



# Journal Club: Comparison of Single-Event Transients in an Epitaxial Silicon Diode Resulting From Heavy-Ion-, Focused X-Ray-, and Pulsed Laser-Induced Charge Generation

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# Ψ Article Information

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## Comparison of Single-Event Transients in an Epitaxial Silicon Diode Resulting From Heavy-Ion-, Focused X-Ray-, and Pulsed Laser-Induced Charge Generation

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**Abstract**—Heavy-ion, focused X-ray, and pulsed laser single-event transient (SET) experiments are performed on a silicon epitaxial diode. Collected charge, transient rise times, and transient fall times are calculated and compared between different sources. The transient shape characteristics depend on the source (ion, X-ray, or laser), even when similar amounts of charge are generated. The observed differences are examined and explained in terms of basic charge collection mechanisms.

**Index Terms**—Focused X-ray, heavy ions, pulsed laser, single-event effects (SEEs), single-event transients (SETs), two-photon absorption (TPA).

### I. INTRODUCTION

ROUND-BASED testing of single-event effects (SEEs) in electronics is an important and necessary step for ensuring the reliability of spacecraft systems. The availability

K. L. Ryder *et al.*, “Comparison of Single-Event Transients in an Epitaxial Silicon Diode Resulting From Heavy-Ion-, Focused X-Ray-, and Pulsed Laser-Induced Charge Generation,” *IEEE Trans. Nucl. Sci.*, vol. 68, no. 5, pp. 626–633, May 2021.

# Overview of Ryder et al. , 2021

- Ryder et al. Compare SETs generated in silicon epitaxial diode using three different charge-generation sources:
  - **Heavy Ions** (BNL 88" Cyclotron)
  - **Focused X-Rays** (Argonne APS)
  - **Pulsed femtosecond laser** (NRL Ultrafast Laser Facility)
- The **goal** is to see how different **spatial** and **temporal** charge-generation profiles change **SET shape (rise time, fall time, collected charge)**, even when the **total deposited charge** is the **same**.
- Ryder et al. claims:
  - Different charge-generation mechanisms produce non-equivalent SET shapes, even with similar total charge
  - Heavy ions, lasers, and X-rays deposit charge differently
  - SET differences stem from electric-field perturbation (“funneling”)
  - Sensitive volume varies with source and bias
  - No universal correlation between test methods
  - Laser/X-ray methods remain useful for SEE mechanism studies

# **ΨIEEE Transactions on Nuclear Science TNS**

- Journal was first published in 1954 as **Transactions of the Institute of Radio Engineers Professional Group on Nuclear Science**
- Under the IRE this journal was published from 1955-1962 as the **IRE Transactions on Nuclear Science**
- IEEE was formed in 1963, following a merger of **IRE** with the **American Institute of Electrical Engineers**.
- Sponsored by the **IEEE Nuclear and Plasmas Sciences Society**
- Current impact factor of ***IEEE Transactions on Nuclear Science*** is **1.9** (measure of the frequency with which the average article in a journal has been cited in a particular year)
- Peer-reviewed scientific journal

## **IEEE Transactions on Nuclear Science**

**1.9**  
Impact Factor

**0.00467**  
Eigenfactor

**0.376**  
Article Influence Score

**3.9**  
CiteScore  
Powered by **Scopus**

## Research Groups

- Vanderbilt University Radiation Effects Group
  - Vanderbilt University Department of Electrical Engineering and Computer Science
  - Vanderbilt University Department of Physics and Astronomy
- The Aerospace Corporation
- U.S. Naval Research Laboratory (NRL)
- Beijing Microelectronics Technology Institute (BMTI)
- KeyW Corporation



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- U.S. Department of Energy/NNSA Contract DE-NA0003525
- NASA Grant 80NSSC20K0424

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# The Context (Technique)

- The author's published this paper during **facility availability is decreasing**
  - Industry standard but aging accelerators testing harder to access
- **Causing alternative SEE testing** methods to become increasingly important
  - **Pulsed Lasers**
  - **Focused X-rays**
    - Offer refined control but different physical charge-generation mechanisms
- Charge-generation profiles **differ dramatically** between **sources**
  - **Heavy Ion:** Linear Energy Transfer (LET) Track
  - **X-rays:** exponential attenuation
  - **Pulsed Lasers:** Gaussian Two-Photon Absorption (TPA)
- **Goal:** Understand whether different sources can—or cannot—replicate each other's SET signatures.

U.S. NRL developed optical configuration that uses a quasi-Bessel beam to generate an extended charge-generation profile



# The Context (Device Physics & Scaling)

- Epitaxial Silicon Diode Structure:
  - ~25  $\mu\text{m}$  active region
  - 19  $\mu\text{m}$  epilayer sits above a heavily doped substrate that limits field funneling at high bias
- Depletion scales with bias:
  - -5 V  $\Rightarrow$  ~4  $\mu\text{m}$  (weak field, strong modulation)
  - -90 V  $\Rightarrow$  ~15  $\mu\text{m}$  (nearly fully depleted; substrate truncation)
- SET behavior depends on how each source perturbs the electric field:
  - ions = narrow/high density, lasers = broader Gaussian, X-rays = wide/weak.
- Low bias  $\Rightarrow$  diffusion + field perturbation create large differences across sources.
- High bias  $\Rightarrow$  strong drift collection makes SETs more similar
- Sensitive volume increases at low bias and converges across sources at high bias

## Slide 7

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**JM1** Need to configure wording to allow for figure to show. Figure is the actual Silicon Diode Structure  
Medina, Jaiden F, 2025-12-02T17:57:11.699

**JM2** The Epitaxial Silicon Diode Structure description comes from the reference [23]  
Medina, Jaiden F, 2025-12-02T18:09:27.193



# The Context (Historical & Scientific BG)

- Heavy-Ion SEE research began in the 1970s
- Pulsed lasers and X-rays have been used for SEE testing for decades
  - Correlation directly to ions is still imperfect, not used for spaceflight qualification
- **Modern challenge:**
  - To find when alternative testing discussed in this paper (laser/ X-ray) can meaningfully supplement heavy-ion data, and when it cannot
- Ryder et al. Contribute to this research by:
  - Quantitatively comparing the three sources (Heavy-Ion, Pulsed Laser, & X-Ray)
  - Holding total generated charge constant
  - Demonstrate fundamental differences in SET shape and sensitive volume

## Slide 8

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**JM1**      Context isn't very needed on slide. Can explain while we speak  
Medina, Jaiden F, 2025-12-02T17:57:33.891

# Ψ Methods - Introduction

- **Epitaxial Silicon Diode (BMTI)**
- Analysis of "Weak vs. Strong field conditions"
- **Top Layer** – Aluminum metal contact allows connection to measuring system with opening
- **p+ silicone layer** – created electric field when diode is reverse biased and where the charge collection begins
- **n- epitaxial layer** – radiation-induced charge generated and collected, and depletion region grows when both reverse biases is applied
- **n+ substrate layer** – gives diode mechanical support and low-resistance path. Heavily doped so depletion region stops expanding.
- **Bottom layer** - serves as bottom electrical connection to diode and ensures current transients are extracted with accuracy and quickly.

