TRIUMF

Experimental SiPM parameter characterization from avalanche triggering probabilities

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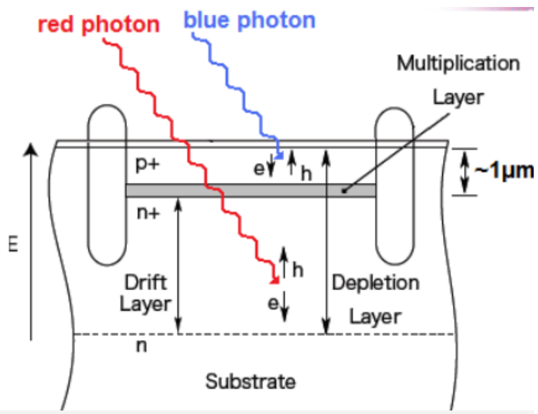
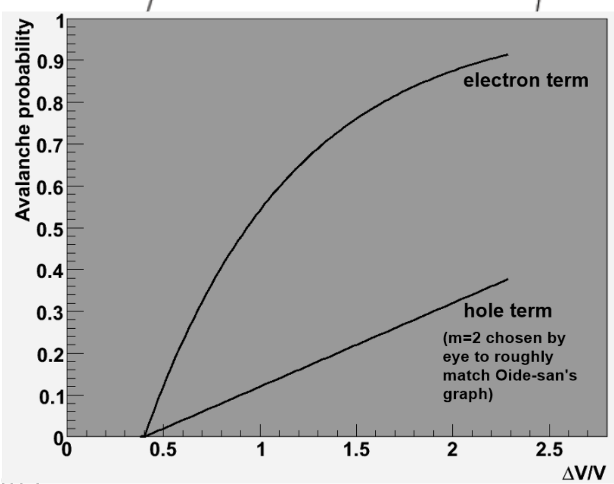
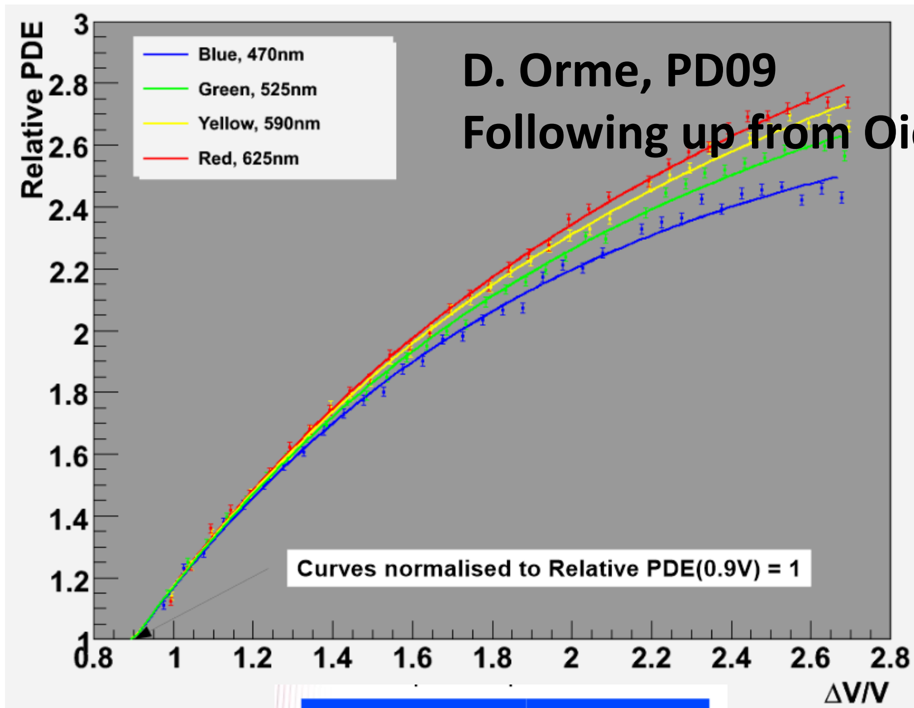
2018-06-06

Discovery, accelerated

Electron vs hole triggered avalanches





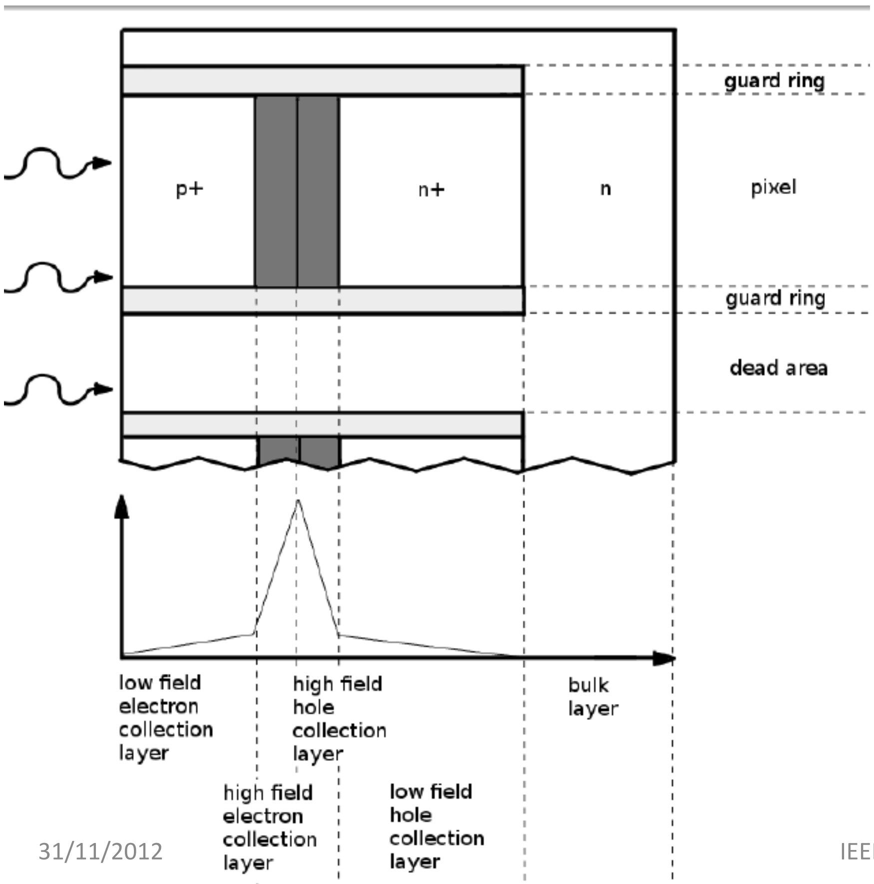


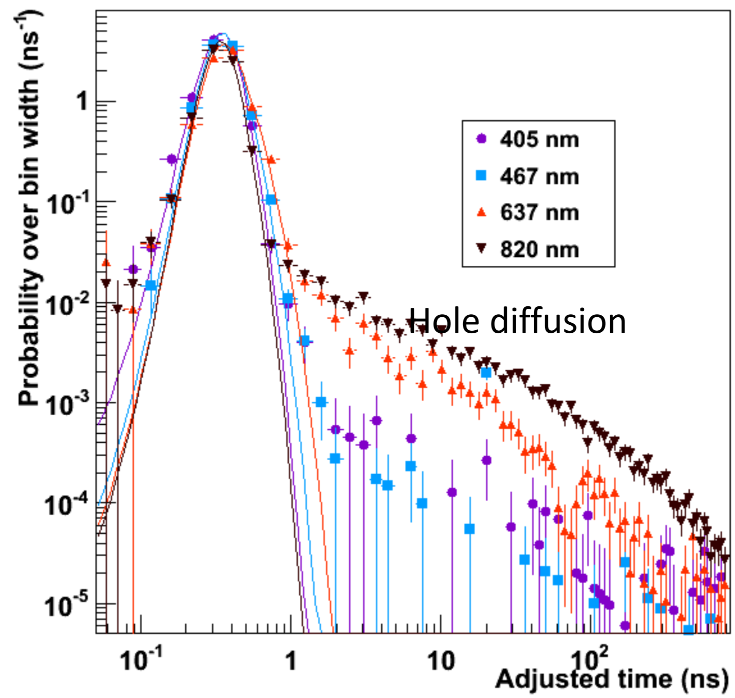
D. Orme, PD09

Following up from Oide PD07

Blue (470nm)	0.6 µm
Green (525nm)	1.2 µm
Yellow (590nm)	2.2 µm
Red (625nm)	2.9 µm

