Stability of irradiated LGAD sensors in the Fermilab high-rate proton beam facility

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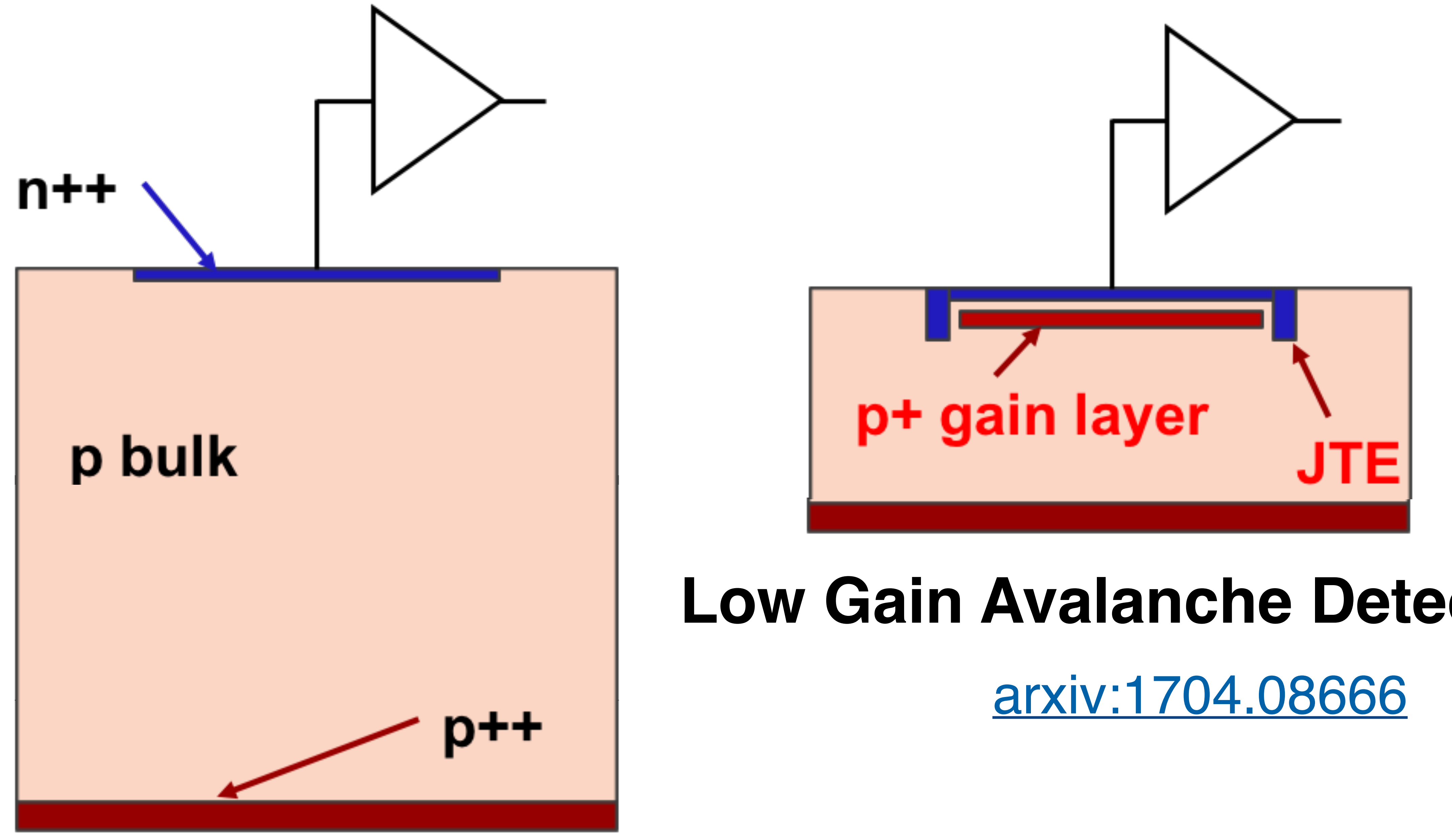
Precision timing with LGADs

- Silicon sensors optimized for timing: Low Gain Avalanche Detectors (**LGADs**)
  - Thin depletion region (50 micron): fast & uniform signals
  - Internal gain: boost signal-to-noise (x10-30)

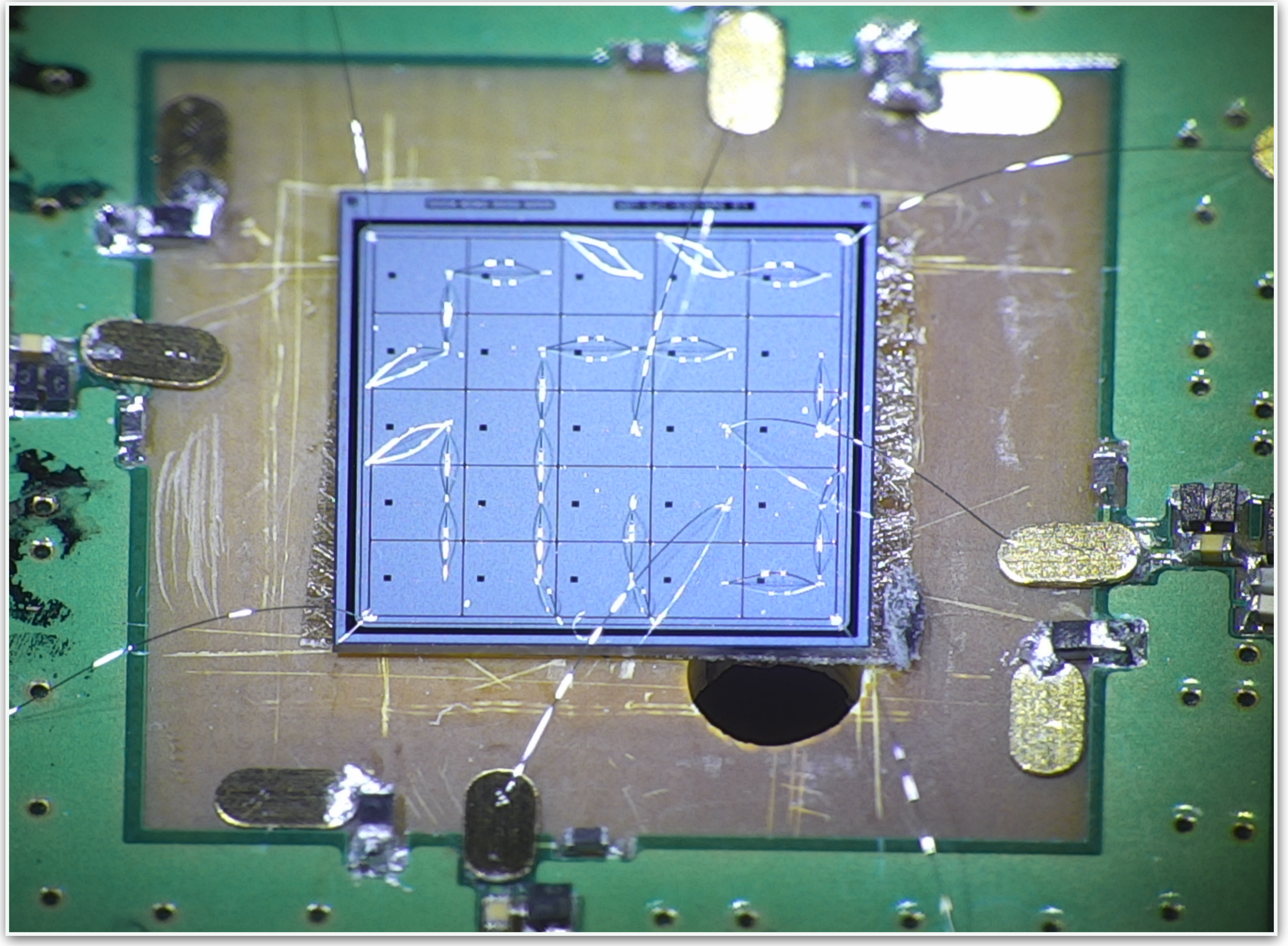


Low Gain Avalanche Detector

arxiv:1704.08666

Traditional silicon detector

HPK LGAD prototype, 1.3 mm pads

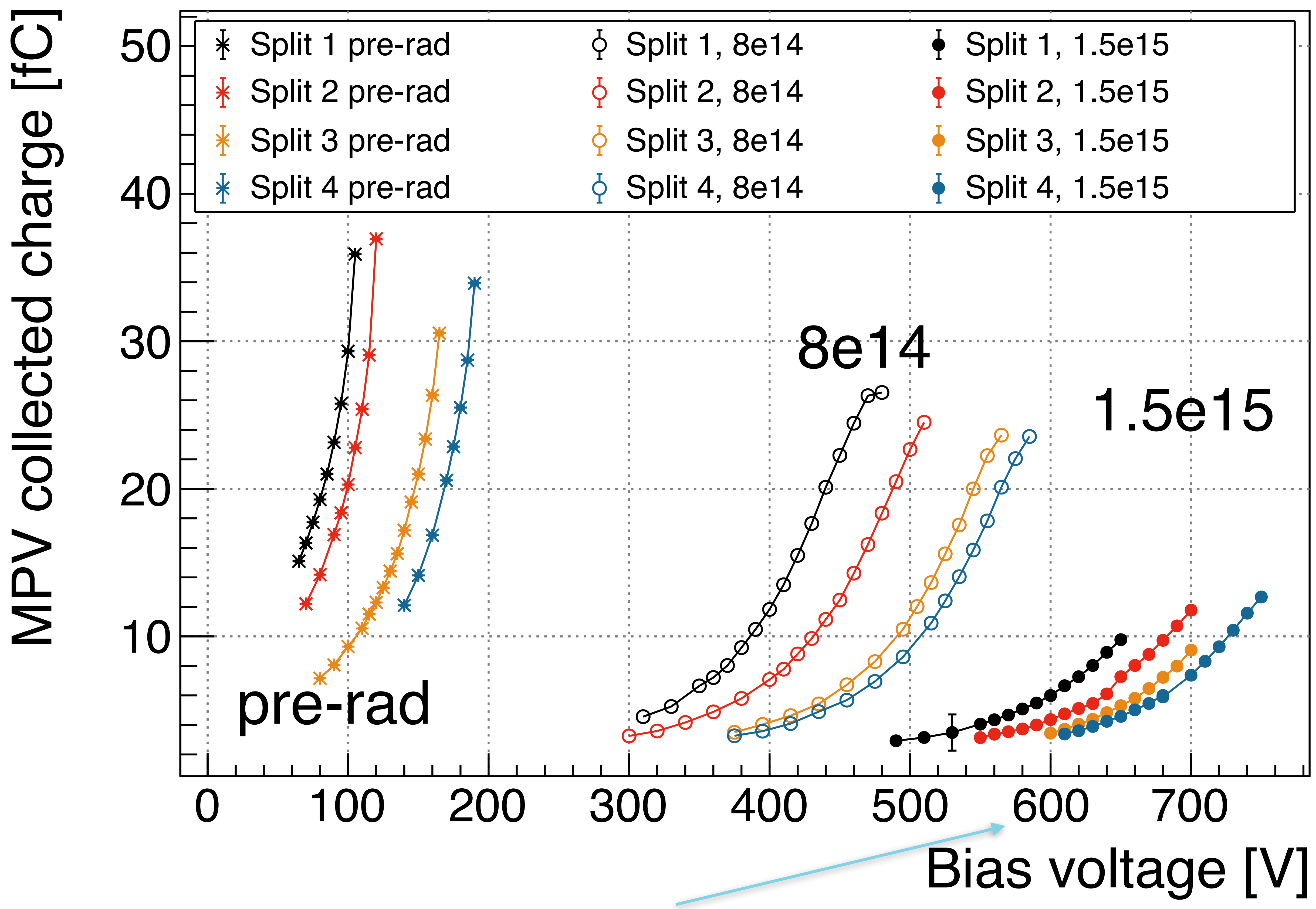


- CMS Endcap Timing Layer: timestamp every track with 30-40 ps resolution!

LGADs under irradiation

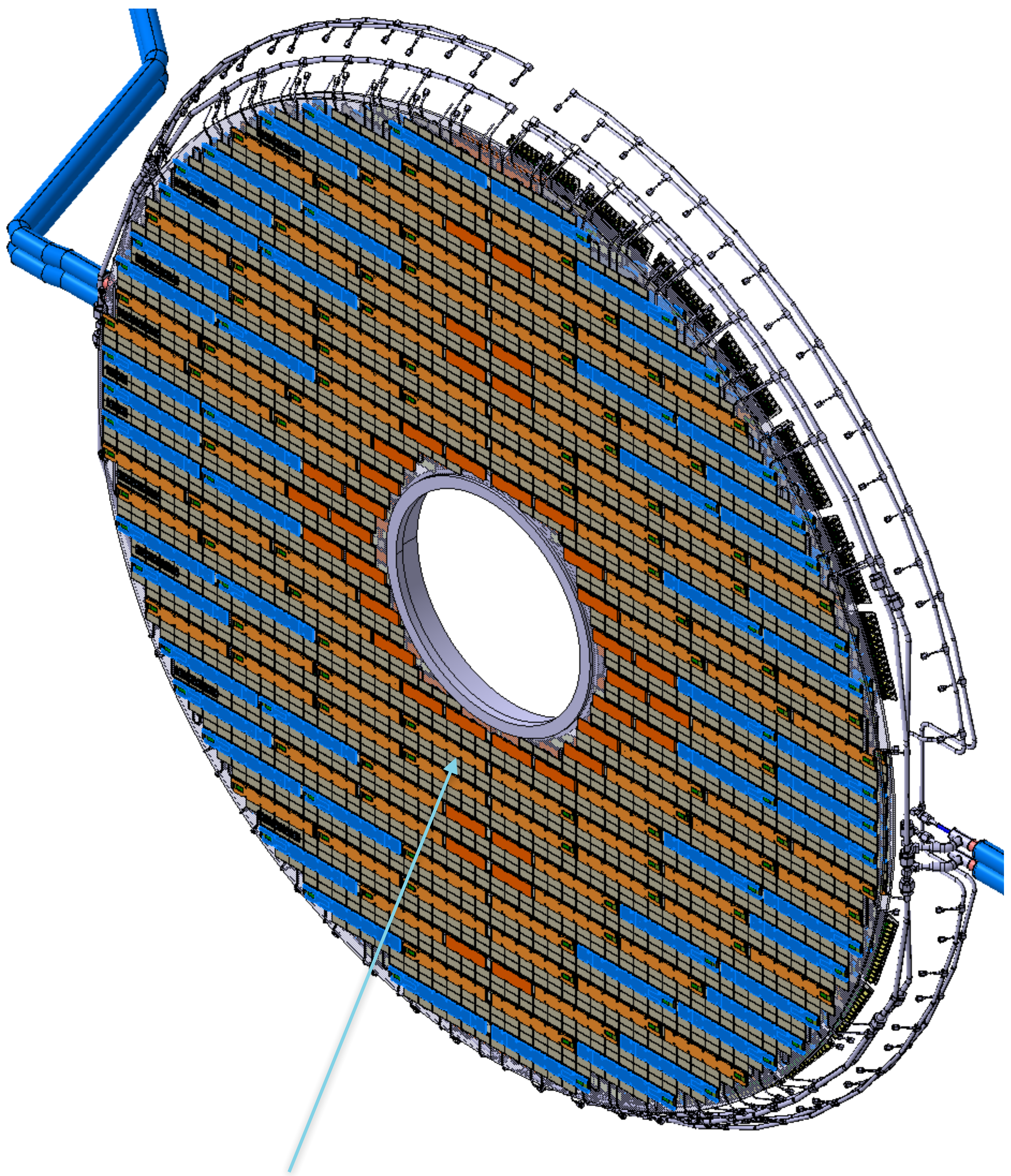
- Gain layer de-activates with irradiation
- Increase bias voltage over time to maintain large signals.

HPK2 prototypes (beta source)



Ultra high E-field: 12 V per micron!

CMS Endcap Timing Layer (1 disk)



Inner radii: reach fluence of 1.5 x 10^{15} neq/cm^2

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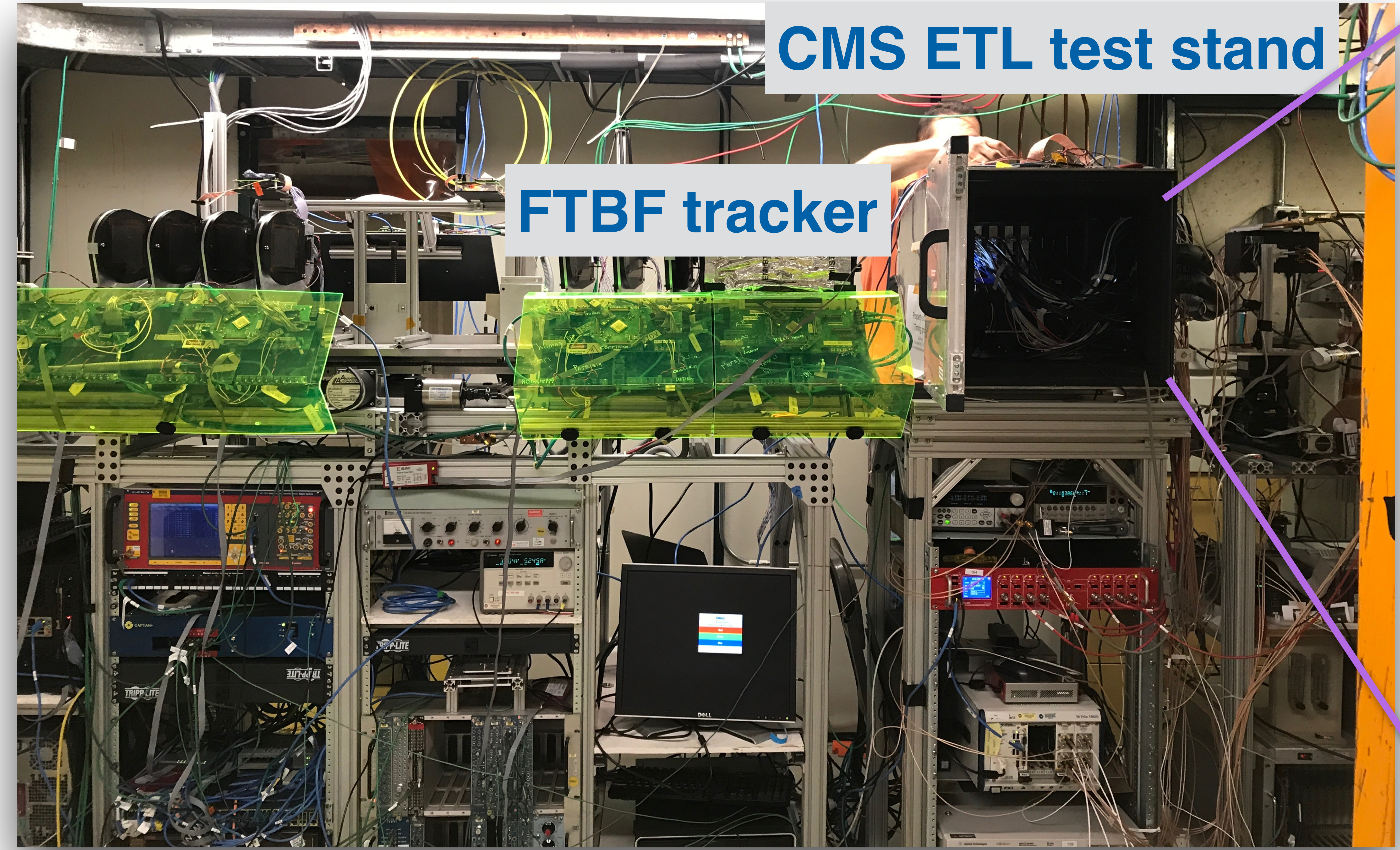
LGAD mortality

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

- Several test beam campaigns at Fermilab dedicated to study of LGAD mortality
  - 30 sensors studied December 2020 - March 2021 → **understand death mechanism**
  - 20 sensors at extreme rate facility December 2021 → **demonstrate safe operation regions**

- 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.