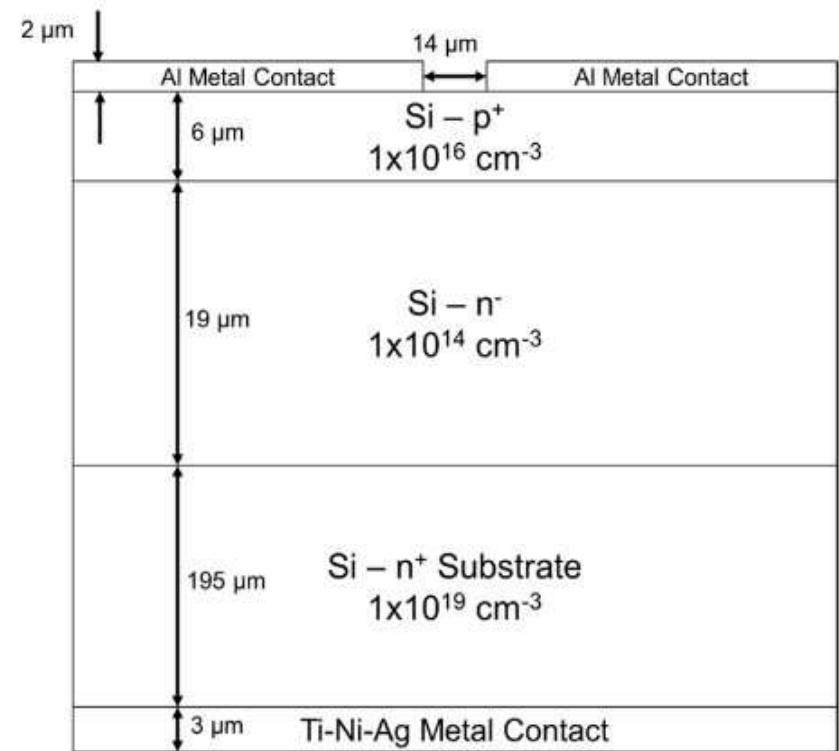


Fig. 1. Cross section of the BMTI diode. The diode is 1.82 mm<sup>2</sup> and 220-μm thick [22].

## Slide 9

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**JM1** Methods Discussed in Reference [25] [26][27]

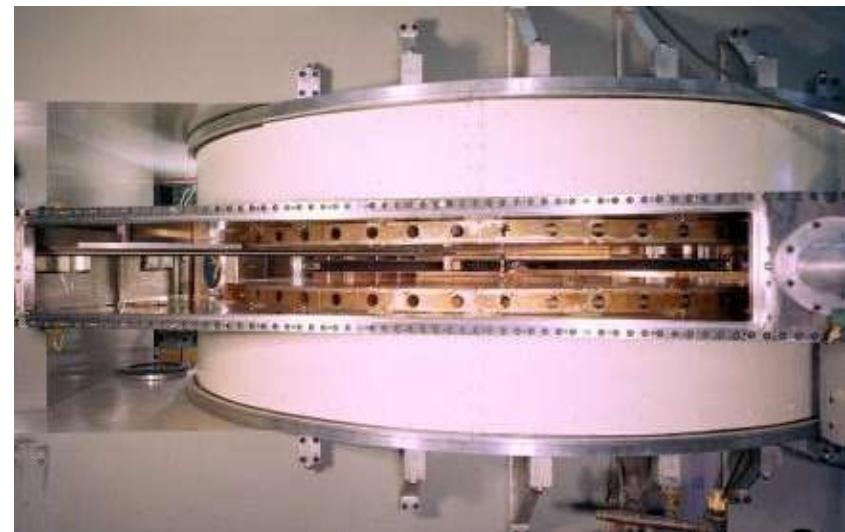
Medina, Jaiden F, 2025-12-02T18:12:47.441

**JM2** From Heavy Ion Microbeam- and Broadbeam-Induced Transients in SiGe HBTs

Medina, Jaiden F, 2025-12-02T18:47:37.144

# $\Psi$ Methods – Heavy Ion

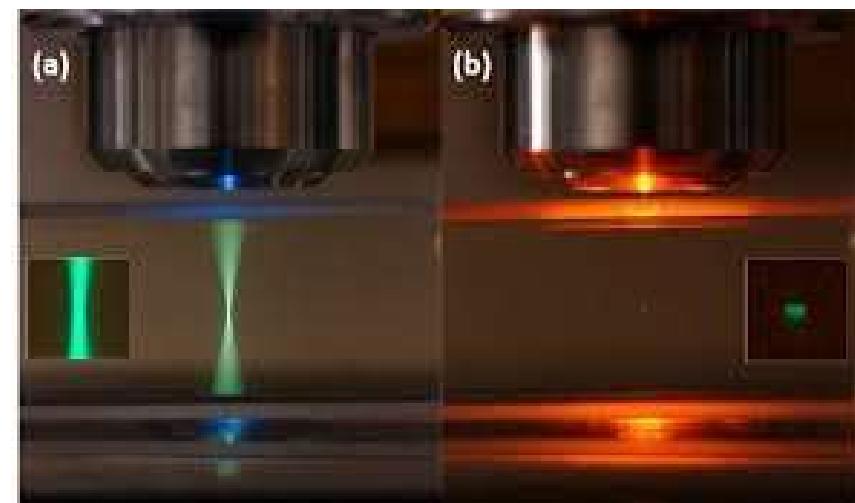
- Lawrence Berkeley National Laboratory (LBNL), 88-Inch Cyclotron
- **Nucleon cocktail (10 MeV)** – ions about the same energy per unit mass so they travel fast enough to deposit the charge deep into diode
- **Xenon = Heavy, Copper = Medium, Silicon = Lighter**
- **LET** – how much charge the ion releases per micrometer as it travels through the silicone layer
- **Purpose** – mimic high-frequency particle strike spacecrafts are exposed to in orbit as when the heavy-ion hits the diode, it creates the measurable SET
- **Heavy-Ion Testing** - "go-to" testing for radiation experiments, serves as baseline



