Continuous high-altitude measurements of cosmic ray neutrons and SEU/MCU at various locations: correlation and analyses based-on MUSCA SEP^3

G. Hubert, R. Velazco, C. Federico, A. Cheminet, C. Silva-Cardenas, L. V. E. Caldas, F. Pancher, V. Lacoste, F. Palumbo, W. Mansour, L. Artola, F. Pineda and S. Duzellier

***Abstract* – In this paper are described measurements at high-altitude of both radiation environment and effects. These measurements integrate cosmic ray neutrons and SEU/MCU on nano-scales devices. Results obtained at Pic-du-Midi are presented and analyzed. Analyses based-on MUSCA SEP^3 calculations shows a good agreement between experimental data and modeling, thus illustrating the importance of the knowledge of the radiative field for a reliable prediction.**

***Index Terms* - Atmospheric neutrons, Single Event Upset, Multiple Cell Upset, SEU/MCU board, MUSCA SEP^3, Neutron spectrometer.**

I. INTRODUCTION

SINGLE Event Effects (SEE) induced by particles (heavy ions, neutrons, protons,….) present in the space and atmospheric natural environments where electronics components operate are well known for many years. Neutrons and protons can indirectly induce errors by creating secondary ions following a nuclear reaction with the nucleus of the target. The carriers generated by primary or secondary ions are collected by the depletion region resulting in a current pulse. Recent papers [1][2][3][4][5][6][7] have confirmed the SEU sensitivity of nano-scale devices to proton's direct ionization.

Particles issued from primary cosmic radiation (mainly protons) which hit the Earth's atmosphere give rise to a complex field of secondary particles. These particles include neutrons, protons, muons, pions etc.

Electronic parts and systems are exposed to ionizing radiation's fluxes which strongly depend on altitude, latitude, longitude and Sun's activity. The causes of SEE in nano-scale devices exposed to the atmospheric environment are neutrons, protons and α-particles. Semiconductor devices technologies scaling down to sub-90nm induce new problematics such as direct ionizing proton [1][2][3][4][5][6][7] and radial ionization profile effects on SEE [8][9][10]. Thus, terrestrial neutrons and protons induced SEU are one of such key issues that can be a major challenge to future nanometric technologies. Particularly, MCU (Multi-Cell Upset) which are defined as simultaneous errors induced by a single event in more than one memory cell, are particularly investigated. Thus, Soft Error Rate (SER) determination is still a challenge to evaluate the technology sensitivity and to extrapolate the trends for future generations of devices.

Different simulation and experimental approaches are in the literature to estimate the SER induced by terrestrial neutron environment: accelerated testing using alpha, neutron or proton source/beams, real-life testing performed in the natural environments [11][12][13][14][15] and combination of experimental and simulation approaches [16]. An alternative approach consists in using the modeling at device and/or circuit level. Each approach has advantages and drawbacks.

In contrast with accelerated testing which is relatively easy to perform, real-life testing is clearly time consuming, although this strongly depends of the embedded capacity. Real-life tests appear as the unique experimental solution to accurately estimate the SER of the tested devices, ensuring that the test does not introduce artificial results. For example, the beam uniformity/fluctuations, the dosimetry errors, the chip disorientation or the limited representativity of the radiation field characteristics alter results and analyses.

Then, to estimate the SER in atmospheric environment, accelerated testing and simulation approaches do not allow for modeling the complexity and the dynamic of the natural environment. Moreover, real-life tests performed in the natural environment provide an objective feedback about the SER of a considered location. Coupled neutron/SEU measurements

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G. Hubert, A. Cheminet, L. Artola and S. Duzellier are with The French Aerospace Lab (ONERA), Toulouse, France (email: guillaume.hubert@onera.fr, firstname.name@onera.fr).

R. Velazco;, W. Mansour and F. Pancher are with TIMA Laboratory, 38031 Grenoble, France (e-mail: firstname.name@imag.fr).

C. Federico is with the Institute of Advanced Studies (IEAV), Brazil (email: claudiofederico@ieav.cta.br).

C. Silva-Cardenas is with the PUCP (Pontificia Universidad Catolica del Peru), Lima, Peru (email: csilva@pucp.edu.pe).

Linda V. E. Caldas is with the IPEN (Institute for Energetic and Nuclear Research), Brazil (email: lcaldas@ipen.br).

