# RADIATION TESTING TUTORIAL

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**NASA Goddard Space Flight Center**

# ACRONYMS

- A/D - Analog-to-Digital
- BiCMOS - Bipolar Complementary Metal-Oxide-Semiconductor
- BJT - Bipolar Junction Transistor
- BNL - Brookhaven National Laboratory
- CMOS - Complementary Metal-Oxide-Semiconductor
- CRÈME - Cosmic Ray Effects on Micro-Electronics
- D/A - Digital-to-Analog
- DDD - Displacement Damage Dose
- EDAC - Error Detection And Correction
- EEEE - Electrical, Electronic, Electromechanical, and Electro-optical
- FIT - Failures In Time
- FPGA - Field Programmable Gate Array
- GaN - Gallium Nitride
- GCR - Galactic Cosmic Rays
- GSFC - Goddard Space Flight Center
- GPU - Graphics Processing Unit
- GUI - Graphical User Interface
- HEMT - High Electron Mobility Transistor
- IEEE - Institute of Electrical and Electronics Engineers
- JFET - Junction Field-Effect Transistor
- JPL - Jet Propulsion Laboratory
- LBNL - Lawrence Berkeley National Laboratory
- LET - Linear Energy Transfer
- MBU - Multiple Bit Upset
- MOSFET - Metal-Oxide-Semiconductor Field-Effect Transistor
- MRED - Monte Carlo Radiative Energy Deposition
- MSU - Michigan State University
- NASA - National Aeronautics and Space Administration
- NRL - Naval Research Lab
- NSREC – Nuclear & Space Radiation Effects Conference
- NSRL - NASA Space Radiation Laboratory
- PEASA - Power Electronics for Aerospace Applications
- REAG - Radiation Effects and Analysis Group
- REDW - Radiation Effects Data Workshop
- RF - Radio Frequency
- SDRAM - Synchronous Dynamic Random Access Memory
- SEB - Single Event Burnout
- SEDR - Single Event Dielectric Rupture
- SEE - Single Event Effects
- SEECA - Single Event Effects Criticality Analysis
- SEFI - Single Event Functional Interrupt
- SEGR - Single Event Gate Rupture
- SEL - Single Event Latchup
- SELC - Single Event Leakage Current
- SET - Single Event Transient
- SEU - Single Event Upset
- SHE - Single Hard Error
- Si - Silicon
- SiC - Silicon Carbide
- SOA - Safe Operating Area
- SPENVIS - Space Environment Information System
- SPE - Solar Particle Events
- SPICE - Simulation Program with Integrated Circuit Emphasis
- SRIM - Stopping and Range of Ions in Matter
- TAMU - Texas A&M University
- TCAD - Technology Computer-Aided Design
- TID - Total Ionizing Dose
- TNS - Transactions on Nuclear Science
- WBG - Wide Bandgap

# OVERVIEW

- **Types of Radiation Testing**
  - TID
  - SEE
  - DDD
- **Device Types**
  - Complex Devices
  - Memories
  - POWER DEVICES!!!
- **Test Setup**
  - Facility
  - Device Prep
  - Test Board
  - Control Equipment
  - Software
- **Simulations**
  - Environment
  - Transport
- **Data Analysis & Reporting**
  - SEE TH
  - Cross Sections and Rates
  - Mitigations
  - Databases
  - Restrictions

# LOGISTICS

- Question break after each section
- Will cover some general cases, so please take statements as widely applicable but not exhaustive
- Covering EEEE parts more broadly; will try to add emphasis on power devices given the audience
- May bounce you to coworkers for complex device help
- There are so many more device types and scenarios not covered here: optical components, charging, detectors, solar arrays…and so on

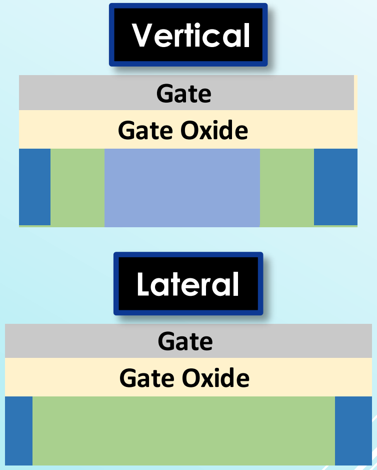
# TOTAL IONIZING DOSE (TID)

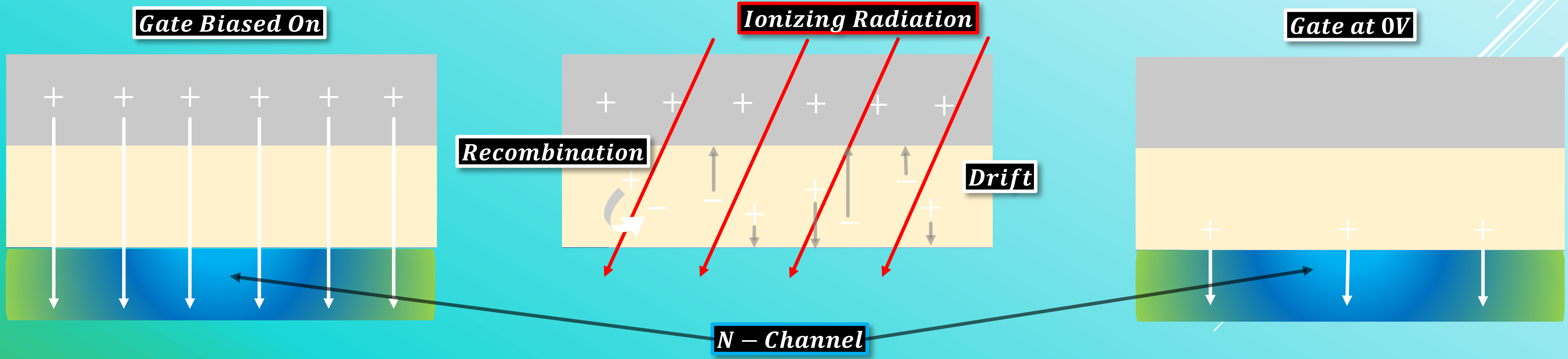
- Caused by ionizing radiation passing through a material
  - Can be photons, protons, neutrons, heavy ions, etc…
- Dose is reported in units of energy deposited per gram
  - 1 rad = 1 Joule/kg
  - 1 Gy = 100 rad
  - Space flight missions are often measured in krad
- This is target material specific, so usually for EEEE parts we are working in units of krad [Si]

# TOTAL IONIZING DOSE (TID)

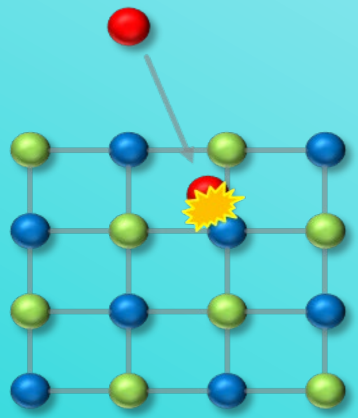
- Ionizing radiation creates charge in the oxide layer
- Bias conditions allow for charge drift
- Negative charges are moved towards the positively biased gate and swept out
- Accumulation of trapped positive charge (holes) in the oxide layer
    - Cumulative Effect
- Gate threshold voltage will shift downward towards zero as charge accumulates

- Power devices have thick oxides
- No gate oxide in diodes or HEMTs
- Extreme dose starts to introduce materials issues (>~Mrads)

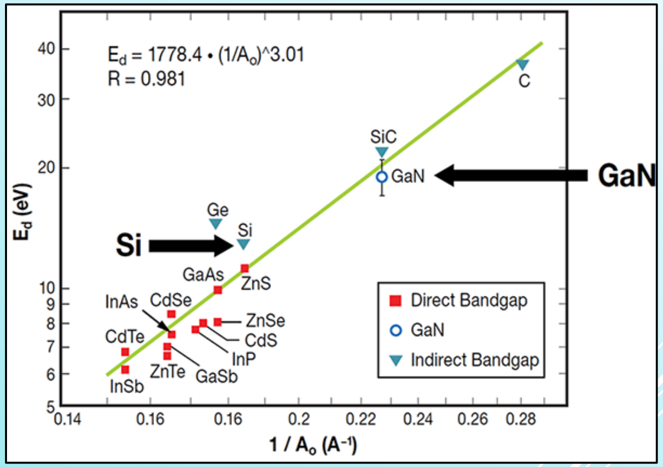


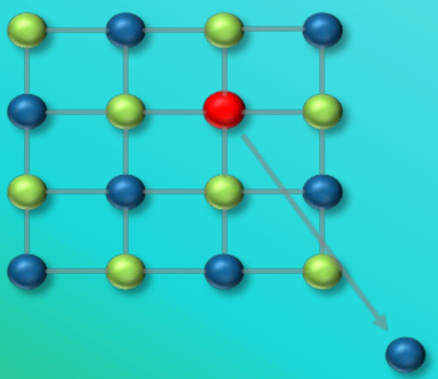
# DISPLACEMENT DAMAGE DOSE (DDD)

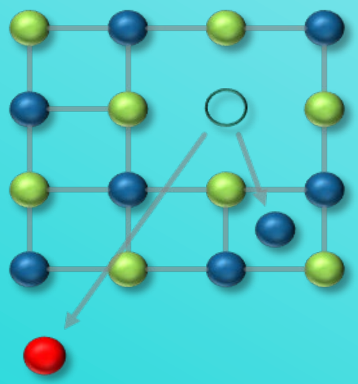


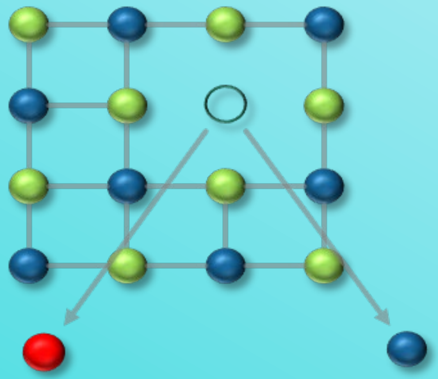
- Displacement of atoms from the lattice
  - Vacancies, interstitials, Frenkel Pairs
- Primarily from Protons and Neutrons
- Cumulative Effect
- Units: MeV/g [Si]
- Parametric shifts as you change the properties of the semiconductor
- Are WBG technologies inherently “rad-hard”?

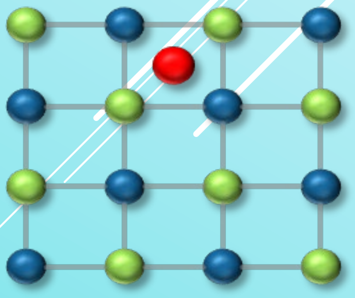



[1] A. Lidow, GaN Talk Blog 2020









# SINGLE EVENT EFFECTS (SEE)

- **Potentially destructive**
  - SEL: loss of device functionality due to a single-event-induced high current state
    - EEEE components with bulk CMOS/BiCMOS
  - SEB: possible device destruction caused by positive current feedback in the drain or collector region, initiated by a single-event
    - Power bipolar transistors, diodes, HEMTs, and power MOSFETs
  - SEGR: possible device destruction due to a high-current state in the gate oxide that can lead to thermal breakdown, initiated by a single ion passing through the gate oxide
    - Power MOSFETs, DC/DC converters, point-of-loads
  - SELC: Ion induced gate-drain or drain-source leakage current caused by a single ion but individual cases add cumulatively
    - Power devices, more typical in newer technologies
  - SHE: a single-event that causes a permanent change to the operation of the device – i.e., a stuck bit

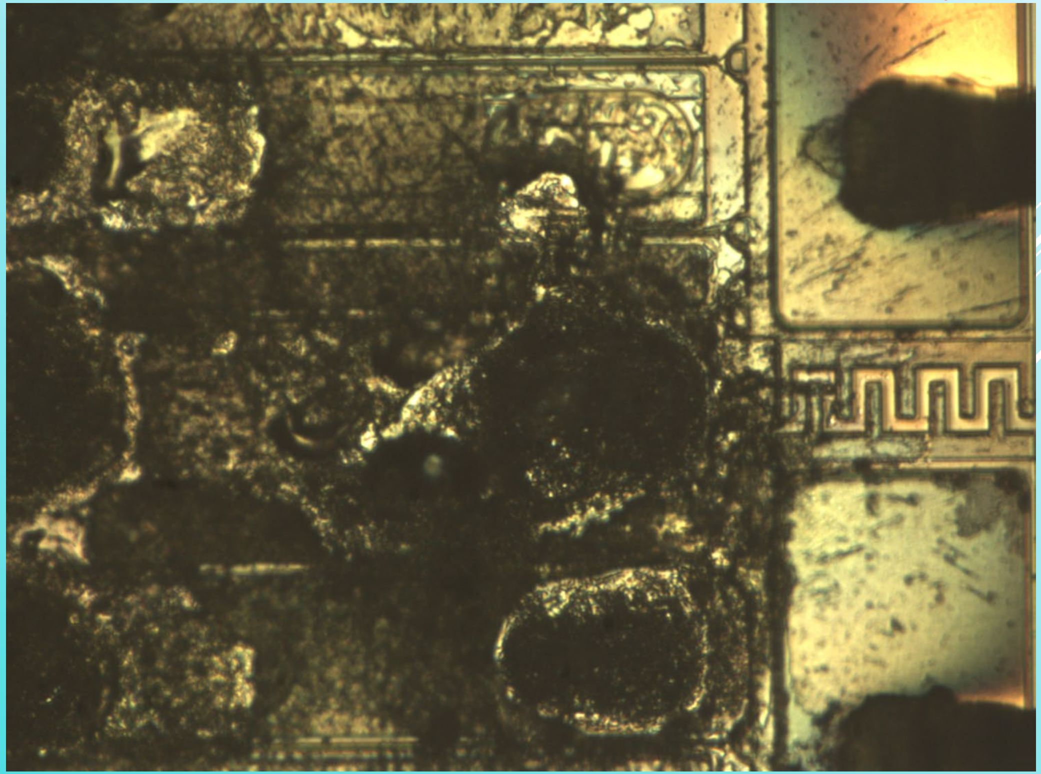
# SINGLE EVENT EFFECTS (SEE)

- **Non-destructive**
  - SEU: a change of state induced by an energetic particle that may occur in digital, analog, and optical components, i.e. a bit flip
  - MBU: an event induced by a single energetic particle such as a cosmic ray or trapped proton that causes multiple upsets or transients during its path through a device or system
  - SET: a brief fluctuation in an analog or digital signal, which may cause data corruption if captured, misbehavior on a critical circuit node, or even damaging effects if amplified and transmitted into a sensitive component downstream
  - SEFI: An interruption in component function or a misconfigured state caused by a single-event upset or transient in a complex component's control functions. SEFI may be recoverable by some combination of reconfiguration, reprogramming, or power cycling depending on the part. Primarily affects components with control logic/registers.
    - SDRAM, Flash, A/D converter, D/A converter, processors

# SINGLE EVENT BURNOUT (SEB)

- Catastrophic failure, Drain-Source Short
- Influenced by ion LET and $V_{DS}$
- Diodes, MOSFET, JFETs, HEMTS, etc…

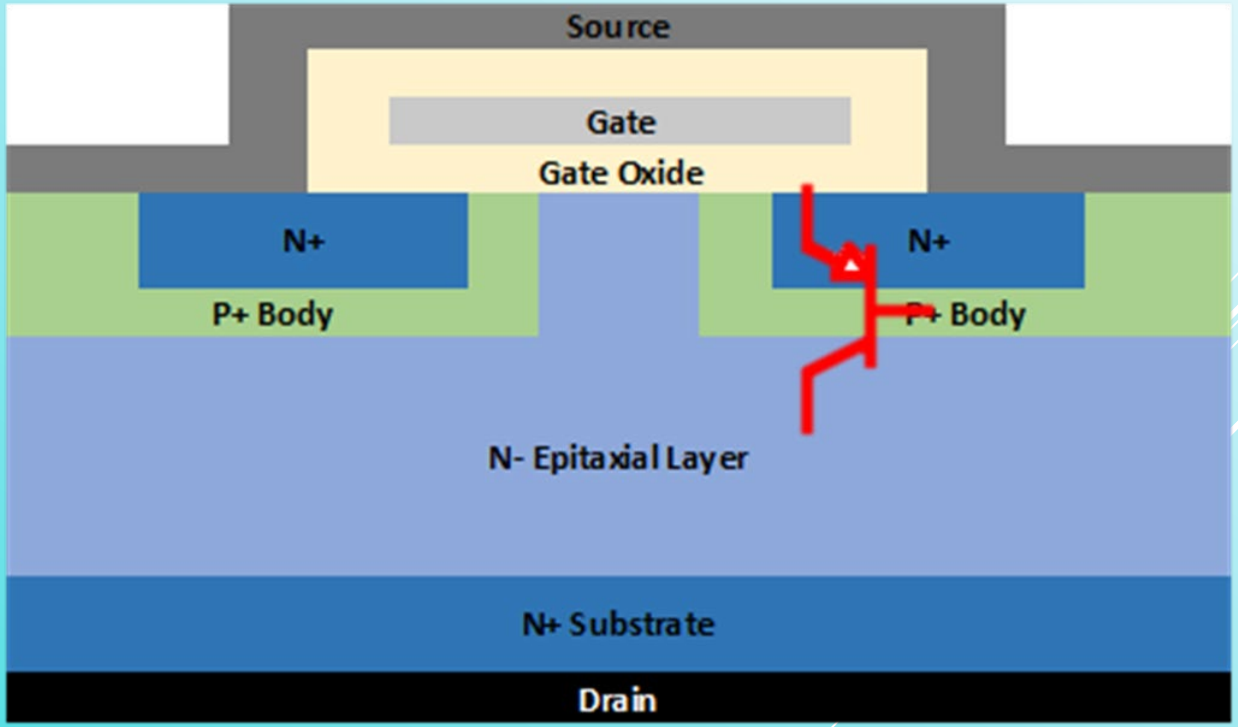
**Laser induced SEB @ NRL!**



# SEB IN SI VS. WBG DEVICES

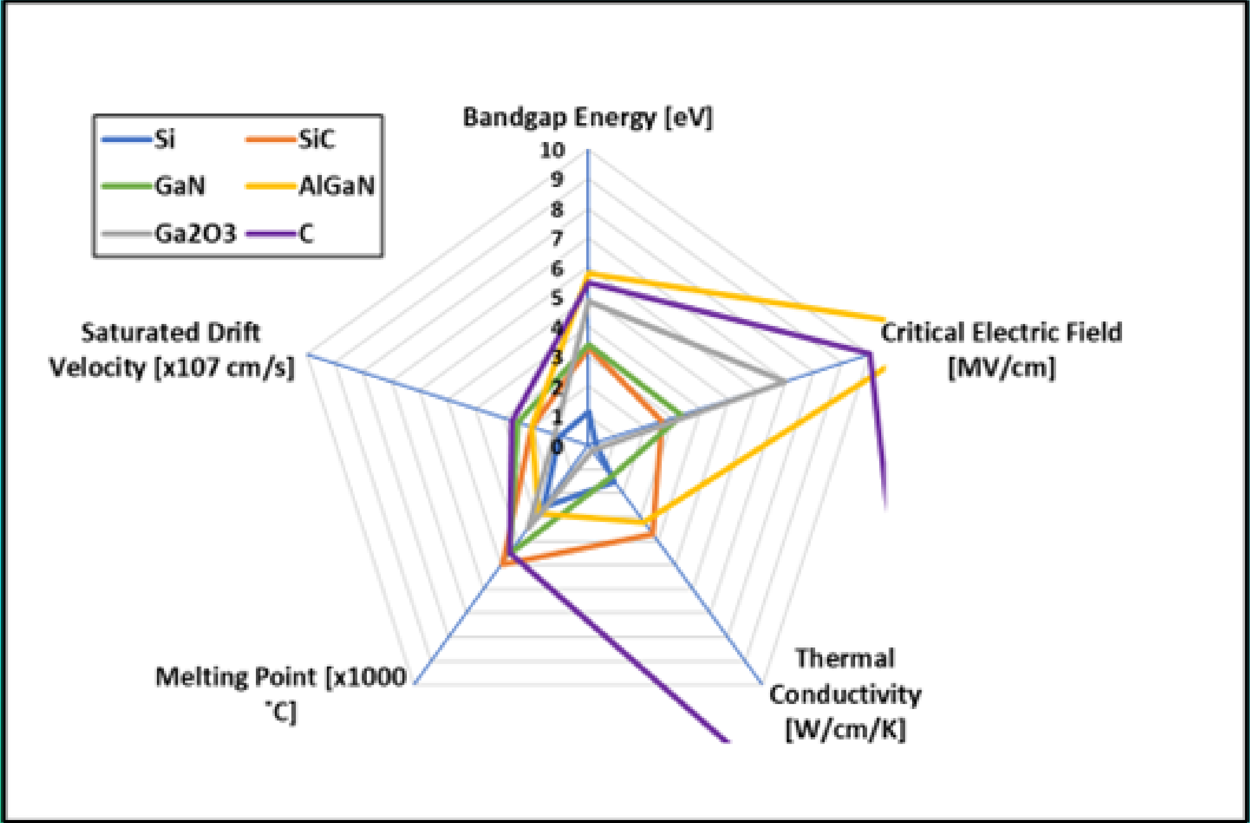
- Parasitic BJT formed by N-well, P-Body and N-Epi layer
- Ionization causes BJT to turn ON due to charge in the body region, resulting in current flow from drain to source
- Positive feedback loop
- Angle, strike location, and penetration depth need to be considered to ensure worst-case test conditions are used

