Irradiation Testing and Simulation of Neutron-induced Single Event Effects

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Chinese Radiation Physics Society (CRPS)

CRPS:

A community which strives to provide chances for the physicists to spread the physics knowledge and information for the advancement of radiation physics and its application.

- ✓ **Founded in 2013, supported by NINT**
- ✓ **Members from more than 100 enterprises, universities and institutions**
- ✓ **Research on radiation environment, radiation effects and hardening**

Welcome to join the activities held by CRPS!

Outline

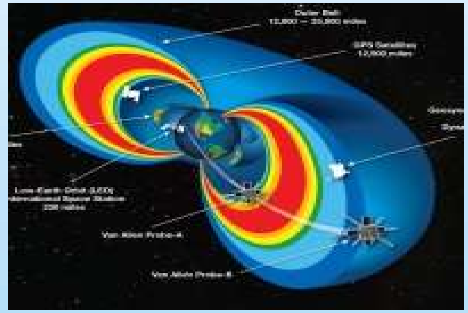
1. Introduction
2. Radiation Environments
3. Irradiation Testing and Results
4. Simulation models and results
5. Conclusion

1. Introduction

Space Radiation Environments:

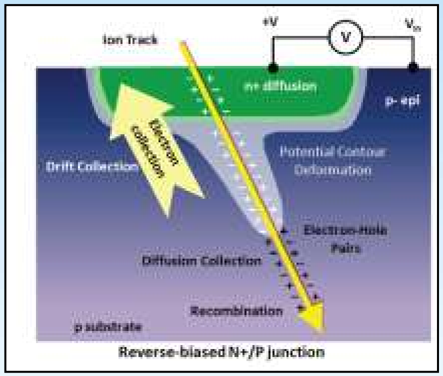
Galactic cosmic ray

Solar flare

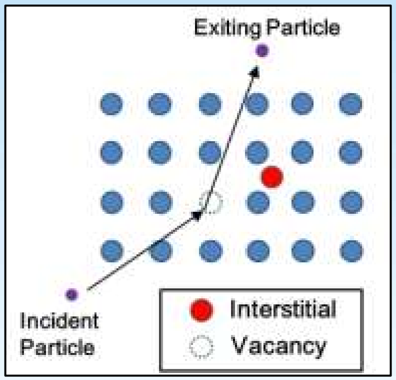


Radiation belts of earth

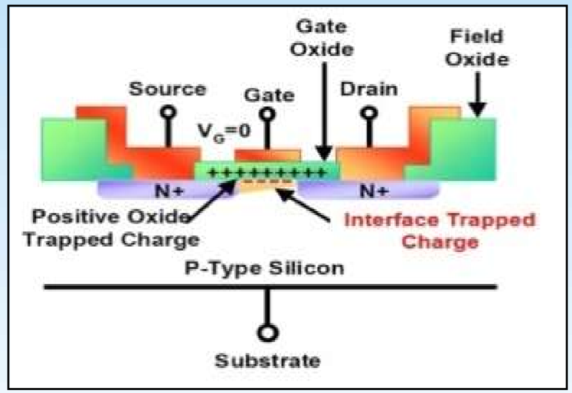
Radiation Effects in Electronic Devices:



Single Event Effects



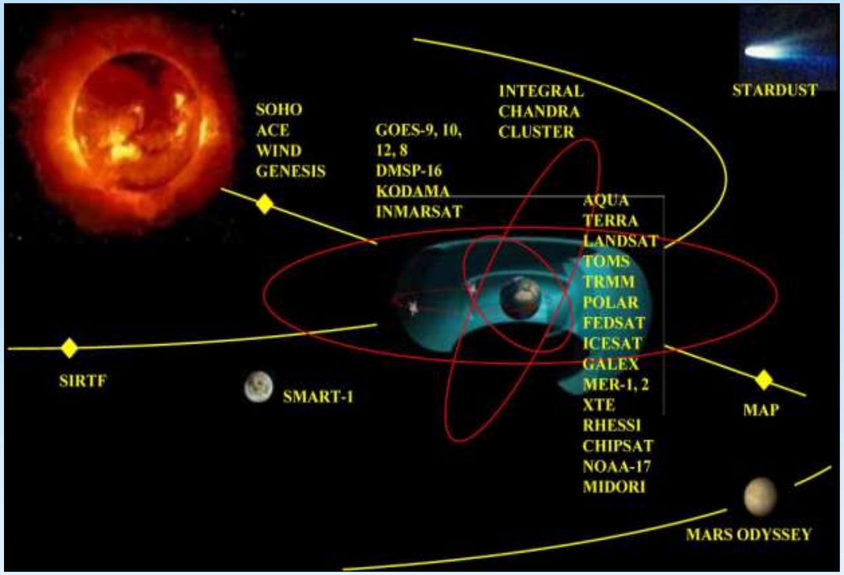
Displacement Effects



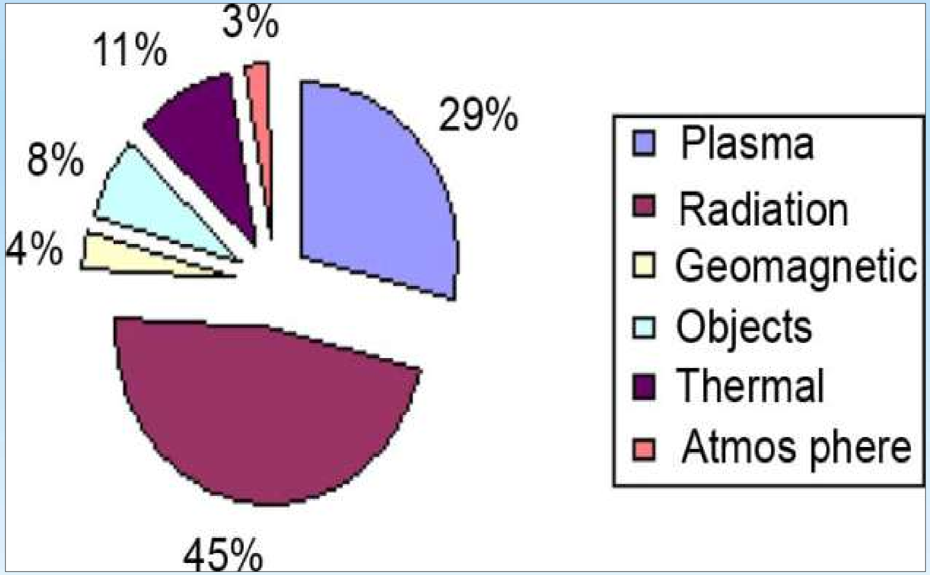
Total Ionizing Dose Effects

1. Introduction

Radiation effects, which can degrade the characteristics and reliability of electric devices, are the main reason for failures of spacecraft, about 45% counted by NASA.



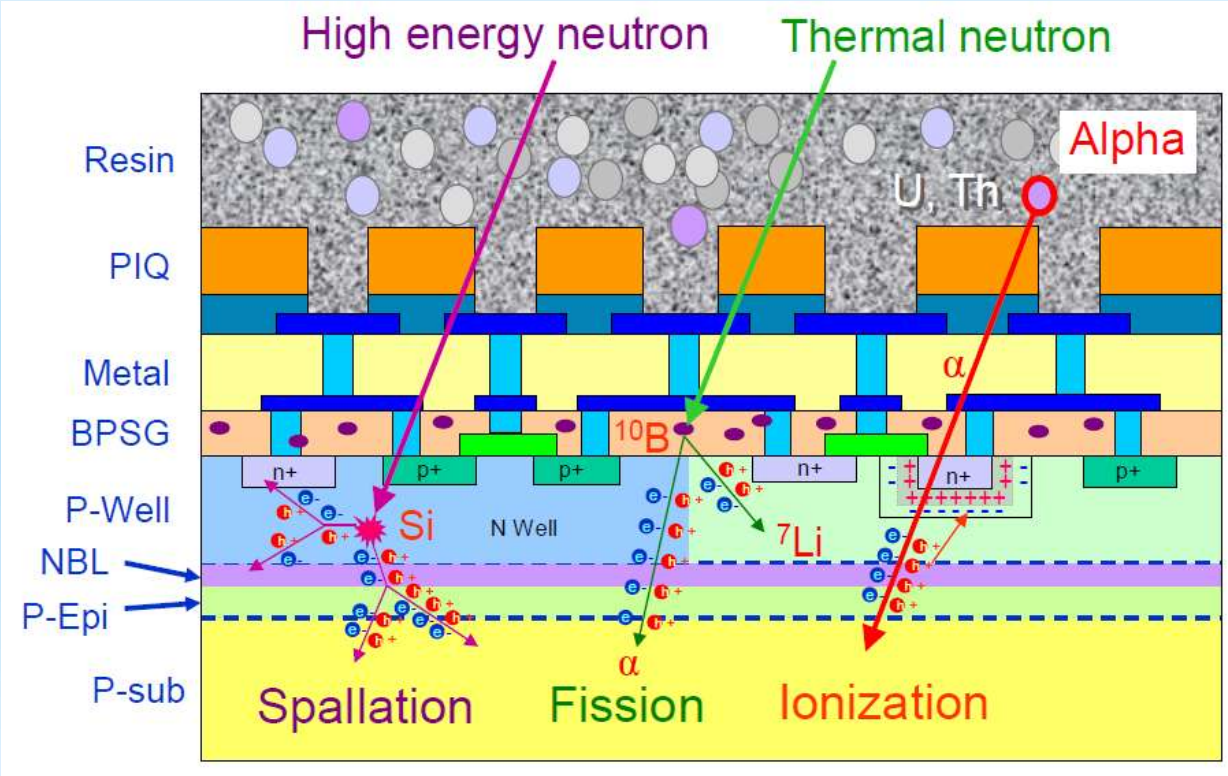
Spacecraft in Space Radiation Environment



Spacecraft Failures Statistics (2013, NSREC)

1. Introduction

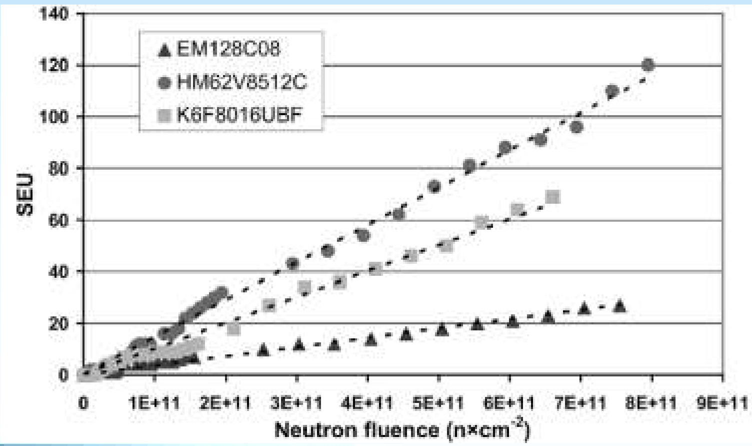
Neutron-induced Single Event Effects (SEE)

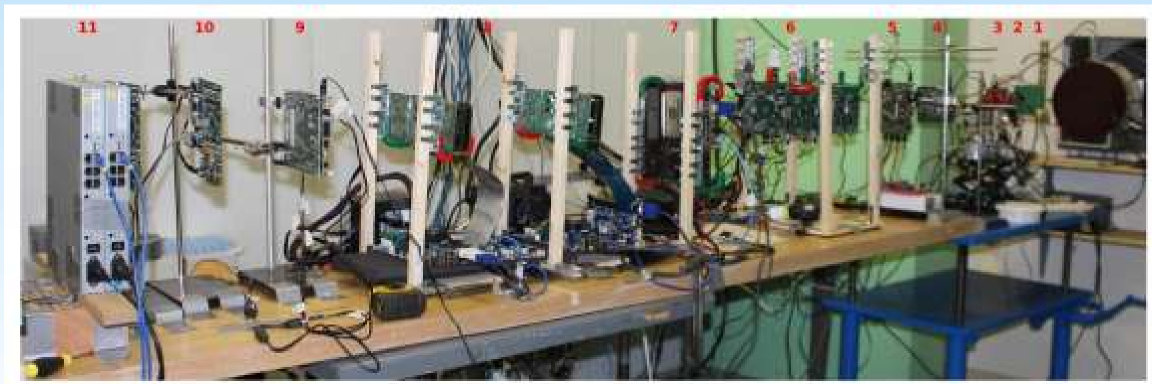


Neutron-induced SEE threatens the reliability of avionics and supercomputers in terrestrial radiation environment.