V. Lacoste is with the French Institute for Radiological Protection and Nuclear Safety (IRSN), France (e-mail: Veronique.lacoste@irsn.fr).

F. Palumbo is with the Consejo Nacional de Investigaciones Cientificas (CNEA), Argentina, (e-mail: fefixpalumbo@cnea.gov.ar).

F. Pineda is with the University of Altiplano, Puno, Peru (email: ferpineda@gmail.com)

associated to modeling approach allow performing better analyses. This synergy can also help to develop an innovative methodology to evaluate the operational SEU/MCU risk.

Real-life SEU/MCU measurements are performed since 2008 by ONERA and TIMA. They are done using an experimental platform including 1 Gbit of SRAM built from commercial memories in 90 nm technology. This platform was activated during commercial long-haul flights [11] and has flown as a piggy-back experiment during balloon flights [17]. To complete these investigations, MUSCA SEP^3 calculations were performed and compared with experimental results [11] [17][18]. Although these comparisons showed a satisfactory relevance, they have put in evidence the significant importance of knowing and modeling the considered radiation environment. Furthermore, in 2011, the so-called HERMEIS neutron spectrometer [19][20][21] has been installed by ONERA at Pic-du-Midi (2885 m, Midi-Pyrénées Observatory, OMP). The HERMEIS spectrometer is coupled with semi-conductor detectors (pixel array and Si diodes) and a scintillator detector. The main objectives of these experiments are the characterization of the neutron field dynamics and the investigation of other particle fields such as protons and muons. The SRAM experimental platform complements this high-altitude experimental setup.

In this paper, will be presented a new collaborative TIMA-ONERA scientific thematic named DAARES (Distributed Acquisitions in high-Altitude of Radiation Environment and SEE) which integrates coupled measurements of cosmic ray neutron fluxes/spectra and SEU/MCU occurring in nano-scales devices at different locations. The results obtained at Pic-du-Midi are presented and are completed by data issued from the activation of the test platforms at a higher altitude (3889 m) in the city of Puno (Peru).

II. EXPERIMENTAL PLATFORMS

In Fig. 1 are depicted both the high altitude sites in which are operating the experiments and the experimental platforms: the SRAM-board and the neutron detectors. As mentioned in the introduction, coupled measurements are established thanks to scientific projects.

Firstly, the DAARES project base on the Pic-du-Midi station, located in the French Pyrenees and which includes radiation field characterizations (neutron spectrometer and semi-conductor detectors) and SEE measurement on the SRAM board. Secondly, there are the Puno experiments which are performed within the framework of the HARMLESS (High Altitude Remotely Monitored Laboratory for the Evaluation of the Sensitivity to SEUs) project[1].

Thus, projects provide a very interesting measurement synergy which will be completed by a modeling approach base-on MUSCA SEP3 platform. Next parts are devoted to describe the stations, the SEU/MCU experiment then the neutron spectrometer/detector.

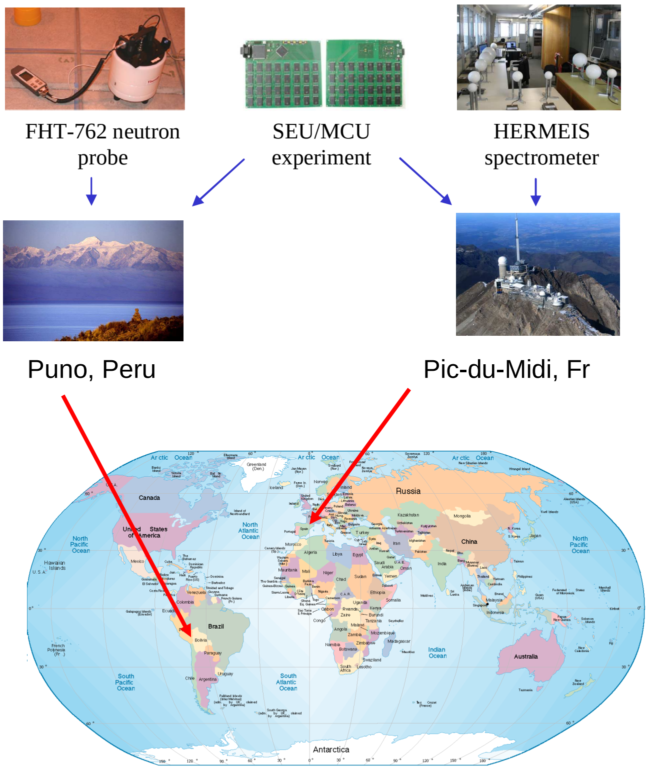

Fig. 1: SEU/MCU and neutron characterization experiments installed at Pic-du-Midi and Puno.

