Studies of LGAD mortality using the Fermilab Test Beam

Ryan Heller, on behalf of the CMS MTD collaboration

38th RD50 Workshop

June 23rd, 2021

Introduction

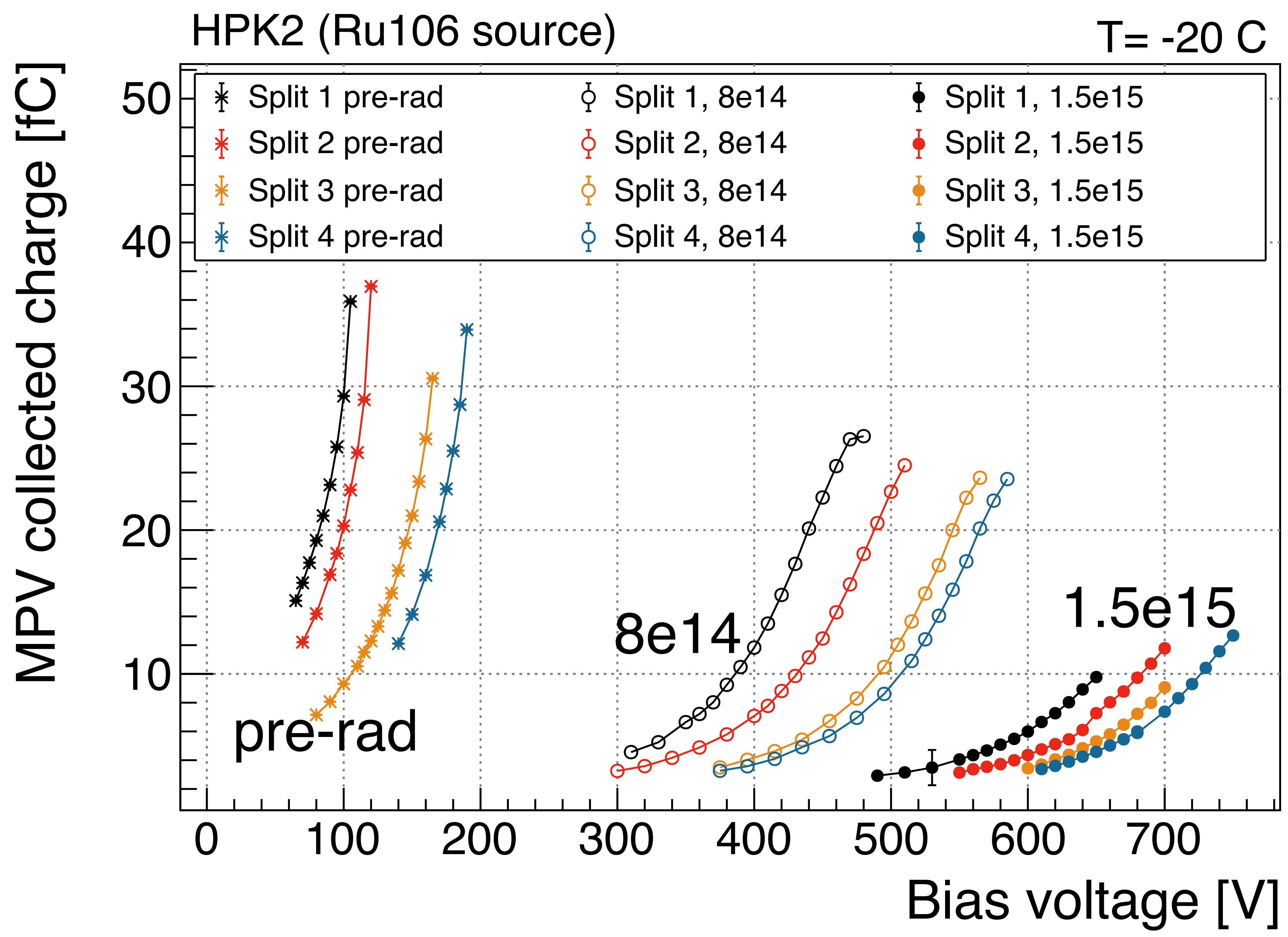
- Anecdotal evidence in past for death of highly irradiated LGADs at test beams.
  - Historically, not clear if caused by environmental/mishandling issue, or intrinsic sensor failure mode.

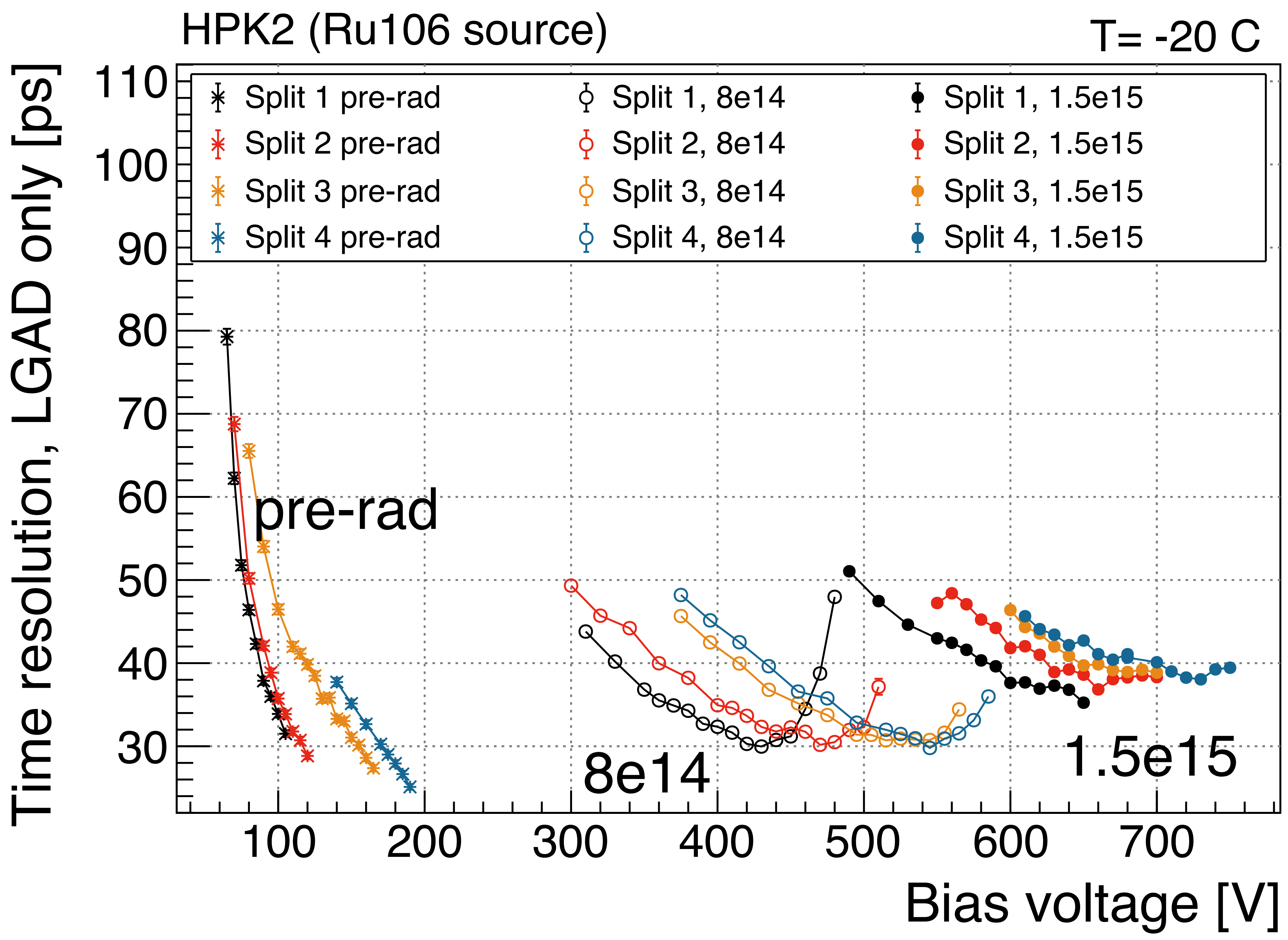
- Two test beam campaigns at Fermilab dedicated to study of LGAD mortality
  - 30 sensors studied in December and March
  - Extensive collaboration between CMS and ATLAS to select & prepare sensors.

- Many key goals accomplished:
  - Refine understanding of cause of death
  - Collect statistics with diverse set of sensors
  - Test treatments to prevent mortality
  - Probe safe regions for operation and develop mitigation strategy.

HPK2 sensors

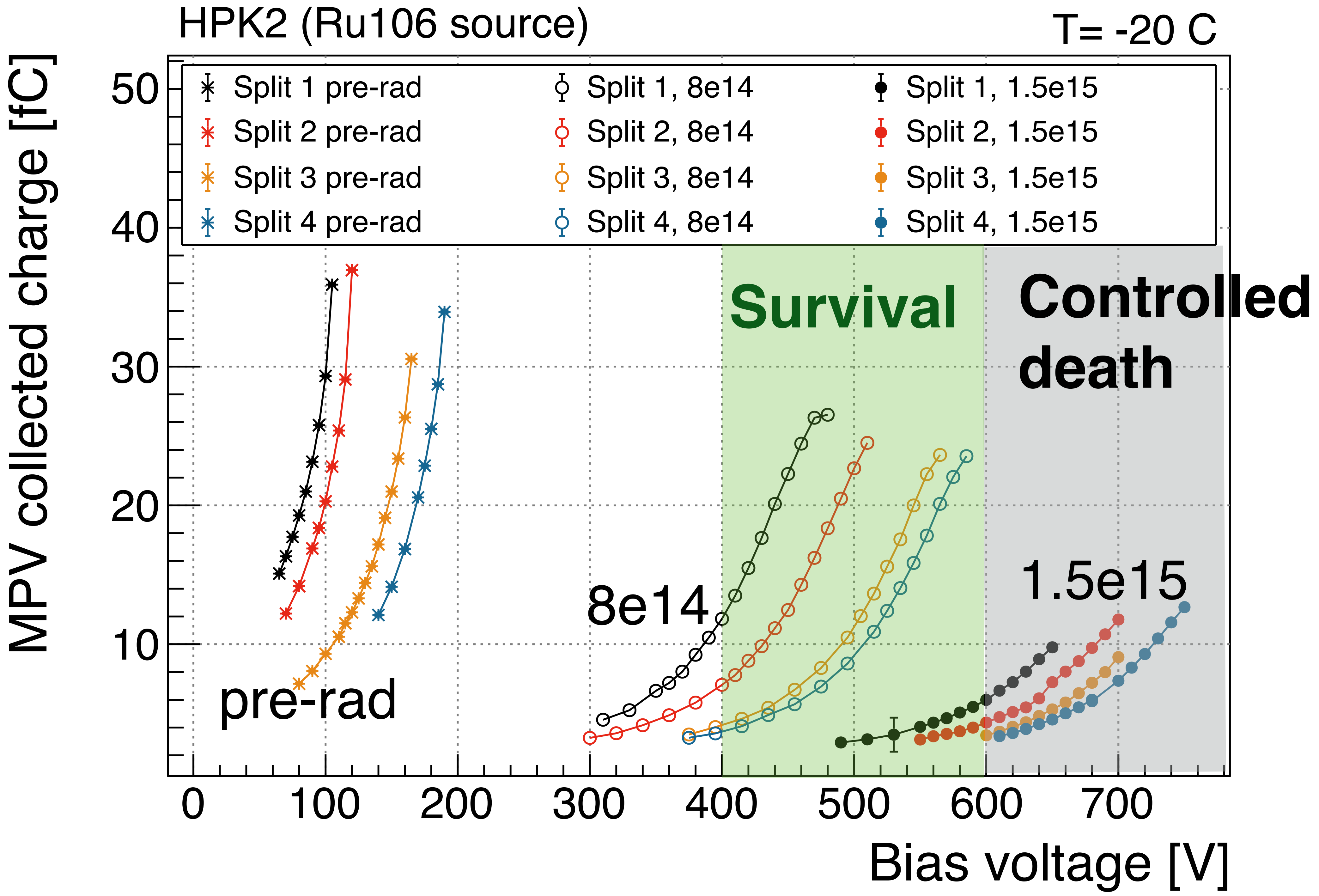
- Focused on latest HPK production, HPK2
  - 4 gain variations, Split 1 — Split 4 (lowest to highest operating voltage)

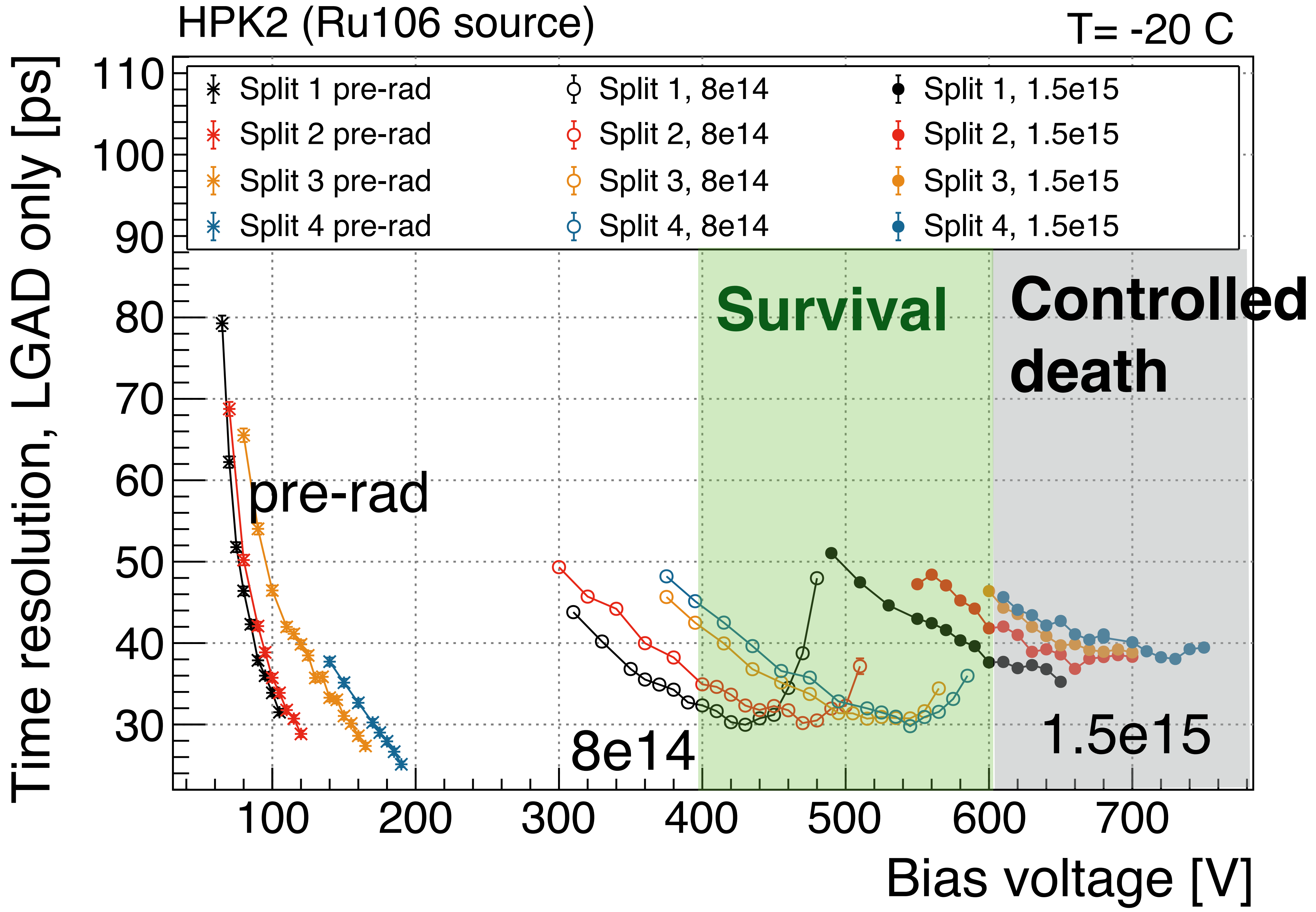




HPK2 sensors

- Focused on latest HPK production, HPK2
  - 4 gain variations, Split 1 — Split 4 (lowest to highest operating voltage)
- Two phases of mortality campaign:
  - Controlled death: > 600 V, primarily 1.5e15 neq/cm²
  - Survival demonstration: 400—600 V, 8e14—1.5e15 neq/cm²

