Angle Dependence of Focused X-Ray-Induced Single Event Transients

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Acronyms

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ANL	**Argonne National Labs**
APS	**Advanced Photon Source**
CC	**Collected Charge**
ehp	**Electron-Hole Pair**
FT	**Fall Time**
LET	**Linear Energy Transfer**
SEE	**Single Event Effect**
SET	**Single Event Transient**
SV	**Sensitive Volume**
TID	**Total Ionizing Dose**

Outline

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- **Angular SEE Testing and the Cosine Law**
- **Review of Focused X-Ray SEE Testing**
- **Experimental Setup and Results**
- **Conclusions**

Angular SEE Testing and the Cosine Law

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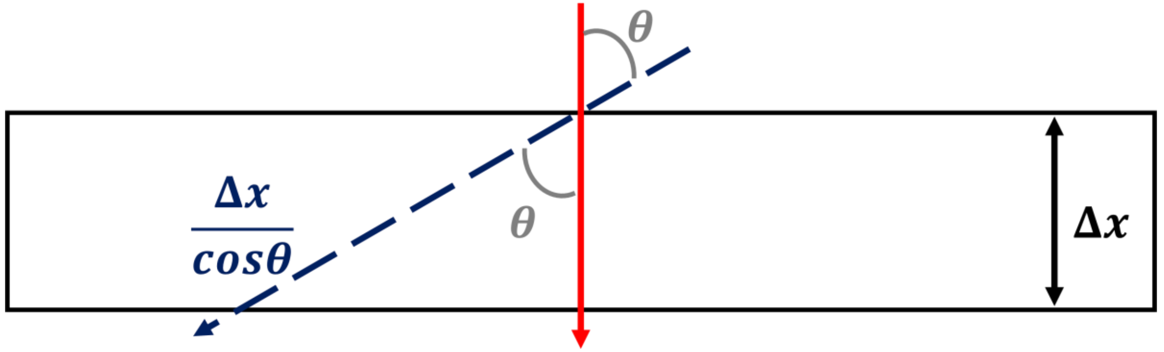
- Ion beams are unidirectional, space radiation is omnidirectional
  - Incident angle can affect susceptibility to certain types of SEEs
  - Incident angle can affect MBUs
- Angular SEE testing emulates omnidirectionality
  - Ability to test around bond wires, troublesome packaging
  - Increases available heavy ion LETs through cosine law



$$Q_{gen} \cong \frac{\rho}{E_{ehp}} \cdot LET_{const} \cdot \Delta x$$

$$\rightarrow Q_{gen} \cong \frac{\rho}{E_{ehp}} \cdot LET_{const} \cdot \frac{\Delta x}{\cos\theta}$$

$$\rightarrow \mathbf{LET_{effective}} = \frac{\mathbf{LET_{const}}}{\mathbf{\cos\theta}}$$

