BELLE2-NOTE-0040

Radiation hardness testing of iTOP SCROD and carrier boards (v.1.0 - Jan 30 2015)

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Abstract

This document describes tests to confirm radiation tolerance characteristics of the iTOP SCROD and carrier boards before final production. Based on estimates from background generation campaigns, a SCROD and carrier board were irradiated by neutron and gamma sources to the equivalent of at least 10 “Belle II years” of exposure. Tests were performed to monitor for board failures. No serious permanent radiation damage was found in this limited sample.

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I. INTRODUCTION

This document describes tests to confirm radiation tolerance characteristics of the iTOP SCROD and carrier boards before final production. Based on estimates from background generation campaigns, a SCROD and carrier board were irradiated by neutron and gamma sources to the equivalent of at least 10 "Belle II years" of exposure. Tests were performed to monitor for board failures. No serious permanent radiation damage was found in this limited sample.

II. EXPECTED BACKGROUND RADIATION

Due to their on-detector location, the SCROD and carrier boards will be exposed to an accumulated dose of radiation over the expected 10 year lifetime of the Belle II experiment. This is estimated in Belle II by Monte Carlo simulations of background from radiative Bhabha (dominant), Touschek, and Couloumb (beam-gas) scattering sources. A Belle II "year" for background simluation purposes is defined as 10^7 seconds of operation. Based on these simulations, the on-detector iTOP electronics are expected to receive approximately 15×10^9 (1 MeV equivalent) neutrons / cm^2 / year (Figure 1), and ∼5 Gy/year radiation dose (Figure 2). These values represent the worst-case values from the simulation, and are rounded up. They are also based on nominal beam conditions with an instantaneous luminosity of 8×10^{35} cm^{-2}s^{-1}. In practice the first few years of operation are expected to be below this level. These estimates are from the 10^{th} background generation campaign [1]. Based on these numbers, we conservatively expect a total neutron fluence of 15×10^{10}cm^{-2} and dose of 50 Gy over the lifetime of the experiment.