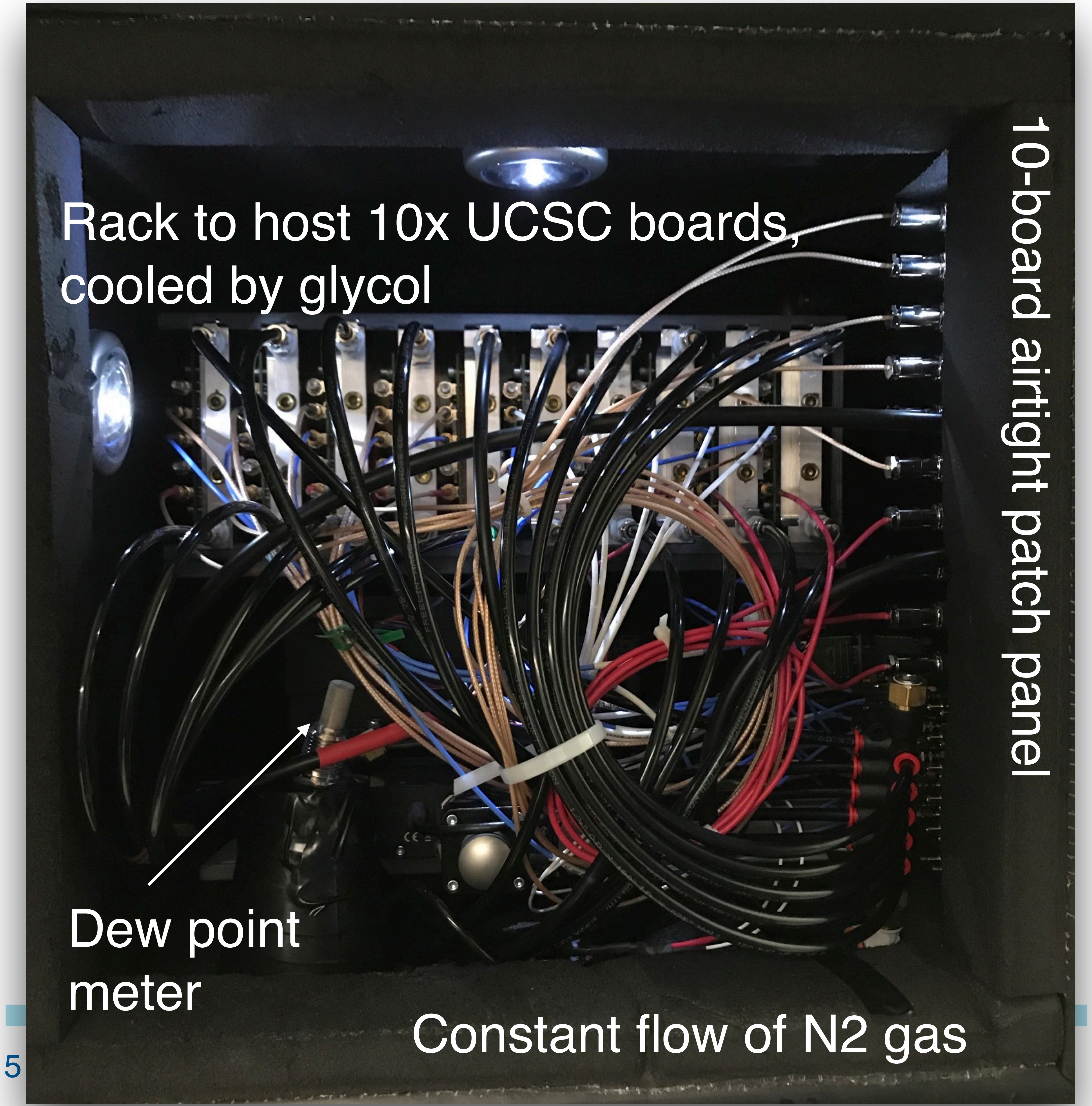




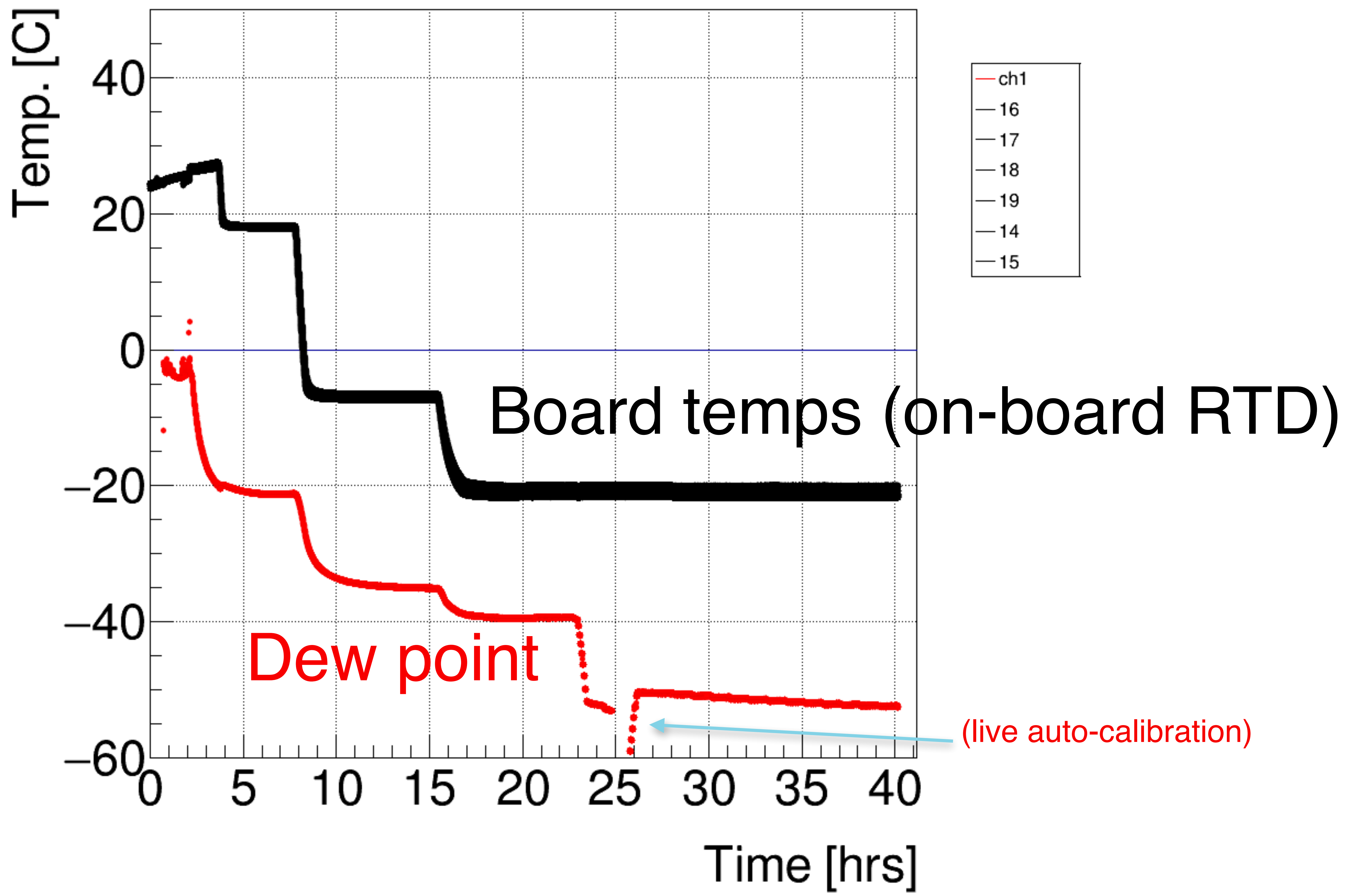
Environmental control and LGAD stability

- Prerequisite for mortality studies: prove LGAD stability in absence of beam!

LGAD coldbox at Fermilab test beam



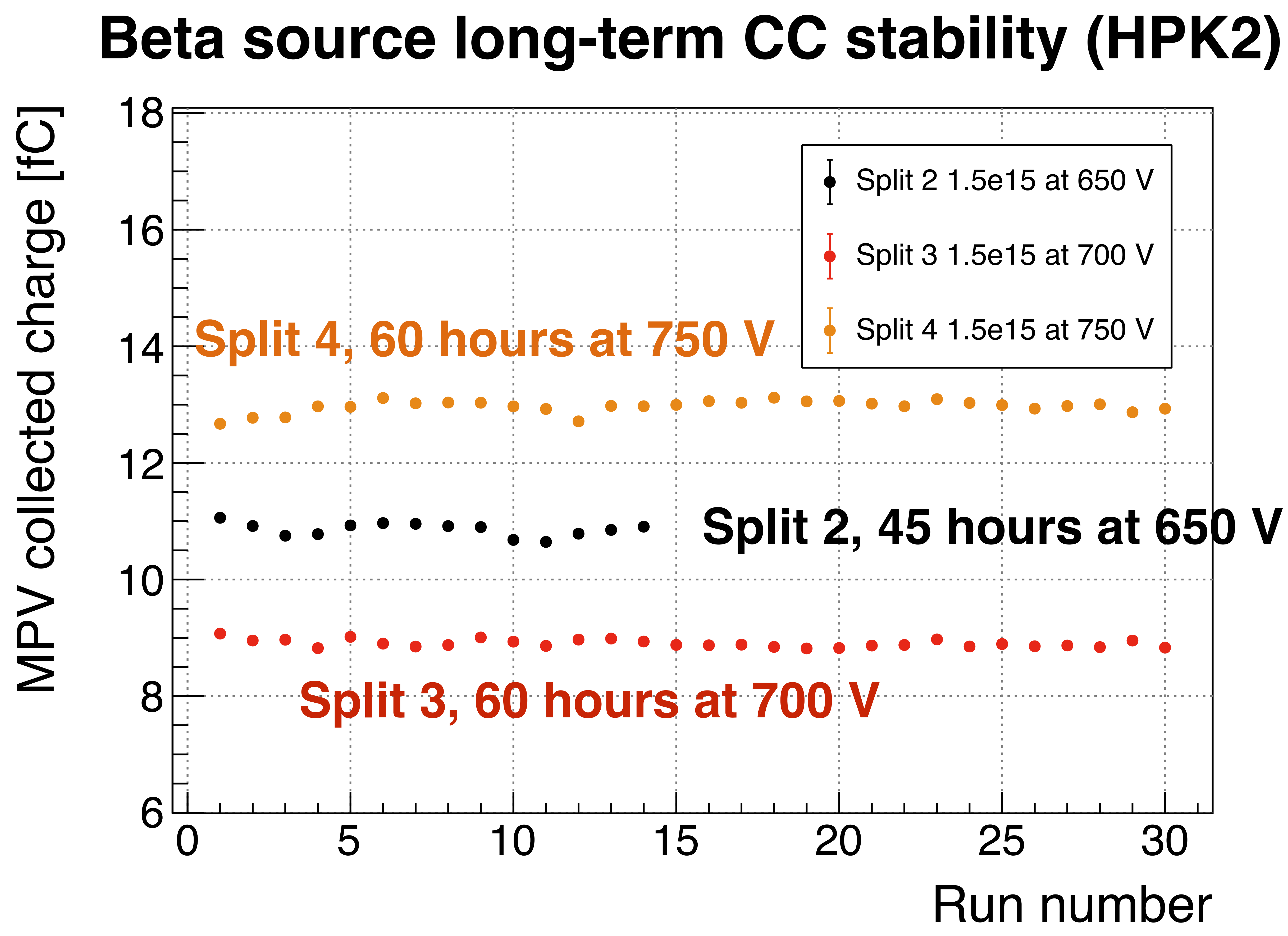
Environmental monitoring, post-installation

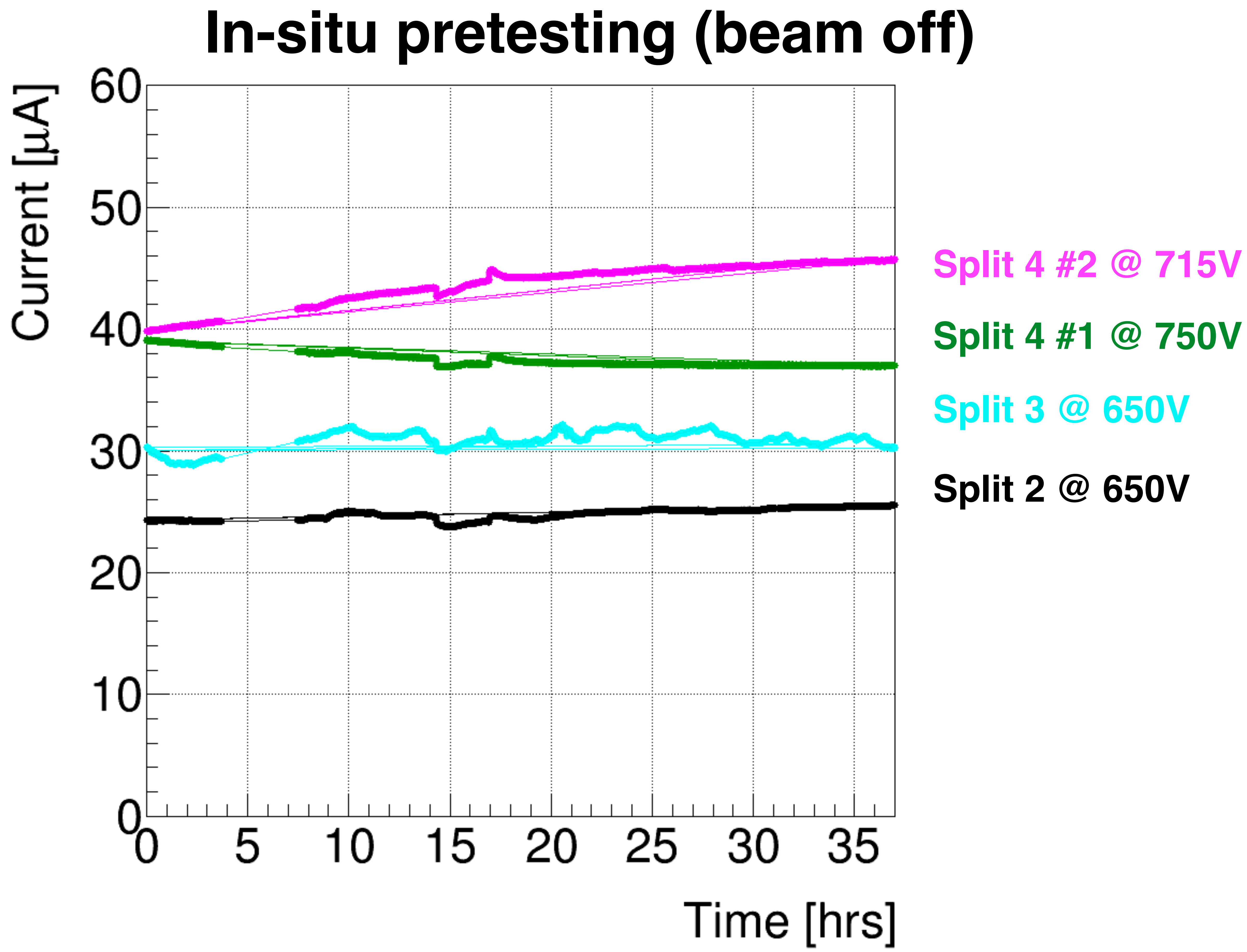


- Cool down only after dry for very long time.
- Dew point 20-30 deg below board temp at all times!

Environmental control and LGAD stability

- Extensive pre-biasing of every sensor in absence of beam.
- LGADs stable even at much higher voltage than reached in beam test!