Si MOSFET

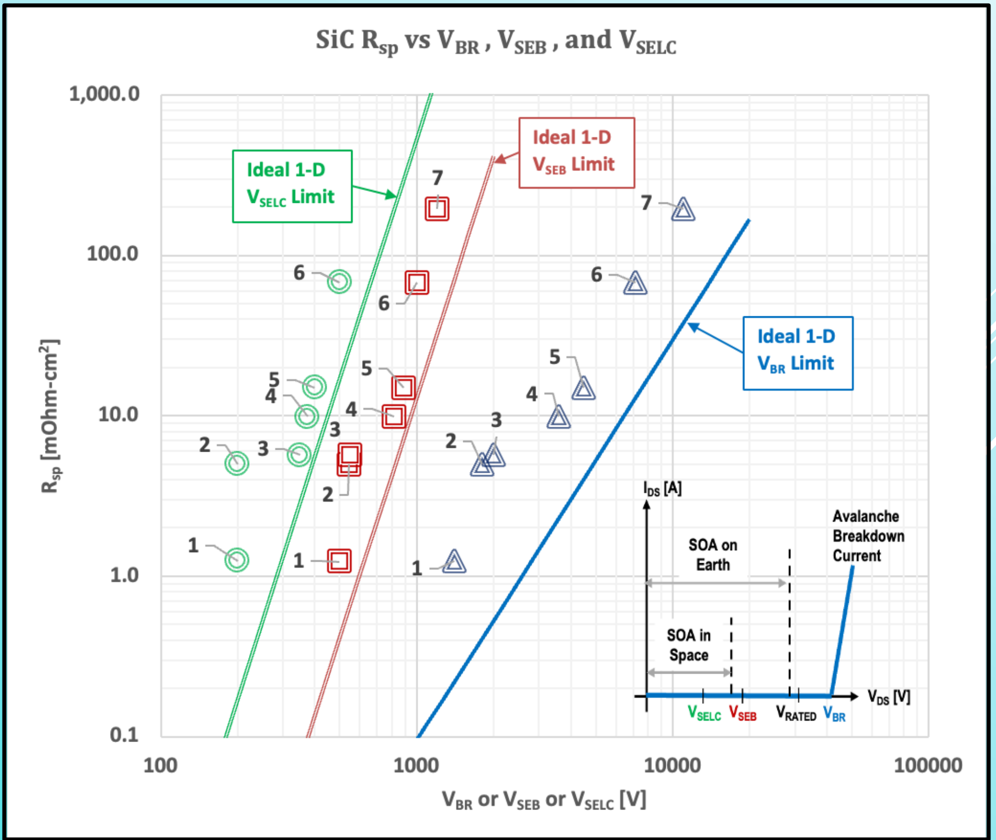


# SEB IN SI VS. WBG DEVICES

- Higher field gradients



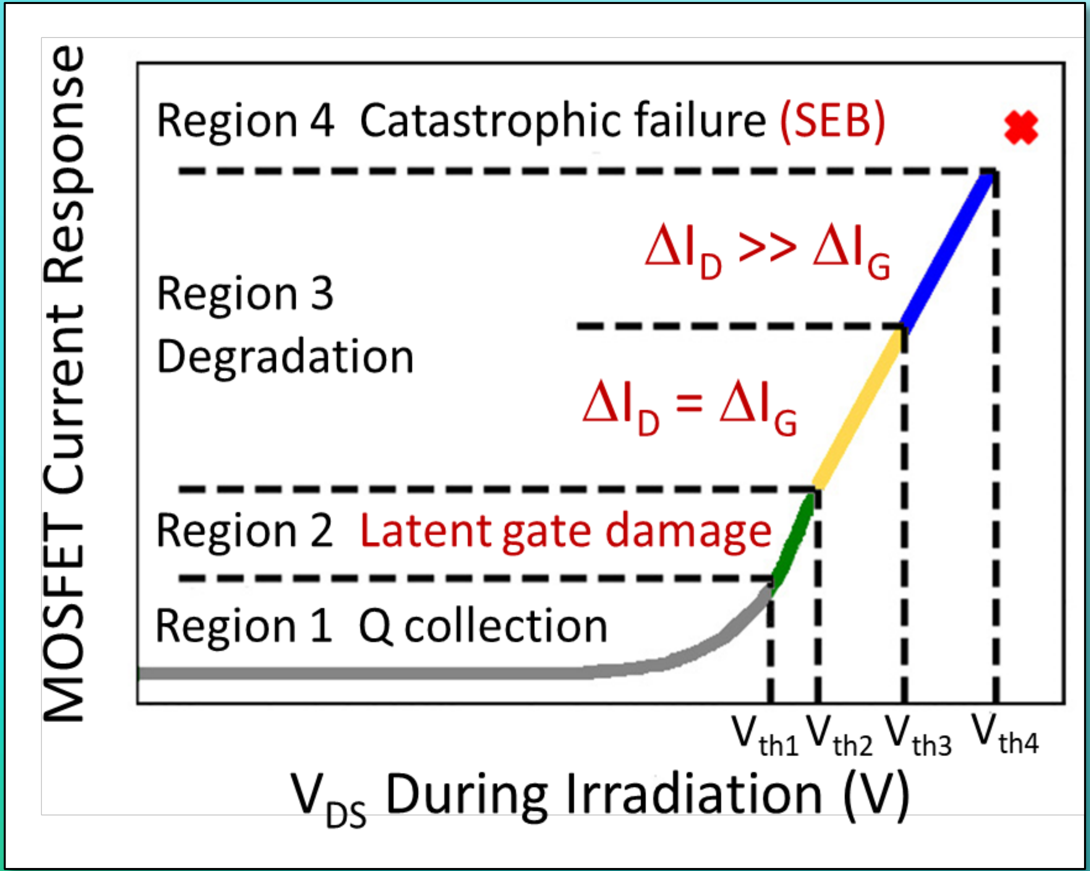

- More direct breakdown - Kosier critical energy model

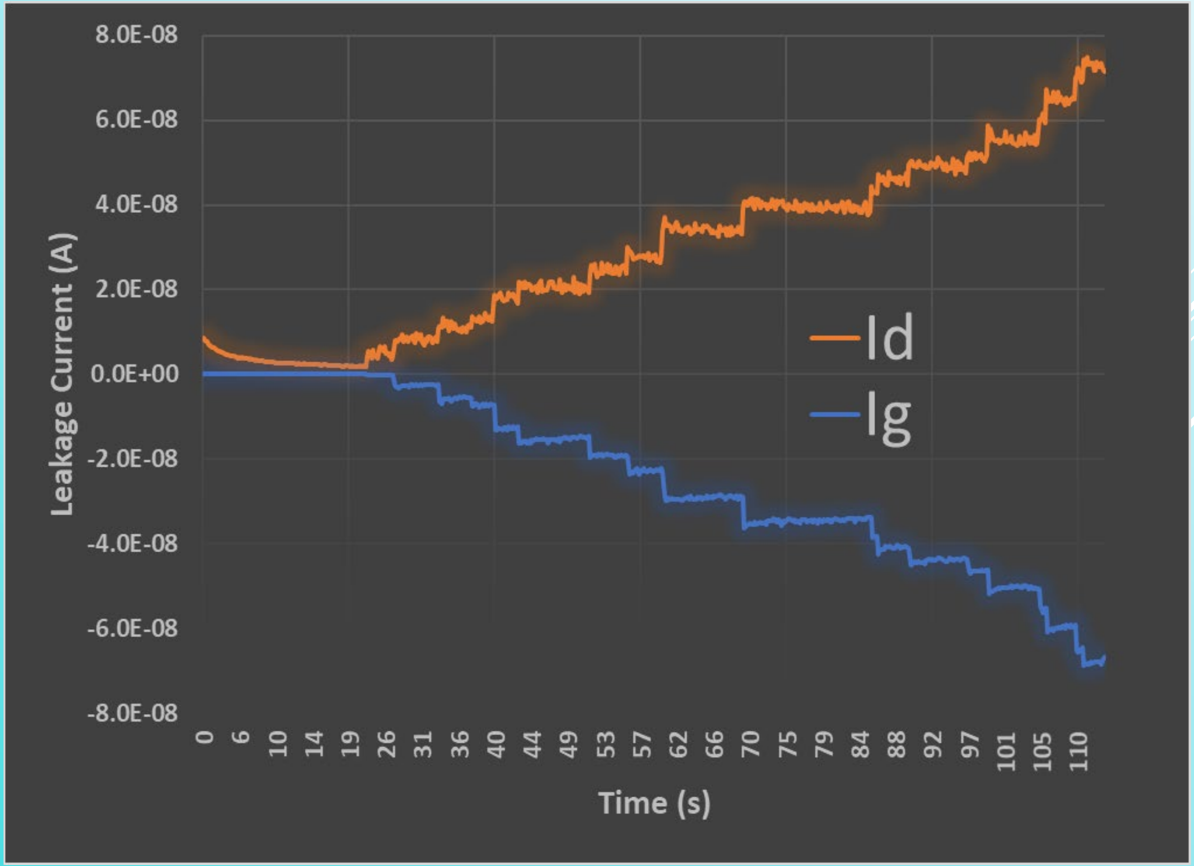



[2] S. L. Kosier, *IEEE TDMR 2026*

# SINGLE EVENT LEAKAGE CURRENT (SELC)

## Distinct regions caused by a single ion (SEE), but can be treated as a cumulative effect



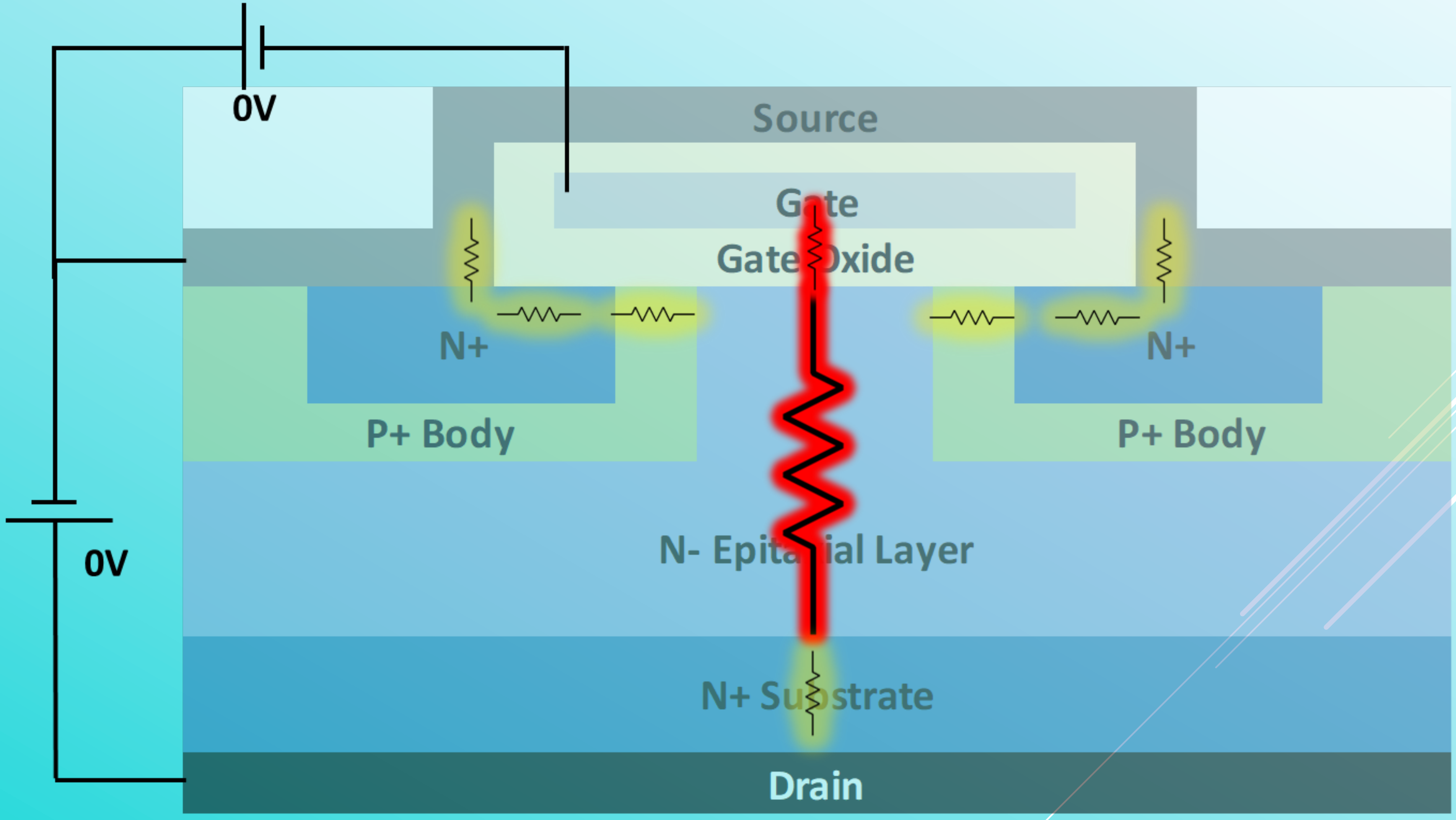




[3] J. -M. Lauenstein, IEEE IRPS 2021, Adapted form [4] C. Martinella, IEEE TNS 2020

# SINGLE EVENT GATE RUPTURE (SEGR)

- Catastrophic failure, destruction of gate oxide
- Influenced by ion LET, $V_{DS,}$ and $V_{GS}$
- Doesn't occur in diodes and HEMTs - no gate oxide
  - Single Event Dielectric Rupture (SEDR)
- Like SEB we need to employ worst-case angle, strike location, penetration depth etc.

# SINGLE EVENT GATE RUPTURE (SEGR)




- Gate oxide
- Epi layer

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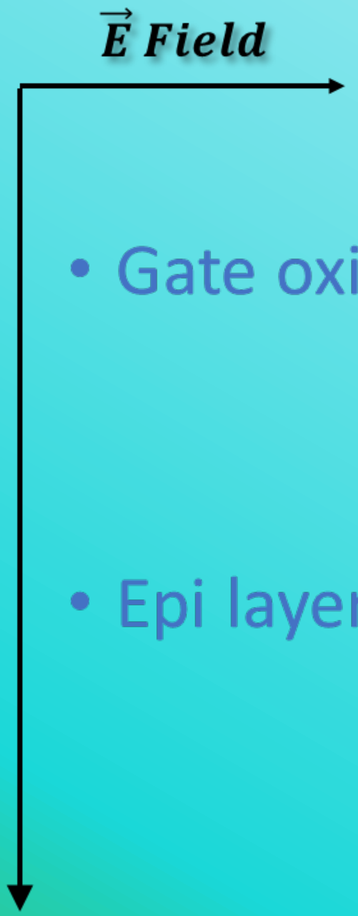


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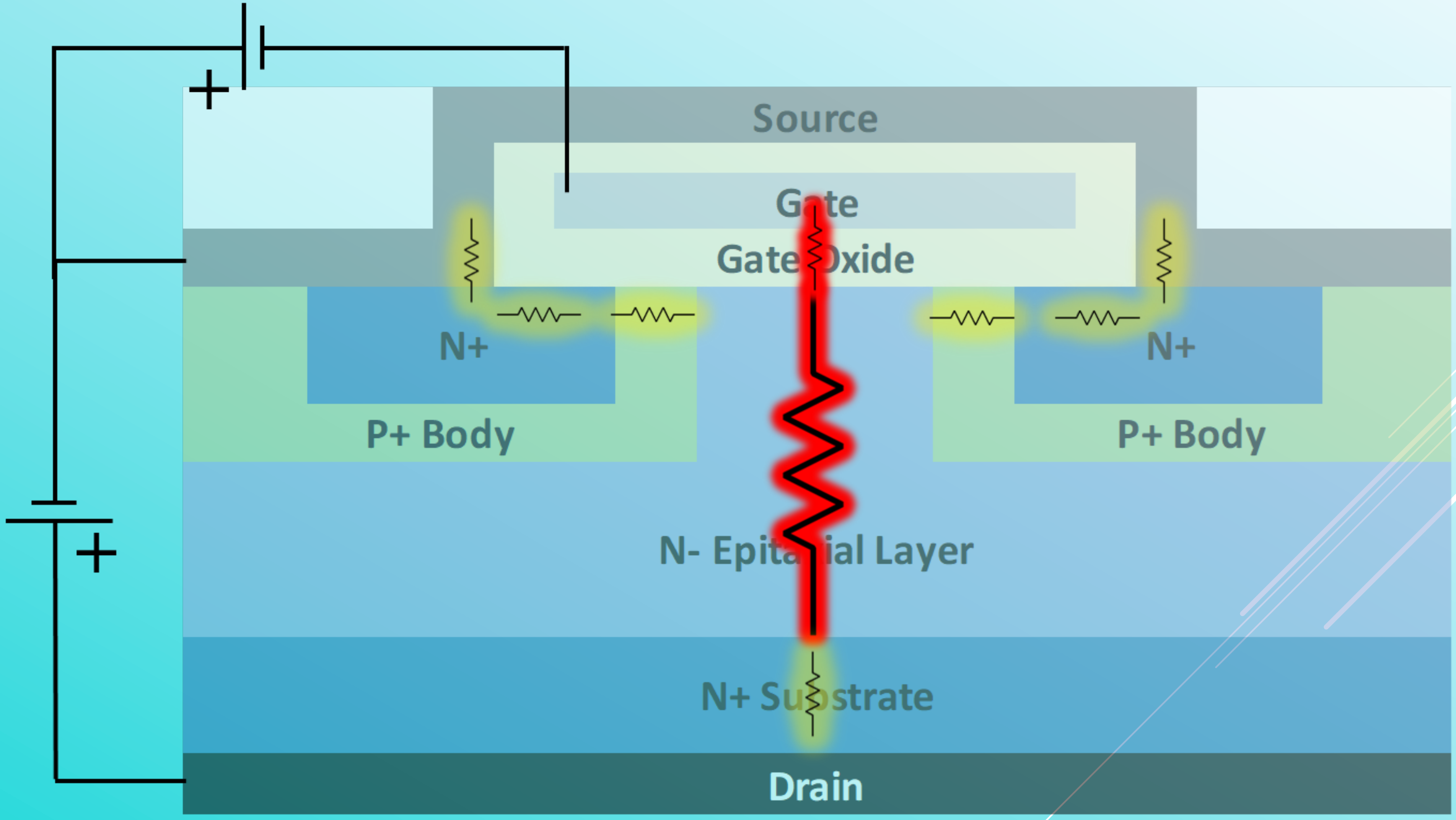
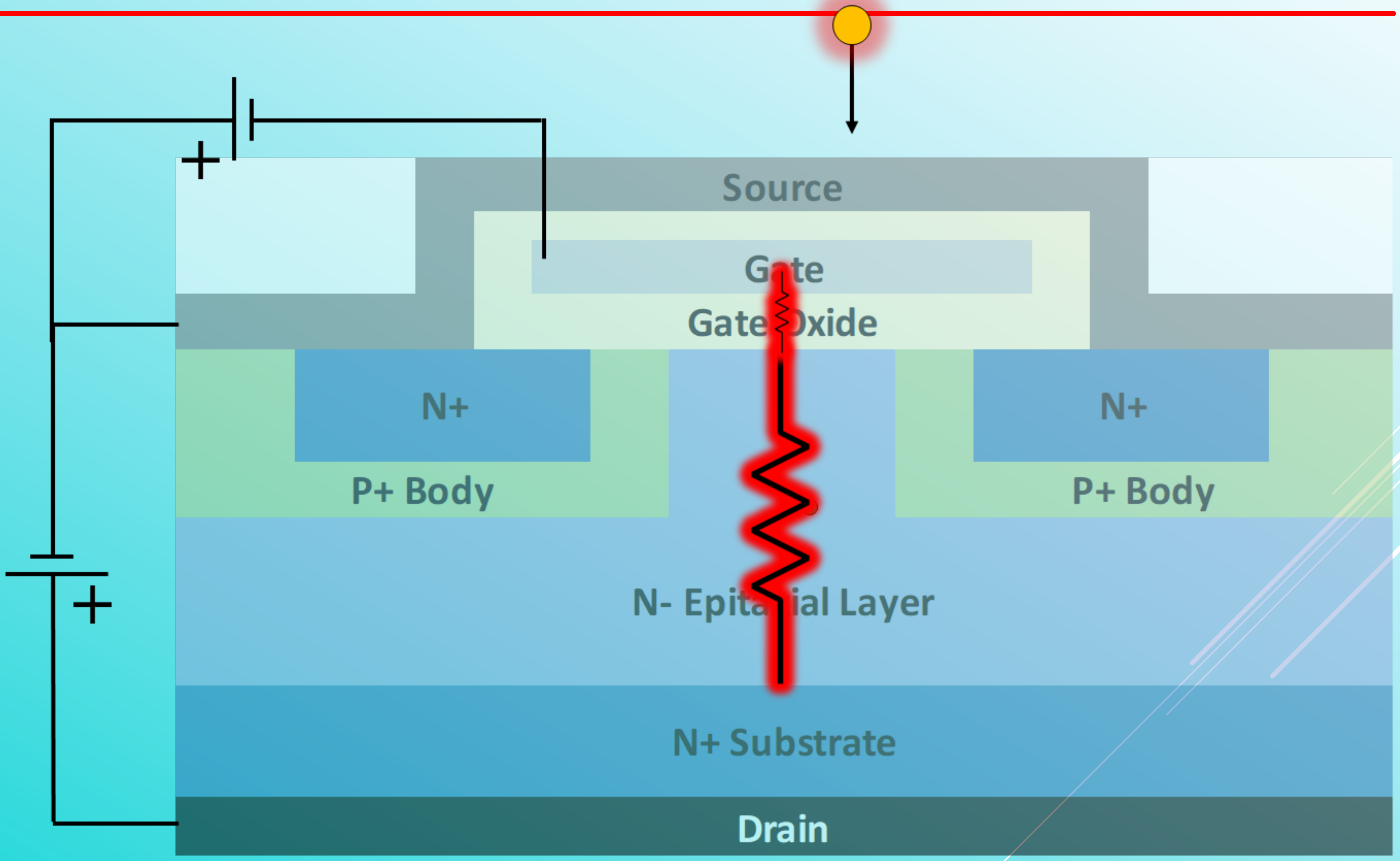


