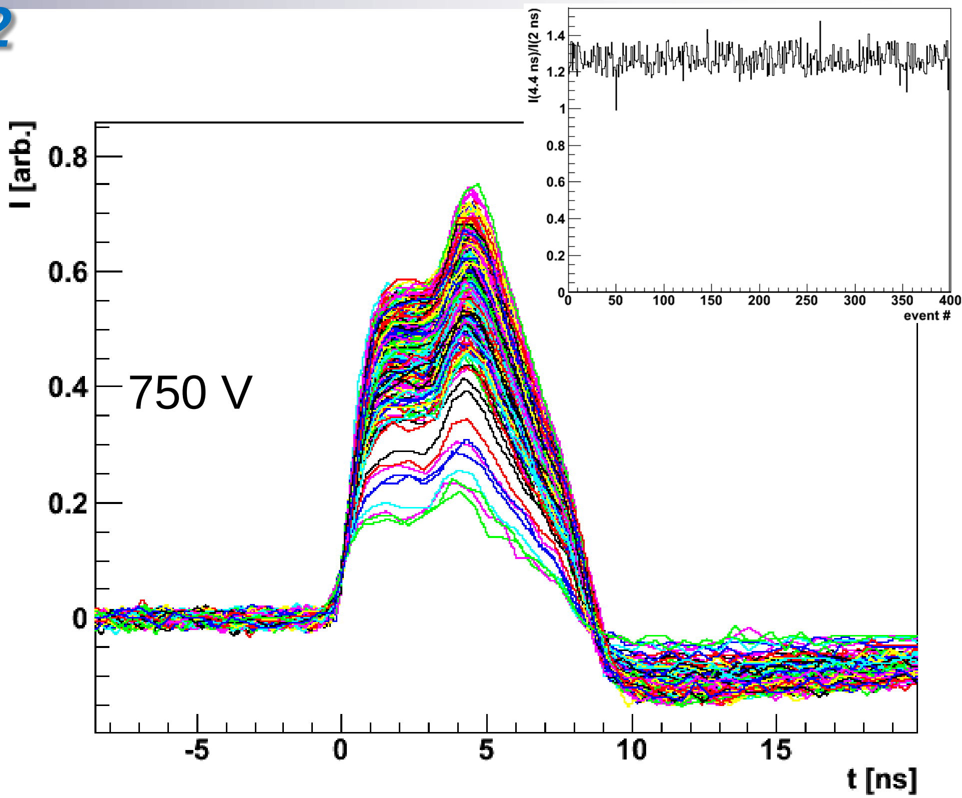




- Multiplication factor for current is around 6 which should be compared to multiplication factor for signal of around 5 (at 230 V); $M_I >= M_Q$

