# Studies of effective inter-pad distance of different HPK and FBK LGADs

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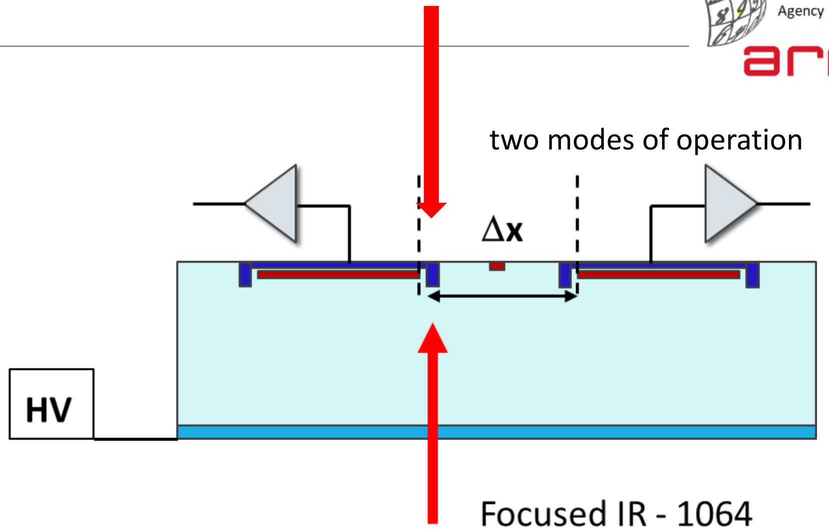
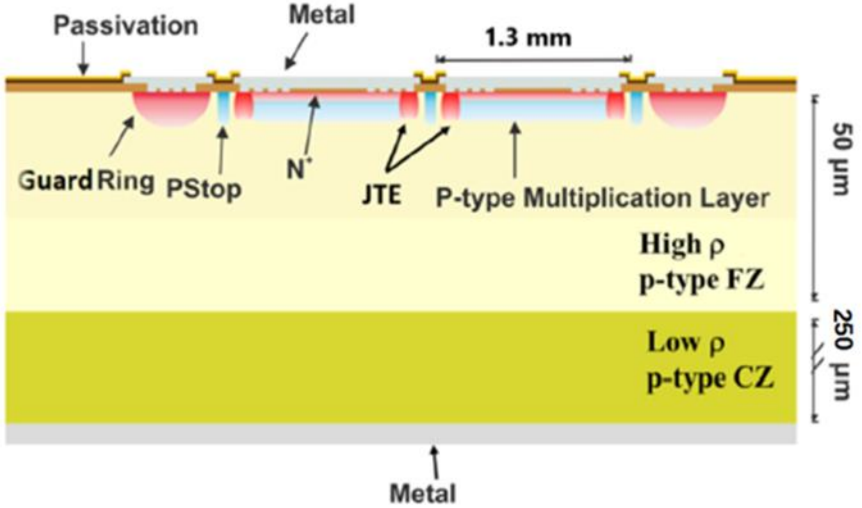
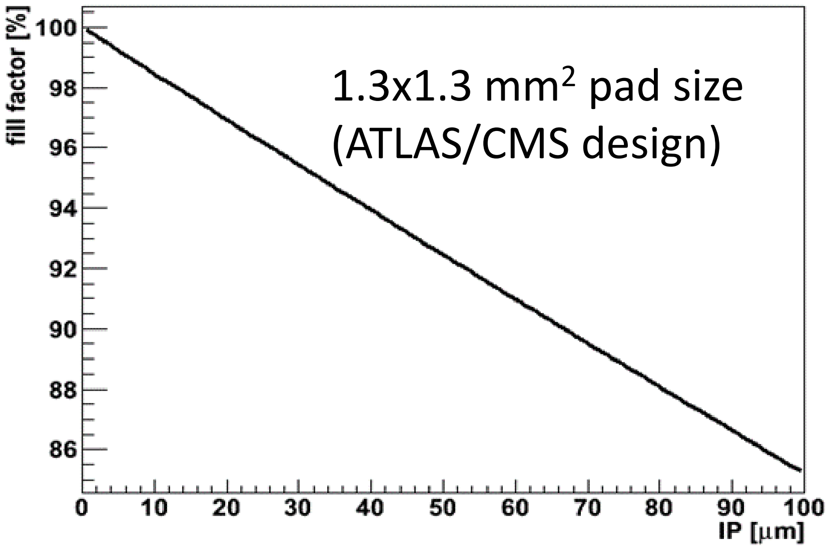
# Motivation

- Inter-pad distance in LGADs determines the "fill factor" of the sensors – sensitive area
- Nominal distance between the pads (region without the gain) can be smaller than the effective region measured by the particles/light
- It is crucial to measure it and understand the performance before and after the irradiation

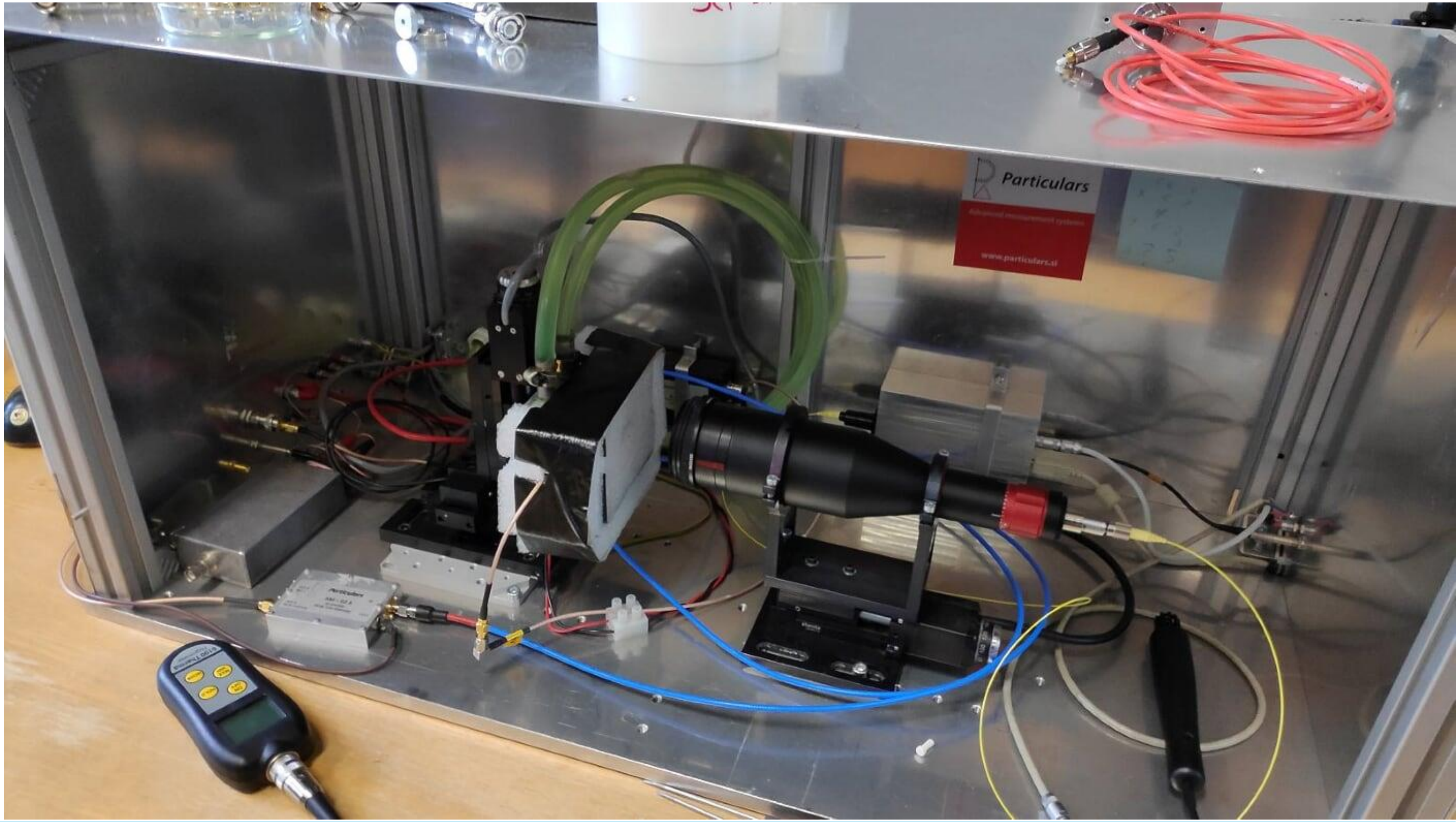


# Experimental setup

- XYZ tables
- Laser beam focusing
- Cooling @ -30°C
- Insulation cap
- Closed environment
- Dry air (dew point well below measuring temperature)



