Terrestrial Cosmic-Ray SEE testing

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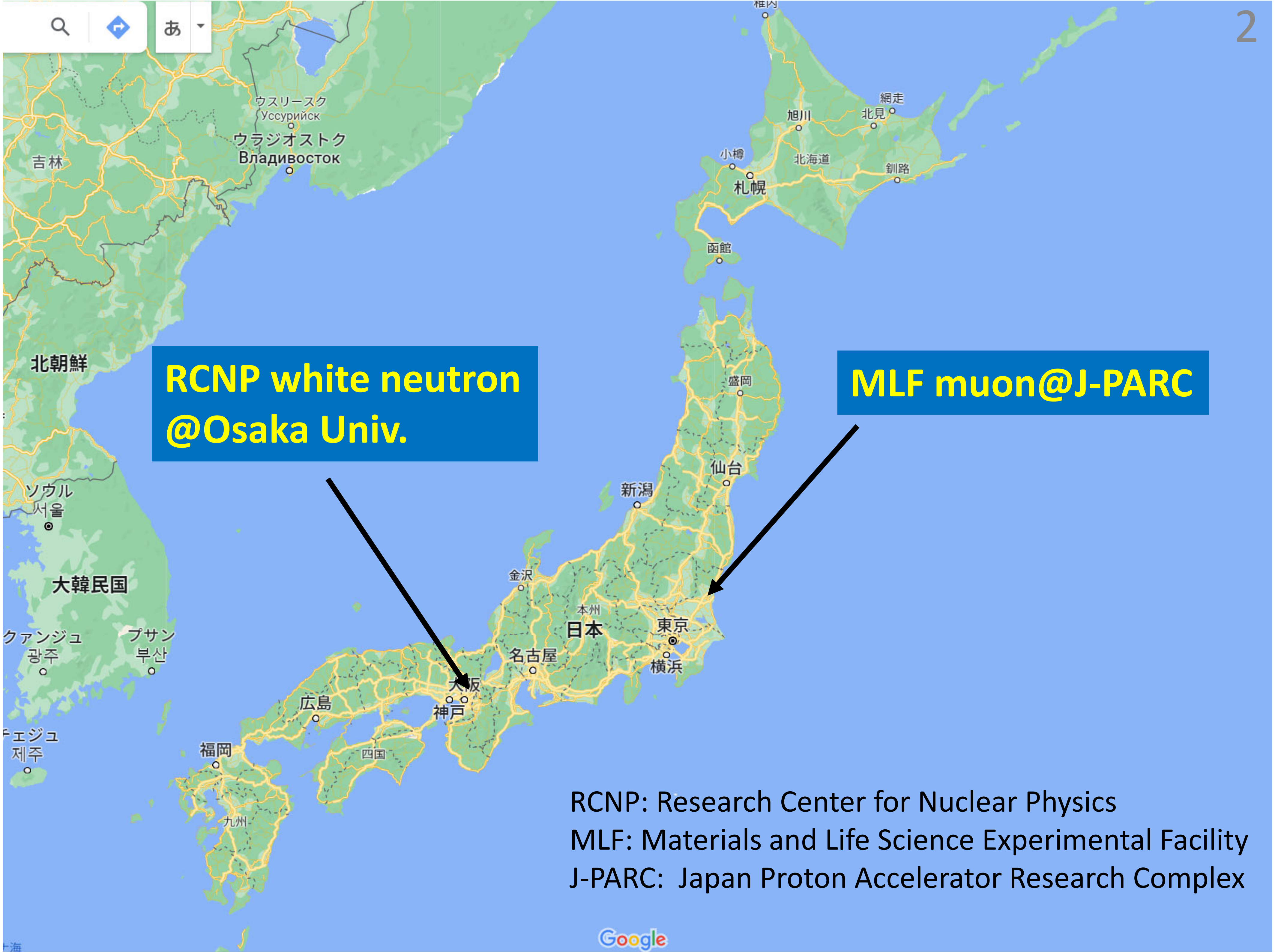
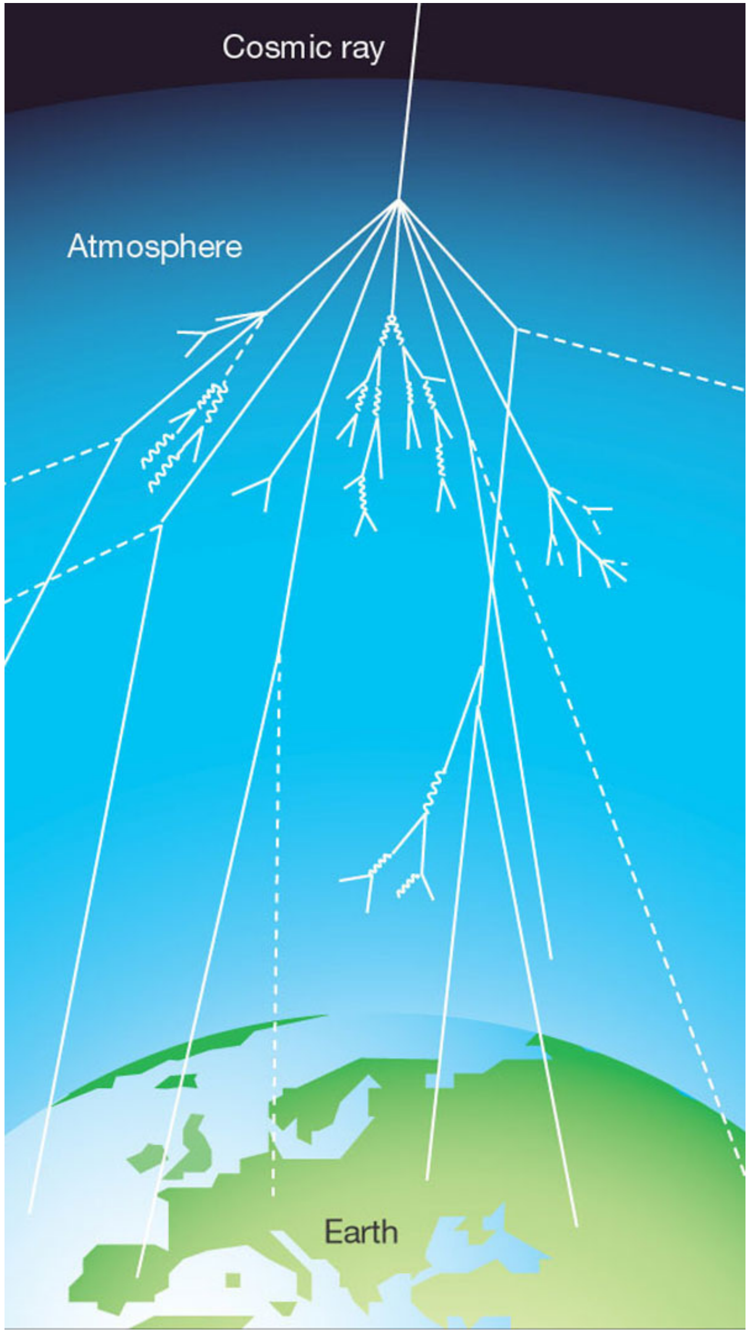
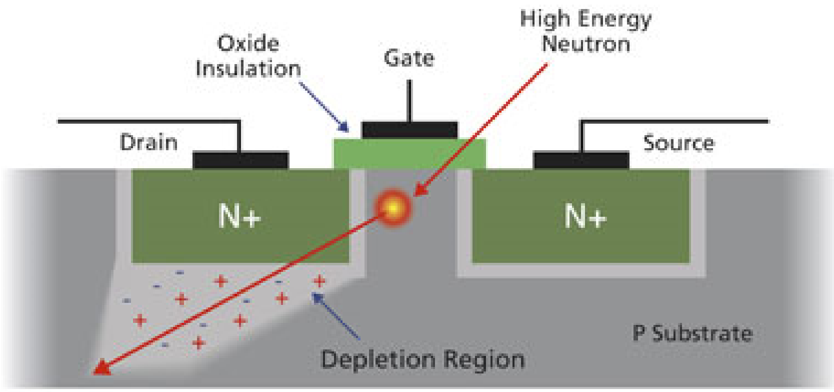