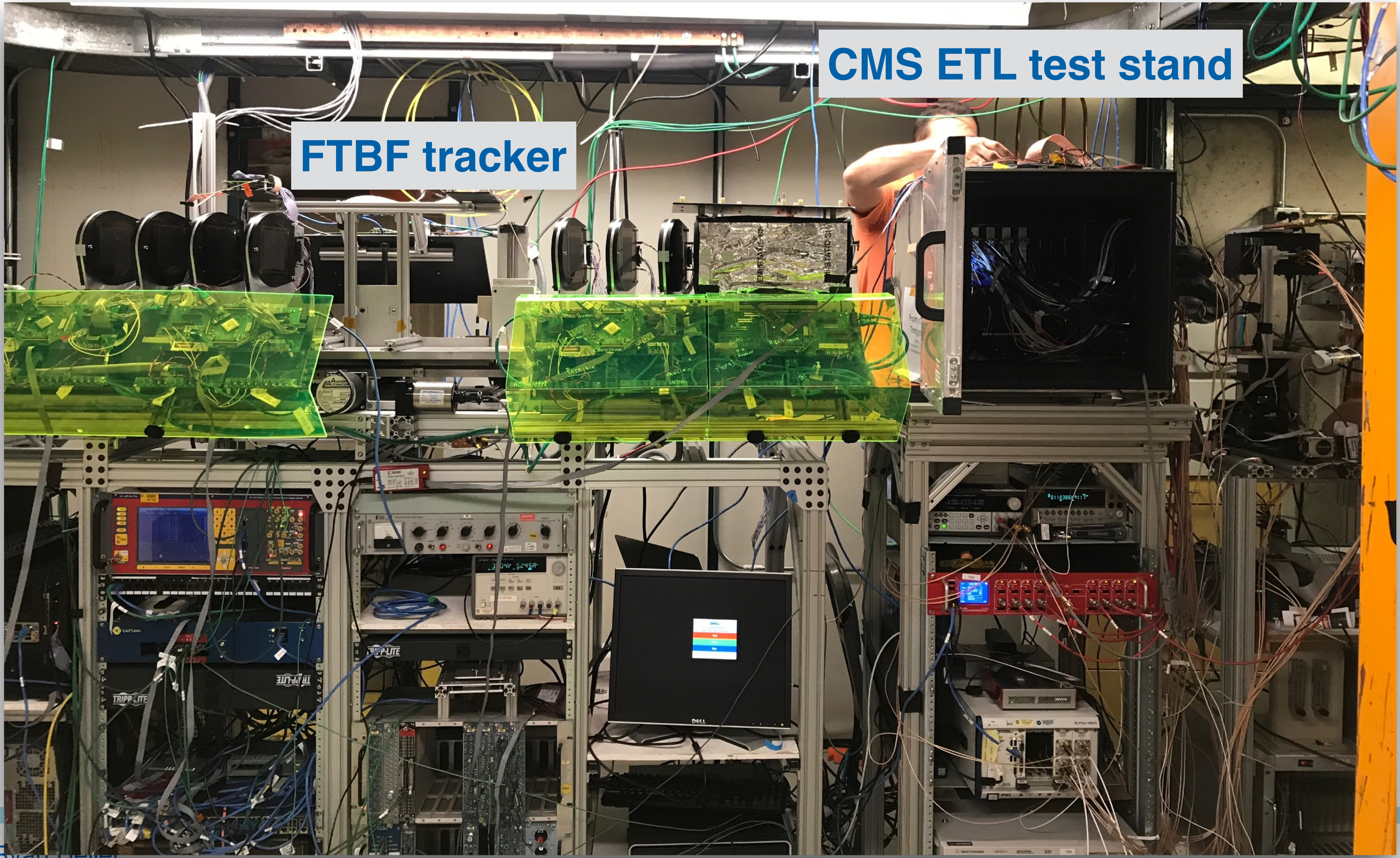




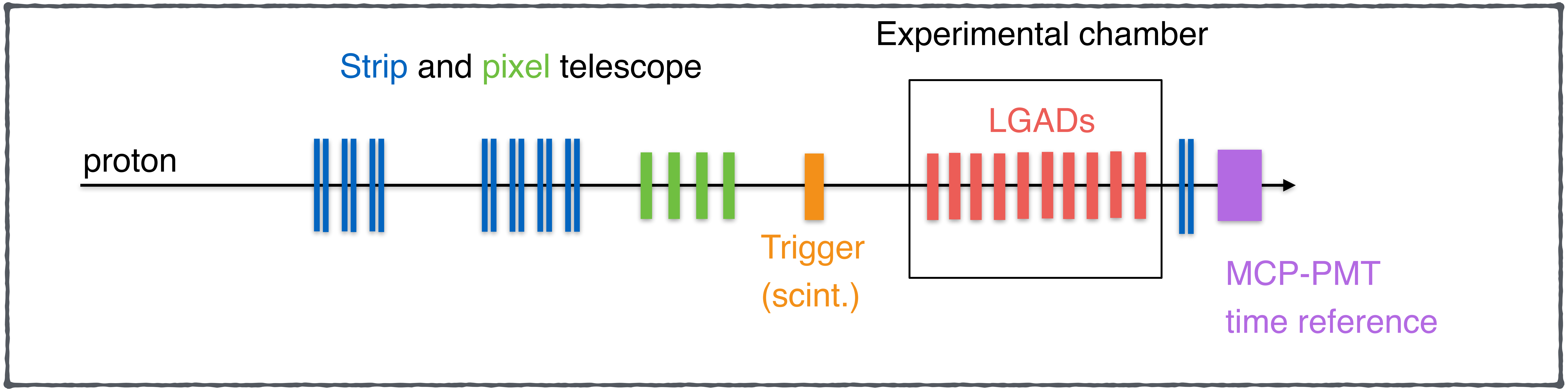
All sensors tested for at least 6 hours in-situ w/ beam off.

Fermilab test beam facility

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



Fermilab test beam facility

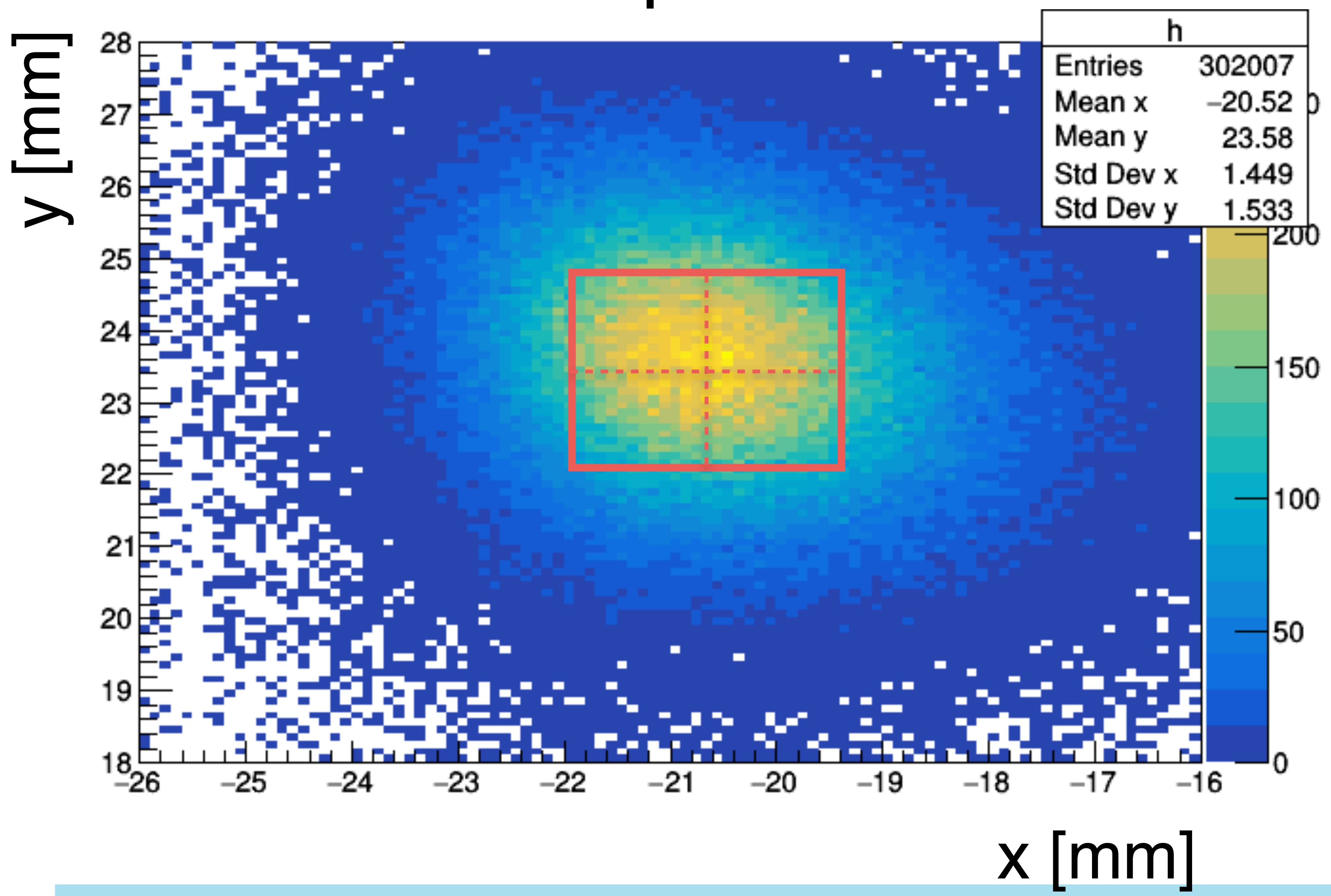


- Measure proton track using facility telescope
  - 40 µm resolution in this configuration
- Read LGAD and MCP time reference with fast, high res oscilloscope.
- Developed high DAQ efficiency ~ 75% (trigger & find track.)
  - Contrast w/ typical LGAD studies: rarely care about trigger efficiency.

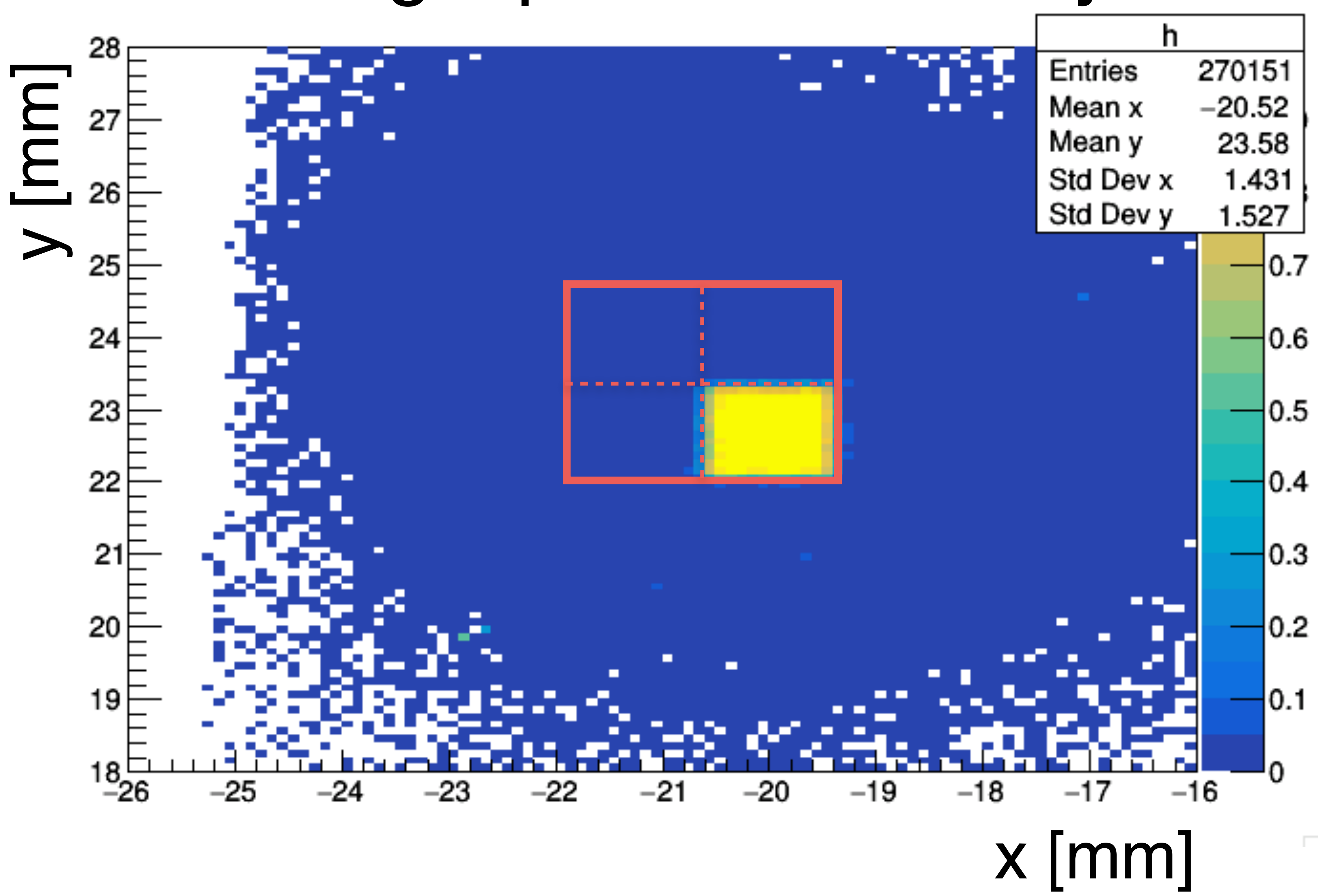
Mortality study procedures

- Measure beam profile with tracker
- Align each sensor with beam using 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 sensor.