Mortality studies at Fermilab Test Beam Facility



Is LGAD burnout caused by protons, or spontaneous?

Impact of gain, bias voltage, irradiation ??

Mortality studies

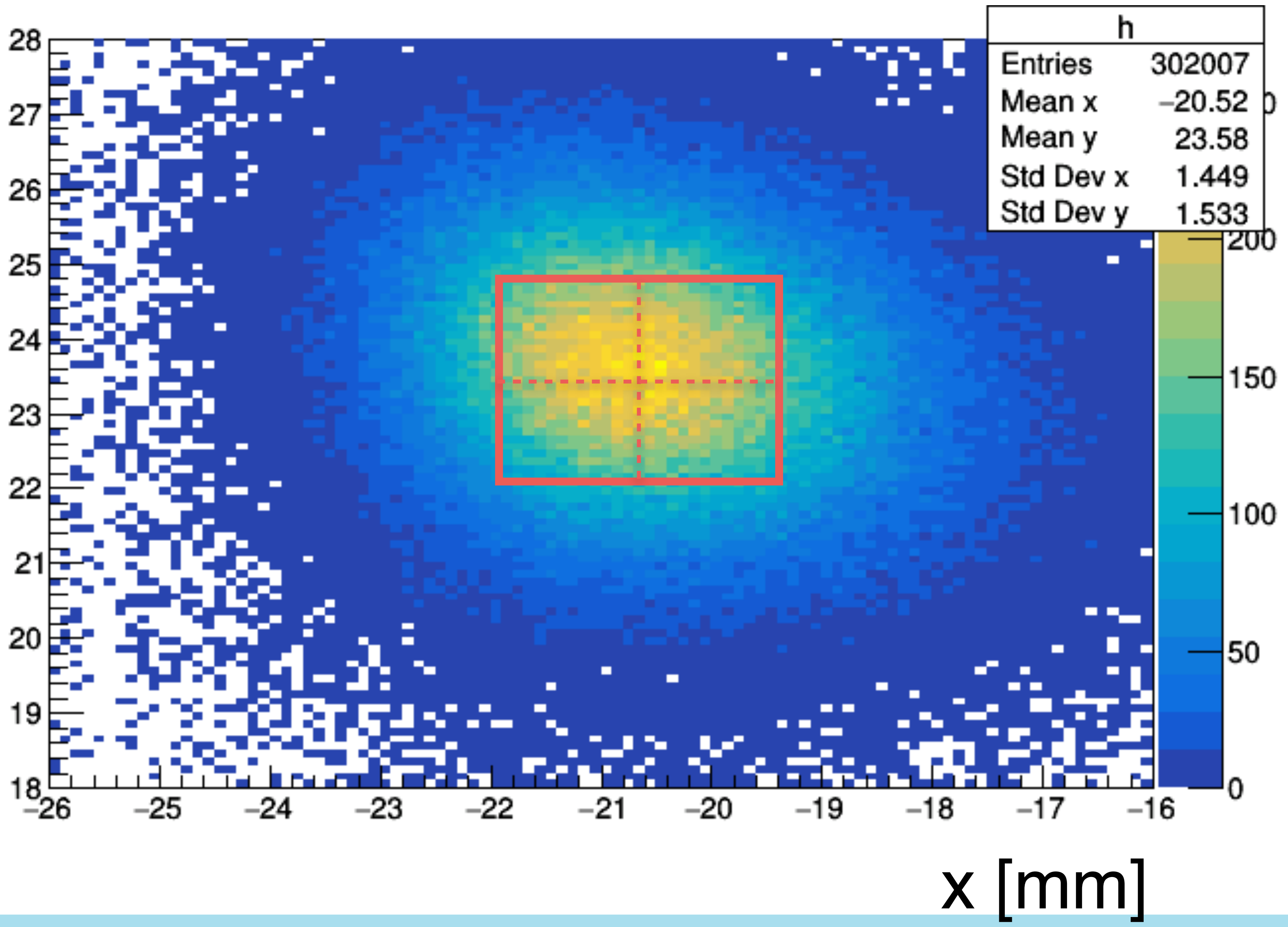
- Measure beam profile with tracker.
- Align each sensor with beam based on single-ch readout.
- Carefully increase bias voltage
  - ~3k protons on sensor per minute. Raise bias 25V after 100-200k protons.

Most sensors in 2x2 geometry

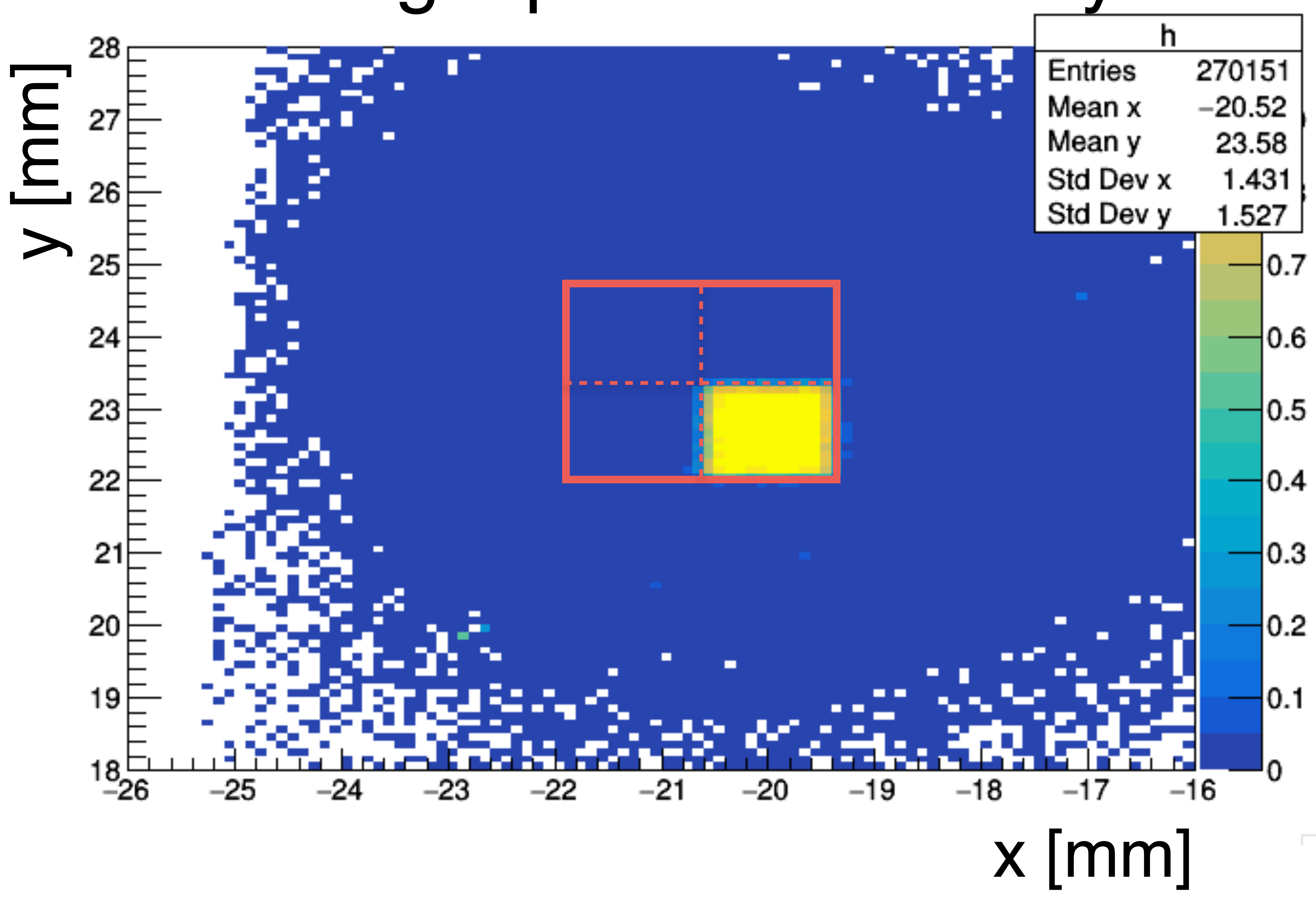
Most from HPK2

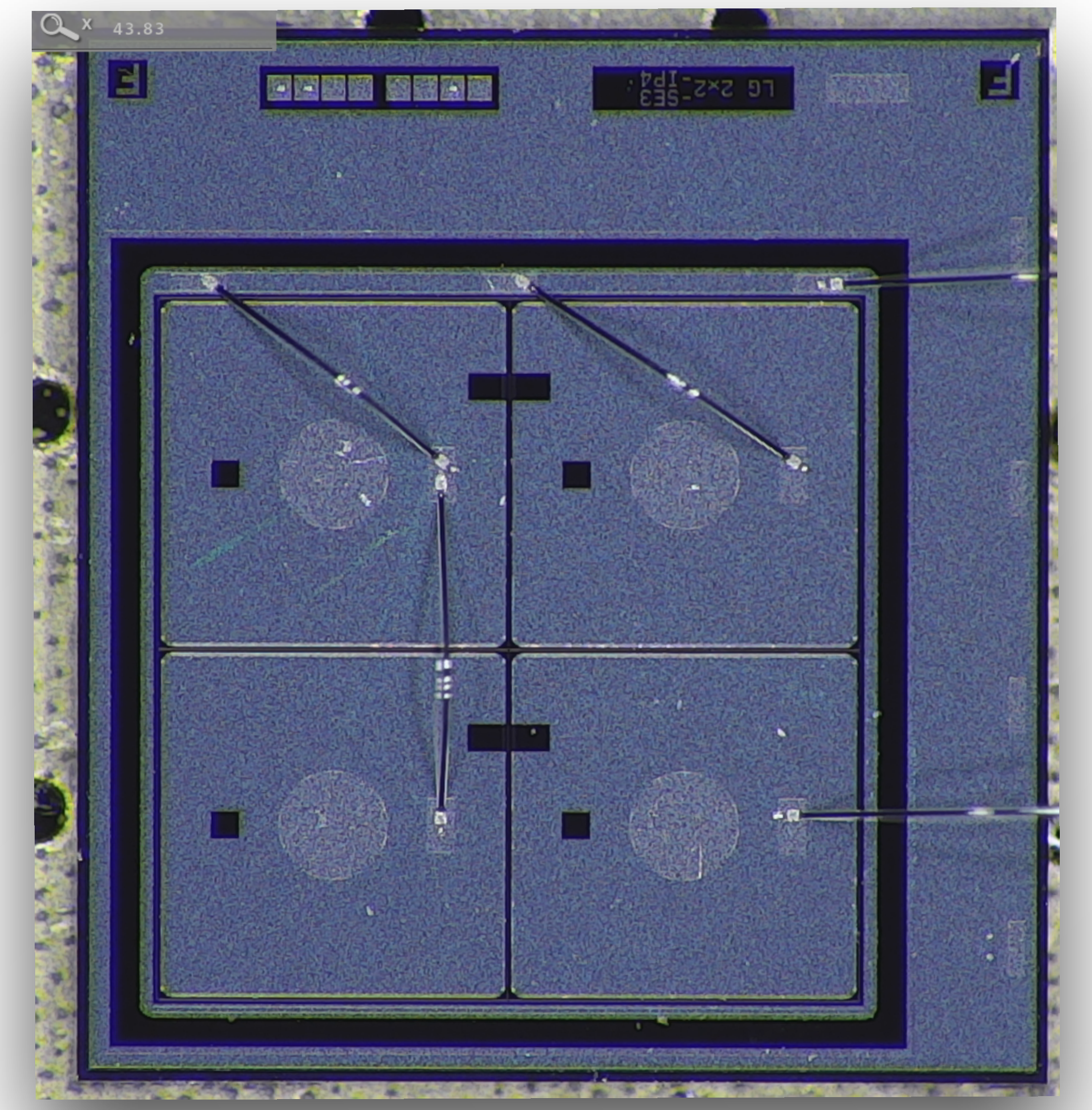
pre-irradiated 8e14-2.5e15 neq

Beam profile



Single pad hit efficiency





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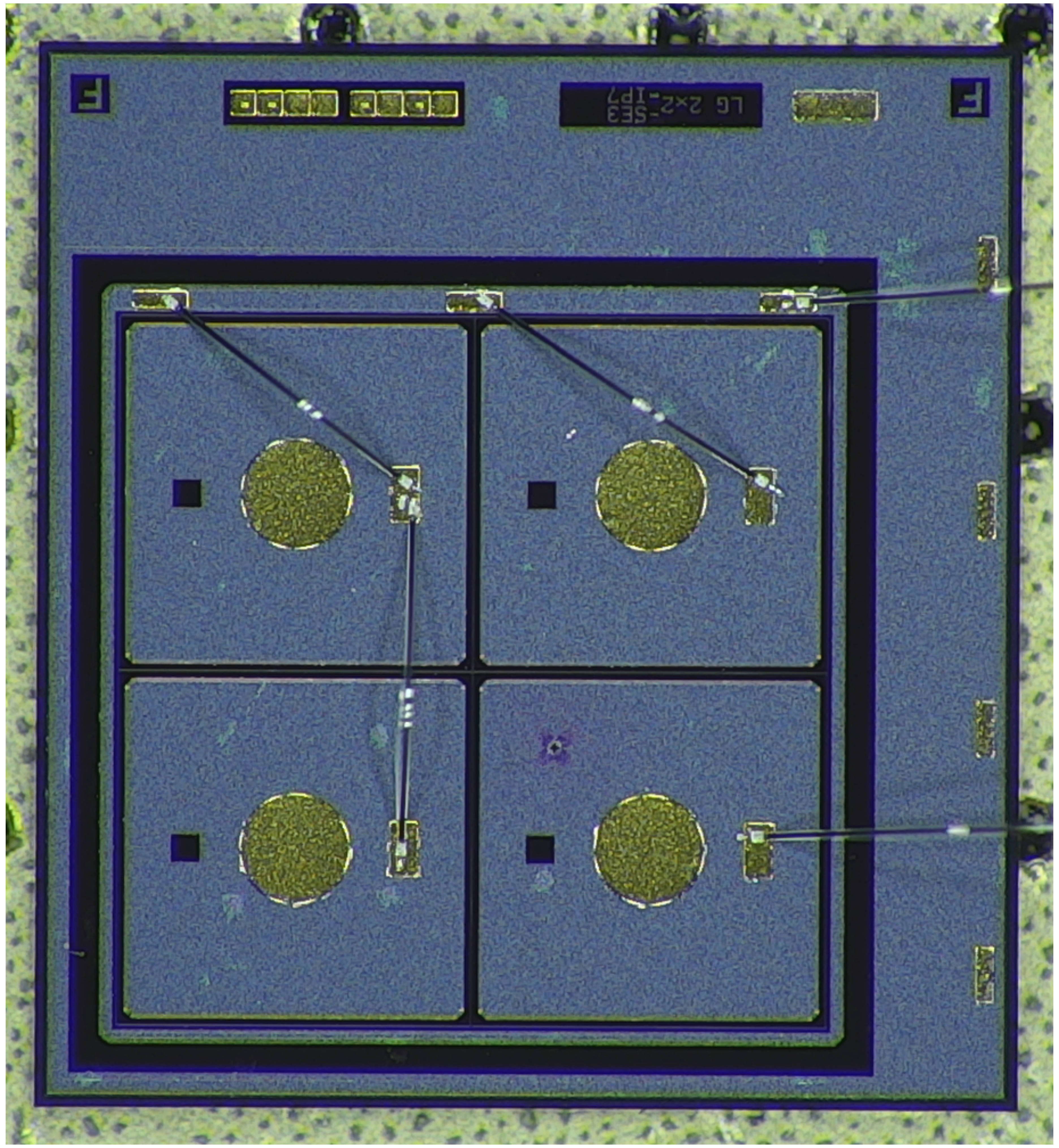
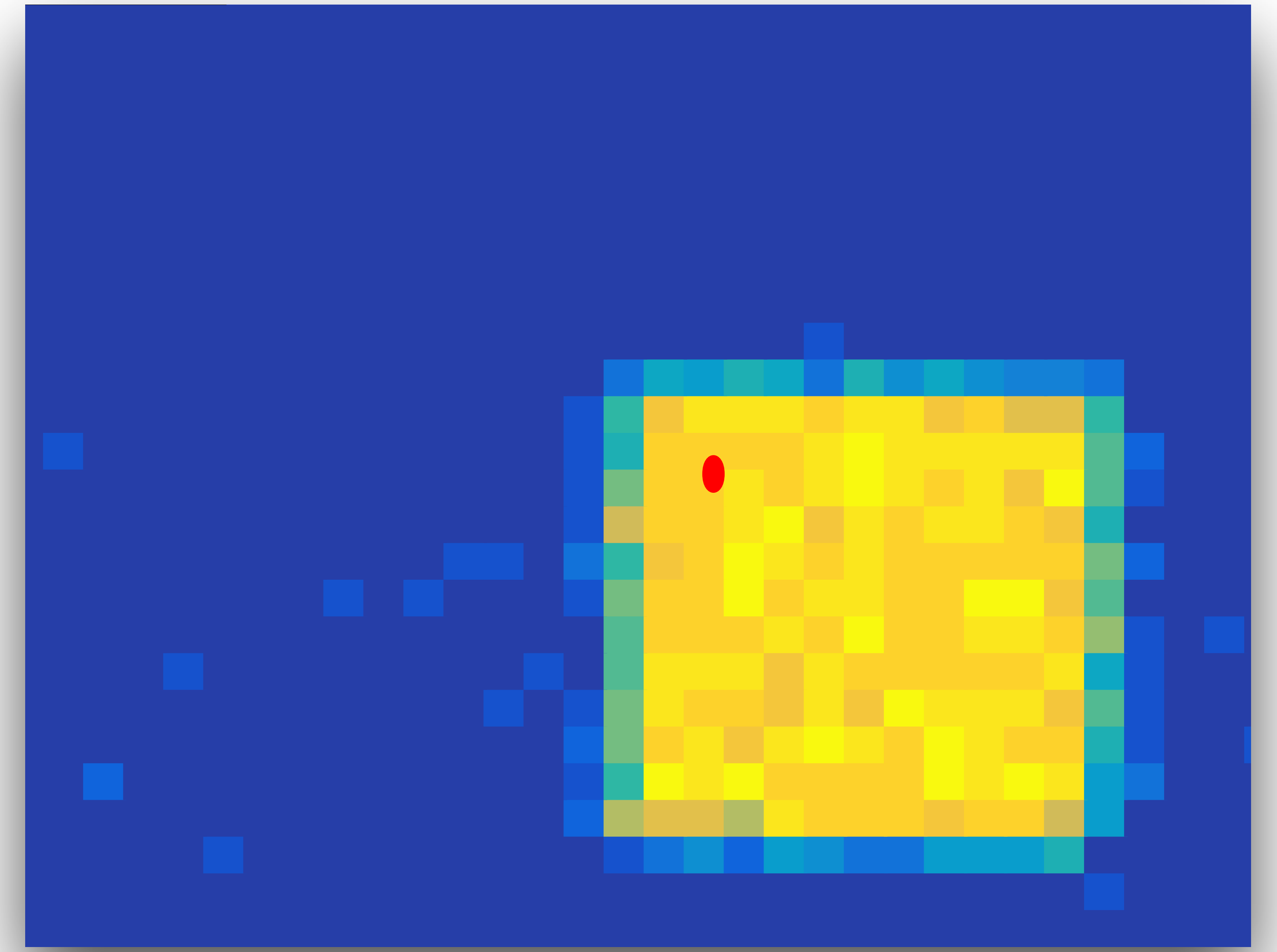
Example burnout event