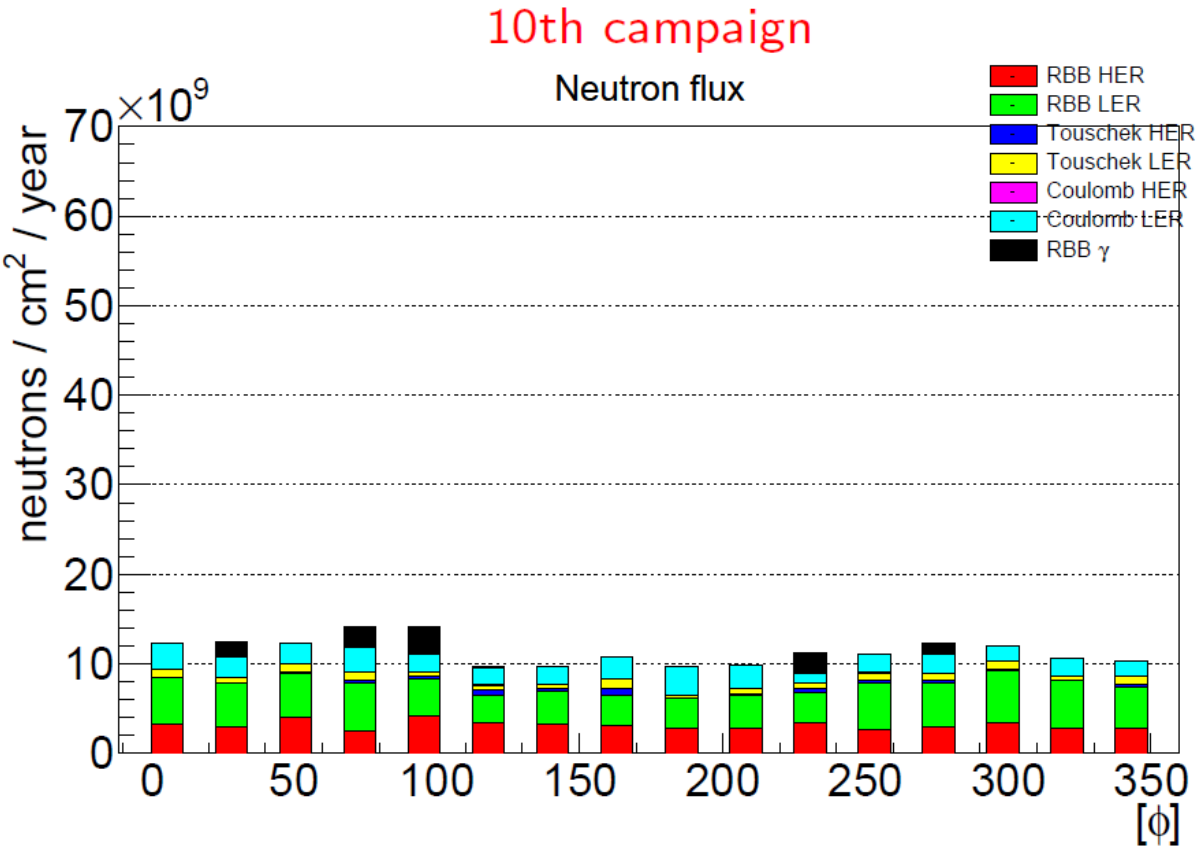

FIG. 1: Expected neutron flux at the iTOP electronics versus phi. One year is defined as a "Belle II" year of 10^7s of operation.

III. IRRADIATION FACILITIES

In order to test to robustness of the iTOP electronics against radiation damage, we planned to irradiate a sample consisting of a SCROD (revision B) and IRSX-equipped carrier board (revision E) at the Radiation Standards and Calibration Laboratory facilities at Pacific Northwest National Laboratory [2]. Amongst the facilities are a Low Scatter Room (LSR) with a Cf-252 source for neutron irradiation, and a High-Exposure Facility (HEF) with a Co-60 source for gamma ray irradiation, which to be used for these tests.

In the LSR, the Cf-252 neutron source enters the room on a high-speed pneumatic "rabbit" via tubing. It is a 4π source, and devices under irradiation can be placed adjacent to the final source position at distances ranging from centimetres to metres away. The estimated neutron flux at a distance of 10 cm is approximately 2.4×10^6 n/cm^2/s, which is where we initially proposed to conduct the testing. A distance of ∼25cm was also considered for greater neutron beam uniformity across the board. However, at this distance the expected time to reach the desired fluence was too long (∼5 days of continuous irradiation). D_2O moderation was also possible with a relative 10% reduction in flux, but in this case the distance of closest approach is increased to more than 15cm, further increasing the necessary time for the irradiation. At the 10cm position, we hoped to achieve one year of Belle II