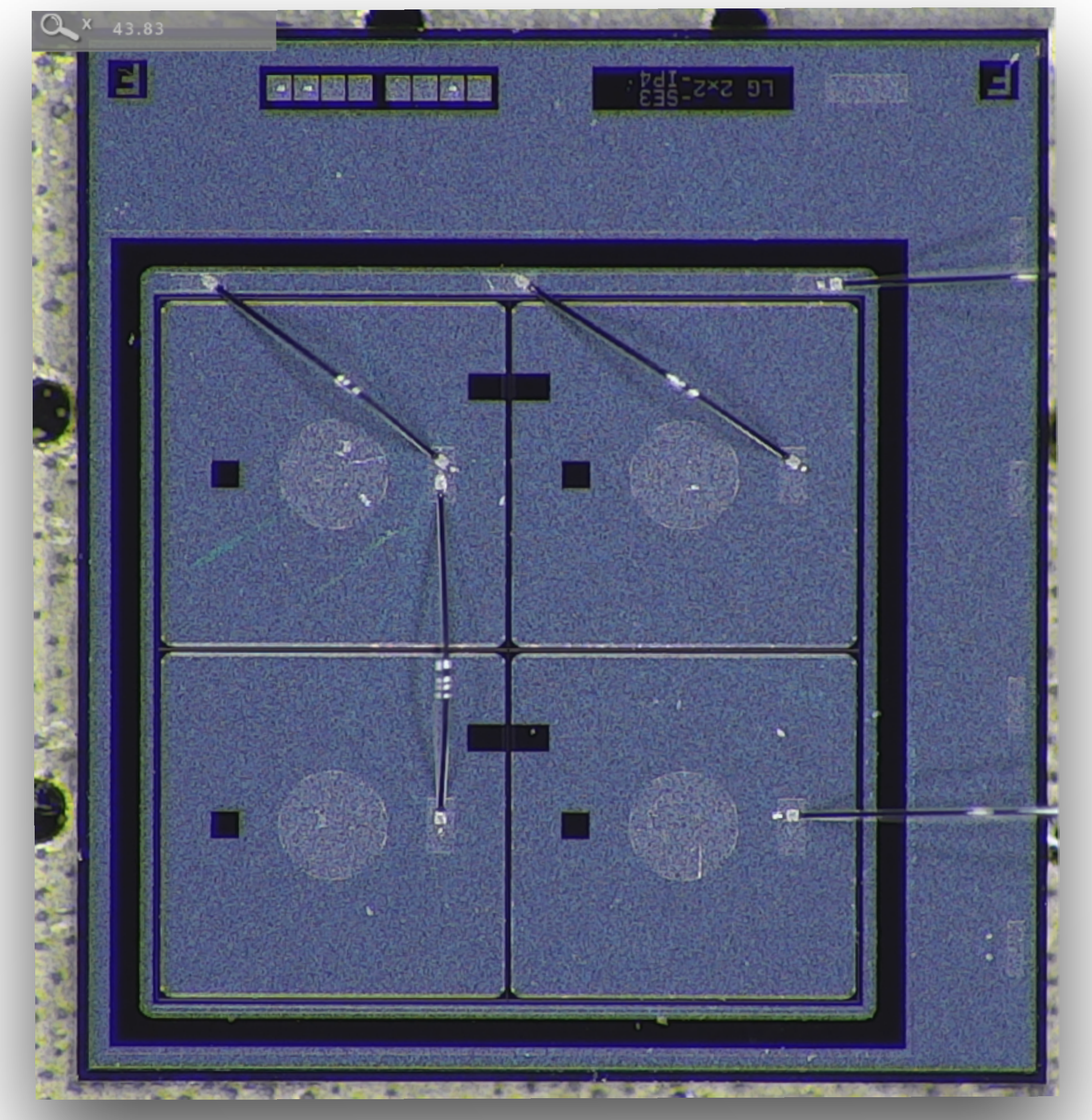
Beam profile



Single pad hit efficiency



Most sensors in 2x2 geometry

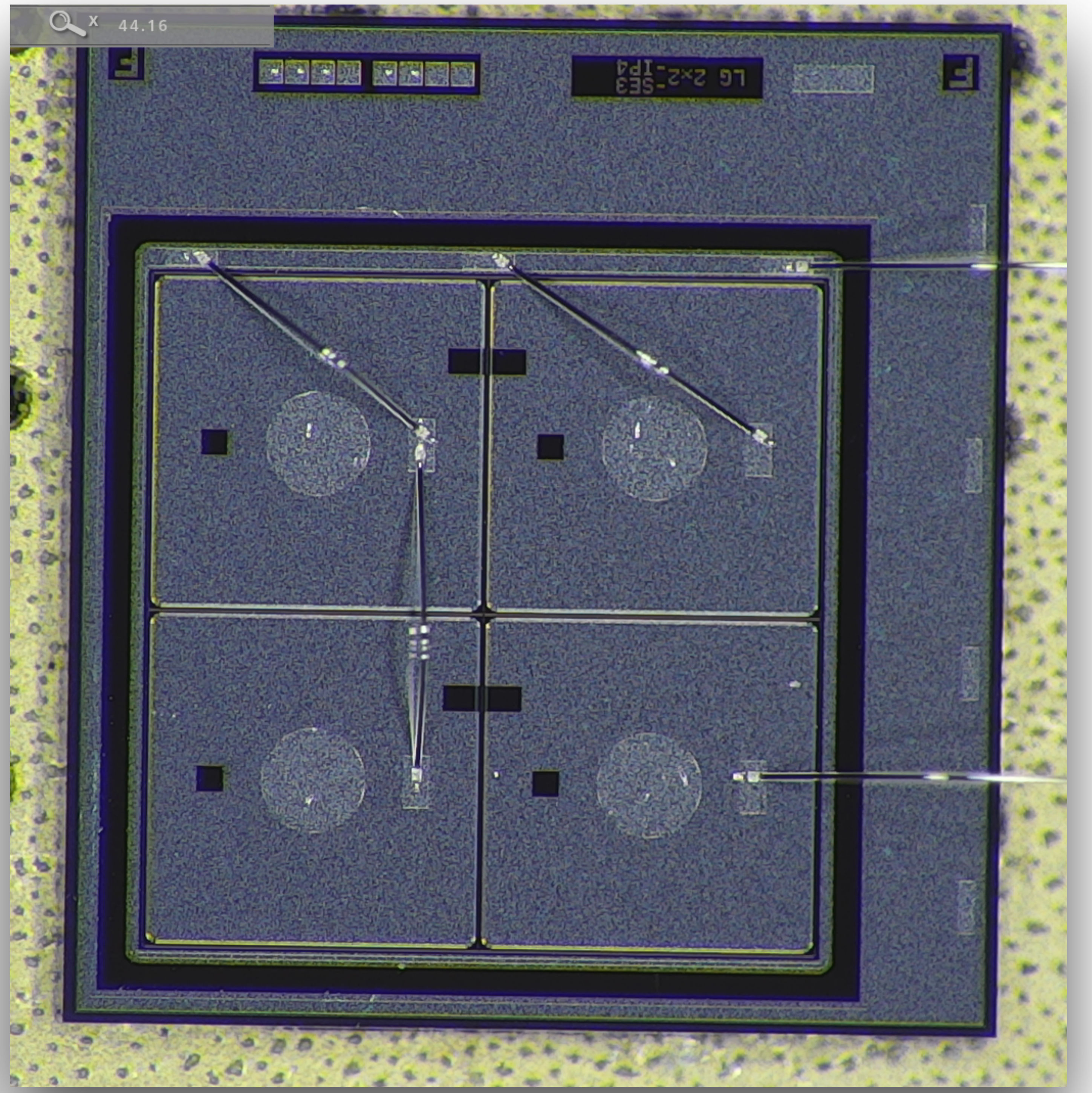


Example death event

- HPK2 split 3 sensor, fluence 1.5e15 neq/cm²
  - 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.

First sign of death: HV short

HPK2 Split 3 SE3 IP4, 1.5e15 neq/cm²

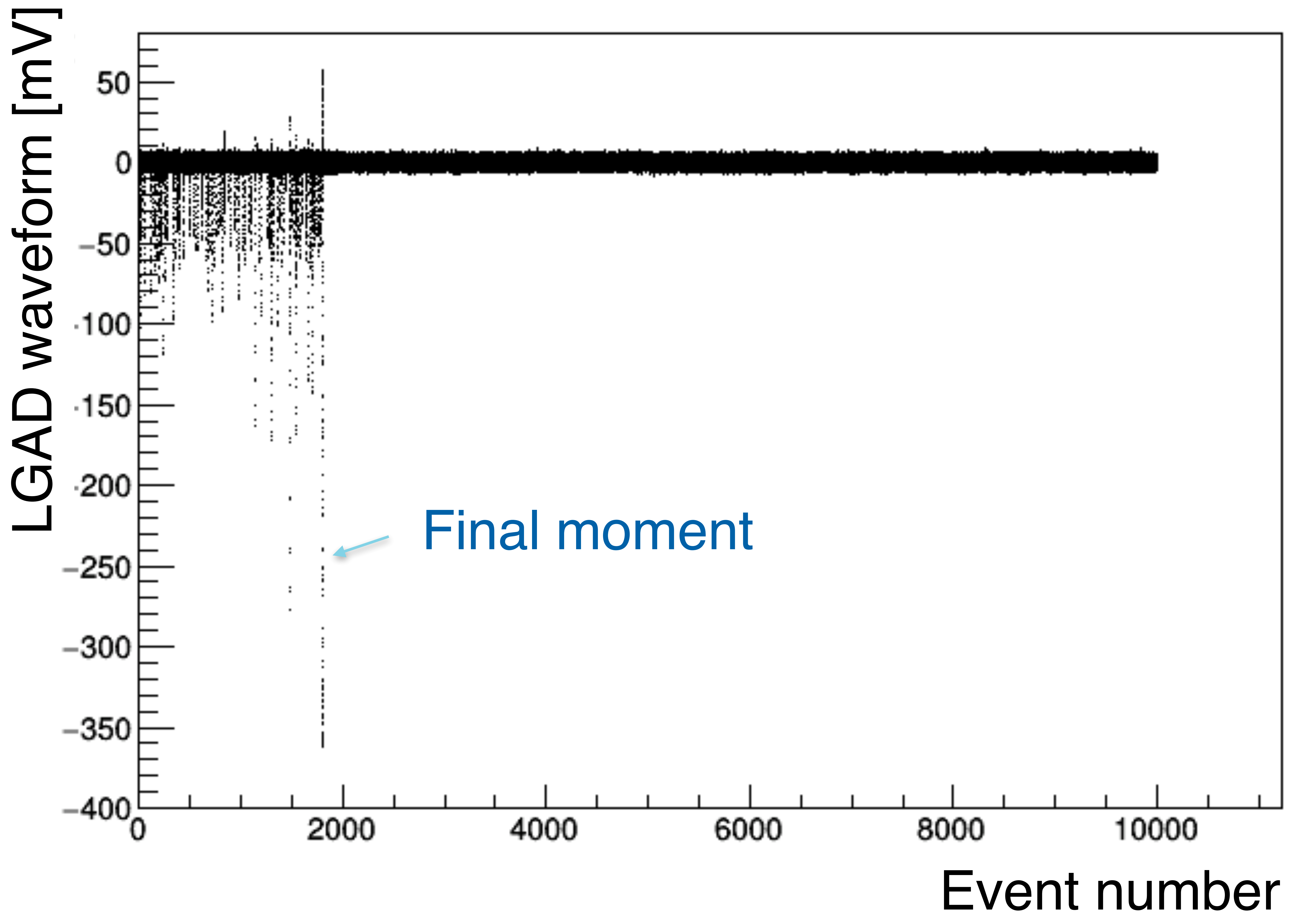


(not yet dead)

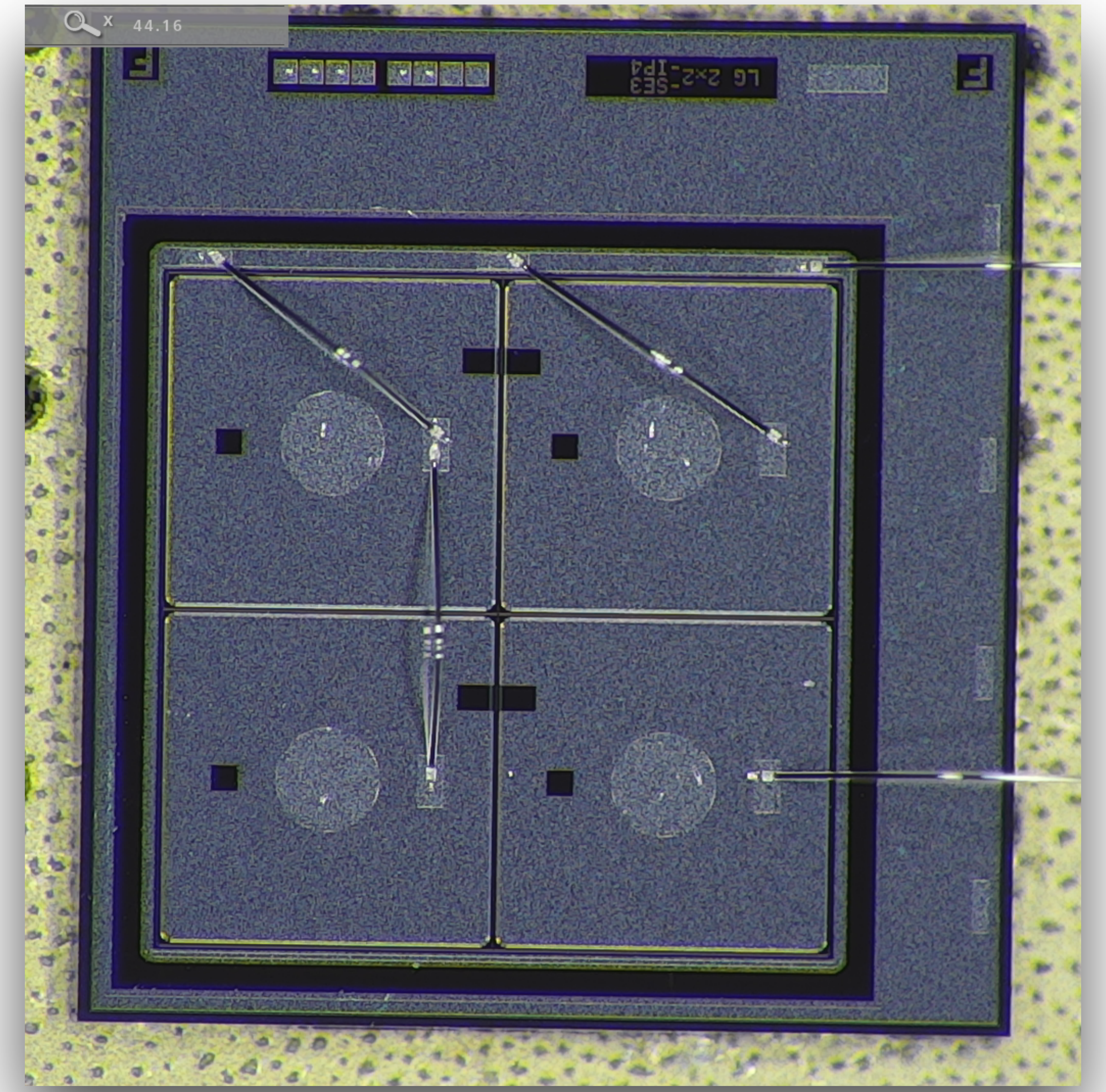
Fermilab

Example death event

LGAD waveforms in 10k triggers during 4s spill.



HPK2 Split 3 SE3 IP4, 1.5e15 neq/cm²

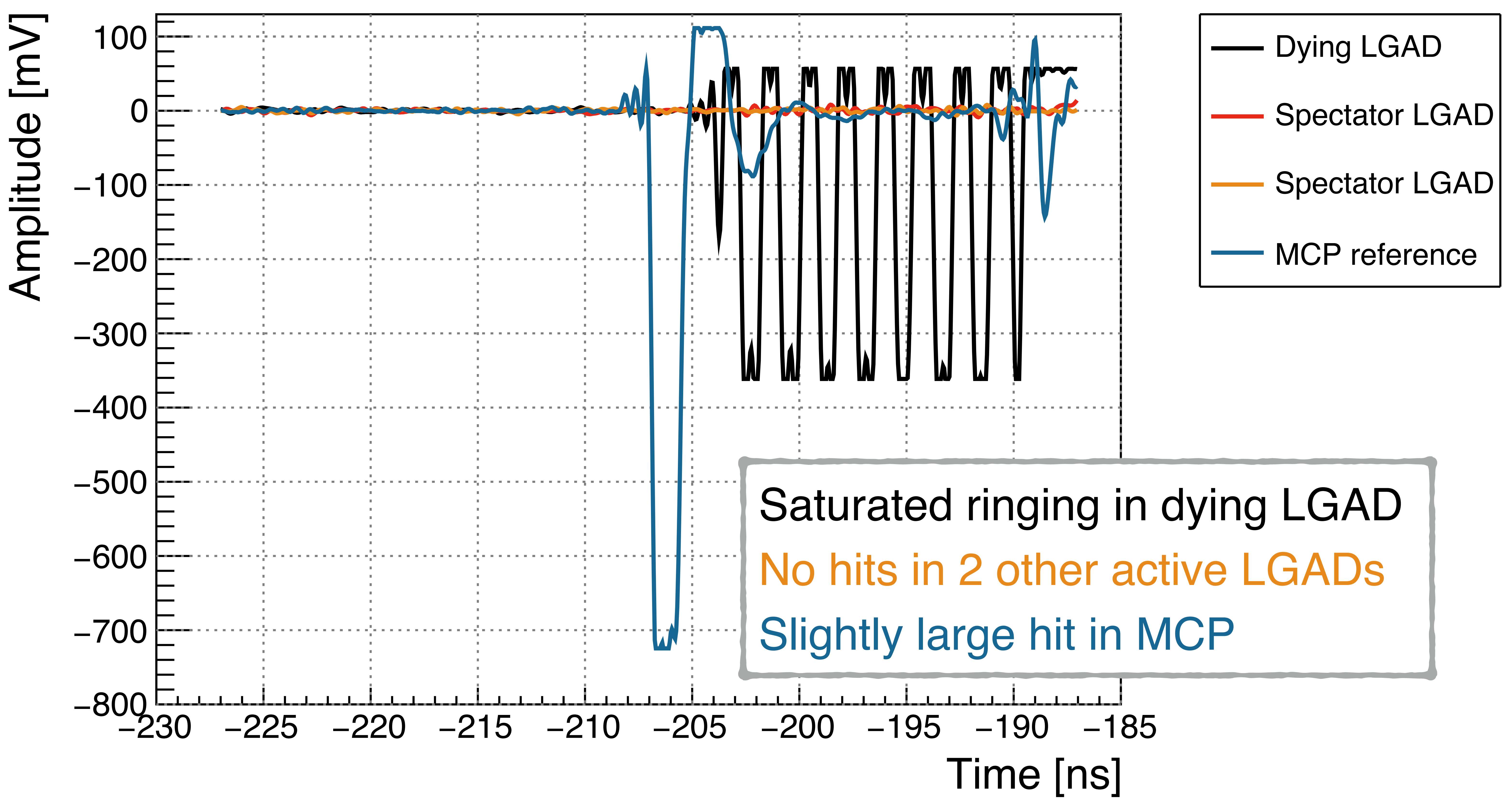


(not yet dead)