HPK 1.5e15 neq/cm^2



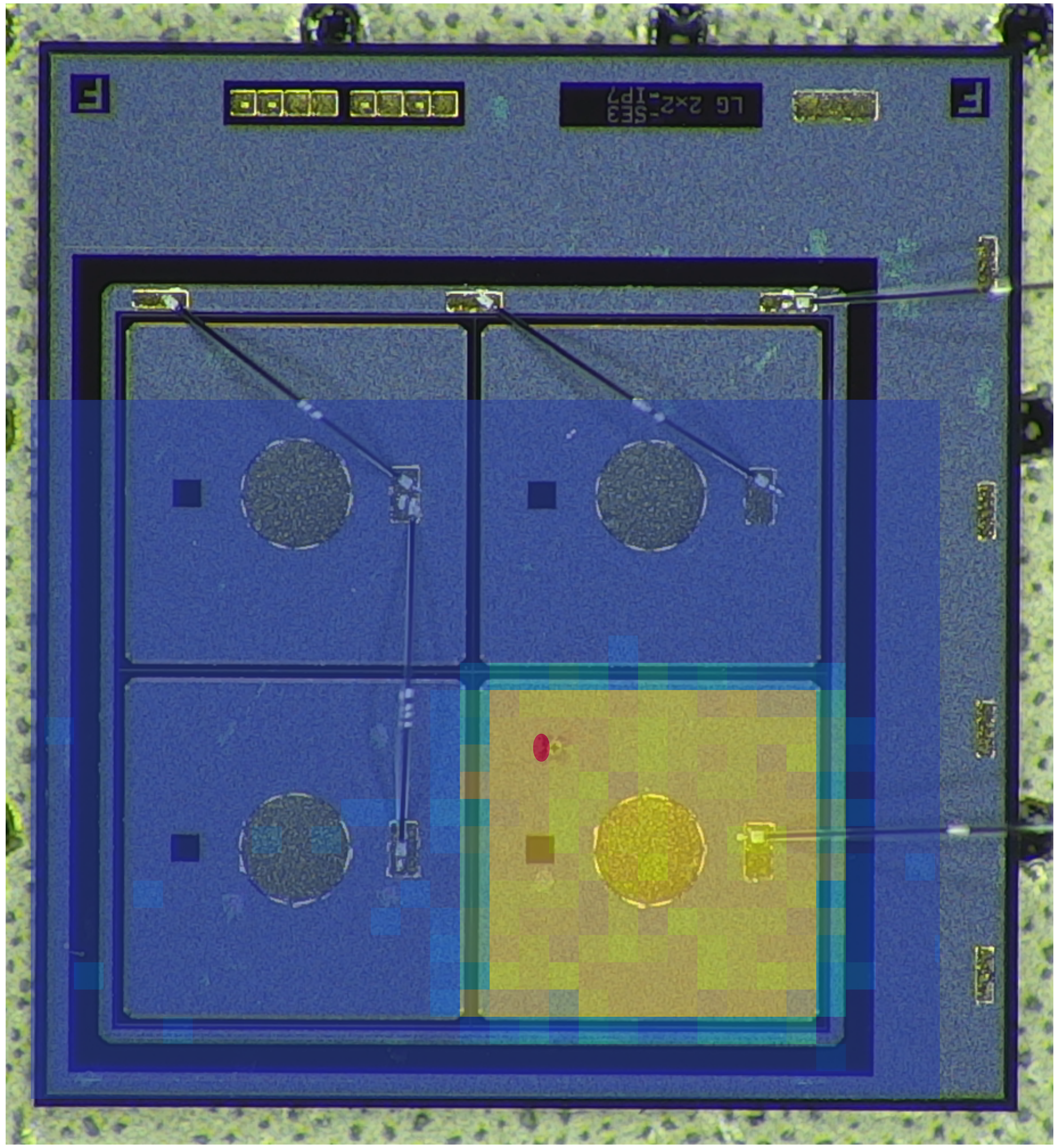
- When death occurs, first observe short on bias supply
- Then, find LGAD waveform indicating moment of death
- Compare track position in fatal event with crater location.



Efficiency map, lower right pad.

Example burnout event

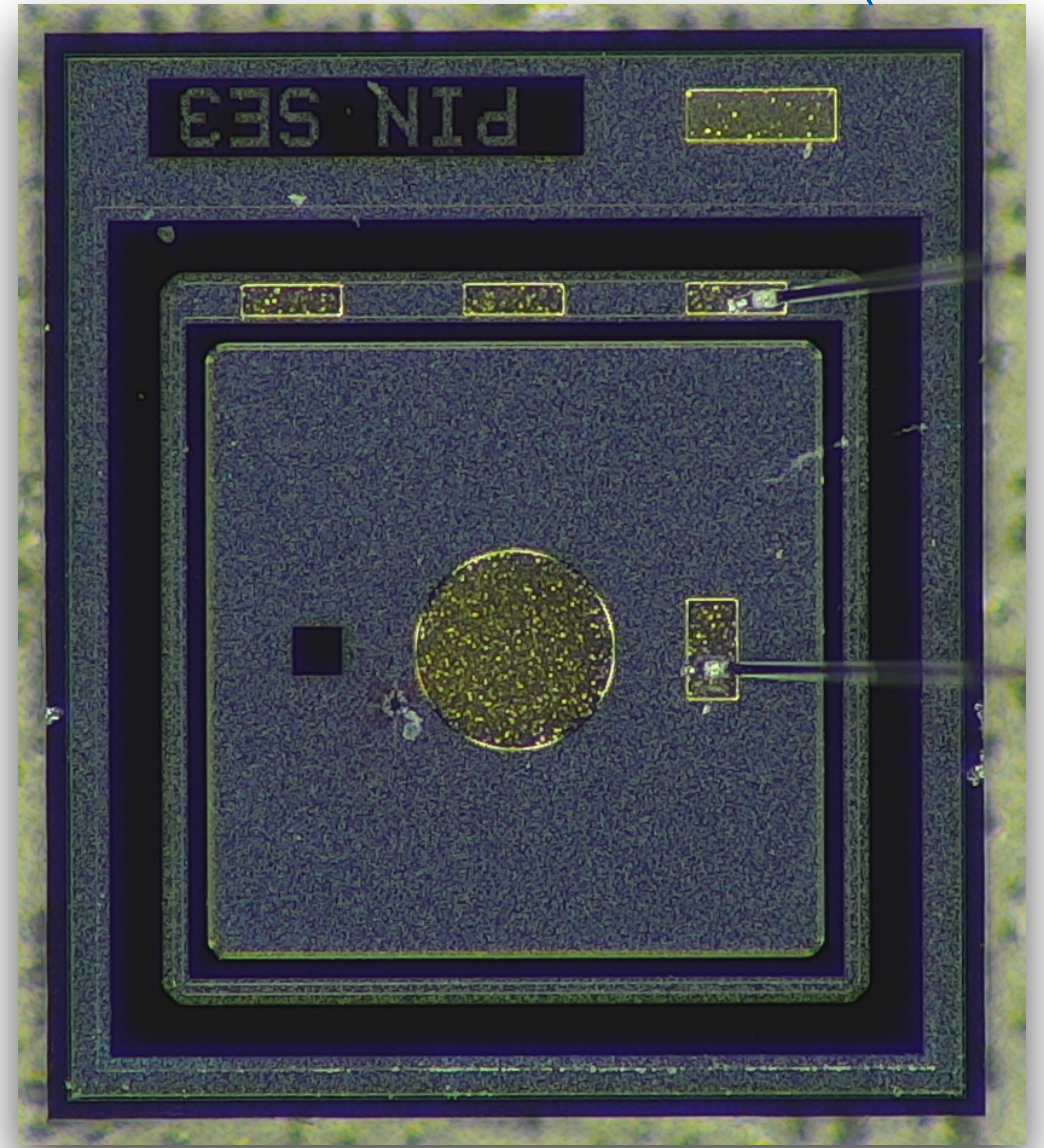
HPK 1.5e15 neq/cm²

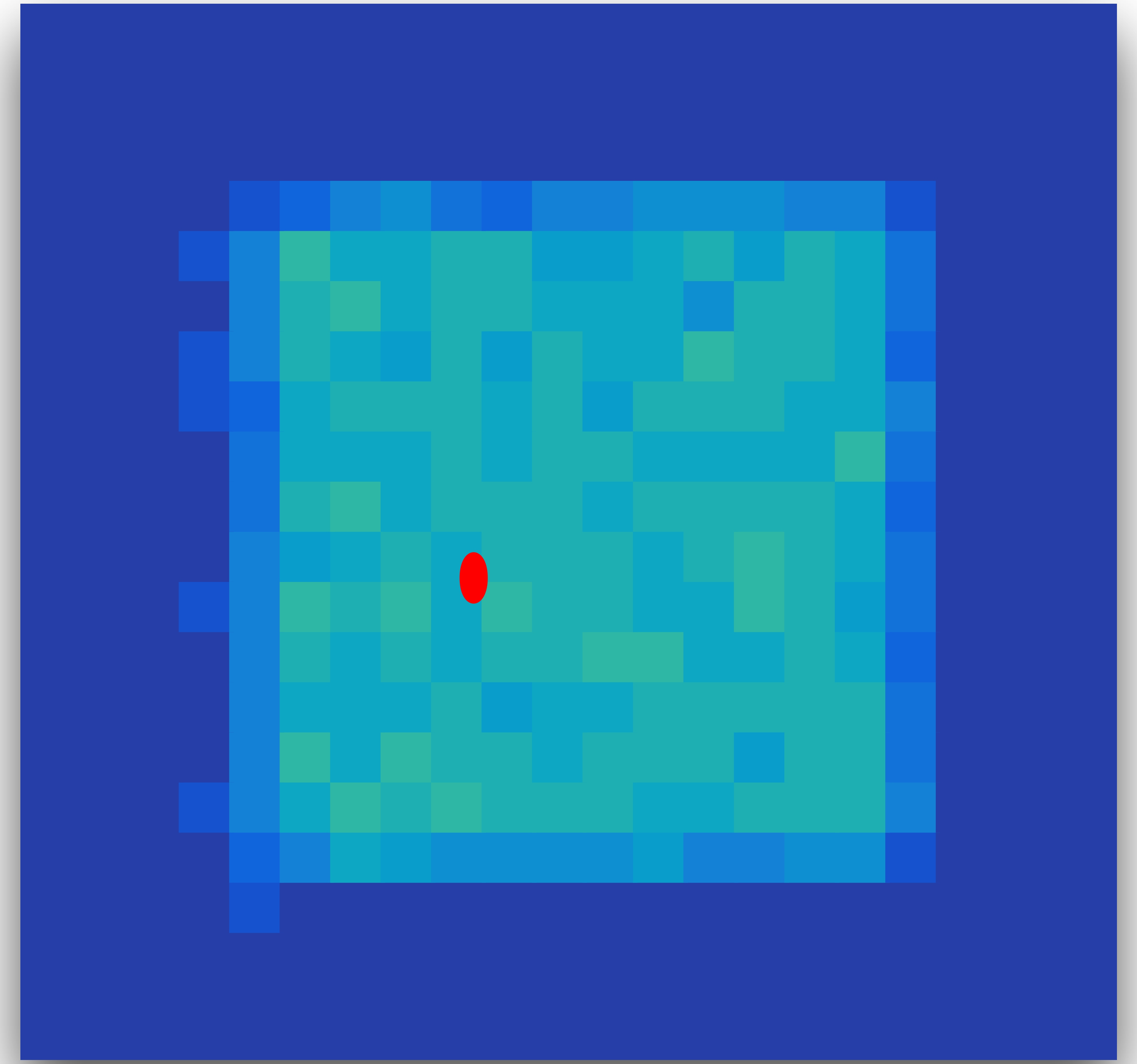


Burnout is decisively caused by proton!

Burnout in PIN diode

Gamma-irradiated HPK PIN diode (50 micron)



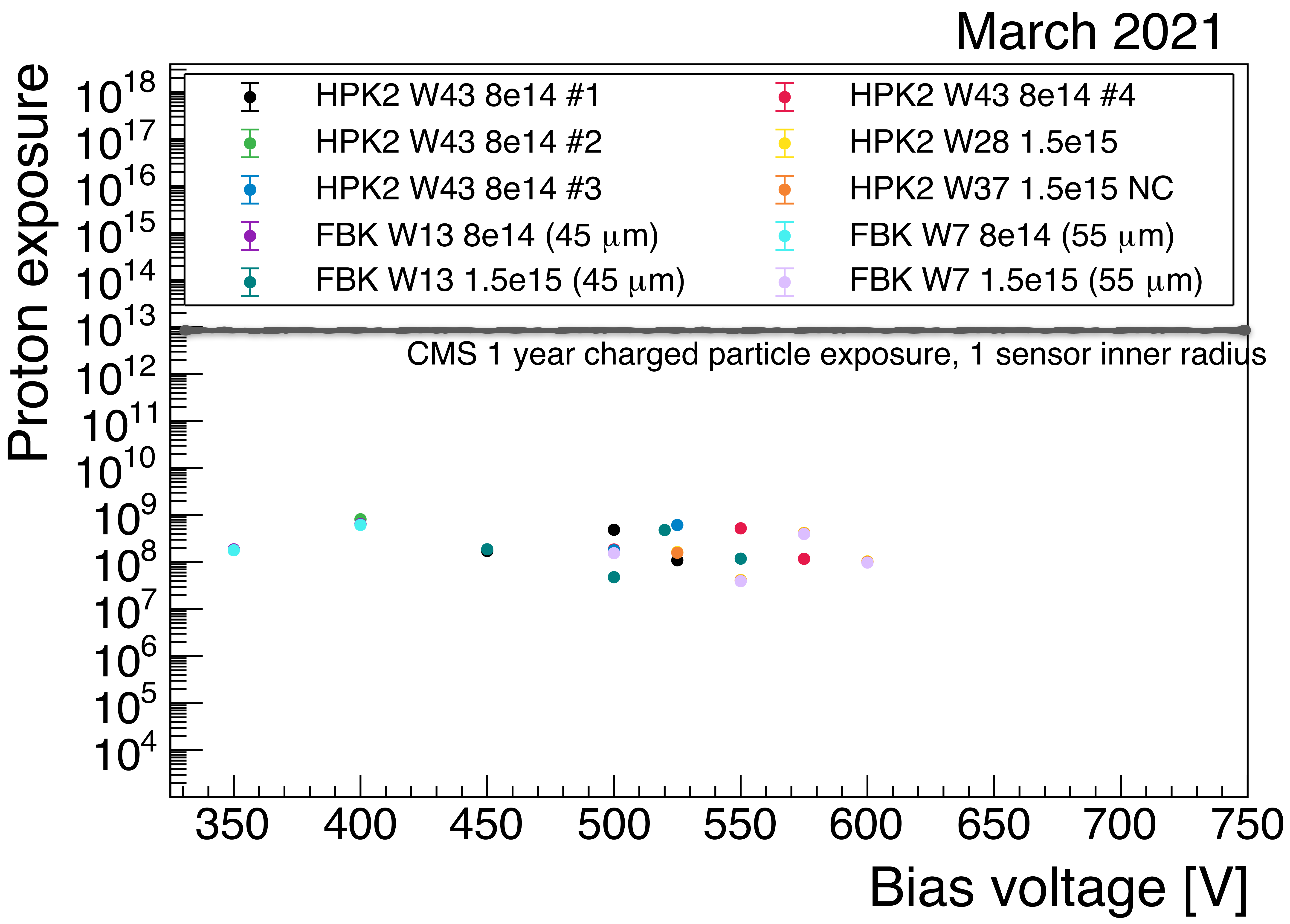


Even diodes die the same way→ gain is not needed.

Conclusions from initial burnout studies (March 2021)

- All 50 micron sensors susceptible to proton-induced burnout at bias ≥ 600 V
  - LGADs or PiN; any fluence: all die the same way.
  - ➡ Gain is not important for death mechanism.
  - ➡ Suceptibilty depends on voltage & thickness ONLY
- Suspected mechanism:
  - Rare, extremely high ionization events with energy deposit > 50-100 MeV
  - Excess charge produces narrow conductive path across diode at extreme field: burnout due to high current density.
- Several attempted treatments didn't prevent burnout:
  - Encapsulation of sensor
  - Reduce HV capacitance
  - Add resistance to protect from HV supply..