RCNP: Research Center for Nuclear Physics
MLF: Materials and Life Science Experimental Facility
J-PARC: Japan Proton Accelerator Research Complex

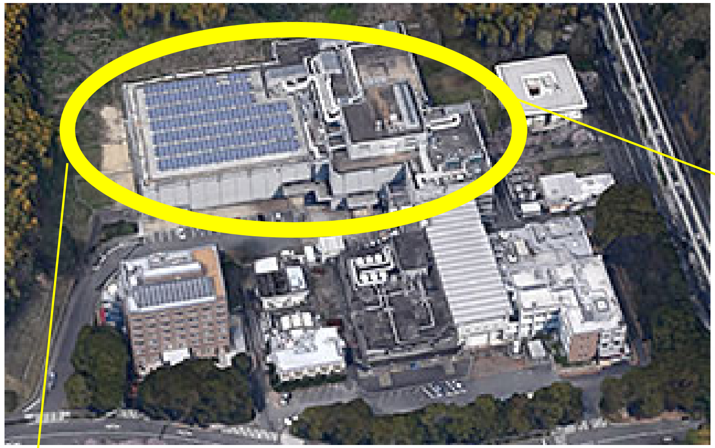
Neutron at terrestrial environment

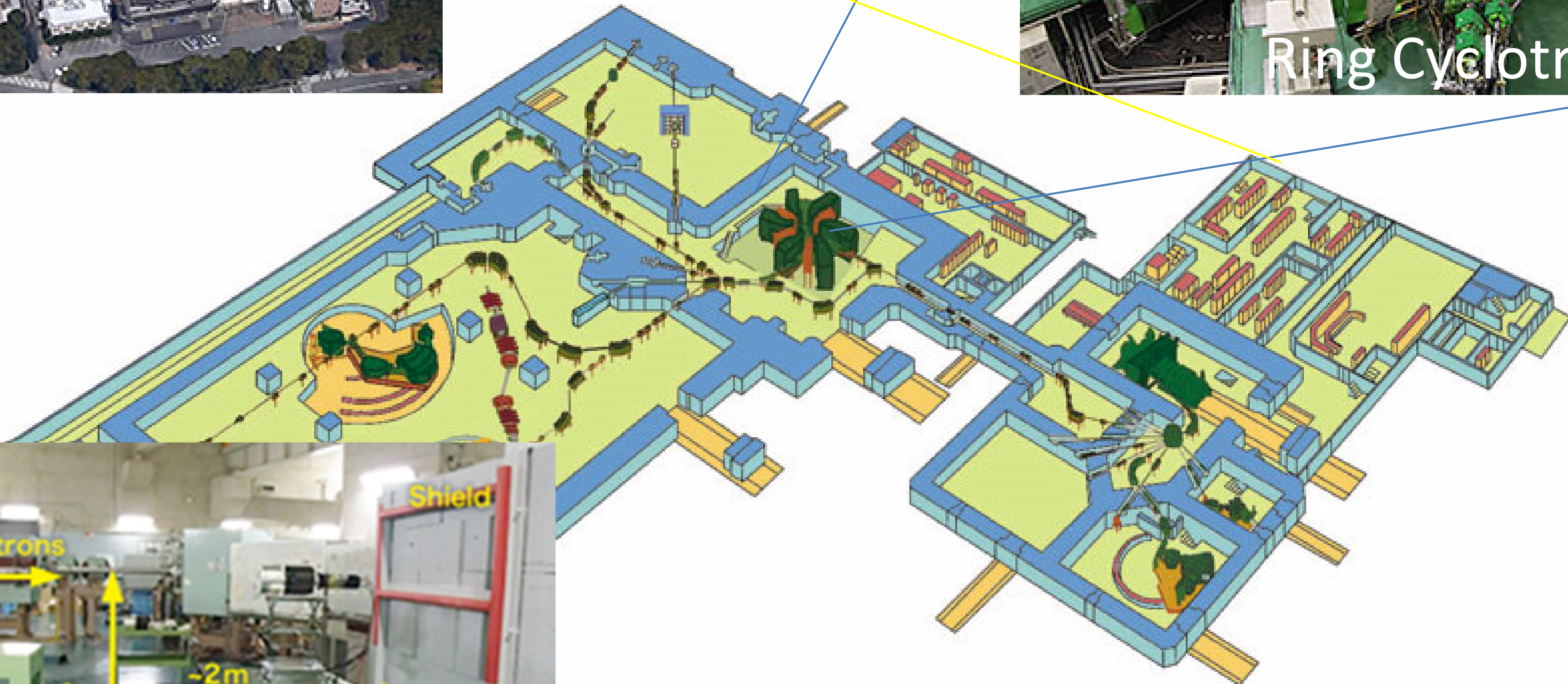


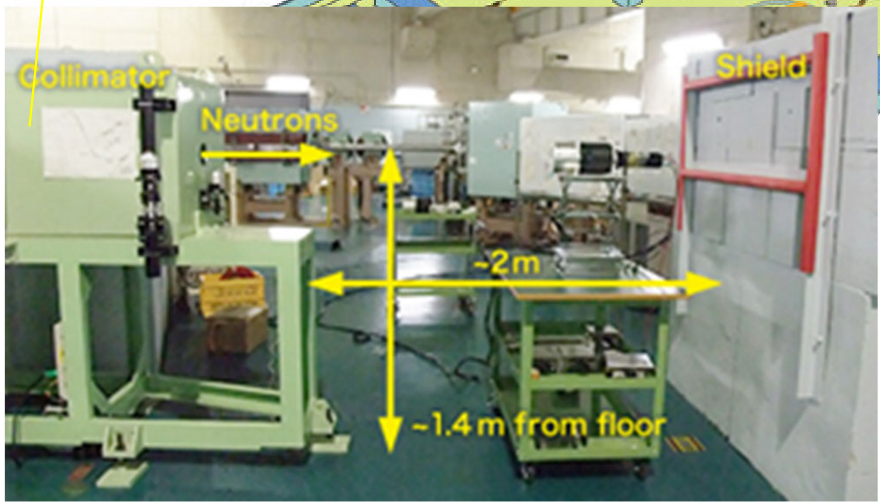
- Cosmic ray induces neutrons
- Nuclear reaction in silicon generates secondary ions and injects charge



