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# Electron-Induced Upsets and Stuck Bits in SDRAMs in the Jovian environment

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**Abstract**

This study investigates the response of SDRAMs to electron irradiation. Stuck bits, SEUs and memory cell degradation is presented in this paper, in a memory that will be part of the ESA JUICE mission.

**Session preference: B: Radiation Effects in Devices and Integrated Circuits**
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## I. Introduction

THERE has been a rise of interest regarding the radiation effects of electrons on components. Much of this interest has been directed towards and motivated by space missions in the Jovian environment such as the European Space Agencys (ESA) JUICE (JUpiter ICy moons Explorer) mission.

This study is on the radiation effects of electron irradiation in a synchronous dynamic random access memory (SDRAM) that will be used aboard JUICE.

One of the main points of interest of this work was to investigate the possibility of stuck bits being induced by electrons. This has, to the best of the authors knowledge, not previously been observed or reported. Previous studies of single event effects (SEE) caused by electron irradiation have been reported in [1]–[4], where single event upsets (SEU) and single event latch-up (SEL) were investigated.

Stuck bits are in this experimental work defined as bits with reoccurring errors, so that the memory cell is returning the same data when it is read ('0' or '1'), independent of the value which was written to the cell. This behaviour is different from other observed SEU, which manifested themselves as a bit error only present in a single reading of the bit in question, but not in any consecutive reads of the cell after it had been rewritten.

In this paper, experimental results of SEE from electrons resulting in stuck bits and bit-flips are presented. The degradation of the cells following these events are studied, and implications of the usage of the studied SDRAM in the JUICE mission are discussed.

## II. Components and experimental setup

The tested component that will fly on JUICE is the ISSI 512 Mb SDRAM IS42S86400B, but two other newer ISSI SDRAM memory models were also tested as presented in Table I. The newer models with smaller node sizes (72 nm and 63 nm instead of 110 nm) were only tested at VESPER with 200 MeV electrons. They did however not show any response in terms of SEUs during the irradiation, which is why they were not subjected to irradiation tests with lower energy electrons.

The tested memory devices were all ISSI 512 Mb Single Data Rate (SDR) SDRAMs, with 536,870,912 bits separated on four banks. The IS42S86400B memory's banks are divided in 8192 rows by 2048 columns by 8 bits, while the IS42S16320D/F memories have 8192 rows by 1024 columns by 16 bits in their banks. They all have an operating frequency up to 143 MHz, with a 3.3 V bias and were packaged in 54-pin TSOP-II packages.

A Terasic DE0-CV FPGA development board was used as a memory control board during the experiments, and the samples were mounted on daughter boards connected to the control board through a GPIO pin interface.

The components were tested through dynamic tests, with read and write operations carried out during the irradiation. The memories were continuously running a March C- test which was slightly modified so that it would not have any stand-alone write or read elements [5]. The IS42S86400B memories were operated at 100 MHz, while the IS42S16320D/F memories were operated at 75 MHz, because the D/F memories could not operate without issues at higher frequencies with the cabling and set-up used in the experiment. During all runs the memories were operated with their nominal refresh frequency 128 kHz.

## III. Test facilities

The tests with high-energy electrons (60 - 200 MeV) were performed at VESPER (The Very energetic Electron facility for Space Planetary Exploration missions in harsh Radiative environments) at CERN (The European organization for nuclear research). Lower energy electron exposures (20 MeV) was performed at RADEF (RADiation Effects Facility) at the University of Jyväskylä, Finland, with the Clinac (Clinical LINear ACcelerator) at RADEF.

TABLE I
Summary of Specimen Used in the Experiment.

| ID | Memory | Electron energy (MeV) | Memory size | Node size (nm) |
|---|---|---|---|---|
| SDF1 | IS42S86400B | 200 | 512 Mb | 110 |
| SDF3 | IS42S86400B | 123 | 512 Mb | 110 |
| SDF4 | IS42S86400B | 61 | 512 Mb | 110 |
| SDF5 | IS42S86400B | 20 | 512 Mb | 110 |
| SDB1 | IS42S16320D | 200 | 512 Mb | 72 |
| SDE1 | IS42S16320F | 200 | 512 Mb | 63 |

TABLE II
SUMMARY OF IRRADIATION RESULTS.

