Custom Focal Plane Arrays of SPADs

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The International SPAD Sensor Workshop 2020

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LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Jet Propulsion Laboratory
California Institute of Technology

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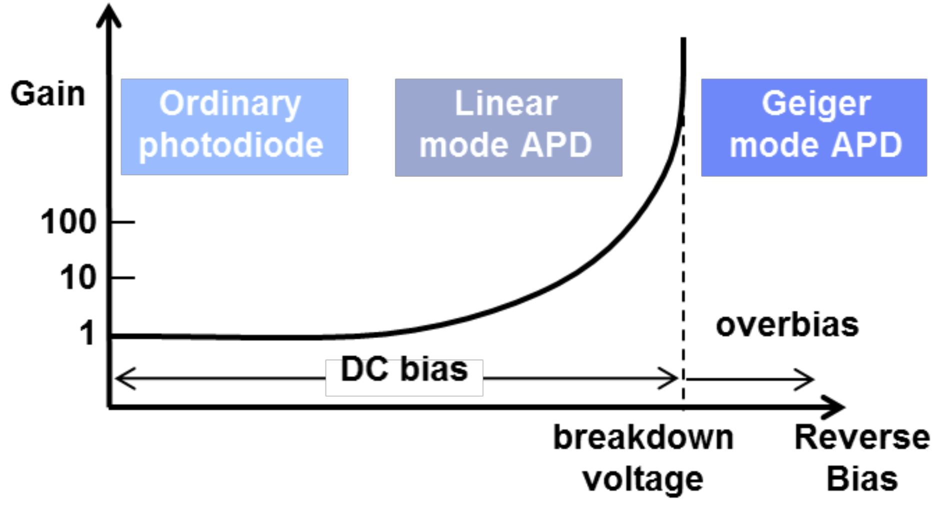
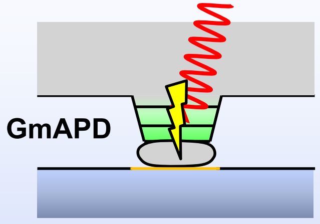
Geiger-Mode Avalanche Photodiode (GmAPD) Detector Technology

Photodiode Modes of Operation for MIT/LL Digital Pixel FPAs



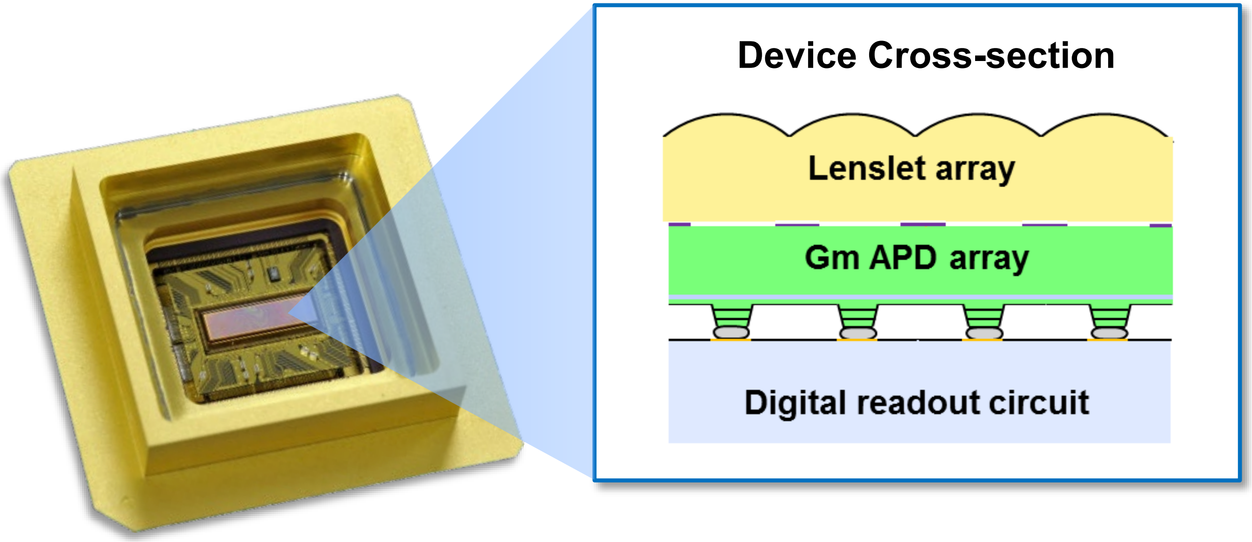
A single photon absorbed by the overbiased APD generates a fast rush of current



Single APD Cross section

Geiger-mode APDs provide:

- Single-photon sensitivity
- Lots of current → easy digitization
- Fast breakdown → excellent (sub-ns) time resolution
- TEC accessible temperatures → low SWAP
- Large format arrays

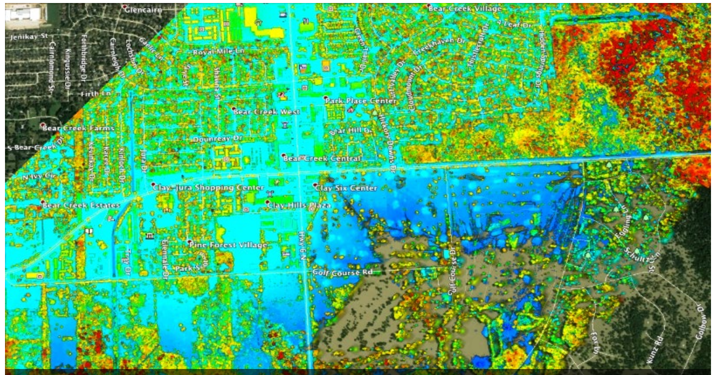


AOSTB Ladar Hurricane Harvey Response

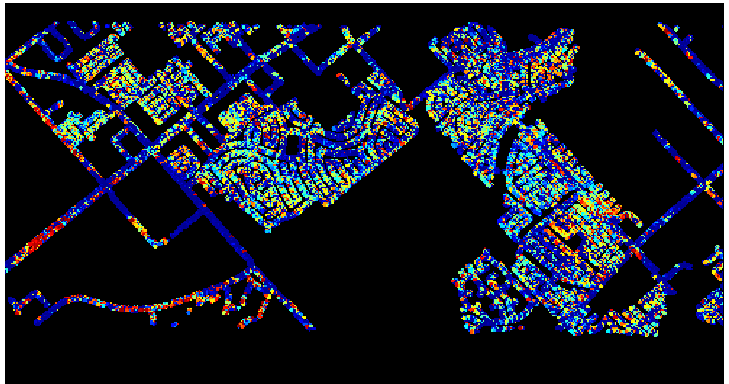
Unprecedented Harvey Damage

- 203,000 homes damaged
- 500,000 vehicles destroyed
- 200 million cubic yards of debris
- 30,000 people displaced
- 13 Superfund sites flooded

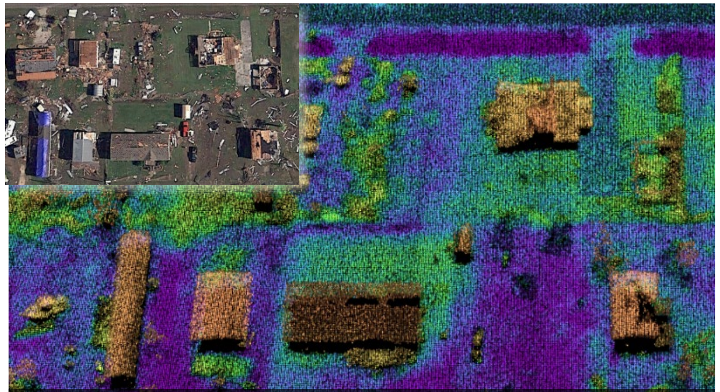
AOSTB Ladar responds to FEMA needs



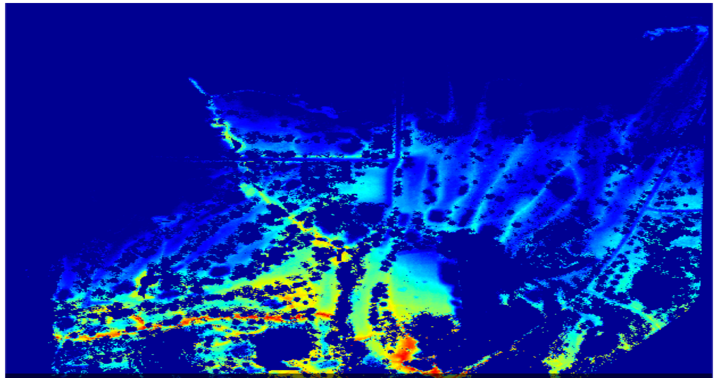
Wide-area Maps



Wide- Area Debris Analysis



Infrastructure Assessment



Flooding Maps

Urgent FEMA Requests

1. Wide-area debris mapping and quantification
2. Infrastructure damage assessment
3. Flood extent and volume

Advanced Ladar sensor potentially game-changing to recovery and public assistance efforts

