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

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17th Trento Workshop on Advanced Silicon Radiation Detectors

March 3rd, 2022

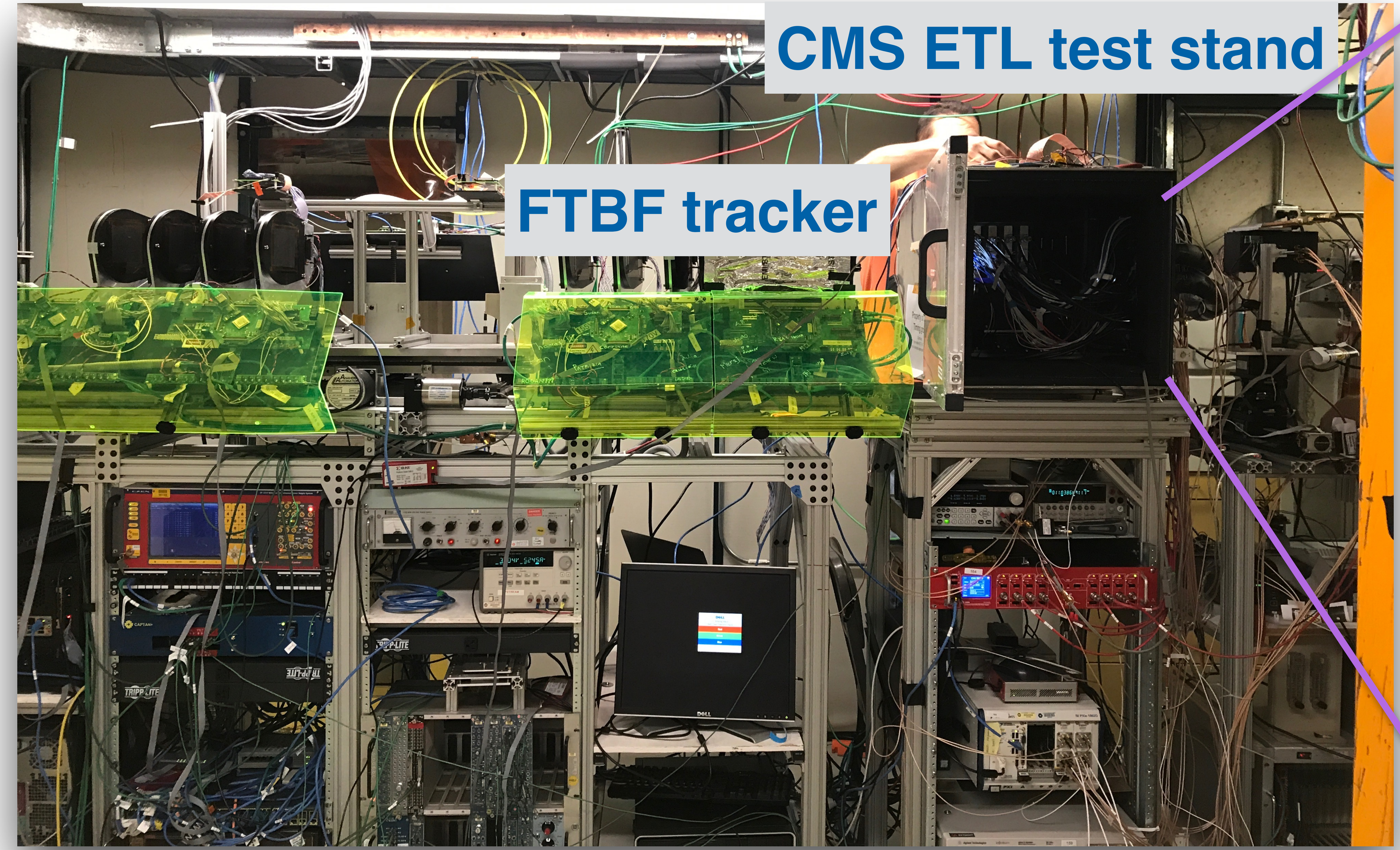
Introduction

- 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.

- 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




Rack to host 10x UCSC boards, cooled by glycol

Precision environmental control & monitoring

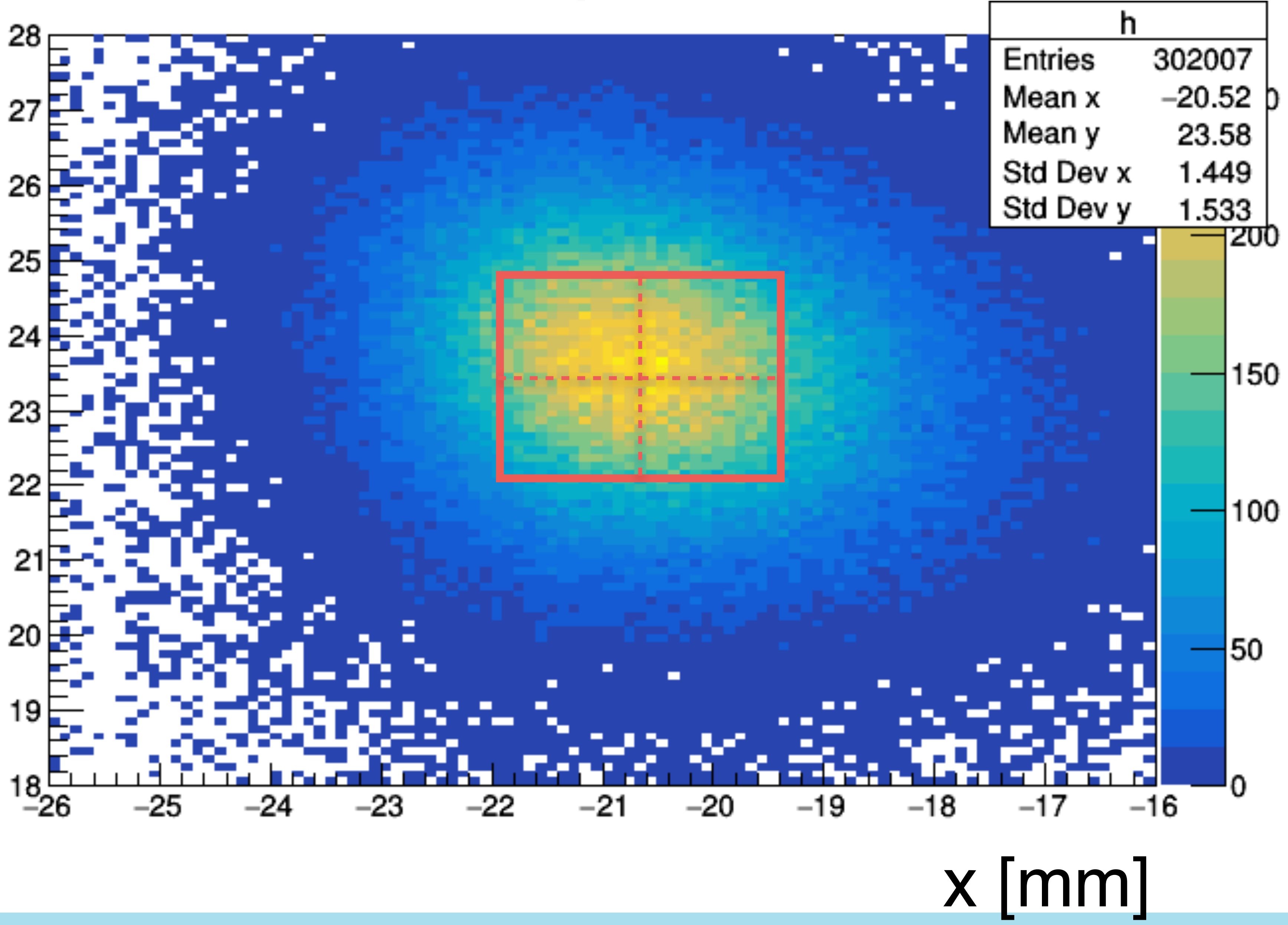
Is LGAD burnout caused by protons, or spontaneous?

Impact of gain, bias voltage, irradiation ??

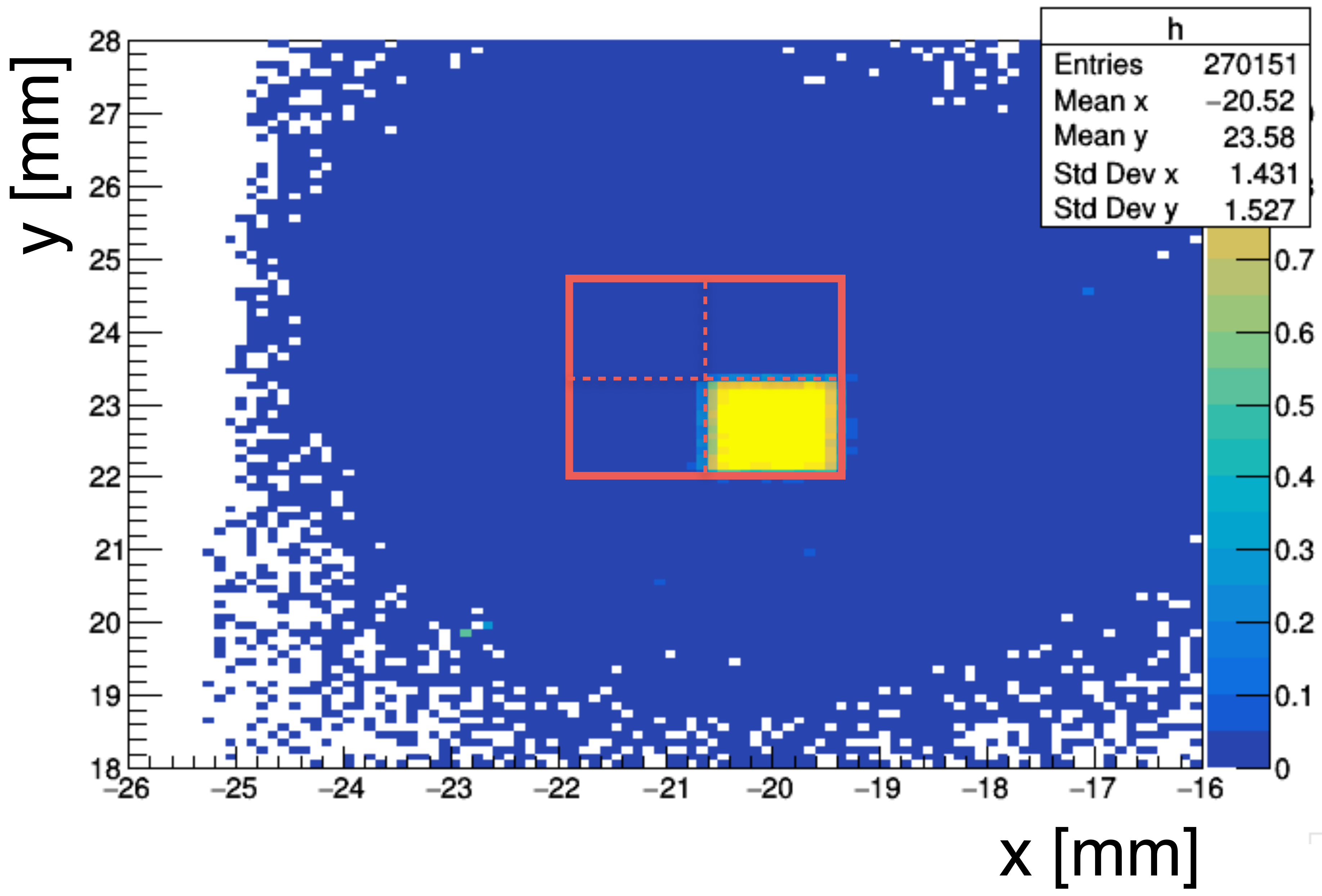
Mortality studies

- 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.