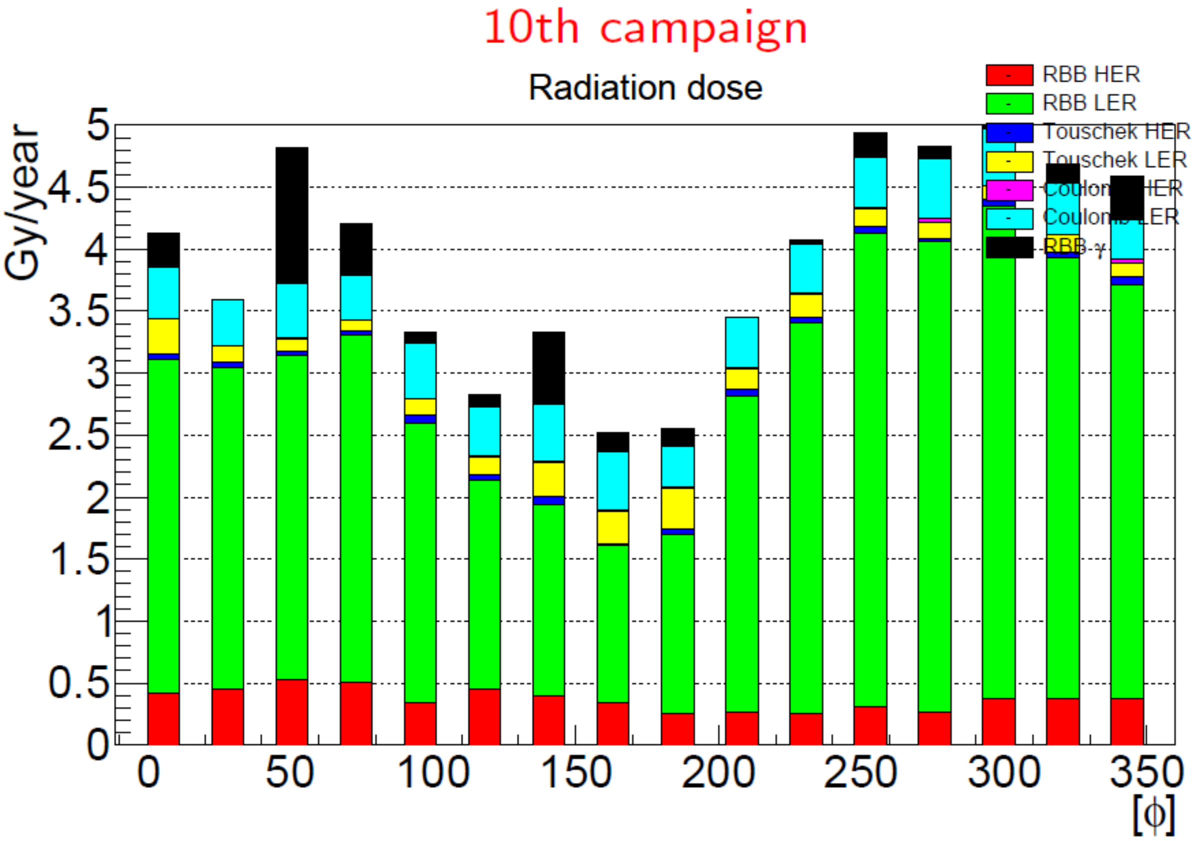

FIG. 2: Expected radiation dose at the iTOP electronics versus phi. One year is defined as a "Belle II" year of 10^7s of operation.

neutrons in approximately 1.7 hours, and the ten-year equivalent in ∼17.4 hours. The main drawback at this location is increased non-uniformity in the flux (up to a 33% reduction at the corner of the board compared to the center). However, due to limited availabilty of the LSR facilities, the trade-off of uniformity versus time was deemed to be of greater importance.

Tests in the HEF planned to use a Co-60 γ-ray source capable of delivering 43 Gy/h[5] at a distance of 1m. At this distance, the desired dose can be achieved relatively quickly, and the field is expected to have less than 5% non-uniformity across the board. The expected Belle II dose for one year of nominal operation is only 5 Gy, which could be accomplished in under 7 minutes of operation. Ten-year-equivalent dose could be delivered in about an hour. Therefore time required to irradiate the sample at the HEF was not expected to be a limiting factor.

In addition to modeling and calibration of the sources, both facilities have various options for *in situ* dose/flux measurement (*e.g.* radiochromic film, thermoluminescent dosimeters, etc.). In principle these could have been employed to improve the radiation exposure estimates, but their range of validity was too limited for the exposure levels planned of these tests.

IV. TEST APPARATUS

The device under test consisted of a SCROD (Revision B, Serial Number 010) and carrier board (Revision E, Serial Number 011) placed vertically in a PCB circuit board holder. A jack was used to position it at the proper height and distance from the radiation source. The support electronics were placed on the floor nearby, as far as reasonably achievable from the source.

Required support equipment for the test included two dual-output power supplies (Agilent U8032A Triple Output DC Power Supply), one arbitrary waveform/function generator (Tektronix AFG3252 Dual Channel Arbitrary/Function Generator), a Xilinx programmer (Xilinx Platform Cable USB II), and an Ethernet media converter (Trendnet TFC-1000MGA). A computer used to communicate with and perform tests on the boards was placed in the room, and the system was controlled and monitored remotely run via Ethernet from outside the radiation area. Figure 3 shows the test configuration. Figures 4 and 5 show the set-up in the LSR (neutron) and HEF (gamma), respectively.

