New impact ionization parametrization based on existing models

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Outline

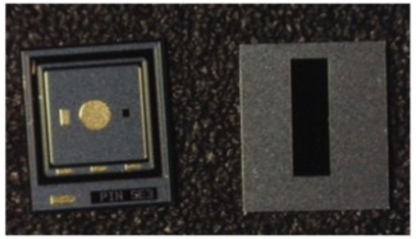
- Input data for the new parametrization.
  - TCAD simulation of CNM-12916 and HPK2 LAGDs (Splits: 1 and 3).
  - Existing impact ionization models: Massey and Overstraeten.
  - Gain measurements as a function of the electric field and temperature with IR-TCT.
- Fitting the parameters of these two models to our data outside TCAD.
  - Solve the impact ionization equation in C++.
- Study of the breakdown voltage as a function of the temperature down to 20K.
- Summary and next steps.

Input data: Electric fields from TCAD

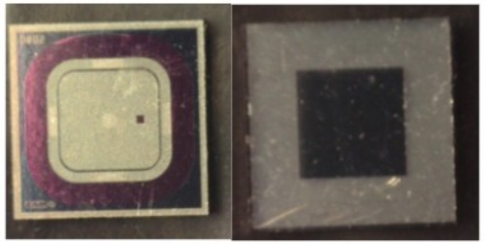
Samples:

- **HPK** LGADs and PAD detectors
  - HPK prototype 2 sensors
  - Area: 1.3 x 1.3 mm^2
  - Thickness: 50 μm
  - 4 different splits (i.e. different gain)

W25 → split 1: higher gain
W36 → split 3: lower gain

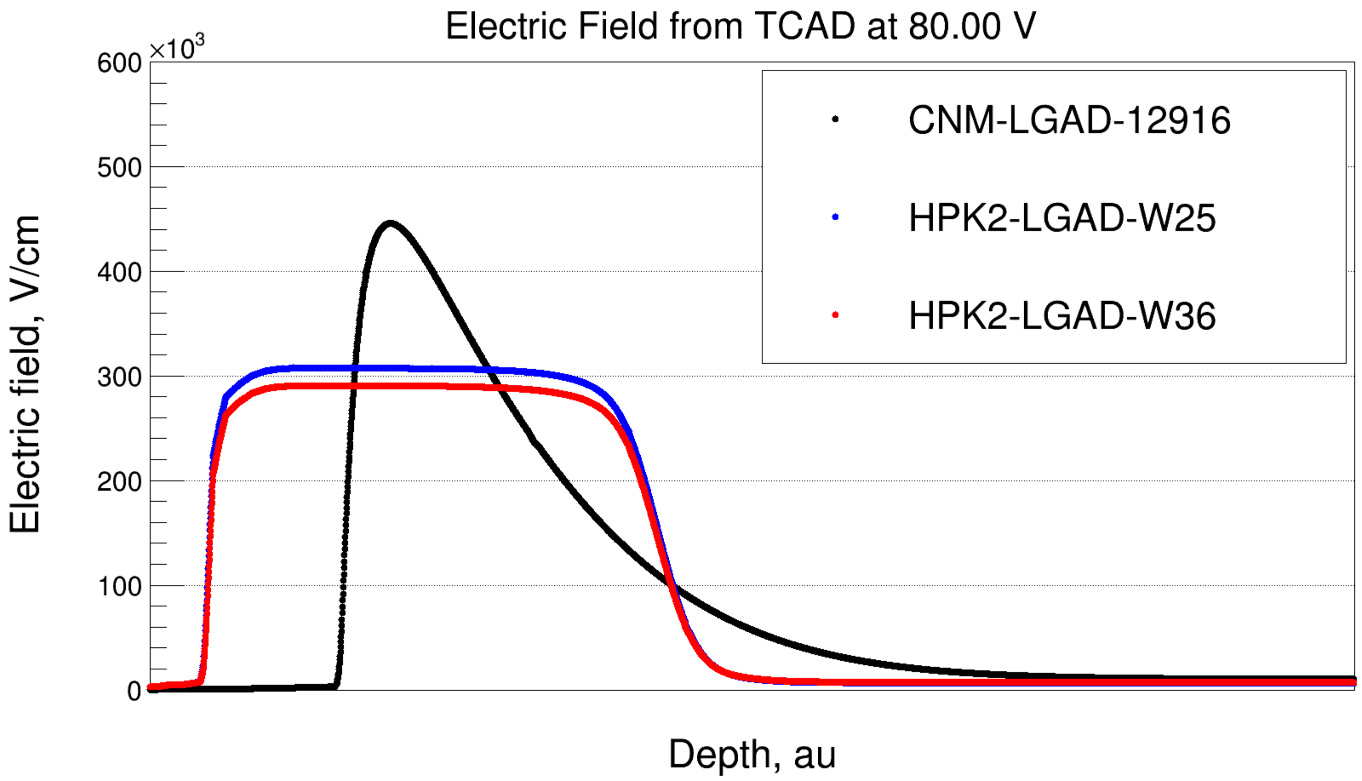


HPK2



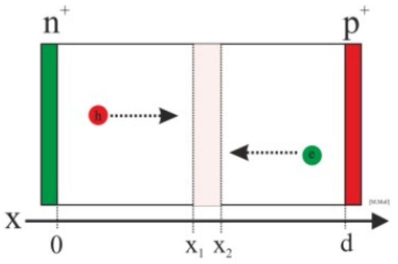
CNM 12916

- **CNM** LGADs and PAD detectors
  - CNM run 12916
  - Area: 1.3 x 1.3 mm^2
  - Thickness: 50 μm



Impact ionization equation

- Consider multiplication of electrons and holes



charge generation [As/cm³]

$$-\frac{dJ_n}{dx} = \alpha_n J_n + \alpha_p J_p + g(x) = \frac{dJ_p}{dx}$$

Alpha (e^-) Beta (h^+)

$$J = J_n(x) + J_p(x)$$

$$-\frac{dJ_n}{dx} = (\alpha_n - \alpha_p) J_n + \alpha_p J + g(x) = \frac{dJ_p}{dx}$$
$$= (\alpha_p - \alpha_n) J_p + \alpha_n J + g(x)$$

- Solution for the total current:

$$J = M_n J_n(d) + M_p J_p(0) + \int_0^d g(x) M(x) dx$$

with

$$M(x) = \frac{\exp\left(-\int_x^d (\alpha_n - \alpha_p)\, d\eta\right)}{1 - \int_0^d \alpha_n \exp\left(-\int_\xi^d (\alpha_n - \alpha_p)\, d\eta\right) d\xi}$$

Gain equation implemented in C++

Impact ionization models:

$\alpha_p = f(E,T)$ and $\alpha_n = f(E,T)$

Overstraeten model

- Five parameters to tune:
  - a_n, a_p, b_n, b_p and γ
  - More computing power

$$\alpha(F_{ava}) = \gamma a \exp\left(-\frac{\gamma b}{F_{ava}}\right)$$

With: $$\gamma = \frac{\tanh\left(\frac{\hbar\omega_{op}}{2kT_0}\right)}{\tanh\left(\frac{\hbar\omega_{op}}{2kT}\right)}$$

Massey model

- Six parameters to tune:
  - A_n, A_p, C_n, C_p, D_n and D_p
  - Less computing power