Beam profile

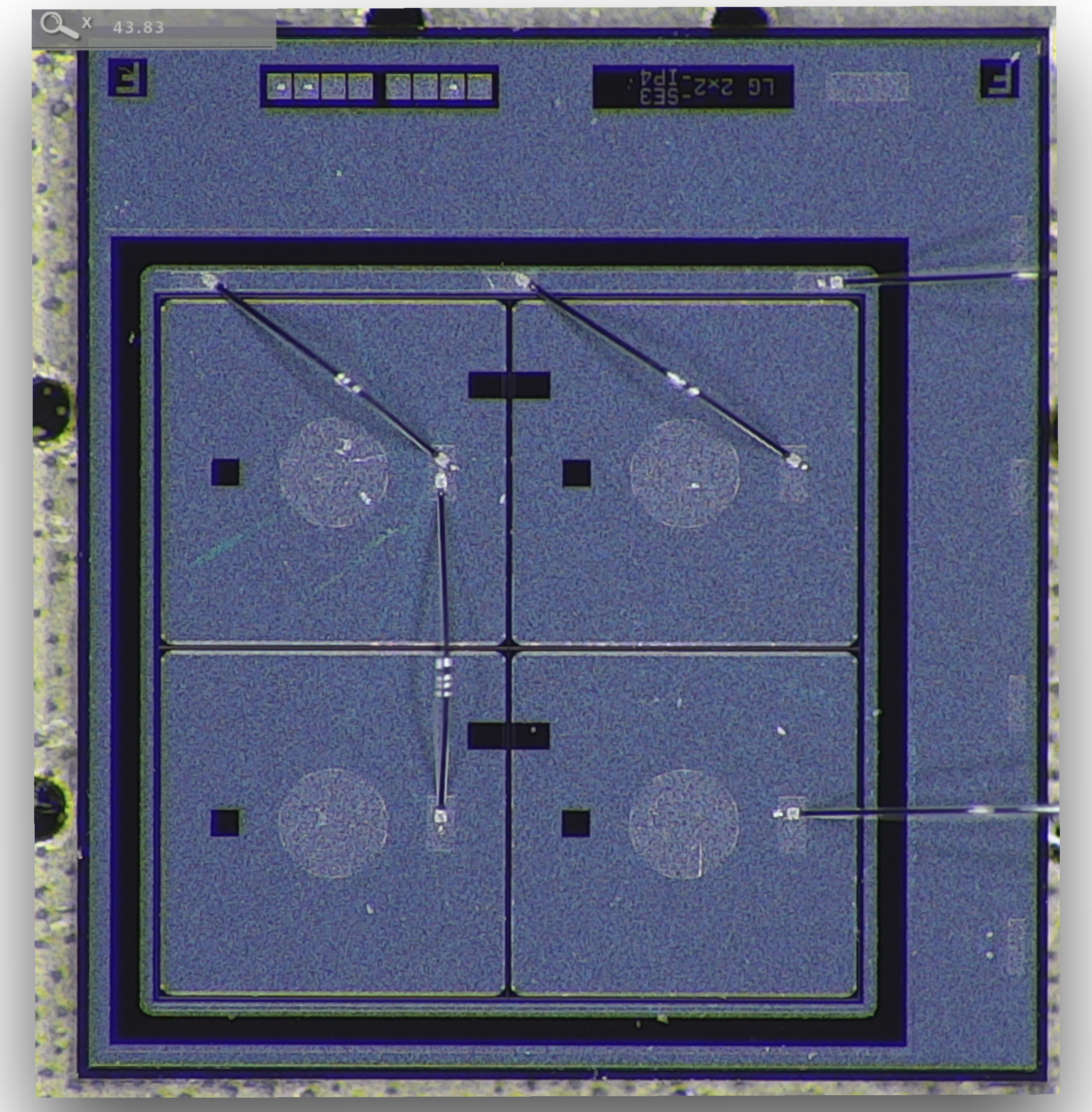


Single pad hit efficiency



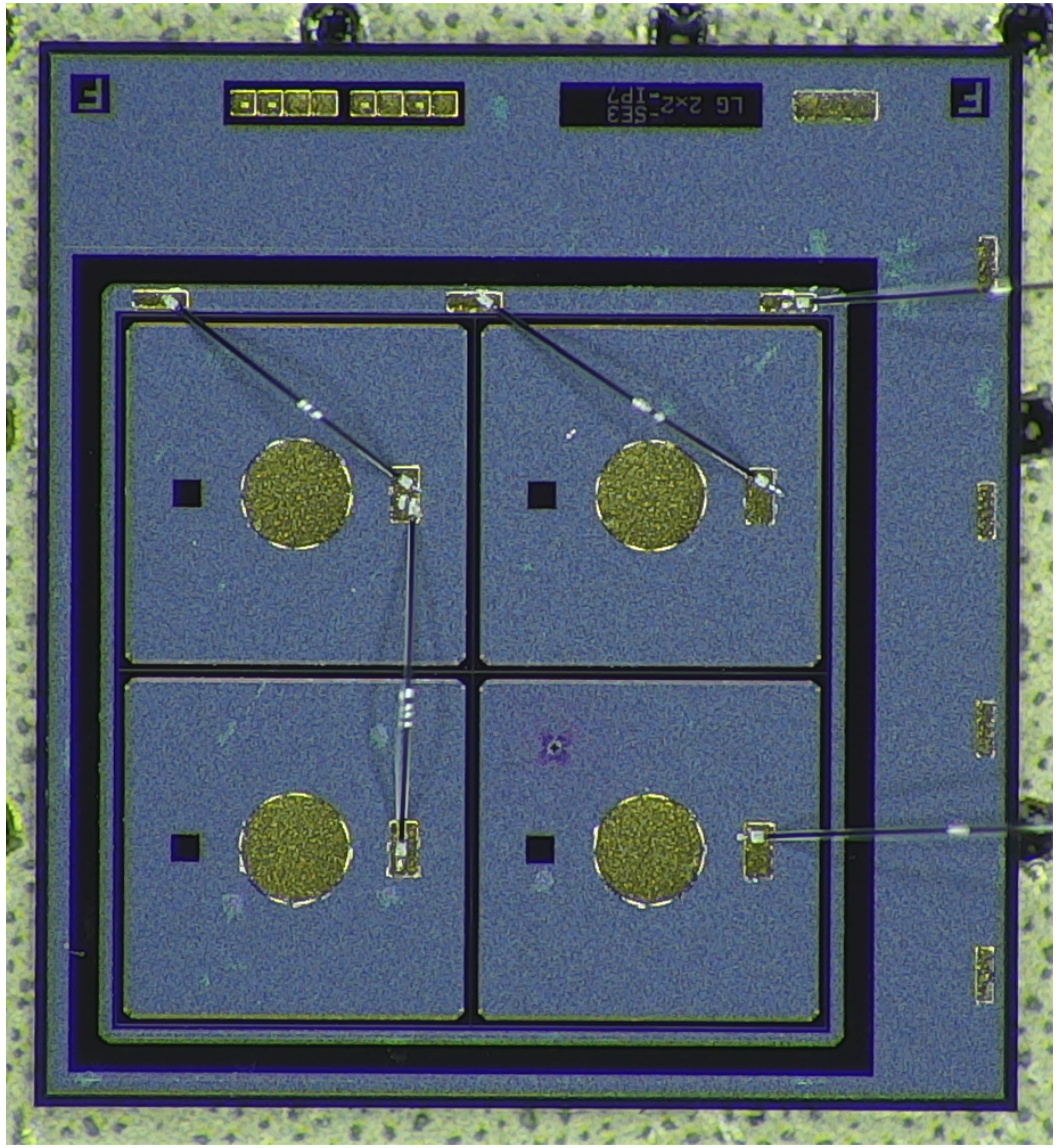
Most sensors in 2x2 geometry

Most from HPK2

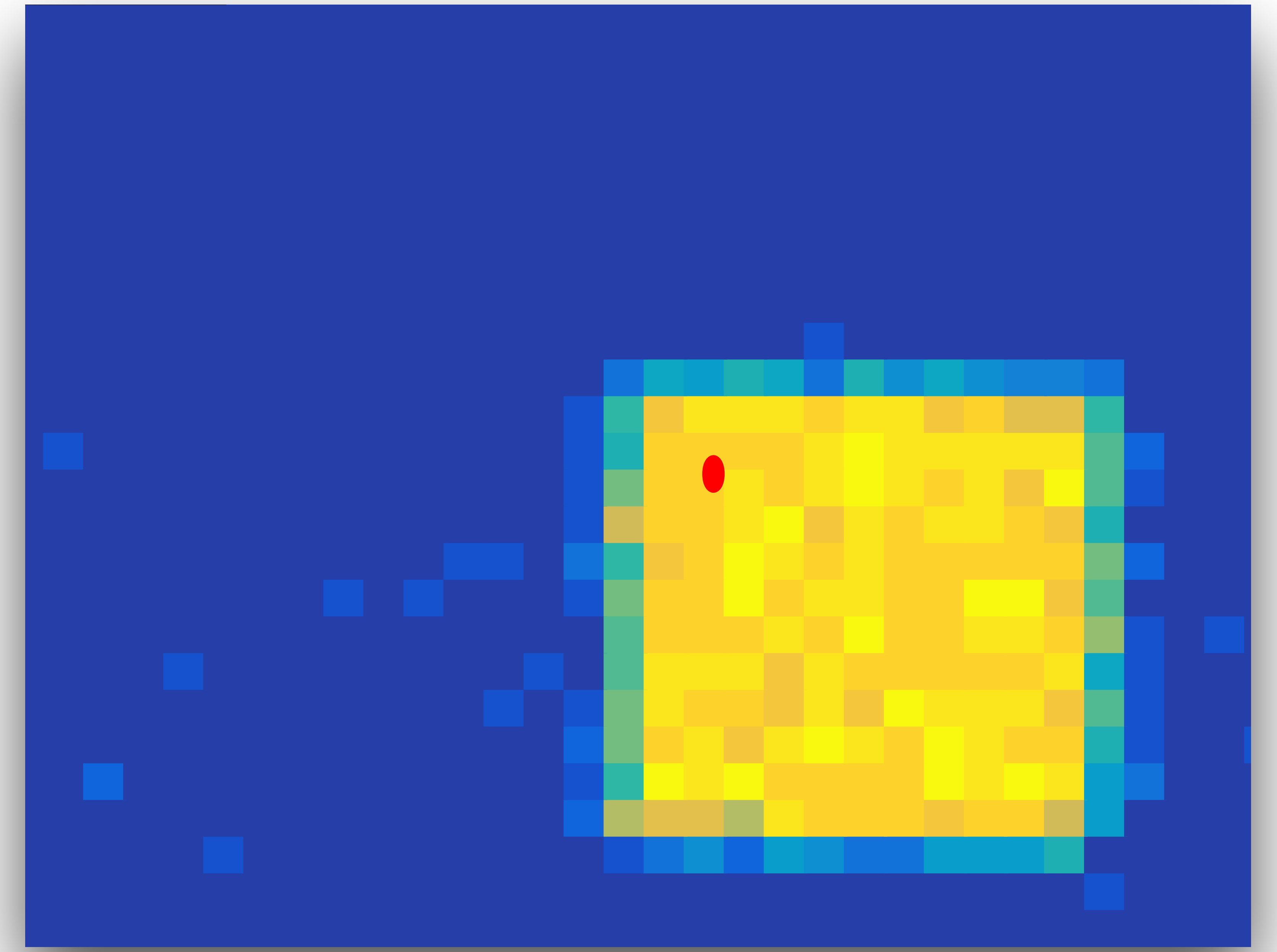


Example burnout event

HPK 1.5e15 neq/cm^2



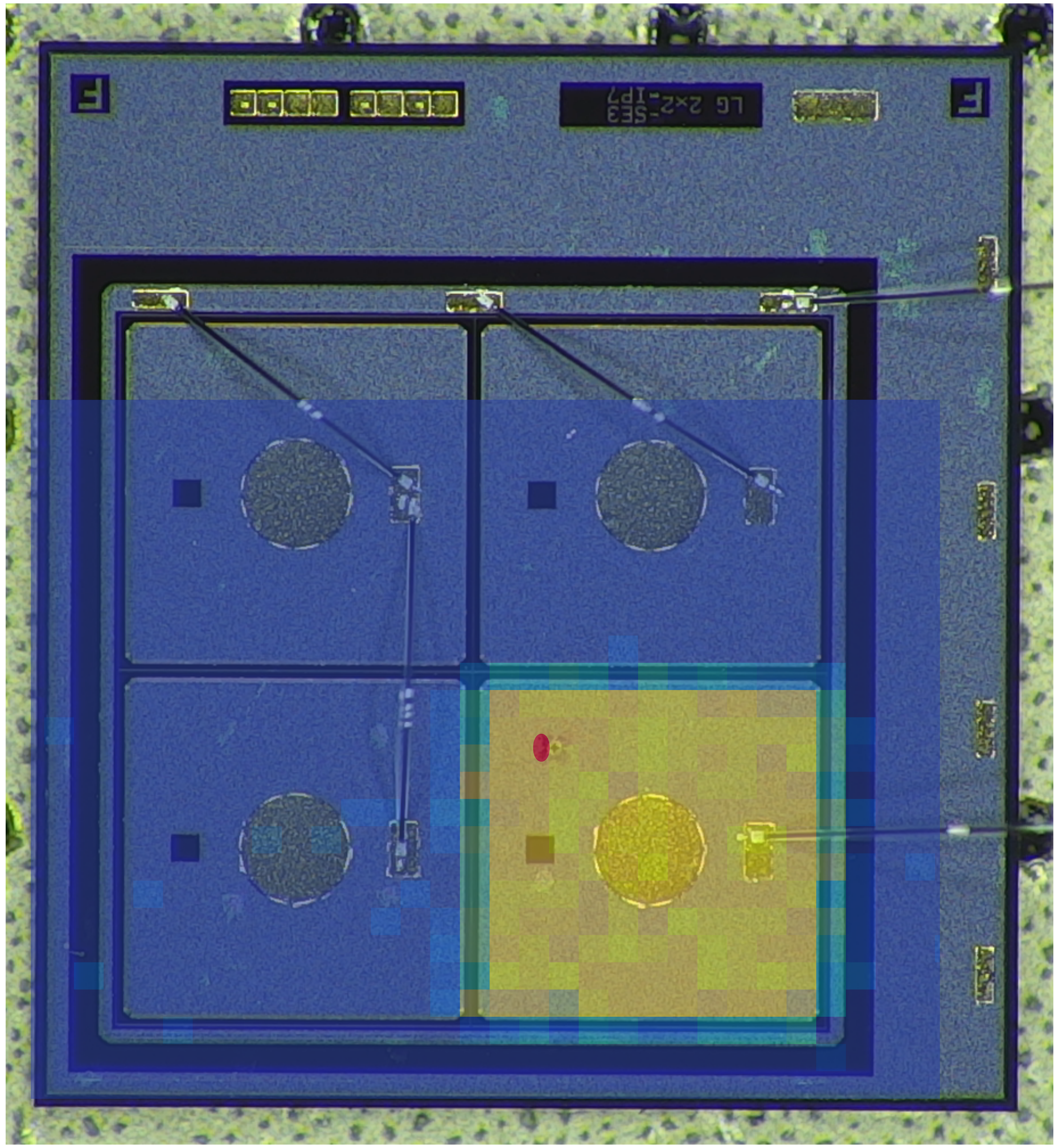
- When death occurs, first observe short on bias supply
- Then, find LGAD waveform indicating moment of death
- Compare track position in fatal event with crater location.