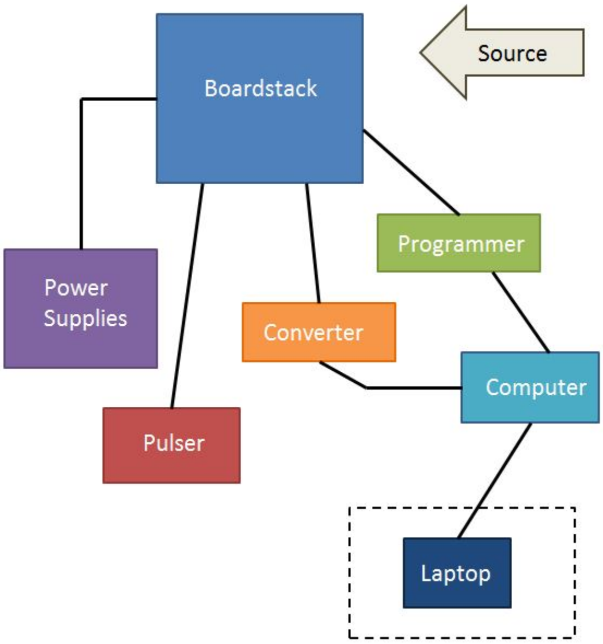

FIG. 3: Block diagram for test procedure.

A continuous pulser test was operated during irradiation by repeating a boardstack calibration script [3]. Voltage and current on the power supplies was monitored continuously via a closed-circuit camera situated in the irradiation room. For the neutron irradiation the calibration scripts were performed repeatedly with a short pause between repetitions for manual loading of FPGA information when changing between channels. For the gamma irradiation the same channel was used repeated via a loop, with a minimal time loss between trials. The progress of the scripts was monitored continuously by a custom GUI and by messages output to a terminal window.

