Real-Time Soft-Error Rate (SER) Testing

J.L. Autran, S. Sauze, D. Munteanu
IM2NP-CNRS, Aix-Marseille Université, Marseille, France

P. Roche, G. Gasiot
STMicroelectronics, Crolles, France

P. Loaiza, M. Zampaolo
LSM, CEA-CNRS, Modane, France

J. Borel
JB R&D, Saint-Etienne en Dévoluy, France

Altitude
SEE
Test
European
Platform

LSM

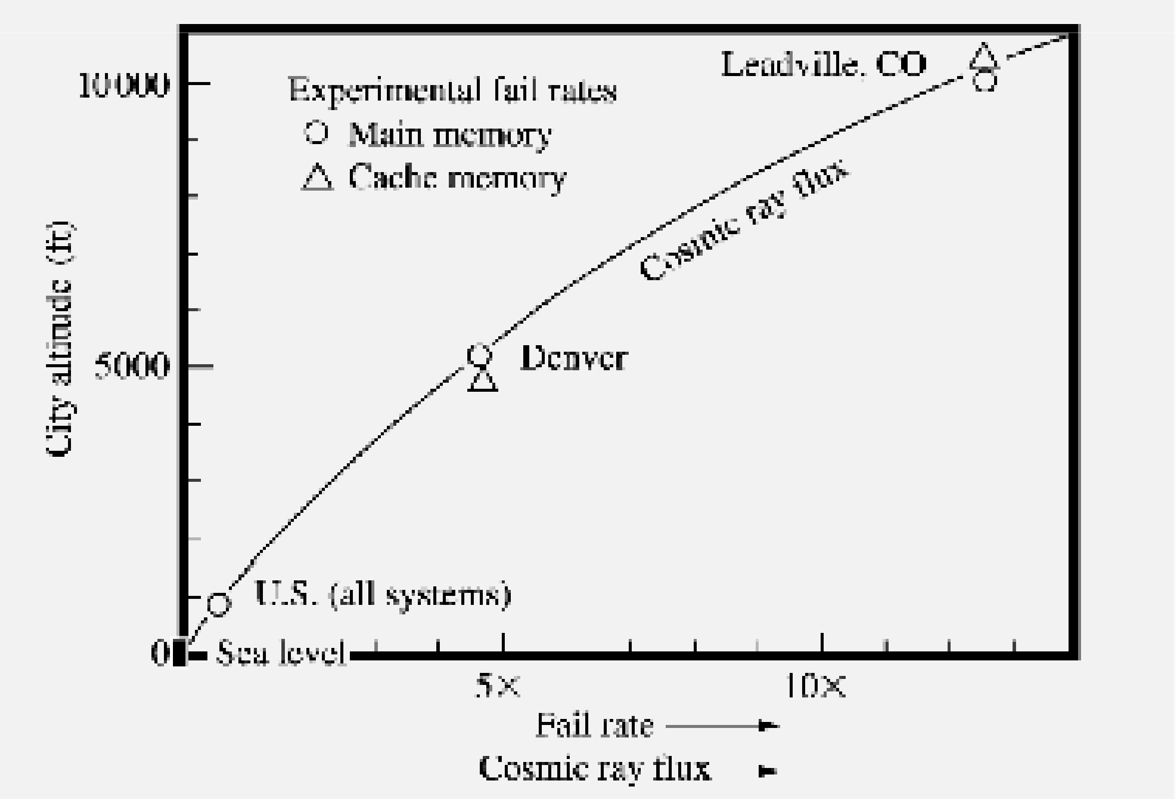
ULISSE Workshop - LSM
Aussois – June 30, 2008

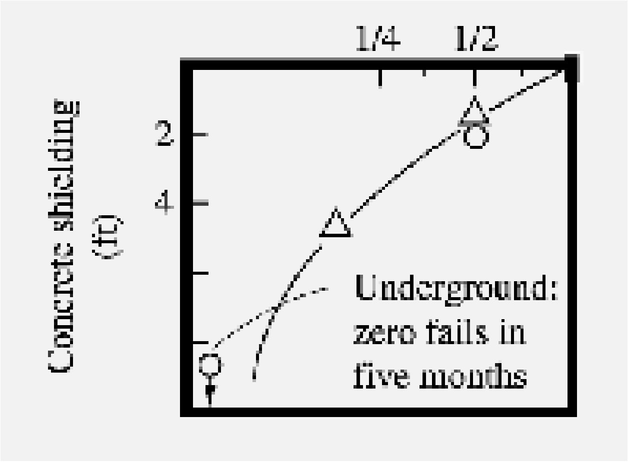
Outline

- *Introduction – Context – Basic mechanisms*
- *Test platforms – Platform characteristics*
- *Devices under test*
- *Automatic Test Equipment*
- *Experimental results*
- *Comparison with accelerated tests and simulations*
- *Conclusions & perspectives*

Introduction - Context

Pionnering work by Ziegler and co-workers (IBM) in the 70s and 80s

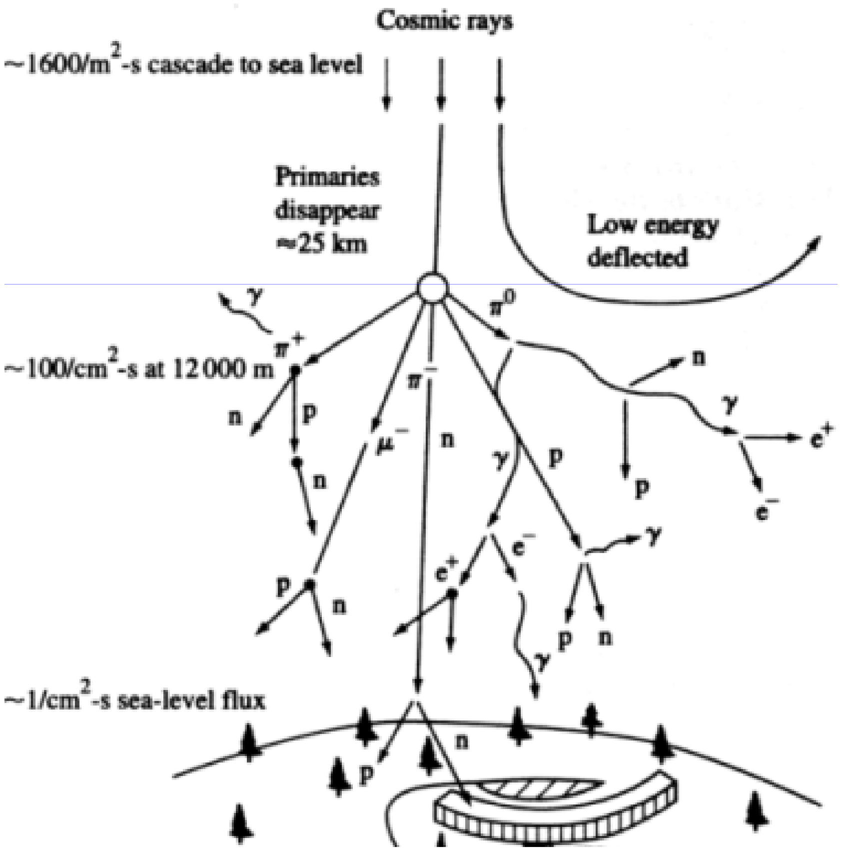


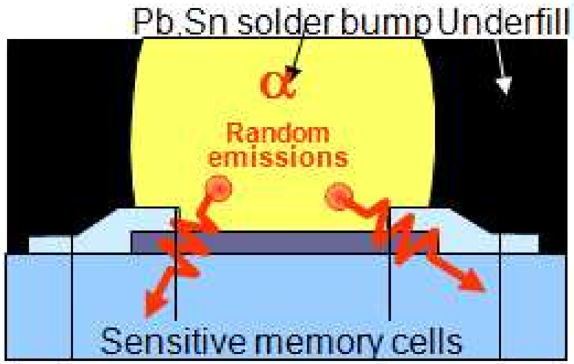


J.F. Ziegler et al.

IBM experiments in soft fails in computer electronics (1978-1994)

IBM J. Res. Develop., Vol. 40, Number 1, 1998





Introduction - Context

- Electronic devices at ground level are primilarly impacted by:

  ✓ Secondary cosmic rays in the Earth atmosphere (neutrons)

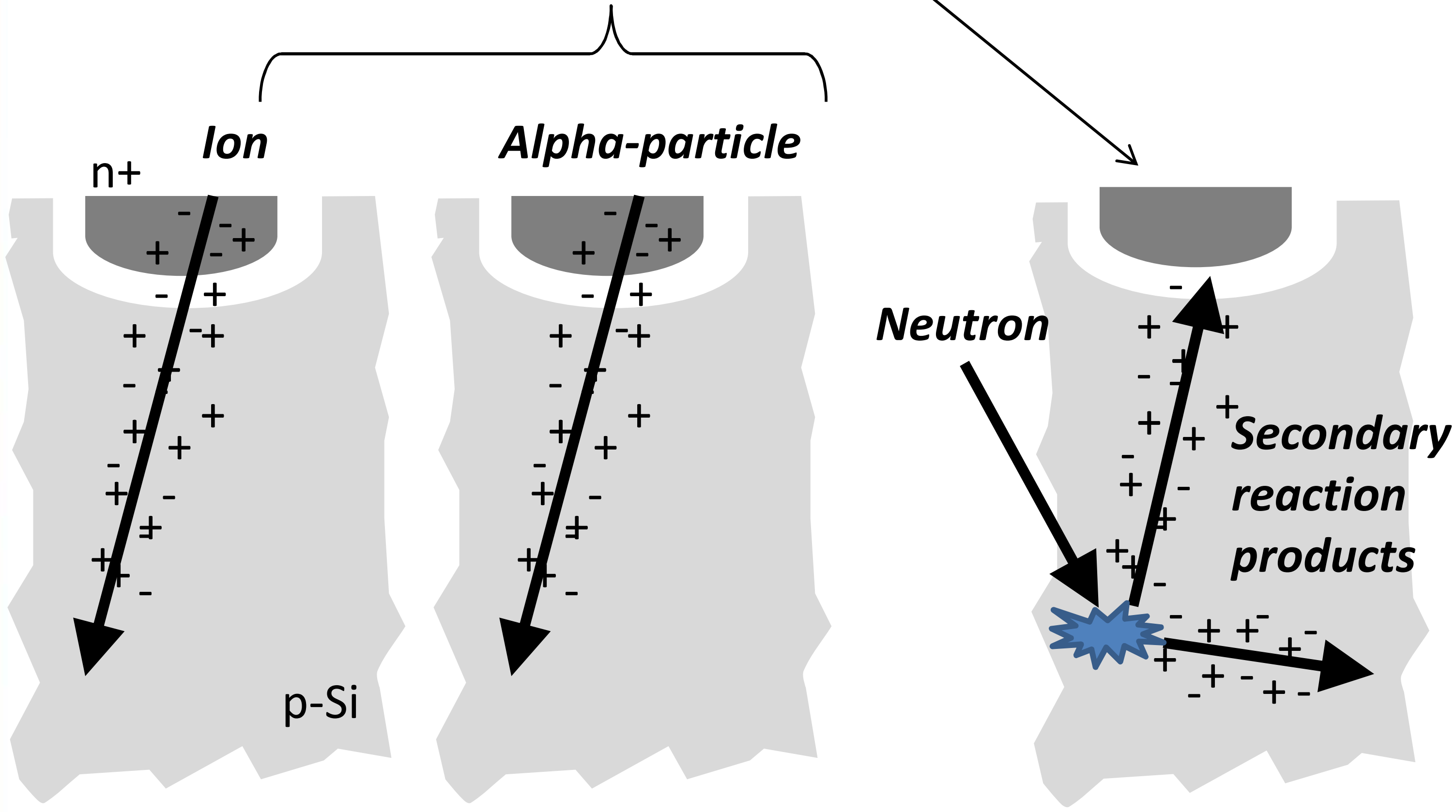
  ✓ Telluric ray produced directly inside ICs due to residual traces (≤ ppB) of radioactive elements (alpha particles)