$$\alpha_{n,p}(E) = A_{n,p} \cdot \exp\left(-\frac{B_{n,p}(T)}{E}\right)$$

With: $B_{n,p}(T) = C_{n,p} + D_{n,p} \cdot T$

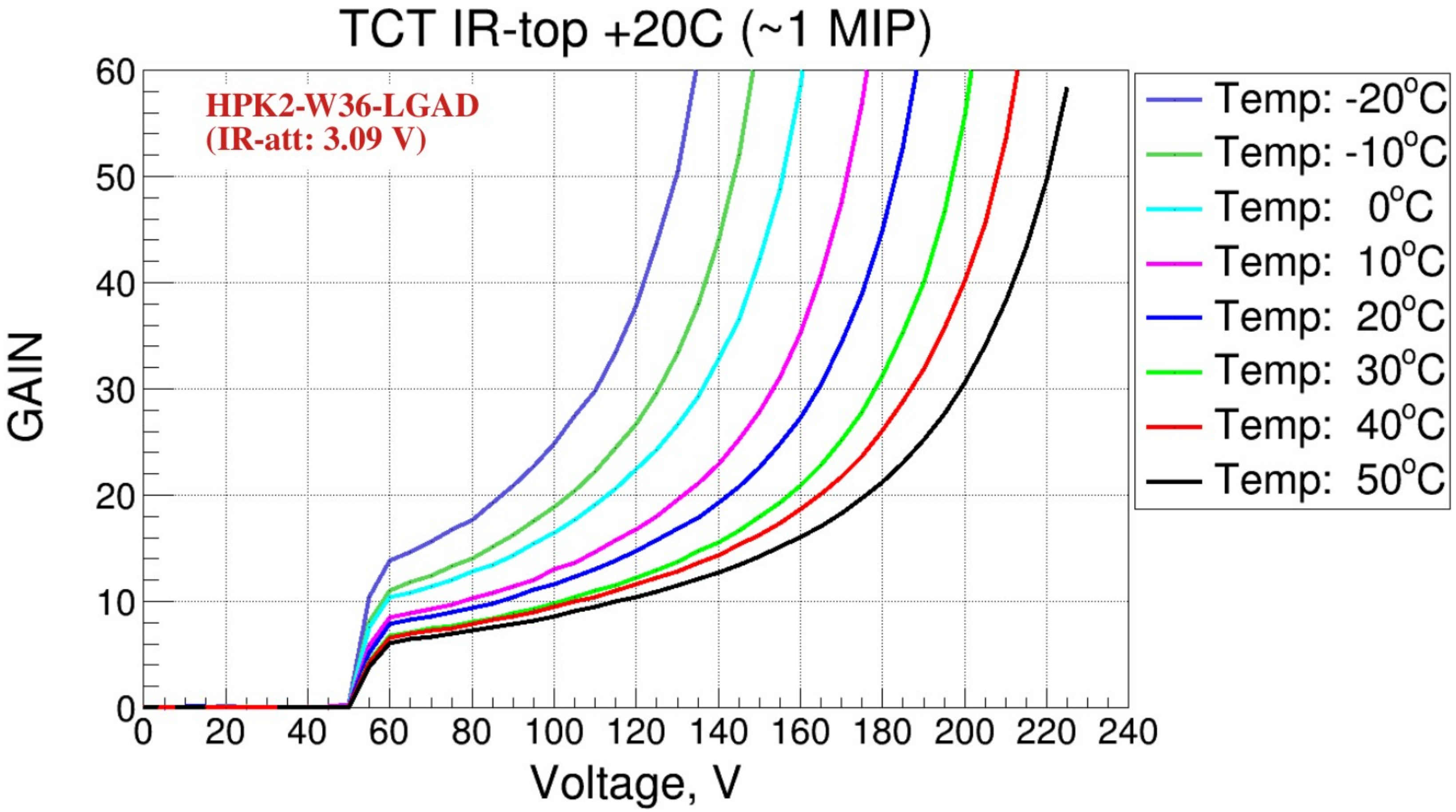
Gain curves measured in TCT

- T: -20 ^{O}C up to +50 ^{O}C
- Averaging: 2048
- Cividec C2 amp
- IR shutter aperture: 6,0 mm
- IR attenuator: 3,09 V
- At +20 ^{O}C we have ~ 1 MIP, this decreases with temperature.
  - -20C < 1 MIP
  - +50C > 1 MIP
- Gain is evaluated:

$$G(V,T) = \frac{Q_{LGAD}(V,T)}{Q_{PIN}(100V,T)^{*}}$$

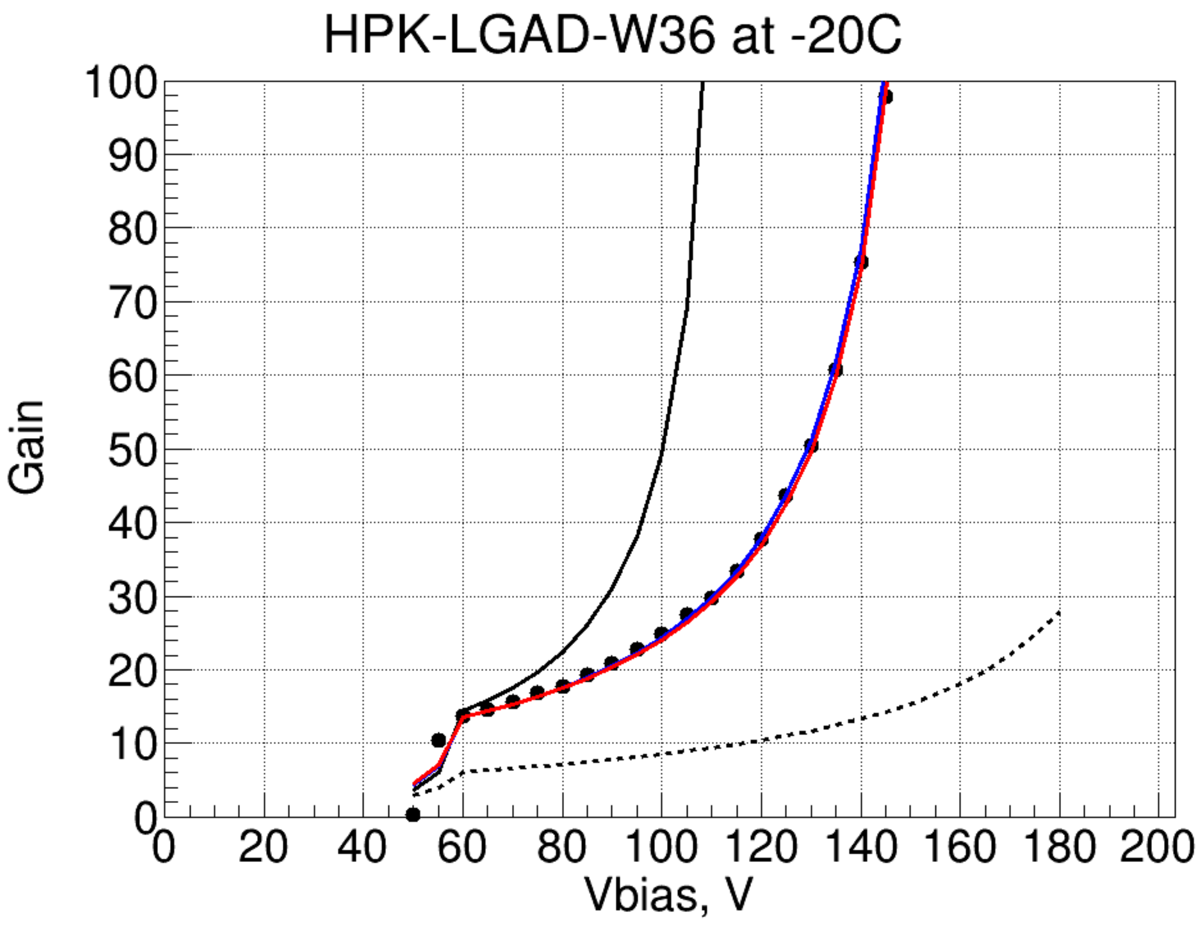
* Q_{PIN} measured at 100V, (V_{FD} ~ 10 V)

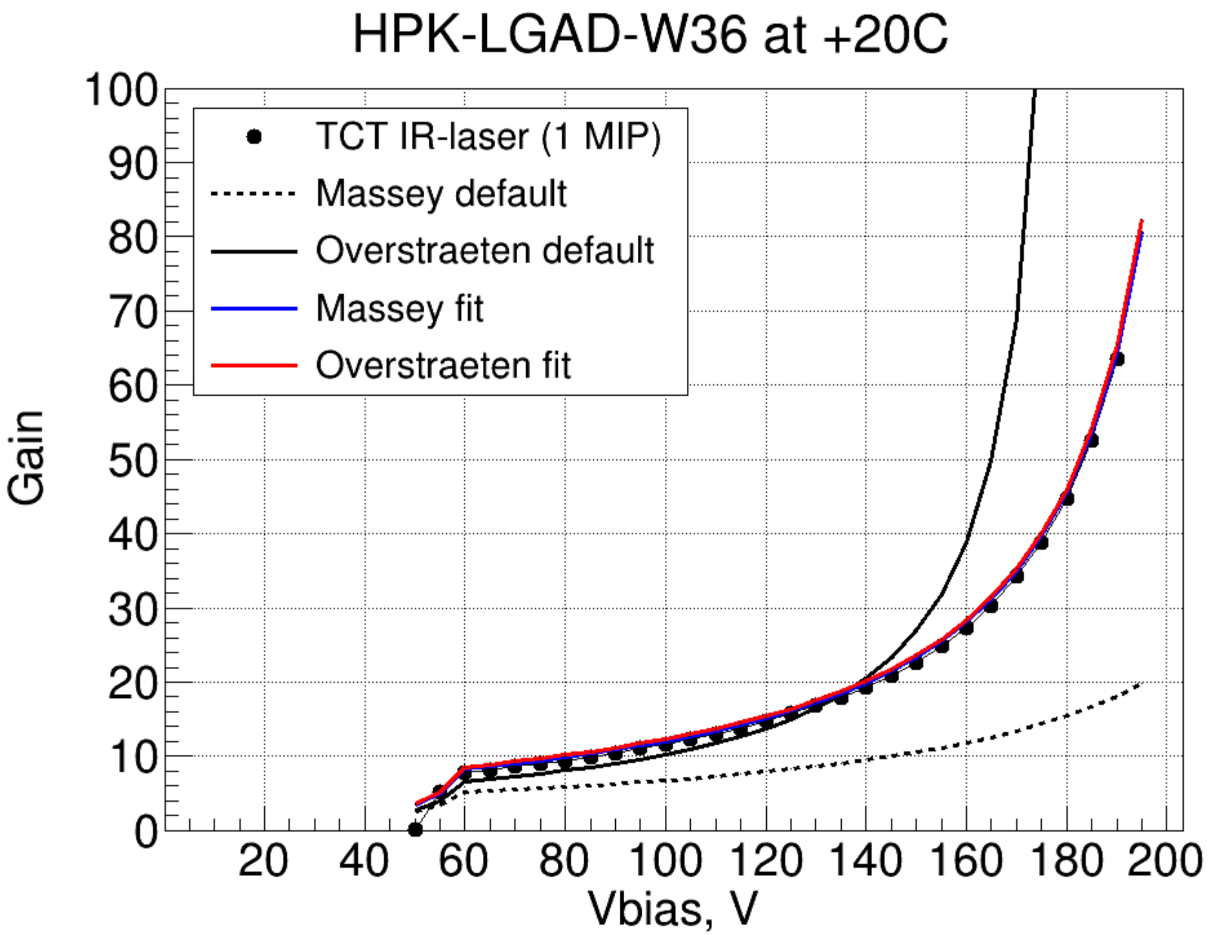
We have data for HPK2-W25 too, but not yet for the CNM-12916



