# Radiation hardness studies of HAB HPK sensors

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# Motivation

- Acceptor removal limits radiation hardness of LGAD devices
  - $B_s + Si_i \rightarrow B_i$ ; $B_i + O_i \rightarrow B_iO_i$ (the complete mechanism not yet fully explained)

- Different ways to mitigate acceptor removal
  - Dope gain layer with carbon – approach for ATLAS HGTD and CMS ETL
  - Narrow B implantation (e.g. HPK-P2)
  - Partial activation of boron - this talk

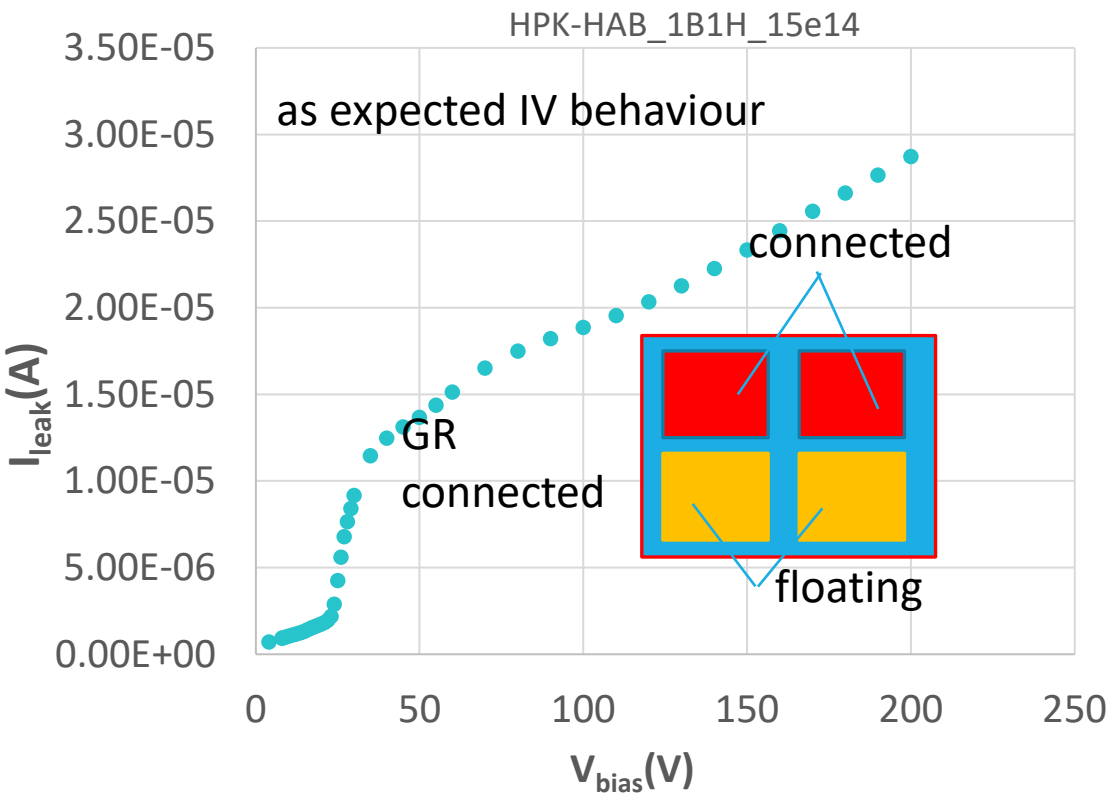
- HPK has produced a Half Activated Boron (HAB) run of LGAD devices
  - Part of boron is implanted, but not electrically activated in the gain layer
  - Not activated boron could ”protect” substitutional boron
  - Early results show potential improvement of radiation hardness (K. Hara, 18th Trento Workshop)

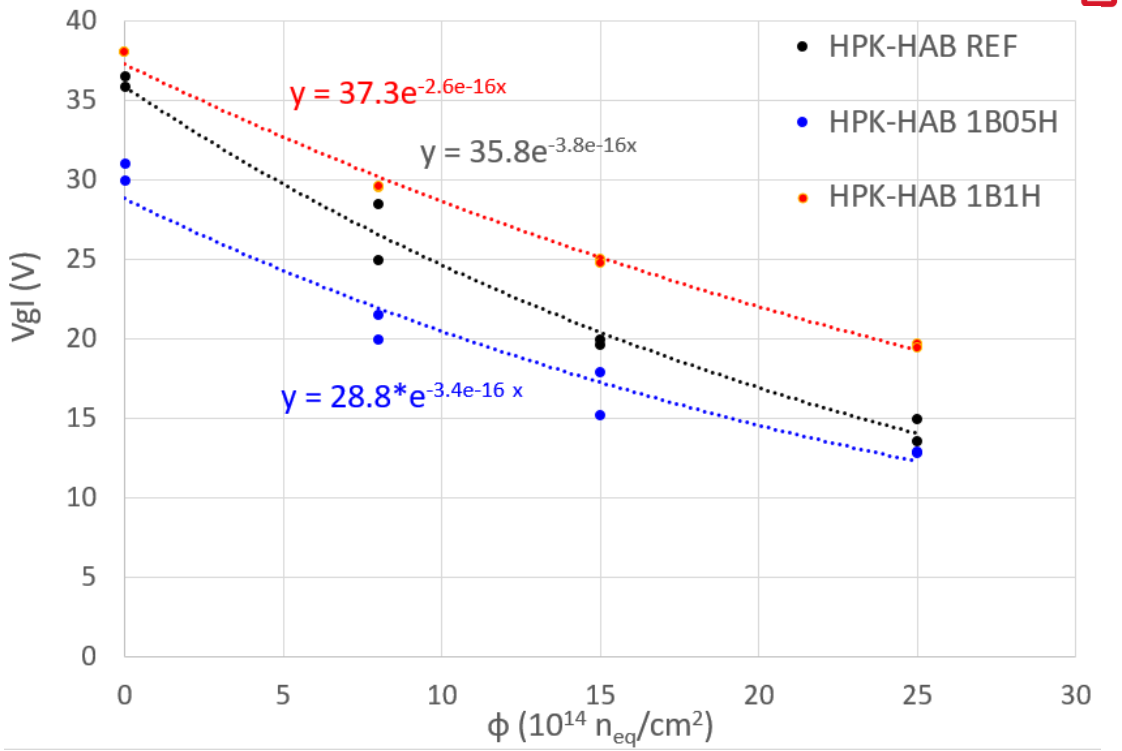
# HPK samples

- HPK provided three sample flavours which were characterized at JSI
  - **Reference** (full boron activation)
  - **0.5 HAB** (same activated boron concentration as reference + non activated boron 0.5x reference)
  - **1 HAB** (same activated boron as reference + non activated boron 1x reference)
- Samples were 2x2 LGAD arrays of 1.3x1.3 $mm^2$ and 50 μm thickness. Each pad had opening in metallization for light injection, but no opening was available in the inter-pad region.
- Samples irradiated with neutrons at JSI TRIGA reactor
  - Equivalent fluences of 8e14, 1.5e15, 2.5e15 $cm^{-2}$
  - annealed before the measurements to 80 min at 60 °C
  - Majority of samples sent to the AIDAINNOVA test beam in June and September and are still being analysed (still working on analysis tools)
- Techniques used in this work : CV-IV, CC/timing performance, TCT

# Acceptor removal constant

Every result we show now is preliminary!



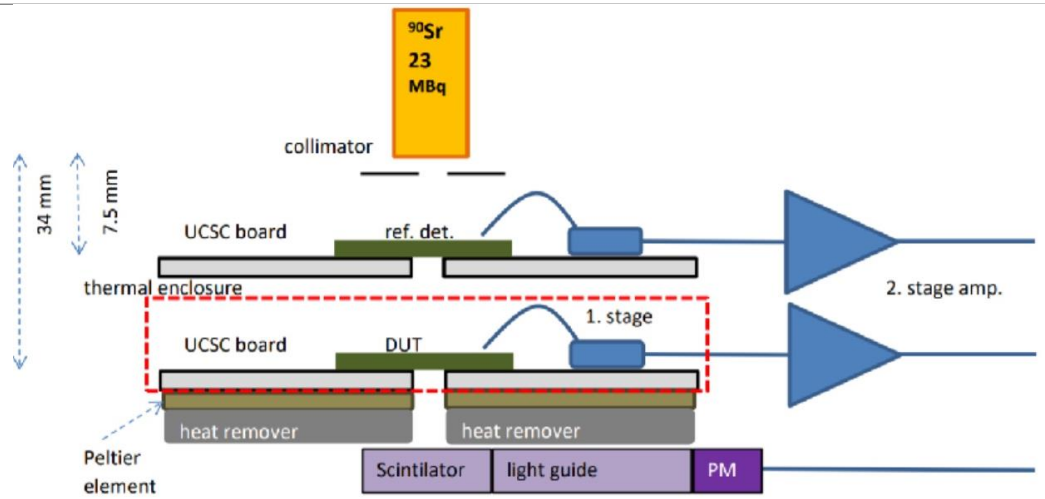

In irradiated samples measured $V_{gl}$ values after FIRST application of bias voltage different from all subsequent measurements.
Here showing results after second biasing.

