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The Mu2e Digitizer ReAdout Controller (DiRAC): characterization and radiation hardness

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Abstract

The Mu2e experiment at Fermilab will search for the neutrino-less coherent conversion of a muon into an electron in the field of a nucleus. Mu2e detectors comprise a straw tracker, an electromagnetic calorimeter and a veto for cosmic rays. The calorimeter employs 1348 Cesium Iodide crystals readout by silicon photo-multipliers and fast front-end, and digitization electronics. The digitization board is named DiRAC (Digitizer ReAdout Controller) and 140 cards are needed for the readout of the full calorimeter. The DiRACs are hosted in crates located on the external surface of calorimeter disks, inside the detector solenoid cryostat and must sustain very high radiation and magnetic field so it was necessary to fully qualify it. Several version of prototypes were validated for operation in a high-vacuum (10^{-4} Torr) and under a 1T magnetic field. An extensive radiation hardness qualification campaign, carried out with photons, 14 MeV neutron beams, and 200 MeV protons, certified the DiRAC design to sustain doses up to 12 Krad, neutron fluences up to $\sim 10^{11}$ 1 MeV n_{eq}/cm^2, and very low occurrences of single-event effects. The qualification campaigns and quality assurance procedures will be reviewed.

1. Introduction

The Mu2e experiment [1] aims to search for Charged Lepton Flavor Violating neutrinoless coherent conversion of a muon into an electron in the field of an aluminum nucleus. Mu2e will utilize an intense pulsed muon beam and a detector system whose primary components for detecting the monoenergetic ≈ 105 MeV conversion electron signal are the straw tracker and the electromagnetic calorimeter.

2. The Electromagnetic calorimeter

The calorimeter facilitates particle identification, enhances track reconstruction at the pattern recognition level, and provides a standalone trigger. It is composed of 1348 pure CsI crystals coupled to SiPMs, each readout by preamplifiers and custom high-frequency Digitizer Readout Controller (DiRAC) boards [2]. The calorimeter is located inside a high vacuum cryostat that hosts a superconducting magnet and to reduce the number of passthroughs and the cable length, the front-end and the read-out electronics are also located inside the cryostat. This poses serious design issues due to the harsh operational conditions.

3. Calorimeter Readout electronic

The calorimeter digitazion board is named DiRAC (Digitizer and RedAdoutController) [3]. It samples up 20 SiPM signals at a frequency of 200 MHz with 12-bits ADC resolution.The main parts of the board are a large FPGA (Microchip®Polafire MPF300T), high speed ADCs (Texas Instruments®ADS4229), an optical transceiver (CERN VTRX) and an ultra-low noise clock jitter cleaner (Texas Instruments®LMK04828). The power on the board is handled by 3 DC-DC converters (Texas instruments®LMZM33606) and 6 LDO (Micrel®MIC69502). The full calorimeter is readout through 140 DIRAC boards.

4. DiRAC environmental specs and qualification tests

The DiRAC [3]has been designed to operate in the presence of high magnetic fields (1T) at a pressure of 10^{-4} Torr,

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addressing issues related to thermal dissipation in a vacuum. Concerning radiation simulation studies estimated that, in the highest irradiated regions, the digitizer boards will be exposed to a total ionizing dose of $\sim$ 0.2 Krad, neutron fluences up to $\sim 10^{10}$ 1 MeV n_{eq}/cm^2 with heavy hadrons (E $>$ 20 MeV) fluence of $\sim$ 10^9 cm^2 per year of run. The Mu2e collaboration requires to qualify the electronic boards for 5 years of life and besides to apply to this qualification a safety factor of 12. Following this requirements board prototypes have been qualified to sustain doses up to 12 Krad, neutron fluences up to $\sim 10^{11}$ 1 MeV n_{eq}/cm^2 and high energy proton fluence of $\sim$ 10^{11} $/cm^2$. To qualify DiRAC board for the hostile environment of Mu2e, it has been subjected to numerous test campaigns [4].

An extensive radiation hardness qualification campaign, carried out with photons, 14 MeV neutron beams, and 60 to 200 MeV protons certified the DiRAC design to sustain doses up to 30 Krad, neutron fluences up to $\sim 10^{12}$ $/cm^2$ and very low numbers of single-event effects occurrences due to heavy hadrons.

For additional safety a dedicated latchup-safe solid state fuse circuit was embedded in the final prototype design to automatically protect the board and recover from fault conditions.

4.1. B field test

The magnetic field test took place in two phases: at the component level to select the DC-DC converter and at the board level to verify the correct operation of the board. The component-level testing campaign began in 2015 and ended in 2019 with the selection of the LMZM 33606 (Texas Instruments®), which showed no decrease in performance at $B = 1$ T. Once the DC-DC converter was selected, a complete board was tested with $0 < B < 1.4$ T at Argonne National Lab (IL). The DiRAC has been tested in the 3 spacial directions. A slight increase in power at 1 T ($\approx$ 10%) (positioning the board in the same direction as will be in the Mu2e) was observed compared to 0 T, confirming the results of the previous test. The board analog section was tested in magnetic fields up to 1.4 T without any variation in signal amplitude.

4.2. Radiation tests

4.2.1. Total Ionizing Dose

Several Total Ionizing Dose (TID) test campaigns were performed since 2018. The TID tests were performed in two phases, at component level, to qualify the components selected for the DiRAC design, and at board level,to verify the correct operation of the board under dose. In particular in the gELBE facility at HZDR laboratory in Dresden the board were irradiated with photons from Bremsstrahlung $0 < E < 14$ with an extimated dose $\approx$ 20 Krad/h It were tested: ADC ADS4229 and regulator LTC6403 up to 18.6 Krad, several TTL gates SN74XXX, VCXO CVHD-950-50 and the Jitter cleaner LMK04828 up to 21.7 Krad. Following it several irradiation tests were performed at the board level at the Calliope facility in the ENEA laboratory in Bracciano, using Gamma rays from Co60. The final pre-production prototype of the DIRAC board was qualified up to 30 Krad of dose.

4.2.2. Displacement

Neutron tests were carried out at the component level using the FNG source at the ENEA laboratory in Frascati. All the main components of the DIRAC were irradiated with a $\sim 10^{11}$ 1 MeV n_{eq}/cm^2 fluence without evidence of damage or worsening of performance.

4.2.3. Single Event Effects

During irradiation at the FNG source, in particular the FPGA, 15 Single Event Upset (SEU) events and 3 possible latch-up events were observed while irradiating the S70FS01GSAGMFI010 flash memory. Latch-ups were limited thanks to the current limit of the power supply. The number of SEUs can be considered negligible compared to the Mu2e run, while the number of latch-ups being potentially destructive required further analysis. In the next prototype of the DIRAC board the flash memory was replaced with the MT25QL01GBBB8ESF-0SIT model which further tests demonstrated to be free from latch-up problems; nevertheless a latch-up protection circuit was added to the design. Irradiation tests with high energy protons were performed at the University of Davis (CA) 60 Mev cyclotron, at the Warrenville Medicine proton center with 200 Mev protons and at the CNAO proton center in Pavia with 60 to 200 MeV protons. The test in CNAO was the final acceptance test and almost all the components were tested with $\sim 3 * 10^{11}$ 1 MeV p/cm^2 at 116 MeV eith no evidence of latch-up and again very few SEU.

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