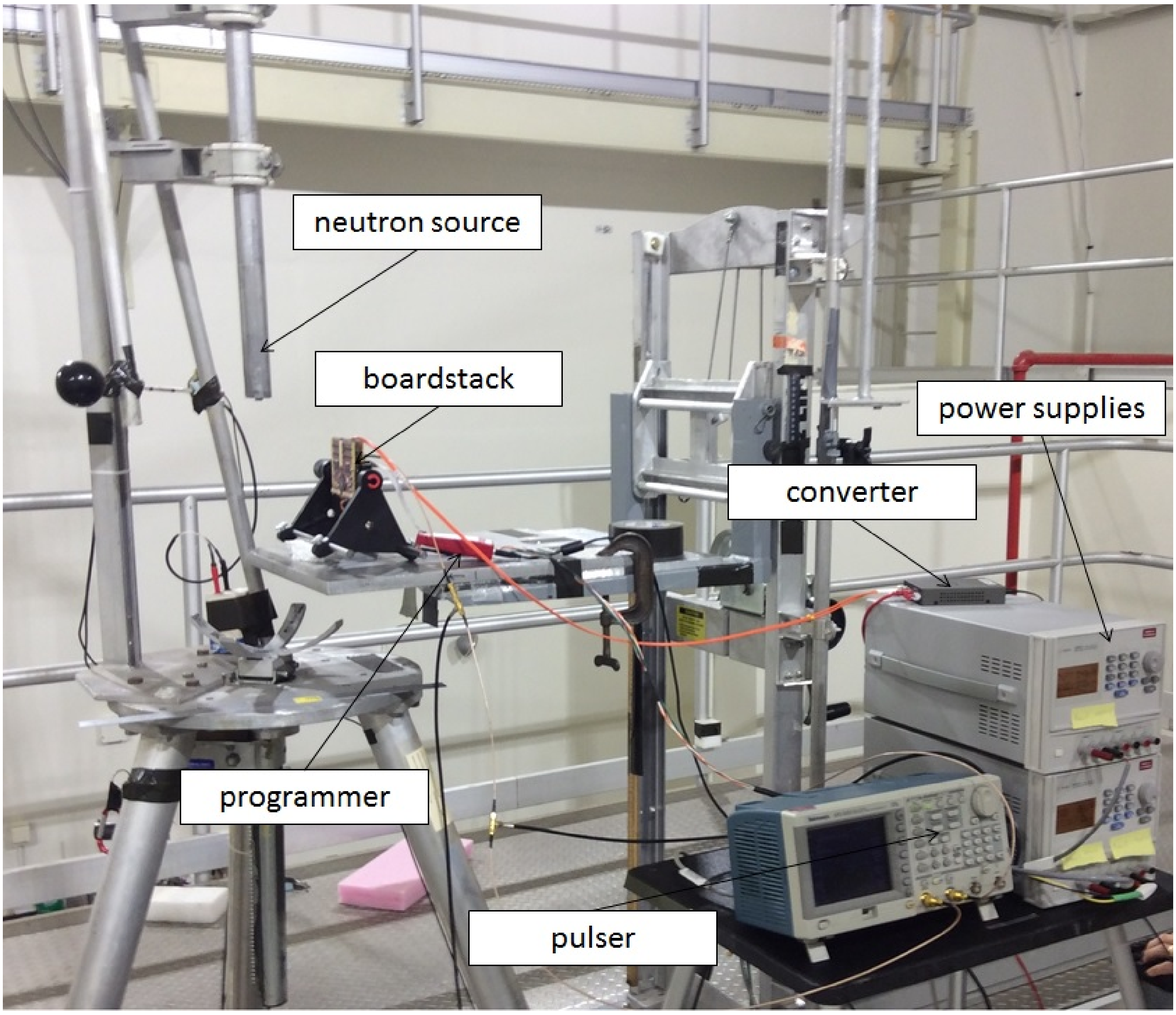

FIG. 4: SCROD and carrier board in the LSR (neutron).

V. TEST RESULTS - NEUTRON IRRADIATION

Due to restricted availability with the neutron irradiation facility and compressed schedule to begin electronics production, the neutron irradiation tests were performed over the two-day period of January 15-16, 2015. In order to accumulate the desired fluence in the time available, the boardstack was placed with the face of the carrier board at a distance of 7.5 ± 0.2 cm from the neutron source (by design, the SCROD was ∼1.7cm further away). This distance was chosen to ensure that the least exposed portion of the board received a minimum of the 10 year Belle II equivalent.

On the day of the test the flux at the center of the carrier board (as reported by the LSR) was 4.6×10^6 n/cm^2/s. Given the geometry of the approximately "active" area of the electronics, the flux at the furthest corner of the boardstack was expected to be 2.1×10^6 n/cm^2/s. The boards were irradiated for a period of 1216.7 minutes[6] as reported by the timekeeping by the facility source operators. This is equivalent to $22.2^{+1.2}_{-1.1}(12.3 \pm 0.5)$ years

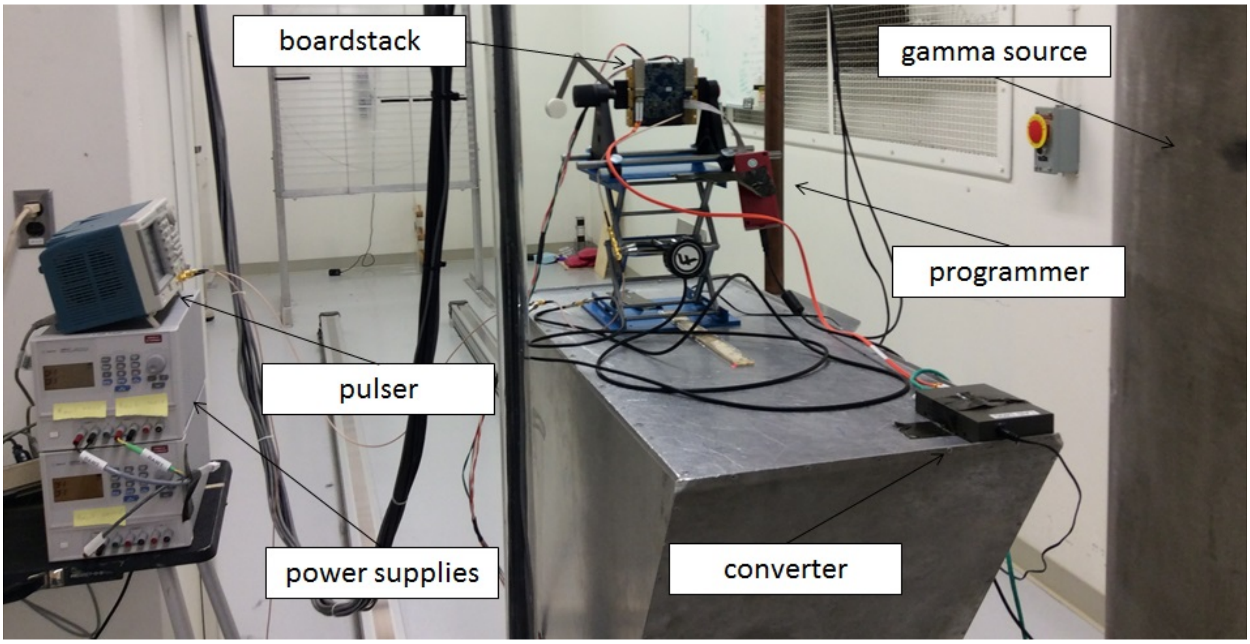

FIG. 5: SCROD and carrier board in the HEF (gamma).

of Belle II operation at the carrier board center (corner), and $16.2^{+0.8}_{-0.7}(10.2 \pm 0.4)$ years at the SCROD center (corner).

