Beam Extinction Requirement for Mu2e

Mu2e Document 1175

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Change Log

Revision No.	Pages Affected	Effective Date
Rev. 1	All	11/12/10
Rev. 2	All-Significant update	2/27/11
Rev. 3	Update	11/24/13
Rev. 4	Addressed comments and clarifications across much of document	12/31/13
Rev. 5	Included comments from S. Werekema	4/26/14
Rev. 6	Reworked discussion of time-dependent extinction. Added references.	6/3/2014
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Rev. 8	**Included Steve's comments**	**6/18/2014**

Beam Extinction Requirement for Mu2e

This note gives the allowable beam extinction level for Mu2e. The bottom line is given in the summary at the end of this note.

I. Introduction

The Mu2e experiment will use a pulsed proton beam. This note describes the requirement on the maximum allowable out-of-time proton flux occurring during the time period between the narrow (~250 ns wide) proton pulses in the Mu2e experiment (extinction requirement). These out of time protons lead to fake conversion electrons during the measurement period. The largest channel for such backgrounds comes from a pion traversing the beam line, stopping in the stopping target, and undergoing radiative pion capture (RPC). The photon from RPC can pair produce in the target, emitting an electron near 105 MeV that can fake a conversion electron. Other background sources affected by the beam extinction include beam electrons, and in-flight pion and muon decays.

II. Discussion

The Mu2e 8 GeV primary proton beam will be pulsed, with the pulses themselves being as narrow in time as possible [1]. The optimal proton pulse spacing period is between one and several times the muonic aluminum lifetime (864 ns). This is well matched by the one-circuit period of stored proton beam in the Debuncher, 1.695 microseconds.

At present, our sensitivity studies use a measurement period (MP) of [700,1595] ns where t=0 corresponds to the center of the proton pulse as it arrives at the production target. While the specification below is derived assuming this particular MP, it should be kept in mind that the MP will be re-optimized once data are in hand. Consequently, we will specify a time window during which a required extinction level must be achieved that includes some additional cushion in order to allow for this later optimization.

The proton flux must be suppressed between proton pulses to avoid backgrounds during the MP. The level of suppression is called the extinction. The requirement is driven by the background from RPC, which increases linearly with the extinction [2]. A requirement on the average extinction is derived in Sec. III assuming a uniform timing distribution for the out-of-time protons and integrating over the period between proton pulses. In reality there will be some time structure to the out-of-time beam. We discuss the time-dependent extinction in Sec. IV.

III. Extinction

We define the extinction as the ratio of out-of-time protons striking the production target to the total protons striking the production target:

$$\text{"extinction"} = \frac{\text{number of out - of - time protons striking the production target}}{\text{total number of protons striking the production target}}$$

where in-time protons are defined to be within +/- 125 ns of the center of the proton pulse. This could be the ratio in a single pulse, or averaged over many pulses.

In order to keep the RPC background below 0.1 event, the extinction is required to be 10^{-10} or smaller. As discussed in [2], this upper limit on the extinction is derived assuming the out-of-time protons (ie. those outside of +/- 125 ns of the center of the pulse) are distributed uniformly in time and can be thought-of as the “average” extinction between proton pulses.

IV. Time-dependent Extinction

The extinction requirement of Sec. III is a useful benchmark to work with and provides an intuitive and readily calculable metric for the proton beamline group to use during their design work. In reality though, the out-of-time protons will not be uniformly distributed in time and it’s necessary to understand how the experimental sensitivity is affected for more realistic time distributions.

Given the long delay between the end of the proton pulse and the start of the MP, it is clear that out-of-time protons that strike the production target just after the proton pulse are less dangerous than those that strike the production target near the start of the MP. The pion decays rapidly as it travels toward the stopping target and disappears (annihilates) as soon as it gets there. Therefore pions produced by out of time protons that arrive well before the beginning of the MP are less likely to produce background than those arriving just before the beginning of the MP). Figure 1 shows the distribution of the pion arrival time at the stopping target for a realistic simulation of the ac-dipole transmission efficiency [3] and solenoid fields [4] for a proton pulse modeled as a delta function at t=0 and for a realistic pulse shape [5]. Note that for the delta function the first pions arrive at the stopping target about 100 ns after their arrival at the production target. This implies that the required extinction level must be met at least 100 ns before the start of the MP. It also implies that it can be relaxed starting about 100 ns before the end of the MP.

