# Real-Time Characterization of Neutron-induced SEUs in Fusion Experiment at WEST Tokamak during D-D Plasma Operation

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**35 words abstract:** We conducted a real-time SER characterization of CMOS bulk 65nm SRAMs subjected to fusion neutrons during deuterium-deuterium plasma operation at WEST tokamak. Neutron spectrometry and numerical simulation have been also performed to analyze experimental results.

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## I. INTRODUCTION

Magnetic and inertial confinement fusion devices studied to develop future carbon-free source of energy are based on deuterium-tritium (D-T) nuclear fusion reactions [1]. Deuterium-deuterium (D-D) nuclear fusion reactions are also used to study their operation before introducing tritium fuel. Both D-D and D-T operations produce a high flux of energetic neutrons, creating a residual neutron field outside the reaction chamber. All future fusion devices will contain a large amount of electronics. Most of it will be installed outside the radiation field. The limited amount of electronics which will stay close to the reaction chamber will be exposed to nuclear radiation and negatively affected by this environment condition. This work, which is part of a study conducted by ITER on the effects on electronics of the radiation environment in certain areas of the ITER tokamak building, is a first tentative to characterize neutron induced SEUs (Single Event Upsets) in SRAM memories exposed to the radiation field in the vicinity of a nuclear fusion reaction. The experiment was conducted at WEST tokamak during a test campaign under D-D plasma operation. WEST (acronym derived from W – tungsten – Environment in Steady-state Tokamak) is an experimental nuclear fusion device operated by the IRFM (Institute for Magnetic Fusion Research) institute from CEA (French Alternative Energies and Atomic Energy Commission) [2]. Its 50 $m^3$ toroidal vacuum chamber is equipped with superconducting toroidal magnets (3.7 T) which allow steady-state plasma operation. The previous configuration of the machine, named Tore Supra, was operated between 1988 and 2011. The upgrade to WEST in 2013-2016 transformed the tokamak from a limiter to a divertor configuration [3], a key-transformation to test and validate the divertor architecture and operation for the international experimental fusion device ITER currently in construction in south of France [4]. Our experiment is based on the use of a well-known and proven real-time soft-error rate (RTSER) testbench with CMOS bulk 65nm SRAMs, previously operating in altitude on the ASTEP platform, underground at the Laboratoire Souterrain de Modane (LSM) and at sea level in Marseille [5-7]. These RTSER measurements have combined with a real-time neutron spectrometry to simultaneously characterize the neutron flux and energy distribution during machine shots. In the following, the experiment is detailed, measurements are reported and also discussed with respect to additional numerical simulations, physics of plasma and machine operation.

## II. EXPERIMENTAL SETUP AND CONFIGURATION

The experimental test equipment embeds 380 memory circuits (3,226 Gbit) manufactured by STMicroelectronics in CMOS 65 with a fabrication processes based on a BPSG-free BEOL that eliminates the major source of $^{10}B$ in the circuits and drastically reduces the possible interaction between $^{10}B$ and very low (thermal) energy neutrons. The test chips contain 8.5 Mbit of single-port SRAM (without deep-Nwell) with a bit cell area of 0.525 $\mu m^2$. The technology core voltage is 1.2 V. The circuits have been assembled on printed boards and tested several years in altitude, underground and at sea level using a dedicated equipment, fully compliant with all the specifications of the JEDEC standard JESD89. Details about the setup and previous RTSER experiments can be found in Ref. [7]. Just before this experiment at WEST facility, the equipment has been continuously working since March 2015 in Marseille, showing a consolidated and stable soft-error rate equal to 226 FIT/Mbit due to atmospheric neutrons (NYC conditions) and 1148 FIT/Mbit due to internal chip radioactivity.

The neutron flux and energy characterization during reactor shots was performed using a commercial DIAMON neutron spectrometer. DIAMON (Direction-aware Isotropic and Active neutron MONitor) is a novel detection system based on a polyhedral moderator body made of high-density polyethylene (HDPE) which hosts a matrix of semiconductor-based thermal neutron sensors [8]. The instrument was carefully calibrated at the neutron calibration facility of Politecnico di Milano using a $^{241}Am$-Be source.

