Energetic Dependence of Neutron-induced SEUs and its Impact on Atmospheric Neutron SER Prediction

Qi Chao

National Key Laboratory of Intense Pulsed Radiation Simulation and Effect

Northwest Institute of Nuclear Technology

ISINN31, Dongguan, China

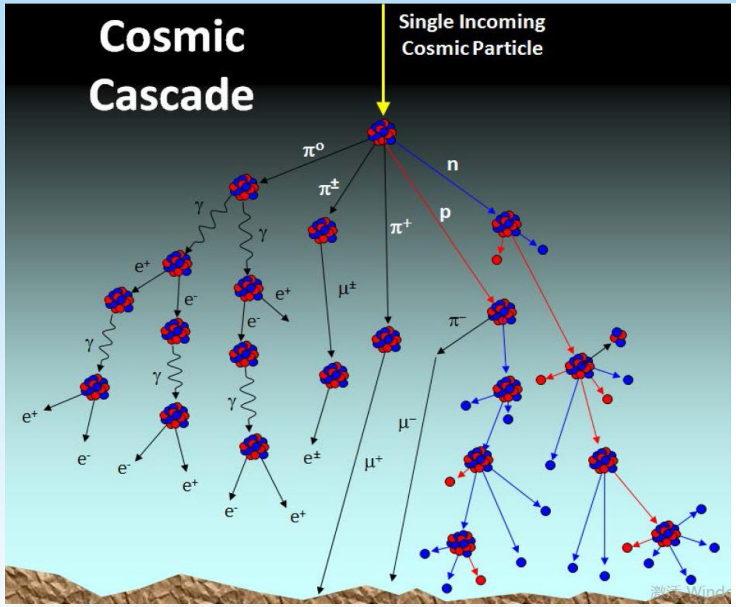
May 26, 2025

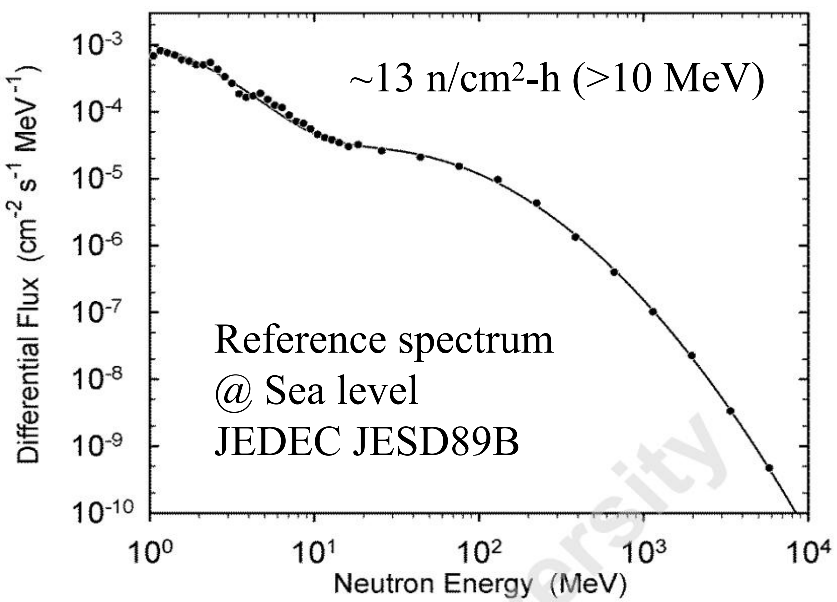
Outline

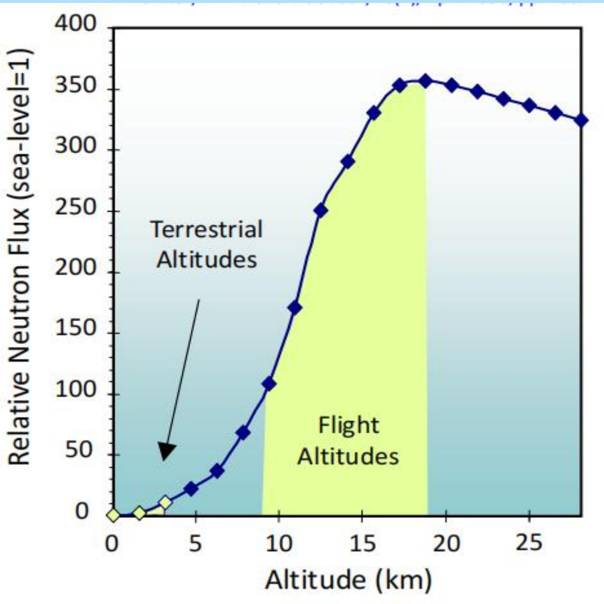
- Introduction
- Energetic dependence of NSEUs
- Underlying mechanisms of the energetic dependence
- Impact on SER prediction
- Summary

Introduction — Cosmic Rays and Atmospheric Neutrons

- **Energetic cosmic rays (mostly protons) that make it through the magnetosphere to the atmosphere cause a cascade of particles**
  - Mostly neutrons (~90%), and also pions, muons at sea level
  - Neutrons observed on the ground come from interactions of energetic protons and ^{14}N or ^{16}O in the atmosphere
  - Energy range from meV (thermal) to GeV
  - Neutron Flux strongly depends on altitude (x 200-300 higher than sea level @ flight altitudes)

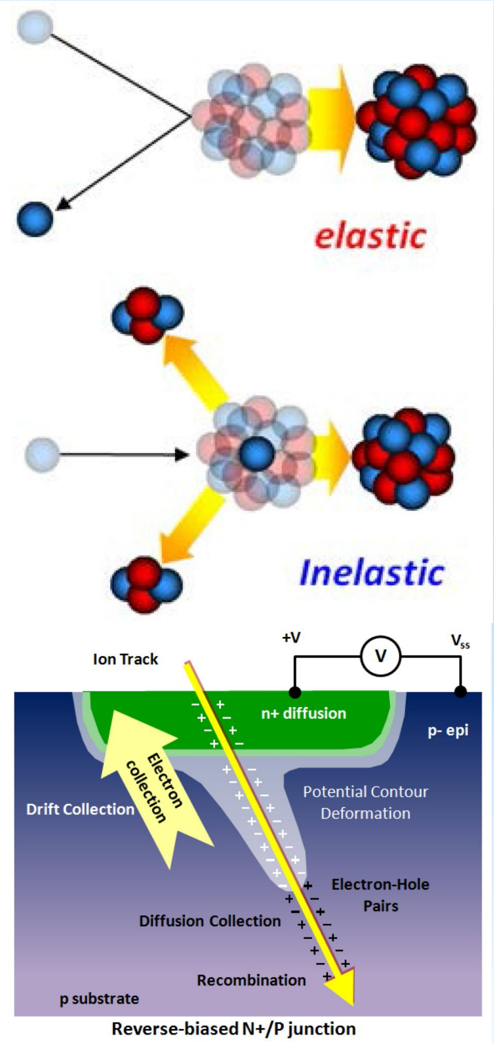






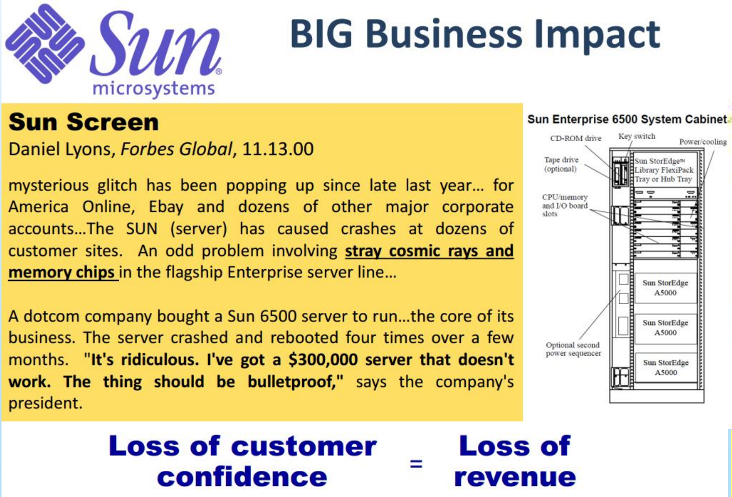
Introduction —— Neutron-induced SEUs

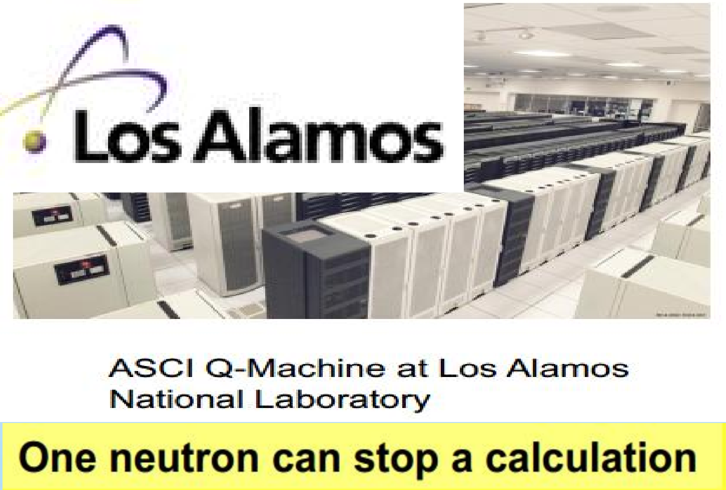
- **Atmospheric neutrons striking integrated circuits interact with Si, O atoms or metals near the transistor, generating recoil ions**
  - One single particle hits a P-N junction, producing unexpected current pulses, and resulting in stochastic effects
  - Non-destructive → Soft Error → **Soft Error Rate (SER)**
    - Single Event Upsets (SEUs): '0'→'1', '1'→'0'
    - Single Event Transients
    - Single Event Functional Interrupts
  - Destructive
    - Single Event Gate Rupture
    - Single Event Burnout
    - Single Event Latch-up
  - SER = SEU Cross-section × Neutron Flux
    - 1 FIT = 1 Failure In 10^9 Hours (114,155 years)

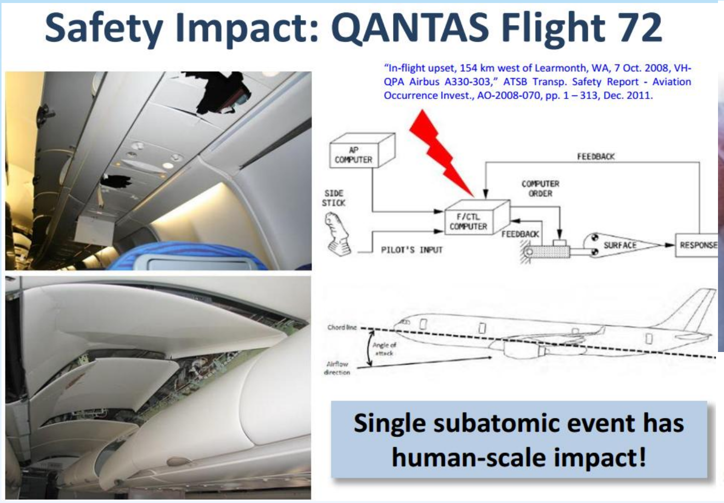


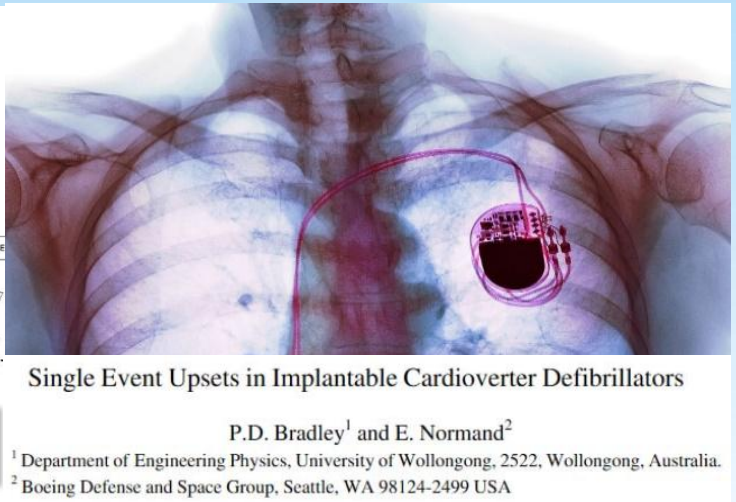
Introduction — Real-life Impacts of Neutron-induced SEUs