1. Introduction

- 1980s: Flight testing in aircraft accomplished by IBM and Boeing confirmed the existence of neutron-induced SEE.
- 2004: Experiments on 0.13 μm ~ 0.18 μm SRAMs accomplished in Ulysse Nulcear Reactor in CEA Saclay Center, France proved neutron-induced SEU.
- 2015: Neutron irradiations at the Los Alamos Neutron Science Center (LANSCE) presented faults in microcontrollers, ARM cores, GPUs, and SRAM-based FPGAs.
- 2017: 14 MeV Neutron-induced SEE testing in SRAMs, SDRAMs, SRAM-based FPGAs and Flash-based FPGAs, including SEU, MCU, SEFI and SEL.





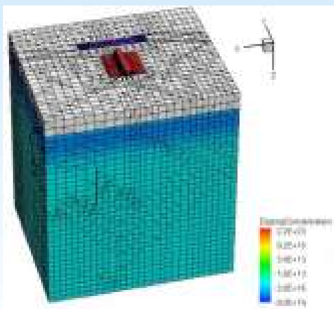
1. Introduction

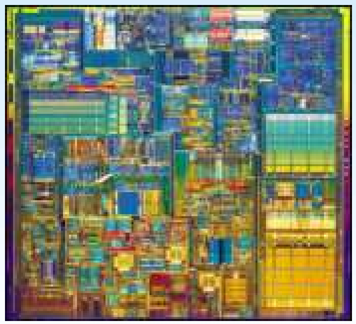
With the scaling down of feature sizes of electronic devices, neutron-induced SEE has a great impact gradually.

Changes

Drastic device shrinking → Very low operating voltage → Increasing complexity → Changes in the structure → High speeds

Increase of sensitivity for SEE → **Functional fault** → **Electronic system failure**





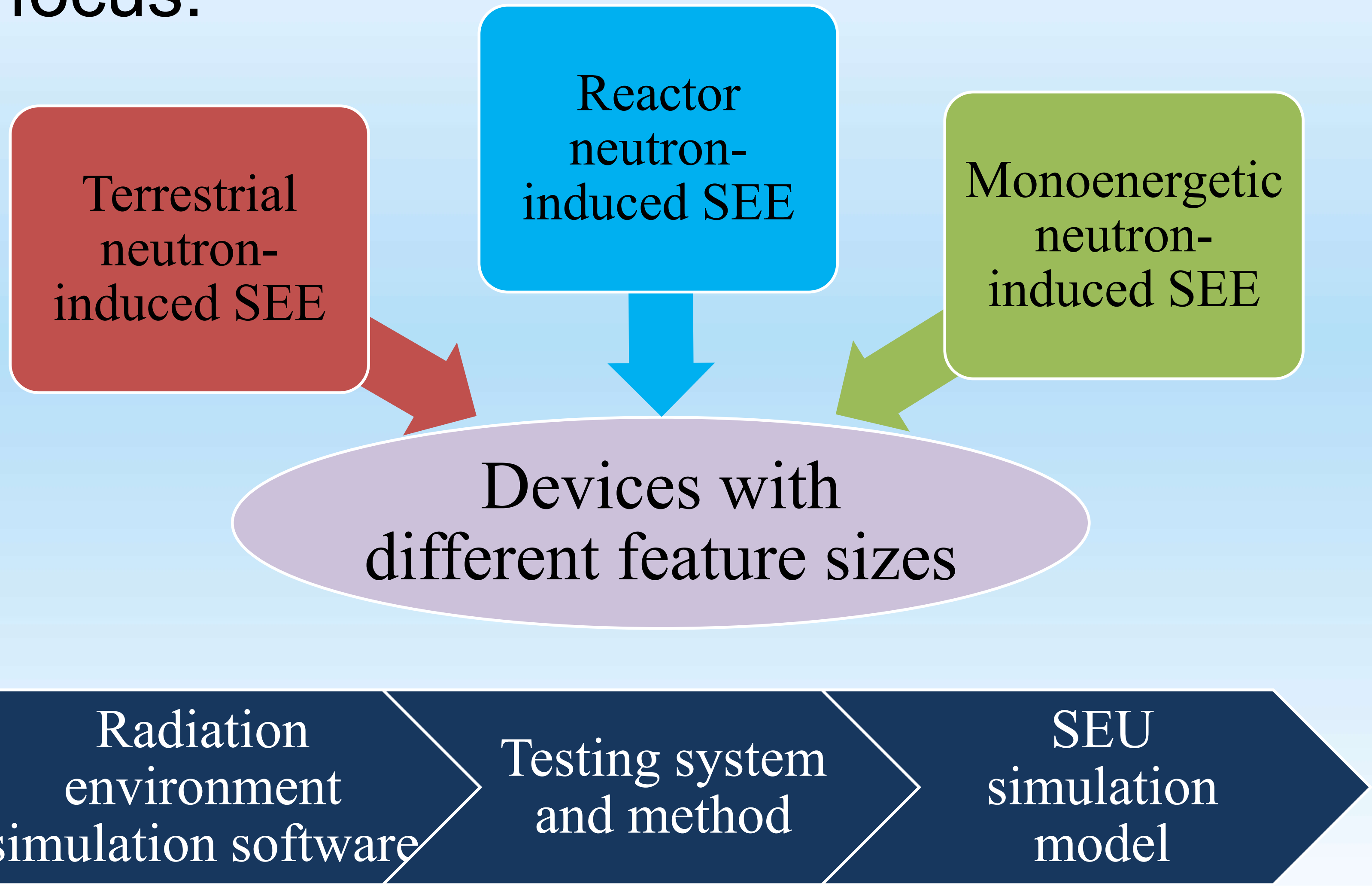
1. Introduction

Challenges

Energy spectrum	• Wide range: eV ~ GeV
Reaction Cross section	• Accuracy of nuclear data
Experiments	• Testing technology

1. Introduction

Our focus:



2. Radiation Environments

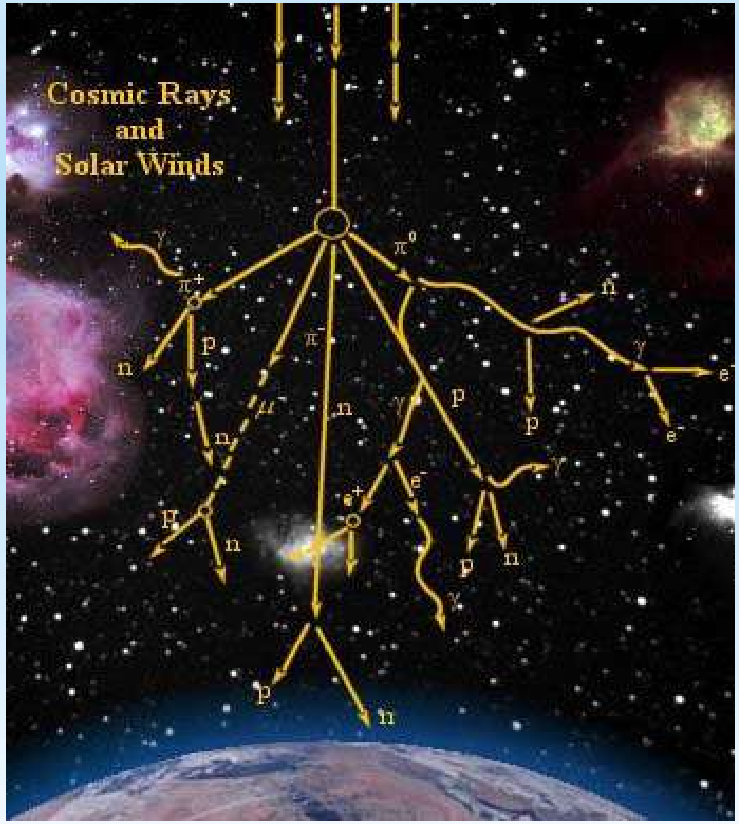
2.1 Terrestrial neutrons

Formation

Cosmic rays (mainly protons) with high energy to the atmosphere of the Earth.

Some protons undergo nuclear spallation reaction with nuclei (mainly nitrogen and oxygen nuclei) in the atmosphere.

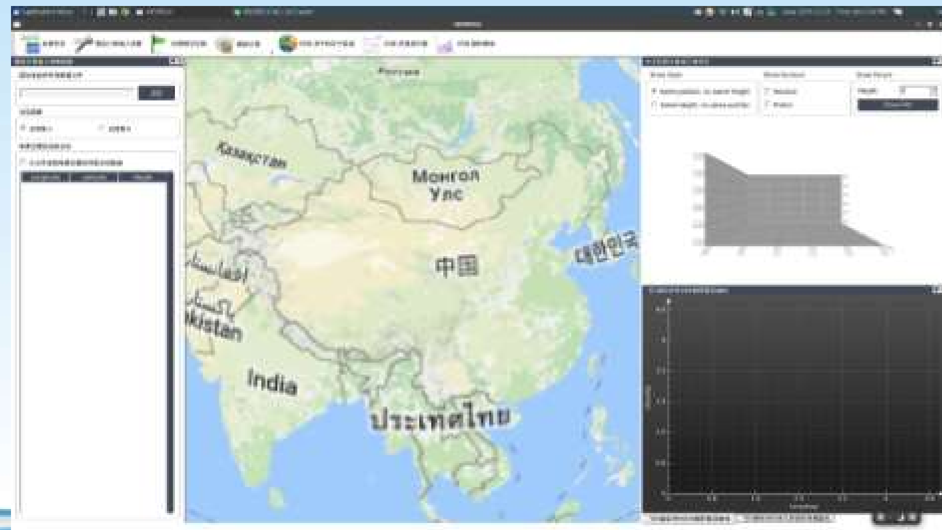
About 92% of the secondary particles are neutrons.



2. Radiation Environments

RESNS2. 0 → Terrestrial Neutron Radiation Environment Simulation Software

- Based on **3D geographic information platform**
- Work on **Windows**, **Linux** or **Parallel Computer System**
- **Fast algorithm based on parallel computing**
- **Neutron/Proton Environment** of arbitrary points or airline
- Evaluation of **SEE cross-section** for typical devices.