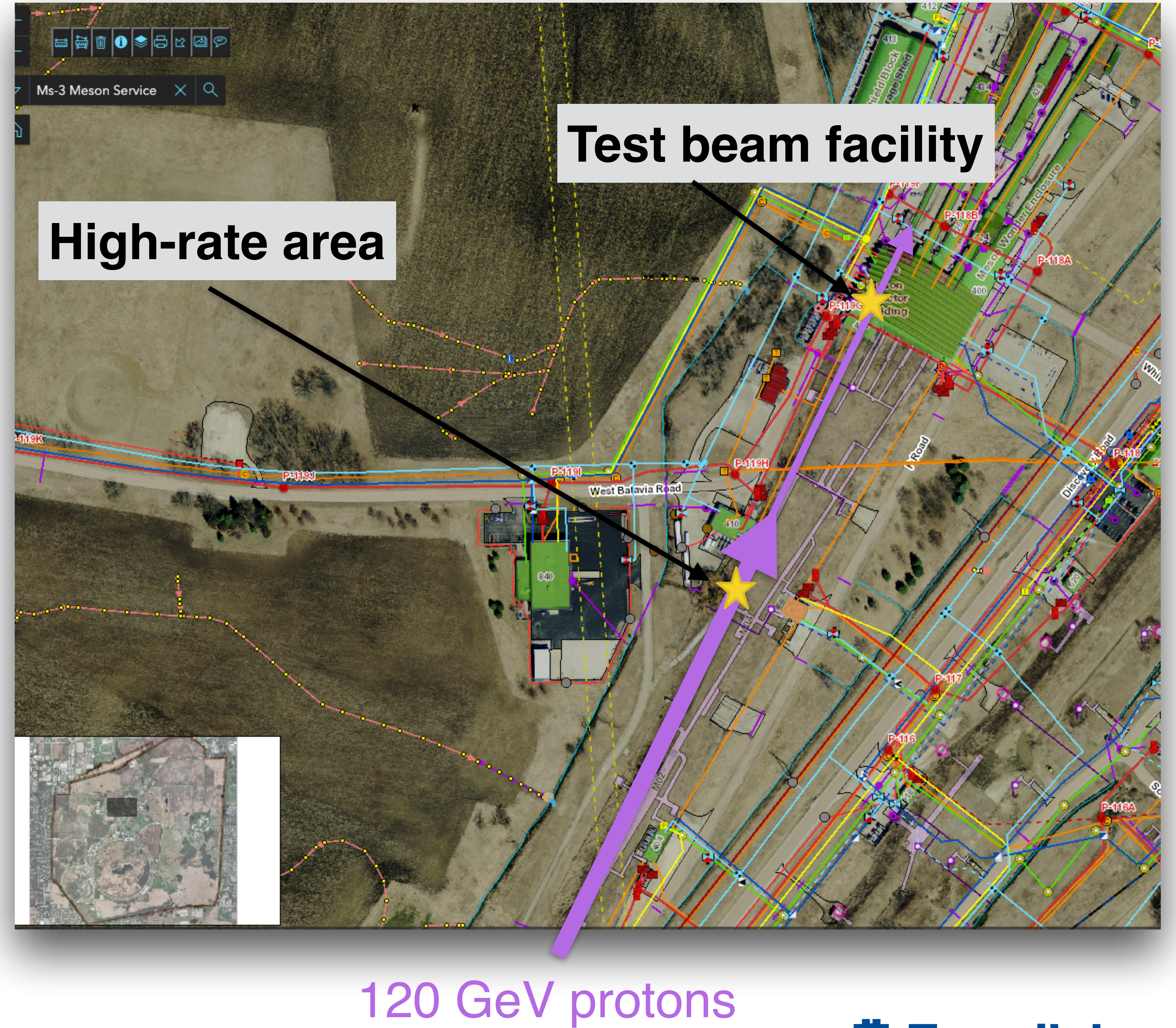
Initial survival demonstrations



- Initial campaign also devoted time to survival demonstration
  - 10 sensors exposed to maximum fluence at test beam facility
  - Probe lifetime at bias slightly lower than burnout threshold.
- No deaths observed in 50 micron sensors ≤ 575 V (11.5 V/um)!
- Exposure ~ 10^9 protons
  - But, not quite comparable to CMS environment…

High-rate survival demonstration

- To achieve flux comparable to CMS, need to use high-rate beam facility, upstream of collimator.
- Achieve ~10^9 protons on target per minute, rather than 10^5



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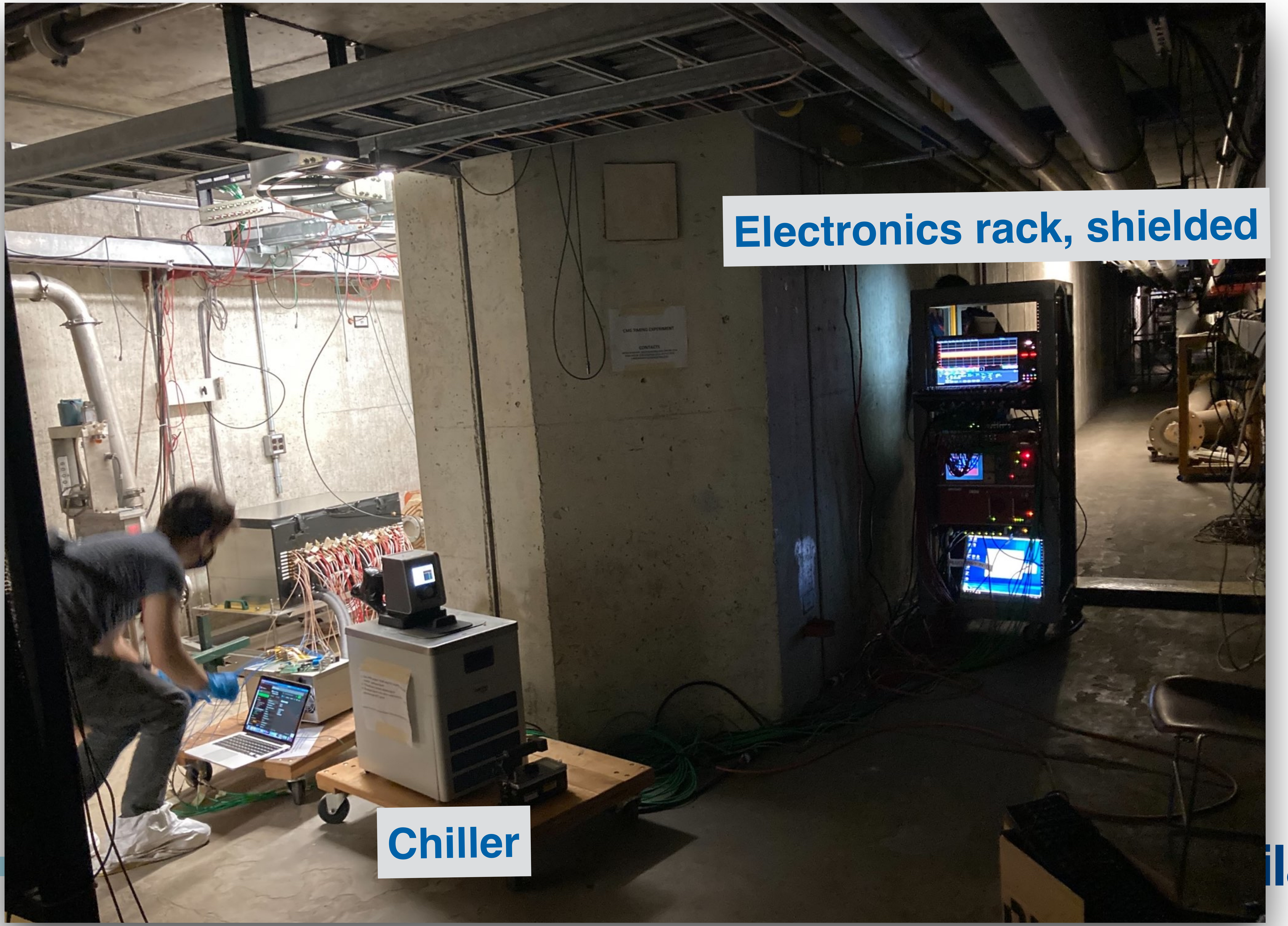
Sensors used

- 17 irradiated sensors (Ljubljana), on UCSC 1-ch boards
- 2 pre-rad sensors for beam monitor, FNAL 26-ch boards
- All sensors in 5x5 geometry.

	Fluence [neq/cm²]	# sensors
HPK2, 50 micron	8e14	x4
	1.5e15	x4
FBK3.2, 45 micron	8e14	x1
	1.5e15	x3
FBK3.2, 55 micron	8e14	x1
	1.5e15	x4

New setup at high-rate area (December 2021)

- Built new setup to support 20 LGADs in high-rate beam
- Hazardous environment..
  - High radiation, frequent SEUs, oxygen deficiency hazard, many barriers to entry

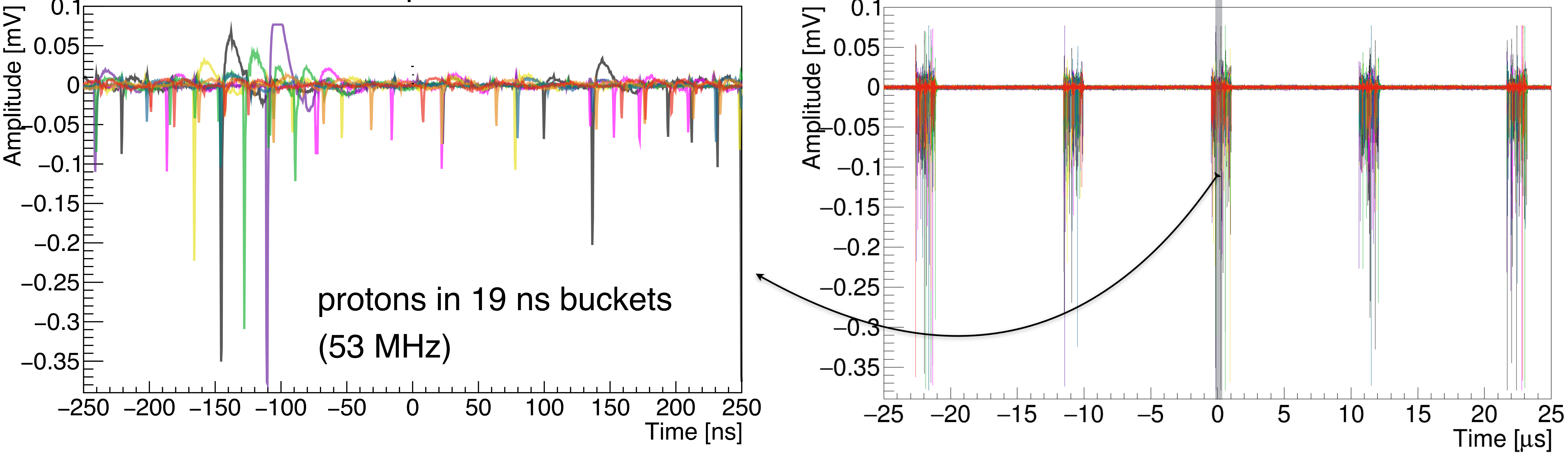


Measuring beam intensity

- Use LGADs themselves to monitor beam intensity!
- Record one waveform per spill, for 10 millisecond duration. Count signals in 8 ch

Count individual protons in 8 channels!

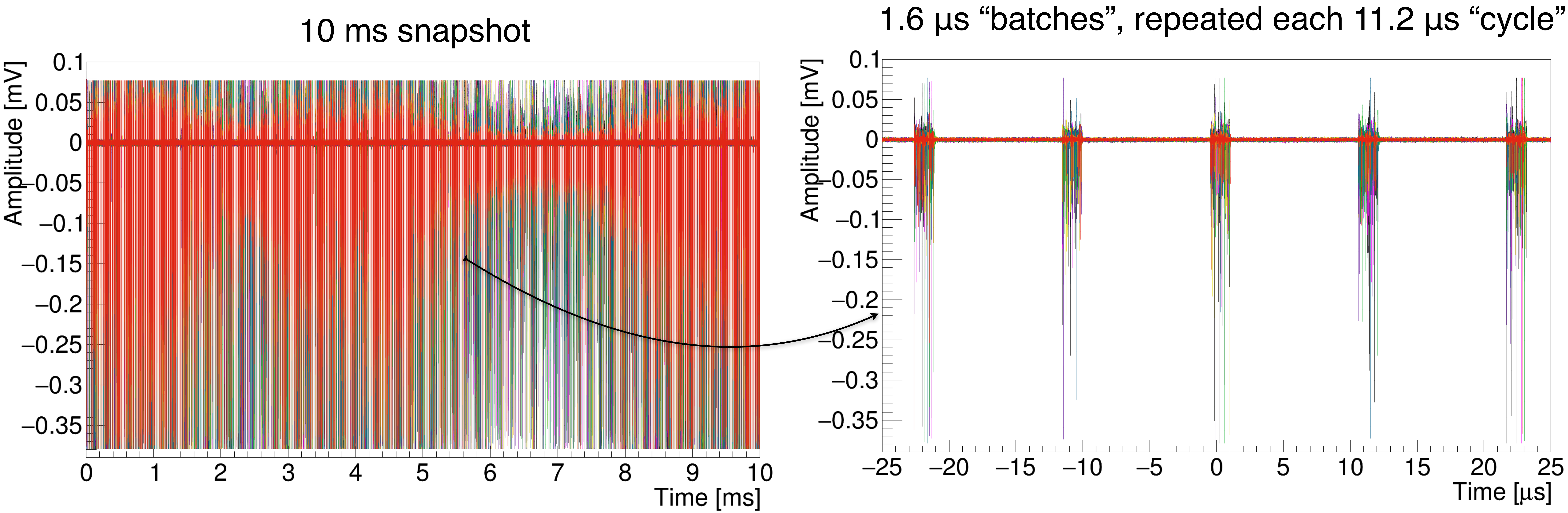
1.6 μs “batches”, repeated each 11.2 μs “cycle”



Receive about 400k batches in 4 s, each minute.

Measuring beam intensity

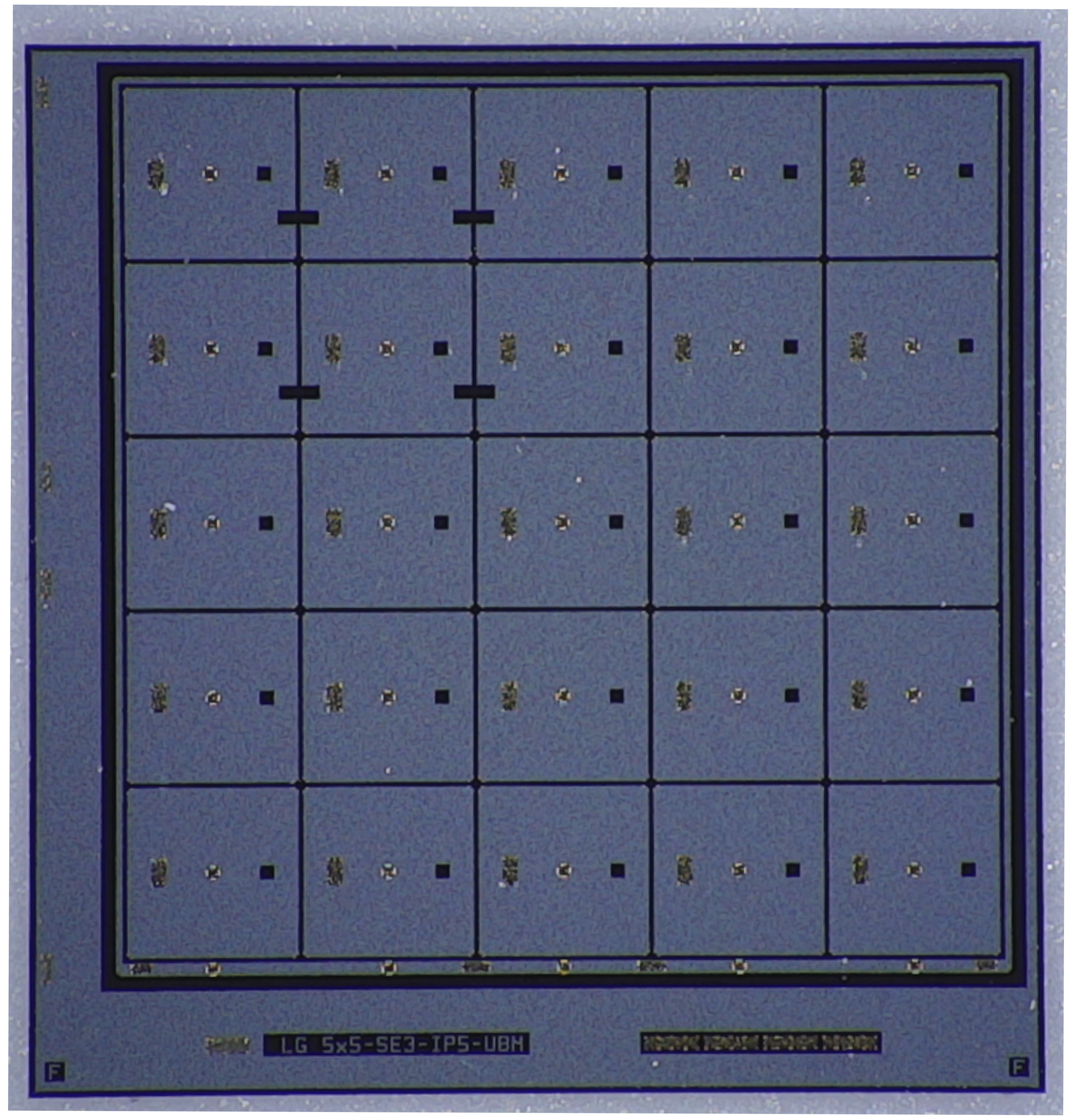
- Use LGADs themselves to monitor beam intensity!
- Record one waveform per spill, for 10 millisecond duration. Count signals in 8 ch

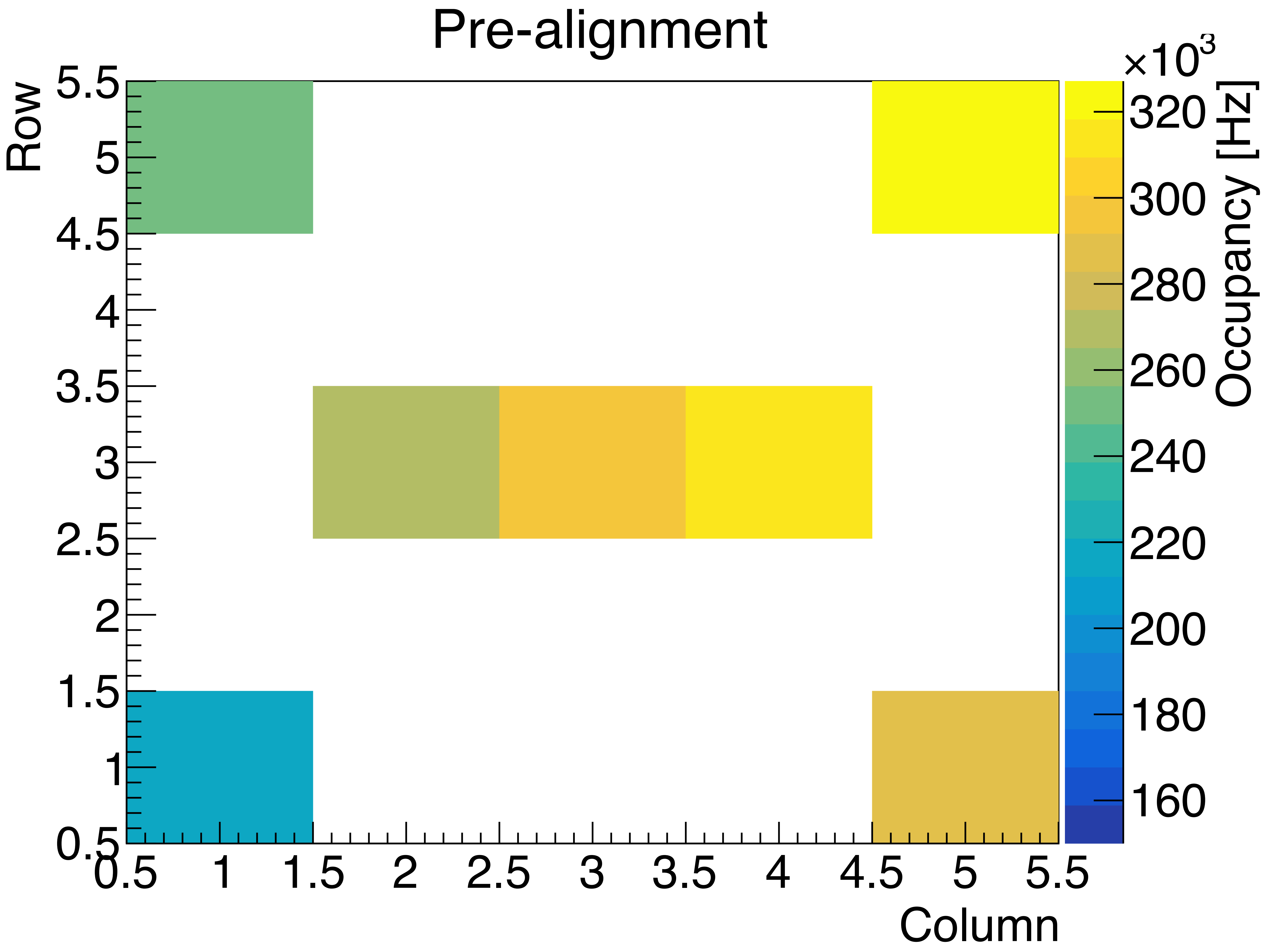


- Long exposures reveal time structure of beam and allow calibrating delivered flux.
  - Large variation on O(1 ms) time scale
  - Moderate variation on O(1 s) time scale.

