AN ESTIMATE OF OUT OF TIME BEAM UPON EXTRACTION FOR MU2E

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Abstract

For future experiments at the intensity frontier precise and accurate knowledge of beam time structure will be critical to understanding backgrounds. The proposed Mu2e experiment calls for $\sim 200ns$ (FW, 40 ns rms) bunches of 3×10^7 8GeV protons and a bunch spacing of 1695 ns. The interbunch beam must be suppressed from the main pulse by a factor of 10^{-10} [1], this is known as the beam *extinction* requirement [2]. Beam from Fermilab's Booster will be formed into 2.5 MHz buckets in the Fermilab Recycler then transferred to the Delivery Ring (formerly the Debuncher) and slow spilled from a single filled bucket in an h=4 RF system. Because the final extinction level is not expected from the Delivery Ring an AC dipole and collimation system will be used to achieve final extinction. Here I present calculations leading to a first estimate of the extinction level expected upon extraction from the Delivery Ring of $\leq 3.36 \times 10^{-4}$. Intrabunch, residual gas scattering and scattering off the extraction septum are included. Contributions from bunch formation are not considered.

MOTIVATION

The Mu2e experiment will search for the coherent conversion of a muon to an electron in the field of a nucleus with an expected sensitivity to branching ratios on the order of 10^{-17} [3], an improvement of 4 orders of magnitude over previous experiments [4, 5, 6]. The Mu2e signal event is an electron with an energy equal to the 105 MeV muon mass — less the negligible nuclear recoil that satisfies momentum conservation. Several main classes of backgrounds can fake this signal event: cosmic rays, eliminated with shielding and a veto system. The intrinsic spectrum of a standard muon decay into an electron and two neutrinos. And pionic atoms which decay via pion capture on the nucleus. This capture leads to a γ with energy high enough to create an $e^+ - e^-$ pair, with a kinematic endpoint for the e^- above the signal energy.

In a standard muon decay the electron energy spectrum drops to zero as one approaches the kinematic endpoint, very near the muon mass, and so detector resolution is the crucial factor in mitigating this background.

In the case of the pionic atoms, the lifetime for the pion capture is much shorter than the 864 ns lifetime of a muonic atom in the stopping target. Because of this, a pulsed beam structure coupled with a detector dead time immediately after the arrival of the beam allows the pionic background time to decay. A significant fraction of muonic atoms remain during the data-taking window until the next beam pulse arrives.

The specific structure of the pulsed beam is set by considerations of the background levels from this radiative pion decay and the lifetime of the muonic atoms. The beam should have a period on the order of several muonic atom lifetimes and be clean enough between pulses to rule out radiative pions from late arriving protons to such a degree that the aforementioned experimental goal can be achieved.

MU2E Extinction Requirement

In Mu2e, the beam structure is based on the 1695 ns period of the Delivery Ring at 8 GeV— formerly Debuncher. This is roughly twice the 864n s muonic atom lifetime in the aluminum stopping target and so a good match for the experiment. The design bunch width is approximately $\pm 100ns$. Analysis of the radiative pion background in this scheme impose the requirement that the beam should be clean to the level of one part in 10^{-10} between pulses [1]. With a pulse intensity of $3 \times 10^7 \pm 50\%$ this means one stray proton in 30 pulses or so.

An initial level of extinction will be provided by bunch formation described above. An AC dipole will be used to sweep the out-of-time beam onto a collimator to achieve final extinction. Because of this AC dipole system, the final 10^{-10} extinction is not necessary in-ring, but we do need to understand what to expect at the AC dipole to ensure it will achieve final extinction. Simulations of the AC dipole have shown that the most likely contribution to out of time beam after the final extinction comes from particles which are very near the in-time window [7]. This is where in-bucket, out-of-bunch particles will reside, thus it is important to understand the structure of the out-of-time beam near the bunch. The rest of this paper presents several calculations detailing the contribution to out-of-time beam from several sources.