# Samples studied

- Samples studied were from the prototype runs from ATLAS/CMS – they were 2x2 arrays (4 pads)
  - FBK-UFSD3.2 run (C - enriched samples were used from W14 and W19)
    - Type4 – 26 μm nominal distance between the pads (single p-stop)
    - Type10 – super safe – 49 μm nominal distance (2 p-stop+bias ring)
  - HPK-P2 run (the split with the highest gain was selected – Wafers 25/28 were selected as the most promising candidate)
    - IP3 – 30 μm (all IP have 2 p-stops)
    - IP4 – 40 μm
    - IP5 – 50 μm
    - IP7 – 70 μm
- Samples were irradiated with reactor neutrons to different fluences of 1e14, 8e14, 1.5e15 and 2.5e15 $cm^{-2}$
  - samples were annealed for 80 min @ 60°C

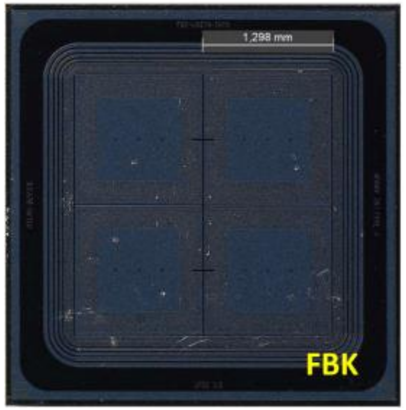
FBK

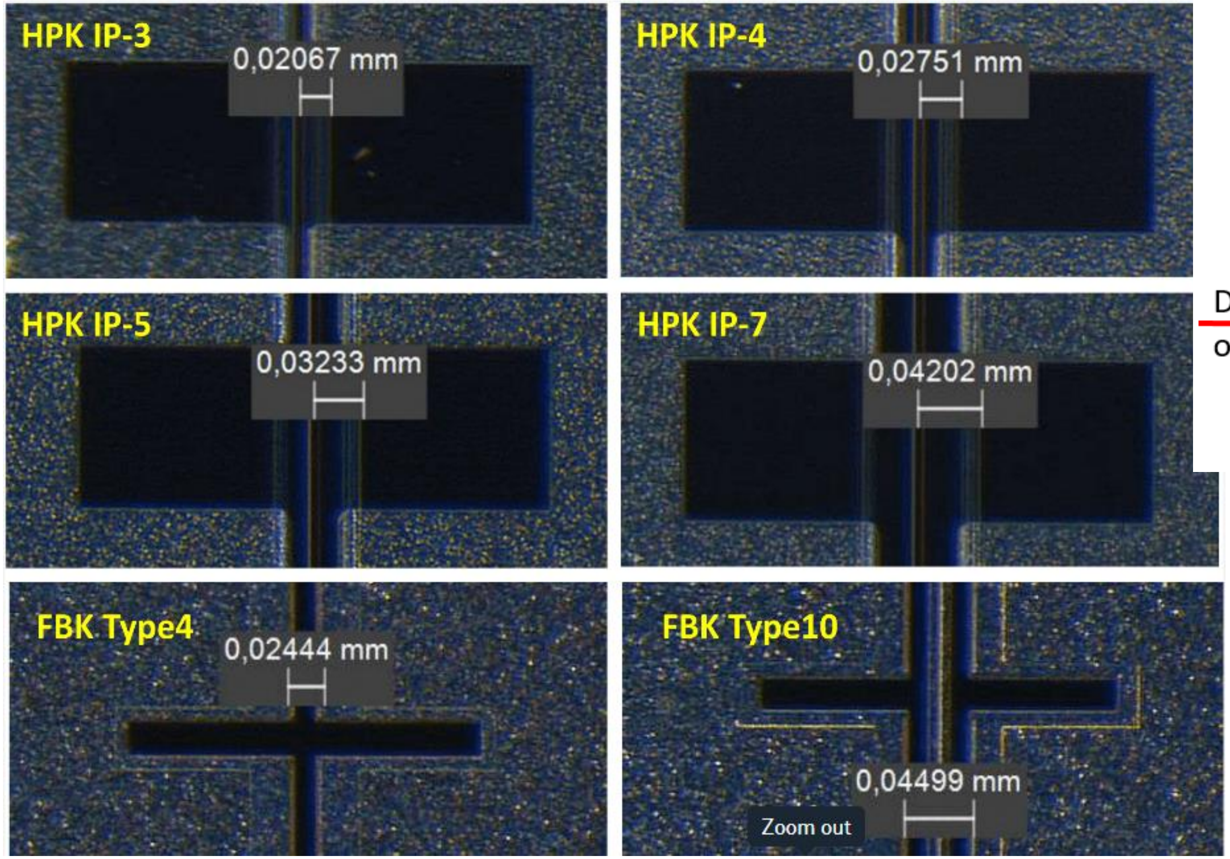
| Wafer # | thickness | GL DEPTH | Dose Pgain | Carbon | Diffusion |
|---|---|---|---|---|---|
| 1 | 45 | Standard | L | 1*A | CHBL |
| 2 | 44 | Standard | L | 1*A - Spray | L |
| 3 | 45 | Standard | L | 0.8*A | L |
| 4 | 45 | Standard | L | 0.4*A | L |
| 5 | 25 | Standard | VVL | A | L |
| 6 | 35 | Standard | VL | A | L |
| 7 | 55 | Standard | L | A | L |
| 8 | 45 | 2 um | L’ | 1*A | CBL |
| 9 | 55 | 2 um | L’ | 1*A | L |
| 10 | 45 | 2 um | L’ | 0.6*A | L |
| 11 | 45 | 2 um | L’ | | L |
| 12 | 45 | 2 um | M’ | 1*A | L |
| 13 | 45 | 2 um | M’ | 0.6*A | L |
| 14 | 45 | 2 um | M’ | 1*A | CBH |
| 15 | 55 | 2 um | M’ | 1*A | H |
| 16 | 45 | 2 um | M’ | 0.6*A | H |
| 17 | 45 | 2 um | M’ | | H |
| 18 | 45 | 2 um | H’ | 1*A | H |
| 19 | 45 | 2 um | H’ | 0.6*A | H |

