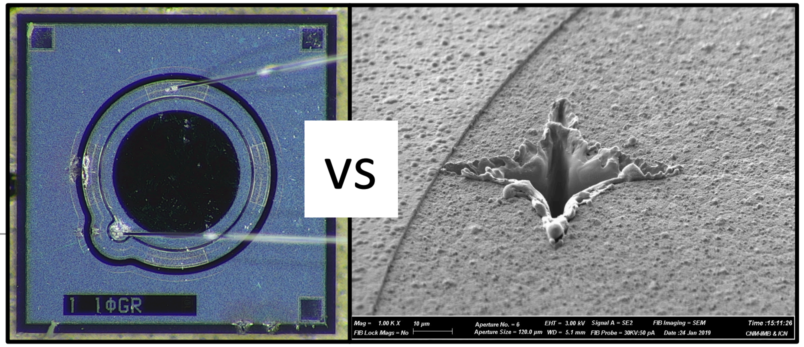
Workshop on Pico-Second Timing Detectors for Physics
University of Zurich
9-11 September 2021

Systematic Study of Heavily Irradiated LGAD Stability using the Fermilab Test Beam Facility

V. Sola on behalf of the CMS Collaboration

Introduction

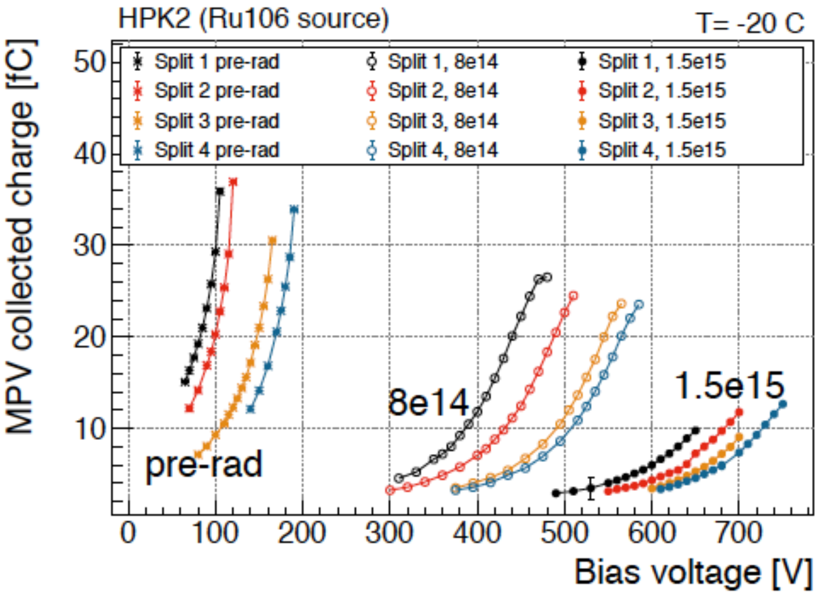


- In past beam tests, fatal events have been observed on highly irradiated LGADs
  - → No evident correlation between the events, a systematic investigation was necessary
- Two beam test campaigns at Fermilab dedicated to investigating thin sensor mortality
  - → Extensive collaboration of ATLAS High-Granularity Timing Detector and CMS Endcap Timing Layer crews to plan the activity, select and prepare sensors
  - → 30 sensors have been tested in December 2020 and March 2021
  - → precise control over all the involved parameters (e.g., temperature, humidity, bias stability)
- Main outcomes of the December and March campaigns
  - → Improve the understanding of the cause for mortality
  - → Collect statistics with a diverse set of sensors
  - → Probe a safe region for operation and develop a mitigation strategy

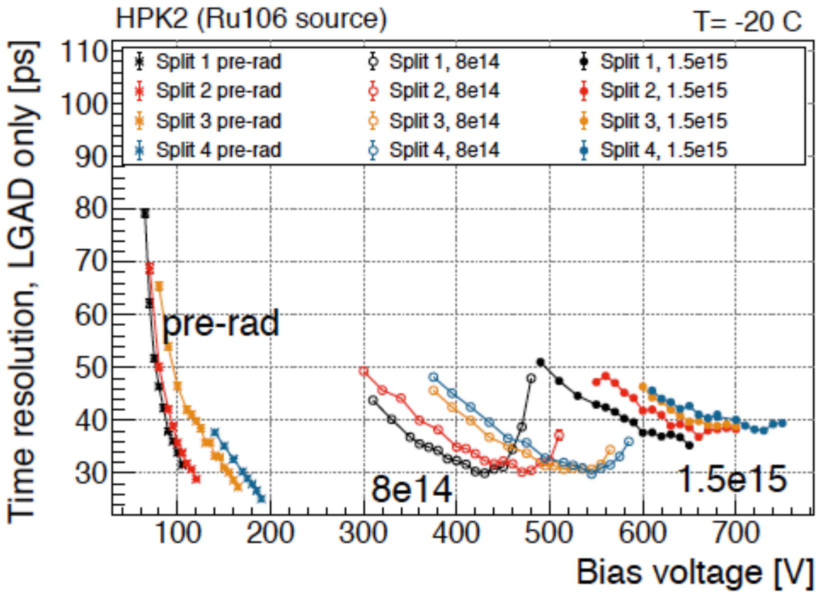
Sensors under Test – HPK2

▻ Focus on latest HPK production: HPK2
→ 4 gain flavours, from Split 1 to Split 4 (lowest to highest operating voltage)

