Mu2e Science Requirements

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Change Log

Revision No.	Pages Affected	Effective Date
original	All	14 July 2014
1	All. Incorporated comments from Mu2e Executive Board	20 July 2014
2	All. Incorporated comments from Mu2e Collaboration	18 August 2014
3	All. Incorporated comments from Mu2e Collaboration	28 August 2014
4	Requirement A. Comments from W.Molzon	02 September 2014
5	Requirements C, E, G, K, N, P. Comments from R. Bernstein	09 September 2014
6	Minor change to end Sec. 1 and added Fig.1 to make science objective explicit	27 May 2015

I. Introduction

The Mu2e experiment will look for a muon to convert into an electron via interaction with a nucleus, $\mu^- N \rightarrow e^- N$. Note that there are no neutrinos in the final state and this reaction is therefore an example of charged lepton flavor violation. This reaction has never been seen experimentally. The conversion rate is normalized to the well known ordinary muon capture rate, $\mu^- N(A,Z) \rightarrow \nu_\mu N(A,Z-1)$, and expressed as $R_{\mu e}$. The world's current best limit on muon-to-electron conversion is from the SINDRUM-II experiment, $R_{\mu e}(Au) < 7 \times 10^{-13}$ at 90% C.L. [1]. The science goal of Mu2e is to improve this sensitivity by a factor of 10,000.

The $\mu^- N \rightarrow e^- N$ experimental signature is very clean since the interaction yields a monoenergetic electron with an energy that is approximately equivalent to the muon mass and is far above the energies of the bulk of secondary particles produced by muon interactions in the target. It is necessary to mitigate background contributions from the high energy tail in the distribution of electrons from muons that decay while in atomic orbit, from muon and pion capture processes, from muon and pion decays-in-flight, from beam electrons, from antiproton annihilations, and from cosmic rays.

Mu2e will use a pulsed beam of 8 GeV protons from the Fermilab Booster, a solenoid system composed of three elements - the Production Solenoid, the Transport Solenoid, and the Detector Solenoid – and a set of active detector elements to perform this search. Mu2e assumes it will receive about 4×10^{20} protons-on-target for physics data-taking and additional protons-on-target for commissioning, calibration runs, and other special studies. The total run time is expected to be 3-4 years. With this number of protons, the factor of 10,000 improvement can be accomplished with a single event sensitivity of about 2.4×10^{-17} and a total background yield of <1 event. This is the overall science objective of Mu2e.

II. Science-driven Requirements

To achieve the target sensitivity and limit the backgrounds, the following requirements must be met:

A. The suppression of prompt backgrounds from beam electrons, muon decay-in-flight, pion decay-in-flight and pion nuclear capture processes requires a pulsed beam. The beginning of a time window to search for conversion electrons is delayed after the proton pulse long enough to allow these backgrounds to dissipate to the required low level by means of decays, interactions in material, or by simply passing by the detectors. The optimum spacing between the pulses depends on several variables including the proton pulse width, the number of pions stopped in the stopping target per proton-on-target, the stopped-pion and stopped-muon arrival time distributions, and the choice of stopping target material.

B. The proton pulse should not be too wide so that the delayed timing search window can sufficiently suppress the prompt backgrounds while still maintaining a high efficiency for muon conversions.

C. The ratio of beam between pulses to the beam contained in a pulse is defined as the beam *extinction*. Protons arriving temporally near the measurement window produce background particles that lack the suppression compared to those in the primary proton pulse that arrive well in advance of the window. The extinction must be small enough to keep yields from the background sources above to an acceptably low level.

D. The magnitude and gradient of the solenoid fields are driven by these experimental goals: maximizing the number of stopped muons per proton-on-target; suppressing long transit-time backgrounds by preventing the local trapping or lingering of particles as they traverse the muon beamline; minimizing beam backgrounds by pitching them forward (out of the detector acceptance) upstream of the detector volume; determining the momentum of electrons originating in the stopping target with sufficient precision to suppress backgrounds from the decay of muons in atomic orbit in the stopping target; suppressing backgrounds induced by through-going cosmic rays; increasing the acceptance of conversion electrons in the detectors.

E. The reconstructed width of the conversion electron energy peak, including energy loss and resolution effects must be narrow enough to keep backgrounds from decays of muons in atomic orbit in the stopping target at an acceptably low level.

F. The ability to separate muons and pions from electrons with high reliability and high efficiency is required to eliminate backgrounds from ~105 MeV/c muons and pions.

G. Suppression of backgrounds from cosmic rays requires a veto surrounding the detector solenoid and surrounding a portion of the solenoid beamline just upstream of the detector solenoid. The overall coverage and efficiency of the cosmic ray veto should be high enough to suppress cosmic-ray induced backgrounds to an acceptably low level.

H. The muon beamline is required to have high efficiency for the transport of low-energy muons so that a sufficient number of stopped muons can be obtained to reach a single-event-sensitivity of about 2.4×10^{-17} with about 4×10^{20} protons-on-target in 3-4 years of data collection.