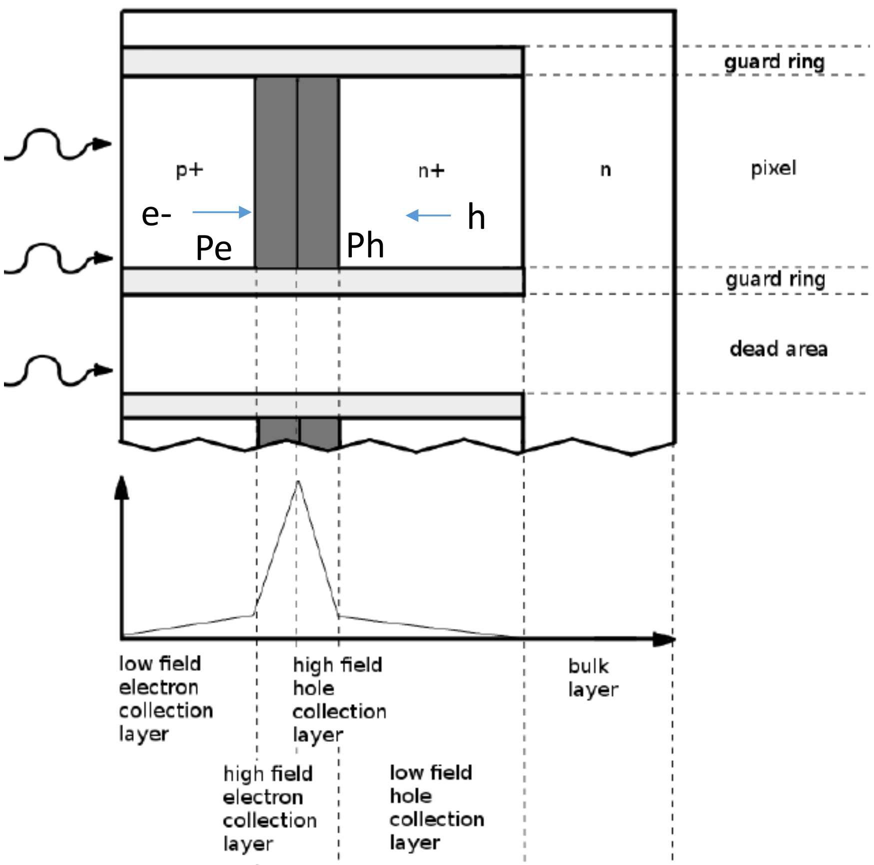
Adding timing information





But what is happening to DN, AP, and XT?

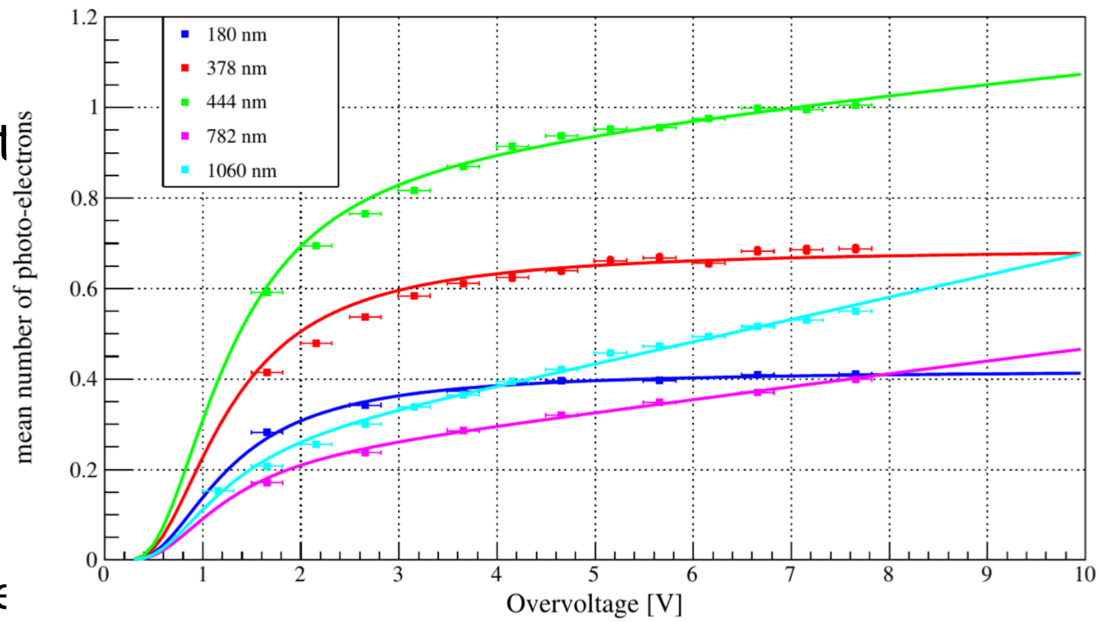
Parameterizing the probability of triggering avalanches



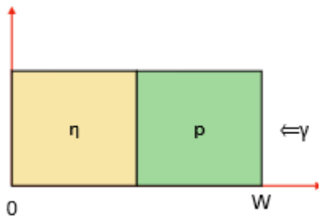
- Assumption 1: no depth dependence of Pe and Ph
  - I.e. avalanche region is small compare to collection region
- Assumption 2: Relate Pe and Ph using McIntyre formalism
  - 1-Ph = (1-Pe)^k* with $k^* = \frac{\int_0^w \alpha_h P_p \, dx}{\int_0^w \alpha_e P_p \, dx}$,
  - And $k^* = (\alpha V_{ov})^{\beta}$ with a and b free par
- Assumption 3: Pe ~ probability of creating at least 1 extra e-h pair:
  - Pe = 1- exp($-\alpha_e \Delta_s$) = 1 – exp[-A exp(-B/V_{ov})]
  - With A and B free parameters

Measuring probability of triggering avalanche

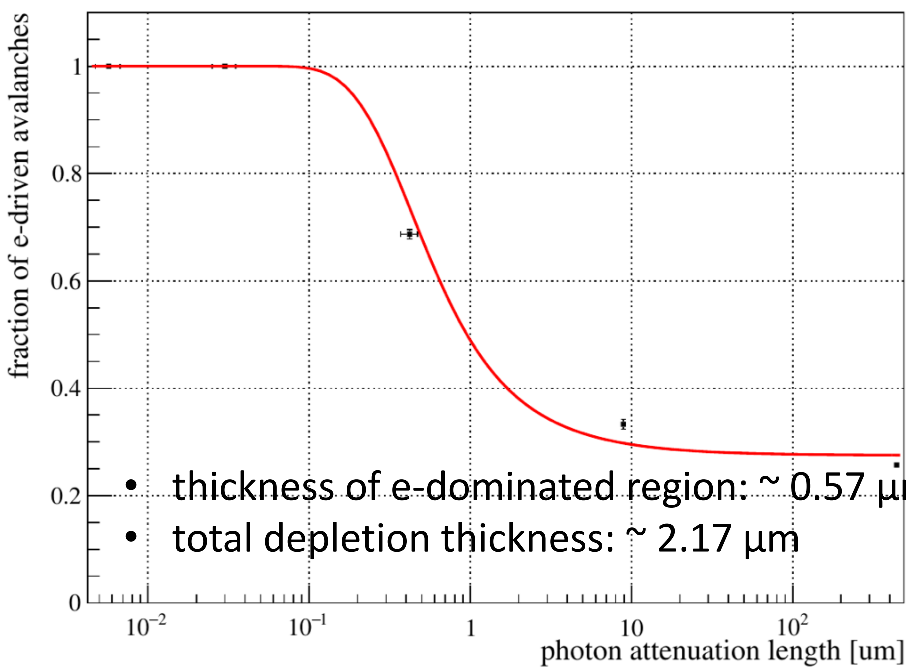
- Hamamatsu VUV4
- Measure <PE> vs V_{ov} for 5 different wavelength
  - $<PE> = \phi\ PDE_{sat}$ [fe $Pe(V_{ov})$ + (1-fe) $Ph(V_{ov})$]
  - $C = \phi\ PDE_{sat}$ floats independently
  - At 180 and 375nm fe=1 therefore fix Pe parameters (A and B)
  - Then at other 3 wavelengths floats fe α, and β



