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SIMULATION OF BUNCH FORMATION FOR THE Mu2e EXPERIMENT

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Abstract

The Fermilab Recycler is an 8 GeV storage ring composed of permanent magnets that was crucial to the success of the Fermilab Tevatron Collider program. It is currently being used to slip-stack protons for the high energy neutrino program and to re-bunch protons for use in the Muon g-2 and Mu2e experiments. For the latter applications, the Recycler re-bunches each 1.6 µs "batch" from the Fermilab Booster into four 2.5 MHz bunches. For the Mu2e experiment, it is crucial that beam more than 125 ns from the nominal bunch center be suppressed by at least a factor of 10^{-5}. While bunch formation is currently in operation for the g-2 experiment, this out of time requirement has not been met, and the reason is not understood. This work presents a simulation of bunch formation in the Recycler, in an effort to understand the reason for this excessive out of time beam and to search for a way to reduce it.

INTRODUCTION

The Mu2e experiment aims to observe conversion to an electron of a muon that has been captured by an aluminium nucleus. This process violates charged lepton favor number and is forbidden by the standard model. A conclusive result, null or otherwise, would shed light on beyond the standard model physics. The Mu2e collaboration aims to improve on the sensitivity of previous measurements of this process by four orders of magnitude. Specifically, the experiment will measure the ratio of the coherent neutrinoless conversion in the field of a nucleus of a negatively charged muon into an electron to the muon capture process.

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z,N)} \tag{1}$$

The first search for a muon to electron conversion took place in 1955 [1]. However, more recent experiments placed a 90% CL limit on the process of 4.6×10^{-12}, and 7×10^{-13} [1]. A key component to the increase in sensitivity is the longitudinal structure of the proton beam shown in Fig. 1. Specifically, the experiment hopes to achieve $R_e = 6 \times 10^{-17}$ at 90% CL limit. The muons will be created via the decay of pions created by 800 GeV protons impinging on a tungsten target. The out-of-time protons will be eliminated using the extinction system located on the M4 beam line just before the tungsten target. The muons will then be captured on an aluminium nucleus and the resulting electrons will be detected [1]. A diagram of the accelerator complex is shown in Fig. 2. The proton pulses are ∼ 250 ns wide and spaced 1.7 µs apart. Each pulse contains 39×10^6 protons. The experimental signature of the process will include a large background from muons decaying in the orbit of the nucleus before capture can occur.

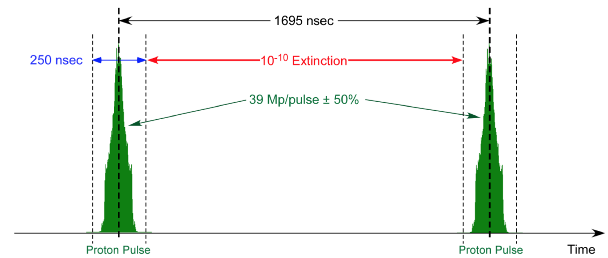

Figure 1: Longitudinal structure of the proton beam after exiting the delivery ring [2].

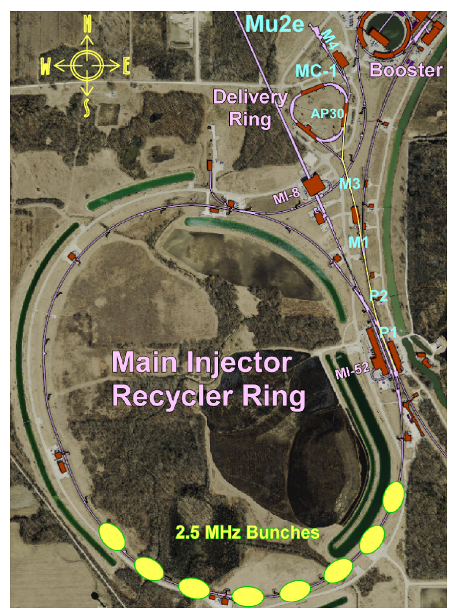

Figure 2: Fermilab accelerator complex.