HPK

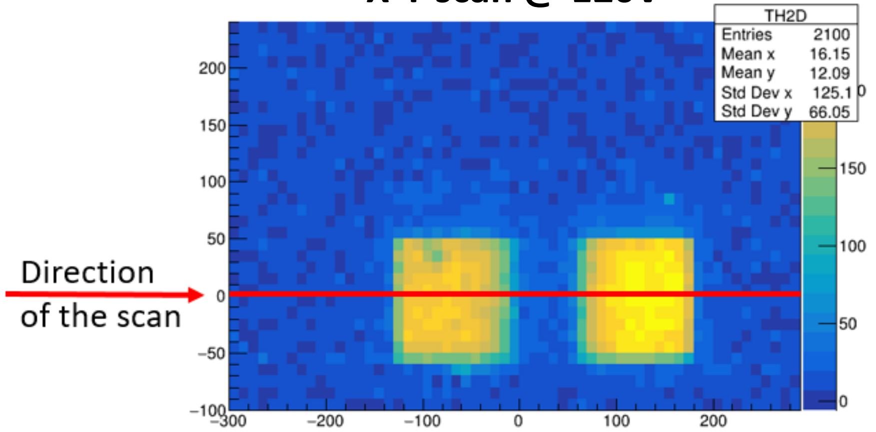
| Wafer | Wafer Layout | Split | Vgl | Target Vbr | Measured Vbr |
|---|---|---|---|---|---|
| 28 | Small | 1 | 50.5V | 160V | 85-155V |
| 33 | Small | 2 | 51.0V | 180V | 85-170V |
| 37 | Small | 3 | 53.7V | 220V | 155-205V |
| 43 | Small | 4 | 54.5V | 240V | 170-235V |

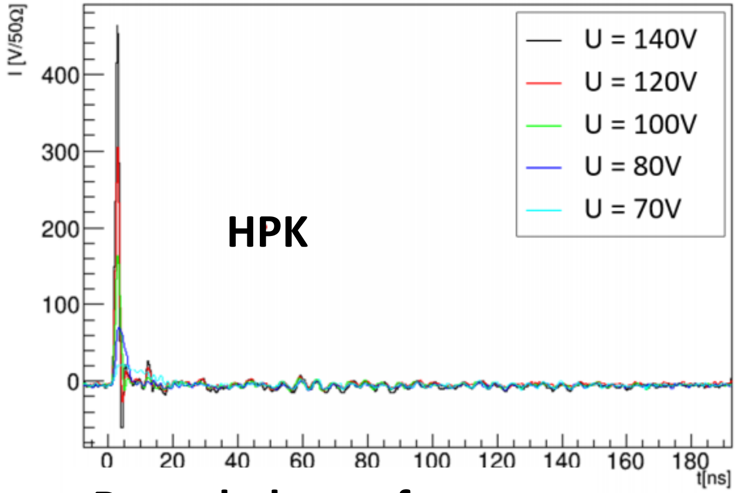
# Samples


**X-Y scan @ 120V**




**Recorded waveforms**

Schematic view of the samples with measured dimensions – the measured distances seem to be slightly bigger than nominal

Two neighbouring pads were connected to two different amplifiers and readout.

# Fitting the charge collection profiles

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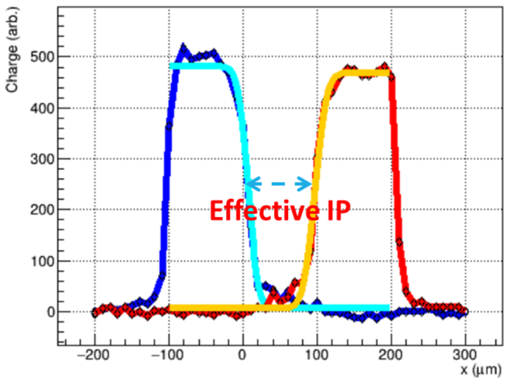
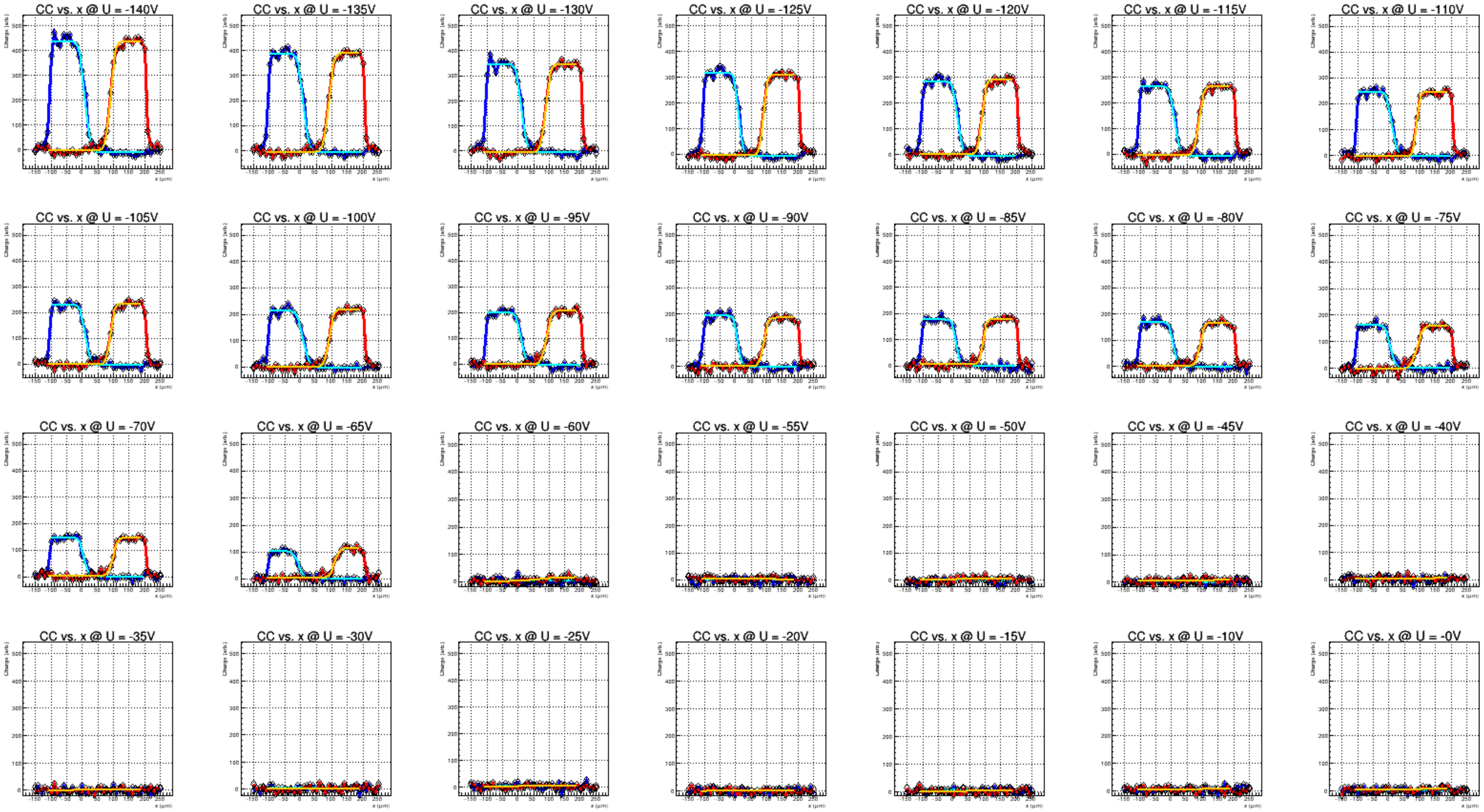
- Two S-curves (Erf functions) were fit to the curves
- The width at the 50% of the maximum was taken as the effective gap distance