I. To mitigate background from muon and pion decay-in-flight, the muon beamline must suppress transport of high-momentum muons and pions. The beamline must also greatly suppress the transport of high momentum electrons.

J. The muon beamline should avoid a direct line-of-sight path of neutral particles (mainly photons and neutrons) from the production target to the muon stopping target and to the nearby detectors.

K. To mitigate backgrounds induced from antiproton annihilation, the muon beam line is required to mitigate the fluxes of antiprotons and secondaries from antiproton annihilations before they arrive at the Detector Solenoid. This is accomplished by placing thin windows in the muon beam line at the appropriate places that absorb almost all antiprotons but very few of the muons.

L. The muon beamline should be evacuated to minimize multiple scattering contributions to the momentum resolution, to suppress beam backgrounds from scattering into the detector acceptance, to avoid Townsend discharge of the HV interconnects in the detector region, and to suppress the number of muon stops on gas atoms in the detector region.

M. In order to measure some of the backgrounds *in situ*, the capacity to take data outside of the search window time interval must exist.

N. For calibration purposes, the capacity to collect positively charged muons and pions in the stopping target with sufficient statistics, while suppressing negatively charged particles, is required.

O. The capacity to reduce the magnetic field in the detector region, in a repeatable way for calibration purposes, and the ability to apply such calibrations to full field operation, is required.

P. The capacity to measure the beam extinction is required. The measurement precision and accuracy must be commensurate with demonstrating that item C above has been satisfied. The measurement must be made on a timescale that does not sacrifice a significant fraction of data should a problem be uncovered.

Q. The capacity to determine the number of ordinary muon captures with a precision that does not significantly affect the uncertainty on the measured conversion rate, $R_{\mu e}$, must exist.

R. The capacity to identify and record events of interest must exist.

S. The detectors must be able to perform in a high-rate, high-radiation environment. The detector geometric acceptance must be maximized for detection of electrons near the conversion electron energy (~105 MeV). Although not strictly a requirement, the general approach would also be to minimize detector acceptance to the large flux of lower energy charged particles emanating from the stopping target.

T. The energy of electrons near 105 MeV must be determined with sufficient absolute precision to allow a meaningful comparison between the predicted DIO endpoint spectrum and the observed data.

These science requirements flow down to the requirements and specifications as shown in the figure and table below.

References

[1] W. Bertl et al. (SINDRUM-II Collaboration), Eur. Phys. J. C47, 337 (2006).

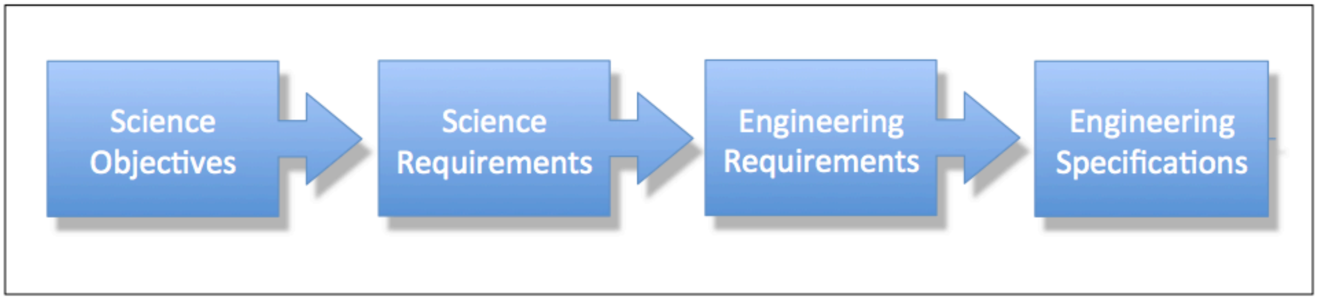

Figure 1: Illustration of how the engineering requirements flow down from the science objectives.

Science-driven Requirement	Engineering Requirements document(s)
A. Pulsed proton beam	Mu2e-docbdb-1105
B. Proton pulse width	1105
C. Proton beam extinction	1175
D. Solenoid field magnitude and gradient	945, 946, 947
E. Momentum resolution	946, 732, 1275, 1437, 1439
F. Particle identification	864
G. Cosmic-ray veto	944
H. Efficient low-energy muon transport	887, 945, 1044, 1437
I. Suppression of high-energy e, μ, π transport	1044
J. No line-of-sight neutrals	947
K. Antiproton mitigation	1044
L. Muon beamline evacuation	1481
M. Collect data outside the search window	732, 864, 944, 1150
N. Collect $\mu+$, $\pi+$ calibration samples	1044
O. Collect data at reduced fields for calibrations	1275
P. Measure extinction	894
Q. Determine number of ordinary muon captures	1438
R. Identify and record interesting events	1150, 864
S. Detectors must perform in high-rate high-radiation environment	732, 864, 894, 944, 1371, 1438, 1439, 1506
T. Achieve sufficient absolute energy calibration	1182, 1275

Table 1 The science-driven requirements and the technical/engineering requirements documents to which they flow down.