Focused X-Ray SEE Testing

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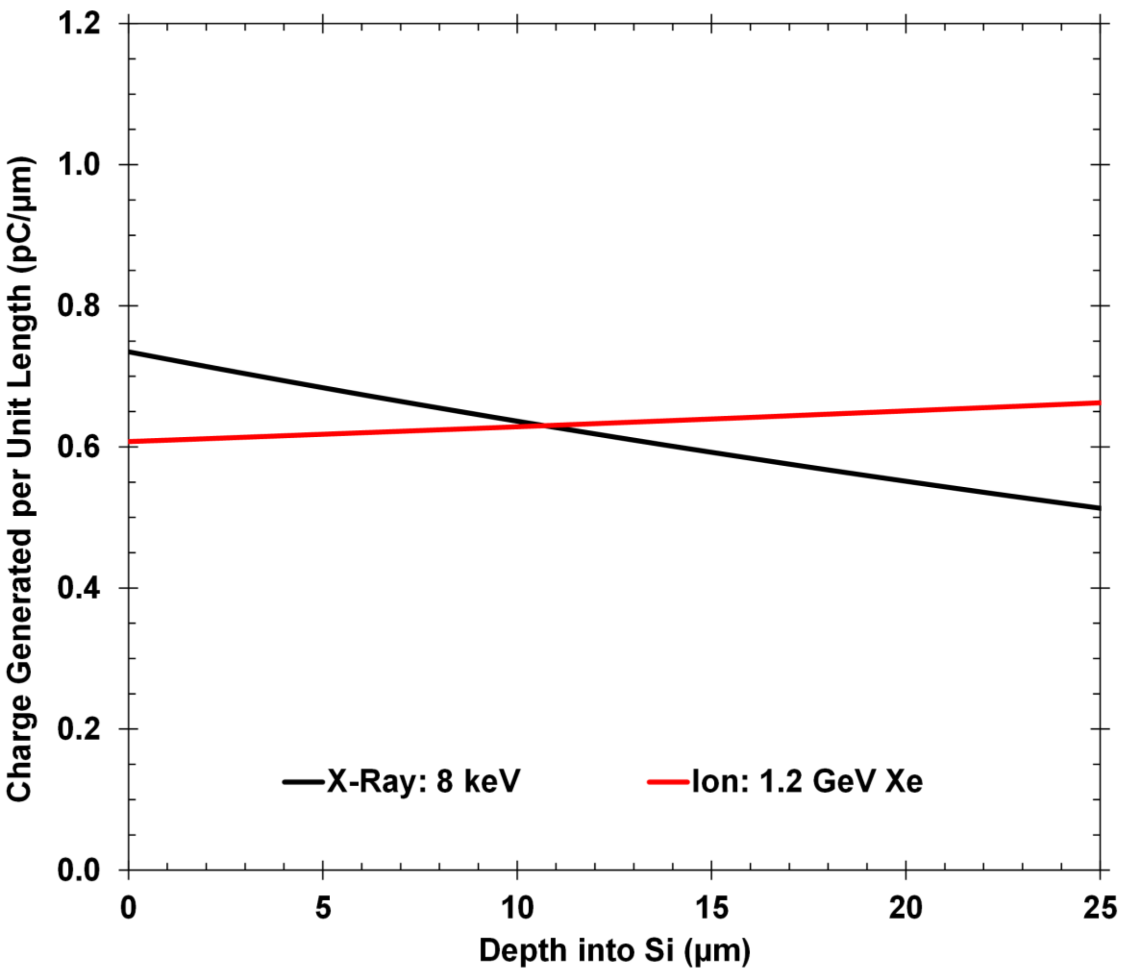

- Single photon absorption
  - Single photon absorbed → single ehp created

$$\frac{dQ_{gen,X-Ray}}{dx} = \frac{E_{pulse}}{E_{ehp}} \cdot \alpha e^{-\alpha x}$$

Material/ Compound	1/α (µm) @ 8 keV	1/α (µm) @ 10 keV	1/α (µm) @ 12 keV
Si	69.6	133.7	228.7
SiC	69.9	134.3	229.8
GaN	31.4	59.4	12.6
Al	77.6	149.6	256.6
W	3.1	5.5	2.5

Focused X-Ray vs Heavy Ion SEE Testing

Radiation Source	Heavy Ions	Focused X-Rays
Known correlation to the space radiation environment	✓	✗
Facility accessibility in U.S.	Few	Few
Spatial, temporal control over charge generation	✗	✓
No accumulation of TID	✗	✗
Penetration of metals	✓	✓