White Neutron Test at RCNP

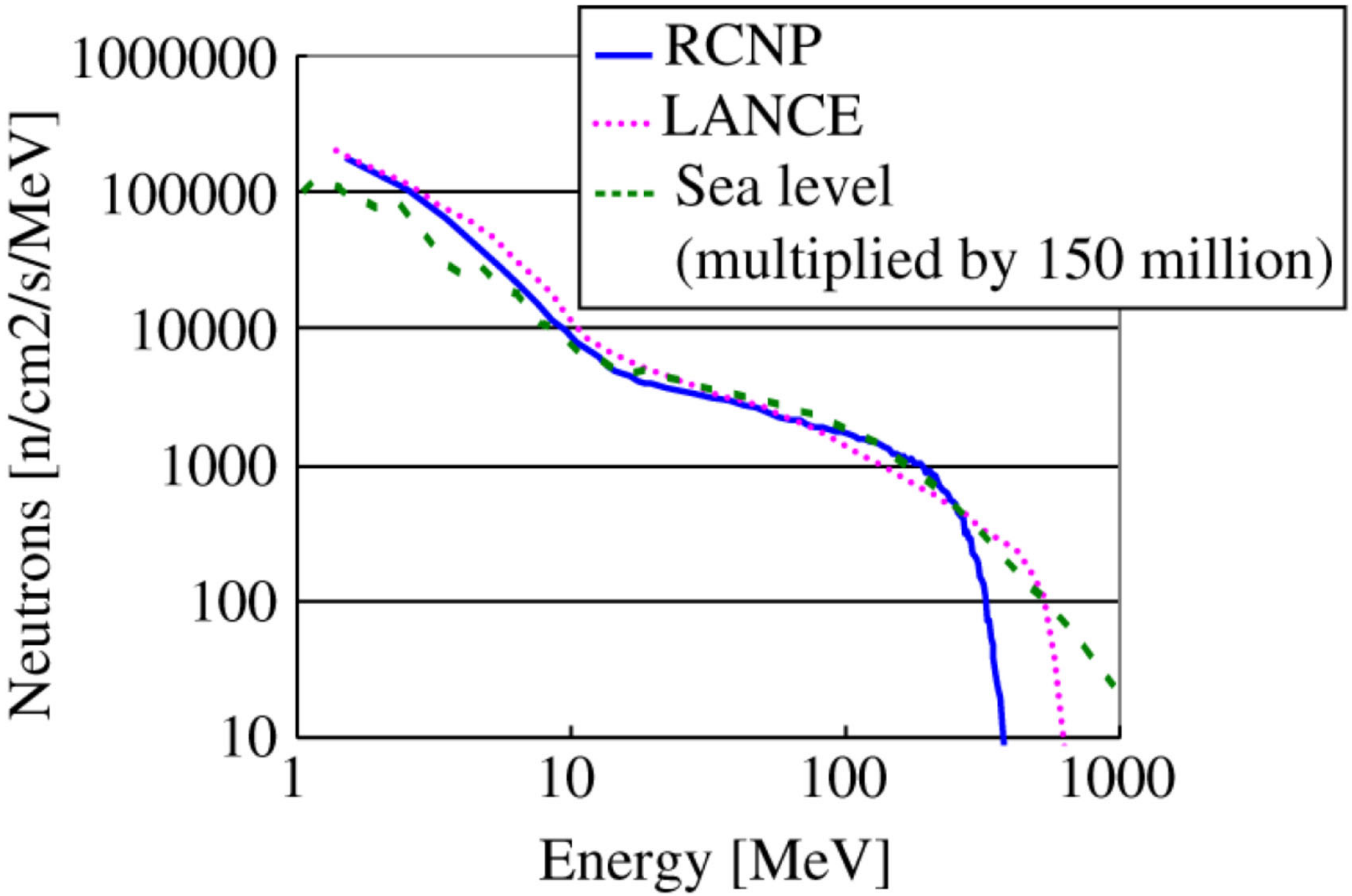






10^8x accelerated

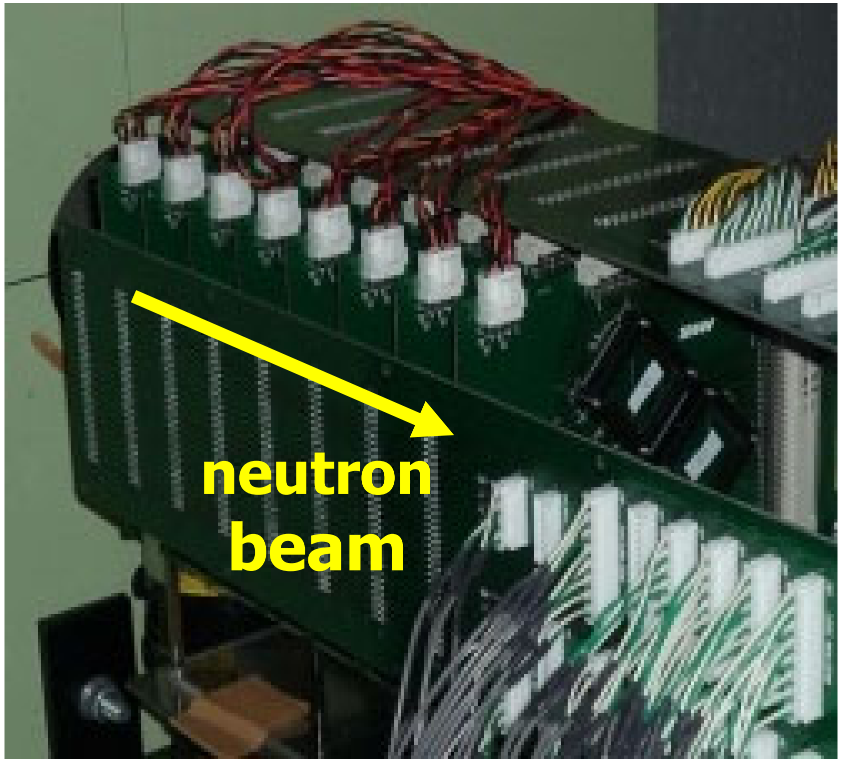
Neutron Energy Spectrum



Neutrons are generated by 400MeV protons

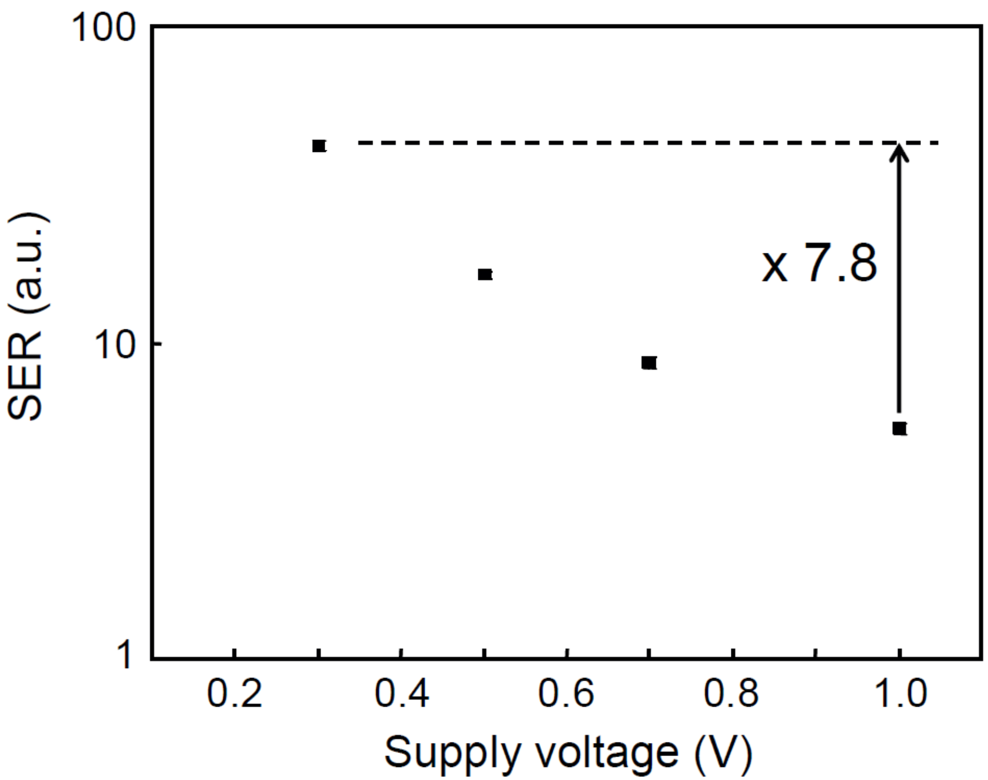
Setup example

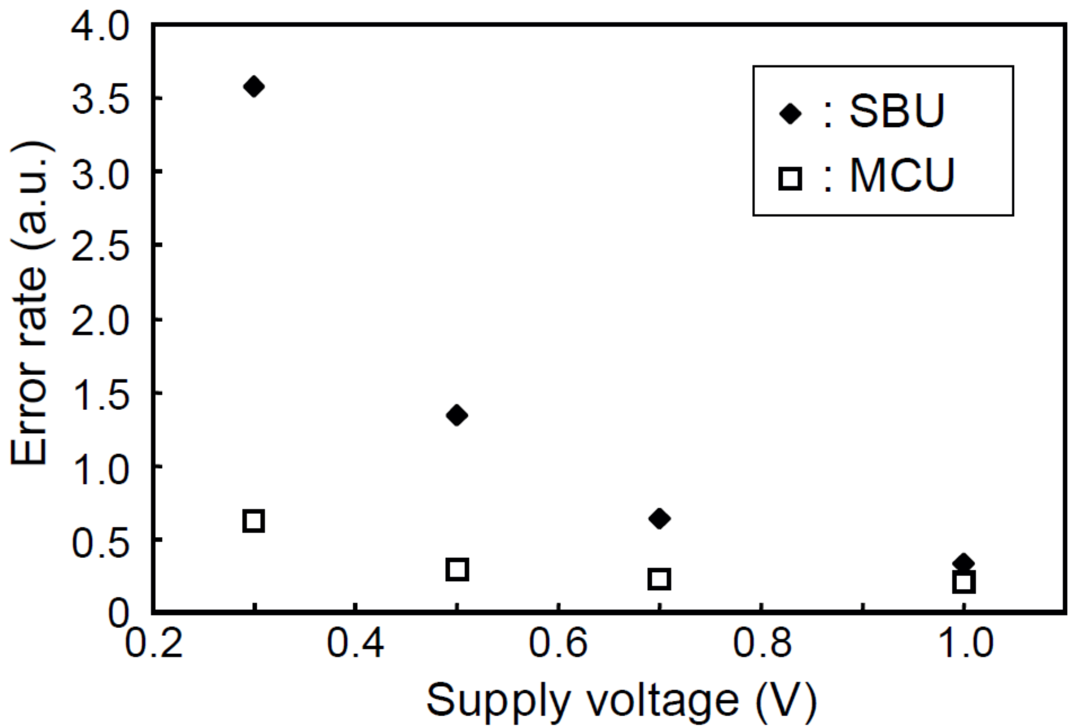