**Charge collection profile**




Example of the voltage scan

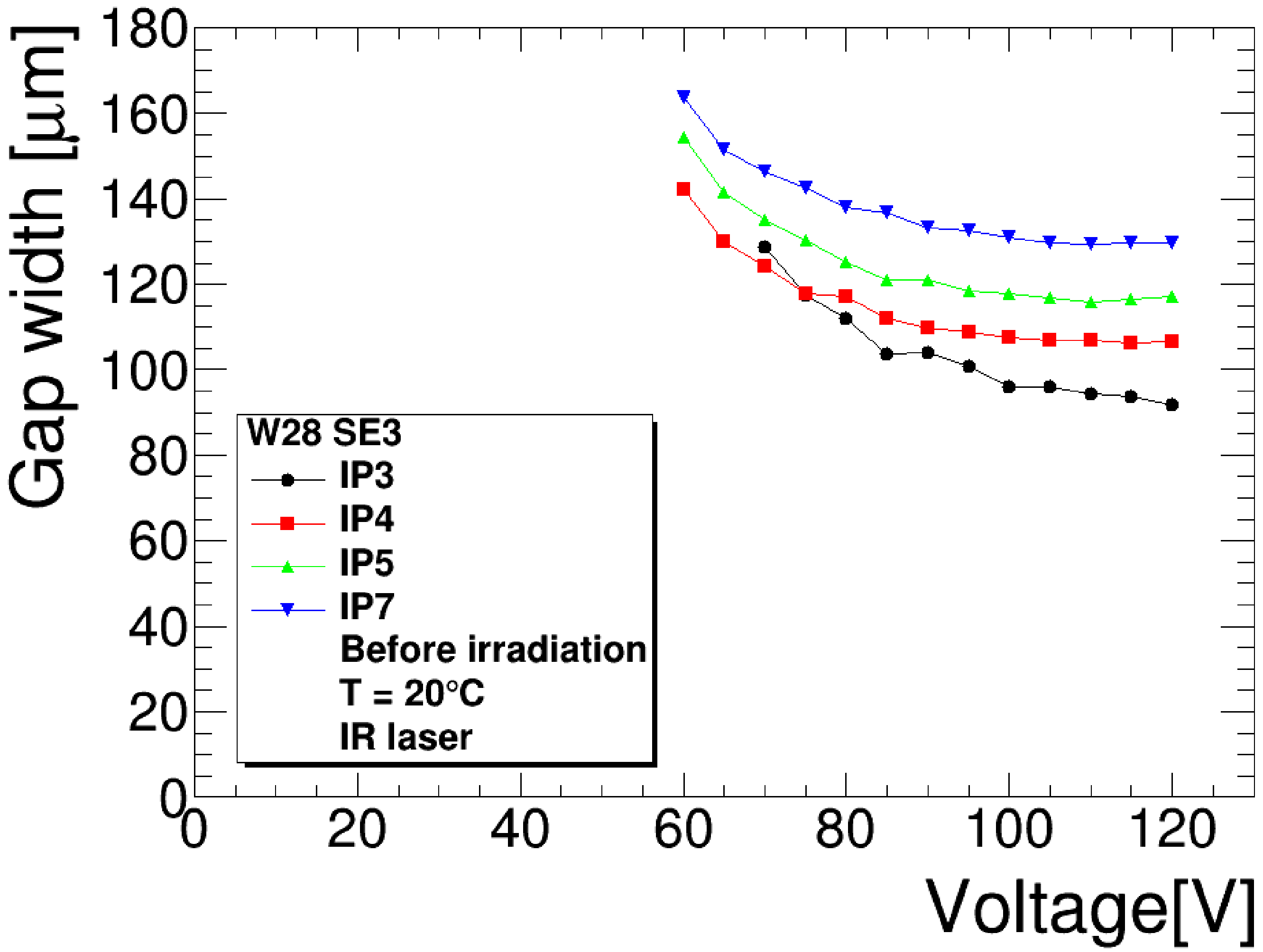


# Measurement of non-irradiated sensors

- HPK of different IPs were measured before irradiation at 20°C
- Effective IP much larger than nomina was measured

**Effective IP = Nominal IP + 50-60µm**
(at high voltages)

- at lower voltages the difference is bigger
- The 10 µm distance between designs can be nicely observed at high bias voltages (verification of the method)



# Measurements after $\phi_{eq} = 1.5\ 10^{15}\ cm^{-2}$

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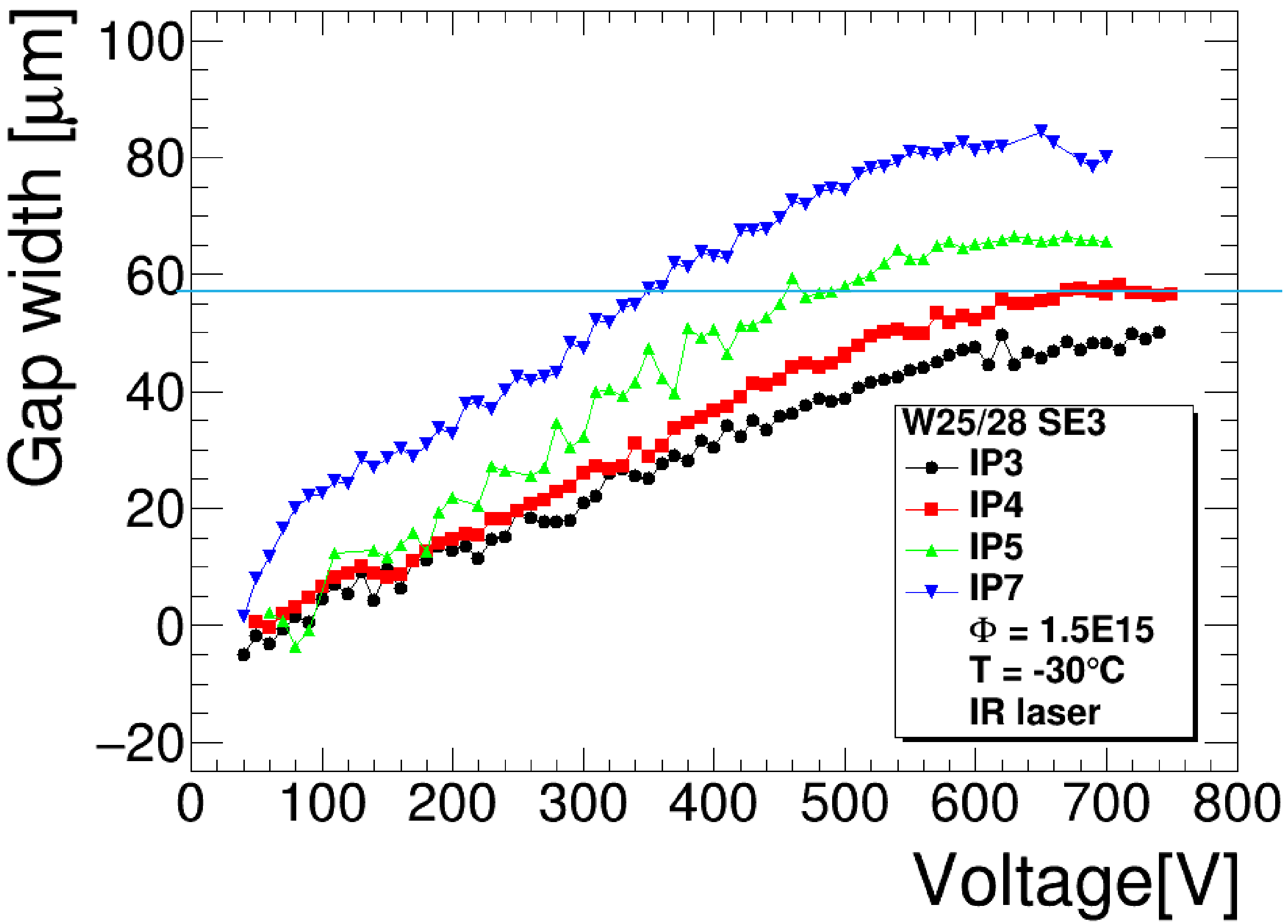
- Effective IP is within ±10μm of the nominal value
- Error from finite width of laser beam and fit variation is estimated to be at 10μm level
- The plateau is reached at high enough bias voltages (>550 V) where gain is significant (G~20)