Experimental Setup

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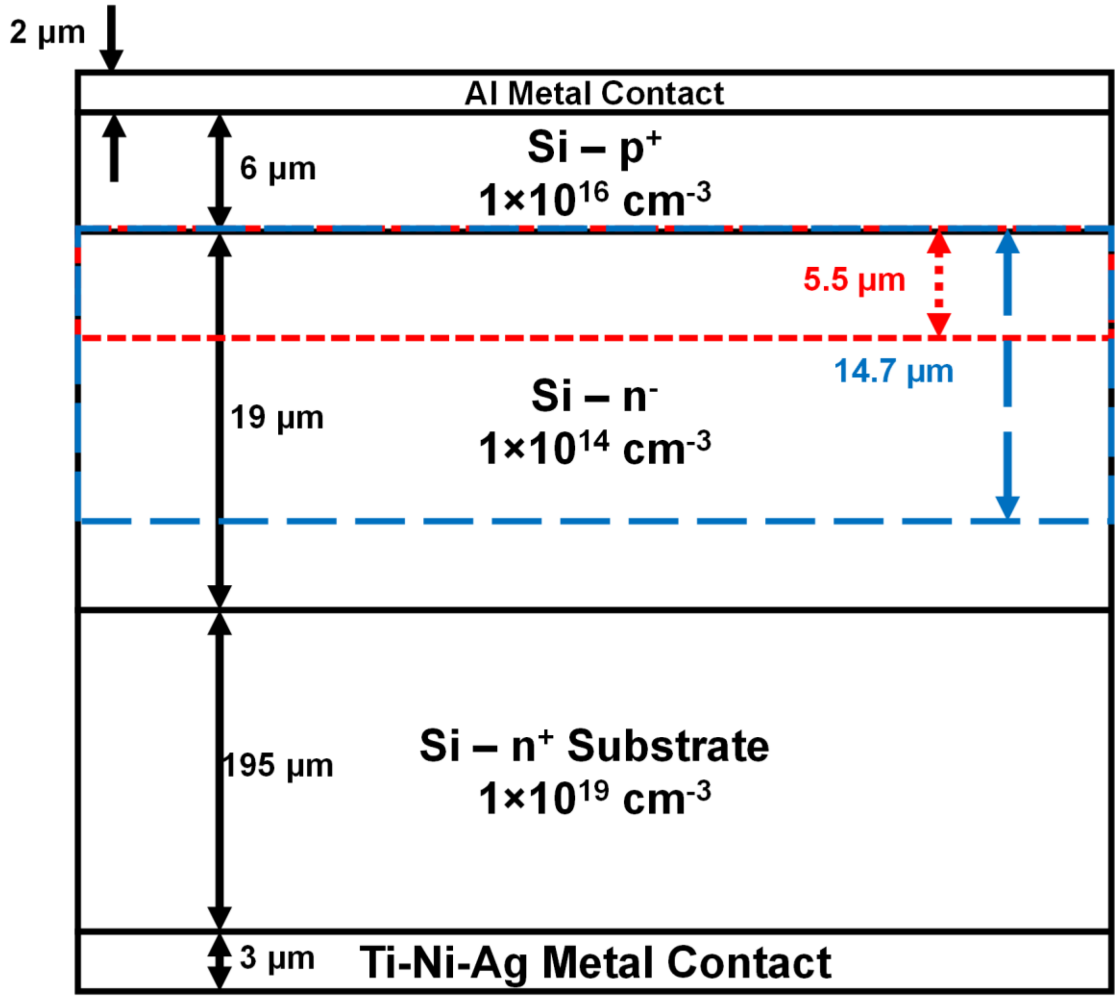
- Large area silicon diode test structure
  - Two bias condition: -5 V, -90 V
  - Incident angles: -5° to 30°
- Focused X-Ray SEE testing performed at ANL APS
- Used 8 keV photon energy
  - Flux = 1.44×10^5 photons/pulse
  - $1/\alpha$ = 69.6 μm