Aligning to beam

- Study occupancy across sensor w/ 8-ch
- Follow gradient to align sensor





- With best alignment, occupancy in edge pads is 80-90% of center (wide beam)
- Final sensor occupancy: **200M protons / sensor / spill**
  - x2000 larger flux per sensor than max achieved in regular test beam (slightly less than expectation)

Aligning to beam

- Study occupancy across sensor w/ 8-ch
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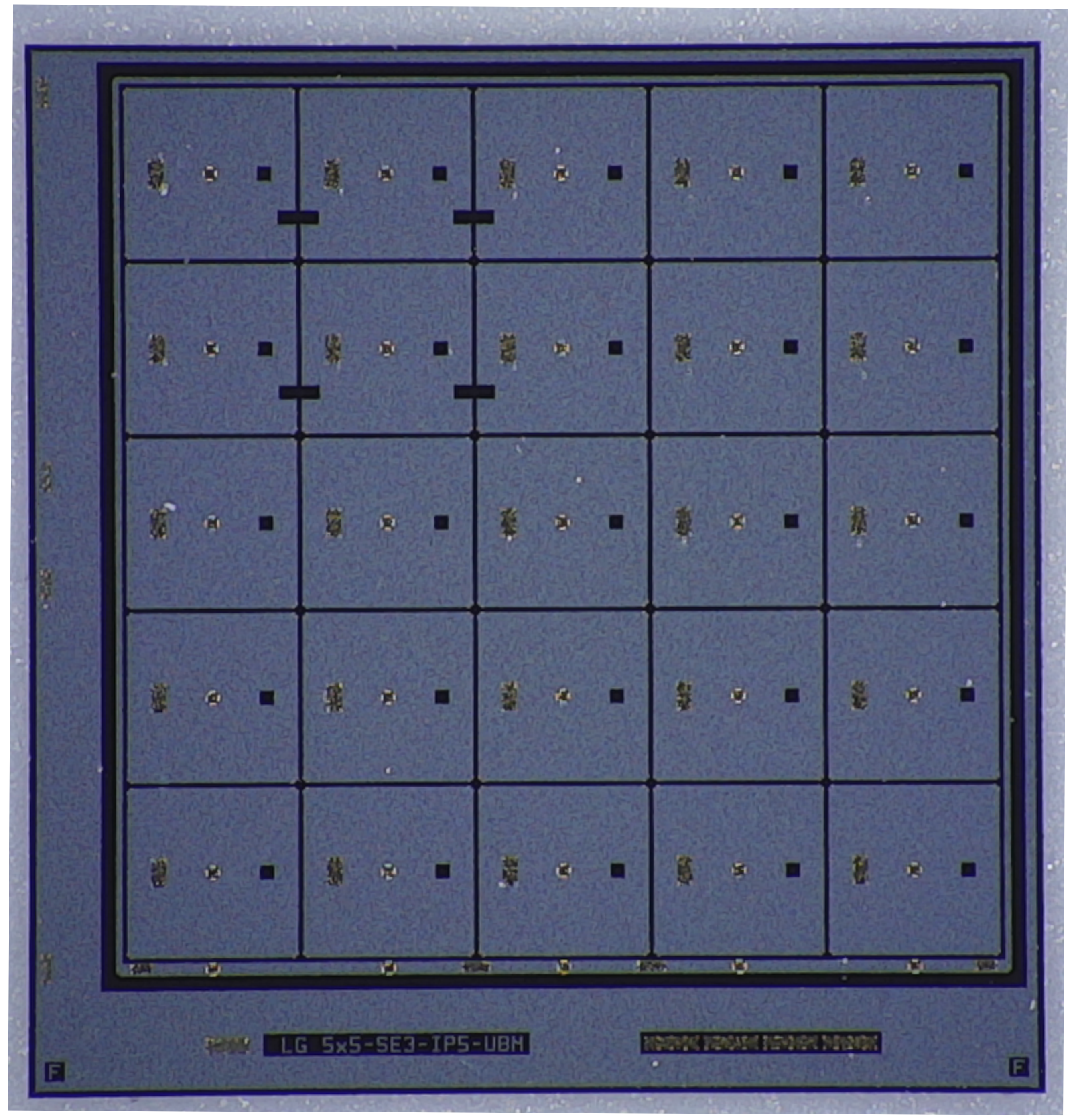

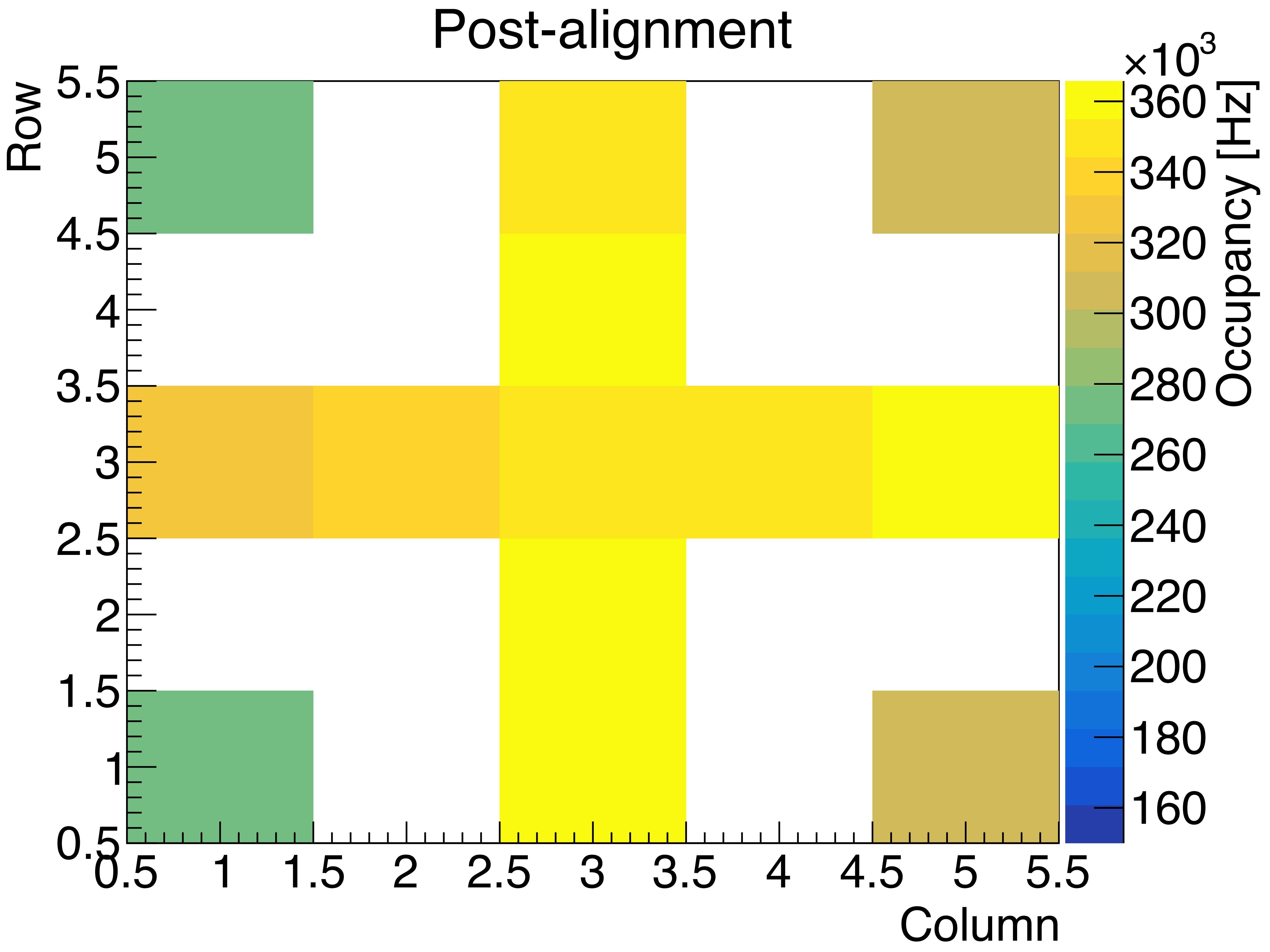

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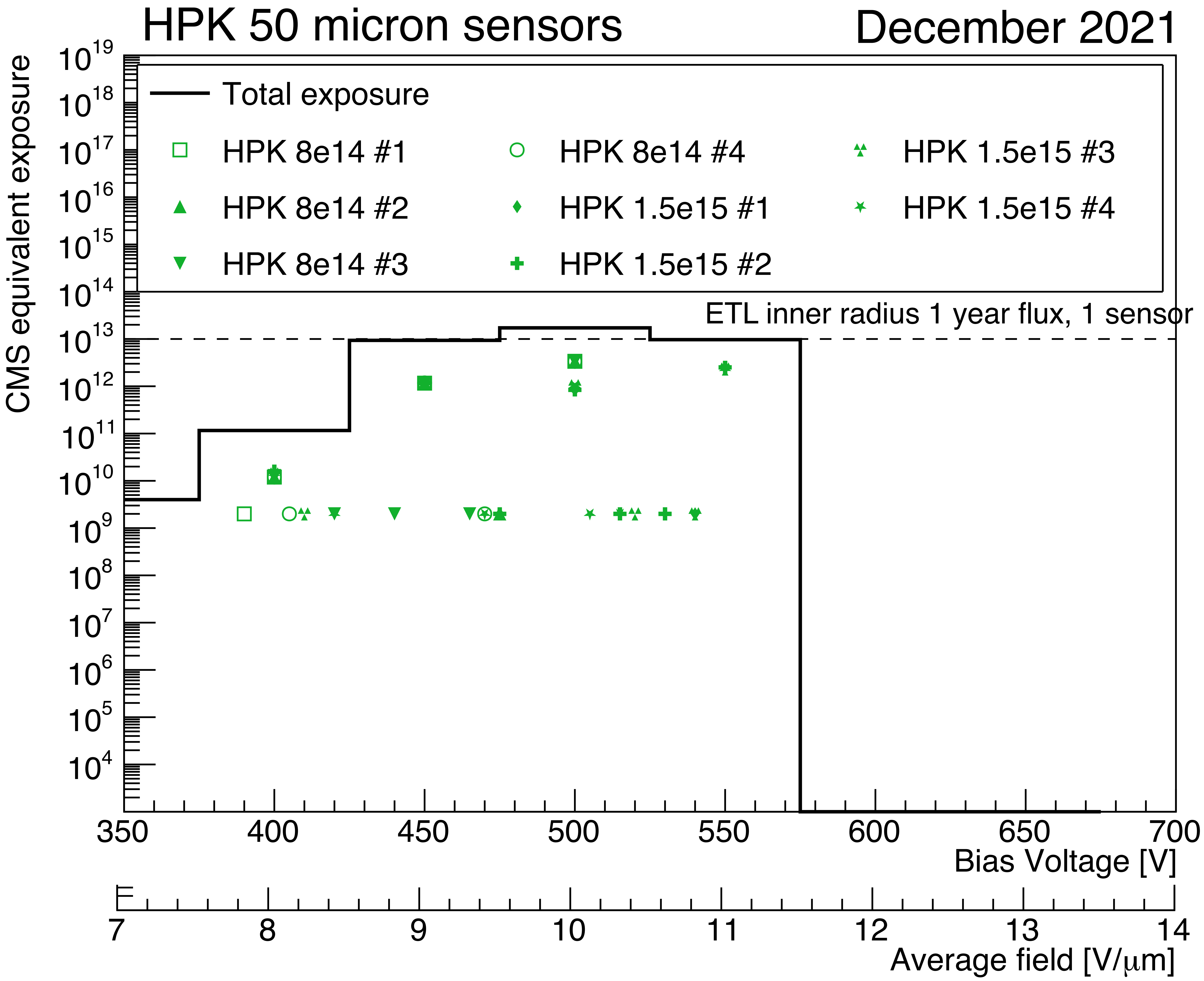
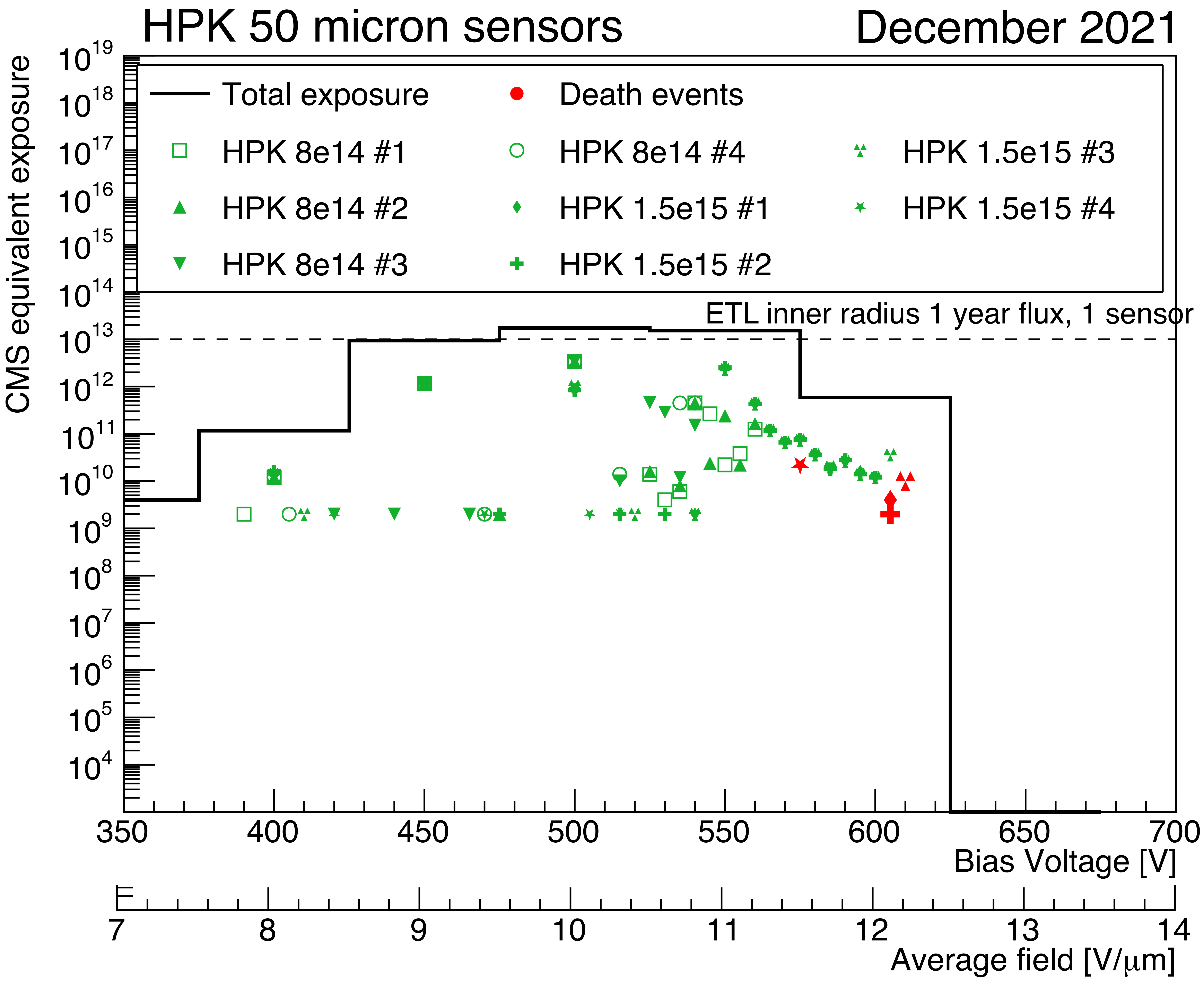
HPK exposures