During the experiment, the test equipment has been placed in the facility hall of the WEST tokamak, successively at three positions ($P_1$ = 7 m, $P_2$ = 6 m and $P_3$ = 5.2 m from the center of the machine). In this publication, after discussing the SEEs of natural origin measured in these 3 positions, we focus our analysis on the SEEs induced by the plasma neutrons at the position $P_3$, in which the test equipment has received the highest neutron fluence. The SRAM circuits with their upper face oriented towards the center of the machine, were placed in the equatorial plane of the tokamak tanks to a mechanical support. The computer controlling the experiment was placed on the machine basement, shielded from neutrons under a borated concrete slab (thickness 80 cm). Figure 1 shows different views and schematics of the implementation of the experiment in the WEST hall.

## III. EXPERIMENTAL RESULTS DURING WEST D-D OPERATION

### A. *WEST reactor operation and fusion neutrons*

The WEST C5 SEE measurement campaign started on December 8, 2020 and finished on January 27, 2021 (50 days). It consisted in a series of several hundreds of machine shots (ranging from 1 to 18s in duration, see Figure 2 left) during which plasma conditions (with different characteristics: temperature, density) are met for D-D fusion following the main reactions: D + D $\rightarrow$ $^3$He(0.82 MeV) + n(2.45 MeV) (50%) and D + D $\rightarrow$ T(1.01 MeV) + p(3.02 MeV) (50%). Once D-D fusion is correctly initiated at the beginning of a machine shot, the concentration of tritium (produced in the second D-D reaction) gradually increases in the plasma and renders possible D-T fusion: D + T $\rightarrow$ $^4$He(3.52 MeV) + n(14.07 MeV). However, this last reaction should remain marginal compared to the first two, given the dilution of tritium in the plasma essentially composed of deuterium.

Total neutron production during the shots was measured using a network of fission chamber distributed around the tokamak in the WEST hall (Figure 2 right). Neutrons transported outside the machine produce, by absorption, reflection and attenuation mechanisms, a complex radiation field outside the machine dominated by thermal and low energy neutrons. Figure 3 shows a typical neutron energy distribution measured during a machine shot by the DIAMON spectrometer. The "high" energy peak is around 1.6 MeV: it corresponds to 2.45 MeV plasma neutrons transported outside the tokamak. Note that a significant neutron flux is measured up to 10 MeV, corresponding to initial 14 MeV neutrons, also transported and moderated through the tokamak structure.

### B. *SEU measurements*

For the whole duration of the C5 campaign, 54 SEU events for a total of 66 bit flips has been measured: 5 events (4 single bit upsets – SBU – and 1 multiple cell upset – MCU – of multiplicity 3) have been recorded during the machine shutdown (nights, week-ends) or machine stops (> 30 minutes) between consecutive machine shots and 49 events (42 SBU, 4 MCU(2) and 3 MCU(3)) have been detected in perfect coincidence with a shot (taking into account the duration of the reading/verification cycle of the test equipment). For these 49 events induced by the machine operation, 41 on 49 have been observed after January 17, 2020, i.e. in the last ten days of the C5 campaign during which steady-state plasma conditions and a maximal efficiency have been obtained in terms of D-D fusion. Figure 4 shows the occurrence of all bit flips as a function of time for the whole duration of the C5 campaign.