| ID | Electron energy (MeV) | Bit-flips | Stuck bits | Fluence at onset of error rate increase (e/cm$^2$) |
|---|---|---|---|---|
| SDF1 | 200 | 11 | 14 | $1.02 \cdot 10^{12}$ |
| SDF3 | 123 | 12 | 18 | $1.41 \cdot 10^{12}$ |
| SDF4 | 61 | 13 | 13 | $2.73 \cdot 10^{12}$ |
| SDF5 | 20 | 6 | 6 | $3.12 \cdot 10^{12}$ |
| SDB1 | 200 | 0 | 0 | - |
| SDE1 | 200 | 0 | 0 | - |

### A. VESPER

High-energy electrons between 60 and 200 MeV are provided at VESPER. The VESPER beam is pulsed, and the electrons arrive in short bunches. Trains of bunches were arriving at the device under test (DUT) at a frequency of 3 GHz, and the bunch trains were separated in pulses with a 10 Hz frequency. 100 bunches per pulse were used in these experiments.

A Beam Current Transformer (BCT) was used to monitor the beam current during the runs, and a YAG (Yttrium Aluminium Garnet) screen and cameras were used to monitor the beam spot shape. A camera was filming the scintillating YAG-screen to monitor the beam profile during the run. The beam spot was approximated to be of Gaussian shape. The shape parameters ($\mu_{x,y}$ and $\sigma_{x,y}$) was logged by the facility, and provided in the beam log along with the pulse charge monitored by the BCT.

This system for beam monitoring worked rather well with a high intensity beam. As the beam intensity gets lower, and as the beam energy gets lower, the beam profile and charge is monitored less efficiently. This is much due to that the beam spot on the scintillating screen gets diffuse in these cases. The beam fluence uncertainty for this beam has been estimated as 20 %.

### B. RADEF

Electrons with energies of 6, 9, 12, 16 and 20 MeV are available at the Clinac at RADEF. This electron beam is also pulsed, and consists of series of 5 µs long pulses with a 5 ms period.

The beam was monitored with in-beam ionization chambers, which were calibrated against an IBA PPC40 dosimeter at maximum dose depth in water. The radiation field has been measured to be uniform within a few percent over the beam area, and this was not monitored actively during the runs. The uncertainty of the reported dose, and electron fluence calculated from this dose, is estimated to be less than 10 %.

## IV. RESULTS AND DISCUSSION

### A. Observed errors

During the irradiation tests two types of errors ascribed to SEE were observed in the IS42S86400B memory, while none were observed in the IS42S16320D/F memories. One type manifested themselves as bit-flips, which resulted in a single erroneous read of a bit in a word. The other type was stuck bits. These were bits which during consecutive write and read operations were stuck to the same value (either '0' or '1'). They were however generally stuck only for a few write/read cycles. On average, between 5 and 10 errors were detected in total per stuck bit for the IS42S86400B memories. The pattern of errors in the stuck bits can be seen in Fig. 1. In the figure, the red dots represent initial errors, with the previous write and read of the same value in the bit not resulting in an error. The blue dots represent the read of the memory where the previous write and read of the same value in the bit did give an error.

Many of these stuck bits in Fig. 1 were Intermittently Stuck Bits (ISB), i.e. bits that switch between appearing as stuck, and being normally operational. This effect has been discussed e.g. in [6]–[8] with stuck bits originating from irradiation with other particle types. ISBs discussed in these publications have, like the ones found here, long periods of time where they are not stuck and causing errors.

The number of errors detected during the tests present a sudden increase at a certain level of fluence. This is shown in Fig. 2 for the SDF3 memory under 123 MeV electron irradiation after 18:30. The same effect was seen in all memories of this model (IS42S86400B), and the point of onset of this error increase is displayed in Table II. The errors up to this point were occurring at random points in time and fluence, and are assumed to originate from SEE induced by the impinging electrons. The rapid increase eventually occurring in all samples of the IS42S86400B memories is in contrast expected to be a cumulative radiation effect.