- **Don't Care**
  - Non-critical applications
  - Small-scale chips/systems
  - Consumer electronics (smart phones, iPAD ...)
  - 1 MFIT Acceptable (~1 Failure / Month)
- **Really Care**
  - High-reliability applications
  - Mission-critical applications
  - Large-scale systems
  - Life support systems (Cardioverter Delibrillators)
  - Automotives, avionics ...
  - < 1 kFIT (~1 Failure / 114 years)









Robert Baumann, "Industrial Challenges and Trends in Terrestrial Single-Event Effects", TI Information – Selective Disclosure, October, 2014.
Steve Wender, "Neutron-Induced Failures in Semiconductor Devices", WPI Seminar, LA-UR-14-23043, May, 2014.
Michael Gordon, "Single Event Upsets and Microelectronics (Why neutrons matter to the electronics industry)", Neutron Monitor Community Workshop, October, 2015

Introduction — Two Types of NSEU Testing

- **Real-time testing using natural flux of neutrons at high elevation**
  - Assess SER in “real-world” conditions
  - Acceleration factor ~10
  - Tests often take months to get adequate statistics
  - Large quantity of devices are required

Model	Tech. node	Capacity /bit	Time /hour	No. of NSEUs
HM62V8100	0.18 µm	8M x 573	6085	195
HM628512B	0.35 µm	4M x 1221	5198	181
HM628512A	0.5 µm	4M x 635	5198	76

~82 n/cm^2-h (>10 MeV)

NSEU test site @ Yangbajing International Cosmic Ray Observatory, Tibet 4300 m

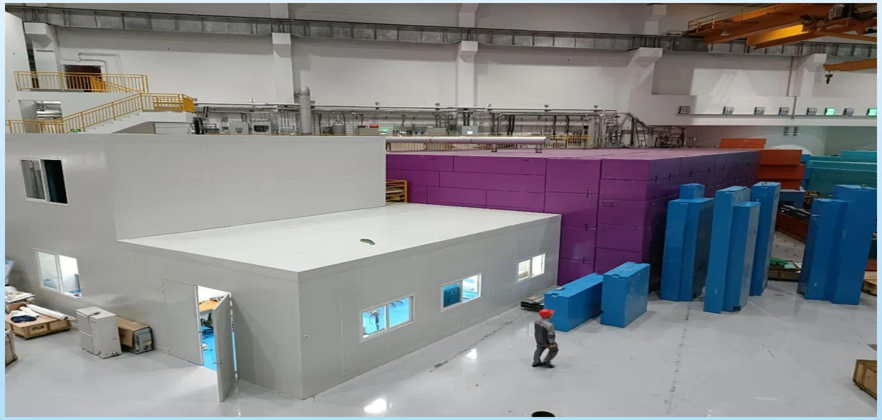
Introduction — Two Types of NSEU Testing

- **Accelerated testing using neutron beams (Spallation Neutron Sources)**
  - Close match to atmospheric neutron spectra
  - Acceleration factor ~10^8
  - Back-n @ CSNS since 2018 (SRAM, FPGA...)
  - Testing usually follows prescription of JESD89B(2021)
  - NSEUs due to <10 MeV neutrons are negligible

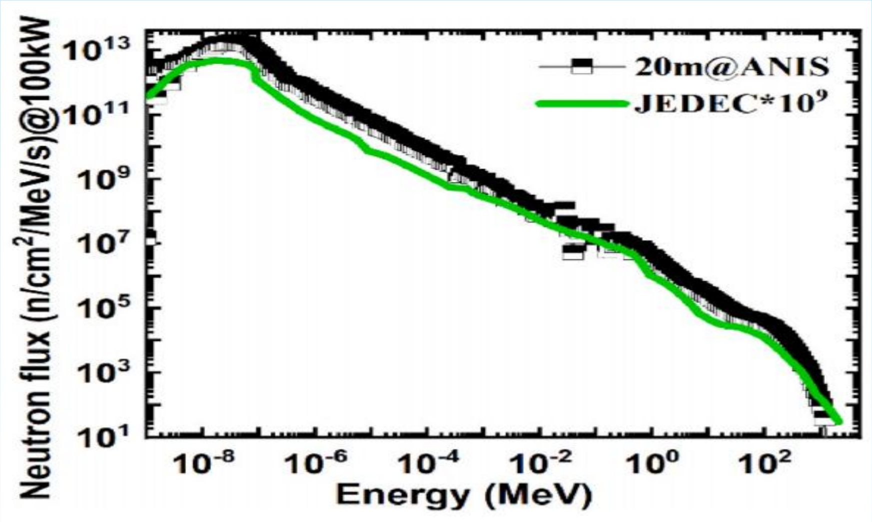
(1) $$\overline{\sigma_{facility}}(E_{\min}) = \frac{N_{upset}}{\Phi_{facility}(E_{\min}) \cdot T \cdot N_{bit}}$$

(2) $$SER_{prediction} = \overline{\sigma_{facility}}(E_{\min}) \cdot \Phi_{atmosphere}(E_{\min})$$

Cutoff energy E_{min} = 10 MeV

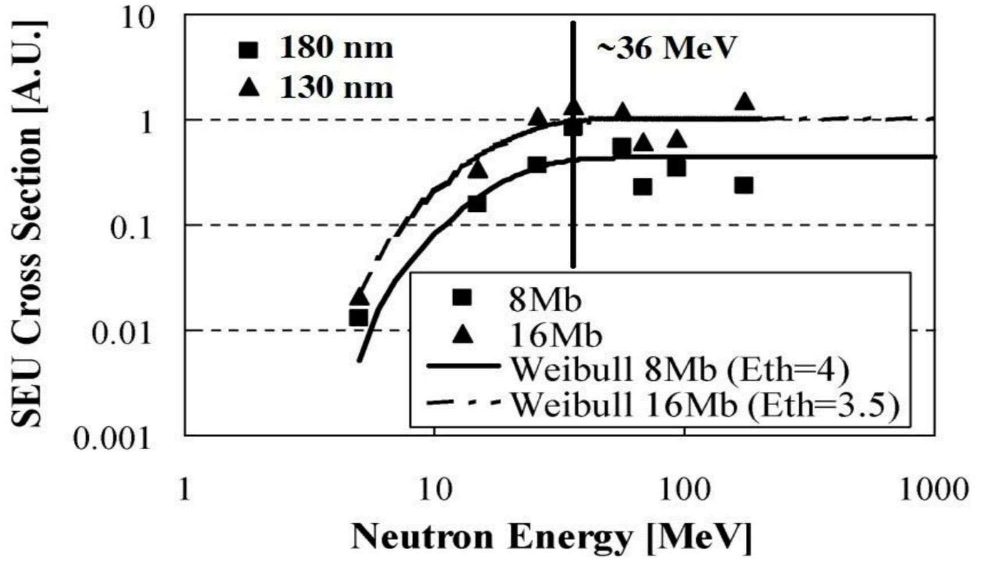


Atmospheric Neutron Irradiance Spectrometer (ANIS) @ CSNS



Introduction — Physical Basis of Accelerated Test

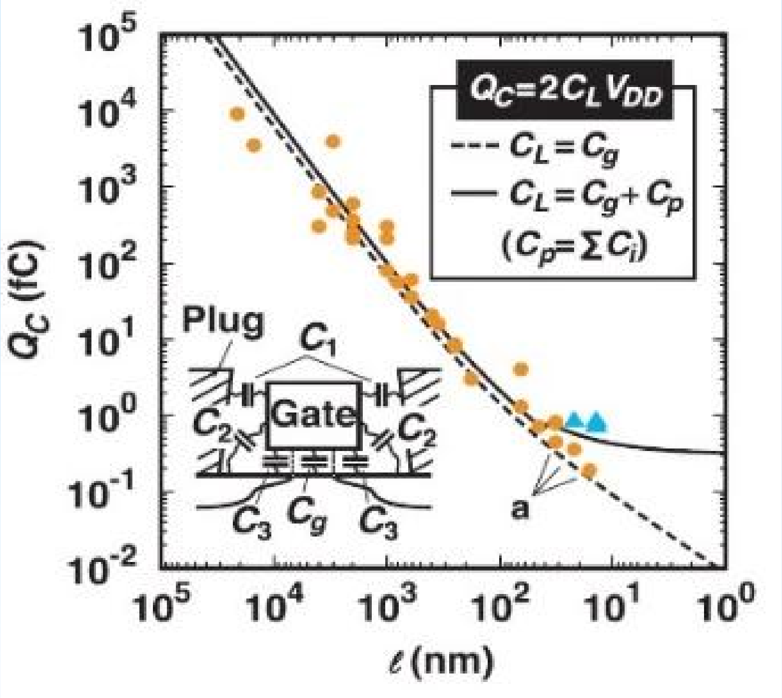
- **Energetic dependence of NSEUs**
  - Threshold energy of several MeV
  - NSEU XS raises as neutron energy increases
  - NSEU XS saturates above tens of MeV
  - Threshold energies required for reactions to occur: higher neutron energies, more reaction channels
  - Heavy ions with larger LET (Linear Energy Transfer), rather than light particles, trigger SEUs: higher neutron energies, release higher energy/LET ions

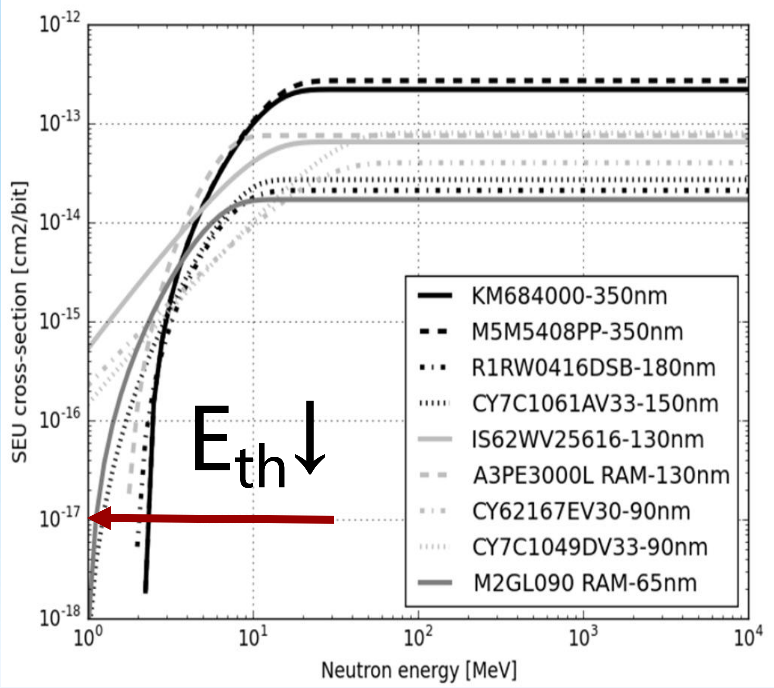


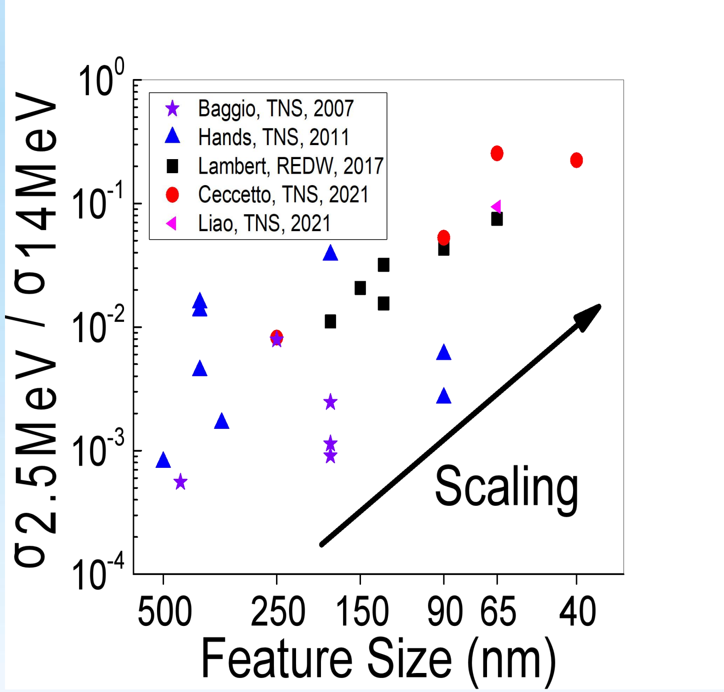
Reaction Channel	Threshold Energy
$^{25}Mg + \alpha$	2.75 MeV
$^{28}Al + p$	4.00 MeV
$^{27}Al + d$	9.70 MeV
$^{24}Mg + n,\alpha$	10.34 MeV
$^{27}Al + n,p$	12.00 MeV
$^{26}Mg + ^{3}He$	12.58 MeV
$^{21}Ne + 2\alpha$	12.99 MeV
$^{27}Mg + 2p$	13.90 MeV
$^{24}Na + p,\alpha$	15.25 MeV