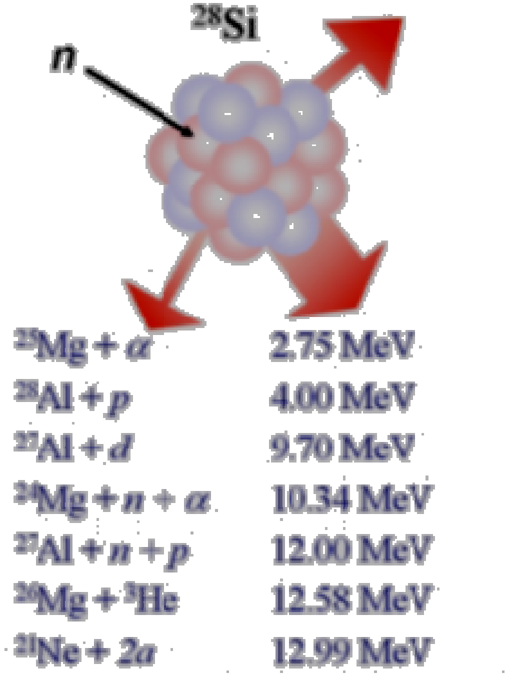
- Neutrons and alpha particles are the main aggressors playing a major role in the occurrence of SEE in SRAMs at ground level

Introduction – Basic mechanisms

Main steps of SEE production in microelectronic devices (1/2)

Direct and indirect matter ionization



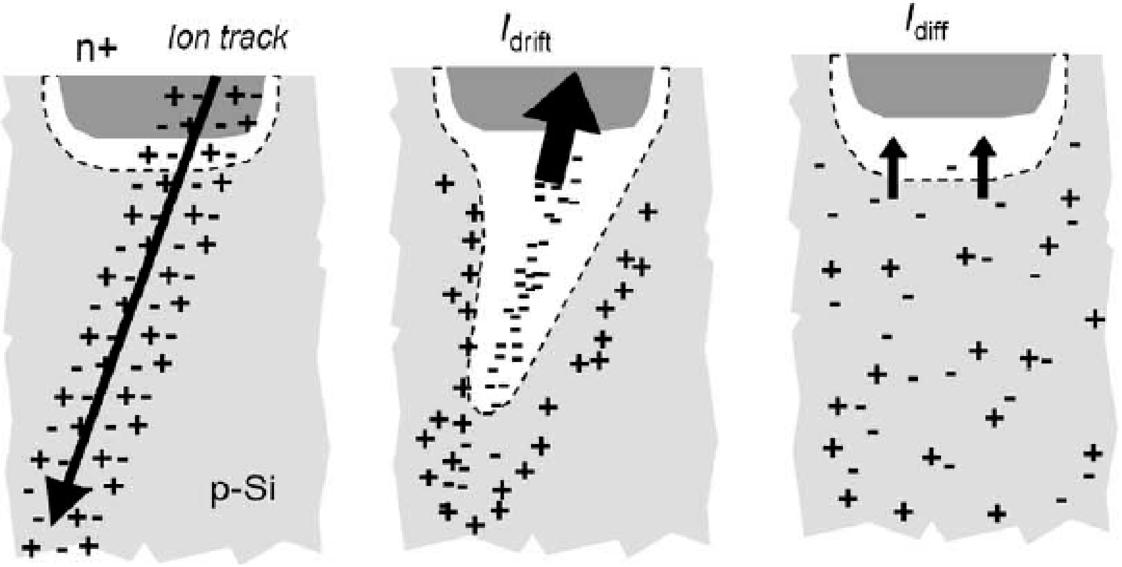


$^{25}Mg + \alpha$	2.75 MeV
$^{28}Al + p$	4.00 MeV
$^{27}Al + d$	9.70 MeV
$^{24}Mg + n + \alpha$	10.34 MeV
$^{27}Al + n + p$	12.00 MeV
$^{26}Mg + {}^{3}He$	12.58 MeV
$^{21}Ne + 2\alpha$	12.99 MeV

Reaction table from F. Wrobel et al., IEEE Trans. Nucl. Phys., Vol. 47, No. 6, Dec. 2000

Introduction – Basic mechanisms

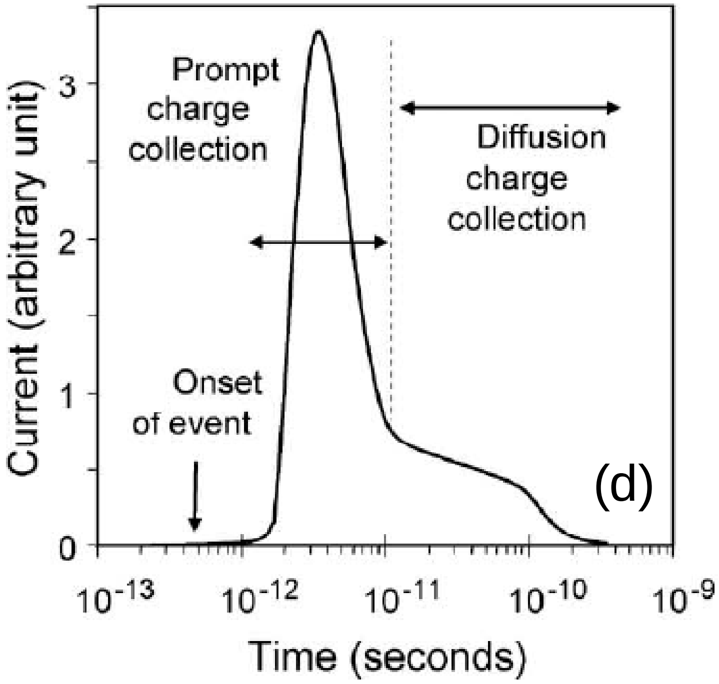
Main steps of SEE production in microelectronic devices (2/2)[*]



① *Charge deposition by the energetic particle striking the sensitive region*

Transport of the released charge into the device (drift and diffusion mechanisms) ②

Charge collection in the sensitive region of the device ③

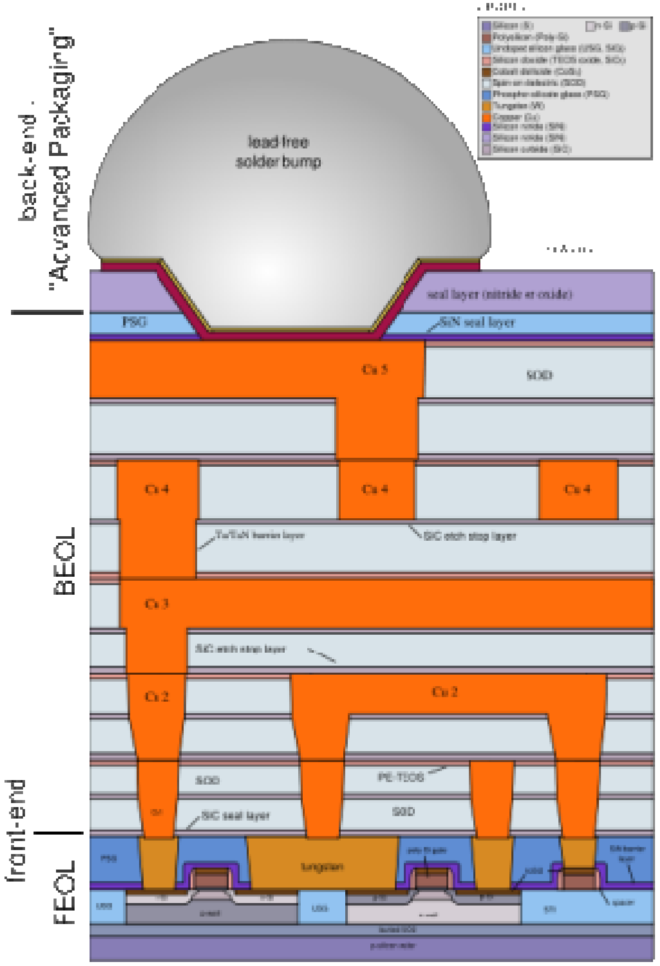


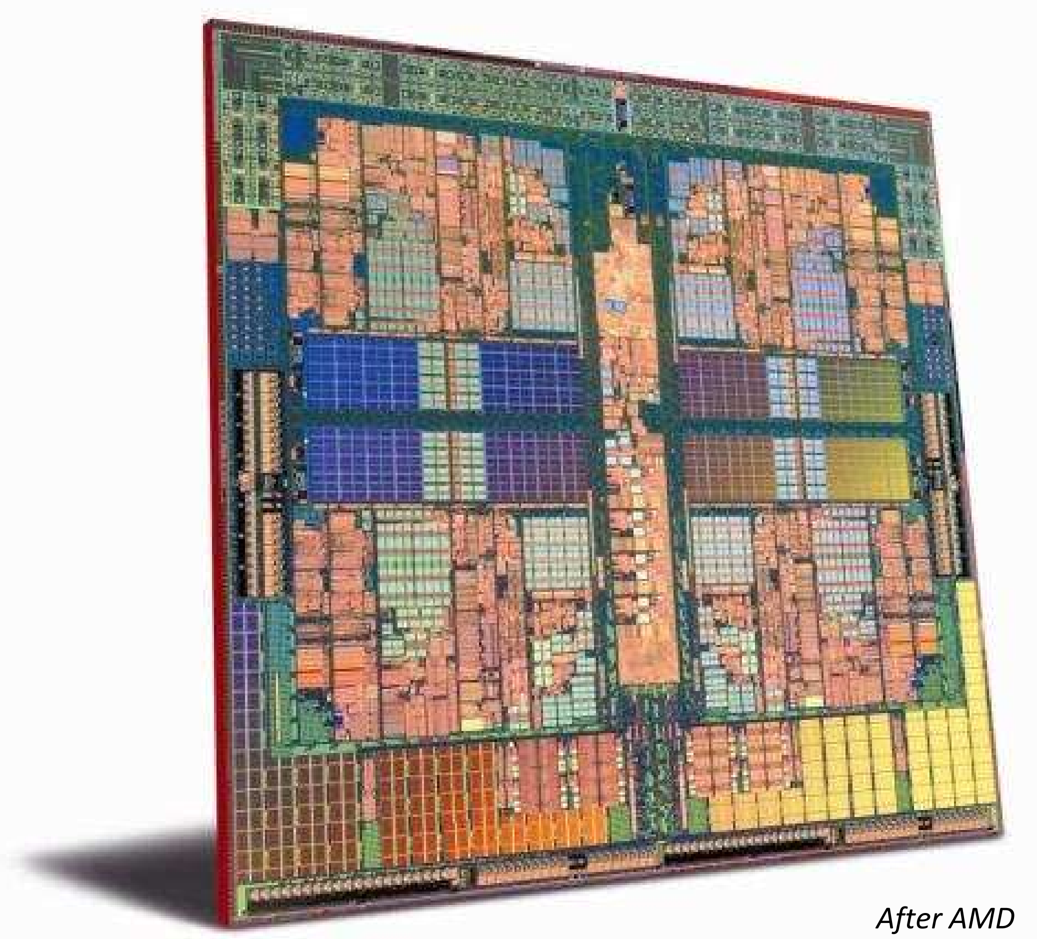
Current pulse caused by the passage of the energetic particle

[*] After R. C. Baumann, ***IEEE Trans. Device Mater. Reliab.***, vol. 5(3), p. 305-316, Sept. 2005.

