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Single-event effect testing of the PNI RM3100 magnetometer for space applications

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Abstract. The results of a destructive single-event effect susceptibility radiation test of the PNI RM3100 magnetometer sensor, specifically the MagI^{2}C ASIC (application-specific integrated circuit) on the sensor board are presented. The sensor is a low-resource commercial off-the-shelf (COTS) magneto-inductive magnetometer. The device was monitored for destructive events and functional interruptions during exposure to a heavy ion beam at the Lawrence Berkeley National Laboratory's 88″ Cyclotron. The RM3100 did not experience any destructive single-event effects when irradiated to a total fluence of $1.4 \times 10^7\,\mathrm{cm}^{-2}$ at an effective linear energy transfer (LET) of $76.7\,\mathrm{MeV\,cm^2\,mg^{-1}}$ while operated at nominal voltage (3.3 V) and elevated temperature (85 °C). When these results are combined with previous total ionizing dose tests showing no failures up to 150 kRad (Si), we conclude that the PNI RM3100 is extremely radiation tolerant and can be used in a variety of space environments.

1 Introduction

As part of the University of Michigan's Magnetometer Laboratory's effort to space qualify the PNI RM3100 magnetometer for space applications, we conducted single-event effect testing on the commercial off-the-shelf (COTS) MagI^{2}C application-specific integrated circuit (ASIC). The PNI RM3100's performance has an accuracy of about 1.2 nT and a noise density of $500\,\mathrm{pT}/\sqrt{\mathrm{Hz}}$ at 1 Hz (e.g., Regoli et al., 2018) and is extremely small size (3 mm × 3 mm × 2 mm), low mass (5 g), and low power (5 mW) making it ideal for multi-magnetometer noise cancellation applications (e.g., Sheinker and Moldwin, 2016; Hoffmann and Moldwin, 2022) that can enable short-boom, boomless, and/or relaxed magnetic cleanliness requirements for magnetometer satellite investigations.

One concern for using COTS electronics for space applications is their long-term reliability and their potential susceptibility to radiation effects, including single-event effects (SEEs; NRC, 2006). There are a variety of SEEs caused by single energetic particles (usually heavy ion cosmic rays, trapped radiation belt protons, or solar energetic protons). Single-event upsets (SEUs) are non-destructive and therefore termed soft errors. They normally appear as transient pulses in logic or support circuitry or as bit flips in memory cells or registers and can give rise to phantom or false commands (e.g., Moldwin, 2008). In contrast to SEU, there are several types of potentially destructive hard errors that damage or destroy electronics. One type is called single-event latchup (SEL) that results in a high operating current, above device specifications and must be cleared by a power reset (NASA Radiation Effects and Analysis Group, 2021). This paper describes the testing done to study the susceptibility of the PNI RM3100 magnetometer for SEL conducted at the Lawrence Berkeley National Laboratory's 88″ Cyclotron (LBNL, 2021).

Table 1. Part information.

Part number	RM3100
Manufacturer	PNI
Device function	Geomagnetic sensor, three-axis
Lot date code	Unavailable
Device technology	CMOS
Quantity tested	2
Package	Printed circuit board, with one plastic-encapsulated, wire-bonded microcircuit
REAG ID no.	21-017

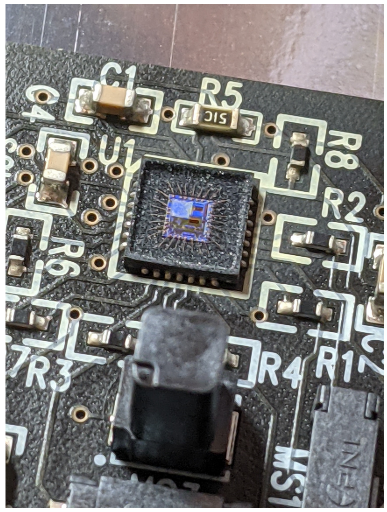

Figure 1. PNI RM3100 ASIC device close-up after decapsulation by SAGE Analytical Labs.

2 Methodology

2.1 Devices under test

The PNI RM3100 is a printed circuit assembly with three sensor coils, an ASIC, and passive components that provide three-axis magnetic field sensing in a low-power and low-cost assembly (Regoli et al., 2018). It operates on a split 3.3 V analog–digital rail and interfaces to a digital host via standard SPI or I2C serial interfaces.