α-TCT after 5e14 cm^{-2}

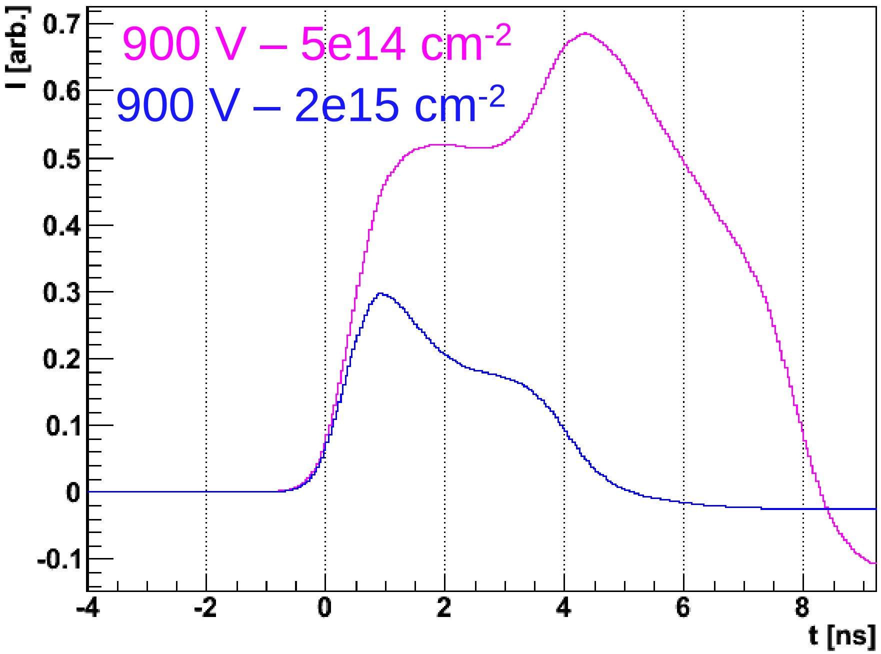


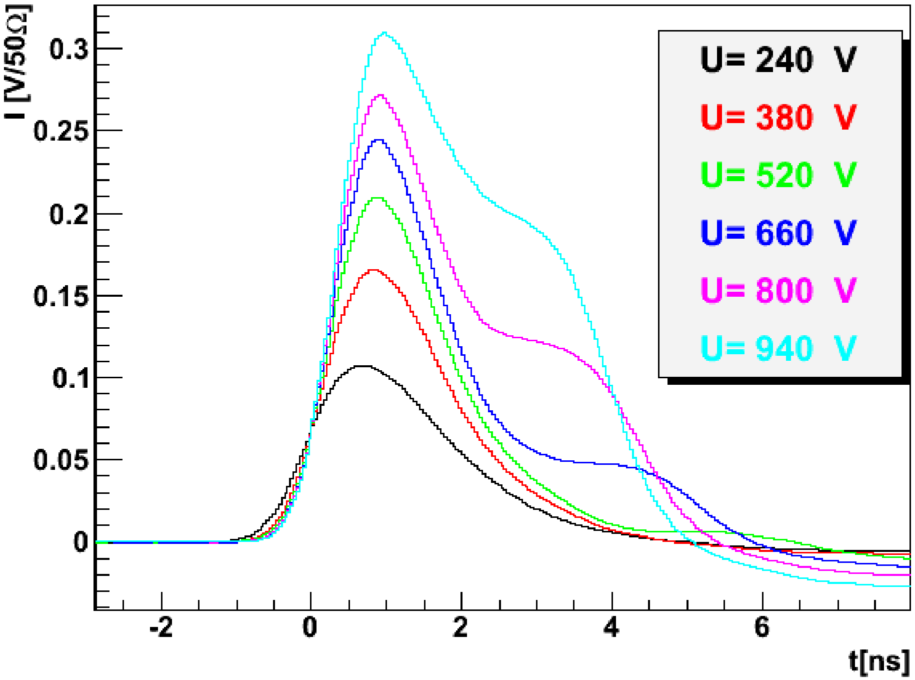


- The response in the investigated range is homogenous
- The shape of the induced current pulse has similar shape as before irradiation, but exhibits much smaller multiplication
- The approximated multiplication: $I_{nirr}(5\text{ ns})/I_{irr}(2\text{ ns}) \sim 2\text{-}3x$ smaller than for non-irradiated detector which agrees with observed degradation of CCE with ^{90}Sr

The reduction of CCE is mainly due to reduction of multiplication and much less due to electron trapping in the bulk.