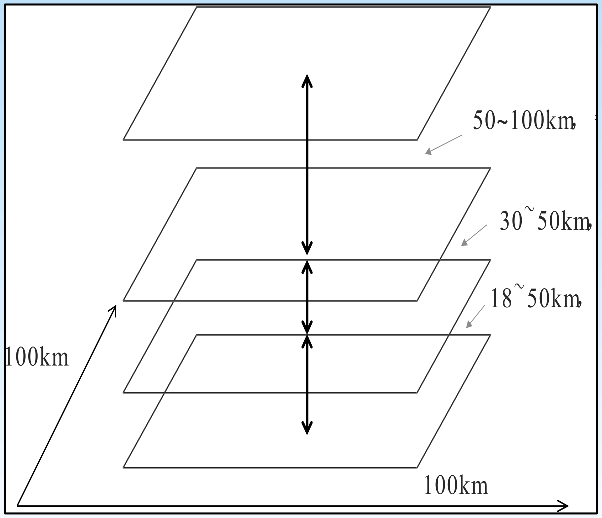


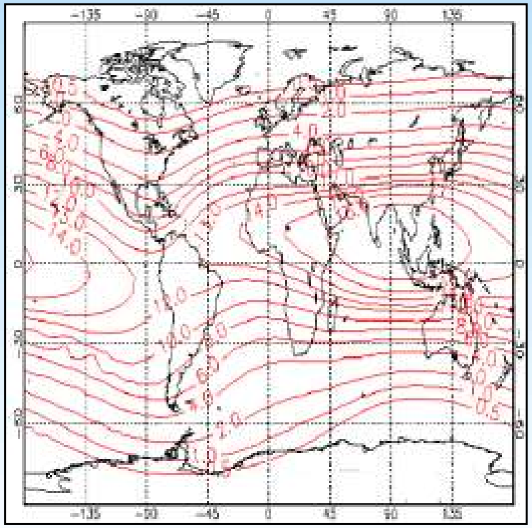
2. Radiation Environments

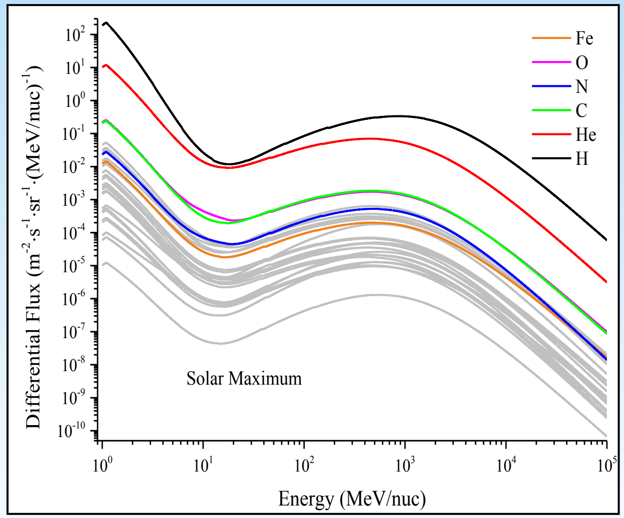
2.1 Terrestrial neutrons

Models for Particle Transport Simulation in RESNS2.0:

Atmospheric Model:	Geomagnetic cut-off rigidities Model	Cosmic ray Model:

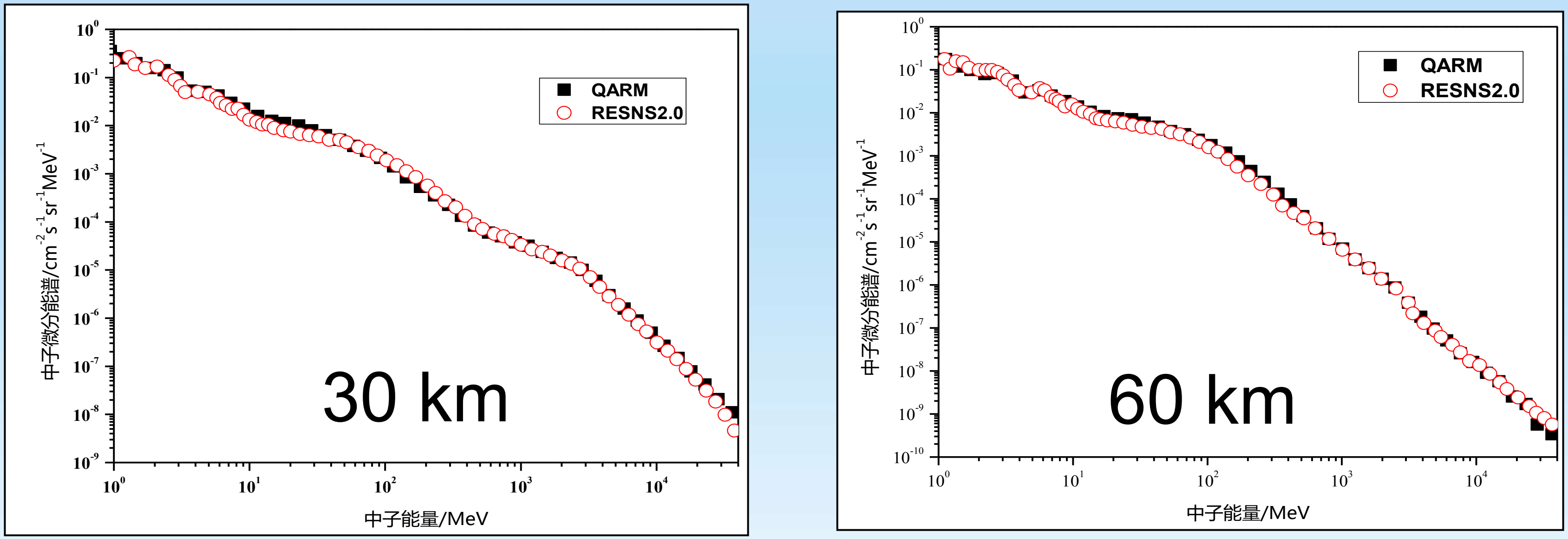






RESNS2.0 Radiation Environment Simulation Software

- Xi’an City, Different Altitude (30 km and 60 km)
- Neutron energy up to 10^4 MeV



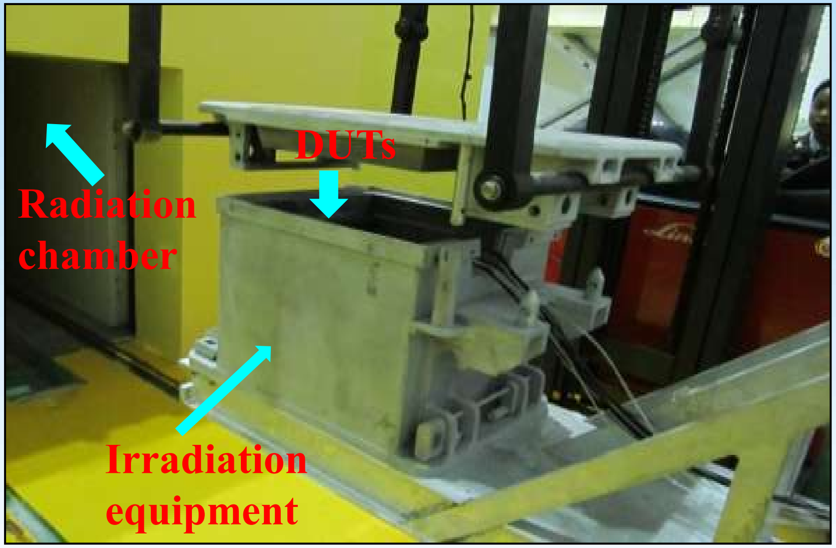
Simulation Results of Terrestrial Neutron Energy Spectrum

2. Radiation Environments

2.2 Reactor neutrons

Xi'an Pulsed Reactor (XAPR): an important facility for the research of neutron radiation effects. It has a specific irradiation platform for electronic devices and components.

Xi'an Pulsed Reactor (XAPR)

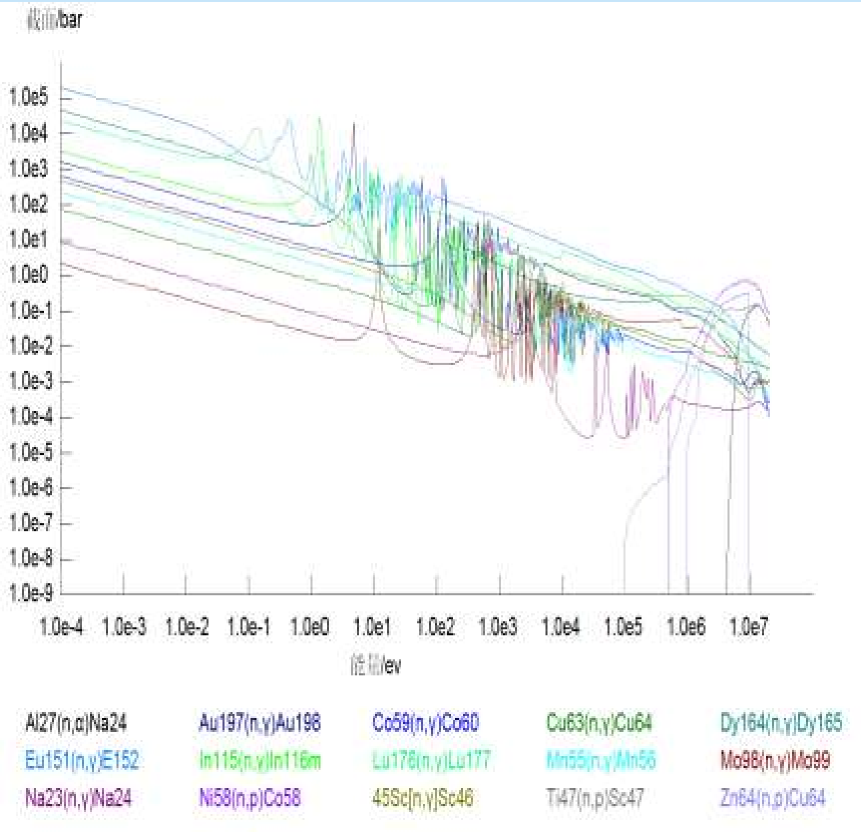


Irradiation platform of XAPR

2. Radiation Environments

2.2 Reactor neutrons

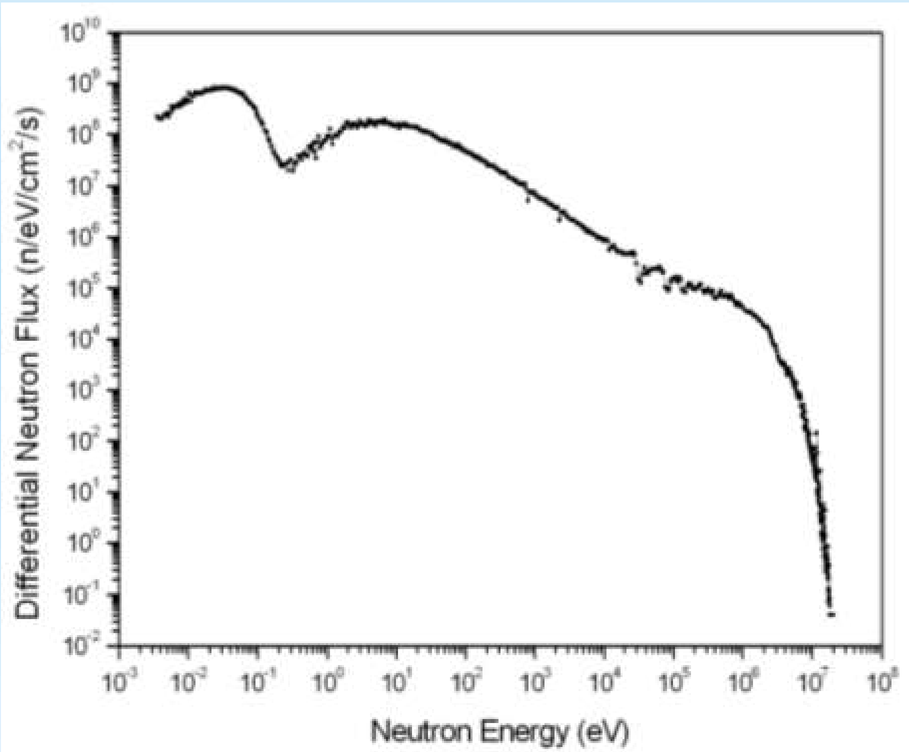
Measurement of Neutron Energy Spectrum: Multi-foil activation method



No	Nuclear reaction channel	mass(μg)	Cooling time(s)	Measure time(s)	count
1	Dy164(n,γ)Dy165	382360	75600	2926	10667
2	Mn55(n,γ)Mn56	92800	78780	815	32750
3	In115(n,n`)In	60450	79740	674	23586
4	Zn64(n,p)Cu64	303600	80520	2083	76117
5	Cu63(n,γ)Cu64	40020	82680	539	39135
6	Na23(n,γ)Na24	84380	83280	637	23573
7	Au197(n,γ)Au198	537.03	84060	664	37763
8	Ni58(n,p)Co58	113110	84780	3134	11746
9	Mo98(n,γ)Mo99	35720	184260	4199	12560
10	Al27(n,α)Na24	84790	163380	20640	11859
11	Lu176(n,γ)Lu177	11190	188520	3044	14931
12	Sc45(n,γ)Sc46	40210	191640	2586	13501
13	Co59(n,γ)Co60	144370	194400	12854	49239
14	Eu151(n,γ)Eu152	79440	207300	6045	299927
15	Ti47(n,p)Sc47	219040	213420	33435	150633

2. Radiation Environments

2.2 Reactor neutrons



Neutron energy spectrum for XAPR

- **Mean energy: ~1 MeV.**
- **Softer neutron energy spectrum compared to atmospheric neutrons.**

2. Radiation Environments

2.3 Monoenergetic neutrons

Neutron energy:
- **14 MeV**
- **2.5 MeV**

Monoenergetic neutron source in China Institute of Atomic Energy

3. Irradiation Testing and Results

Field-testing of terrestrial neutron-induced SEU

A series of SRAMs with different feature sizes were selected to accomplish the terrestrial neutron-induced SEU field-testing.