Throughout this paper, PNI RM3100 is used as common terminology for the device under test (DUT), though only the sole active microelectronic device (the MagI^{2}C ASIC) was irradiated. The RM3100 does not contain any other components susceptible to single-event effects.

The DUTs for this experiment were commercially procured from PNI by the University of Michigan and provided to the NASA Goddard Space Flight Center for SEE testing. Table 1 describes the DUT. The plastic package was opened to expose the die for testing, but part markings were not recorded prior to obliteration by combined laser and chemical decapsulation. Decapsulation was performed to ensure reasonable accuracy of LET through the device's sensitive volume. Figure 1 shows the DUT with the ASIC decapsulated.

2.2 Test description

The SEE testing was conducted on two decapsulated PNI RM3100 ASICs at the Lawrence Berkeley National Lab 88$''$ Cyclotron, Berkeley Accelerator Space Effects (BASE) Facility. The beam used a 16 MeV amu^{-1} tune with a flux varying up to 1×10^5 cm^{-2} s^{-1}. Testing was conducted to 1×10^7 cm^{-2} at each unique test condition to rule out destructive SEE. Additional tests were performed until single-event functional interrupts (SEFIs) were observed (e.g., Koga et al., 1997). SEFIs are soft errors that cause the component to reset or lock-up but do not require power cycling of the device in contrast to SEL. The test required an effective linear energy transfer (LET) of at least 75 MeV cm^2 mg^{-1} for destructive single-event effect testing. The 16 MeV amu^{-1} Xe beam provided a nominal LET of 49.3 MeV cm^2 mg^{-1} in vacuum, and higher effective LETs were created by irradiating at angles following a $1/\cos(\theta)$ rule, until the required 75 MeV cm^2 mg^{-1} was reached. Figure 2 shows the PNI-RM3100 in the beam line prior to the test.

Table 2 describes the test conditions that the PNI RM3100 were subject to during the SEE testing.

2.3 Test methods

The RM3100 was controlled by a PJRC Teensy 4.0 ARM™ Cortex-M7 microcontroller (running at 528 MHz), which communicated with the RM3100 via the SPI bus at 1 MHz. The microcontroller received instructions from a host PC running a Python test script. Power supply connections for analog power (AVDD) and digital power (DVDD) were provided independently to isolate any single-event latchup, if observed. For dynamic tests, the RM3100 was configured into continuous measurement mode, with otherwise default register settings, and readings were logged twice per second. For static testing, power was applied to the device without reading or writing to any registers.

The primary test was for single-event latchup. Power was supplied at the nominal 3.3 V and the device was operated at 85 °C in static or dynamic mode. Power supply currents were monitored for signs of single-event latchup (a sudden, significant increase in current only correctable by power cycling).

Characterizing soft errors was a secondary objective of the test. Magnetic readings inside a cyclotron facility are inherently noisy and no attempt was made to calibrate or reference the values to a known standard. Instead, data were monitored for large changes. These errors are collectively counted as SEFIs, and signatures included sudden data offsets, possible changes in measurement range, frozen data from one or more channels, and lack of communication. They are most likely caused by upsets to the internal control registers, but no at-