α-TCT after 2e15 cm^{-2}

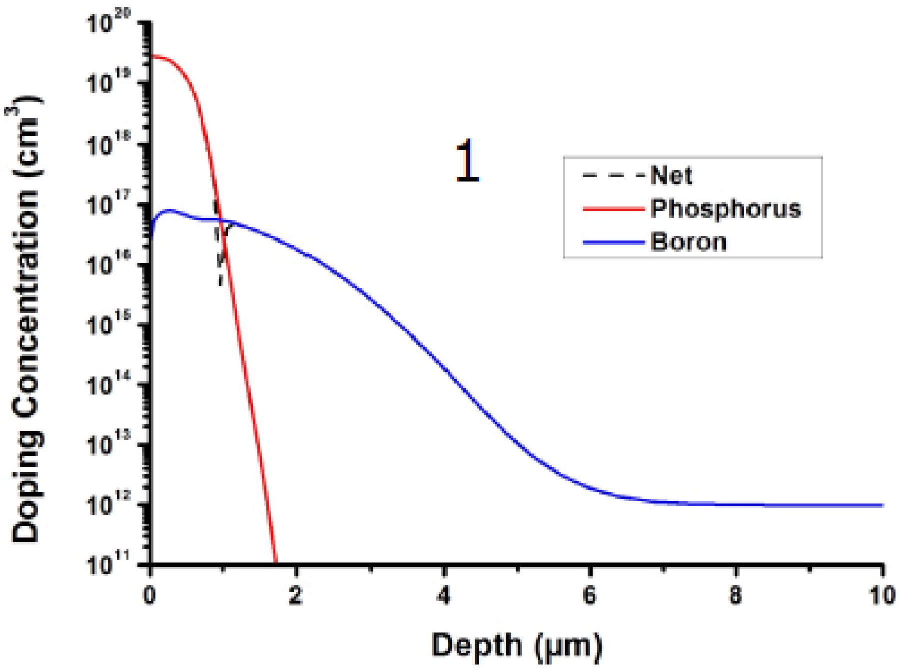


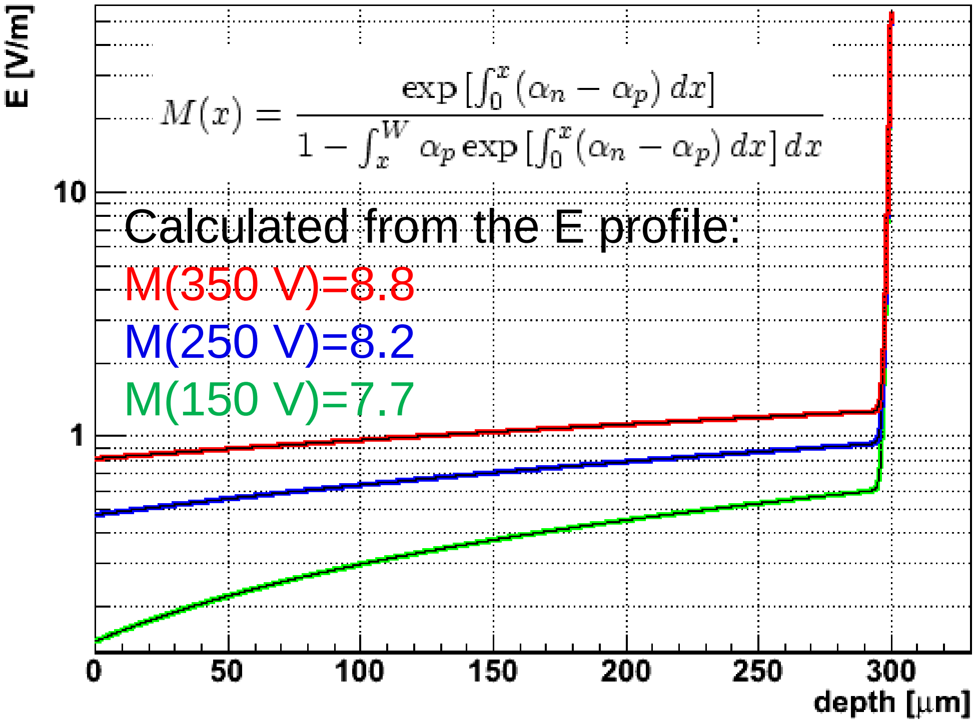


- Voltage scan shows the appearance of the kink:
  - large impact of electron trapping
  - **there is no indication of hole drift in the induced current**

The reduction of CCE is mainly due to reduction of multiplication, but also due to electron trapping in the bulk.