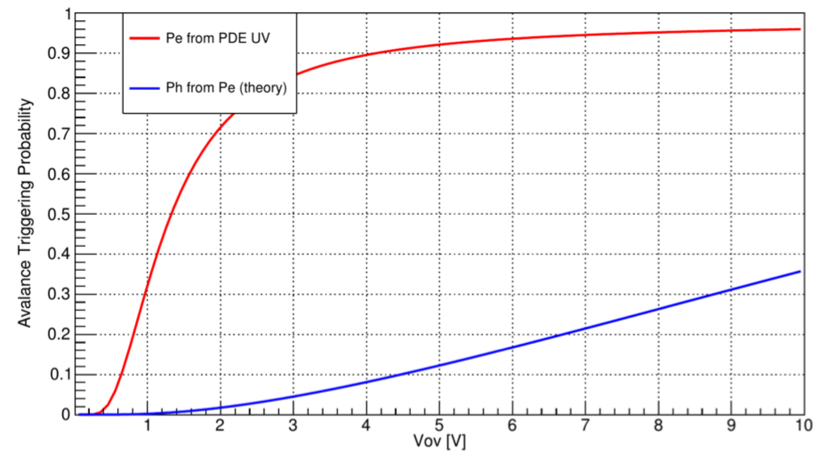
Measuring probability of triggering avalanche



$$fe(\mu)=\frac{1-\exp[-(w-x_{pn})/\mu]}{1-\exp[-w/\mu]}$$



- thickness of e-dominated region: ~ 0.57 µm
- total depletion thickness: ~ 2.17 µm



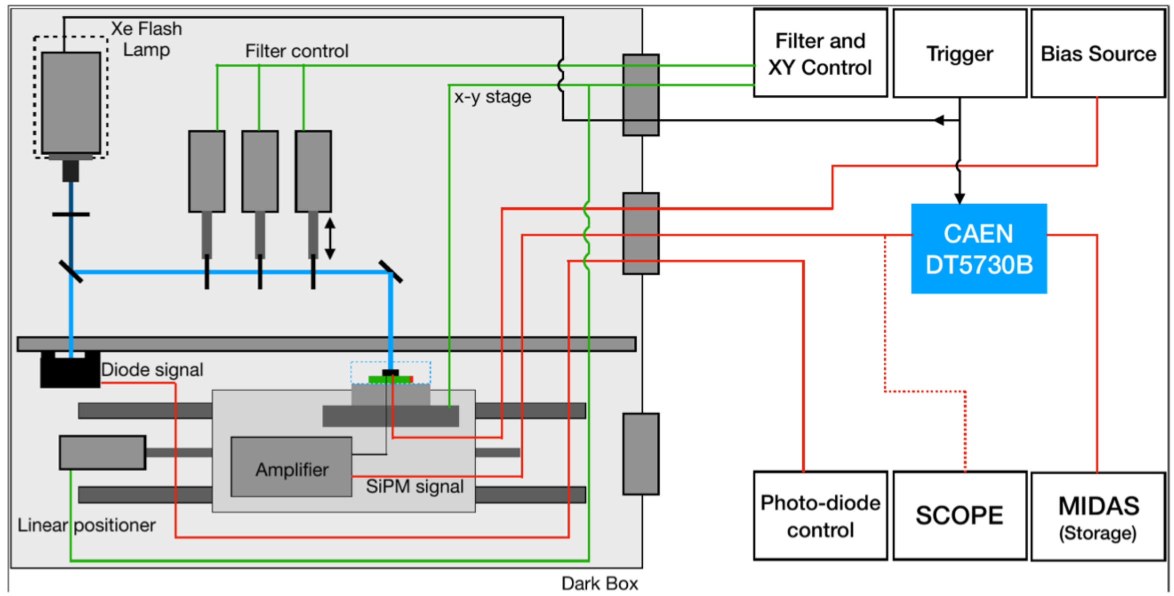
- Now use these functions to investigate DN, AP and XT

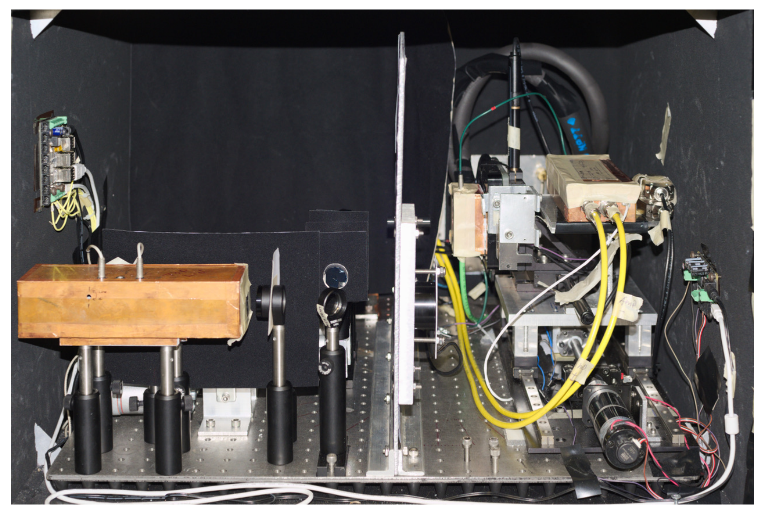
TRIUMF characterization setup

- Light-tight box
- Waveform analysis

- Wavelengths analyzed:
  - 180 nm (Xe flash lamp)
  - 378 nm (Hamamatsu laser)
  - 444 nm (Hamamatsu laser)
  - 782 nm (Hamamatsu laser)
  - 1060 nm (LED)

- The Xe flash lamp:
  - filtered by 1 fixed + 3 movable VUV filters
  - monitored by photodiode