IDEAL BEAM STRUCTURE AND DIFFUSION

A single Booster batch will be transferred to the Recycler and bunched into four 2.5 MHz buckets. One bucket at a time will be transferred to and slow spilled from the Delivery Ring. The slow spill will take 54 msec [8]. This gives the extracted beam a period equal to the 1695 ns period of an 8GeV proton beam in the Delivery Ring and a bucket width of 425 ns. Note that the 425 ns buckets are more

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than twice the width of the transmission window. Extinction levels here will initially be set by the efficiency of the bunch formation and will decay as the beam diffuses during extraction. This paper does not consider bunch formation, only the bunch diffusion after transfer from the Recycler to the Delivery Ring.

Scattering Off Extraction Septum

Because particles approaching the septum in along the separatrix in transverse phase space must necessarily remain with in the machine aperture until they are extracted, some of the particles which are 'lost' on the septum may remain in the machine as well. Scattering off the septum will cause an energy loss for those particles that do remain in the machine. Once a particle has left the bounds of the bunch in longitudinal phase space through energy loss, synchrotron motion can move it to a position out of time over the course of the spill, see Fig. 1.

A simple G4 Beamline simulation was used to calculate the contribution to out of time beam due to energy loss caused by scattering off the extraction septum. Because I am not considering contributions from bunch formation in the Recycler, I began with an idealized bunch of appropriate energy distribution for a bunch longitudinally matched to the Delivery Ring with a maximum extent of $\pm 100ns$ from the synchronous particle in the phase coordinate. I modeled the extraction septum as a line of 100 μm wires separated by 1.6 μm distributed over 2m, consistent with existing equipment. An electric field of 7 MV/m is included directed toward the extraction side of the septum, modeled as a constant field bisecting the wires in the plain normal to the beam motion. Transversely, all protons are distributed evenly over the width of a septum wire with no angular distribution. After passing through the septum wires only particles on the recirculation side of the septum are kept, this is the only transverse cut made.

The initial and final energy distributions are shown in Fig. 2 as a dotted and solid lines respectively. The shoulder from energy loss is evident in the plot and the region of interest indicated in red. The figure of merit from this plot, the integral of the low energy shoulder, is 0.0168 protons per proton on target.

The total number of protons out of bunch(oob) after scattering off the septum will be:

$$N_{oob} = \epsilon_{ex} \times N_{Extracted} \times I_{EnergyLoss} \quad (1)$$

where ϵ_{ex} is the extraction *inefficiency*. The upper bound [8] for $\epsilon_{ex} = 5\%$, but I will use the desired upper limit of 2%. $I_{EnergyLoss} = 0.0168$ is the integral of particles outside the bunch energy range in Fig. 2 per proton on target. Because we care about beam extinction, the relevant number is $N_{oob}/N_{Extracted}$. Effectively, extinction relative to septum scattering is given by $\epsilon_{ex} \times I_{EnergyLoss} = 0.02 \times 0.0168 = 3.360 \times 10^{-4}$. Even though this only represents the effect of one pass through the extraction septum, it is reasonable to assume that this will only happen once for any given particle. If the particle remains in the machine, it's position in phase space makes it likely that it will be extracted soon, or go outside of the machine aperture.

This number is still likely high. I am considering any particle which is out of the bunch in the energy coordinate to contribute to the out of time beam. In a simulation of full 6D phase space, it will probably become apparent that much of this out of bunch beam does not survive for a sufficient number of turns to contribute to out of time beam, by being extracted before completing a quarter synchrotron turn, or by being lost somewhere in the machine. In addition, a more realistic transverse cut after the scattering events will also likely reduce this number before any tracking is done, but a better model of the extraction region and machine aperture is needed to set bounds on the phase space. Thus the number given represents a rough upper bound.