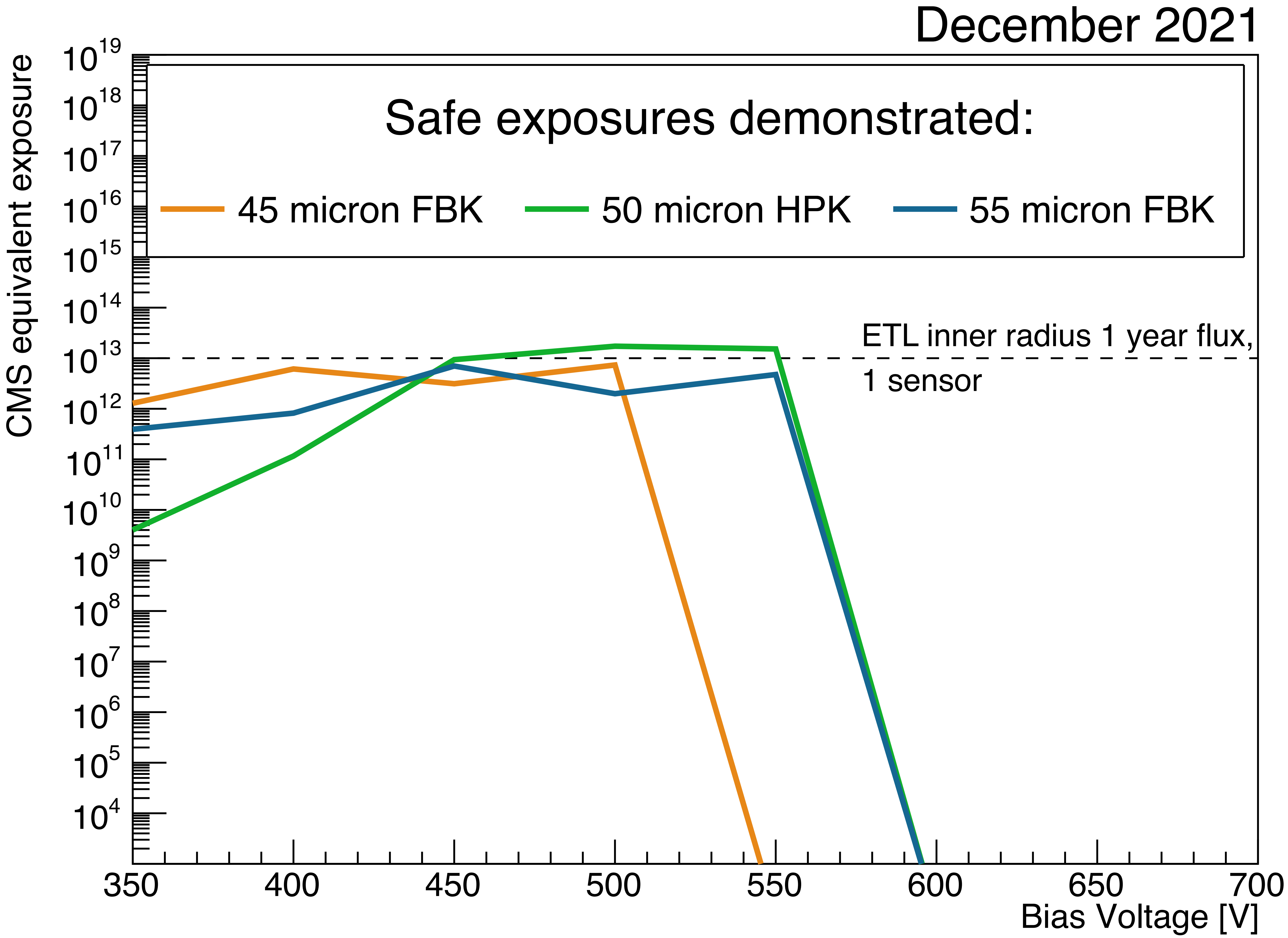
- Delivered 10^{13} protons at 450, 500, and 550 V with no deaths!
- Comparable exposure to 1 year flux for a sensor in ETL
- Similar results for 45 and 55 micron sensors from FBK

HPK exposures



- After survival phase, continue ramping to look for deaths beyond 11 V/um
- 4x HPK 1.5e15 deaths:
  - 575 V, 605 V, 605 V, 610 V
  - 11.5-12.2 V/um

Exposure summary



- Demonstrated safe operation with flux comparable to 1 year at CMS in all 3 thicknesses!
- SEB threshold seems to roughly scale with thickness (~ constant field)
- **FBK sensors with high radiation tolerance avoid dangerous region for entire life of detector.**

Summary

- Two intensive test beam campaigns completed in 12 months.

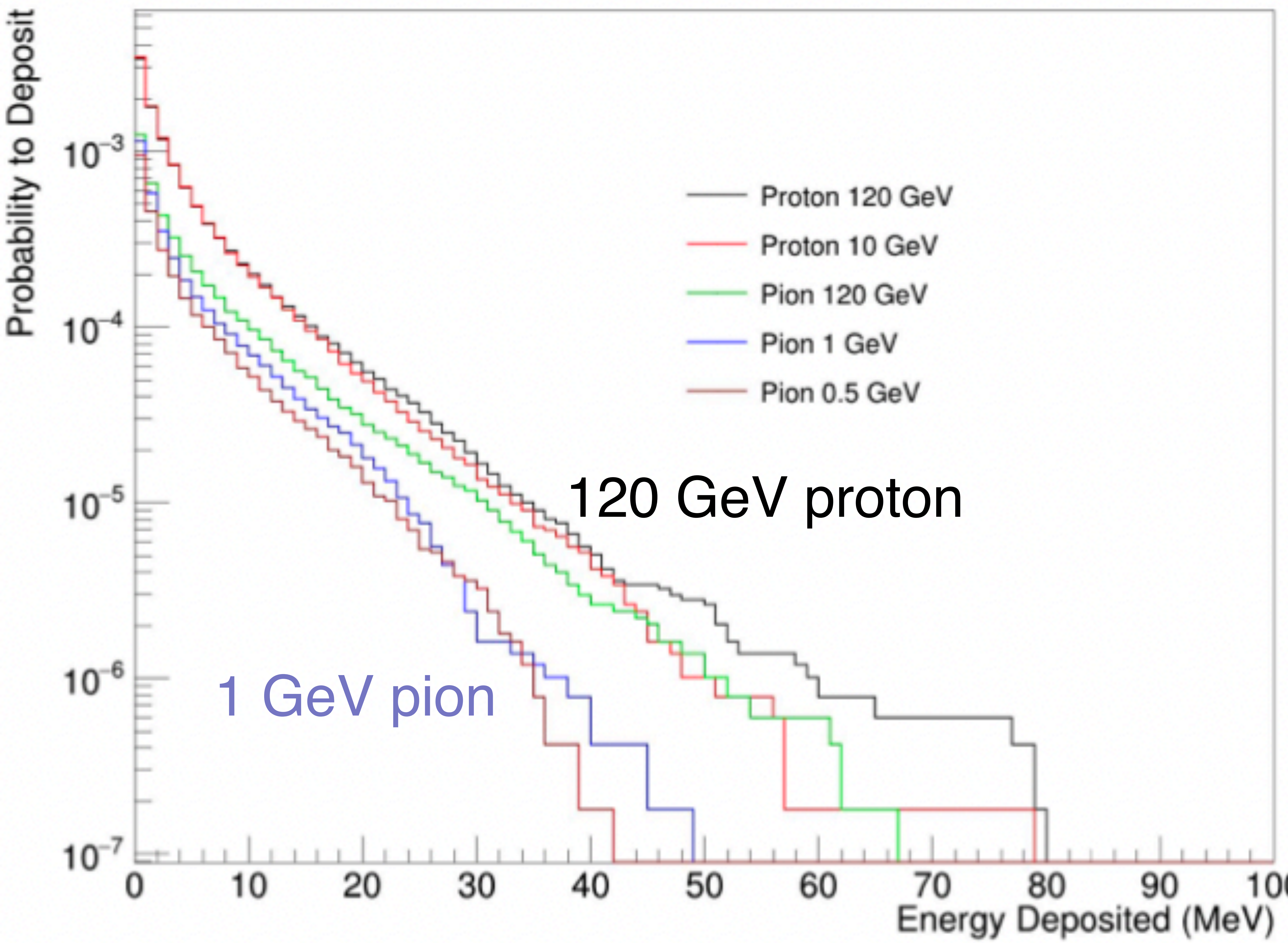
- Understanding of single-event burnout mechanism greatly improved
  - Definitively caused by single-particle interaction
  - Susceptibility driven by thickness and bias voltage.

- Safe regions of operation established through realistic, high-rate tests probing flux comparable to the HL-LHC environment.

- Burnout can be avoided for full life of the CMS ETL without cost to performance.

Proposed burnout mechanism

Probability to deposit at least X MeV in 50 μm (GEANT4)

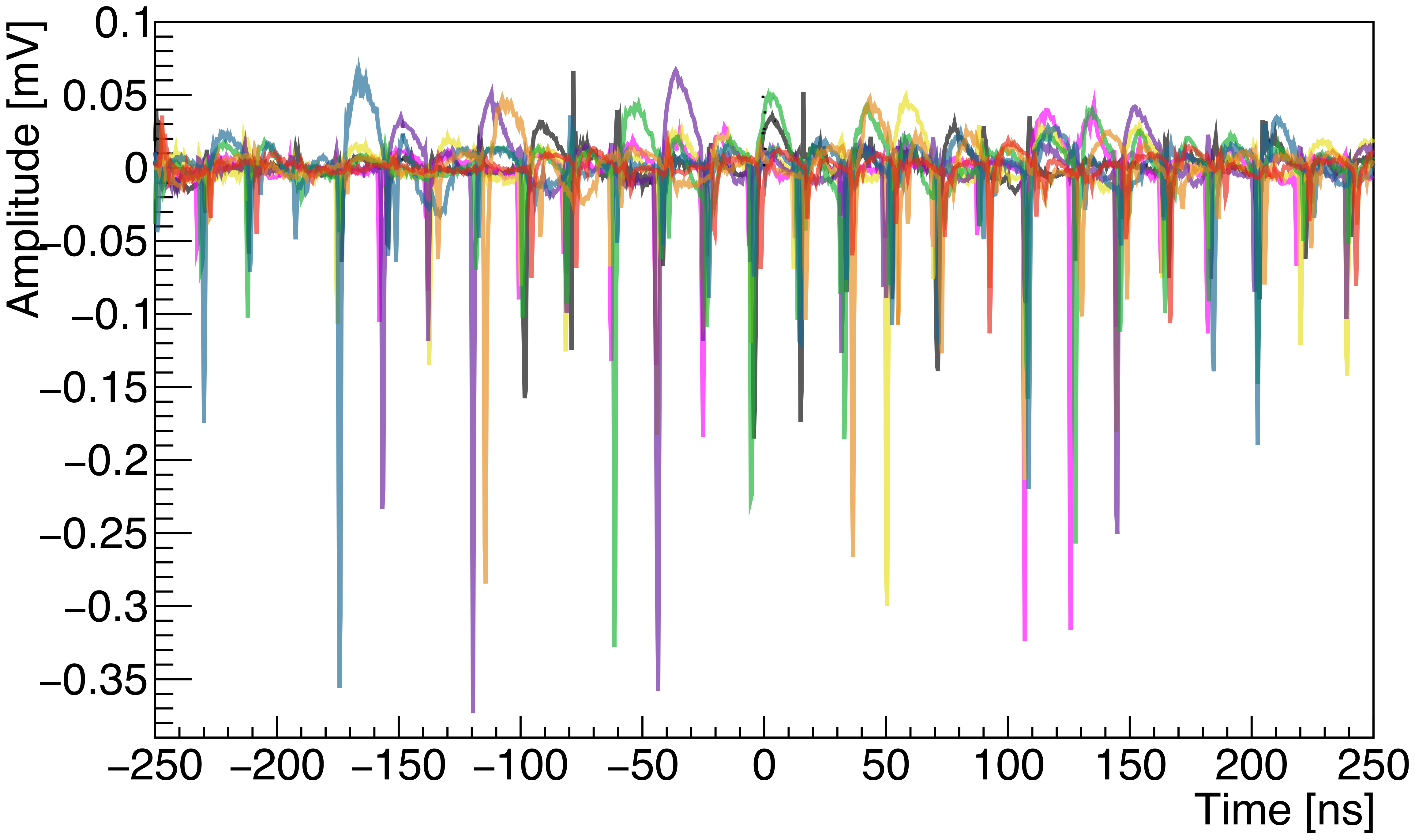


- Rare, large ionization event "Highly Ionizing Particle"
  - Excess charge leads to highly localized conductive path
  - Large current in narrow path → "Single Event Burnout"
- Estimate >20 MeV deposit needed based on rate
- 120 GeV protons are ~ 10x more likely to yield burnout than typical LHC charged particles (e.g. 1 GeV pion)
- Need to probe farther in tail to ensure safety at lower bias voltage…

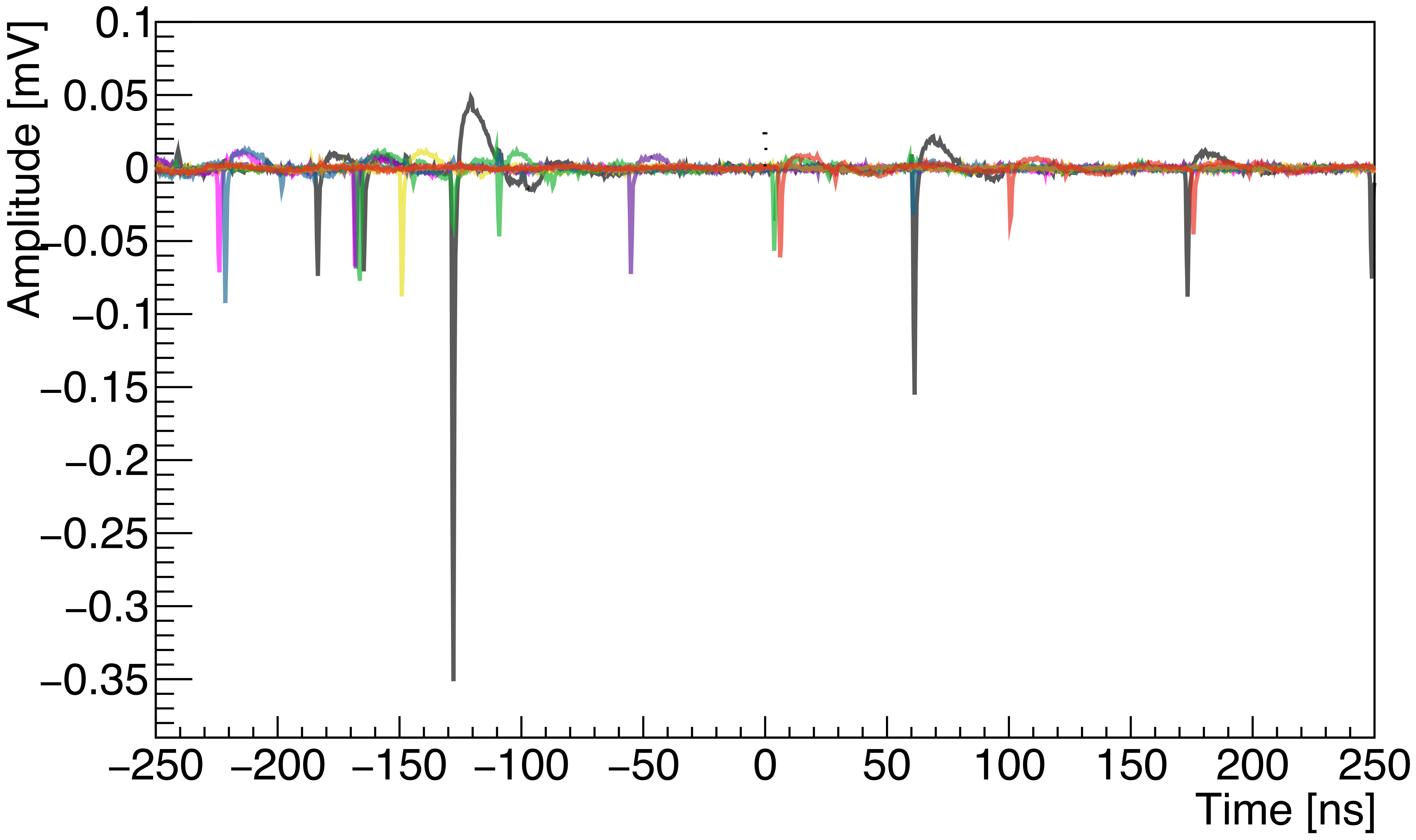
Measuring beam intensity

- Use LGADs themselves to monitor beam intensity!
- Record one waveform per spill, for 10 millisecond duration. Count signals in 8 ch

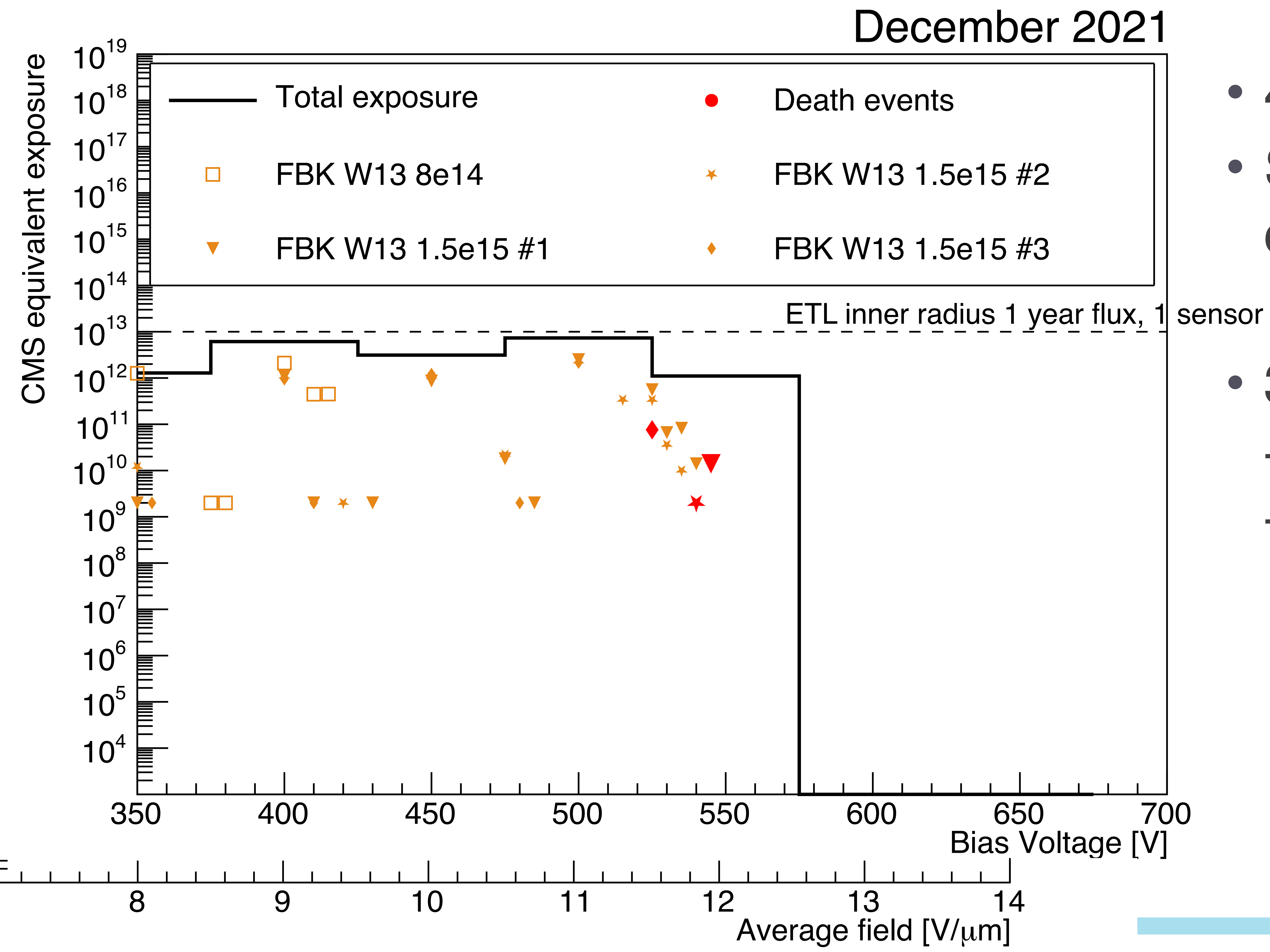
High-occupancy batch (4 ms after trigger)