Ion	Energy (MeV)	Surface Incident LET (MeV-cm <sup>2</sup> /mg)	Range in Si ( $\mu\text{m}$ )	Radial Dimension ( $\mu\text{m}$ )
Xe	1230	59	90	0.1
Cu	660	21	108	0.1
Si	29	6	142	0.1

# Ψ Methods – Pulsed Laser

- Naval Research Lab's UltraFast Laser Facility (NRLULF)
- **Purpose** – use very fast and high focused beam of light to generate electron-hole pairs inside of the silicon layer of the diode
- **Laser Wavelength** – 1260 nanometers, relevant as silicon does not naturally absorb light.
- Charge is generated by using **Two-Photon Absorption** (silicon absorbs photons combined energy and creates charge)
- **Three different pulse energies** – 400, 750 and 990 picojoules
- **Two focal positions** - at the surface of diode and other deepened in the silicon



Pulse Energy (pJ)	Focal Positions (μm)	Depth of Focus (μm)	FWHM Spot Size (μm)
990	0, 10.5	8.1	1.36
750	0, 10.5	8.1	1.36
400	0, 14	8.1	1.36

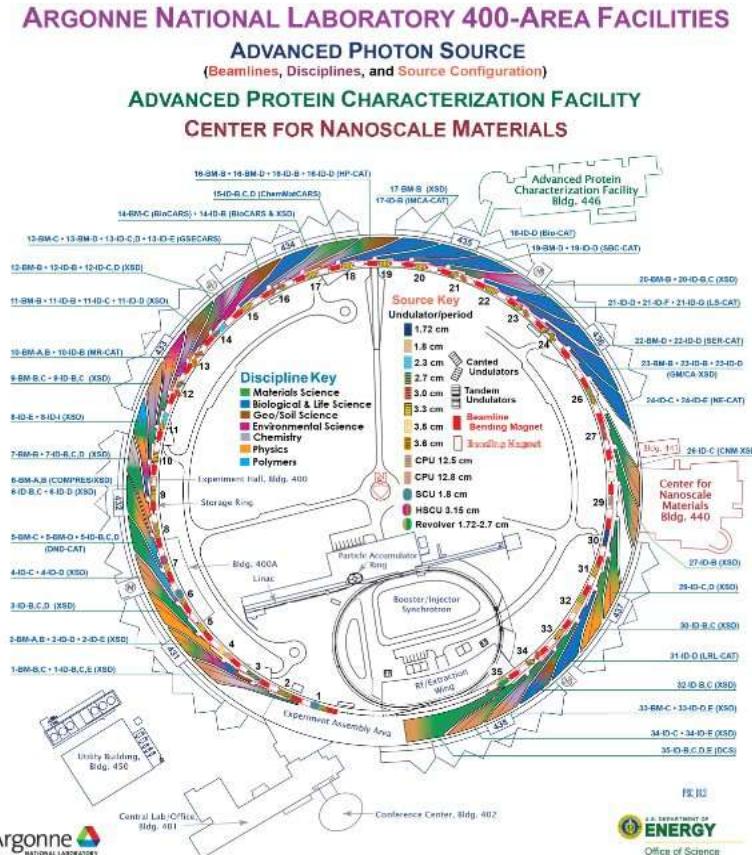
## Slide 11

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JM1      From A Dosimetry Methodology for Two-Photon Absorption Induced Single-Event Effects Measurements  
Medina, Jaiden F, 2025-12-02T18:47:56.491

# **Ψ Methods – Focused X-Ray**

- Advanced Photon Source (APS) at Argonne National Laboratory
  - **Purpose** – use very focused beam of high energy photons to deposit energy and generate charge in the device tested.
  - **Three different photon energies tested** - 8, 10 and 12 keV, relevant due to different layer penetration
  - **Three different flux levels tested** – control how much charge is deposited in device
  - X-ray beam is highly focused, allowing them to **deposit charge precisely where they want** inside of the device tested.



Photon Energy (keV)	Fluxes ( $\times 10^4$ photons/pulse)	Attenuation Length (μm)	FWHM Spot Size (μm)
12	5.4, 10, 19	229	$1.7 \times 1.9$
10	8.3, 17, 31	134	$1.7 \times 1.9$
8	4.4, 7.7, 14	69.9	$1.7 \times 1.9$

# $\Psi$ Transient Shape Analysis

- Amount of SETs captured for each of the experimental conditions:
  - Ion: 10,000 SETs
  - Laser: 200 SETs
  - X-ray: 500 SETs
- Double exponential function:
  - Used to remove noise and ensure consistency
- $f(t) = \begin{cases} 0, & t < a \\ I(e^{-\tau_1(t-a)} - e^{-\tau_2(t-a)}), & t \geq a \end{cases}$ 
  - $I \propto$  Amplitude
  - $a$  = the starting time of the SETs
  - $\tau_1$  &  $\tau_2$  = SET rise and fall times
- Following function results in an  $R^2$  value:
  - No fit resulting in an  $R^2$  value  $< 0.80$
  - Most fits result in an  $R^2$  value  $> 0.90$

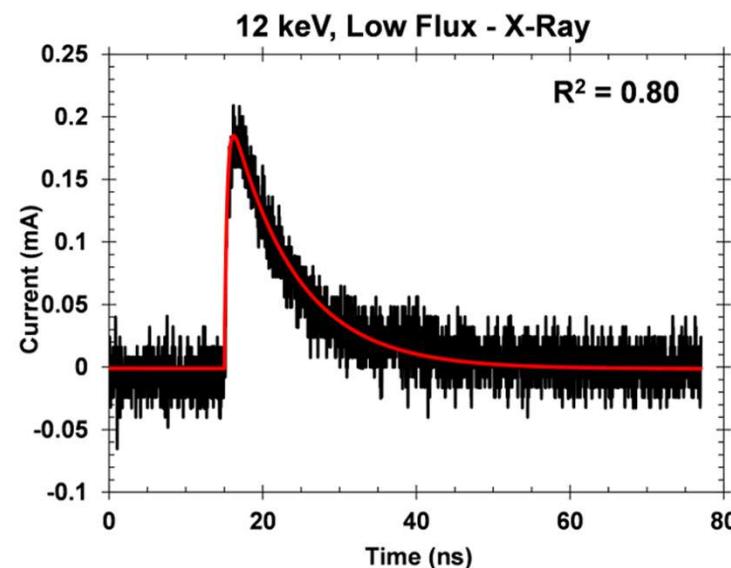


Fig. 2. Experimental (black) and fitted (red) SET from the 12-keV, low-flux X-ray experiments at a -5-V bias. This SET has the lowest  $R$ -squared value, 0.80, for any of the experimental SETs shown here.