A. *High Altitude Stations*

The neutron radiation field characterization (fluxes and/or spectra) as well as SEU/MCU continuous measurements are simultaneously performed at the top of Pic-du-Midi and in the city of Puno (Peru), the table I summarizes the characteristics of these two sites.

TABLE I. CHARACTERISTICS OF BOTH ALTITUDE LOCATIONS

	Pic-du-Midi, France	**Puno, Peru**
Altitude (m)	2885	3889
Latitude	42°55'N	15°50'S
Longitude	0°08'E	70°01'W
Cut-off rigidity	5.6 GV	5 GV
Neutron flux relative to New York City	8.5	9
Neutron experiment	HERMEIS spectrometer	FHT 762 neutron probe
SEU/MCU experiment	2 Gbit 90nm SRAM	1 Gbit SRAM 130nm (704 Mb) / 90nm (320 Mb)
Start Operating	May 2011	March 2012

B. *SEU/MCU experiment*

The experimental platforms operating at Pic-du-Midi include two SRAM boards (1 Gbit each). The architecture of these boards was detailed in a previous work [11][17][18].

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[1] HARMLESS is a project started in 2011 in the frame of STIC-AmSud The HARMLESS network includes partners from Peru, Brasil, Argentina and France.

The board used for the Puno experiment is based on a similar design but mixing SRAM chips issued from different technologies (130 and 90nm).

C. Neutron detection experiments

The neutron environment is measured at the Pic-du-Midi and the city of Puno using two distinct and complementary systems (see Fig.1).

At the Pic-du-Midi station, the HERMEIS system, made of *Bonner multi-spheres* is used [11]. HERMEIS (Fig. 2) was developed by the IRSN Laboratory of Neutron Metrology and Dosimetry and the Space Environment Department of ONERA (DESP) which has installed this spectrometer to study the dynamics of the energetic distributions, from meV to GeV, of cosmic-ray induced neutrons [20][21]. The Fig 2 presents a picture of the HERMEIS neutron spectrometer.

Fig. 2: HERMEIS neutron spectrometer located in the Pic-du-Midi station (altitude, latitude and longitude are respectively equal to 2.885 km, 42°55'N and 0°08'E).

The HERMEIS neutron spectrometer consists fo 10 homogeneous polyethylene (PE) spheres with increasing diameters (3", 3.5", 4", 4.5", 5", 6", 7", 8", 10" and 12"). The high pressure (10 atm.) ^{3}He spherical proportional counter (2") placed in the center of the spheres allows high detection efficiency. Additionally, the spectrometer includes two PE spheres with inner tungsten and lead shells (8" and 9", respectively) in order to increase the response. The counts given by each sphere are automatically stored every five minutes with the mean meteorological conditions. Then, in previous works, the fluency responses were calculated and the method allows for deducing the spectrum from detection levels was developed.

The neutron measurements performed at Puno were made with a *Thermo Scientific Monitor* composed by one ^{3}He proportional probe inserted inside a cylinder (tungsten and Polyethylene layers). Layers are specified to obtain the response for thermal neutrons up to 5 GeV [22]. This equipment allows for evaluating the dynamics of the neutron flux levels but no the energetic distributions.

The calibration of HERMEIS and the neutron detector were performed at CERF (CERN-EU high Energy Reference Field, [23]) in order to ensure an appropriate response for the high energy neutron field.

III. SEU/MCU MODELING AND GLOBAL METHODOLOGY

The SEE prediction methodologies presented here aim at proposing suitable approaches for modern electronics. The RPP (Rectangular Parallelepiped) concept is largely used for micro-scales technological nodes and relies on the assumption that the deposited charge within a RPP volume provides a good description of the ion induced SEE mechanism.