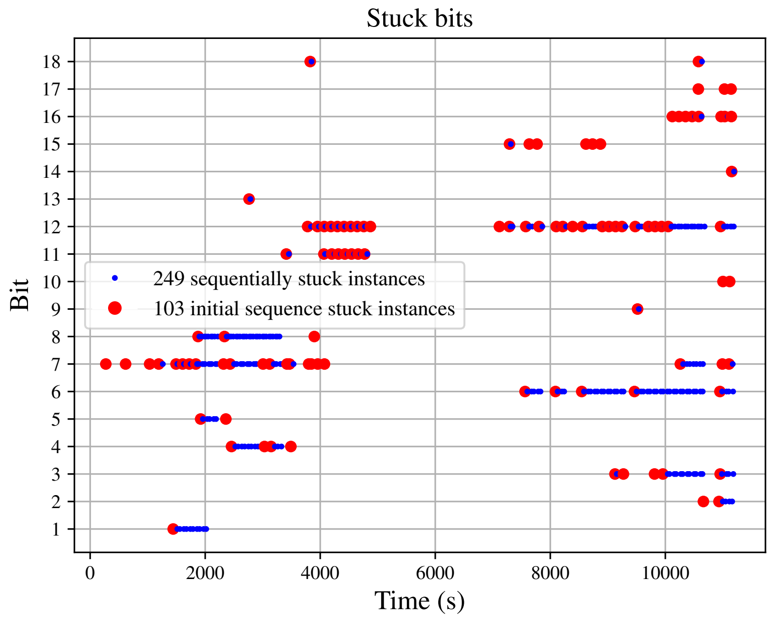


Fig. 1. Time structure of the errors from stuck bits in memory SDF3 under 123 MeV electron irradiation during modified March C- test loops. The bits are numbered as 1 - 18, with each row displaying the behaviour of one of the observed stuck bits.

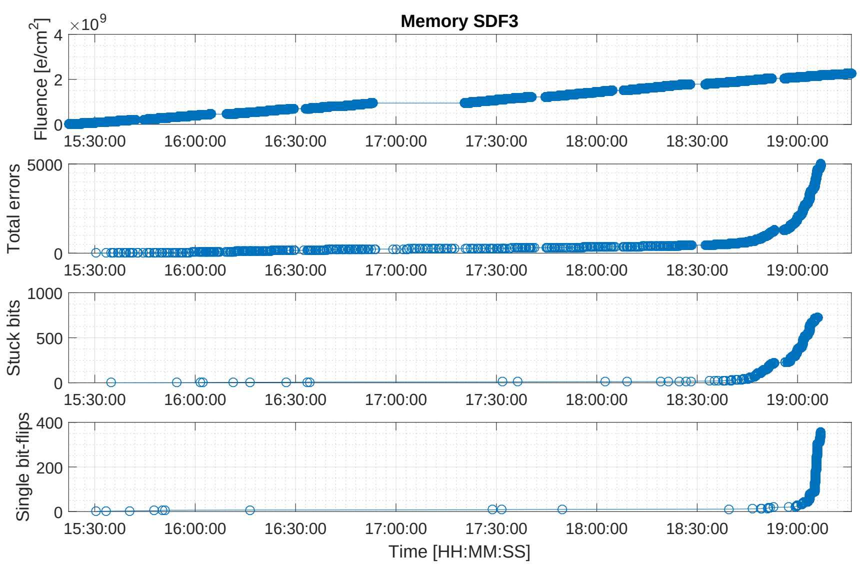


Fig. 2. Errors during the runs in SDF3 with 123 MeV electrons at VESPER. The total errors graph also counts the repeating errors from stuck bits, while the stuck bits graph only shows the onset of new stuck bits.

This error rate increase, and the consecutive annealing of these bits shown later in the paper, present competing effects which might lead to the memory suffering from a similar break down as is seen here, or not, depending on factors such as the electron flux, and how the memory is used. The flux dependence, and behaviour under different test modes, will be studied further during the spring of 2020 in planned experiments at VESPER and RADEF. These results will be included in the final version of the paper.

### *B. Stuck bit and SEU cross section*

The calculated cross sections for the errors obtained before the increase in error rate are presented in Fig. 3. The error bars in the figure represent a 95 % confidence interval with a 20 % beam fluence uncertainty. A similar number of stuck bits and single bit-flips were observed at each of the tested energies, thus the risk of getting a single bit-flip in the component is similar to the risk of getting a stuck bit.