Type	Manufacturer	Capacity (work mode)	Feature size /μm	Power supply
HM628512A	HITACHI	4 M(512 k×8 bit)	0.50	5.0 V
HM628512B	HITACHI	4 M(512 k×8 bit)	0.35	5.0 V
HM62V8100	RENESAS	8 M(1 M×8 bit)	0.18	3.0 V
HM62V16100	RENESAS	16 M(2 M×8 bit)	0.13	3.0 V

3. Irradiation Testing and Results

Field-testing of terrestrial neutron-induced SEU

Yangbajing International Cosmic Ray Observatory,
Chnese Academy of Science, Tibet

- Longitude and latitude: 30.1° N and 90.5° E,
- Altitude: 4300 m

Field-testing plant in Yangbajing

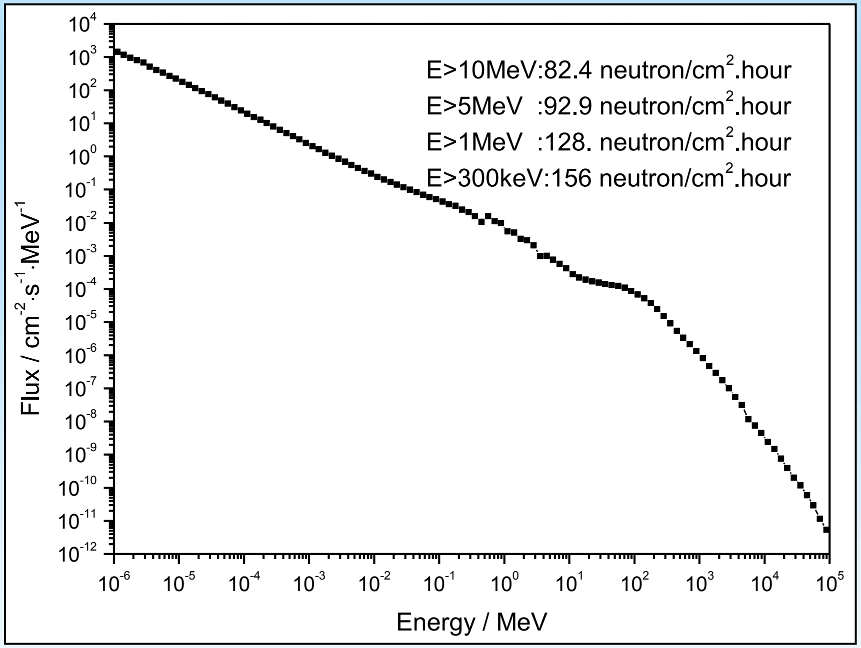
Testing system in Yangbajing

3. Irradiation Testing and Results

Field-testing of terrestrial neutron-induced SEU

Estimation of terrestrial neutron fluence in Yangbajing:

- E>300keV： 156 n/cm²/s　　E>5MeV： 92.9 n/cm²/s



Terrestrial neutron differential spectrum

Measurement: Bonner ball system

Simulation software: RESNS2.0

3. Irradiation Testing and Results

Field-testing of terrestrial neutron-induced SEU

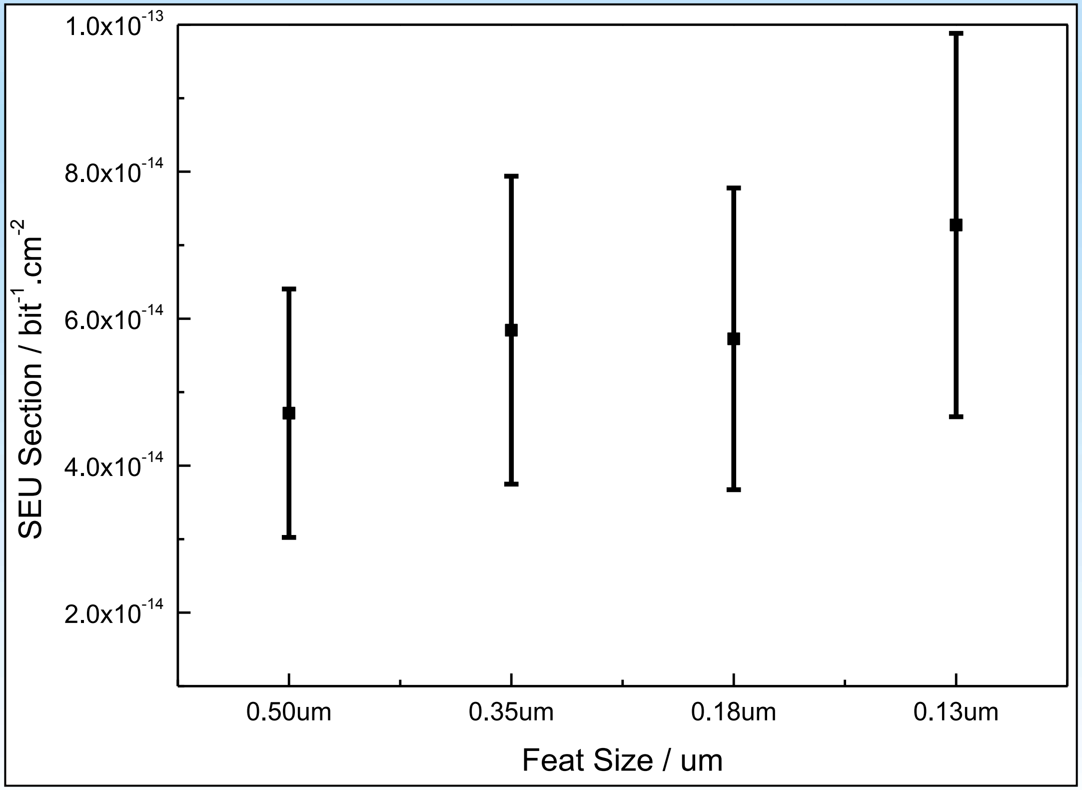
Upset rate and upset cross section:

Item	HM628512A	HM628512B	HM62V8100	HM62V16100
Feature size(um)	0.5	0.35	0.18	0.13
Capacity	4 M×1300	4 M×1480	8 M×576	16 M×260
Test time（hours）	5198	5198	6085	5198
Upset number（bit）	76	181	195	82
Upset rate(#/bit·h)	5.49×10^{-12}	6.80×10^{-12}	6.67×10^{-12}	8.47×10^{-12}

3. Irradiation Testing and Results

Field-testing of terrestrial neutron-induced SEU

Terrestrial neutron-induced SEU cross section in Yangbajing in the series of SRAMs with different feature sizes:



3. Irradiation Testing and Results

Reactor and monoenergetic neutron-induced SEU

SRAMs irradiated in Xi'an pulsed reactor and monoenergetic neutron source:

HITACHI series

Type	Capacity	Feature size	Power supply
HM6116	16 kbit	>1.50 μm	5.0 V
HM6264	64 kbit	1.50 μm	5.0 V
HM628128	1 Mbit	0.80 μm	5.0 V
HM628512	4 Mbit	0.50 μm	5.0 V
HM62V8100	8 Mbit	0.18 μm	3.0 V or 3.3 V
HM62V16100	16 Mbit	0.13 μm	3.0 V or 3.3 V

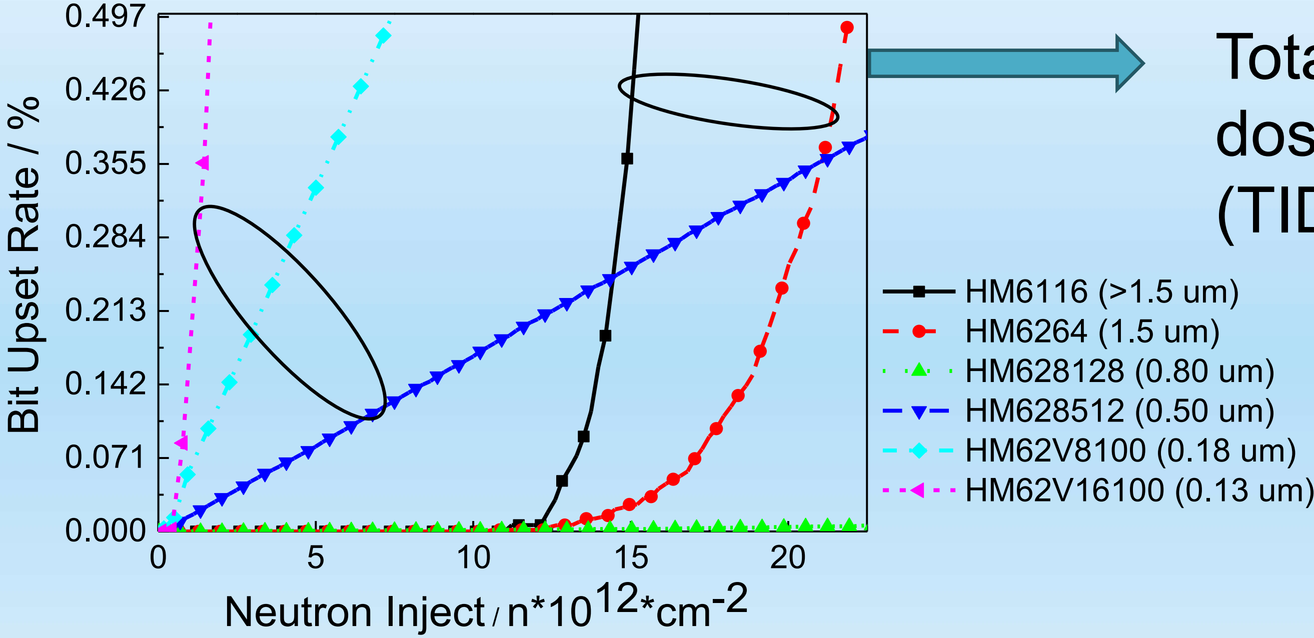
ISSI series

Type	Feature size(nm)	Memory capacity (M-bit)	Power supply
IS61WV204816	40	32	3.3
IS64WV25616	65	4	3.3
IS61WV12816	90	2	3.3
IS62WV1288	130	1	3.3

3. Irradiation Testing and Results

Reactor neutron-induced SEU in SRAMs with different feature sizes:

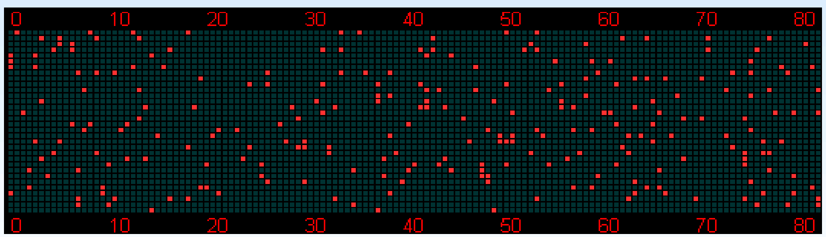
Neutron-induced SEE



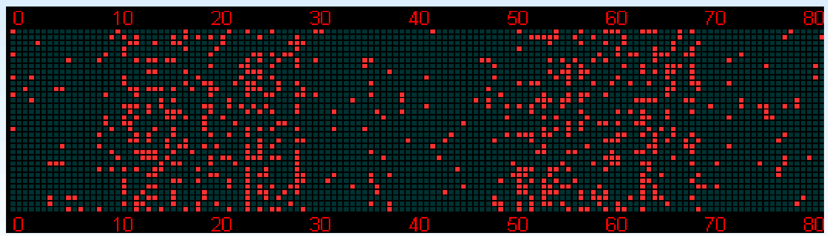
Total ionizing dose effects (TID)

Bit upset rate *versus* neutron fluence

Uniform



Non-Uniform



Upset Bitmap

3. Irradiation Testing and Results

Reactor and monoenergetic neutron-induced SEU

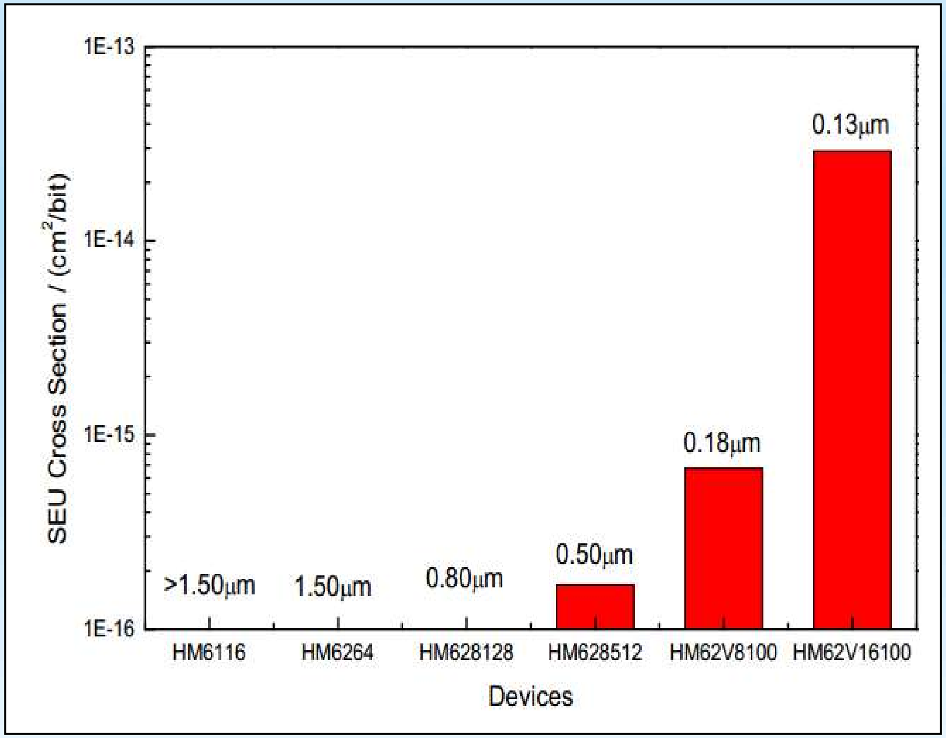
The feature of neutron-induced SEU in SRAM:

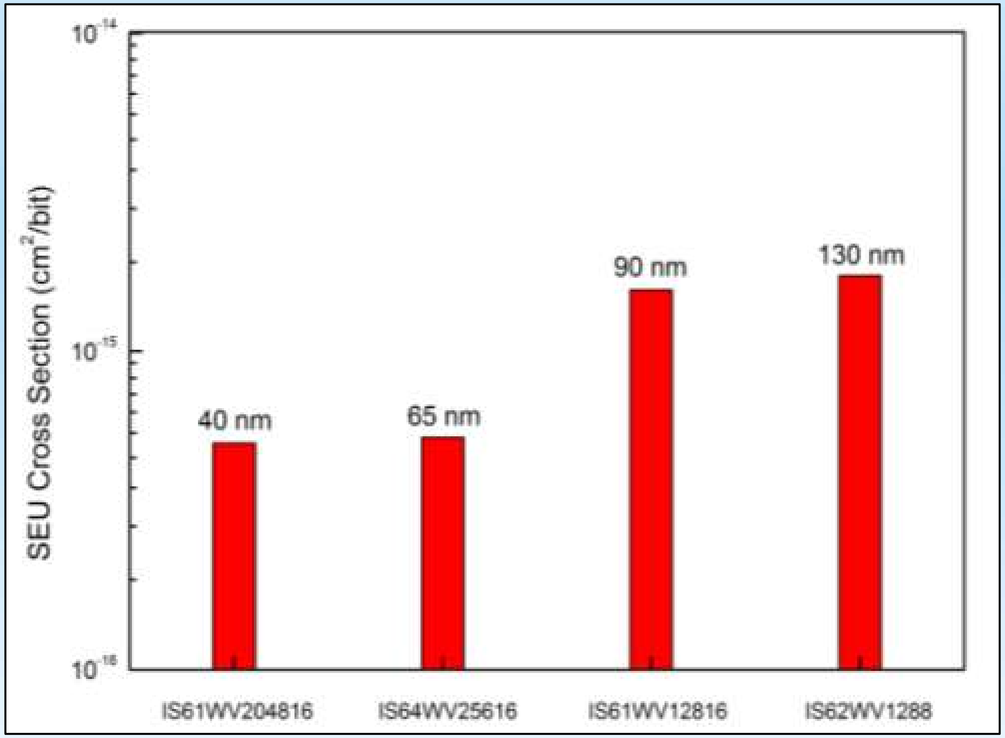
- **Linearity:** Upset number changes linearly with neutron fluence.
- **Non-threshold:** Upset occurs once the device is irradiated with neutrons. There is no threshold of neutron fluence.
- **Uniform:** Upset bitmap in terms of logical address is uniform.

3. Irradiation Testing and Results

Reactor and monoenergetic neutron-induced SEU

- Feature size:





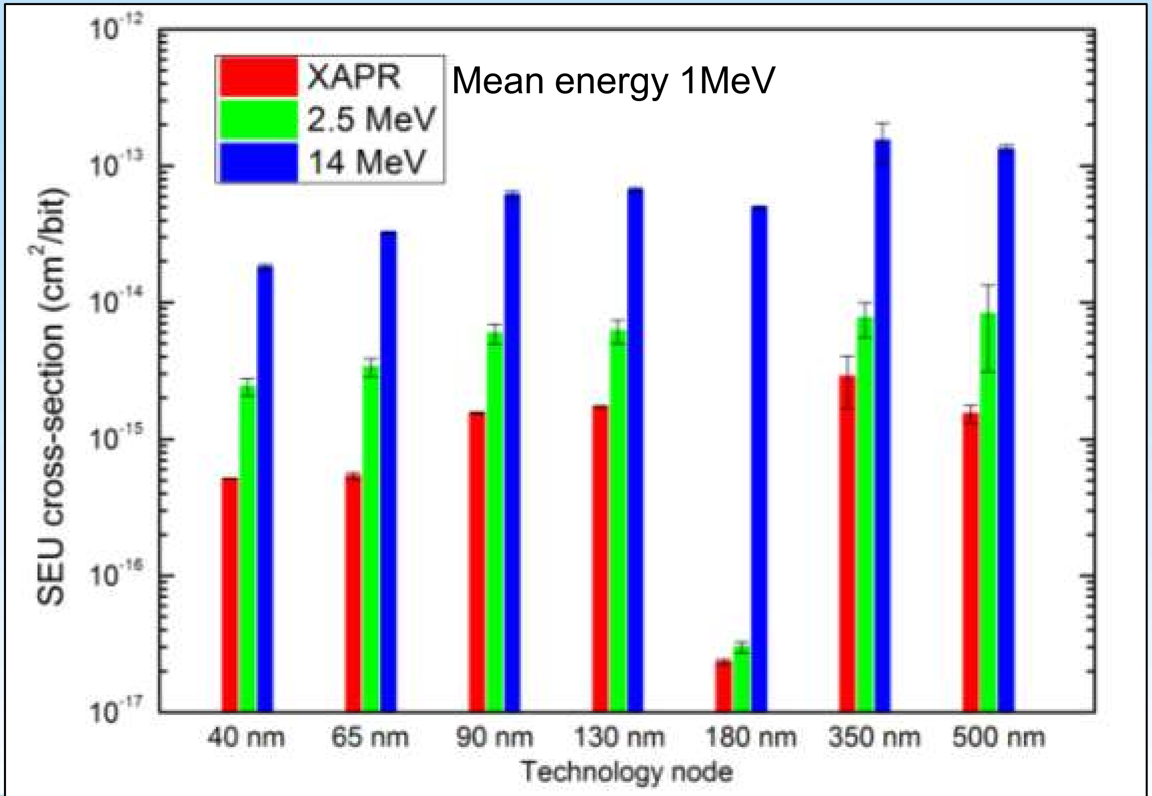
HITACHI series

ISSI series

3. Irradiation Testing and Results

Reactor and monoenergetic neutron-induced SEU

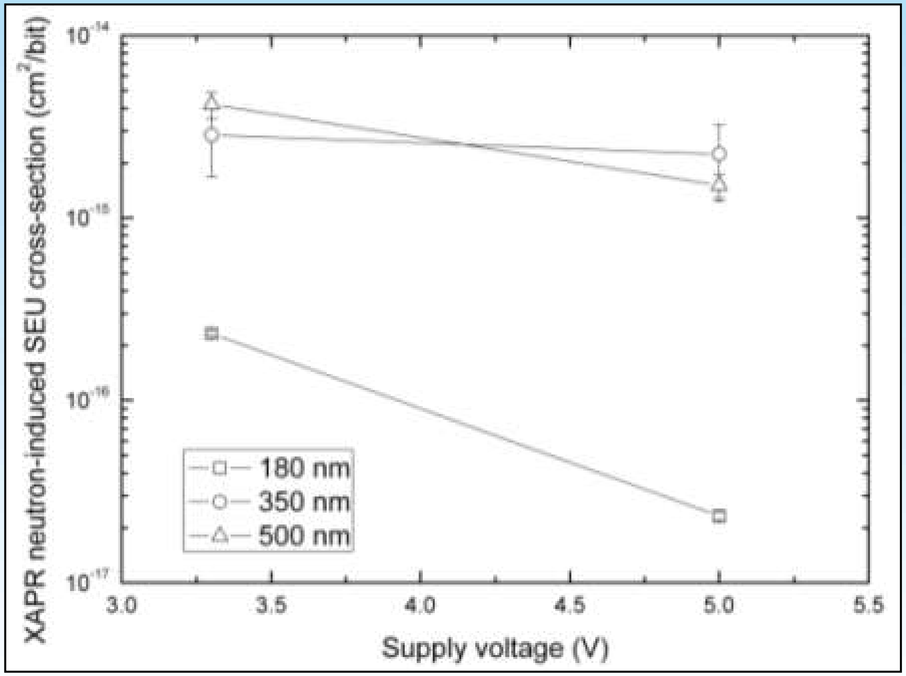
- Feature size:
- Neutron energy: SER increases with the increasing neutron energy