The degree to which the extinction can be relaxed and the time period during which it can be relaxed depend upon the selection requirements being made, most significantly the definition of the MP. In the end it is the integrated number of background events falling in the MP that counts. To help illustrate this point we use a full simulation to calculate the probability that a pion produced in the production target at time *t* will yield an RPC background event. Figure 2 displays this probability as a function of the proton arrival time at the production target. For this plot we used the standard track selection criteria [6] and defined the measurement period to be 700 < t_0 < 1695 ns, where t_0 is determined from the track fit and corresponds to the time the tracked crossed the midpoint of the Mu2e tracker. Note that t_0 is offset from the arrival time of the proton at the production target due to the transit time from the production target to the stopping target (~200 ns on average) and due to the time-of-flight from the stopping target to the tracker mid-point (~40 ns on average). All these effects are included in Figure 2.

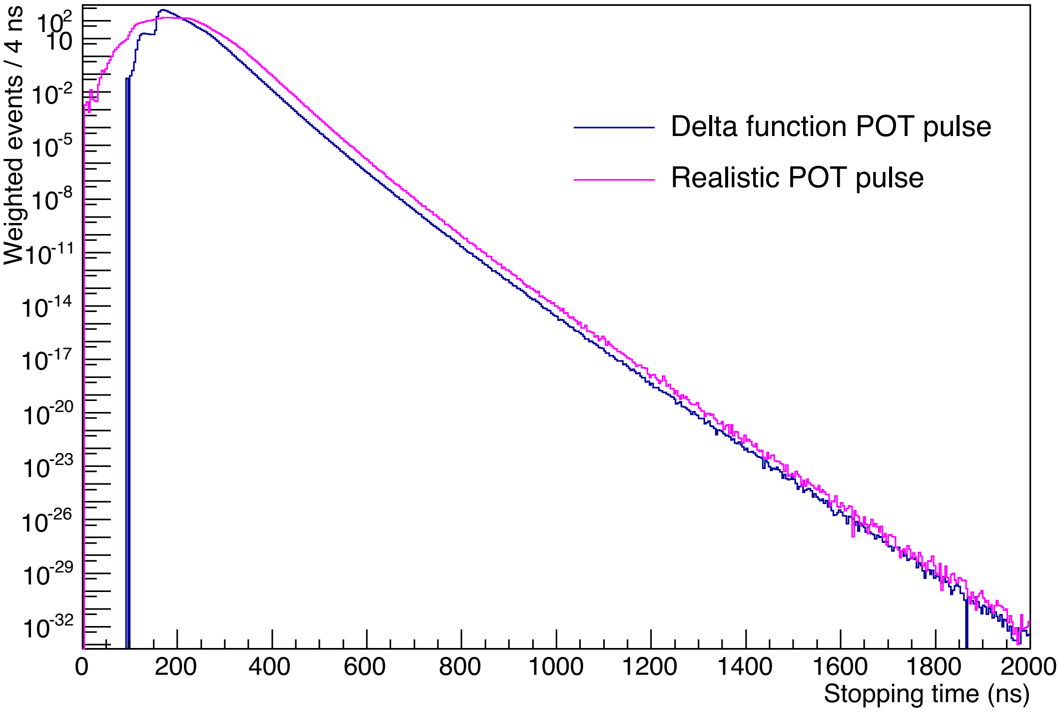

Figure 1 The distribution of pion arrival time at the stopping target using a realistic distribution for the proton arrival time at the production target (pink) and using an ideal proton pulse distribution, a delta function at t=0 (blue).

The time-dependent extinction (for this particular set of selection requirements) can be qualitatively inferred from Figure 2. The time-dependent extinction requirement is at its most stringent from 450 < *t* < 1450 ns (where *t* corresponds to the proton arrival time at the production target) but can be progressively relaxed outside those times. In principle one can convolute any given proton time distribution with Figure 2 to estimate the RPC background. An acceptable time-dependent extinction is one that does not significantly affect the experimental sensitivity. Obviously, if the selection requirements change then Figure 2 would be affected and so, too, would the time-dependent extinction requirements.