What is the reason for decrease of multiplication?





$$M(x)=\frac{\exp\left[\int_0^x(\alpha_n-\alpha_p)\,dx\right]}{1-\int_x^W\alpha_p\exp\left[\int_0^x(\alpha_n-\alpha_p)\,dx\right]dx}$$

Calculated from the E profile:

M(350 V)=8.8

M(250 V)=8.2

M(150 V)=7.7

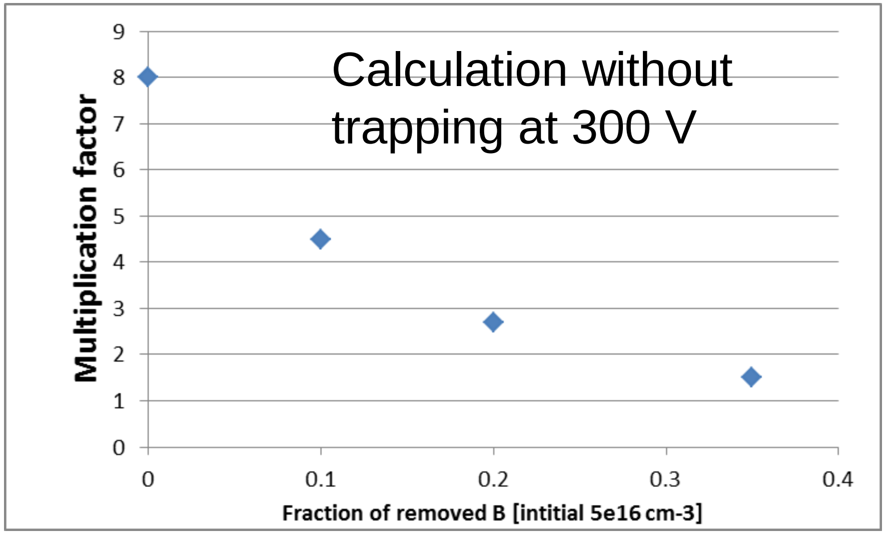
Calculated multiplication for non-irradiated detector is approximately equal to the measured value of multiplication at all voltages!

What happens if initial acceptor concentration is reduced – boron concentration?

What is the reason for decrease of multiplication?

The removal of initial acceptors significantly impacts the performance!

The increase of radiation induced acceptors is obviously too slow to compensate for removal.



Calculation without trapping at 300 V

Seems to be small and incomplete (only visible for MCz)

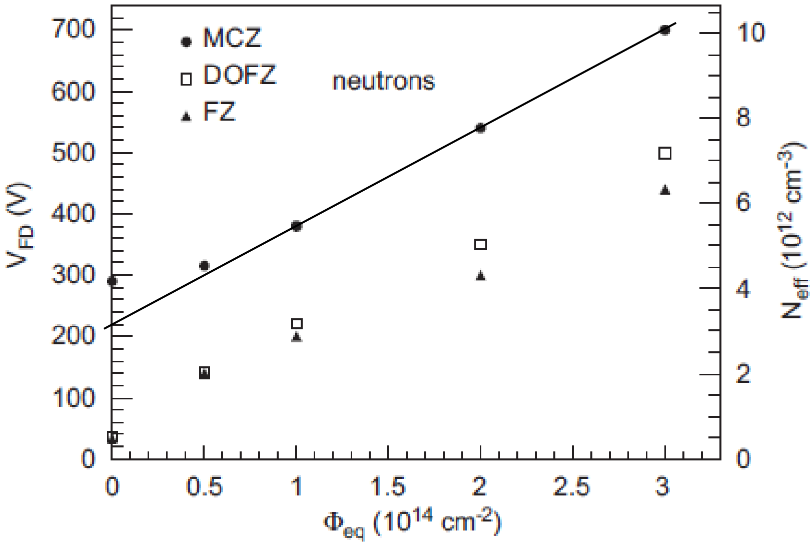
OLD REFERENCE

Removal of initial acceptors with neutrons *(R. Wunstorf, NIMA 377 (1996) 228.))*