## IV. RESULTS ANALYSIS AND DISCUSSION

The events observed during the whole campaign (50 days = 1200 h) are the result of two radiation sources working in parallel: the natural radiation background and the artificial machine environment. For the first one, the observations perfectly agree with the neutron (226 FIT/Mbit) and alpha SER (1148 FIT/Mbit) previously measured. Indeed, the number of expected events for 1200 h is $226 \times 3226 \times (1200/10^9) = 0.87 \approx 1$ for atmospheric neutrons and $1148 \times 3226 \times (1200/10^9) = 4.44 \approx 4$ for chip internal radioactivity, that corresponds to a total of 5 events. We effectively observed 4 SBU and 1 MCU not correlated with a machine shot. For the artificial machine environment, the analysis of our results has been performed for steady-state conditions of the machine, i.e. for the 41 SEU events correlated to machine shots and observed in the ten last days of the C5 campaign, at position P3 = 5.2 m from the centre of the machine. They correspond to 36 SBU, 3 MCU(2) and 2 MCU(3) representing a total of 48 bit flips. For these SEU events, an accurate neutron fluence has been determined combining DIAMON and fission chamber measurements. Figure 5 shows the cumulated bit flip distributions for these events as a function of the cumulated neutron fluence (the total cumulated duration for the corresponding shots is 1252 s). This distribution exhibits a very regular slope after $7\times10^6$ n/cm$^2$ when reproducible steady-state conditions have been reached. From this slope, it results a bit flip SER = $4.28\times10^7$ FIT/Mbit and an acceleration factor of the WEST radiation field with respect to the natural background of about AF $\approx$ 190,000. To understand the quite surprising occurrence of MCU events in such a low energy neutron irradiation, we performed Geant4 and TIARA numerical simulations to compute: i) a complete set of interaction databases of monoenergetic neutrons with a natural silicon target (1 cm$^2$ $\times$ 20 μm) for energies ranging from 1 MeV to 14 MeV by step of 1 MeV and ii) a corresponding set of SEE event databases for the 65nm SRAM subjected to 1 to 14 MeV neutrons. All details and extensive results of these simulations will be given in the final paper for both nuclear and circuit-response databases.

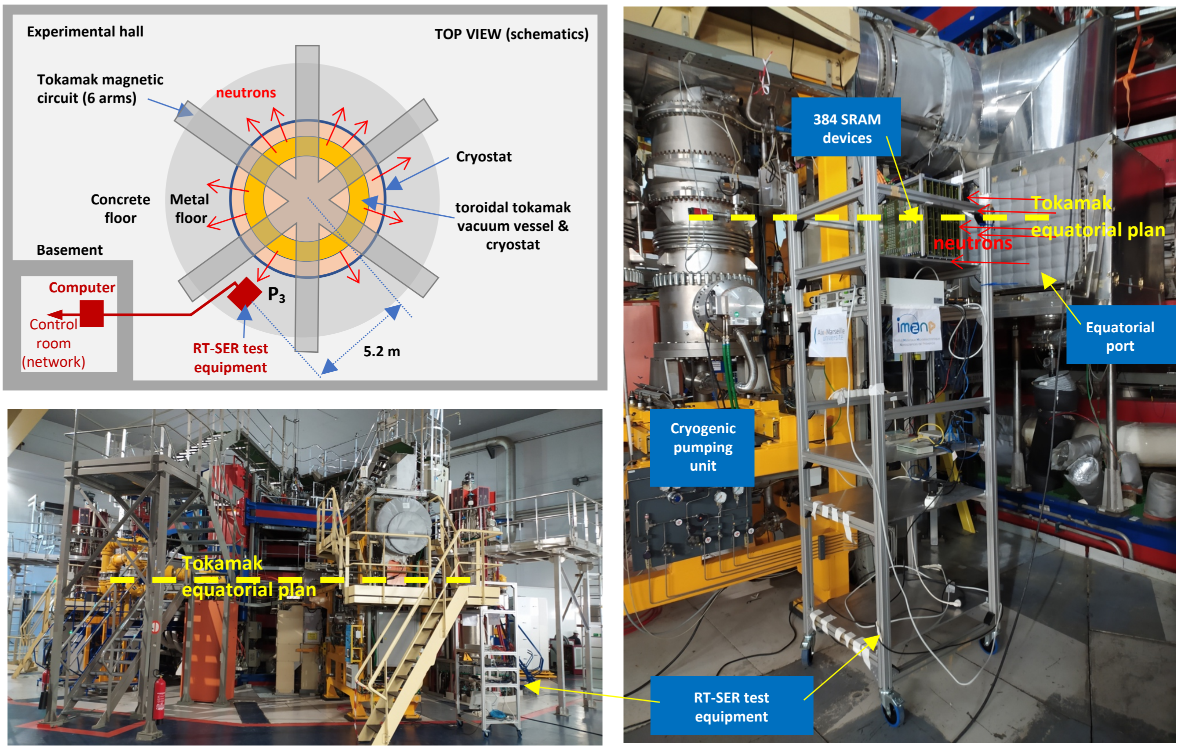


Figure 1. Global and detailed views of the RT-SER test equipment installed in the vicinity of the tokamak in the WEST experimental hall. The schematics represents a top view of the installation showing the location of the test bench, at 5.2 m from the center of the tokamak.