# Ψ Charge-Generation Calculations, Heavy-ion

- The charge generated from a heavy ion can be calculated using the ion's LET curve
  - Integrating an ion's LET curve and converting energy into charge using the electron-hole pair creation energy, the amount of charge generated in a region of a device can be calculated using the equation

$$Q_{\text{gen,ion}} = \frac{\rho}{E_{\text{ehp}}} \int_l \text{LET}(x) dx = \frac{1}{E_{\text{ehp}}} \int_l \frac{dE_{\text{elec}}(x)}{dx} dx$$

- $\rho$  = density of the semiconductor material
  - 2.329 g/cm<sup>3</sup> for Si
- $E_{\text{ehp}}$  = the electron-hole pair create energy of the semiconductor
  - 3.6 eV/ehp in Si
- $l$  = 25 μm active region
- LET curves are found using stopping range of ions in matter (SRIM)

## Slide 14

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**JM1**      LET is the amount of energy lost per unit length by the ion to the surrounding semiconductor  
Medina, Jaiden F, 2025-12-03T19:05:15.139

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# Charge-Generation Calculations, Pulsed Laser & X-ray

- **Pulsed Laser (TPA):**
  - Charge-generation profiles computed using **Lumerical FDTD**
    - Accounts for **surface reflections, interference**, and other optical effects
  - Simulation volume: **40  $\mu\text{m}$  radius x 25  $\mu\text{m}$  depth**
  - Laser modeled with experimental parameters (Gaussian beam, **1.36  $\mu\text{m}$  FWHM spot, 130 fs pulse**)
  - Profiles generated for each focal position
- **Focused X-ray (APS):**
  - Charge generation follows **Beer's law**
  - Total generated charge computed using:

$$Q_{\text{gen},x\text{-ray}} = \frac{E_p}{E_{\text{ehp}}} (1 - e^{-\alpha l})$$

JM1

- APS beam parameters: **1.7 x 1.9  $\mu\text{m}$  FWHM spot, 120 ps pulsedwidth**
- Attenuation lengths in Si: **69.6, 133.7, 228.7  $\mu\text{m}$  for 8, 10, 12 keV photons**
- Produces a **broad lateral profile and long temporal charge-generation pulse**

TABLE IV

SUMMARY OF CHARGE GENERATED

Source	Charge Generated in Active Region (pC)
Heavy Ions	1.6 – 16
Pulsed Laser	2.3 – 18
Focused X-Ray	2.9 – 24

## Slide 15

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**JM1**

The ions and pulsed laser have similar transit times, while the focused X-rays have transit times three orders of magnitude slower, due to the long pulsewidth. These differences in spatial and temporal distributions of generated charge play a role in the observed differences in SET shape  
Medina, Jaiden F, 2025-12-03T19:51:09.245

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wowza  
Adams, Brady M, 2025-12-03T19:53:47.748