Introduction — Changes in energetic dependence

- **Energetic dependence changes as feature size shrinks down to 100 nm and below**
  - Critical charge↓（Qc ∝ $L^{1.5}$）：Operating voltage ↓、node capacity ↓
  - Qc has decrease to ~1 fC or below (~6000 electrons)
  - Threshold energy reduces to 1 MeV and below
  - Capability of <10 MeV neutrons to provoke SEUs raises significantly





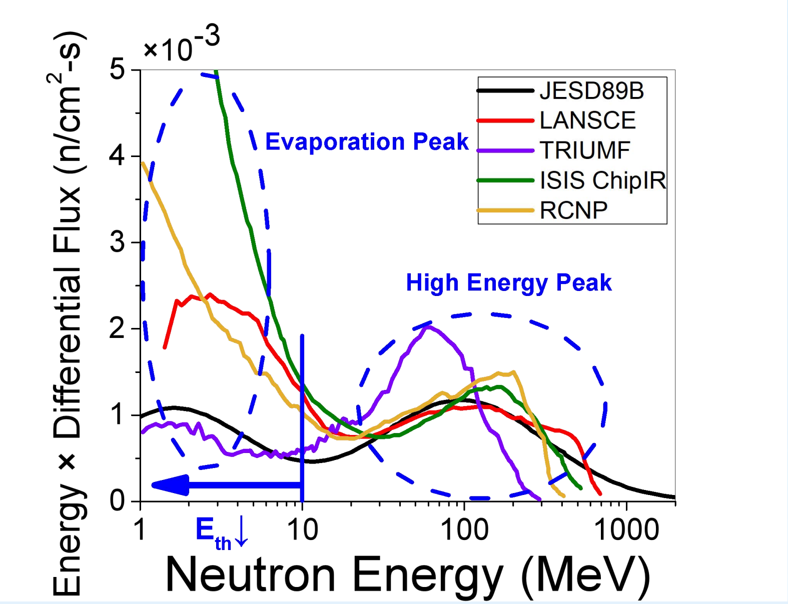


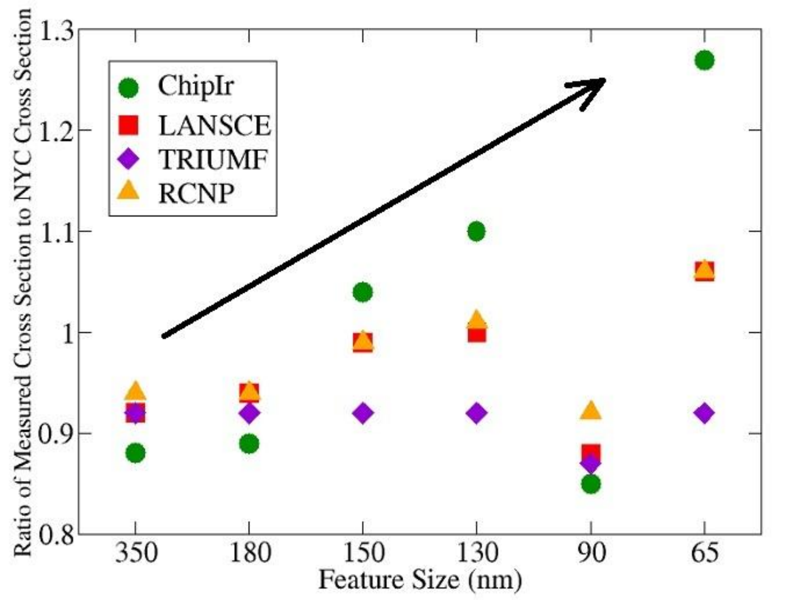
TNS(Kobayashi, 2021)　　*NSREC Workshop (Lambert, 2017)*

Introduction — Overestimation of SER

- **Spallation source beam lines with excessive < 10 MeV neutrons, could overestimate SER**
  - Extra < 10 MeV NSEUs are taken into account in prediction

$$SER_{prediction} = \overline{\sigma_{facility}}(E_{\min}) \cdot \Phi_{atmosphere}(E_{\min})$$





@65 nm node

ISIS ChipIR: +30%

TNS (Quinn, 2019)

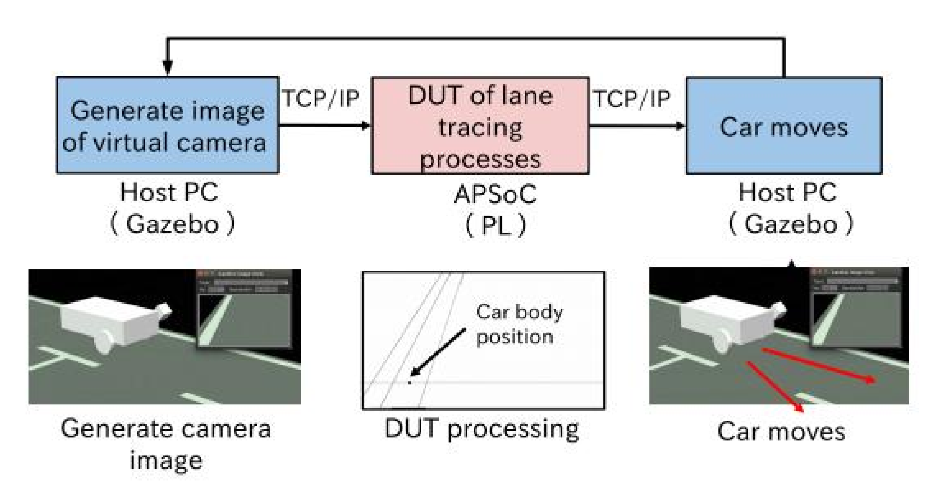
J-PARC BL10: +50%

TNS (Kuroda, 2020)

TNS (Quinn, 2019)

Introduction — Overestimation of SER

- **There is an ever-growing need for SER testing on cutting-edge integrated circuits**
  - Artificial intelligent computing
  - Multicore CPU for servers
  - High performance GPU for automous driving
- **To make better use of beam lines with abundant < 10 MeV neutrons, researchers have been making efforts to tackle with the SER overestimation issue**
  - Reduce the cutoff energy in SER prediction
  - The effects depend on the energetic dependence of the specific integrated circuits, and the spectrum characteristics of the specific neutron beam line.
  - The universal value suitable for all integrated circuits do not exsist.



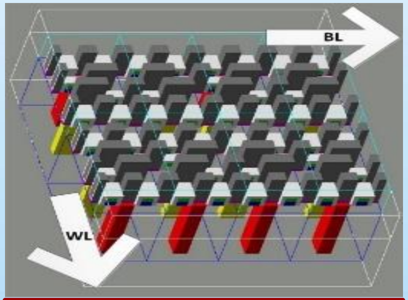
$$SER\ ratio = \frac{SER_{prediction}}{SER_{atmosphere}} = \frac{\int_0^{\infty}\sigma(E)\frac{d\Phi_{facility}(E)}{dE}dE}{\int_{E_{\min}}^{\infty}\frac{d\Phi_{facility}(E)}{dE}dE} \Bigg/ \frac{\int_0^{\infty}\sigma(E)\frac{d\Phi_{atmosphere}(E)}{dE}dE}{\int_{E_{\min}}^{\infty}\frac{d\Phi_{atmosphere}(E)}{dE}dE}$$

Wang Liao (TNS, 2021): 6 MeV for 65 nm SRAM

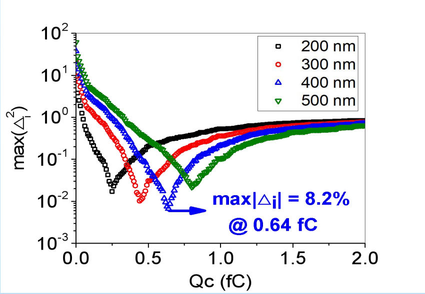
Takami (TNS< 2024): 2 MeV for 12 nm and 28 nm SRAM

Introduction

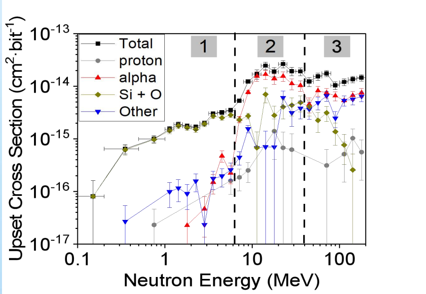
☐ Framework of our study on NSEUs and SER prediction based on a 40 nm SRAM



NSEU MC Modeling

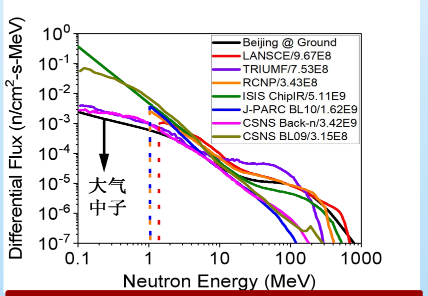


MC Simulation



Energetic Dependence

➕



Major Spallation Sources

Tests with various neutron sources

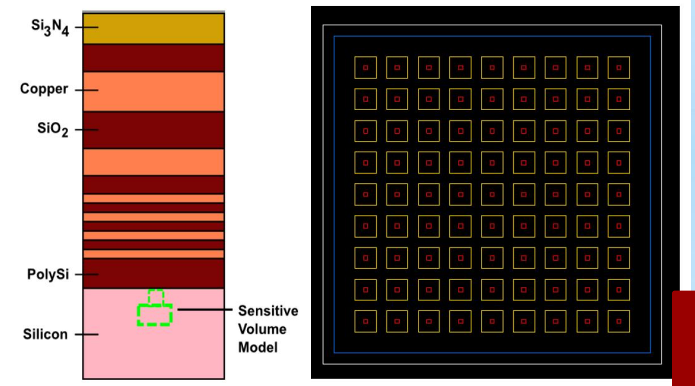
Including non-monoenergetic neutrons

- **Underlying mechanism responsible for the energetic dependence changes**
- **Impact on SER prediction**
- **Novel prediction method**

Monte-carlo modeling of NSEUs

- **A Geant4 detector model has been established based on microscopic analysis**
  - Light ions: full coverage of stack layers, and large size array for detection
  - Elastic recoils: nuclear recoil cascade calculation allowed (PhysListEmStandardNR)

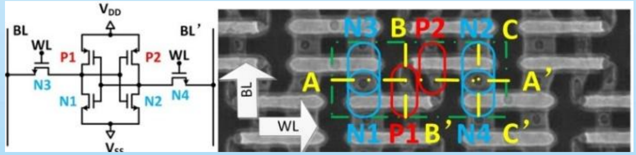
Traditional Modeling



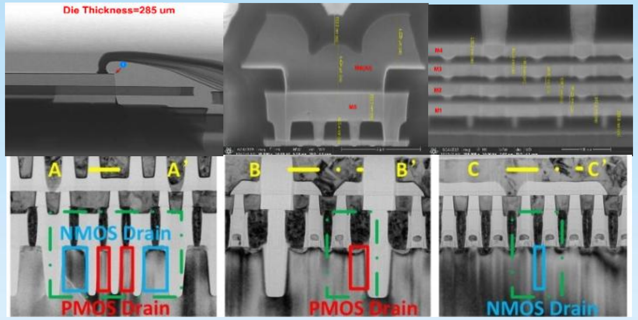
（1）Simplified Stack layers：passivation layer→part of substrate
（2）Simplified Structure：W plugs、Si_3N_4 sidewalls
（3）Small array size：~10 x 10 array