# SINGLE EVENT GATE RUPTURE (SEGR)

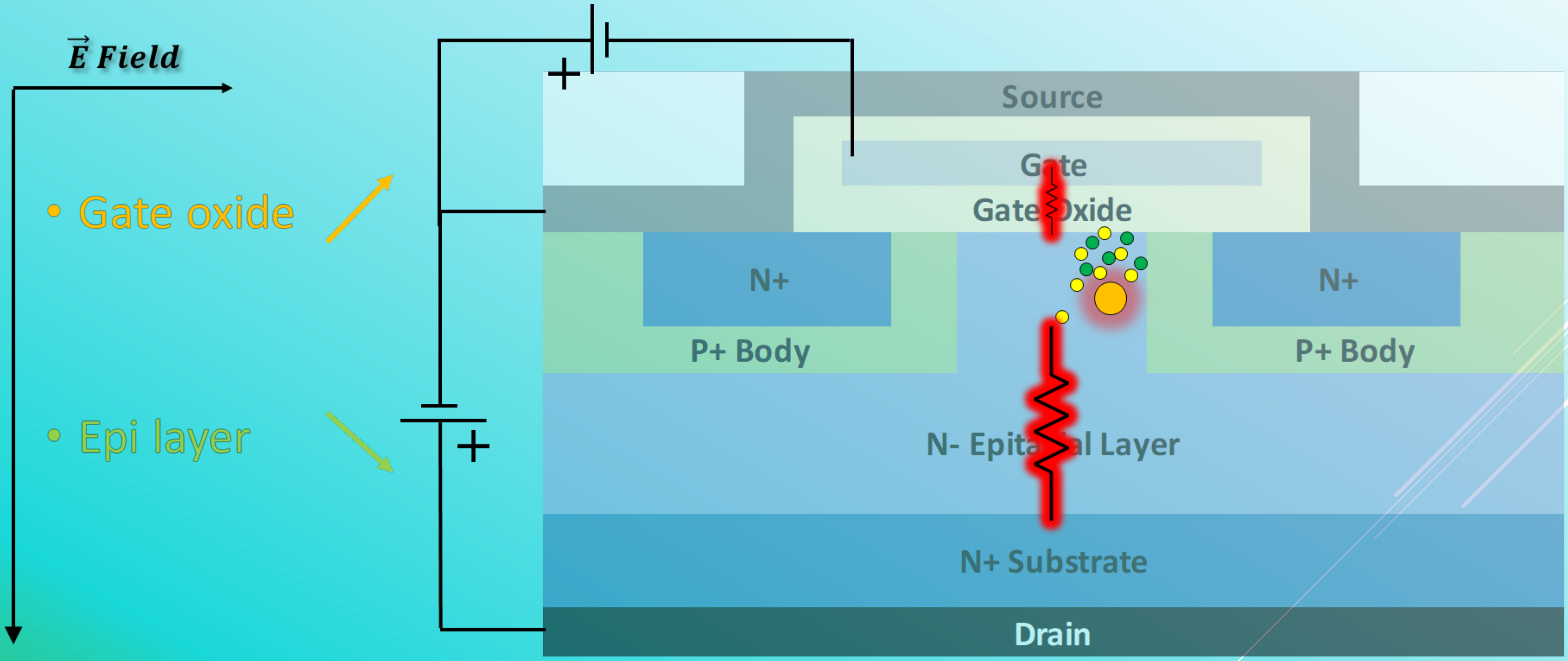
$\vec{E}$ *Field*

- Gate oxide
- Epi layer



# SINGLE EVENT GATE RUPTURE (SEGR)

PEASA Space Power

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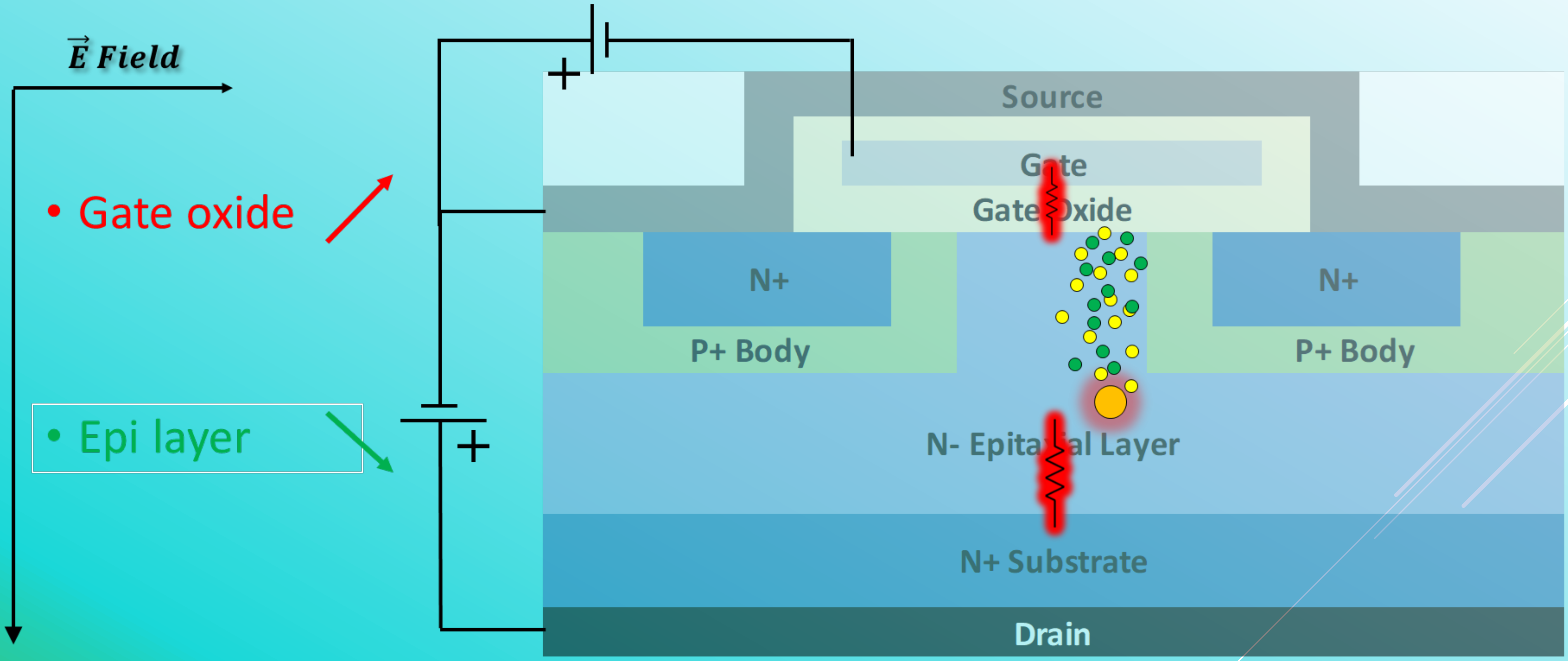

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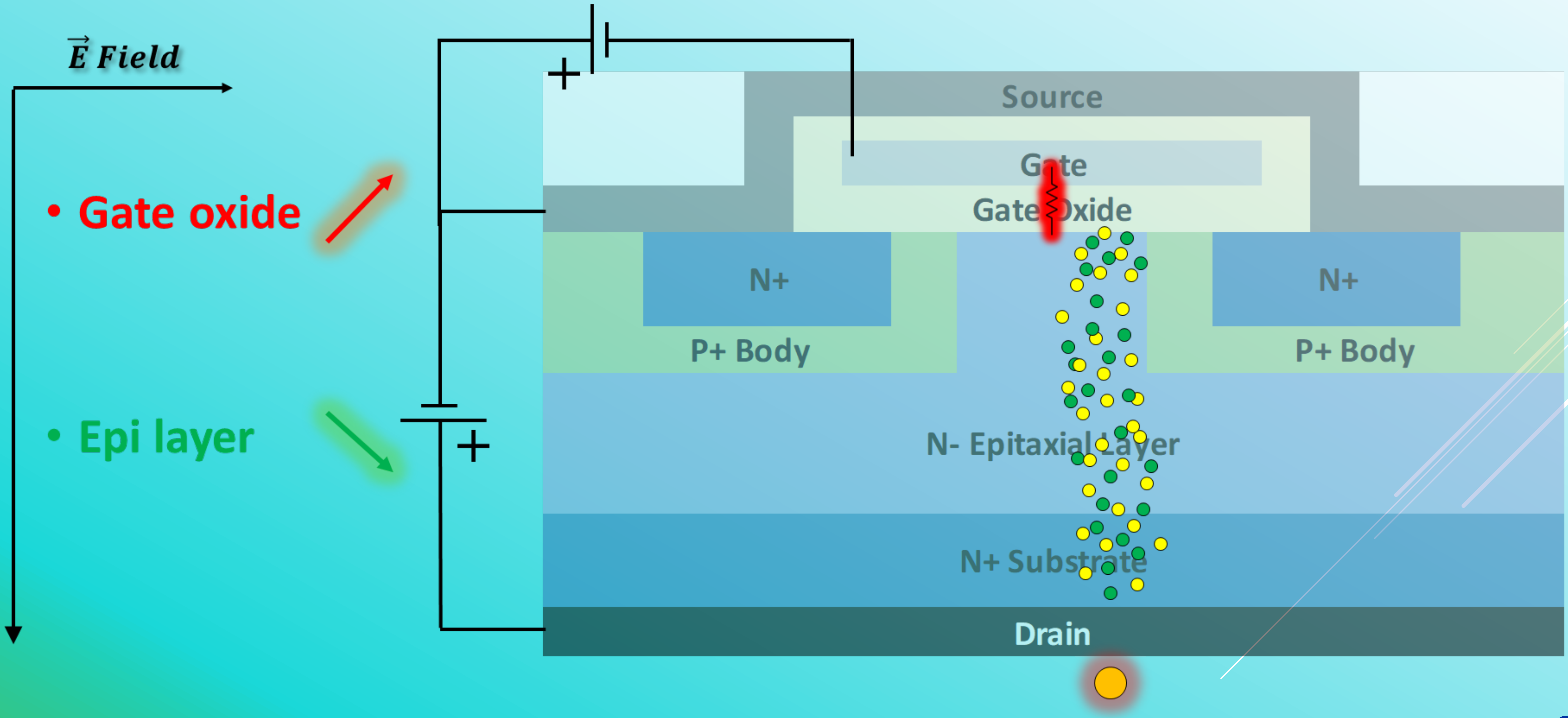

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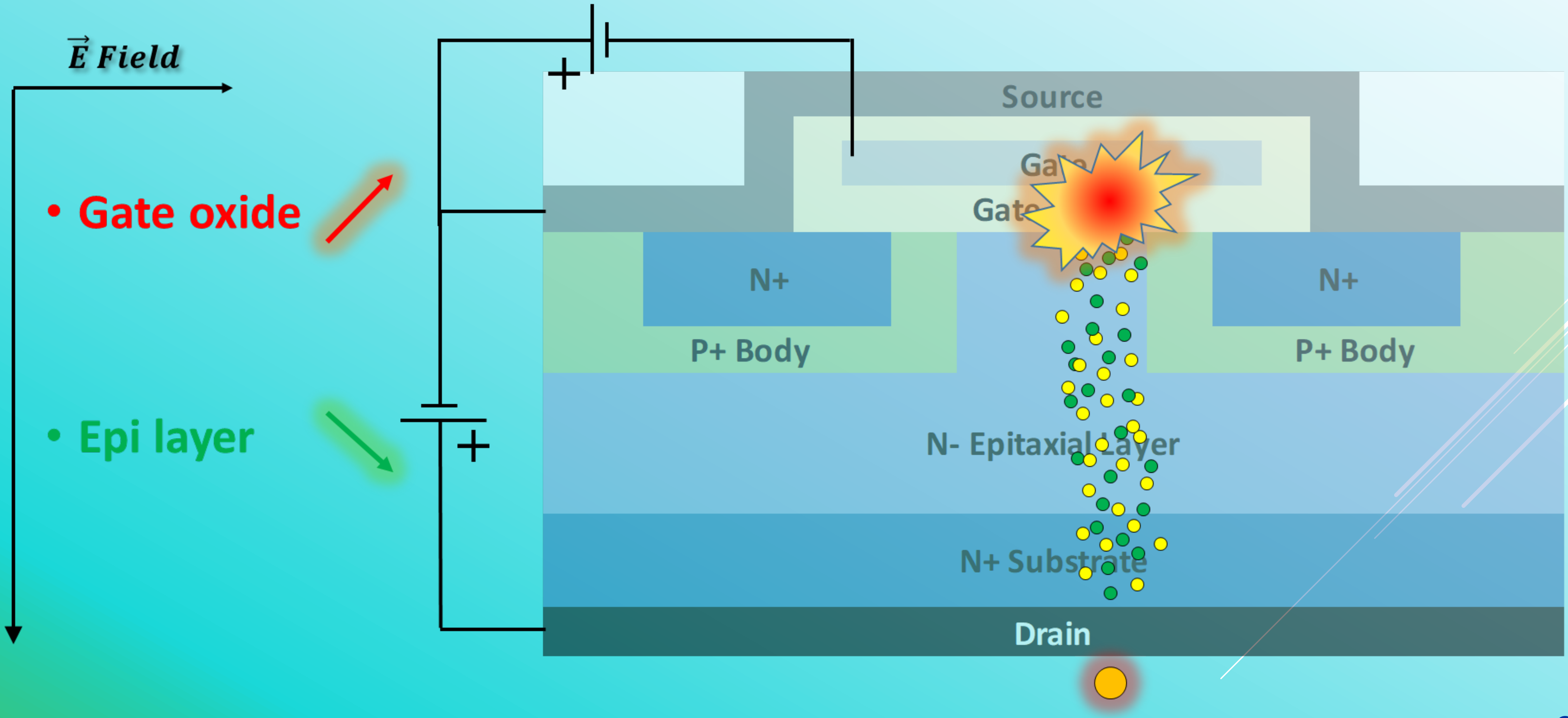
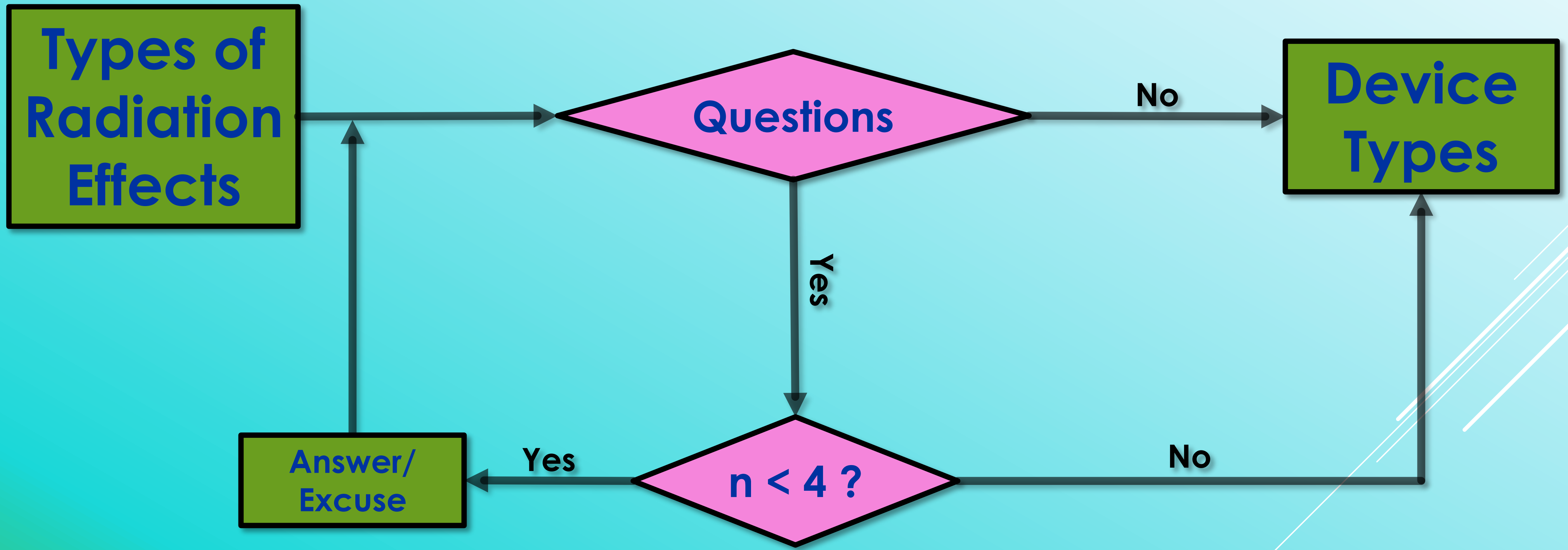
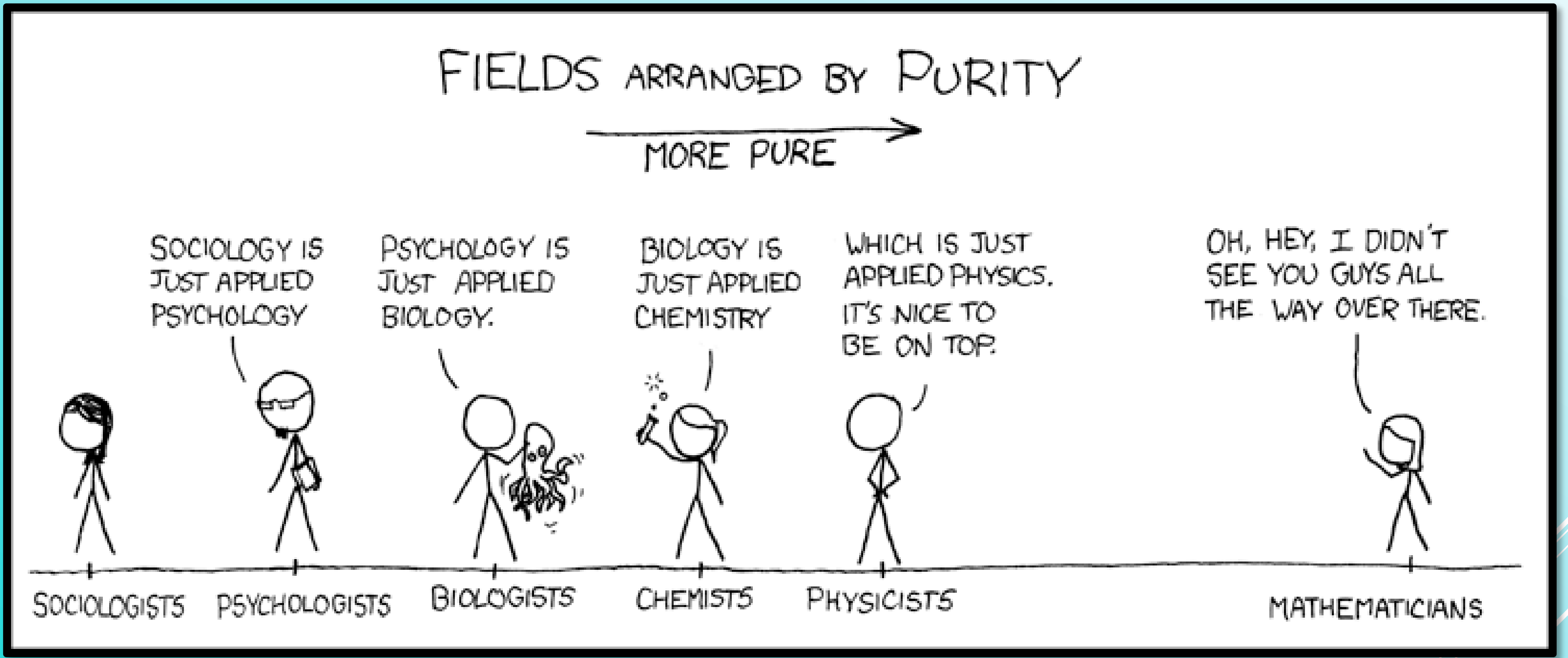


# QUESTION BREAK



# DIFFERENT POINTS OF VIEW




https://xkcd.com/435/

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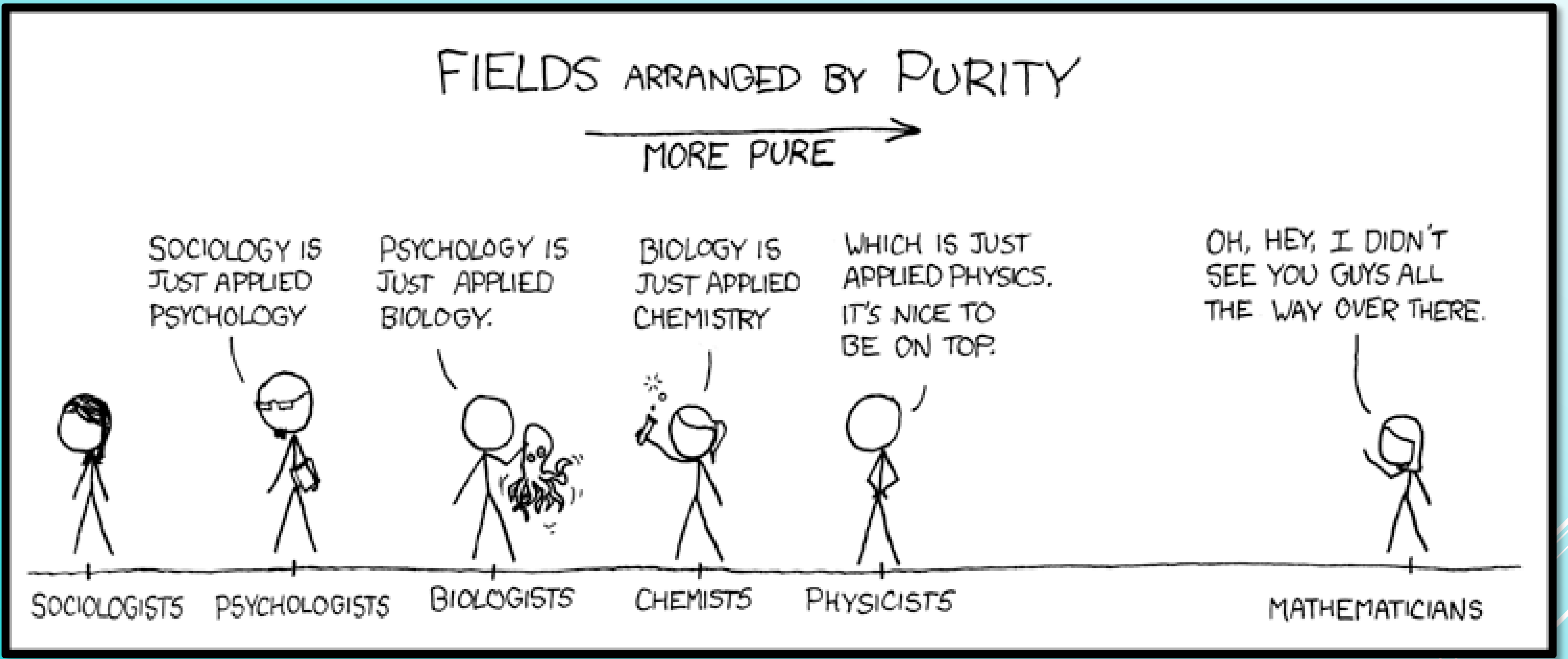



https://xkcd.com/435/

Fields Arranged by Usefulness/Practicality

# DEVICE TYPES – ONE VIEWPOINT

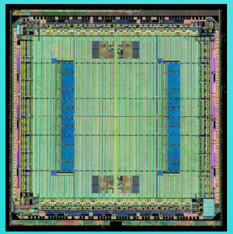
**Devices Arranged by Purity →**

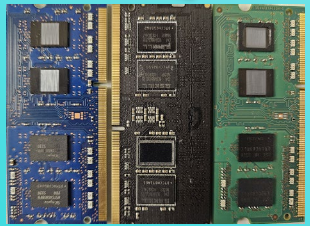
You're just an amalgamation of the rest of us

You're just a big array of me!

You're nothing more than a fancy version of me

Oh, Hey! I didn't see you guys all the way over there!