Tuning the parameters: HPK2-W36-LGAD

Data for **all temperatures fitted together**. Some temperatures shown below:

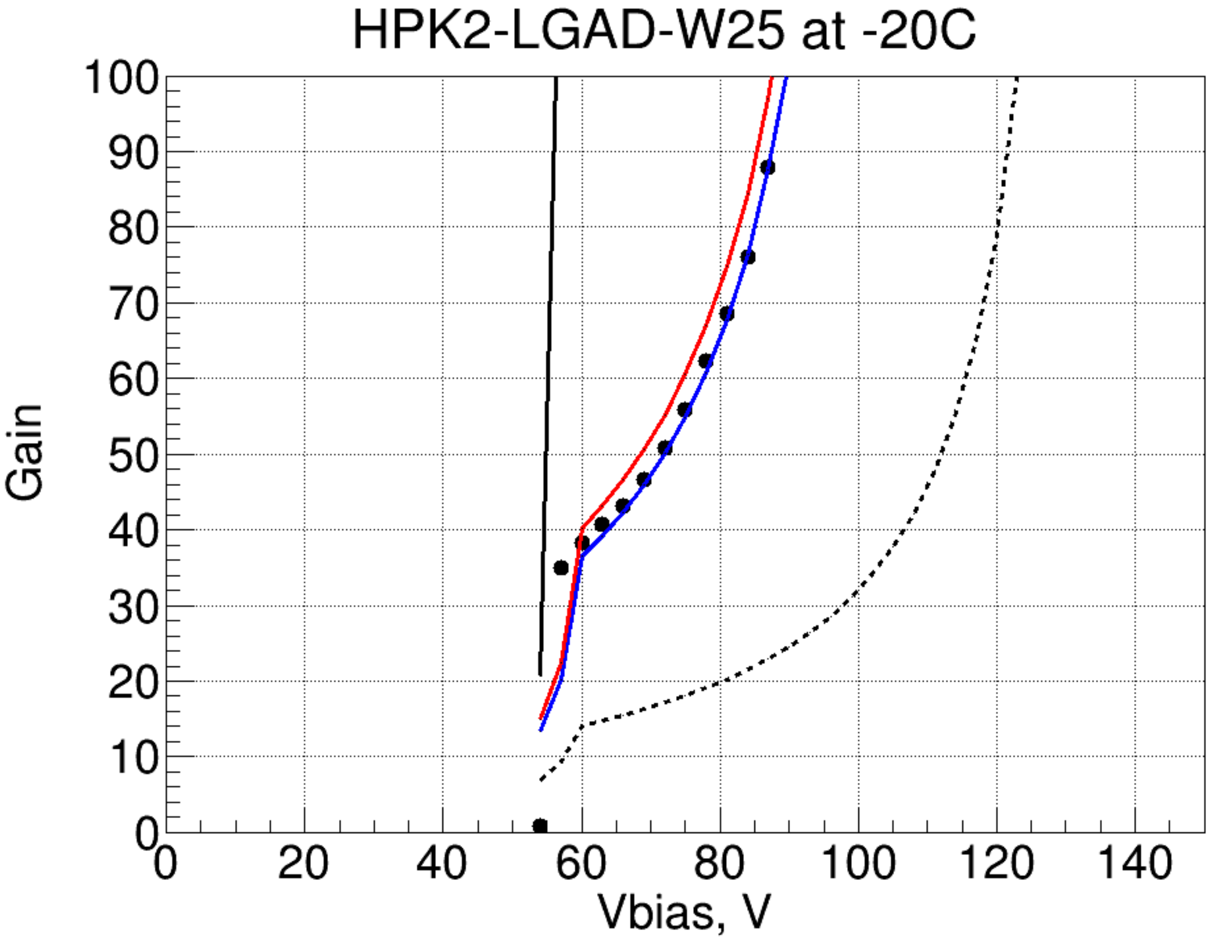


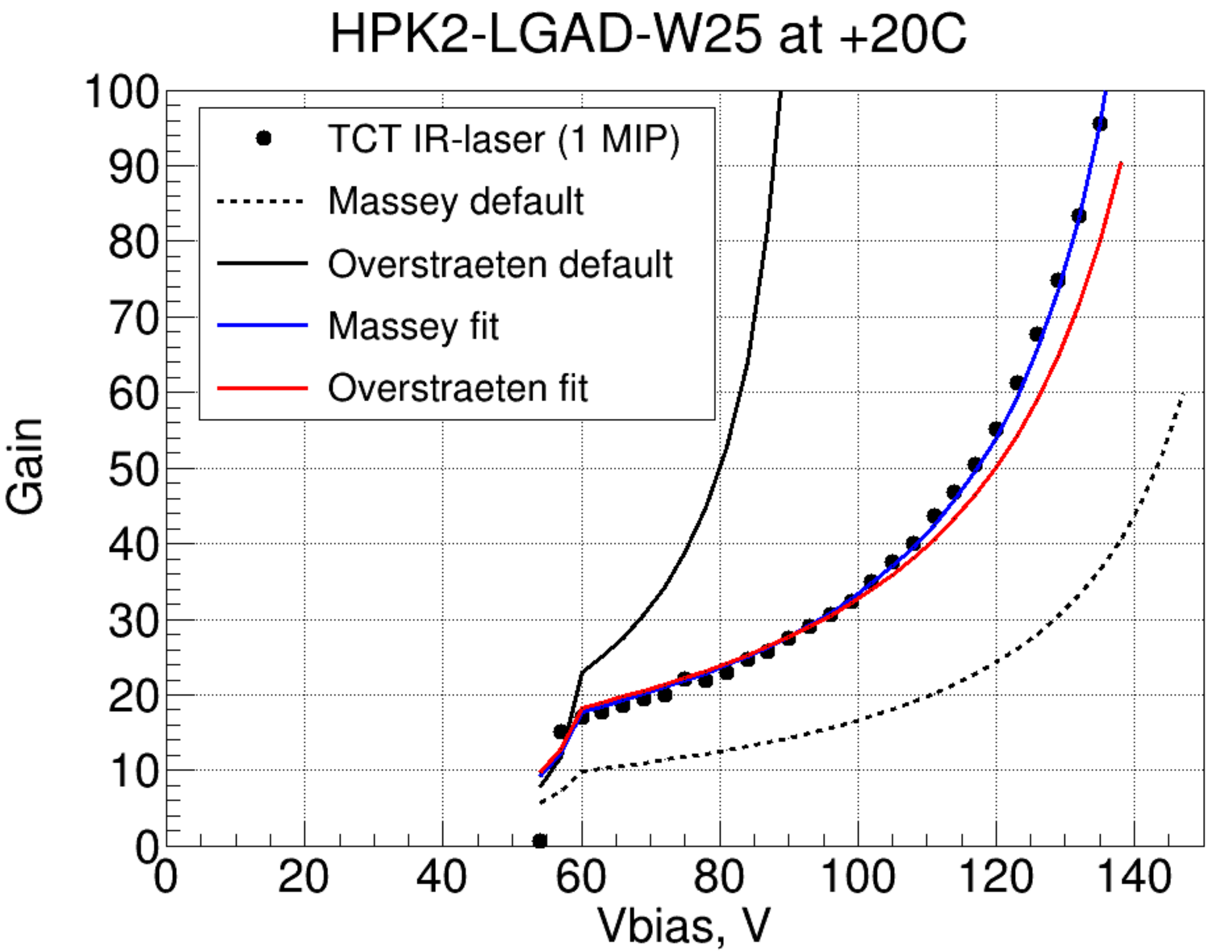


After tuning the parameters with the measured data, we get an excellent agreement with both models.

Tuning the parameters: HPK2-W25-LGAD

Data for **all temperatures fitted together**. Some temperatures shown below:

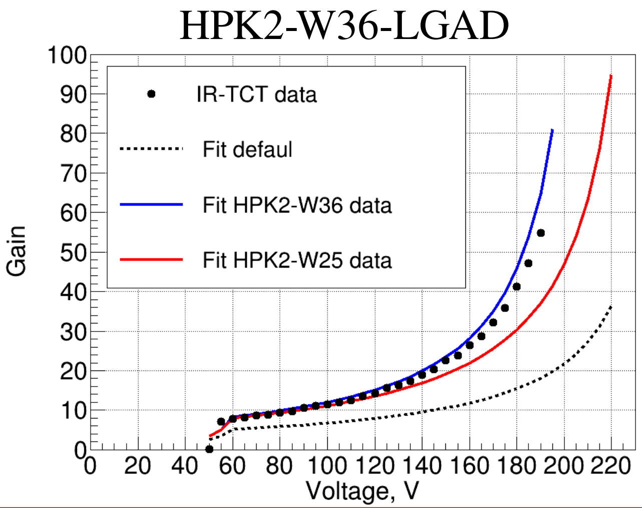


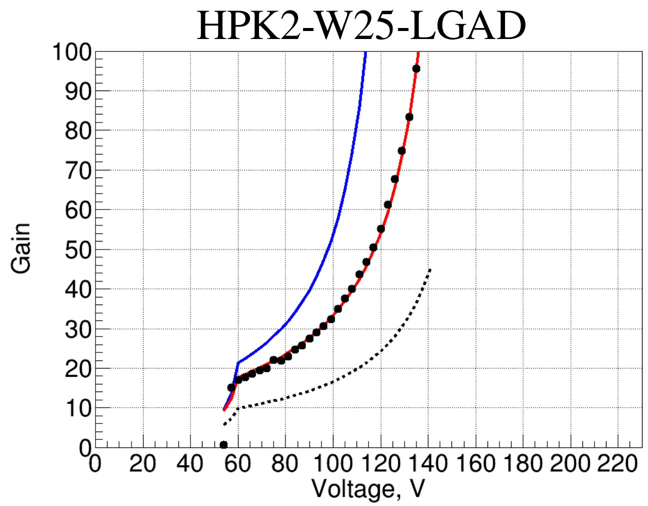


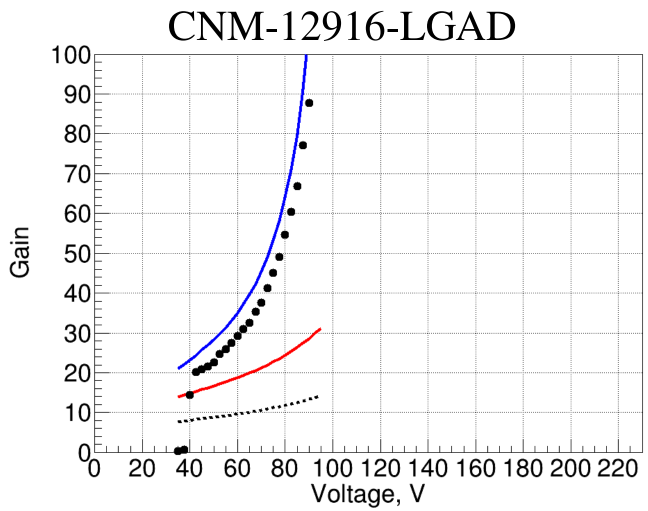
Again a good agreement with both models, but we have to use a **different parametrization** than for W36.