MPV Collected Charge

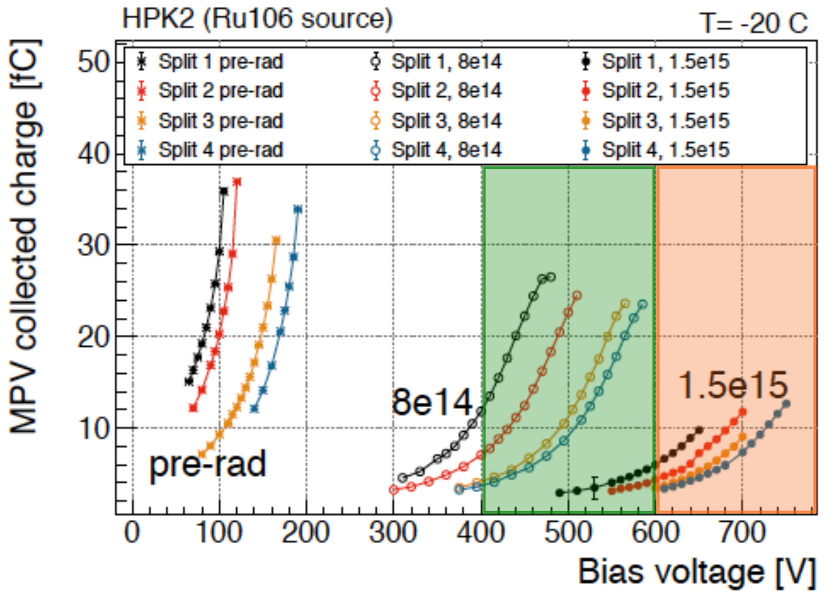


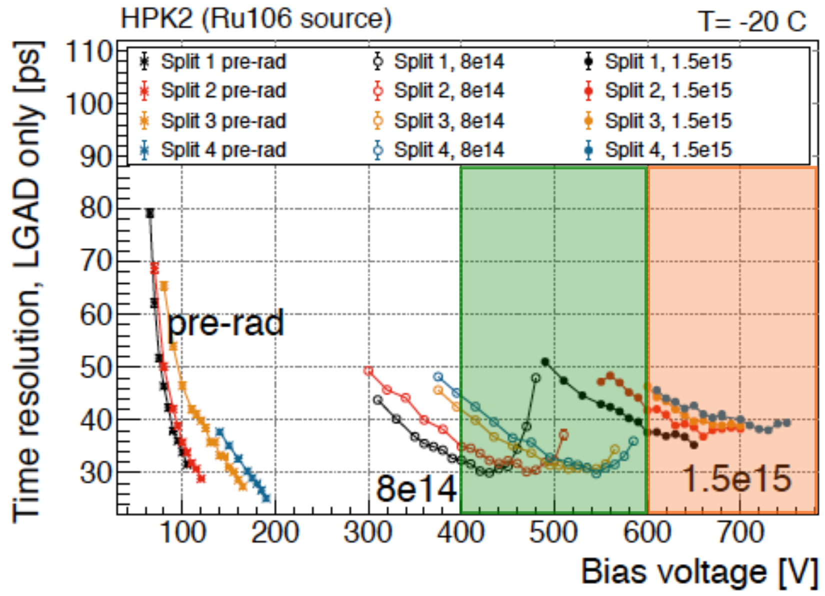
Time resolution



Sensors under Test – HPK2

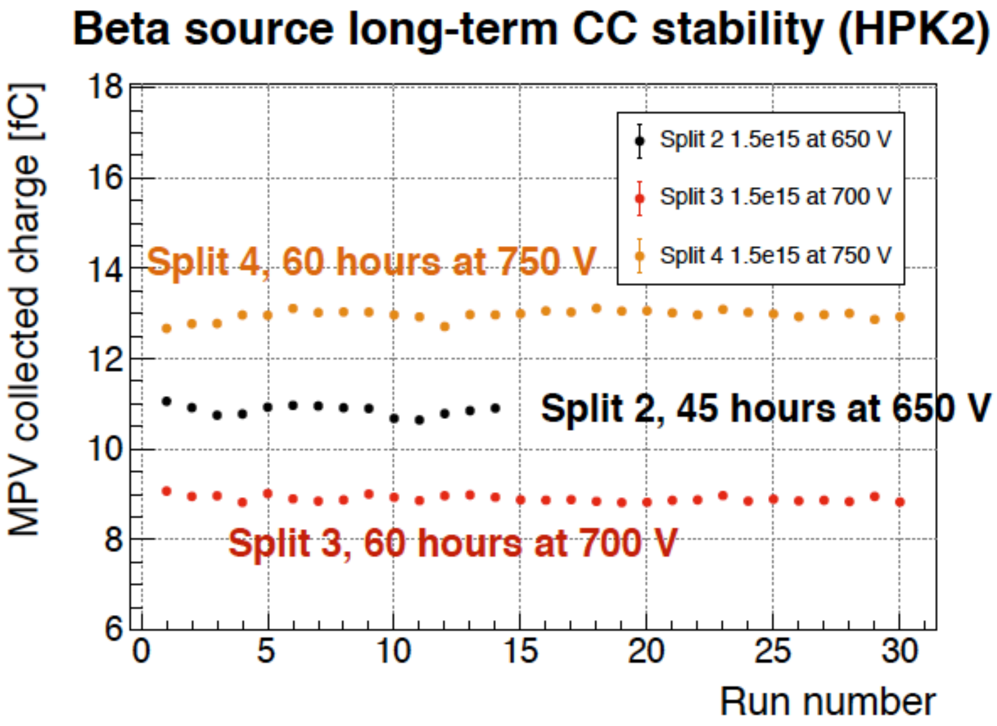
- Focus on latest HPK production: HPK2
  → 4 gain flavours, from Split 1 to Split 4 (lowest to highest operating voltage)
- Two phases of beam test campaign
  → Sensor death: > 600 V, primarily 1.5E15 n_{eq}/cm^2
  → Survival region: 400—600 V, 8E14 – 1.5E15 n_{eq}/cm^2

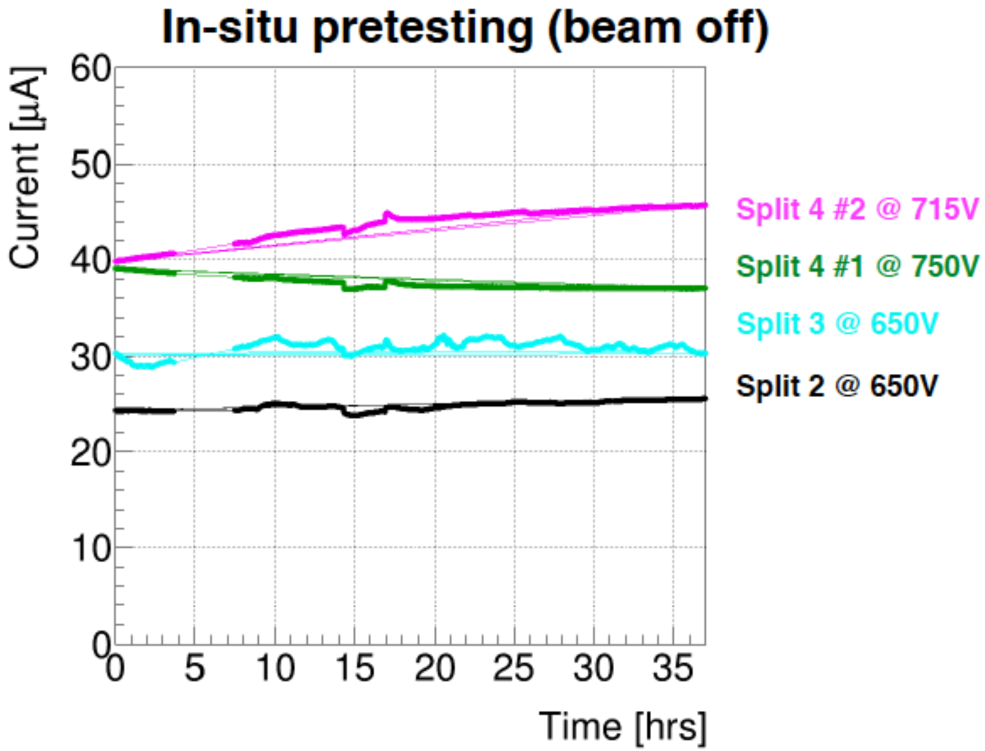




LGAD Stability Check

- Prerequisite for mortality studies: prove LGAD stability in absence of beam
  - ⟶ Extensive pre-biasing of every sensor in absence of beam
  - ⟶ LGADs show a stable behaviour at much higher voltage than reached in beam test

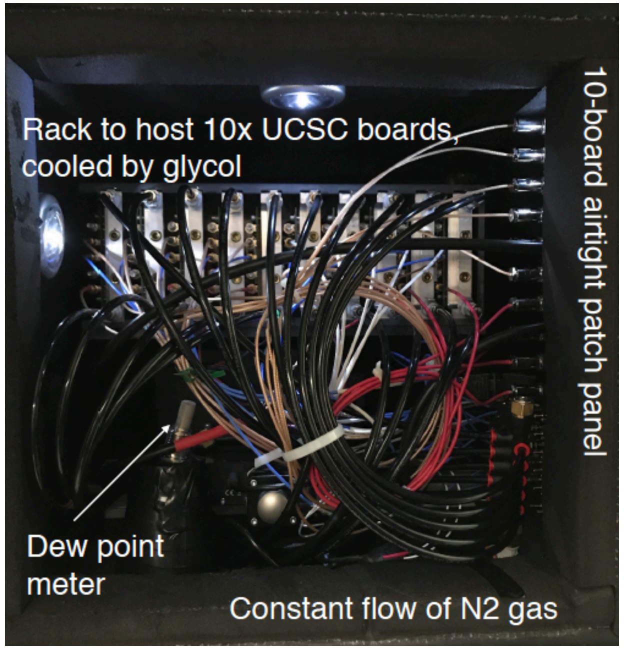




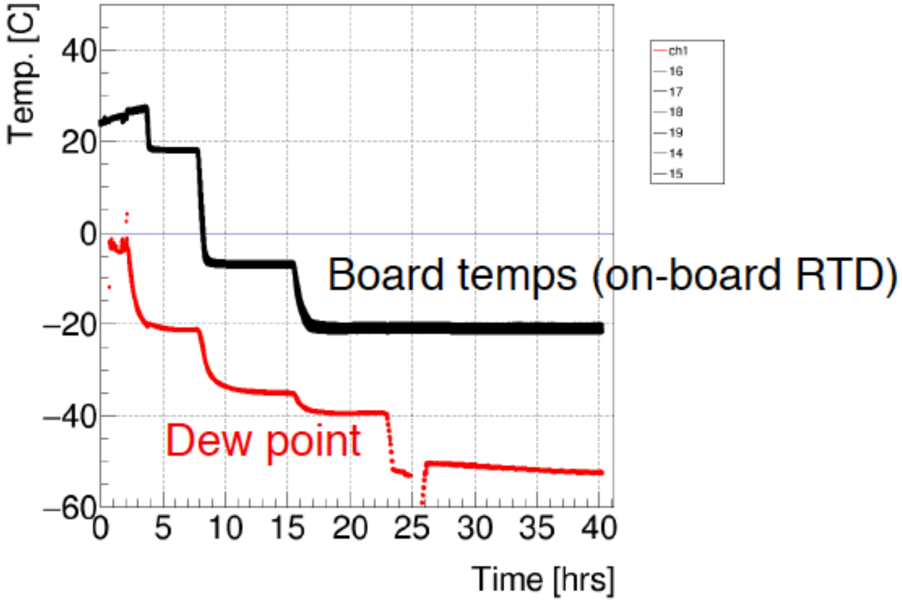
Environmental Control in Beam Tests

- ▻ Precise control over all the parameters inside the cold box
  - ⟶ Cool down only after dry for a very long time
  - ⟶ Dew point 20–30ºC below the board temperature at all times