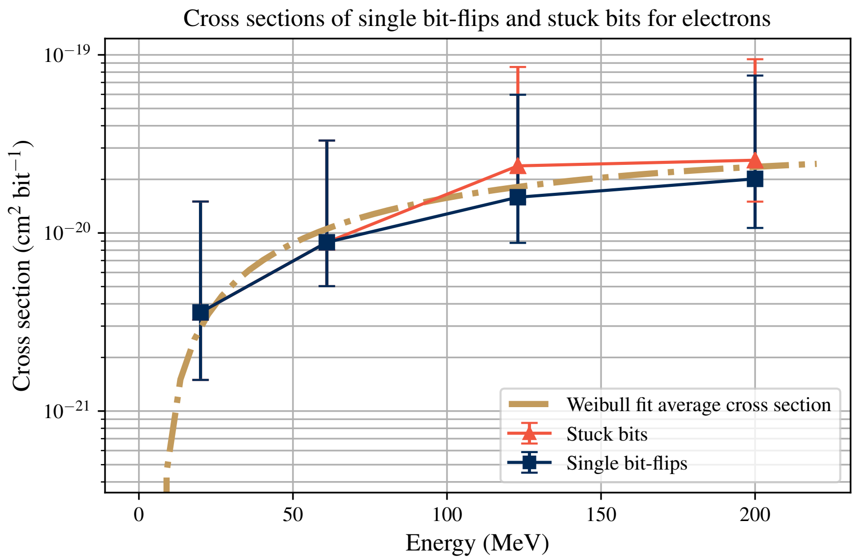


Fig. 3. Stuck bits and single bit-flip cross sections to electron irradiation under dynamic testing. The Weibull fit of the average cross section is also presented, which will be used later for a discussion of the memory behaviour in the Jovian environment.

### *C. Retention time distributions*

The stuck bit has been damaged by the incident radiation, so that the storage capacitor in the memory cell is not anymore able to hold its charge between data refresh events in the memory. For the single bit-flip, the memory cell storage capacitor is discharged, but after rewriting the memory it is not so damaged that it is not capable of holding the charge between the refresh periods. During post-irradiation analysis, a trend was found that the bits that got stuck during irradiation are more damaged than the ones that suffered a bit flip. This trend is shown in Fig. 4, where the bits that were stuck show errors at lower refresh frequencies, and have a generally larger portion of the population failing at a given refresh frequency.

The trends of the bits that were stuck and had bit-flips during irradiation fall rather close to each other in Fig.4, and with similar trends. This can indicate that the mechanisms behind the different failure modes are similar to each other, but differ mainly in the severity of the event. There are many studies that suggests displacement damage caused by single particles creating leakage paths from the storage capacitor as the cause for stuck bits in DRAMs, e.g. [7], [9], [10]. Since the bits that only had a single bit-flip display similar behaviour in Fig.4 to the bits that were stuck, it is possible that the cause for the single bit-flips found in this study is the same as for the stuck bits. Looking at the behaviour in Fig. 1, some bits are stuck only twice or a few times, while others are stuck many more times. It is therefore reasonable that the same kind of failure would result in an error at only one occasion.

These distributions were produced by changing the refresh frequency $F_R$ of the memories (the abscissas in the figures are the inverse of this, $1/F_R$), then writing the memory with all ‘0’ pattern, waiting 60 s, then reading back the memory. Thereafter the procedure was repeated for an all ‘1’ pattern. The sum of the words with errors in these tests is presented on the vertical axis.

The retention time distribution in SDF5 during irradiation with 20 MeV electrons can be seen in Fig. 5. This figure shows the number of words with bits that are stuck at different refresh frequencies at points with increasing dose. The nominal refresh frequency of the memories, 128 kHz, is marked in the figure with a dotted black line.

The retention time distribution in SDF5 post irradiation with 20 MeV electrons can be seen in Fig. 6, where the annealing of the memory is shown. The memories were kept in room temperature, and without bias when not characterized. A complete reversal to the pristine case is not seen in the annealing at this point. Instead the bits failing at a high $F_R$ are annealed to a large extent, but the total distribution is approaching a level shifted up to the left of the pristine one in Fig. 6. This shift of the memory cells data retention time to shorter times would indicate a permanent or long lasting damage to them. In the final version of the paper will also be included a high-temperature annealing study, where it will be investigated whether the retention time distribution of the cells will approach the pristine one.