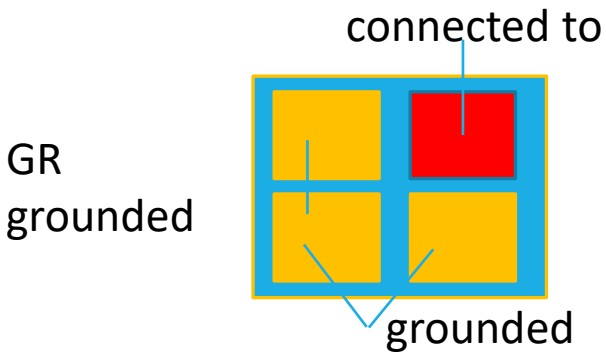
**Acceptor removal coefficients**
**c (REF)= 3.8e-16 cm²**
**c (1B05H)= 3.4e-16 cm²**
**c (1B1H)= 2.6e-16 cm²**

small effect of HAB on acceptor removal

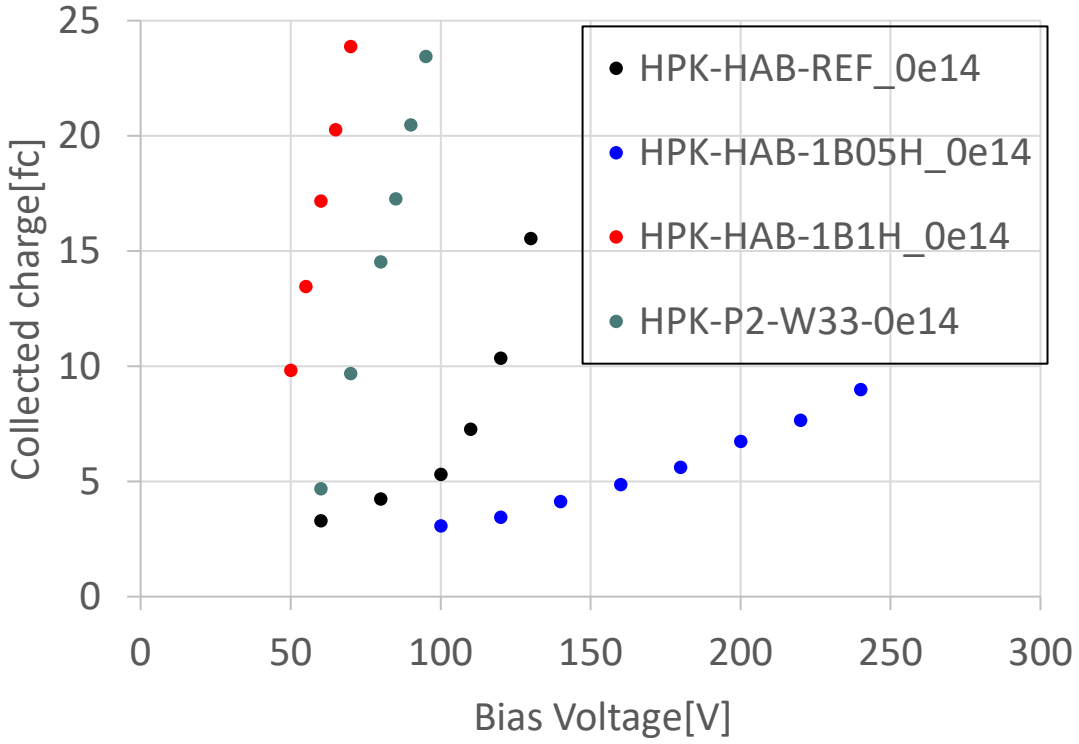
# Measurements with Sr90

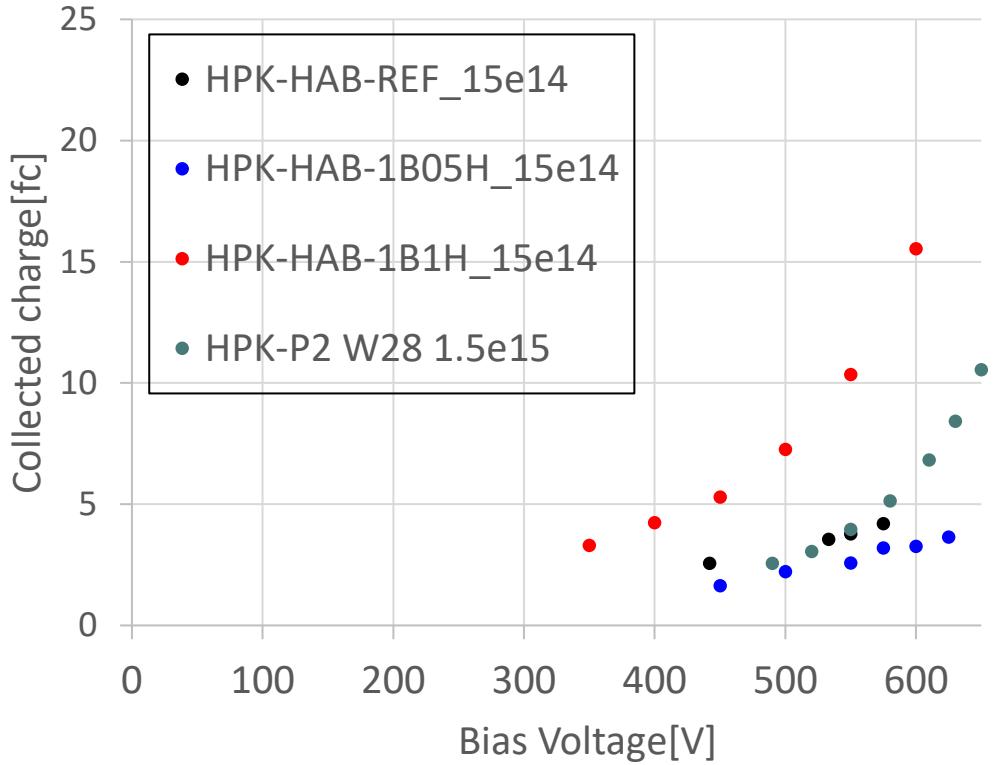
- JSI “Timing” setup with Sr90
- DUT cooled to -30 °C
- Coincidence trigger on PMT + reference LGAD -> DUT doesn’t take part in trigger!
- Measurement of charge and time resolution as function of voltage
- Measurements done with fluences 0e14, 15e14, 25e14 $cm^{-2}$
  - at 25e14 signal peak can not clearly separated from pedestal in the spectrum
  - a single pad was measured with the rest at GND