EXTINCTION

The ratio of out of time protons to total number of protons in a pulse is defined as the extinction. The goal is to obtain a ratio of 10^{-10} by the time the protons reach the tungston production target. The extinction is in part accomplished with the formation of the bunches in the delivery ring.

At the delivery ring the extinction is at the 10^{-5} level. However, the extinction system depicted in Fig. 3 will be responsible for reducing the ratio another five orders of magnitude. The system will involve three collimators and two one meter long AC dipole magnets, that will be referred to as the AC Dipole. The tail collimator will remove the

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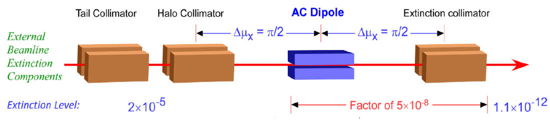

Figure 3: Extinction system consisting of three collimators and two magnets [2].

protons scattered by the electrostatic septum upon extraction from the delivery ring. The halo collimators will remove the high amplitude protons (i.e. the protons at the edge of the separatrix in phase space) so that they will not be pushed back into the space of the target by the AC dipole.

The extinction collimator will then stop all protons de-excited by the dipole. As stated above, the AC dipole will be responsible for kicking out-of-time beam into the extinction collimator.

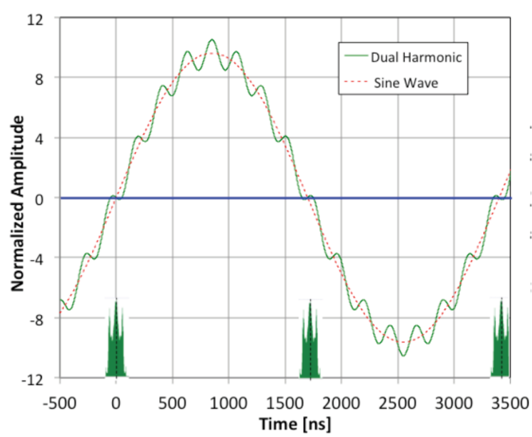

Figure 4: The AC dipole waveform overlaid with proton pulses at the transmission points [3].

The AC dipole will be driven by two harmonics: one at 300 kHz and 4.5 MHz. The 300 kHz harmonic is half of the bunch frequency and the 4.5 MHz harmonic is used to maximize the transmission window for the in time protons in the pulse. Figure 4 shows the AC dipole waveform overlaid with proton pulses at the transmission points.

Simulations

Major contributions to the out-of-time protons is caused by the frequency mismatch between the Booster and the Recycler, the machine impedance and space charge effects. The Recycler has large longitudinal impedances at 2.5 MHz and 53 MHz. For these reasons, incorporating space charge effects and longitudinal impedance in the Recycler RF model is extremely important. Beam Longitudinal Dynamics (BLonD) simulation framework allows for the incorporation of both of these effects [4].

The Booster has a frequency of 53 Hz and the Recycler frequency is 2.5 MHz. For this reason, the Recycler must synchronously capture eight 53 Hz bunches into a 2.5 MHz bucket of the Recycler using a voltage ramp depicted in Fig. 5. Because the ramp must be executed in a timely manner, it is impossible to prevent the filamenting of the particles in the RF bucket of the Recycler. Figure 6 shows a simulation of the eight Booster bunches after being captured into the Recycler bucket. This filamenting creates variations in the time distribution of the bunches that extend outside the 125 ns window required for the in time protons.

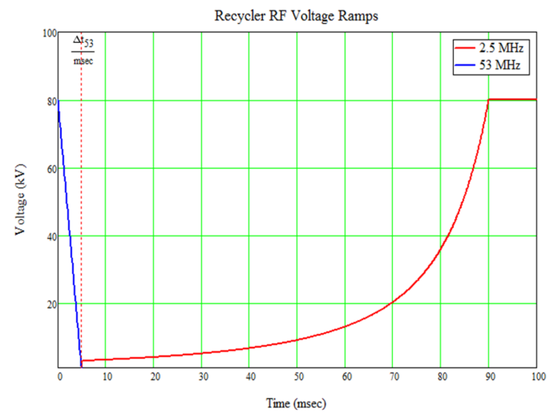

Figure 5: Re-bunching sequence of the Recycler [2].