## V. In-flight predictions

Based on the cross sections presented in Fig. 3, and the expected electron environment during the JUICE mission [11] which is depicted in Fig. 7 along with the cross section Weibull fits, an estimation of the number of upsets in

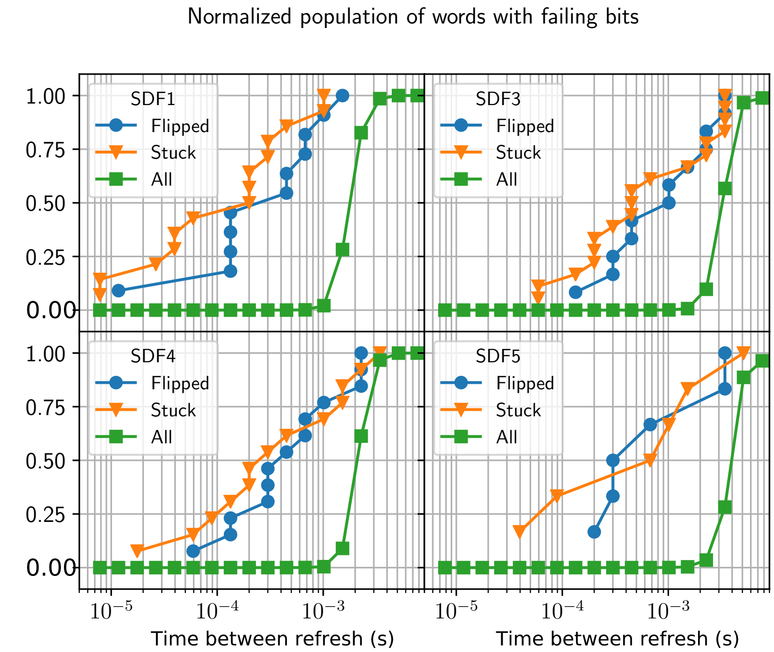


Fig. 4. The amount of words with bits that fail at certain refresh frequency of the memory (abscissa is $1/F_R$). The populations that are shown are the bits which had only one bit-flip during irradiation, bits that were stuck, and all bits in the memory. Data taken post irradiation for the four SDF# memories.

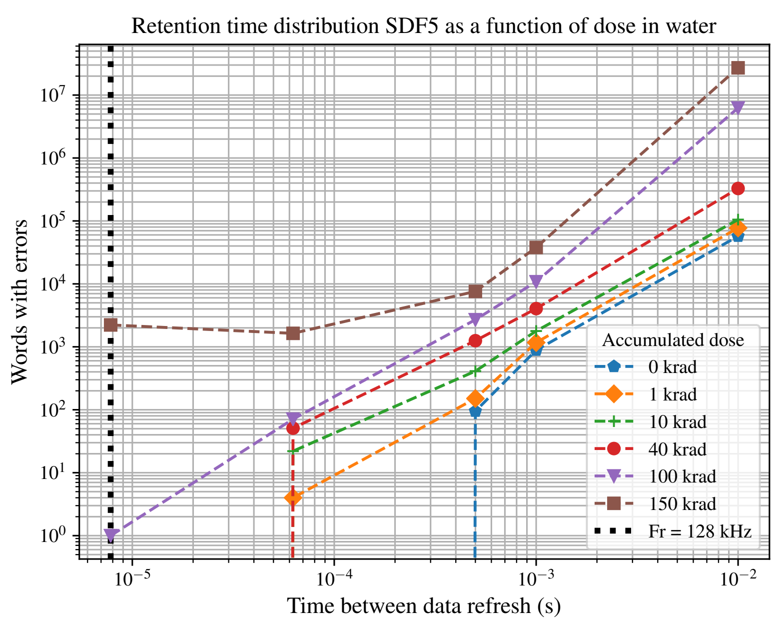


Fig. 5. Retention time distribution of SDF5 during 20 MeV electron irradiation at 5 different refresh frequencies. The doses in the figure are doses in water at maximum dose depth.