# $\Psi$ Charge Generation

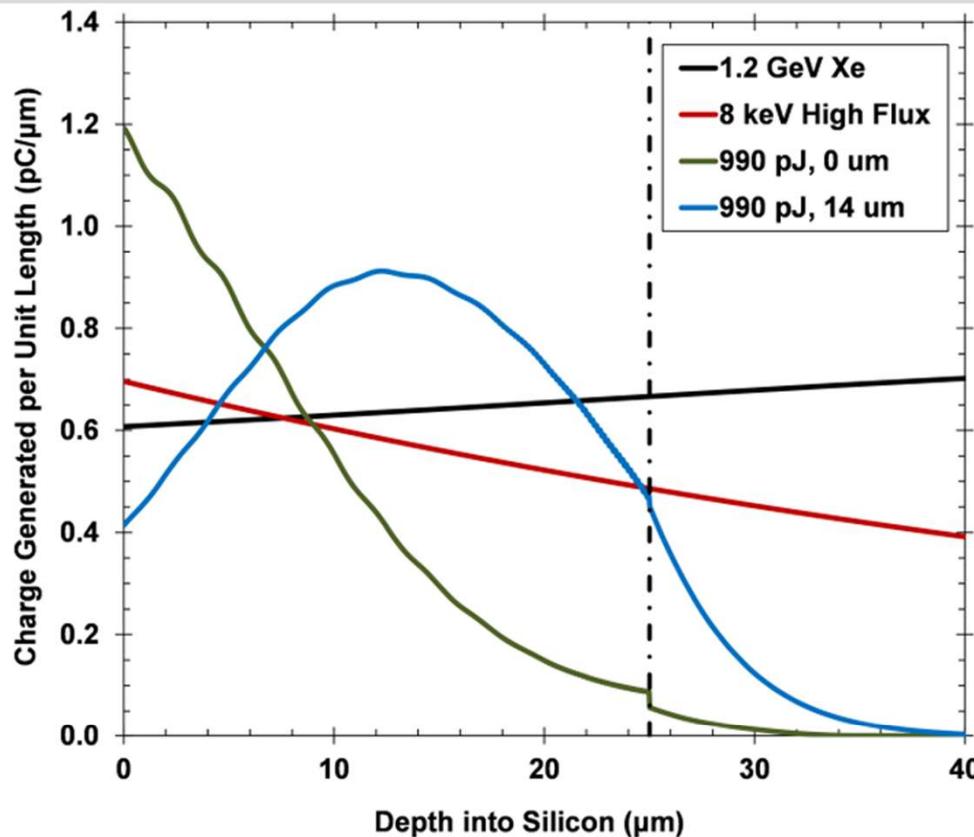
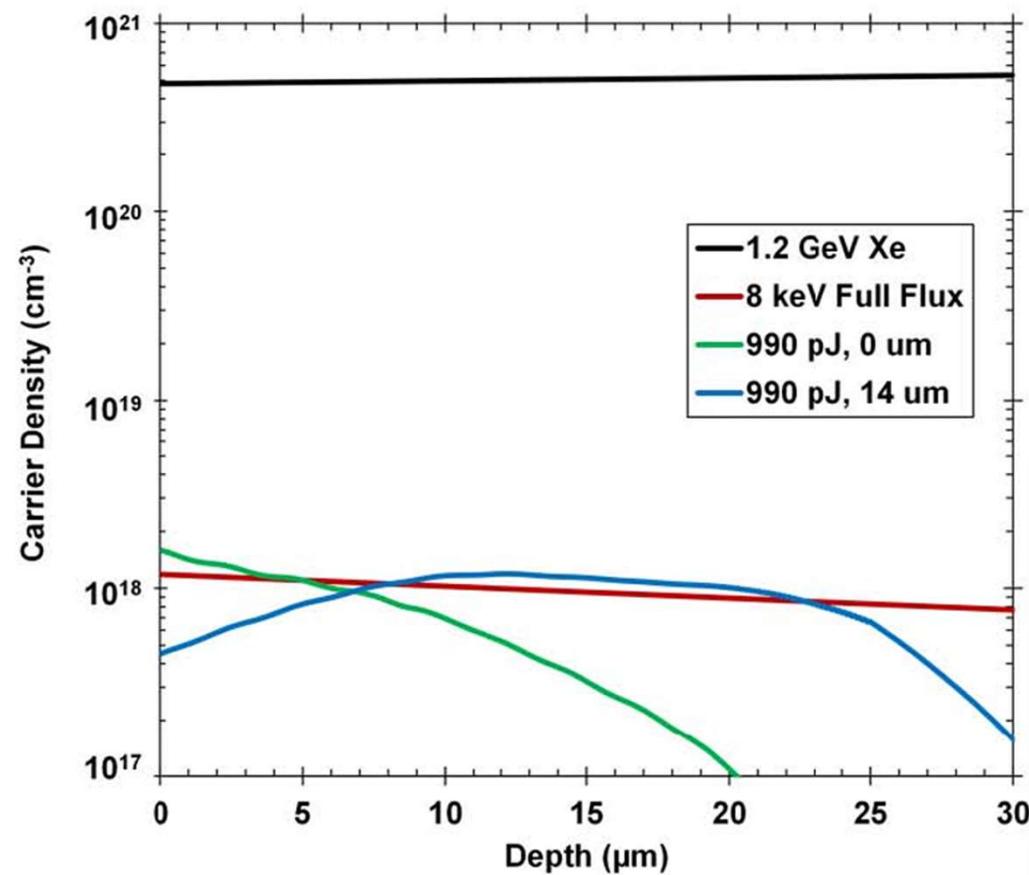
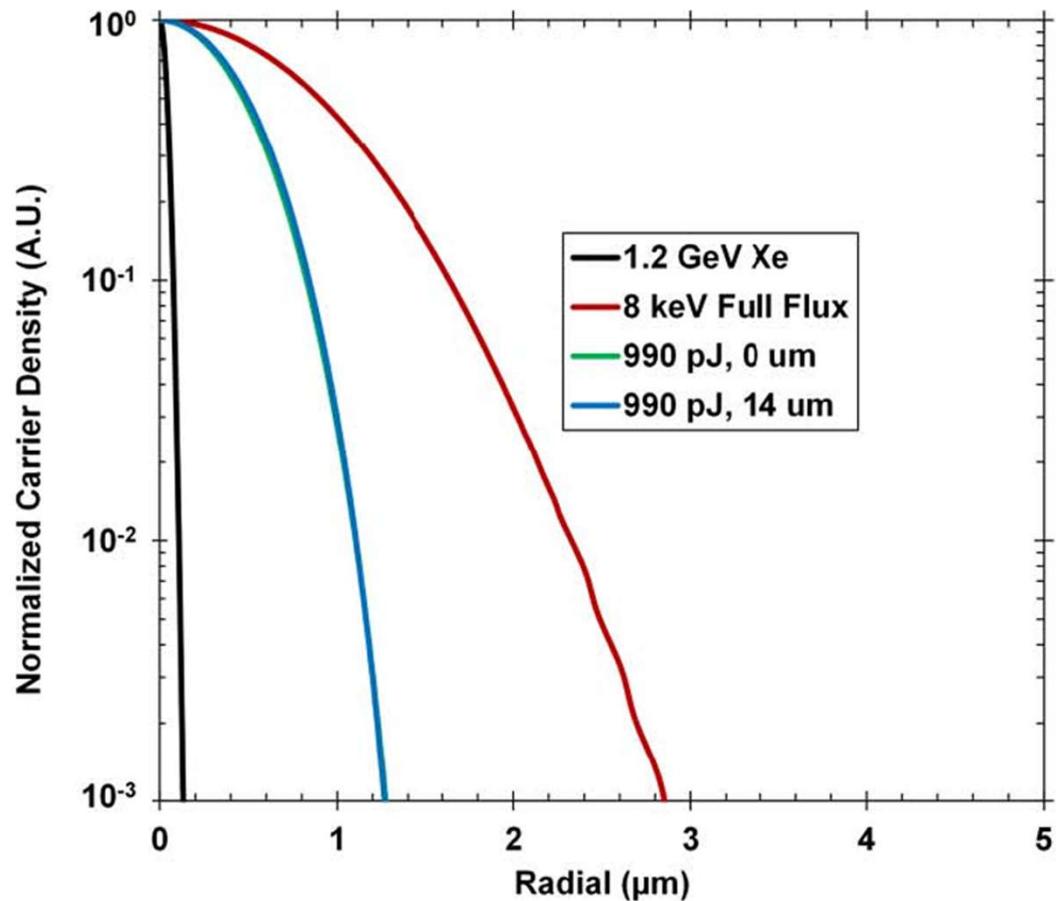


Fig. 3. One-dimensional charge-generation profiles in Si for the 1.2-GeV Xe ion (black), 8-keV high-flux X-ray pulse (red), 990-pJ laser pulse with a focal position of 0  $\mu\text{m}$  (green), and 990-pJ laser pulse with a focal position of 14  $\mu\text{m}$  (blue). The dashed black line shows the boundary between the active region and substrate in the diode.