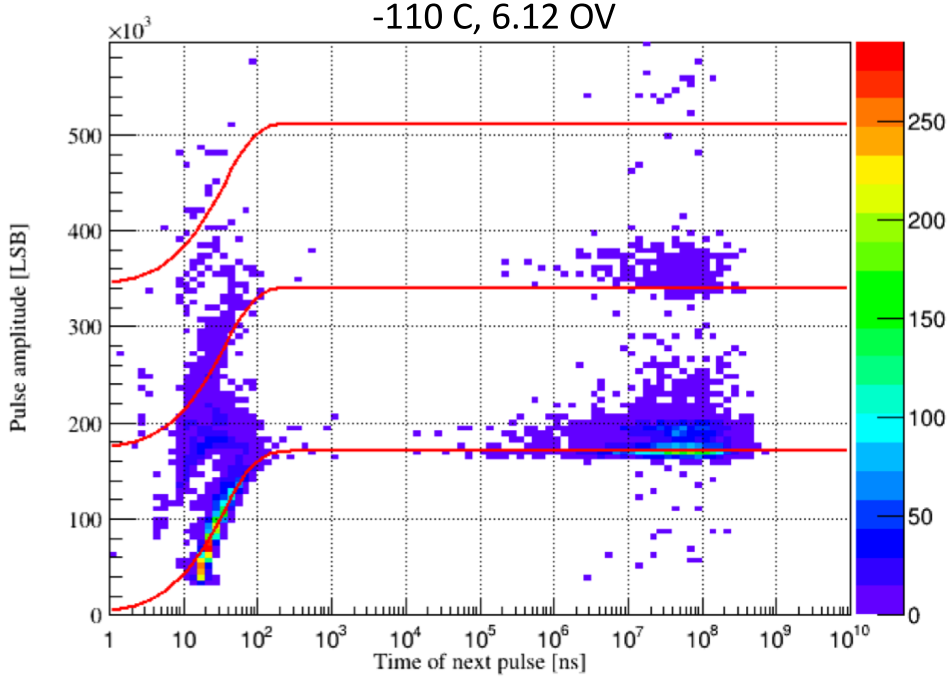




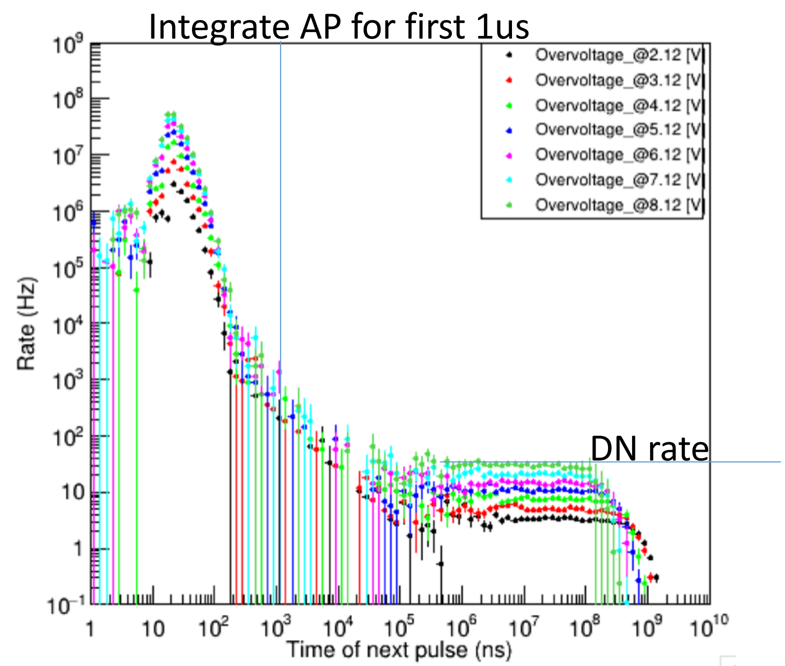
- **Objective: Find a model for DN, AP, CT and IV**

Measuring after-pulsing and dark noise with time to next pulse technique

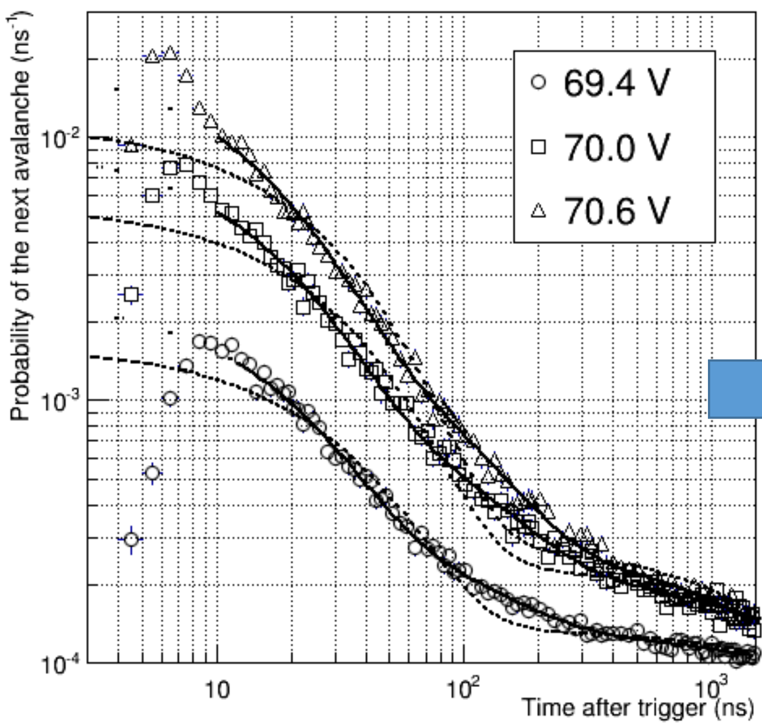
-110 C, 6.12 OV

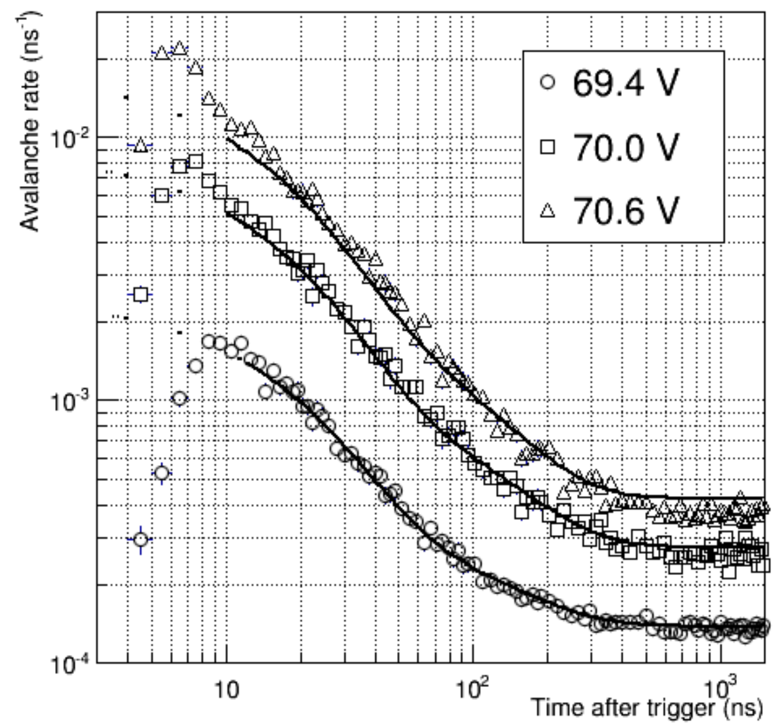


-110 C data



Time to next pulse to rate method





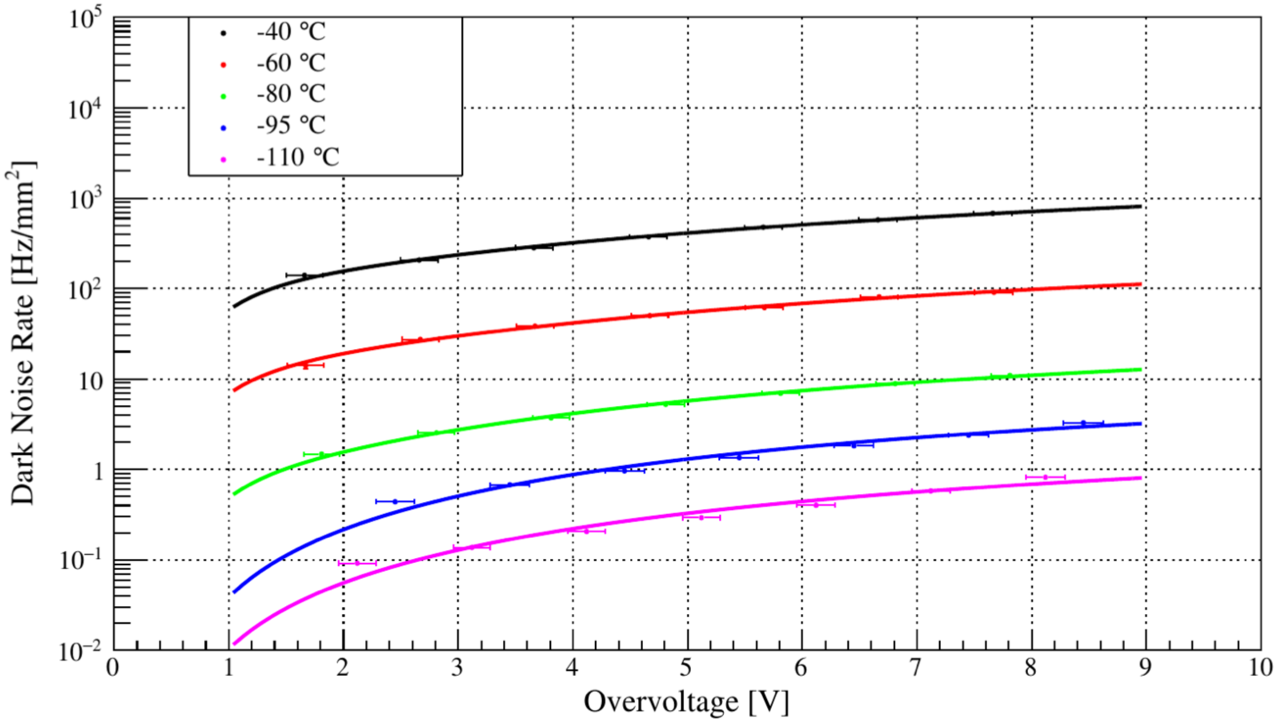
https://www.sciencedirect.com/science/article/pii/S016890021730921X?via%3Dihub