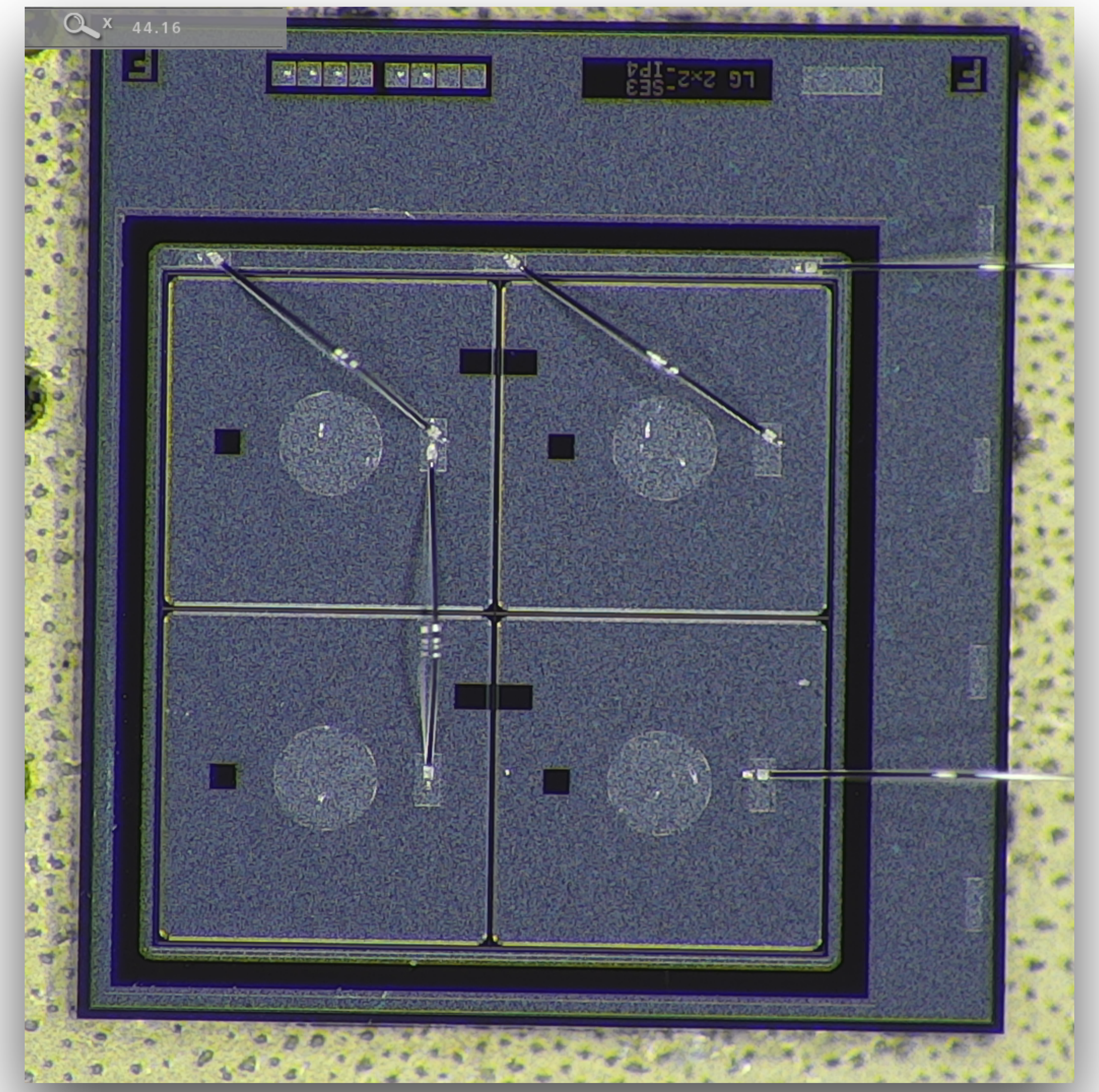
Fermilab

Example death event

Waveforms in fatal event



HPK2 Split 3 SE3 IP4, 1.5e15 neq/cm²



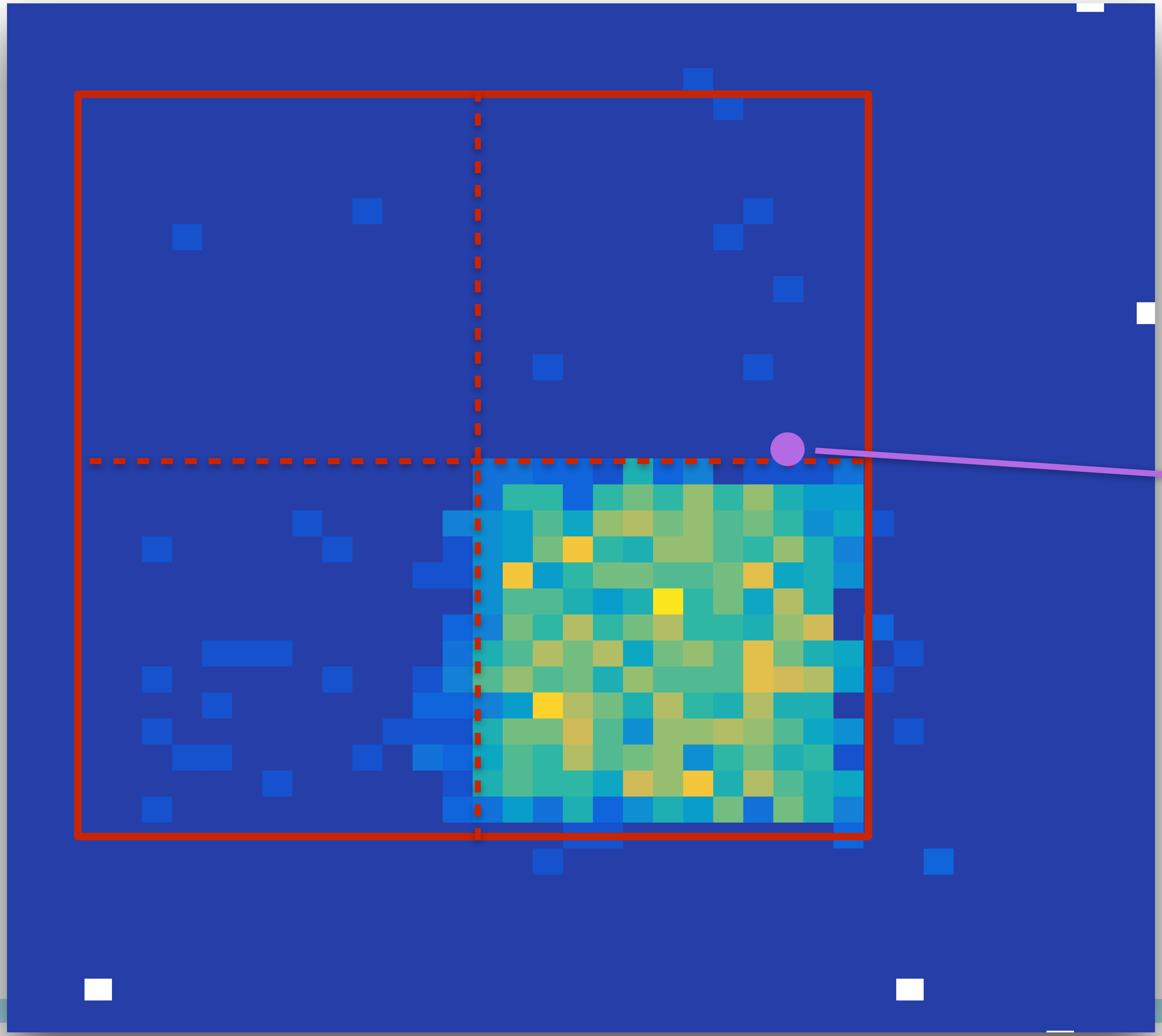
(not yet dead)

Death within 1 ns of proton arrival.