LGAD cold box at the Fermilab test beam

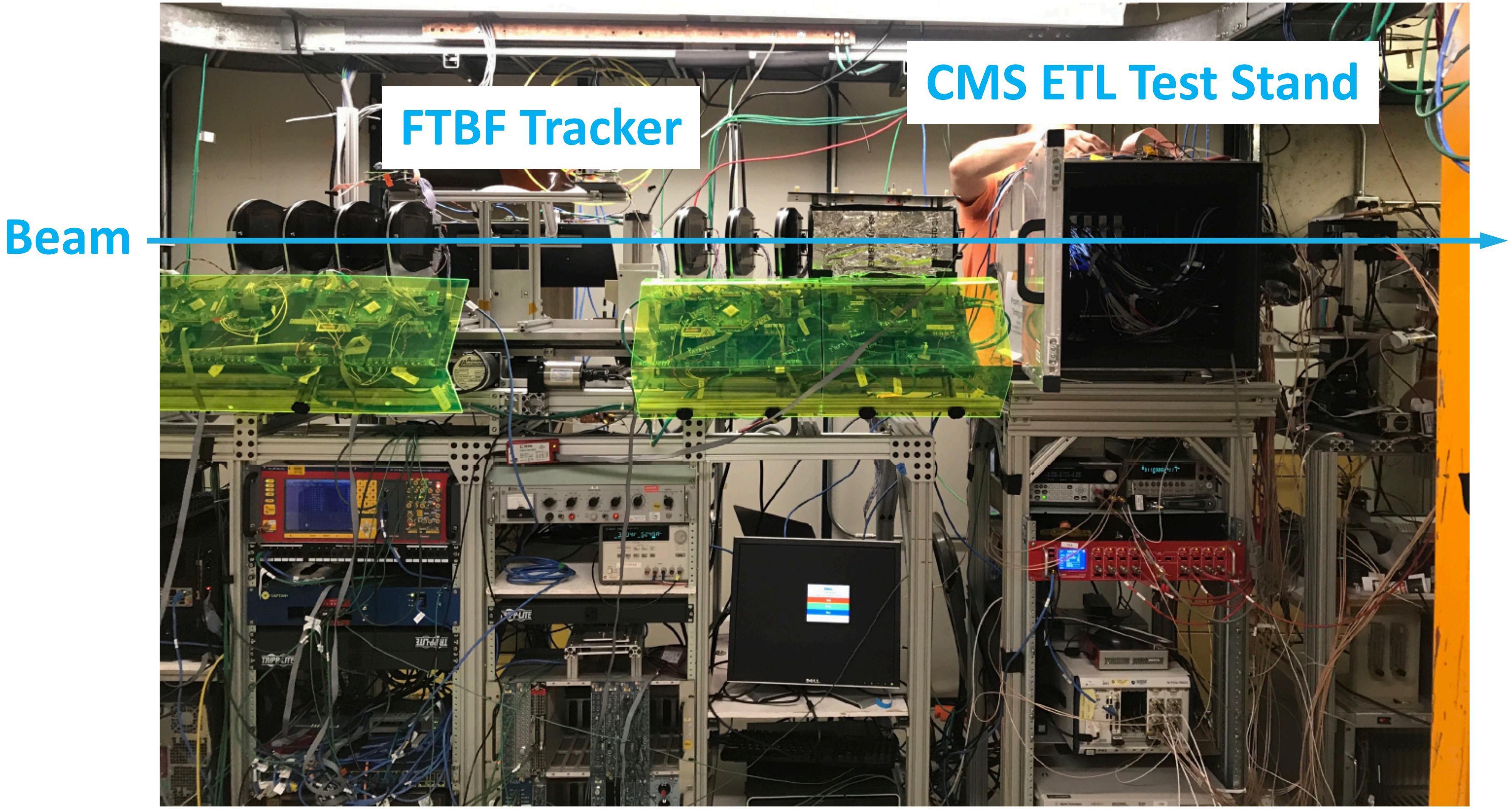


Environmental monitoring, post-installation



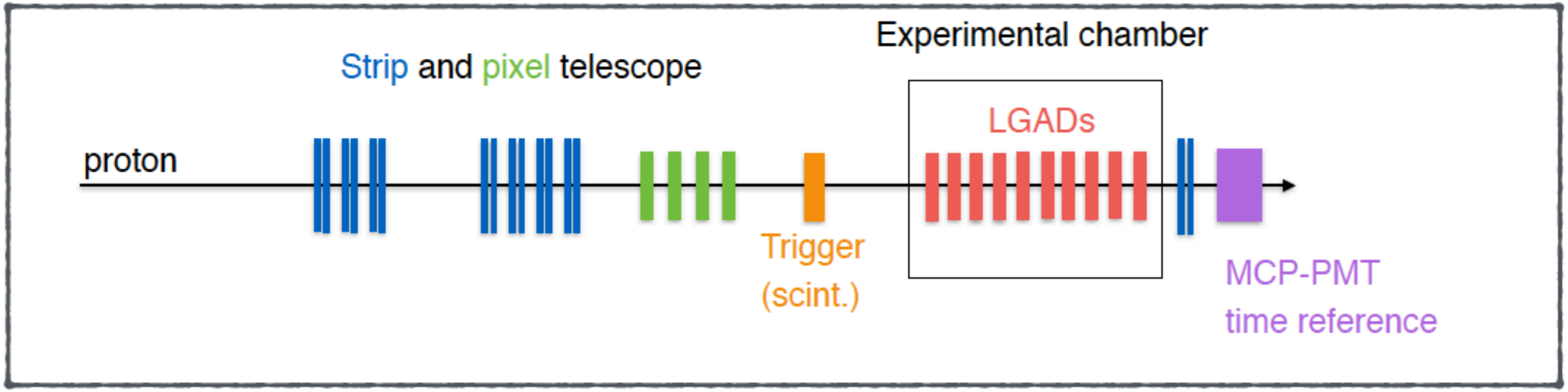
Fermilab Test Beam Facility

- 120 GeV protons, arriving in 4 second spill, once per minute



Fermilab Test Beam Facility

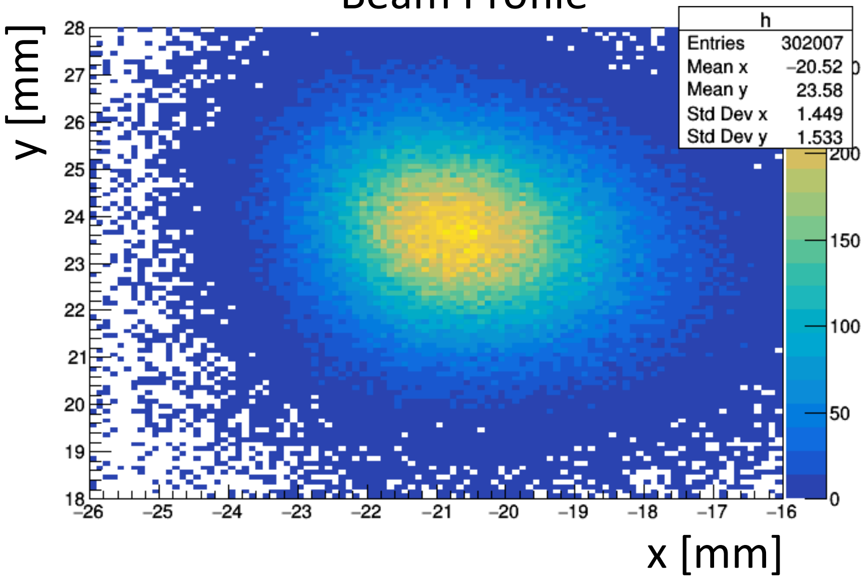
- Measure proton track using facility telescope
  → 40 μm resolution in this configuration
- Read LGAD and MCP time reference with a fast, high-resolution oscilloscope
- Developed high DAQ efficiency ~ 75% (trigger & find track)
  → Contrast with typical LGAD studies: rarely care about trigger efficiency



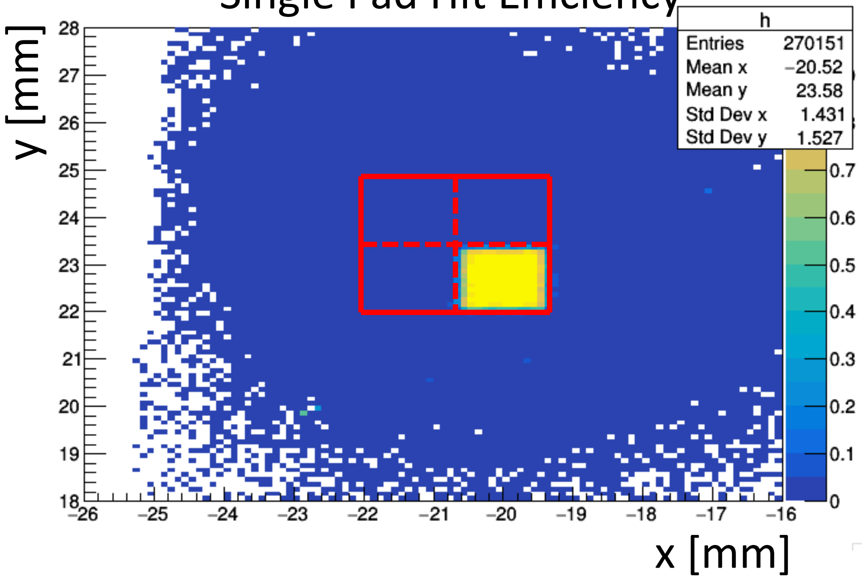
Mortality Study – The Procedure

- ▻ Measure beam profile with tracker
- ▻ Align each sensor with the beam using a motion stage
  - → Occupancy: 3k hits per spill per 2x2 sensor (10k protons total per spill)
- ▻ Slowly increase bias voltage and monitor operation
  - → Increase 25V after 100-200k protons on the sensor