Efficiency map, lower right pad.

Example burnout event

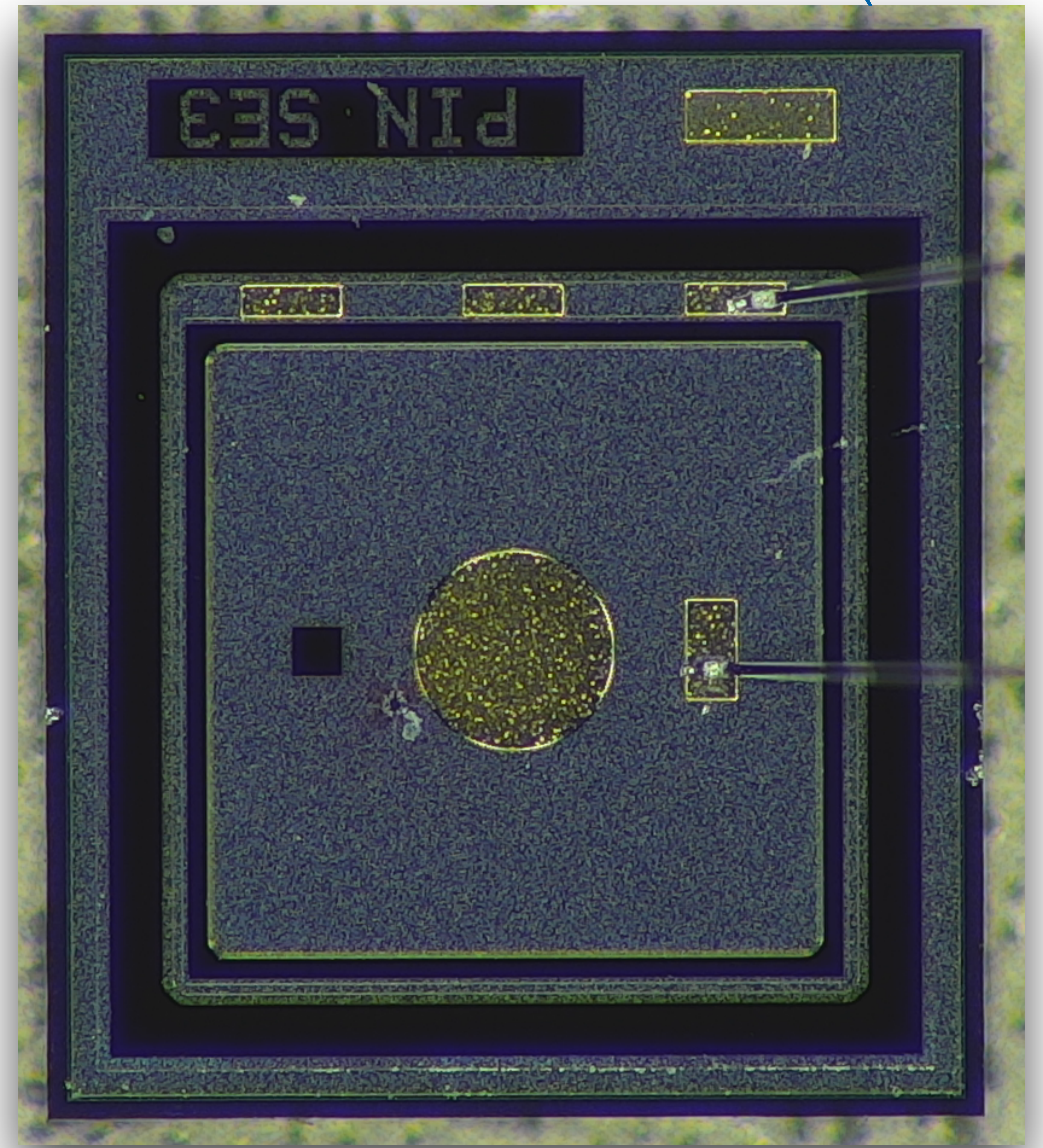
HPK 1.5e15 neq/cm^2

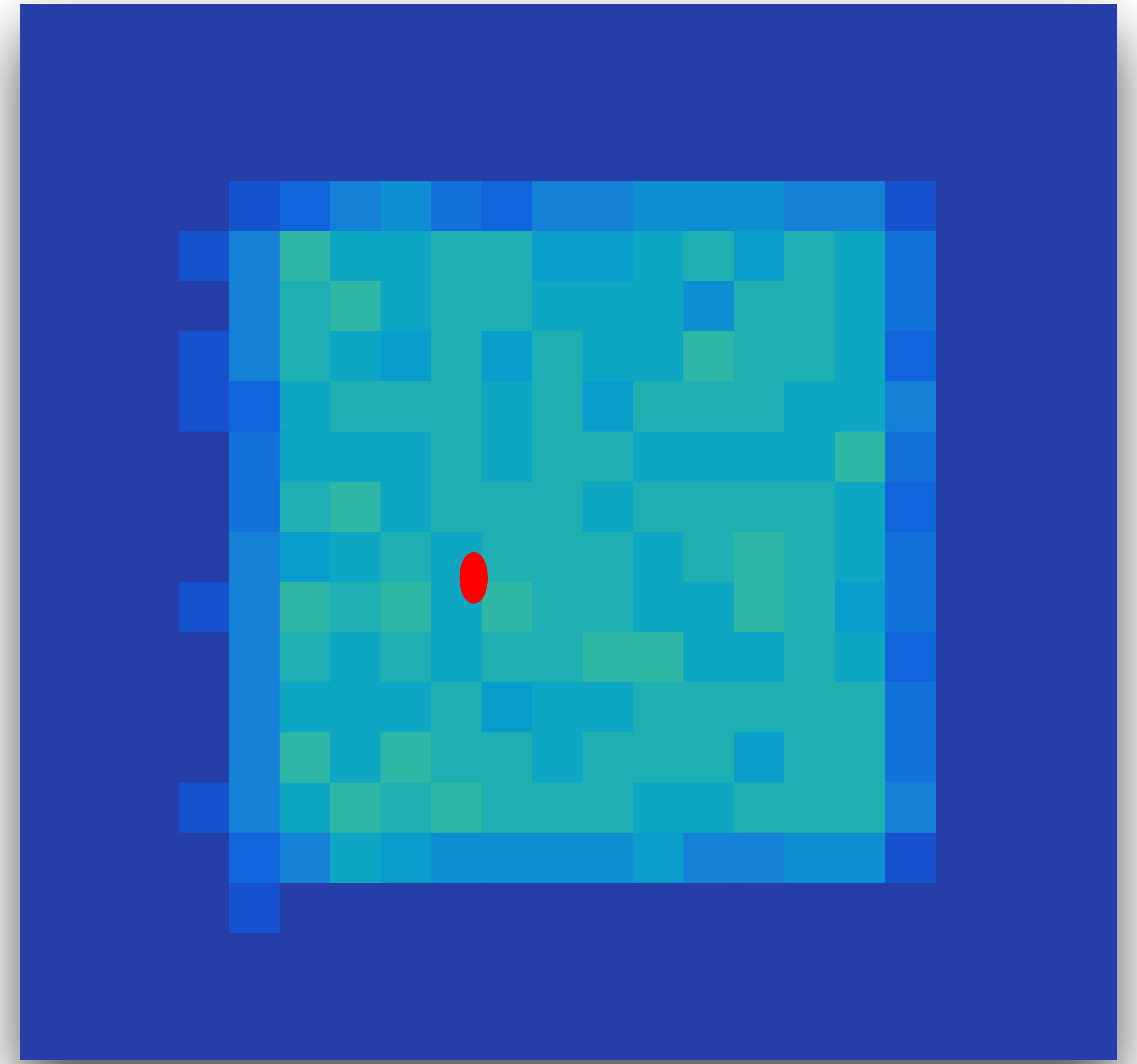


Burnout is decisively caused by proton!

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)

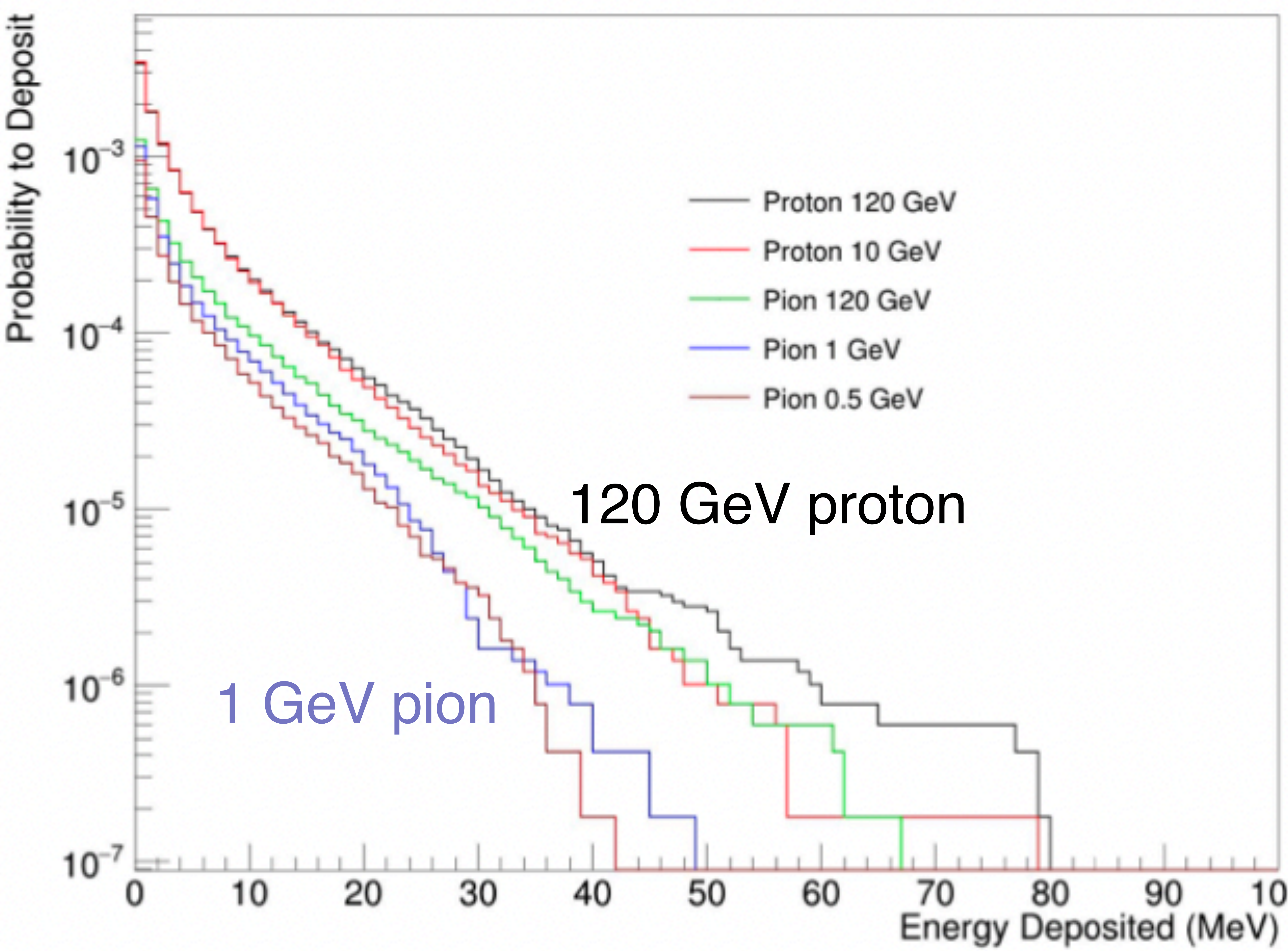
- 50 micron sensors susceptible to proton-induced burnout at bias ≥ 600 V
  - LGADs or PiN; any fluence: all die the same way.
  - ➡ Gain is not important for death mechanism.
  - ➡ Suceptibilty depends on voltage & thickness ONLY

- Burnout location: no major preference or weak spot
  - 1/3 at pad edge, 1/3 near bonding sites, 1/3 generic location.