Introduction – Basic mechanisms

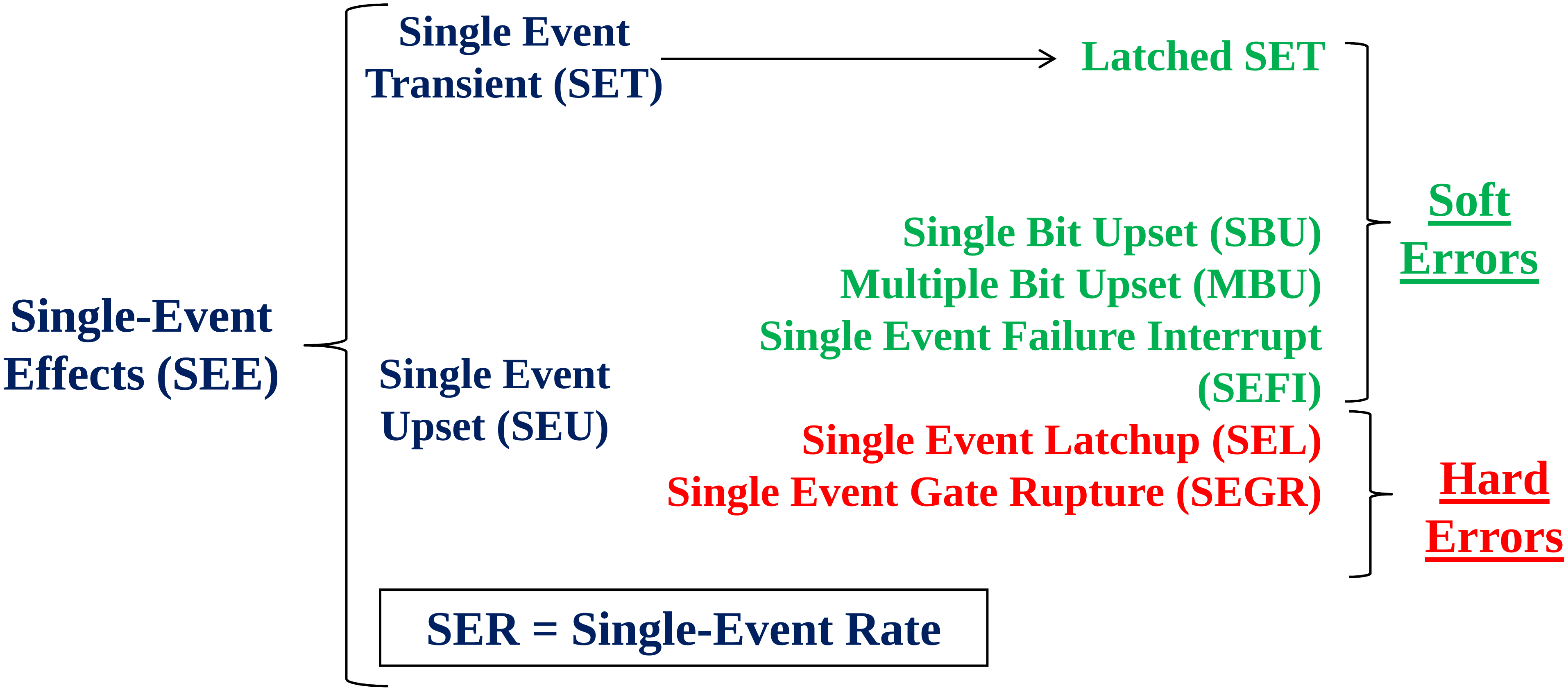
Charge deposition, transport and collection occur in a <u>high complexity media</u> : the CIRCUIT





After AMD

Introduction – Terminology



Single-Event Effects (SEE)

Single Event Transient (SET) → **Latched SET**

Single Event Upset (SEU)

Single Bit Upset (SBU)
Multiple Bit Upset (MBU)
Single Event Failure Interrupt (SEFI)

Single Event Latchup (SEL)
Single Event Gate Rupture (SEGR)

Soft Errors

Hard Errors

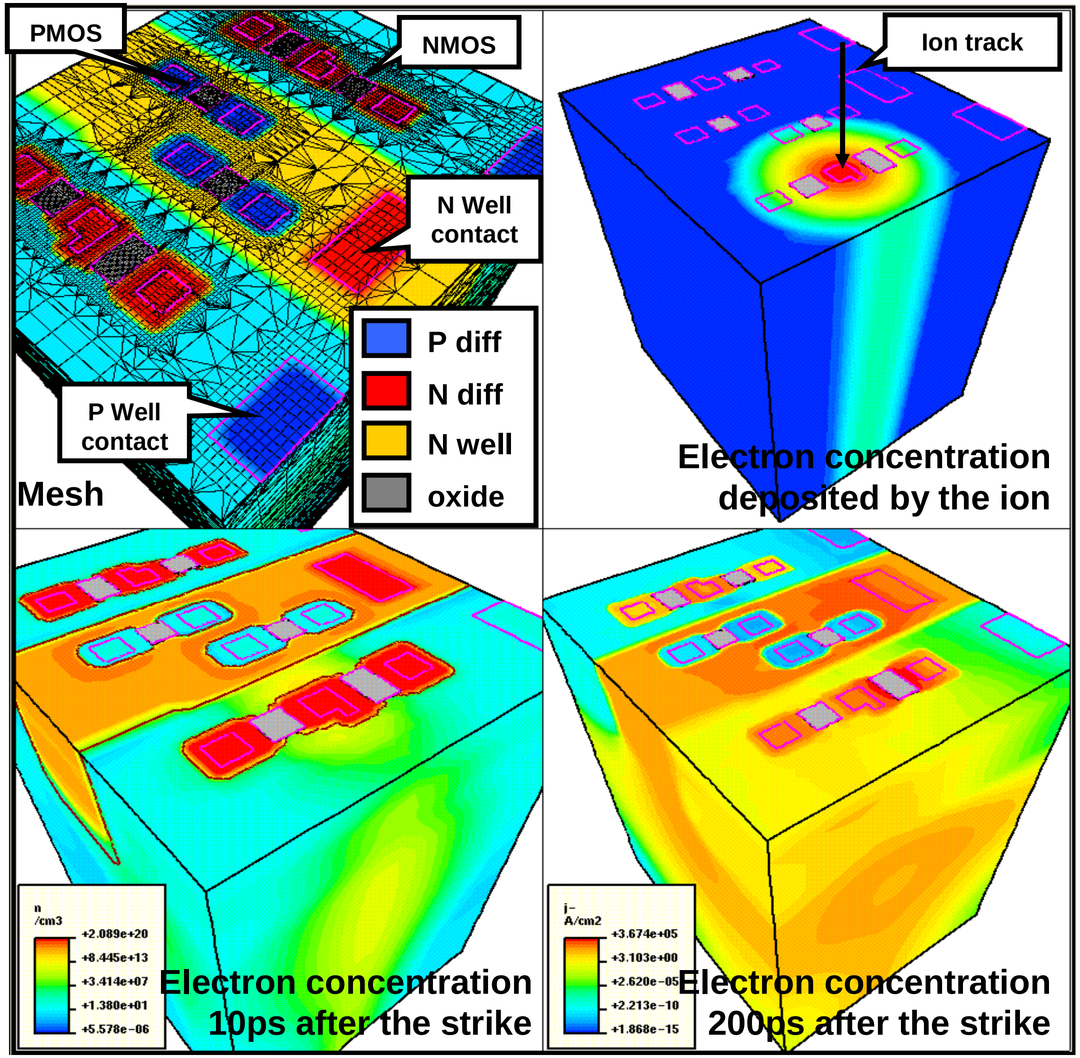
SER = Single-Event Rate

---

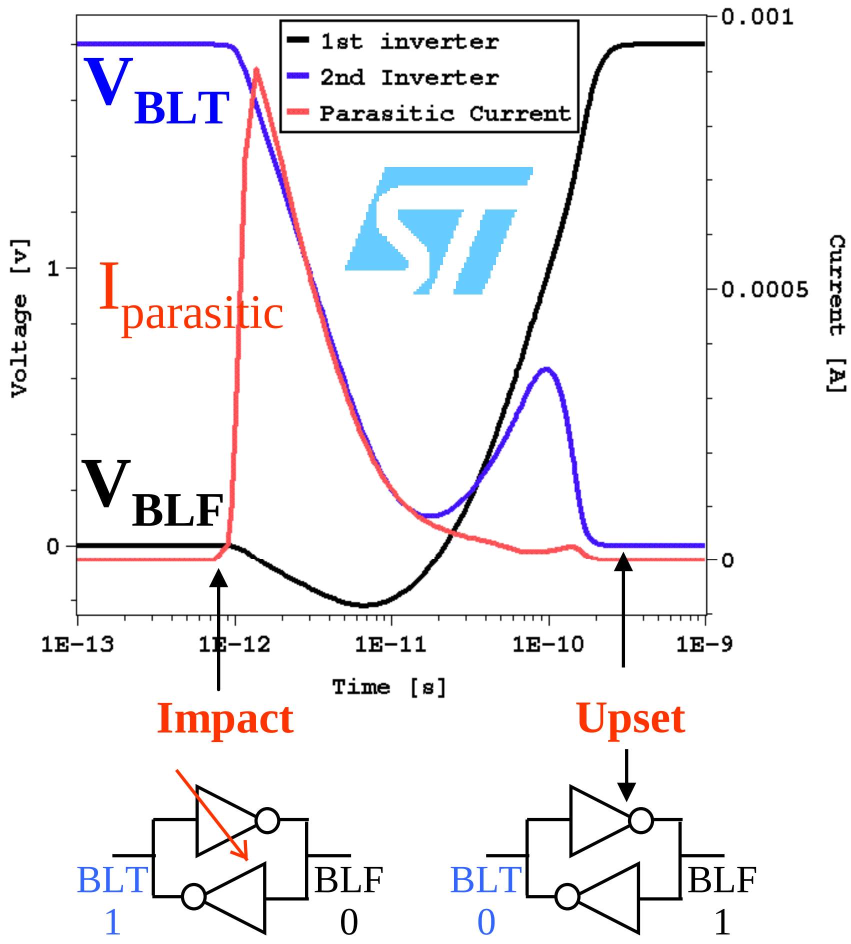
* **JEDEC Standard JESD89A**
Measurement and Reporting of Alpha Particles and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices, http://www.jedec.org/download/search/JESD89A.pdf

Introduction – Basic mechanisms

SEU = **Single Event Upset** (SRAM memory)