3. Irradiation Testing and Results

Reactor and monoenergetic neutron-induced SEU

- Feature size:
- Neutron energy: SER increases with the increasing neutron energy
- Supply voltage: Cross-section increases with lower supply voltage



4. Simulation models and results

4.1 Simulation of LET

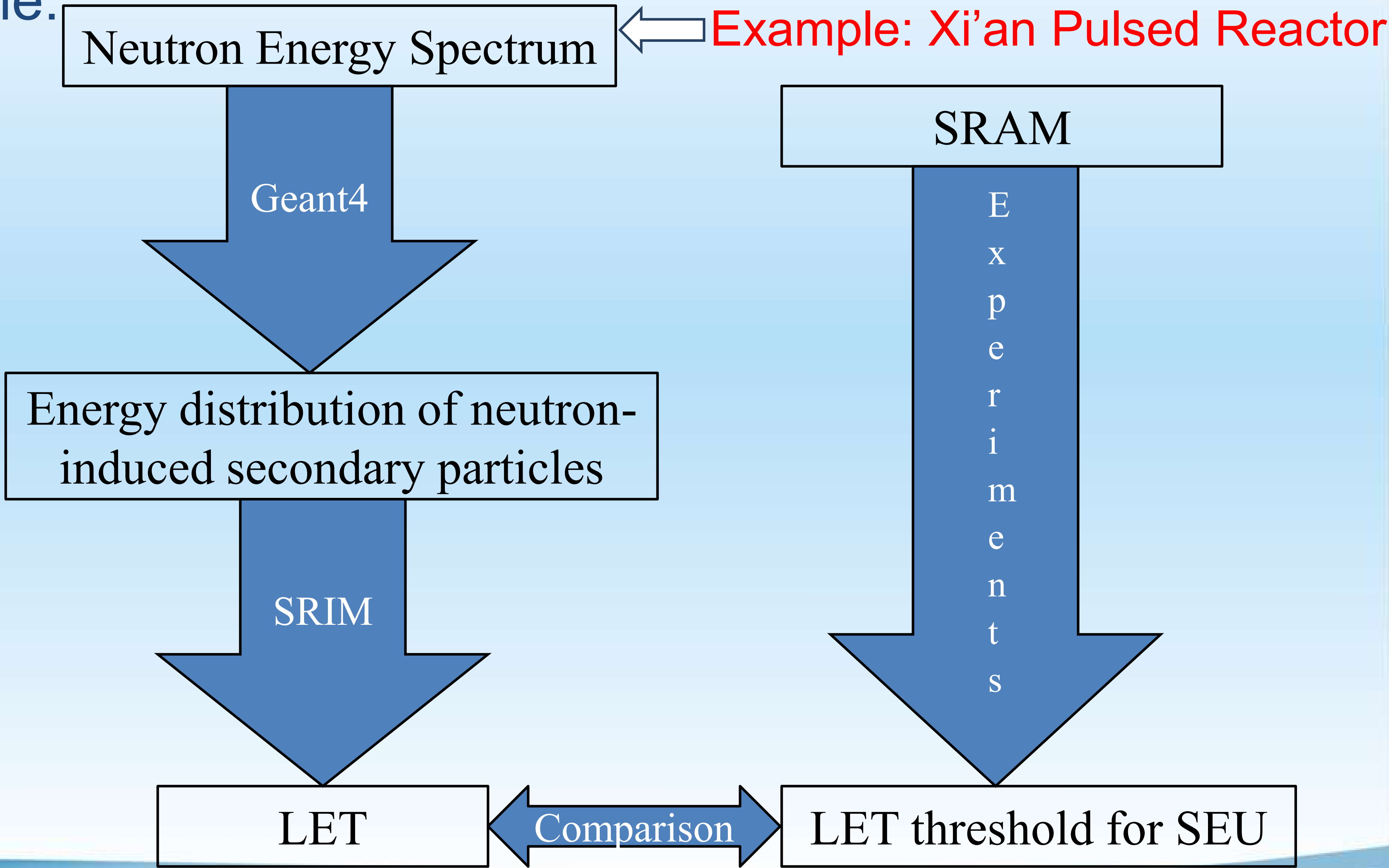
- LET of neutron-induced secondary particles

4.2 Simulation of SEU Cross Section

- Neutron-induced SEU cross section in SRAM

4.1 Simulation of LET

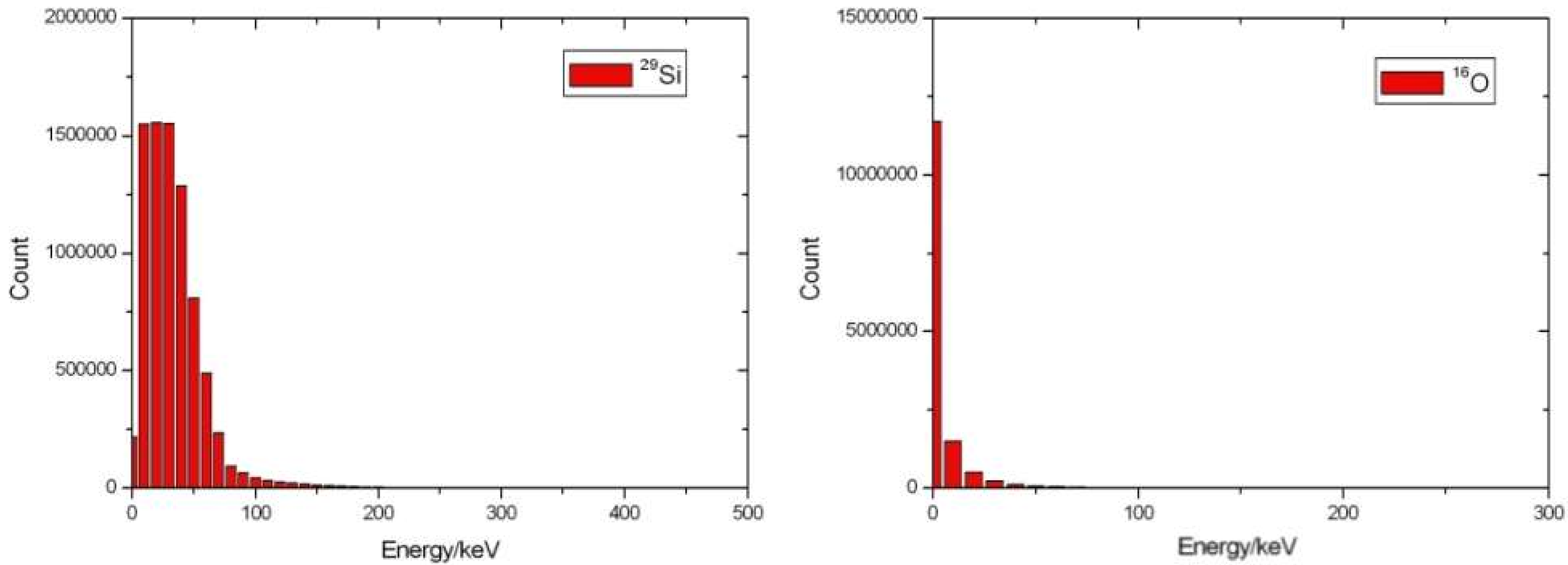
Outline:



4.1 Simulation of LET

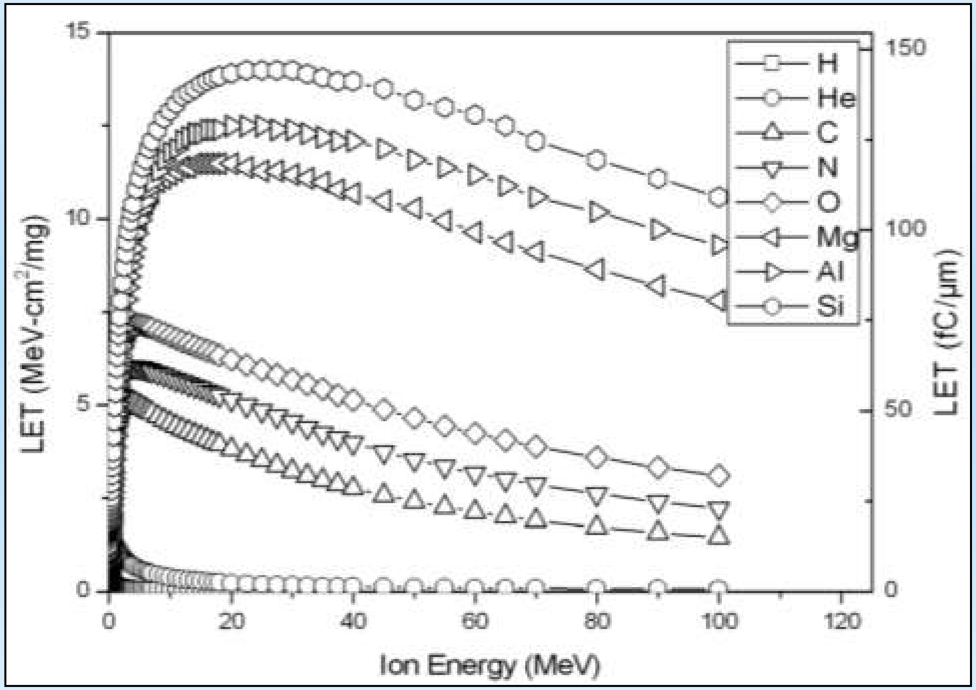
Simulation of energy distribution of neutron-induced secondary particles by Geant4:

- ^{29}Si and ^{16}O shown for example



4.1 Simulation of LET

Simulation of LET of neutron-induced secondary particles by SRIM:

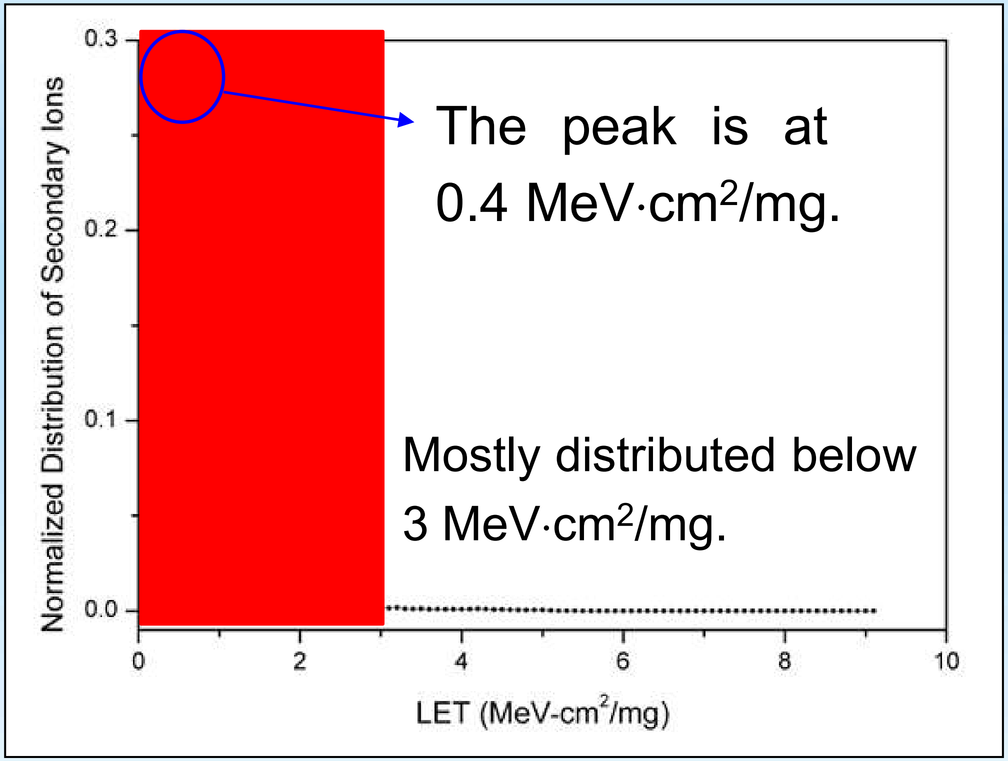


Ion species	Energy (keV)	Maximum LET (MeV·cm^2/mg)
^{28}Si	0-2080	8.16
^{29}Si	0-810	4.49
^{30}Si	0-1360	6.19
^{31}Si	0-10	2.20
^{27}Al	0-2130	7.01
^{28}Al	0-1930	6.52
^{30}Al	0-870	3.83
[illegible]	[illegible]	[illegible]
^{25}Mg	0-3840	9.18
^{26}Mg	0-3460	8.70
^{27}Mg	0-2460	7.31
^{16}O	0-3190	7.04
^{17}O	0-1510	5.61
^{14}N	0-10	1.03
^{15}N	0-2820	5.98
^{16}N	0-2310	5.81
^{12}C	0-4990	5.14
^{13}C	0-5000	5.14

