PPS Upgrade: Fast timing with Silicon Detectors

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PPS and HL-LHC

- The PPS consists of two spectrometer arms, each contains:
  - Tracker to measure the proton trajectory
  - Timing system to determine time of flight (difference between the two arms indicates the z position of the primary vertex)

- Timing from PPS can be compared to/combined with timing of central detector

- The HL-LHC will have a significantly increased pileup, up to 200 pileup events:
  - Timing is critical in order to handle the pileup background

PPS Timing for HL-LHC

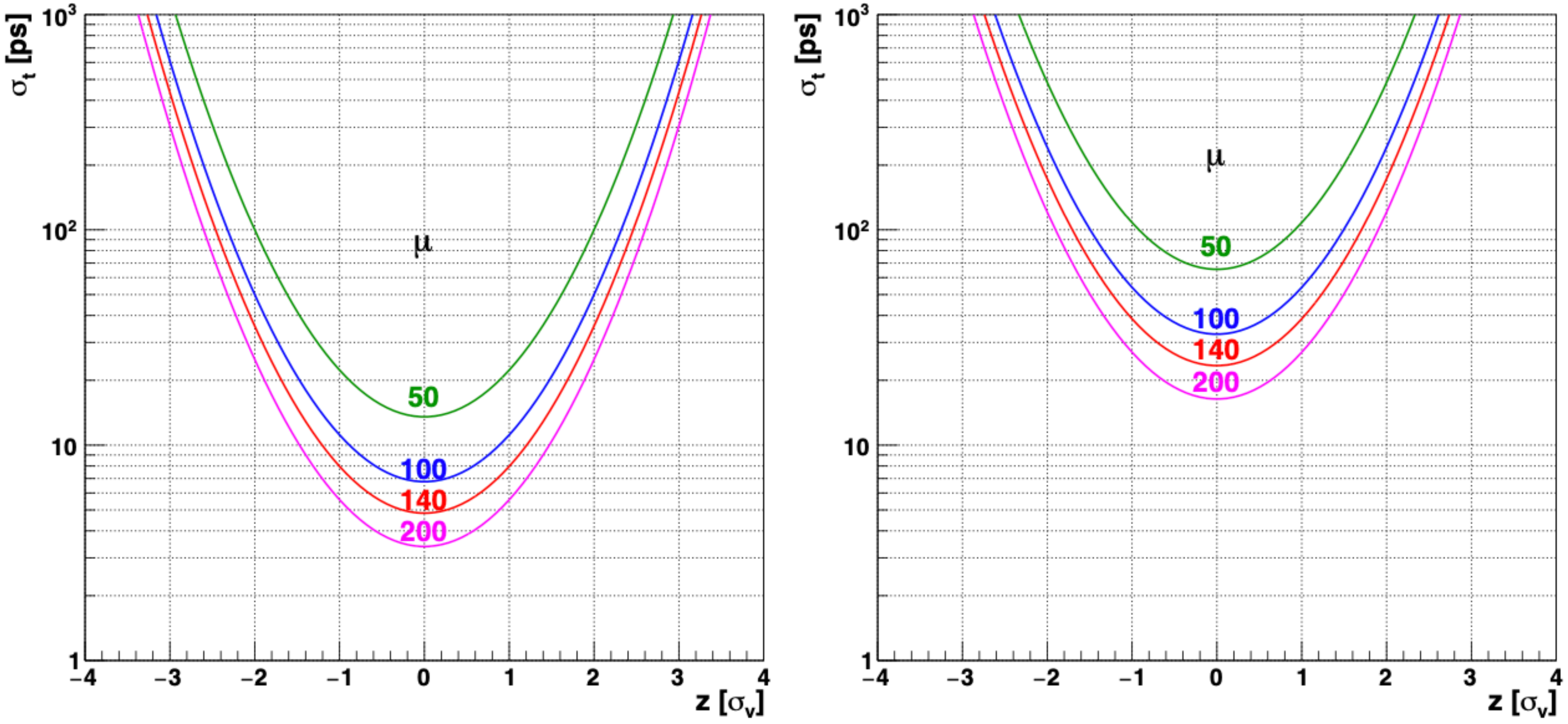


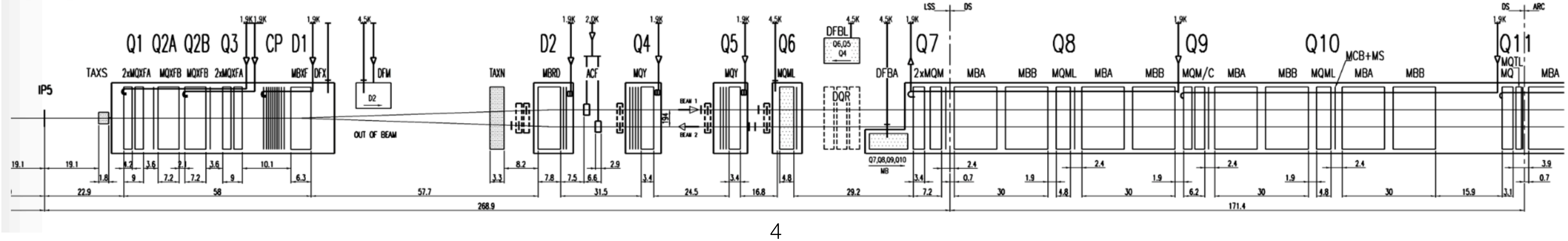
Figure 47: Time resolution required per spectrometer arm to resolve the mean vertex distance at a position z (in units of the longitudinal vertex width σ_v) from the IP centre. Four different pileup multiplicities are shown: $\mu = 50$ (LHC Run 2), 100, 140 (nominal HL-LHC performance), and 200 (ultimate HL-LHC performance). Left: for standalone PPS timing. Right: combining the PPS timing with the MTD system, selecting a time-slice of $\pm 50\,\mathrm{ps}$ around the central bunch crossing time.

Taken from CMS Note 2020/008 (arXiv 2103.02752)

PPS and HL-LHC

- During LS3 the beampipe and magnets around CMS will be redesigned
  - The current PPS detector will be removed

- Four different locations in the new design have been identified for possible PPS stations:
  - 196 meters from the interaction point
  - 220 meters from the interaction point
  - 234 meters from the interaction point
  - 420 meters from the interaction point (more challenging position since it needs a special mechanical design -> possibly staged construction)



PPS Timing Detectors

- Different detector technologies are being considered:
  - LGAD - Reuse the detector being developed for the Endcap Timing Layer, both the sensor (Low Gain Avalanche Diode) and the readout chip (ETROC)
  - Diamond - Used in the current PPS detector, great radiation hardness but no readout for HL-LHC rates and required amount of channels
  - 3D Pixels - Still in R&D, have been shown to allow for simultaneous tracking and timing with one sensor
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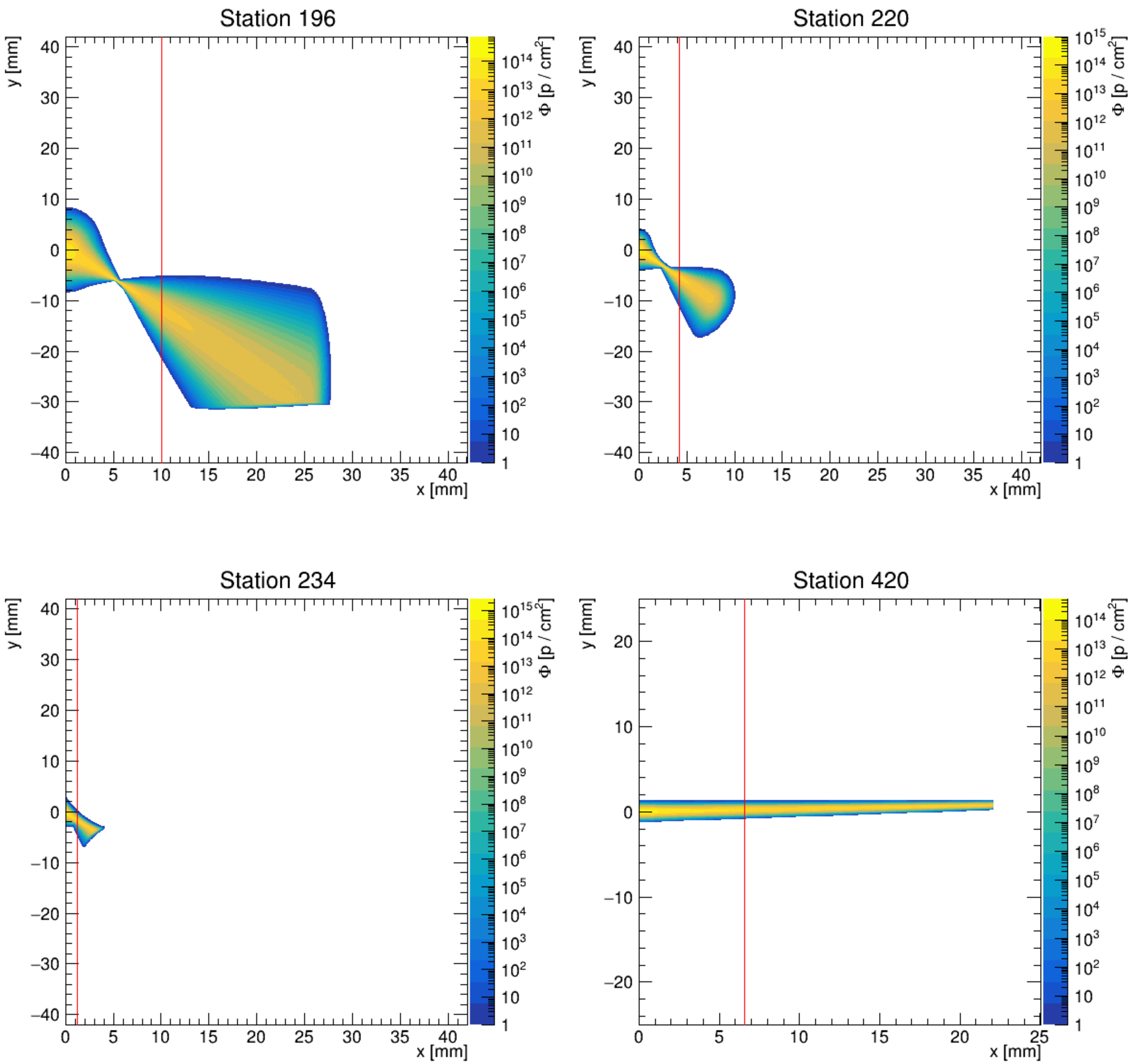
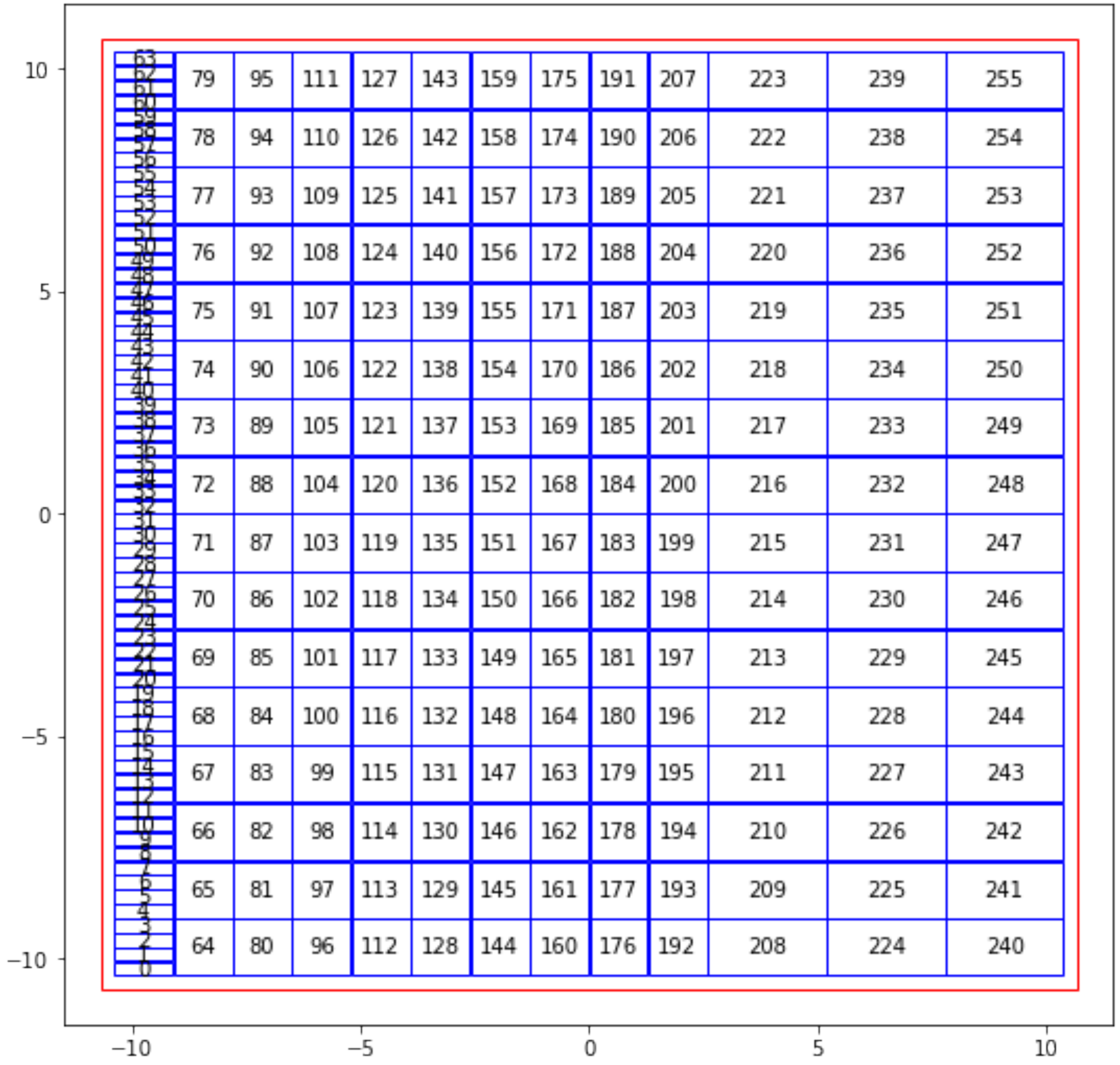
PPS Particle Fluence Maps