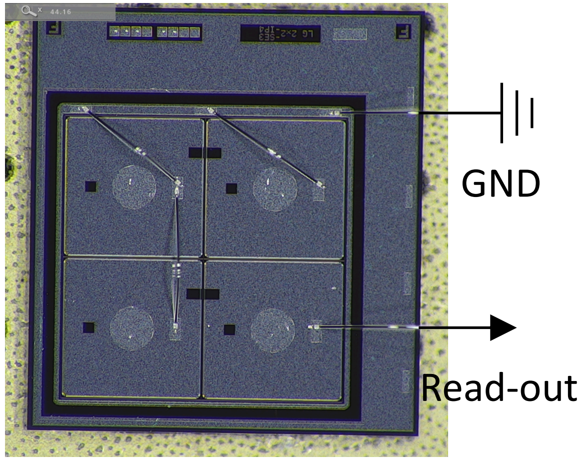
Beam Profile



Single Pad Hit Efficiency



Most of the sensors are 2×2 arrays



Only 1 pad is readout
The 3 spectator pads are grounded

Observed Death Events

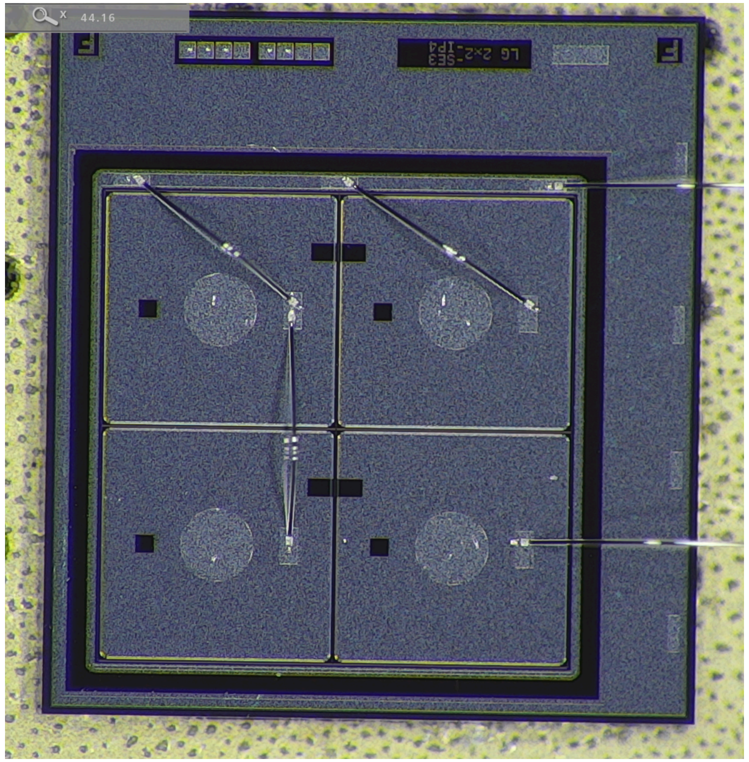
- ▻ Over 21 sensors tested → All died

Sensor Type	# of sensors	Fatal Voltage	# of protons at Fatal V	Notes
HPK2 @ 1.5E15 n_{eq}/cm^2	7	625 – 675 V	10k – 30k	"Standard candle"
HPK2 @ 2.5E15 n_{eq}/cm^2	4	625 – 675 V	10k – 30k	Role of gain & fluence?
HPK2 PINs @ 1.5E15 n_{eq}/cm^2 or 0.1 MGy	3	625 – 700 V	10k – 30k	
50D and HPK3.1	2	675 – 700 V	10k – 30k	Role of thickness?
Remove HV capacitance (add 10M HV resistor in 1 case)	3	670 – 700 V	500k – 2M	Treatments to prevent death? (using standard HPK2 1.5E15 n_{eq}/cm^2)
Encapsulated sensor	2	625 – 675 V	10k – 30k	

Death Event – Example 1

- HPK2 split 3 sensor, fluence 1.5E15 n_{eq}/cm^2
  - → Pre-biased in-situ for 6 hours at 700 V
  - → Operated in beam for 2 hours at 500-600 V
  - → Destroyed after 2 minutes at 625 V

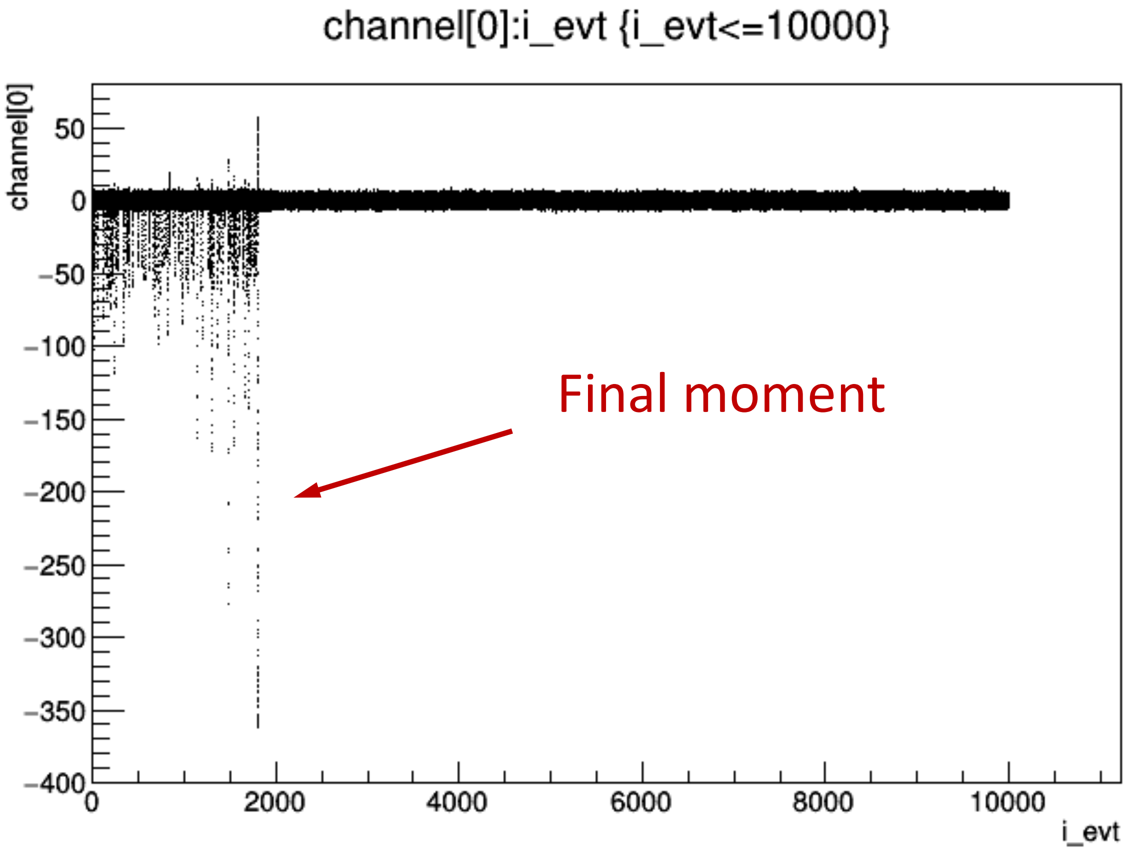
HPK2 split 3 SE3 IP4, 1.5E15 n_{eq}/cm^2



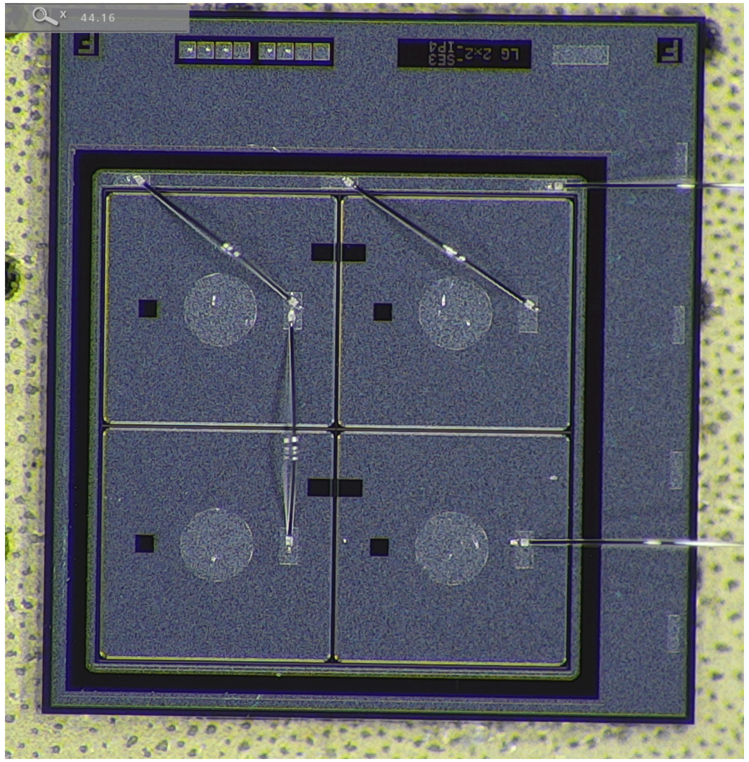
(still alive)

Death Event – Example 1

- LGAD waveforms in 10k triggers during 4s spill



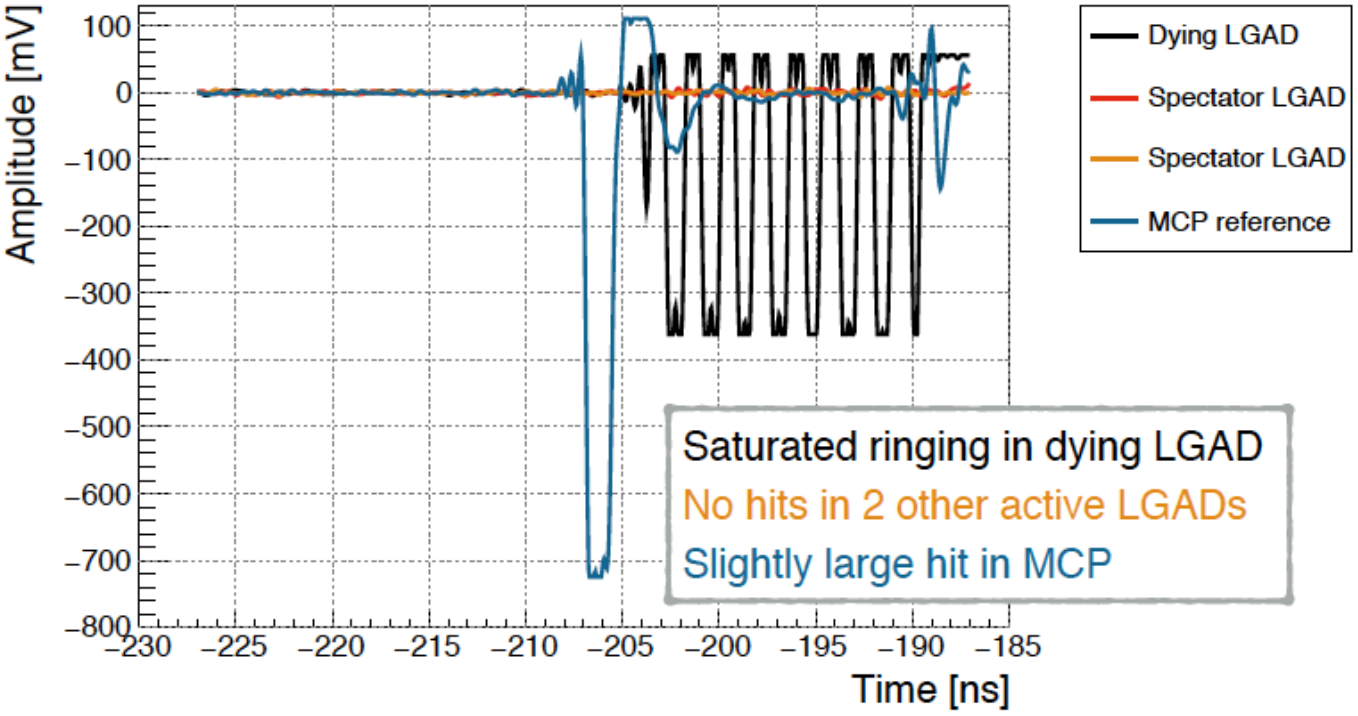
HPK2 split 3 SE3 IP4, 1.5E15 n_{eq}/cm^2