Tuning the parameters: comparing all LGADs

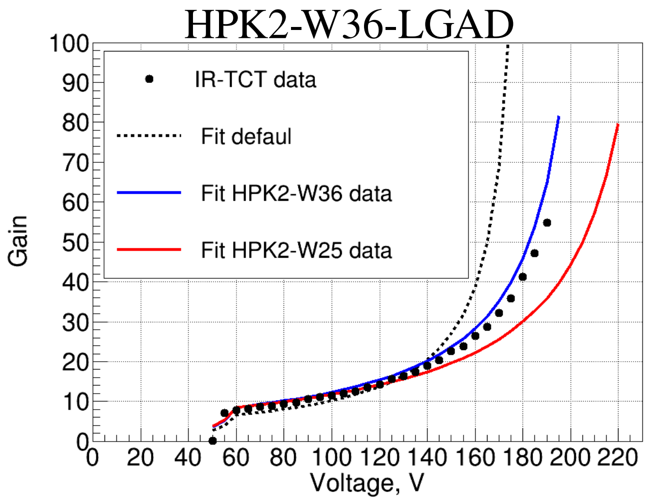
Massey
Temp: 20°C

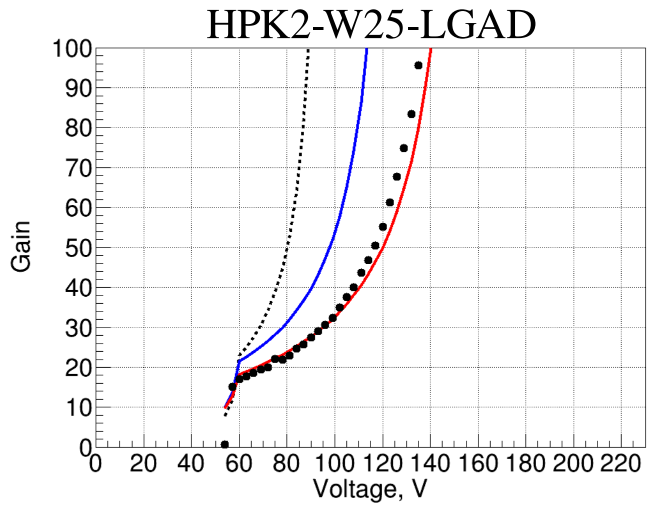


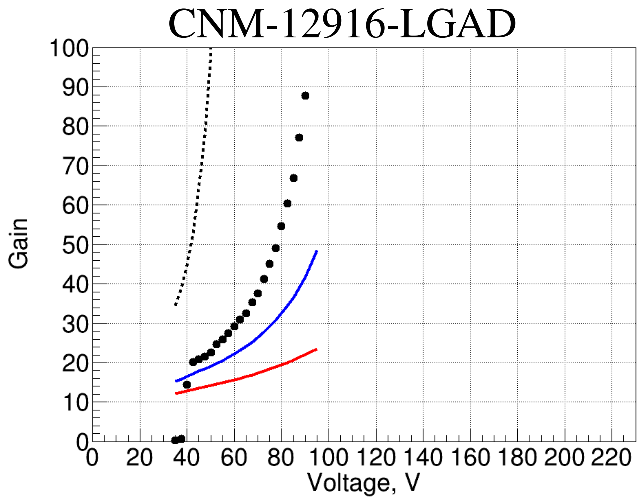




Overstraeten
Temp: 20°C

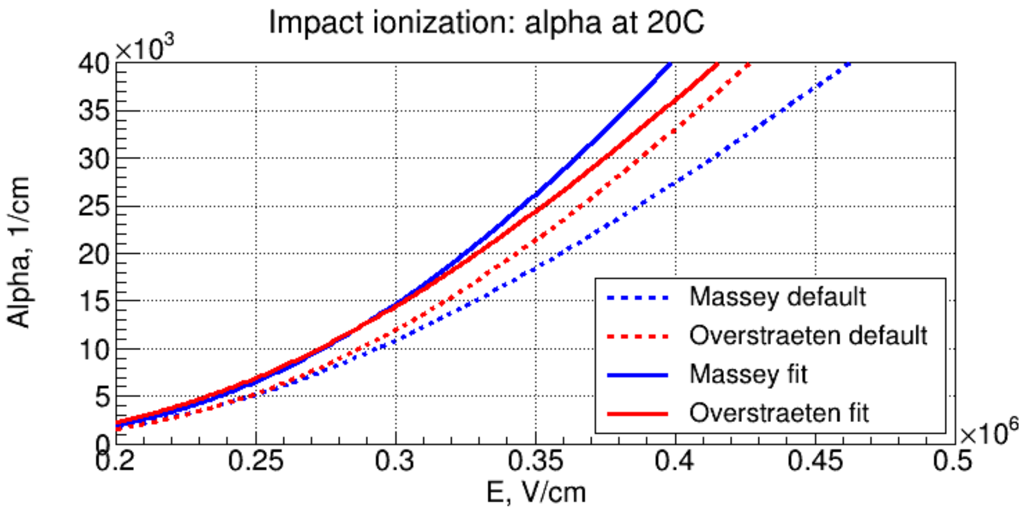


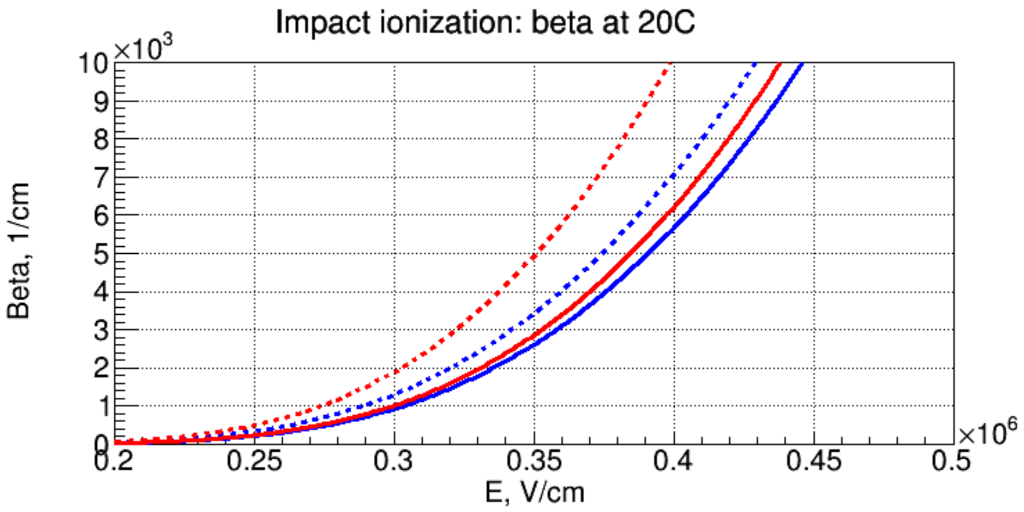


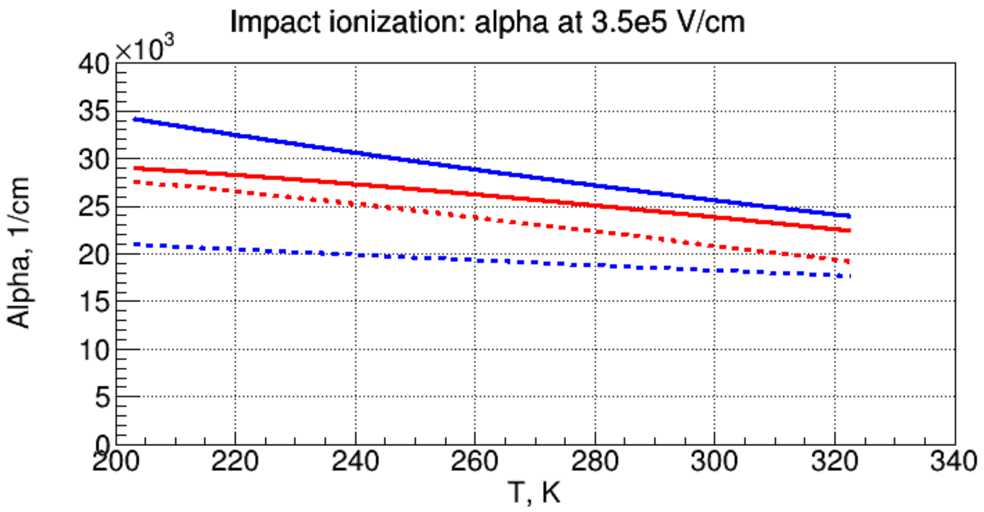


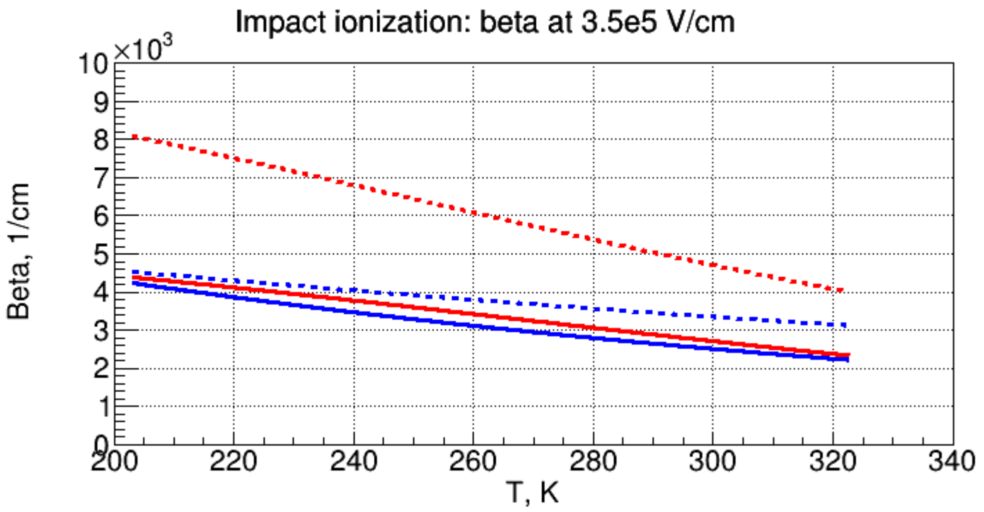
It is very difficult to fit all the curves with one set of parameters in both cases (Overstraeten and Massey).

Alpha and beta comparison: HPK2-W36-LGAD



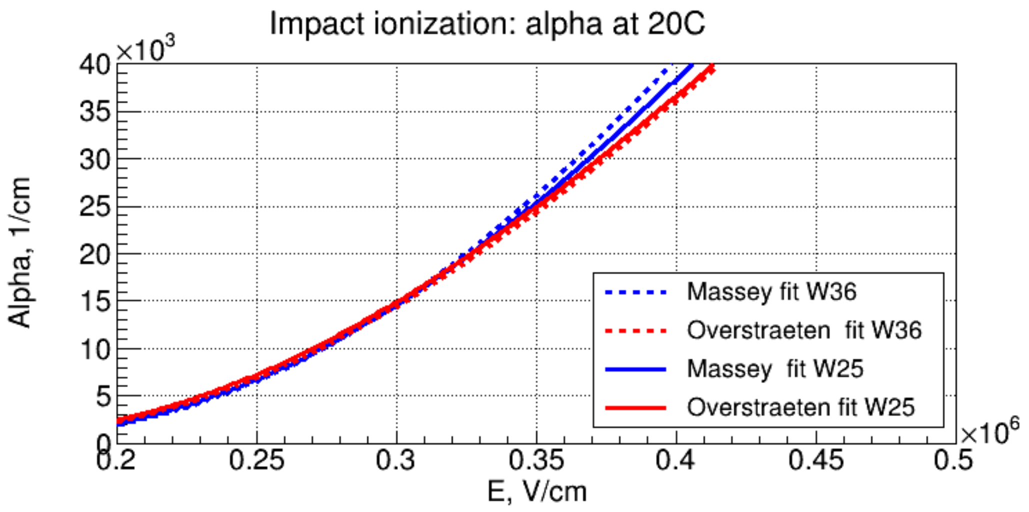


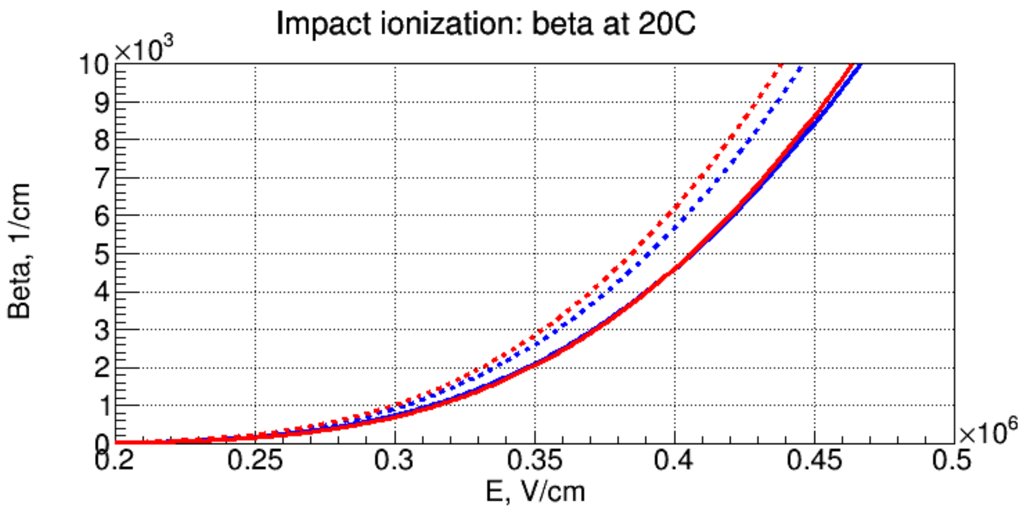


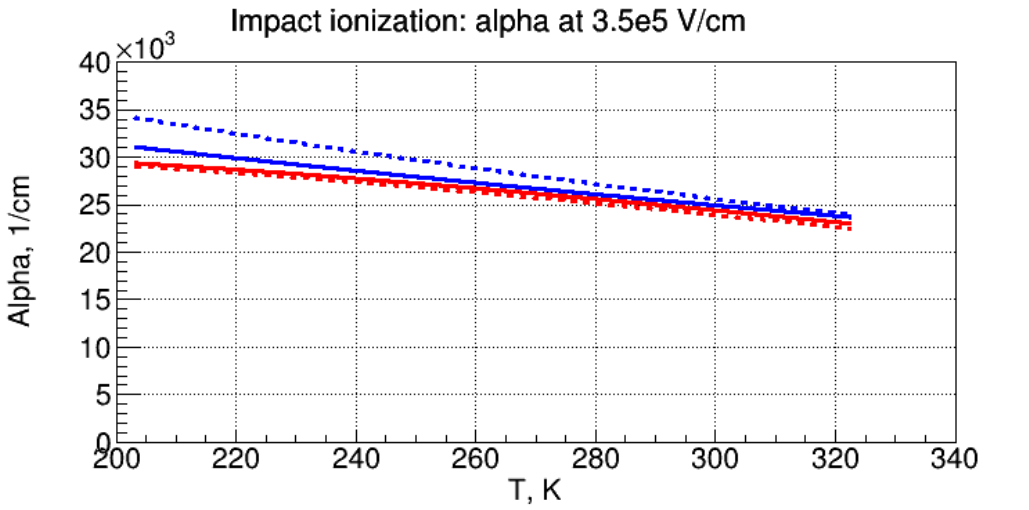


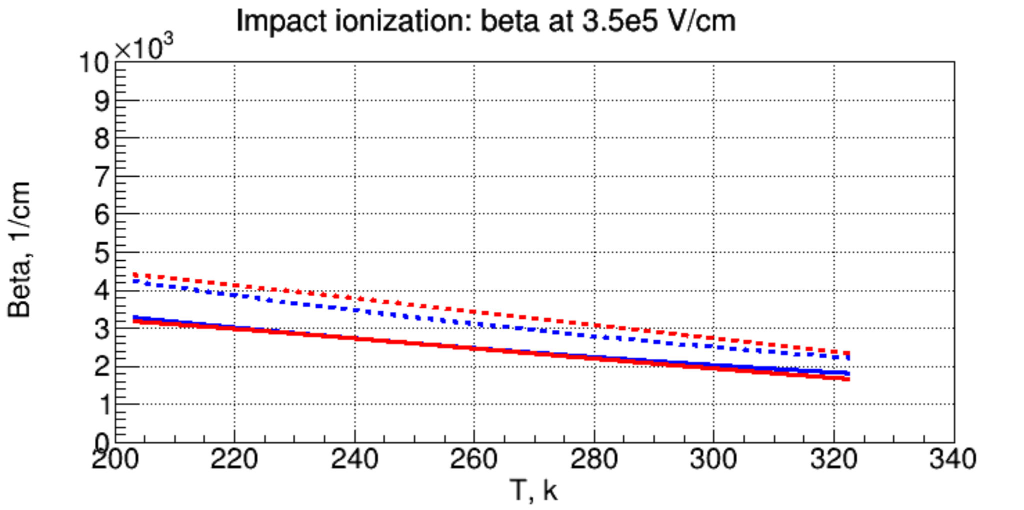
Alpha and beta are significantly different with the new parametrization.