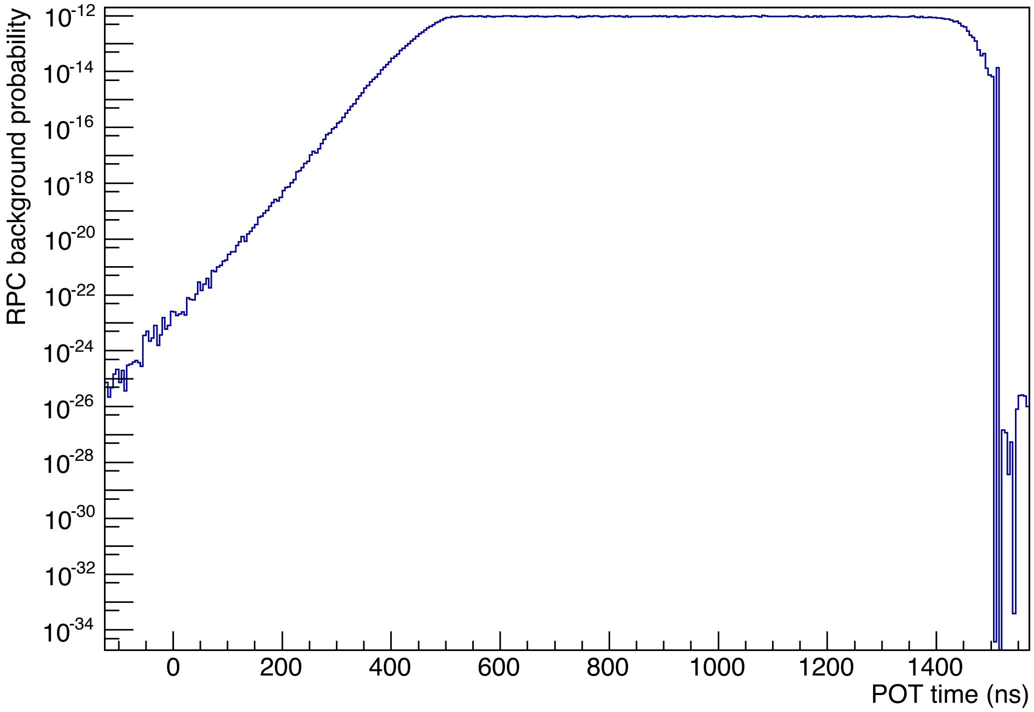

Figure 2: The probability that a pion created at the production target will give rise to an RPC background event satisfying all the selection criteria discussed in the text as a function of the proton (that creates the pion) arrival time at the production target.

Since the RPC background yield depends on the details of the proton time distribution, including the shape of the out-of-time protons, it is difficult to succinctly specify a requirement for the out-of-time extinction. This is exacerbated by the fact that small changes in the MP can significantly affect the RPC background yield so that the optimization of the MP is another important component in determining whether or not a given proton time distribution is acceptable or not. To address these issues we have developed an analytic tool that calculates the degradation in experimental sensitivity due to a given proton time distribution by comparing the 3σ sensitivity of Mu2e for the given distribution to the same sensitivity for an ideal proton beam (ie. a delta function at t=0 and perfect extinction) [7]. The MP is optimized to provide the best 3σ sensitivity for each proton time distribution separately. All the dominant background sources (ie. DIO, RPC, and cosmic-ray induced) are considered in the optimization. We adopt as our requirement that the time-dependent extinction, and the resulting out-of-time proton distribution it generates, should not degrade the Mu2e sensitivity by more than 20% as determined using the methodology of Ref. [7]. An easy to use interface has been developed that takes as input a histogram of the proton time distribution and returns the degradation in sensitivity. Studies of other backgrounds in addition to RPC, for example in-flight muon and pion decays and beam electrons demonstrate that these backgrounds have no significant effect on the extinction requirements.

V. Conclusions

To mitigate what would otherwise be an overwhelming background from pion-capture processes, it is necessary to suppress out-of-time protons. We require that the average extinction, defined in Sec. III, be 10^{-10} or smaller. This is derived assuming the out-of-time protons are uniformly distributed in time. For a more realistic distribution in time an analytic method has been developed to quantify the effect on the experimental sensitivity. We require that the sensitivity, relative to an ideal proton beam, be degraded by no more than 20% as defined in Ref. [7].

References

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