Maximum LET of neutron-induced secondary particles in XAPR: **9.28 MeV·cm^2/mg from ^{24}Mg**

4.1 Simulation of LET

Simulation of LET of neutron-induced secondary particles by SRIM:



LET spectrum of neutron-induced secondary ions

Devices	LET threshold for SEU (LET_{th})
0.18-0.5 μm SRAM	0.3~0.7 MeV·cm²/mg

Neutron-induced secondary particle		SRAM
LET_{max}	$>$	LET_{th}

4.2 Simulation of SEU Cross Section

Simulation model

Particle transport model

- Interaction process of incident neutrons and device materials
- Energy deposition in sensitive volume of the device

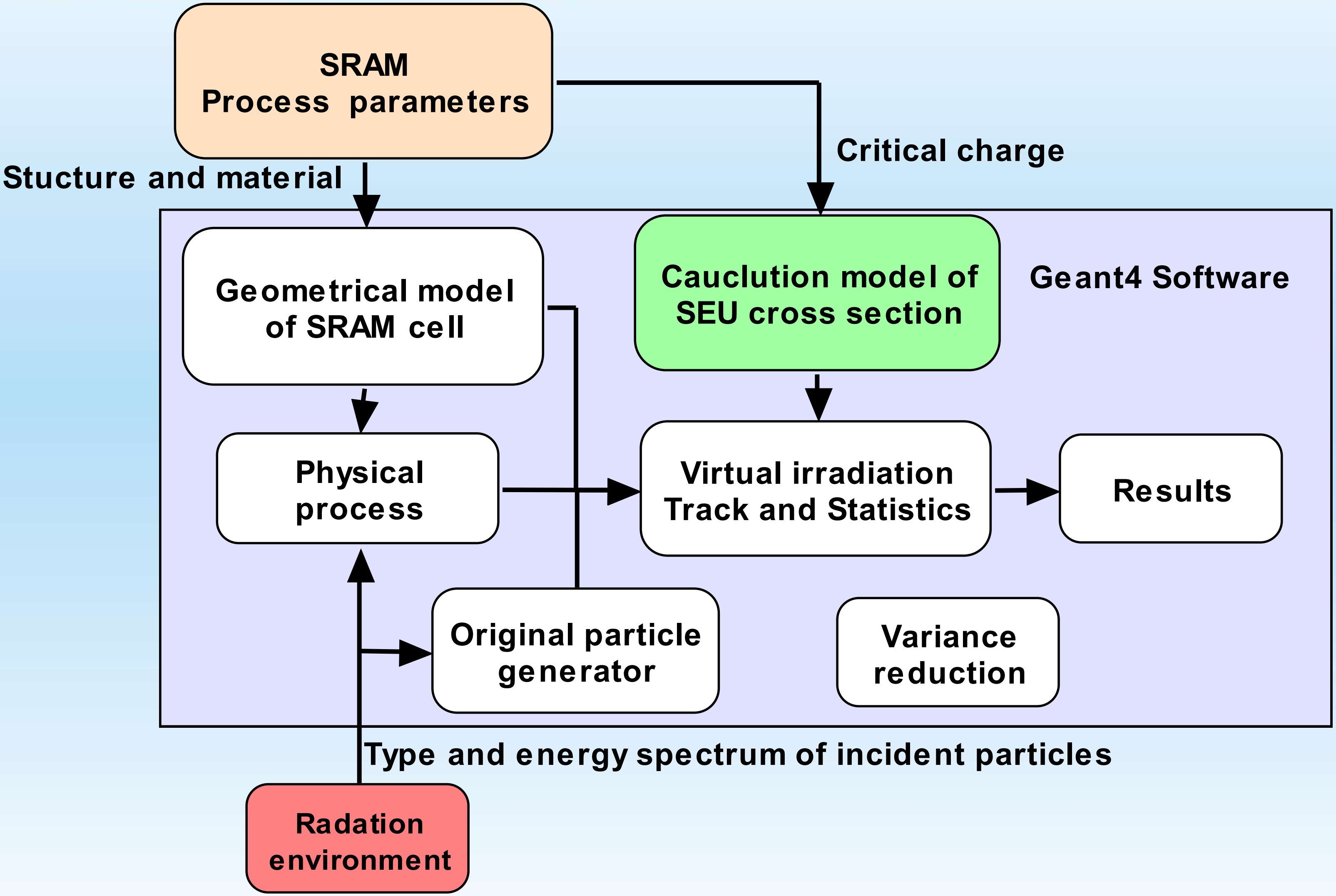
→

SEU model in SRAM cell

- Generation process of electron-hole pairs
- Charge collection and upset process

Inserting of sensitive volume and critical charge, simulated by Geant4

4.2 Simulation of SEU Cross Section

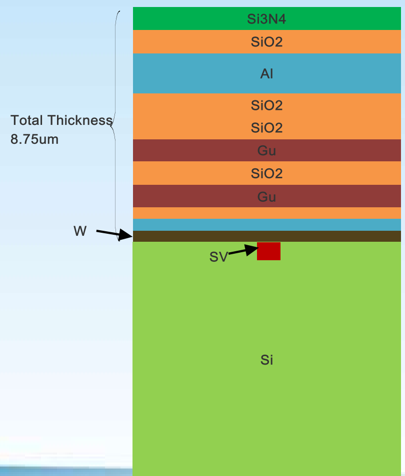


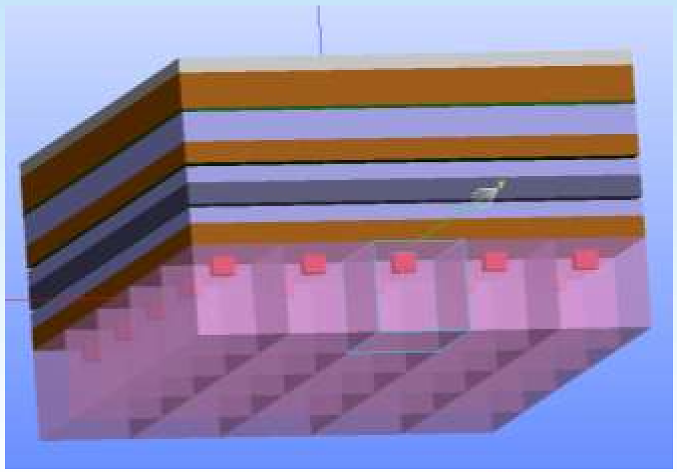
Particle transport simulation of neutron-induced SEU in SRAM cell

4.2 Simulation of SEU Cross Section

Geometrical model of memory cell

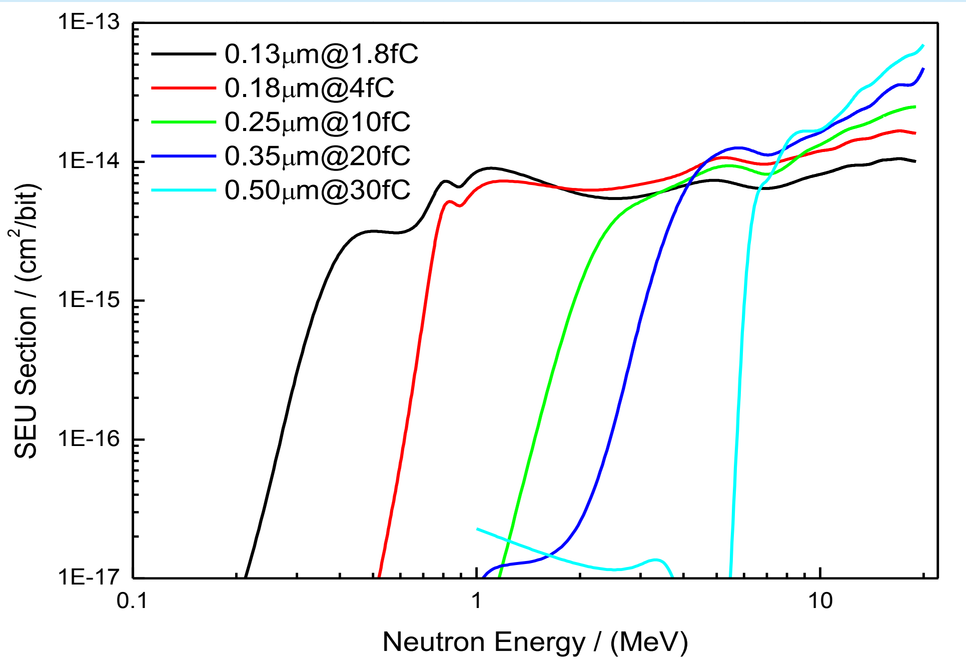
Feature size/μm	Cell area/μm^2	Sensitive volume/μm^3
0.13	4.166	0.0431
0.18	7.987	0.1143
0.25	15.41	0.3063
0.35	30.20	0.8404
0.50	61.63	2.45