NIM A vol 875 (2017) p. 87

Dark Noise Rate

$R(V_{ov}) = R0*[fe_{DN}*Pe(V_{ov}) + (1-fe_{DN})*Ph(V_{ov})]$

Assumption: R0 does not depend on V_{ov}



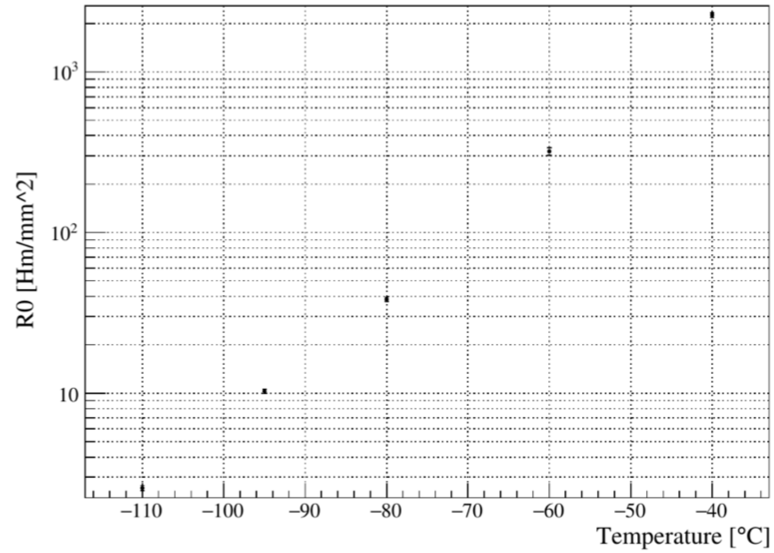
Dark Noise Rate: Parameters

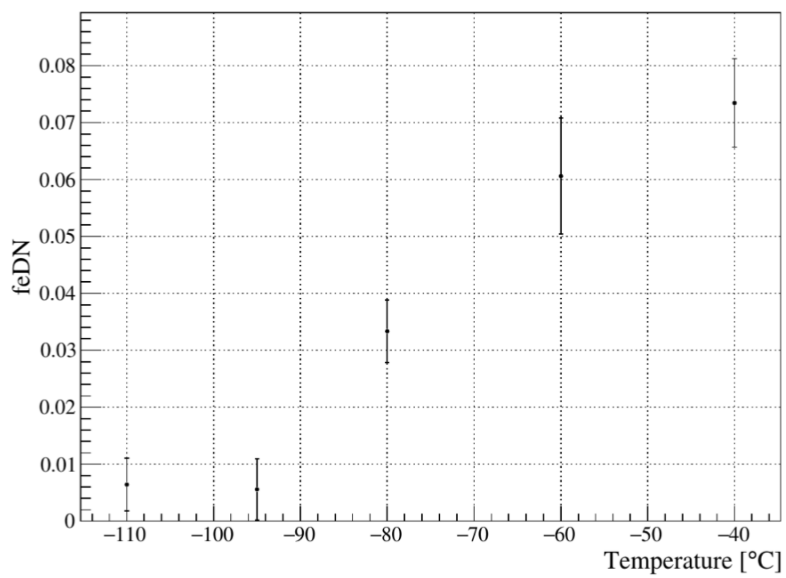
R(Vov) = R0*[feDN*Pe(Vov) +(1-feDN)*Ph(Vov)]

- Vov: overvoltage
- R0: rate of thermally generated electron-hole pairs
- feDN: fraction of electron-driven avalanches
- Pe: avalanche triggering prob. for electrons
- Ph: avalanche triggering probability for holes

Conclusion (for Hamamatsu VUV4):

- feDN < 0.1
- Dark noise dominated by holes

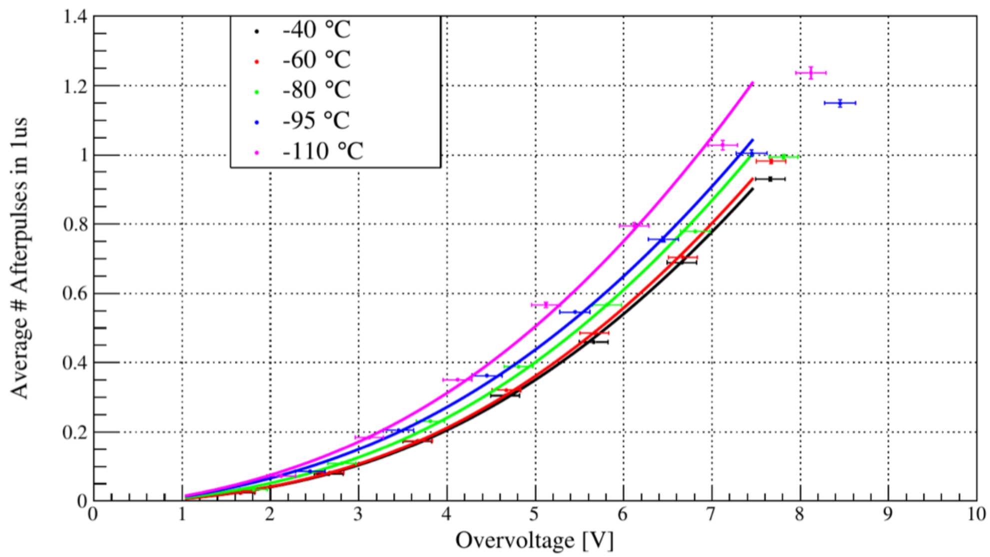




Afterpulsing --> mean number of AP per pulse

- AP = $(C/e)*V_{ov}*P\_ap*[feAP*Pe(V_{ov}) + (1-feAP)*Ph(V_{ov})]$
- Assumption: AP scale with the gain

- C: capacitance
- e: electron charge
- P_ap: probability to produce an afterpulse
- feAP: fraction of electron-driven avalanches
- Pe: avalanche triggering prob. for electrons
- Ph: avalanche triggering prob. for holes