Experimental Results – Collected Charge

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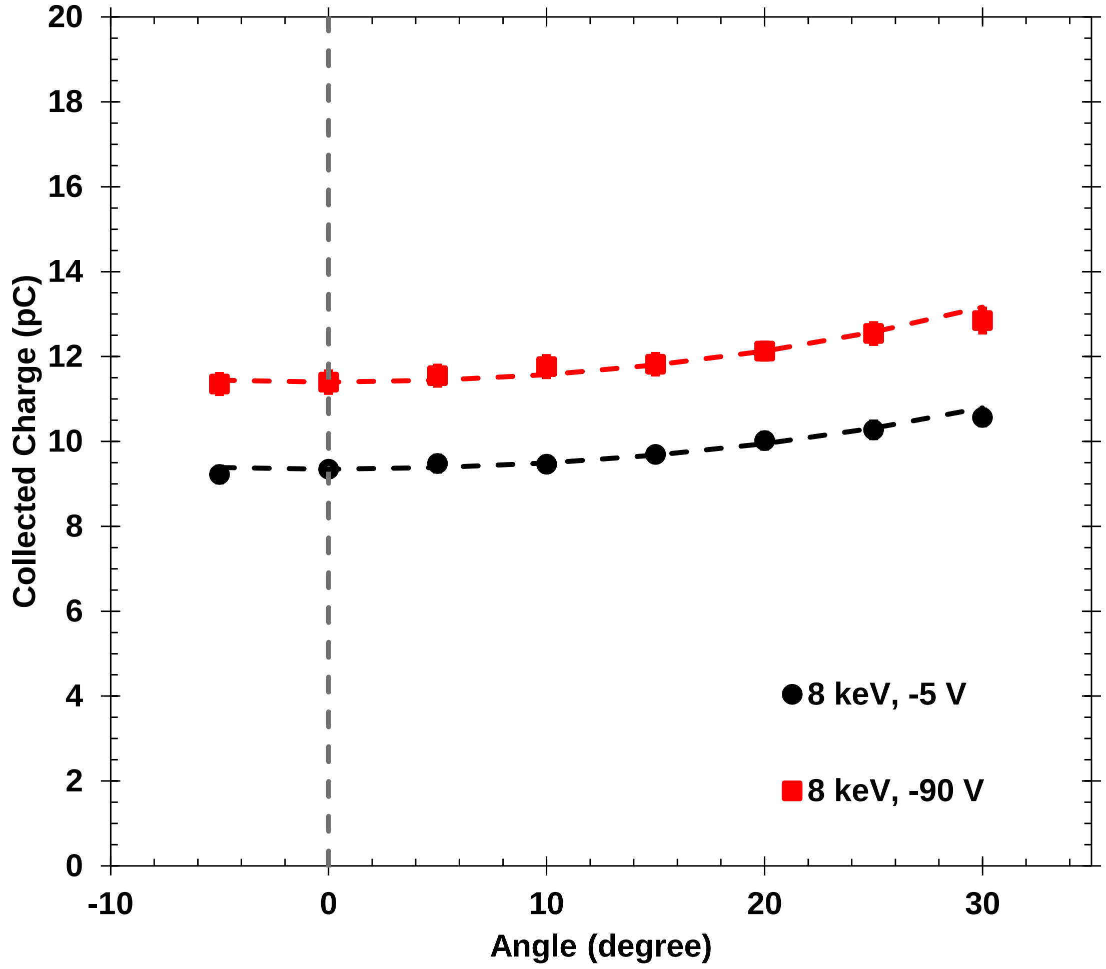

- Collected charge = integral of the current SET
- $CC_{\theta,predicted} = \frac{CC_{0,exp}}{\cos\theta}$
  - Predicted results = dashed lines
  - Experimental results = points
- Both bias conditions show agreement with predicted cosine law ✓