Low-occupancy batch (7 ms after trigger)



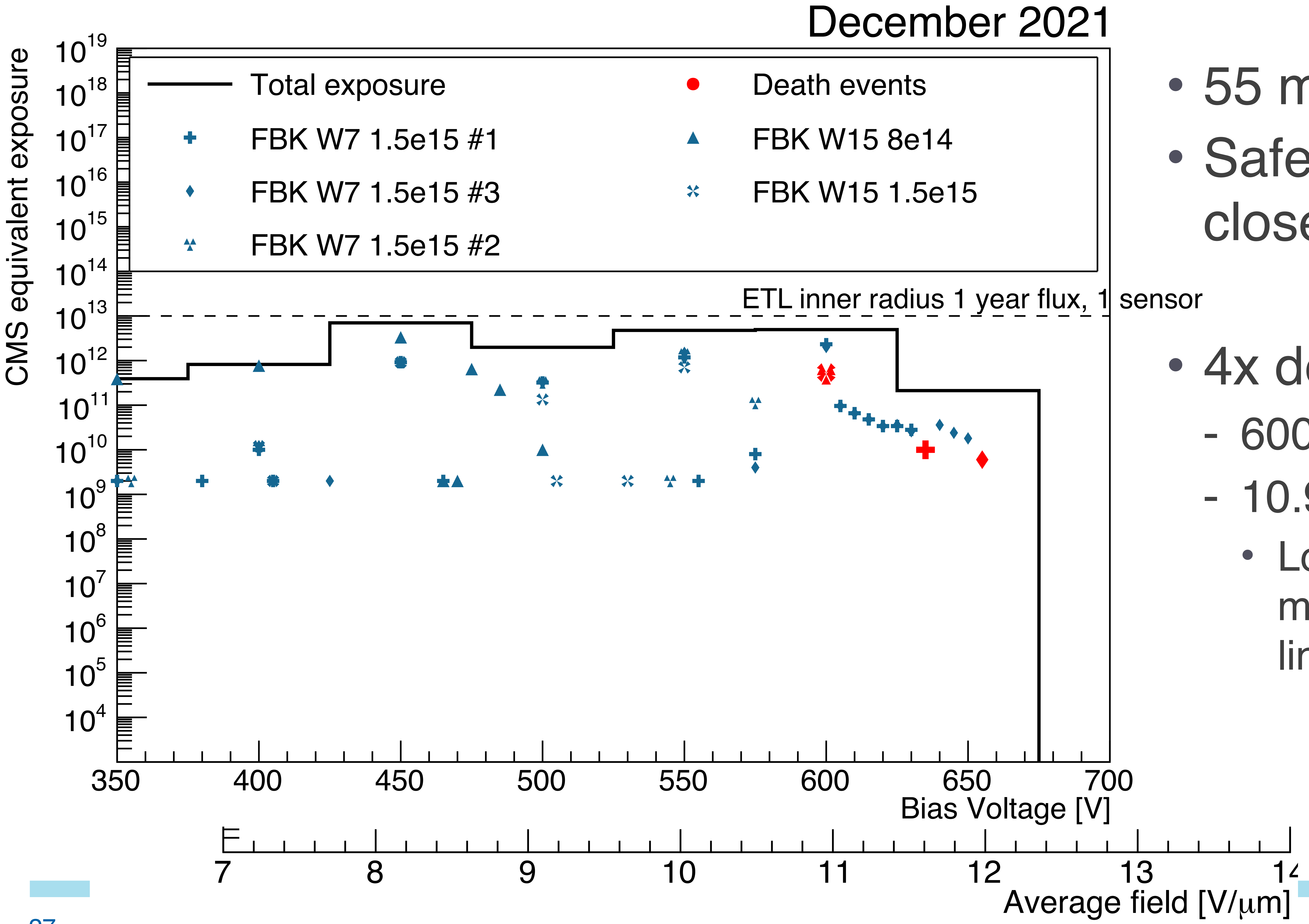
45 micron FBK



- 45 micron FBK sensors
- Safe operation at 9-11 V/um, close to CMS 1-year flux.

- 3x deaths in 1.5e15:
  - 525 V, 540 V, 545 V
  - 11.7 V/um to 12.1 V/um

55 micron FBK



- 55 micron FBK sensors
- Safe exposures in 8-10 V/um, close to CMS 1-year flux.
- 4x deaths in 1.5e15:
  - 600 V, 600 V, 640 V, 645 V
  - 10.9 V/um to 11.9 V/um
    - Lower field at death than 45 or 50 micron sensors—scaling is not quite linear

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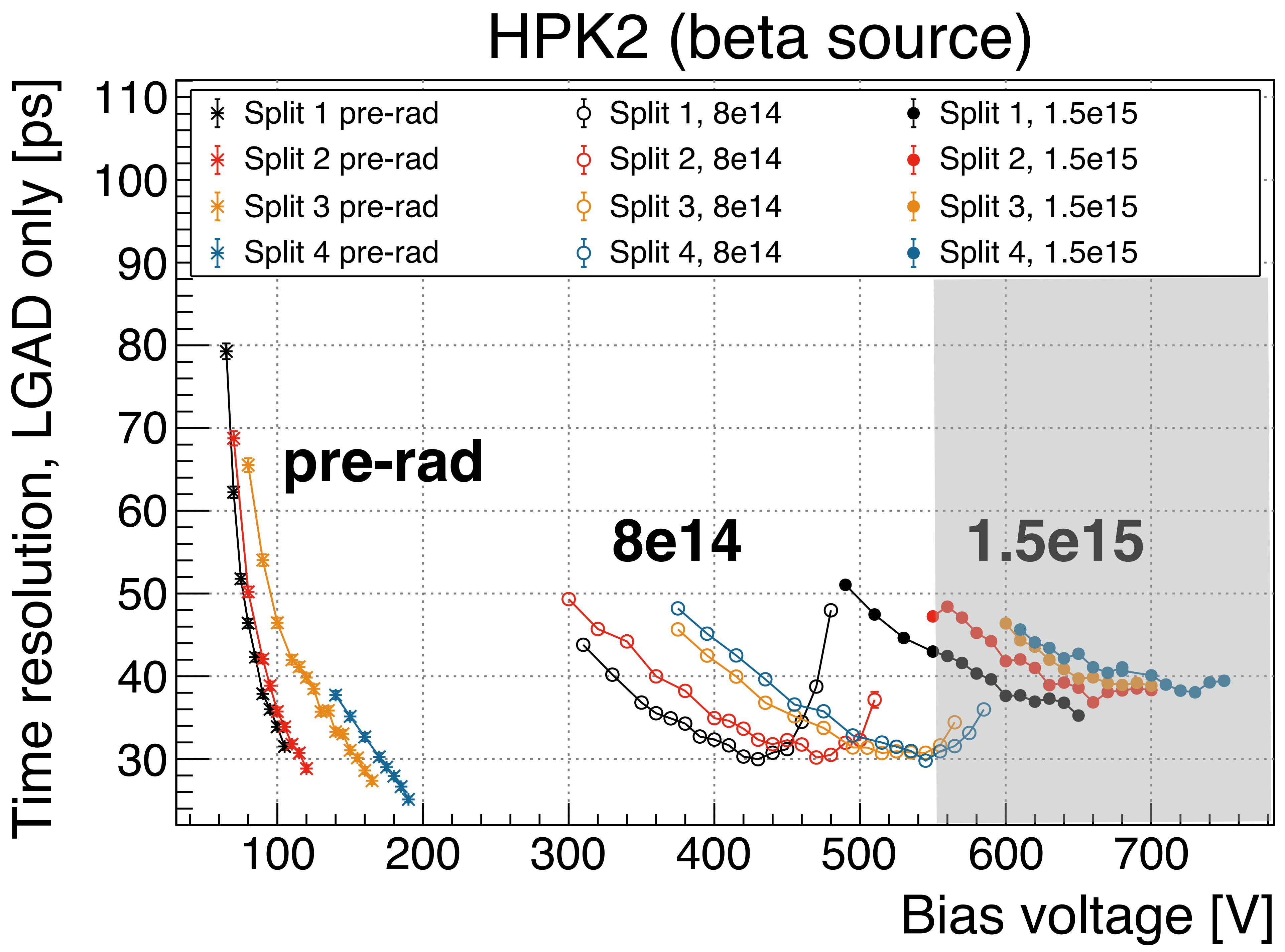
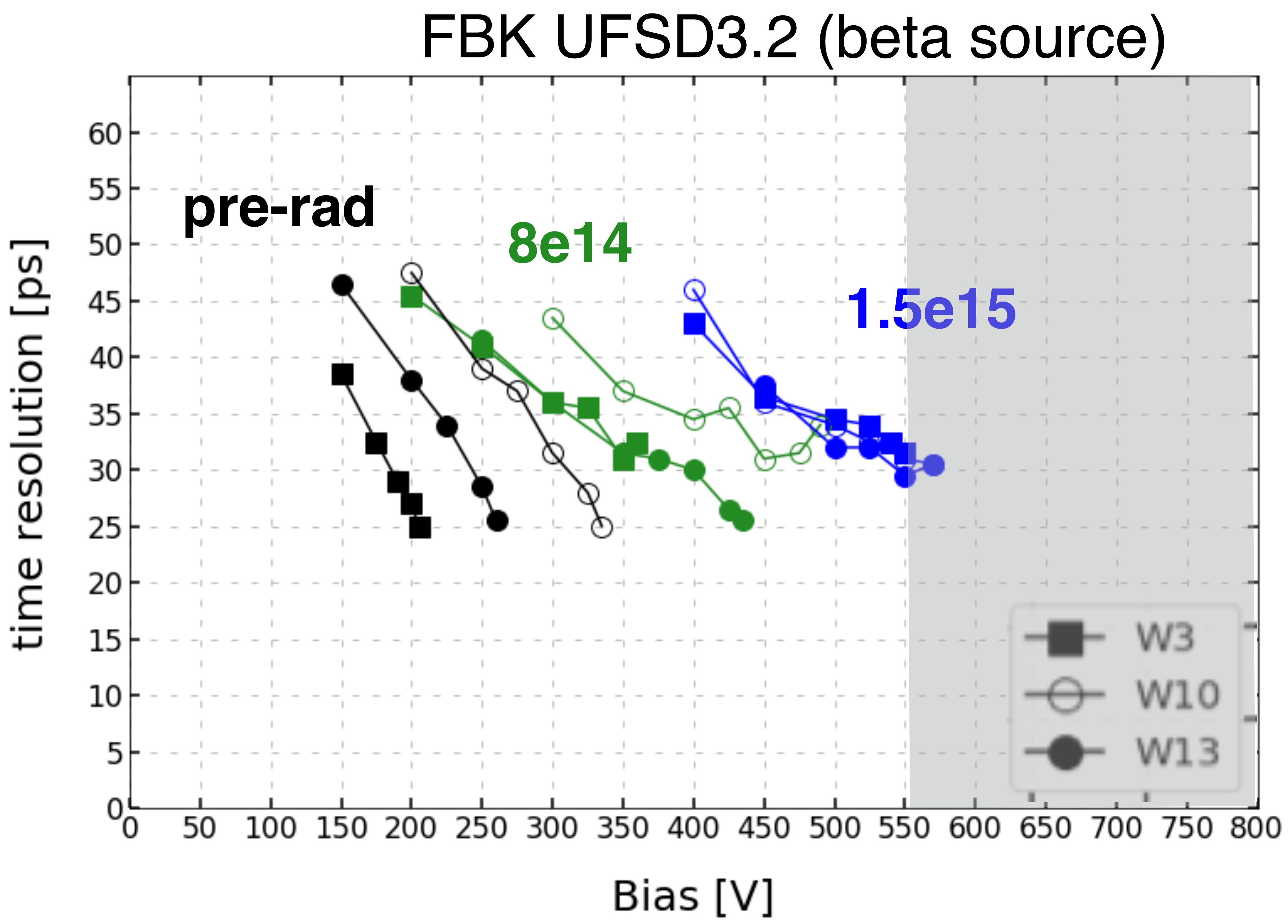
Context for CMS Endcap Timing Layer (ETL)

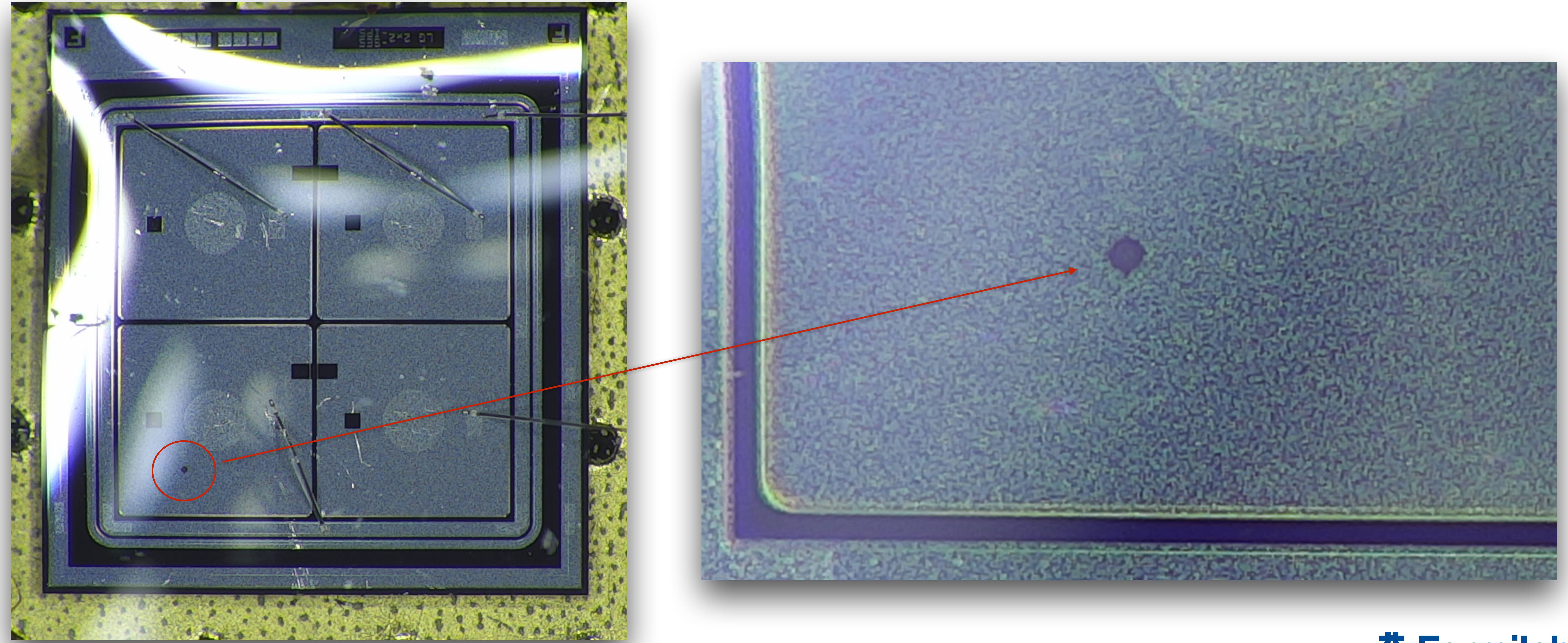
- To avoid burnout, LGADs should remain at voltage ≤ 550 V (50-55 micron)
  - HPK sensors can deliver σ < 35 ps up to 1e15 neq/cm², then degrade slowly.
  - FBK sensors can deliver σ < 35 ps to end of life (1.5e15)
- Only ~10% of sensors will exceed 1e15 neq/cm², only in final ~20% of lifetime
  - Relevant only for few percent of ETL sensor-years
  - For case of FBK sensors: **no performance impact at all**!