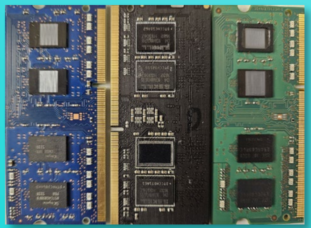


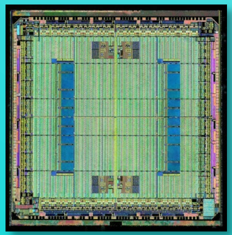



**FPGA** | **Memories** | **Transistors** | **Diodes** | **Raw Semiconductor Material**

**← Devices Arranged by Usefulness/Practicality**

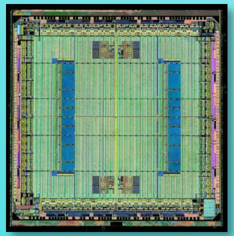
# DEVICE TYPES



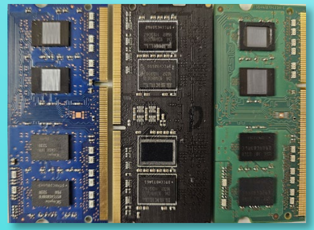
- Raw Semiconductor Material
  - Bulk material properties can influence TID and DDD
  - Secondary consequences like field gradient can affect SEE
- Power Devices (Diodes & Transistors)
  - May be simple but are usually critical and abundant
- Memories
  - Getting more complex and starting to look at net and resultant effects instead of fundamental mechanisms
- FPGA, etc.
  - Complex systems looking at fixing any problems after the fact or reducing their impact

# COMPLEX DEVICES



- The device pretty much is what it is, so we are just trying to quantify and possibly mitigate what the manufacturer gives us
- It is unlikely we will be able to manufacture a complex device specifically for rad tolerance ($$$$). At best, we may be able to figure out what part of the device the vulnerability is in and possibly institute a mitigation, such as more frequent power cycles, re-writes, or triplicate voting.
- Radiation testing for complex devices is centered around accepting that there will be effects and trying to establish rates and institute mitigations

# MEMORIES

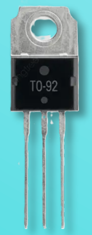


- Similar to complex devices, when we look at memories, the cost of manufacturing and the feature size limits us to quantifying errors and rates as opposed to designing them out
- However, now that we are working with a more fundamental building block, we can start to compare different technologies, such as volatile memory vs non-volatile memory

# RAW SEMICONDUCTOR MATERIAL

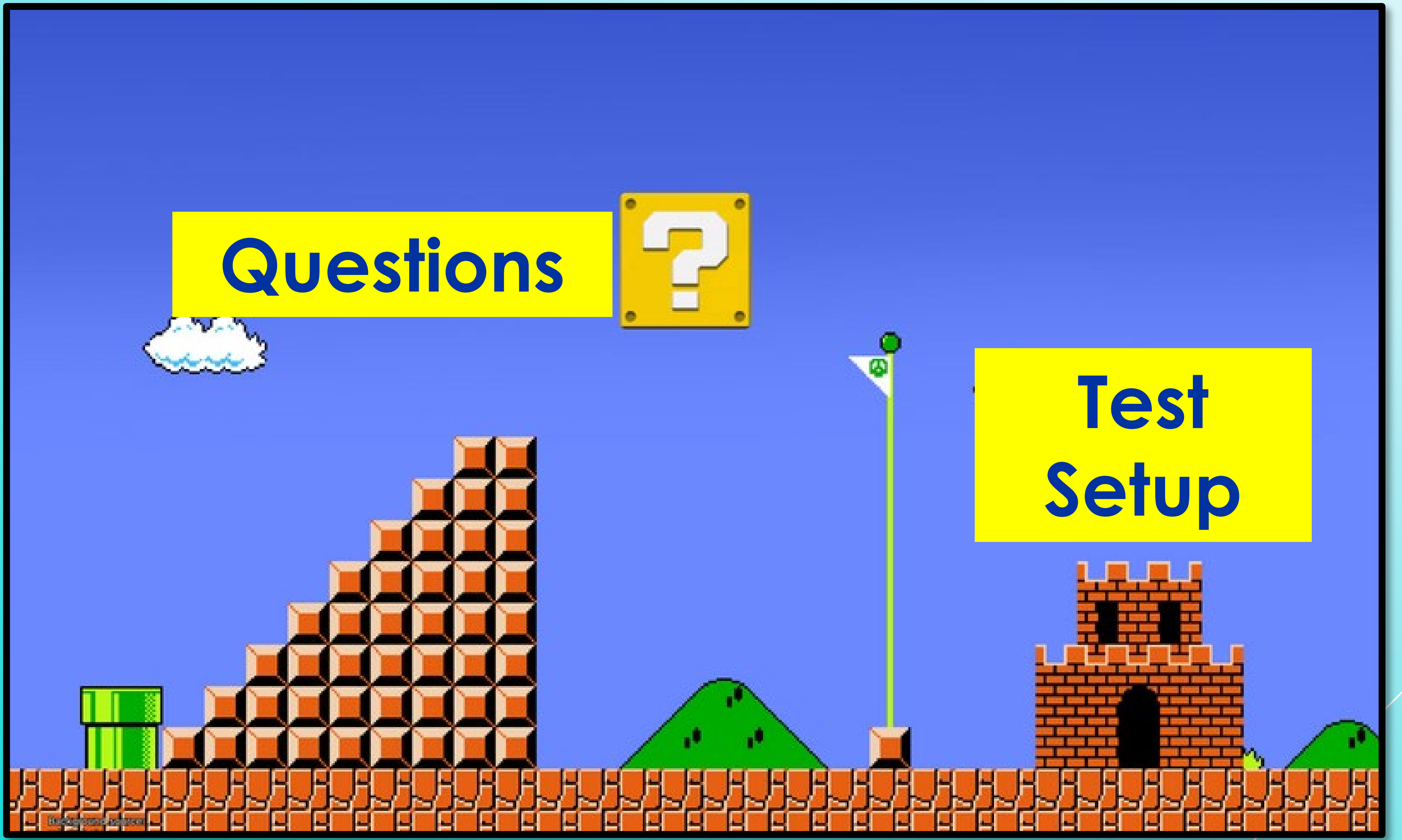
- We can say some things about a technology based on what materials it contains, including the bulk semiconductor, but also things like the oxides involved
- This is usually limited to DDD and TID
- DDD is the most applicable because, as we covered earlier, the primary effect is a change to the lattice structure in the bulk semiconductor material
- TID is one step more abstract because while the interaction between ionizing radiation and each material in the device will affect things like pair production or degradation it may not be the root cause
- Much less directly affected by the basic material interaction is the SEE, as these often have more to do with the ion path through the material (or track structure) and the electric fields that are present
- Wide band gap devices like GaN and SiC are often incorrectly touted as “inherently rad-hard” based on the binding energy and lattice constants of the materials that do in fact offer resilience against DDD, but the increased electric field gradients can actually make these energy dense technologies more susceptible to SEE

# POWER DEVICES




- Transistors, MOSFETs, JFETs, HEMTs, BJTs, Diodes, etc.
- Primary concern  Catastrophic or Destructive SEE (DSEE)
- Therefore, looking at higher LET requirements
  - Often zero tolerance for failure below LET = 37 MeV(mg/$cm^2$)
- Still need to keep an eye out for SELC and SET

# QUESTION BREAK



# FACILITIES

**TID**
- Abundant across the country
- Primarily Radioisotope based

**DDD**
- Lots of options (protons or neutrons)
- Medical facilities

**SEE**
- 4 primary "full-coverage" US facilities
- Expensive, limited availability, technically most challenging

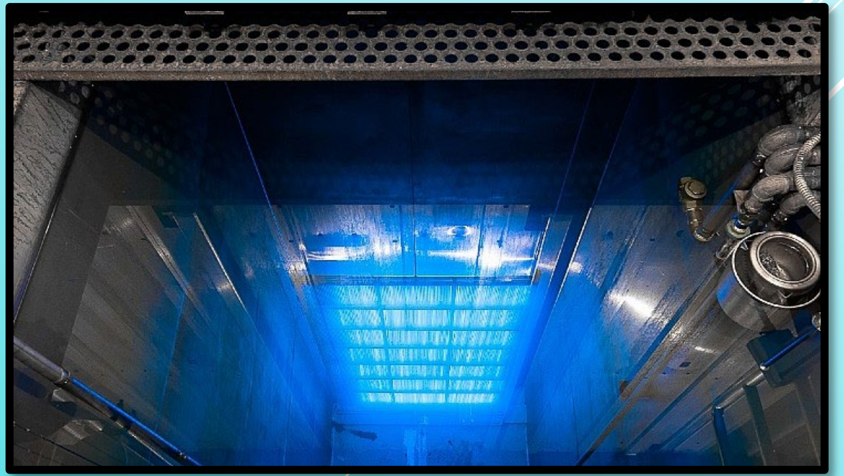
# TID FACILITIES

TID

- Radioisotope (Co-60, Cs-137) or electron accelerators/ x-rays
- A few $k per day


https://www.researchgate.net/figure/Cobalt60-irradiator-The-Gammacell-220-R-MDS-Nordion-Ottawa-Canada-an-example-of-a_fig1_51439831

- Present at many universities, national labs, sterilization facilities, and other industrial applications
- Most people who are heavily in the business have a facility (like GSFC!)
  - Safety and security requirements
  - Can be cheaper in the long run
- TM 1019, ELDRS, and Dose rates
- No Activation



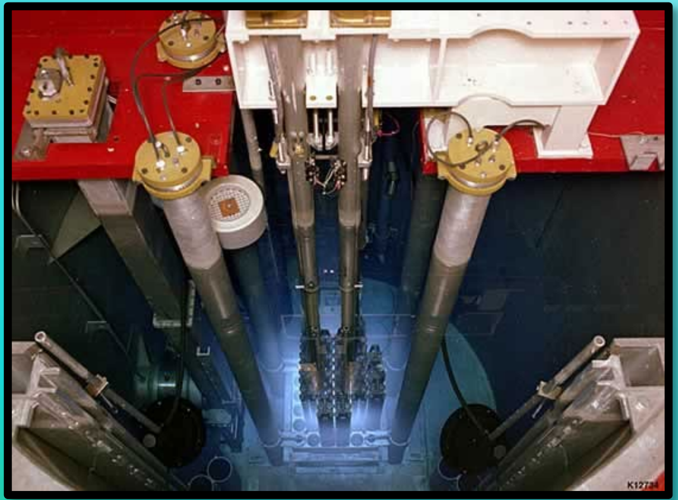
https://world-nuclear-news.org/Articles/The-critical-production-of-cobalt-60-in-nuclear-re

# DDD FACILITIES

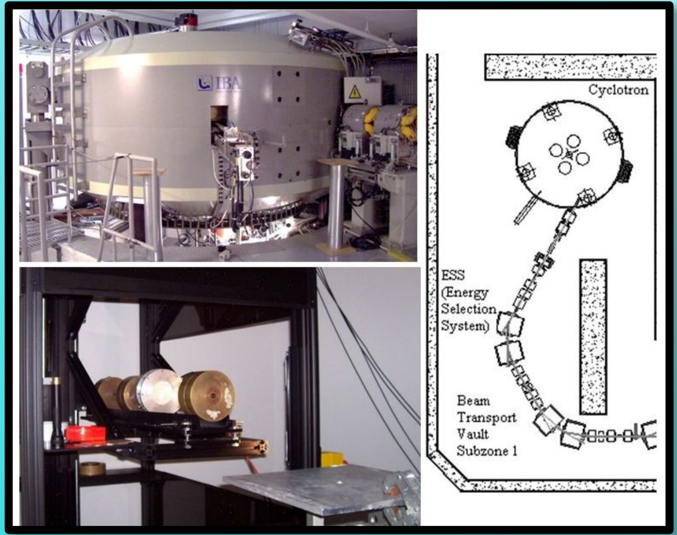
DDD

- Lots of options (protons or neutrons)
- Medical facilities

## Research Reactor

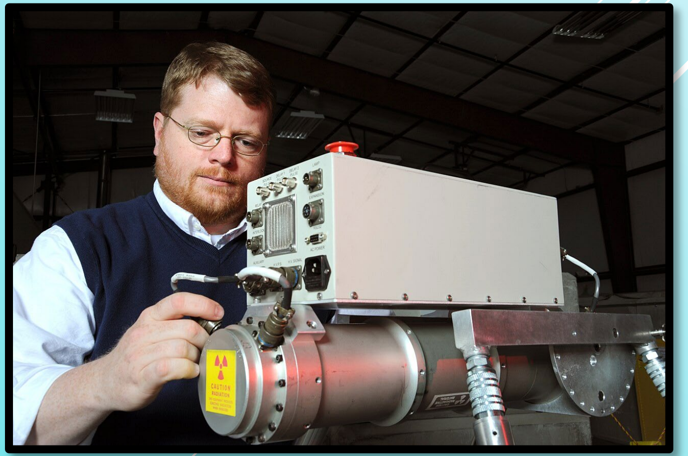


## Proton Accelerator




https://mghrad.mgh.harvard.edu/about/

## Neutron Generator



https://en.wikipedia.org/wiki/Neutron_generator#/media/File:Experiment_using_an_electronic_neutron_generator.jpg

# SEE FACILITIES

PEASA Space Power

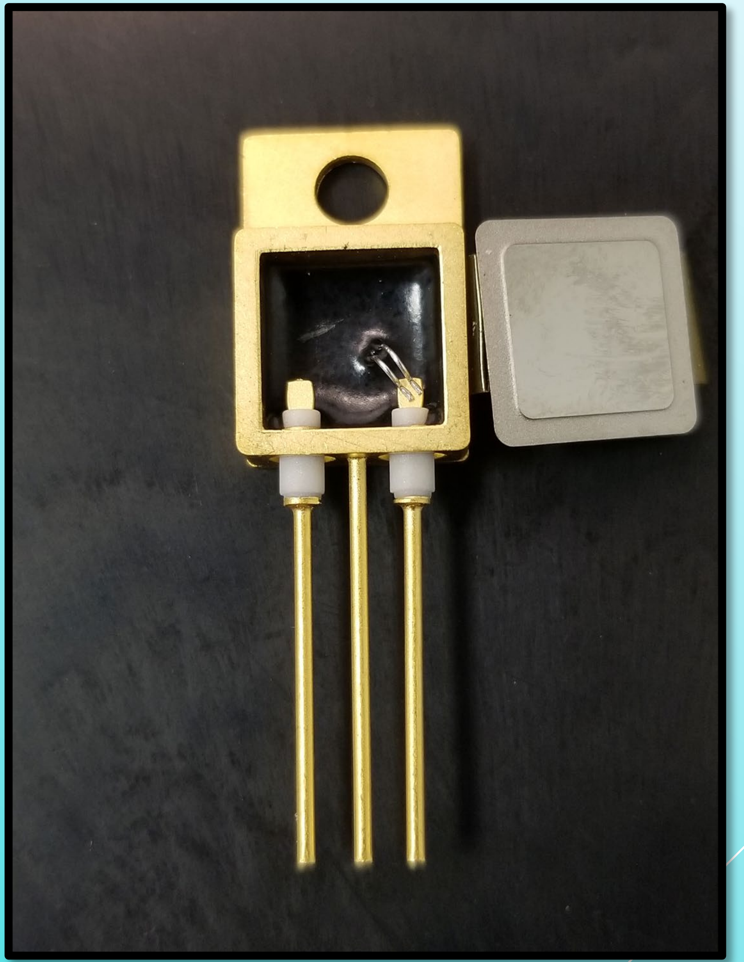
SEE

- 4 primary "full-coverage" US facilities
- Expensive, limited availability, technically most challenging

| Institution | Machine | Energy | Cost | Availability |
|---|---|---|---|---|
| TAMU | K150 | Mid | $ | Moderate |
| | K500 | High | $ | Rare |
| BNL | Booster Synchrotron | Very High | $$$ | Very Rare |
| | Tandem | Mid | $ | Good |
| MSU | FSEE | High | $$ | Moderate |
| | KSEE | High | $$ | ? |
| LBNL | 88-Inch | Mid | $$ | Moderate* |

# DEVICE PREPARATION

- De-lidding and Die Thinning
  - Up to TeV in space but limited to ~GeV in the lab
  - Sometimes need to be creative about access
- Parylene Coating
  - Competing issues like arcing or breakdown
  - These tradeoffs get even more complicated when you look at things like RF power or thermal challenges with high power chips (like GPUs)



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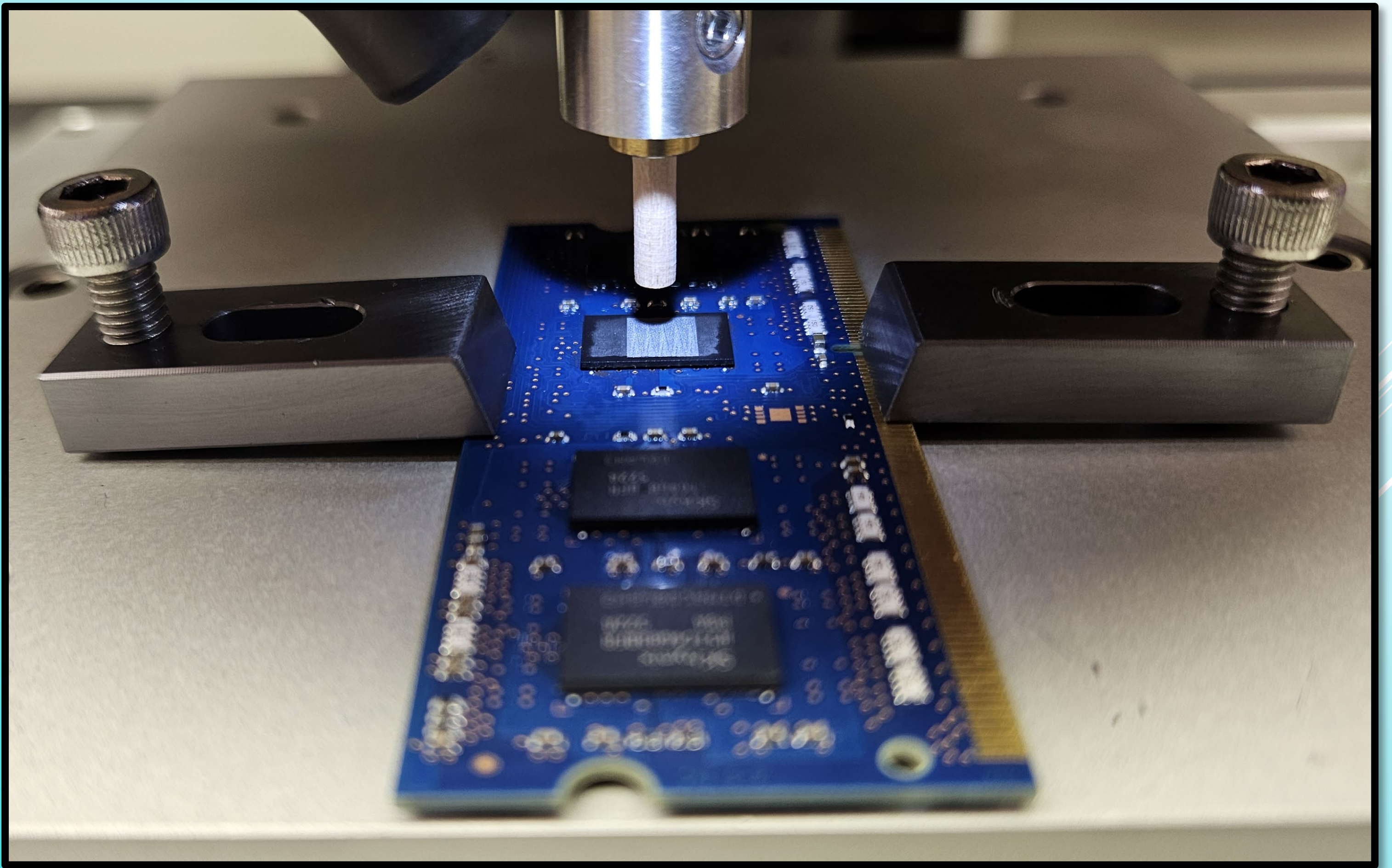
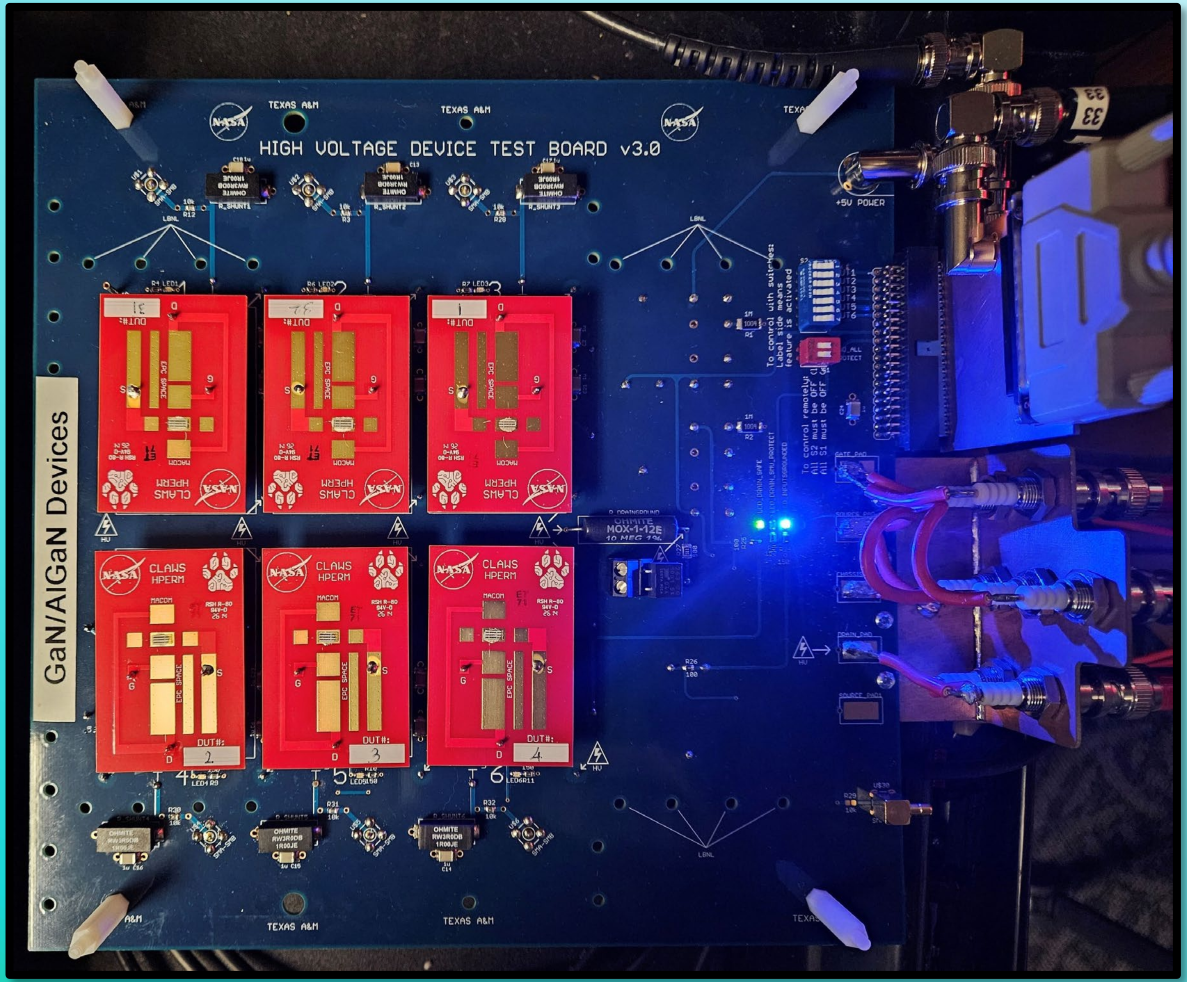
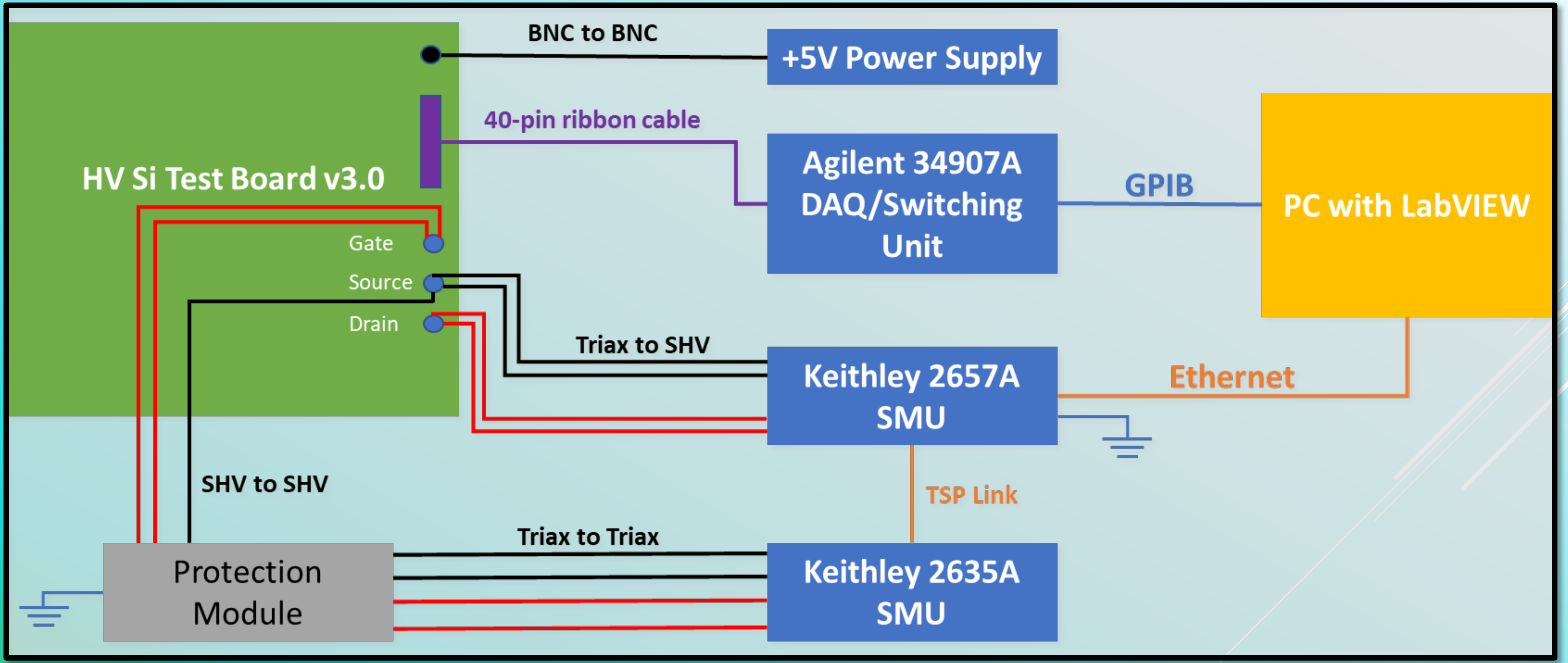