- Several attempted treatments didn’t prevent burnout:
  - Encapsulation of sensor
  - Reduce HV capacitance
  - Add resistance to protect from HV supply..

Proposed burnout mechanism

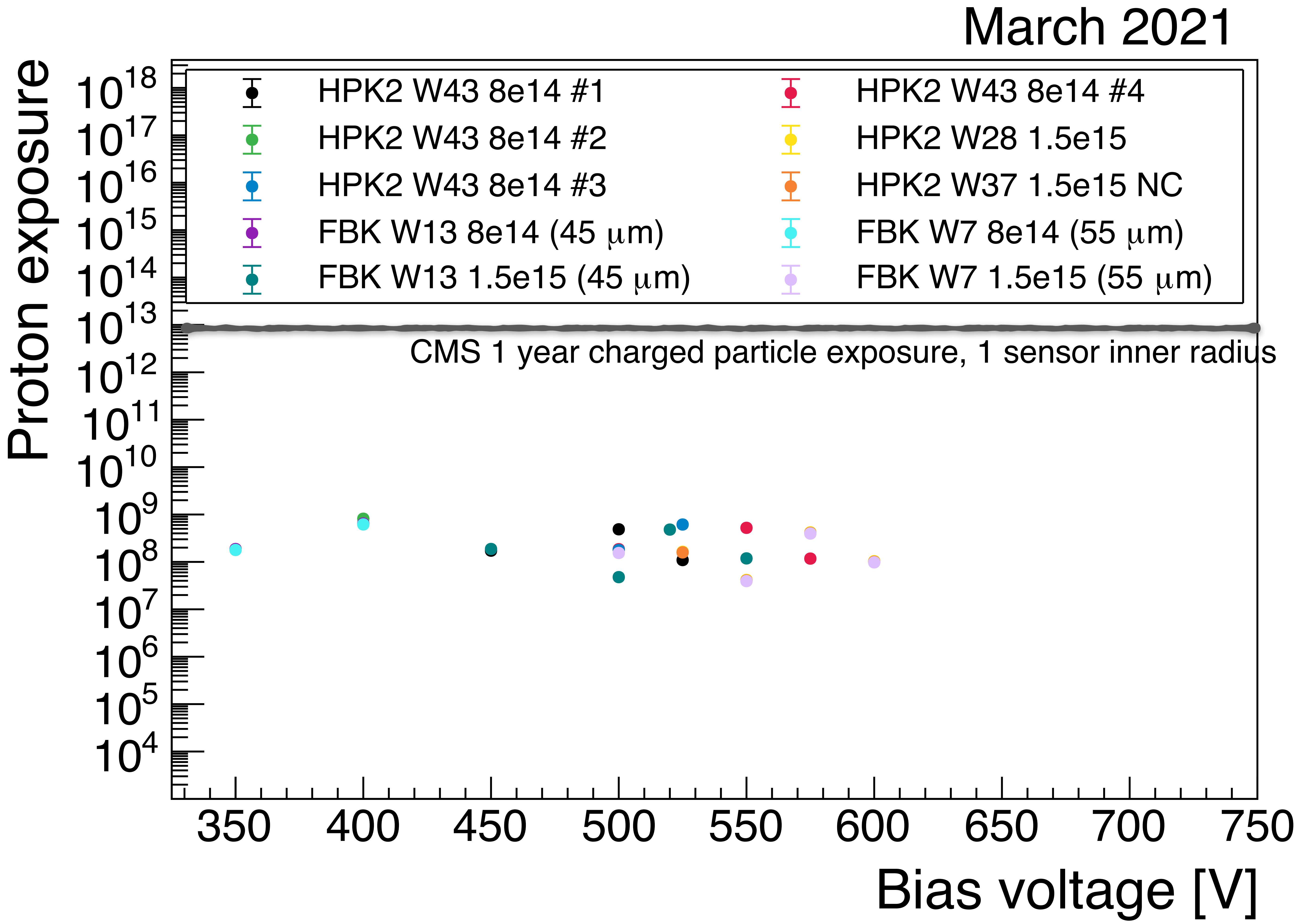
Probability to deposit at least X MeV in 50 μm (GEANT4)



- 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…

Initial survival demonstrations

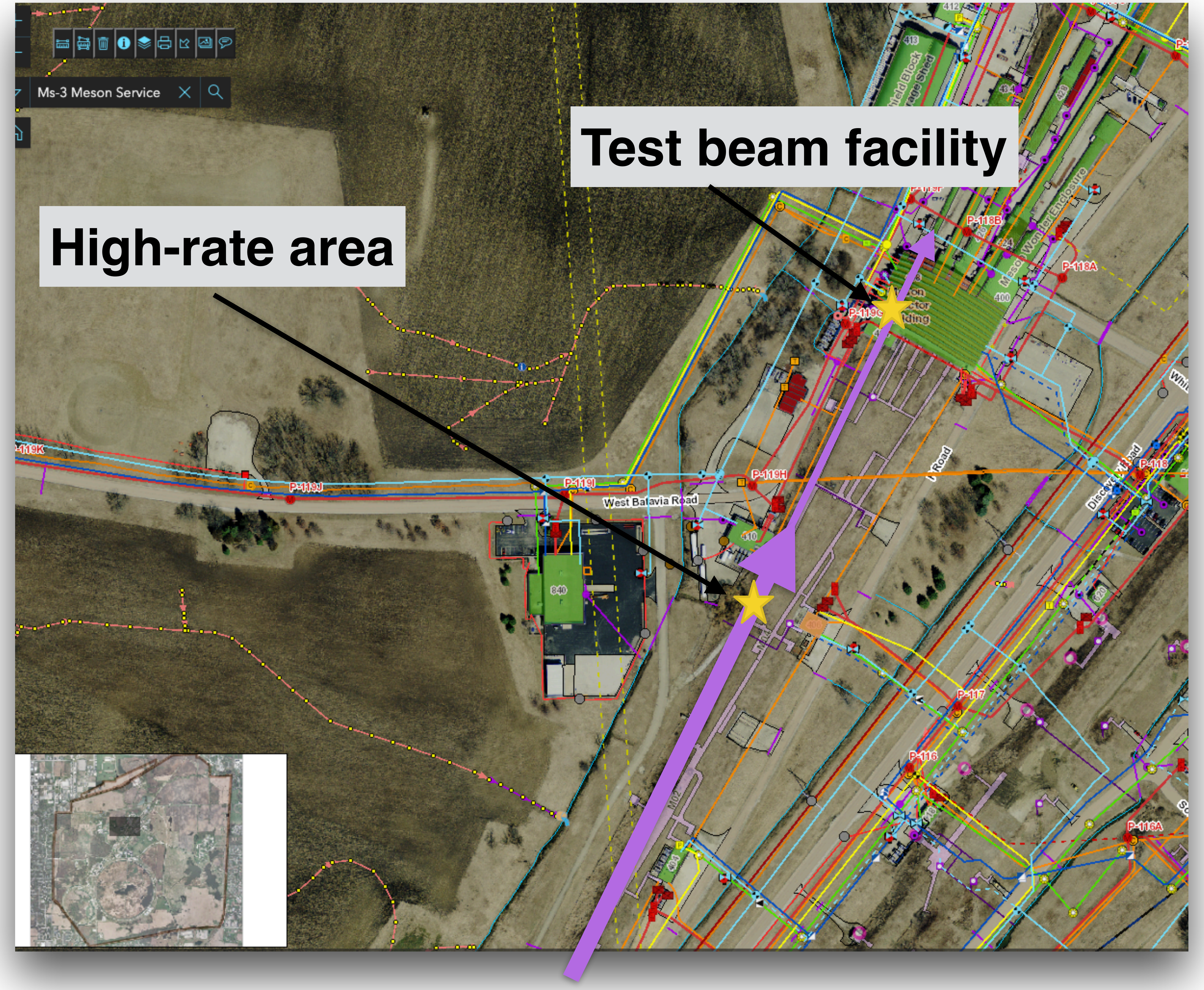


- Initial campaign also devoted time to survival demonstration
  - 10 sensors exposed to maximum fluence at test beam facility
  - Probe lifetime at bias slightly lower than burnout threshold.
- No deaths observed in 50 micron sensors ≤ 575 V (11.5 V/um)!
- Exposure ~ 10^9 protons
  - 2 orders of magnitude beyond scale of GEANT sim
  - Still, 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



120 GeV protons

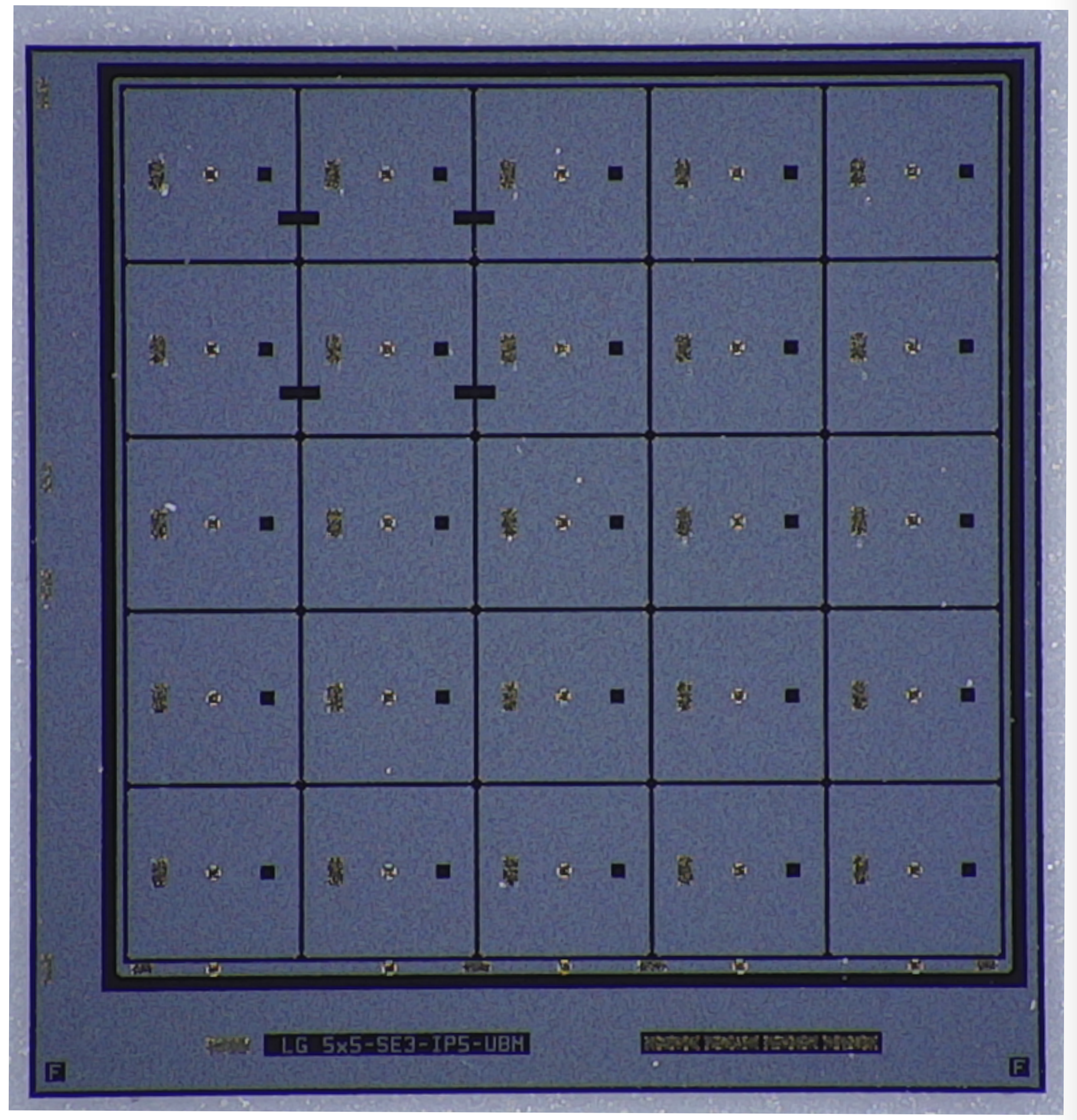
New setup at high-rate area (December 2021)