Snapshots courtesy of P. Roche

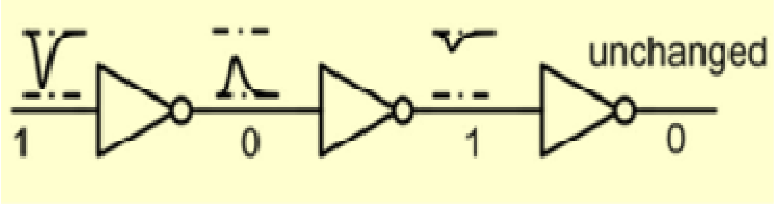


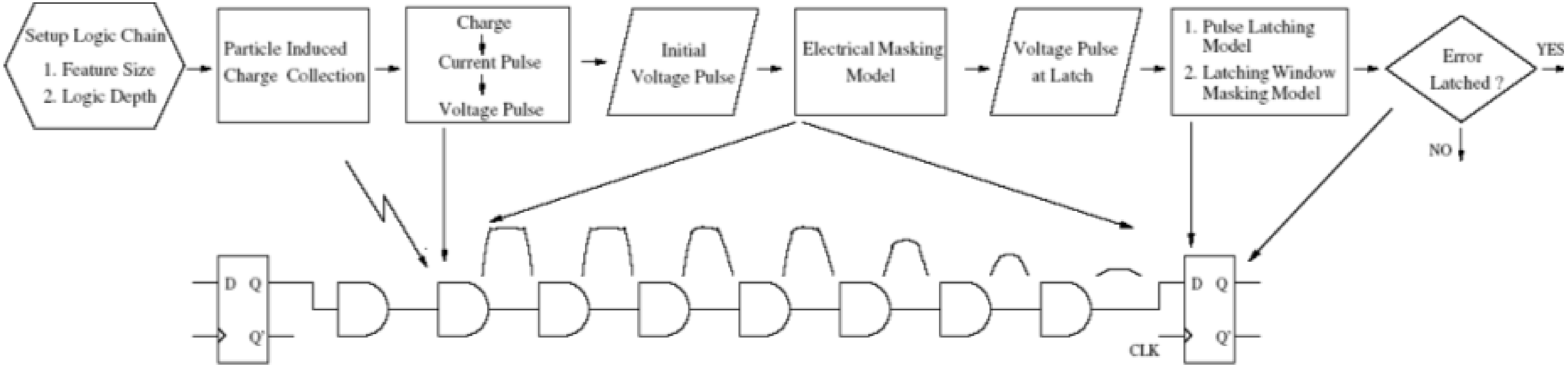
Introduction – Basic mechanisms

DSET = **Digital Single Event Transient**

= constitute a temporary voltage or current transient generated by the collection of charge deposited by an energetic particle in a digital circuit

*Even if the DSET does not induce an SEU in the struck circuit, it can **propagate** through the subsequent circuits and may be stored as incorrect data **when it reaches a latch or memory element***





P. Shivakumar et al., in ***Proc. Int. Conf. Dep. Systems & Networks***, DSN 2002.

Introduction - Context

⇒ ***Objective of this work**: perform real-time testing of SRAMs to evaluate neutron* **and alpha particle-induced SER**

Verify once during the technology qualification phase that both accelerated testing and simulation are accurate

***Principle of the experiment**: long-term (several months) exposure of a large amount (Gbits) of circuits to the natural radiation environment*

- ✓ ***In altitude**: to amplify the atmospheric neutron flux (typically by a factor of 3 to 15 at ground level)*
- ✓ ***Underground**: to remove the atmospheric neutron contribution (observed soft-errors are expected to be due to alpha particles)*

Test platforms

LSM

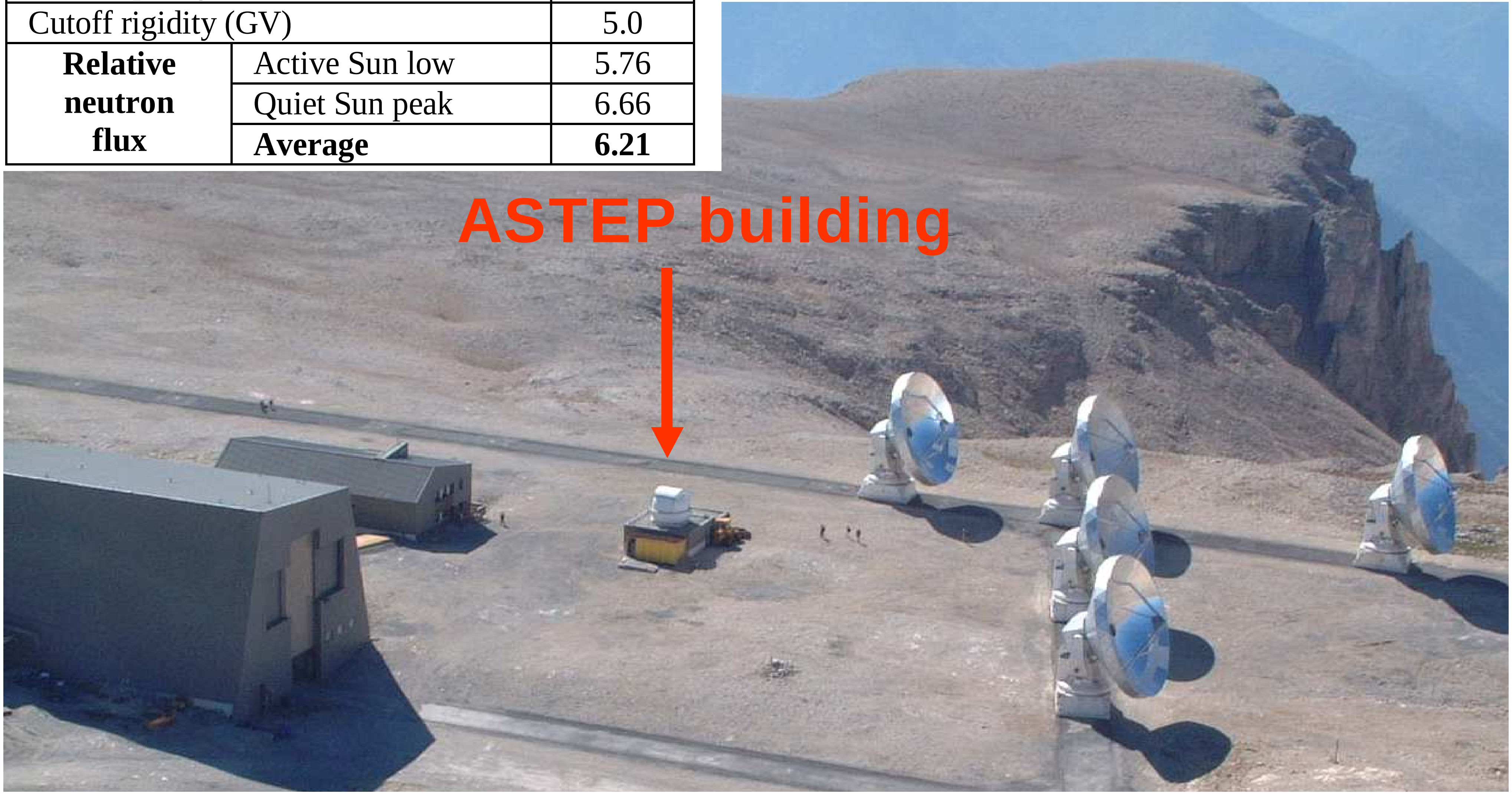
-1700 m under rock

Altitude
SEE
Test
European
Platform

+2552 m in Alp mountains

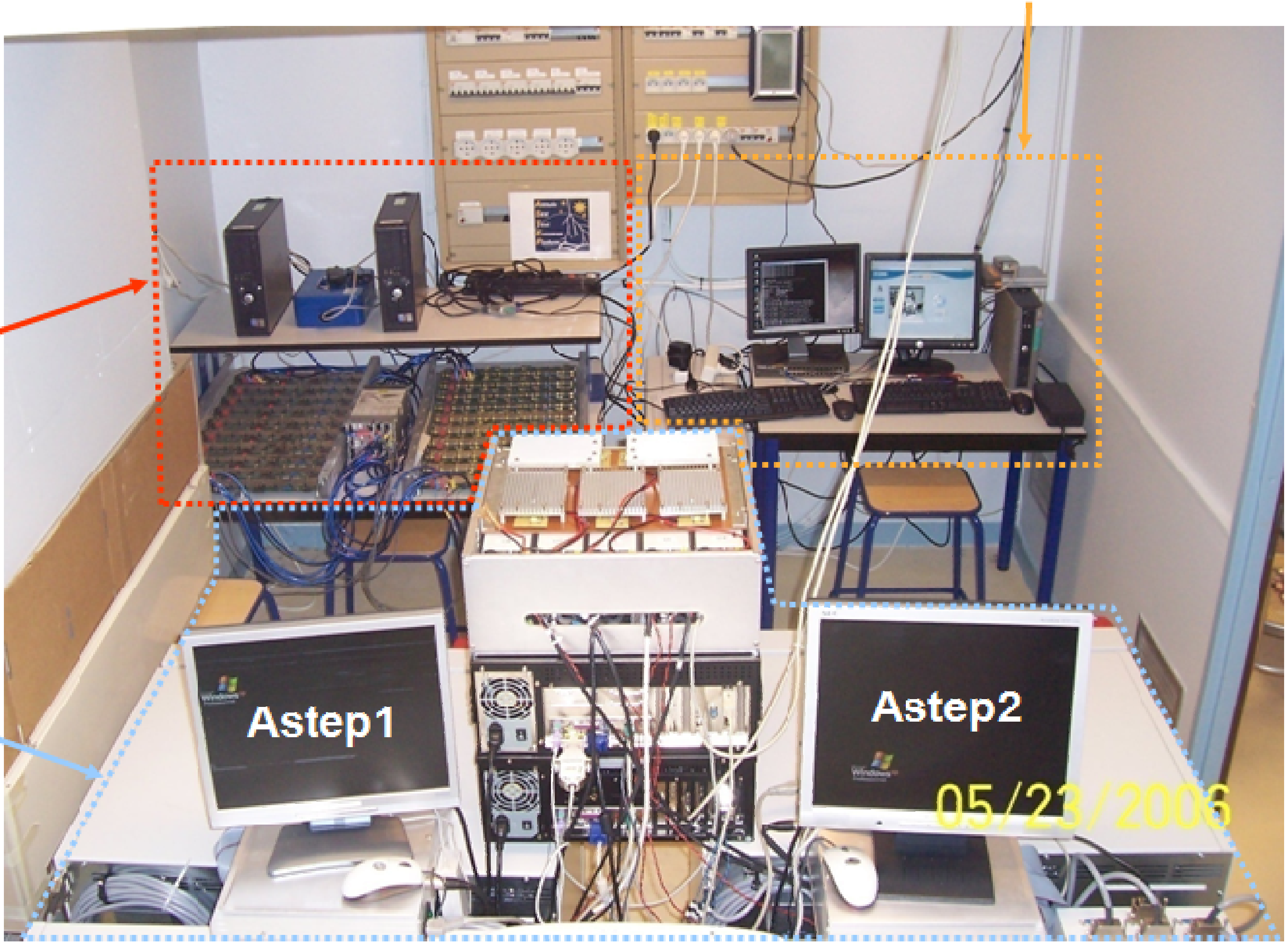
The Altitude SEE Test European Platform

ASTEP, Plateau de Bure, France		
Latitude (°N)		44.6
Longitude (°E)		5.9
Elevation (m)		2552
Atm. depth (g/cm^2)		757
Cutoff rigidity (GV)		5.0
Relative neutron flux	Active Sun low	5.76
	Quiet Sun peak	6.66
	Average	**6.21**