- Neutron irradiation test was performed at RCNP
  - Flux of wide spectrum neutron beam is $2.41 \times 10^{9} cm^{-2} h^{-1}$



VDD Dependency of SBU and MCU

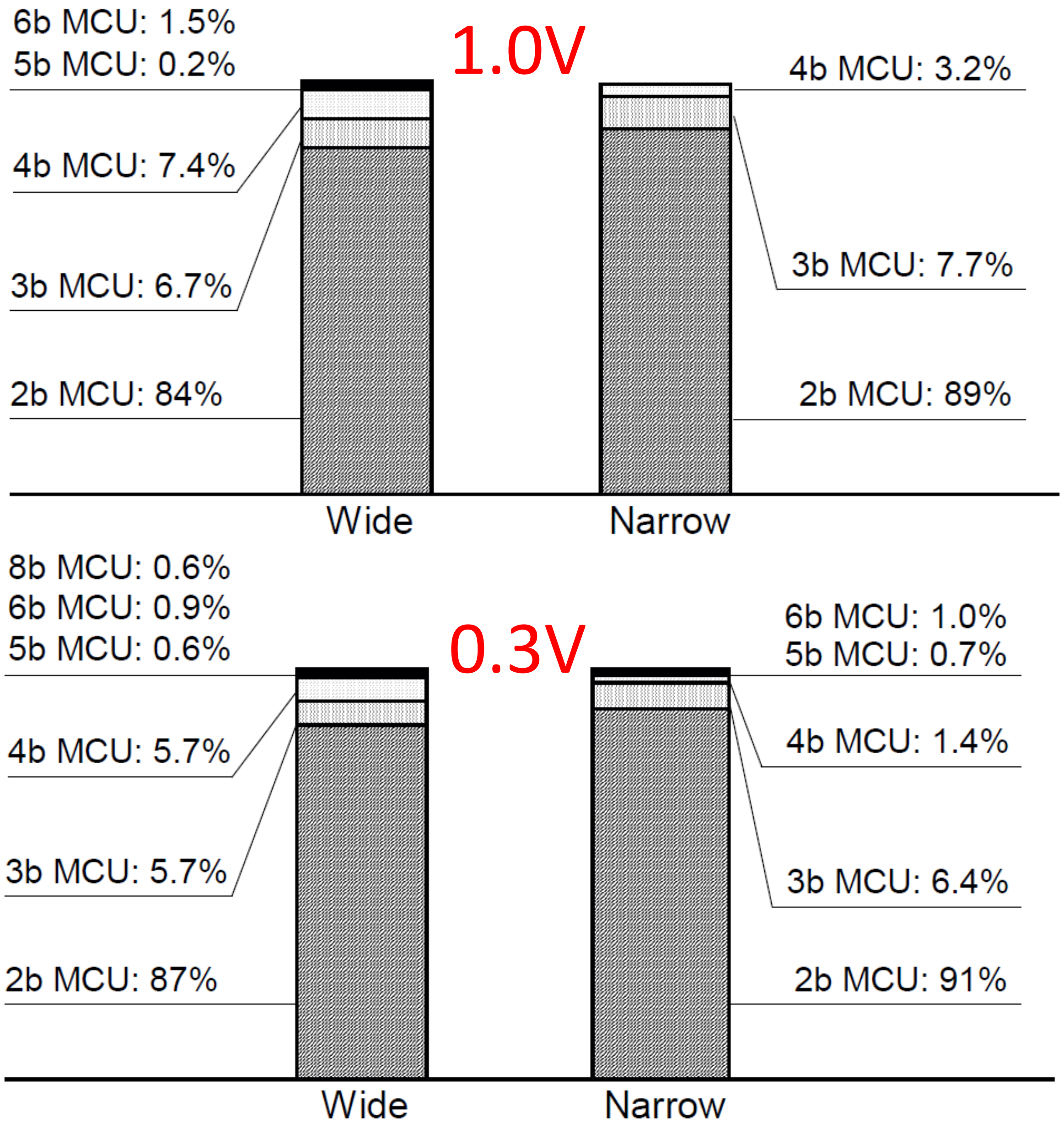
- Compared to 1.0V, SER at 0.3V is 7.8x higher
- Both SBU and MCU increase as Vdd decreases
  - SBU more drastically





