Mu2e-II: a 2-level TDAQ system based on FPGA pre-processing and trigger primitives
Letter of Interest for Snowmass 2021

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The Mu2e experiment at Fermilab will search for a charged lepton flavor violating process where a negative muon converts into an electron in the field of a nucleus. Mu2e-II, an upgrade of the Mu2e experiment, has been proposed to improve the expected sensitivity of at least an additional order of magnitude over Mu2e. In this paper we discuss the conceptual idea for the TDAQ system of Mu2e-II based on 2 levels: a L1 hardware layer (based on FPGA) followed by a High Level Trigger stage.

I. INTRODUCTION

Lepton flavor violation (LFV) has been observed in the neutral sector (neutrino oscillations), but not in the charged sector. In the Standard Model, the predicted rate of charged lepton flavor violating (CLFV) processes is below 10^{-50}s [1]. However, many theories beyond the SM predict CLFV processes with rates observable by currently constructed HEP experiments [1]. The Mu2e apparatus includes three superconducting solenoids: (1) the production solenoid, where an 8 GeV proton pulsed-beam (period 1.7 μs) hits a tungsten target, producing mostly pions; (2) the transport solenoid, which serves as a decay "tunnel" for the pions, and makes also charge and momentum selection, creating a low-momentum μ^- beam; (3) the detector solenoid, which houses an aluminum Stopping Target, where the muons get stopped and form muonic atoms, and the detector system (in a 1T solenoidal magnetic field) optimized to detect electrons and positrons from the conversions. The entire detector solenoid and half of the transport solenoid are covered with a cosmic-ray veto system (CRV), made out of 4-layers of extruded scintillator bars.

We propose to search for the muon to electron conversion process with a significantly improved discovery potential over currently planned projects. This idea has already been outlined in a previous expression of interest [2]. The anticipated single event sensitivity (SES) of Mu2e is 3×10^{-17} for scattering on an aluminum nucleus. The current best limit is from SINDRUM II on gold, $R_{\mu e} < 7 \times 10^{-13}$ [3].

II. ASSUMPTION AND REQUIREMENTS FOR THE TDAQ SYSTEM

Mu2e-II relies on the existence of a more powerful source of protons, the PIP-II linac [4], under construction at Fermilab. This will provide $\sim 1.4 \times 10^9$ 800 MeV protons/pulse for Mu2e-II, compared with 3.9×10^7 8 GeV protons/pulse at Mu2e, with 1.7 μs pulse spacing. In addition to that, Mu2e-II plans to increase the beam duty cycle by a factor $\times 5$ w.r.t. Mu2e. The Mu2e-II experimental setup is not finalized yet and it is currently under discussion as part of the Snowmass-2021 process. In the following, we will assume that Mu2e-II will adopt a similar experimental setup as Mu2e with higher granularity.

The requirements for the TDAQ system were derived combining the experience from Mu2e and making the following assumptions: (i) increase in the number of detector channels by a factor ~ 2, (ii) increase in the duty-cycle by a factor ~ 5. The direct consequences of these assumptions are: (a) an increase in the event data-size by a factor ~ 3 (Mu2e is expected to have ~ 200 KB/event) , (b) an increase in the amount of dose delivered to the detector system and thus also on the front-end electronics, (c) a reduced period where no beam is delivered to the apparatus, which in Mu2e is 1 s out of 1.4 s. Thus, the total data rate is expected to increase by a factor ~ 10. So, assuming a maximum storage capacity on tape of ~ 14 PB/year (twice that of Mu2e), the required trigger rejection rate would need to increase by a factor 5 w.r.t. Mu2e, which corresponds to a rejection of a few thousands.

III. FROM MU2E TO MU2E-II

Mu2e uses *artdaq*[5] and *art*[6] software as event filtering and processing frameworks respectively. The detector Read Out Controllers (ROC), from the tracker and calorimeter, stream out continuously the data, zero-suppressed, to the Data Transfer Controller units (DTC). The data of a given event is then grouped in a single server using a 10 GBytes switch. Then, the online reconstruction of the events starts and makes a trigger decision. If an event gets triggered, we pull also the data from the CRV and we aggregate them in a single data stream. Figure 1 shows a scheme of the Mu2e data readout topology described above.

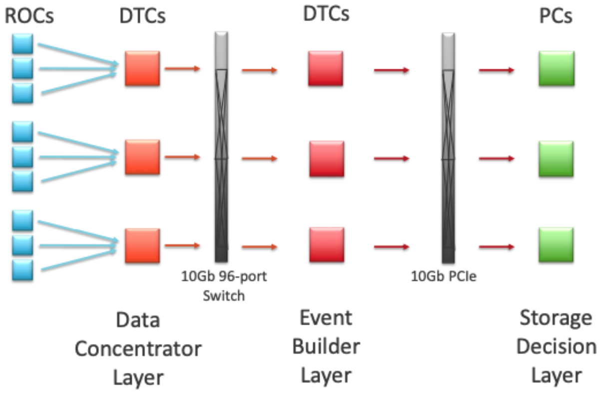

FIG. 1. Mu2e data readout topology.

The Mu2e main physics triggers use the info of the reconstructed tracks to make the final decision. The Mu2e Online track reconstruction is factorized into three main steps: (i) hits preparation, where the digitized signals from the subdetectors are converted into reconstructed hits, (ii) pattern-recognition to identify the group of hits that form helicoidal trajectories, and finally (iii) track fit through the hit wires, which performs a more accurate reconstruction of the track. More details can be found here [7].

For Mu2e-II, we propose a 2-level trigger system that takes advantage of a L1 hardware trigger and a high-level trigger (HLT) layers. The L1 level exploits: (i) calorimeter cluster reconstruction and (ii) track pattern-recognition. The major challenges are represented by: (a) the amount of data that needs to be transferred a single board and (b) the implementation of the Online reconstruction algorithms on FPGA. For the first one, a solution is to develop ROC boards based on FPGA board with large enough DDR memories (a few GB) that will transmit to the L1 trigger board only trigger primitives. The L1-board will run trigger algorithms using these primitives as input and in case a given event is triggered, the primitives will be sent to the HLT that will eventually send a pull-request to the ROCs in case the event passes the HLT selections. In this configuration, the ROCs are connected directly to the HLT layer in order to mitigate the flux of data flowing through the L1 board and simplify the data handling in the L1 board. We note that in the proposed TDAQ system, the only components housed inside the detector solenoid are the ROCs. This is rather important because it will allow us to choose a non rad-hard components (especially the FPGA and optical transceiver) for the L1 board.

Interestingly, the Mu2e run plan offers the possibility to test (parasitically) a prototype of a L1 trigger board in the second phase (after the LBNF shutdown). The FPGA market already offers products like demo boards with a large number of optical links and FPGA units installed on it [8, 9]. By using a few of these demo boards, it would be possible to implement the DAQ chain of a portion of the detector system to characterize the hardware and the algorithms performance. This test would give us a valuable feedback for the R&D finalization for the Mu2e-II TDAQ system.

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