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Sensor Chip Assembly (SCA)

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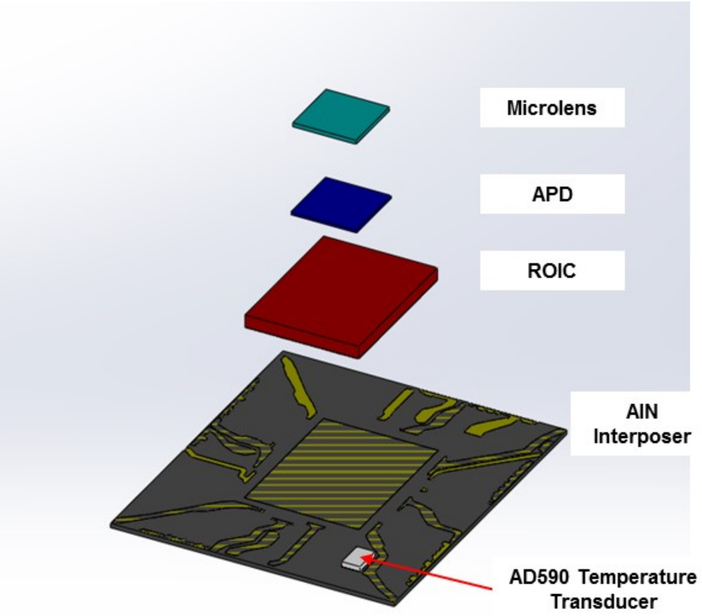
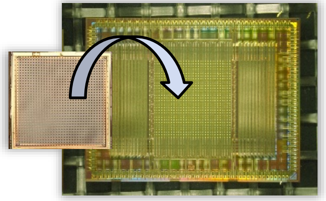
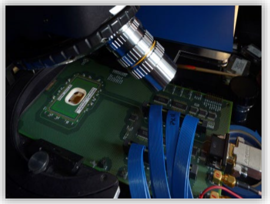
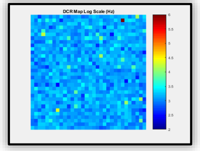
- **InP/InGaAsP APD array bump bonded to ROIC with indium bumps**
  - **Probe-card testing and underfill after bump bonding APD to ROIC**
- **ROIC precision placed and epoxied on AIN interposer**
- **GaP microlens array actively aligned to APDs and attached with epoxy**
  - **~0.5 um accuracy**
- **Temperature sensor epoxied on interposer**
  - **Monitors SCA temperature**

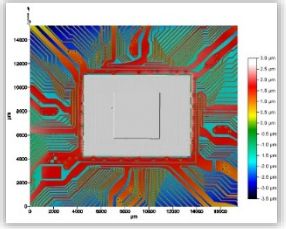
SCA Components

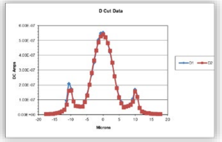












Bond/UF → Probe-Card Test → Go/No-Go: Pixel Yield → Interposer → Microlens → Go/No-Go: Lens Align

Typical InP-based Detector Performance

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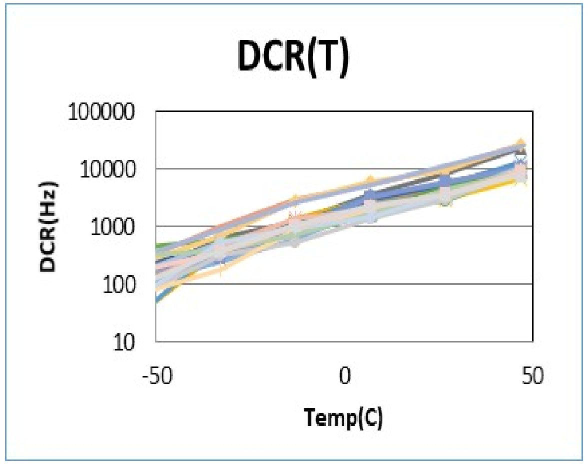

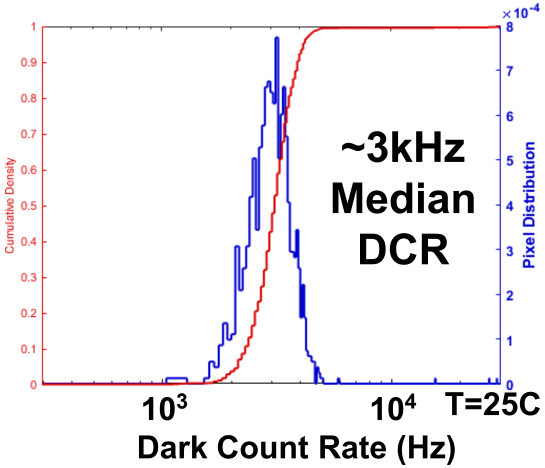

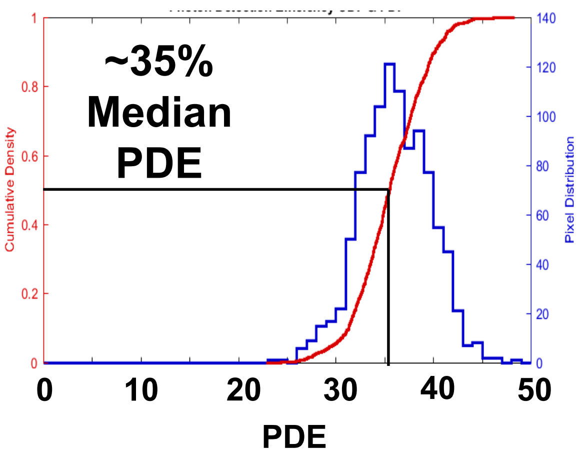

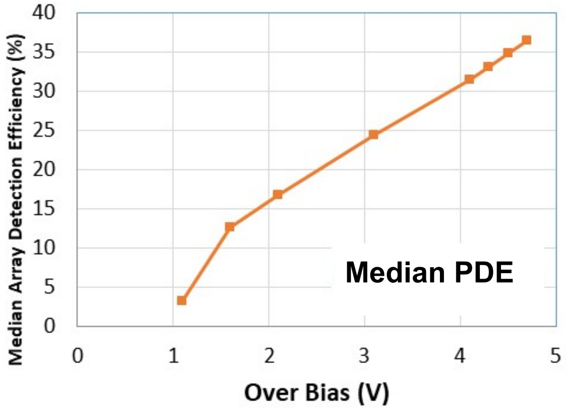

- Median dark count rate ~3 kHz at room temperature (25 C)
  - DCR varies in expected manner with temperature
- PDE achieves > 30% PDE at >4 V overbias
  - Readout integrated circuit can achieve overbias values up to ~6 V

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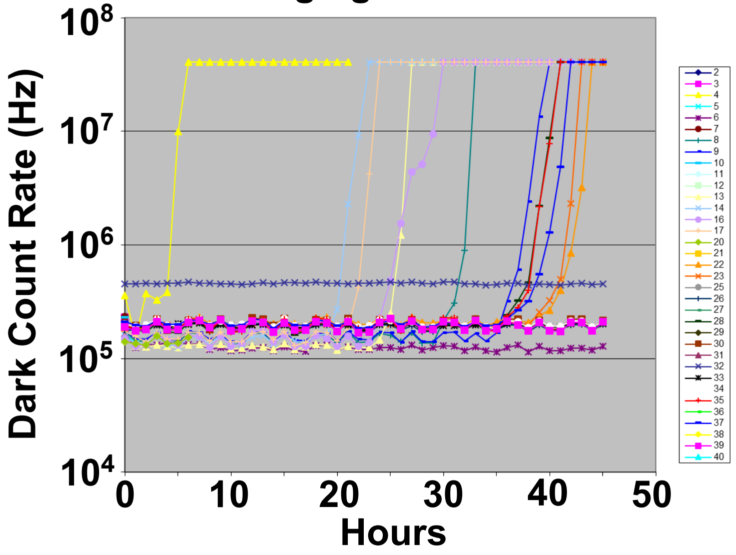
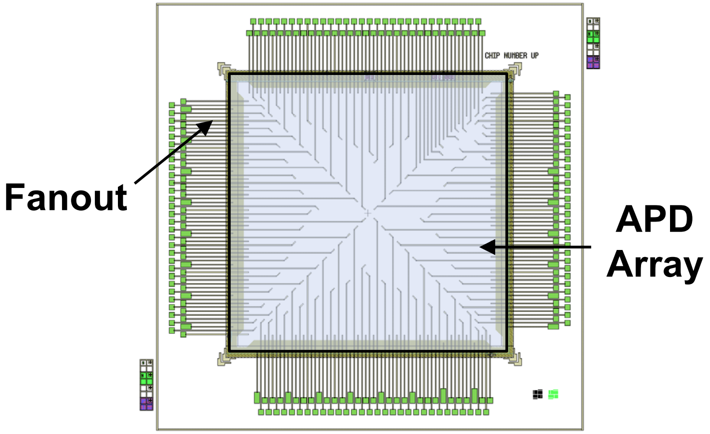
InP-based Geiger-mode APD Reliability