**After irradiations the nominal and effective IP become similar**

# Measurements after $\phi_{eq} = 1.5\ 10^{15}\ cm^{-2}$

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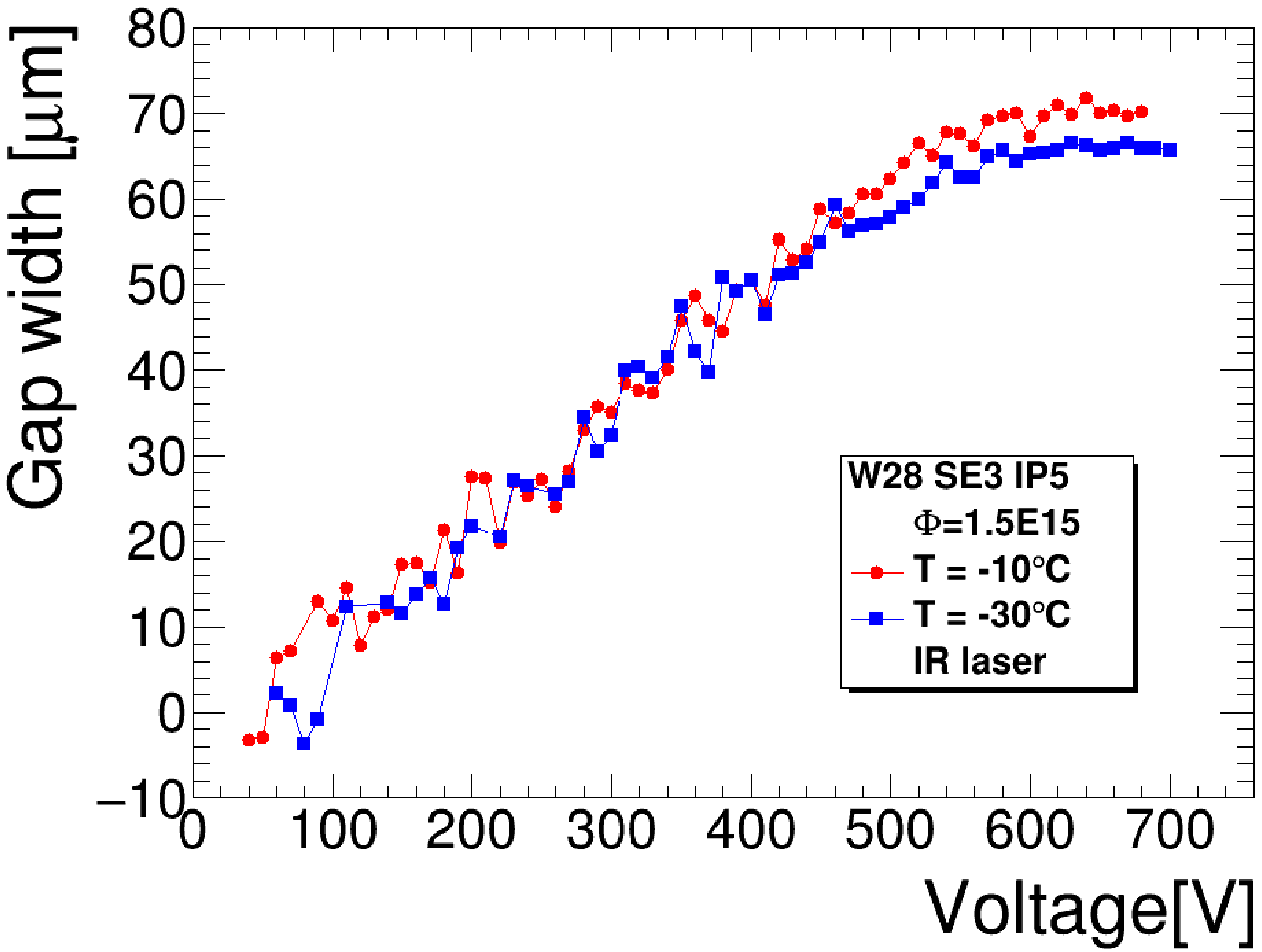
- No observed difference with different temeperature - the measured IP distance at -10°C and -30°C are identical -> space charge doesn't change much with temperature
- Drop in current at -30°C allows for more comfortable measurements at higher voltages
- Dry air is used → dew point below -30°C