$$N_A = N_{A,0}\,(1-\exp(-c\cdot\Phi))$$

$$c = 2e\text{-}13\ cm^2$$

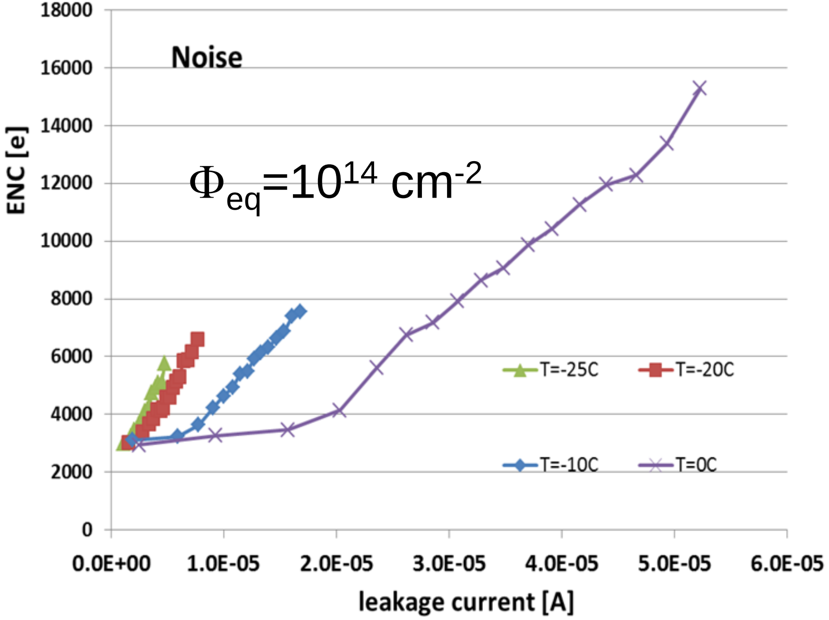
NEWER MEAS.



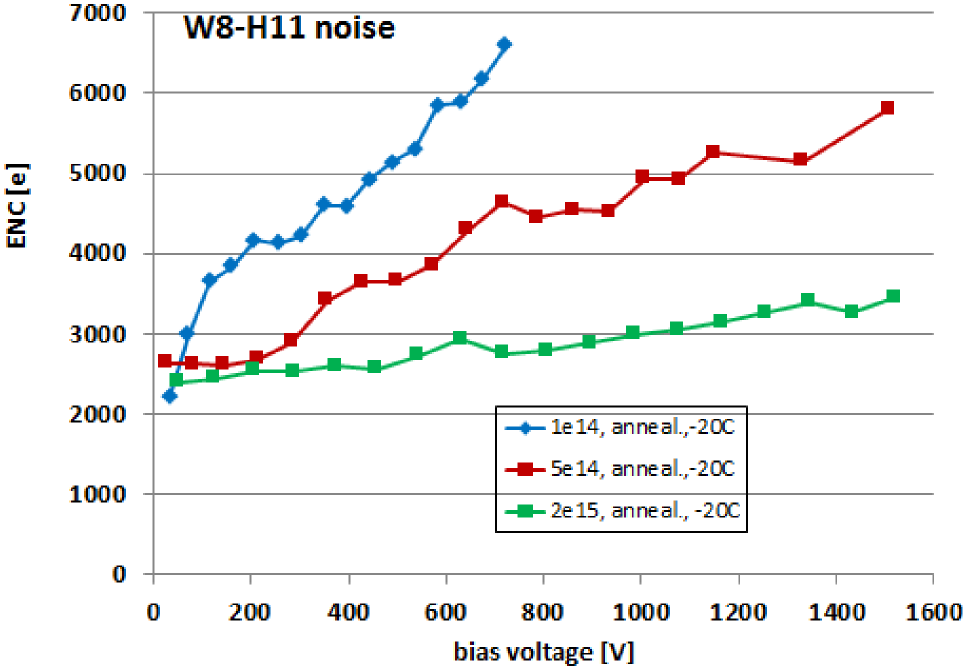
Too strong or incomplete removal!