- **Failure mechanisms of Geiger-mode APDs**
  - DCR increase – primary "wear-out" mechanism for GmAPDs
    - Time to failure function of total amount of charge through APD and temperature
  - Dark current increase
    - Accompanies DCR increase during wear-out of APD
  - Electrical shorting
    - APDs that failed in this mode typically exhibited anomalous behavior in initial testing and can be screened for during assembly and burn-in
  - These failure mechanisms apply statistically to individual detector elements
- **Accelerated aging of APD arrays on fanout enables calculation of failure rates**
  - Increase charge flow through APDs to cause measurable failure rate
  - Scale to charge environment on ROIC to predict final FIT (failure in time) rates for detector pixels

Aging Data

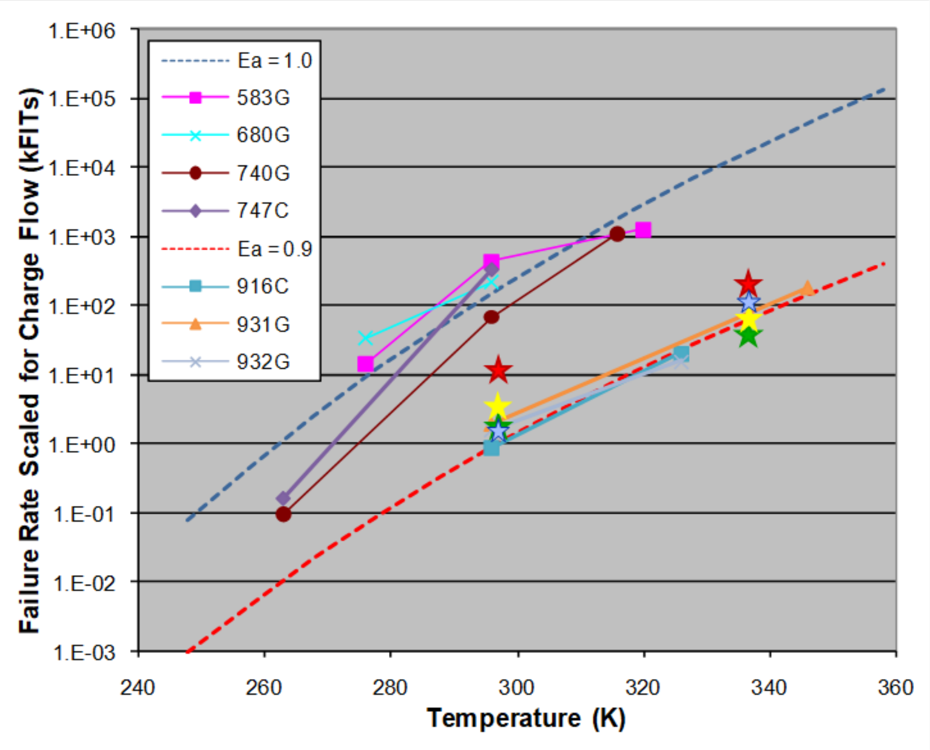


32x32 Fanout Geometry



Thermal Activation of Failure Rates

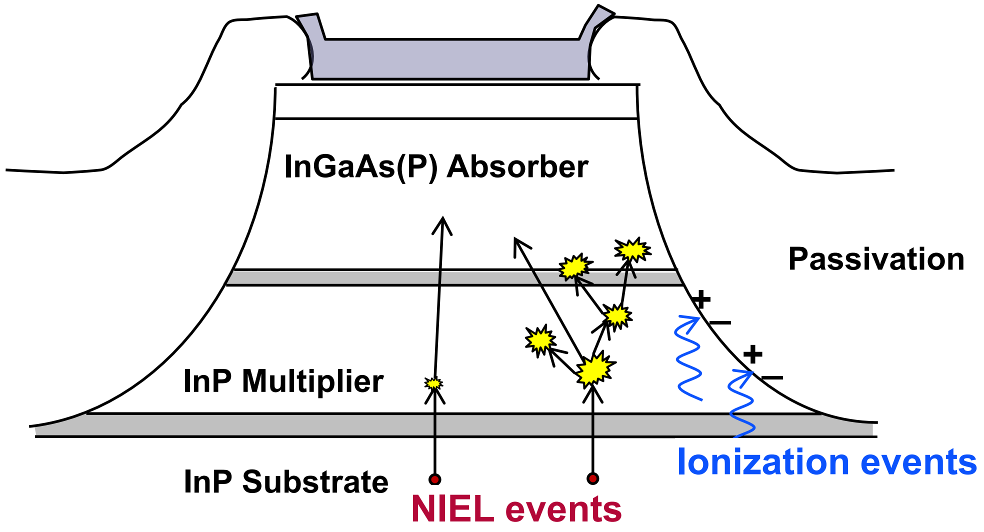
$$FailRate(I,T) \propto I \times \exp\left[\frac{-E_A}{kT}\right]$$

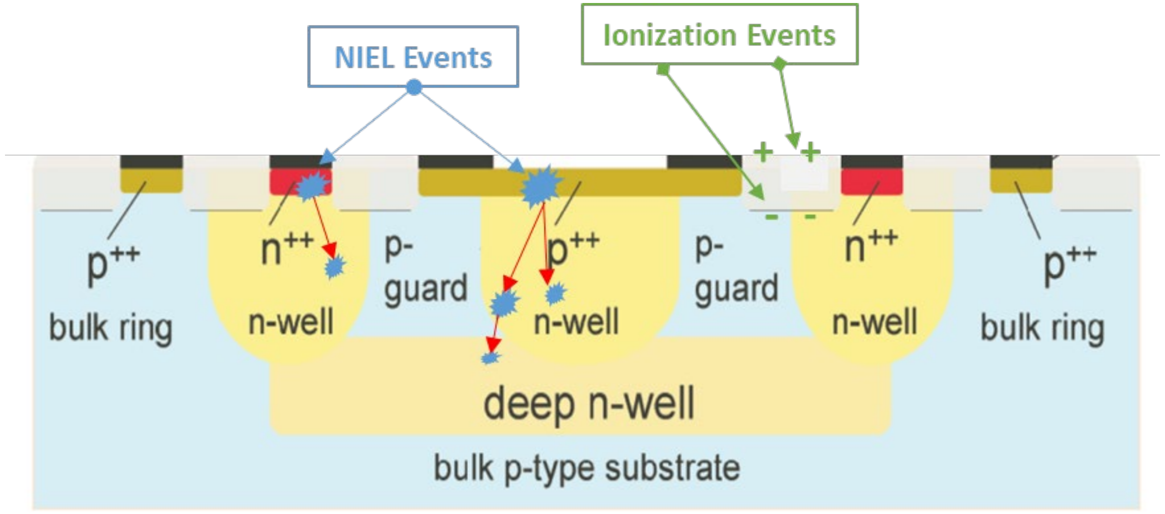


- **Failure rate scaled for charge flow difference between fanout and ROIC (charge acceleration factors >100x)**
- **Failure rate measured as a function of temperature**
- **Failure rates for qualification lot (Blue stars) and flight lots (Green/Yellow stars) in agreement with past standard (good) fab lots**
- **Scaling to nominal operating temperatures (-10 to +10C) yields <200 FITs over this range of temperatures**
  - **MTBF >> mission time**
    - **1kFITs: ~8000 years at 2hr/week ops**
    - **200 FITs: ~40k years for this op-tempo**

GmAPD radiation damage mechanisms

- **Radiation Effects:**
  - ***Ionizing*** **– at the surface as charge is embedded in passivation layer**
  - ***Non-ionizing ("NIEL")*** **– in the bulk, where displaced atoms generate electronic trap centers, leading to an increase in the dark count rate (DCR)**
- **Primary concern for *Geiger-mode* APDs is the increase in DCR due to displacement damage**