Alpha and beta comparison: HPK-W25-LGAD





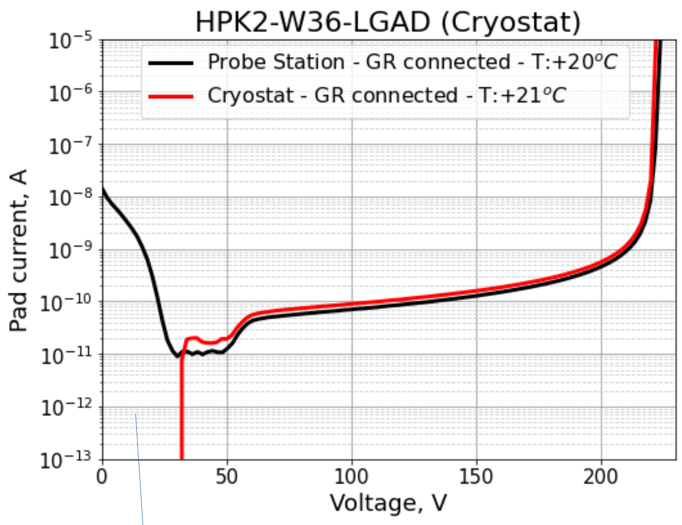


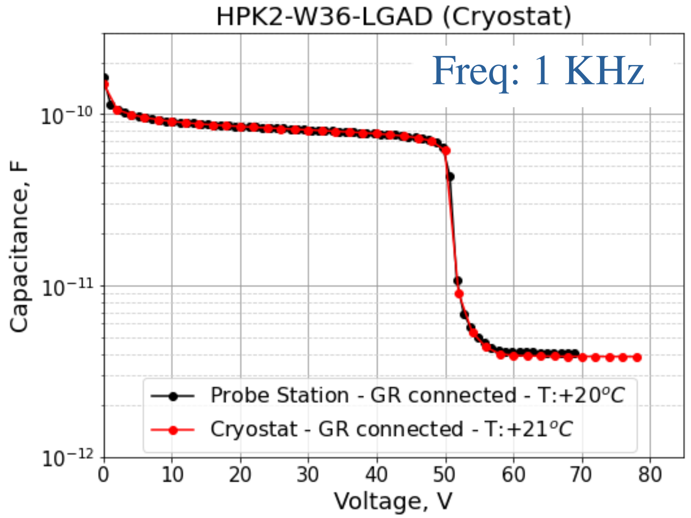


Alpha and beta differ when we fit independently HPK2-W36-LGAD and HPK2-W25-LGAD

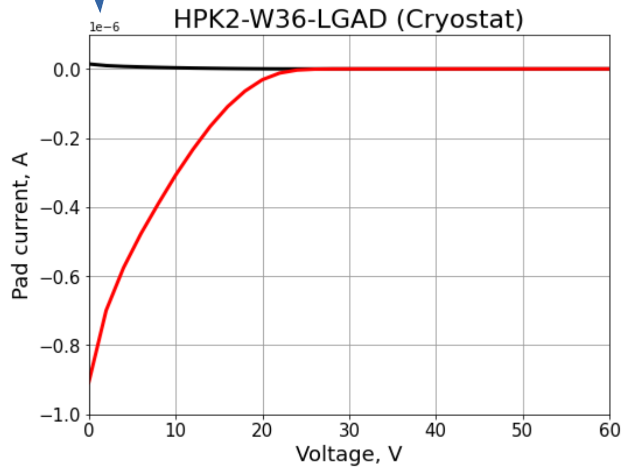
Gain and breakdown voltage in the cryostat:

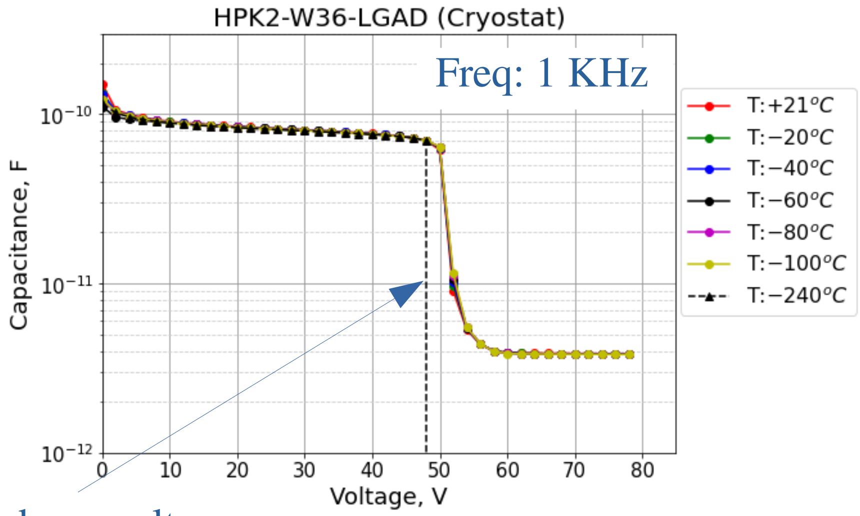
Comparing results with the probe station





At low voltage the current changes polarity in the cryostat. This is an effect of the GR in the HPK2 that we do not fully understand yet.

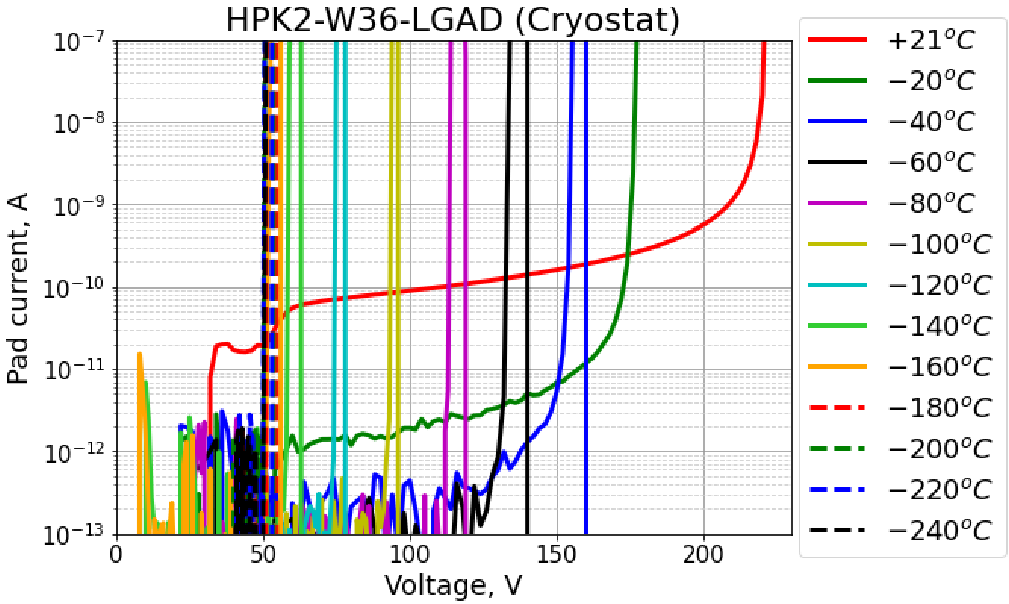


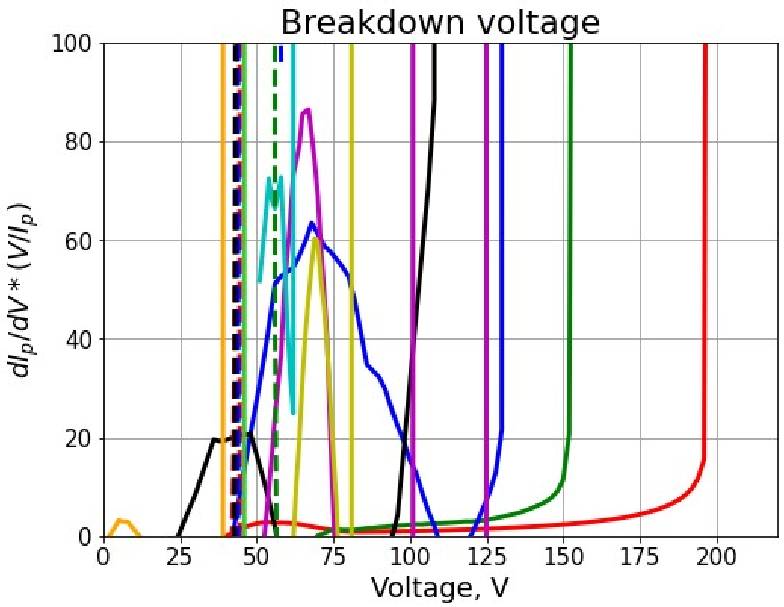


Breakdown voltage

Gain and breakdown voltage in the cryostat:

Breakdown voltage and gain





- At low temperatures is very complicated to estimate the breakdown voltage.

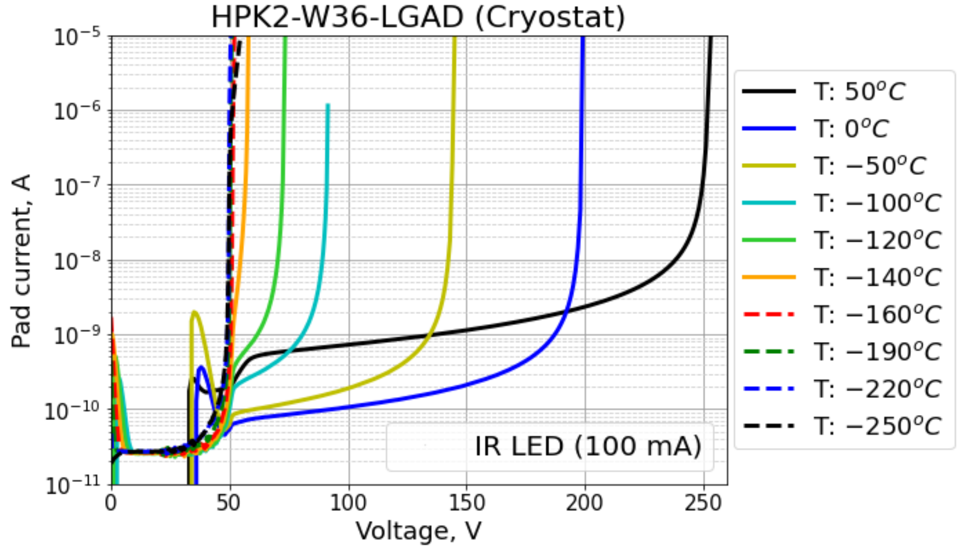
- Only from the IV curves is not possible to get the gain.
  - At low temperatures there is not enough current.
  - A big amount of the current that we measure in the unirradiated LGADs is not coming from the bulk and therefore is not amplified.