μm	SRAM	PMOS Drain	NMOS Drain
Length	0.763	0.066	0.134
Width	0.352	0.120	0.070

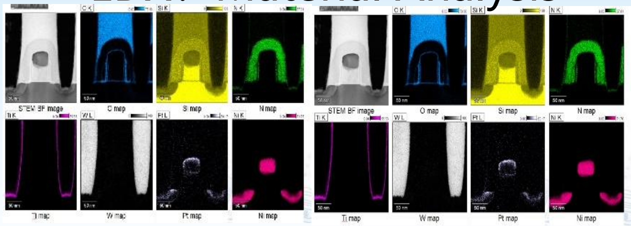
SEM：Planar Structure



SEM：Vertical Structure

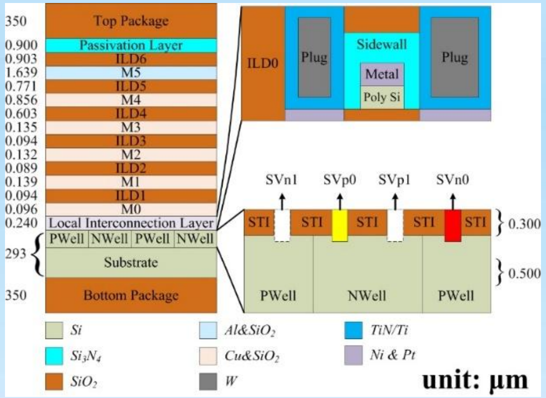


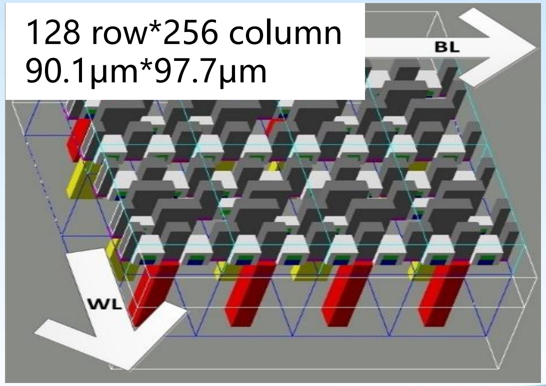
EDX：Material Analysis



Hight of RPP sensitive volume

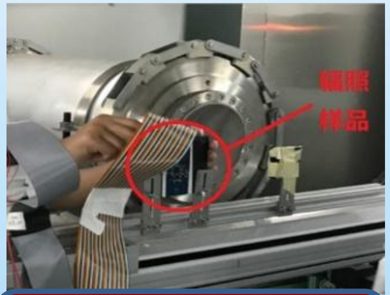
Funneling Length：200/300/400/500 nm





Irradiation tests with various neutron sources

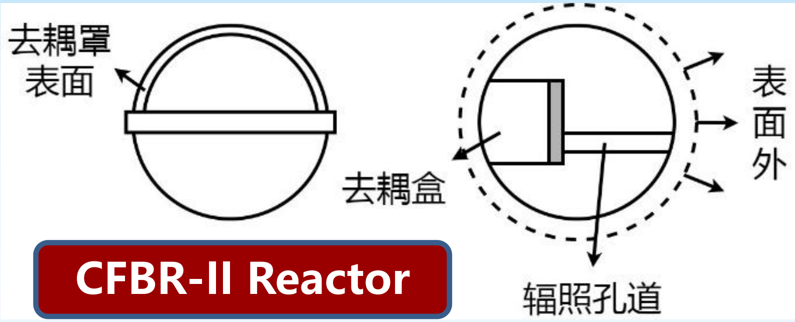
➤ Neutron Sources



Neutron Generator | **CSNS Back-n**

d-T: 14 MeV
d-D: 2.5 MeV

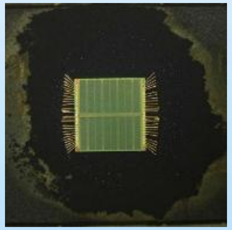
0.1 eV~
200MeV



CFBR-II Reactor

Close to pure fission spectrum, average ~1 MeV

➤ Devices under test



Commercial 40-nm SRAM

➤ Test system

Custom on-line test system

➤ Test Method

Pre-Irradiation

Writing Given Data Pattern

During Irradiation

Cycled readback

Compare and upset analysis

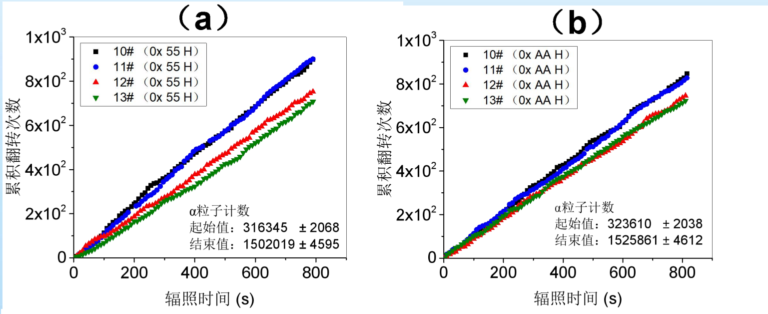
$N_{upset}(t)$

$$\overline{\sigma_{facility}}(E_{\min}) = \frac{N_{upset}}{\Phi_{facility}(E_{\min}) \cdot T \cdot N_{bit}}$$

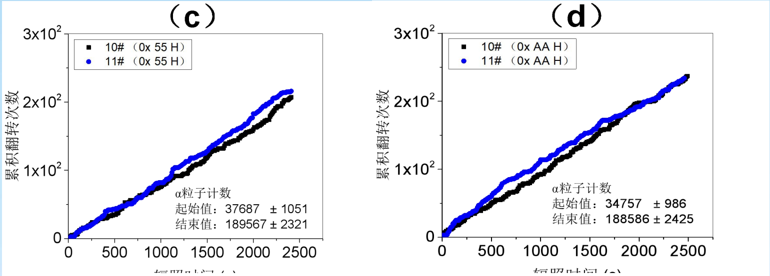
Upset Cross-Section per bit: cm^2/bit

Irradiation test results

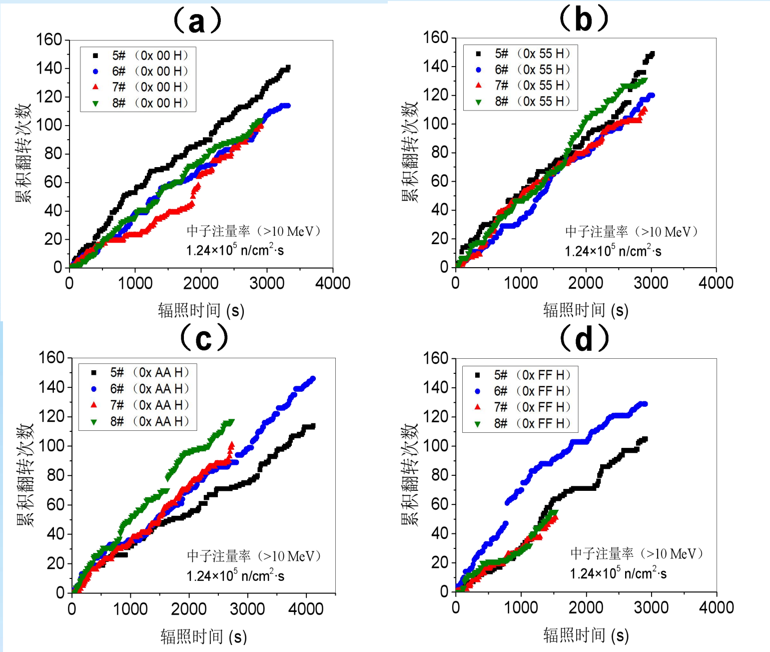
- N_{upset} (t) and $\sigma_{facility}$ have been obtained experimentally