Encapsulated sensors

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



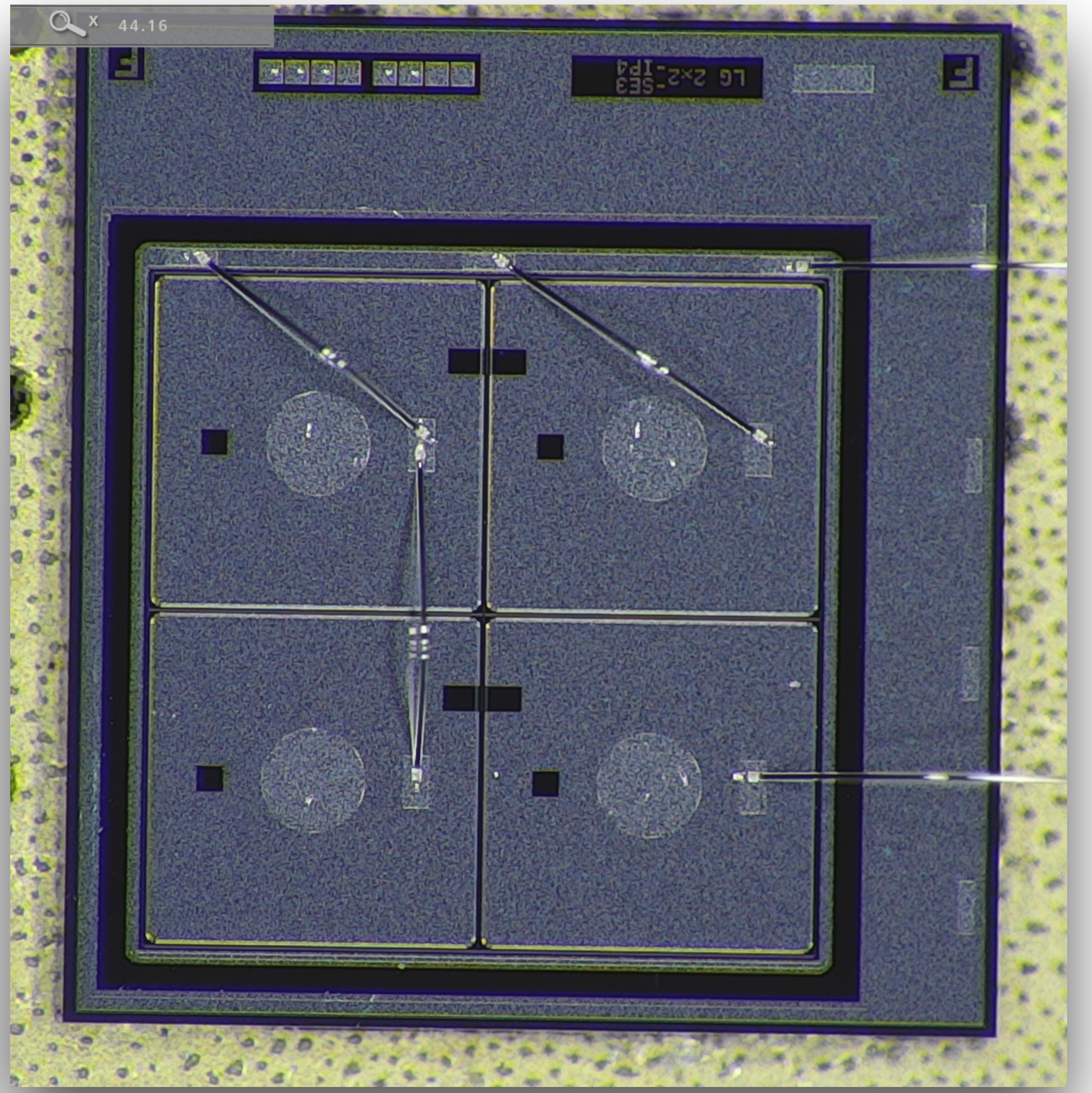
Example death event

- 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.

Custom	ISet	VSet	VMon	Pw	ChStatus	RUp	RDwn	Trip	ImonRange
00.000	300.00 uA	100.0 V	0.0 V	Off	Disabled	10 Vps	10 Vps	10.0 sec	Hi
00.001	31.00 uA	225.0 V	0.0 V	Off	Off	5 Vps	5 Vps	10.0 sec	Low
00.002	31.00 uA	1.0 V	0.0 V	Off	Off	1 Vps	5 Vps	10.0 sec	Low
00.003	31.00 uA	1.0 V	0.0 V	Off	Off	1 Vps	5 Vps	10.0 sec	Low
00.004	31.00 uA	1.0 V	0.0 V	Off	Off	1 Vps	5 Vps	10.0 sec	Low
00.005	31.00 uA	1.0 V	0.0 V	Off	Off	1 Vps	5 Vps	10.0 sec	Low
00.006	300.00 uA	4400.0 V	0.0 V	Off	Disabled	100 Vps	500 Vps	10.0 sec	Hi
00.007	31.00 uA	2800.0 V	0.0 V	Off	Disabled	10 Vps	10 Vps	10.0 sec	Hi

First sign of death: HV short

HPK2 Split 3 SE3 IP4, 1.5e15 neq/cm²



(not yet dead)

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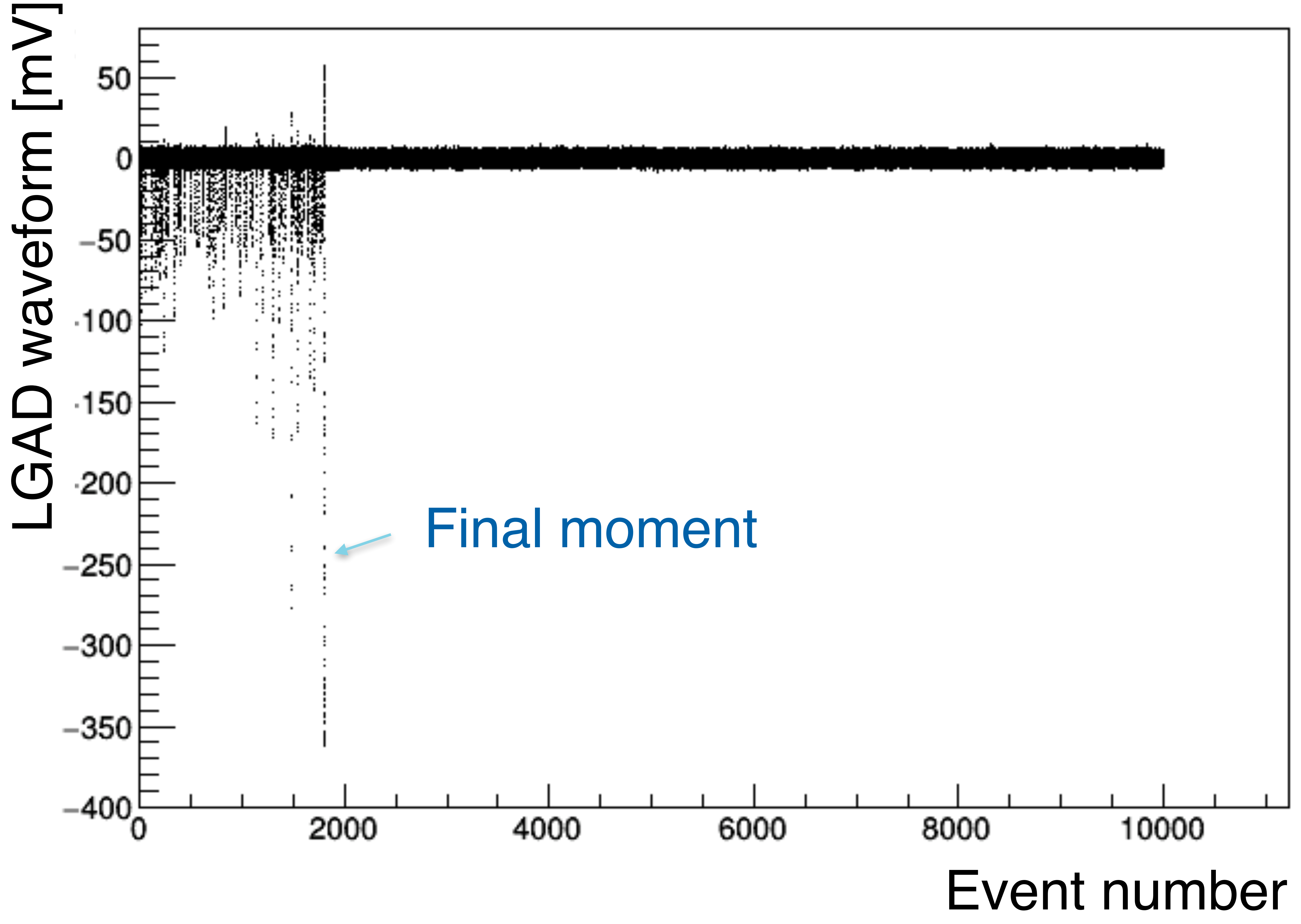
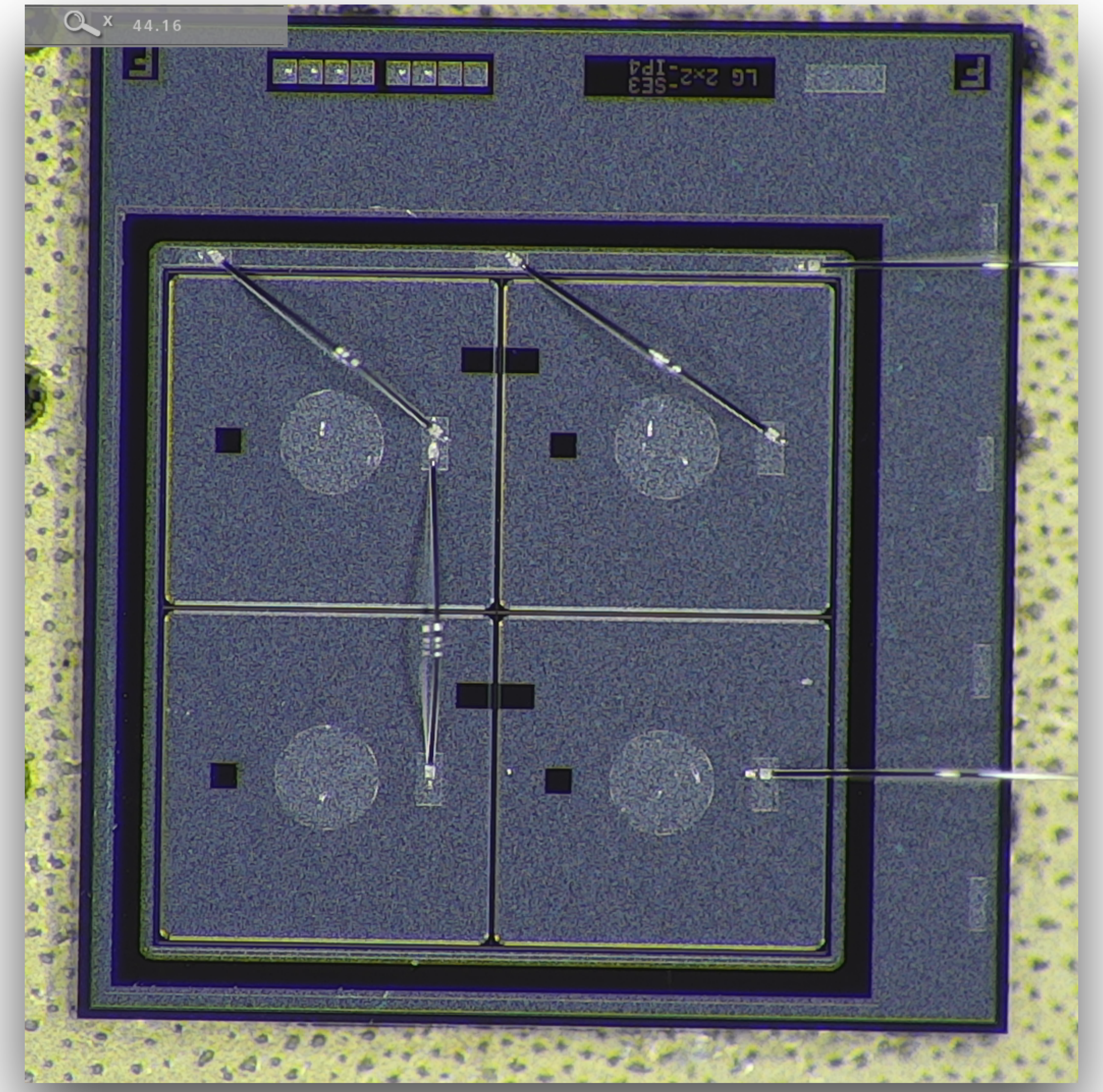
Example death event

LGAD waveforms in 10k triggers during 4s spill.



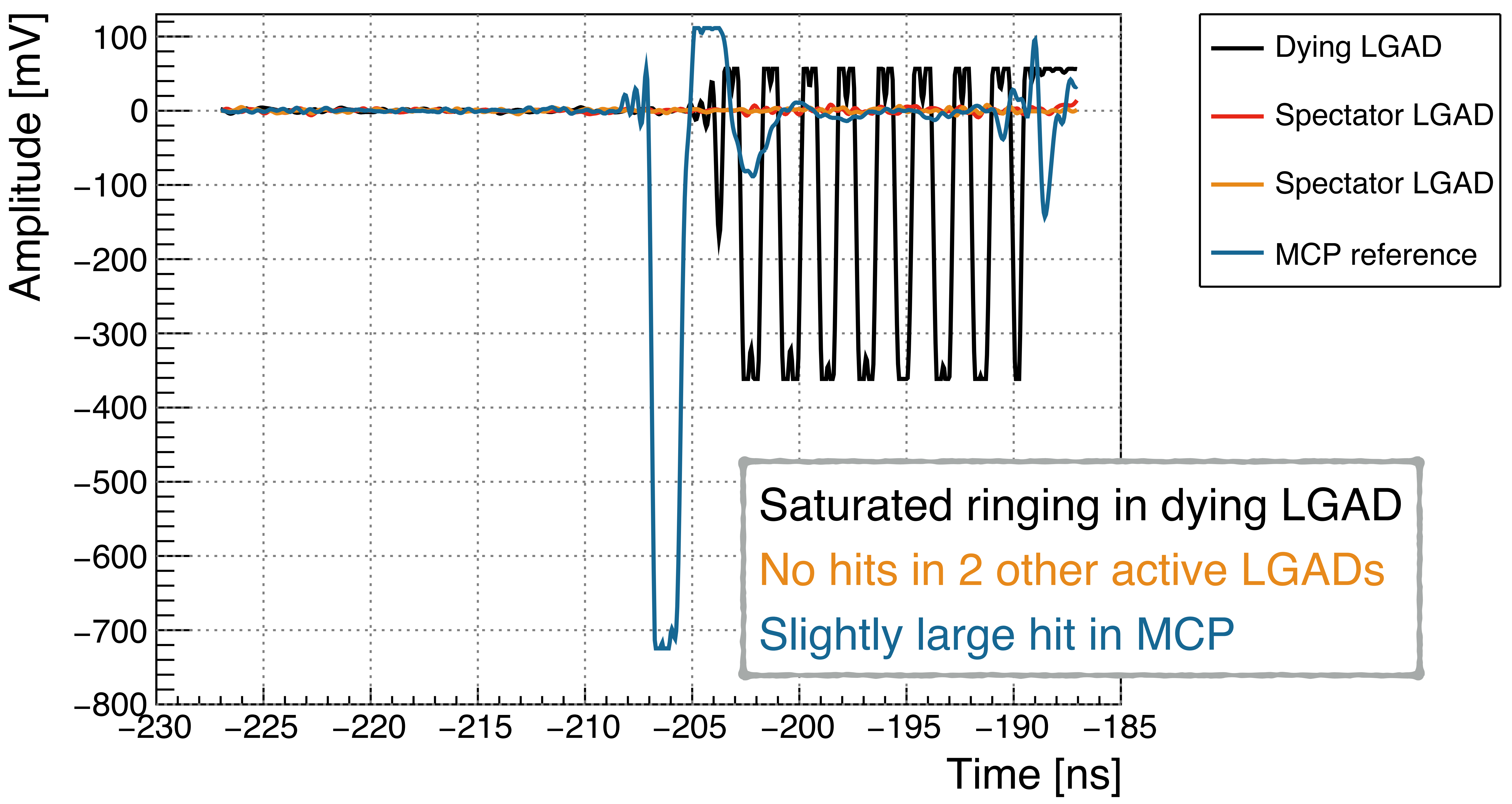
HPK2 Split 3 SE3 IP4, 1.5e15 neq/cm²



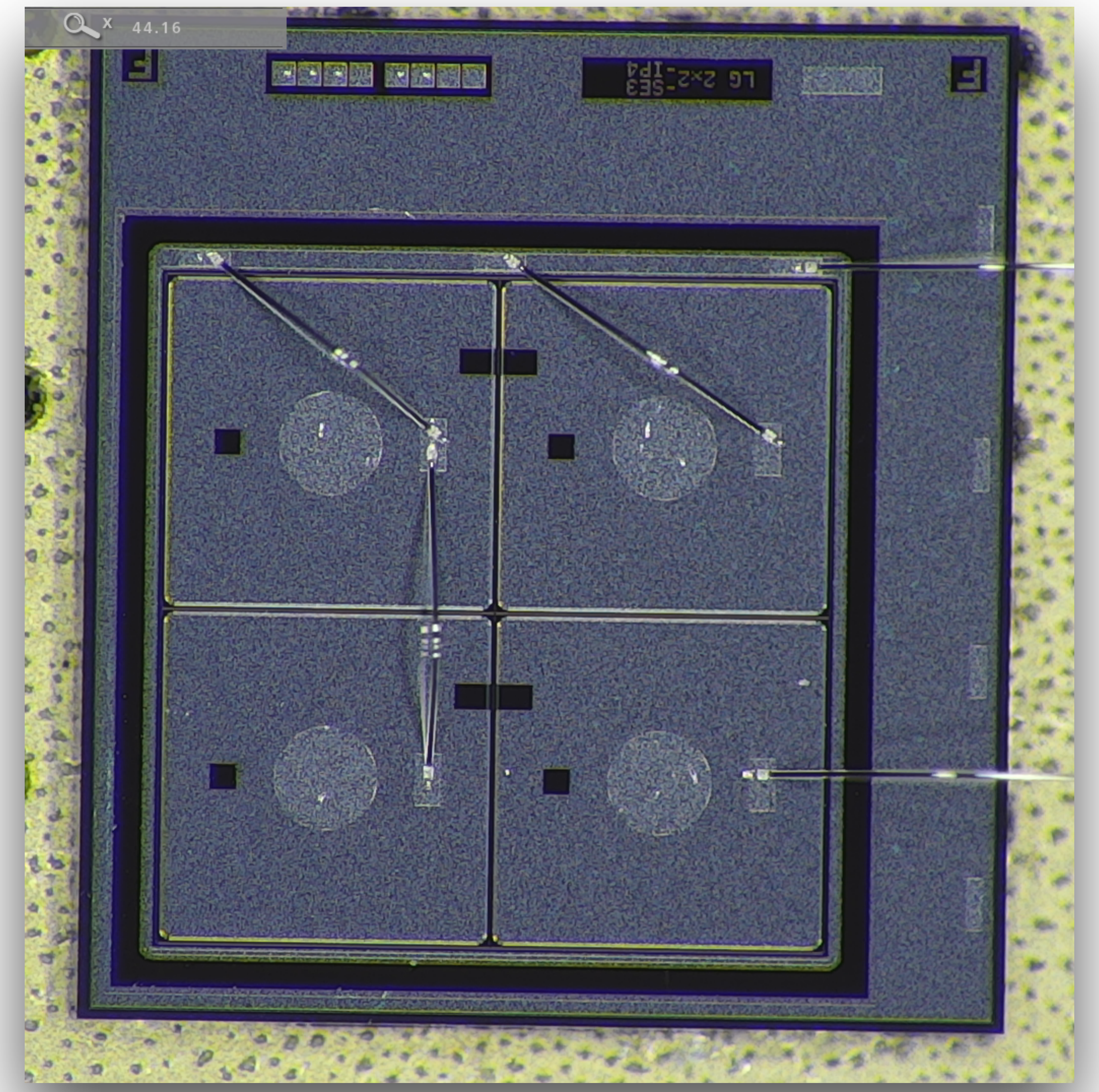
(not yet dead)

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.