H. Fuketa, M. Hashimoto, Y. Mitsuyama, and T. Onoye, ``Neutron-Induced Soft Errors and Multiple Cell Upsets in 65-nm 10T Subthreshold SRAM,'' *IEEE Trans. Nuclear Science*, vol. 58, no. 4, pp. 2097--2102, August 2011.

#Bits Distribution of MCU



MCU with large bits happens at low voltage.

Simple ECC could be insufficient.

UPDATE at RCNP

- Accelerator renovation has finished in 2022 after long shutdown.
- Beam size expansion from Φ100mm to Φ300mm is scheduled in 2023.
- 10x beam intensity enhancement is scheduled in five years.

Muon: potential source of soft error

Muon accounts for 70% of secondary particles on earth

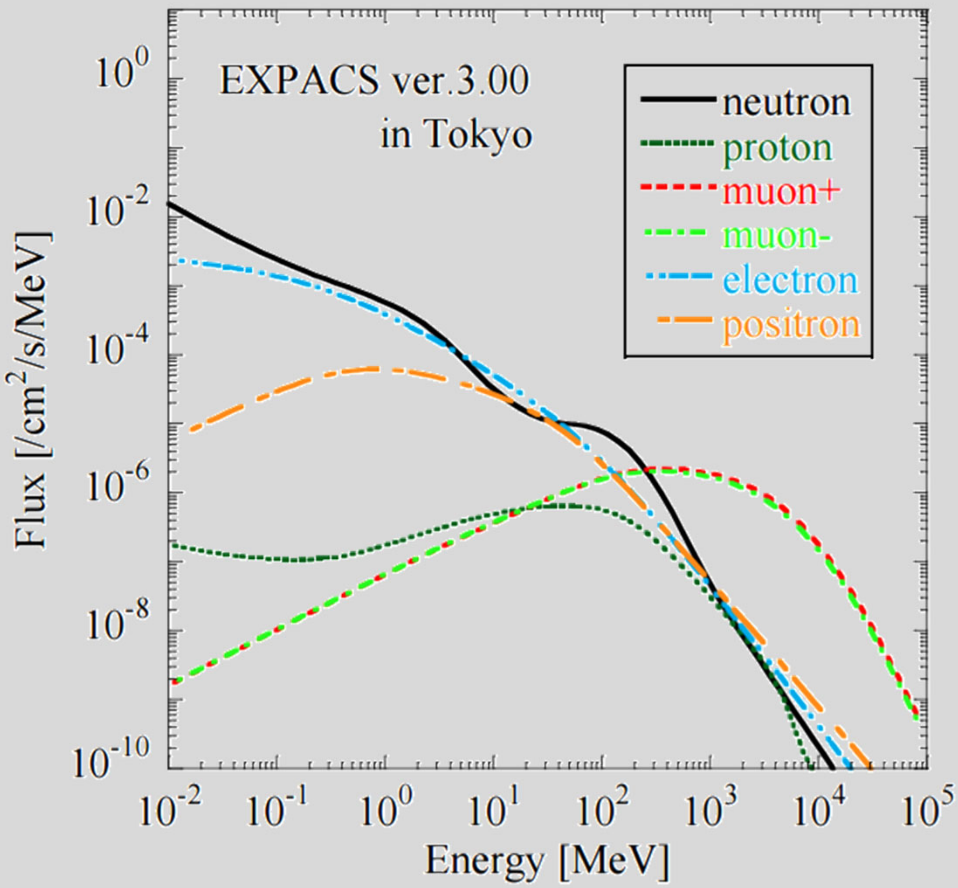
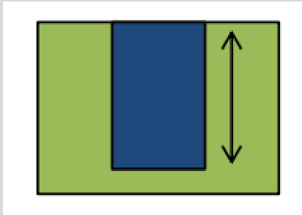


Fig. Flux spectra from EXPACS: T. Sato et al., EXPACS, *Radia. Res.*, 166, 544-555, 2006

Decrease in critical charge

Deposited charge can exceed critical charge of modern devices!



Sensitive volume depth 0.5μm

Energy	dE/dx	Deposited Charge in 0.5μm
1GeV	0.47keV/μm	0.02fC
40KeV	73keV/μm	**1.80fC**

Previous works: muon-induced SEU

Positive muon:

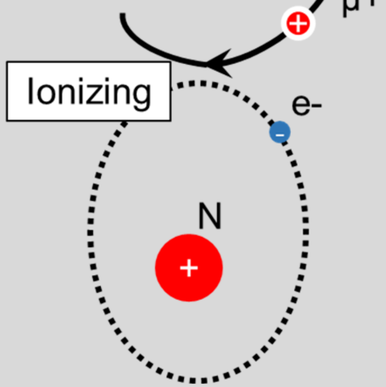
Experiments [1-4]

14nm,22nm, etc.