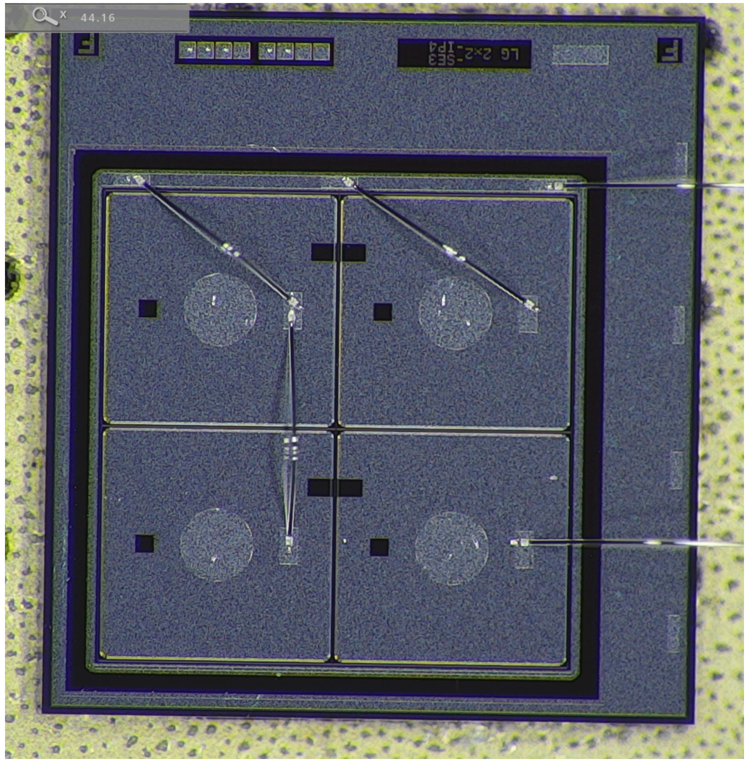
(still alive)

Death Event – Example 1

Waveforms in fatal event



HPK2 split 3 SE3 IP4, 1.5E15 n_{eq}/cm^2



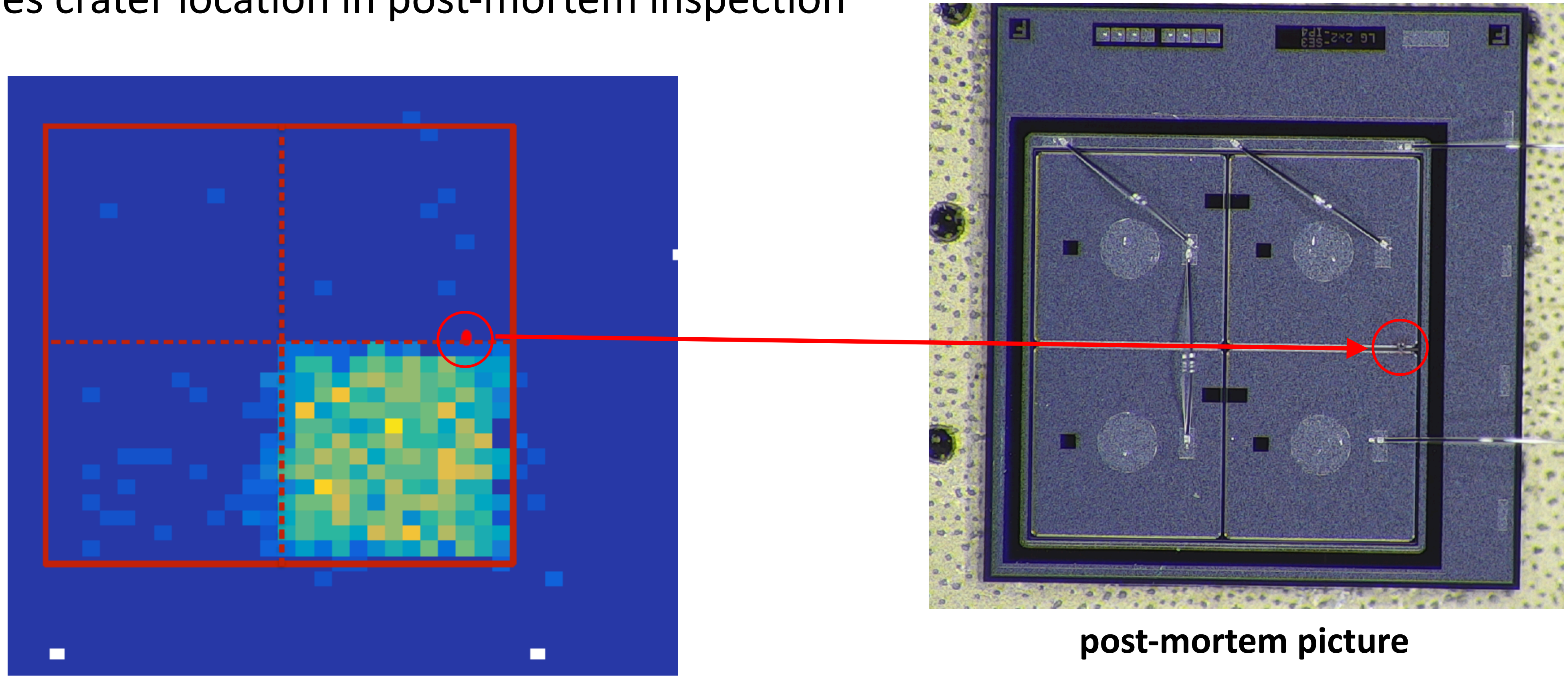
(still alive)

→ **Death within 1 ns of proton arrival**

Death Event – Example 1

- Reconstruct proton track in fatal event
- Matches crater location in post-mortem inspection