No change in the current draw from the board stack was observed. The values remained within 0.01A (0.01V for constant current) for the duration of the tests, within the measurement uncertainty and with no trends observed. During the irradiation, 11 calibration script failures occured. One could be attributed to human error. For the remaining 10, the symptom was the lost/corrupted ability to send/receive commands with the boardstack. In all cases operation could be recovered by simply reprogramming the FPGAs, and no permanent failures occured. As shown in Fig. 6, the failure rate was approximately constant in time (0.46 ± 0.01 errors per hour), and therefore apparently unrelated to cumulative damage to the boards.

Assuming that the 10 errors incurred were due to single event upsets in the Zynq chips (as evidenced by the loss of communication and recoverable nature with reprogramming, *e.g.* no apparent permanent damage), we make a rough estimate on the frequency of errors expected during nominal Belle II operation. These tests featured a single SCROD (one ZYNQ XC7Z045 chip) and a single carrier board (one ZYNQ XC7030 chip). Given the positions of these chips on the boards, the Z-7045 received about 15 Belle years of neutron fluence, while the Z-7030 received 20 years. We scale by the number of programmable logic cells in each device (350k Z-7045, 125k Z-7030) [4], and the expected number of components in the entire iTOP system (1 SCROD and 4 carriers per boardstack, 4 stacks per bar, 16 bars total). The result is approximately 70 ± 23 errors per "Belle II year" for the entire system.