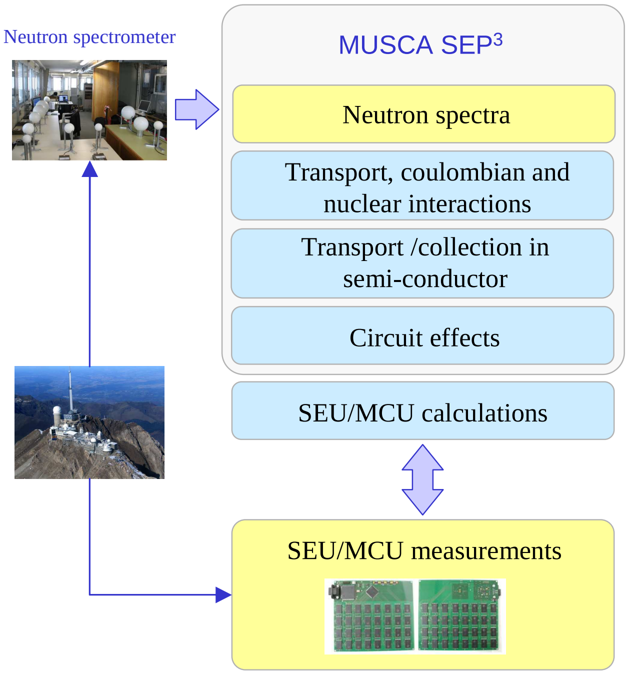

Fig. 3: Global methodology applied in this work.

Nowadays, device sensitive structures can no longer be represented in such a simplistic way because of their complex geometry, small dimensions and close proximity with other adjacent sensitive zones. Moreover, the technological integration led to modified collection mechanisms.

New methodologies based on multi-level physical approaches were proposed as a new paradigm [2][24][25][26][27][28][29][30][31][32][33][34].

Among these methodologies, MUSCA SEP^3 firstly presented in 2009 [2], consists in modeling the whole device within its local and global environments, and the detailed characteristics of the radiation field environment (nature, direction and spectrum). Results presented in [2][6][35][36] have shown that each physical level is critical for SEE risk calculation including the environment description.

This work provides the opportunity to simultaneously measure the neutron environment and the SEU/MCU response of nano-scales devices (see Fig. 3). The radiation field static and dynamic characteristics are monitored with a neutron spectrometer while the 90nm technological model has been developed and validated with technological analysis and SEU/MCU ground tests [17]. The 130nm topology has been deduced from a shrink of the 90nm based-on ITRS roadmap [37].

An interesting consequence of these experiments in the SEE modeling field is that the technological and SEE occurrence models can be optimized thanks to neutron and SEU/MCU measurements coupled with MUSCA SEP^3 analyses. Thus, models can be used for operational calculations considering complex profiles.

IV. RESULTS AND ANALYSES

The Fig 4 proposes a summary of measurements (integrated fail number) performed in the Pic-du-Midi station and in Puno for both tested technologies. In the next, performed analyses and cross-comparison will be presented.

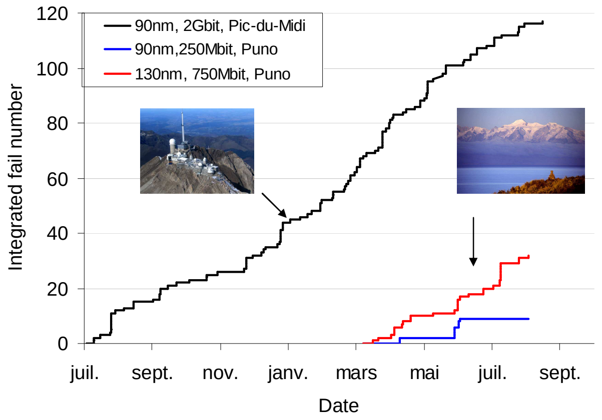

Fig. 4: SEU measurements in the Pic-du-Midi station and in Puno between july 2011 and August 2012.

Data acquisitions in the Pic-du-Midi were started in May 2011 and they allowed for obtaining a significant fail number (> 100 SEU). Moreover, measurements performed in Puno are more recent (March 2012) and the fail number, although significant for the 130nm devices, induced several problems for analysis.