Quantification of FPA Radiation Damage (DDD*)

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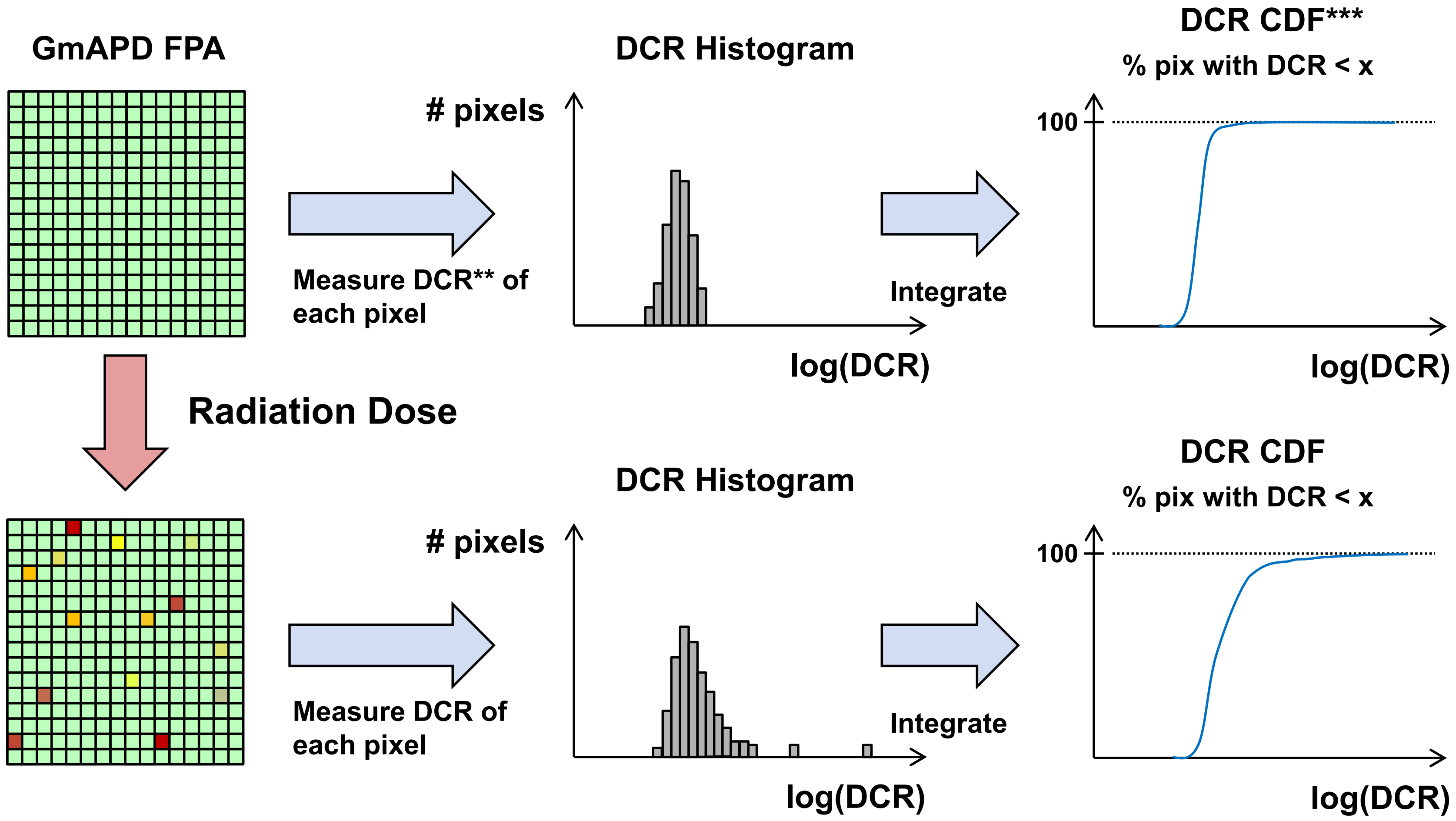

*DDD = Displacement Damage Dose, **DCR = Dark Count Rate, ***CDF = Cumulative Distribution Function

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DDD*-Induced Change to DCR (InP)

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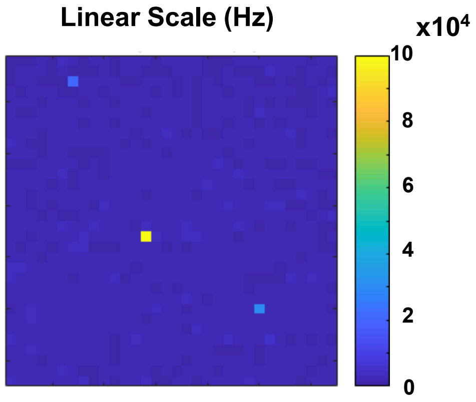
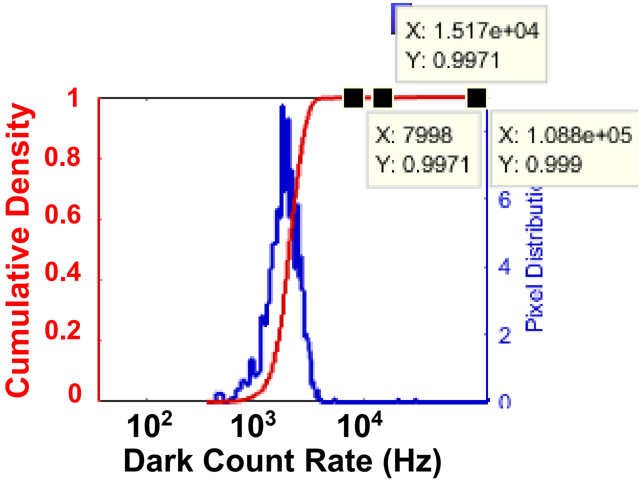
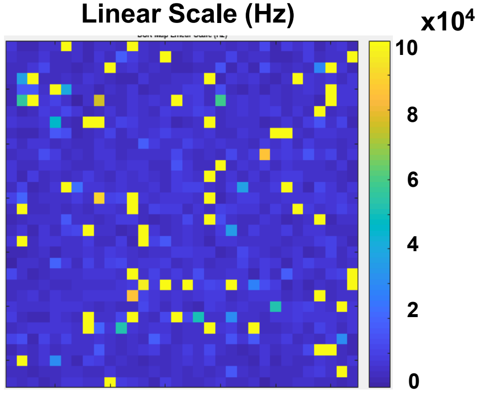
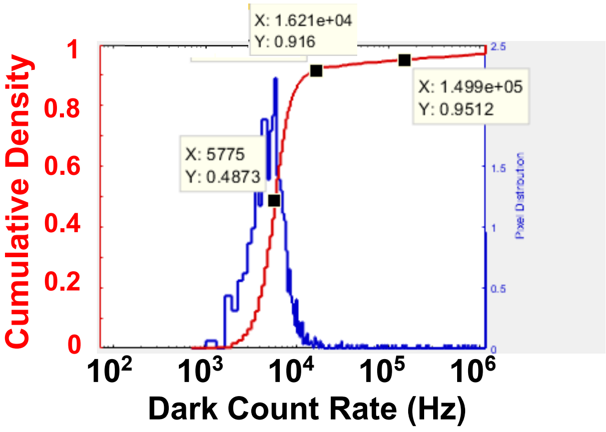
Pre-Dose Pixel DCR Map



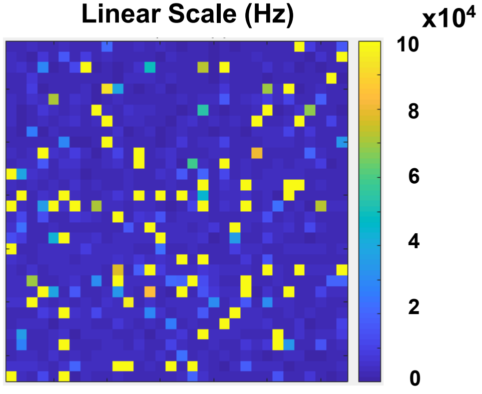


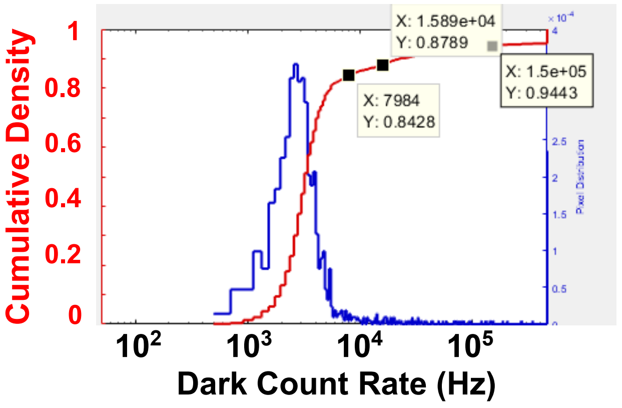
9.4e8 p+/cm^2 of 70MeV protons





2.3e9 p+/cm^2 of 70MeV protons





- **Results are representative (i.e. not the same FPA for all 3 measurements)**

***DDD = Displacement Damage Dose**

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DDD*-Induced Change to DCR (Si)