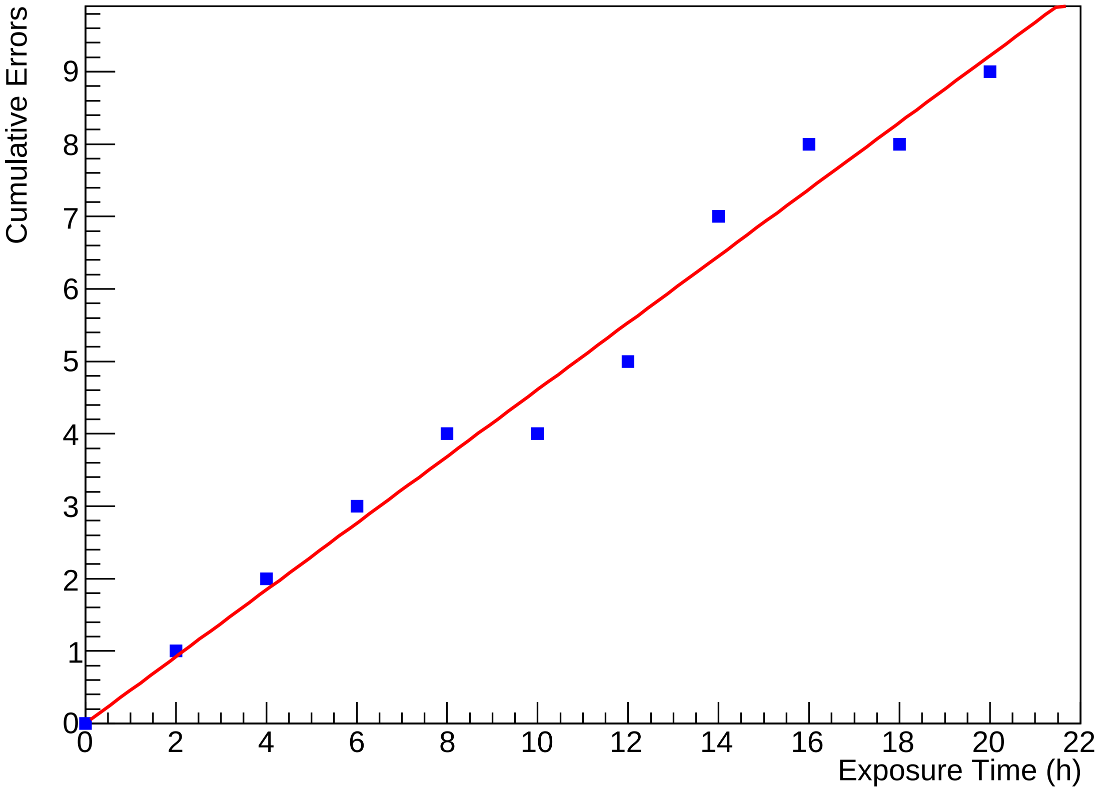

FIG. 6: Cumulative number of errors versus neutron exposure time.

VI. TEST RESULTS - GAMMA IRRADIATION

The gamma irradiation took place the morning of January 23, 2015. The same apparatus was located with the front center face of the SCROD located 1.30 ± 0.01m from the source. This location was chosen to lower the rate to minimize deadtime to SEUs during error recovery, as seen in the neutron irradiation. At this position the source strength was given as 25.1 Gy/h on the day of the test. The boards were exposed for 120.5 ± 0.5 minutes, equal to 50.5 ± 0.8 (49.1 ± 0.8) Gy for the center of the SCROD (corner of the carrier). These values represent the conservative minimum dose received: the boards were subject to an accumulated dose from the neutrons and gammas accomapnying the Cf-252 source in the previous test. These effects have not been fully characterized by the irradiation facility, but an estimate of an additional ∼5 Gy is probably reasonable. Therefore both boards received at least the 10 "Belle II year" equivalent.

During the test, no failures were observed. The only change observed in the system was a slight drift in the monitored voltages and currents. RAW2 current varied from 2.27 ± 0.02 A to 2.35 ± 0.02 A (see Figure 7) over the testing period (constant voltage), while RAW1 varied from 1.57 ± 0.01 V to 1.60 ± 0.01 V (constant current). These values represent a less than 5% change in operating current over the operational lifetime of Belle II.

