Extinction Monitor Requirements

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Change Log

Revision No.	Pages Affected	Effective Date
Rev. 1	All	May 24, 2010
Rev. 2	New figure on p3. Implementation of some comments.	January 18, 2011
Rev. 3	New figure and changed text on page 3	March 30, 2012
Rev. 4	Table 2, changed primary requirements from time to number of protons on target. Miscellaneous cleanup.	November 27, 2013
Rev. 5	Miscellaneous typos and clarifications.	June 11, 2014
Rev. 6	Minor Typo	June 24, 2014
Rev. 7	Page 1	June 27, 2014
Rev. 8	Removed separate upstream extinction monitor requirements and merged them into the downstream monitor requirements.	September 18, 2014
Rev. 9	Addressed comments and rearranged some sections.	September 19, 2014
Rev. 10	Minor typo in Table 1 caption.	September 22, 2014
Rev. 11	Fixed confusing wording in integration spec.-EjP	September 29, 2014

Extinction Monitor Requirements

The Mu2e experiment proposes to use a proton beam pulsed at approximately 0.6 MHz to produce a muon beam to search for the conversion of muons to electrons in the field of a nucleus. The use of a pulsed beam is motivated by the fact that a significant background is produced when other secondary beam particles travel from the production target, through the transport solenoid, and into the detector solenoid during the measurement interval. These secondary-induced backgrounds are prompt relative to the 864 ns lifetime of muons captured on aluminum, thus they are referred to collectively as *prompt backgrounds* and include pions that radiatively capture on the stopping target, muons or pions that decay in flight, and beam electrons. For secondaries arising from the primary proton pulse, this background can be reduced to an acceptable level by simply holding off the measurement period for ~670 ns after the center of the ~250 ns wide proton pulse[1]. This leaves a measurement window of ~900ns, as illustrated in Figure 1.

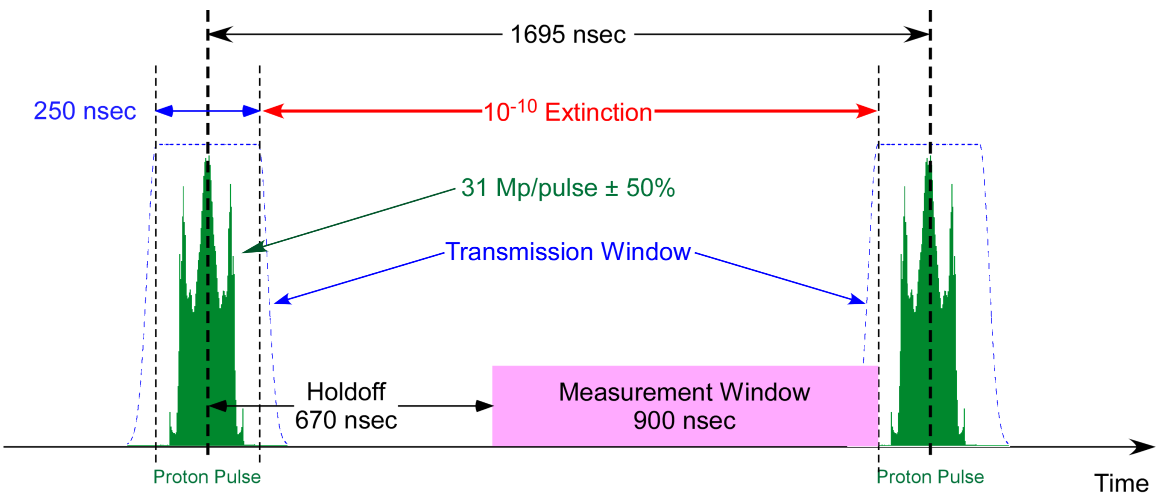

Figure 1: Graphical illustration of a Mu2e beam cycle showing the proton pulse along with holdoff and measurement windows. All values are approximate.

The same background can occur during the measurement window if primary protons hit the production target outside of the beam pulse, thus putting a limit on the number of protons allowed to hit the production target between pulses. We define the *beam extinction* as the ratio of the number of protons striking the production target between pulses to the number striking it during the pulses. It has been established (Mu2e-Doc-1175) that an extinction of approximately 10^{-10} is required to reduce these backgrounds to an acceptable level. The extinction requirement varies with the exact time that the proton strikes the target between the pulses, and 10^{-10} is a representative number assuming that the out-of-time particles are distributed uniformly between pulses.