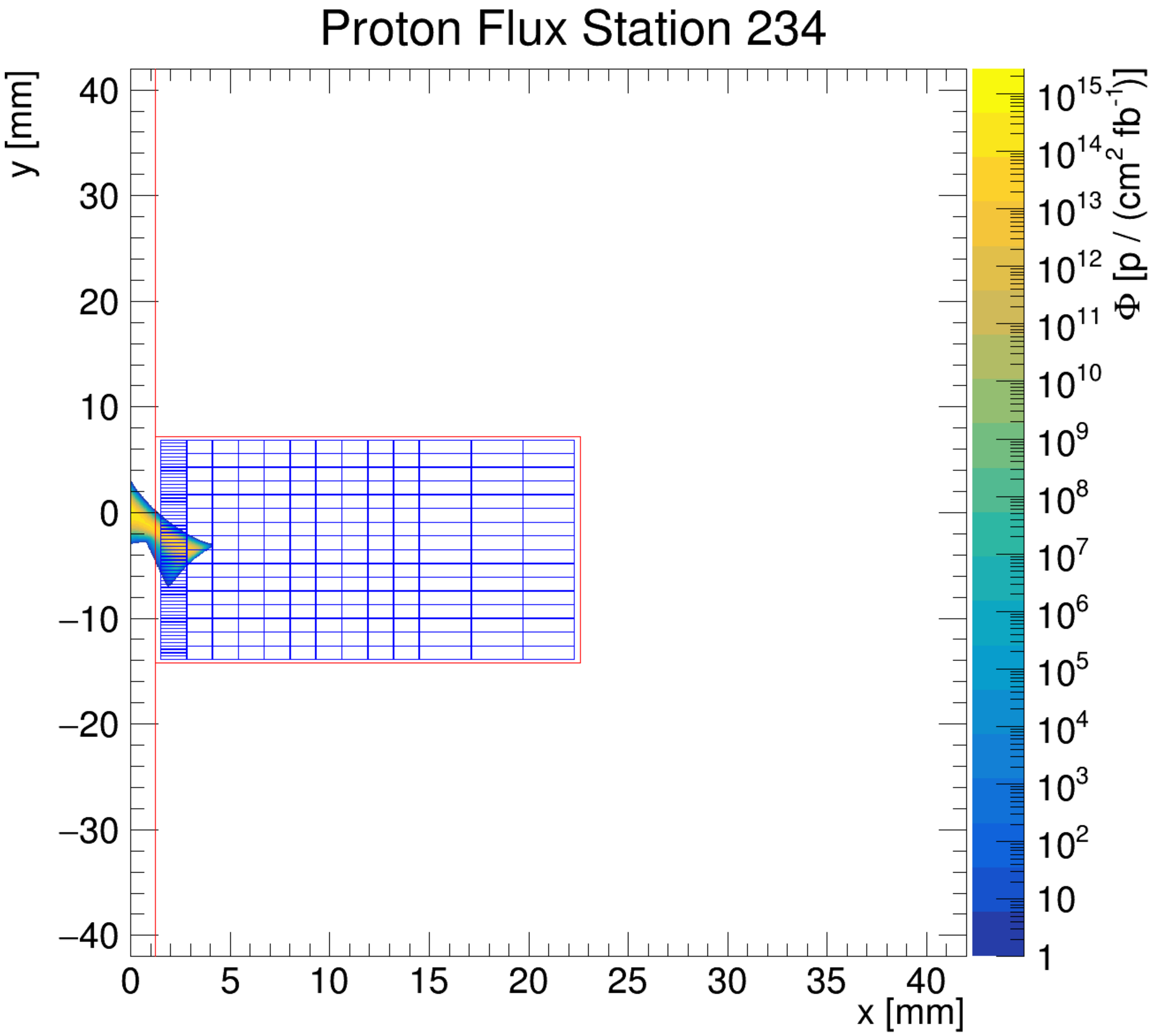
- Simulated particle fluence after 1 fb^{-1} of data from diffractive processes (nb: background not included)
- HL-LHC beam at coordinate (0, 0)
- Red line marks the approximate edge of the sensors during physics runs
- Very large gradient that the sensors must cope with
  - Sensor pad size affects channel occupancy → column of pads closest to the beam has to be split, compared to the ETL design, in order to keep the detector efficiency high



Plots produced with raw data provided by M. Deile

4-Split LGAD Sensor





Fill Factor

- For a "Standard LGAD", the interpad distance (space between pads) is approximately 100 μm
  - This gives a standard ETL LGAD a fill factor of approximately 85%
  - With PPS segmentation, the overall fill factor is ~81%, but the fill factor of the first column is ~64%

- A Trench Isolated LGAD can achieve interpad distances as low as 10 μm
  - The PPS segmented LGAD can reach an overall fill factor of ~98% and a fill factor of the first column of ~96%

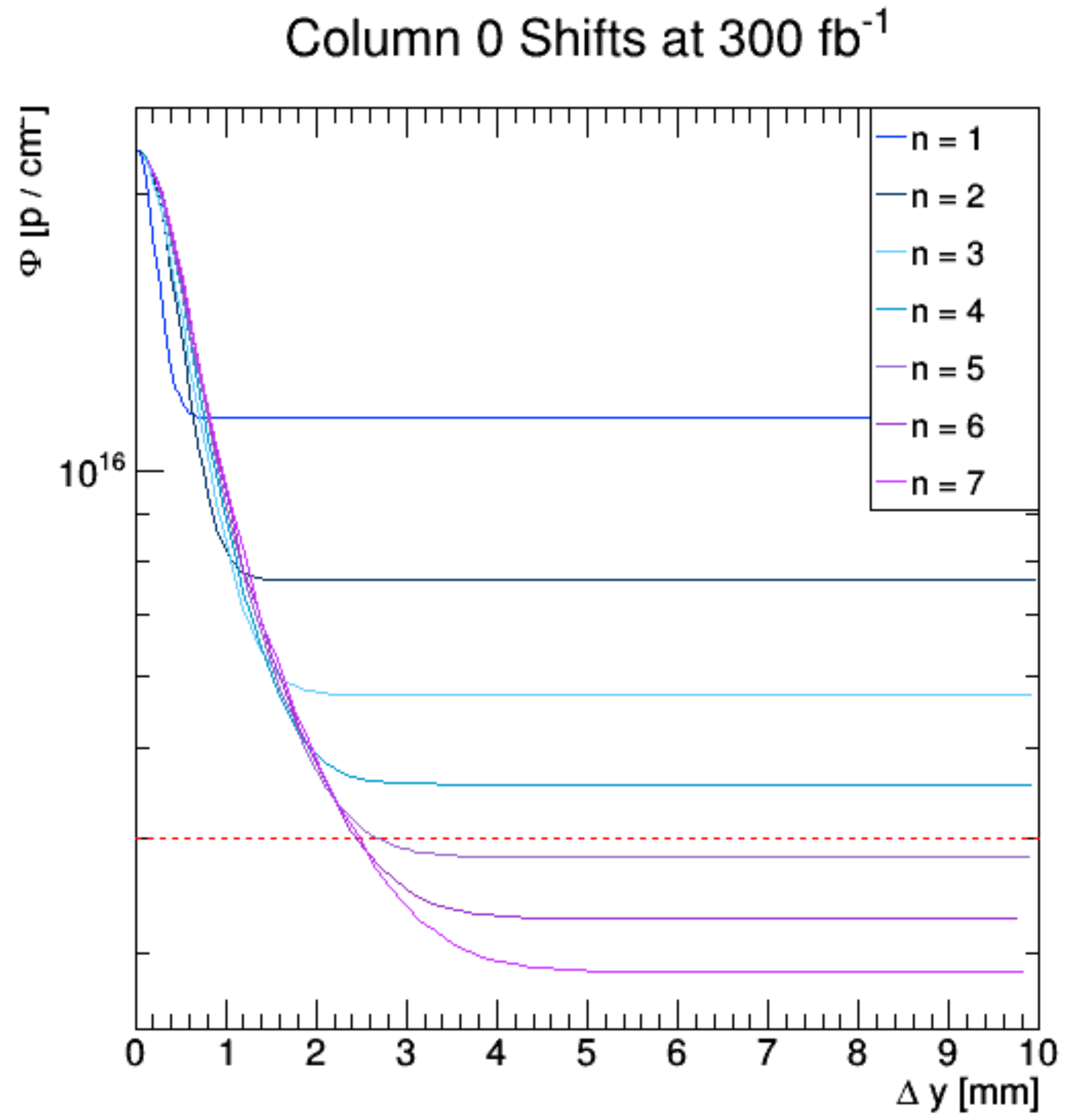
- Reducing the interpad spacing is fundamental to achieve good efficiency in PPS

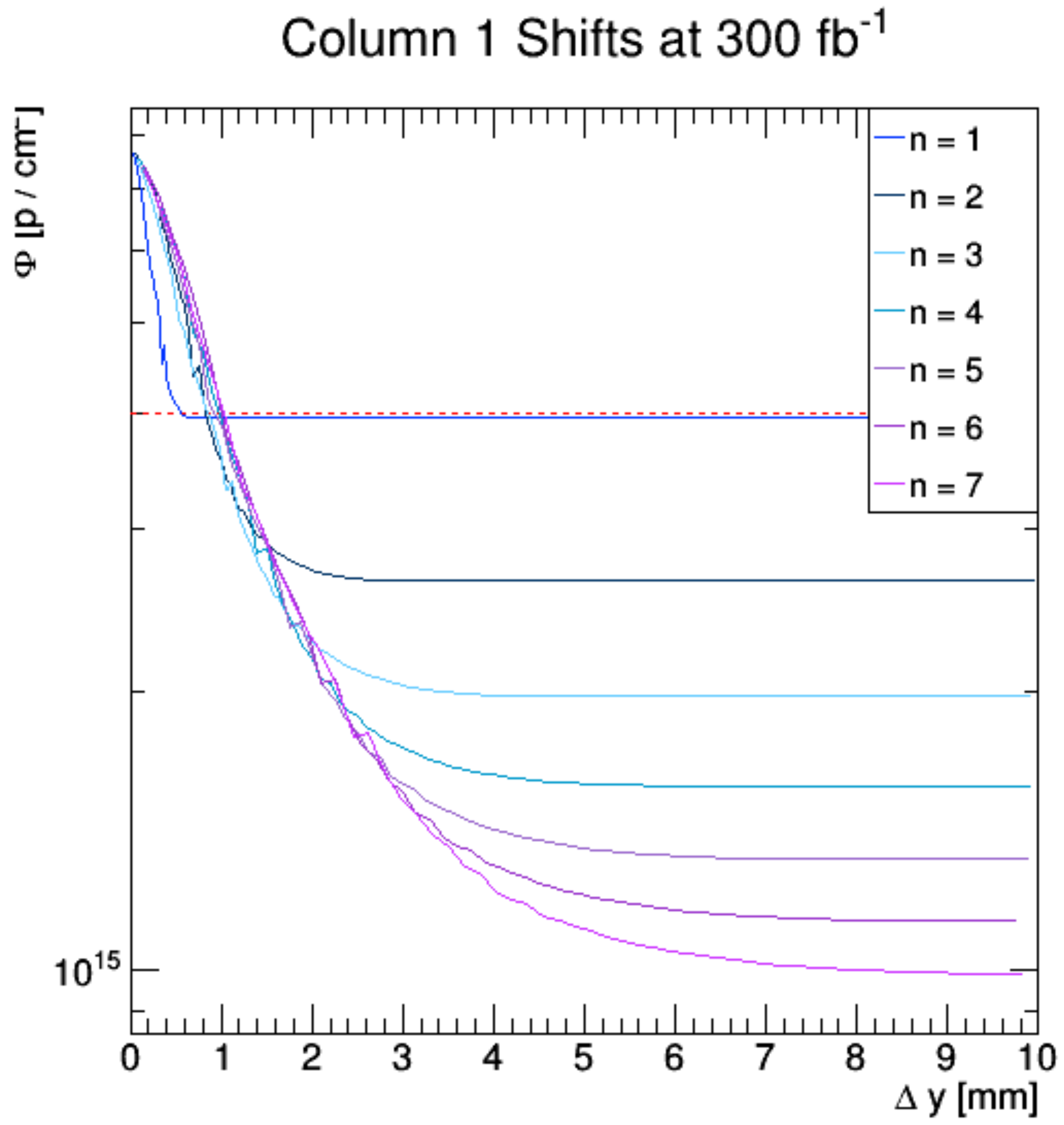
Peak Dose

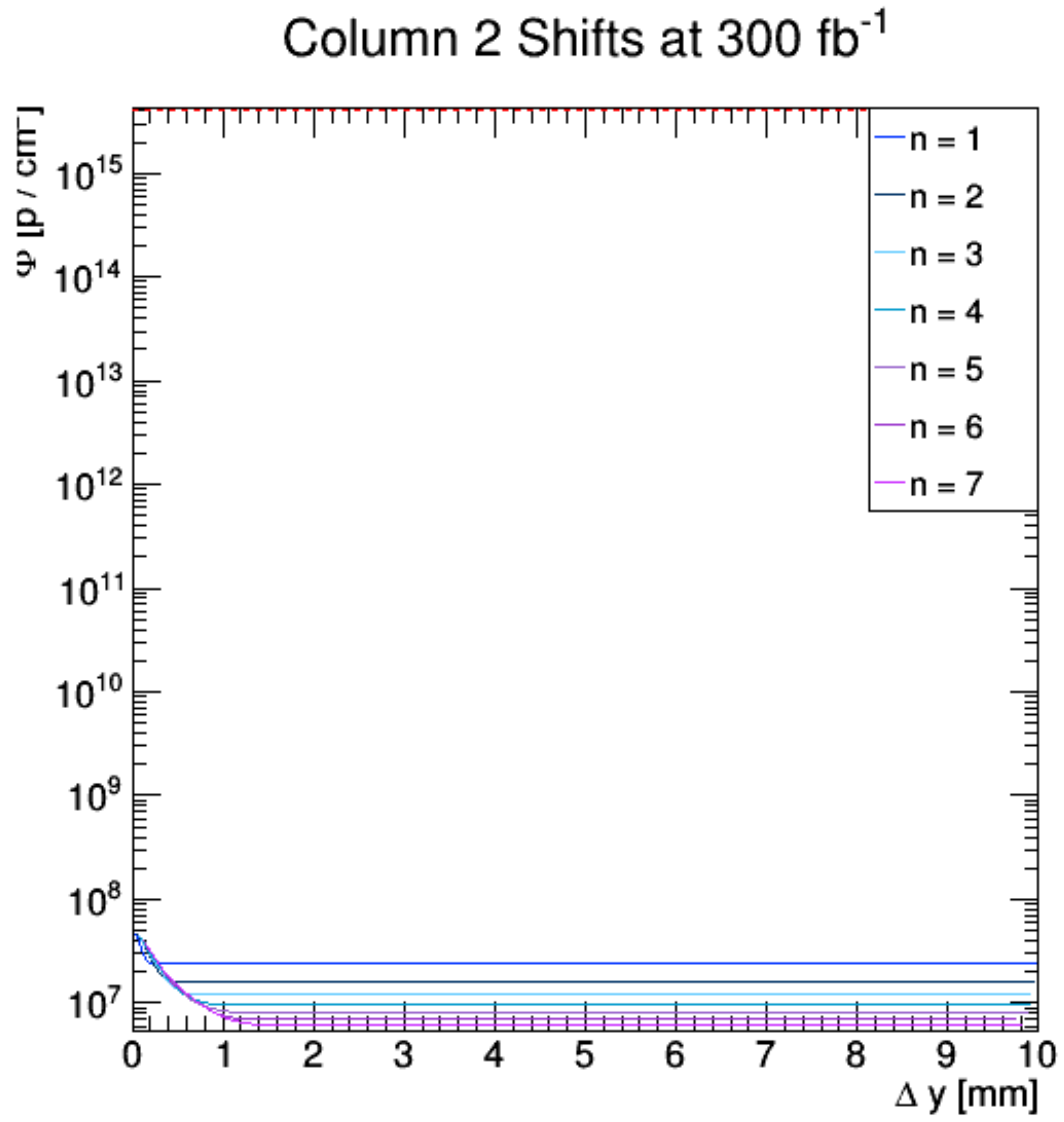
- Peak PPS dose (assuming diffractive flux maps) over 1 year of HL-LHC exceeds LGAD radiation tolerance (~2E15 neq ≅ 4E15 p/cm^2):
    - Station 196: 5.47E14 p/cm^2
    - Station 220: 3.72E15 p/cm^2
    - Station 234: 2.29E16 p/cm^2
    - Station 420: 6.35E15 p/cm^2
- Shift sensor vertically throughout the year to mitigate radiation damage