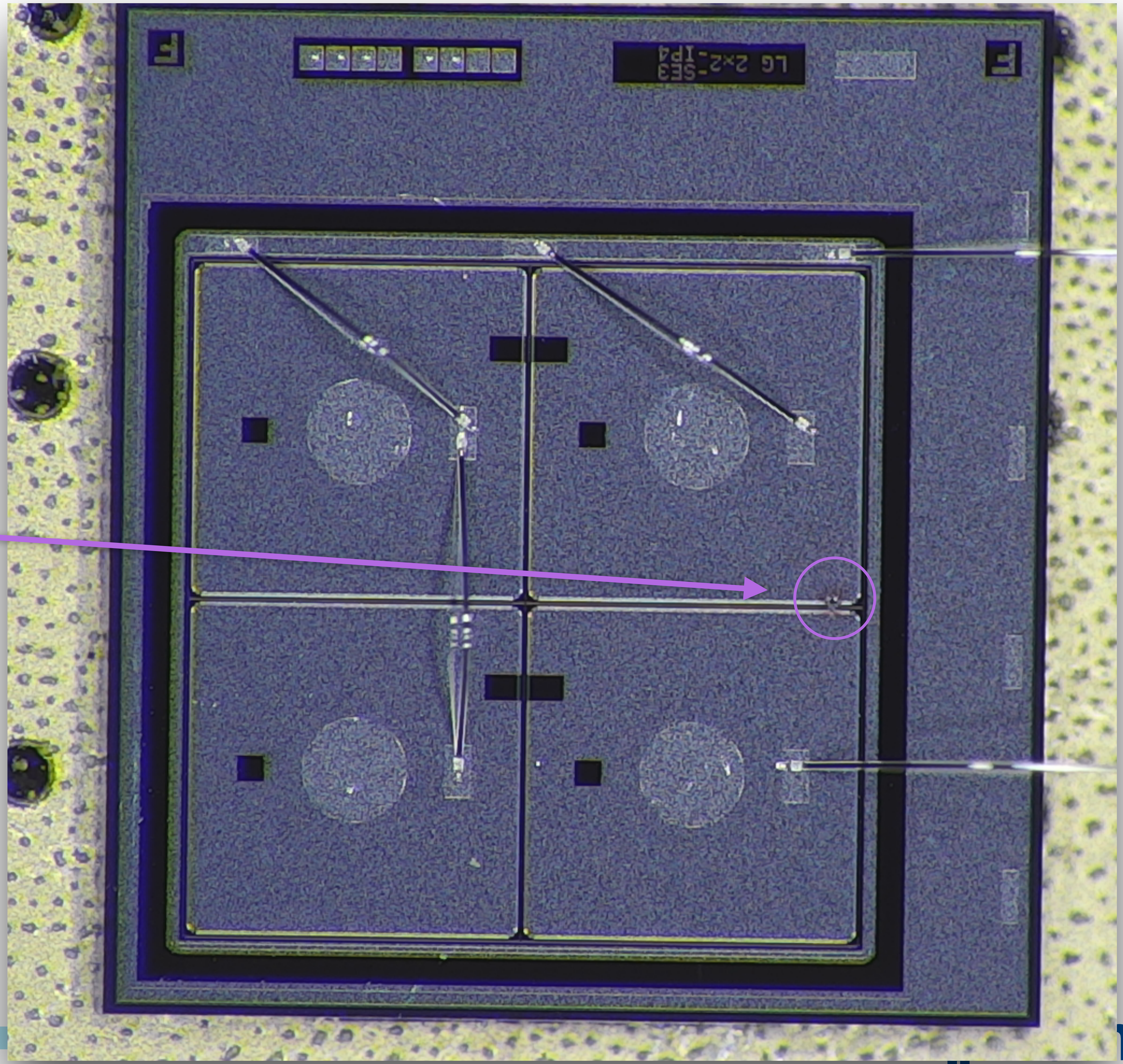
Fermilab

Example death event

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

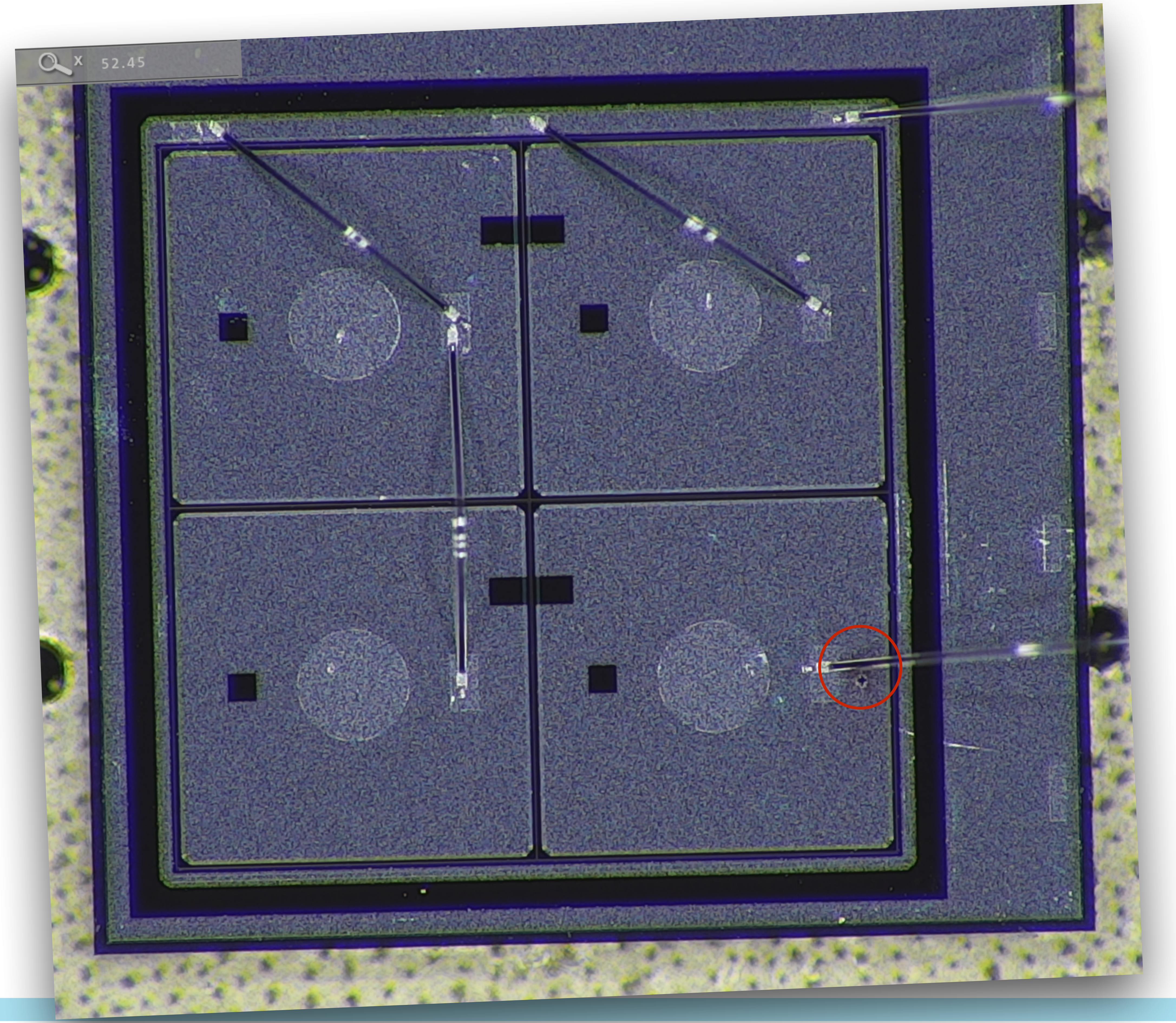


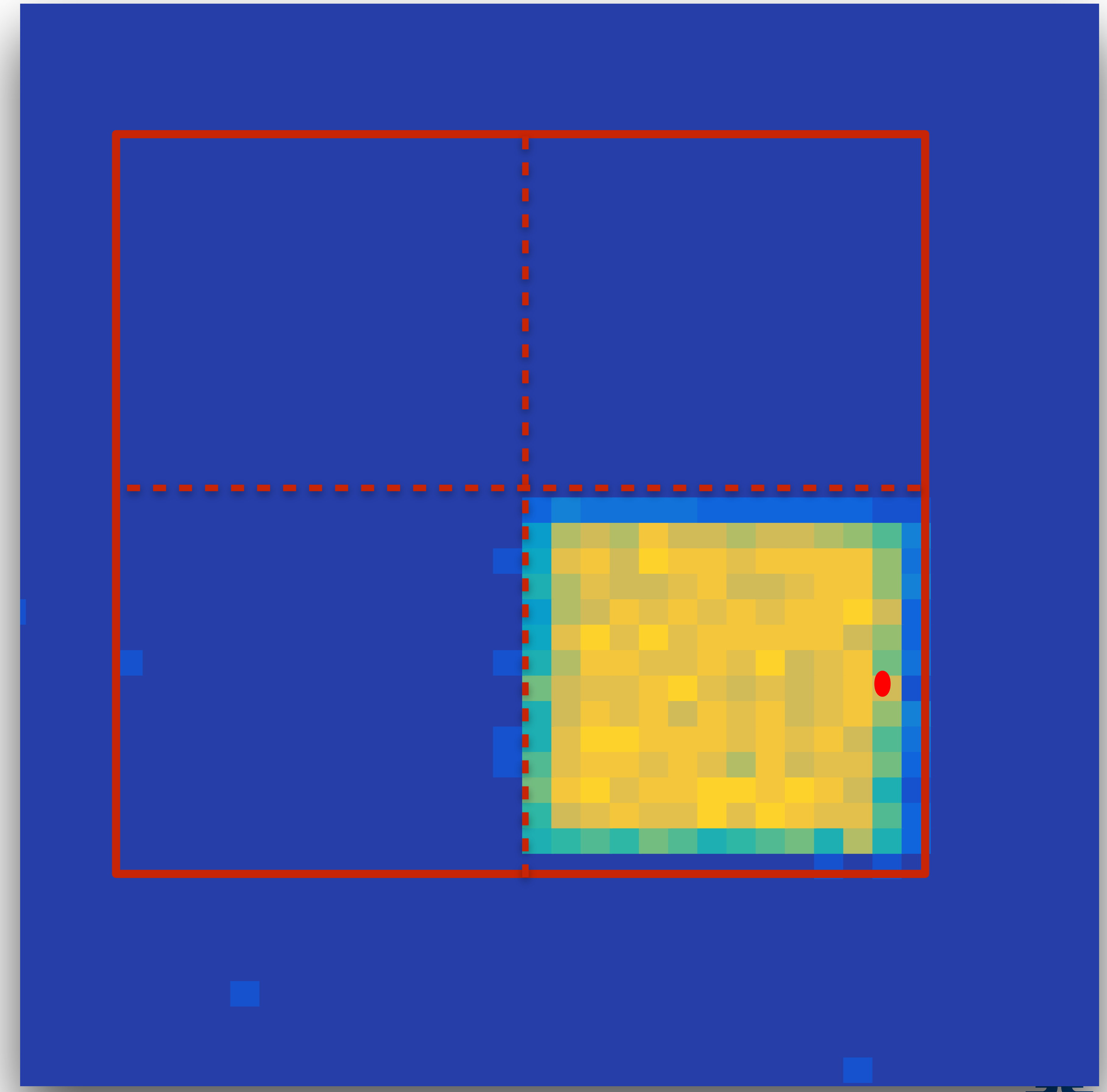
Post-mortem photo



Example death events

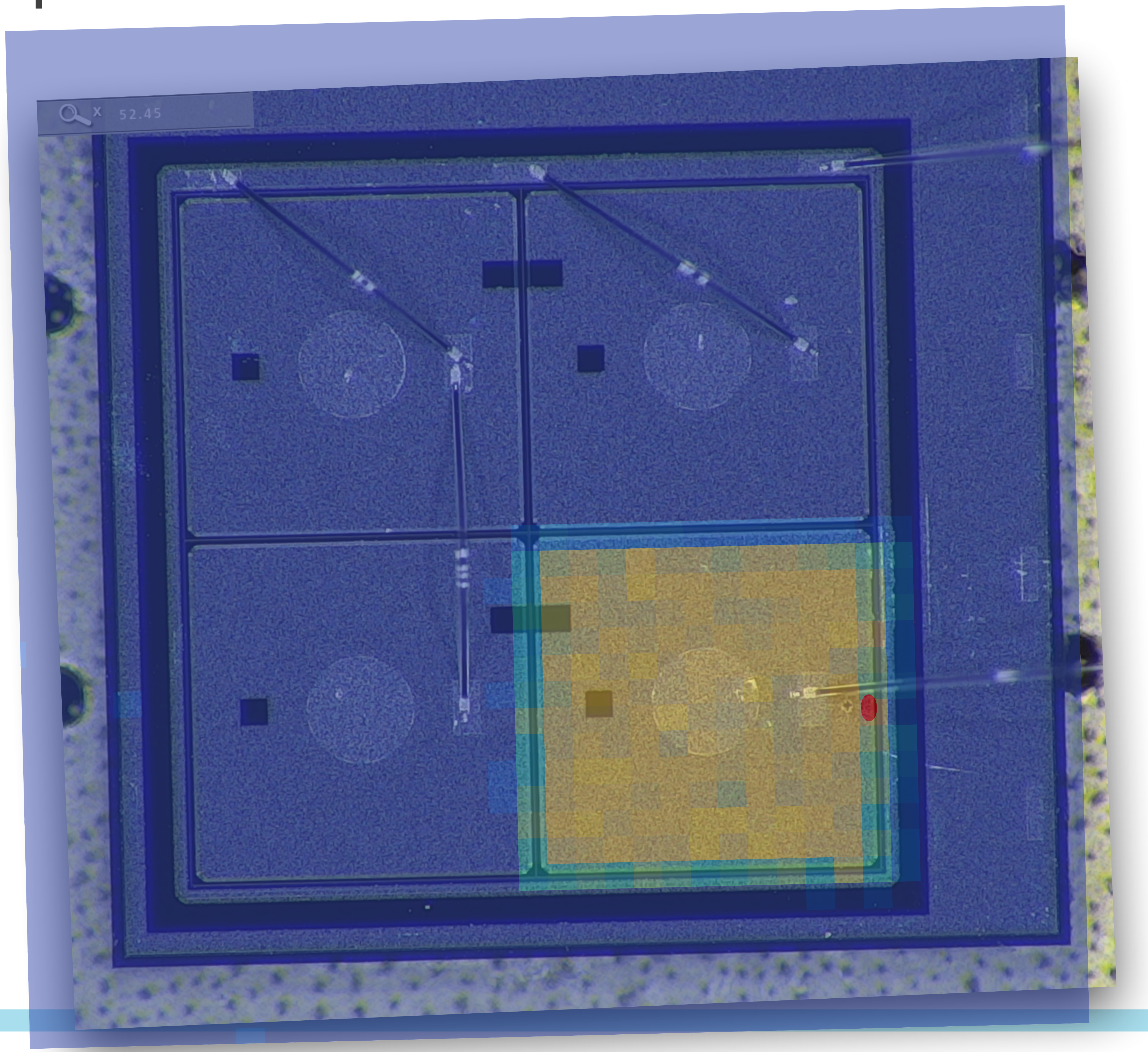
- HPK2 Split 3, 2.5e15 neq/cm^2, pretested at 775 V for 6 hours
- Operated in beam at 600 V for 1 hour, died after 30 min at 625 V





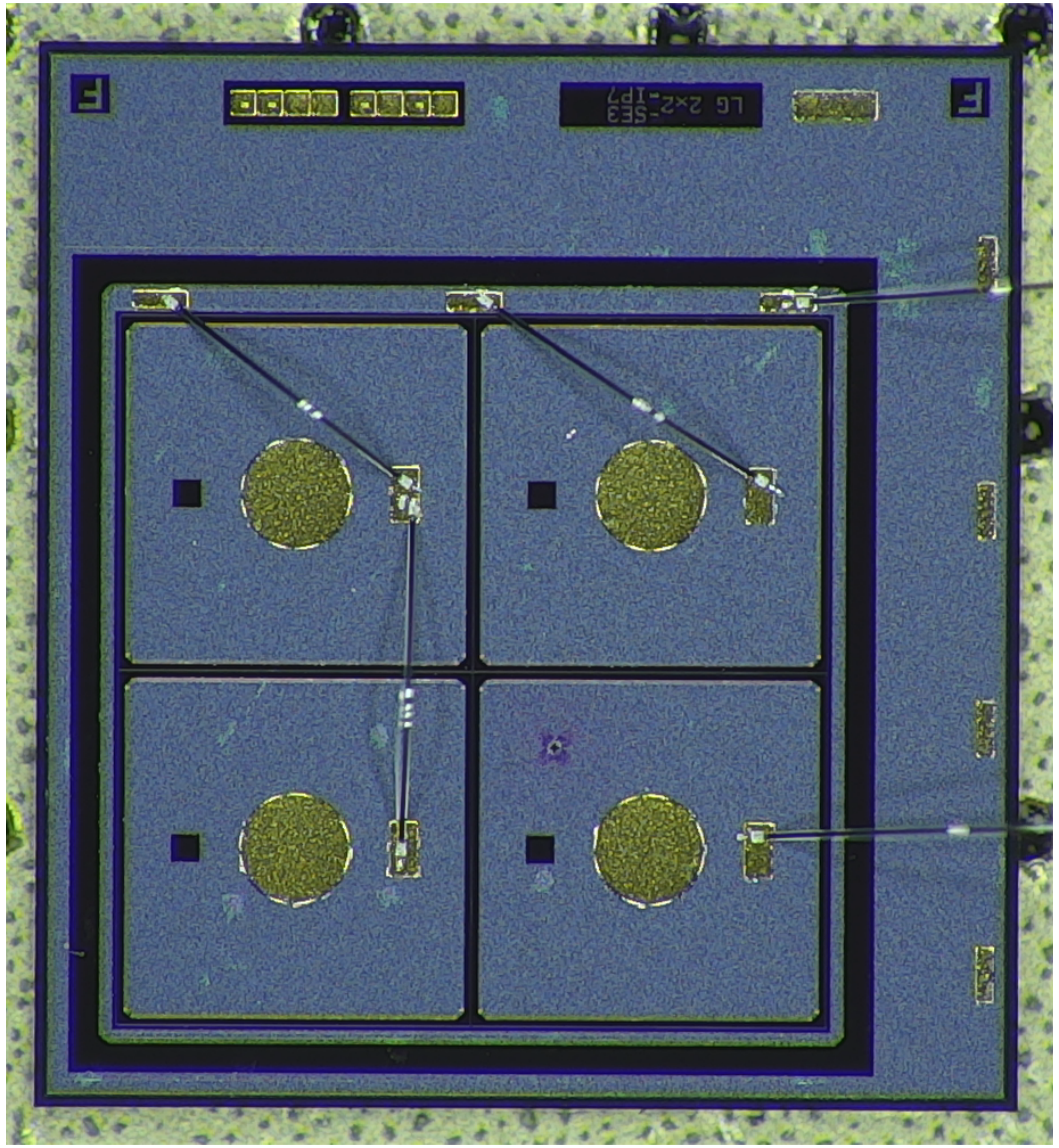
Example death events

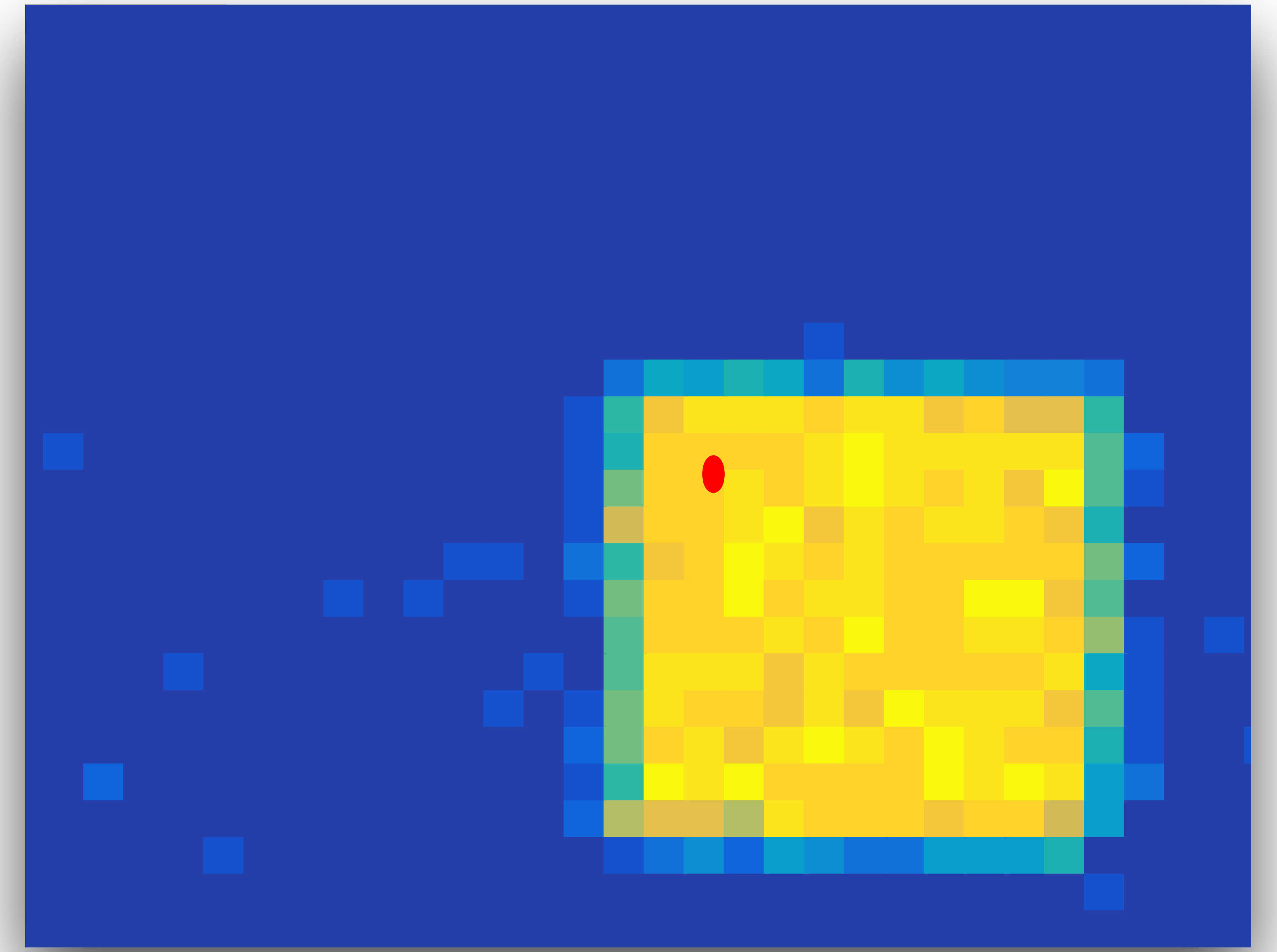
- HPK2 Split 3, 2.5e15 neq/cm², pretested at 775 V for 6 hours
- Operated in beam at 600 V for 1 hour, died after 30 min at 625 V



Example death events

HPK 3.1 1.5e15 neq/cm²

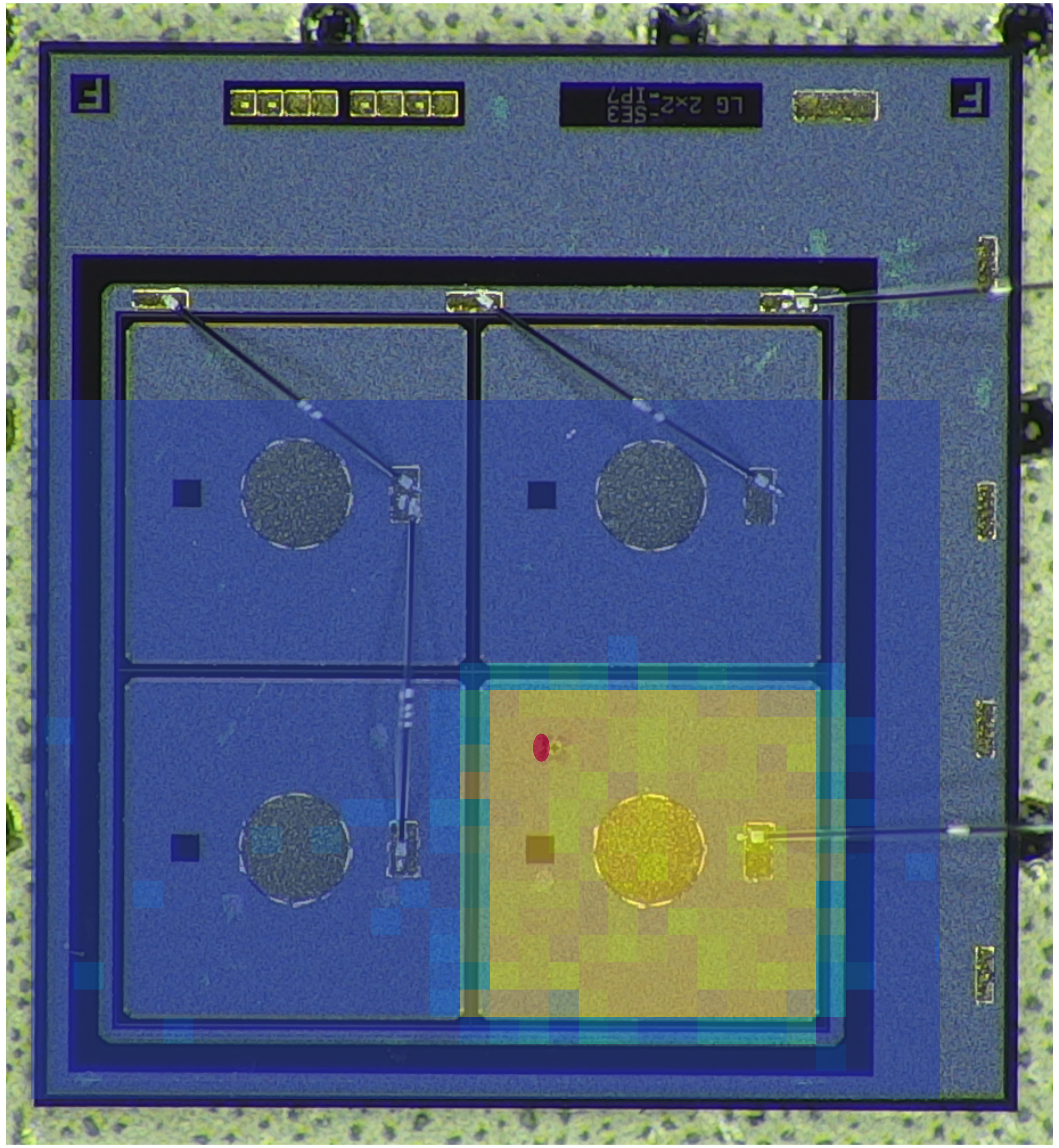




Fermilab

Example death events

HPK 3.1 1.5e15 neq/cm²



Fermilab

Summary of deaths observed

Sensor type	# of good sensors	Fatal voltage	$N_{protons}$ at fatal voltage	Notes
HPK2 @ 1.5e15 neq	7	625-675 V	10–30k	**“Standard candle”**