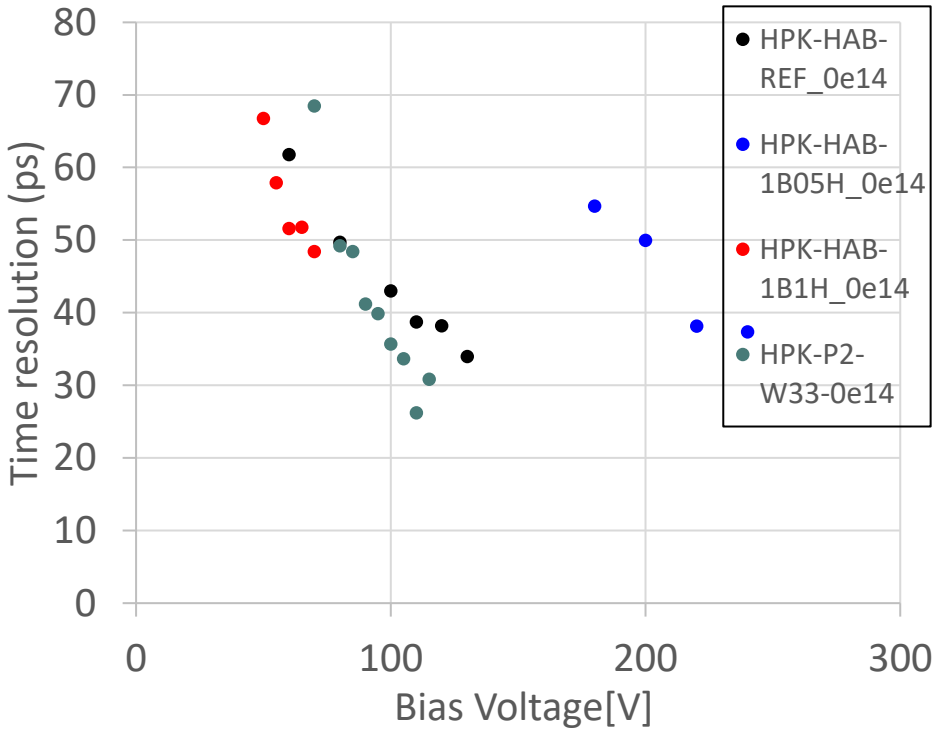
# $^{90}$Sr: collected charge

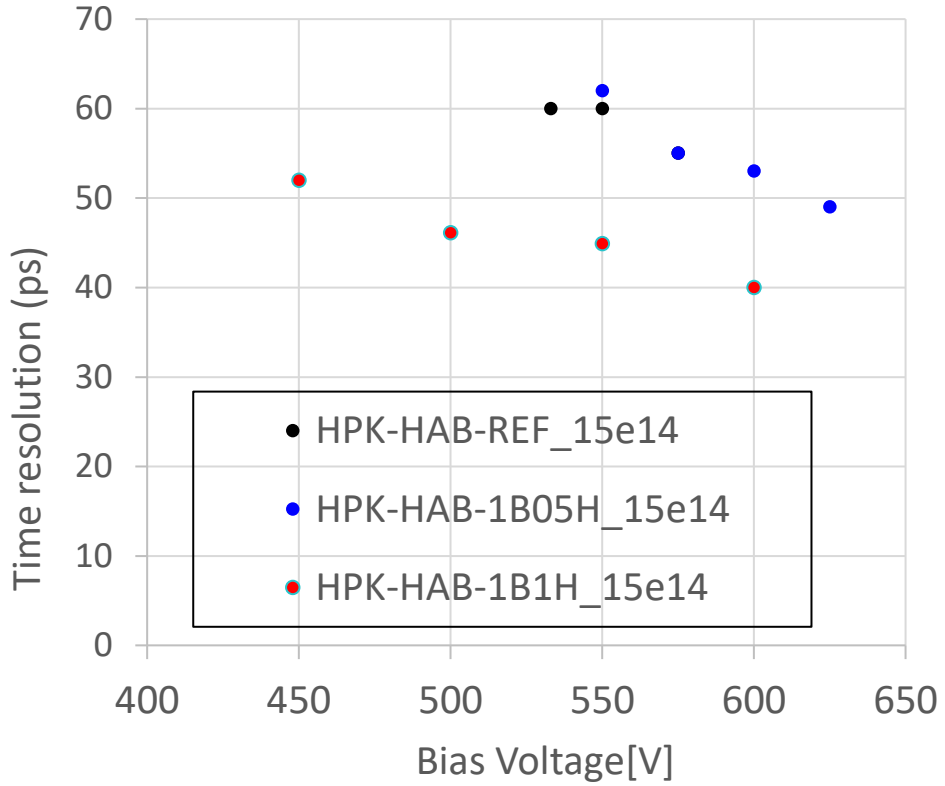



- CC is correlated with $V_{gl}$ (also the break down voltage) as expected – the 1B1H breaks down early
- Collected charge significantly degraded at 15e14 $cm^{-2}$ – results compatible with $V_{gl}$ measured after this fluence
- Sample with highest implanted boron (1HAB) shows lowest degradation (10 fC at 550 V), but has also the highest initial $V_{gl}$
- For beam operation the highest safe voltage is ~550 V (11 V/μm) **– single event burnout**

# Sr90: Time resolution



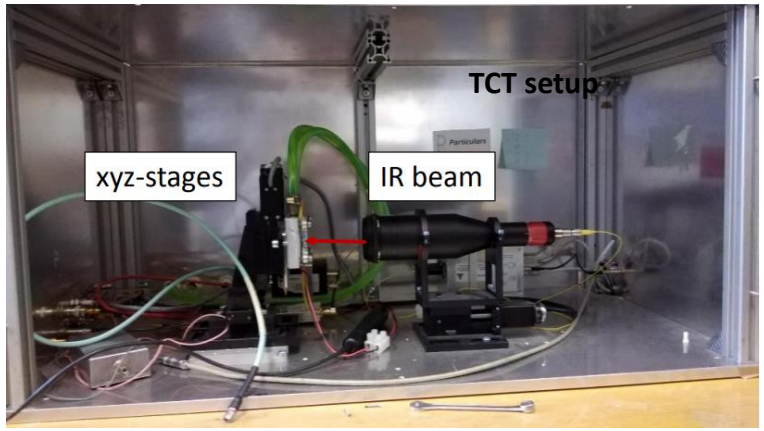

- Expected behavior for non-irradiated sensors:
  - due to early break-down 1B1H doesn't get close to Landau fluctuation limited time resolution
  - small gain of 1B05H prevents better time resolution
- after 15e14 $cm^{-2}$ achievable time resolution just below 50 ps is reached for 1B1H -> corresponds to highest gain
- Leakage current of irradiated samples confirms smaller gain for 1B05H and reference

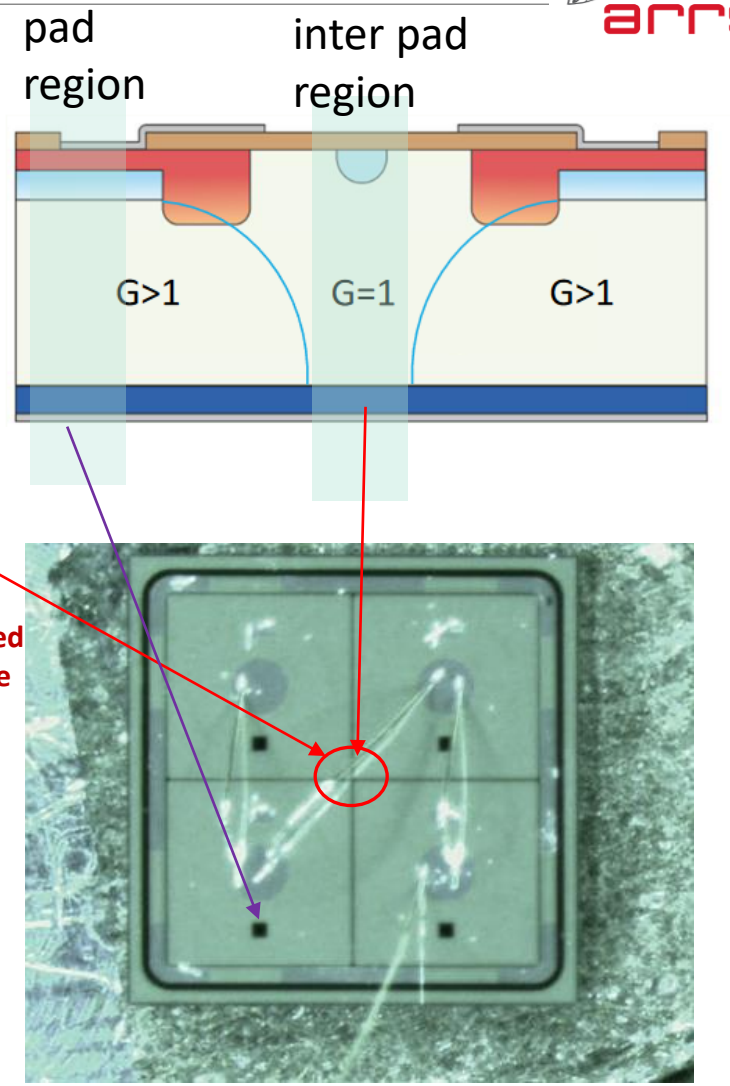
# TCT measurements

https://indico.cern.ch/event/1270076/contributions/5461468/attachments/2670554/4629315/Skomina_RD50_MNE.pdf