TABLE IV  
SUMMARY OF CHARGE GENERATED

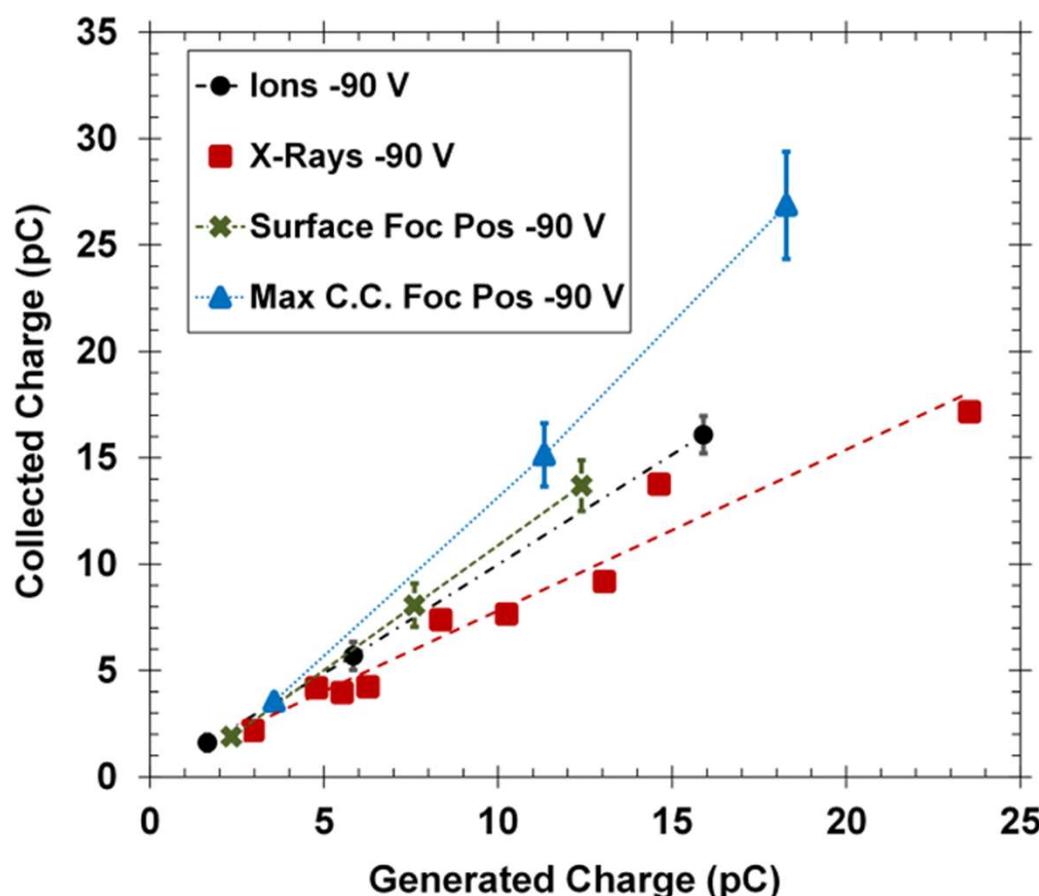
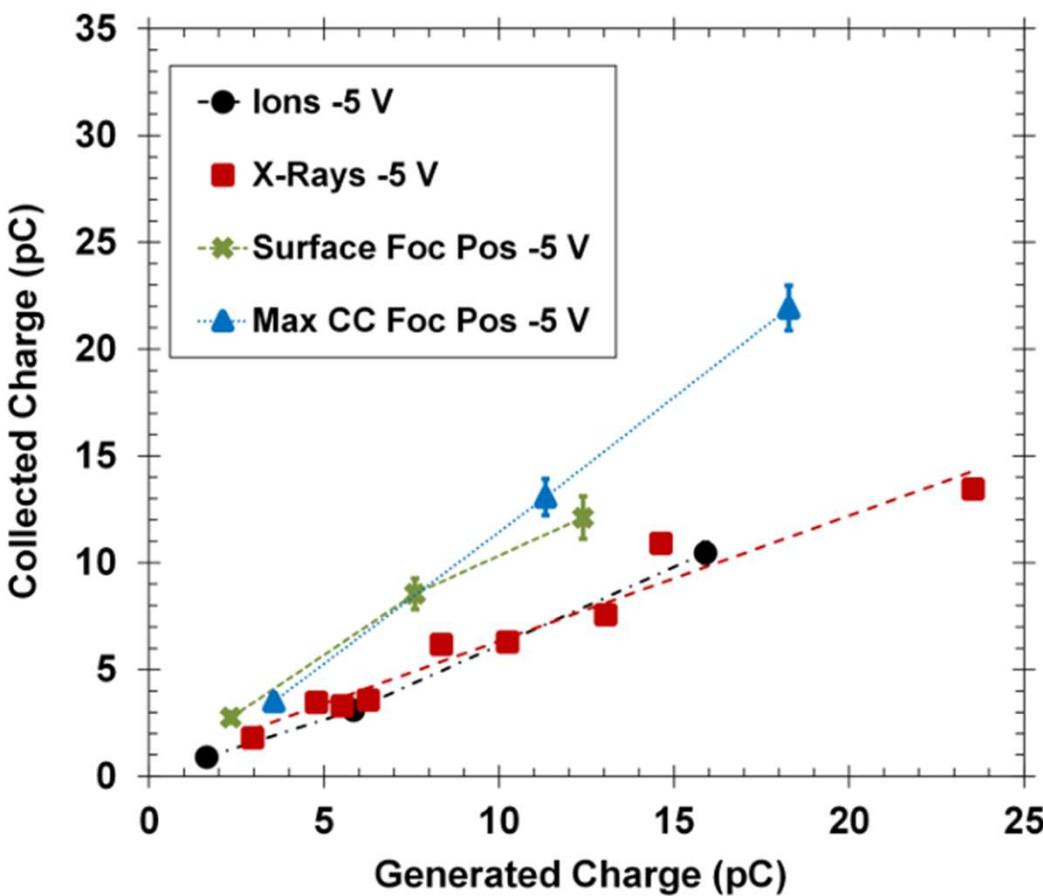
Source	Charge Generated in Active Region (pC)
Heavy Ions	1.6 – 16
Pulsed Laser	2.3 – 18
Focused X-Ray	2.9 – 24