Noise and multiplication

Dependence of noise on current at constant V_{bias} (changing current by temperature)

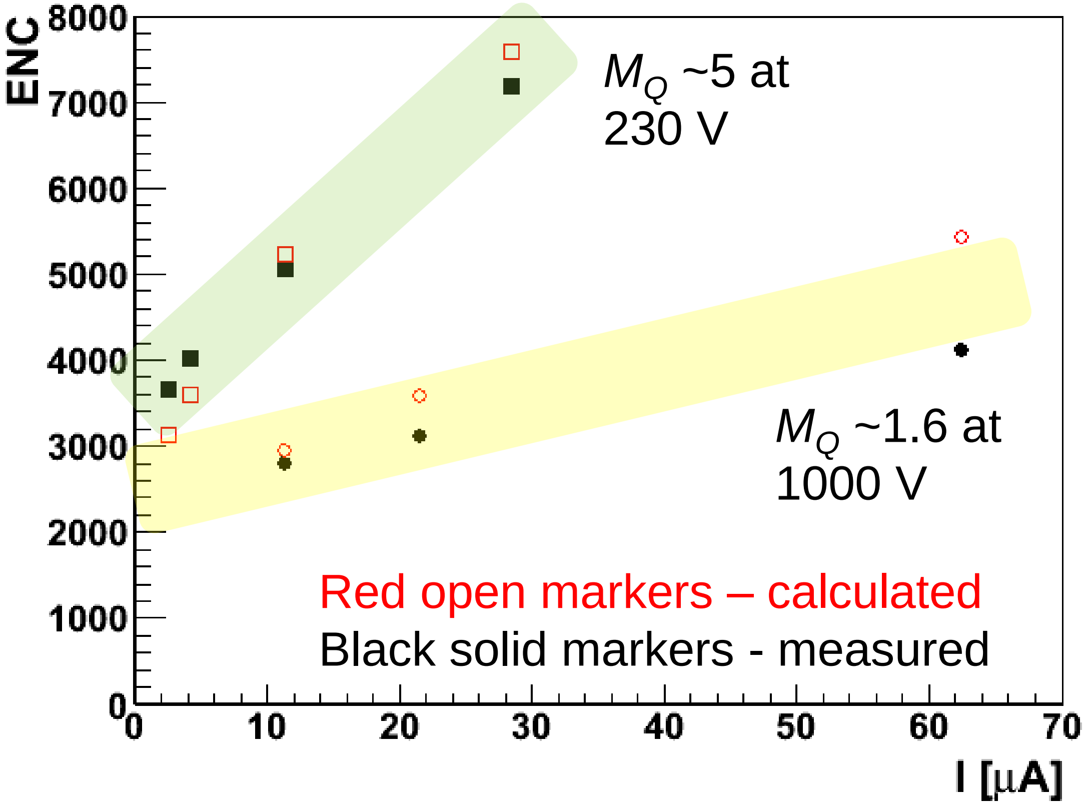


Dependence of noise on V_{bias} for different fleunces



- ➢ Multiplication factor dominates noise at the lower fluence (not a $\sqrt{I_{leak}}$ dependence)
- ➢ As the multiplication decreases the noise decreases in spite of larger generation current

Calculation of the noise



M_Q ~5 at 230 V

M_Q ~1.6 at 1000 V

Red open markers – calculated

Black solid markers - measured

$$ENC^2 = ENC_{MI}^{\;2} + ENC_S^{\;2}$$

ENC_S=2300 e – series noise

$$ENC_{MI} = MI \cdot \sqrt{F} \cdot ENC_I$$

$$ENC_I = e/2 \cdot \sqrt{I_{gen} e_0 \tau}$$

ENC_I –noise due to generation current without amplification – short noise (CR-RC shaping)

$F = 2$ for $M \gg 1$, $F=1$ for $M \sim 1$

$\tau = 25$ ns

$I_{gen} = \alpha \cdot \Phi_{eq}$ $M_I \sim M_Q$

Good agreement between measured and calculated noise.