Sensor Shifts & Dose

Station 234





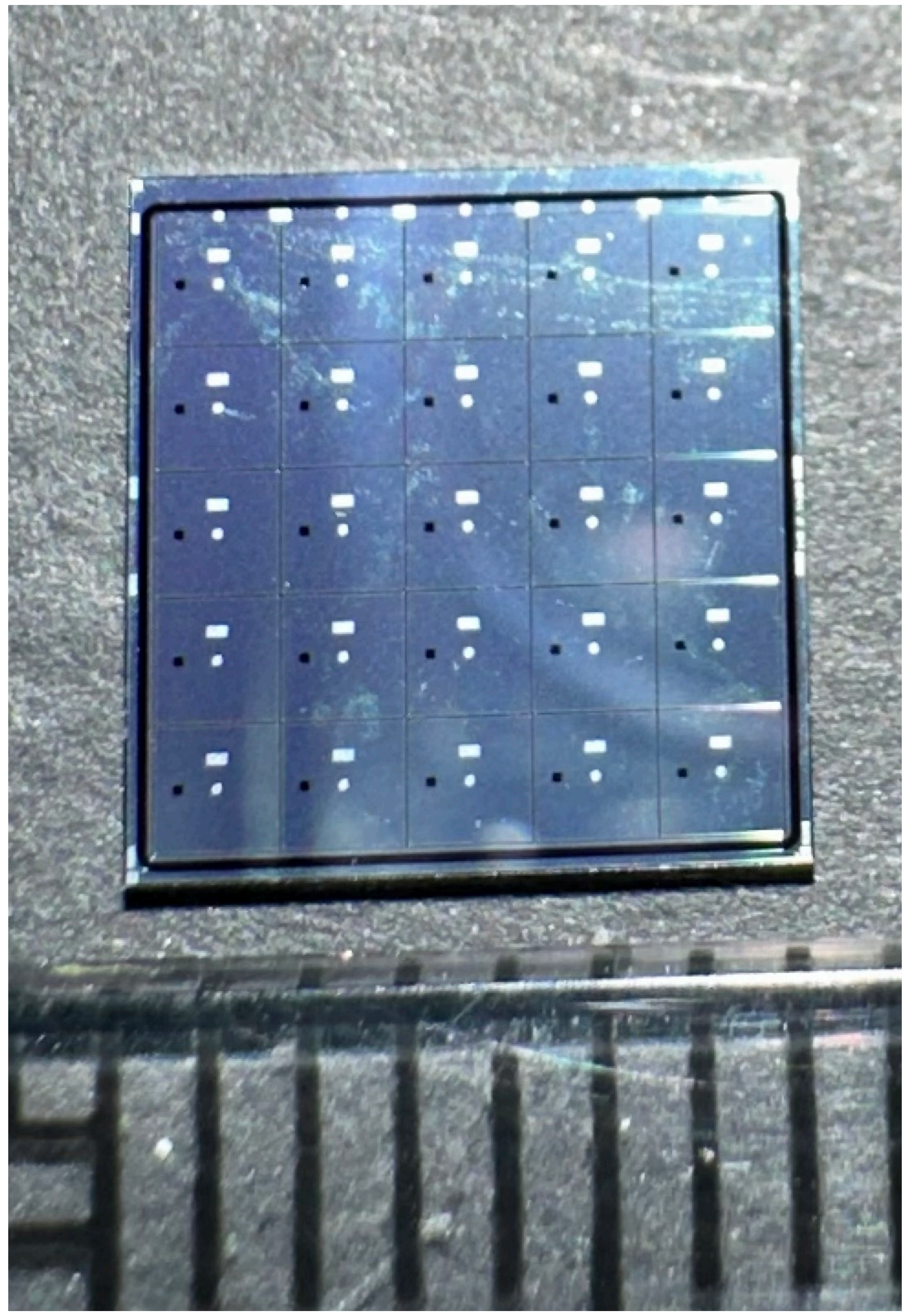


LGAD Irradiation

- Non uniform irradiation profile and dose is the largest challenge for PPS → Study LGAD performance with non-uniform irradiation
- LGAD samples from FBK-UFSD4 production
- Each sample is a matrix of 5x5 pixels, each pixel is a square with 1.3 mm side
- Samples have different characteristics:
  - Guard ring design (GR3_0 or GR3_1)
  - LGAD Interpad design (T9 or T10)

Sample Name	Reference	Irradiation
PPS_LGAD_01	FBK UFSD4 W18 GR3_1 T9 6-4	1E16 p/cm^2
PPS_LGAD_02	FBK UFSD4 W18 GR3_1 T10 6-4	5E15 p/cm^2
PPS_LGAD_03	FBK UFSD4 W18 GR3_0 T9 6-4	NA
PPS_LGAD_04	FBK UFSD4 W18 GR3_0 T10 6-4	1E16 p/cm^2
PPS_LGAD_05	FBK UFSD4 W18 GR3_0 T9 4-6	5E15 p/cm^2

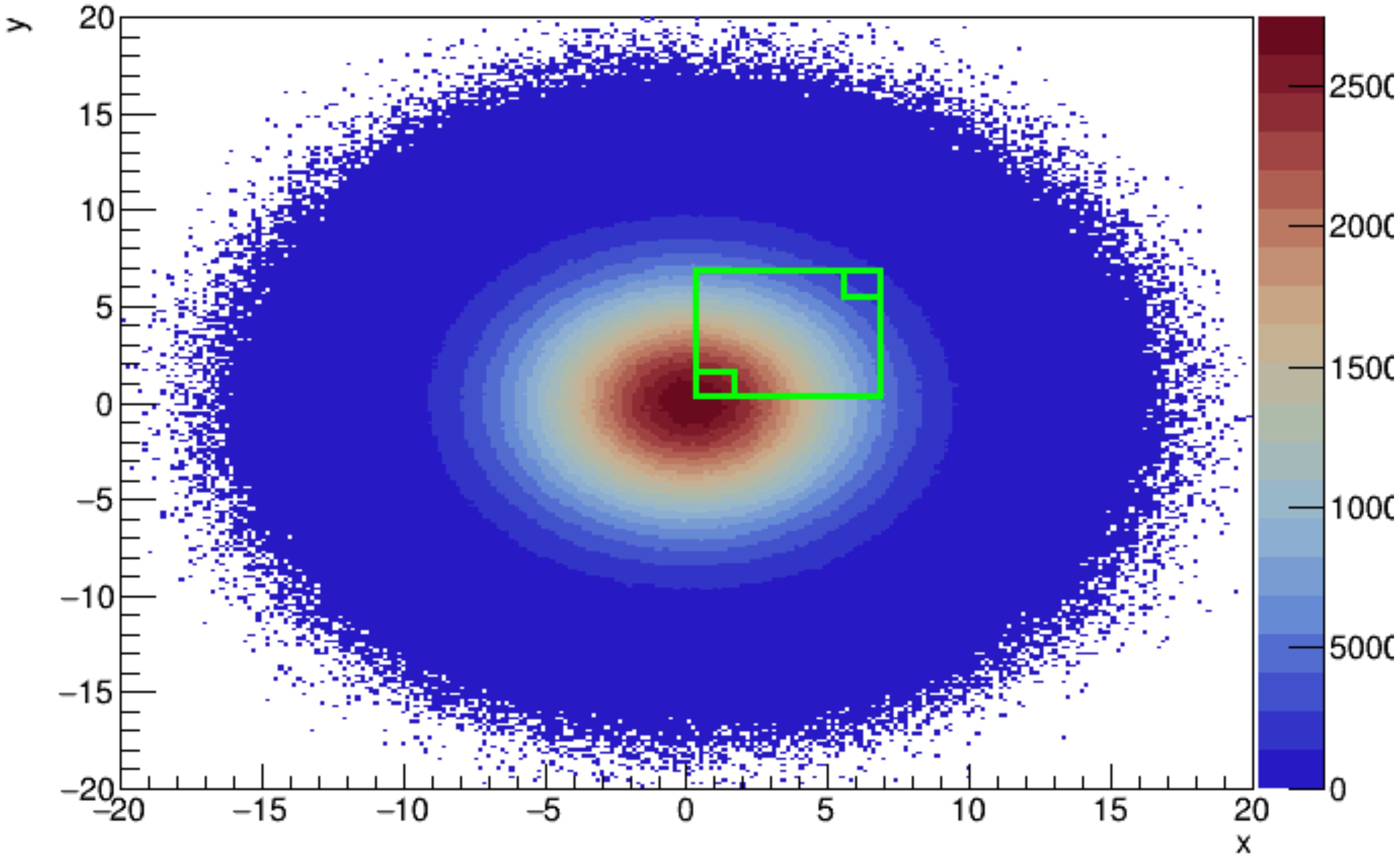
	GR3_0	GR3_1
T9	2	1
T10	1	1



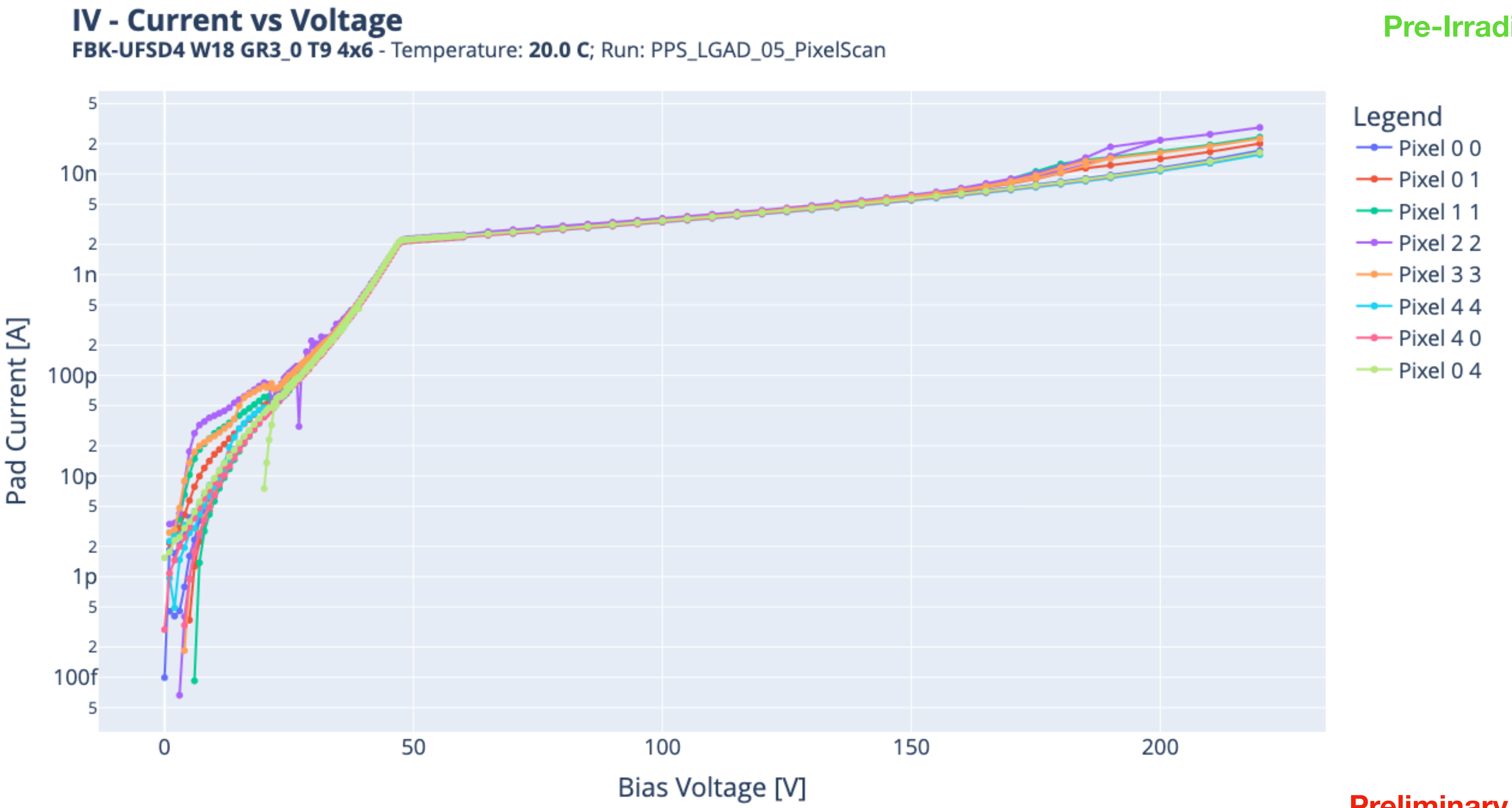
Samples provided by Roberta Arcidiacono

Irradiation Profile

- Offset the sensor with respect to the beam in order to achieve an irradiation gradient
- Factor of ~10 with this size of sensor
- Irradiation performed at the CERN IRRAD facility