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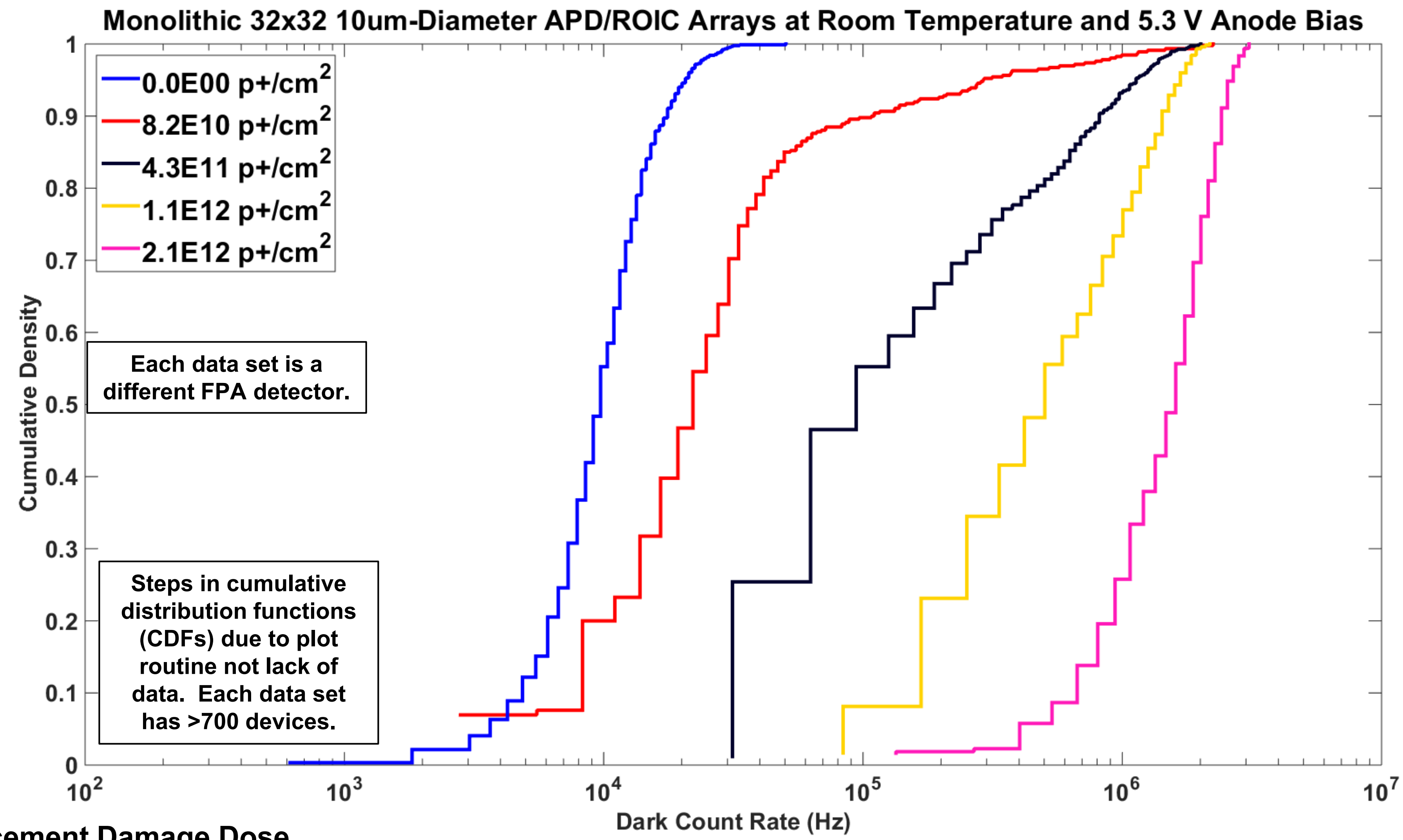

*DDD = Displacement Damage Dose

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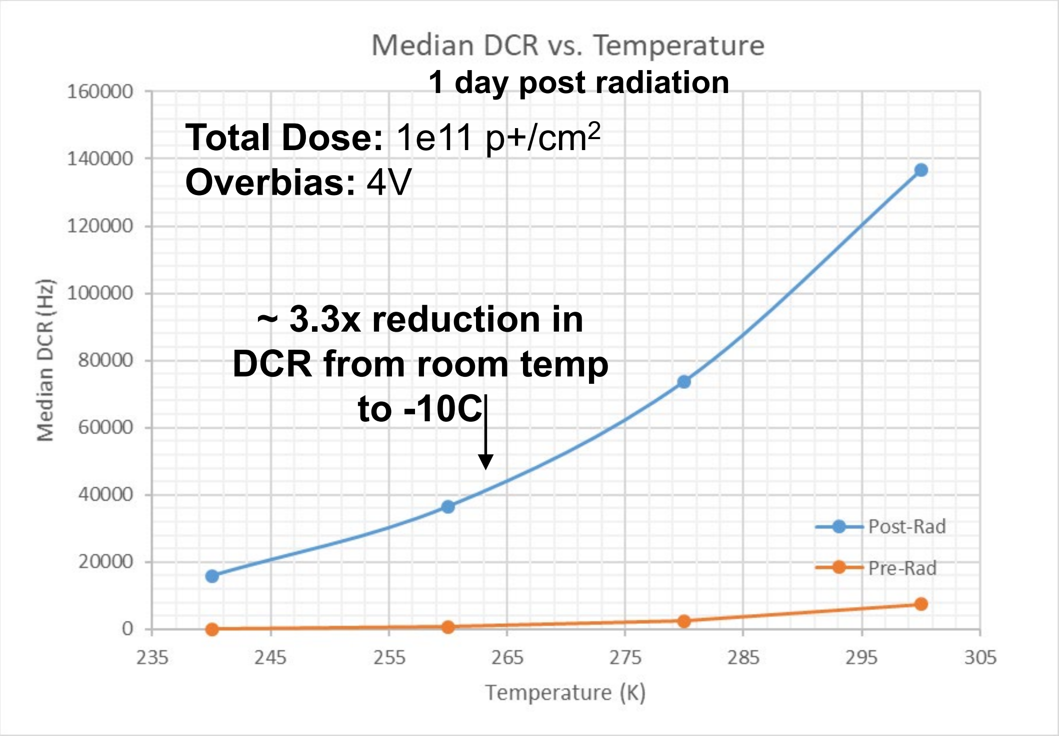
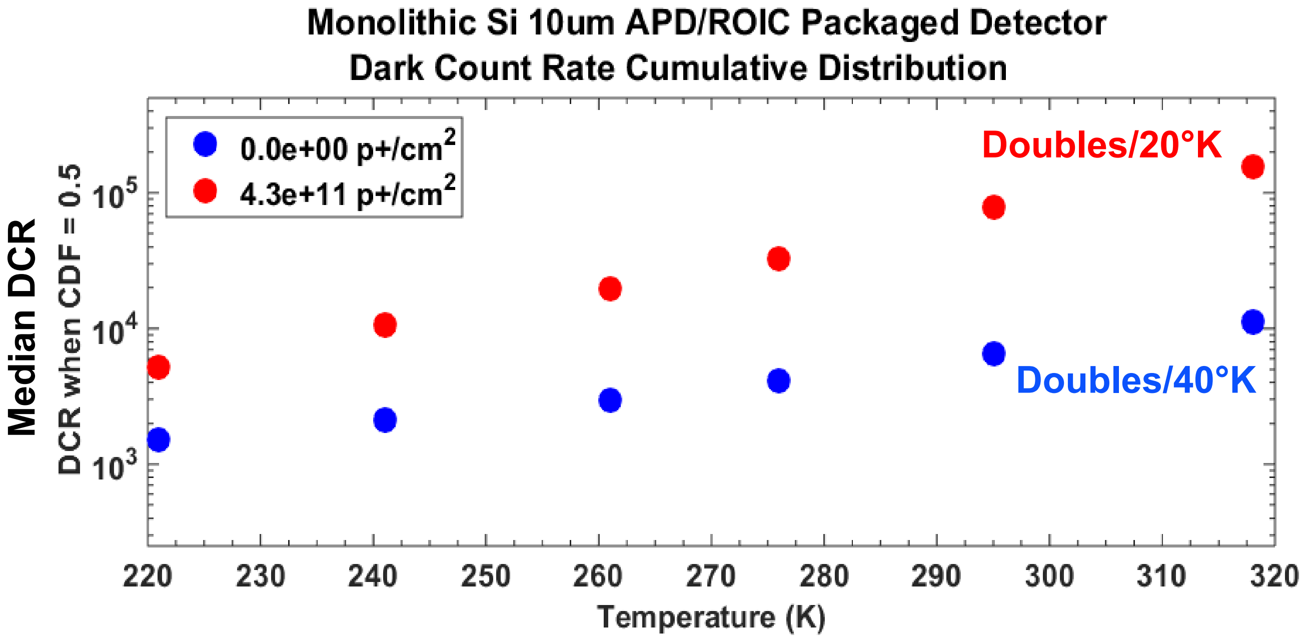
DDD-Induced Median DCR vs. Temperature (Si)