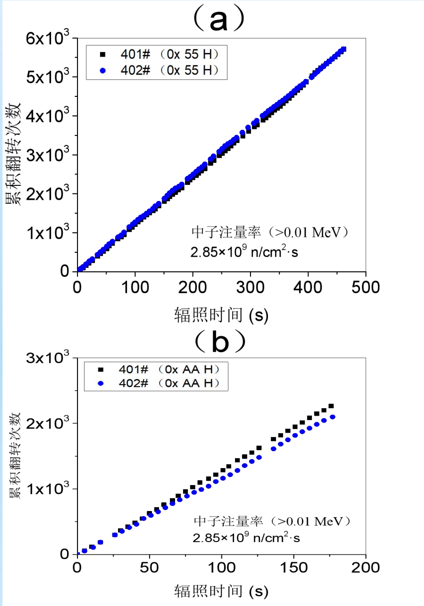
14 MeV: 4 samples @ 0x 55/ AA H



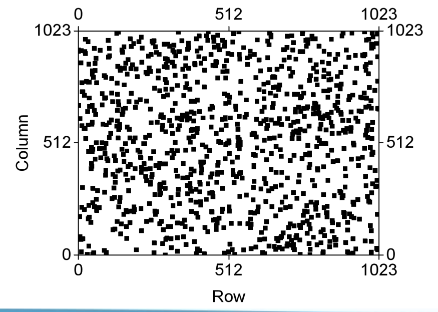
2.5 MeV: 2 samples @ 0x 55/ AA H



CSNS: 4 samples @ 0x 00/ 55/ AA/ FF H



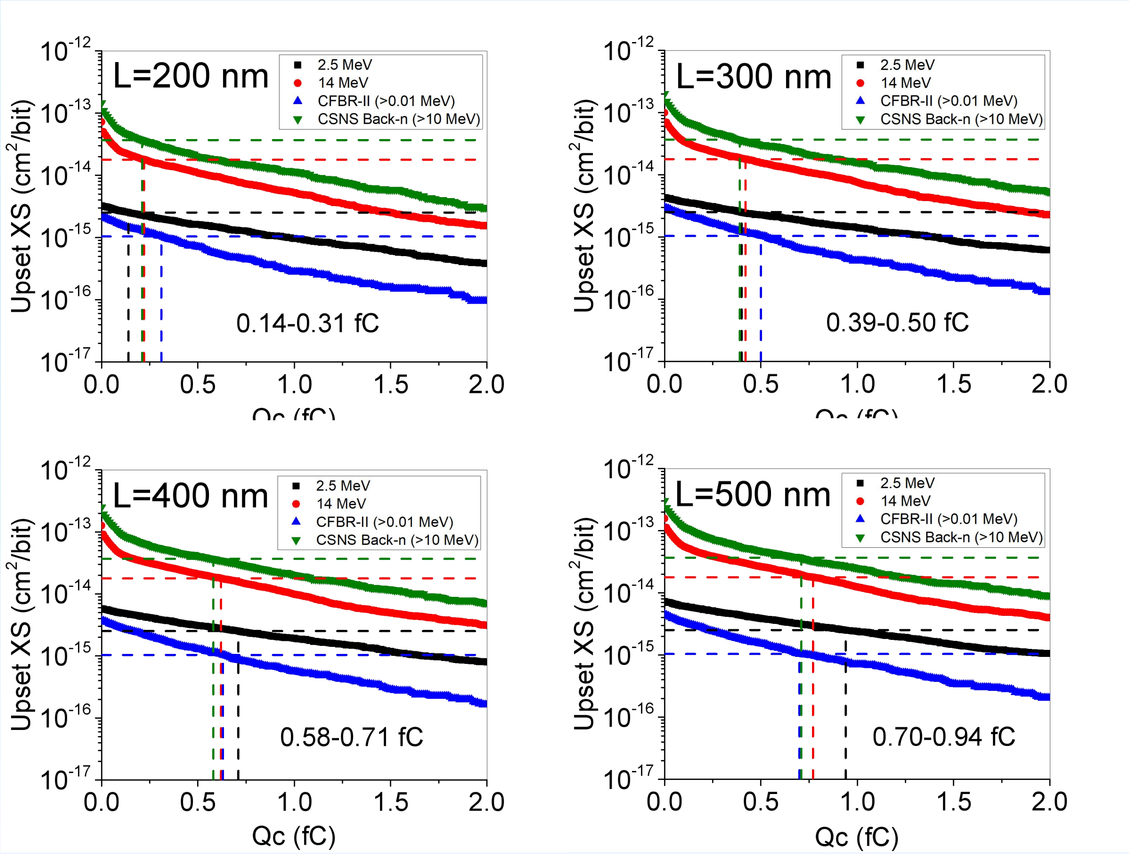
CFBR-II: 2 samples @ 0x 55/ AA H

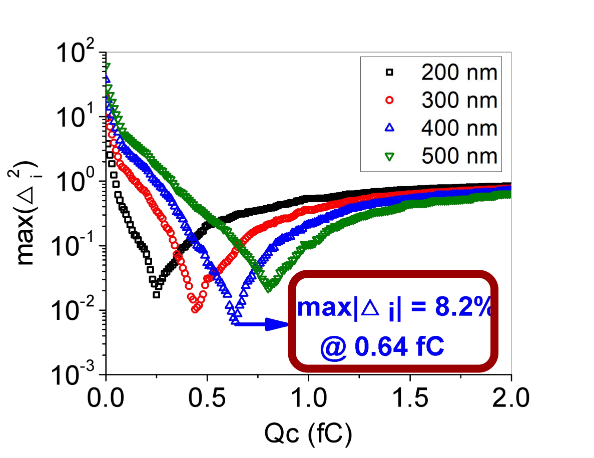


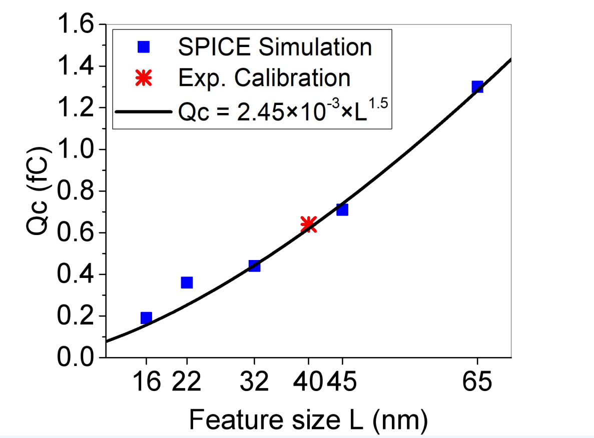
	2.5 MeV	14 MeV	CFBR-II (>0.01 MeV)	CSNS Back-n (>10 MeV)
NSEU XS	2.52×10^{-15}	1.78×10^{-14}	1.04×10^{-15}	3.68×10^{-14}
Uncertainty	22%	12%	11%	15%

Experimental calibration of MC calculations

- Calibrate the model parameters of funneling length and critical charge using experimental cross-section data



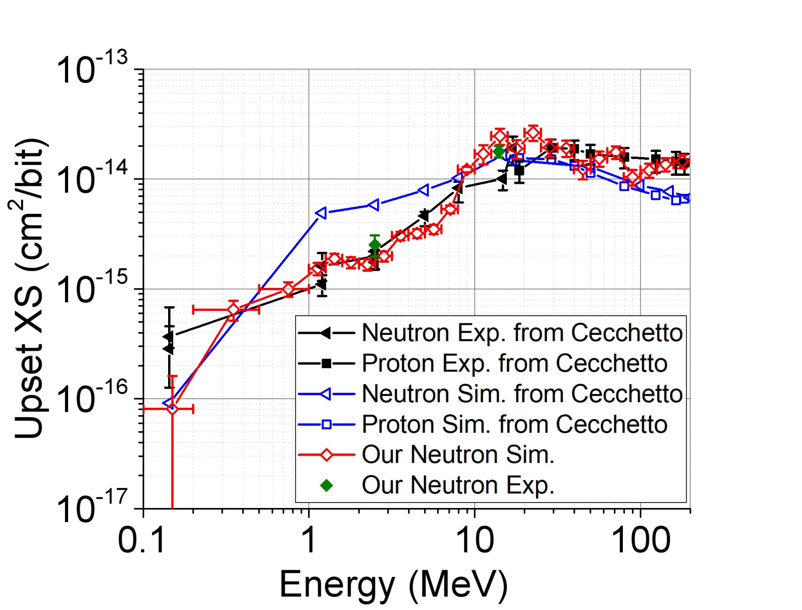


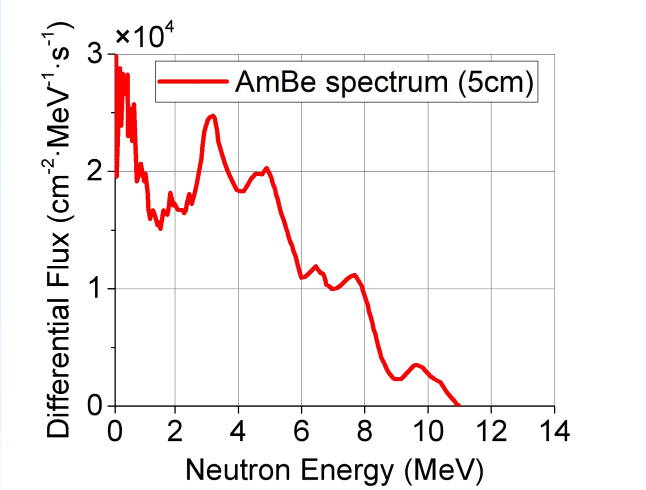


Parameter combination of 400 nm/0.64 fC meets the need of NSEU calculations

Validation of upset cross-section calculations

- **Validate the calculation results with reported experimental cross-section data.**
  - Experimental data on the same SRAMs from CERN in 2021
  - 7 mono-energetic data points (0.144~17 MeV neutron)
  - 8 mono-energetic data points (18.6~184 MeV proton)
  - AmBe neutron source





AmBe SER (Exp.):
39 SEU/Mbit-day

8.5% error

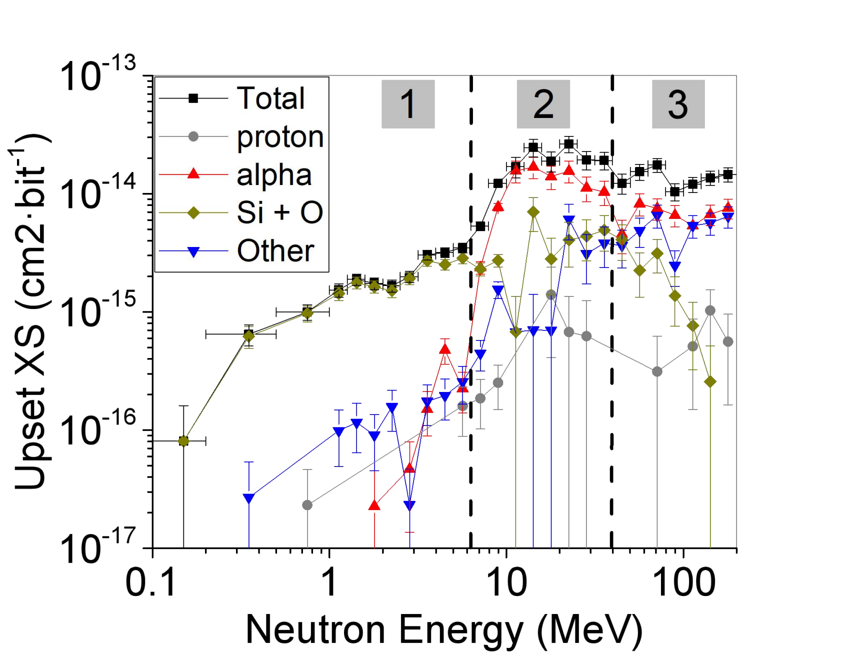
Calculated:
42.3 SEU/Mbit-day

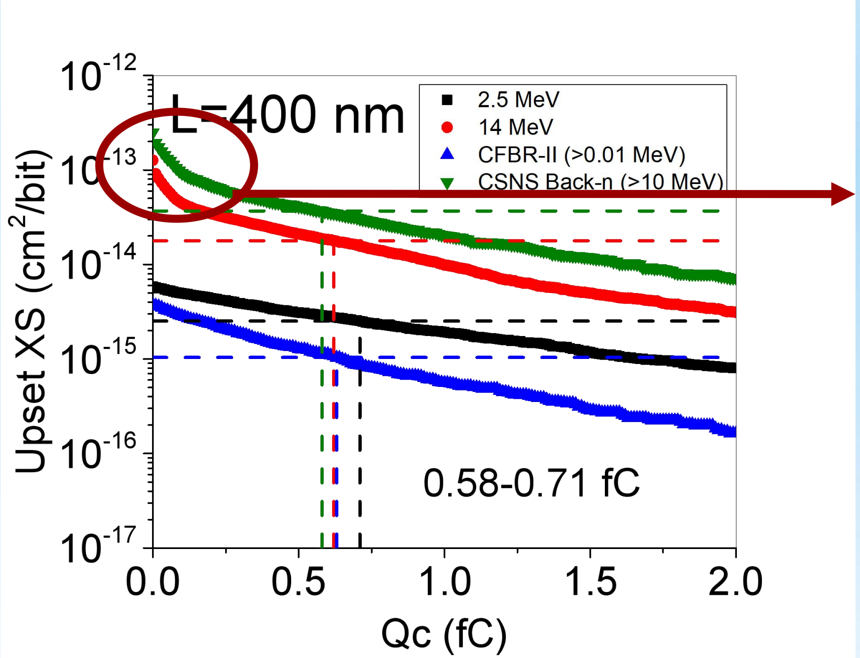
$$SER = \int_0^\infty \sigma(E) \frac{d\Phi(E)}{dE} dE$$

The calculated energetic-dependence data agree well with experimental data

Dominant particles in different energy range

- **According to particles dominating SEUs, the energy range can be divided into 3 regions.**
  ① <6 MeV: Si and O recoils are dominant
  ② 6~40 MeV: alpha particles are dominant
  ③ >40 MeV: alpha particles are comparable to the sum of other heavy ions (Mg, Al, C, N)





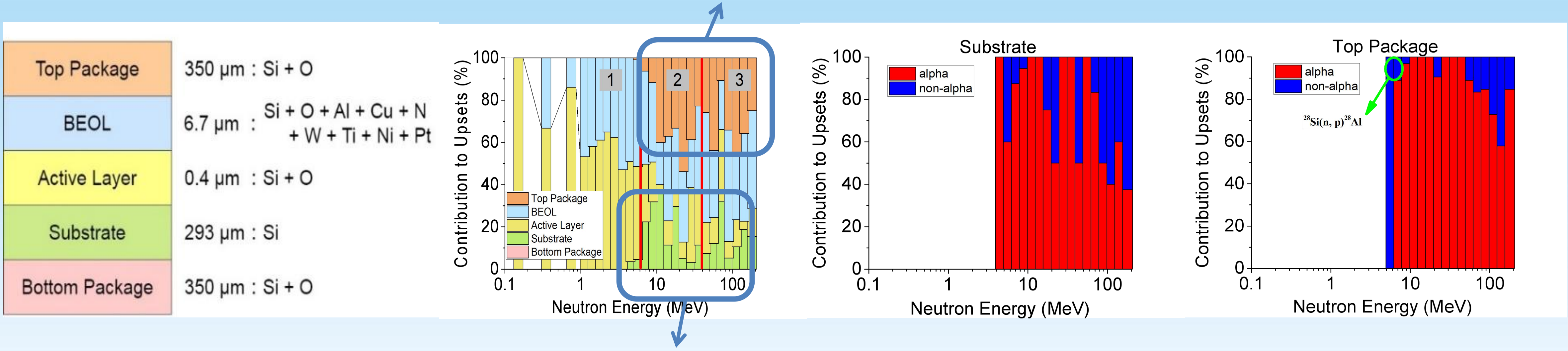
Protons are important only when Qc<0.2 fC

Compared to older technologies, the role of heavy ions due to nuclear reactions are relatively weakened.