[1] The current modeling suggests that the distribution will likely have tails, which will require a transmission window approximately 250 ns wide.

The pulsed beam is produced by slowly extracting an RF bunched beam from the Delivery Ring, resulting in proton pulses ~250 ns wide, separated by the 1.7 μs revolution time in the ring. The expected extinction of the extracted beam of 10^{-4} to 10^{-5} (Mu2e Doc-2696) makes it likely that a secondary extinction device will be required to improve the quality over that coming directly from the Delivery Ring. A secondary extinction device, consisting of AC dipoles and collimators that deflect and absorb inter-pulse protons, will be installed in the proton beam line that transports protons from the Delivery Ring to the production solenoid target. Preliminary calculations show that an additional suppression of better than 10^{-6} can be achieved (Mu2e DocDB 2083).

Regardless of the extinction level that the beam delivery scheme achieves, the experiment can only base its background estimate on the extinction level it can *measure*, so it's vital to be able to measure extinction with at least the sensitivity as that required by the analysis. In addition, once the required extinction level is achieved, it's possible that hardware problems could cause it do degrade, so the extinction must be continuously monitored during the time data is being taken.

The ultimate monitoring technology would provide single event sensitivity capable of seeing a single inter-pulse proton, while maintaining a dynamic range that can withstand the full 10^{7} protons in the primary beam pulse. This solution is not currently considered a technically feasible, so instead an integral device that measures the extinction over many Mu2e cycles will be employed. A critical parameter is the integration time, or number of Mu2e cycles that must be integrated in order to achieve the desired extinction sensitivity. For the physics analysis, the relevant timescale is the duration of the experiment. However, to prevent significant data loss due to an unexpected change in beam conditions or equipment failure, an integration time on the order of a few hours is acceptable.

The experiment will use a statistical method for measuring extinction, which relies on using a monitor with a limited acceptance to eliminate saturation during the bunch, and then overlaying and integrating subsequent bunches to build up a time distribution of particles in and out of the nominal bunch. A time resolution of 10 ns (RMS) for individual particles is sufficient. For the potential case where particularly bad spills occur with many leaked inter-bunch protons, the monitor response should have a dead-time <10 ns. It is important that the extinction monitor is able to directly monitor the intensity of the primary proton beam in addition to the protons that arrive between spills. In this way the extinction rate can be directly determined with minimal reliance on simulation of detector acceptances and efficiencies. A 10% error in measuring the primary proton beam due to rate-dependent inefficiencies would result in a 10% error on the measured extinction rate. The rate-dependence over the dynamic range from single protons up to the 10^{7} protons expected in the primary pulse should therefore be linear (or at least understood) at the 10% level.

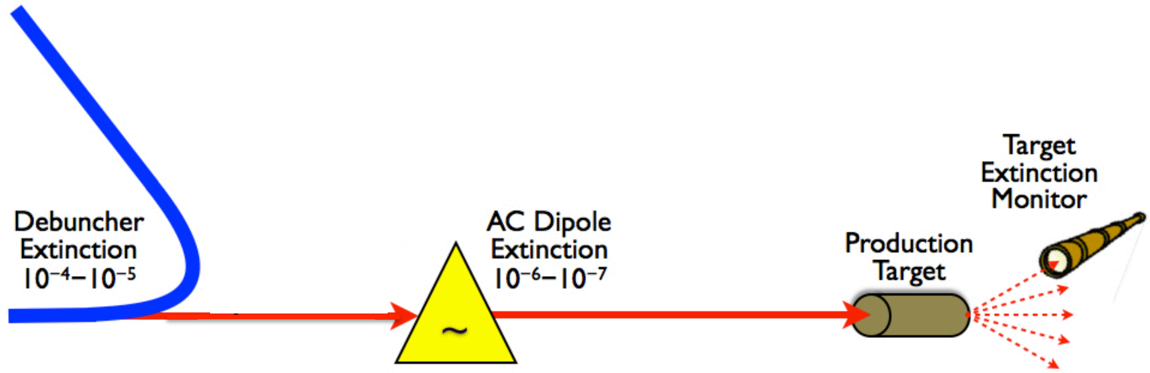

Figure 2: Illustration showing the position and conceptual operation of the extinction monitor.

The placement and conceptual operation of the extinction monitor are depicted in Figure 2. The monitor serves a number of purposes.