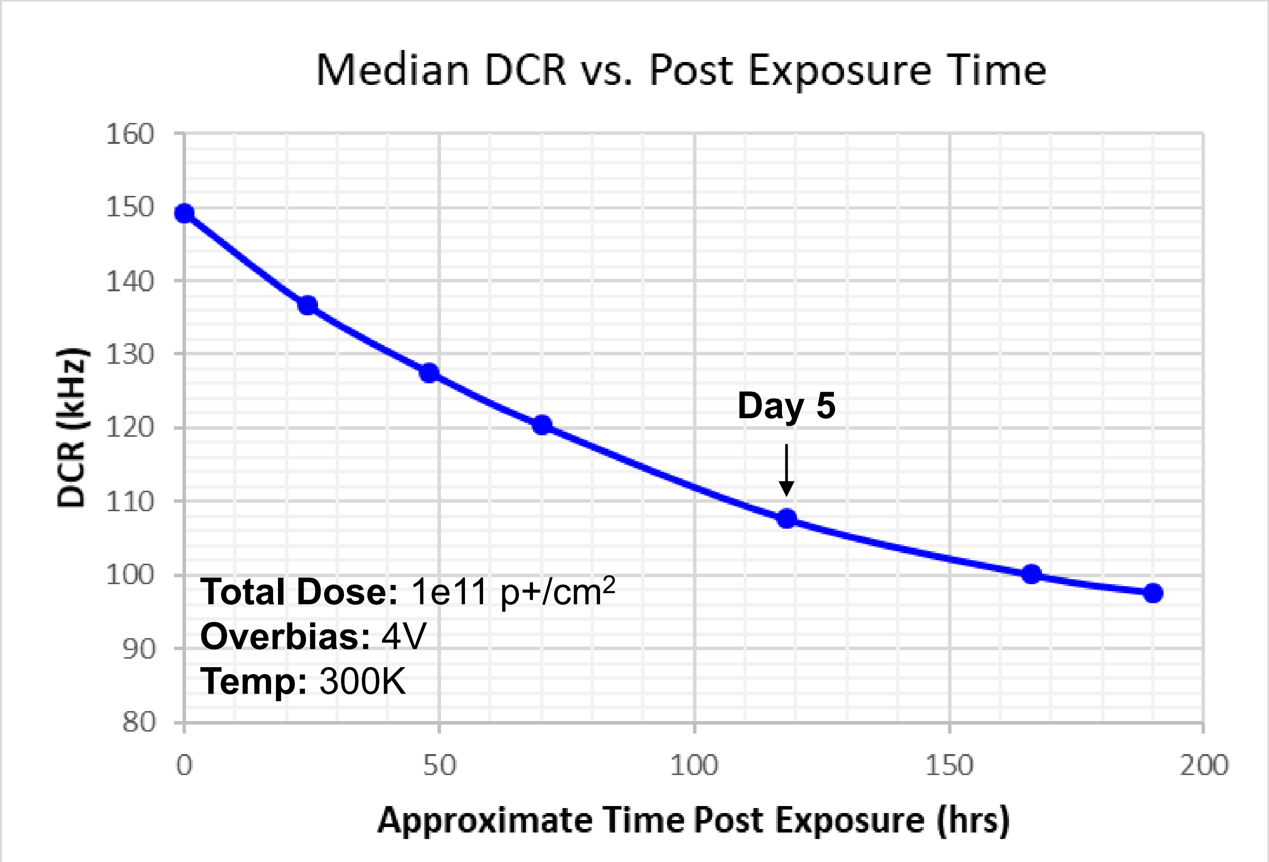




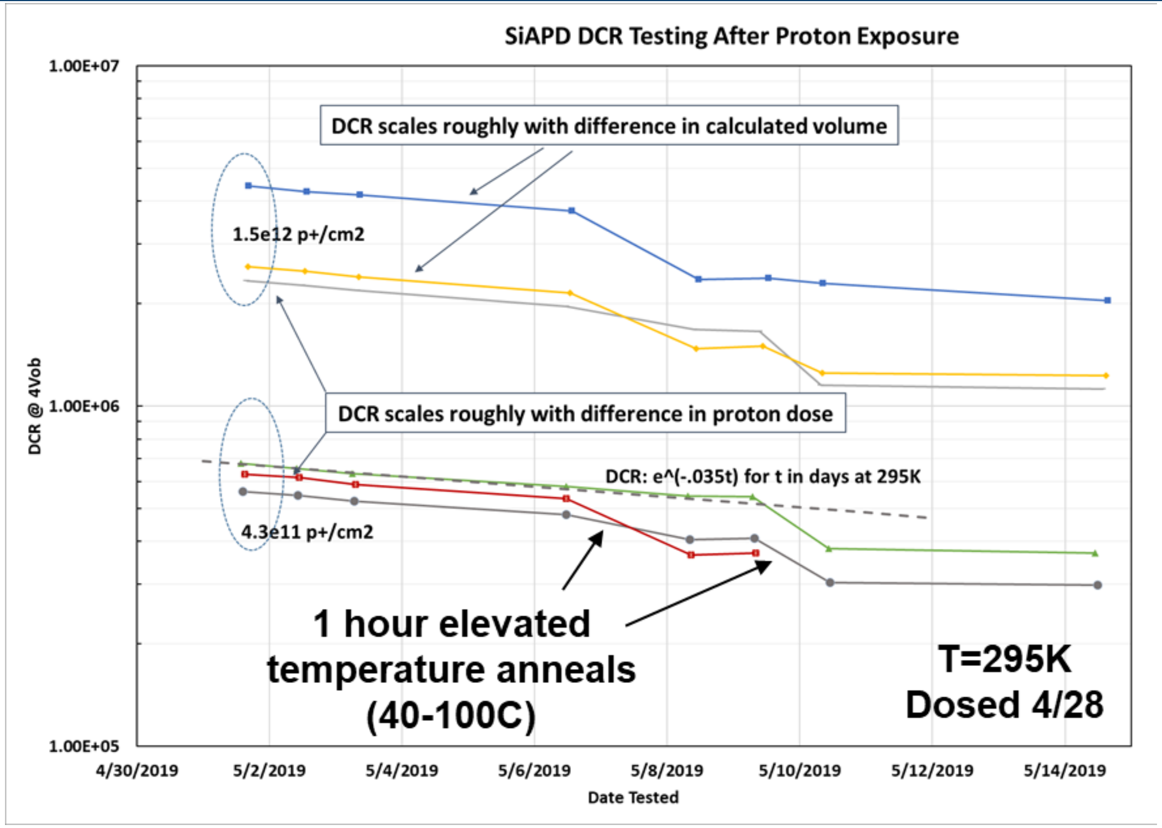
- **Mean dark count rate shown as a function of temperature pre- and post-radiation**
- **Lower temperatures show overall benefit to reduction in dark count rate**
- **Analysis continues to identify cause of change in the slope for measured DCR**

DDD-Induced Median DCR vs. Time (Si)

- **DCR decreases by ~30% over 5 day period**
- **Scaling for temperature on Day 5: ~32kHz DCR @ -10C, ~41kHz DCR @ 0C**



DDD-Induced Median DCR with Anneals (Si)



- Annealing at elevated temperatures shows more than one activation energy
  - e^(-0.031t) to e^(-0.037t), where t is days
- Elevated temperature anneals result in permanent decrease in DCR
  - 1-hour anneal at 100C ~ same as 290 hours at 23C

DDD-Induced DCR vs. SPAD Diameter (Si)