Altitude
SEE
Test
European
Platform

www.astep.eu



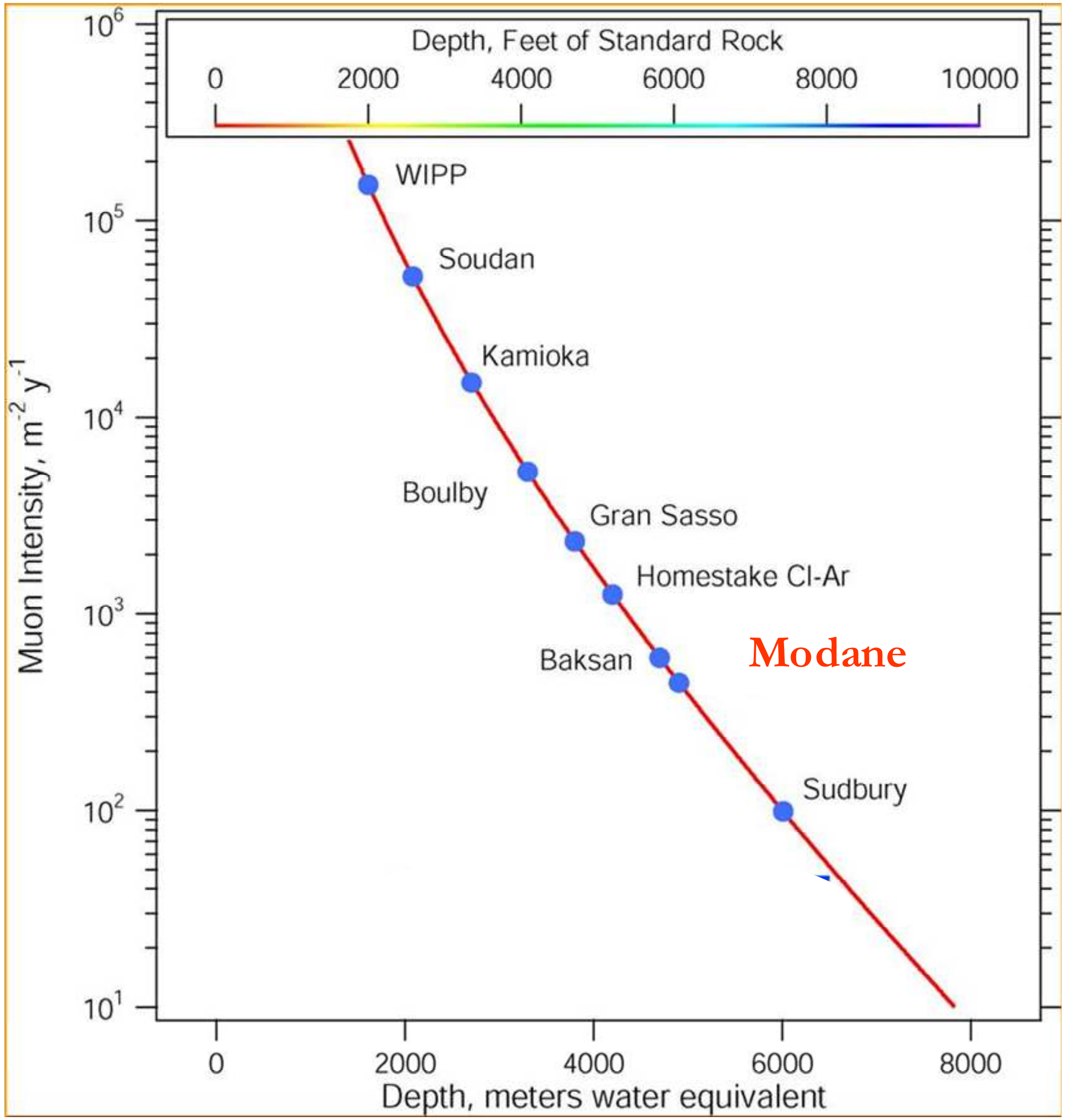
ASTEP main control PC (internet firewall, weather monitoring, control webwam...)

XILINX "Rosetta" Experiment hosted by ASTEP

XILINX

ASTEP System-SER

The Modane Underground Laboratory (LSM)



ULTRA LOW NOISE ENVIRONMENT

Depth: - 4800 m water equivalent

4×10^{-6} neutrons/cm^2/s [2-6 MeV]

4.2 muon/m^2/day

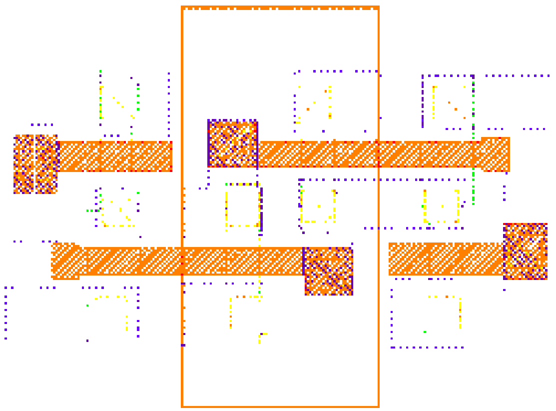
Radon < 20 mBq/m^3

Residual radioactive activity:

	^{238}U	^{232}TH	^{40}K
Mountain roc	(0.84±0.2) ppm	(2.45±0.2) ppm	(0.213±0.03) Bq/g
Tunnel concrete	(1.9±0.2) ppm	(1.4±0.2) ppm	(7.73±1.3) 10^{-2} Bq/g

Devices under test

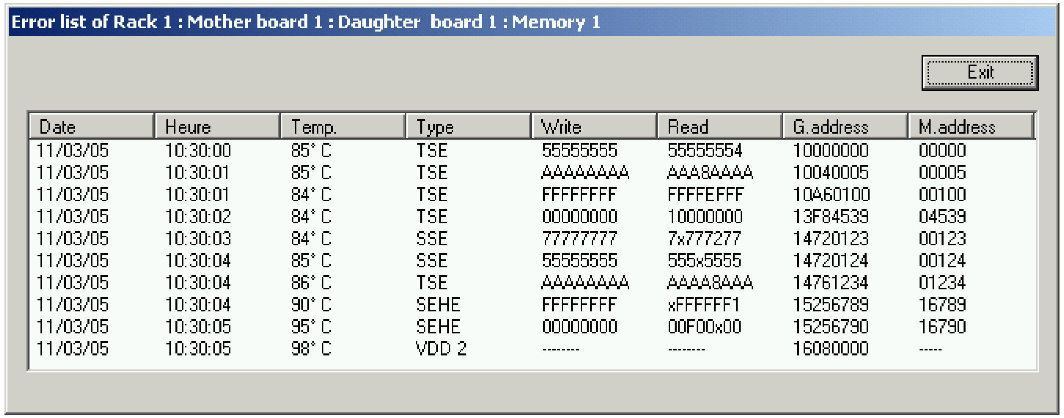
- SRAM test vehicle designed and manufactured by STMicroelectronics in CMOS 130 nm
- Fully characterized and simulated testchip :
  - ✓ *alphas* (ST and IM2NP with Am^{241})
  - ✓ *neutrons* (ST at Triumf & Los Alamos)
  - ✓ *TCAD* (ST with Synopsys tool suite)
  - ✓ *SER Simulation* (proprietary codes)
- 4 Mbits per device
- 912 devices
- Total capacity > 3.6 Gbits