1. The monitor measures the ultimate quantity of interest for the physics analysis, namely, how many secondaries are produced between pulses.
2. The monitor can be used to continuously monitor the performance of the AC dipole.
3. The monitor can measure the incoming primary proton beam properties, e.g. bunch temporal width and beam intensity throughout the spill.
4. The monitor measures the time distribution of inter-bunch protons to aid in diagnosing their source and later optimize how the measurement window is defined.
5. The monitor can be used to establish data quality cuts for the final analysis.

The environment of the target monitor has the potential to be quite radioactive. The lifetime of the device should be long enough that at most one replacement is required during the initial Mu2e data run where $\sim 4\times 10^{20}$ protons-on-target (POT) are expected. Furthermore, in the event that minor repairs to the device are needed, the time to cool down and access the device should be kept to less than 4 hours to prevent significant loss of data. Note the acceptable access time here really depends on the mean-time-between-failures. If a pessimistic scenario of a monthly failure is assumed then the experiment will lose two days of data over the course of a year to cool-down (repair time not included). Because of the difficulty of accessing the target monitor, every effort should be made to make it durable and trouble-free.

The target monitor should be available as soon as beam can be delivered to the production target.

Specification	Value
Sensitivity (90% C.L.)	10^{-10}
Extinction accuracy	10%
Integration time	6×10^{16} POT (~3 hours at design intensity)
Timing resolution (RMS)	<10 ns

Specification	Value
Dead-time	<10 ns
Rate-dependent error over dynamic range	<10%
Initial readiness	When the production target is ready
Access time (assuming monthly access is needed)	4 hrs
Radiation hardness (minimum protons delivered before replacement is required)	4×10^{20} POT

Table 1: Specifications for the extinction monitor.

An overview of the specifications is given in Table 1. In addition to the items listed in the table, the following general considerations apply.

1. The monitor should be operating at all times during data acquisition.
2. Monitor data should be available as part of the online monitoring tools.
3. Data from monitor must be synchronized to the beginning of the spill, so that the time evolution of out of time beam within the spill can be studied.
4. The monitor should measure the primary proton pulse characteristics in addition to the extinction.

In addition to the extinction monitor, it will be important to monitor the proper operation of the AC dipole system. This will be done by continuously observing the amplitude and phase of the harmonic components via the controller system and by using beam loss monitors to detect anomalous losses on the primary collimator, with a sensitivity of ~.1% of the nominal bunch size.

Problem	Effect	Proposed Monitor/Remediation
RF noise in Delivery Ring	Particles leak out of the nominal bucket and appear out of time.	Occasionally running without the AC dipole to monitor out of the Delivery Ring with sensitivity at the 10^{-5} level.
Non-optimal momentum collimation in Delivery Ring	Particles migrating out of the nominal bucket will not be effectively extinguished	Same as above.
Incorrect (low) amplitude of RF	This will result in partial debunching of beam and reduced efficiency in the momentum collimation	Same as above + reduced amplitude in the RF will result in a longer bunch, a continuous monitor of the bunch length is vital
Non-uniform slow extraction	Problems with slow extraction system could change the transverse parameters of the extracted beam	Same as above + monitoring of the transverse beam profile should give an early indication if there is any significant problem with the slow extraction.
Incorrect magnitude of the magnetic fields in the individual AC dipole elements	Beam will not be sufficiently deflected by the AC dipole elements	Continuous monitoring of field within magnet, and target extinction monitoring at the 10^{-10} level.

Incorrect phase of the AC dipole elements with each other or with the beam	Beam transmission efficiency will be reduced	Phase monitor of AC elements and beam, and target extinction monitoring. Also, any significant phase error will reduce transmission efficiency.

Table 2: Potential problems that could result in poor extinction.

This direct monitoring should insure that the AC Dipole is operating correctly; however, more subtle problems with the bunch formation could lead to degraded extinction of the beam coming out of the Delivery Ring. For this reason, it will be useful, particularly during commissioning, to turn off the AC Dipole and run beam straight to the production target. In this case, we should be able to measure extinction at the 10^{-5} level that is expected from the Delivery Ring, with about $2x10^{14}$ protons on target. This would require 30 seconds at the nominal beam intensity and duty factor, and would allow quick feedback for any required tuning. Table 2 lists potential problems with the extinction system, along with how the extinction monitor and other methods will be used to address them.