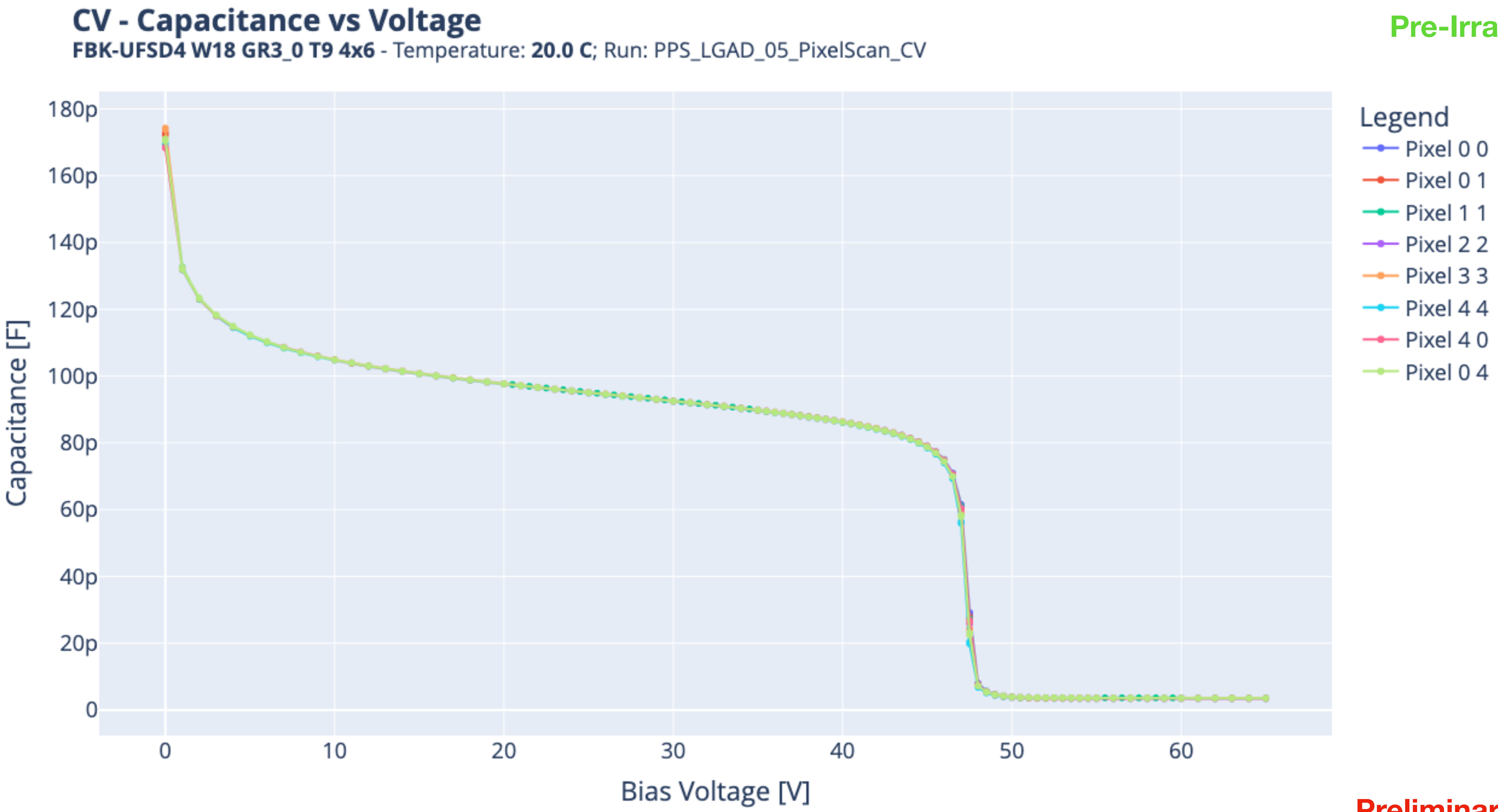
IV Curves of Pads in 1 Device



Pre-Irradiation

Preliminary Results

CV Curves of Pads in 1 Device

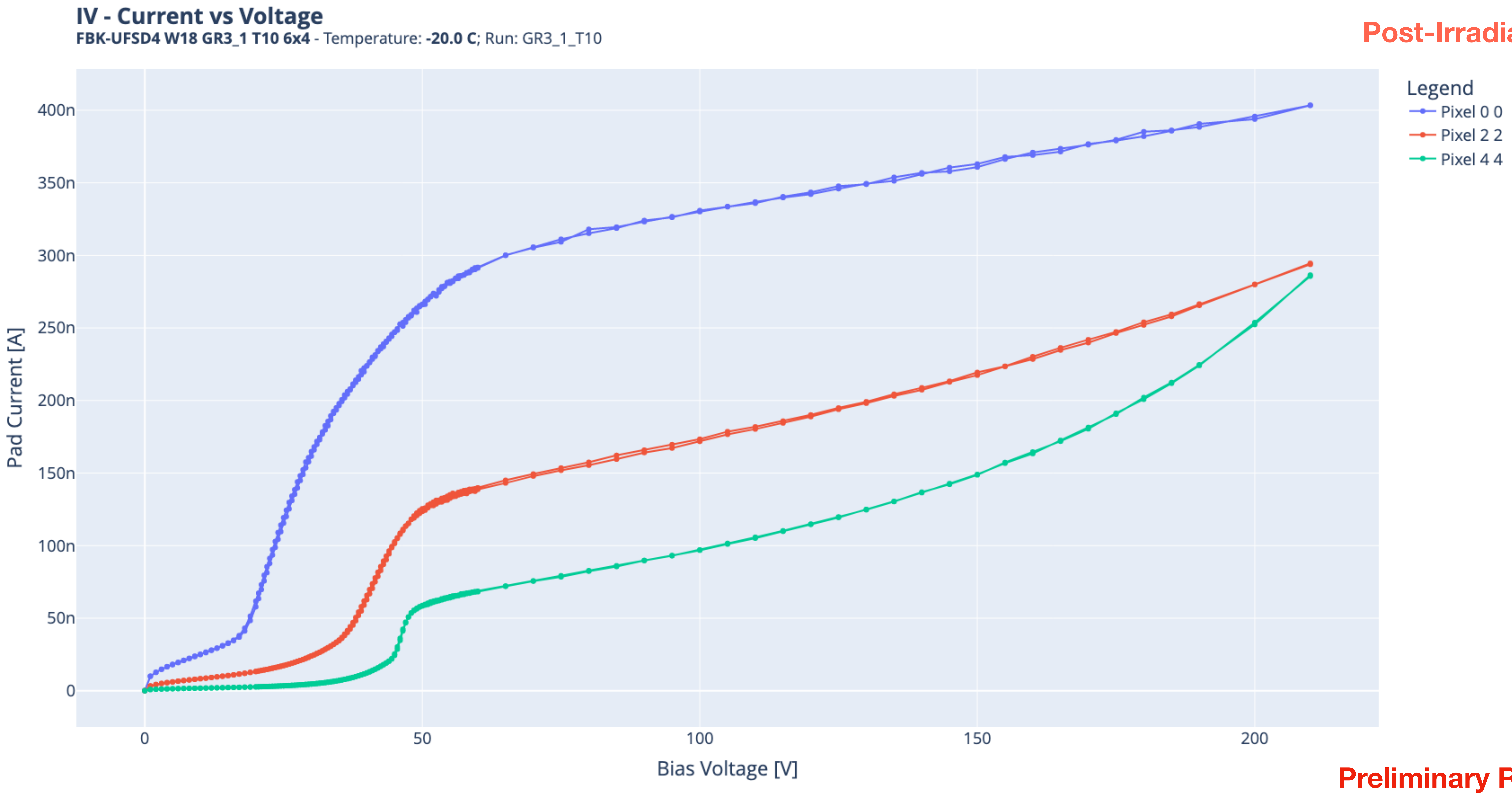


Pre-Irradiation

Preliminary Results

IV Curves of Pads in 1 Device

Post-Irradiation



Preliminary Results

Conclusion

- PPS Upgrade for HL-LHC under R&D → Non-uniform irradiation and large localized dose are the biggest challenges, some of which can be mitigated with known techniques

- Measurement and analysis of non-uniformly irradiated samples is ongoing. Next steps, measure CV curves of irradiated samples and measure timing performance with a laser setup

- Ongoing conversation with FBK for the production of TI LGADs with a radiation hard gain layer and PPS pad design

Backup

Sensor Pad Size

- Start by calculating the average expected occupancy (μ) for a single pad:
  - Particle fluence over 1 fb^{-1} can be converted to particle fluence for each bunch crossing with:

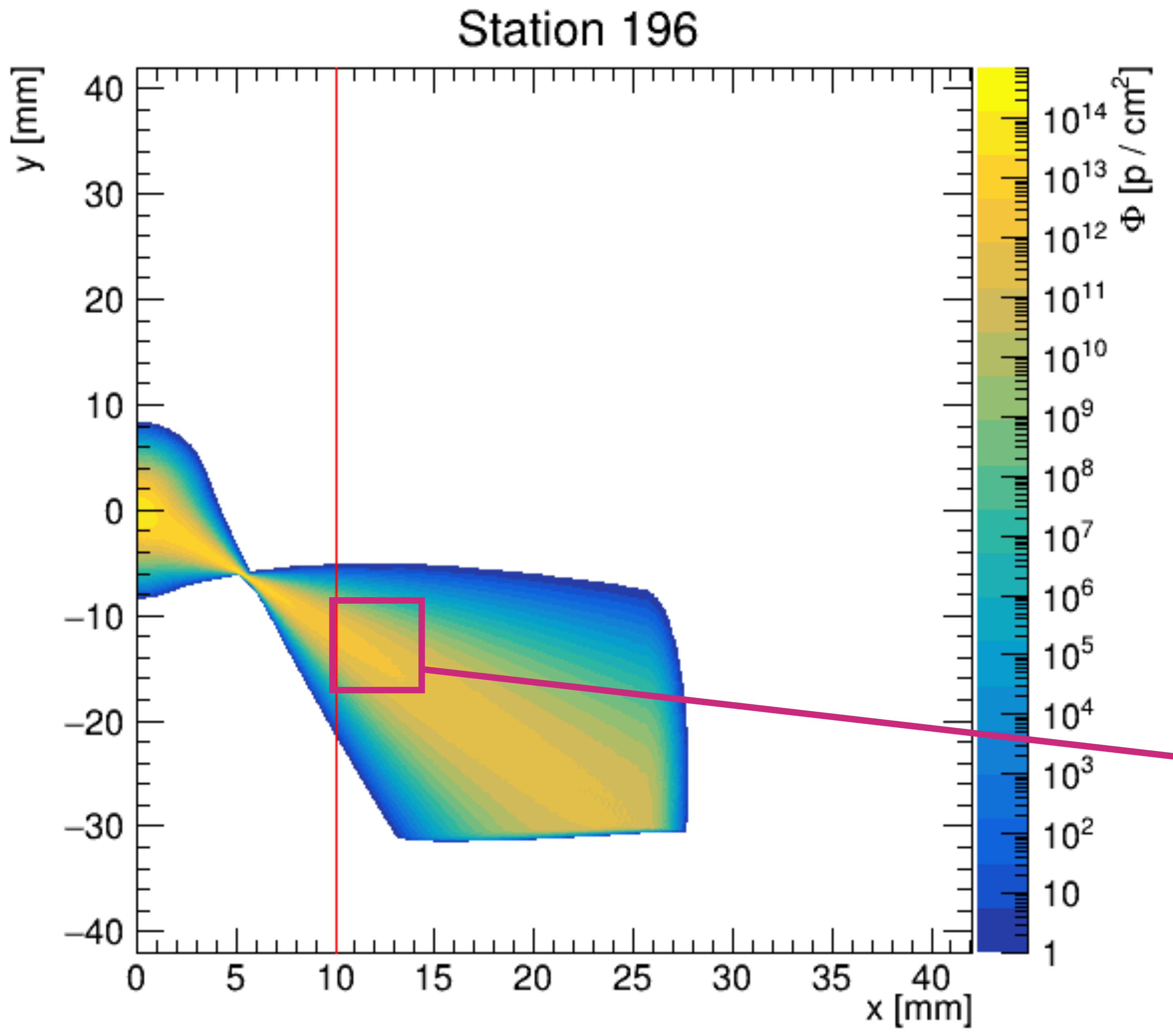
$$\Phi_{BX} = 1.6 \times 10^{-12}\ \Phi_{fb\text{-}1}$$