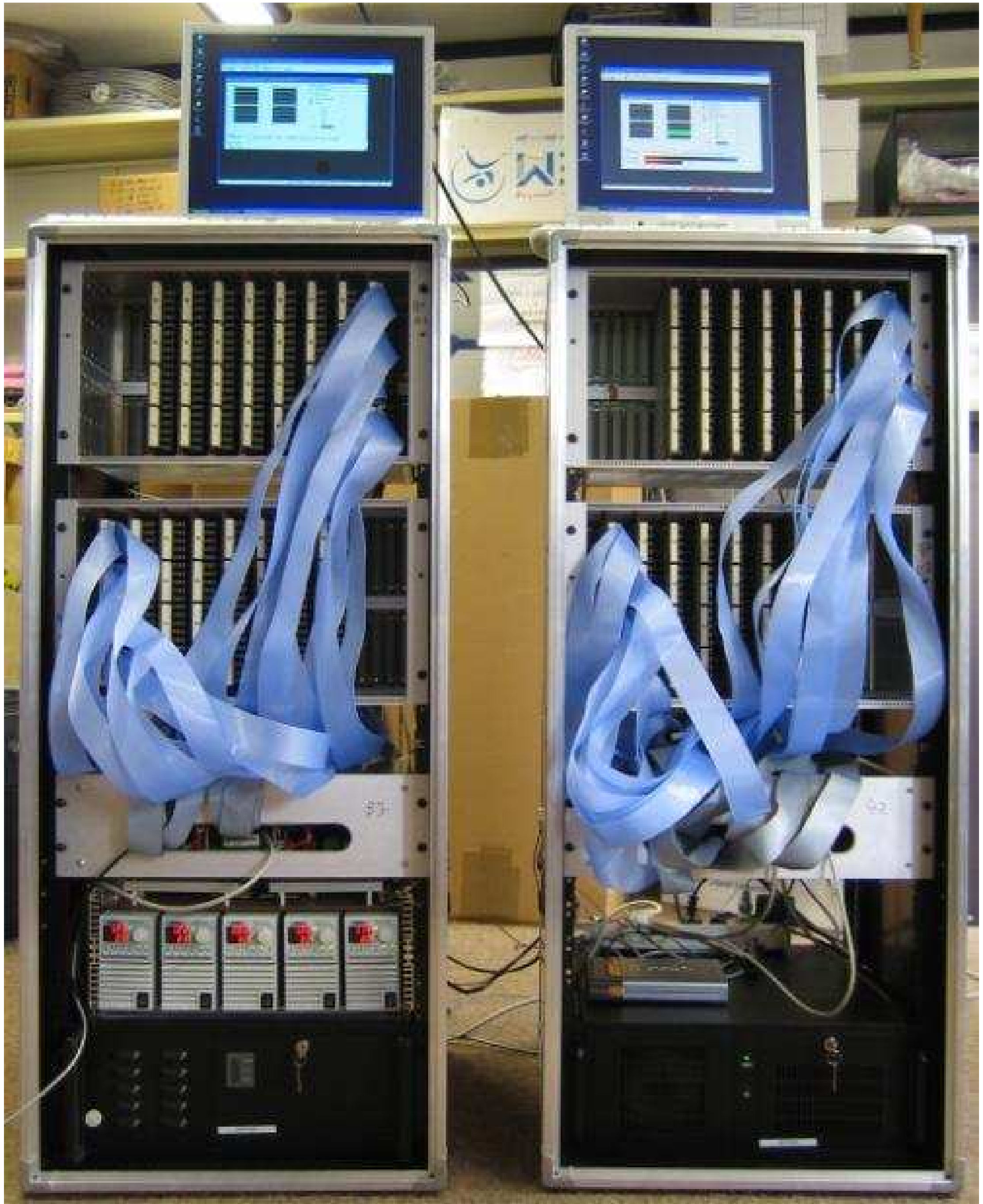
Bitcell area = 2.50 µm²

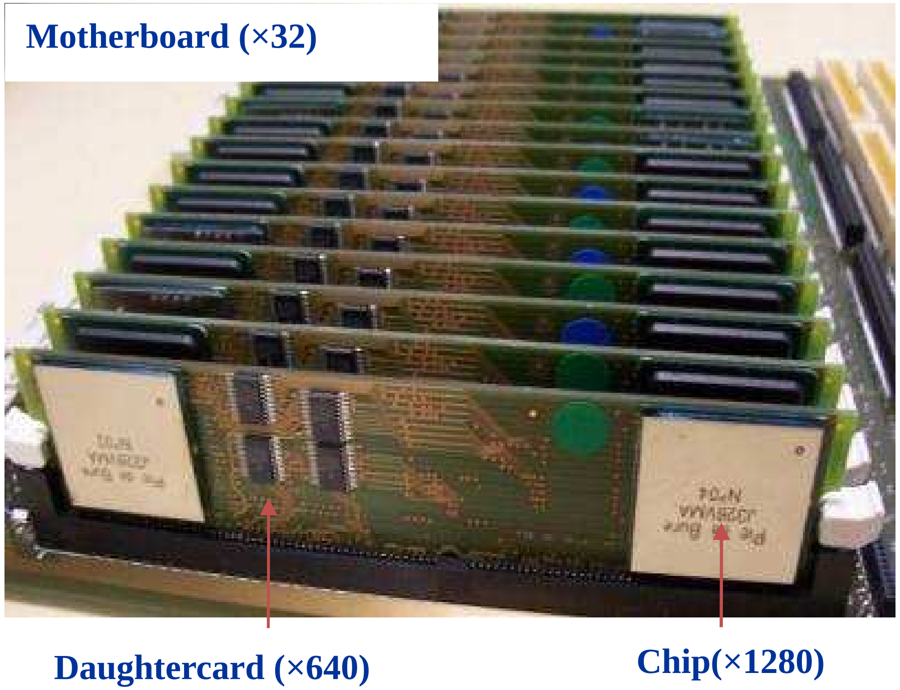
The Automatic Test Equipment (ATE)

- Data writing (32 bits) with selected pattern
- For each memory point, Writing and rereading with data control
- If data correct, go test the next memory point
- If data state not correct, try to reread twice the data
- If data correct after rereading, error identified as **"Transient Soft Error"**
- If data still not correct, test twice to rewrite and to reread.
- If control valid after rewriting and rereading, error identified as **"Static Soft Error"**
- If control not valid after rewriting and rereading, error identified as **"Single-Event Hard Error"**



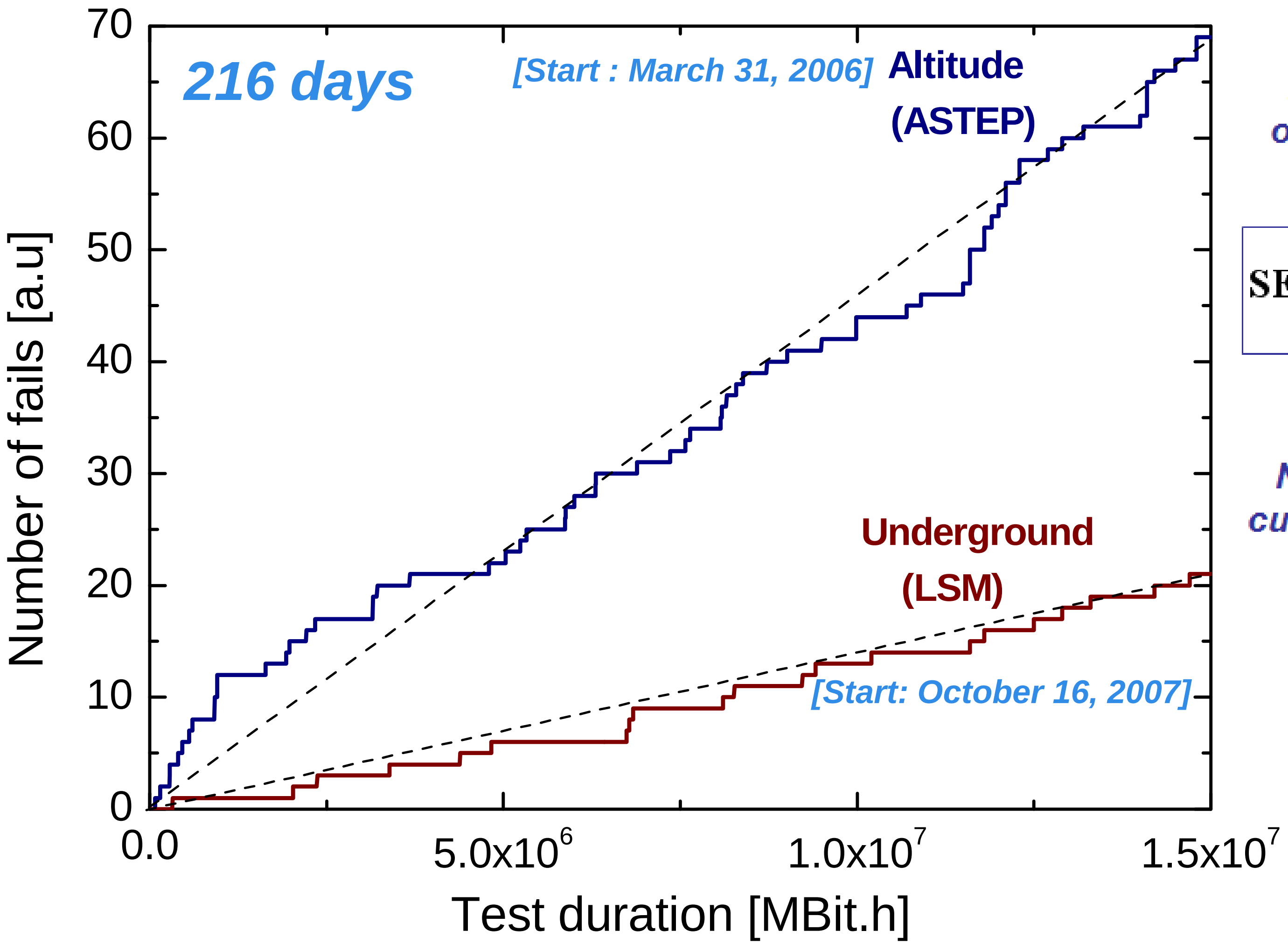
Date	Heure	Temp.	Type	Write	Read	G.address	M.address
11/03/05	10:30:00	85° C	TSE	55555555	55555554	10000000	00000
11/03/05	10:30:01	85° C	TSE	AAAAAAAA	AAA8AAAA	10040005	00005
11/03/05	10:30:01	84° C	TSE	FFFFFFFF	FFFFEFFF	10A60100	00100
11/03/05	10:30:02	84° C	TSE	00000000	10000000	13F84539	04539
11/03/05	10:30:03	84° C	SSE	77777777	7x777277	14720123	00123
11/03/05	10:30:04	85° C	SSE	55555555	555x5555	14720124	00124
11/03/05	10:30:04	86° C	TSE	AAAAAAAA	AAAA8AAA	14761234	01234
11/03/05	10:30:04	90° C	SEHE	FFFFFFFF	xFFFFFF1	15256789	16789
11/03/05	10:30:05	95° C	SEHE	00000000	00F00x00	15256790	16790
11/03/05	10:30:05	98° C	VDD 2	--------	--------	16080000	-----




Motherboard (×32)
Daughtercard (×640)
Chip(×1280)

Experimental Results

Number of fails measured in both altitude and cave during 216 days (>7 months)



Number of errors observed at time T_r

$$\mathrm{SER} = \frac{N_r}{\Sigma_r} \times 10^9 \ \mathrm{(FIT/MBit)}$$

Number of Mbit.h cumulated at time T_r

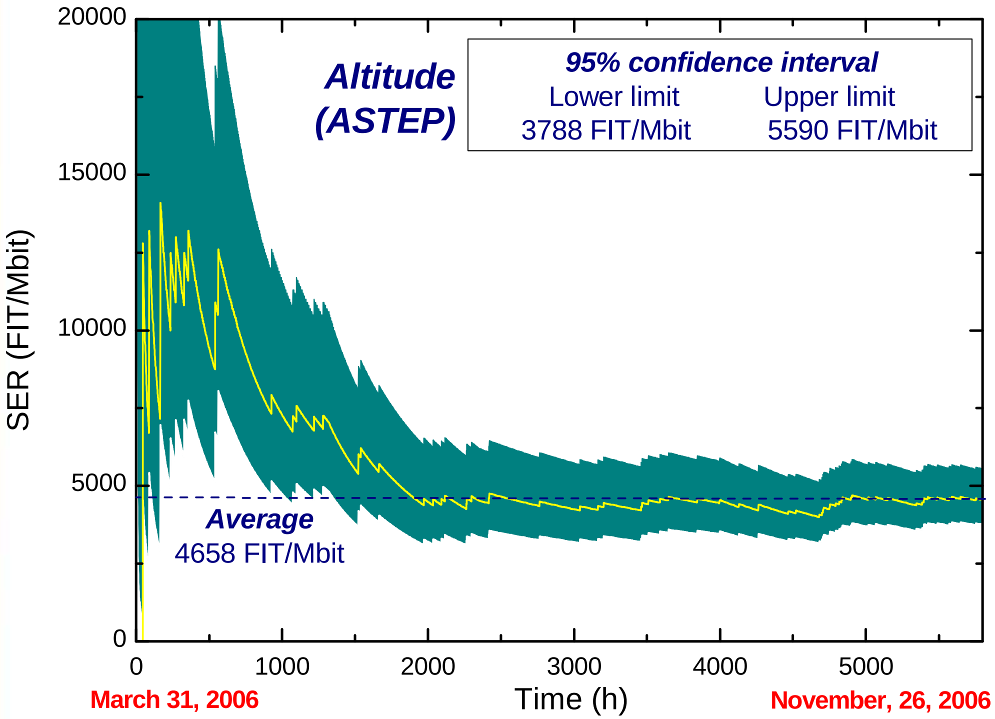
$$\Sigma_r = \int_0^{Tr} 4 \times N(t)\,dt$$