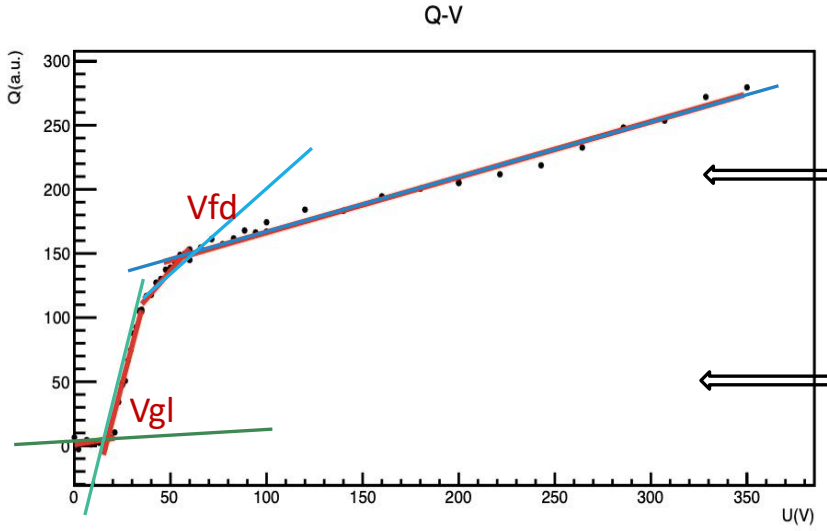
- TCT setup at IJS with focused infrared light
- Test method: top-TCT in both Interpad and pad region
- measurements on non-irradiated and 15e14 $cm^{-2}$ samples

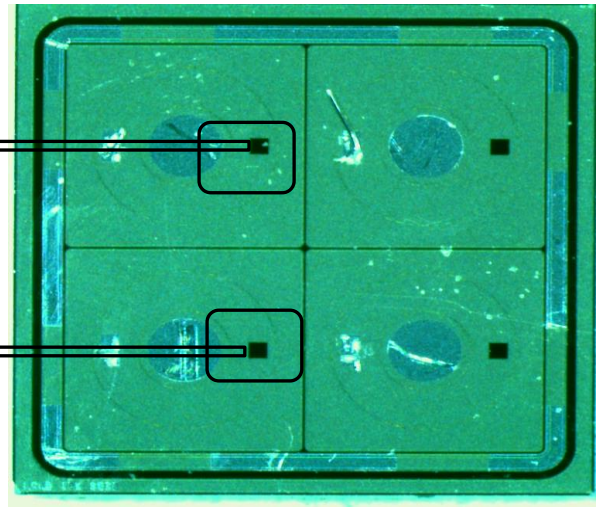
- measuring charge as function of voltage in inter-pad region / in 4 pads (2x2 array of pads)
  - similar to method for ATLAS-HGTD irradiation test during QC
  - inter-pad region behaviour similar to PIN diode without gain
  - room temperature measurements (the correlating with low T has been shown for numerous ATLAS-HGTD samples)
- Extracted Parameters: $V_{gl}$ , $V_{fd}$ and Gain
- HPK sample for TCT is wire-bonded with all pads together, GR floating

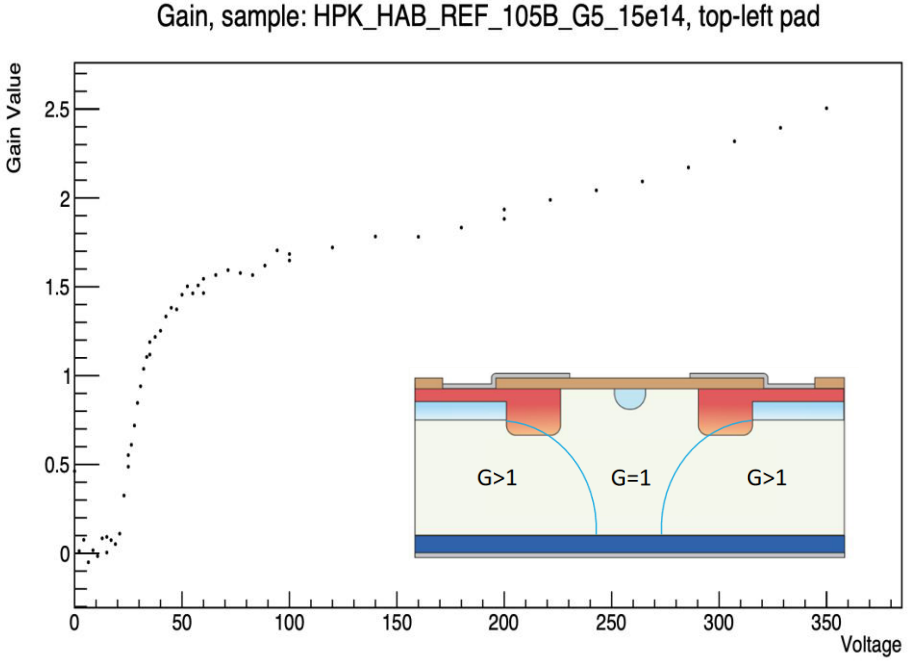


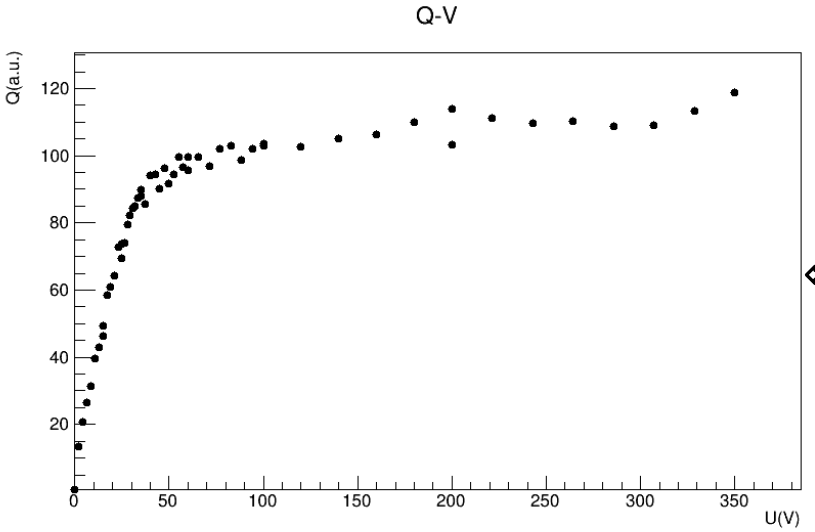



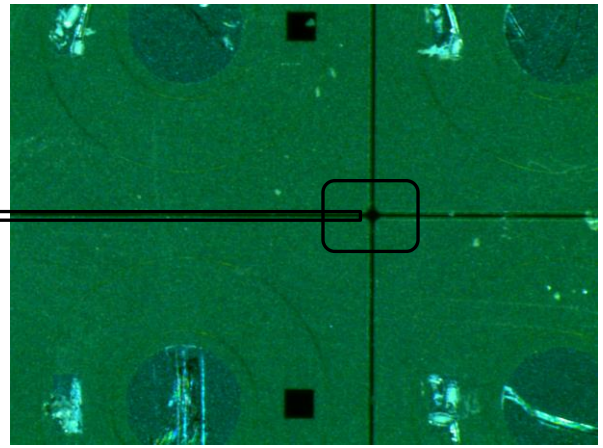
# TCT measuring method – example for 15e14 cm$^{-2}$ 1B05H