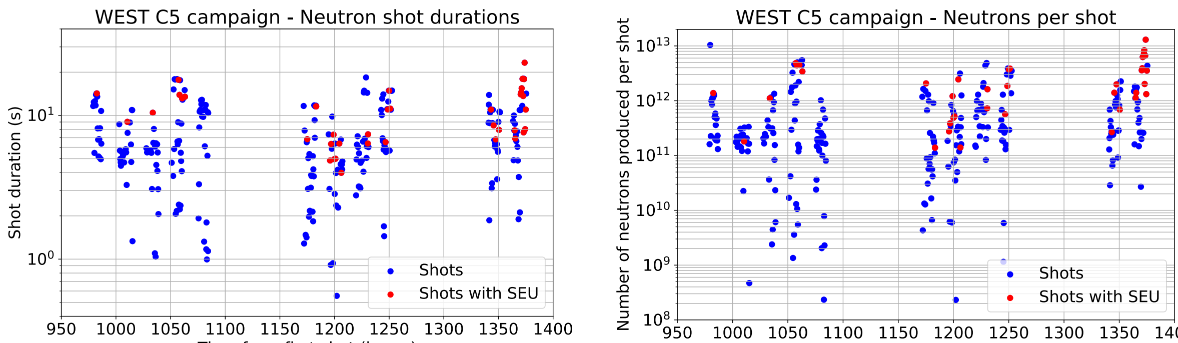


Figure 2. Distribution of shot duration (left) and of total number of neutrons produced per shot (right) as a function of time. Shots corresponding to $P_3$ position start after 1,150 h; shots in coincidence with SEU detection are in red.

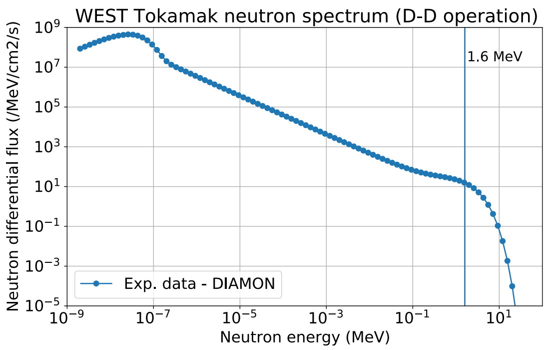


Figure 3. Differential neutron spectrum measured by the DIAMON spectrometer during shot #56359 at the level of the rack of the SRAM circuits.

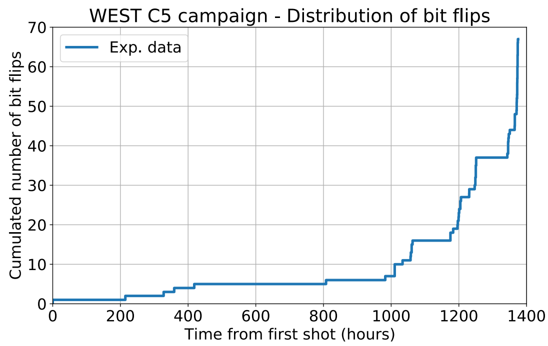


Figure 4. Distribution of bit flips as a function of time for the whole WEST C5 campaign.

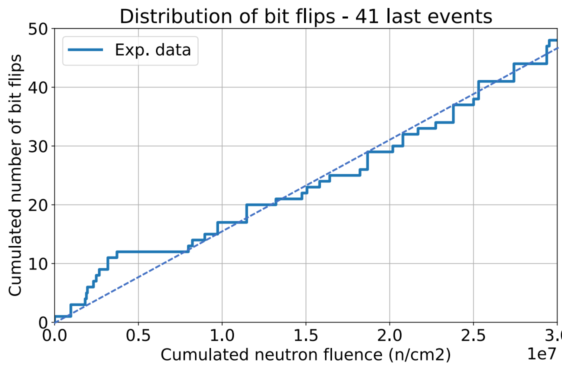


Figure 5. Distribution of bit flips as a function of the cumulated neutron fluence after January 18, 2021 and until the end of the WEST C5 campaign (test equipment at position P1 = 5,20 m).