# TEST BOARD

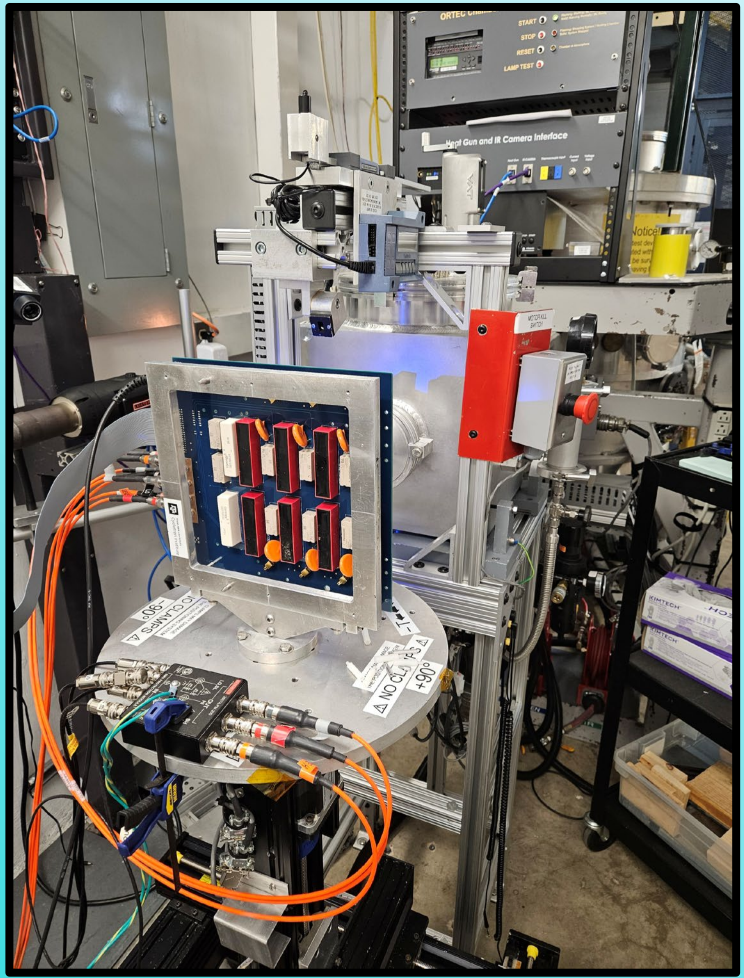

TEXAS A&M
HIGH VOLTAGE DEVICE TEST BOARD v3.0
+5V POWER
GaN/AlGaN Devices
CLAWS HPERM
OHMITE MOX-1-12E 10 MEG 1%

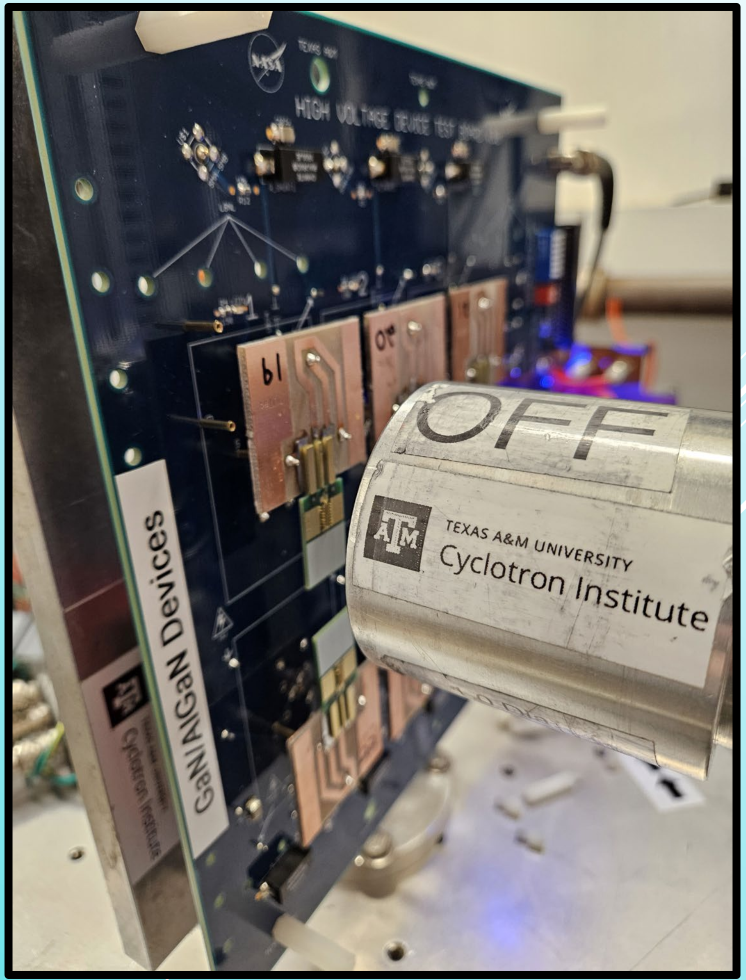
# CONTROL EQUIPMENT



# IN THE BEAM!

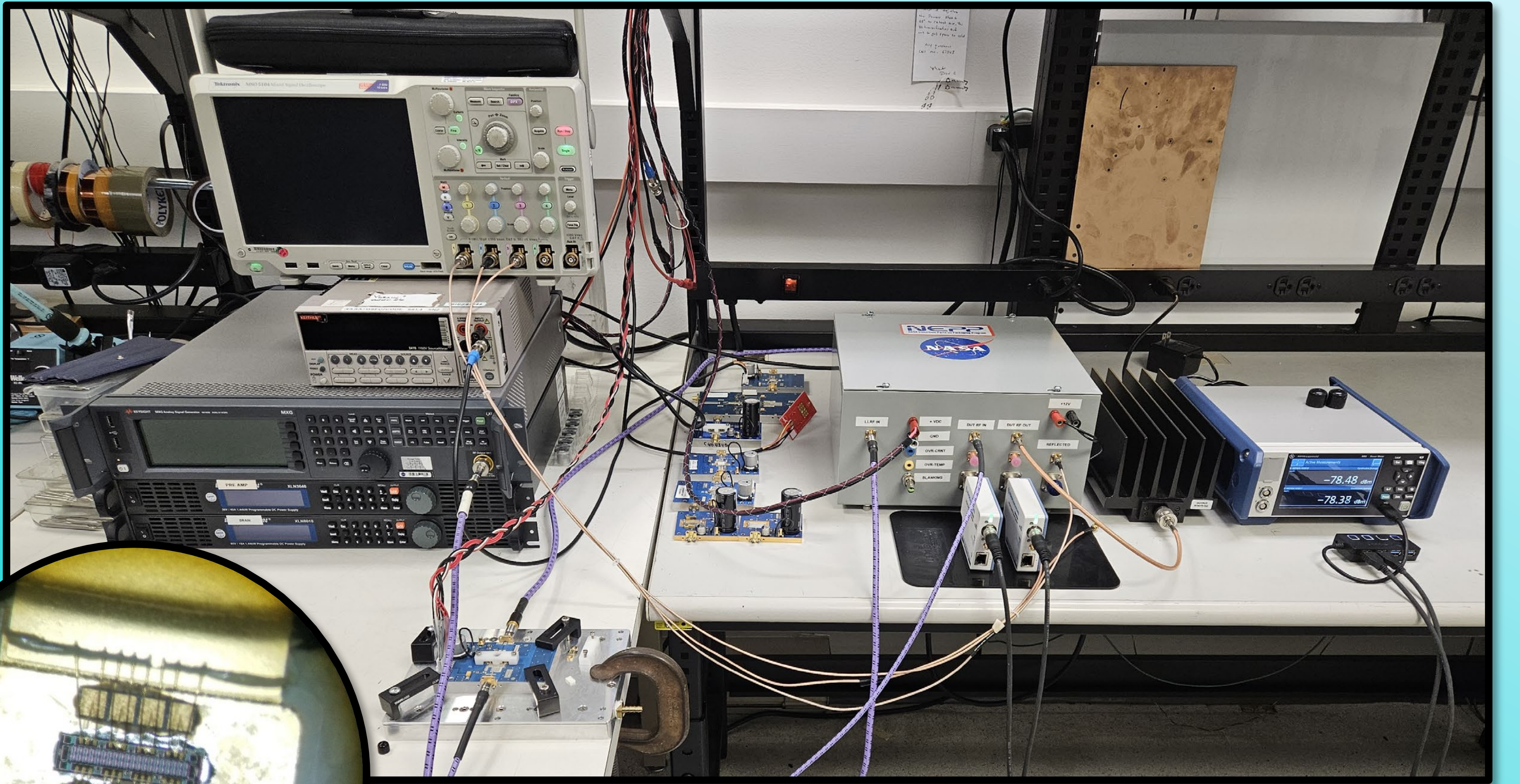
Si/SiC Devices

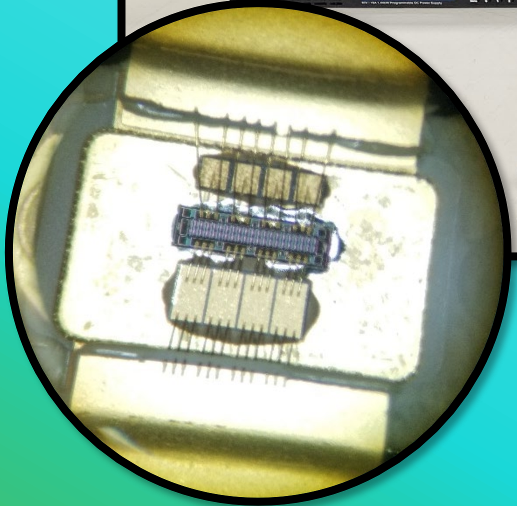



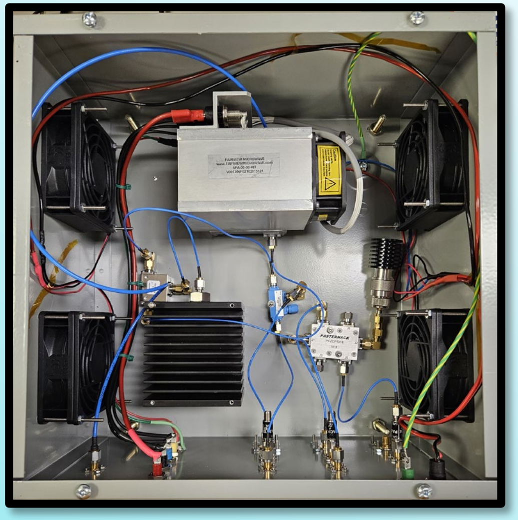


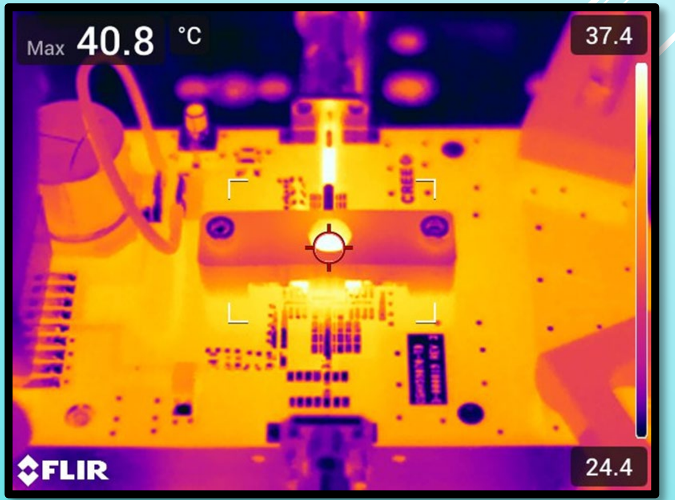
GaN/AlGaN Devices
OFF
TEXAS A&M UNIVERSITY
Cyclotron Institute

# IN THE BEAM!



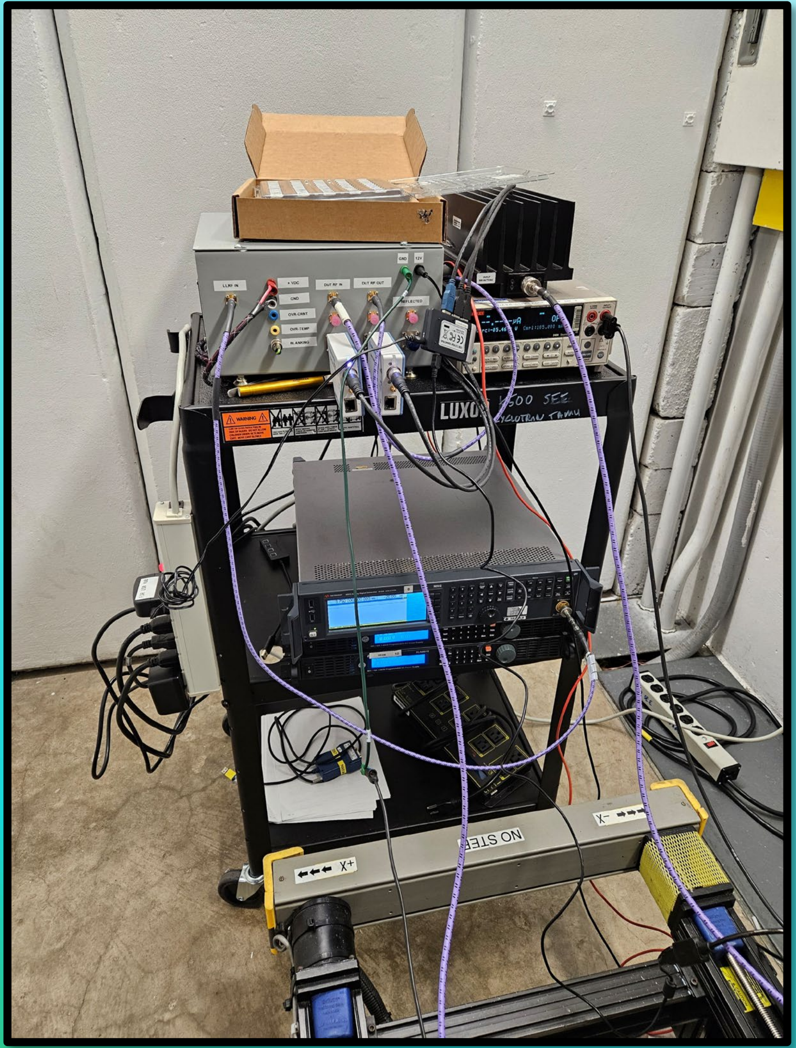


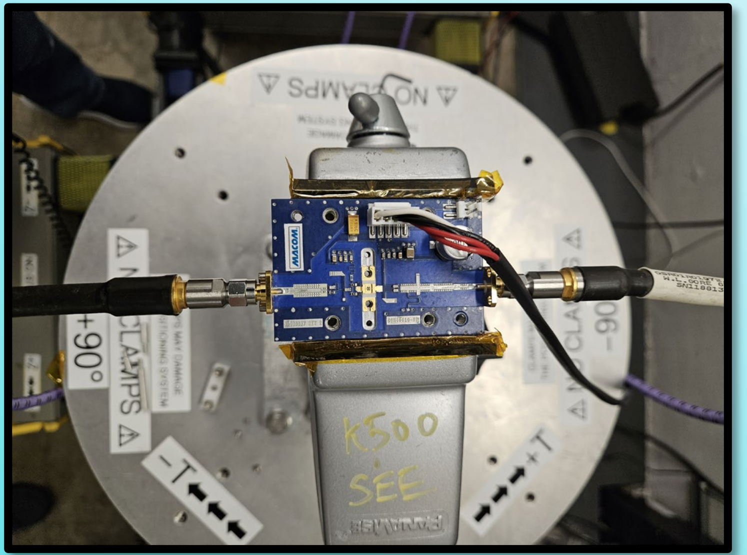





## NASA RF Test Set

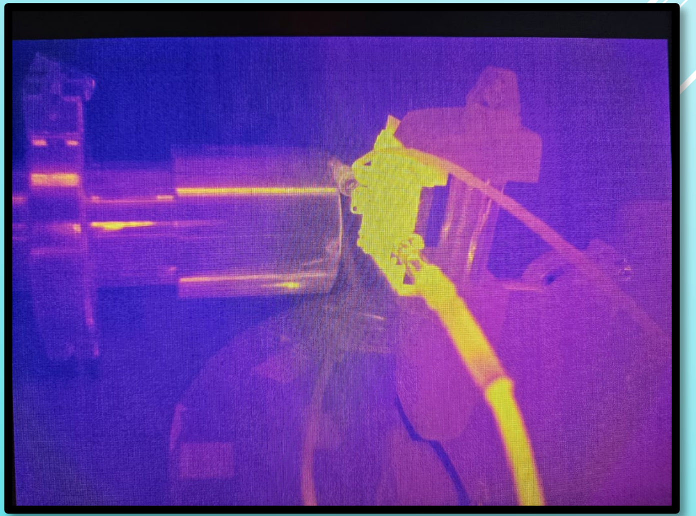
# IN THE BEAM!