Next parts are devoted to present results and analyses and to propose a cross-comparison of the data.

A. Results obtained at Pic-du-Midi

The SEU/MCU platform and the neutron spectrometer are operational respectively since July and May 2011.

Typically, SER (Single Event Rate) is measured in terms of FIT (failure in Time), 1 FIT being a single failure in 10^9 device hours. A good practice consists in specifying the SER in FIT/Mbit. Then, in Fig 5 are presented the SER dynamics observed in the Pic-du-Midi and results allow for distinguishing the SEU and MCU events. SER levels are consistent with previous works [12].

In Fig. 6 are presented results analyzed from raw spectrometer measurements performed between May 2011 and August 2012. It is necessary to distinguish two periods resulting from the snow accumulation on the roof of the experimental room during the winter period (November 2011 – March 2012) when the neutron spectrum is significantly attenuated.

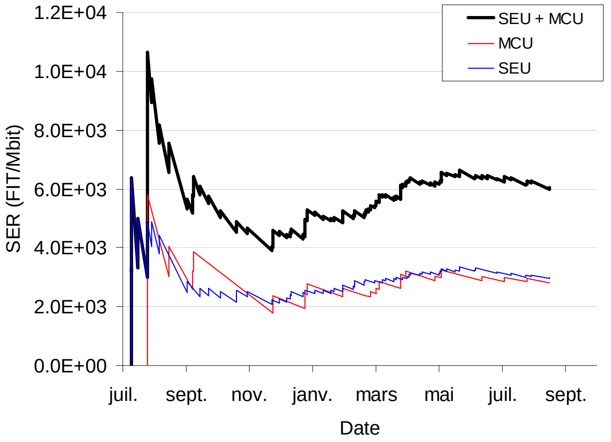

Fig. 5: Measured SER in FIT/Mbit in Pic-du-Midi, measurements performed between May 2011 and August 2012.

The spectrum presented in Fig. 6 is issued from count rate data processing and results in an average spectrum. Results are completed with QARM [38] calculations.

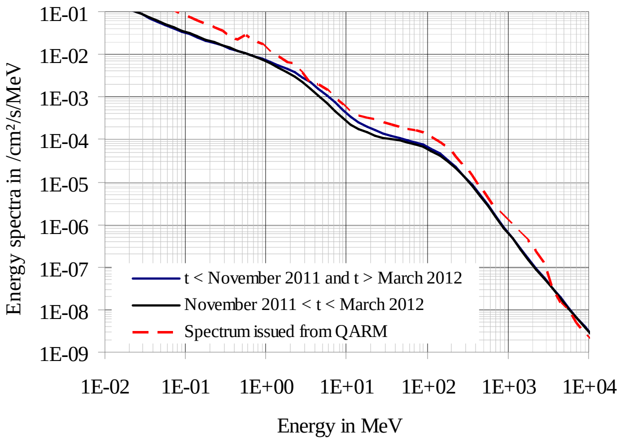

Fig. 6: Neutron energy spectra issued from QARM and measured by HERMEIS at Pic-du-Midi between May 2011 and April 2012.

The QARM results are obtained by considering the single position radiations service, the main used parameters being respectively the altitude (2.885 km), the latitude (42°55'N) and the longitude (0°08'E). In addition, input data consider the 2012 march 01 (median date) and input conditions consider GCR for incident spectrum and a Kp value equal to 2. Spectrum resulting from QARM calculation corresponds to an average value and do not integrate the spectrum dynamic.

Nevertheless, the HERMEIS spectrometer is able to monitor the neutron field with a dynamic in the hour scale. These hourly spectra are used to model the neutron field in MUSCA SEP^3.

Figs. 7 and 8 present the total and the SEU/MCU events measured comparing them with the predicted rates. The Fig 7 presents some results: as mentioned the integrated fail number is deduced from measurement and calculations, but, calculations are performed considering spectrum issued respectively from the HERMEIS spectrometer (located close to the SEE experiment) and from the QARM calculations.