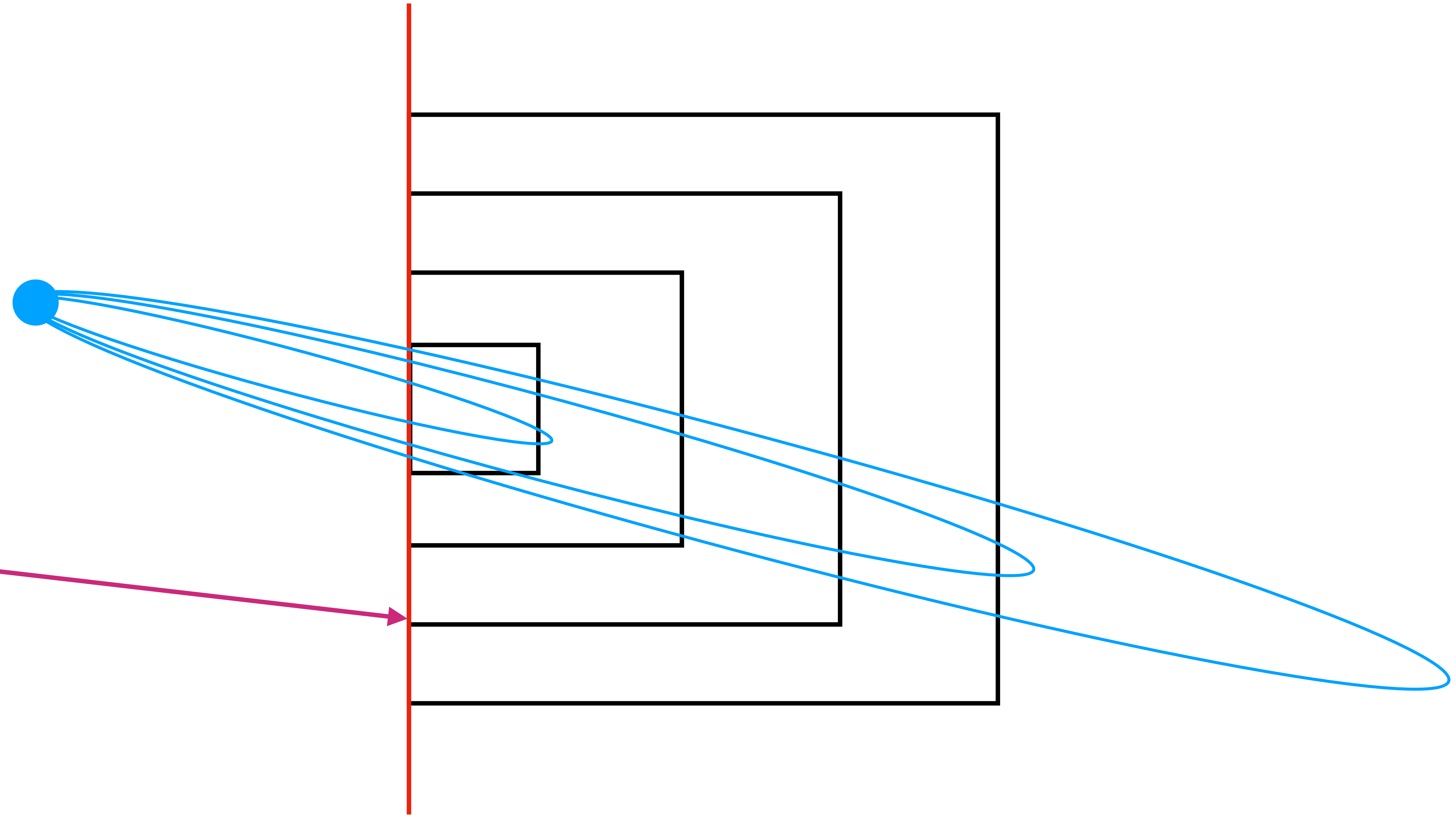
  - Place the pad centered at the position with maximum particle fluence on the sensor area (worst case scenario)
  - Calculate the pad occupancy in two different scenarios:
    - Assume uniform fluence over the whole pad area equal to the maximum fluence (worst case scenario):

$$\mu = \Phi_{BXmax} * A = \Phi_{BXmax} * l^2$$

    - Integrate particle fluence map over the pad area: $\mu = \int_{x_{edge}}^{x_{edge}+l} dx \int_{-\frac{l}{2}}^{\frac{l}{2}} dy\, \Phi(x, y)$

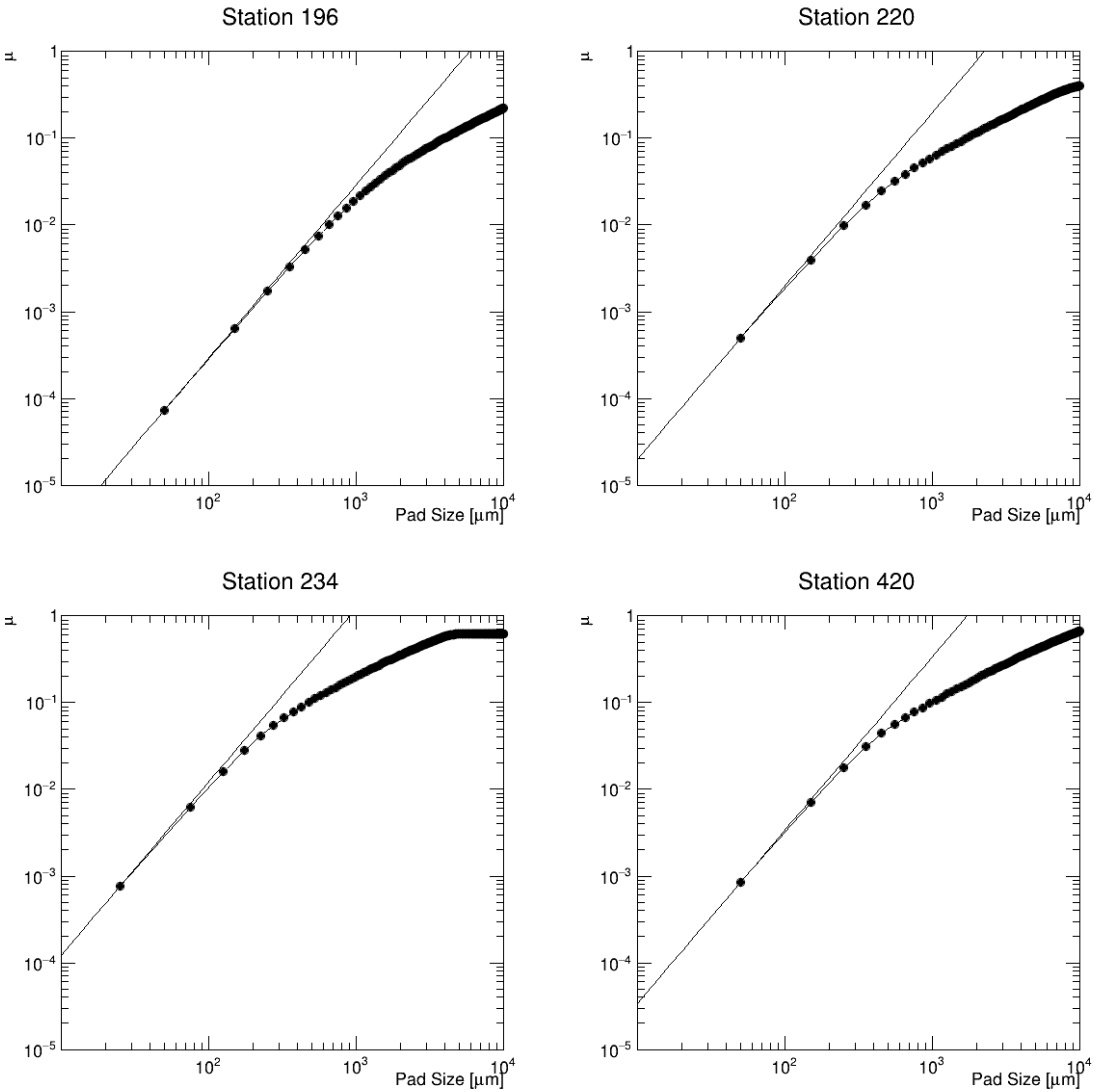
Sensor Pad Position



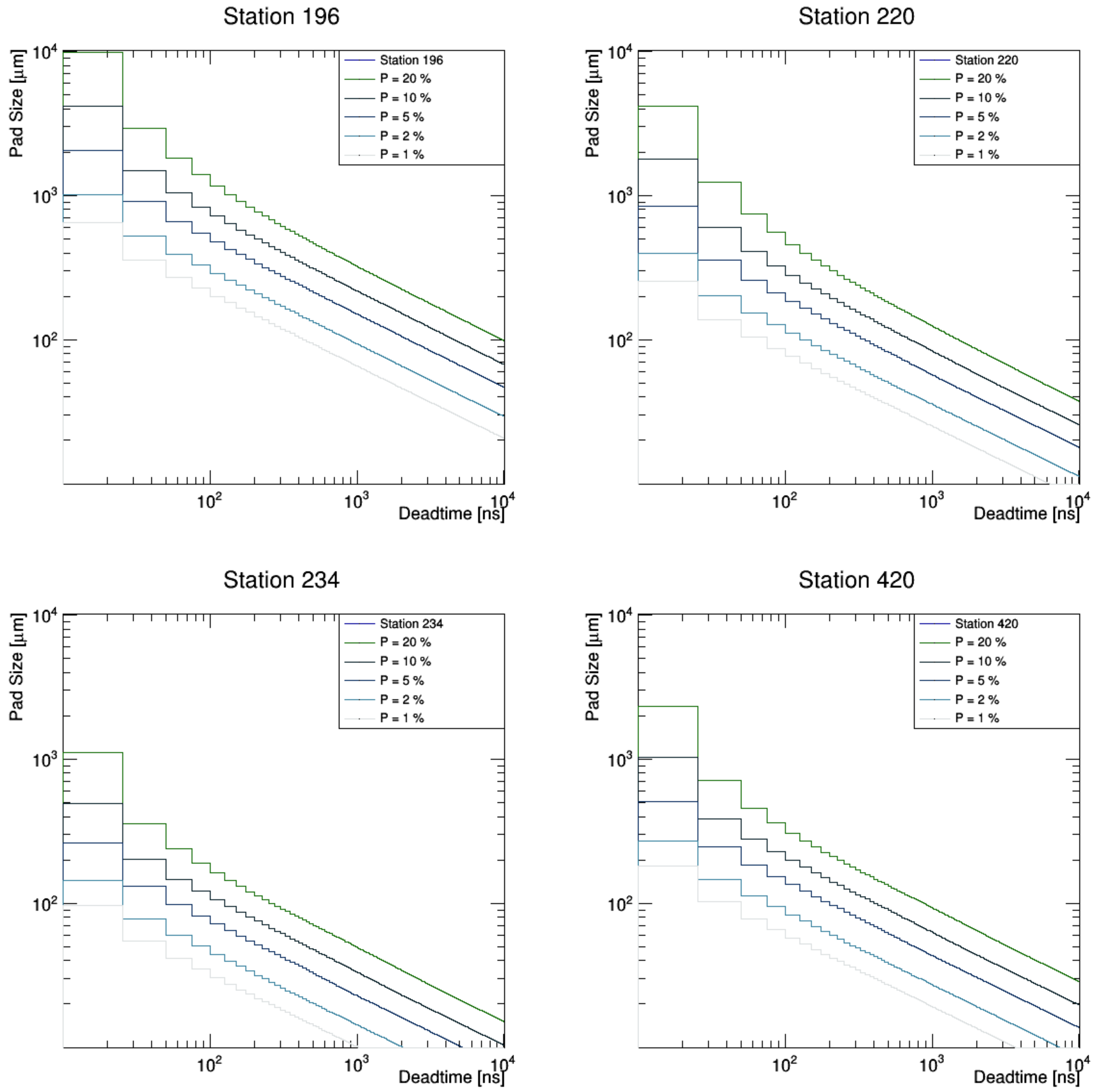


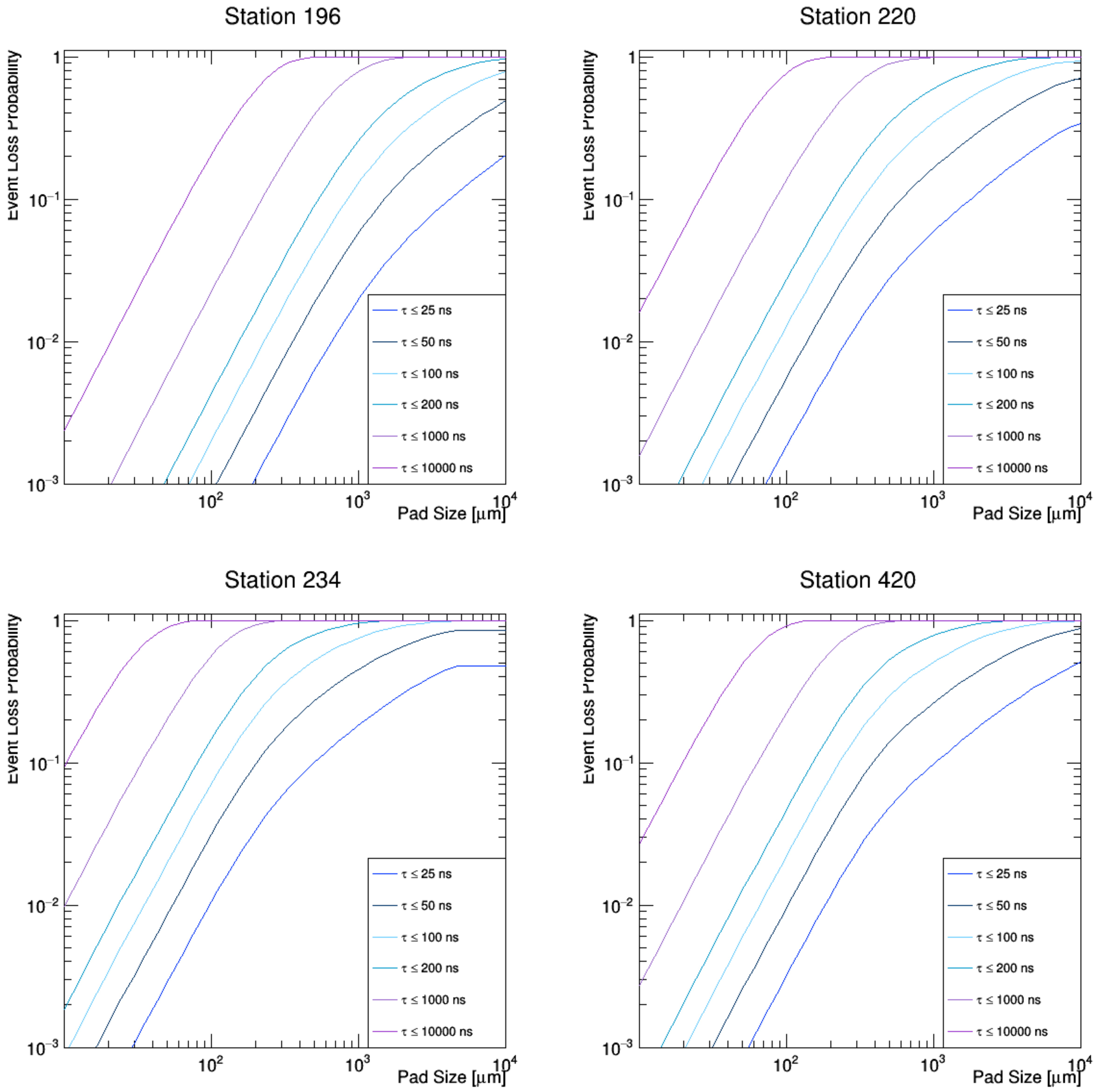
Sensor Pad Occupancy

- Uniform fluence scenario overestimates the occupancy (more evident at large pad sizes
- Occupancy, system deadtime and pileup probability are related
  - Pileup probability is the probability to see more than one proton in the same pad over the system deadtime, i.e. the event loss probability
  - Detector technology defines the deadtime, together with desired probability gives maximum pad size