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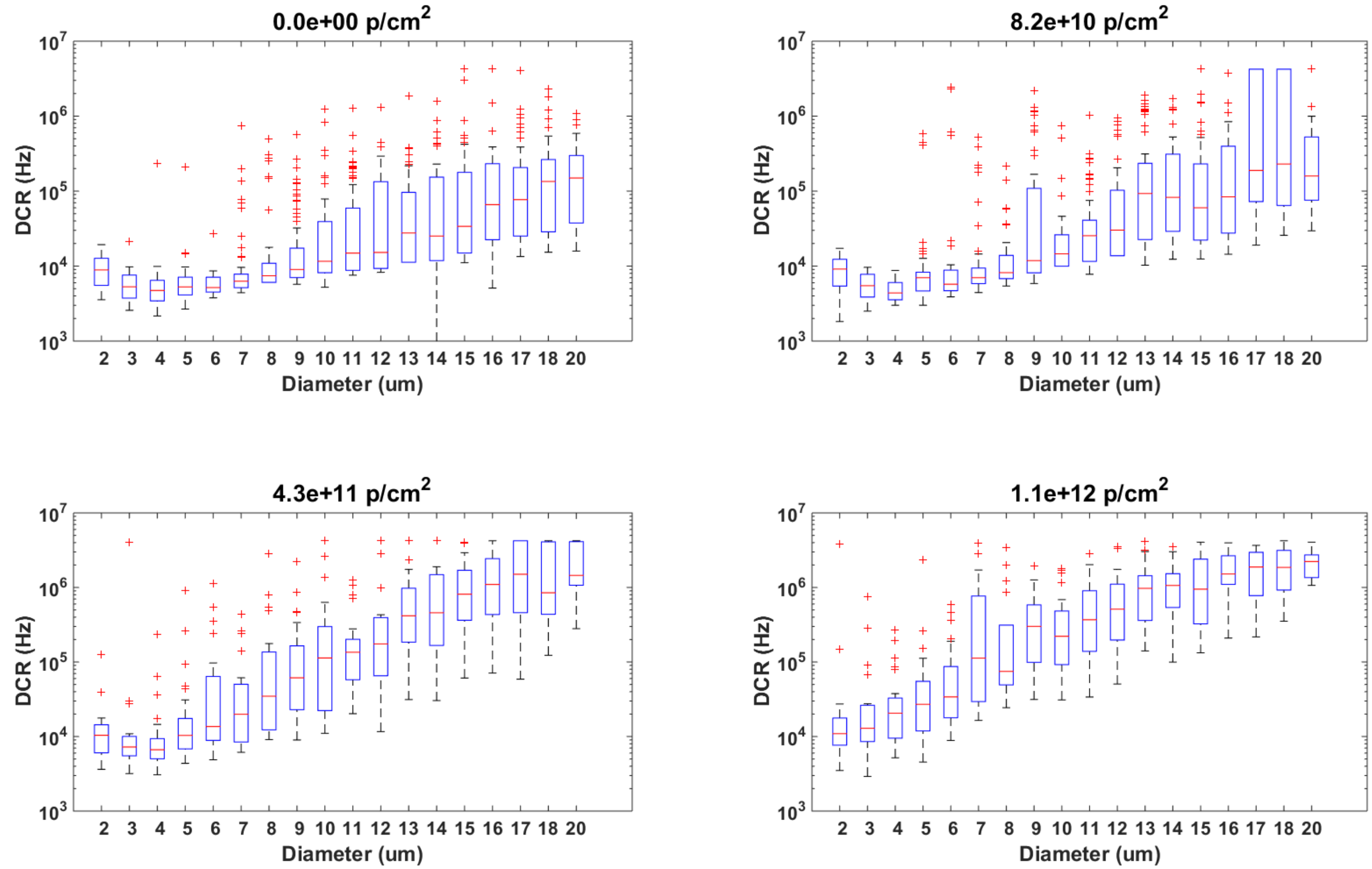

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Live Testing with 70 MeV Protons (Si)

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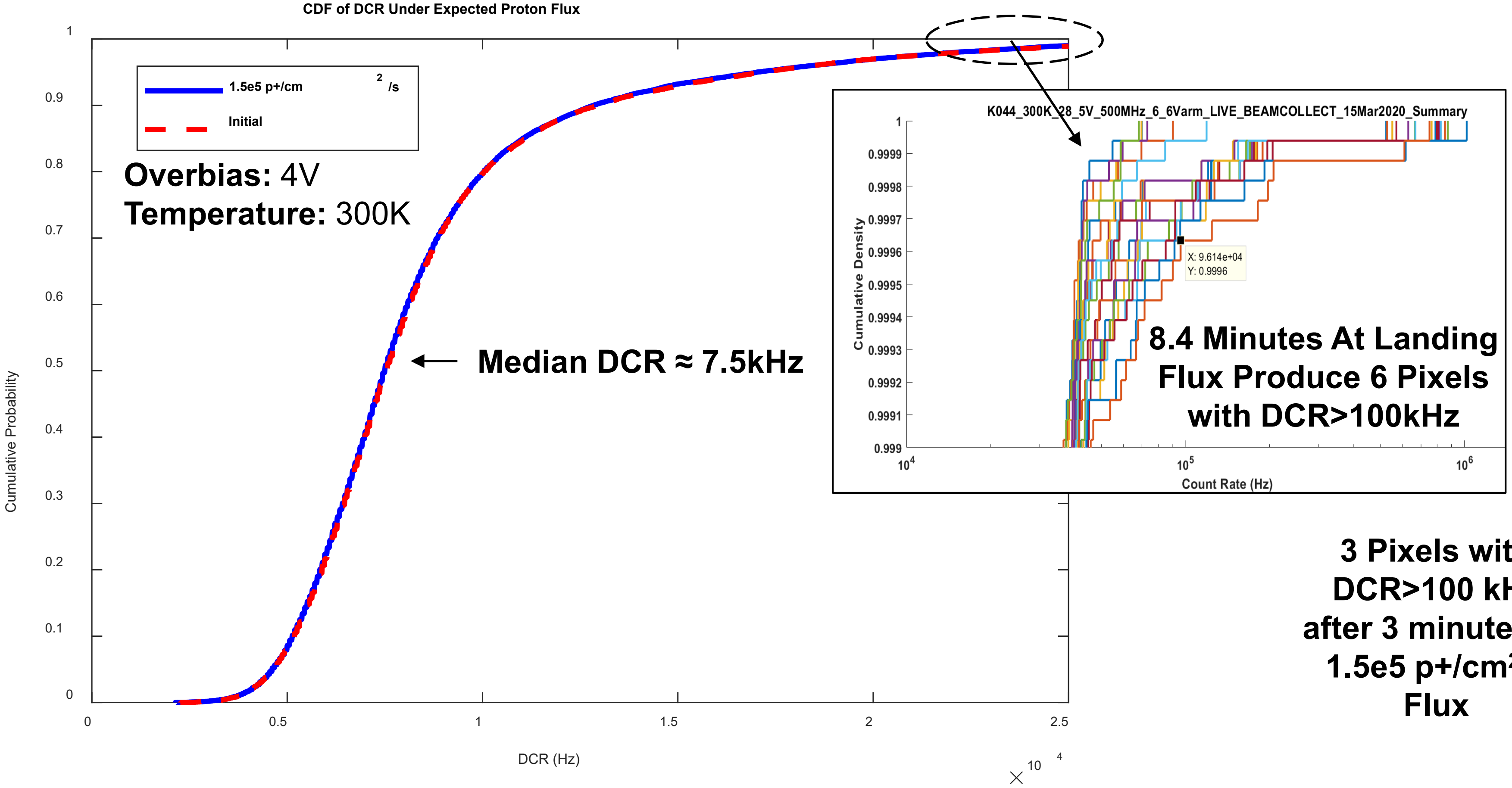
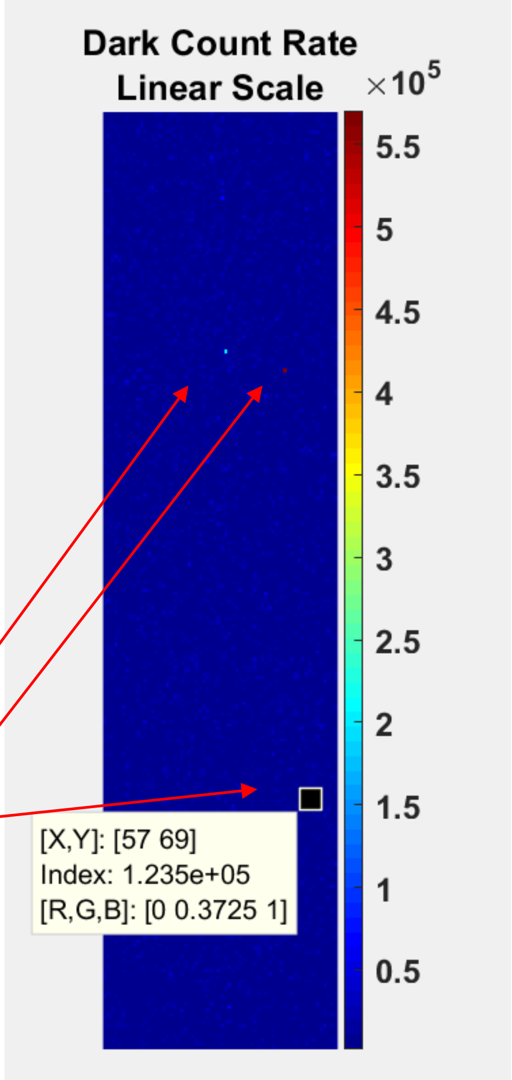
- No Change in median DCR under exposure to target proton flux of 1.5e5 p+/cm²/s
- Proportional increase in # of high-DCR pixels