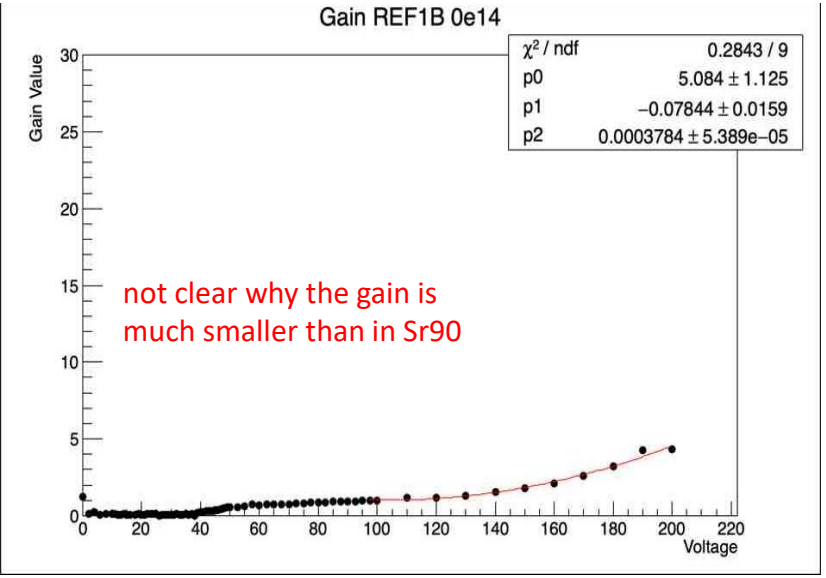



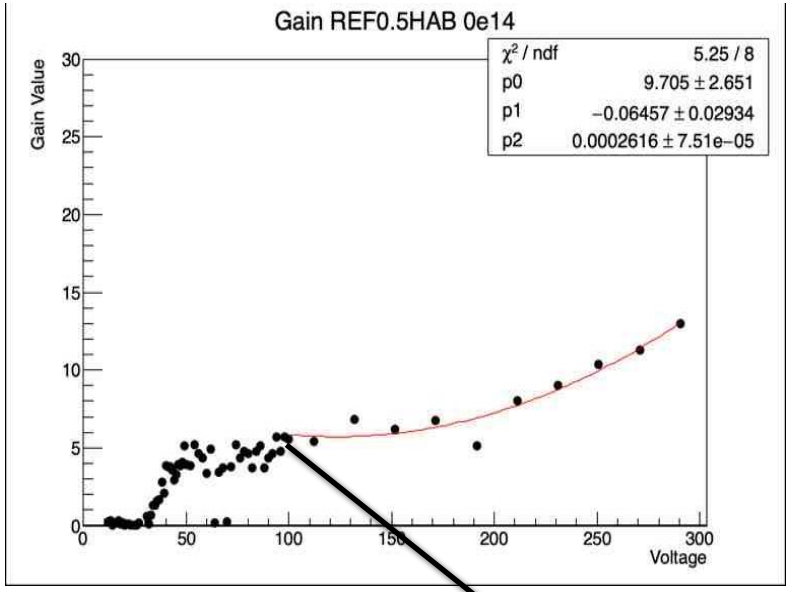
Measurement method:

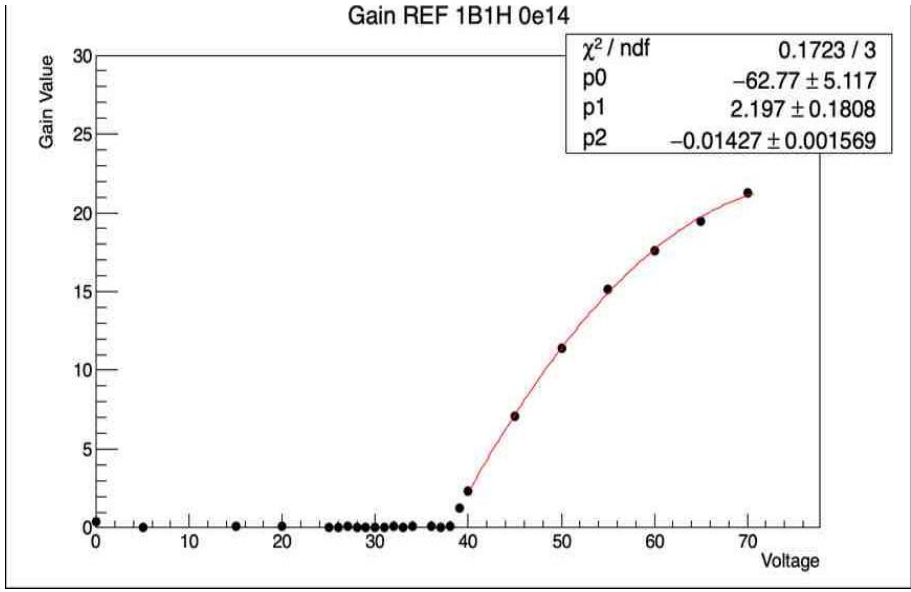
- QV in LGADs
- QV in Inter-pad (PIN like behaviour)

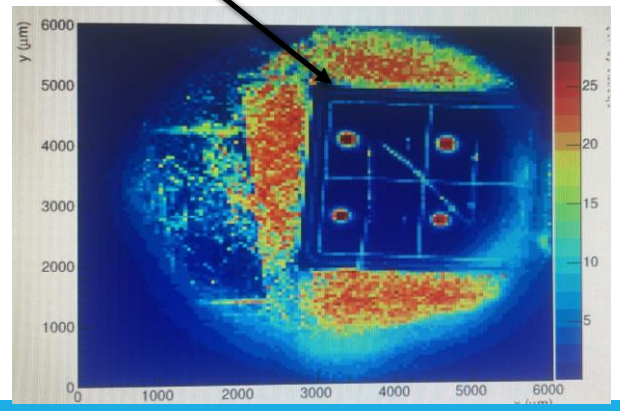
- $Gain(V) = \frac{Q\ (LGAD)}{Q\ (PIN)}$

# Gain-unirradiated HPK samples



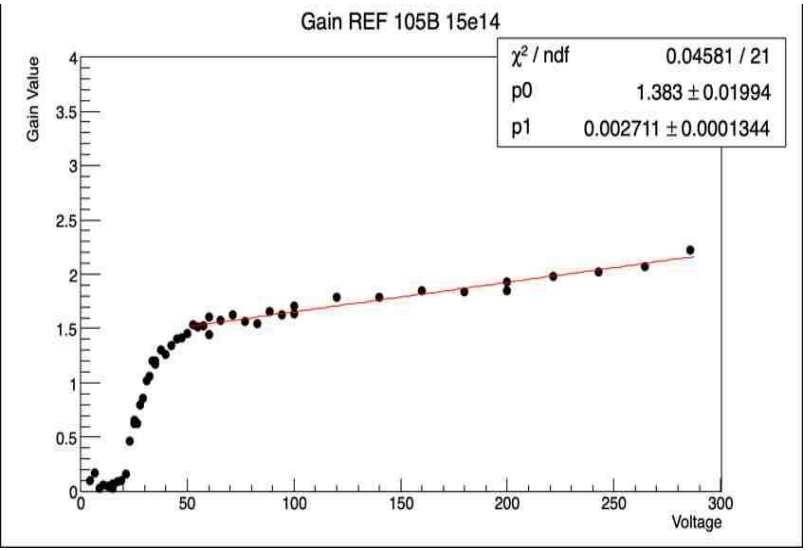



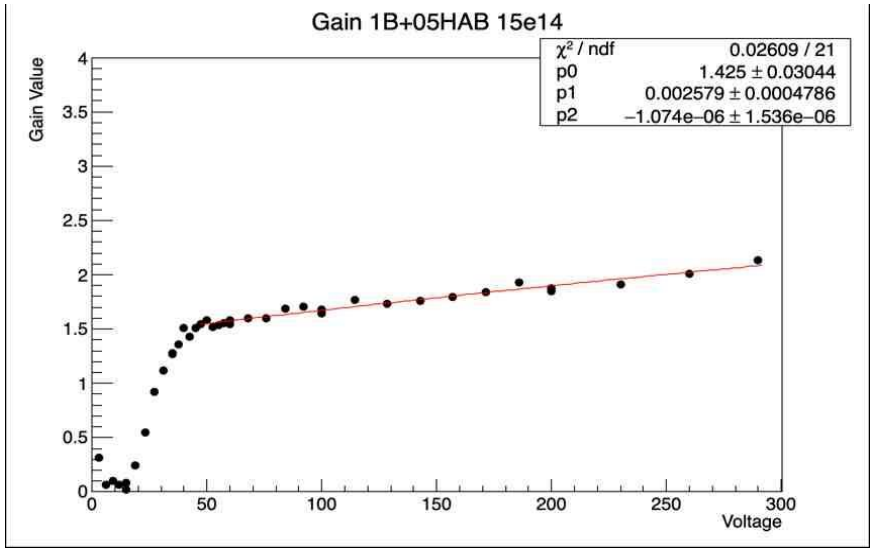



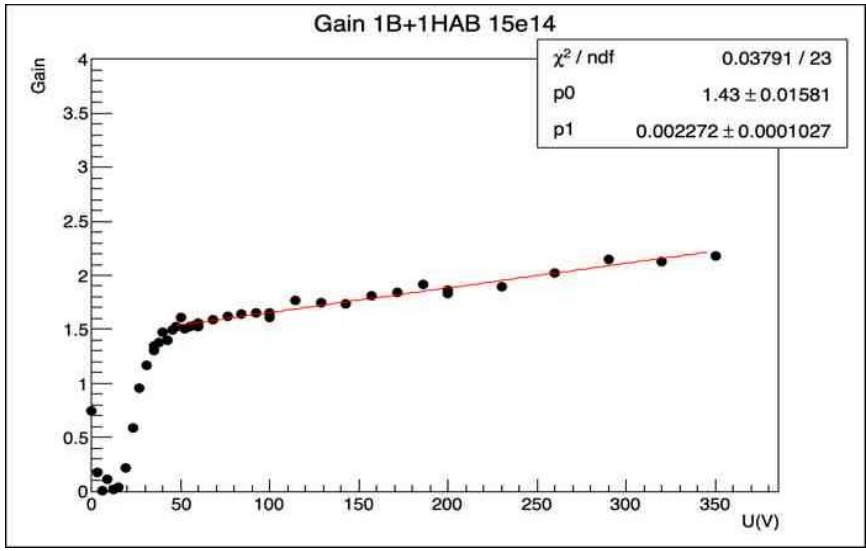

- For unirradiated HPK samples we observe rapid increase in gain
- Here is depicted gain for single pad for all 3 flavors
- Minimal fluctuations between four pads
- Somewhat more problematic behavior of 1B05H sample

| | Vgl (V) TCT/CV |
|---|---|
| Reference | 30/29.7 |
| 0.5 HAB | 29.89/30 |
| 1 HAB | 37.6/38 |