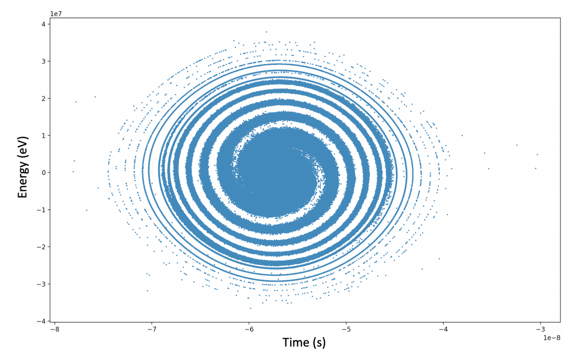

Figure 6: A simulation of the proton beam in the Recycler after the re-bunching sequence has been executed. The motion of protons in longitudinal phase space consists of a counter-clockwise rotation about the center of the RF bucket. Rotation near the center of the bucket (small amplitude motion) is faster than that the near the edge of the bucket. This gives rise to a filamenting of the beam in longitudinal phase space as the beam makes repeated revolutions around the bucket. This filamenting is clearly visible in the above plot.

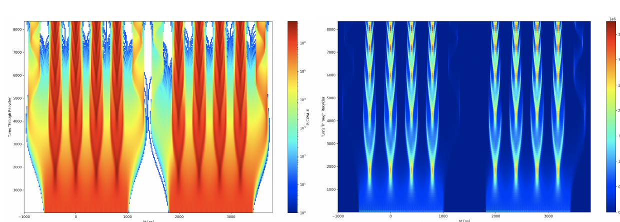

Figure 7: A simulation using BLonD of the re-bunching sequence in the Recycler with no space charge or impedance effects included.

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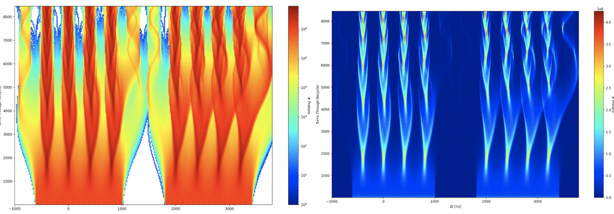

Figure 8: A simulation using BLonD of the re-bunching sequence in the Recycler with space charge and impedance effects included. Impedance was calculated using 6× the shunt resistance.

The effects of including impedance and space charge in the simulations can be seen in Figs 7 and 8. The formation of "ghost" bunches can be clearly seen along side the two batches (each composed of four bunches), increasing the number of out-of-time protons significantly.

Figure 9 shows the simulated extinction just prior to extraction from the Recycler to the Delivery Ring. At the end of the re-bunching cycle, the extinction level is simulated to be 2.01×10^{-4}, almost one order of magnitude above the requirement of 10^{-5} and an order of magnitude higher than in would be without impedance and space charge effects included.

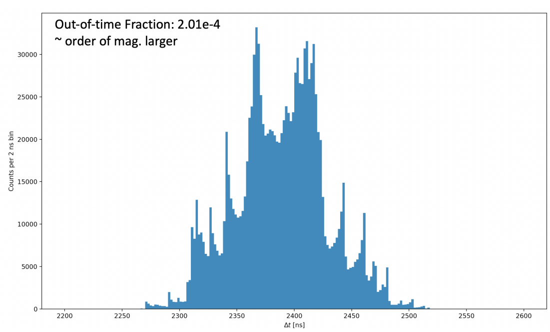

Figure 9: Simulated extinction, with 6× the measured shunt resistance as the impedance, as a function of time where t = 2400 ns is the center of the Recycler's RF bucket.

CONCLUSION

The effects of the re-bunching cycle, impedance and space charge were described and results of simulations were presented here. While the extinction requirement of 10^{-5} is predicted to be out of reach for the Recycler due to these effects, future work simulating the Delivery Ring must be completed before conclusions can be made about achieving the full requirement. In addition, several mechanisms can be put in place to reduce the out-of-time beam. For example, beam loading compensation can be used to reduce the effects of the machine impedance.

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