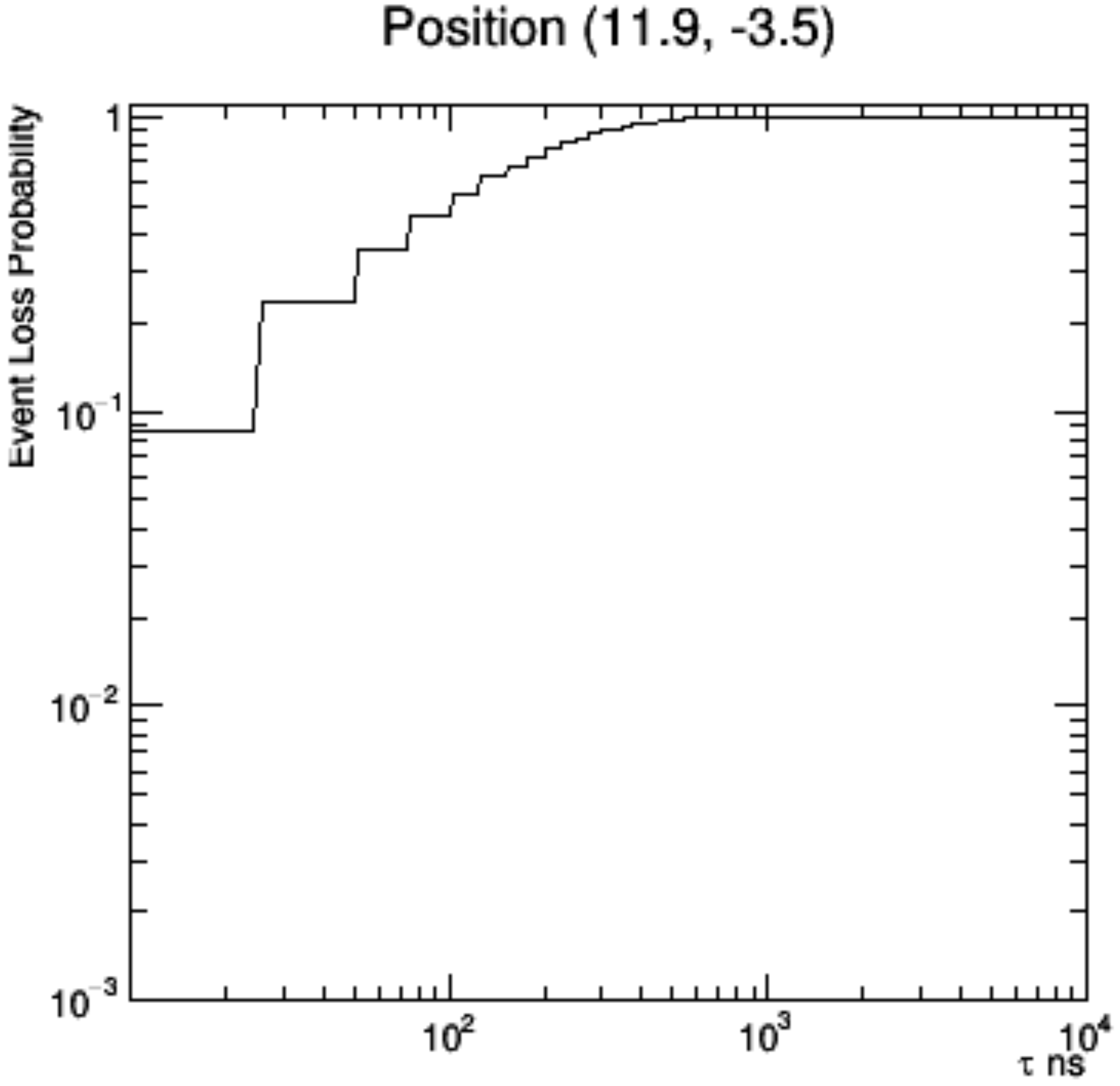


Pad Size vs Deadtime vs Loss Probability





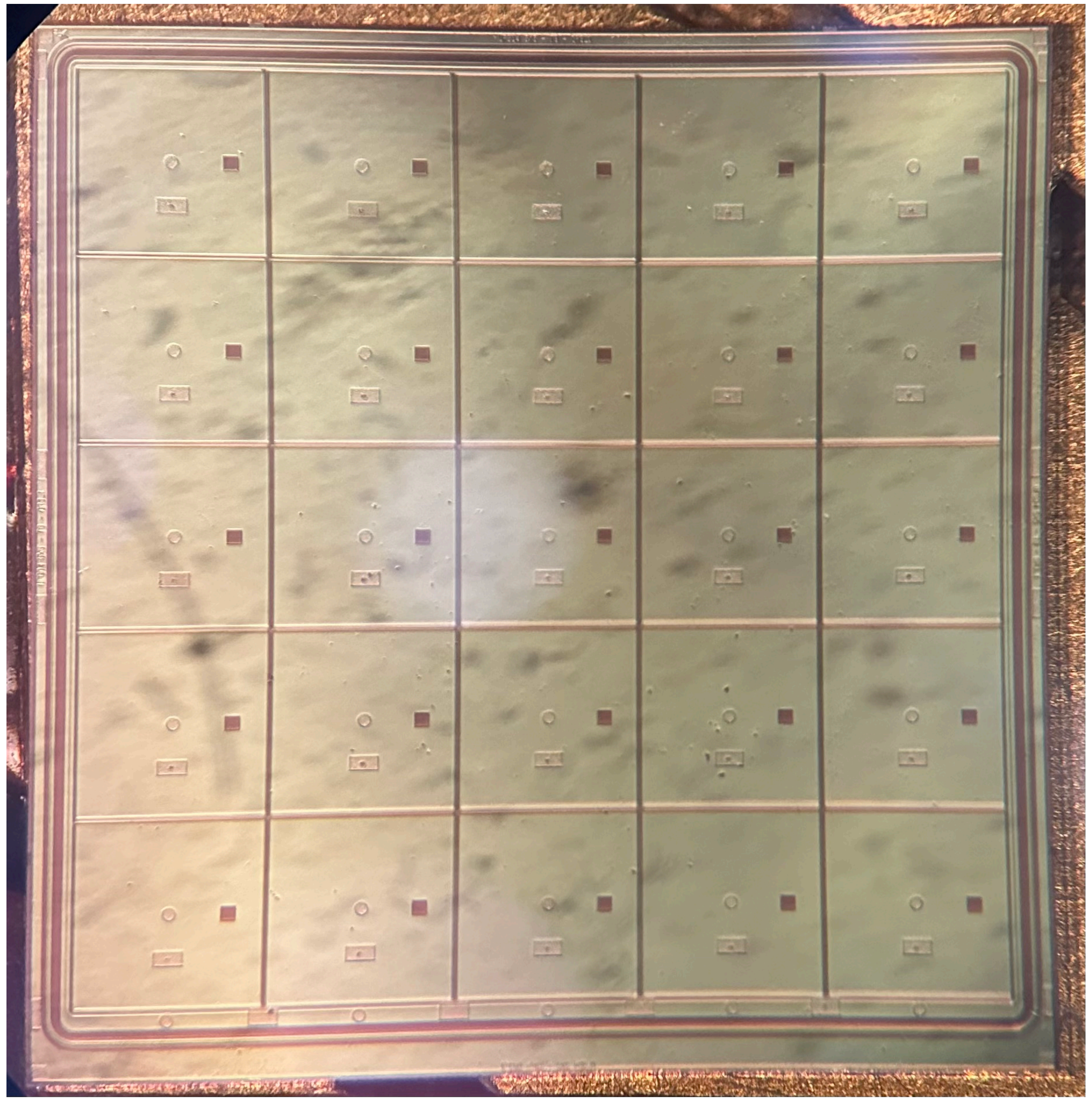
4-Split Loss Probability



- Only one with Loss probability < 10%

LGAD Pixel Naming

- Pixels are named according to their row and column:

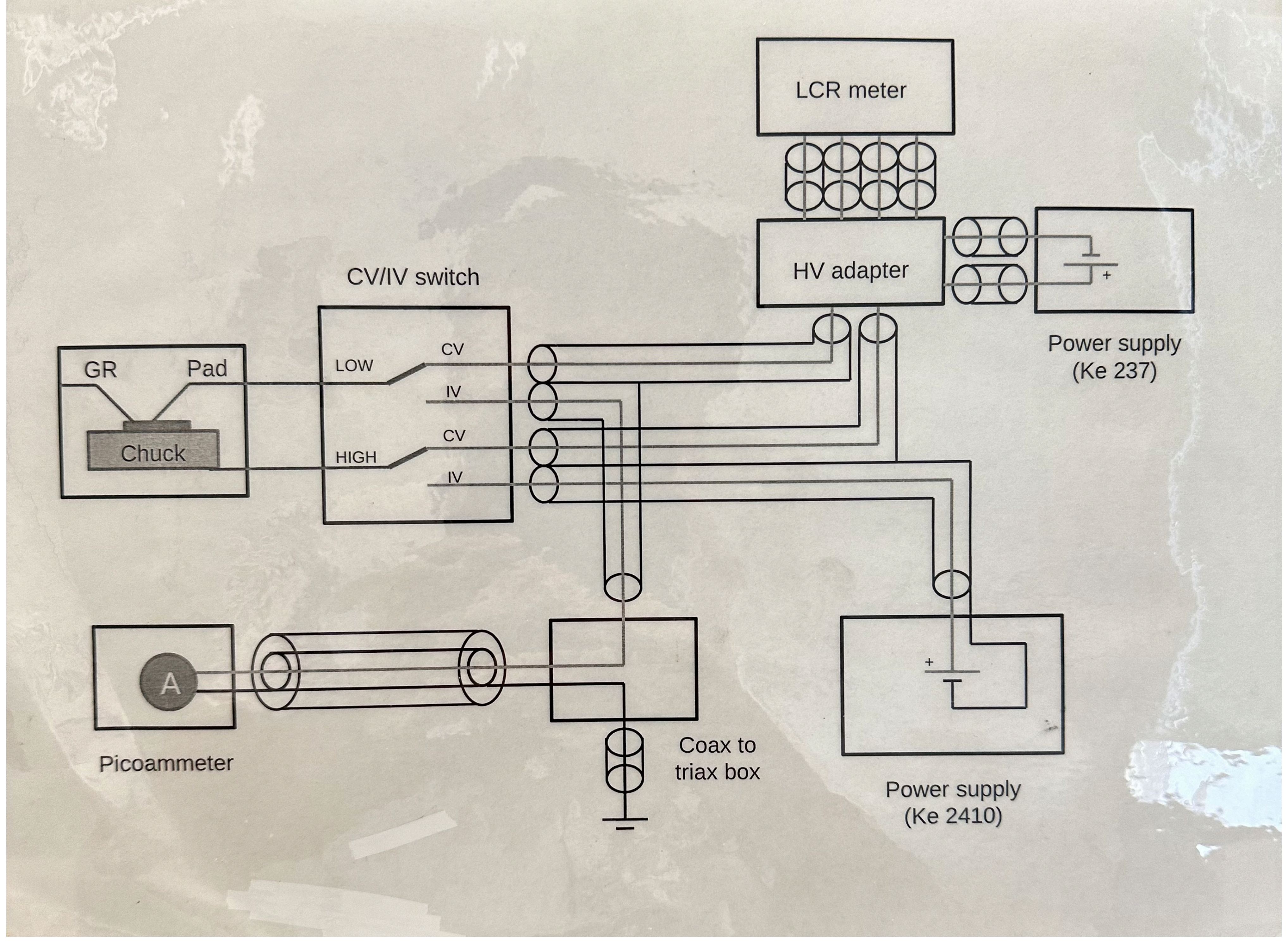


40	41	42	43	44
30	31	32	33	34
20	21	22	23	24
10	11	12	13	14
00	01	02	03	04
Guard Ring Contacts				

- Each Pixel contains:
  - 1 Circular bump bonding pad
  - 1 Square wire bonding pad
  - 1 opening in metal layer for the laser
- Guard Ring Contacts:
  - Row of alternating bump bonding pads and wire bonding pads

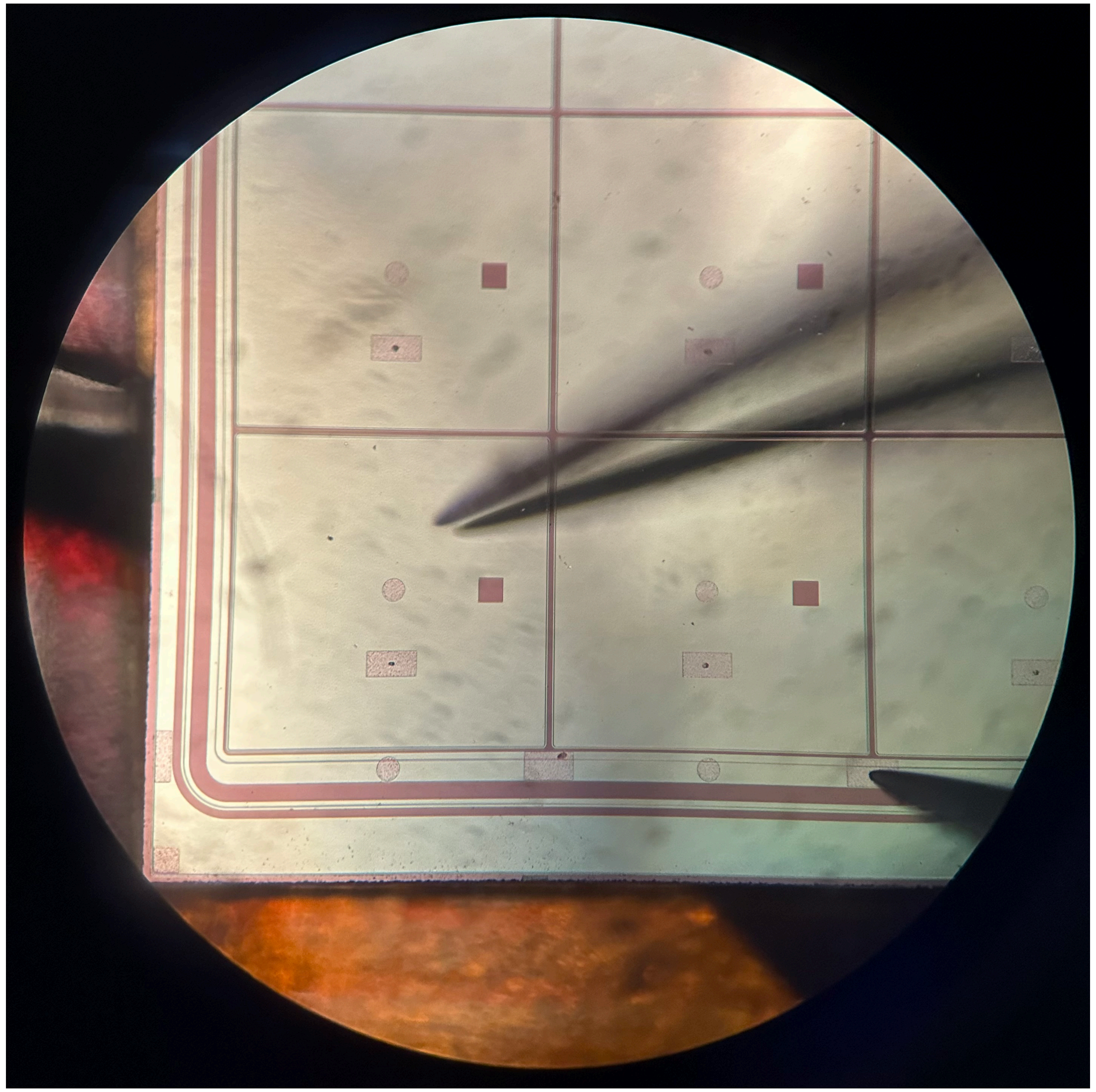
CVIV Setup at CERN

- Setup to measure the I vs V and C vs V characteristic curves of silicon devices:
  - Precise source with measurement capabilities for providing the voltage - 2x Keithley 2410 SourceMeter
  - Precise ammeter for measuring the current - Keithley 6487 Picoammeter
  - LCR meter for measuring capacitance and conductance - Agilent E4980A
- Chuck with probes for mounting the devices:
  - Vacuum line, so the devices can be securely attached
  - Cooling loop goes through the chuck
  - Chuck is one of the contacts
  - 2 Probes provide additional contacts
- Chiller to provide cooling - required for irradiated samples
- Source of “Dry Air” for flushing when cooling (avoid condensation)
- Dark metal box, serves as a Faraday Cage and avoids stray light
- Microscope for adjusting the probes