Rotational & Translational Stage

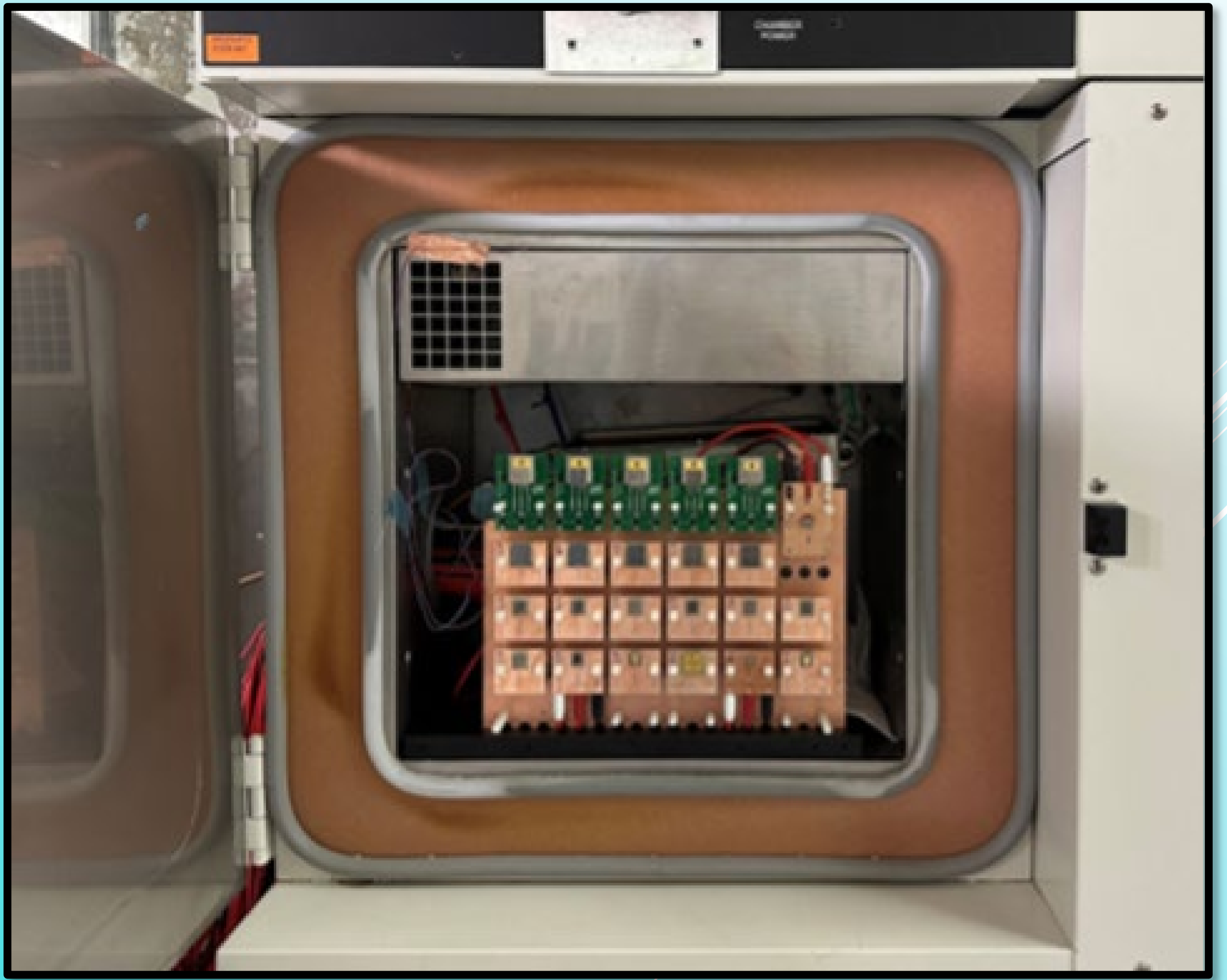
Thermal Camera & Heat gun



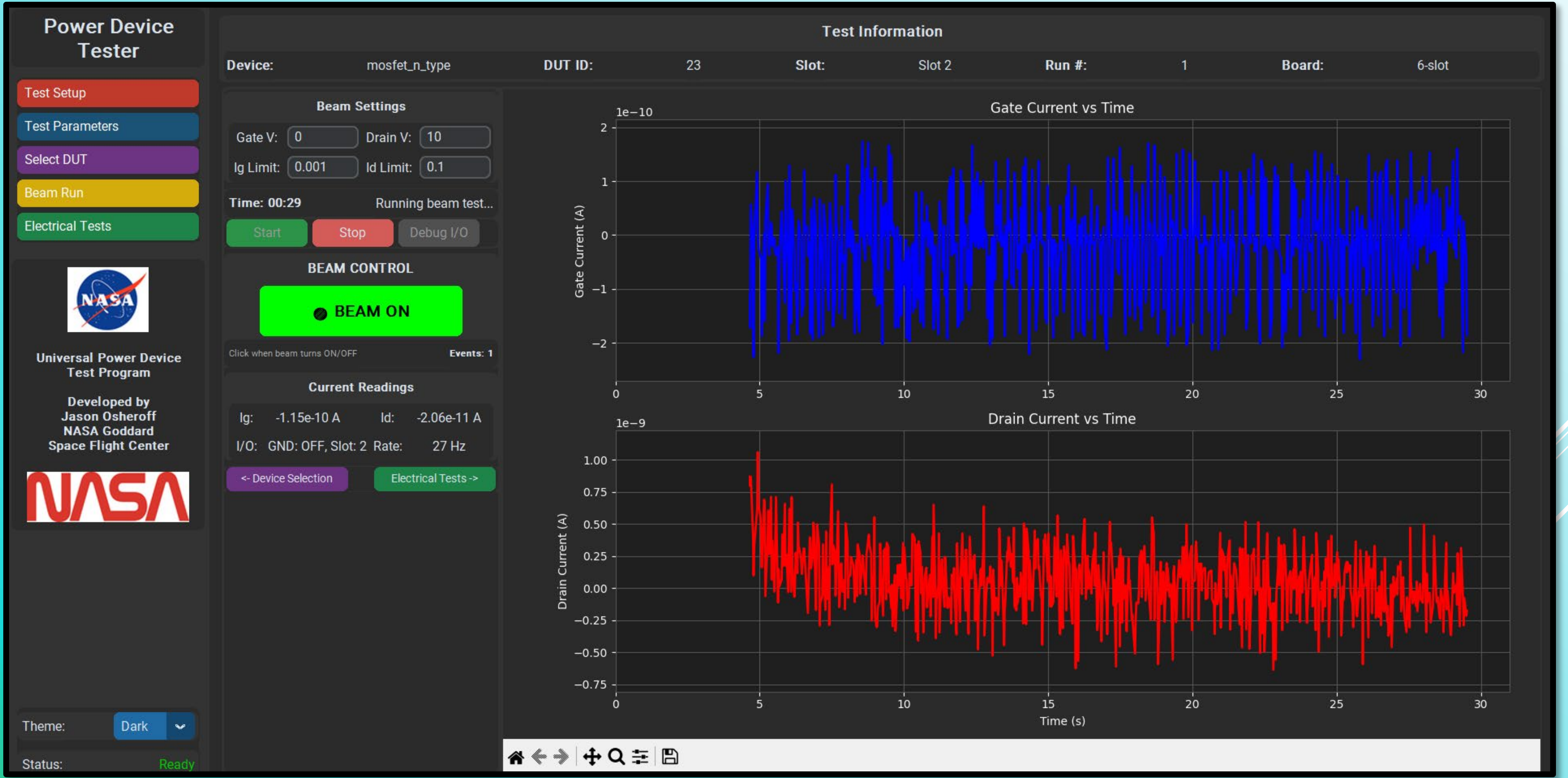
# IN THE BEAM!

**TID tends to be more "set and forget" however it can get complicated!**

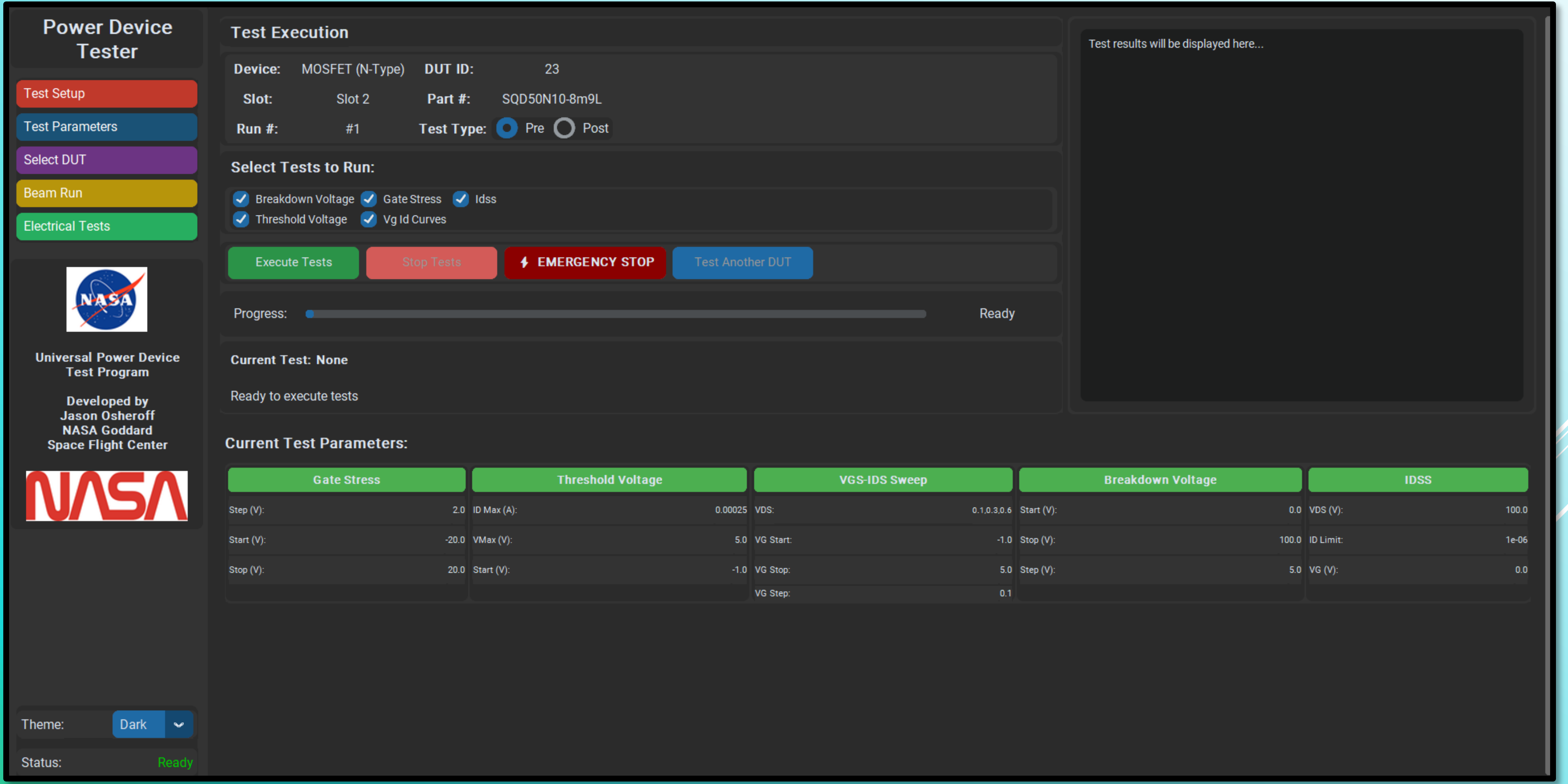
- Temperature -5C
- Shielding from fridge door
- Low dose rate can take months
- 24/7 monitoring



# SOFTWARE – BEAM RUN

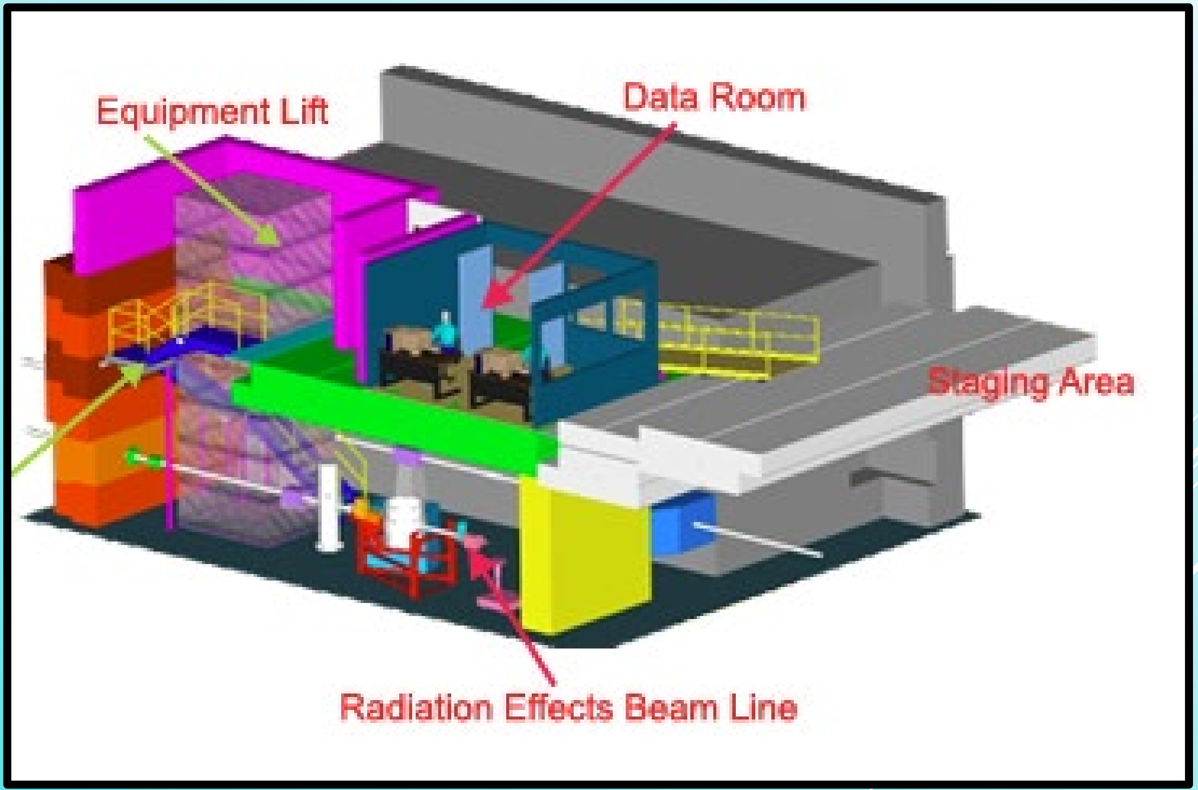


# SOFTWARE – PARAMETRIC TESTING



# TEST SETUP

- Design a test bench
  - Universal tester
  - Manufacturer supplied eval card
  - Duct tape and jumper cables
- Portability
  - Pelican crates
  - Extension Cables
  - Remote control
- Device preparation
  - Delidding, thinning, parylene coating…
- Facility limitations
  - Voltage limits and other lab safety
  - Cable runs/feedthroughs/patch panels
  - Physical DUT positioning




https://cyclotron.tamu.edu/ref/

# BEAM AND BIAS SELECTION

- Irradiation Conditions
  - Temperature
  - Bias
  - Angle
- Beam selection
  - LET
  - Range
  - Degraders
- Optimization of beamtime
  - Beam/Tune change times
  - DUT or test set swapping
  - Personnel

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Cyclotron Institute

cyclotron.tamu.edu/ref
phone: 979-845-1411
fax: 979-845-1899

## Available K500 Heavy Ion Beams

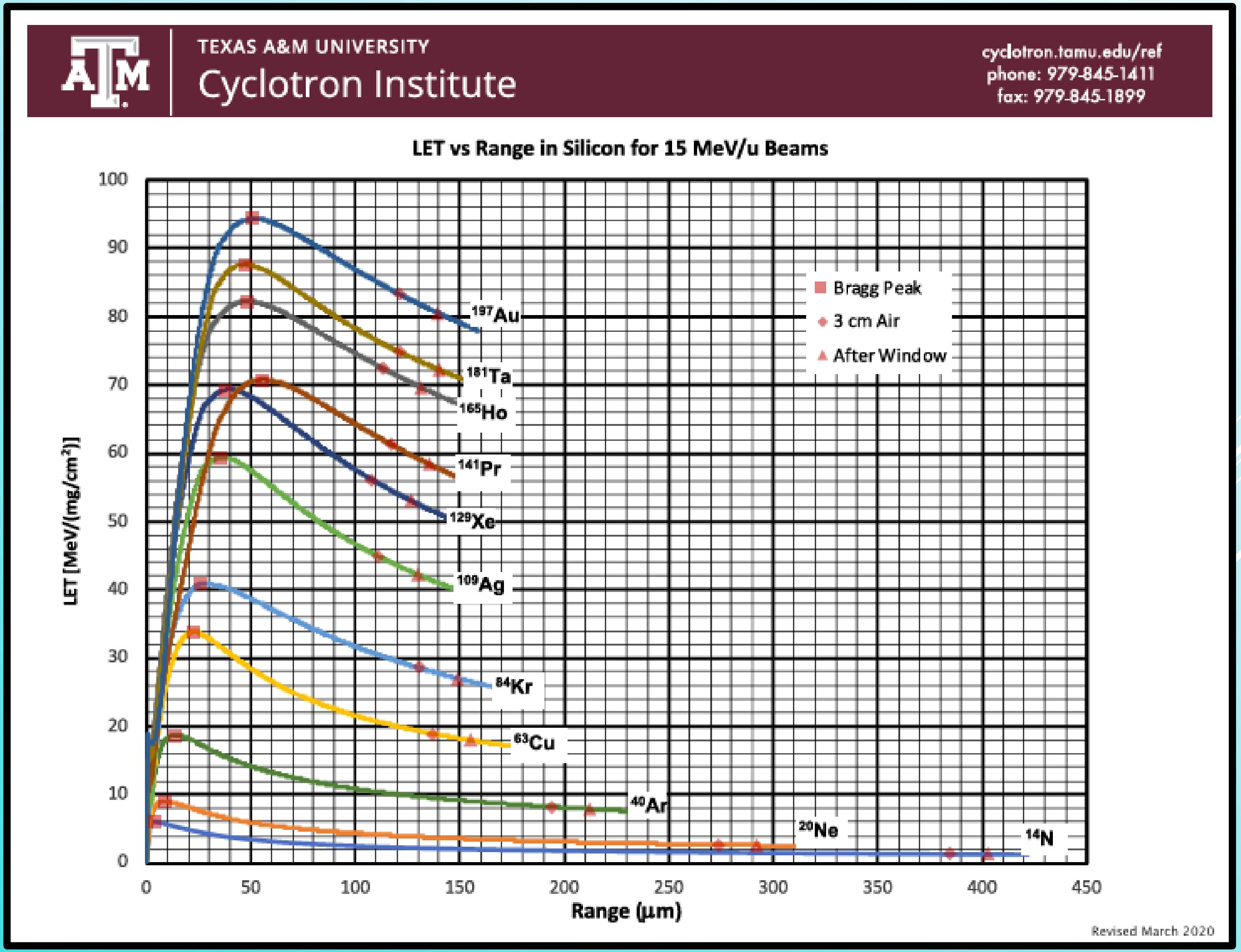
(LET and range values are for SI)

| | Ion | Mass [amu] | A MeV | Total Energy [MeV] | Energy at Bragg Peak [MeV] | Range to Bragg Peak [microns] | Range in vacuum [microns] | LET in vacuum [MeV/(mg/cm2)] | Range after window [microns] | LET after window [MeV/(mg/cm$^2$)] | Range after 3 cm air [microns] | LET after 3 cm air [MeV/(mg/cm2)] | Range at Bragg [microns] | LET at Bragg Peak [MeV/(mg/cm2)] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15 A MeV | $^{4}$He | 4.003 | 15 | 60 | 0.5 | 1446.9 | 1449.2 | 0.10 | 1430 | 0.10 | 1412 | 0.10 | 2.3 | 1.5 |
| | $^{14}$N | 14.003 | 15 | 210 | 4 | 418.0 | 421.7 | 1.3 | 403 | 1.3 | 385 | 1.3 | 3.7 | 6.1 |
| | $^{20}$Ne | 19.992 | 15 | 300 | 14 | 302.9 | 311.3 | 2.5 | 292 | 2.6 | 274 | 2.7 | 8.4 | 9.0 |
| | $^{40}$Ar | 39.962 | 15 | 599 | 45 | 217.5 | 231.0 | 7.6 | 212 | 7.9 | 194 | 8.2 | 13.5 | 18.7 |
| | $^{63}$Cu | 62.930 | 15 | 944 | 130 | 151.7 | 174.4 | 17.1 | 155 | 18.0 | 137 | 18.9 | 22.7 | 34.0 |
| | $^{84}$Kr | 83.912 | 15 | 1259 | 180 | 142.0 | 168.0 | 25.7 | 149 | 27.0 | 131 | 28.6 | 26.0 | 41.0 |
| | $^{109}$Ag | 108.905 | 15 | 1634 | 351 | 112.9 | 148.5 | 40.0 | 130 | 42.3 | 111 | 44.9 | 35.6 | 59.4 |
| | $^{129}$Xe | 128.905 | 15 | 1934 | 451 | 107.0 | 145.5 | 50.4 | 126 | 53.1 | 108 | 56.1 | 38.5 | 69.3 |
| | $^{141}$Pr | 140.908 | 15 | 2114 | 651 | 99.2 | 154.8 | 55.8 | 135 | 58.4 | 117 | 61.3 | 55.6 | 70.8 |
| | $^{165}$Ho | 164.930 | 15 | 2474 | 699 | 102.4 | 150.8 | 67.0 | 132 | 69.6 | 114 | 72.4 | 48.4 | 82.3 |
| | $^{181}$Ta | 180.948 | 15 | 2714 | 698 | 110.9 | 158.9 | 70.0 | 140 | 72.3 | 122 | 74.8 | 48.0 | 87.7 |
| | $^{197}$Au | 196.967 | 15 | 2954 | 800 | 107.6 | 158.7 | 77.9 | 140 | 80.5 | 121 | 83.3 | 51.1 | 94.4 |
| 25 A MeV | $^{4}$He | 4.003 | 24.8 | 99 | 0.5 | 3520.5 | 3523.0 | 0.07 | 3504 | 0.07 | 3486 | 0.07 | 2.3 | 1.5 |
| | $^{14}$N | 14.003 | 24.8 | 347 | 4 | 1004.9 | 1008.6 | 0.8 | 990 | 0.9 | 972 | 0.9 | 3.7 | 6.1 |
| | $^{22}$Ne | 21.991 | 24.8 | 545 | 16 | 794.8 | 804.2 | 1.7 | 785 | 1.7 | 768 | 1.7 | 9.4 | 9.0 |
| | $^{40}$Ar | 39.962 | 24.8 | 991 | 45 | 485.2 | 498.7 | 5.4 | 480 | 5.5 | 462 | 5.6 | 13.5 | 18.7 |
| | $^{63}$Cu | 62.930 | 24.8 | 1561 | 130 | 333.9 | 356.6 | 12.7 | 338 | 13.0 | 320 | 13.3 | 22.7 | 34.0 |
| | $^{84}$Kr | 83.912 | 24.8 | 2081 | 180 | 305.3 | 331.3 | 18.9 | 312 | 19.3 | 295 | 19.9 | 26.0 | 41.0 |
| | $^{107}$Ag | 106.905 | 24.8 | 2651 | 351 | 240.5 | 275.9 | 30.7 | 257 | 31.6 | 239 | 32.6 | 35.4 | 59.4 |
| | $^{129}$Xe | 128.905 | 24.8 | 3197 | 451 | 230.3 | 268.7 | 39.3 | 250 | 40.5 | 232 | 41.8 | 38.4 | 69.3 |
| 40 A MeV | $^{14}$N | 14.003 | 40 | 560 | 4 | 2345.1 | 2348.7 | 0.6 | 2330 | 0.6 | 2312 | 0.6 | 3.6 | 6.1 |
| | $^{20}$Ne | 19.992 | 40 | 800 | 14 | 1670.4 | 1678.9 | 1.2 | 1660 | 1.2 | 1642 | 1.2 | 8.1 | 9.0 |
| | $^{40}$Ar | 39.962 | 40 | 1598 | 45 | 1064.7 | 1078.2 | 3.9 | 1060 | 3.9 | 1042 | 3.9 | 13.5 | 18.7 |
| | $^{78}$Kr | 77.920 | 40 | 3117 | 170 | 602.4 | 626.9 | 13.9 | 608 | 14.1 | 590 | 14.3 | 24.5 | 41.0 |