HPK2 split 3 SE3 IP4, 1.5E15 n_{eq}/cm^2



post-mortem picture

Death Event – Example 1

- Reconstruct proton track in fatal event
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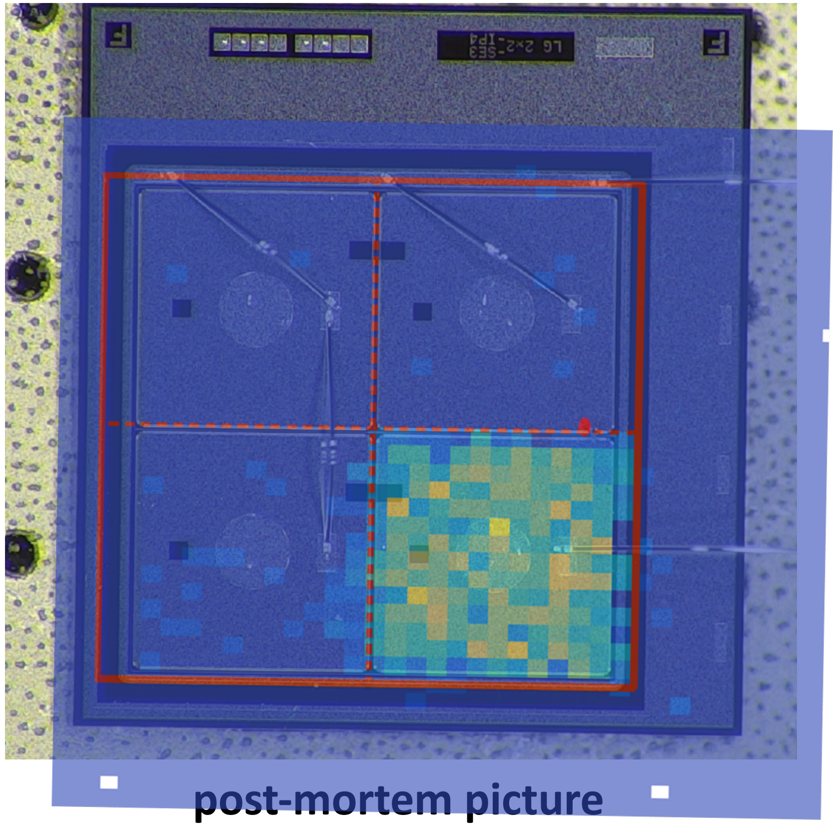
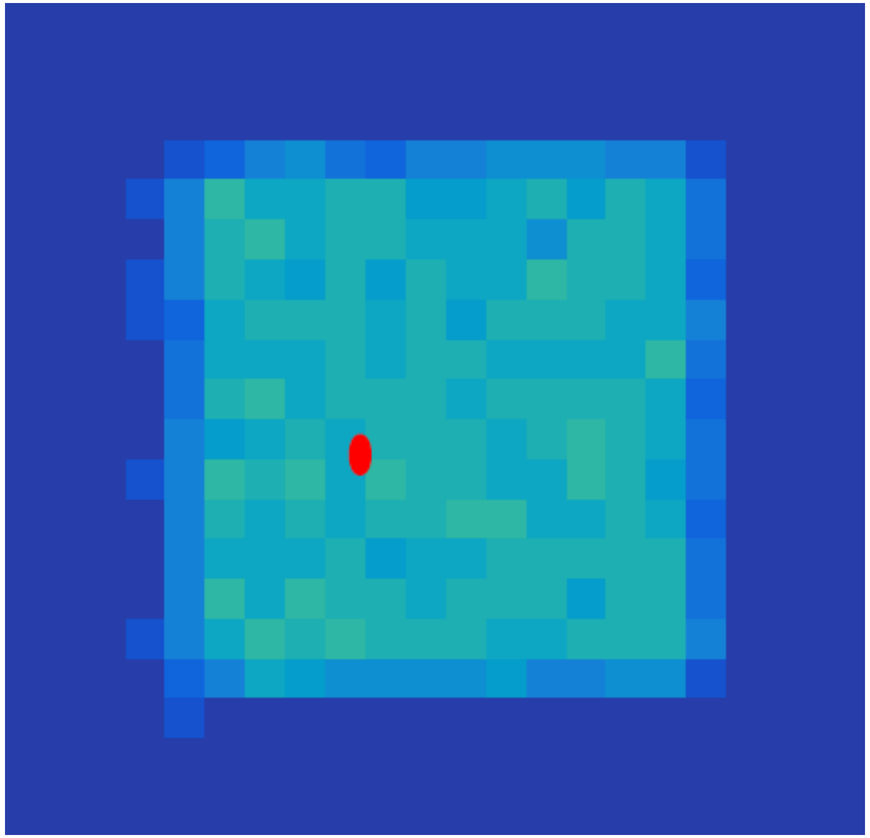
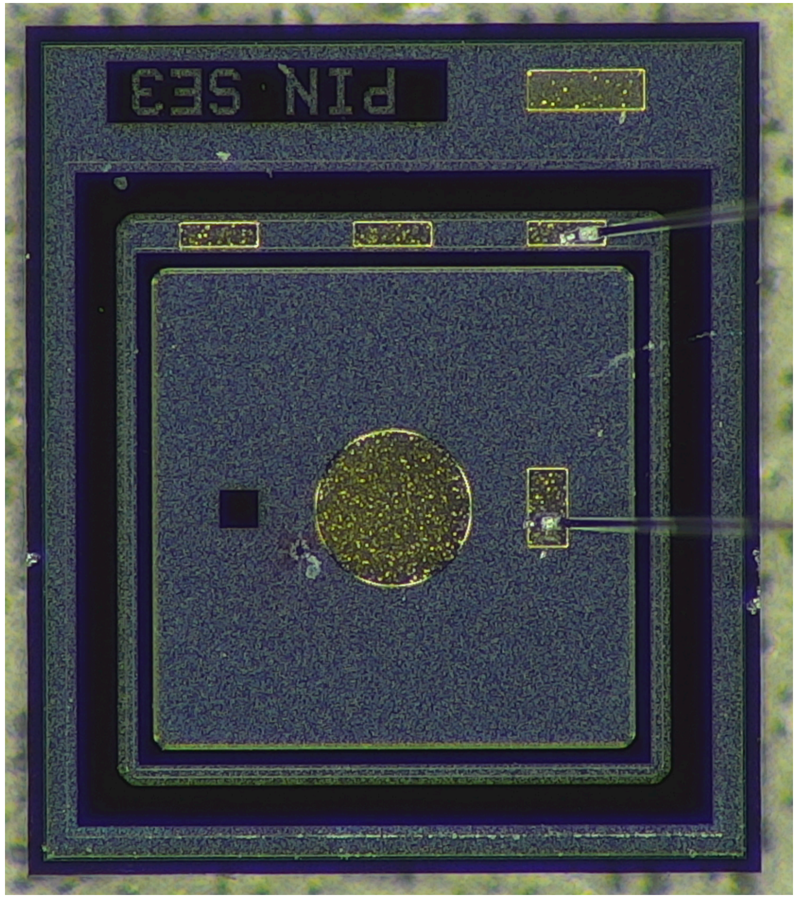
HPK2 split 3 SE3 IP4, 1.5E15 n_{eq}/cm^2



Death Event – Example 2

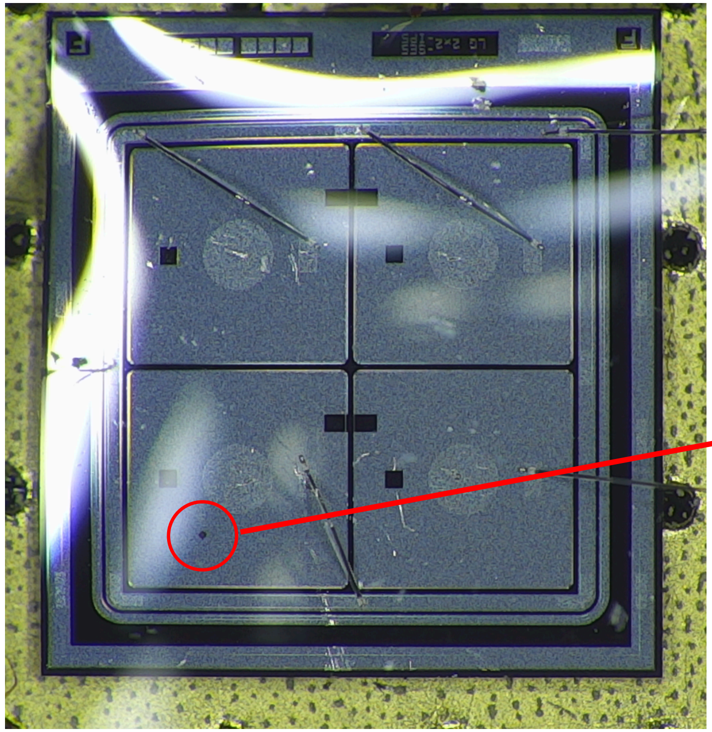
- **PiN at 0.1 MGy, HPK2 W36 (B115)**

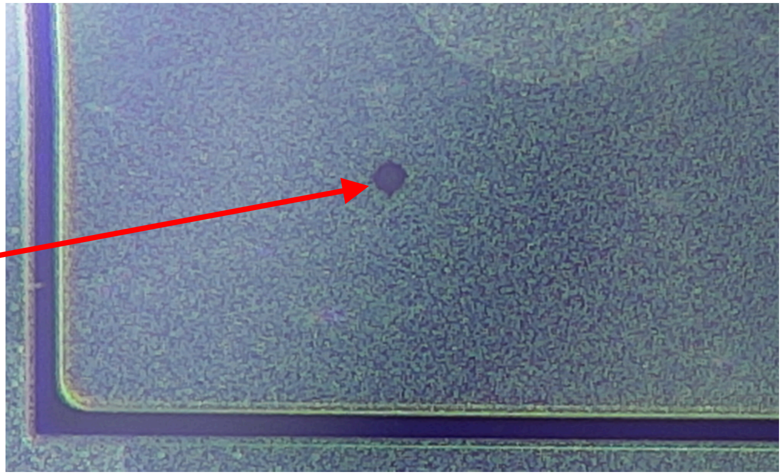




Death Event – Example 3

- Encapsulated sensors
  - → Two sensors completely covered with wire bond encapsulant (Sylgard 186)
  - → Crater clearly originates underneath encapsulation
  - → No effect on lifetime or other properties

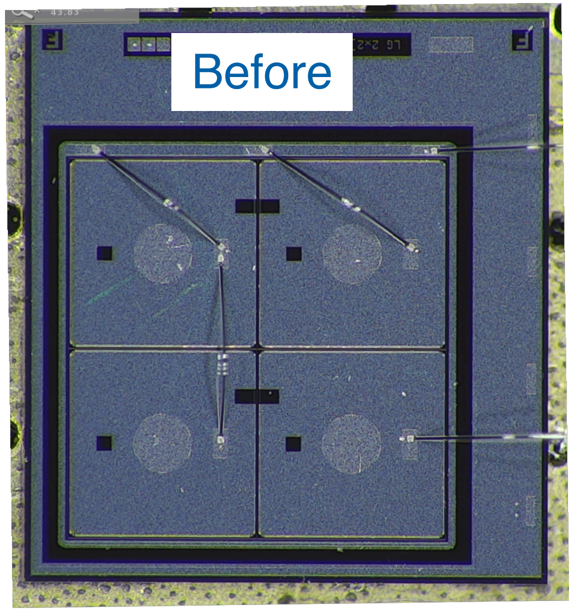


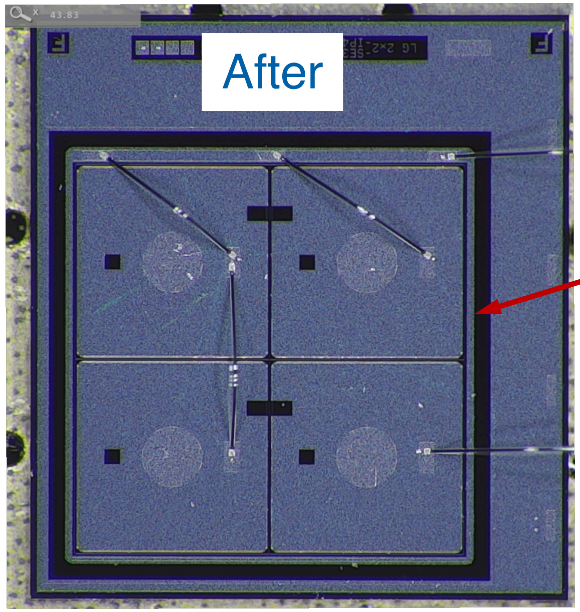


Death Event – Example 4

- Death of sensor with no HV filtering capacitors
  - → Remove 10 nF of filter capacitors in parallel with sensor on UCSC board
  - → Increase lifetime by ~50x
  - → Less dramatic death