Impact of stack layers

- **Besides active layer, BEOL, alpha particles originating from top package and substrate also make great contribution to SEUs.**
  - Significant energetic dependence is observed in terms of stack layer contribution
  - Above ~6 MeV, contribution from top package and substrate are important
  - Among various secondary particles responsible for the contribution, most are alpha particles

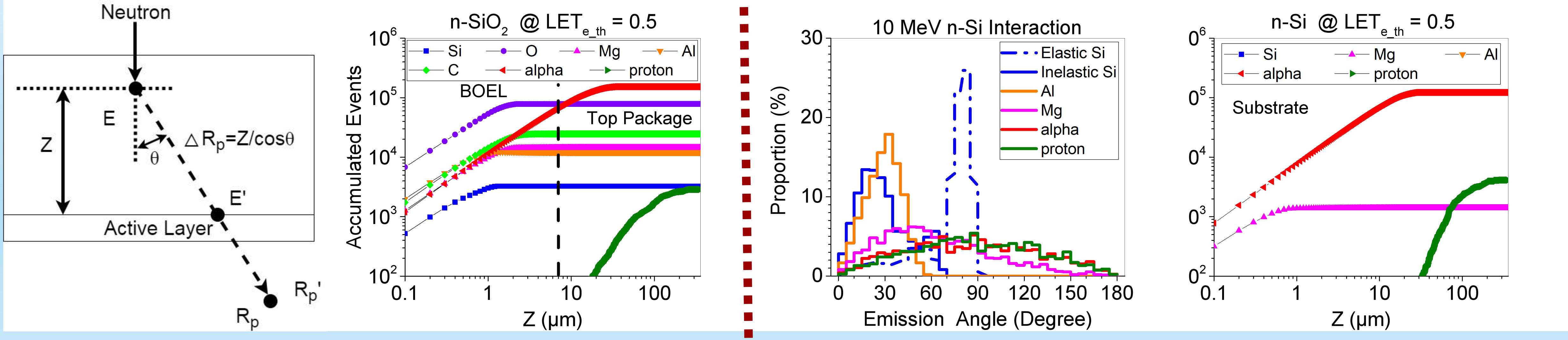
Top package contribution



Substrate contribution

Impact of stack layers

- **Simplified model is established to look into the role of top package layer and substrate.**



Top pacakge layer: long range of alpha particles

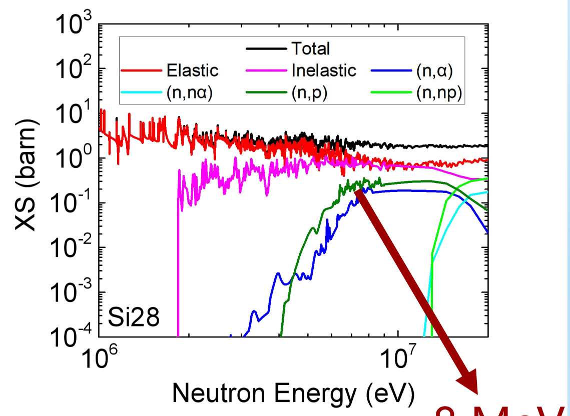
- For each type of secondary particle, as the thickness of material increases, SEUs raise, and finally saturate when the thickness reaches the maximum range of the particle.
- The maximum range of alpha particles (~40 μm) is far more longer than heavy ions (1~3 μm), thus the active volume for neutron reactions is larger.

Substrate: 90° symmetrical emission of alpha particles

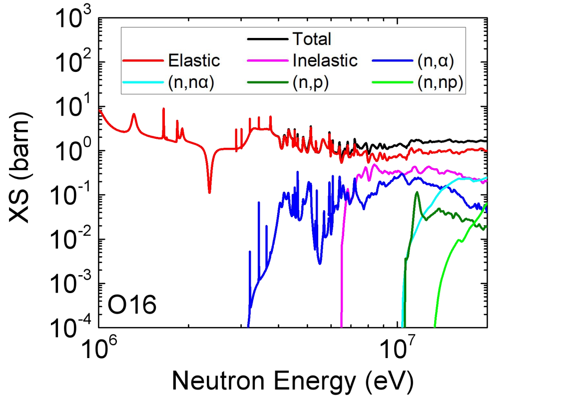
- Half of generated alpha particles are capable of entering the sensitive volume.
- Most heavy ions tend to be forward-emission, thus contribute less to SEUs.

Impact of alpha yield

- The energetic dependence greatly impacted by alpha yield in the middle energy range.

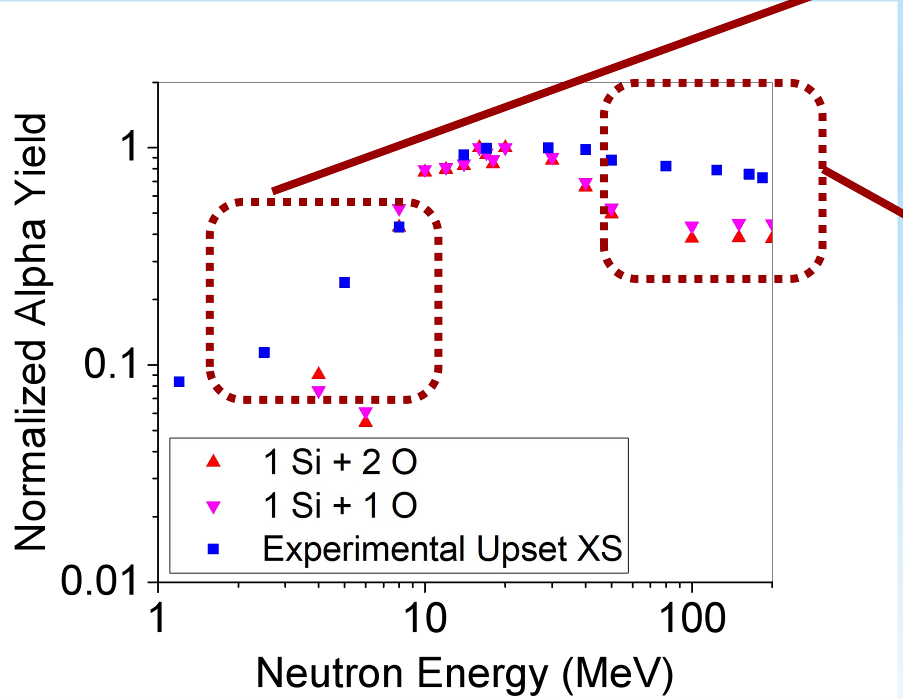


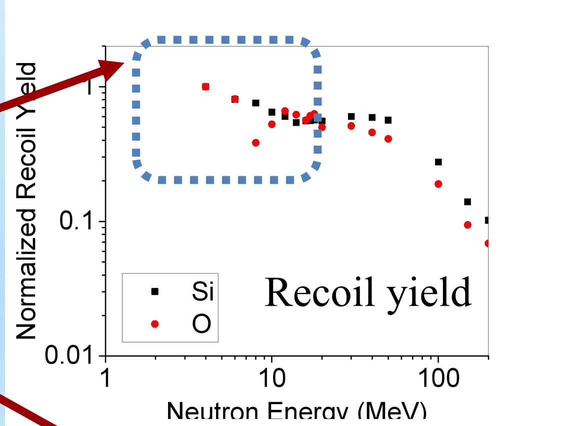
~8 MeV

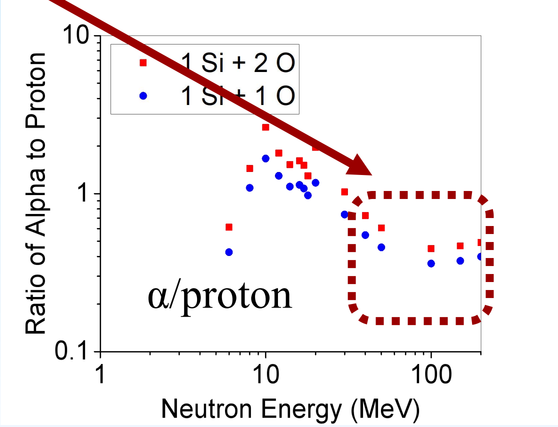


8~30 MeV region

Normalized α yield agrees well with the energetic dependence of NSEUs







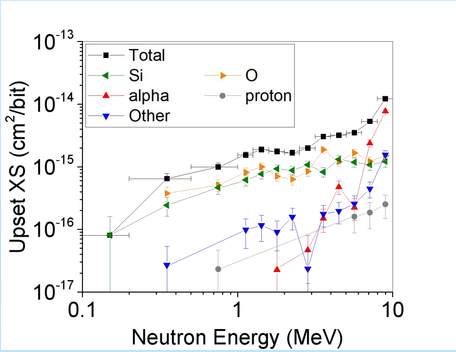
Low (n, xα) cross-section, elastic recoils dominate

More Al, N from (n, xp), raising the heavy ion contribution

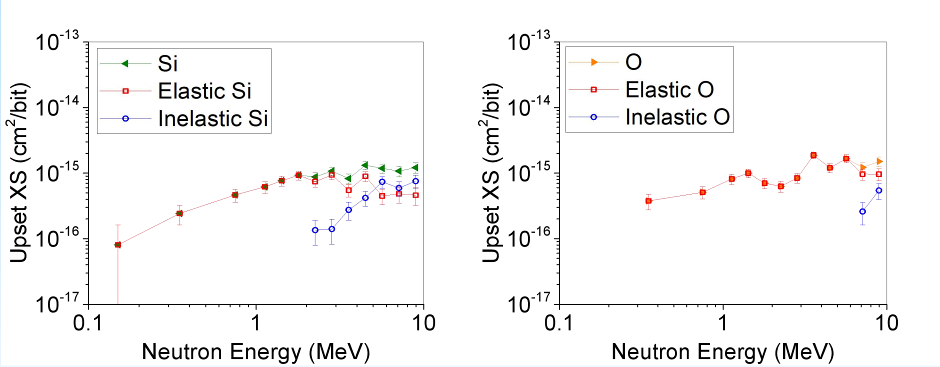
Contribution of elastic recoils below 10 MeV

- **Elastic scattering is the dominant mechanism responsible for NSEUs below 10 MeV.**

NSEU Cross-section



Si、O VS others



Elastic VS Inelastic

Atmospheric Neutrons: **64%** from elastic recoils

Energy /MeV	Neutron /%	Upset /%	Elastic /%	α /%	Others /%
0.1-1	20.2	1.5	100	0	0
1-10	29.5	11.0	58.6	25.3	16.1
10-200	38.2	64.0	11.1	55.5	33.4
>200	12.1	23.5	1.6	50.6	47.8

CSNS Back-n: **67%** from elastic recoils

Energy /MeV	Neutron /%	Upset /%	Elastic /%	α /%	Others /%
0.1-1	46.2	8.5	100	0	0
1-10	43.1	32.1	58.7	22.7	18.6
10-200	10.7	59.4	11.5	67.6	20.9
>200	~0	0	-	-	-

Spectrum Characteristics below 10 MeV

- The dominance of elastic recoils in the < 10 MeV region, is due to much larger proportion of < 6 MeV neutrons than 6-10 MeV neutrons.

Energy /MeV	Atmos. /%	ISIS ChipIR /%	J-PARC BL10 /%	CSNS Back-n /%	CSNS BL09 /%
0.1-1	20.1	86.1	-	46.4	75.1
1-6	25.0	9.9	86.3	36.7	22.0
6-10	4.4	0.8	5.3	5.9	1.1
10-200	38.2	2.6	8.4	10.9	1.7
>200	12.3	0.6	~0	0.1	0.1

Elastic reoils dominance

45%~97%

1%~6%

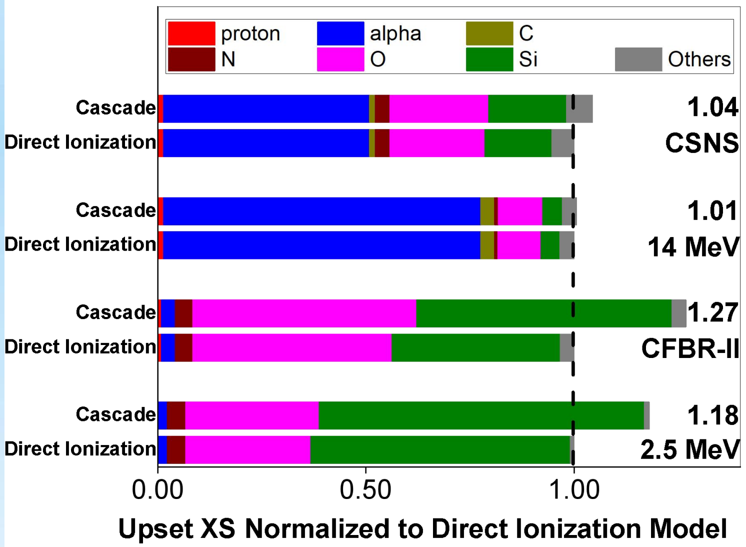
Alpha dominance

Elastic scattering is the most important mechanism responsible for the SER overstimation issue.