# Gain-irradiated HPK samples -1.5e15 neq/cm$^2$




- At full depletion voltage gain approximately 1.5
- Gain increases to 2.5 at 350 V (max. achievable voltage with this method)
  - Leakage current scales the same – good indication of gain
  - Modest gain
- Extracted Vgl indicates significant acceptor removal/gain degradation

| | **Vgl (V) TCT/CV** |
|---|---|
| Reference | 17.27/19.8 |
| 0.5 HAB | 16.33/16.4 |
| 1 HAB | 16.2/19.4 |

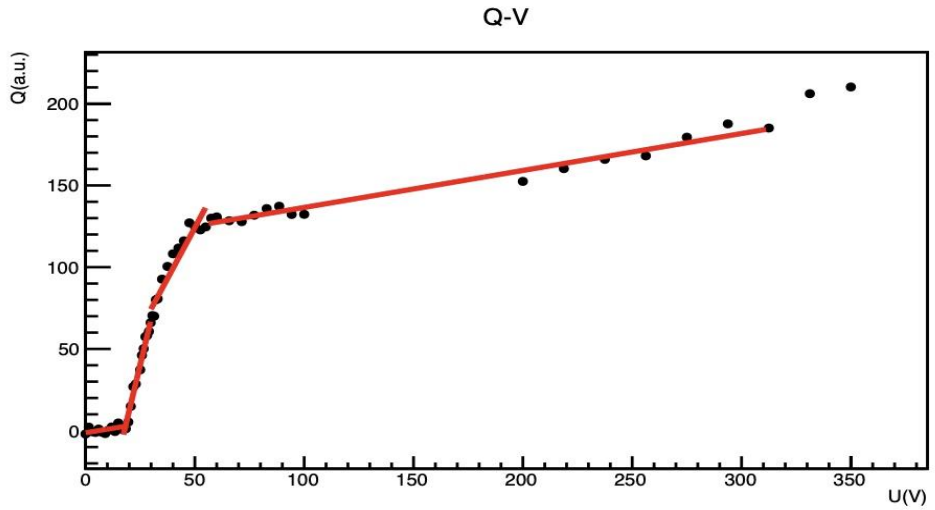
# Conclusion

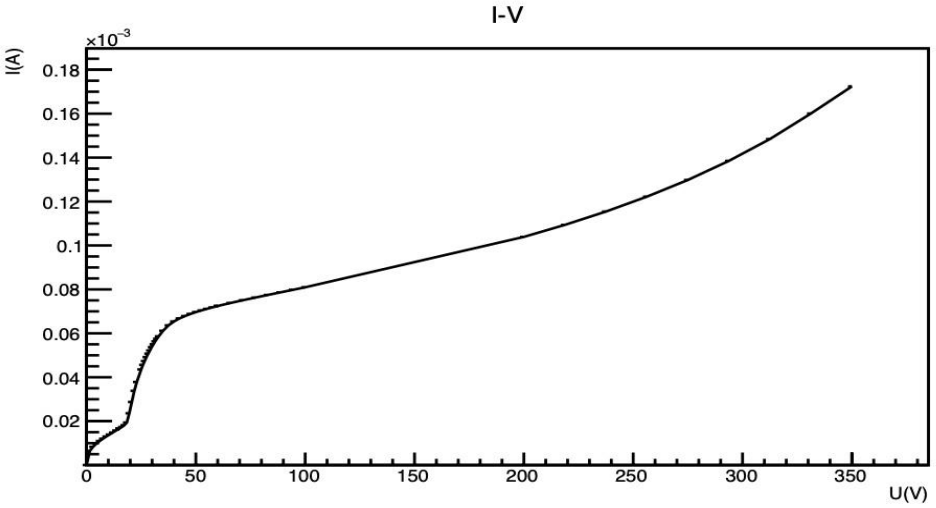
- Investigated HPK samples with partially activated boron as a way to mitigate acceptor removal by CV/IV, CC/Timing and TCT measurements
- Measured samples were irradiated to fluences of 0e14, 15e14 and 25e14 $cm^{-2}$ (IJS TRIGA neutrons)
- CV/IV measurements:
  - acceptor removal constant shows improvement with respect to older runs, but the values are around 3x larger than that of best C-enriched gain layer designs (>2.5e-16 $cm^2$)
  - partial activation of boron shows only marginal improvement of radiation hardness
  - leakage current and CV of the samples don't exhibit any unexpected features
- Timing Sr90 measurements:
  - Significant degradation of collected charge after irradiation – compatible with Vgl measurements
  - Due to highest doping before irradiation the best performance after 15e14 $cm^{-2}$ is measured for 1B1H sample, but the performance is comparable with HPK-P2 (ATLAS/CMS prototype run from 2020), while 1B05H and reference samples are worse
  - The collected charge below 600 V can not be separated from the noise peak/pedestal at 25e14 $cm^{-2}$
- TCT analysis:
  - Extracted $V_{gl}$ and Gain from TCT in LGAD/inter-pad region – gain can be measured at lower bias voltages and room temperature
  - Only marginal gain up to 350 V for irradiated samples showing not sufficient radiation hardness
  - Measurements of Vgl compatible with CV

**Samples with partially activated boron have slightly improved radiation hardness, but not on the level required for e.g. ATLAS-HGTD.**