However, the Fig. 7 clearly puts in evidence the impact induced by the radiation field knowledge. Indeed, results issued form QARM overestimate (factor ~ 2.2) the experimental SER while calculations integrating HERMEIS spectra are particularly relevant.

It is important to nuance the overestimate level, indeed, the spectrum deduced from QARM do not take into account the induced by the mountain and structures (building). This can not justify the overestimate factor, but it can reduce its real level.

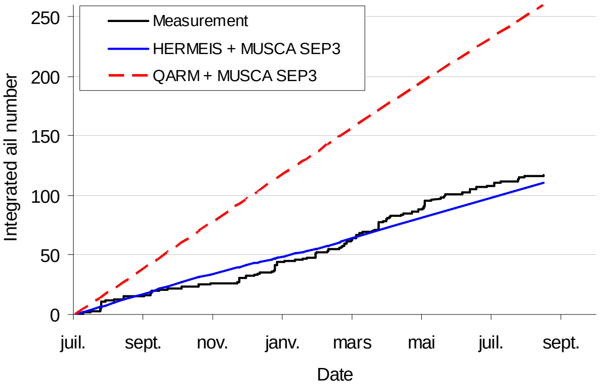

Fig. 7: Measured and calculated total events (MUSCA SEP3 using the HERMEIS spectra and QARM as inputs).

The Fig 8 is particularly interesting because it allows for evaluating the modeling relevance as a function of event type (SEU or MCU). The comparison between the SEU and MCU modeling and measurements are very satisfactory. The MUSCA SEP3 approach based-on multi-level descriptions, i.e., the radiation field thanks to neutron spectrometer and the technology thanks SEE ground tests and analyses, is thus validated.

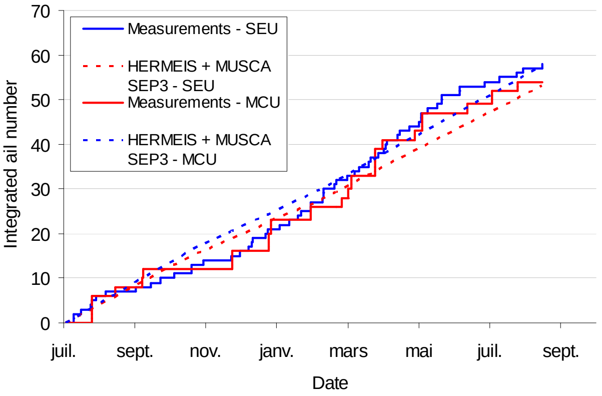

Fig. 8: Measured and calculated SEU/MCU events including the SEU and MCU events (MUSCA SEP3 using the HERMEIS spectra as inputs).

MCU results and modeling relevance can be affined by performing multiplicity analyses. Measurements indicate a high proportion of MCU with multiplicity up to six (6 bit-flips due to a single particle were detected at the same instant in March 2012). Table II presents predicted and measured event occurrences separating single and multiple events and specifying the event multiplicity.

TABLE II. EVENT MULTIPLICITY ISSUED FROM REAL-LIFE EXPERIMENTS AND FROM MUSCA SEP^3 CALCULATIONS

Event type (SEU/MCU)	Measurements May 2011 → March 2011	Calculated event number (average value)
Total	83 SEU	73.7 SEU
SEU	41 SEU	38.3 SEU
MCU	42 SEU	35.4 SEU
2 bit	7 events → 50 %	54 %
3 bit	3 events → 21 %	22 %
4 bit	2 events → 14 %	13.8 %
5 bit	1 event → 7 %	6 %
6 bit	1 event → 7 %	3.5 %

Predicted MCU occurrences are consistent with measurements. However, the experimental statistics is insufficient for MCU of high multiplicity and can explain the difference (factor 2 underestimation for a multiplicity of 6). Furthermore, the 6-event may correspond to a rare failure mode such as SEUs in the peripheral part of the memory array (registers, address decoder …). Continuous monitoring is still on-going and will allow improving these analyses.

Analyses based-on the spectrum knowledge and MUSCA SEP3 allow for investigating the neutron energy range contribution to SEU and MCU.

B. *Results obtained in Puno*

Experiments in Puno have started in March 2012. Preliminary data allow for investigating the neutron flux at two positions: outdoors and indoors (plastic and glass roof) where the SRAM test platform is operating.