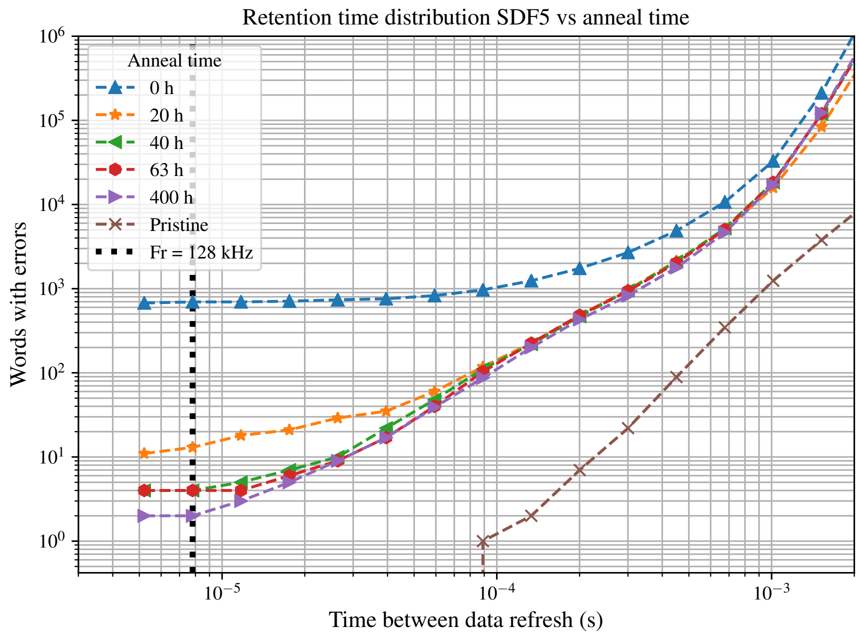


Fig. 6. Retention time distribution of SDF5 after 20 MeV electron irradiation after different annealing times.

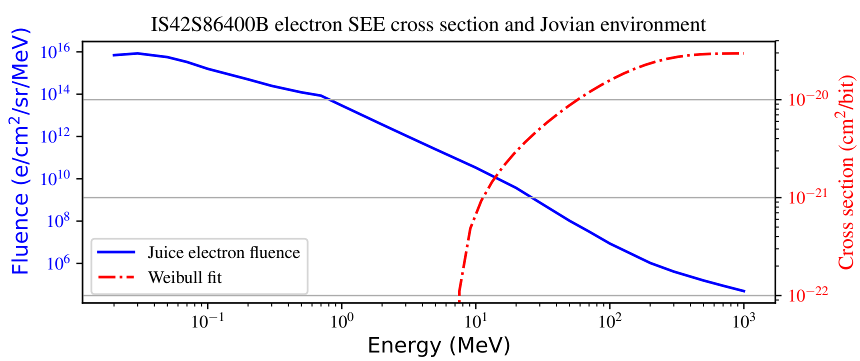


Fig. 7. Total differential electron fluence of the JUICE mission from [11], along with the Weibull fits of the electron cross sections.

the IS42S86400B memory during the JUICE mission is calculated. The mission duration is in total planned to be 11.1 years, with different phases of the mission receiving different fluxes of particles [11].

As a first estimation, the presented differential fluence is multiplied with $4\pi$ to assume an isotropic fluence, and also as an approximation an isotropic sensitivity of the component. So far the component has only been tested with electrons at a normal incidence angle. The cross section was then multiplied with the electron fluence, and then integrated, to obtain a first estimation of the number of upsets. The result was 2.44 upsets, which means about 5 events counting both stuck bits and bit-flips.

The number of upsets vary however greatly with variations in the cut-off energy of the Weibull fit, and thus the behaviour of the memory under lower-energy electron irradiation is of relevance. With a lower cut-off energy at 1 MeV, instead of 7 MeV as was used here, the number of errors per upset mode increases to 20. Irradiation with lower energy electrons (down to 6 MeV) is planned to be performed in the RADEF facility to investigate this.

This prediction will be further expanded upon, by transporting the electron fluence trough the space-craft wall, and working with the sensitive volumes of the cells. Other important considerations to further expand upon of the behaviour of the memory in space is the effect of acquired dose versus the annealing of the bits. The implications of the dose rate behaviour and points of error rate increase will also be discussed and related to the different phases of the JUICE mission.

## VI. Conclusion

In this paper is shown that high-energy electron irradiation can cause stuck bits and bit-flips in SDRAMs as SEEs, and consequences of this for the JUICE mission is discussed. The mechanism behind the two failure modes are suggested to be one and the same, based on the similarity of the cell degradation and the similarity of the reaction cross sections.

The electron irradiation is found to degrade the memory cells on a long term time scale, but annealing of the most damaged cells during testing was observed. Further annealing studies at high temperatures will be conducted.

The effects that are found are related to the JUICE environment, and further predictions and studies of the behaviour of the memory in the Jovian environment will be conducted.

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