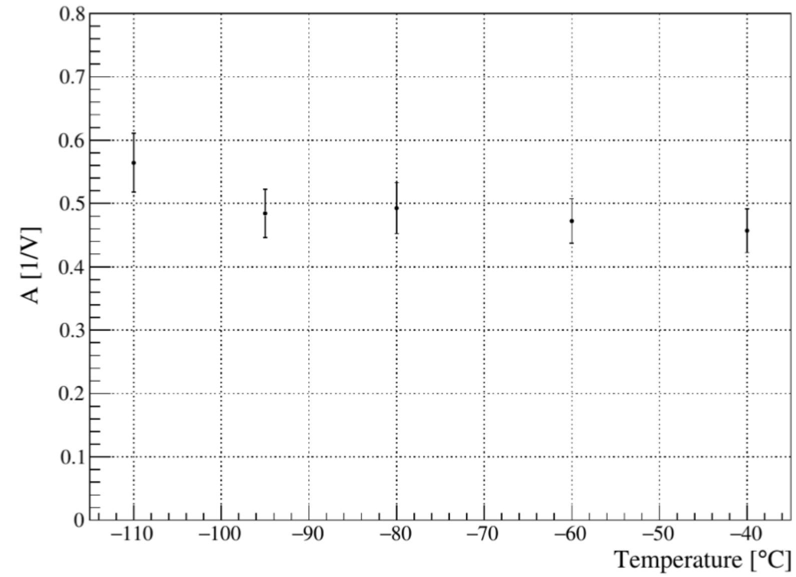


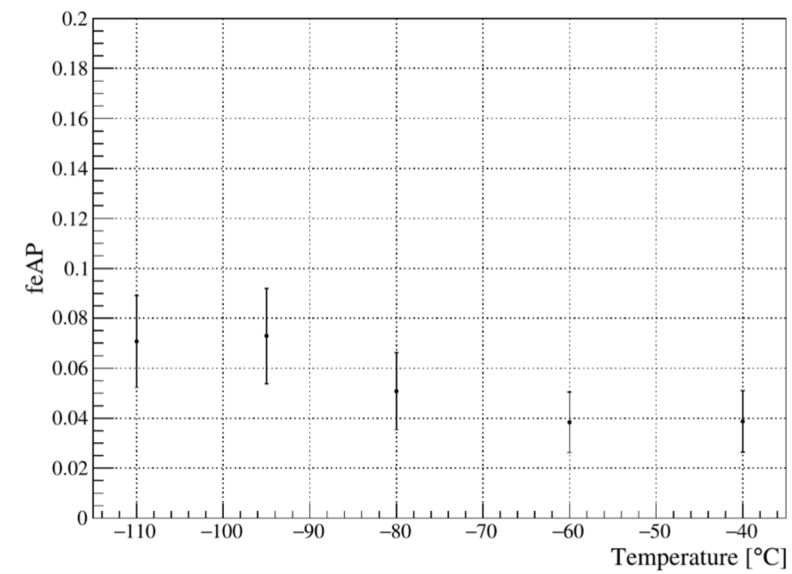
Afterpulsing: Parameters

- AP = A*Vov*[Pe*feAP + Ph*(1-feAP)]

> - Pe: avalanche triggering prob. for electrons
> - Ph: avalanche triggering probability for holes
> - A: absorbs afterpulsing probability and capacitance
> - feAP: fraction of electron-driven avalanches

- Conclusion (for Hamamatsu VUV4):
  - feAP < 0.1
  - afterpulsing dominated by holes





Direct Crosstalk

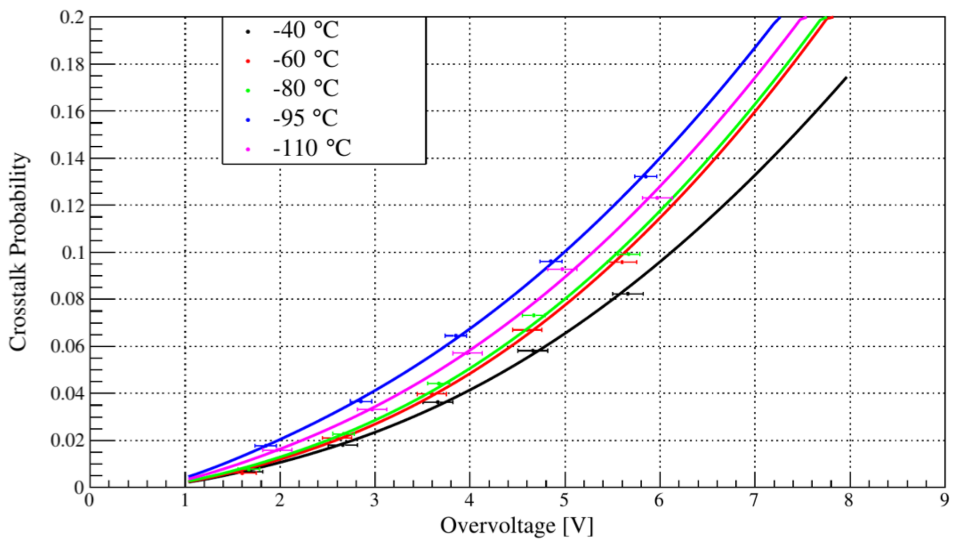
Crosstalk is estimated by:

Estimated as:

$$crosstalk\ probability = \frac{number\ of\ pulses\ with\ (charge > 1.5\ P.E.)}{number\ of\ pulses\ with\ (charge > 0.5\ P.E.)}$$

CT = (C/e)*P_ct*Vov*[Pe*feXT + Ph*(1-feXT)]

- C: capacitance
- e: electron charge
- Vov: overvoltage
- P_ct: probability to produce optical photon
- feXT: fraction of electron-driven avalanches
- Pe: avalanche triggering prob. for electrons
- Ph: avalanche triggering probability for holes



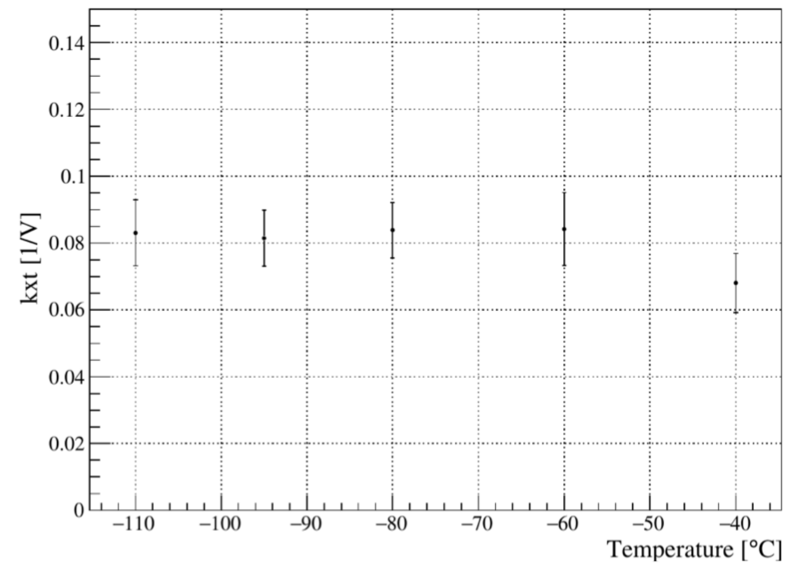
Direct Crosstalk: Parameters

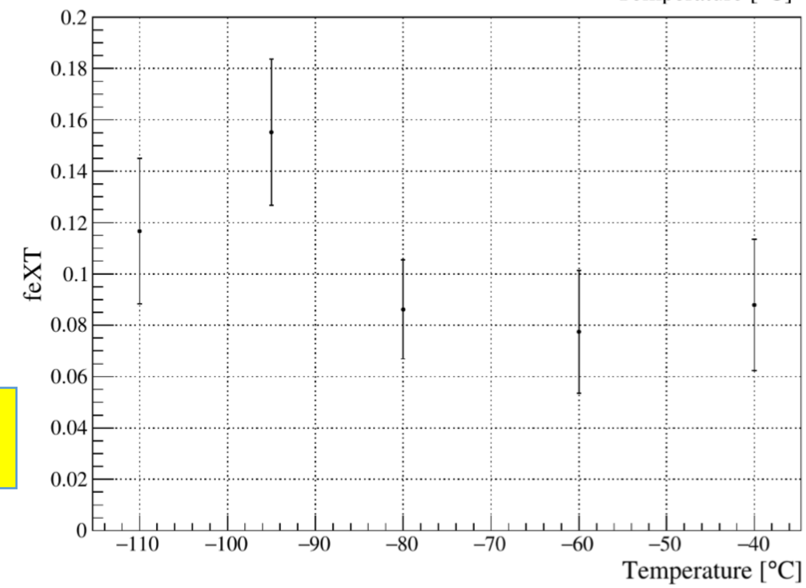
- CT = kxt*Vov*[Pe*feXT + Ph*(1-feXT)]

- kxt: absorbs probability to produce optical photon, electron charge, and capacitance
- feXT: fraction of electron-driven avalanches
- Pe: avalanche triggering prob. for electrons
- Ph: avalanche triggering probability for holes

- Conclusion (for Hamamatsu VUV4):
  - feXT < 0.2
  - crosstalk dominated by holes

Now with DN, AP, CT can we predict and fit the IV curve in reverse bias? Yes!