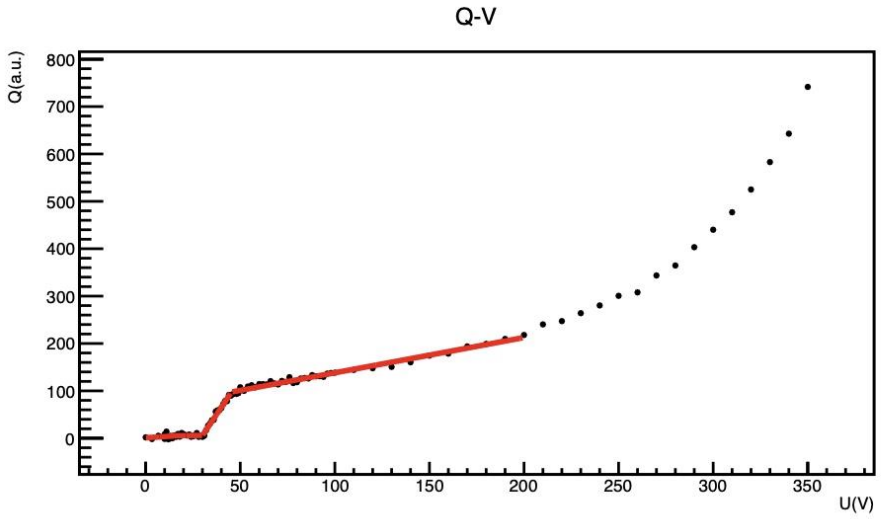
# BACKUP

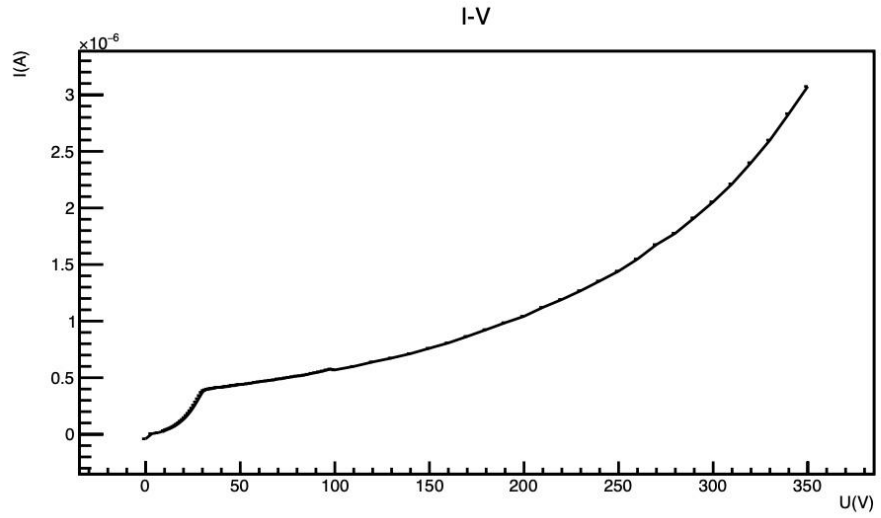
## HPK_HAB_1B+1HAB_15e14



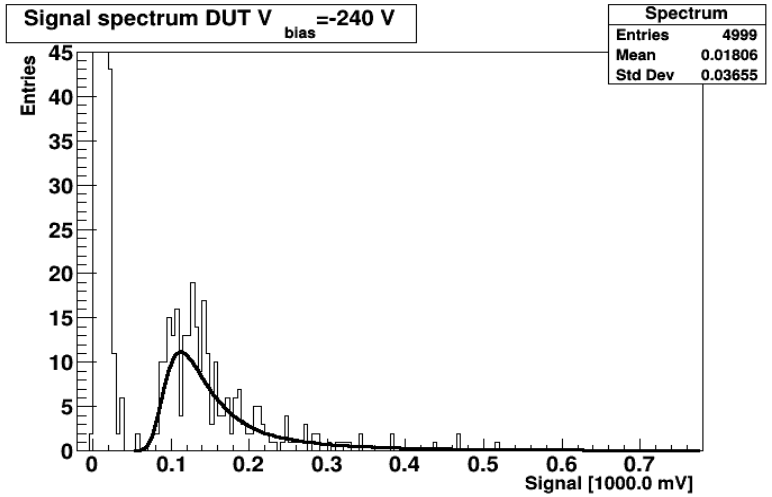

## HPK_1B+0.5_HAB_0e14

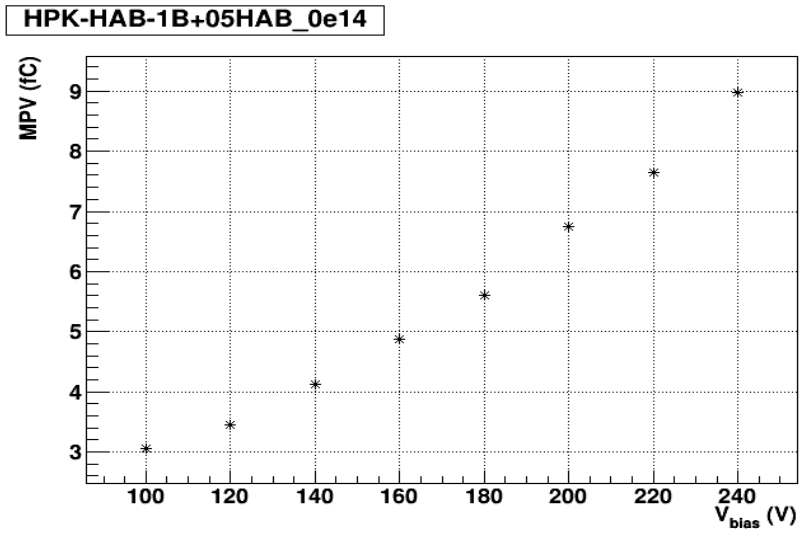


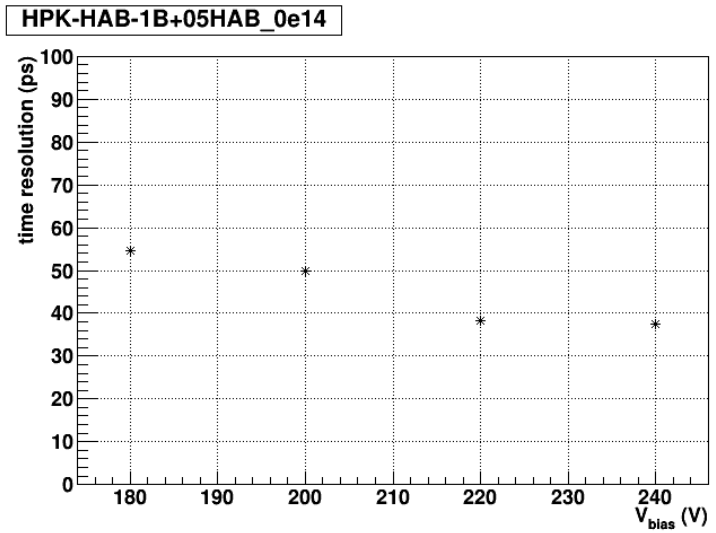



# CC-Timing results

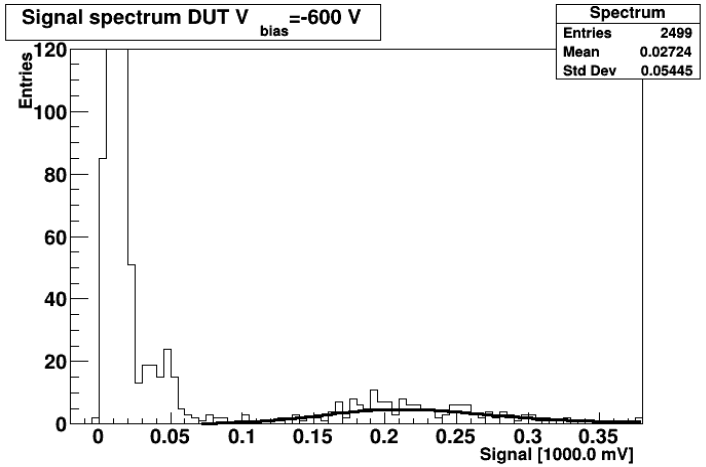
## HPK_HAB_1B+0.5HAB_0e14

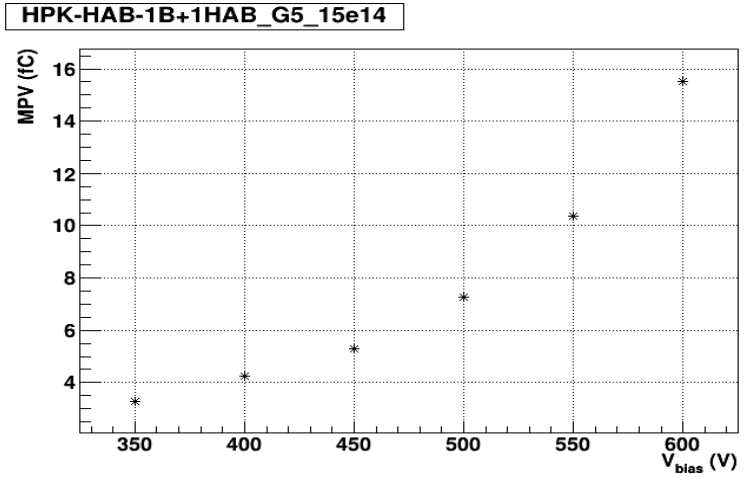


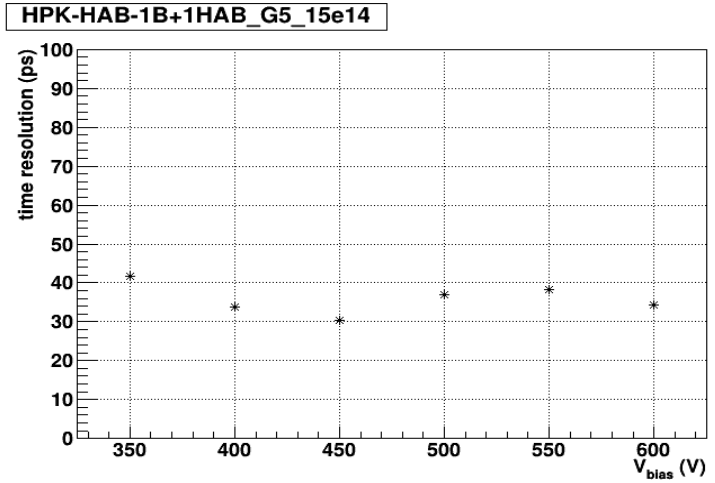



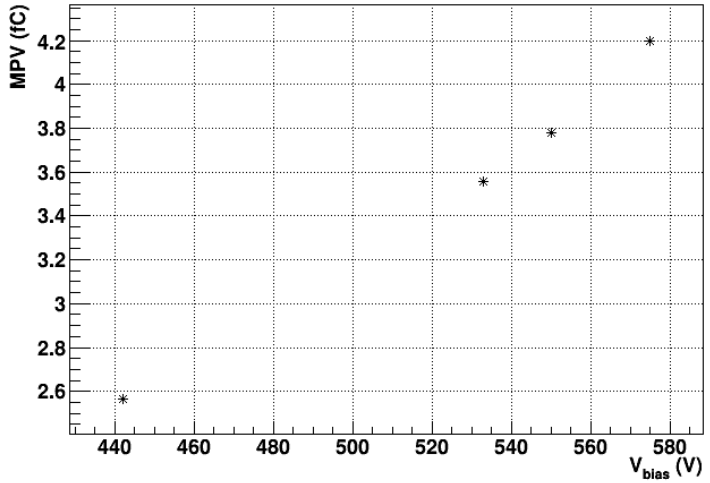

## HPK_HAB_1B+1HAB_G5_15e14



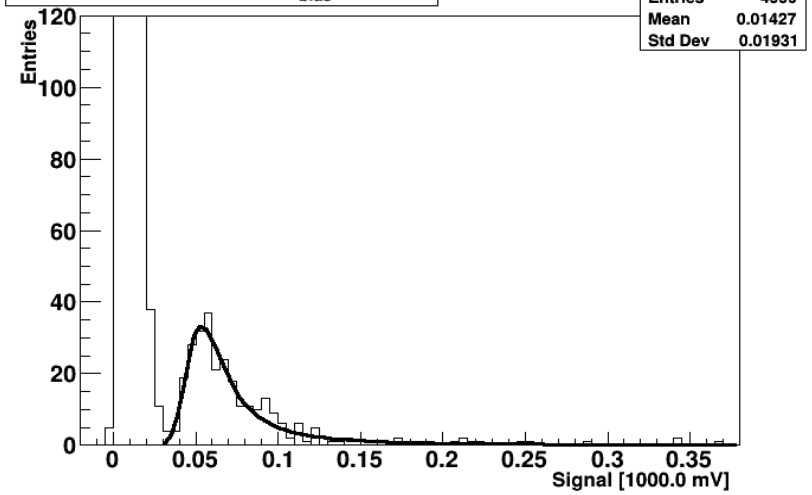



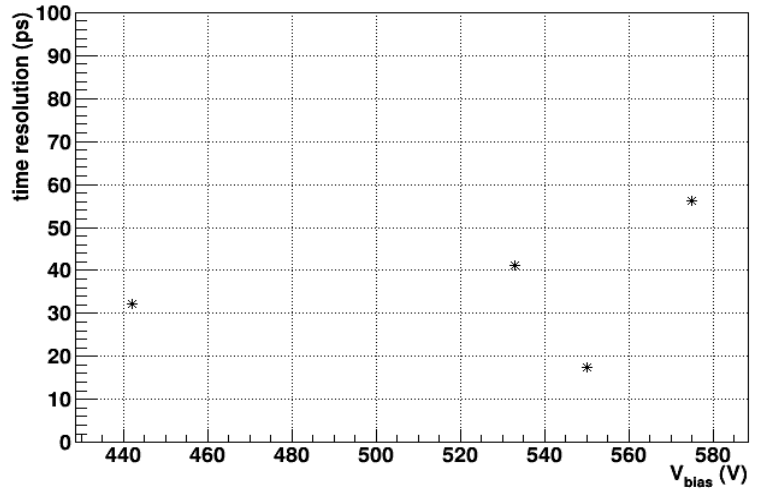
HPK-HAB_REF-1.05B_G5_15e14



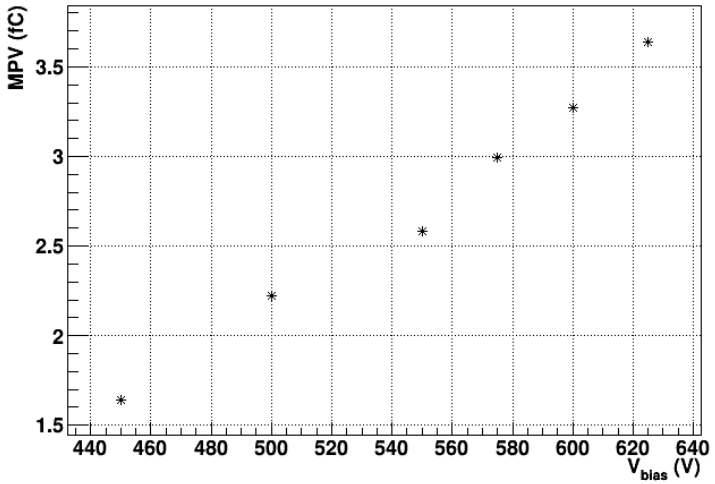

Signal spectrum DUT $V_{bias}$=-575 V



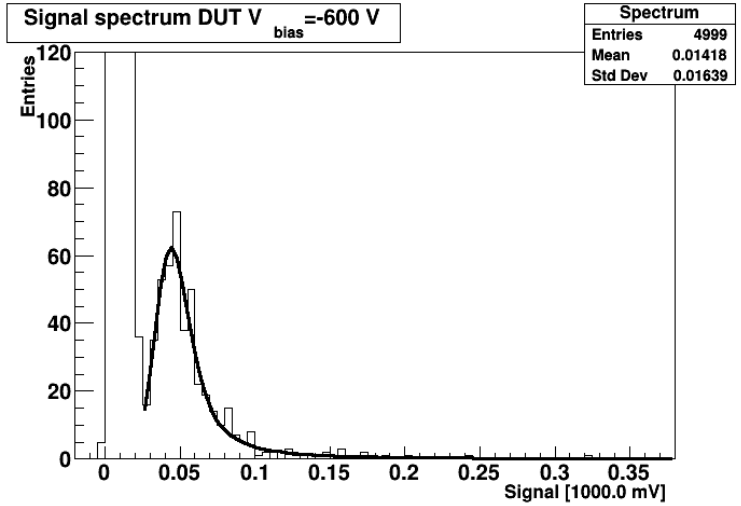

HPK-HAB_REF-1.05B_G5_15e14



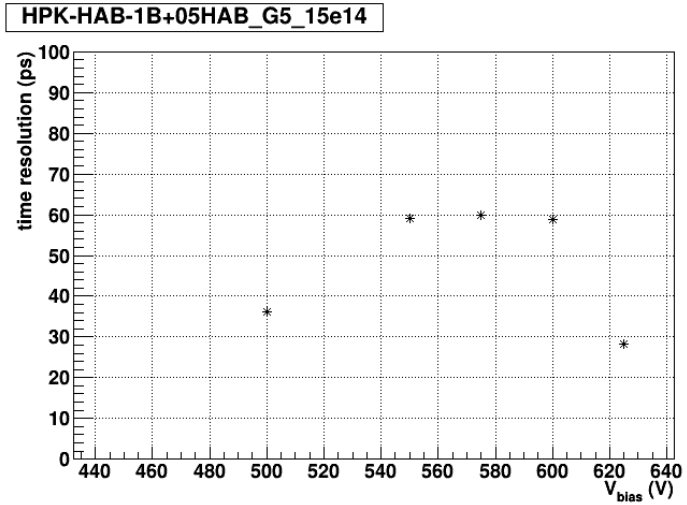

HPK-HAB-1B+05HAB_G5_15e14




Signal spectrum DUT $V_{bias}$=-600 V