Fermilab

Summary of deaths observed

Sensor type	# of good sensors	Fatal voltage	$N_{protons}$ at fatal voltage	Notes
HPK2 @ 1.5e15 neq	7	625-675 V	10–30k	**"Standard candle"**
HPK2 @ 2.5e15 neq	4	625-675 V	10–30k	**Role of gain & fluence?**
HPK2 PiNs (1.5e15 neq or 0.1 MGy)	3	625-700 V	10–30k	

Summary of deaths observed

Sensor type	# of good sensors	Fatal voltage	$N_{protons}$ at fatal voltage	Notes
HPK2 @ 1.5e15 neq	7	625-675 V	10–30k	**"Standard candle"**
HPK2 @ 2.5e15 neq	4	625-675 V	10–30k	**Role of gain & fluence?**
HPK2 PiNs (1.5e15 neq or 0.1 MGy)	3	625-700 V	10–30k	
35 micron HPK 1.1	Excluded in pre-beam testing due to early breakdown			**Role of thickness?**
80 micron HPK 80D	Destroyed in pre-beam testing (surface breakdown at 850 V; target voltage 950 V ~ 12 V/µm)			
50 micron 50D & HPK3.1	2	675-700 V	10-30k	

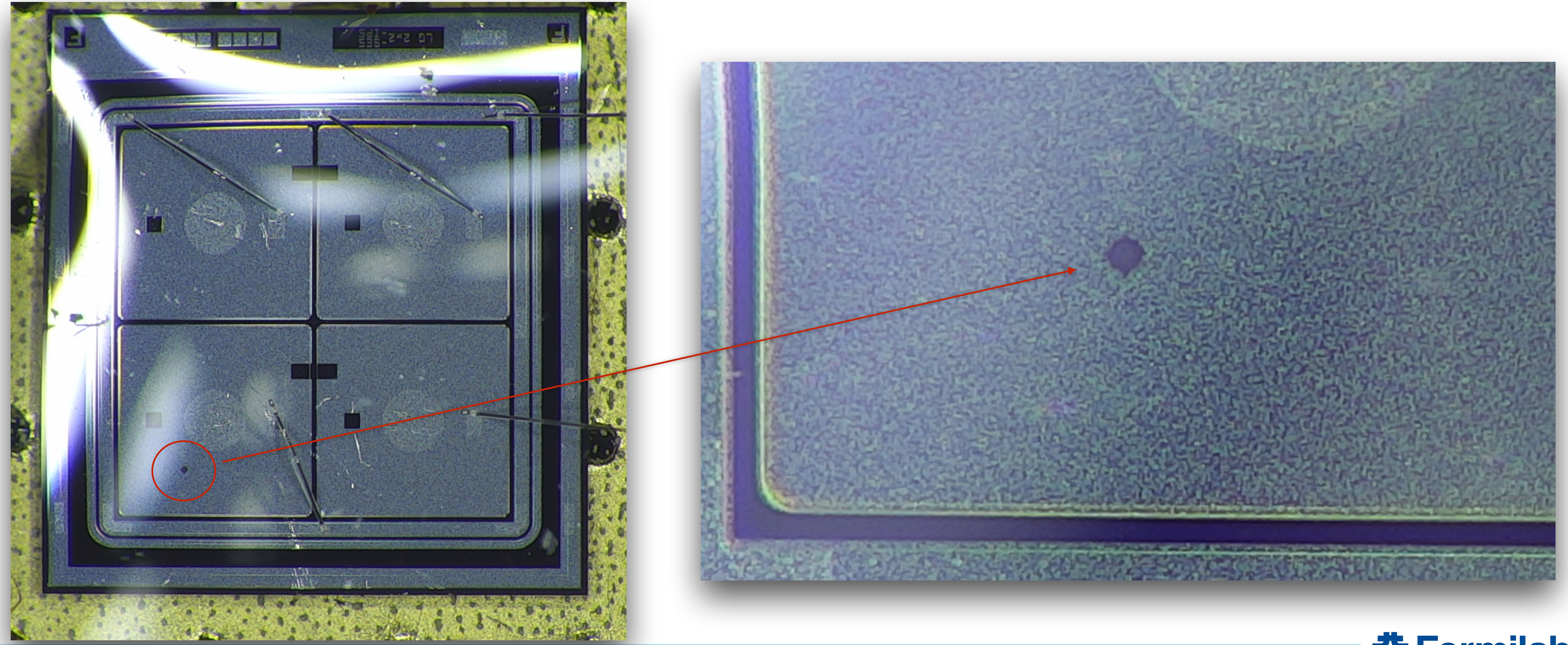
Fermilab

Summary of deaths observed

Sensor type	# of good sensors	Fatal voltage	$N_{protons}$ at fatal voltage	Notes
HPK2 @ 1.5e15 neq	7	625-675 V	10–30k	**"Standard candle"**
HPK2 @ 2.5e15 neq	4	625-675 V	10–30k	**Role of gain & fluence?**
HPK2 PiNs (1.5e15 neq or 0.1 MGy)	3	625-700 V	10–30k	
35 micron HPK 1.1	Excluded in pre-beam testing due to early breakdown			**Role of thickness?**
80 micron HPK 80D	Destroyed in pre-beam testing (surface breakdown at 850 V; target voltage 950 V ~ 12 V/µm)			
50 micron 50D & HPK3.1	2	675-700 V	10-30k	
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)**
Encapsulated sensor	2	625-675 V	10–30k	

Encapsulated sensors

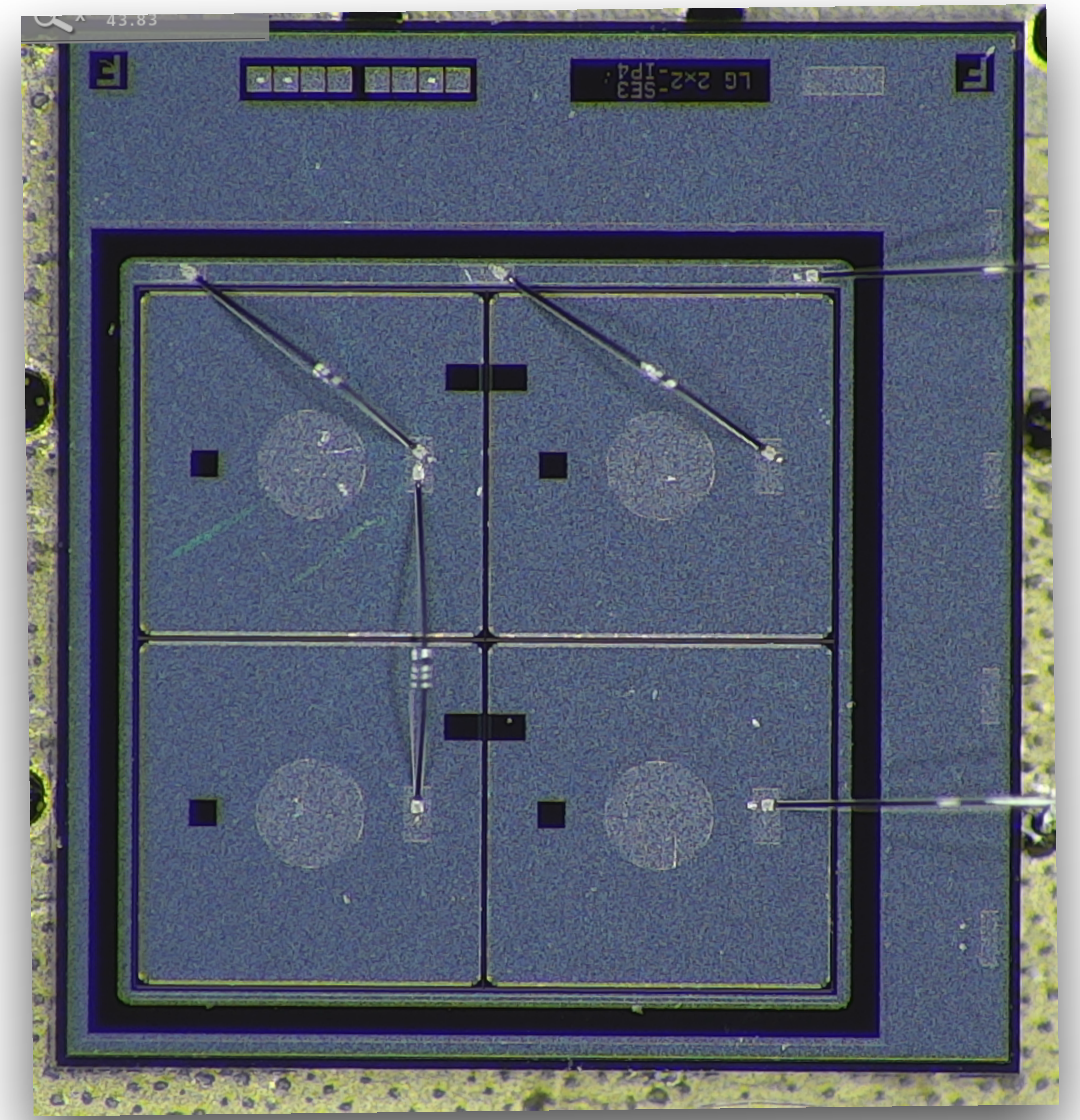
- Two sensors completely covered with wirebond encapsulant (Sylgard 186)
- Crater clearly originates underneath encapsulation. No effect on lifetime or other properties.



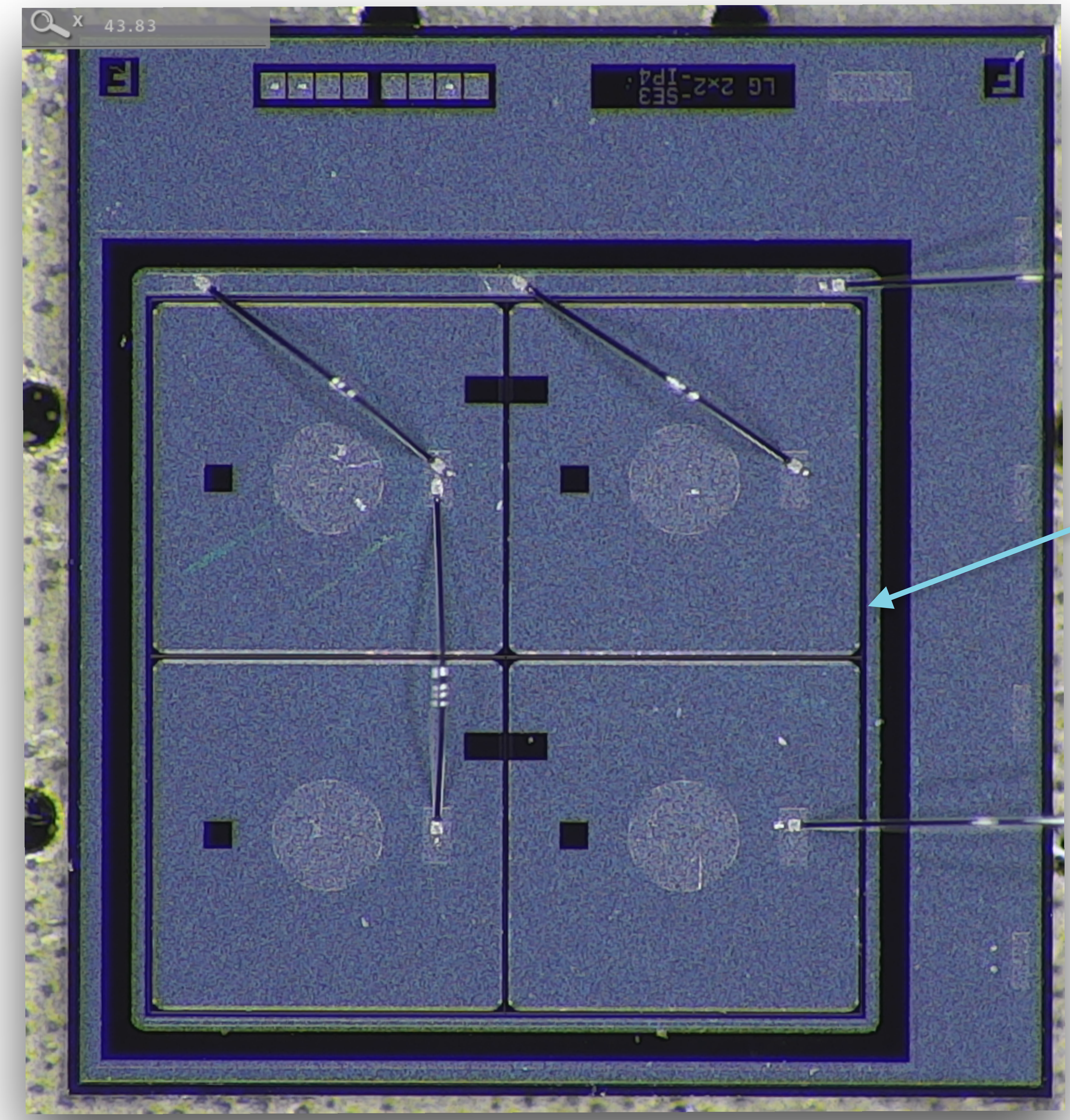
Death of sensor with no HV capacitors

- Remove 10 nF of filter capacitors in parallel with sensor on UCSC board
- Increase lifetime by ~50x; and ultimately less dramatic death.

Before



After



Fatal track points here

No clearly visible features post-mortem.

Sensor still weak diode after death! (BD @ ~200 V). Contrast w/ full capacitance: perfect short.

Conclusions from controlled death batches

- PiNs, and 2.5e15 neq LGADs die at similar conditions as 1.5e15 neq LGADs.
  - ➡ Gain is not necessary for death mechanism.
  - ➡ Mortality is function of sensor thickness and voltage only (to first order)
    - $\geq$ 600 V for 50 micron sensors.
- Proton track in fatal event always points to crater.
  - ➡ Death is caused by localized single proton interaction.
- HV capacitance accelerates death and increases severity of death events.

  -But, not possible to escape capacitance in 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

- Second phase: demonstrate survival of sensors at 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 conservative voltage
  - 350M at target operating voltage
  - 100M at aggressive voltage beyond optimal operating point.

- Periodic monitoring of sensor occupancy to verify flux estimate.