# $\Psi$ Results – Carrier Density

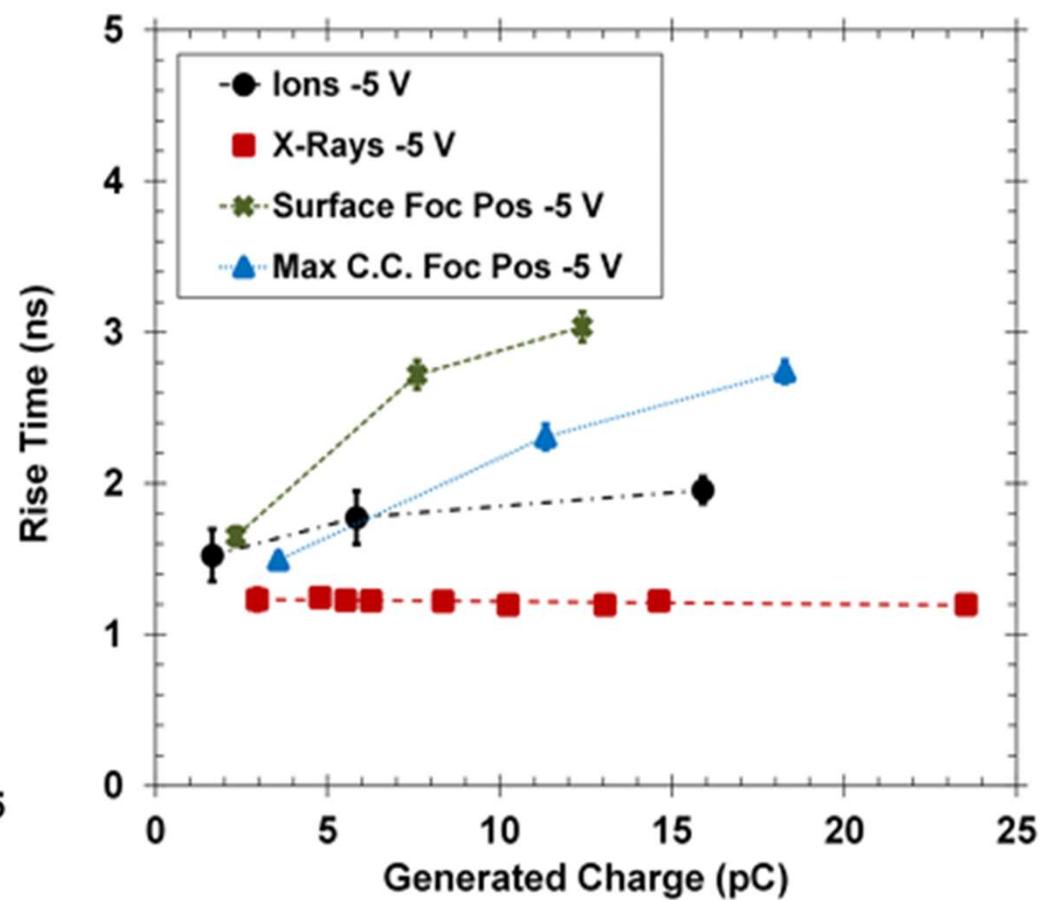
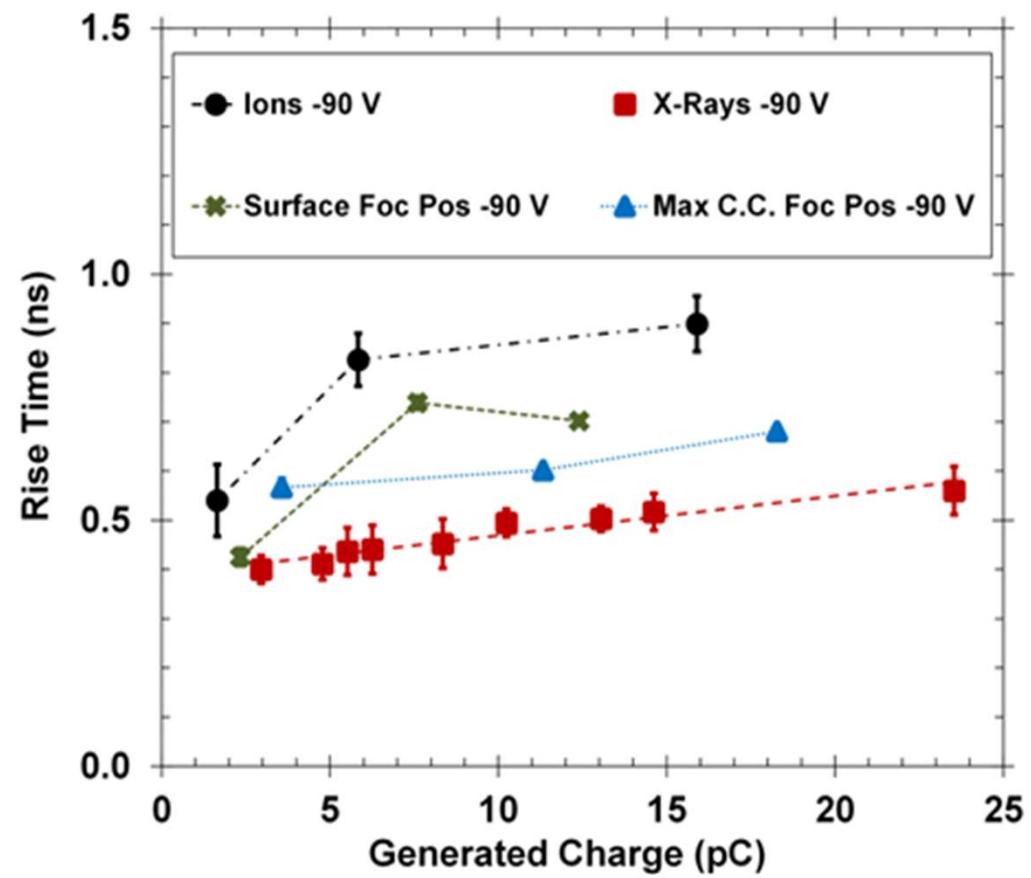