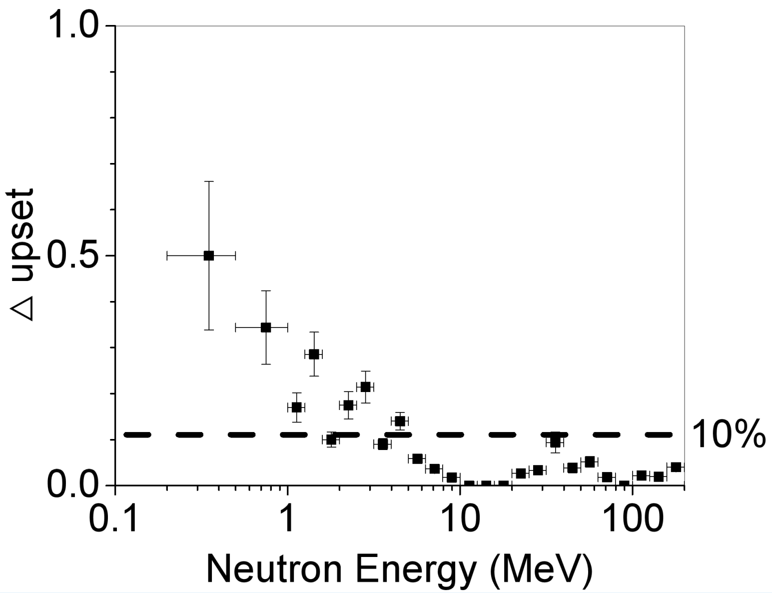
Indirect ionization of elastic recoils

- The role of indirect ionization of elastic recoils in inducing SEUs is investigated.

$$\triangle_{upset} = \frac{\sigma_{Cascade} - \sigma_{Direct\ Ionization}}{\sigma_{Direct\ Ionization}}$$



Reactor、2.5 MeV: +27%、+18%



Below ~5 MeV: +10%~50%

Neutron energy ↑

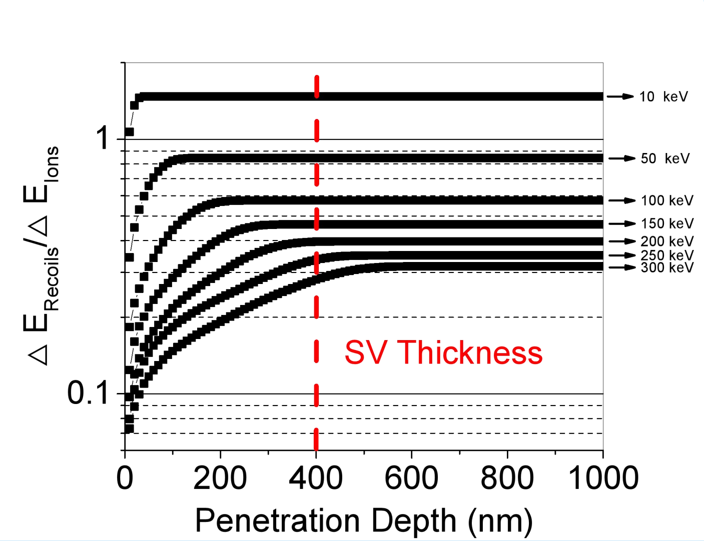
(1) Energy of recoils ↑, nuclear energy loss ↓;
(2) Contribution of alphas↑, role of elastic recoils is weakened。

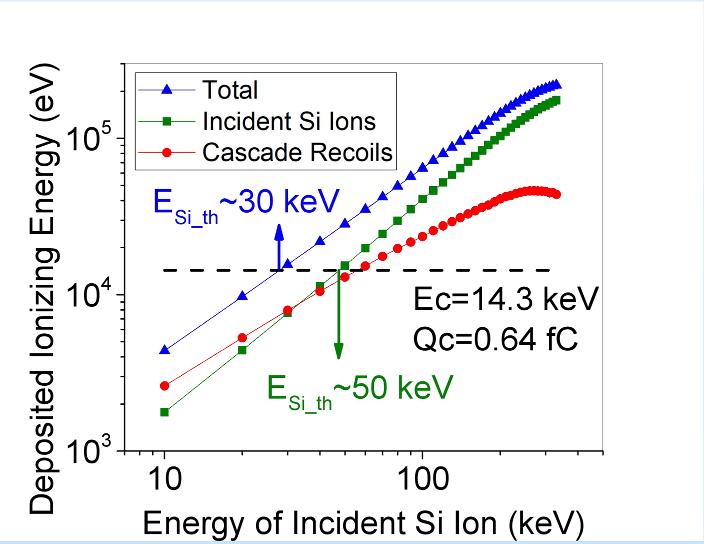
Role of indirect ionization is weakened

Below ~5 MeV, cascade recoils generated from elastic PKAs contribute greatly to NSEUs

Indirect ionization of elastic recoils

☐ The ionization energy deposition of low-energy Si ions is investigated.

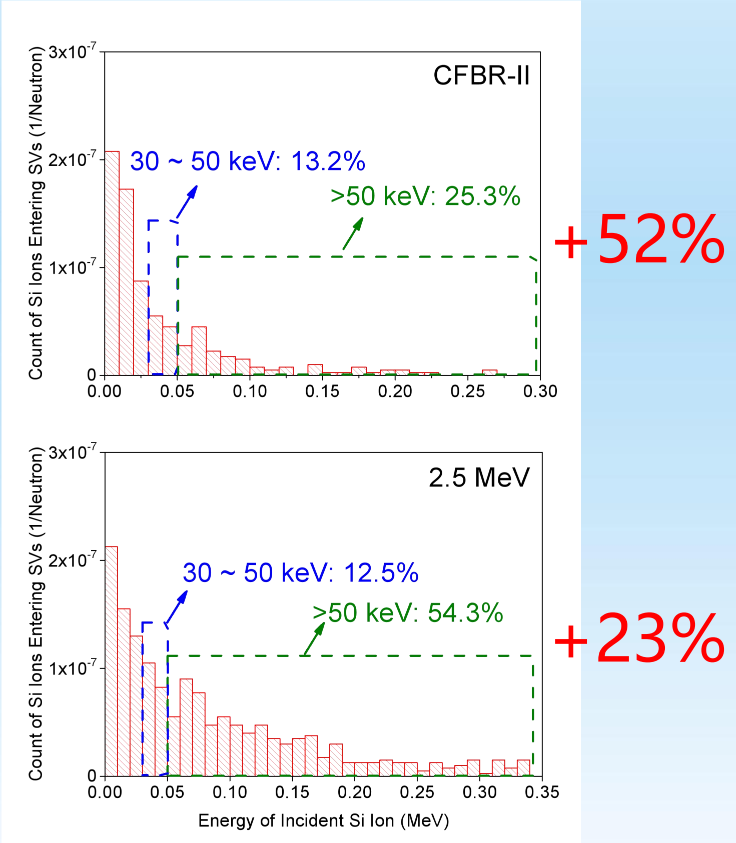




With the lower energy of impinging Si ion, the indirect ionization energy increases relatively

For the critical charge of 0.64 fC, indirect ionization decrease the threshold energy of Si ion from ~50 keV to ~30 keV

Energy spectrum of impinging Si PKAs

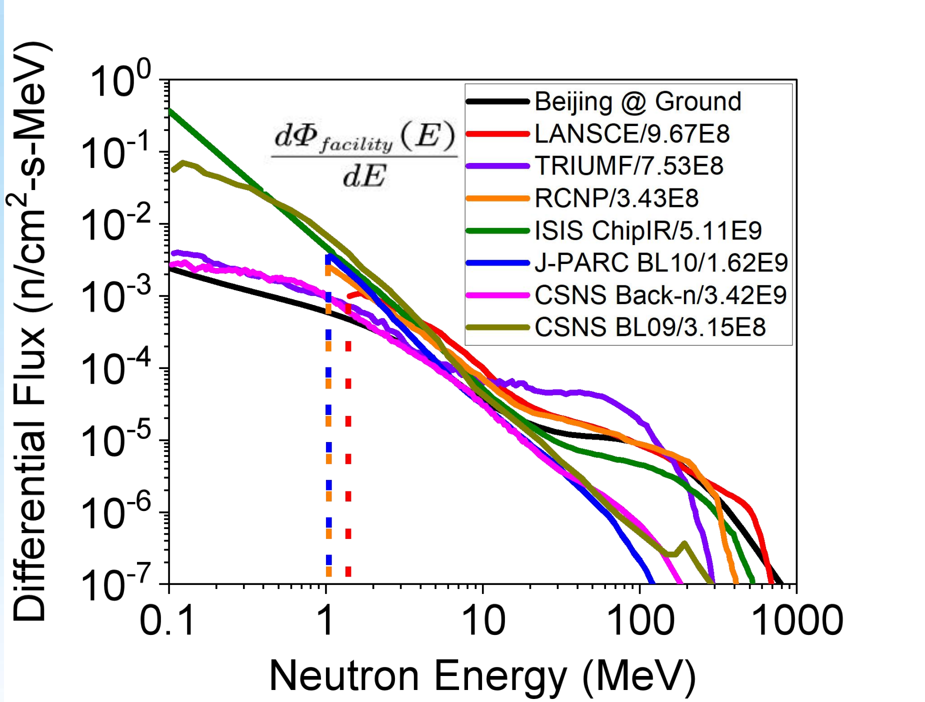


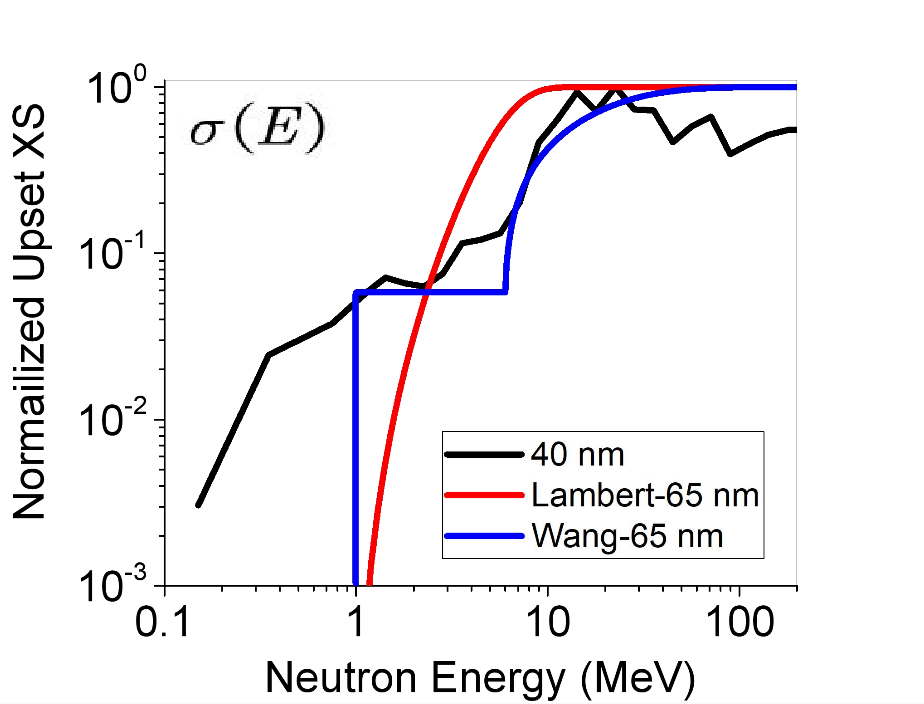
Indirect ionization due to cascade recoils plays an important role in provoking SEUs.