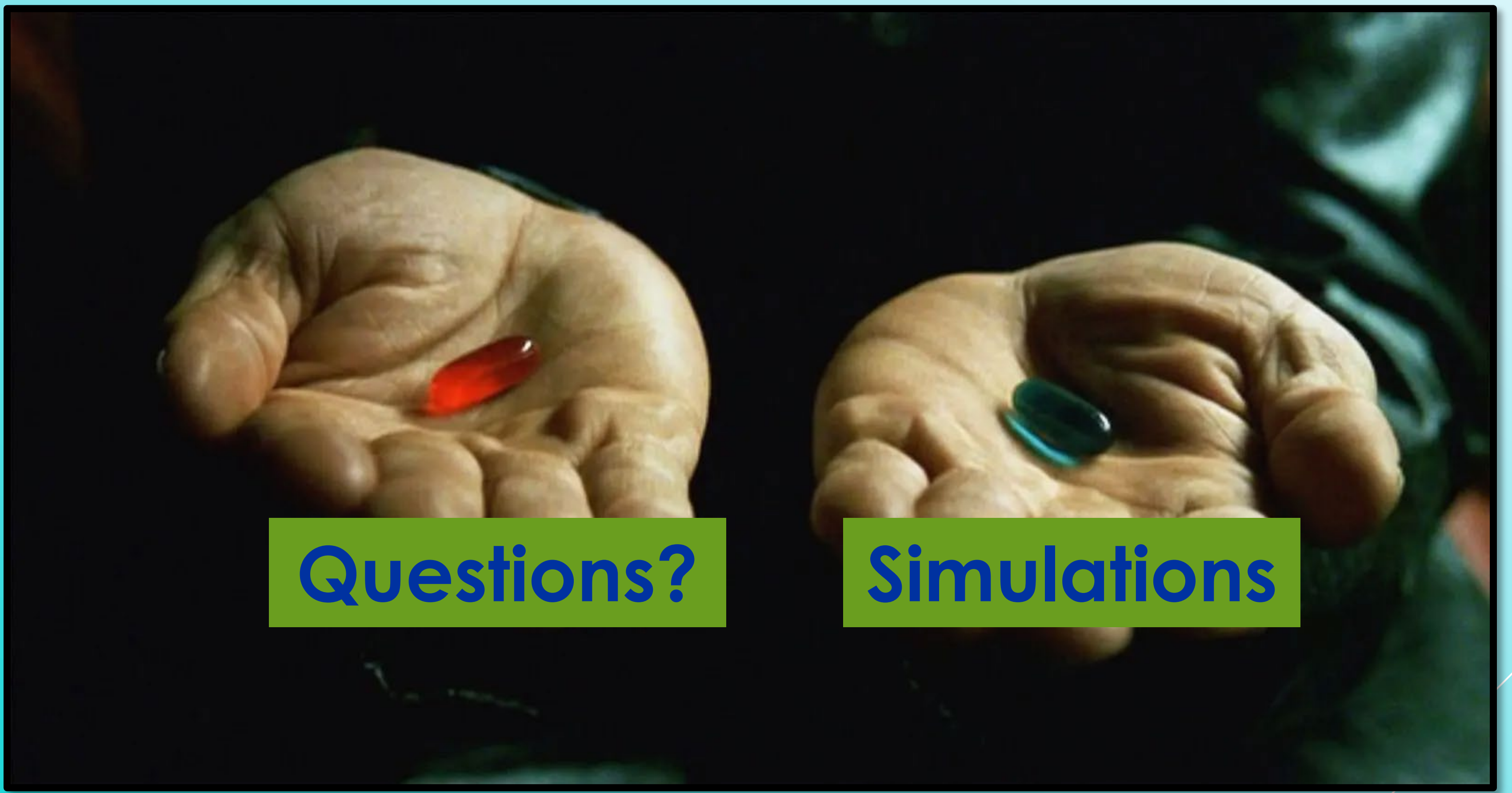
October 2021

# BEAM AND BIAS SELECTION

- Irradiation Conditions
  - Temperature
  - Bias
  - Angle
- Beam selection
  - LET
  - Range
  - Degraders
- Optimization of beamtime
  - Beam/Tune change times
  - DUT or test set swapping
  - Personnel



# QUESTION BREAK

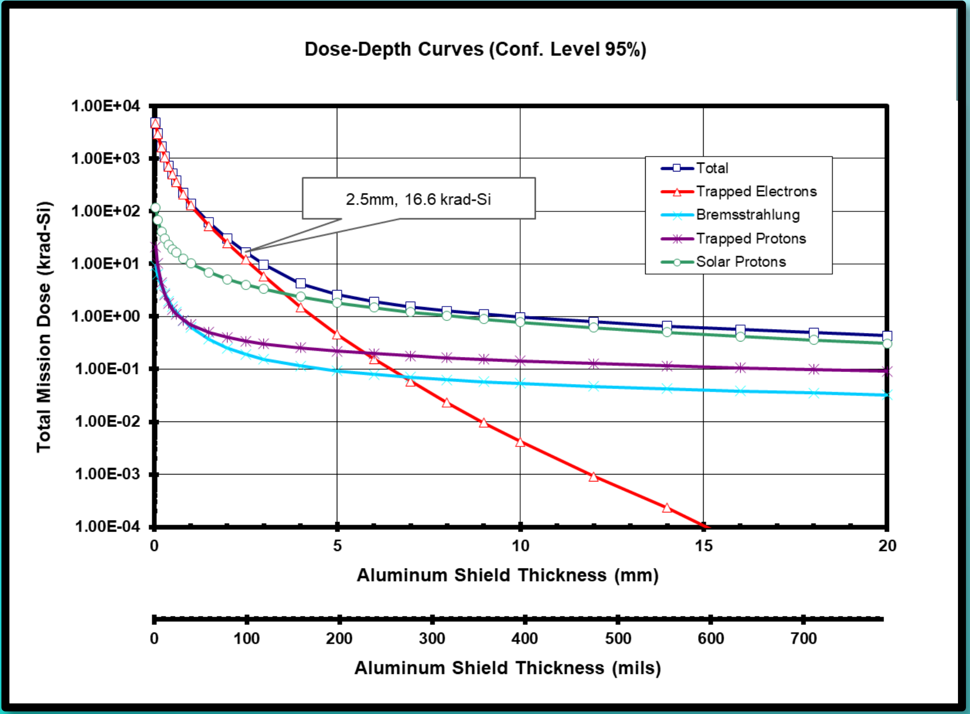


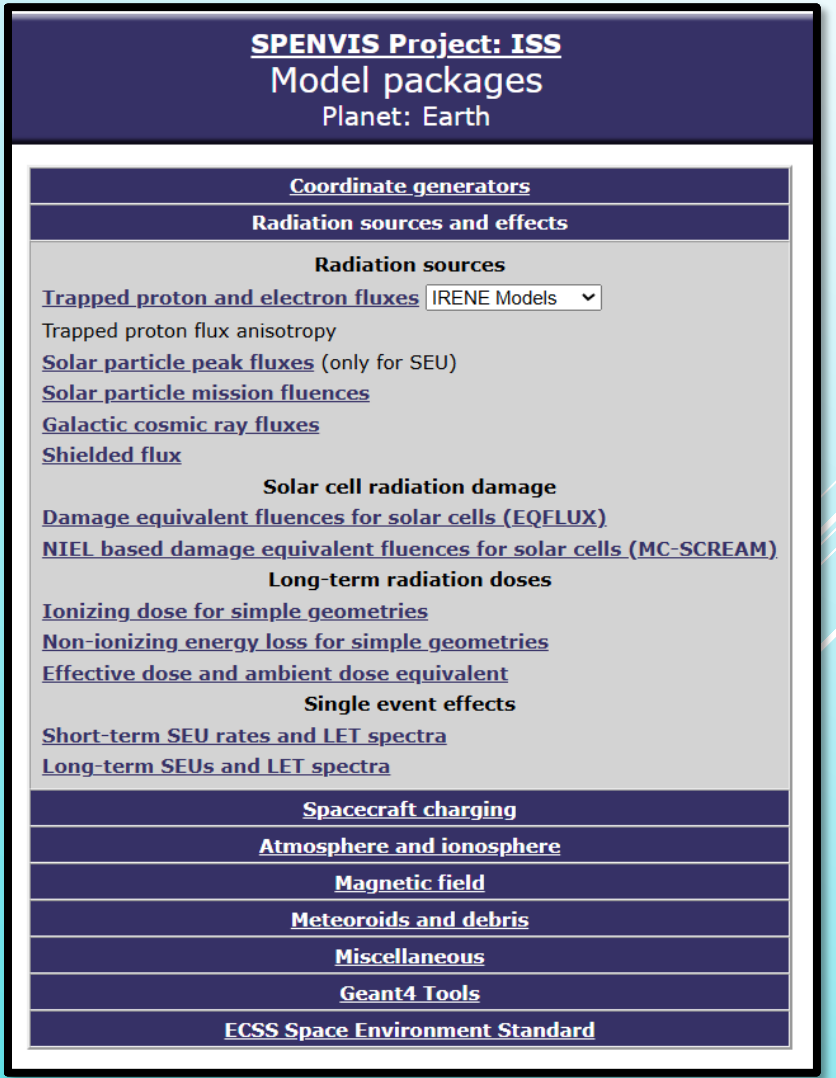
# SIMULATIONS

- Environment simulation tools
  - Simulations of the environment are often the best we can do based off models and real data taken by previous missions
  - Works well for various earth orbits and some planetary orbits that we have been investigating for decades, but becomes difficult with new frontier missions
  - “Strategic” environments are better understood from terrestrial test data
- Particle transport codes
  - These tools become very important when investigating complex geometries or secondary effects, like knock-on atoms or activation
- Radiation effects simulations “SPICE-like”
  - Very useful for device design but not a replacement for testing

# ENVIRONMENT SIMULATIONS

- Spenvis
  - Free online tool from ESA
  - Easy to learn basics to get TID & DDD estimates for missions

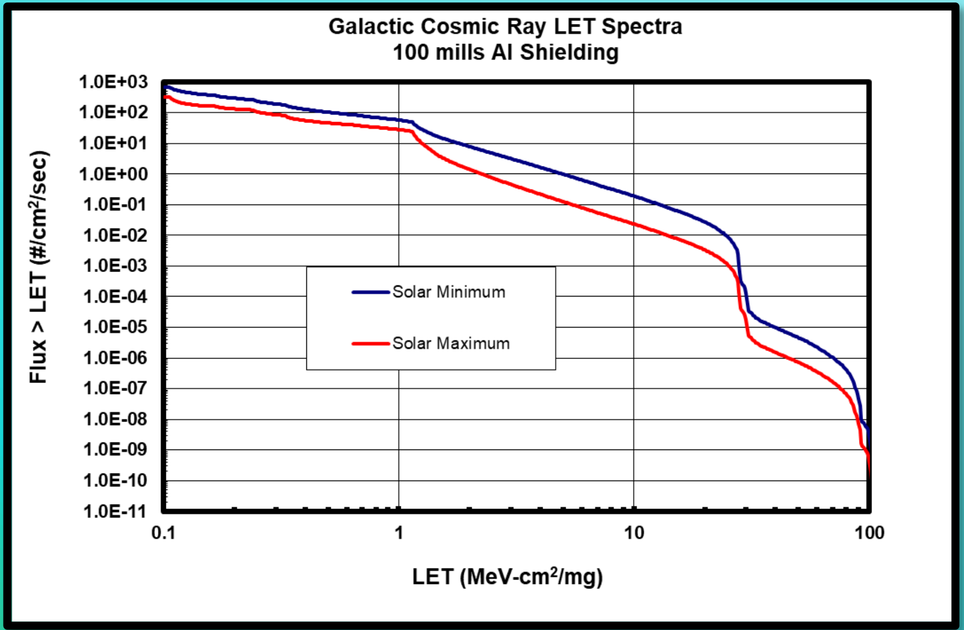


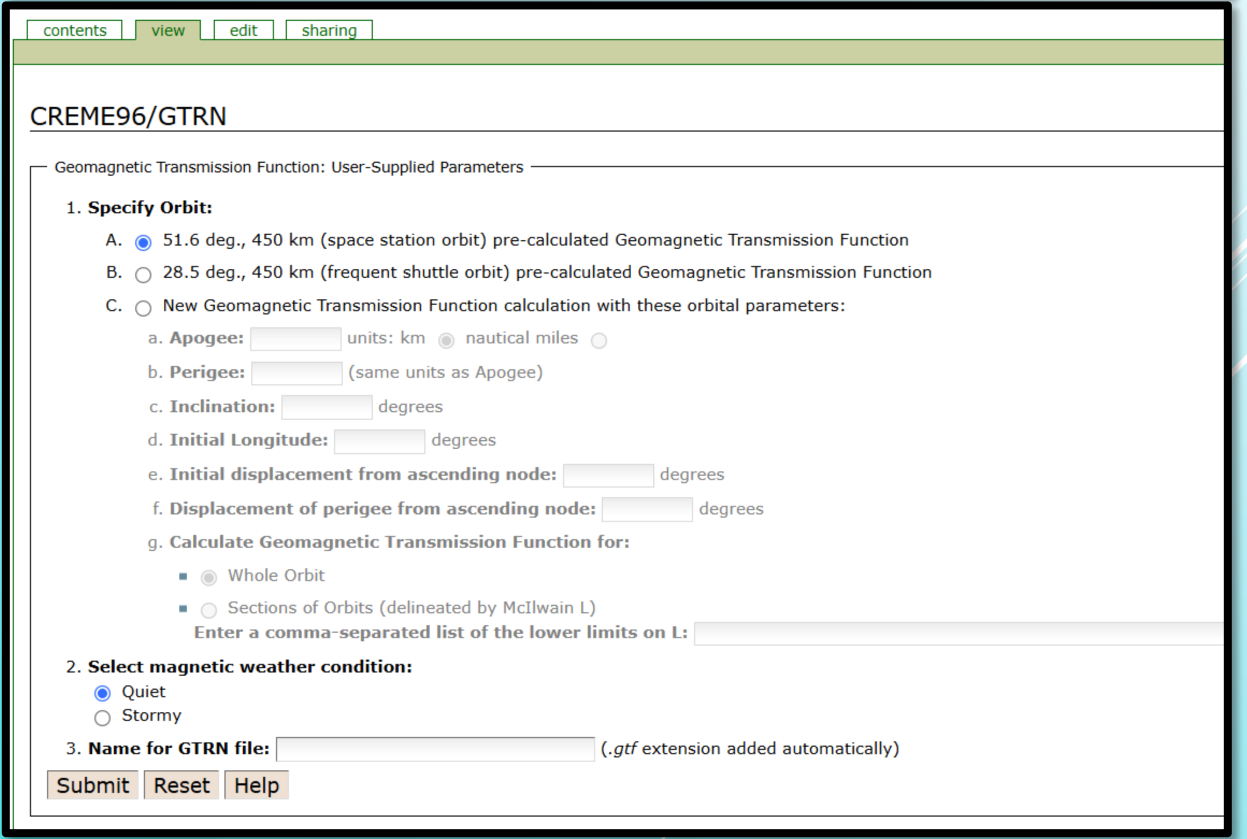

https://www.spenvis.oma.be/

# ENVIRONMENT SIMULATIONS

- CRÈME96
  - Also free and online
  - SEE environment modeling and basic transport
  - Steeper learning curve



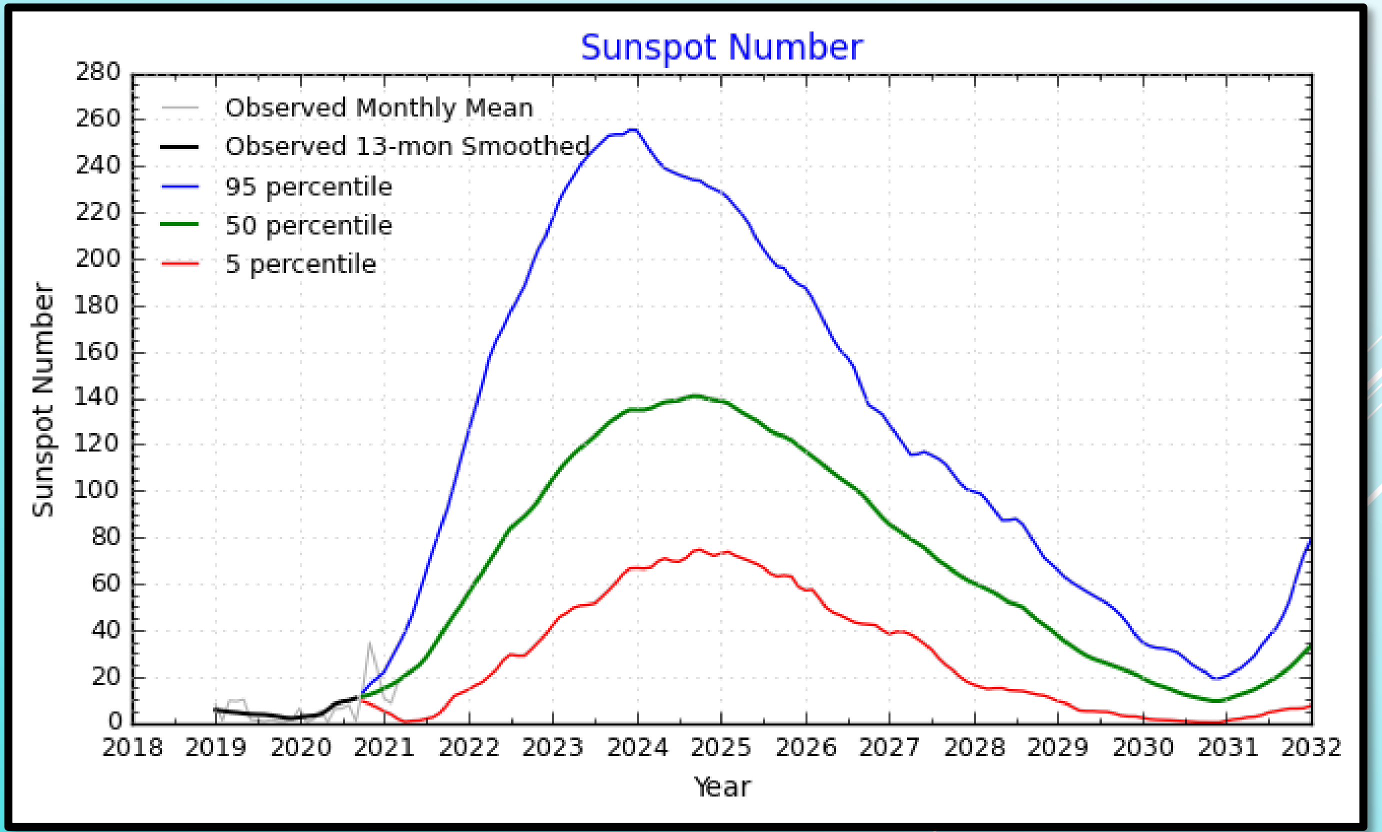

VANDERBILT UNIVERSITY School of Engineering ISDE




https://creme.isde.vanderbilt.edu/

# GALACTIC COSMIC RAYS (GCR) & SOLAR PROTON EVENTS (SPE)

- Solar maximum
  - Galactic cosmic ray fluxes lower
  - Solar particle events are more frequent and of greater intensity
- Solar minimum
  - Galactic cosmic ray fluxes higher
  - Solar particle events are less frequent and of lower intensity




https://www.nasa.gov/msfcsolar

# RADIATION TRANSPORT SIMULATIONS

- SRIM - http://www.srim.org
  - NSRL Stack up tool - https://www.bnl.gov/nsrl/stackup/
- NOVICE - https://empc.com/novice-software-2/
- FASTRAD - https://www.fastrad.net/
- MCNP - https://mcnp.lanl.gov/
- FLUKA - https://fluka.cern/
- GEANT - https://geant4.web.cern.ch/

# NSRL STACK UP TOOL

- GUI Based on SRIM tables
- Geared toward NSRL but works for generic beams
- Very useful for quick checks
- Limited materials but they are always adding

## E / ΔE / Δx Calculator

| | |
|---|---|
| Target: | Silicon |
| Ion: | Bi-209 |

2.32 g/cm$^3$

| Energy [MeV/u] | dE/dx [MeV/(mg/cm$^2$)] | Range [mm] | Z Straggling [mm] | XY Straggling [mm] | | |
|---|---|---|---|---|---|---|
| 128 | 30.3279 | 2.5249 | 0.0947 | 0.0074 | 2058.172775 | ions/cm$^2$/rad |

| Range [mm] | Energy [MeV/u] | dE/dx [MeV/(mg/cm$^2$)] | Z Straggling [mm] | XY Straggling [mm] | | |
|---|---|---|---|---|---|---|
| 127.75 | 1995.4664 | 11.7741 | 4.2320 | 0.2030 | 5301.487097 | ions/cm$^2$/rad |

| dE/dx [MeV/(mg/cm$^2$)] | Energy [MeV/u] | Range [mm] | Z Straggling [mm] | XY Straggling [mm] | | |
|---|---|---|---|---|---|---|
| 75 | 20.6485 | 0.2237 | 0.0067 | 0.0015 | 832.2666667 | ions/cm$^2$/rad |
| | 1.1073 | 0.0220 | 0.0007 | 0.0008 | 99.9545 | 11.7606965 |
| | | | | | max dE/dx | min dE/dx |