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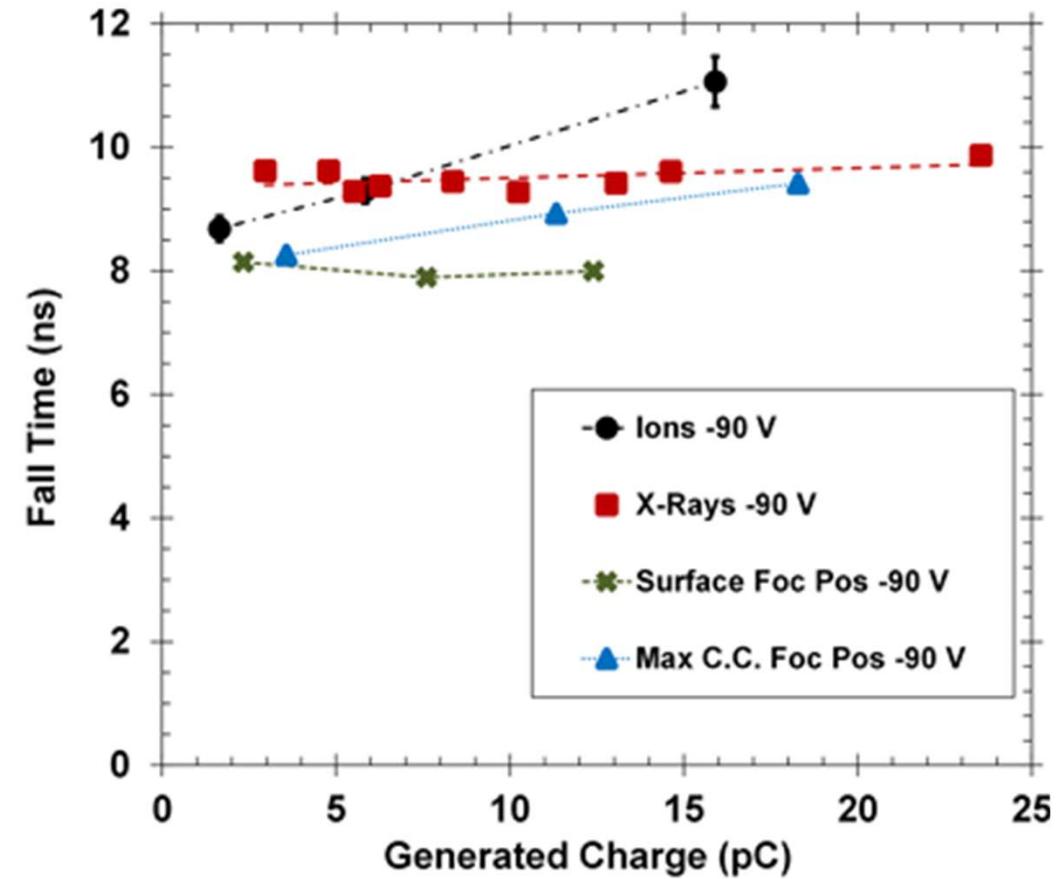
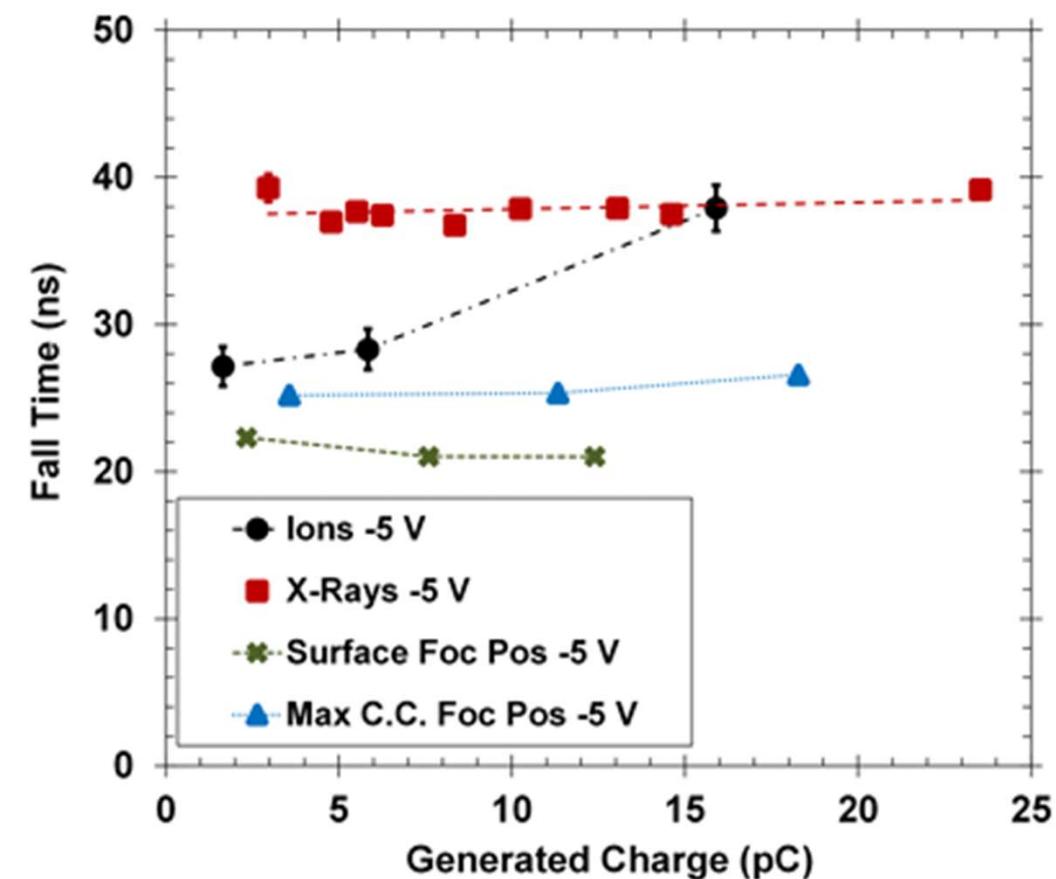
# Results – Collected Charge



# $\Psi$ Results – Rise Time



# $\Psi$ Results – Fall Time



# $\Psi$ Conclusions

- Heavy ions, lasers, and X-rays can generate similar total charge, but **SET shapes remain fundamentally different**. Differences arise from each source's **spatial and temporal charge-generation profile**, which alters electric-field perturbation and carrier transport.
- At low bias ( $-5$  V), SET rise/fall times differ strongly across all sources. At high bias ( $-90$  V), **strong drift collection** makes SETs appear more similar—but **not equivalent**.
- X-ray SETs show little dependence on generated charge, while ion and laser SETs show stronger dependence, especially at low bias.
- **No universal correlation** exists between heavy-ion, laser, and X-ray testing.
- Alternative methods are useful for **mechanism studies**, but **cannot replace heavy-ion testing** for predictive SEE evaluation.

# $\Psi$ New Facilities and Findings

- **Research Motivation** – aging heavy-ion testing facilities infrastructure
- Results of research of focused X-rays and pulsed lasers **pushed to upgrade and build new heavy-ion testing facilities**
- **Facility for Rare Isotope Beams (FRIB)**, at Michigan State University, opened in 2022 and was certified by 2025.
- **Lawrence Berkeley National Laboratory** in California, opened since 1931 and the network infrastructure was upgraded in 2022.
- **Texas A&M University's Cyclotron Institute**, facility upgrades have been ongoing since 2024, including the activation of the 88-inch cyclotron.





# Discussion Questions

- Do you think the authors justified why comparing heavy-ion, laser, and X-ray SETs is important for modern radiation testing? Why or why not?
- The authors state that “equivalent total generated charge does not guarantee equivalent SET shape.” Does the evidence they present convincingly support this claim?
- How effectively did the authors isolate device-physics effects (depletion width, funneling, drift vs. diffusion) from differences in the radiation sources themselves? Could any confounding factors remain?
- Is using a simple epitaxial silicon diode an effective choice for studying SEE physics? Would using a more complex device (e.g., transistor, SRAM cell) potentially change the conclusions?
- The authors conclude that no universal correlation exists between heavy-ion, laser, and X-ray testing. Do you agree? Are there specific conditions under which partial correlation might still hold?

## Slide 23

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**JM1**      Not the right questions

Medina, Jaiden F, 2025-12-02T18:13:13.160

**HM1 0**      hehe

Helou, Micaela, 2025-12-02T18:14:02.334

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