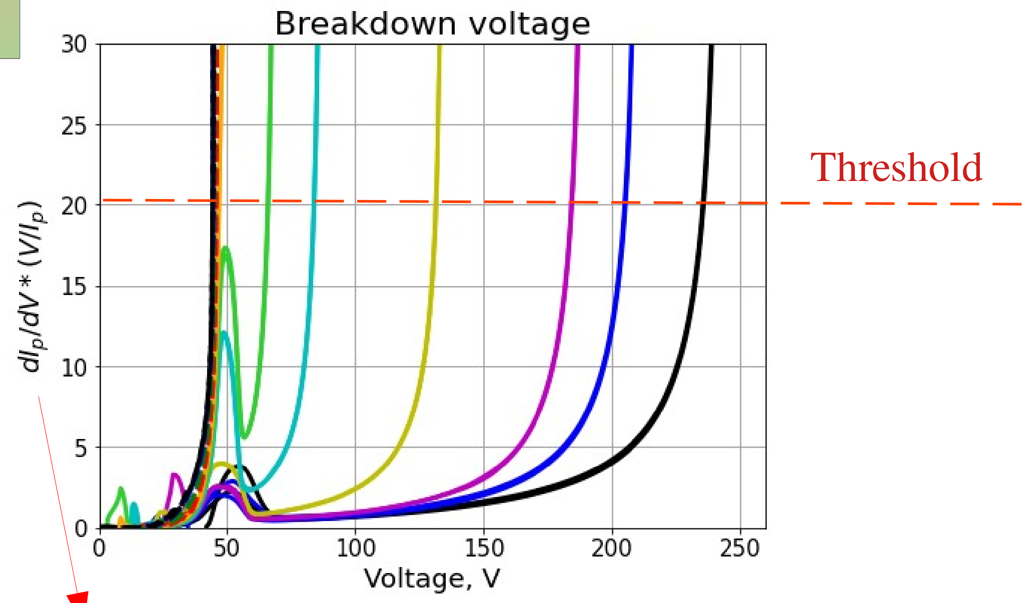
We need to increase the bulk current illuminating with LEDs

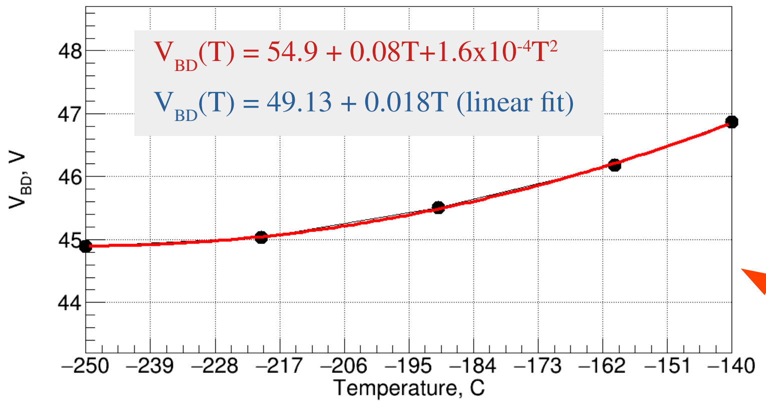
Gain and breakdown voltage in the cryostat:

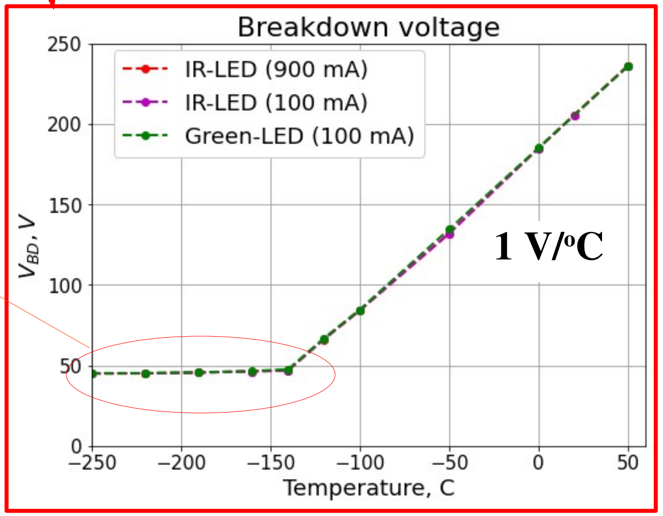
Breakdown voltage and gain

IR-LED (940 nm)
LED current: 100 mA
Top illumination









The change in the slope occurs when V_{BD} is equal to V_{GL}.

This is because the BD is happening before the bulk depletes.

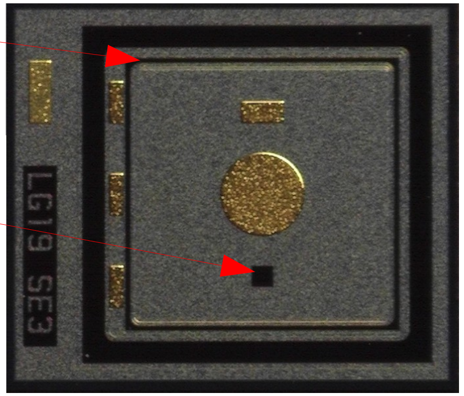
Gain and breakdown voltage in the cryostat:

Breakdown voltage and gain

To evaluate the gain things are a bit more complicated and measurements are still ongoing ...

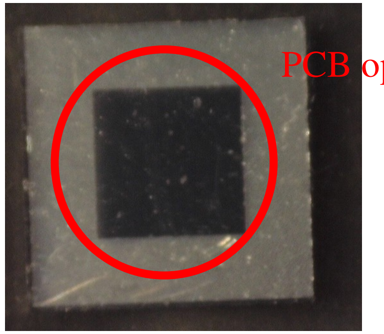
A_1
(Area that does not contribute to the gain)

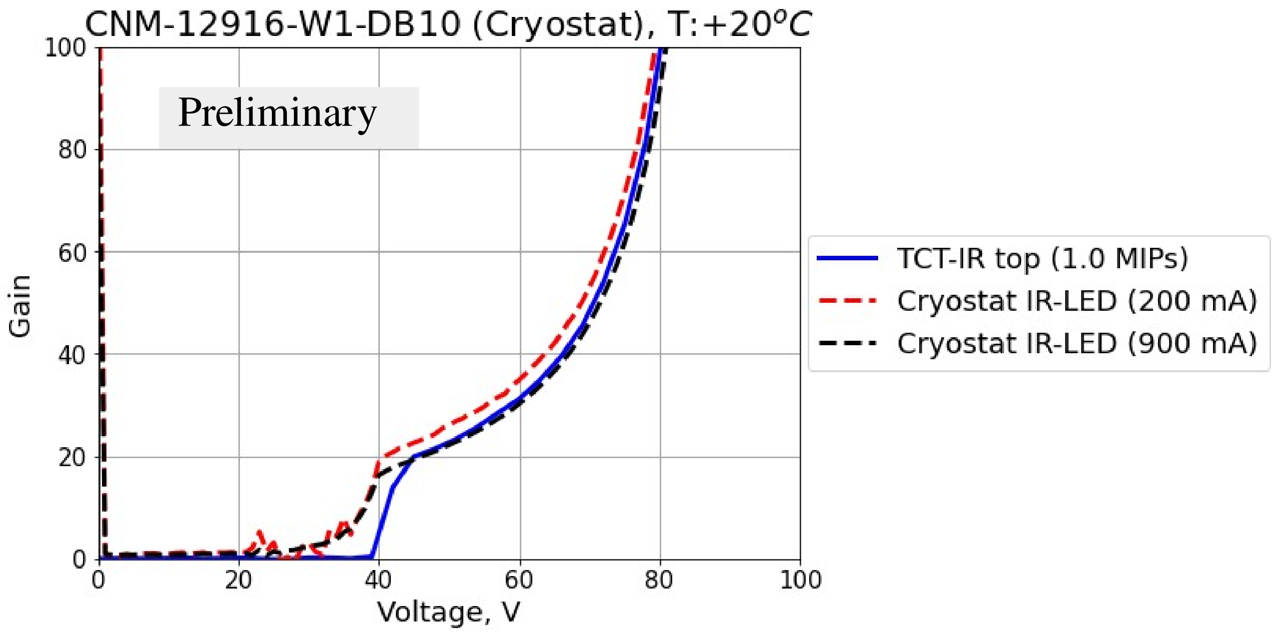
A_2
(Area that contributes to the gain)



We need to go from top illumination to bottom illumination to avoid correction that can lead to big uncertainties in the results.