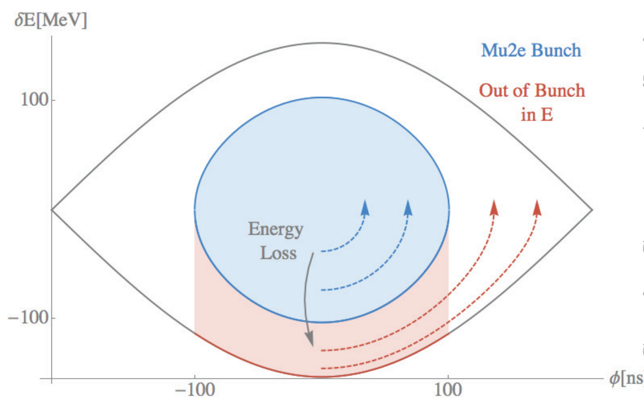

Figure 1: Longitudinal phase space bucket in the FNAL Accumulator. Energy loss will put protons in the red region, which will end up out of time after some number of turns.

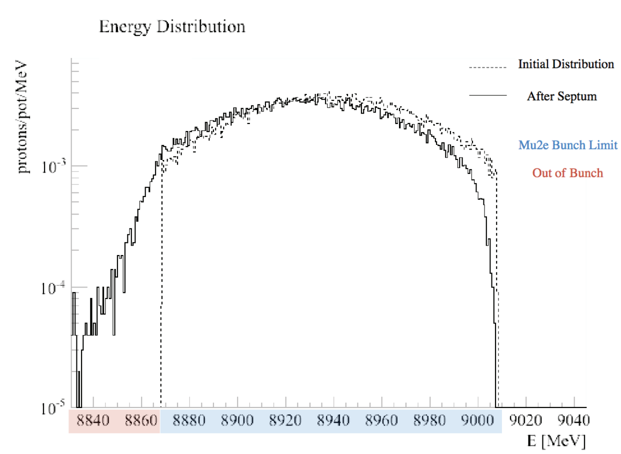

Figure 2: Energy distribution before and after passing through septum wires and applying transverse cuts. The low energy shoulder will wind up as out of time beam and integrates to 0.0168 protons/pot.

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Intra-beam and Residual Gas Scattering

To estimate the longitudinal emittance growth due to intrabeam scattering during the spill I've used the formulation of Bjorken and Mtingwa [9].The slow spill will take 54 msec [8], during which the bunch will diffuse in longitudinal phase space due to intrabeam scattering. Using machine parameters from the Fermilab lattice repository for the existing Debuncher layout longitudinal emittance lifetime is calculated to be $\tau_l = 1188hrs$. This gives an emittance growth of only ~ 1 part in 10^8 over the course of a 54 msec spill. Most of this will be due to spreading of the relatively dense core, which would contribute little to the out of time beam.

A quick calculation to rule out the importance of residual gas scattering is as follows. The number of collisions in a turn is equal to the distance traveled, D, divided by the mean free path, ℓ times the number of particles which travel the distance. If we consider a ratio of number of collisions in the vacuum to the tungsten wires, we can write $\ell_{vac}/\ell_W = \rho_W/\rho_{vac}$, where ρ is number density of the material and I've assumed similar cross sections. Only 2% of the beam intersects the septum, whereas all of the beam sees the residual gas. As for D, the total length of material in the wires is $2000 \times 1.6\mu m$ — see previous section — whereas the distance travelled in the gas is the machine circumference, $505.m$.

With machine vacuum of $10^{-9}torr$, the density of the residual gas is $3 \times 10^7/cm^3$ and the density of the tungsten wires is $6 \times 10^{22}/cm^3$. For extraction inefficiency of 2%, there are more interactions in the septum wire in a single turn than due to residual gas by a factor of $\sim 6 \times 10^5$. Residual gas interactions represent a negligible contribution.

CONCLUSION

An estimate of the upper limit of extinction upon extraction from the Delivery Ring of $\leq 3.360 \times 10^{-4}$ dominated by septum scattering has been given. Future corrections to this estimate should include more realistic transverse considerations. Notably, a full simulation of extraction which takes into account energy loss and transverse scattering for particles which are 'lost' on the extraction septum. Because this will result in more restrictive transverse cuts, due to considerations of real machine aperture, the extinction level should be improved. Even without extensive simulation, coupled with the expected performance of the AC dipole [7] in-ring extinction seems to be on course to achieve the goal set by Mu2e.

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