# HPK IP5 - measurements

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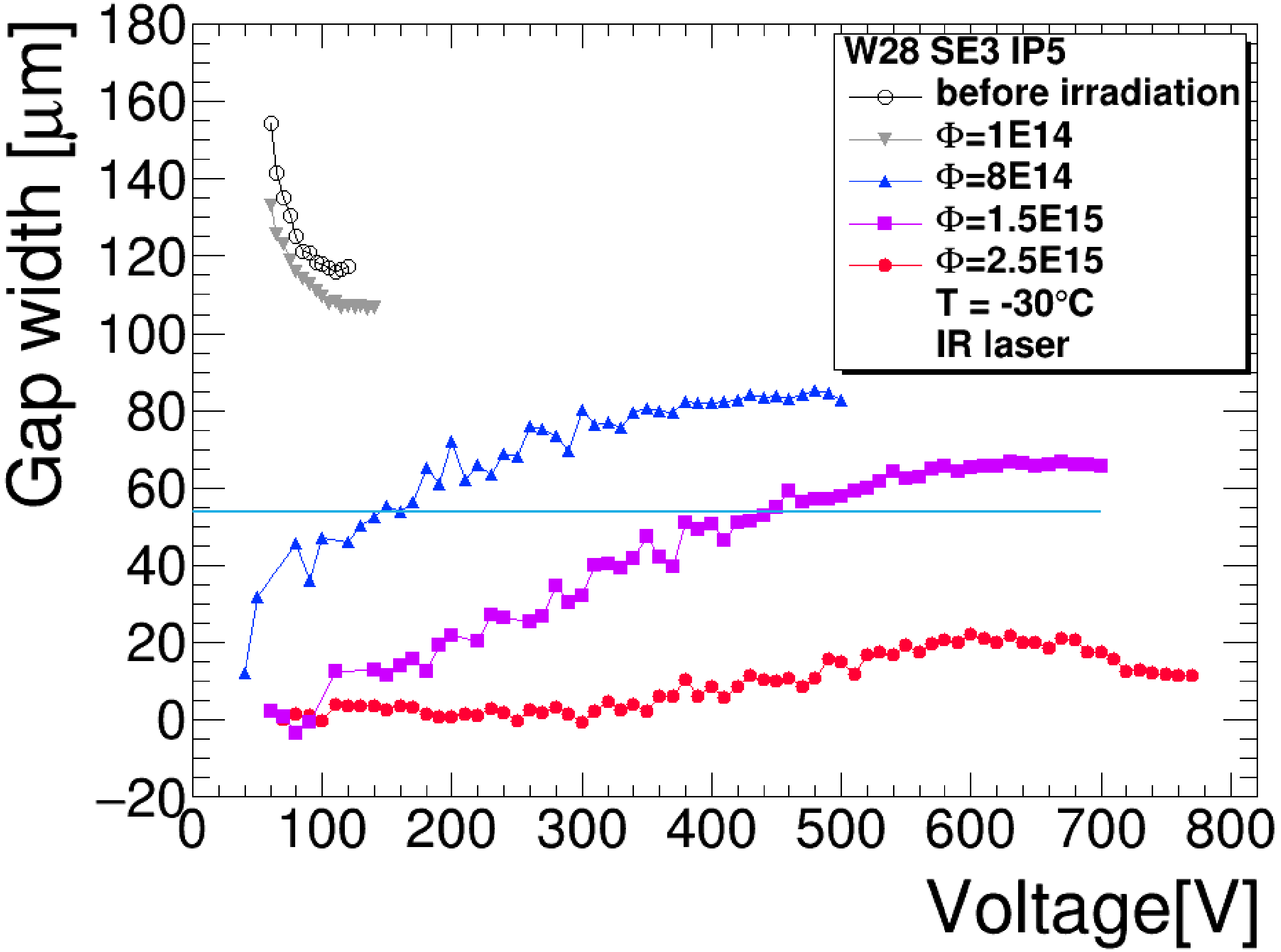
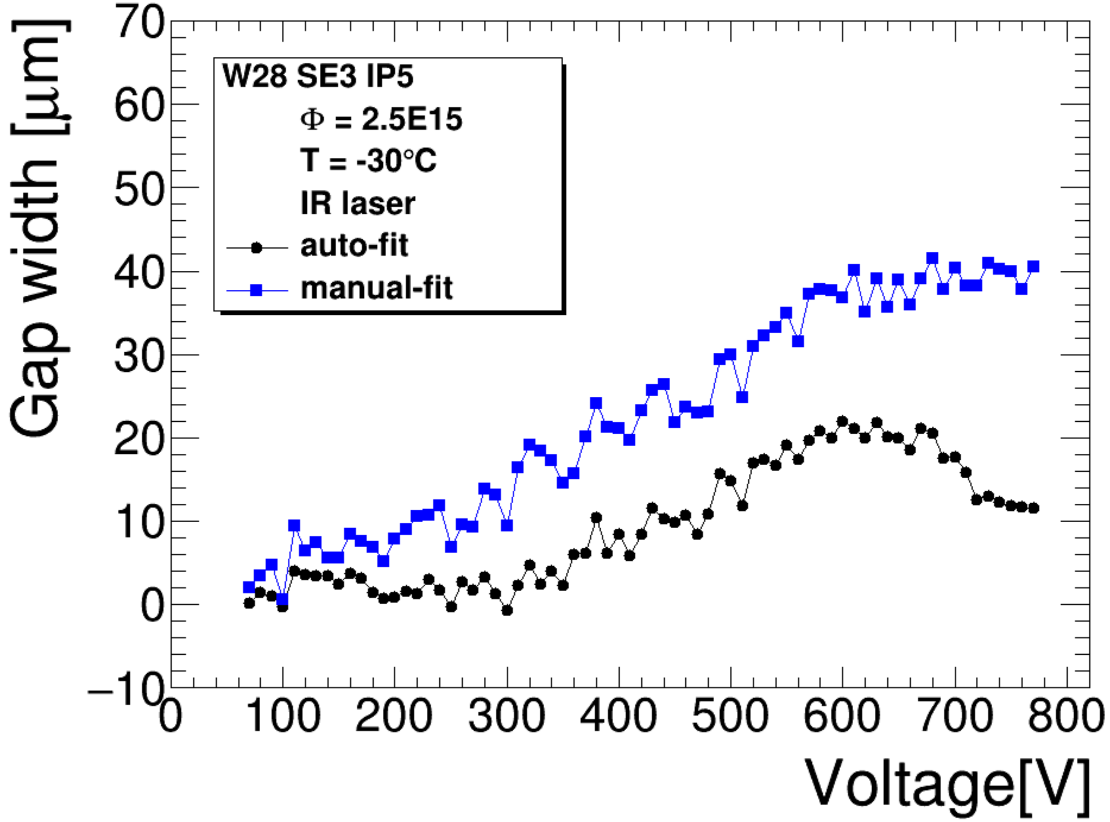
- IP5 seems to be a safe compromise between early breakdown in case of floating pads and small enough nominal IP distance
- There is a big change between 1e14 $cm^{-2}$ and 8e14 $cm^{-2}$ in voltage dependence of IP
- At high fluences there is an indication that we start to see some gain from carriers drifting to the JTE - difficult to fit S-curves
- We had not problems of sensors breaking down even at almost 800 V.



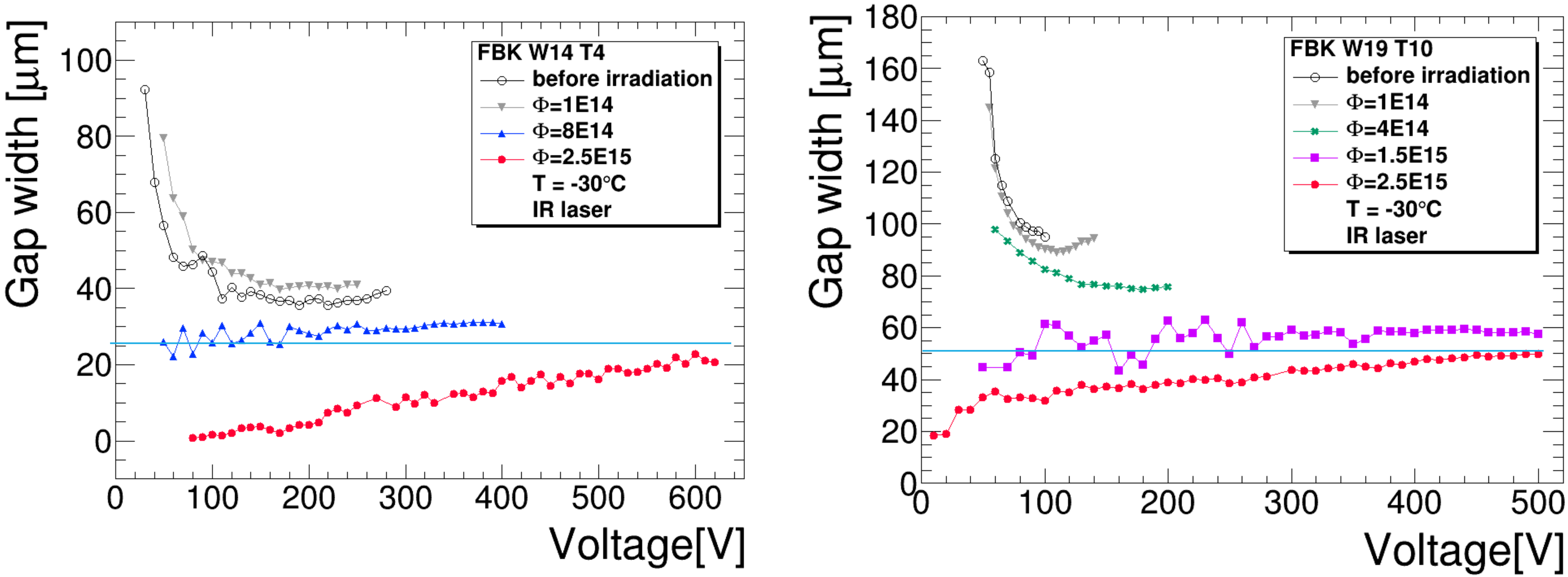
# HPK IP5 - measurements

- Changing the fit (ommiting the JTE) gives us a result which is much closer to nominal IP