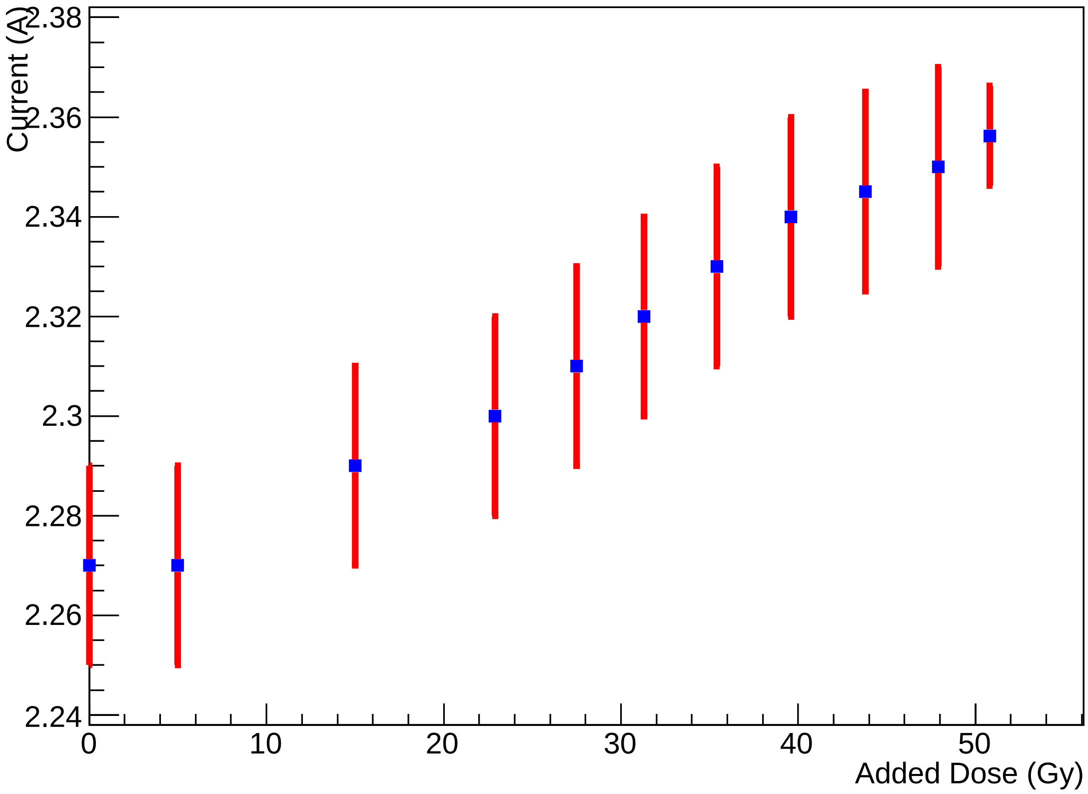

FIG. 7: RAW2 current versus dose from the gamma irradiation campaign.

VII. POST-TEST COMMENTS

After conducting the tests, the facility and boards were surveyed for radioactivity. There was some initial neutron activation of the boards, so they were left to cool at the LSF. They were surveyed again and cleared by a radiological control technician approximately 5.5 days after the tests concluded.

To monitor the general long-term stability of the boards under test, they were moved out of the irradiation area after the gamma irradiation testing was completed and set on a repeated calibration loop. The system continued to operate for 8787 minutes without error before being shut down. Comparing this stable operation of at least 6 continuous days outside of the radiation environment with the errors seen during the neutron bombardment points to radiation-induced single event upsets as their probable cause.

It is known that temperature can affect the current draw of the boards. This was considered as a possible cause for the variation seen during the gamma irradiation, since the boards began “cold”, then operated for approximately 30 minutes before irradiation. Although temperature readings were not taken during these tests, during subsequent running without irradiation, the voltages and currents were monitored while repeating the same operating conditions (*i.e.* half an hour after start-up). Over a 102 minute period, the values were found to only fluctuate within ±0.01 V and A, consistent with no change. In a separate trial the boards were left operating for several days while lying on the lab bench in a carrier-board-down position. In this case the RAW1 (constant current) voltage changed from 1.60 ± 0.01 V to 1.54 ± 0.01 V while RAW2 (constant voltage) current changed from 2.35 ± 0.02 A to 2.39 ± 0.02 A. The boards became nearly too hot to touch barehanded. Once they were returned to a mounted position with better airflow (as during the tests), the voltage and current values had returned to nominal (1.63 ± 0.01 V and 2.35 ± 0.02 A, respectively) after 15 minutes. These trends with temperature (particularly RAW1) are generally contrary to those seen during the gamma irradiation, giving further support to the hypothesis that the drift seen there was due to radiation effects.

VIII. CONCLUSIONS

An iTOP SCROD and carrier board combination were subjected to a neutron fluence and gamma dose equivalent to at least 10 years of Belle II operation at design beam conditions. During the neutron irradiation, single event upsets causing communication loss were observed consistent with an expected rate of 70 ± 23 errors per operating year. In all cases, the situation was immediately recoverable with simple reprogramming of the FPGAs. During the gamma irradiation, the current draw changed by a small amount, $< 5\%$. No critical operations failures occured. We conclude that no serious permanent damage was incurred by the boards or its components within this limited study.

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[1] T. Nanut, "Top beam background", November 2014 Belle II General Meeting, `http://kds.kek.jp/getFile.py/access?contribId=171&sessionId=13&resId=0&materialId=slides&confId=16670` (2014).

[2] D.E. Bihl *et al.*, "Radiation and Health Technology Laboratory Capabilities", PNNL-10354 Rev. 2, `http://www.pnl.gov/main/publications/external/technical_reports/PNNL-10354rev.2.pdf` (2005).

[3] M. Andrew *et al.*, "Module01 readout integration", 29 Jan 2015 iTOP Group Meeting (PID Morning Meeting), `http://kds.kek.jp/getFile.py/access?contribId=0&resId=0&materialId=slides&confId=17705` (2015).

[4] Xilinx, Inc., "Zynq-7000 All Programmable SoC Overview", DS190v1.7 (2014).

[5] Dose expressed in air. The conversion for the board composition as defined in the simulation model (dominantly Si, O, and Cu, with Fe, Sn, Ta, Al, H, N, C, Sb, and Zn) is within $< 4\%$ for gamma rays from Co-60.

[6] Uncertainty on the timing was small compared to the position measurement, and can be neglected.