4MBits/chip

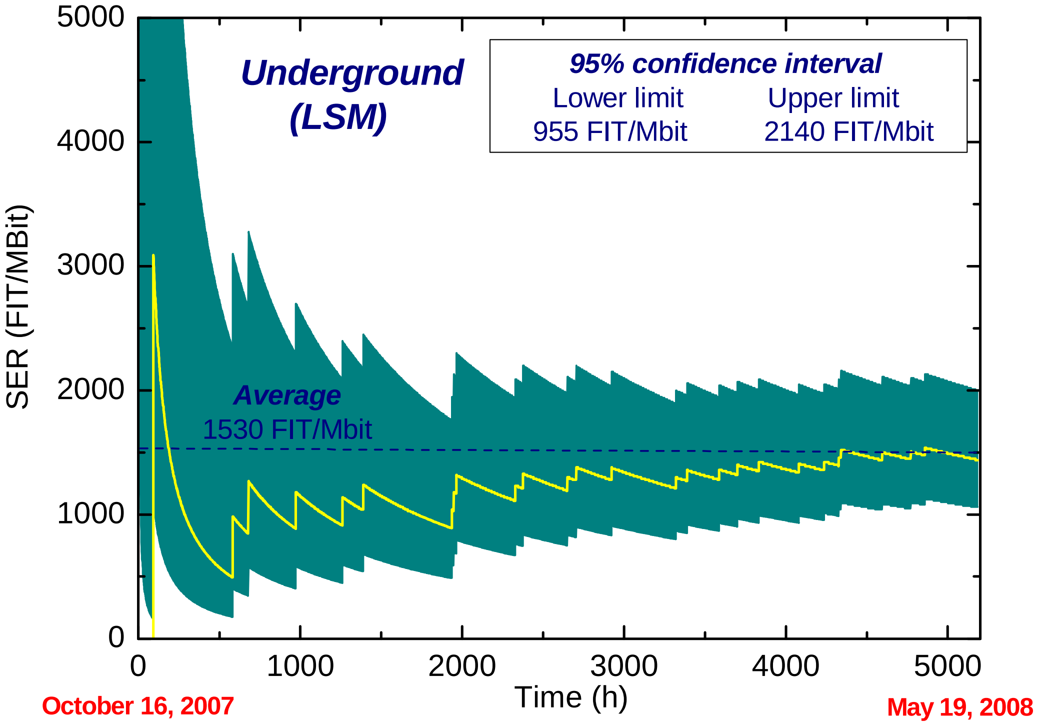
Number of chips under test at time t

Experimental Results

Soft-Error Rate measured in both altitude and cave



March 31, 2006 **November, 26, 2006**



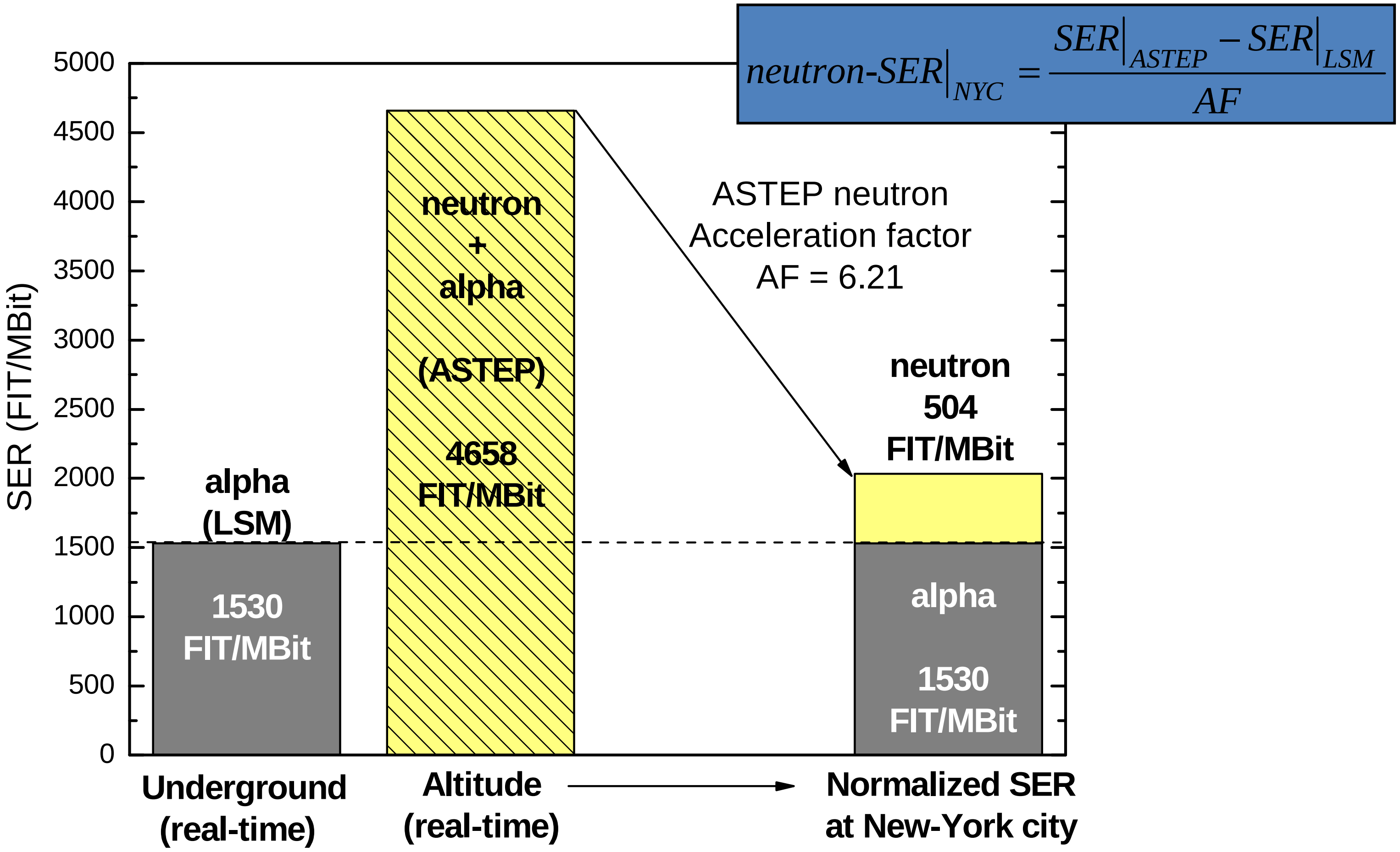
October 16, 2007 **May 19, 2008**

Neutron-SER cannot be directly extracted due to alpha contribution

Data directly gives access to alpha-SER (neutron contribution negligible)

Experimental Results

Neutron and alpha-SER extraction



$$neutron\text{-}SER\big|_{NYC} = \frac{SER\big|_{ASTEP} - SER\big|_{LSM}}{AF}$$

ASTEP neutron
Acceleration factor
AF = 6.21

Comparison with accelerated tests

- Alpha SER
  - Real-time @ LSM (this work) 1530 FIT/Mbit
  - Accelerated test @ ST (1) 380 FIT/Mbit

(1) Using an Am^{241} α-source and assuming an alpha-emissivity of 10^{-3} $\alpha/cm^2/h$ for the semiconductor processing and packaging materials

  - α-counting measurements using gas proportional counters @ ST give ~2×10^{-3} $\alpha/cm^2/h$

⇒ Real-time testing @ LSM allows us to more accurately quantify the α-emission rate for the chip materials:

$$10^{-3} \times (1530/380) = \underline{4\times10^{-3}\ \alpha/cm^2/h}$$

⇒ Confirms the ultra-low alpha-emission level of chip materials within the experimental error margins for the α-counting and lot-to-lot variations

Comparison with accelerated tests and SER simulation

- Neutron SER

✓ Real-time @ ASTEP (this work)	504 FIT/Mbit
✓ Accelerated test @ TRIUMF [1]	665 FIT/Mbit
✓ 3D SER simulation [2]	700 FIT/Mbit

⇒ Values in good agreement (±15%) within the experimental error margins for the different techniques

[1] J.L. Autran et al. IEEE Transactions on Nuclear Science, 2007, Vol. 54, n°4, p. 1002-1009.

[2] P. Roche et al., IEEE Transactions on Nuclear Science, 2003, Vol. 50, N°6, pp. 2046-2054.

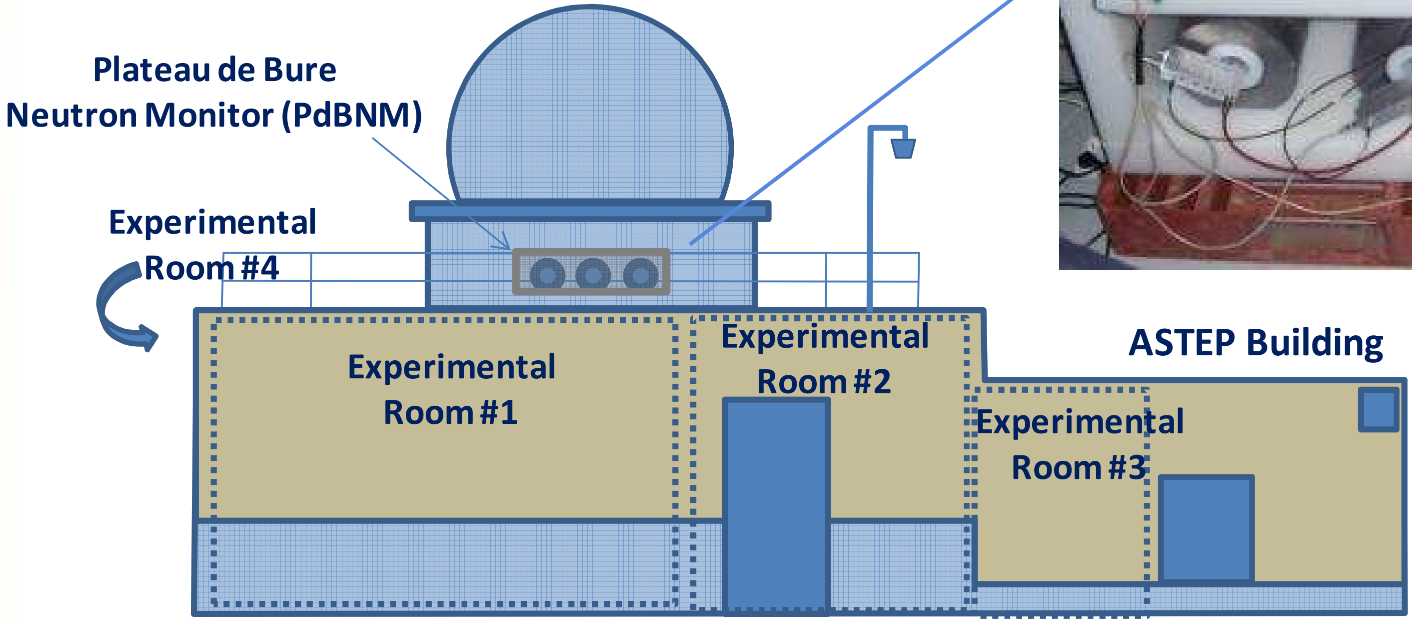
Conclusion

- This work: real-time soft-error rate testing of 3.6 GBits of bulk 130 nm SRAMs in both altitude and underground environments.
- Combination of these two tests allowed us to separate the components of the SER induced by atmospheric neutrons from that caused by on-chip alpha-particle emitters.
- Here, the alpha contribution is found to be three times larger than the neutron contribution at sea-level.
- This work shows the importance of combining real-time, accelerated and α-emission characterizations, to accurately quantify the soft-error rate of a given technology.
- Such a multi-characterization approach should ensure that the different extracted values are consistent with the underlying calculation hypothesis and are within experimental error margins.