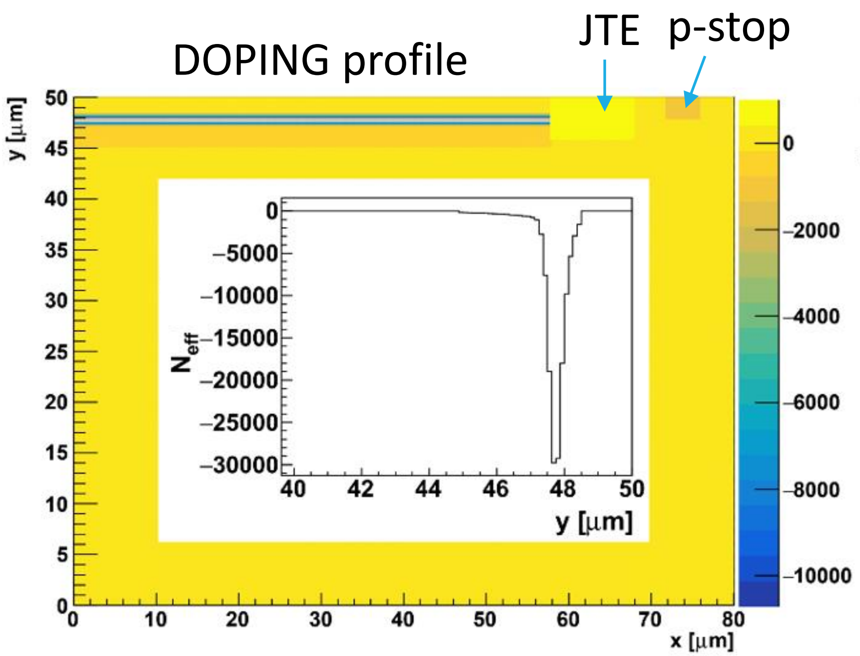
# FBK measurements

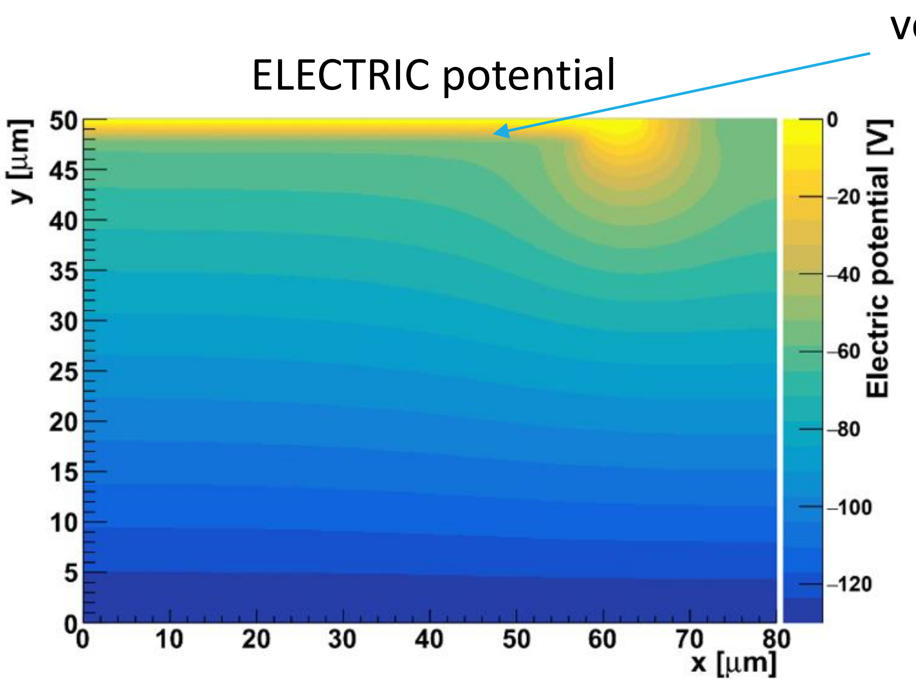
- FBK design Type4 has the smallest IP, but the danger of going to early breakdown in case of floating pads
- Fluence dependence is similar as for HPK devices, but in general IP performance is slightly better



# Simulations

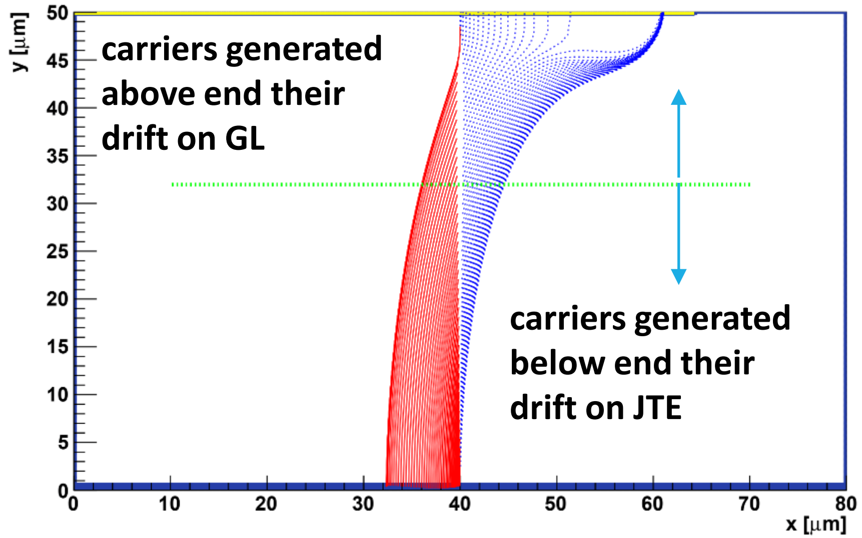
- We wanted to simulate the performance and see if it is possible to get a qualitive and quantitative agreement
- KDetSim simulation package was used to simulate the device (kdetsim.org)
- The doping profiles as extracted from the CV measurements were used to simulate gain layer
- The dimensions taken from microscope pictures were used for p-stop/JTE placement
- Doping level of JTE was adjusted in simulations (not known)