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

Sensors used

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

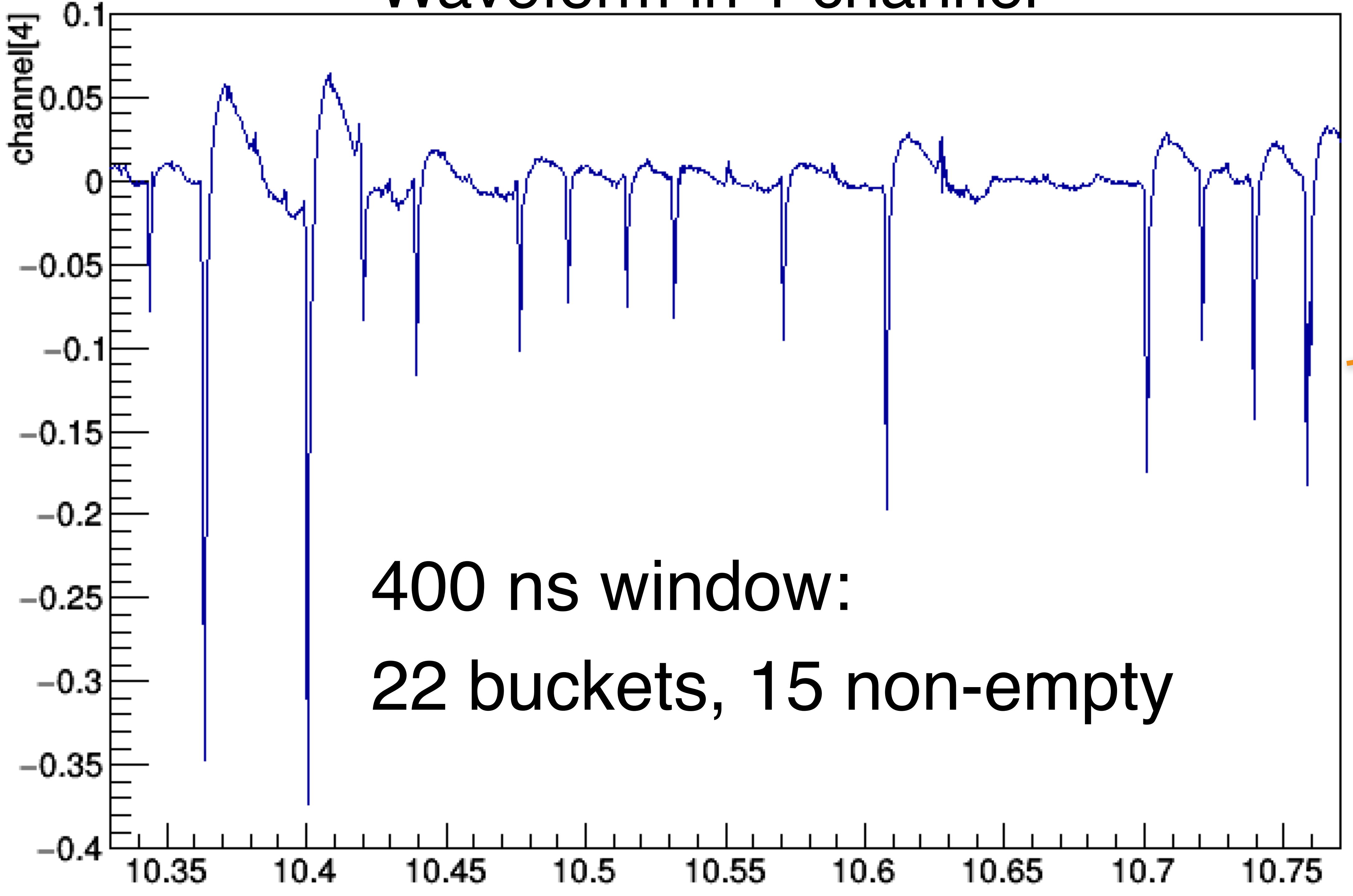
	Fluence [neq/cm²]	# sensors
HPK2, 50 micron	8e14	x4
	1.5e15	x4
FBK3.2, 45 micron	8e14	x1
	1.5e15	x3
FBK3.2, 55 micron	8e14	x1
	1.5e15	x4



Measuring beam intensity

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

Waveform in 1 channel

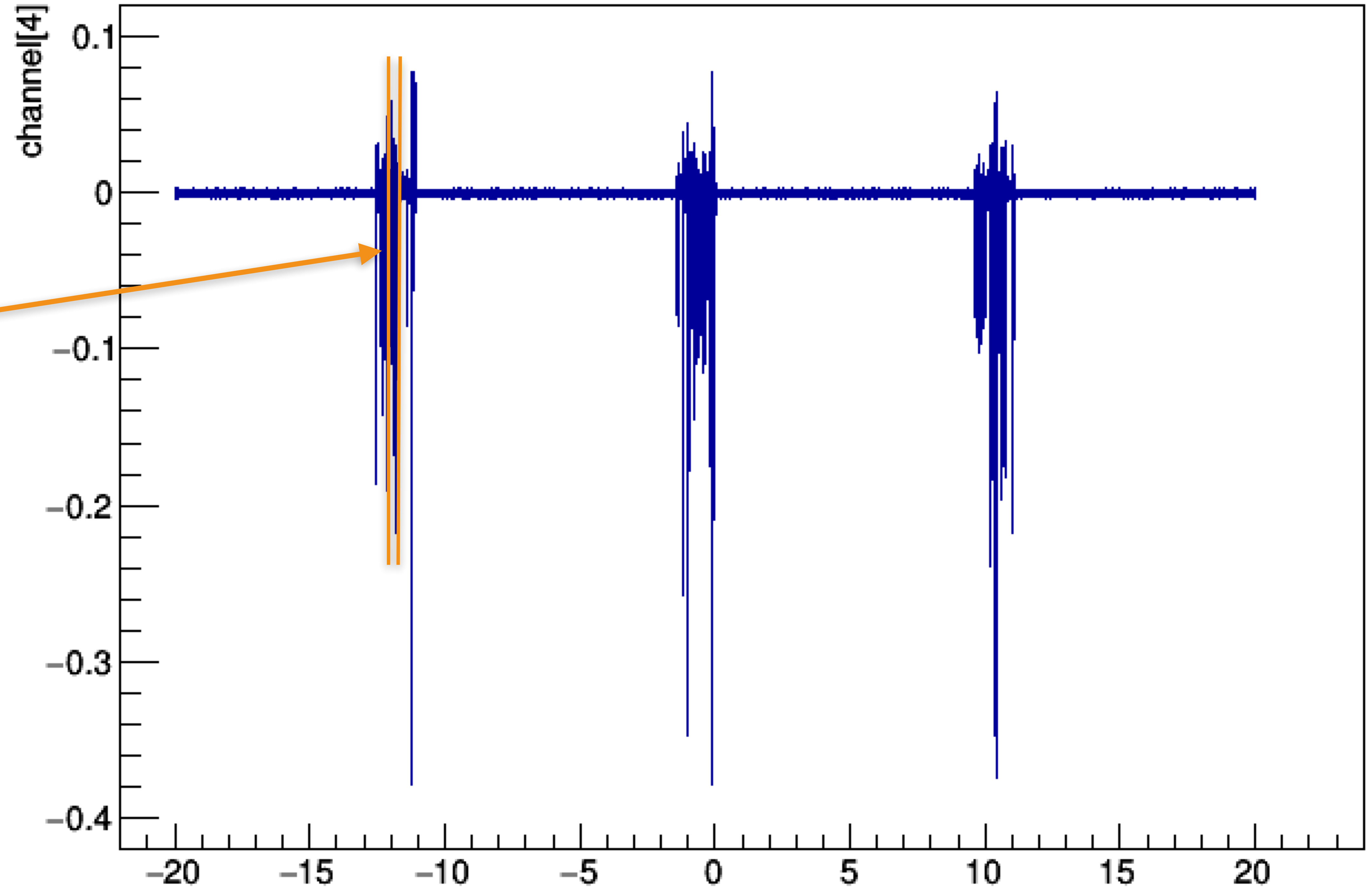


400 ns window:

22 buckets, 15 non-empty

t, microseconds

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



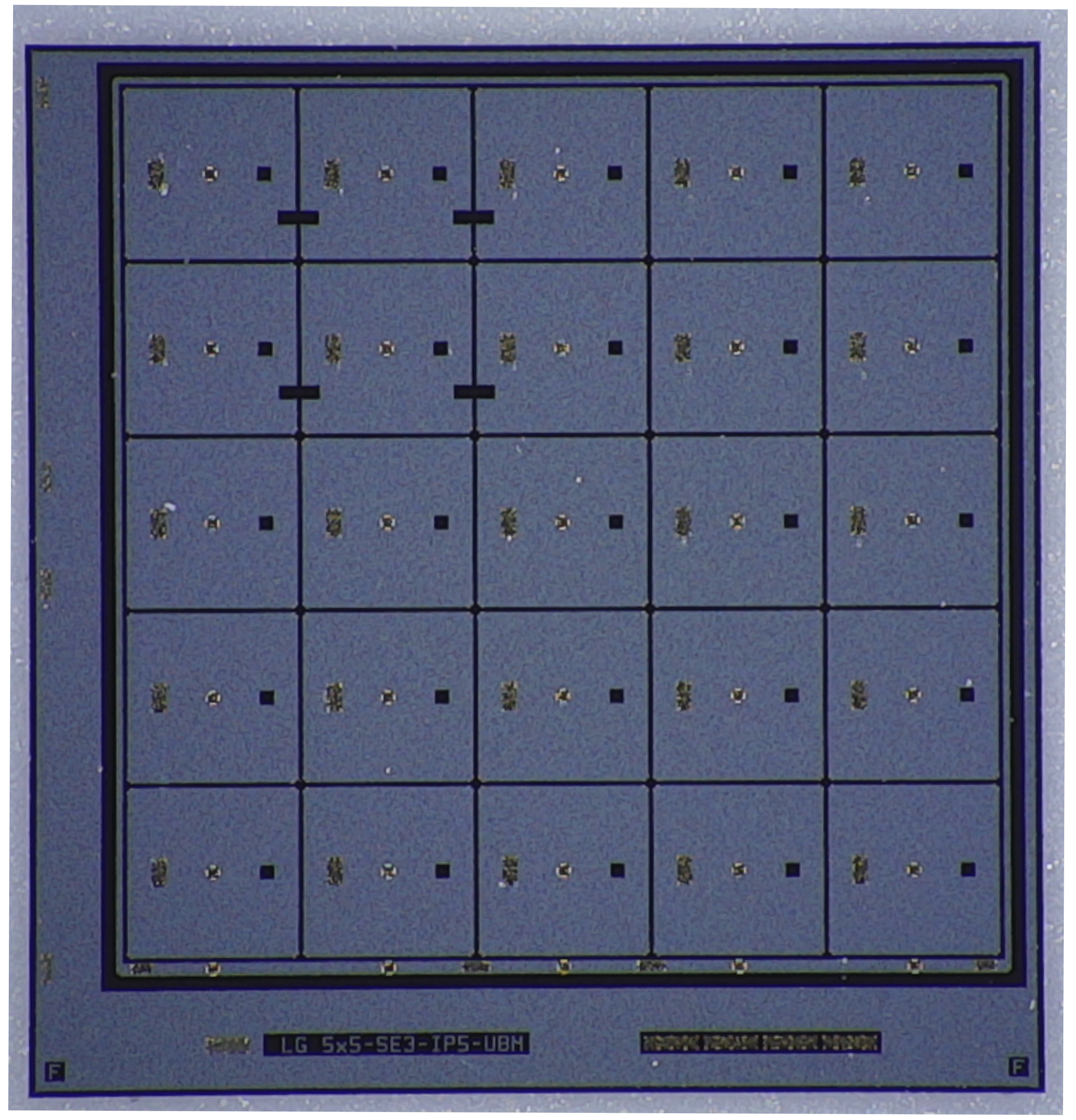
t, microseconds

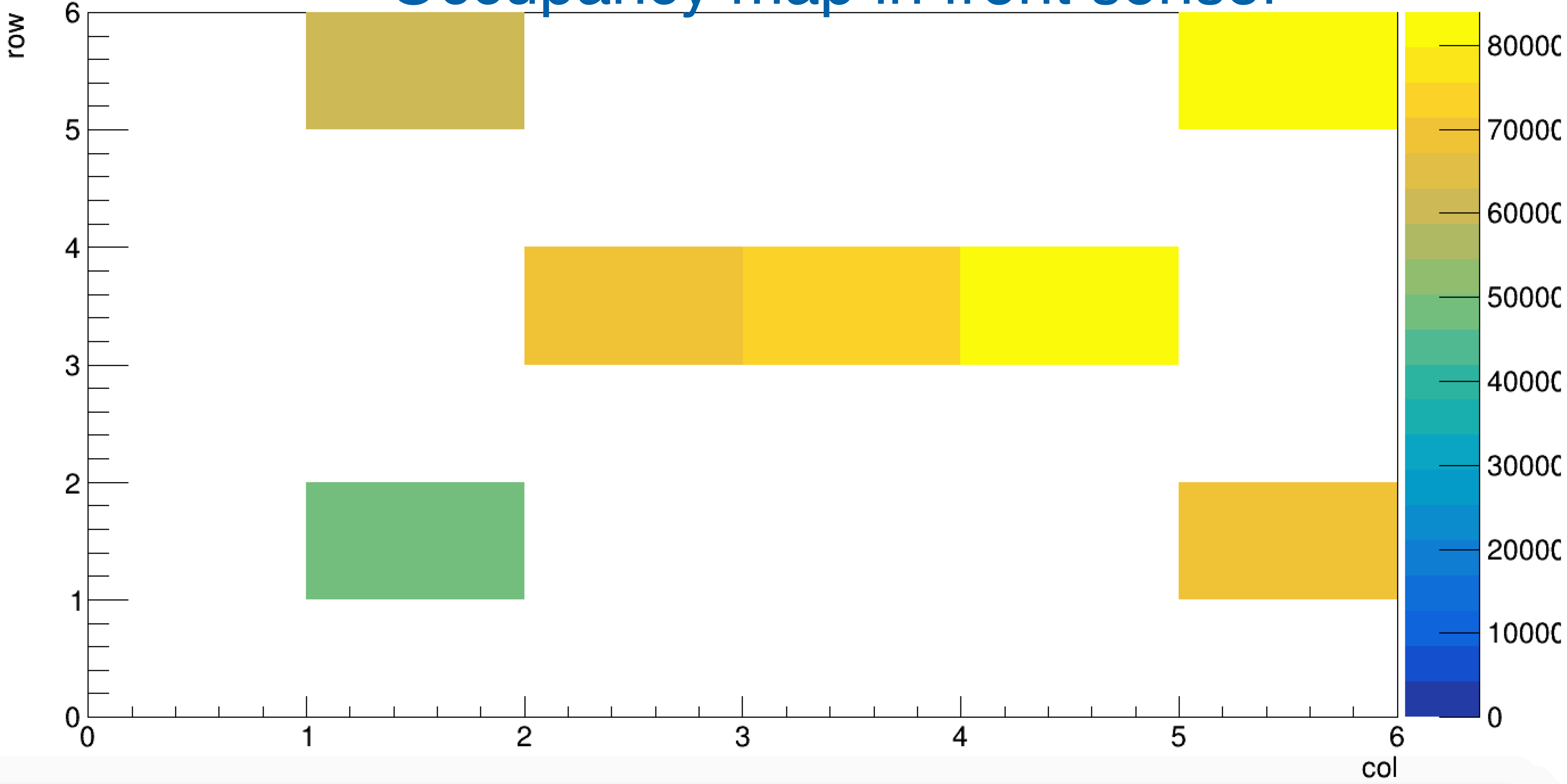
Receive about 400k “batches” in 4 s, each minute.

- Long exposures reveal time structure of beam and allow calibrating delivered flux.

Aligning to beam

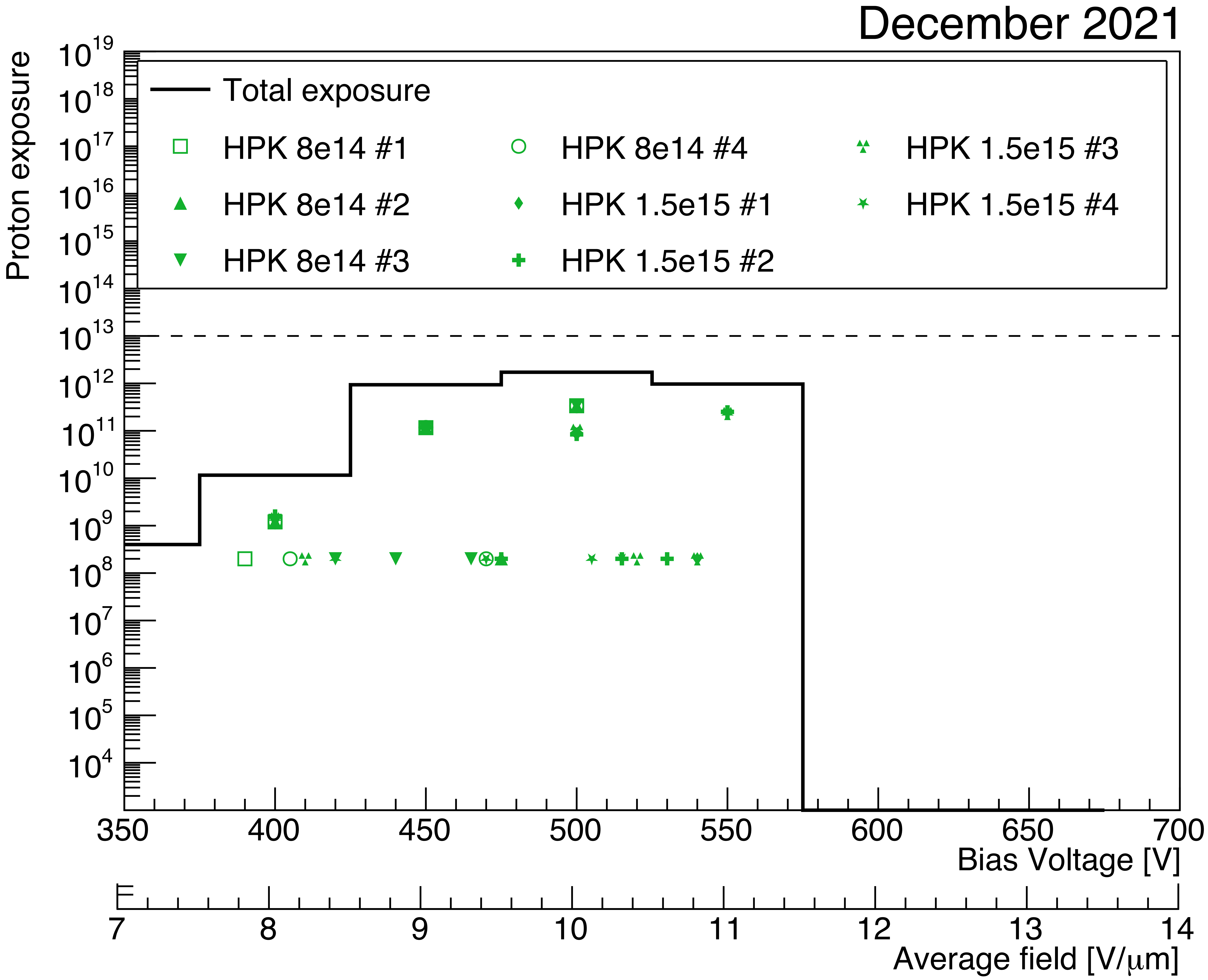
- Study occupancy across sensor with 8-channel oscilloscope
- Follow gradient to align sensor with beam using motion stage




Occupancy map in front 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 March test beam (slightly less than expectation)

