An Enhanced Cosmic Ray Veto Detector for Mu2e-II
A Letter of Interest for Snowmass 2021

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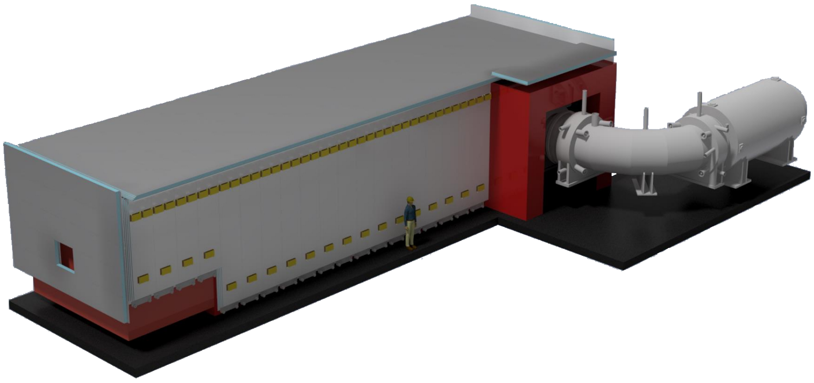
Mu2e-II, a proposed upgrade to Mu2e, can only achieve its planned additional order of magnitude in sensitivity of the $\mu^- \to e^-$ conversion rate over the Mu2e goal if the background due to cosmic-ray muons, which is the dominant background, can be reduced.The present Mu2e detector's performance will have to be significantly improved in order to keep the cosmic-ray induced background low enough to achieve a single-event sensitivity, given the higher beam rates and longer live time for Mu2e-II. We outline here plans for an enhanced cosmic-ray veto detector for Mu2e-II.

Charged lepton flavor violation (CLFV) provides an extremely sensitive window into a broad range of new-physics scenarios; hence a new generation of experiments using this probe will commence at the beginning of this decade [1–4]. A further generation of experiments with much improved sensitivities are being planned for the next decade. One of these is the Mu2e-II experiment [5], an upgrade to the Mu2e experiment. The goal of Mu2e-II is to improve the Mu2e sensitivity by an order of magnitude through an increase in muon intensity by a factor of three in concert with an increase of a factor of three in the integrated live time [6].

The Mu2e detector is surrounded by a large-area cosmic-ray veto (CRV) which identifies cosmic-ray muons and vetoes conversion-like events (in the offline analysis) found in coincidence with track-stubs found in the CRV. The detector consists of four layers of rectangular scintillating counters, each 50 mm wide by 20 mm thick, and with lengths ranging from 1 to 7 meters. The counters are outfitted with wavelength-shifting fibers placed in channels embedded in the scintillator extrusions, and read out by silicon photomultipliers (SiPMs) situated on each end of the counters [7]. The counters envelop the concrete shielding placed around the solenoid that houses the detector elements.



The Mu2e CRV surrounding the detector apparatus. The solenoids that transport the secondary muon beam to an opening in the CRV can be seen at right. The detector solenoid which houses the stopping target region and apparatus cannot be seen as it lies under the CRV and concrete shielding.

Simulations indicate that the largest conversion-like background to Mu2e is that produced by cosmic-ray muons: over 50% of the total background budget. A significant part of that background is due to cosmic-ray muons that enter the apparatus through a opening in the CRV (muon beam gap) needed to allow the secondary muon beam to reach the detector region.

The increases in beam intensity and running time for Mu2e-II pose several challenges to the CRV. First, in order to achieve the proposed Mu2e-II single-event sensitivity goal, the backgrounds need to be kept well below a single event. The largest anticipated background for Mu2e is induced conversion-like electrons produced from cosmic-ray muons [8]. Such backgrounds scale with live time: the design increase in live time for Mu2e-II of a factor of three means that those backgrounds will increase by the same factor in the absence of any improvements. Second, non-cosmic-ray induced rates in the CRV from particles produced by the primary proton beam as well as from the secondary muon beam are large and are a source of deadtime in the CRV, as well as very high rates in the front-end electronics in certain hot regions of the CRV. The Mu2e-II increase in beam rate demands measures to keep the deadtime and rates at a reasonable level. Third, the increase in the total delivered beam means an increased radiation dose to the SiPMs and the front-end electronics. Finally, aging of the light yield in the present CRV, which is presently determined to be between 7% and 9% per year, will significantly reduce its efficiency.