The accuracy of SER prediction

- **SER prediction using 7 spallation sources is analyzed, based on 40 nm SRAM and 2 types of 65 nm SRAM data.**
  - > 1 : Overestimation
  - <1 : Underestimation

$$SER\ ratio = \frac{\int_0^\infty \sigma(E)\frac{d\Phi_{facility}(E)}{dE}dE}{\int_{E_{min}}^\infty \frac{d\Phi_{facility}(E)}{dE}dE} \Bigg/ \frac{\int_0^\infty \sigma(E)\frac{d\Phi_{atmosphere}(E)}{dE}dE}{\int_{E_{min}}^\infty \frac{d\Phi_{atmosphere}(E)}{dE}dE}$$





The accuracy of SER prediction

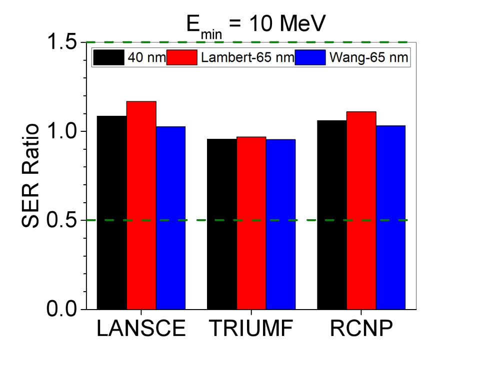
- SER prediction using 7 spallation sources is analyzed, based on 40 nm SRAM and 2 types of 65 nm SRAM data.

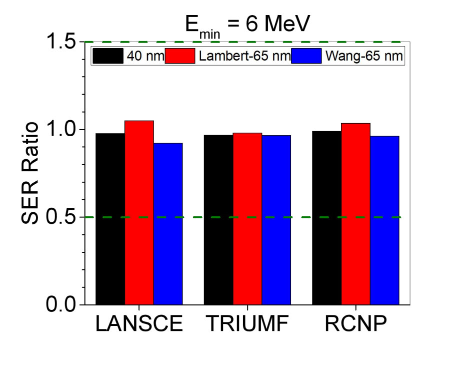
Emin = 10 MeV

Emin = 6 MeV

Group 1

Closer to atmospheric spectrum

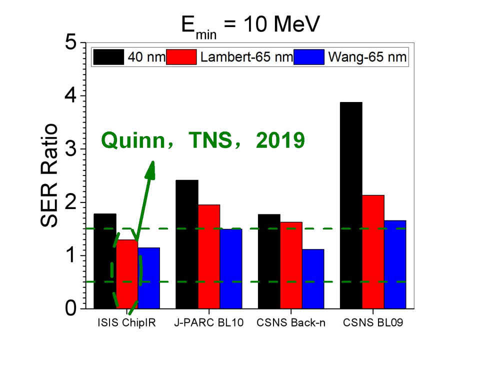


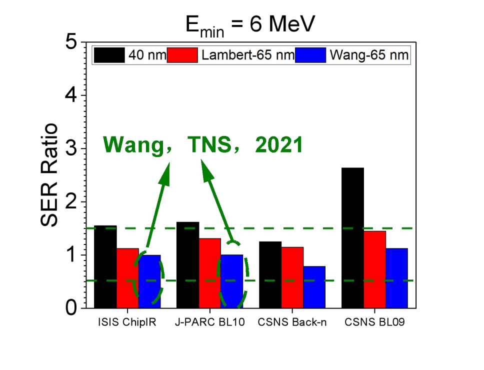


0.92~1.17, insensitive to neither E_{min} nor $\sigma(E)$

Group2

Excessive <10 MeV portion





10MeV:

Overestimation:+50%, maximum~300%;

6MeV:

65 nm SRAM < 50%

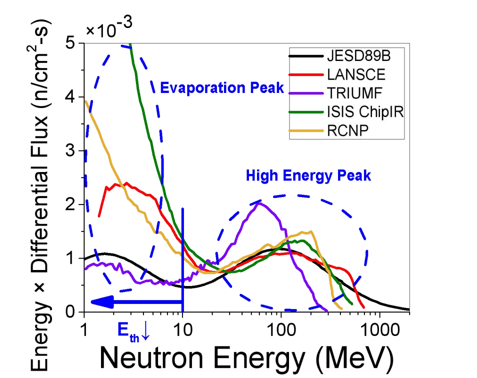
40 nm SRAM > 50%,

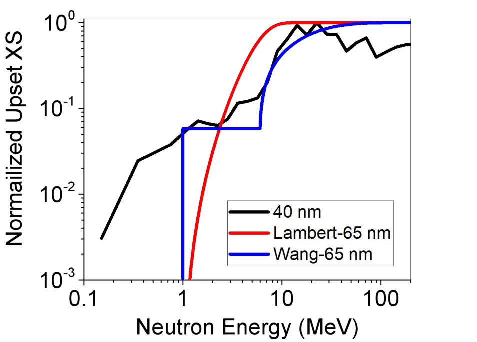
Maximum ~160%

Piece-wise mean cross-section equivalence

- The feasibility of prediction method based on piece-wise mean cross-section equivalence.

$$SER = \sigma_{<10\ MeV} \cdot \Phi_{0.1/1-10MeV} + \sigma_{>10\ MeV} \cdot \Phi_{>10MeV}$$





Neutron Source	$\sigma_{>10\ MeV}$ /cm²/bit	$\sigma_{<10\ MeV}$ /cm²/bit	$\sigma_{>10\ MeV}$ /cm²/bit	$\sigma_{<10\ MeV}$ /cm²/bit	$\sigma_{>10\ MeV}$ /cm²/bit	$\sigma_{<10\ MeV}$ /cm²/bit
	40 nm SRAM		Lambert-65 nm SRAM		Wang-65 nm SRAM	
Atmospheric	**1.63×10^{-14}**	**3.98×10^{-15}**	**1.70×10^{-14}**	**4.15×10^{-15}**	**3.93×10^{-14}**	**3.83×10^{-15}**
TRIUMF	1.62×10^{-14}	3.81×10^{-15}	1.70×10^{-14}	4.27×10^{-15}	3.79×10^{-14}	4.01×10^{-15}
ISIS ChipIR	1.64×10^{-14}	5.05×10^{-15}	1.70×10^{-14}	2.44×10^{-15}	3.74×10^{-14}	3.06×10^{-15}
CSNS Back-n	1.85×10^{-14}	3.70×10^{-15}	1.70×10^{-14}	3.74×10^{-15}	3.23×10^{-14}	3.61×10^{-15}
CSNS BL09	1.79×10^{-14}	4.26×10^{-15}	1.70×10^{-14}	1.92×10^{-15}	3.21×10^{-14}	2.87×10^{-15}
LANSCE	1.62×10^{-14}	3.31×10^{-15}	1.70×10^{-14}	4.70×10^{-15}	3.79×10^{-14}	3.89×10^{-15}
RCNP	1.60×10^{-14}	2.77×10^{-15}	1.70×10^{-14}	3.36×10^{-15}	3.81×10^{-14}	3.48×10^{-15}
J-PARC BL10	1.98×10^{-14}	2.31×10^{-15}	1.70×10^{-14}	1.93×10^{-15}	3.05×10^{-14}	2.92×10^{-15}

Neutron Source	40 nm /FIT/Mbit		Lambert-65 nm/FIT/Mbit		Wang-65 nm /FIT/Mbit	
Atmospheric	**153**	**1.00**	**160**	**1.00**	**342**	**1.00**
TRIUMF	152	0.99	161	1.00	332	0.97
ISIS ChipIR	159	1.04	152	0.95	323	0.94
CSNS Back-n	170	1.11	158	0.99	284	0.83
CSNS BL09	168	1.09	149	0.93	278	0.81
LANSCE	149	0.97	163	1.02	331	0.97
RCNP	145	0.95	156	0.98	331	0.97
J-PARC BL10	174	1.14	149	0.93	265	**0.78**

Maximum error of 22%

SER prediction combined with 14 MeV data

- An SER prediction method combined with 14 MeV data is proposed.

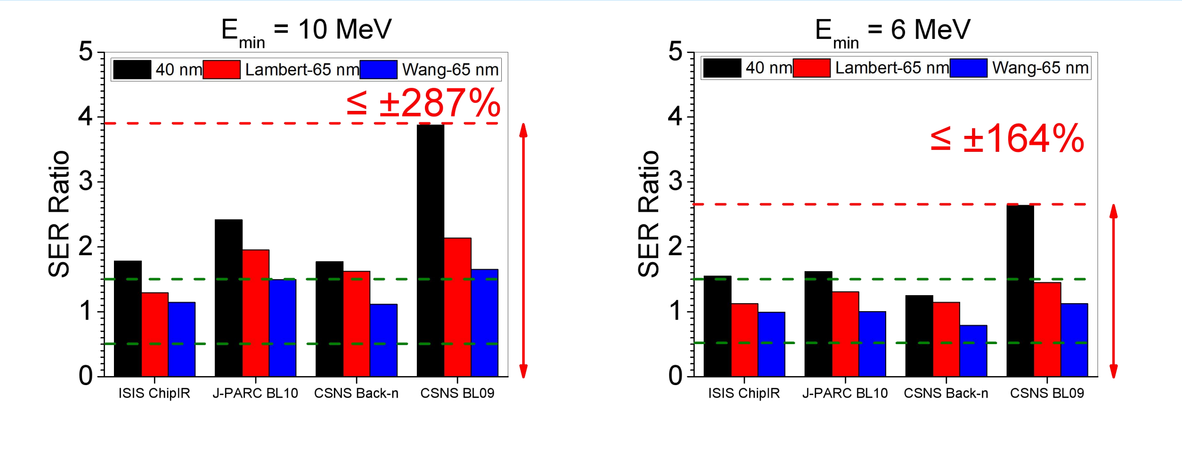
Spallation Neutron Source

$$SER = \sigma_{<10\ MeV} \cdot \Phi_{0.1/1-10MeV} + \sigma_{>10\ MeV} \cdot \Phi_{>10MeV}$$

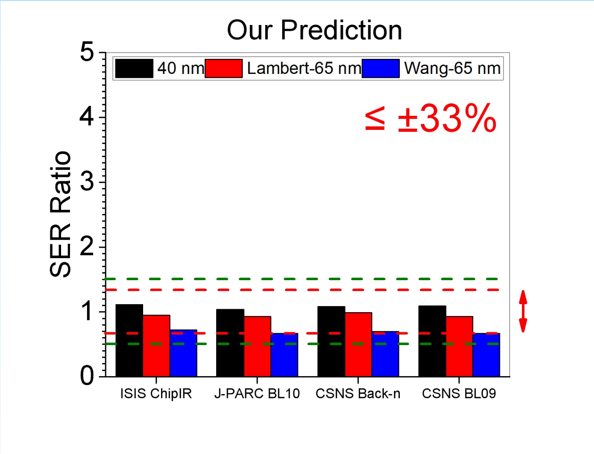
σ_{14MeV} **14 MeV Neutron Source**

Atmospheric Neutrons

$$SER = \sigma_{<10\ MeV} \cdot \Phi_{0.1/1-10MeV} + \sigma_{>10\ MeV} \cdot \Phi_{>10MeV}$$



Traditional Prediction Method



Our Method

Maximum error of 33%

- Introduction
- Energetic dependence of NSEUs
- Underlying mechanisms of the energetic dependence
- Impact on SER prediction
- **Summary**

Summary

- A Geant4-based monte-carlo simulation model dedicated to simulating NSEUs of nano-scale ICs has been established, and calibrated to experimental results from four mono-energetic or continuous-spectrum neutron sources. The simulation results consistently fit well with the experimental data within a very wide energy range.
- Alpha particles originating from nuclear reactions is the most important secondary particles to induce upsets above ~6 MeV, due to high efficiency in provoking SEUs compared to short range heavy ions.
- Elastic scattering is the dominant NSEU mechanism below ~6 MeV, and the most important source responsible for the SER overestimation issue. Further, the indirect ionization by cascade recoils also has a significant impact in the neutron energy below ~5 MeV.
- Remarkable overestimation exsists when using spallation neutron sources with abundant low-energy neutrons. A proposed prediction method combining spallation neutron sources and 14-MeV mono-energetic neutron sources, yields much better prediction results compared to traditional spallation-neutron-source-based methods.

Thanks for your attention!