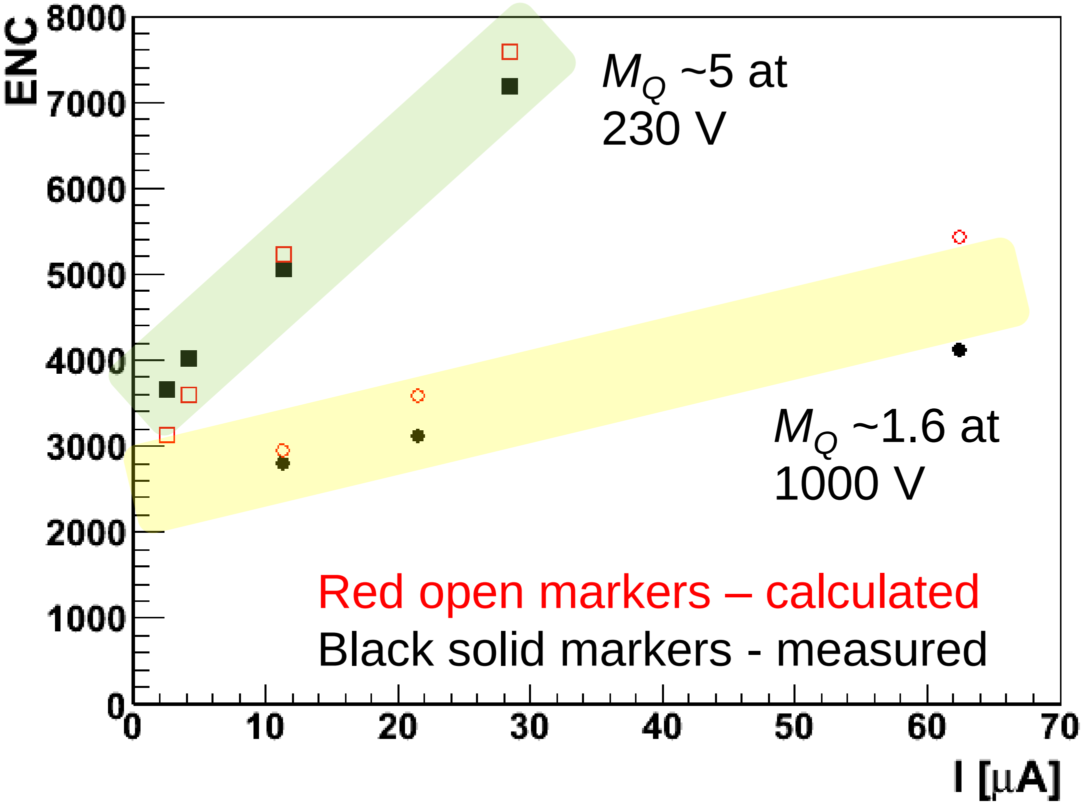
Conclusions

- Diodes with gain perform formidably before the irradiation with gain of ~10 for ^{90}Sr electrons
  - Spectra are Landaus
  - Moderate increase of multiplication after V_{fd} (voltage drop over entire bulk)
  - α-TCT signals (back exposure) show expected behavior; drift of electrons, multiplication, drift of holes
  - From α-TCT signals one can conclude that multiplication is uniform in the investigated region
- Excellent break-down performance of the diodes before and after irr.
- After irradiation the multiplication drops significantly
  - At 2e15 cm^{-2} is around ~1.5 at 1000 V
  - Current and noise scale as expected with multiplication

Future work -> What is the reason for degradation of the multiplication factor?

- What moderates the field (**initial acceptor removal**, hole trapping)?
- What happens at very high fluences?

Calculation of the noise



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$$\boxed{ENC^2 = ENC_{MI}{}^2 + ENC_S{}^2}$$

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τ = 25 ns

$I_{gen} = \alpha \cdot \Phi_{eq}$ $M_I \sim M_Q$

Good agreement between measured and calculated noise.

$$\boxed{\frac{S}{N} = \frac{M_Q Q}{\sqrt{ENC_S{}^2 + M_I{}^2 I_{gen} \frac{e^2 F e_0 \tau}{4}}}}$$

S/N improves with multiplication if:

$$\boxed{ENC_S{}^2 \gg M^2 I_{gen} \frac{e^2 F e_0 \tau}{4}}$$