Table III summarizes the obtained fluxes and allows for estimating the accelerator factor with respect to the NYC reference.

TABLE III. NEUTRON FLUXES MEASURED IN PUNO VS. NYC REFERENCE

Location	Neutron Flux (n/cm2/s)	Relative to New York City
New York City, estimated for the same period and conditions, using the EXPACS code [18]	0.013	1
Puno - external	0.117 ± 0.011	9
Puno - internal	0.098 ± 0.011	7.5

The SEU/MCU measurement board, including SRAM parts issued from 130 nm and 90 nm technologies, is operational since March 2012. The Fig. 9 presents respectively the measurements and the calculations issued from MUSCA SEP3, which take into account the neutron flux relative to New York City (see table I) and the embedded capacities (respectively 2 Gbit and 704 Mbit).

Integrated fail number are relevant for the 130nm technology, but insufficient for the 90nm technology (9 SEU with a majority of MCU).

Calculations issued from MUSCA SEP3 are relevant for the 130nm. To model the neutron environment, we have considered respectively the flux level issued from the neutron detector measurements and the neutron spectrum shape deduced from HERMEIS measurements and analysis. Results presented in Fig. 9 and Fig. 10 show a good agreement, particularly when SEU and MCU events are discriminated.

Although results are correct for the 90nm technology (Fig. 9), observed fail event are not sufficient to perform a relevant comparison. However, orders of magnitude are consistent between the Pic-du-Midi and Puno data, and this reinforces our approach.

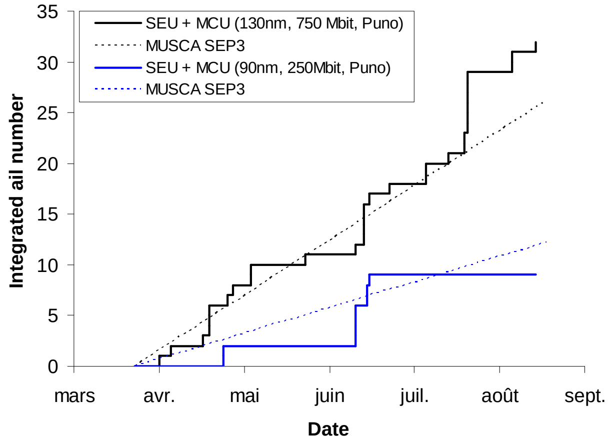

Fig. 9. Measured and calculated SEU/MCU events issued from 130nm and 90nm devices located in Puno.

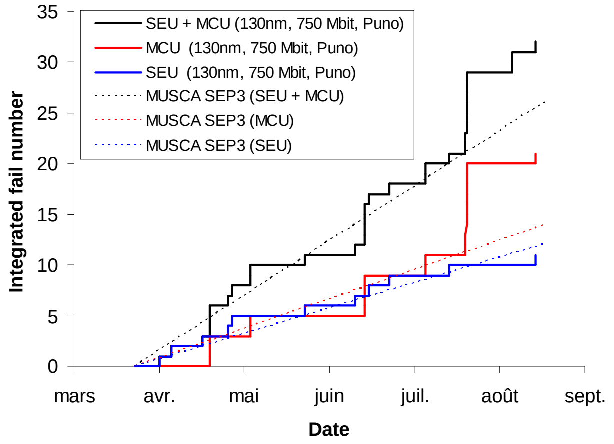

Fig. 10. Measured and calculated SEU/MCU events including the SEU and MCU events, 130nm devices located in Puno.

C. *Synthesis of results and cross-comparison*

To synthesize the results, Fig 11 and 12 present the calculated and the measured SER (in terms of FIT/Mbit) obtained respectively in the Pic-du-Midi and Puno but also for both devices.

These two figures illustrate the excellence of data issued from Pic-du-Midi, especially for the SEU and MCU analyses. Globally, the Fig 11 shows an acceptable agreement when all events are considered (SEU and MCU).

Moreover, cross-comparisons show that 130nm devices are more sensitive to radiation effects than 90nm devices (Puno results), proving also that the radiation field at Puno is slightly more important than the one at Pic-du-Midi. This is conform to Neutron fluxes relative to New York City and issued from calculations.