IV curves – reverse bias

Only two parameters floating !

Gain, linear with Vov

I = C*Vov*{R0(T)*[feDN*Pe(Vov)+(1-feDN)*Ph(Vov)]}
 * [1 + q*AP(Vov)/(1-q*AP(Vov)) + CT(Vov)] + I0

Geometrical series

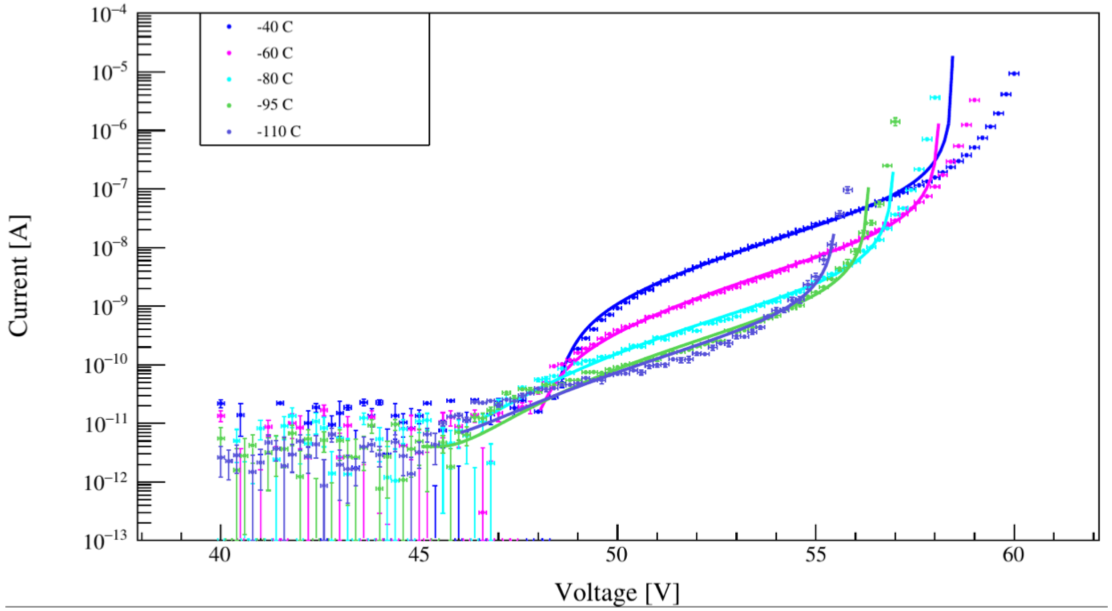
Higher order mixed terms
of afterpulsing and
crosstalk neglected!

<u>Floating parameters:</u>

- C: capacitance
- q: average fraction of charge carried by afterpulse

<u>All other parameters fixed by previous analysis!</u>

- R0: rate of thermally generated electron-hole pairs
- feDN: fraction of electron-driven avalanches
- Nap: average number of afterpulses per pulse
- Nxt: average number of crosstalk events per pulse
- I0: leakage current
- Pe(Vov): avalanche triggering prob. for electrons
- Ph(Vov): avalanche triggering probability for holes
- I0: leakage current

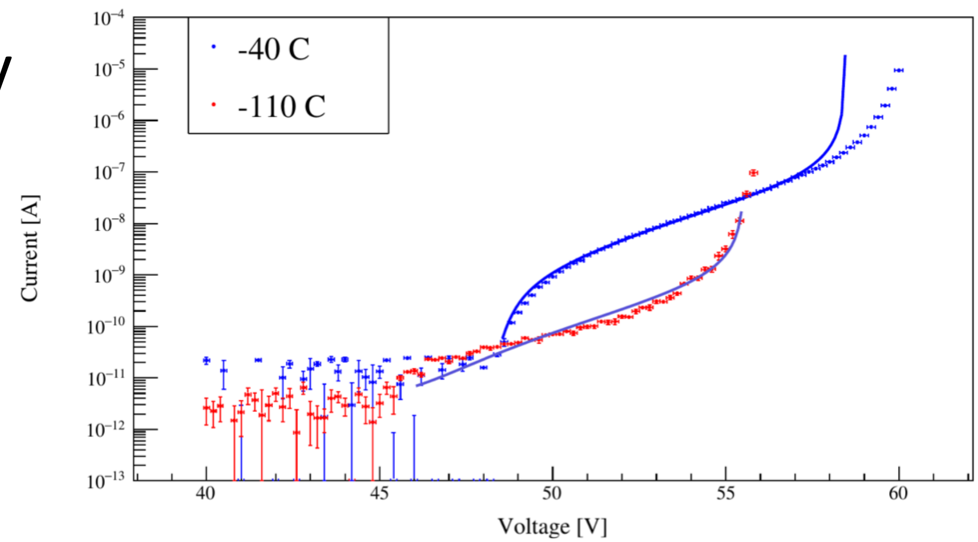


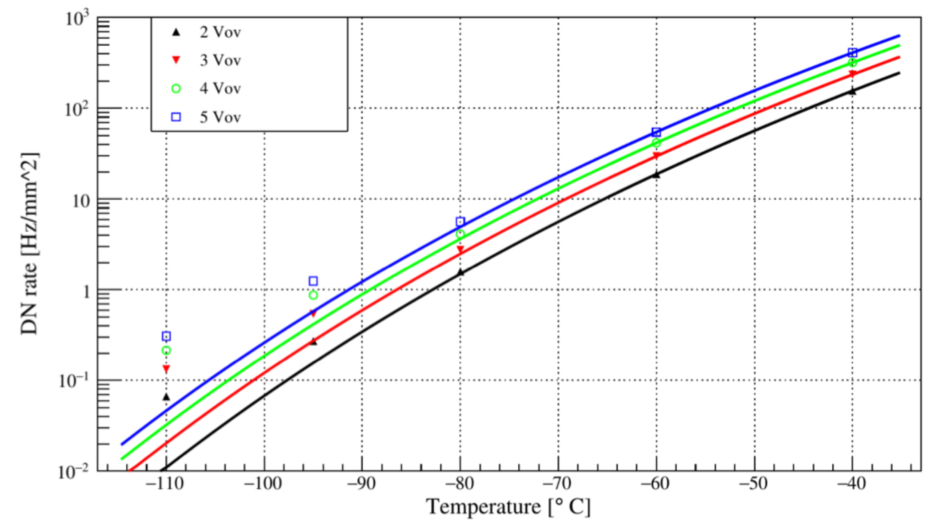
Current troubles with IV

At high OV :

- Afterpulsing is overestimated
  Run-away not modelled properly

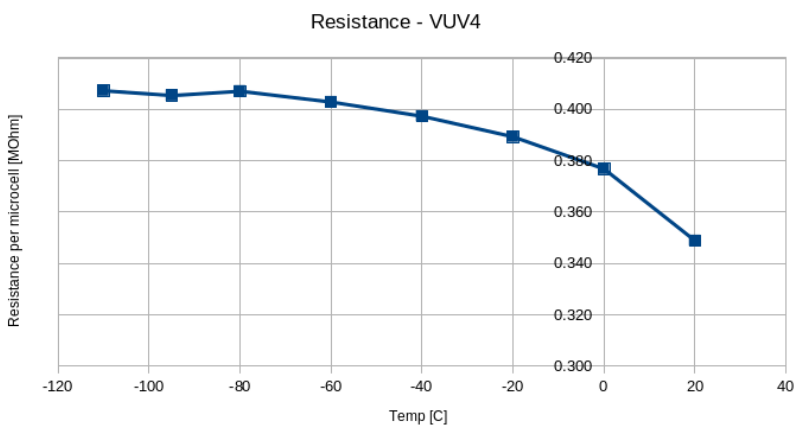
- At low temperatures:
  - General shape looks different
  - Problem with the data or additional processes must be considered ?