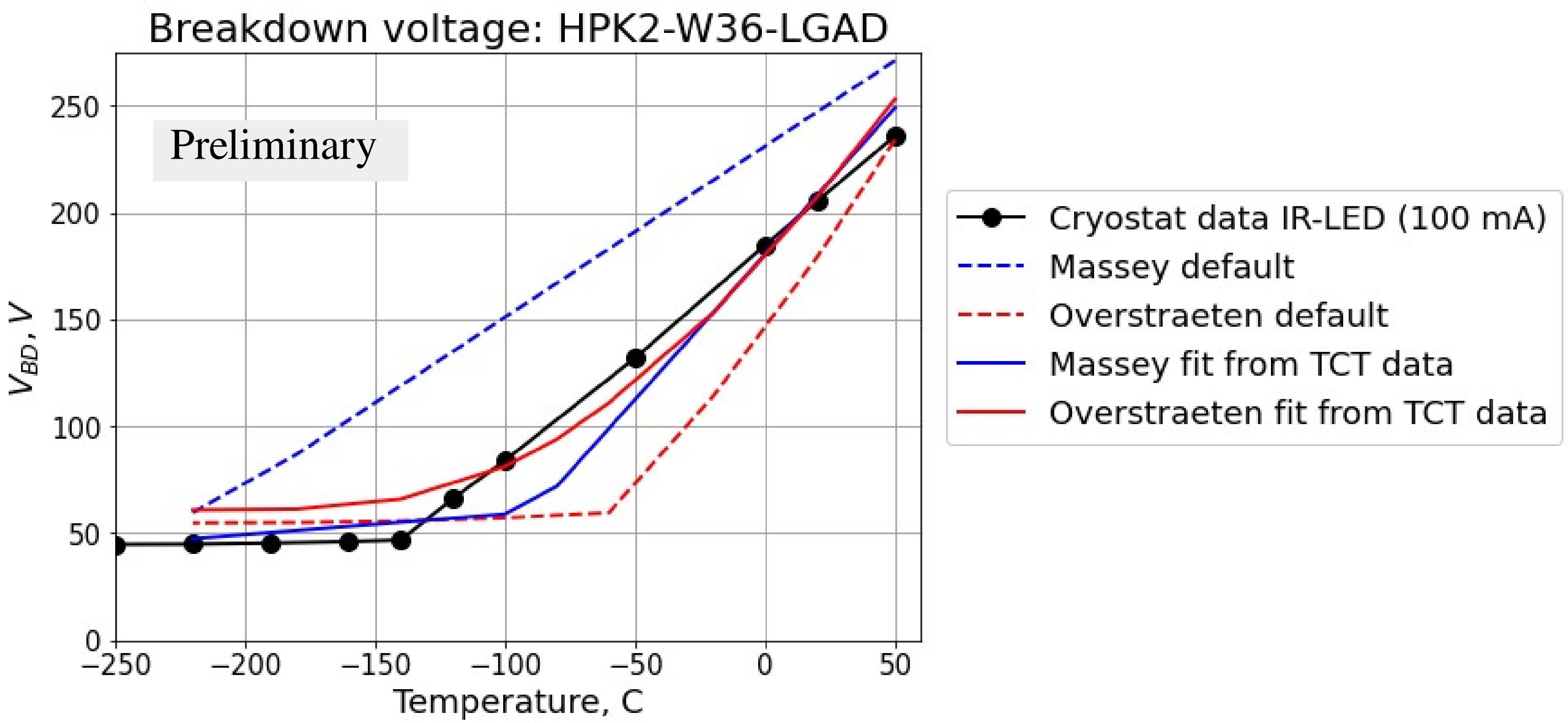
For the first trial we move to the CNM, because of their larger opening in the back side





Gain and breakdown voltage in the cryostat:

Applying the different impact ionization models to the V_{BD} data



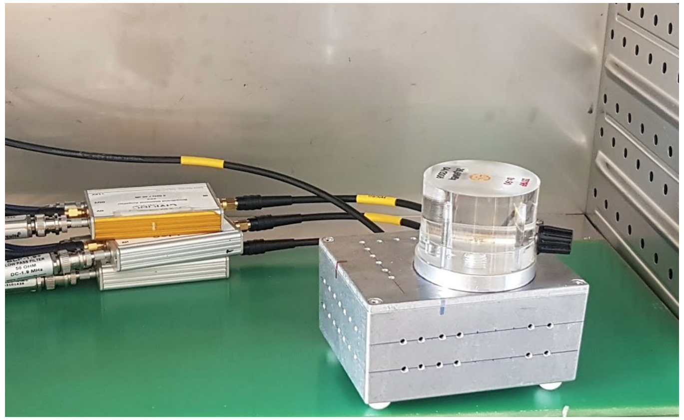
- Our new model gives better agreement in terms of the breakdown voltage than the default ones.
- Note: the fitting with the TCT data was not targeting the breakdown voltage region.
- Next step: include this data in the fitting function to optimize alpha(E, T) and beta(E, T).

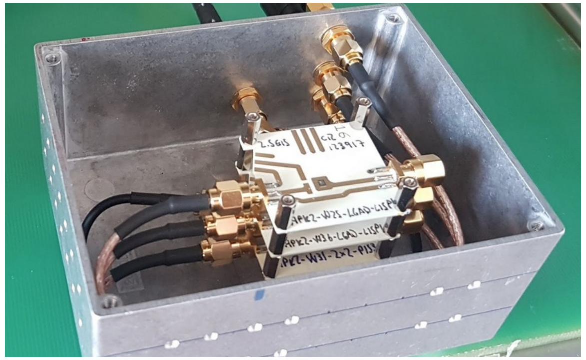
Sr-90 measurements

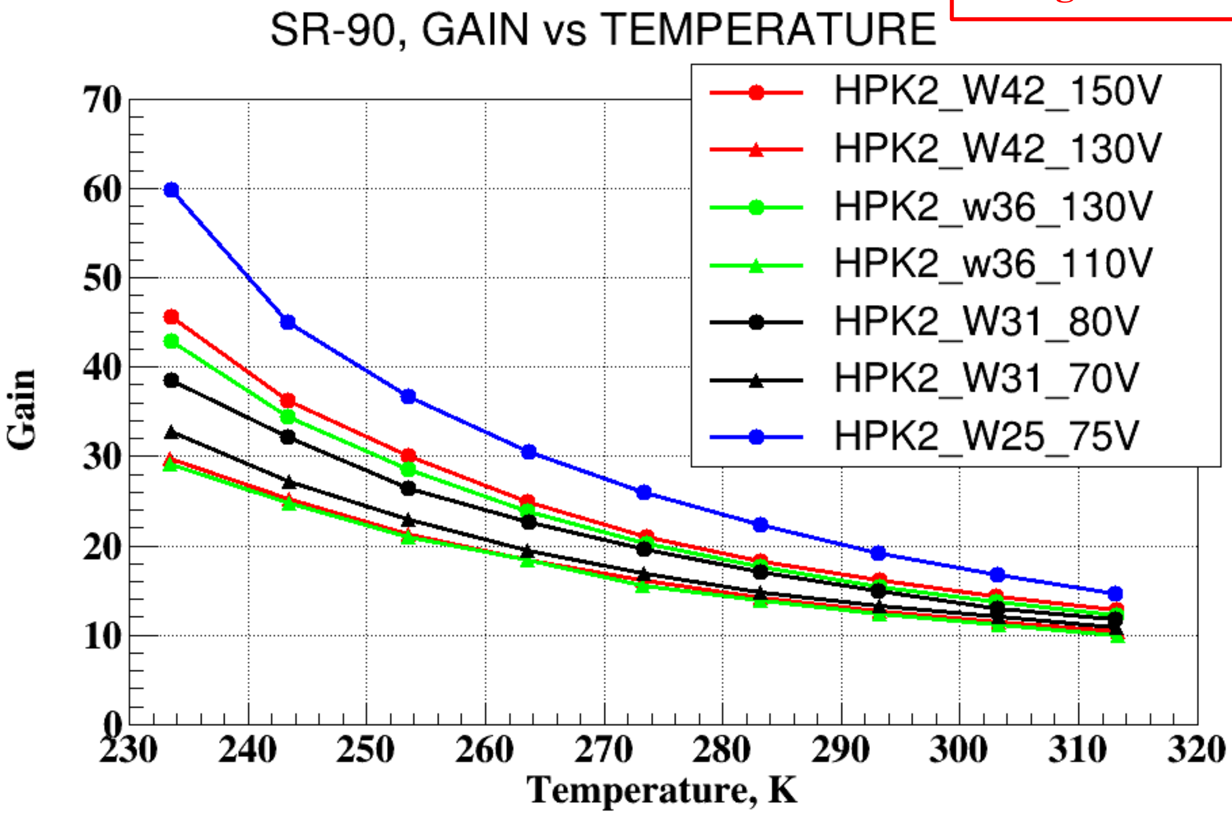
Gain at low electric field as at different temperatures

- Measured the gain with the Sr-90 source in all the HPK2 and CNM-12916 LGADs from -40ºC to 40ºC.
- The Vbias was kept constant during the temperature scan for the DUT.

More data to cross check our parametrization and/or include in our fitting function. Work in progress !







Summary and next steps

- Gain calculation done in C++ using Efield data from TCAD and existing impact ionization models:
  - Massey.
  - Overstraeten.
- Looking for new parameters that can fit better our data. First step using IR-TCT data:
  - The new parameters provide a good agreement with the experimental results.
  - We could not fit all our data with a single parametrization yet.
- Measurements of the breakdown voltage and gain were conducted in the cryostat down to 20K.
  - This data will be included in the fitting function, but we have already a good agreement.
- Next steps:
  - SIMS measurements in at least one more device: HPK2-W36-LGAD.
  - Measure the uncertainty in the experimental data, gain dispersion between identical devices?
  - Using different impact ionization models: existing ones or maybe a new model is needed?

Thank you for your attention!