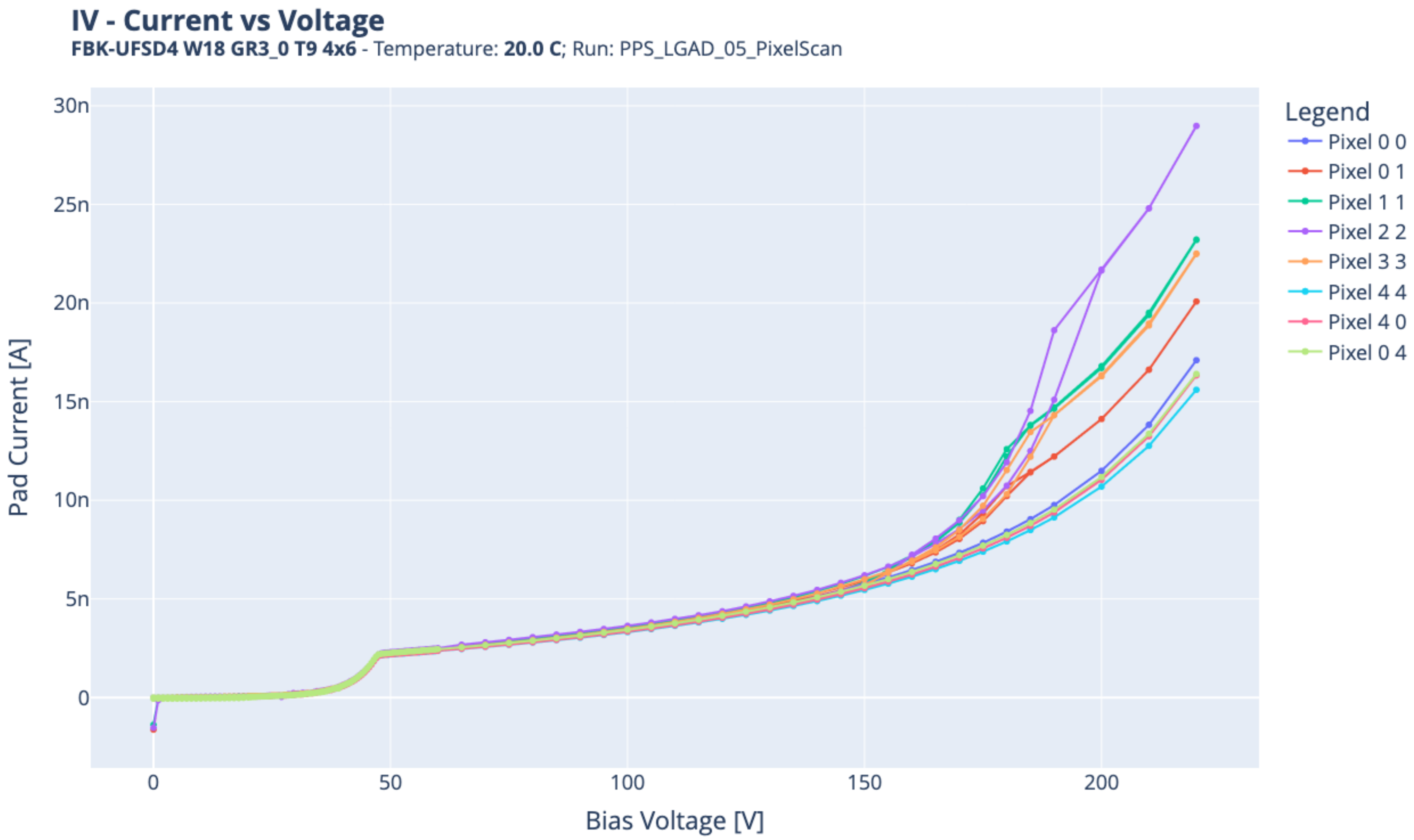
Measurement Procedure

- LGAD Sample is placed on chuck
- Probes are adjusted and made to contact the wire bonding pads:
  - Always use the 2nd wire bonding pad for the guard ring
- Make sure the “dry Air” is flowing
- Close the box
- Measure IV, CV (if these measurements are not done, wait enough time for the gas to fully flush the box interior, ~10 minutes)
- Cool the setup to -20 C: cooling takes at least 15 minutes
- Measure IV, CV
- Warm the setup to 20 C: warming up takes at least 5 minutes