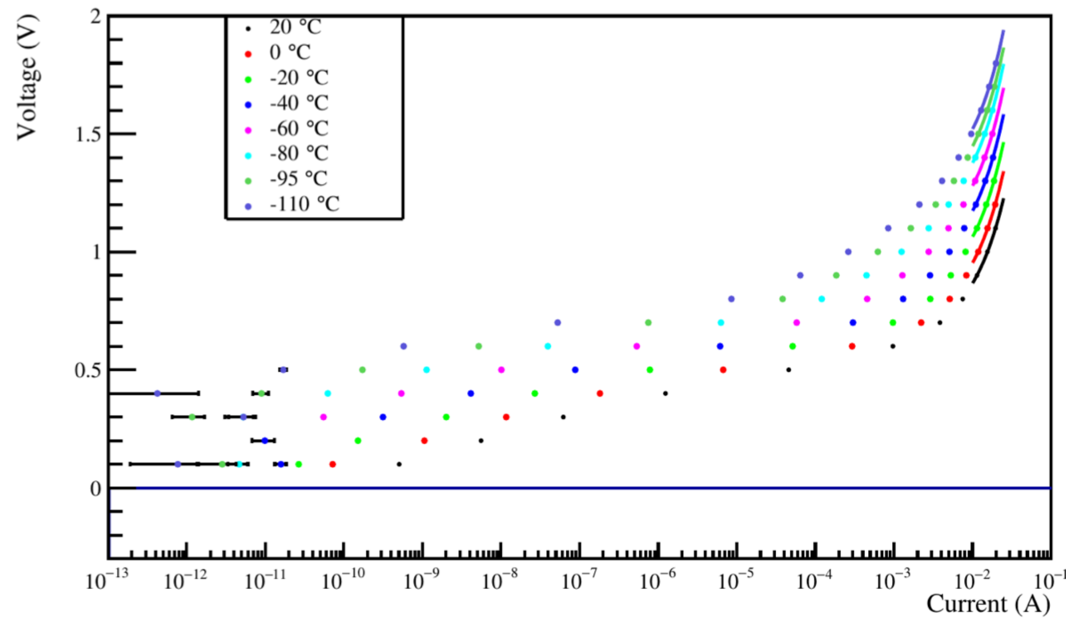




IV curves – forward bias

- Measure resistance fitting high current part
- Trying to measure temperature fitting full spectrum
  - V at constant I is also an option

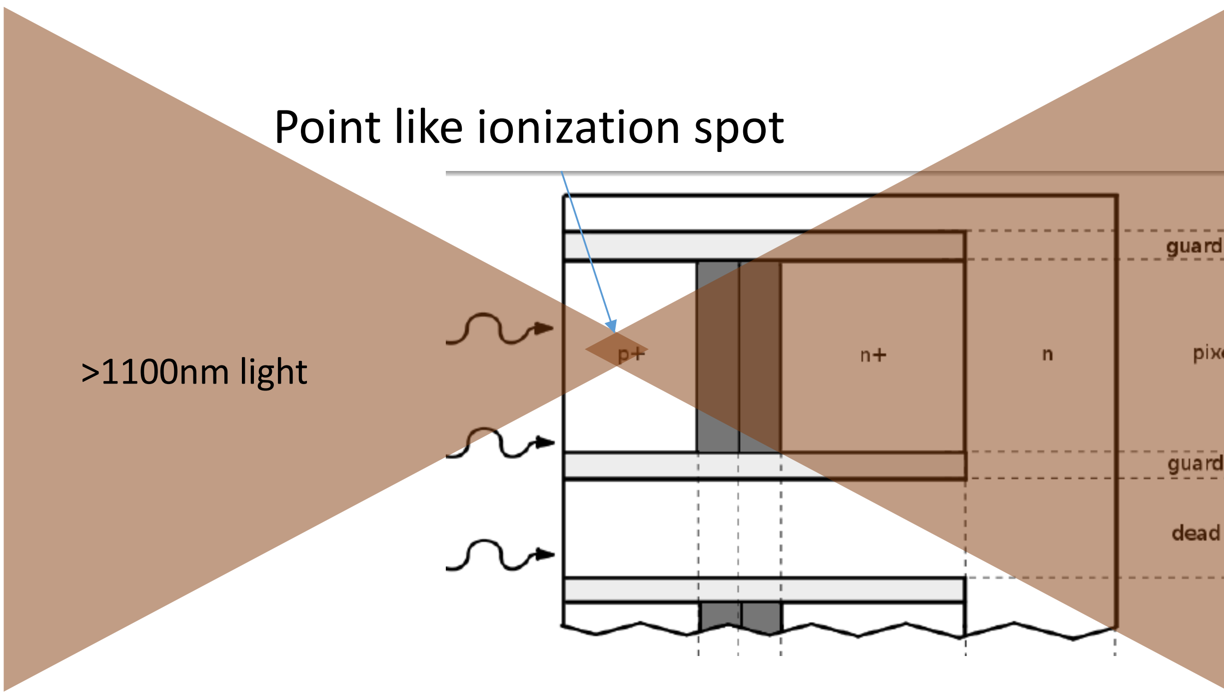


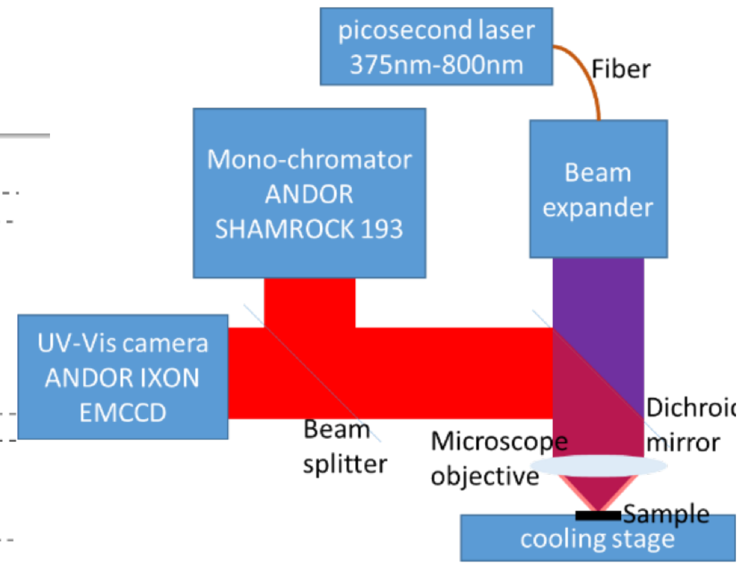


Summary. Model reasonably succesful

- Extracting probability of triggering avalanche from over-voltage dependence of PDE
- Applying to DN, AP and XT
  - Good overall agreement
  - Parameters seem to make sense
- Putting together all parameters for predicting IV curve
- End goal is to extract all parameters from IV
  - But need robust model
- Address several issues
  - Runaway region (divergence)
  - Transition from linear to Geiger mode
- Use two-photon ionization for better separating e- and h avalanches

Outlook: “next generation” characterization setup





Interested in a workshop to discuss this topic

The end

IV curves – reverse bias Parameters

- I = C*Vov*{R0*[feDN*Pe(Vov)+(1-feDN)*Ph(Vov)]} * [1 + q*Nap(Vov)/(1-q*Nap(Vov)) + Nxt(Vov)] + I0

geometrical series

- C: capacitance
- Vov: overvoltage

- R0: rate of thermally generated electron-hole pairs
- Pe: avalanche triggering prob. for electrons
- Ph: avalanche triggering probability for holes
- feDN: fraction of electron-driven avalanches
- q: average fraction of charge carried by afterpulse
- Nap: average number of afterpulses per pulse
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- I0: leakage current