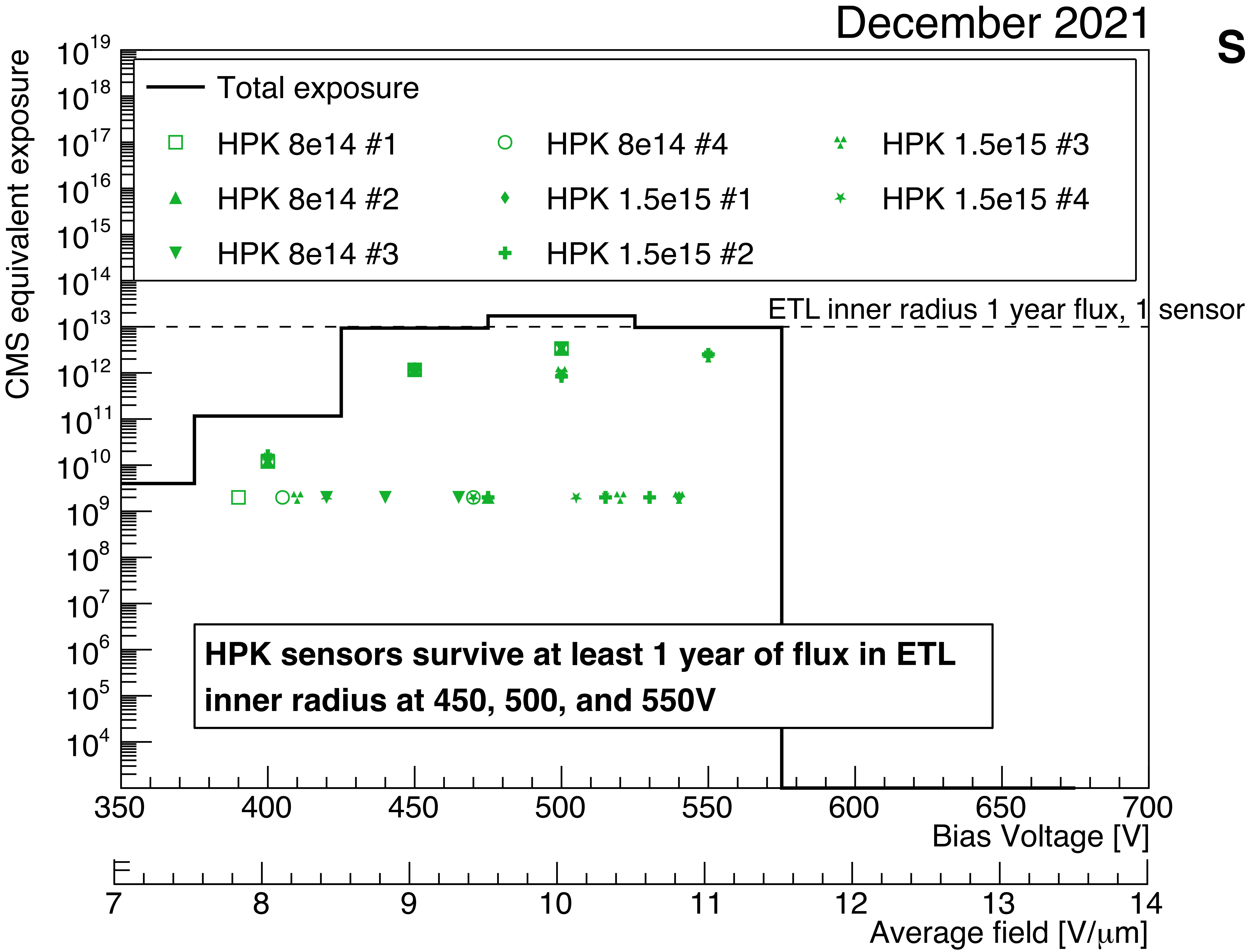
HPK exposures



- 50 micron HPK sensors

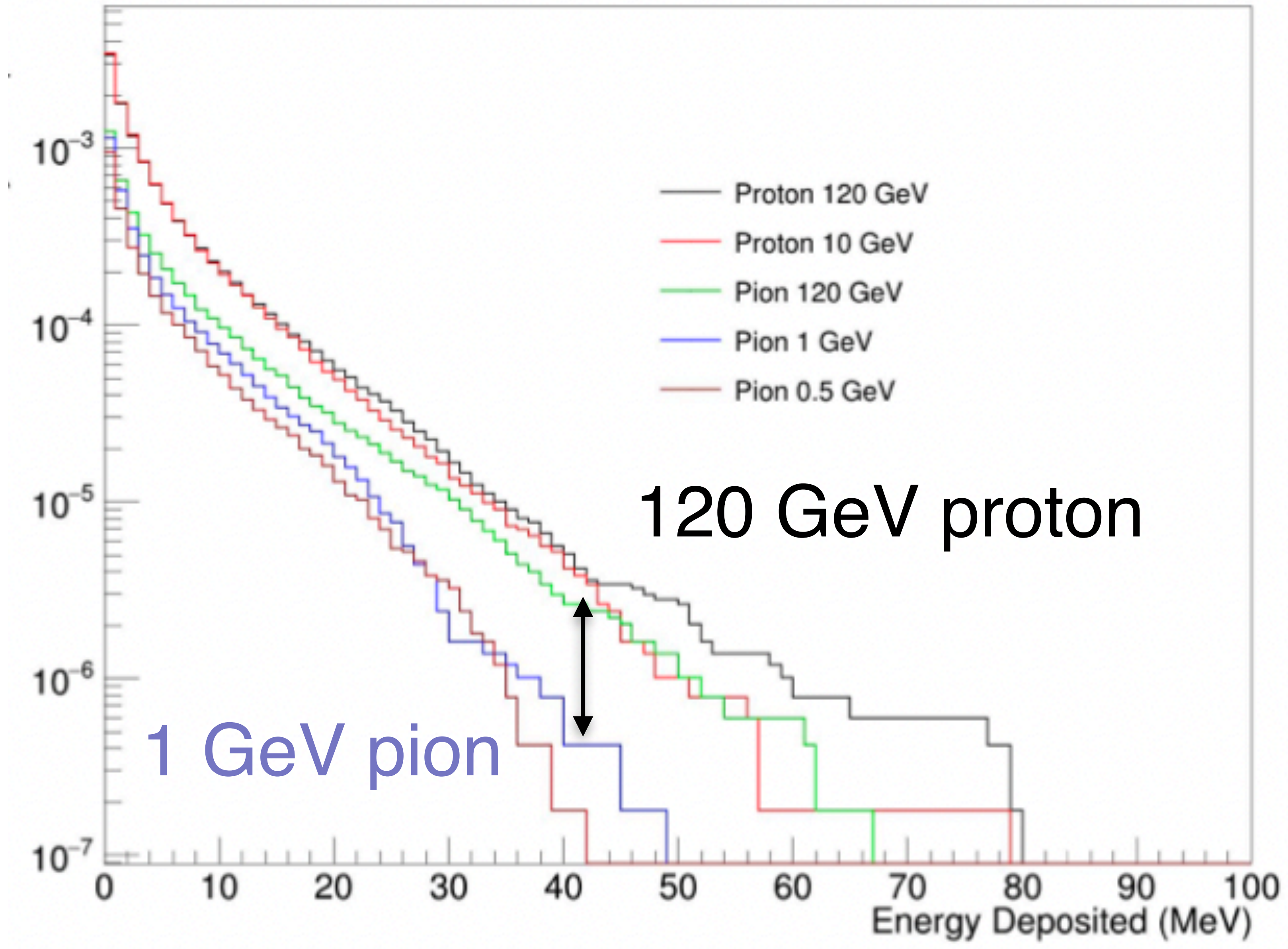
Delivered 10^{12} protons at 450, 500, and 550 V with no deaths!

HPK exposures



HPK sensors survive at least 1 year of flux in ETL inner radius at 450, 500, and 550V

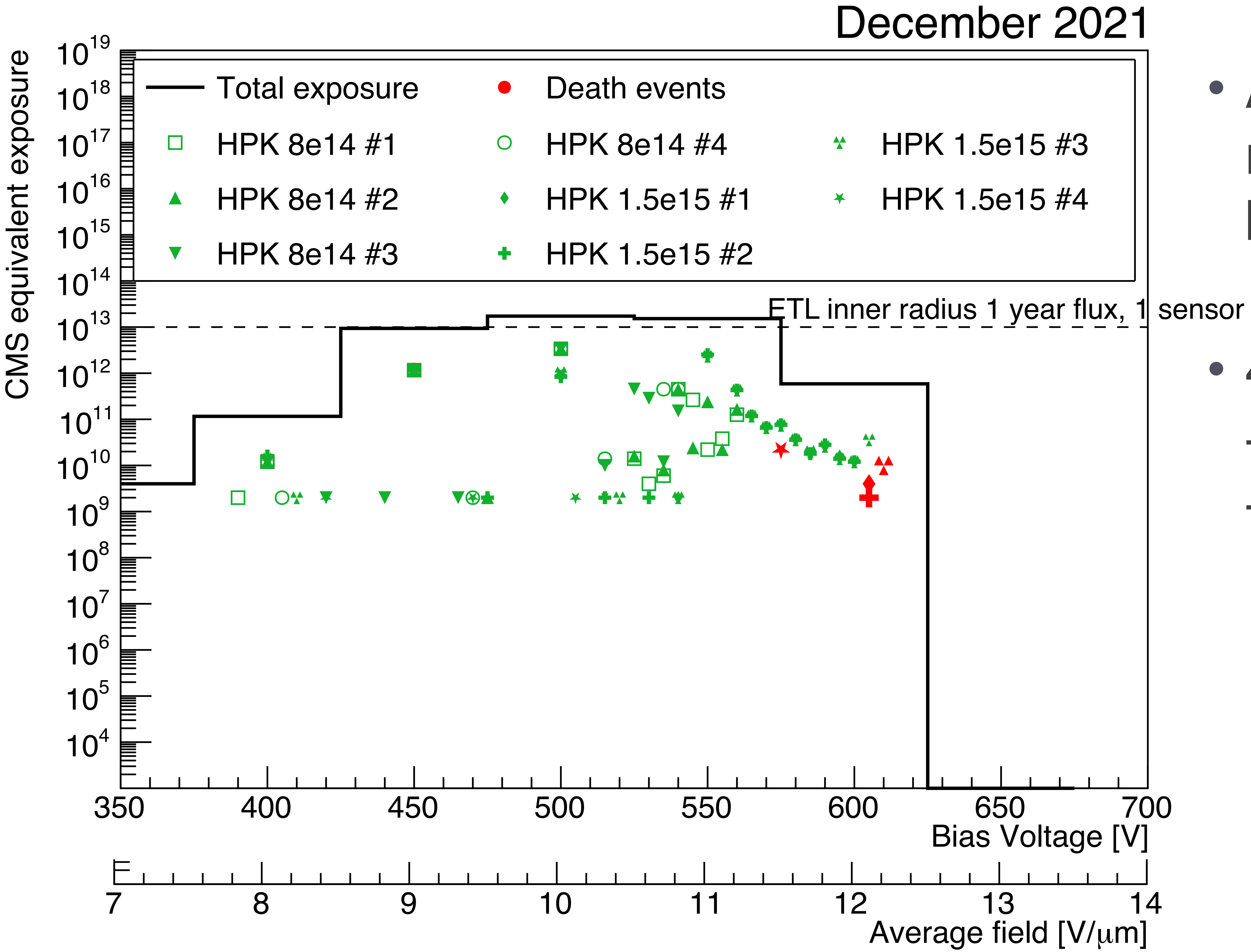
Scaling to highly-ionizing risk in CMS



120 GeV proton is ~10x more likely to deposit large deposit than typical CMS particle.

Scale test beam exposure by x10 to find CMS equivalent exposure.