HPK2 Split 4 1.5E15 SE3IP4





Fatal track points here

No clearly visible features post-mortem

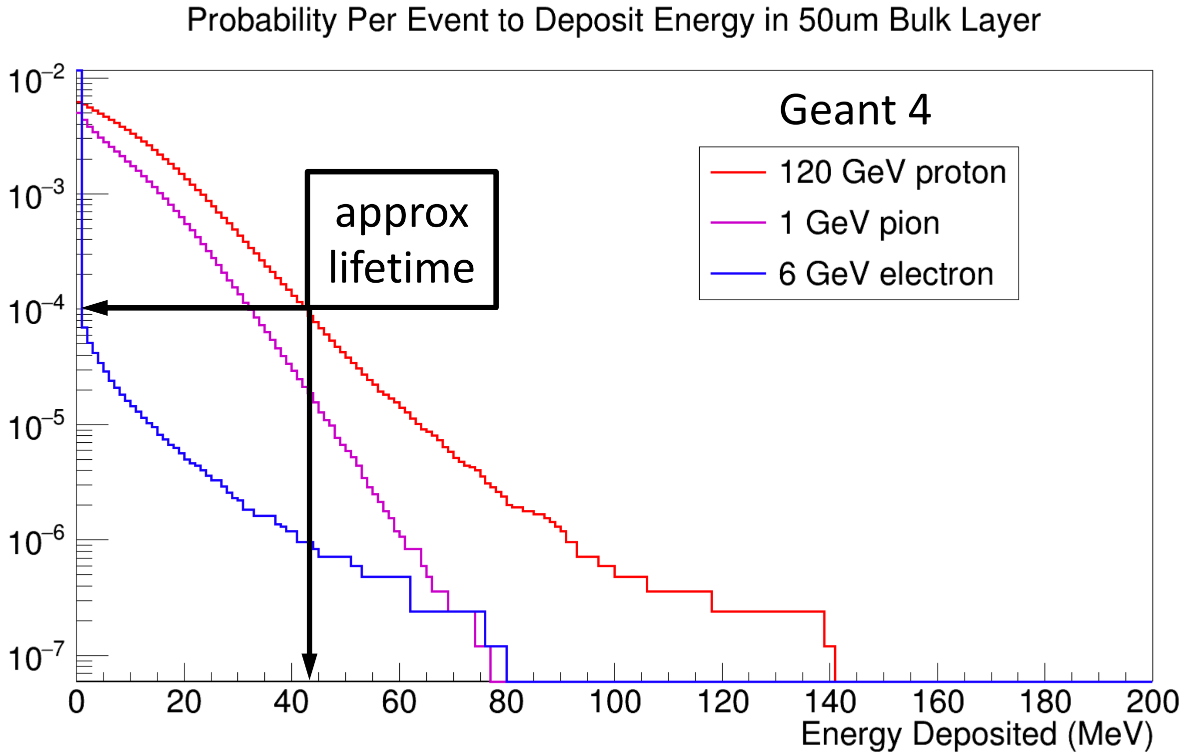
→ Sensor still weak diode after death! (BD @ ~200 V)

Proposed Death Mechanism

- Rare, large ionization event “Highly Ionising Particle”
  → Excess charge leads to highly localized conductive path
  → Large current flows in a narrow path – “Single Event Burnout”

- Estimate 40-50 MeV deposit needed
  → Rare, but possible in DESY 6 GeV electron beam (has been observed)
  → Common at LHC

- Some ability to model in TCAD, but not really “predictive” so far



Proposed Death Mechanism

- Rare, large ionization event "Highly Ionising Particle"
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- **The energy to melt and vaporise a cylinder of silicon with height of 50 µm and diameter of 10 µm is about 150 µJ**
  → The energy stored in the HV filtering capacitance of the read-out board used in the testing is ~ 2 mJ
  → The energy stored in a 2×2 sensor array with pad area 1.3×1.3 mm^2 is ~ 3 µJ
  → The energy stored in a 16×16 sensor array with pad area 1.3×1.3 mm^2 is ~ 200 µJ

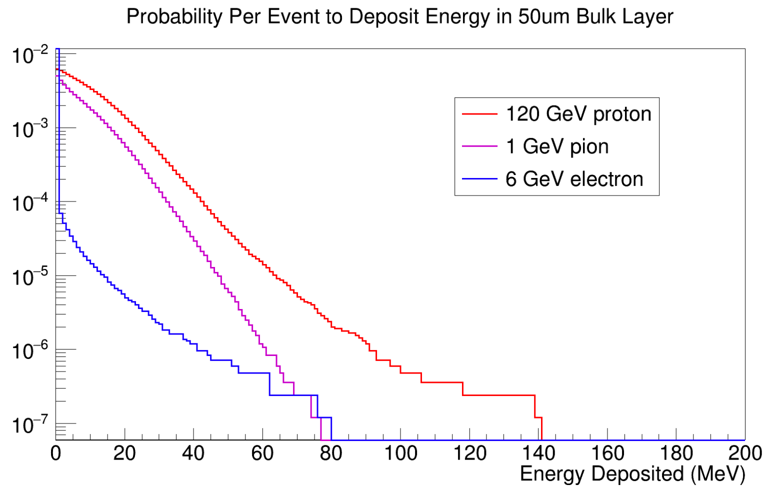
[U = 1/2CV^2, with V = 600 V]

Conclusion from Mortality Studies

- PiNs, and 2.5E15 n_{eq}/cm^2 LGADs die at similar conditions as 1.5E15 n_{eq}/cm^2 LGADs
  - → Gain is not necessary for the death mechanism
  - → Mortality is a function of sensor thickness and voltage only (to first order)
  - → ≥ 600 V for 50 μm thick sensors
- Proton track in a fatal event always points to crater
  - → Death is caused by localized single proton interaction
- HV capacitance accelerates death and increases the severity of death events
  - → But, not possible to escape capacitance in a full-sized array (~1 nF)
- Crater location: no major preference
  - → 1/3 at pad edge, 1/3 near bonding sites, 1/3 generic location
  - → No preference for readout / non-readout pad

Survival Stress Testing

- ▻ The second phase: demonstrate survival of sensors at a reasonable operating voltage with as many hits as possible
- ▻ Use maximum intensity: 1M protons per spill (~120k per sensor per minute)
  - ⟶ Beam slightly defocused to illuminate 10 sensors simultaneously
- ▻ Proton fluences achieved (per sensor):
  - ⟶ 150M at a conservative voltage
  - ⟶ 350M at target operating voltage
  - ⟶ 100M at aggressive voltage beyond the optimal operating point
- ▻ Periodic monitoring of sensor occupancy to verify flux estimate



Survival Batch Results

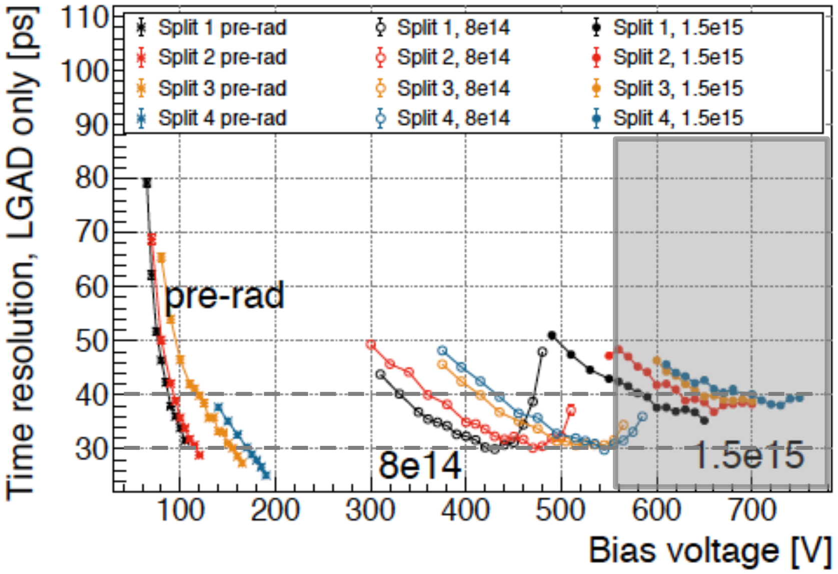
Sensor Type	# of sensors	Tested Voltage	Notes
HPK2 split 4 @ 8E14 n_{eq}/cm^2	4	500 – 575 V	No deaths
HPK2 @ 1.5E15 n_{eq}/cm^2	2	500 – 575 V	No deaths
FBK UFSD3.2 @ 8E14 n_{eq}/cm^2 (W7 & W13)	2	400 V	No deaths
FBK UFSD3.2 @ 1.5E15 n_{eq}/cm^2 (W7 & W13)	2	500 – 600 V	No death until operating voltage exceeded safety

- Bottom line: **No death observed in 50 µm sensors with bias < 575 V**
  - → Probed with ~500M protons (50,000x more than needed for death at 625 V)
- FBK: hint that thinner sensors die at a lower voltage
  - → W13 – 45 µm: died at 550 V
  - → W7 – 55 µm: survived 100M at 600 V (still alive)