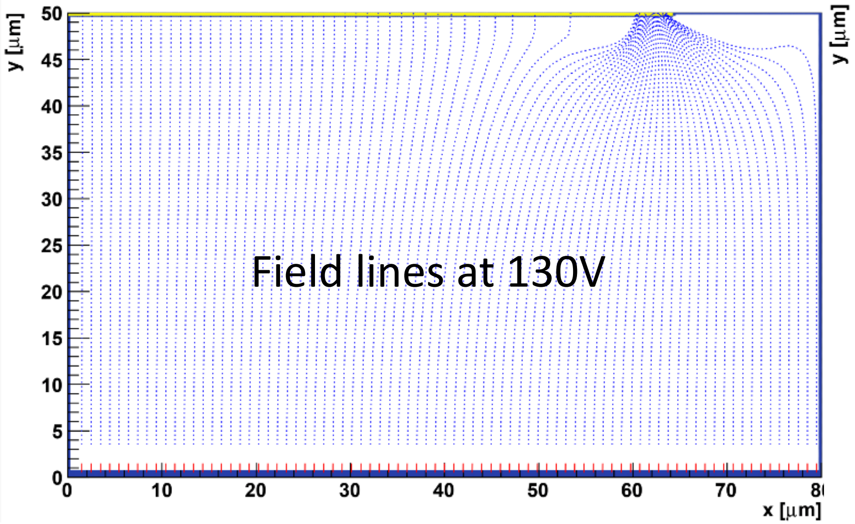



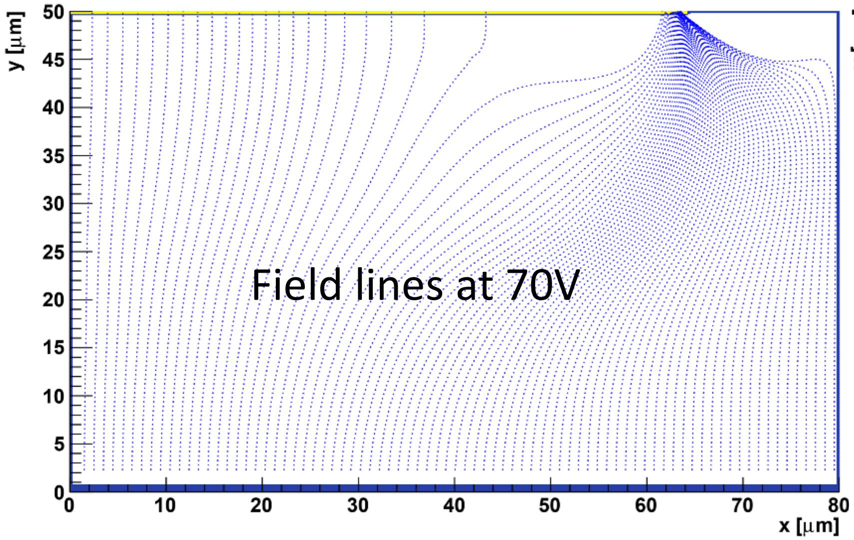

HPK-IP5
device at room temperature
biased to 130 V

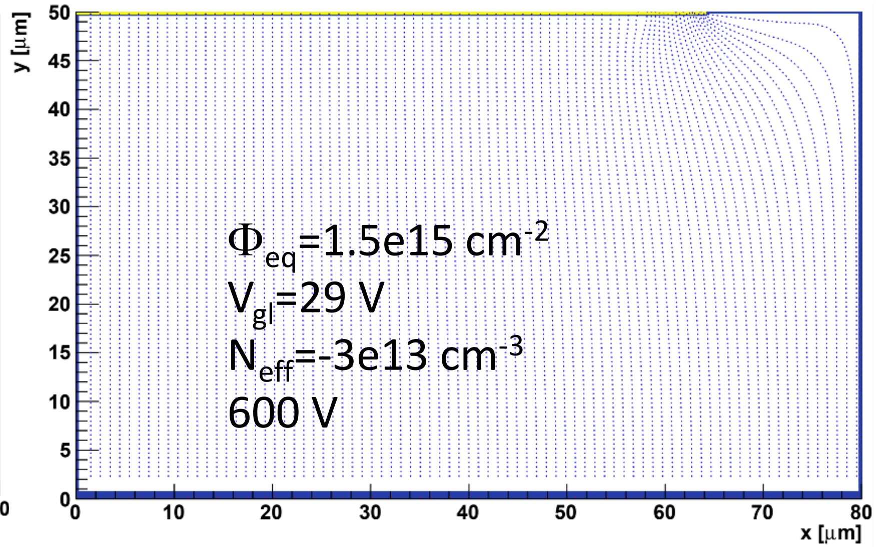
# Simulations




- The carriers generated underneath the gain layer end their drift on the JTE and don’t undergo multiplication
- The gap is effectively larger at smaller bias voltages as also observed in measurements
- **If the gain is reduced (irradiation) and effective space charge increases the effect disappears and the nominal and effective distance becomes similar.**



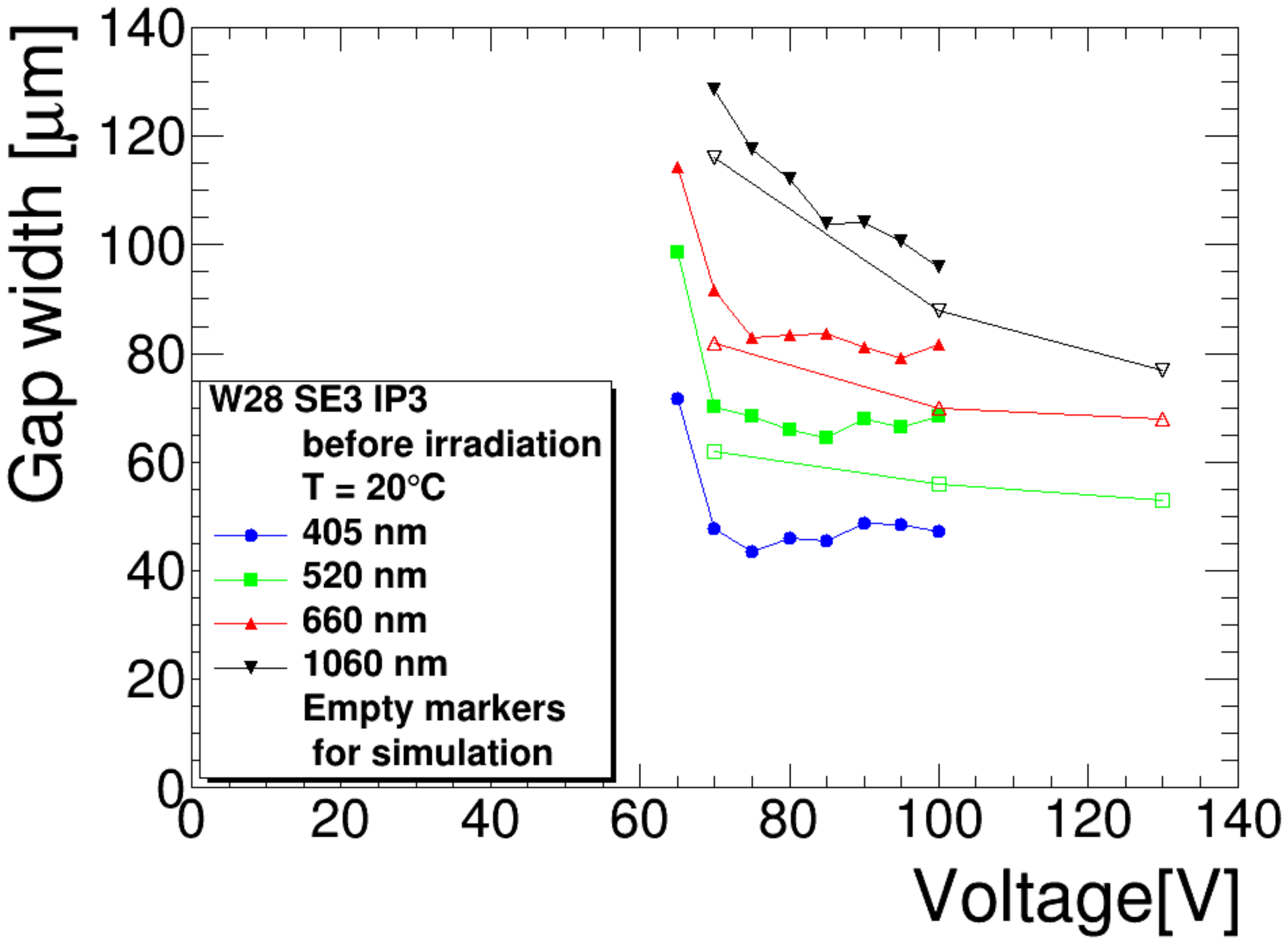



# Illumination with various lasers

**To check the simulation predictions we used light of different penetration depth**

- Laser light with wavelengths 405, 520, 660 and 1060nm were used
- Penetration depths 100nm, 1µm, 3.5µm, 1mm
- Probe the sample at different depths
- Blue → close to nominal geometry
- IR → effective geometry (MIP-like)
- Good agreement of measurement and simulation (KDetSim)



# Conclusions

- Effective inter-pad gap was measured for HPK and FBK LGAD prototypes using Scanning -TCT
- For non-irradiated detectors the difference between nominal and effective inter pad gap can be very large (up to 60 $\mu$m for HPK devices)
- After irradiation the difference disappears
- The measurements were simulated and good agreement quantitative and qualitive was found.
- Use of light of different wavelengths confirms the simulations