Perspectives

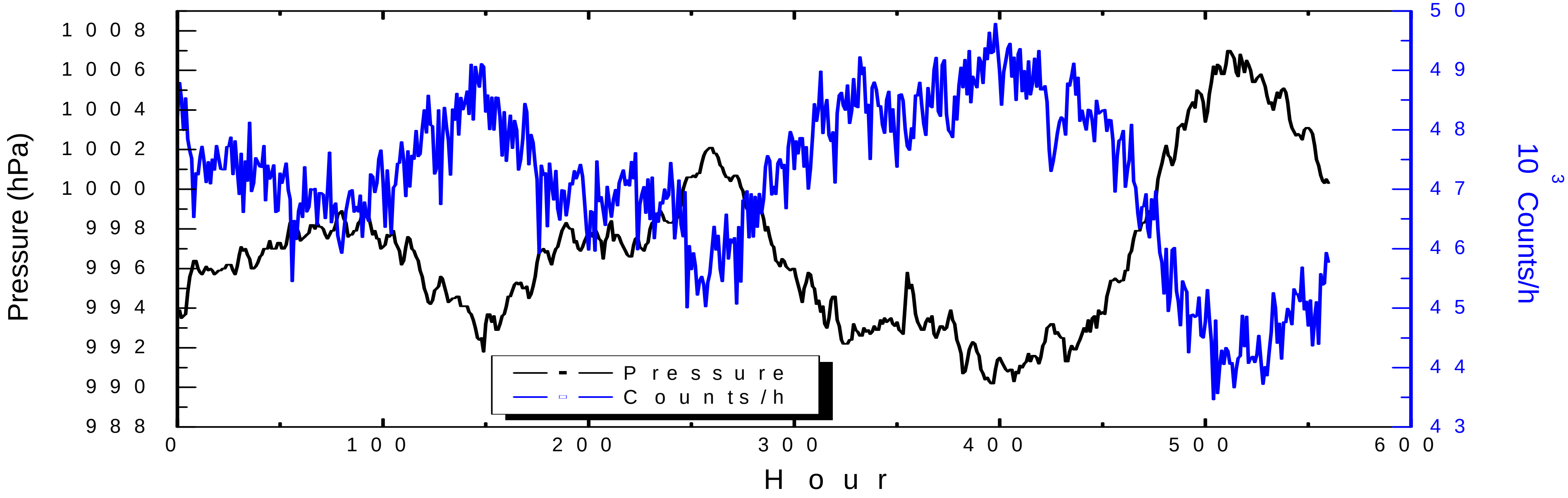
Simultaneous measurements of SER and cosmic-ray neutron flux

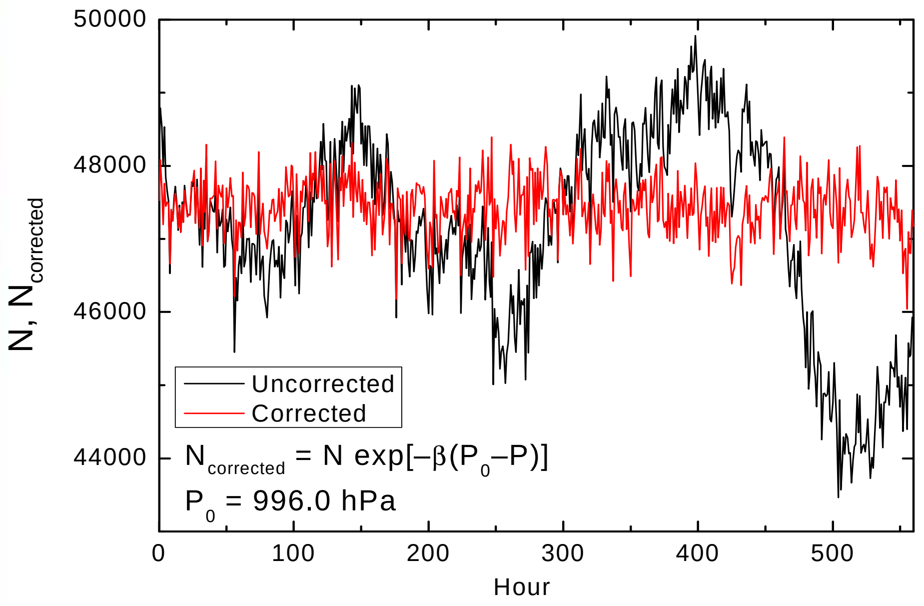
→ IM2NP recently developed a **high performance neutron monitor (super 3-NM64)** to provide **in situ** and **real-time data** of the atmospheric neutron flux impacting SER experiments on the ASTEP Platform.

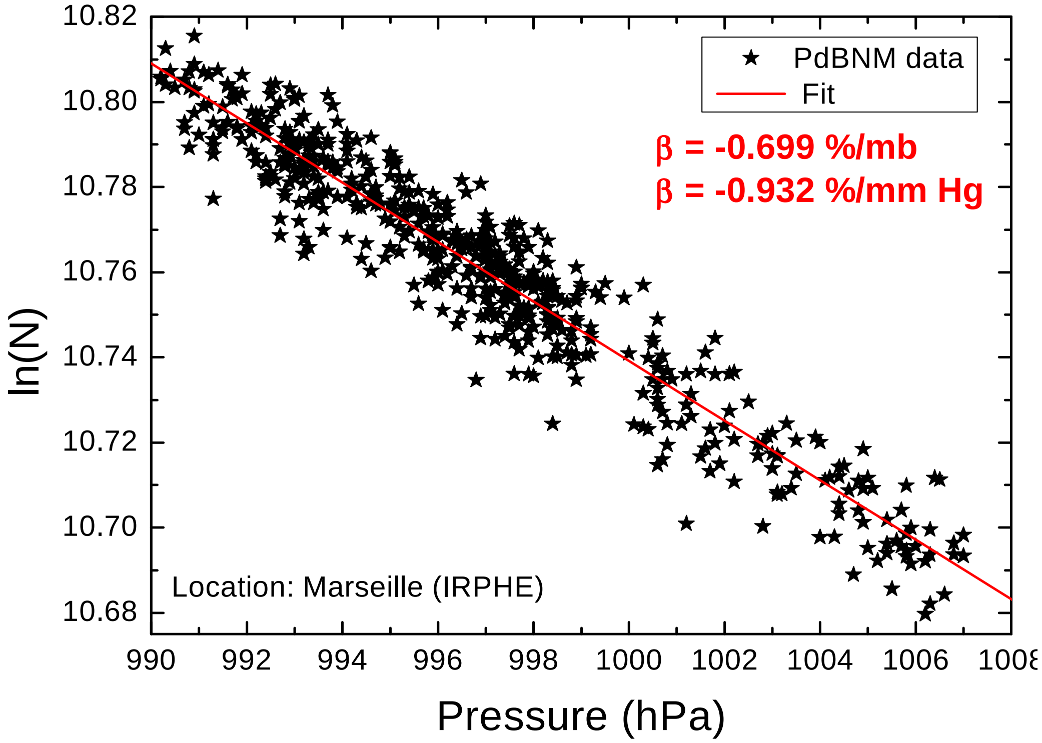


03/07/2007


11/07/2007


Pressure (hPa)
1008
1006
1004
1002
1000
998
996
994
992
990
988
0
100
200
300
400
500
600
Hour
50
49
48
47
46
45
44
43
10^3 Counts/h
Pressure
Counts/h


N, $N_{corrected}$
50000
48000
46000
44000
0
100
200
300
400
500
Hour
Uncorrected
Corrected
$N_{corrected} = N \exp[-\beta(P_0 - P)]$
P_0 = 996.0 hPa


ln(N)
10.82
10.80
10.78
10.76
10.74
10.72
10.70
10.68
990
992
994
996
998
1000
1002
1004
1006
1008
Pressure (hPa)
PdBNM data
Fit
β = -0.699 %/mb
β = -0.932 %/mm Hg
Location: Marseille (IRPHE)

Perspectives

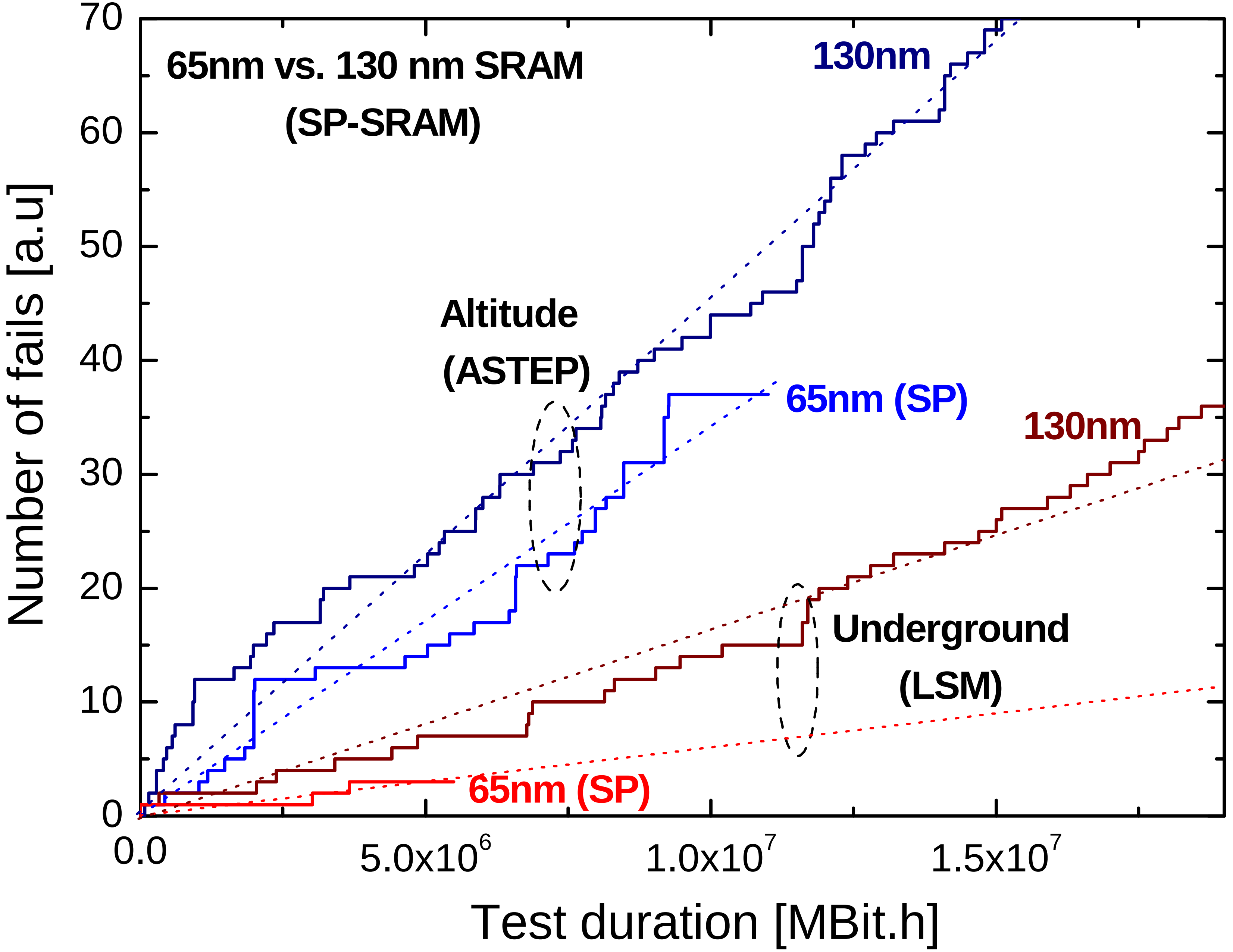
New combined Altitude/Cave experiment** (currently in progress) **on 65nm Bulk SRAMs with 2 identical setups

The 65nm setup at ASTEP

*Experiment started on **January 21, 2008***

The 65nm setup at LSM

*Experiment started on **April 11, 2008***


65nm vs. 130 nm SRAM
(SP-SRAM)
130nm
Altitude
(ASTEP)
65nm (SP)
130nm
Underground
(LSM)
65nm (SP)
Number of fails [a.u]
Test duration [MBit.h]
0
10
20
30
40
50
60
70
0.0
5.0x10^6
1.0x10^7
1.5x10^7

Acknowledgments

CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

IUF

MEDEA+ System Innovation on Silicon

bertin technologies

iram Institut de Radioastronomie Millimétrique

LSM

INSTITUT CARNOT STAR

iRoC TECHNOLOGIES

Contact:

Jean-Luc AUTRAN, IM2NP-CNRS, Marseille, France

jean-luc.autran@im2np.fr ; info@astep.eu

www.astep.eu