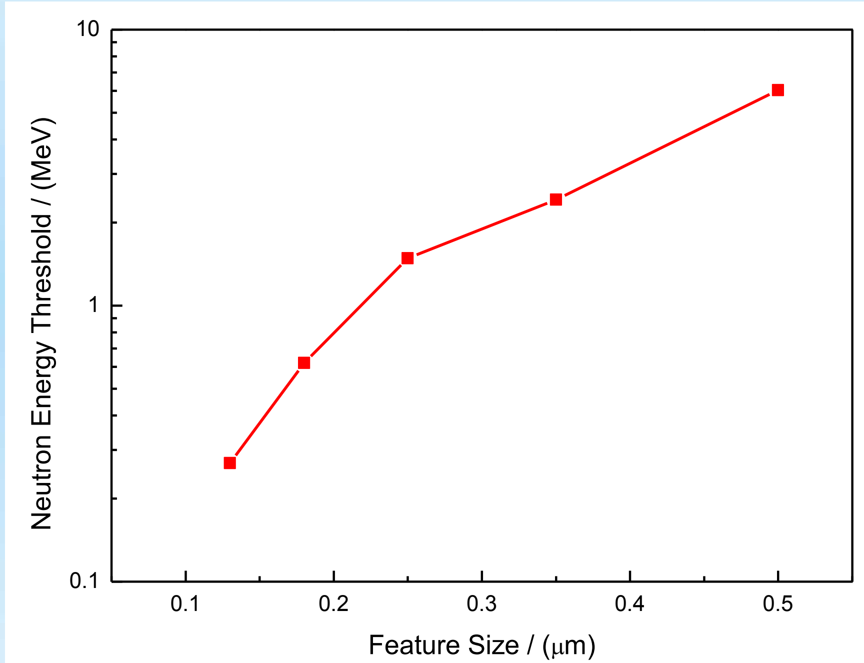




4.2 Simulation of SEU Cross Section

Influence factors of SEU cross section: Neutron energy



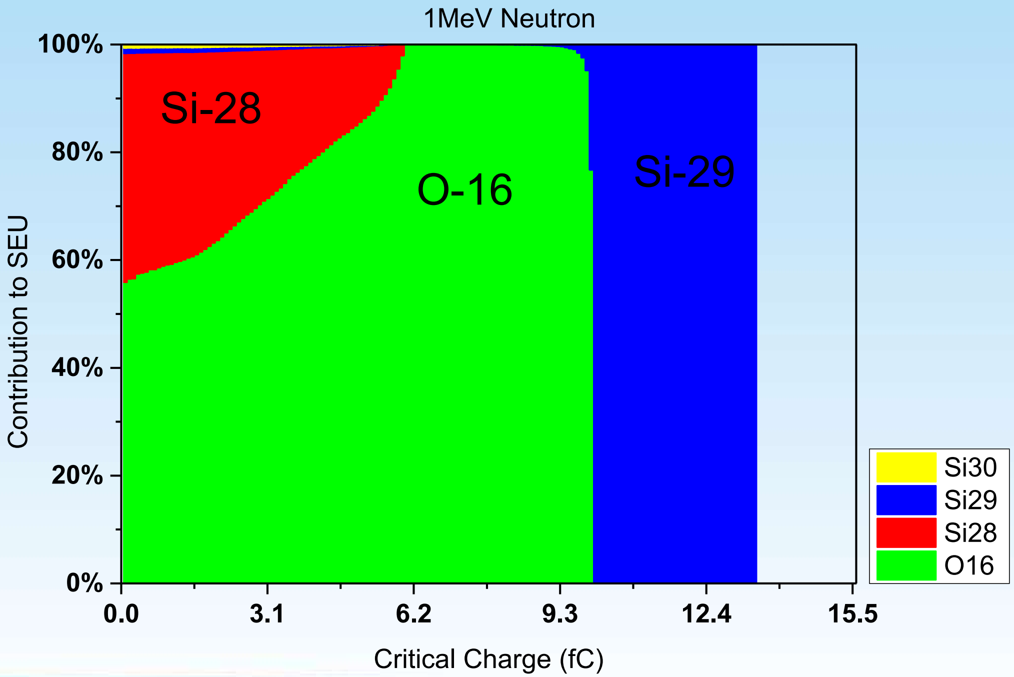


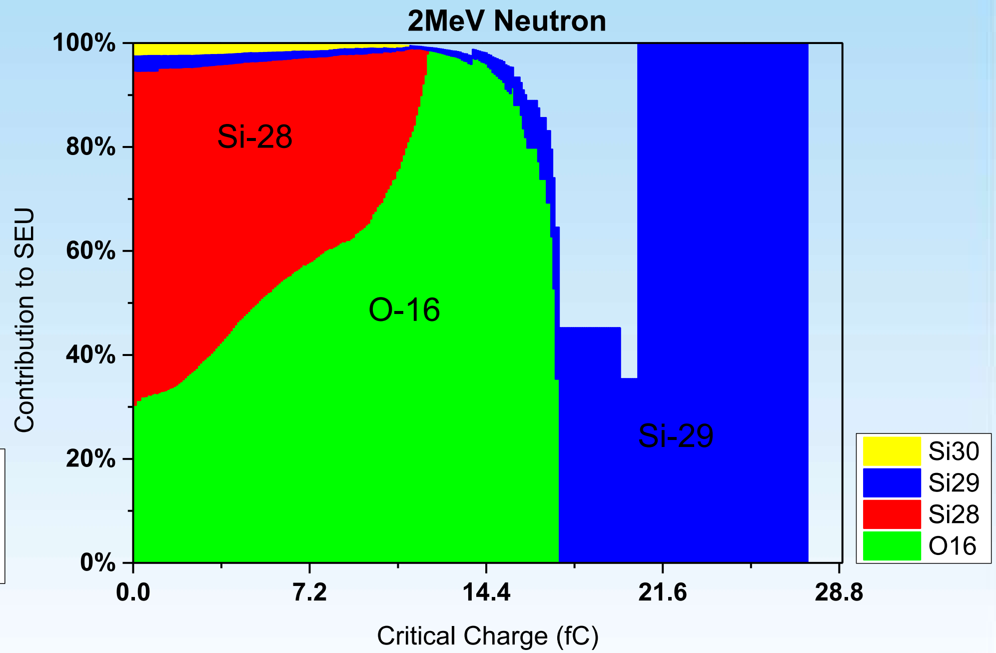
There is an energy threshold for incident neutrons which induce SEU. The energy threshold decreases with the decreasing of feature sizes.

4.2 Simulation of SEU Cross Section

Reactor neutron-induced secondary particles contributing to SEU

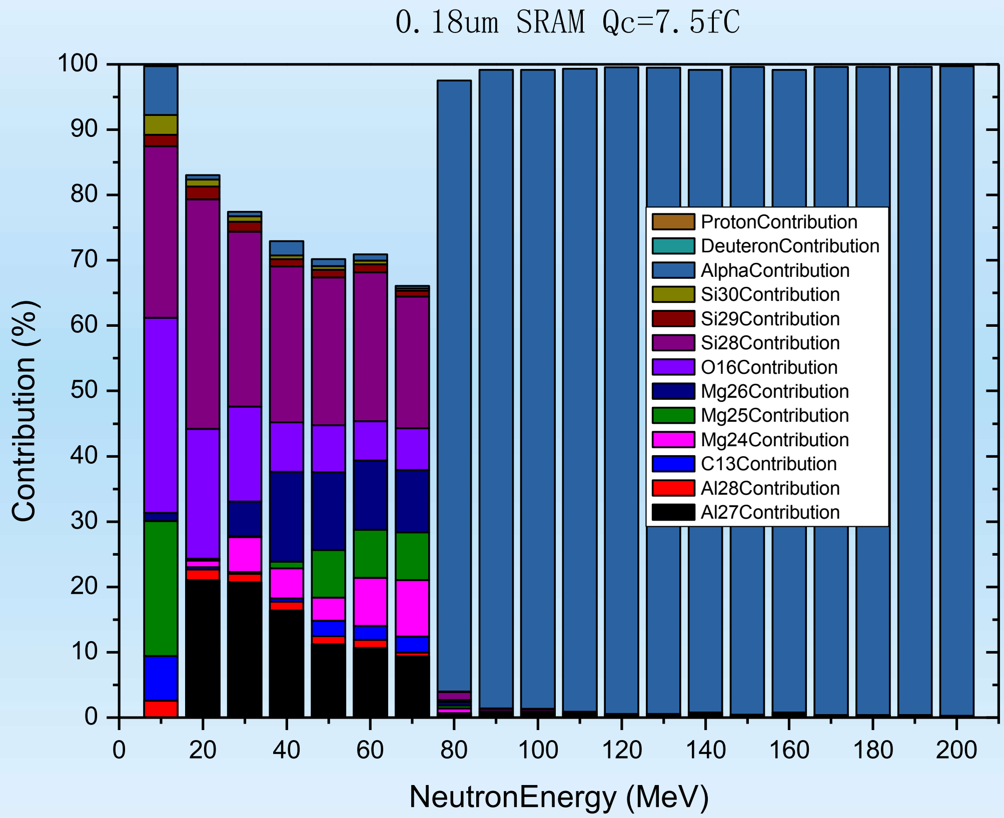
- For reactor neutron-induced SEU, 80% of energy deposition are from ^{28}Si and ^{16}O produced by neutron interaction with SiO_2





4.2 Simulation of SEU Cross Section

Terrestrial neutron-induced secondary particles contributing to SEU

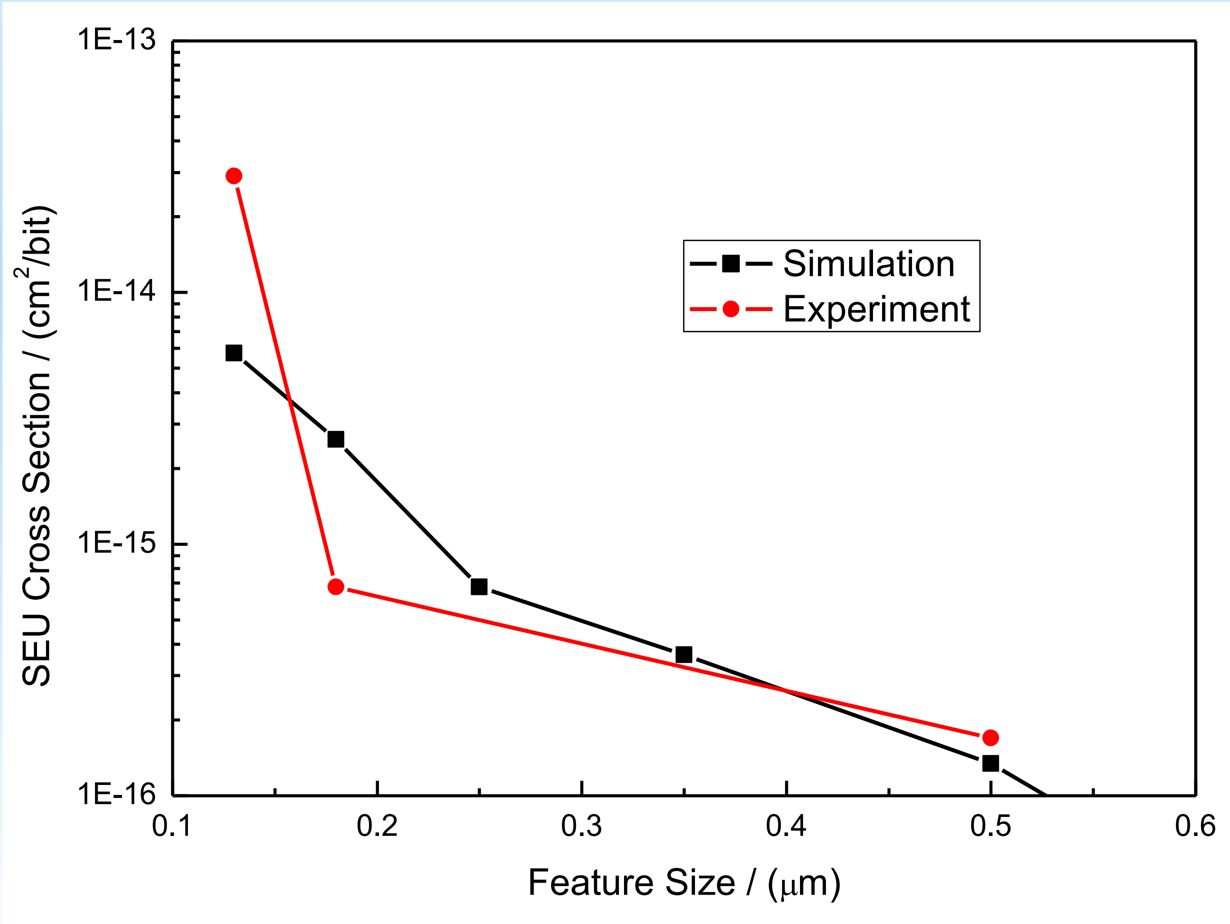


Contributions to charge deposition of secondary particles in 0.18 μm SRAM cell

- α particle and heavy ions both have contributions to SEU.
- For low energy neutrons, contribution of heavy ions is critical.
- For high energy neutrons, almost all contribution is from α particle.

4.2 Simulation of SEU Cross Section

Simulation results of reactor neutron-induced SEU cross section in Xi'an Pulsed Reactor:



5. Summary

Software	• RESNS2.0 software package • Terrestrial neutron radiation environment simulation
Testing system & method	• Testing system and method for neutron-induced SEU • SEU data of SRAMs with different feature sizes in various neutron radiation environments
Simulation model	• Neutron interaction with devices material • Neutron-induced SEU calculation and prediction

The results are useful to understand the mechanism of neutron-induced SEE and benefit to hardening technology.

Thank you!