Experimental Results – Transient Fall Time

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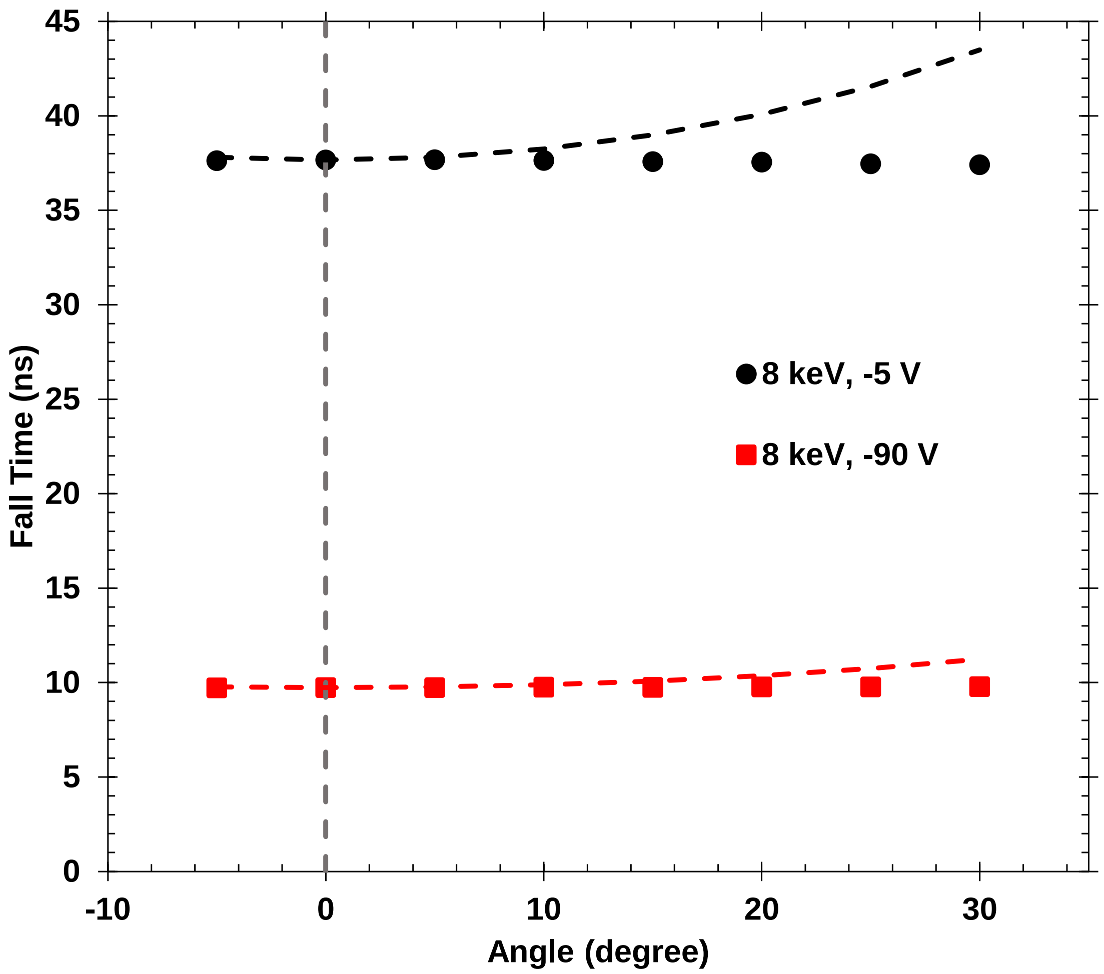
- Fall time = time from peak current to 1% of peak current

- $FT_{\theta,predicted} = \dfrac{FT_{0,exp}}{\cos\theta}$
  - Predicted results = dashed lines
  - Experimental results = points