## Multiple Layers Calculator

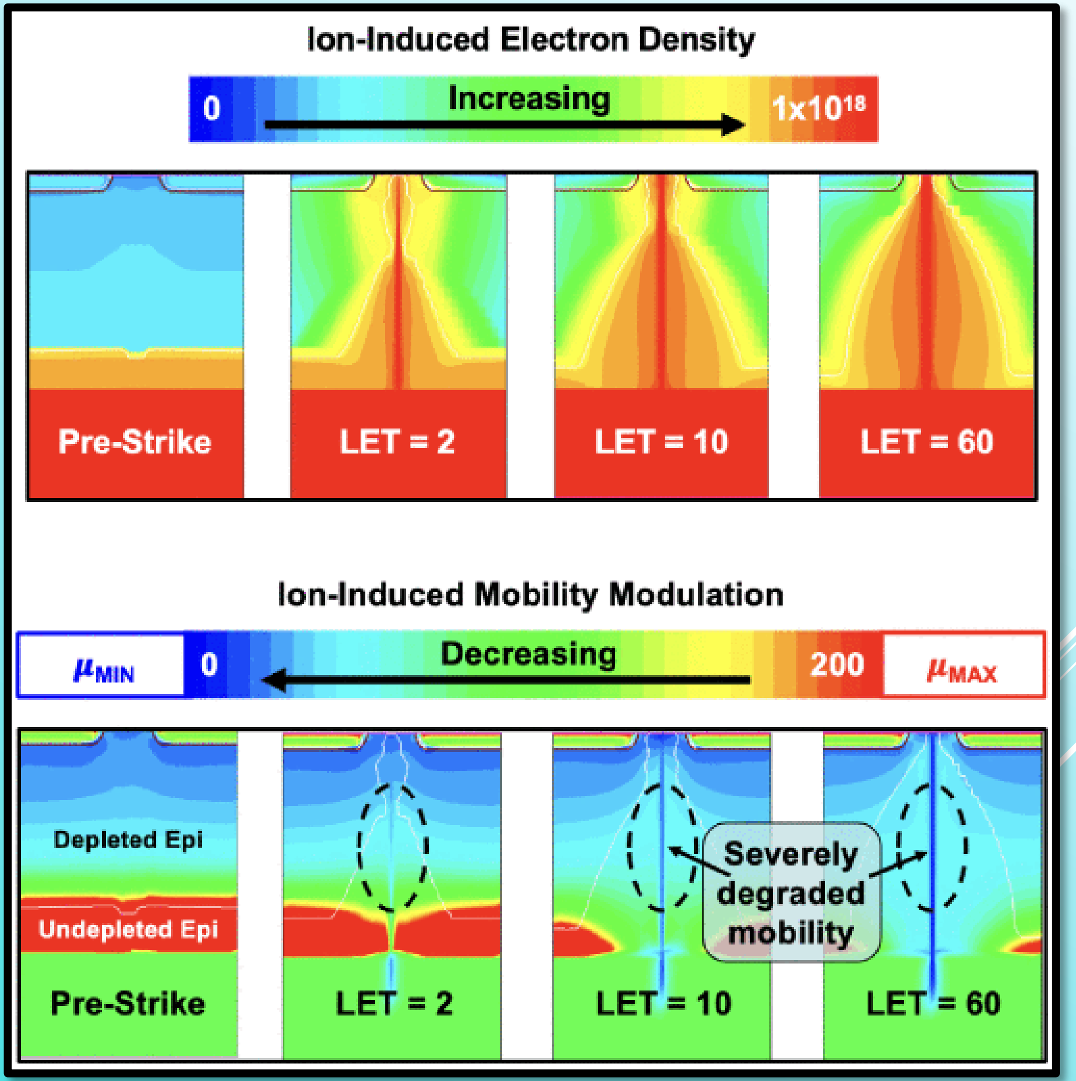
Beam Energy [MeV/u]: 600

| | Material | Thickness [mm] | Exit Energy [MeV/u] | Residual Range [mm] | Entrance LET | Exit LET |
|---|---|---|---|---|---|---|
| Layer 1: | Air | 5432.1 | 550.47 | 40644.32 | 15.59 | 16.06 |
| Layer 2: | Gold | 0.05 | 545.96 | 4.26 | 9.70 | 9.73 |
| Layer 3: | Water | 14.3 | 413.88 | 28.05 | 18.36 | 20.48 |
| Layer 4: | Silicon | 2.1 | 374.64 | 13.00 | 16.51 | 17.23 |
| Layer 5: | CdTe | 0.1 | 371.05 | 7.06 | 12.62 | 12.68 |
| Layer 6: | Kapton | 0.8 | 360.23 | 17.57 | 19.58 | 19.85 |
| Layer 7: | $CO_2$ | 10.8 | 360.05 | 14164.42 | 19.04 | 19.05 |
| Layer 8: | Concrete | 35 | 0.00 | -23.43 | 18.40 | 0.00 |
| Layer 9: | Water | 0 | 0.00 | 0.00 | 0.00 | 0.00 |
| Layer 10: | Water | 0 | 0.00 | 0.00 | 0.00 | 0.00 |

# RADIATION EFFECTS SIMULATIONS

- TCAD
- MRED

- Can simulate charge
- Looks at fields and materials properties




[5] D.R. Ball in IEEE TNS 2026

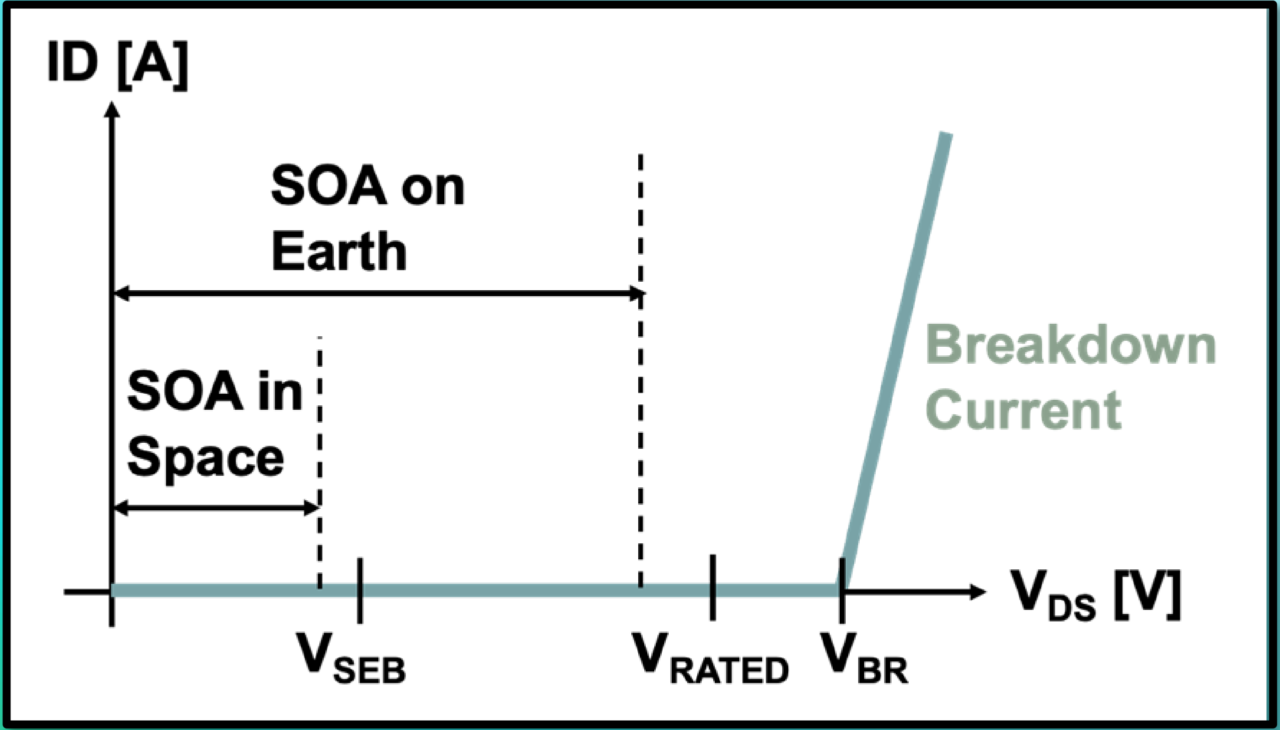
# QUESTION BREAK

Questions on Simulations

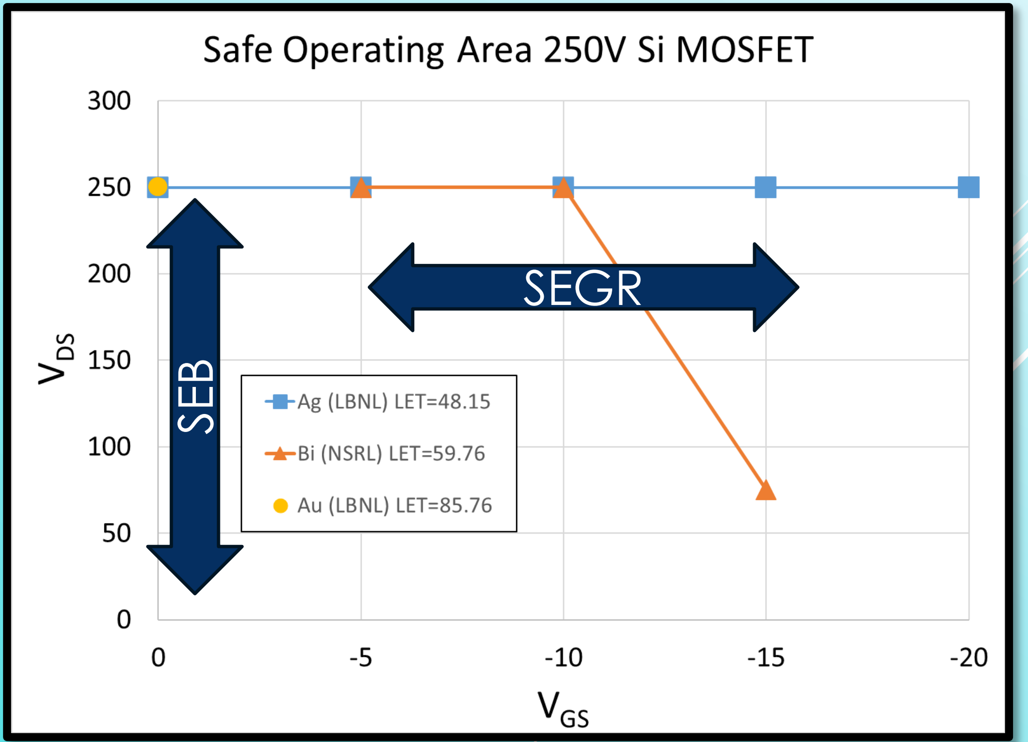
Data Analysis and Reporting

# POWER DEVICE SEE SOA

## Typical reporting of $V_{SEB}$ and SOA




[6] S. L. Kosier, IEEE TNS 2025



# DATA ANALYSIS

- Weibull Curves
  - Pick an LET
  - Count Ions until SEE
  - Gather Statistics
  - Fit Curve
- Convolve with LET Distribution and sensitive volume to get error rate!
- See R. Ladbury for more

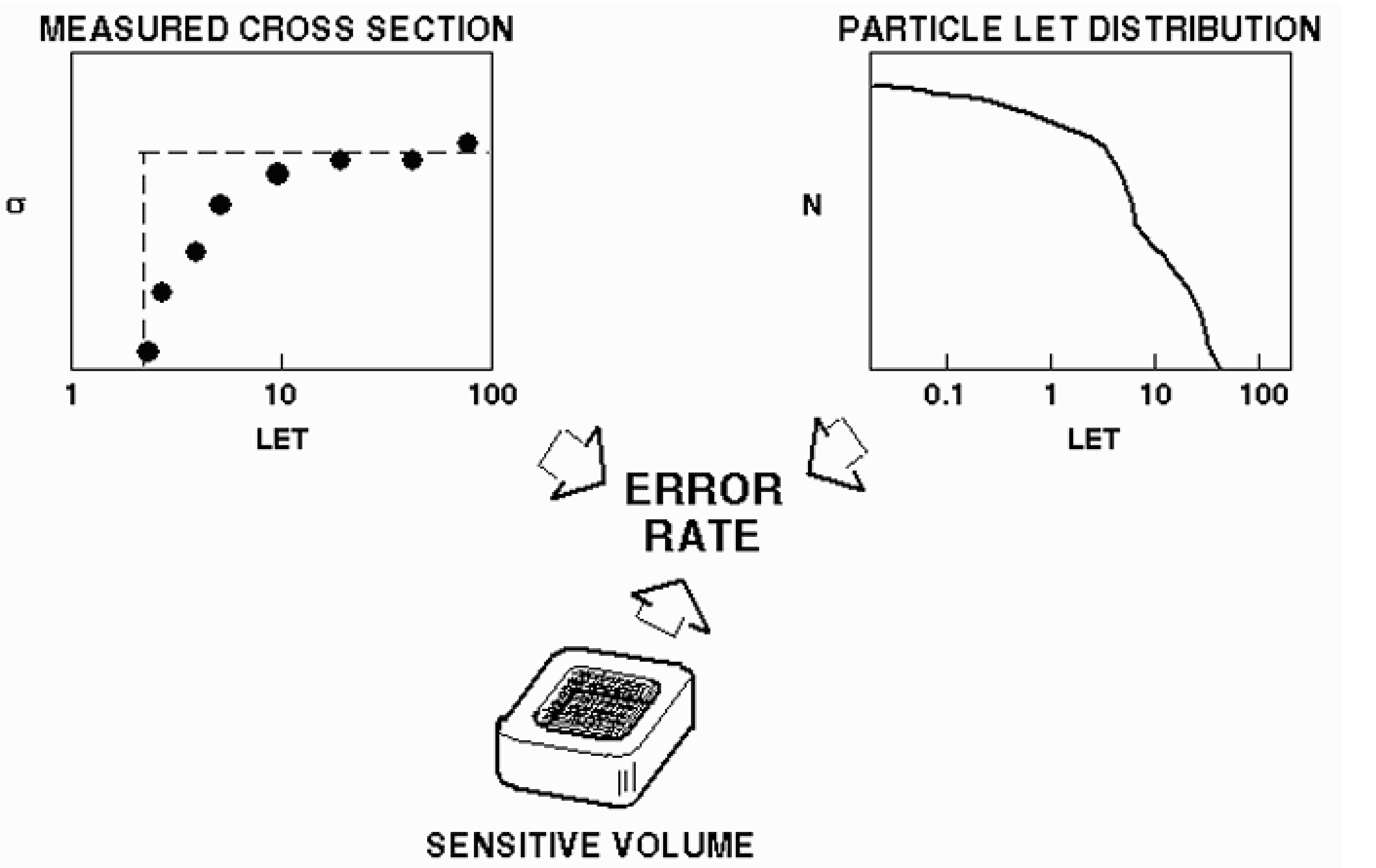
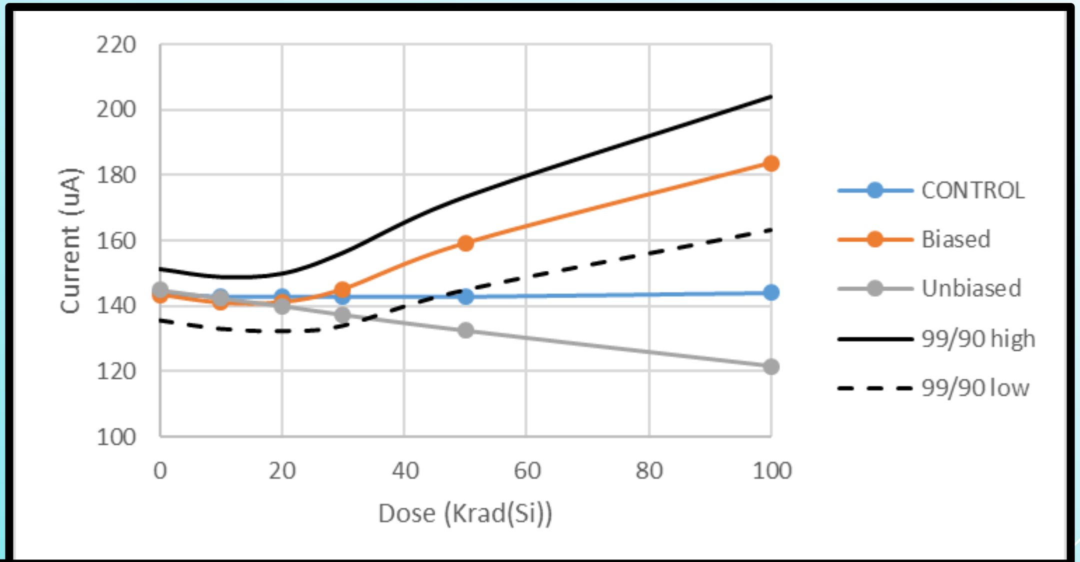


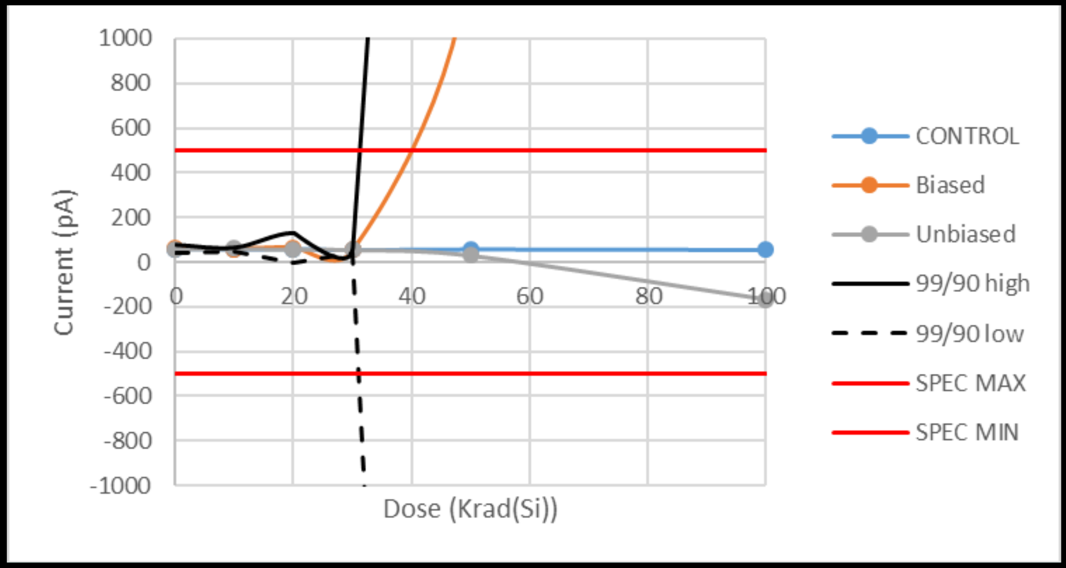

Figure 4.3: An illustration of the three main functions that are used in SEE error rate calculations.

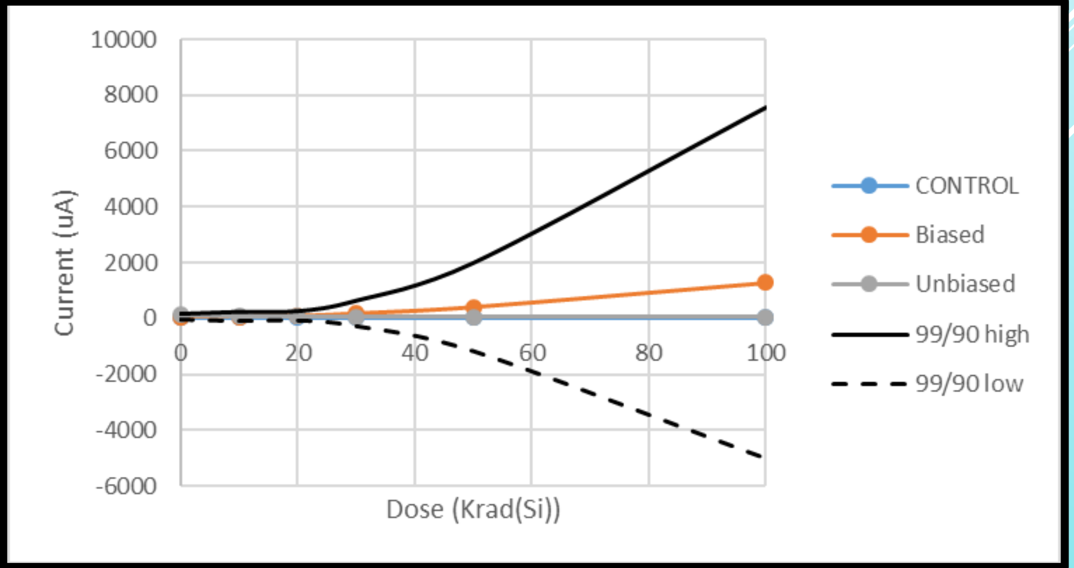
[7] K.A. LaBel, NASA GSFC 1996

# DATA ANALYSIS

- Parametric degradation and KTL values
- Standard deviation and sample size matter
  - Bottom left: Obvious parametric failure
  - Top right: Parametric drift in one direction
  - Bottom right: Little apparent drift but real divergence due to data spread and KTL statistics



# REPORTING

- Satisfying mission specific requirements
  - Qualification – Testing only under conditions expected for the specific mission at hand
    - Pass/Fail
- Broader comprehensive reporting to aid future missions
  - Characterization – Full parameter space analysis to aid in part selection for a broad range of applications
- Databases
  - Both types of testing/reporting can be useful for other groups.  Often, even just a hint of whether a candidate part may be viable for a certain environment is helpful to other projects and can save on cost and schedule.

# INSTITUTION DEPENDENT REPORTING

- Manufacturers
  - Often comprehensive testing with limited reporting for the intended use case
  - They want to share data to prove their part will perform in the advertised environment
  - Often little is available on the fringe cases or at the limit of performance to ensure satisfied customers, but this often means parts can be pushed a little further than what they are sold as
- Universities
  - Tend to thrive on publications leading to comprehensive testing and transparency
  - Often investigating an underlying mechanism or new technology so results can be overly academic or focused on experimental devices not available commercially

# INSTITUTION DEPENDENT REPORTING

- Government
  - Falling into one of 2 camps: data is often classified or open and available to the public depending on the application for which the device is being investigated
- Industry
  - Like government, this is usually a mixed bag where people are either widely publishing results or, depending on the proprietary nature of the application or technology, these results may be kept internal

# RADIATION EFFECTS DATABASES

- NASA GSFC https://nepp.nasa.gov/radhome/RadDatabase/RadDataBase.html
- JPL https://www.jpl.nasa.gov/go/space-radiation/radiation-database/
- ESA https://esarad.esa.int/
- IEEE TNS https://ieeexplore.ieee.org/Xplore/home.jsp
- NSREC REDW https://www.nsrec.com/

Private examples

- Zero G https://www.zerogradiation.com/radiation-database
- The Rad Team https://radiationteam.com/radiation-parts-database/
- Nucleon https://nucleonspace.com/#features

# MITIGATION STRATEGIES

- Shielding
- Derating
- Power Management
  - Power cycling
  - Reduce time at worst case bias
- Error Detection And Correction
- Redundancies
  - Voting
- Replacement? (Lunar Missions)
- Quantify and Accept Risk

# REFERENCES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[3] J. -M. Lauenstein, M. C. Casey, R. L. Ladbury, H. S. Kim, A. M. Phan and A. D. Topper, "Space Radiation Effects on SiC Power Device Reliability," 2021 IEEE International Reliability Physics Symposium (IRPS), Monterey, CA, USA, 2021, pp. 1-8, doi: 10.1109/IRPS46558.2021.9405180.

[4] C. Martinella et al., "Heavy-Ion Microbeam Studies of Single-Event Leakage Current Mechanism in SiC VD-MOSFETs," in IEEE Transactions on Nuclear Science, vol. 67, no. 7, pp. 1381-1389, July 2020, doi: 10.1109/TNS.2020.3002729.

[5] D. R. Ball et al., "Unifying Model for Estimating SELC/SEB in SiC Power Devices Using a Nonlinear Ion Track Resistance," in IEEE Transactions on Nuclear Science, vol. 73, no. 4, pp. 1225-1234, April 2026, doi: 10.1109/TNS.2026.3666825.

[6] S. L. Kosier et al., "Physical Model for SiC Power Device Heavy-Ion Burnout Based on Pre-Strike Depletion Capacitance Energy Storage," in IEEE Transactions on Nuclear Science, vol. 72, no. 4, pp. 1418-1424, April 2025, doi: 10.1109/TNS.2025.3546892.

[7] LaBel, K. A., Gates, M. M., Barth, J. L., Johnston, A., & Marshall, P. (1996, February 15). Single event effect criticality analysis. NASA Goddard Space Flight Center. https://nepp.nasa.gov/docuploads/6D728AF0-2817-4530-97555B6DCB26D083/seecai.pdf

# THANK YOU!

# Questions?

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NASA GSFC REAG

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