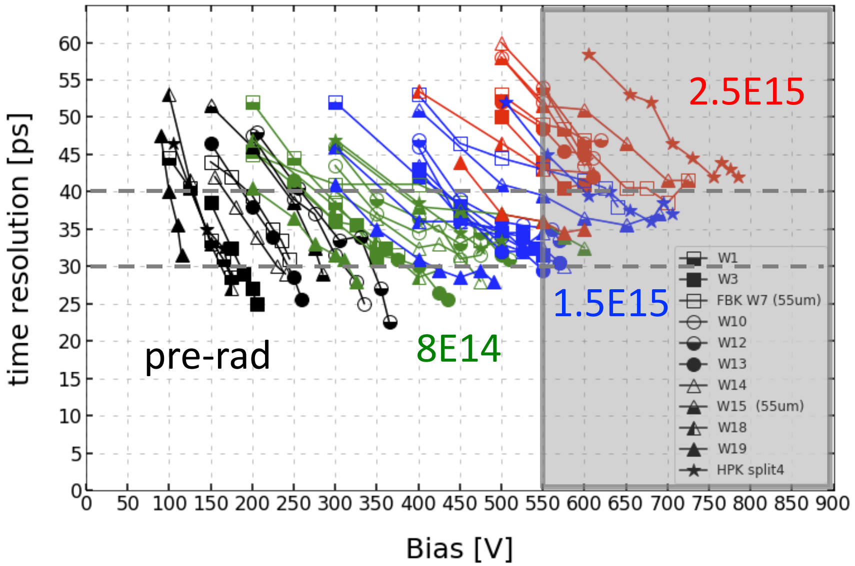
Context of ETL

- **50 µm LGADs should remain at a voltage ≤ 550-575 V in CMS/ATLAS**
- HPK sensors at 8E14 n_{eq}/cm^2: happily operate within this regime
  → This represents majority of sensors for ETL
- HPK sensors at 1–1.5E15 n_{eq}/cm^2: reduced performance, but not catastrophic
  → HPK2 split 1 & 2 achieve 40-50 ps at 550V
- Most of the FBK wafers deliver required performances at all ETL fluences

HPK2 – Beta source



FBK UFSD3.2 – Beta source



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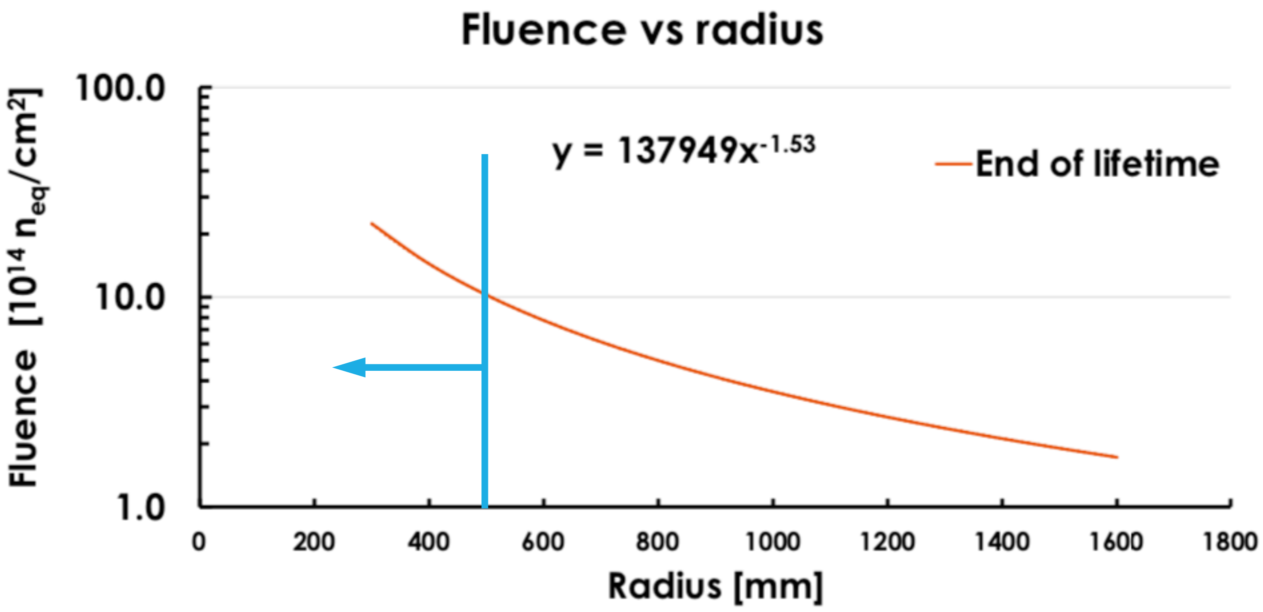
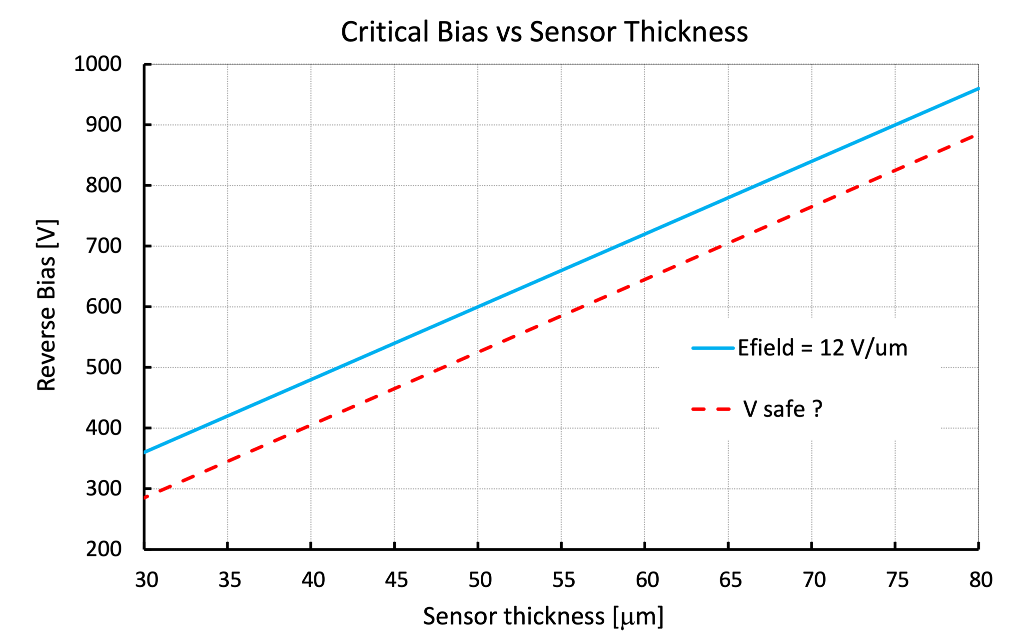
Only HPK sensors at innermost radii require reduced voltage

Few percent of ETL area

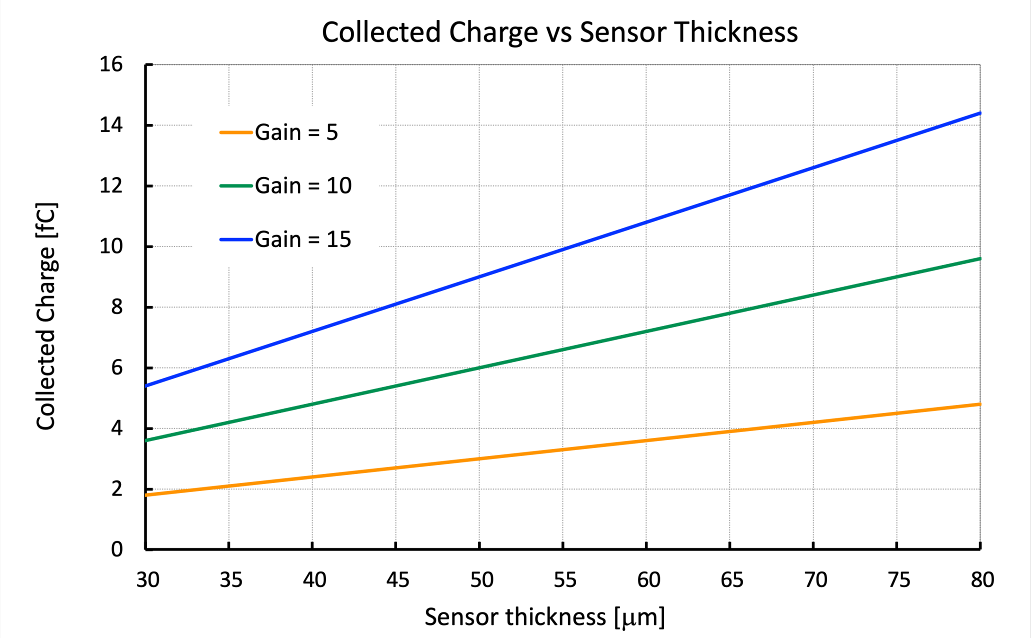


Sensor Thickness & Collected Charge

- ▻ Sensors die when the electric field is ~ 12 V/μm
  - → What is the safe margin for operation?
  - → Is the sensor mortality a threshold effect?
- ▻ For the same electric field value, thicker sensors provide a higher collected charge



Here, $V_{safe} = V_{critical} - 75$ V



Assuming 75 e-h pairs per μm

Summary

- Extensive study of LGAD mortality carried out at the Fermilab Test Beam Facility
- Understanding of death mechanism significantly improved
  - → Caused by single HIP interaction
  - → Unrelated to gain or sensor fluence – only the bias
    - ⇒ It may be a critical field of ~12 V/µm, but need to better probe other thicknesses
  - → Simulation in GEANT and TCAD ongoing
- The first indication of safe operating voltage has been established
  - → HPK sensors < 1E15 n_{eq}/cm^2 require no mitigation
  - → HPK sensors > 1E15 n_{eq}/cm^2 will be slightly under biased in final years
  - → FBK sensors can reach the operating point at all fluences
- Follow-up with an extreme rate stress test in 2021/2022 at FNAL High-Rate Facility (~ 10^8 – 10^9 protons per spill on each sensor)