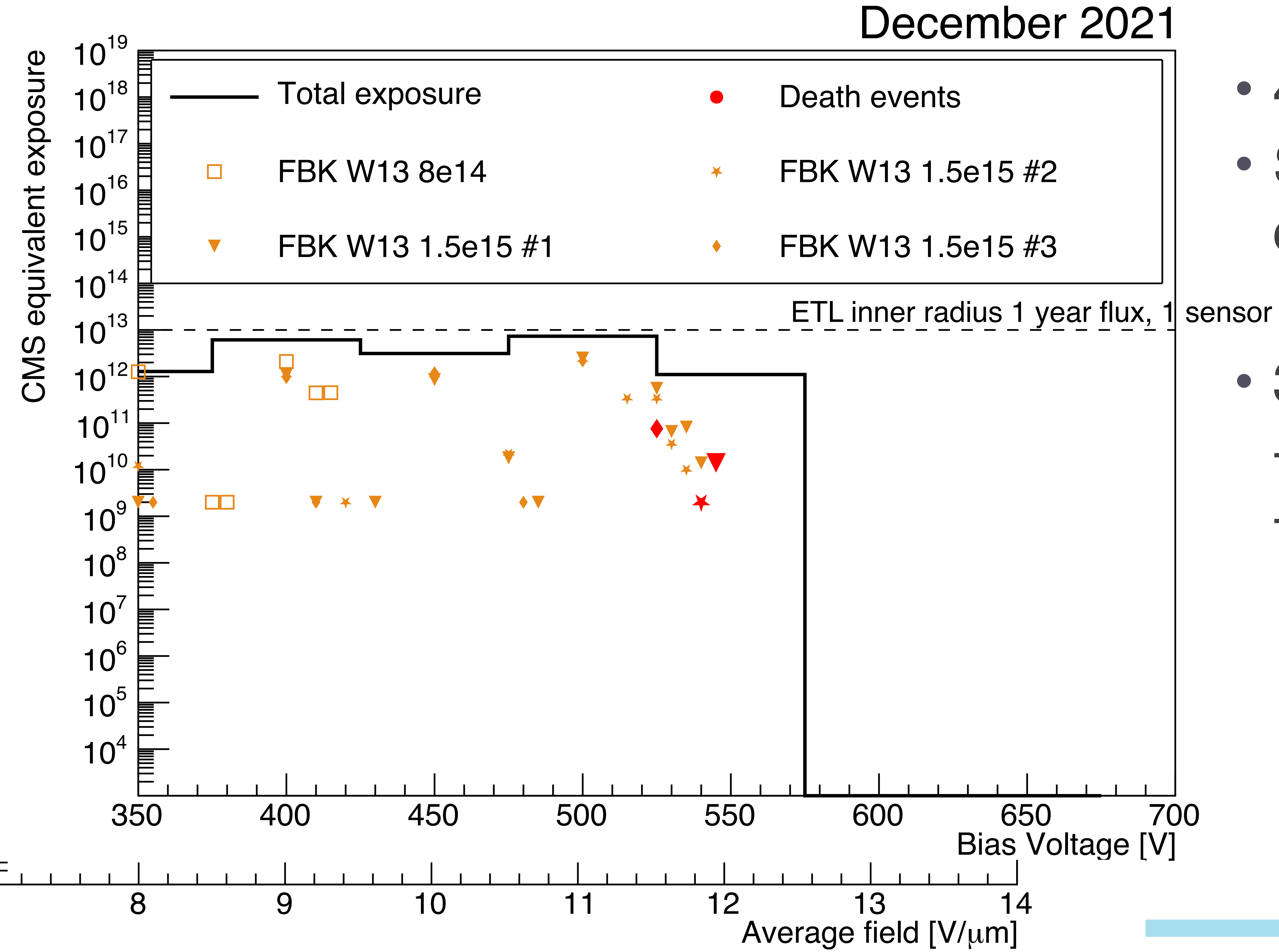
HPK exposures



- 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

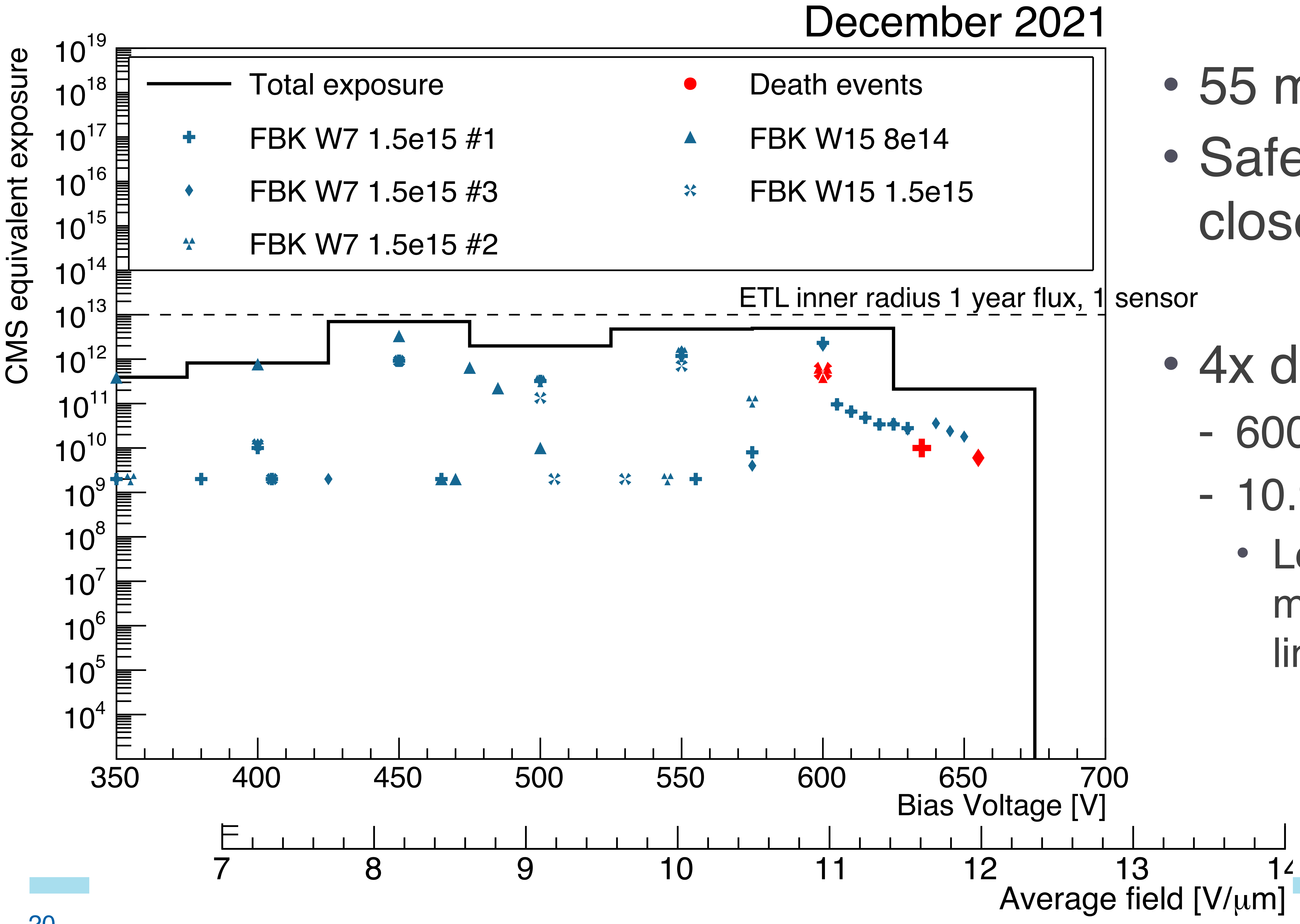
45 micron FBK



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

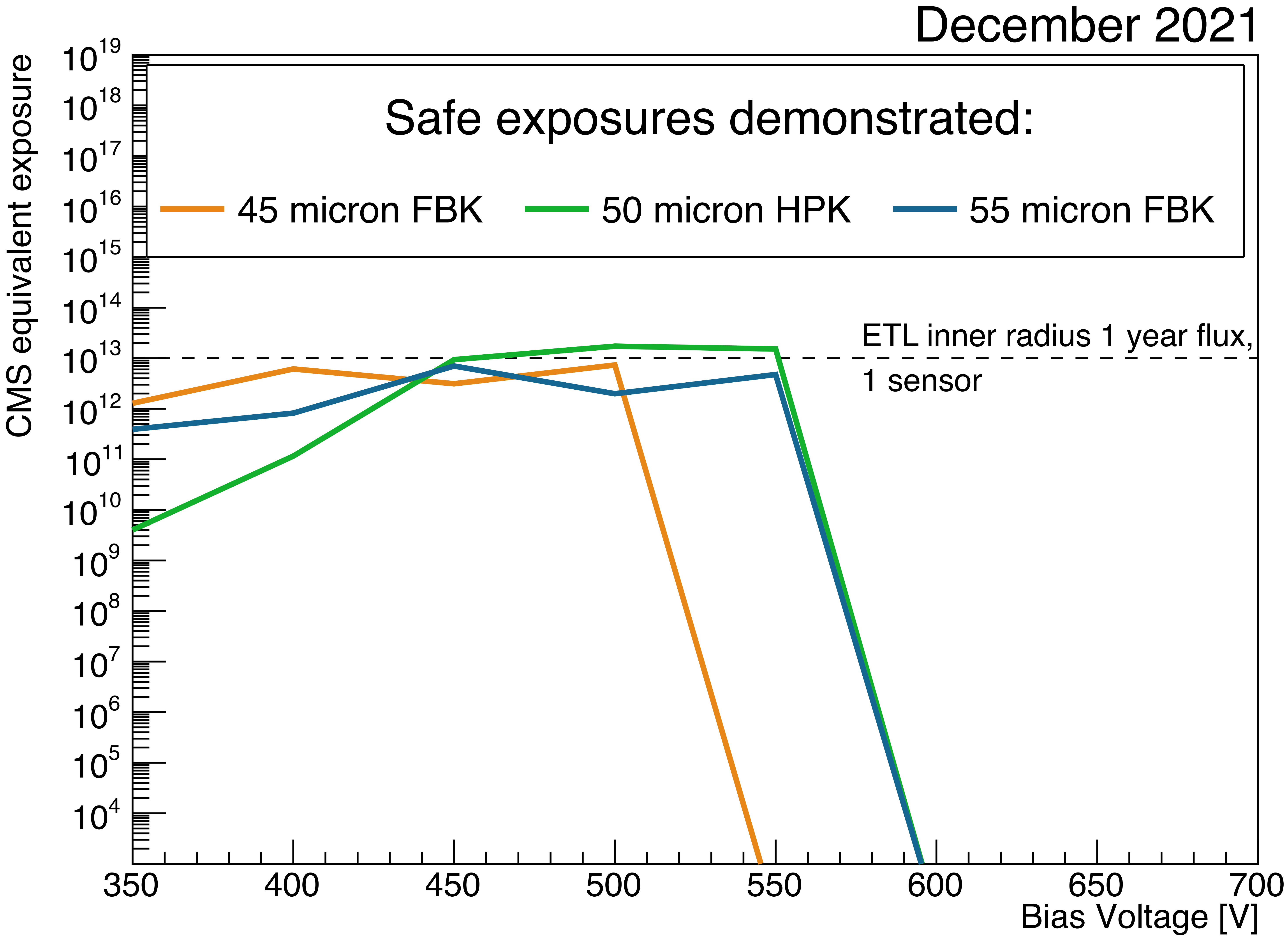
- 3x deaths in 1.5e15:
  - 525 V, 540 V, 545 V
  - 11.7 V/um to 12.1 V/um

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

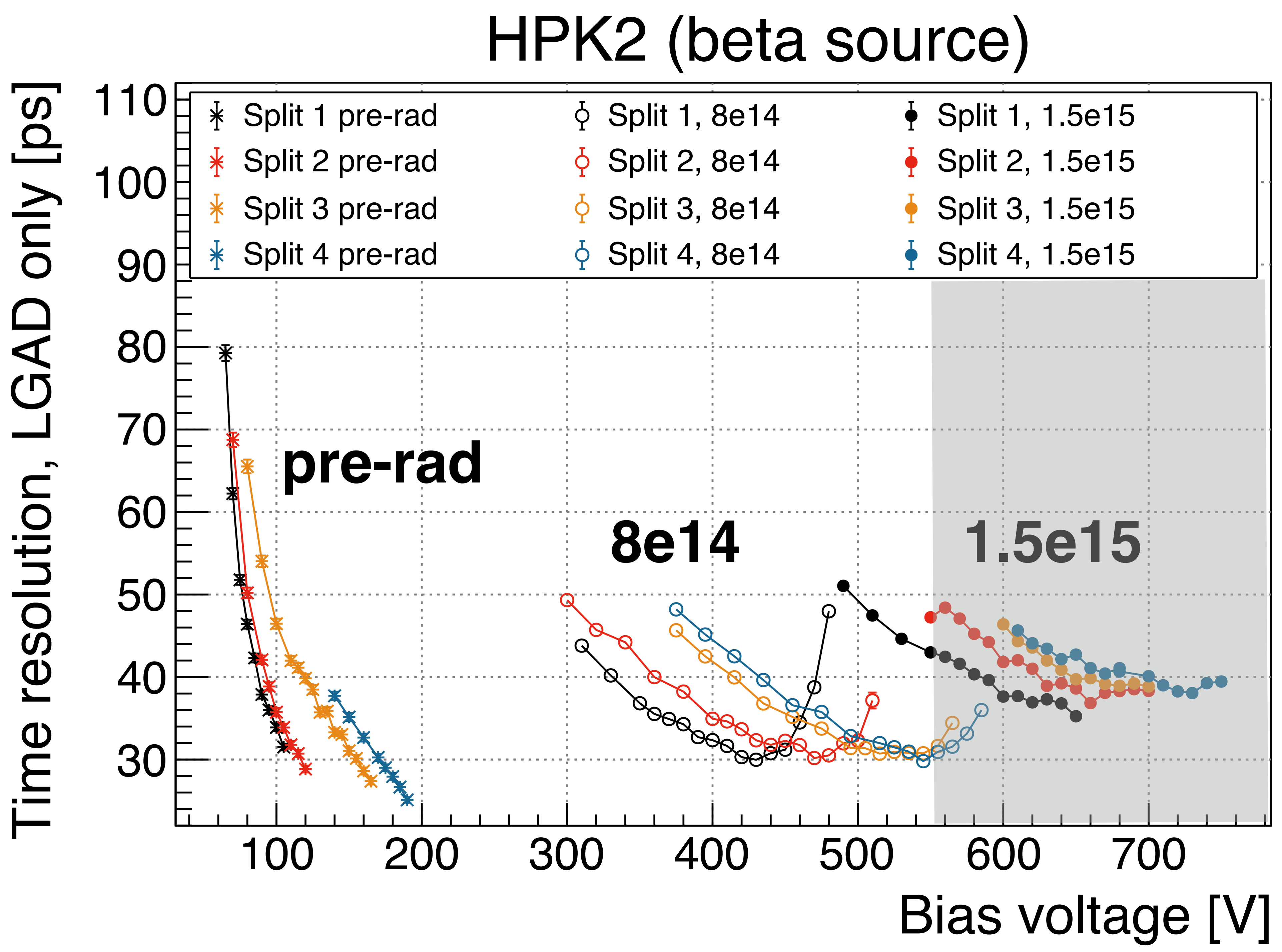
Exposure summary

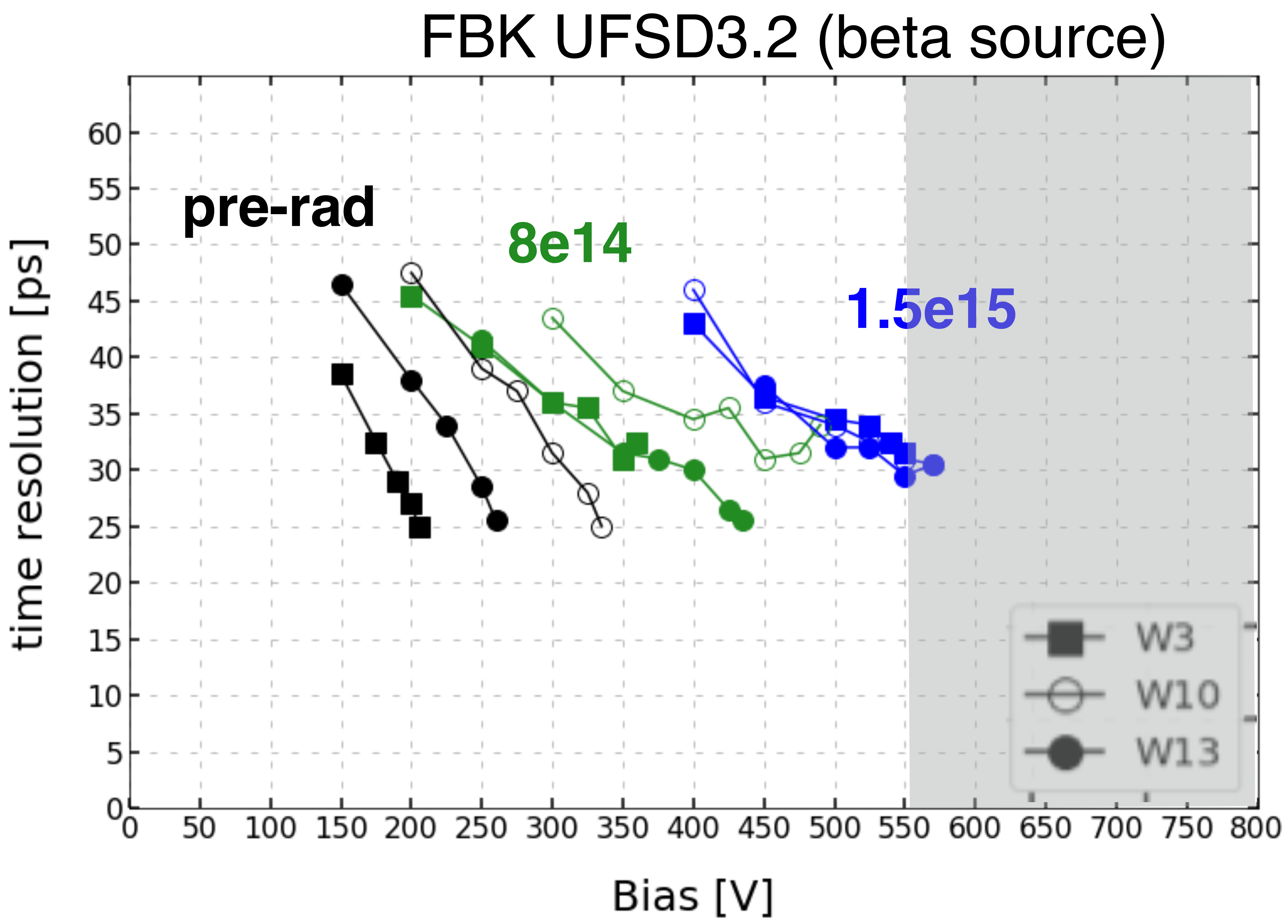


- Demonstrated safe operation with flux comparable to 1 year at CMS in all 3 thicknesses!
- SEB threshold roughly scales with thickness (~ constant field)
  - 55 um doesn't quite scale as expected, but perhaps true thickness is less than nominal.
    - May be related to guard ring design issue resolved in subsequent FBK production. Optical inspection pending.

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**!





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.