Simulation [2,4]

Charge Generation

Ionization



Negative muon:

Experiments [5]

Only in 1980s

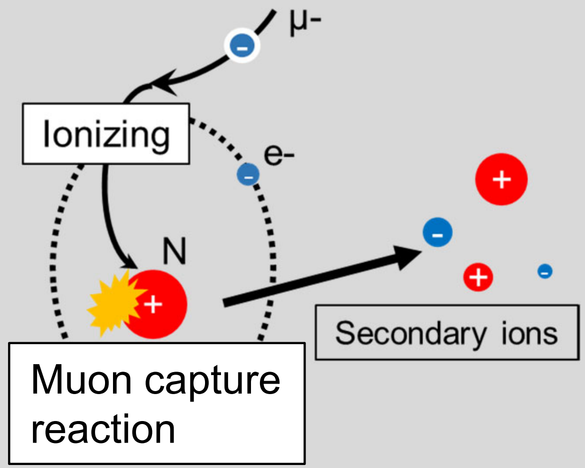
Simulation [2,4]

Charge Generation

Ionization

Muon capture

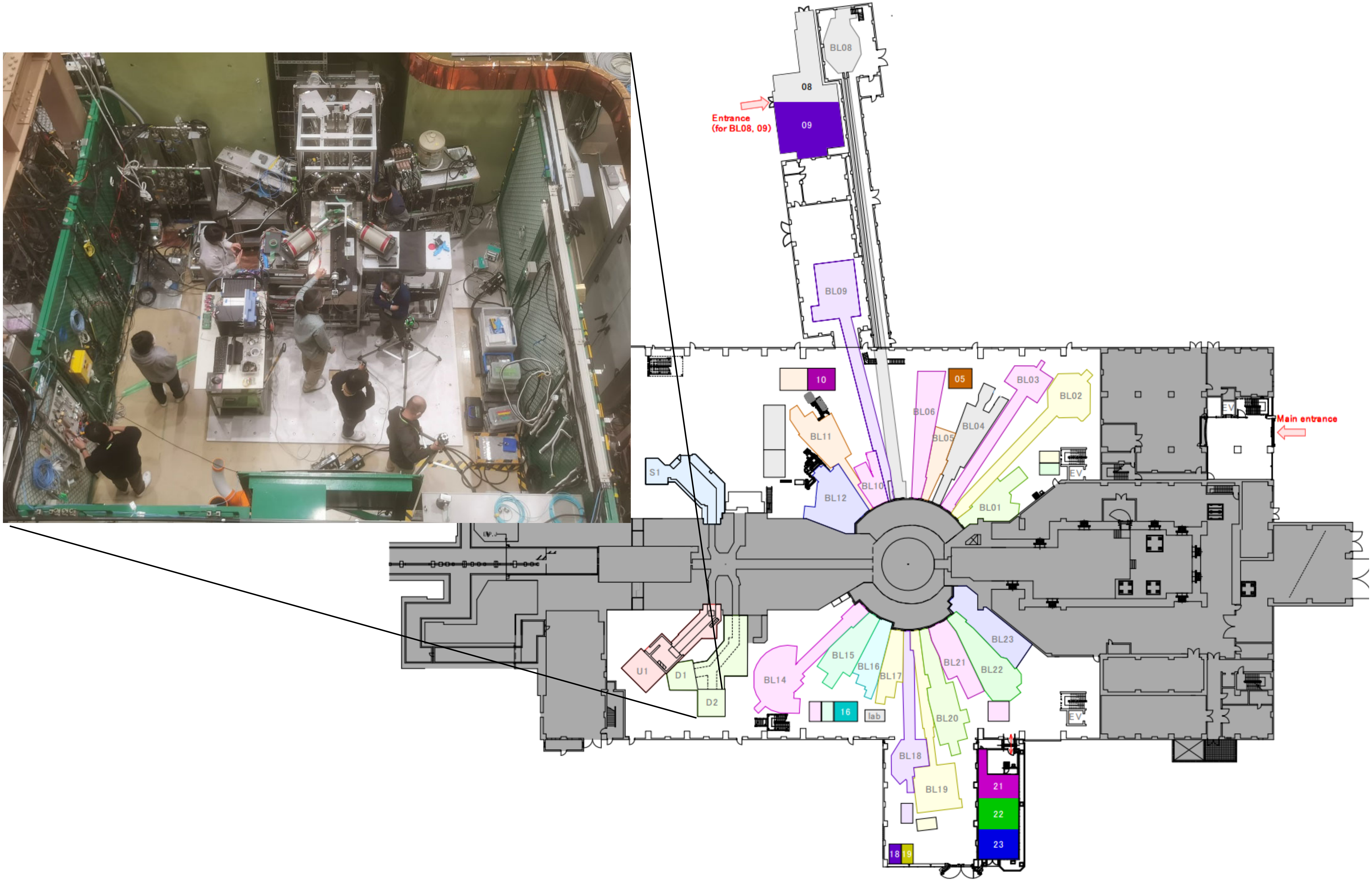
Secondary ions can deposit large charge



Impact of negative muon capture has not been studied in experiments.

[1],[2]: Sierawski et al., *TNS*, 2010 & *IRPS*, 2014,
[3]:Seifert: *IRPS*, 2015 [4]: S.Serre, *RADECS*, 2012 [5] :J. Dicello, *Nucl. Inst. MPR*,1987