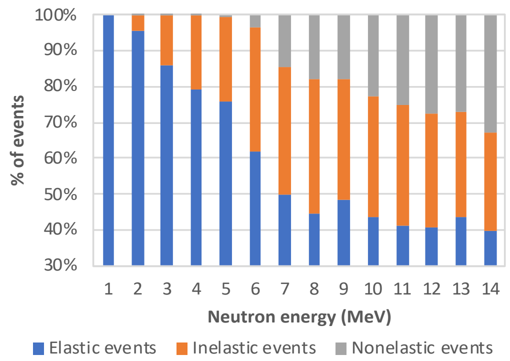


Figure 6. Distribution of elastic, inelastic and nonelastic events in monoenergetic neutron-silicon interactions resulting from Geant4 (version 4.10.07) simulations.

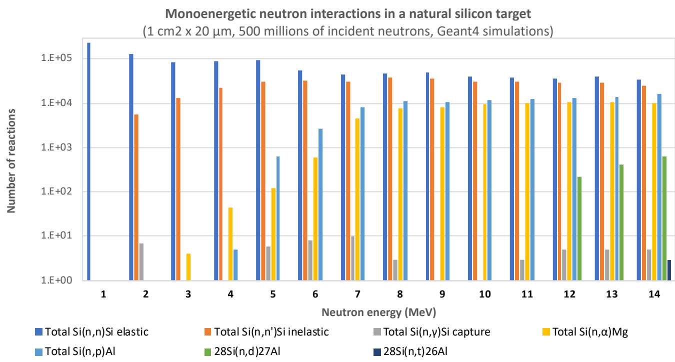


Figure 7. Number of n-Si interaction event per type of reactions in a natural silicon target (1 $cm^2 \times 20$ µm) subjected to $5{\times}10^8$ millions of monoenergetic neutrons with energy ranging from 1 to 14 MeV.

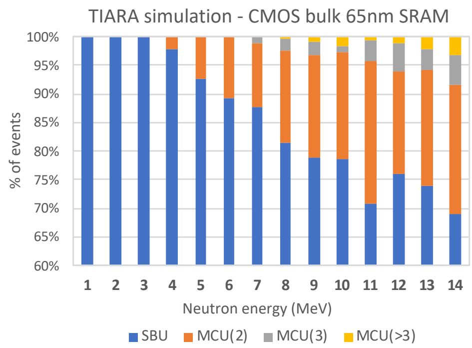


Figure 8. Distribution of SBU and MCU events obtained by TIARA simulation for the 65nm SRAM subjected to neutrons from 1 to 14 MeV.

Figures 6 and 7 respectively show the distribution of elastic, inelastic and nonelastic events and the number of events per reaction type resulting from the interaction of $5{\times}10^8$ millions of monoenergetic neutrons with a natural silicon target of 1 $cm^2 \times 20$ µm. Below 4-5 MeV, quasi only elastic and nonelastic interactions occur, producing Si recoils with short ranges in the target that are not able to induce MCUs in the simulated SRAM (this point will be detailed and discussed in the final paper). Consequently, our results suggest that the observed MCUs may be due to residual number of neutrons effectively detected above 5 MeV (Figure 3). This hypothesis is supported by TIARA Monte Carlo simulations performed on a matrix of 15×15 SRAM circuit (Figure 8) showing that MCU events effectively occur in significant proportion only for neutrons above ≈5 MeV. Considering now the upper part (E >1 MeV) of the WEST spectrum of Figure 3 as an input for Geant4 and TIARA simulations, additional simulation results (Figure 9) seem to confirm this hypothesis, suggesting the non-negligible impact on electronics of D-T neutrons in D-D fusion experiment despite of their relative low flux. Additional results including the analysis of SER values will be included in the extended paper, as well as projections and discussion for other fusion machine environments (JET, ITER).

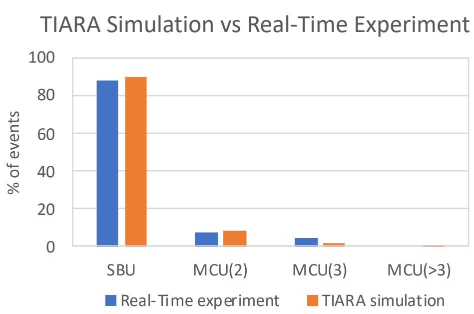


Figure 9. TIARA simulation considering the upper part (E > 1 MeV) of the WEST spectrum of Figure 3 as the input neutron source and comparison with the real-time experiment presented in this paper.

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