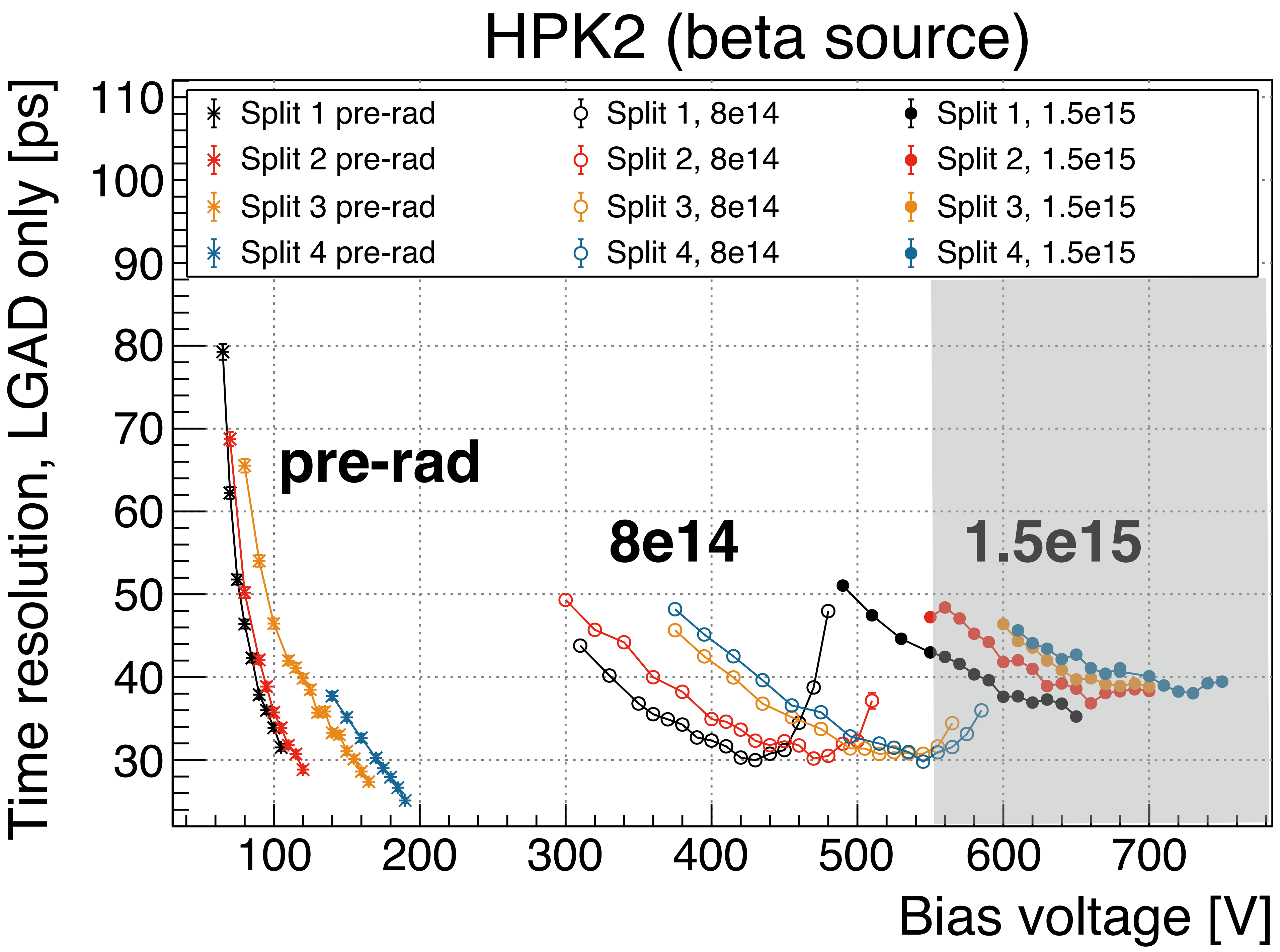
Survival batch results

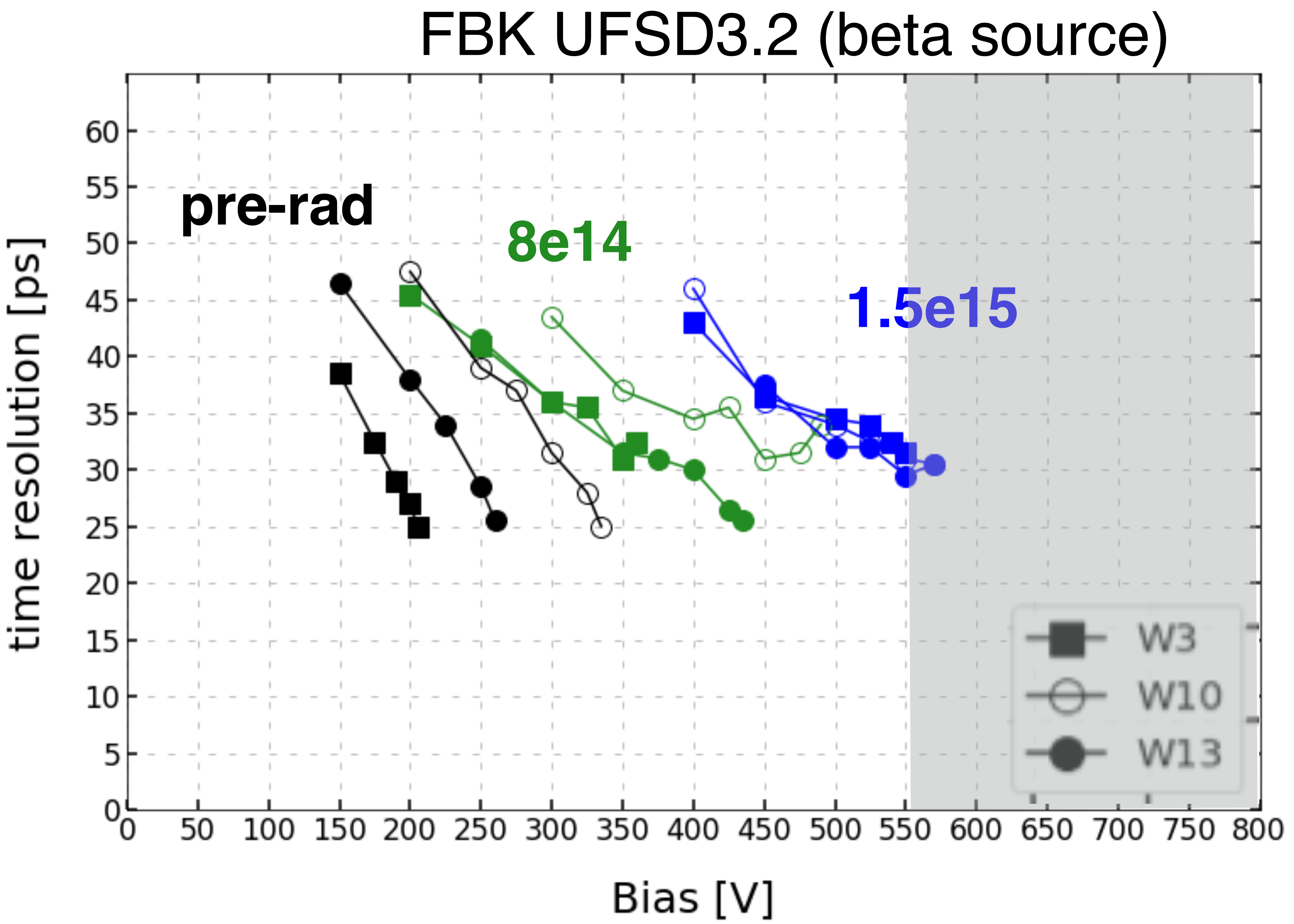
Sensor type	# of good sensors	Voltage tested	Notes
HPK2 split 4 @ 8e14 neq	4	500-575 V	No deaths
HPK2 @ 1.5e15 neq	2	500-575 V	No deaths
FBK UFSD3.2 @ 8e14 (W7 & W13)	2	400 V	No deaths
FBK UFSD3.2 @ 1.5e15 (W7 & W13)	2	500-600V	No death until operating voltage exceeded.

- Bottom line: **No death observed in 50 micron sensors with bias < 575 V.**
  - Probed with ~500M protons (50000x more than needed for death at 625 V)
- FBK: hint that thinner sensors die at lower voltage.
  - 45 micron W13: died at 550 V
  - 55 micron W7: survived 100M at 600 V (still alive)

Context for ETL

- **50 micron LGADs should remain at voltage ≤ 550-575 V in CMS/ATLAS.**
- HPK sensors at 8e14 neq: happily operate within this regime.
  - This represents majority of sensors for ETL.
- HPK sensors at 1–1.5e15 neq: reduced performance, but not catastrophic.
  - HPK2 split 1 & 2 achieve 40-50 ps at 550V.
- Some FBK wafers deliver required performance < 550V at all ETL fluences.



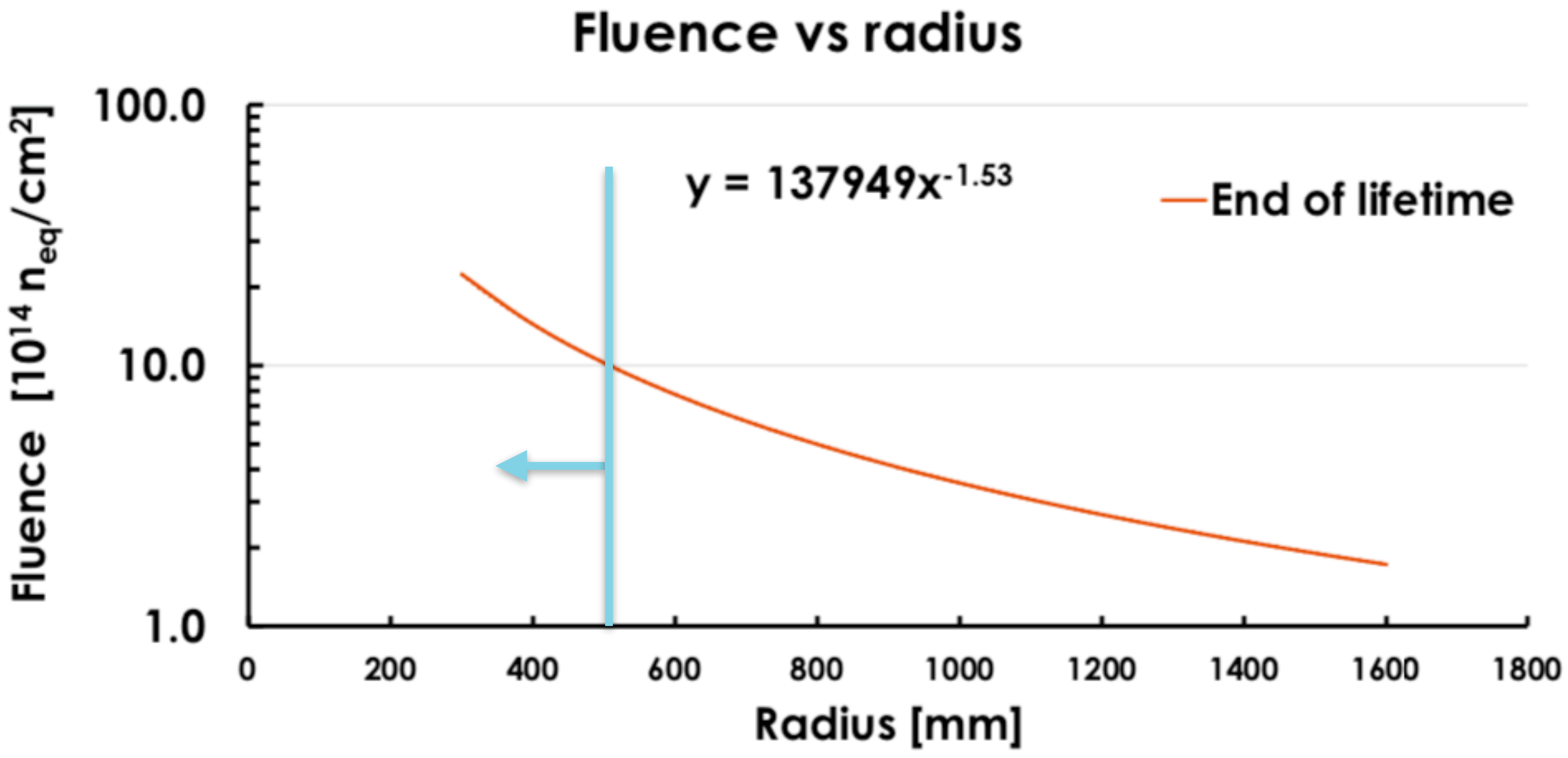


nilab

Context for ETL

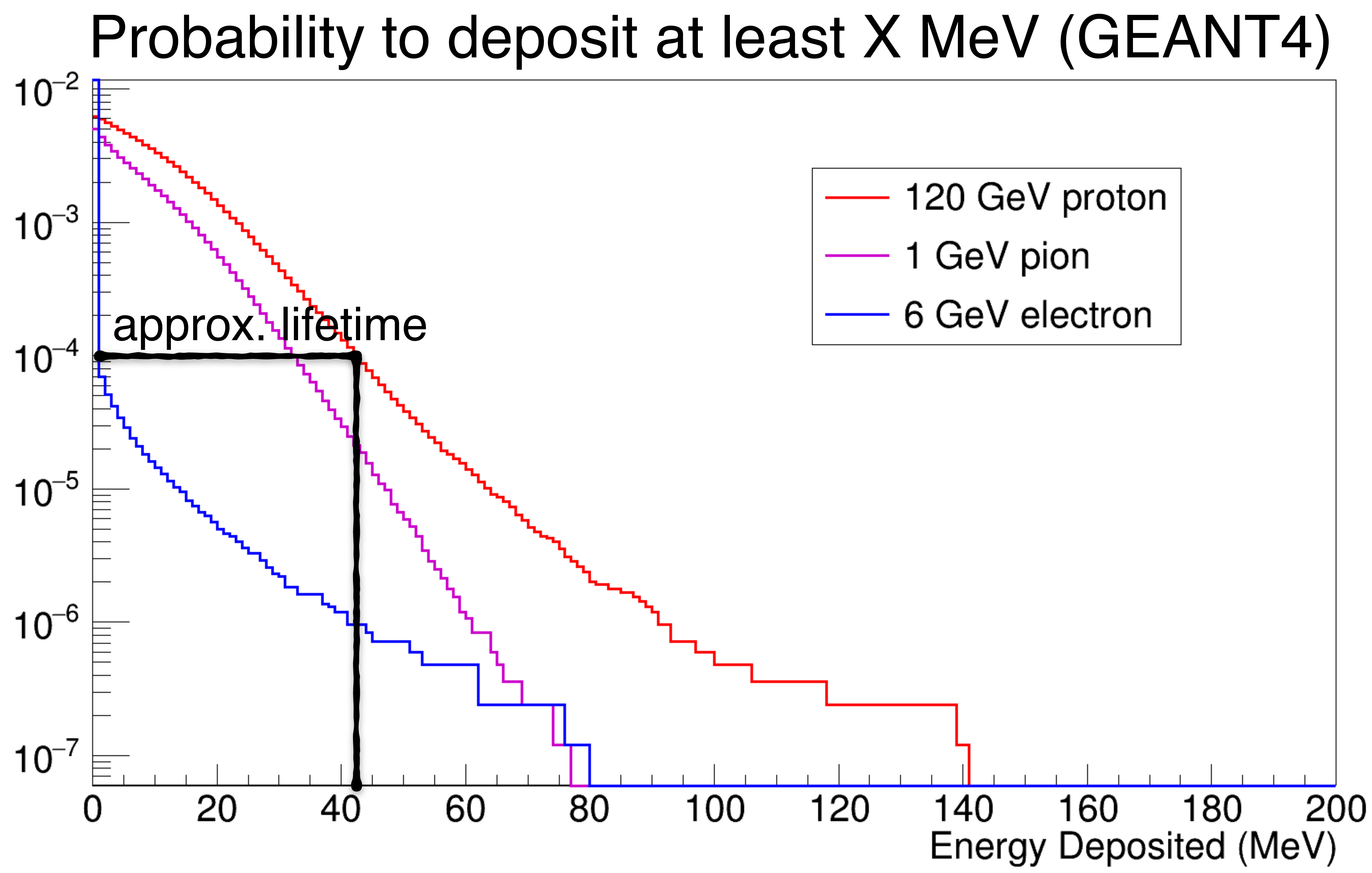
- **50 micron LGADs should remain at voltage ≤ 550-575 V in CMS/ATLAS.**
- HPK sensors at 8e14 neq: happily operate within this regime.
  - This represents majority of sensors for ETL.
- HPK sensors at 1–1.5e15 neq: reduced performance, but not catastrophic.
  - HPK2 split 1 & 2 achieve 40-50 ps at 550V.
- Some FBK wafers deliver required performance < 550V at all ETL fluences.

Only HPK sensors at innermost radii require reduced voltage.
Few percent of ETL area.



ilab

Proposed death mechanism



- Rare, large ionization event “Highly Ionizing Particle”
  - Excess charge leads to highly localized conductive path
  - Large current in 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.

Summary

- Extensive study of LGAD mortality carried out at the Fermilab Test Beam
- Understanding of death mechanism significantly improved
  - Caused by single HIP interaction
  - Unrelated to gain or sensor fluence—only the bias
    - May be critical field: ~12 V/micron, but need to better probe other thicknesses
  - Simulation in GEANT and TCAD ongoing
- First indication of safe operating voltage established
  - HPK sensors < 1e15 neq require no mitigation
  - HPK sensors > 1e15 neq will be slightly underbiased in final years.
  - FBK sensors can reach operating point at all fluences.
- Follow-up with extreme rate stress test in 2021/2022 at FNAL high-rate facility (~10^8—10^9 protons per spill on sensor.)