MUSE in J-PARC MLF



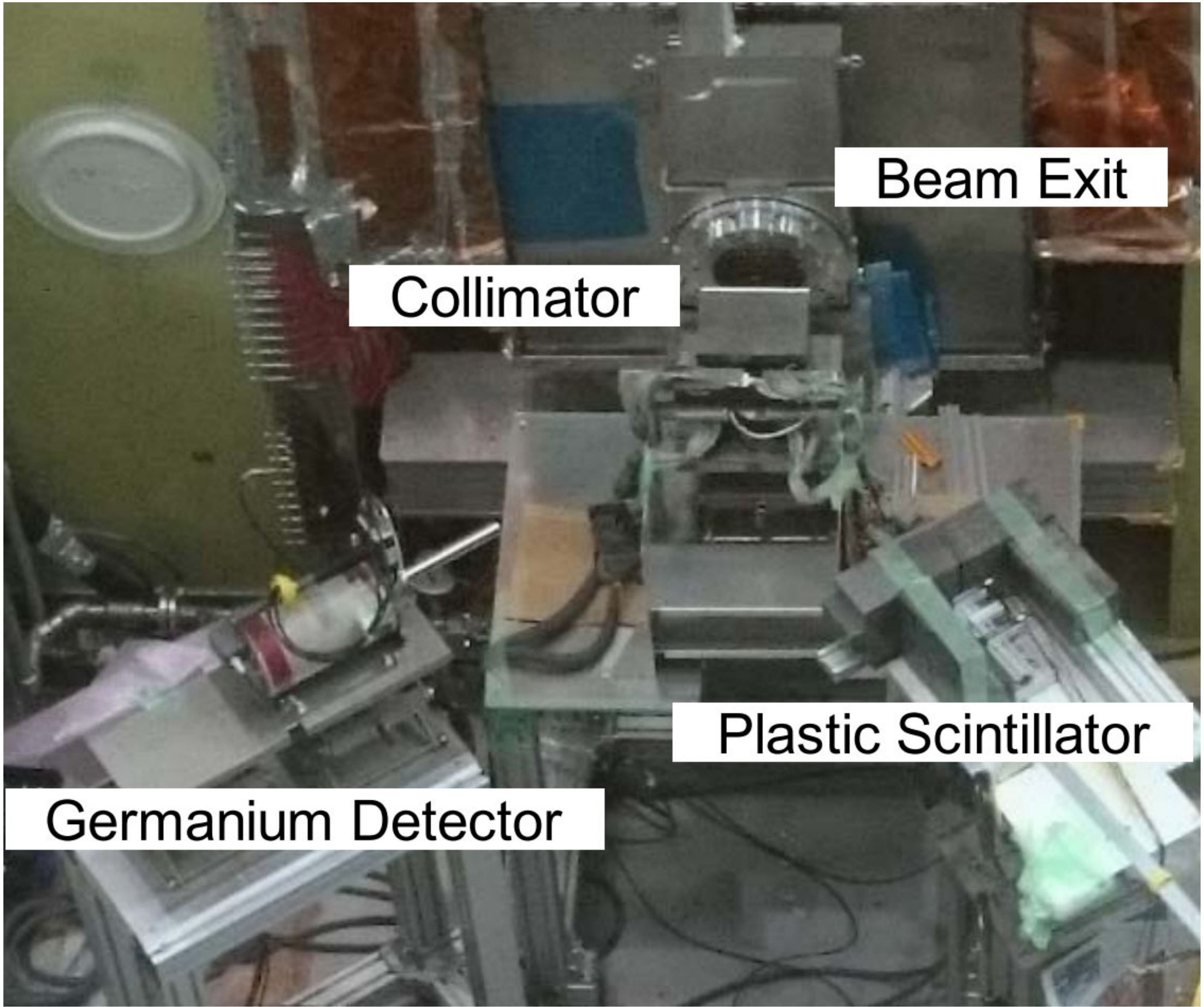
Muon beam at D2 line

High intensity for both positive and negative muons

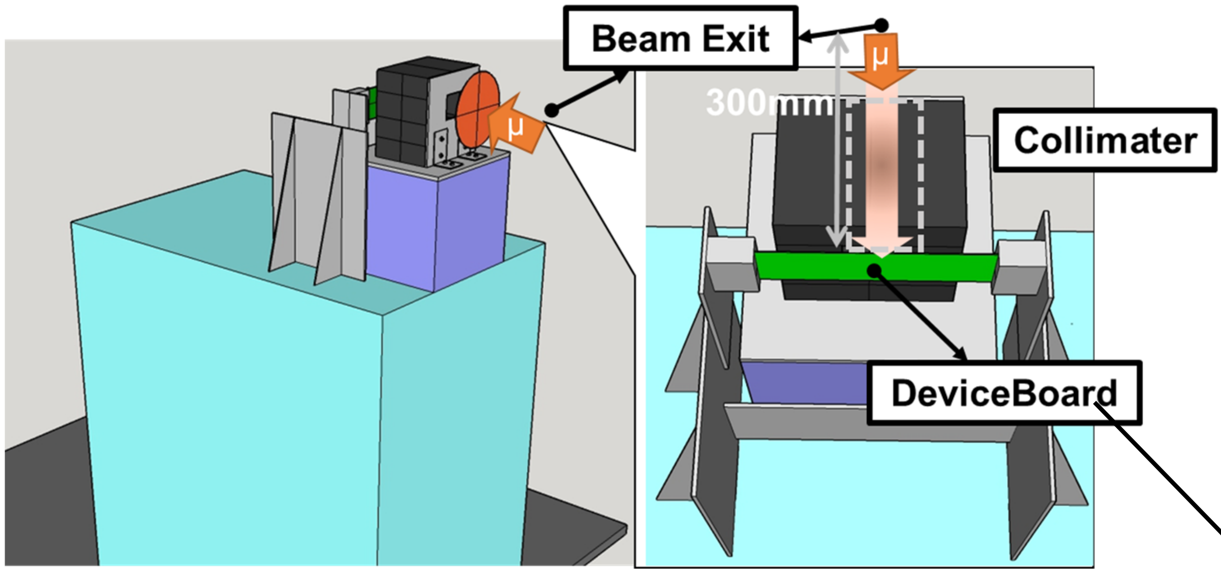
- Pions are first generated through nuclear reactions between a 3-GeV proton beam and a graphite target. The pions decay into muons in a superconducting solenoid magnet.
- Momentum < 50MeV/c
  - Momentum can be changed instantly
  - Momentum spreading σ=5%
- Pulsed beam (single or double, 25Hz)
- 8.0×10^6 μ/s (double pulse, in case of 800kW proton beam)

Setup example

S. Manabe, et al., "Negative and Positive Muon-Induced Single Event Upsets in 65-nm UTBB SOI SRAMs," IEEE TNS, Aug. 2018.