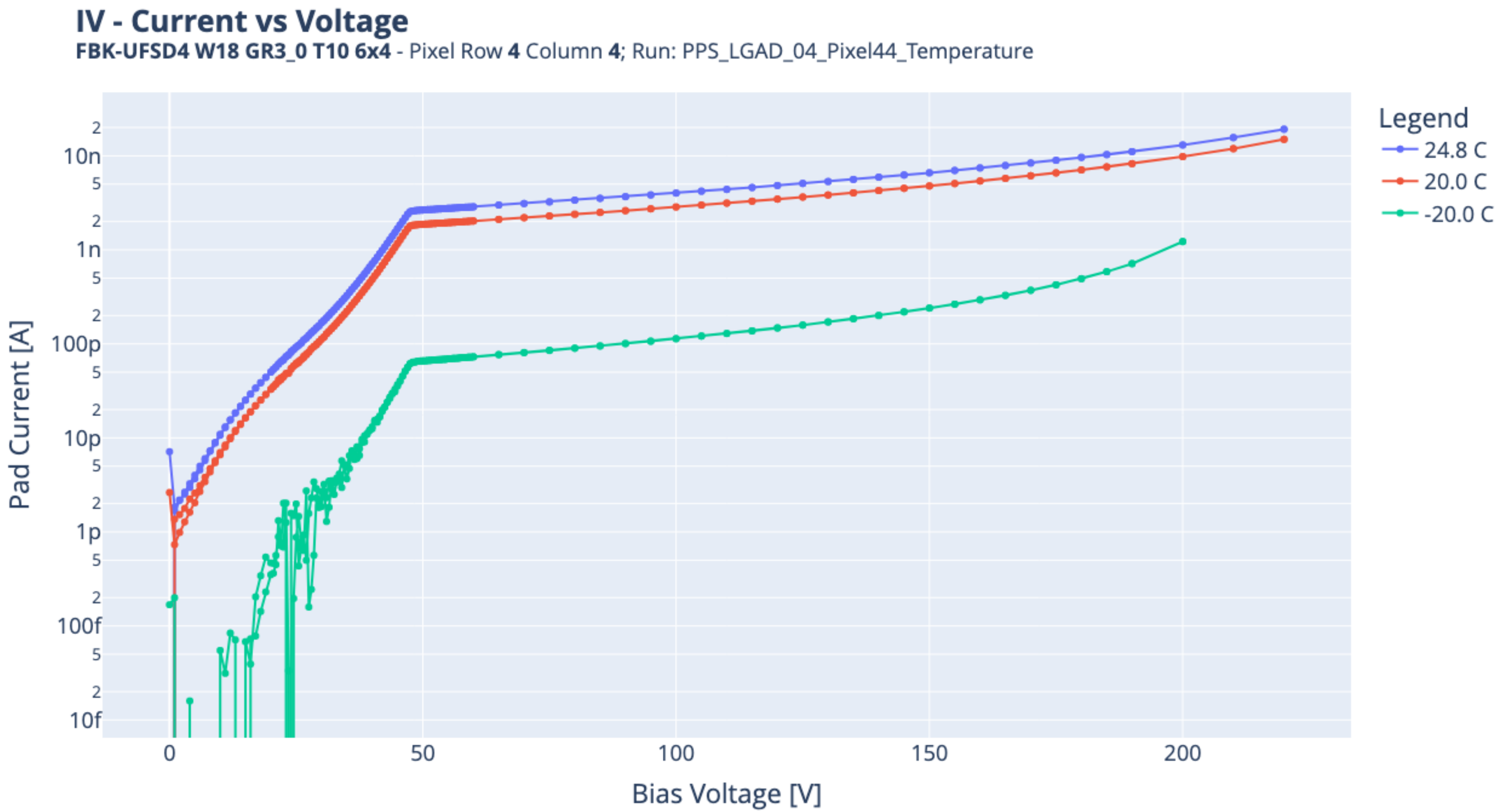


Bottom probe is contacting, Top probe is not contacting

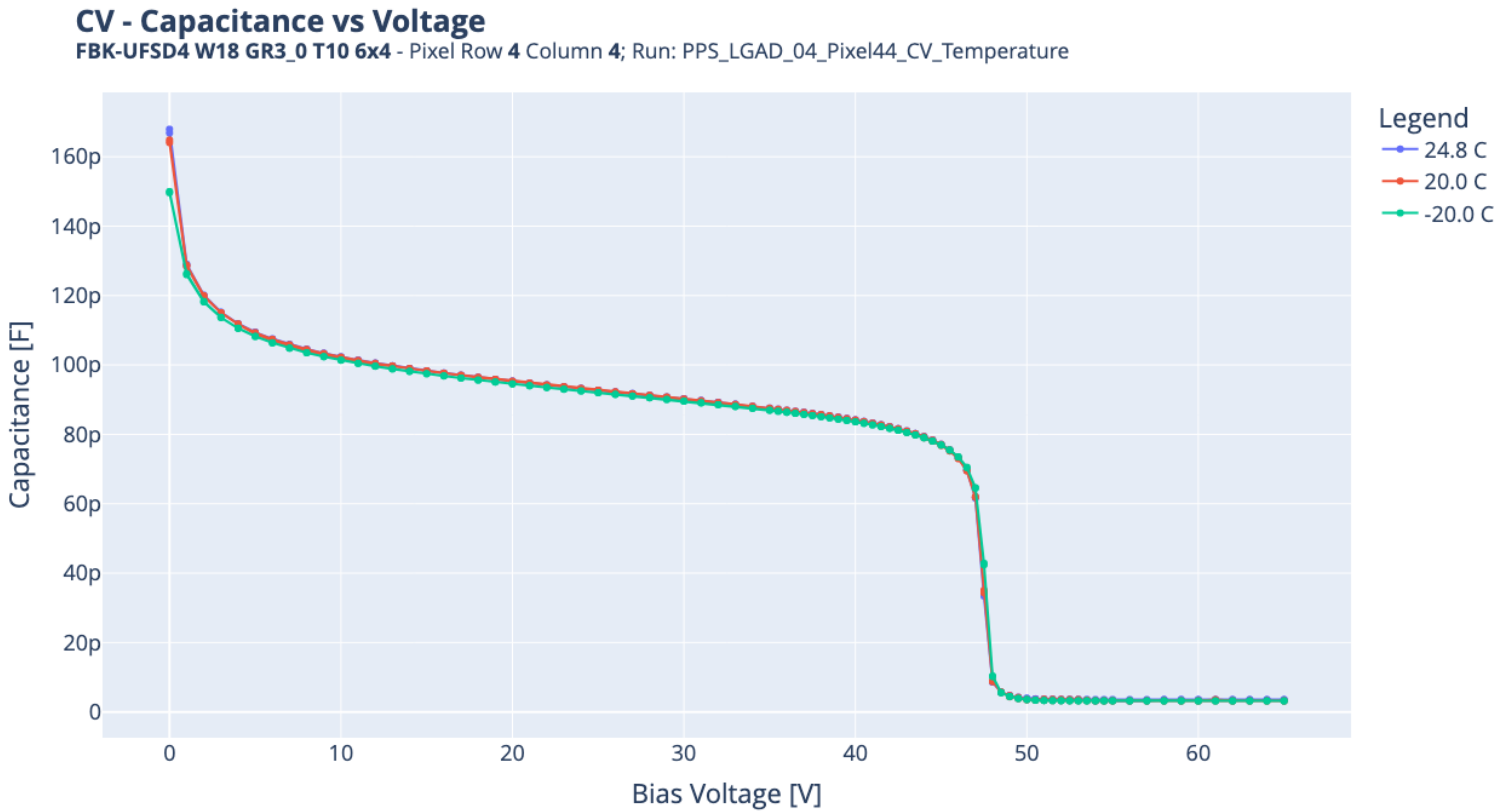
IV Curves of Pads in 1 Device



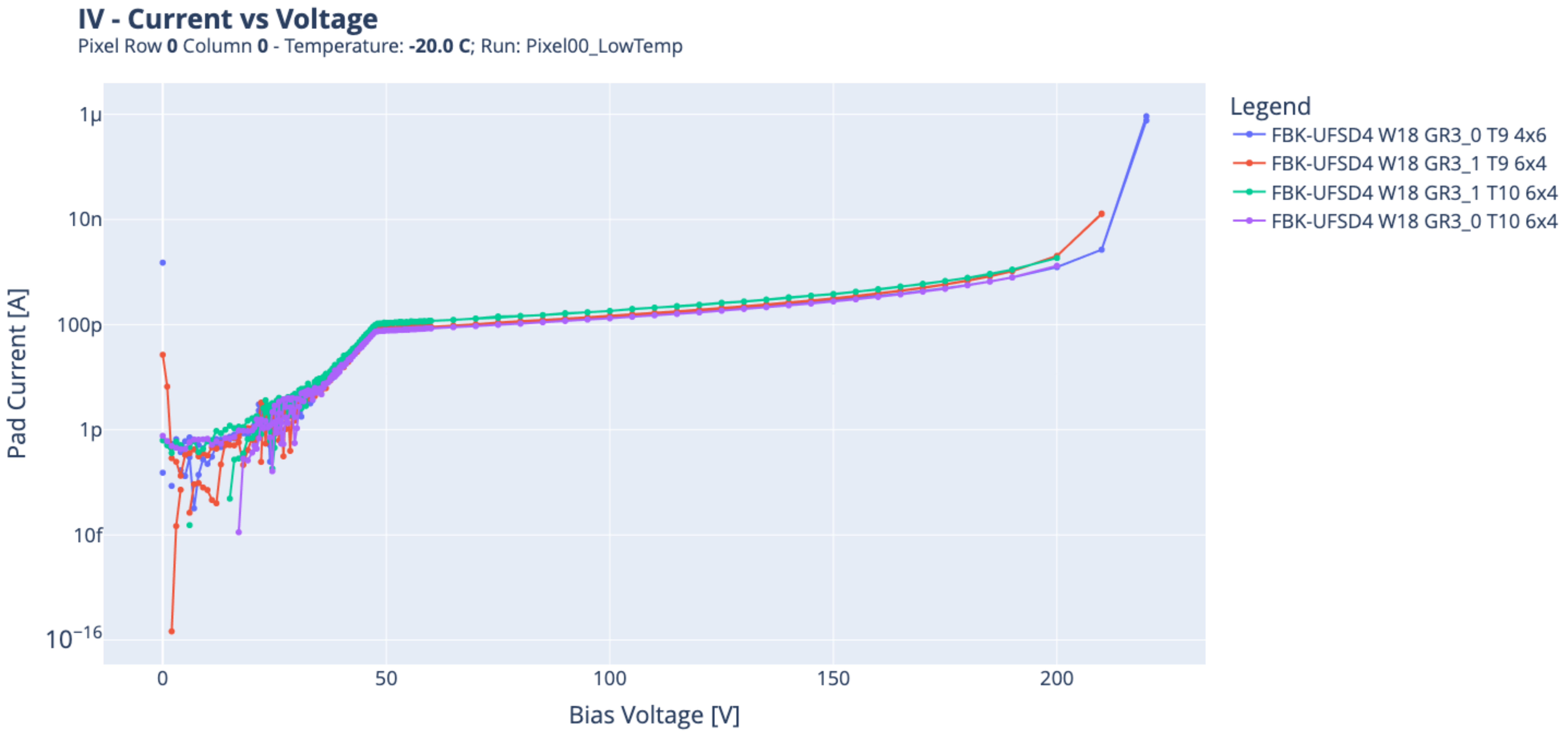
Temperature Effect - IV



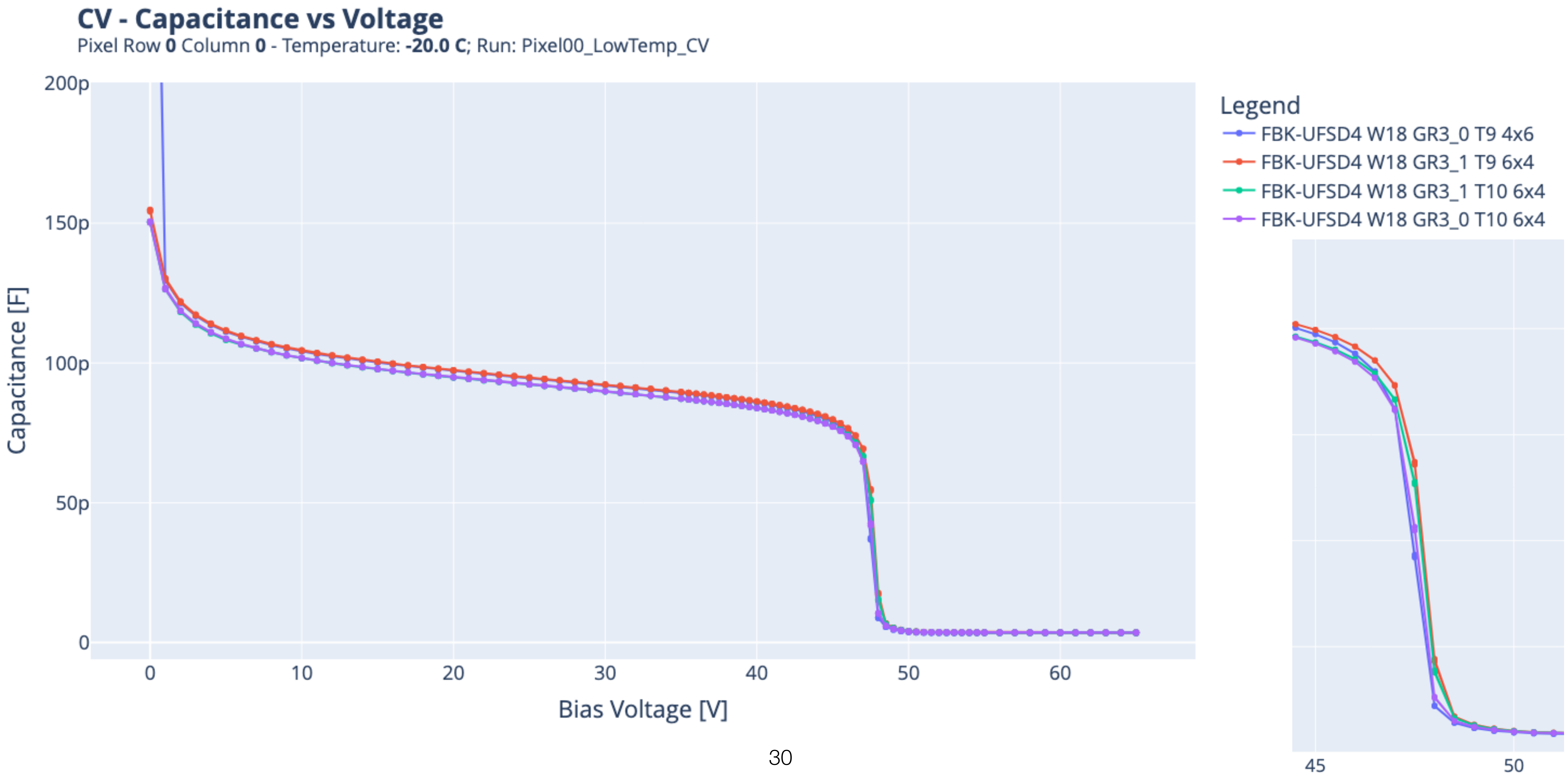
Temperature Effect - CV



IV Across Devices



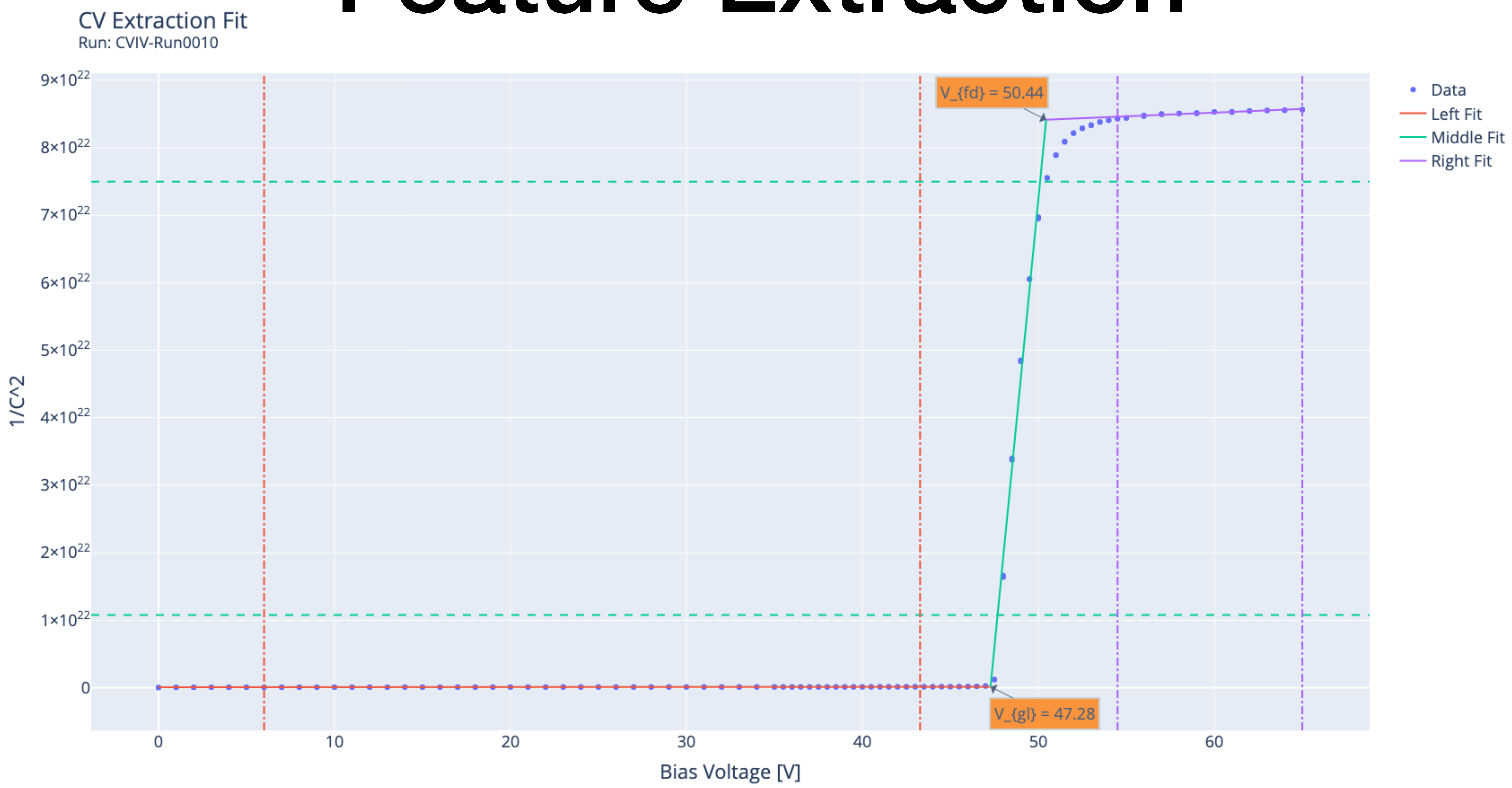
CV Across Devices



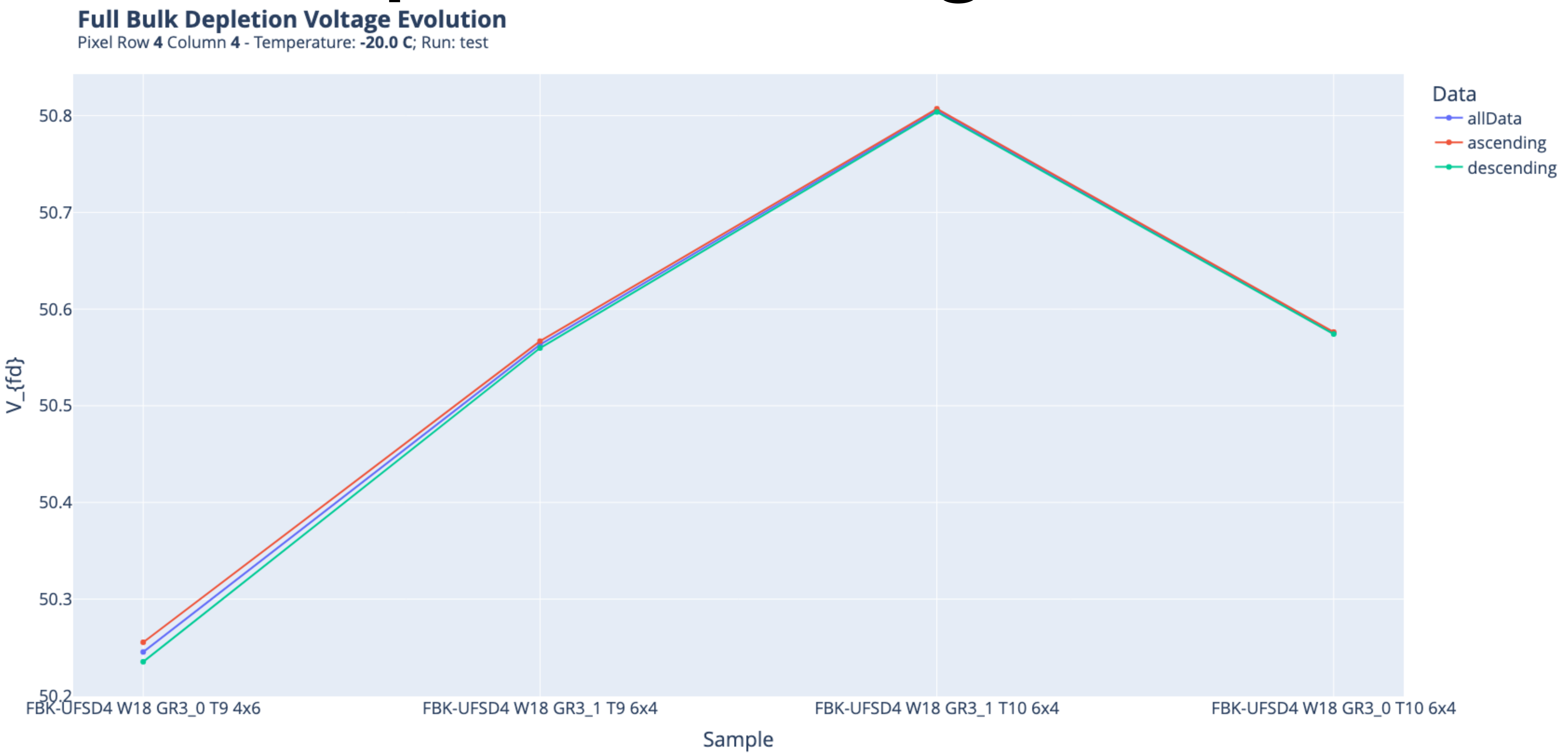
Feature Extraction

- Extract some relevant parameters from the CV curve:
  - Transform C vs V plot into $1/C^2$ vs V plot
  - Fit each section with a straight line
  - The points where the straight lines intersect define the Gain Layer Depletion Voltage (V_{gl}) and the Full Bulk Depletion Voltage (V_{fd})

Feature Extraction



Full Depletion Voltage vs Device



Full Depletion Voltage vs Pixel

Gain Layer Depletion Voltage vs Pixel