HPK-HAB-1B+05HAB_G5_15e14



# TCT results for HPK samples

- Vgl 1/2/3/4- voltages for gain layer depletion for first/2nd/3rd/4th pad
- Vfd 1/2/3/4-voltages for depletion of the bulk

| Sample name | Fluence (neq/cm²) | Vgl1 (V) | Vfd1 (V) | Vgl2 (V) | Vfd2 (V) | Vgl3 (V) | Vfd3 (V) | Vgl4 (V) | Vfd4 (V) |
|---|---|---|---|---|---|---|---|---|---|
| HPK_1B+1HAB_G8 | 1.50E+15 | 18.2708 | 50.459 | 16.0784 | 49.2573 | 16.4099 | 48.6787 | / | / |
| HPK_HAB-1B+05HAB_G5 | 1.50E+15 | 16.5073 | 42.3672 | 16.334 | 44.162 | 16.1854 | 45.6856 | 16.3366 | 59.09 |
| HPK_HAB_REF_1.05B_G5 | 1.50E+15 | 17.26 | 55.73 | 17.2965 | 56.5627 | 17.2983 | 55.9771 | 17.2506 | 56.1904 |
| HPK_HAB_05HAB | 0.00E+00 | 30 | 45.4058 | 28.6944 | 46.8783 | 27.6756 | 42.3771 | 33.2117 | 44.3157 |
| HPK_HAB_REF_1B | 0.00E+00 | 26.3666 | 32.9645 | 26.5046 | 35.5623 | 23.8224 | 37.145 | 27.3365 | 35.8261 |