- Neither bias condition shows a dependence on angle ✓



Experimental Results –Sensitive Volume

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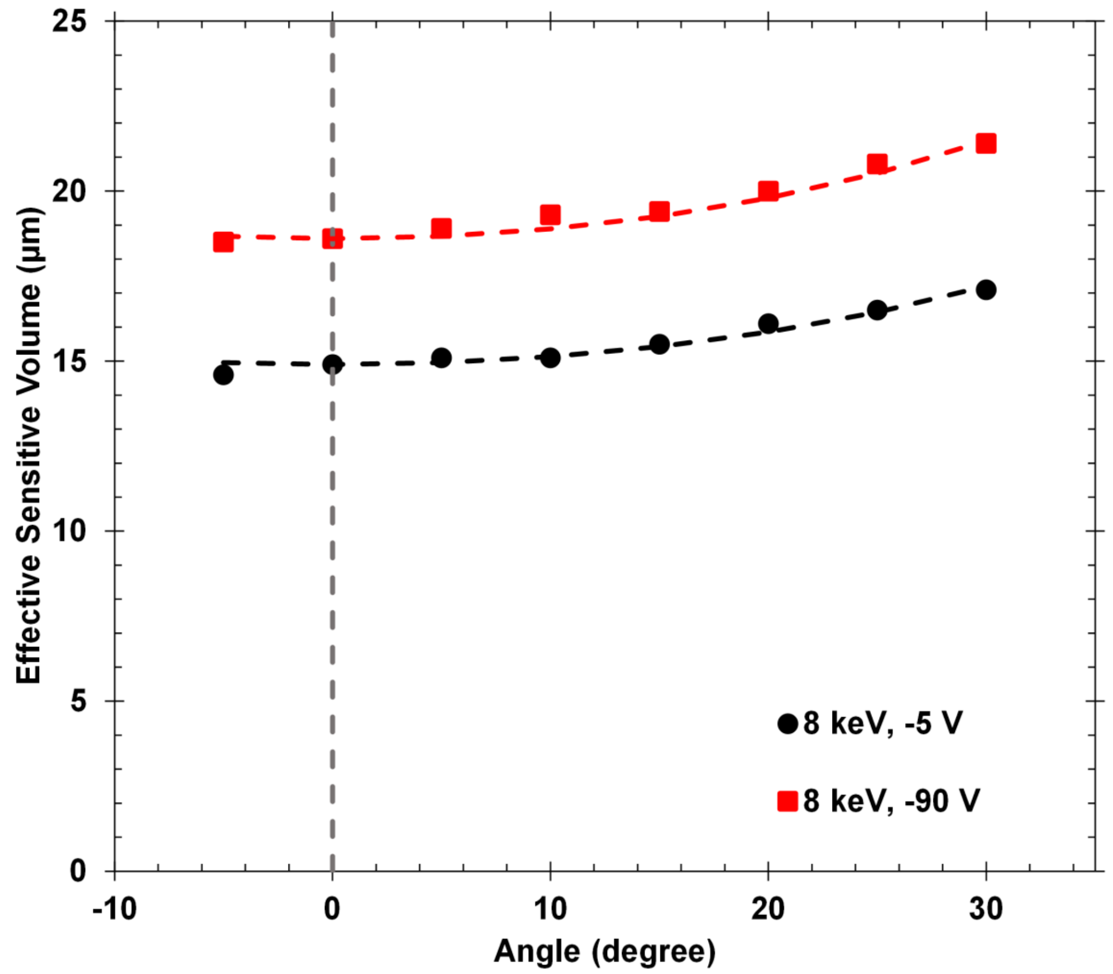

- Collected charge sensitive volume depth
- $CC = \frac{E_{pulse}}{E_{ehp}}\left(e^{-\alpha x_1} - e^{-\alpha x_2}\right)$
  - Assumed $x_1 = 0$ (at surface of diode)
- $SV_{\theta,predicted} = \frac{SV_{0,exp}}{\cos\theta}$
  - Predicted results = dashed lines
  - Experimental results = points
- Practical demonstration of cosine law example ✓

Summary

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- Angular focused X-Ray SET experiments were performed on a large area silicon diode

- Collected charge followed the cosine law at two bias conditions
  - Demonstrates that charge generated increases proportionally to $1/cos\theta$

- Transient fall time was independent of incident angle, as expected
  - Demonstrates the charge collection mechanisms are not fundamentally changing with angle

- Sensitive volume followed cosine law at both bias conditions
  - Confirms observations from collected charge, rise time

Conclusions

- **Focused X-Rays increasingly of interest for SEE investigations**

- **Focused X-Ray SEE investigations have been performed on a variety of devices**
  - K. L. Ryder *et al*., *IEEE TNS*, vol. 68, no. 5, pp. 626-633, May 2021.
  - D. Nergui *et al.*, *IEEE TNS*, vol. 67, no. 1, pp. 91-98, Jan. 2020.
  - S. D. Lalumondiere *et al.*, *IEEE TNS*, vol. 65, no. 1, pp. 478-485, Jan. 2018.

- **Demonstration of angular focused X-Ray SEE testing increases potential use cases for this alternative SEE testing technique**