The current Mu2e CRV detector will not be able to keep the conversion-like cosmic-ray induced background to less than one event for Mu2e-II. Nor will it be able to keep the dead time to a reasonable level. Increased radiation doses also pose a problem. Hence a redesign of the CRV is needed for Mu2e-II. The purpose of this Letter of Intent is to present R&D efforts needed for such an upgraded CRV.

Much of the proposed work lies in the realm of simulations of different designs. These simulations are very time consuming: the probability of a cosmic-ray producing a conversion-like event is extremely small. Fortunately, the Mu2e CRV group has devoted a considerable effort in developing and qualifying a sophisticated set of fast simulation tools. These have given important additional insights into the nature of the cosmic-ray backgrounds and their sources; insights that were not available when the design of the original Mu2e CRV was finalized. These tools should allow different designs to be evaluated expediently.

The work that needs to be done can be broken up into the following areas.

- Improving the shielding in order to minimize increases in the deadtime and rates and radiation doses in hot areas.
- Improving the existing CRV design in order to achieve the goal of less than an one conversion-like background event, while keeping the rates and deadtime at a reasonable level.
- Entertaining radically new designs.
- Exploring ideas on how to veto background events due to cosmic-ray muons entering the apparatus through the muon beam gap.

The background rates and radiation doses to the CRV come from two sources: the primary proton beam interactions in the production target and from stopped-muon produced secondaries. Shielding around the production target and around the detector solenoid in which the apparatus lies need to be augmented. Much of that shielding is normal concrete. Improved shielding using barite and/or boron loaded concrete, as well as boron-loaded plastics, will be explored.

Monte Carlo studies indicate that a significant amount of the background from muons passing through the muon beam gap can be eliminated by adding shielding in critical areas around the solenoid that transports the secondary muon beam to the stopping target. These studies need to be refined using the Mu2e-II beam parameters and detector design. Another idea that could possibly identify such gap-muons would be adding a special detector at the end of the transport solenoid, just before the stopping target region, although there are many challenges in implementing such a device.

The present Mu2e CRV design has long rectangular counters. We propose to investigate a CRV detector that is based on finer granularity counters in order to reduce the single-counter rates and to reduce the false coincidence rates in reconstructing track stubs from hits in different layers of the CRV. In addition, the Mu2e CRV inefficiency is driven by unavoidable gaps between counters. Monte Carlo studies have shown that a large proportion of the muons not detected by the CRV comes from muons traversing the gaps, even though the scintillator layers are offset to minimize such effects. Improved designs, such as the use of triangular-shaped counters, will be studied in order to reduce such inefficiencies. The aging of similar triangular counters has been measured by MINERvA [9] and appears to be significantly less than that measured by Mu2e. The source of the large aging measured by Mu2e is not understood and needs to be explored.

Although the Mu2e CRV is quite large — it covers over $300\,\mathrm{m}^2$ — only a small fraction of that area has high enough rates to be a concern. Such regions could be outfitted using special high-rate detectors such as resistive plate counters (RPCs) or high-rate wire chambers.

The efficiency of the CRV depends critically on the light yield of the counters. The light yield can be improved by using SiPMs with a higher efficiency (PDE). The technology has rapidly improved since the current Mu2e CRV devices were purchased: better SiPMs are available, not only with higher PDEs, but also more radiation hard.

Another way to increase the light yield is to pot the fibers in their channels with silicone resin, epoxy, or other materials. Preliminary studies show increases up to 50% can be achieved. Further studies are needed to develop fast filling techniques, leak-free counters, and to measure the aging rate for each filling material.

A more exotic design that should be considered to enhance, or perhaps replace, the CRV is the use of a much smaller detector that would immediately surround the stopping target. A promising technology is ultra-thin silicon pixel detectors such as those to be used in the Mu3e detector [10]. Mu3e has done quite a bit of development work on this technology — including designing high-density interconnects and cooling — in preparation for the fabrication of a $1\,\mathrm{m}^2$ device, approximately the size of what the Mu2e-II CRV would need. The effect of the support structure and related infrastructure needed to bring the signals out must be simulated, as well as the radiation dose. An advantage of this design is that it would be able to detect a good fraction of the muons that go undetected through the muon beam gap in the present CRV design.

Finally, the efficiency of the CRV depends on the software algorithms used to identify hits in the counters and to combine them into track stubs. Although code has been developed for the Mu2e CRV, it has not been fully optimized. Work in exploring other reconstruction techniques, including multivariate methods, will be done.

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