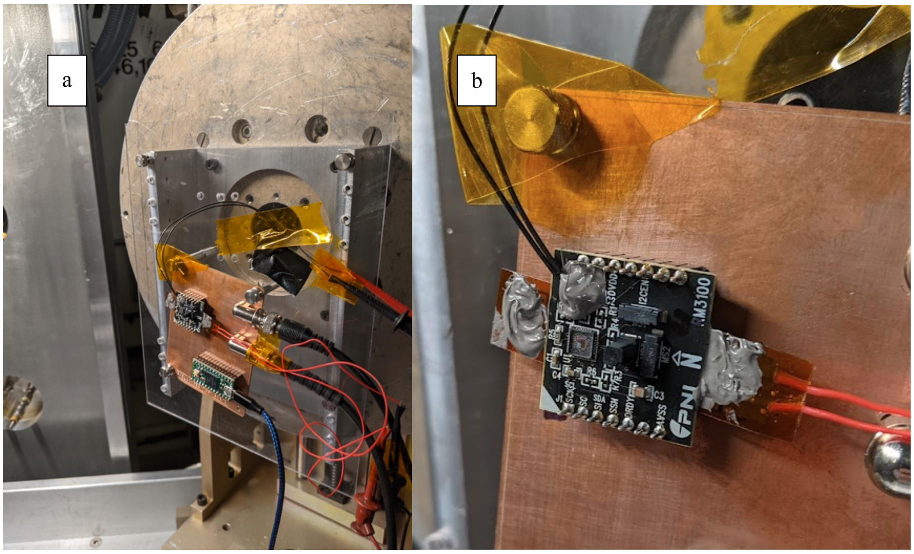

Figure 2. **(a)** The PNI RM3100 mounted within the beam line for SEE testing. **(b)** Close-up of the decapsulated PNI ASIC with a polyimide heating strip attached to the back of the PNI RM3100.

Table 2. Test Conditions.

Parameter/mode	Description
Test temperature	Ambient temperature and 85 °C package temperature
Operating mode	Static (power only) and dynamic (continuous measurement mode enabled)
Power supply voltage	3.3 V nominal and 3.6 V worst case
Parameters of interest	Power supply current (I_{CC}), functional changes in output data

Table 3. Data test run log. LETeff is effective linear energy transfer and No. dSEE is number of detected single-event effects.

Facility setup			Test configuration			Run data			Results
Ion	LET	LETeff (MeV cm^2 mg^{-1})	Voltage (AVDD, DVDD)	Function	Temp (°C)	Run time (s)	Eff. fluence (cm^2)	Avg flux (cm^2 s^{-1})	No. dSEE
Xe	49.3	76.7	3.3	Power only	85	566.2	4.08×10^6	7.21×10^3	0
Xe	49.3	76.7	3.3	Power only	85	744.8	1.00×10^7	1.34×10^4	0

tempt was made to read back or automatically correct register values during testing.

2.4 Test results

The RM3100 did not experience any single-event effects when irradiated to a total fluence of 1.4×10^7 cm^{-2} at an effective LET of 76.7 MeV cm^2 mg^{-1} while operated at nominal voltage (3.3 V) and elevated temperature (85 °C) for the durations of the tests. Table 3 shows the test conditions.

SEFIs were observed but were rare, and most presented as sudden large changes to the measured values on one or more axes and required a power cycle to restore operation. SEFI events were not recorded as the purpose of the test was to screen for destructive events; therefore a SEFI rate cannot be quantified but would be very low. The threshold LET (LETth) was demonstrated to be greater than 3.7 MeV cm^2 mg^{-1}. The saturated cross-section appears to be less than 1×10^{-5} cm^2, but data are limited.

3 Discussion and conclusions

The heavy ion beam test results on the susceptibility of the PNI RM3100 magnetometer to SEE found no single-event latchup events for LET >75 MeV cm^2 mg^{-1} at an elevated temperature of 85 °C. SEFIs were extremely rare. Combined with previous total ionizing dose (TID) tests at the University of Michigan and the NASA Goddard Space Flight Center (GSFC Radiation Effects Facility, NASA Radiation Effects and Analysis Group, 2021) that found no failures up to 150 kRad (Si) (Regoli et al., 2020), the PNI RM3100 is appropriate for use on missions in a variety of space environments (LEO polar, MEO, HEO, GEO, and deep space).

In addition to TID and SEE testing, the University of Michigan's Magnetic Laboratory is conducting a full range of thermal and thermal-vacuum testing on the PNI RM3100 exploring both the survival and operation temperature limits, and the results will be published in the future to enable the broad use of a COTS magnetometer for both CubeSat and NASA Class C space missions. Currently the PNI RM3100 has been selected for flight on NASA's Artemis Lunar Gateway Heliophysics Environmental and Radiation Measurement Experiment Suite (HERMES) platform as part of the Noisy Environment Magnetometer in a Small Integrated System (NEMISIS) magnetometer and NASA's Heliophysics Flight Opportunities for Research and Technology (H-FORT) Ionospheric Composition and Velocity Experiment (ICOVEX) satellite. Gateway is scheduled for launch no earlier than 2024, while ICOVEX is scheduled for launch in mid-2025.

Data availability. All raw data can be provided by the corresponding authors upon request.

Author contributions. MBM and EW planned the experiment; EW performed the measurements and analyzed the data; MBM wrote the paper draft and obtained the funding; EW, EZ, and TMB reviewed and edited the paper.

Competing interests. The contact author has declared that neither they nor their co-authors have any competing interests.

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