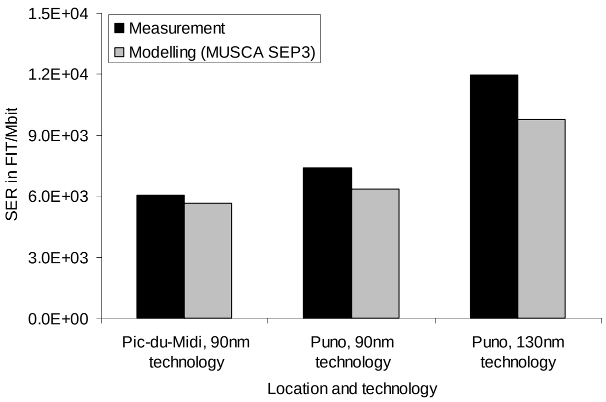

Fig. 11: Comparison between the measured and calculated total SER in FIT/Mbit for the 90nm and the 130nm devices and for the both high-altitude locations (Pic-du-Midi and Puno).

Results presented in the Fig 12 allow for identifying some anomalies, among which the measured and calculated MCU SER. As previously mentioned, results obtained for the 90nm devices are statistically insufficient, but results will refine it over time exposition.

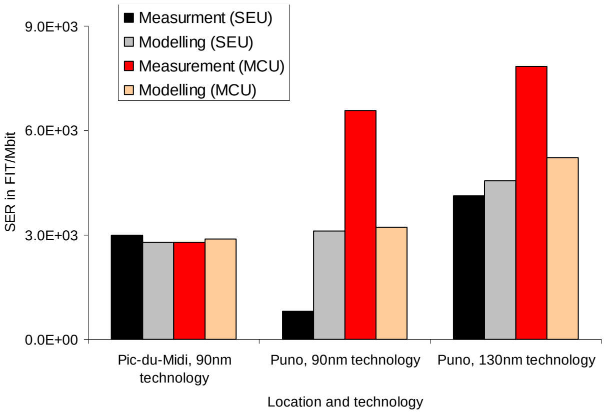

Fig. 12: Comparison between the measured and calculated SER (distinguishing the SEU and MCU events) for the 90nm and the 130nm devices and for the both high-altitude locations (Pic-du-Midi and Puno).

The results obtained in Puno for 130 nm SRAMs are very interesting, particularly the difference observed for MCU events. Indeed, a high multiplicity error certainly due to the impact of a single particle, 6 SEU) was detected on July 22 and had a significant impact on analyses.

V. CONCLUSION AND PERSPECTIVES

This work presents test platforms and experimental data issued from simultaneous and continuous measurements coupling SEU/MCU and neutron dynamics in high-altitude. Results obtained at the sites where the platforms were activated – Pic-du-Midi station and Puno (Peru) were presented in details. These coupled measurements are integrated in the framework of in two international projects

(HARMLESS and DAARES).

A very good agreement is observed between measurements performed at the two considered sites and calculations issued from MUSCA SEP3. Compared to previous work [11][17][18], the relevance is improved and reinforces the fact that the radiation field knowledge is a key issue for predictive approaches on nano-scales devices. In addition, results demonstrate the relevance of modeling for the SEU and MCU analyses.

An important aspect of this work is the end-user approach. Indeed, the SRAM boards are based-on commercial devices which details are initially unknown. Thus, few SEE ground tests and technological analyses are sufficient to develop relevant models used in MUSCA SEP3.

As a conclusion, high-altitude stations, i.e. the Pic-du-Midi and Puno, dedicated to on-line SEE and neutron measurements allow for proposing a synergy between SEE measurements, radiation field characterizations and SEE modeling. This synergy constitutes a relevant way to evaluate and to investigate the SEE trends for nano-scales devices, and furthermore it will allow for anticipating the SEE trends.

An important perspective consists in extending our approach according to two complementary ways: on the one hand to explore other locations (high altitude or magnetic singularity as SAA and polar environment), and on the other hand to develop new SRAM boards embedding more integrated devices. New measurements began in 2012 in the Aiguille-du-Midi (French Alpes) and some SEU and MCU were occurred. Moreover, new SRAM boards, built from SRAM devices in 65 nm are in progress and will be operational at the end of 2012.

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