3 Pixels with DCR>100 kHz after 3 minutes of 1.5e5 p+/cm²/s Flux



*Results shown from testing with low flux prior to total DDD testing

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Microlens Coupling into Small SPADs

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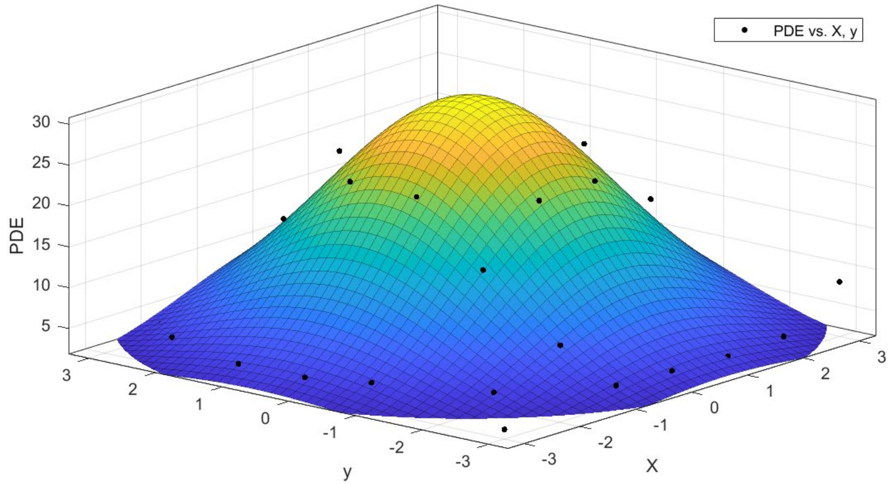
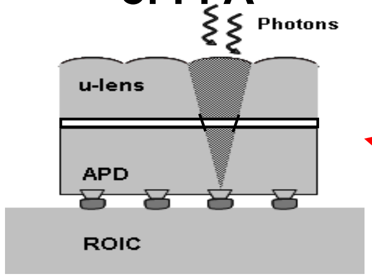
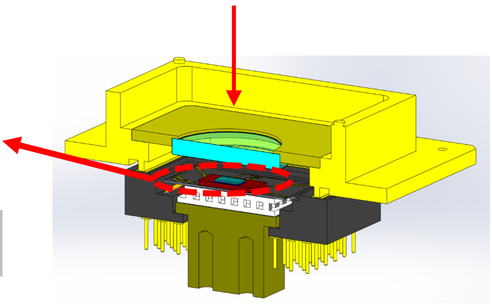
- **Microlenses improve coupling of incident photons into active area**
- **Small diameter active area GmAPDs reduce sensitivity to displacement damage**
  - **Angle of acceptance determined by microlens design and APD diameter**
  - **MLAs are refractive GaP designs**

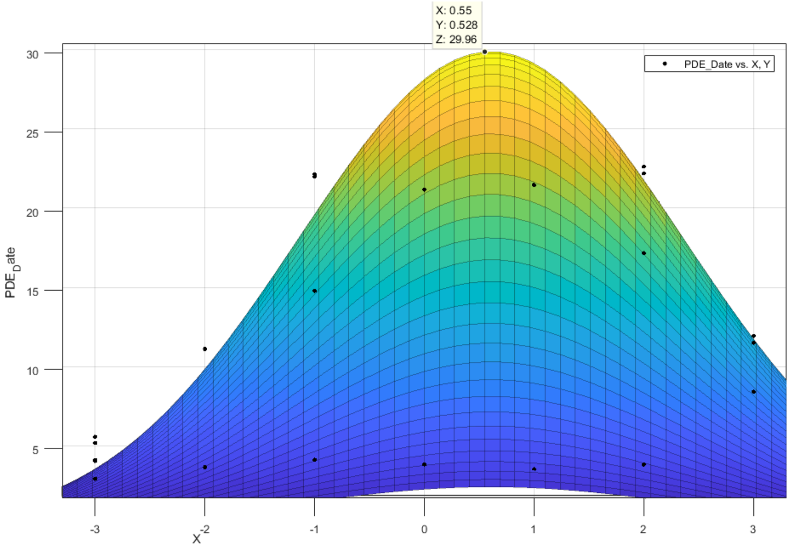


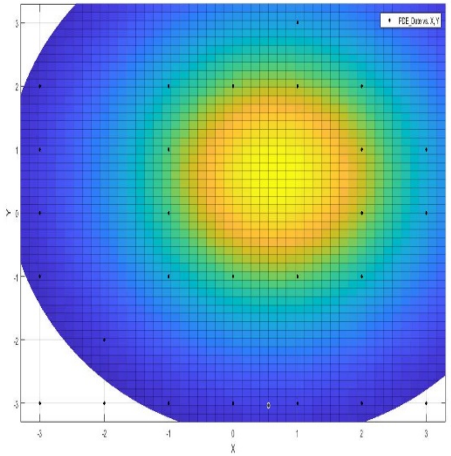
Cross-Section of FPA



Incident Light







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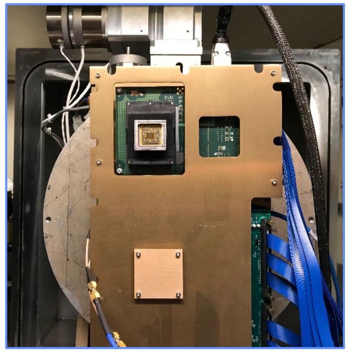
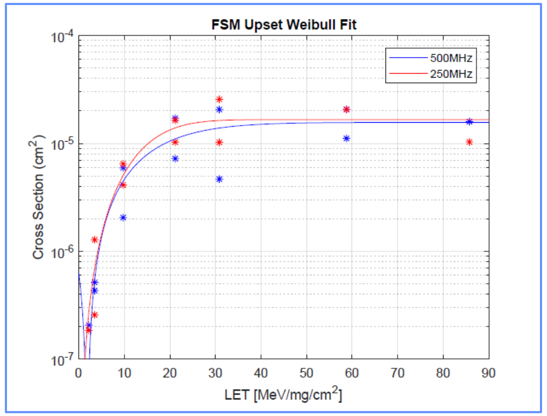
Single Event Effects in ROIC

Device in Test Chamber



Example Weibull Results



Upset Rate Estimates (Per Day)

Environment	Frequency	Fire Map	Timestamp	FSM	Counter
Nominal	500 MHz	2.030×10^{-4}	1.393×10^{-4}	3.119×10^{-5}	3.165×10^{-4}
Nominal	250 MHz	4.801×10^{-4}	1.471×10^{-3}	8.002×10^{-5}	9.482×10^{-5}
5-min. Worst Case	500 MHz	1.968	1.522	2.814×10^{-1}	2.405
5-min. Worst Case	250 MHz	3.788	3.830×10^{2}	3.921	1.031

- **Heavy ion testing of ROICs to simulate SEE from space GCR/heavy ion environment**
- **Upset rates due to SEEs in ROIC determined to be low**
  - **Very low probability of upsets, even in worst case 5 minutes**

Summary

- MIT Lincoln Laboratory has partnered with the Jet Propulsion Laboratory to explore space-qualification GmAPD-based imagers
- In a space environment, the radiation effects primarily impacting GmAPD-based cameras are:
  - Displacement damage resulting in increased per-pixel DCR as a function of environment and lifetime
  - Single event effects impacting the custom readout integrated circuit (ROIC)
- A trade space of semiconductor, APD size, and temperature determine end-of-life performance and can be used to optimize performance for different requirements