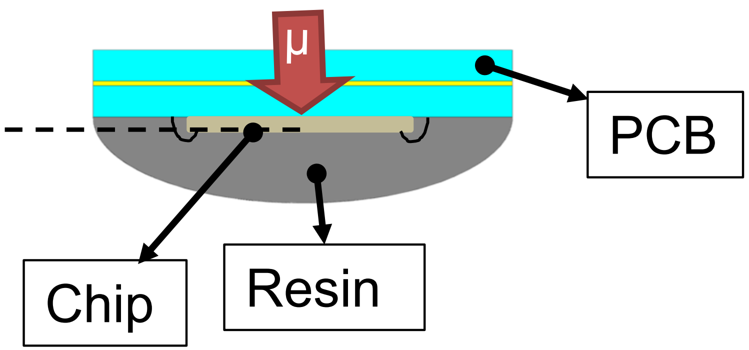


Experimental setup



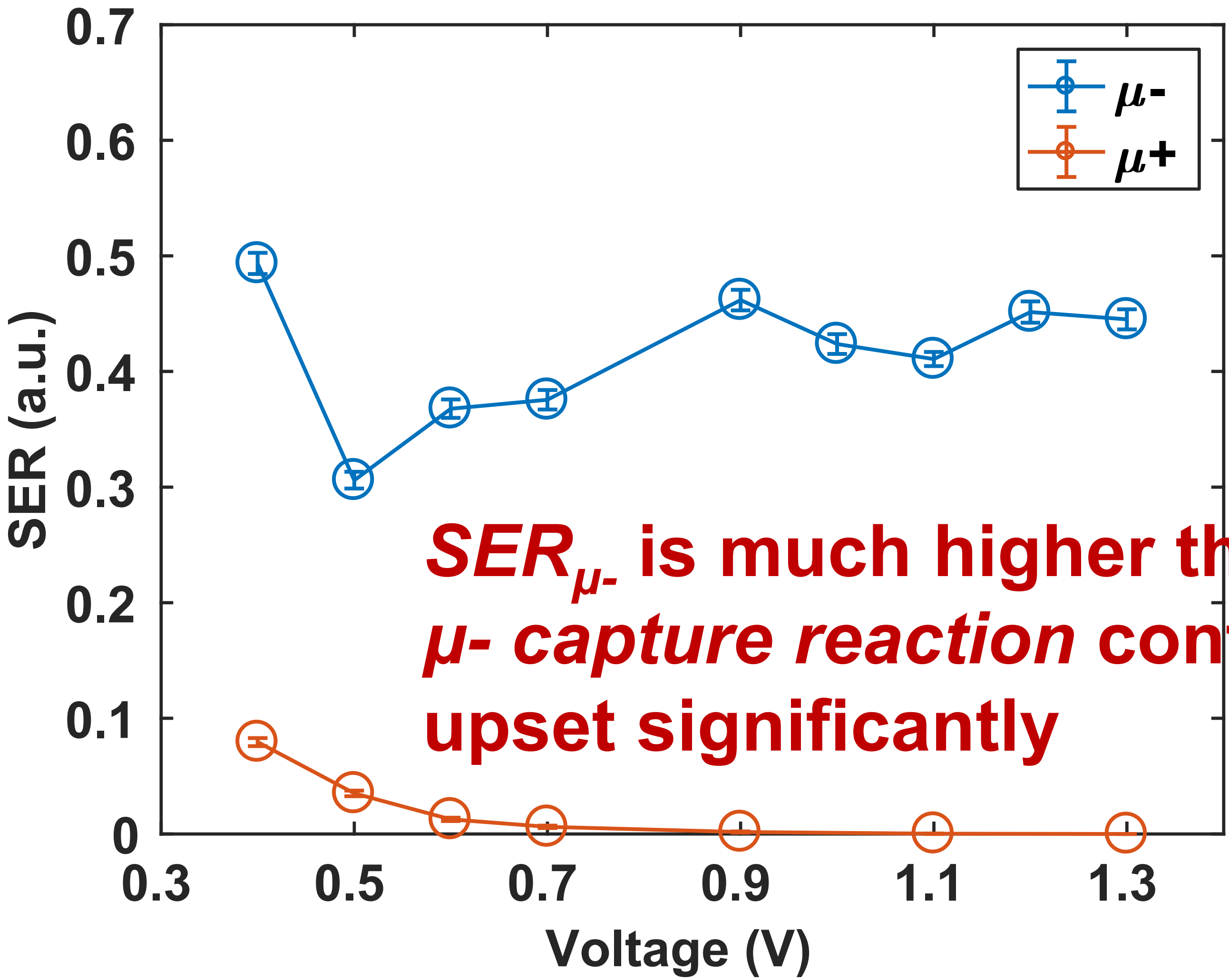
Beam facility:
MUSE
(muon science facility)
of MLF, J-PARC

Control momentum of muon (@38MeV/c)
for making muons stop inside chips near transistors



Chip on Board

Positive vs. negative muons in bulk

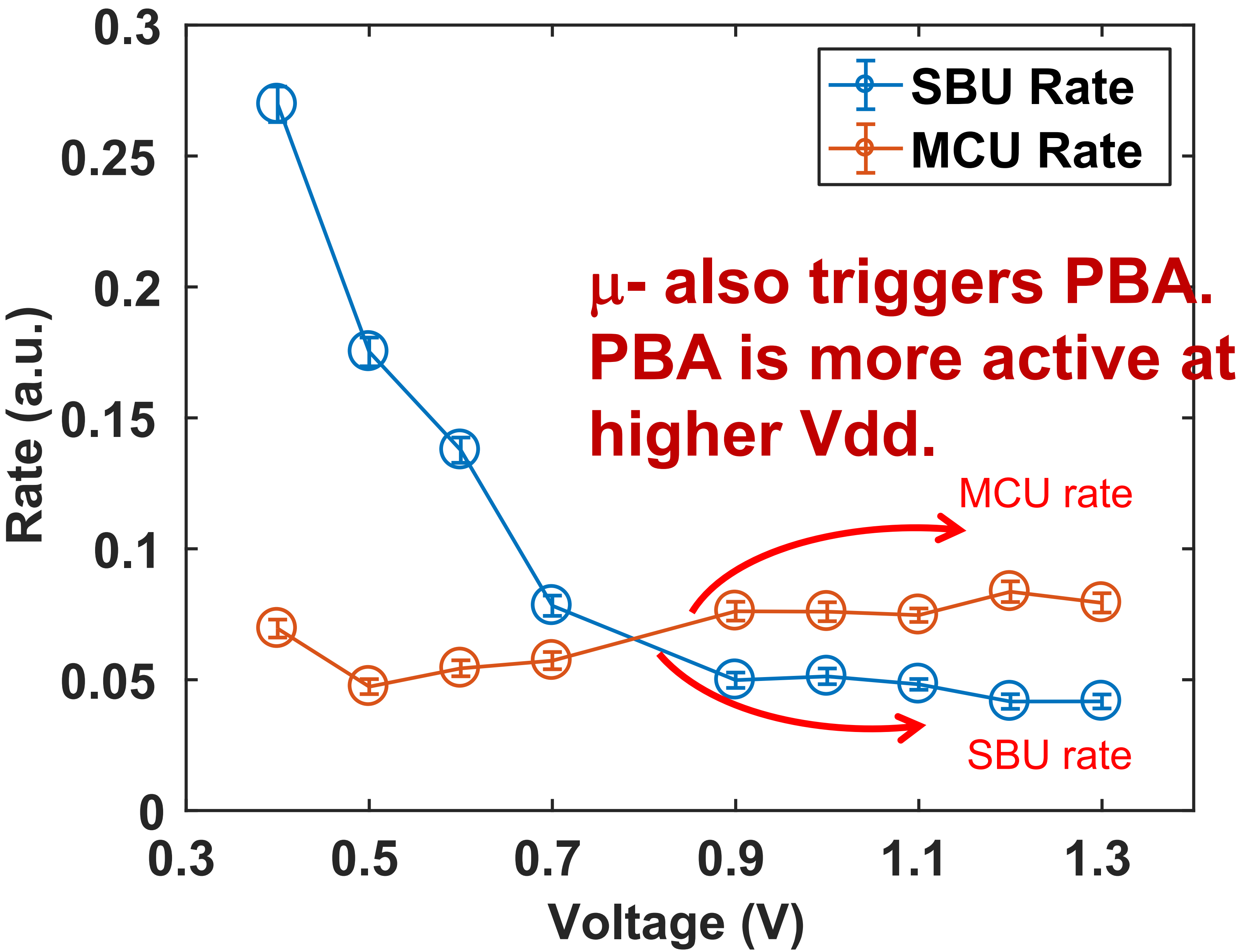


$SER_{\mu-}$ is much higher than $SER_{\mu+}$

***μ- capture reaction* contributes to upset significantly**

W. Liao, et al., "Measurement and Mechanism Investigation of Negative and Positive Muon-Induced Upsets in 65nm Bulk SRAMs," *IEEE Trans. Nuclear Science*, August 2018.

μ- MCU and SBU rates in bulk



μ+ cannot trigger PBA and its MCU rate is much lower than that of μ-

Conclusion

Introduced two facilities for terrestrial SEE testing

- RCNP white neutron @ Osaka Univ.
  - https://www.rcnp.osaka-u.ac.jp/index_en.html
  - White neutrons, 10^8x accelerated
- MLF muon beam @ J-PARC
  - https://mlfinfo.jp/en/
  - Positive and negative muons, < 50MeV/c, 8.0×10^6 μ/s

Both facilities are accepting proposals from all over the world.