Fermilab Proton Beam for Mu2e

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Abstract. Plans to use existing Fermilab facilities to provide beam for the Muon to Electron Conversion Experiment (Mu2e) are under development. The experiment will follow the completion of the Tevatron Collider Run II, utilizing the beam lines and storage rings used today for antiproton accumulation without considerable reconfiguration. The proposed Mu2e operating scenario is described as well as the accelerator issues being addressed to meet the experimental goals.

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PREFACE

Through the NOνA Project [1] plans are made that will allow the Fermilab 120 GeV Main Injector to run with a 1.333 sec cycle time for its neutrino program (NuMI), with twelve batches of beam from the Booster synchrotron being accumulated in the Recycler synchrotron and single-turn injected at the beginning of the MI cycle. Recent upgrades have increased the maximum average Booster repetition rate from roughly 2.5 Hz to 9 Hz. A further upgrade to the Booster RF system to be performed over the next several years will allow the Booster to run at its maximum rate of 15 Hz. At 15 Hz, there remain eight Booster cycles during each MI period that could in principle be used for an 8 GeV (kinetic energy) beam experimental program, with $\sim 4 \times 10^{12}$ protons (4 Tp) per cycle.

The Muon to Electron Conversion Experiment (Mu2e) [2] requests a total delivery of 4×10^{20} protons on target (POT) per year for two years of running. Muons are to be produced and brought onto an aluminum stopping target in narrow (<200 ns) time bursts, separated by intervals of about 1.5 μs, somewhat larger than the lifetime of muonic aluminum. Muon to electron conversion data would be taken between bursts, after waiting a sufficient time ($\sim$700 ns) for the prompt background to subside. A suppression (extinction) of the primary proton beam between bursts by a factor of 10^{-9} relative to the burst itself is necessary to control the prompt background.

Meeting Experimental Requirements

The proton delivery method proposed by the experiment is to send Booster beam through the Recycler and directly inject into the Accumulator, where several Booster batches would be momentum stacked. Thus, in this scenario, the Recycler is used as a simple beam transport, and the Accumulator/Debuncher rings are used to generate the desired beam properties. Since this is carried out with 8 GeV kinetic energy proton beams, no new beam lines are required, and all magnetic elements operate at their present-day field strengths. A schematic of the beam line system is presented in Figure 1.

Six of the eight free Booster cycles are used to feed 4 Tp per pulse to the Mu2e experiment, three batches at at time. Figure 2 shows the proposed time line of events during MI operation. Three consecutive batches are momentum stacked into the Accumulator ring and then coalesced into a single bunch using an $h = 1$ RF system. This beam is then transferred into the Debuncher ring where a bunch rotation is performed and a single short bunch, of $\sim$40 nsec extent (rms), is captured into an $h = 4$ RF system. The total process to this point would occur within five Booster cycles. The beam then would be resonantly extracted from the Debuncher over the next 9 Booster cycles. This single bunch would produce a train of 40 nsec (rms) bursts being emitted from the Debuncher at 1.7 μsec intervals (the revolution period of the Debuncher ring) producing a structure well suited to the Mu2e experiment. Beam would be transported through an 8 GeV beam line to the experiment, presumably located to the west of the Debuncher/Accumulator tunnel. During this extraction from the Debuncher, the Accumulator can be re-filled with three more Booster batches to await transfer to the Debuncher. As can be seen in Figure 2, a total of six batches per Main Injector cycle time of 1.33 sec can be slow spilled to the experiment with a duty factor of 90%. If each batch contains 4 Tp, then the Debuncher will start with 12 Tp and if spilled over 9/15 sec at 1.7 μsec per burst will yield 3.4×10^7 protons per burst onto the target, with an average spill rate of 18 Tp/sec and a total of 1.8×10^{20} protons on target within a “Snowmass year”.

The rings being used – the Debuncher and Accumulator, and the Recycler ring – presently contain stochastic cooling (and, in the Recycler, electron cooling) equip-

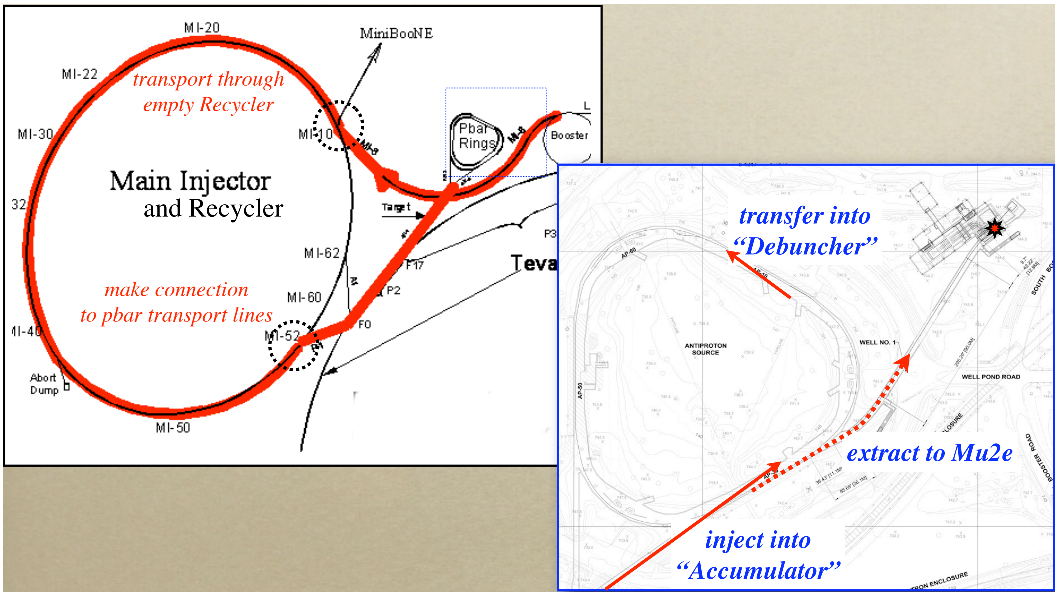


FIGURE 1. Beam transport scheme for Mu2e operation.

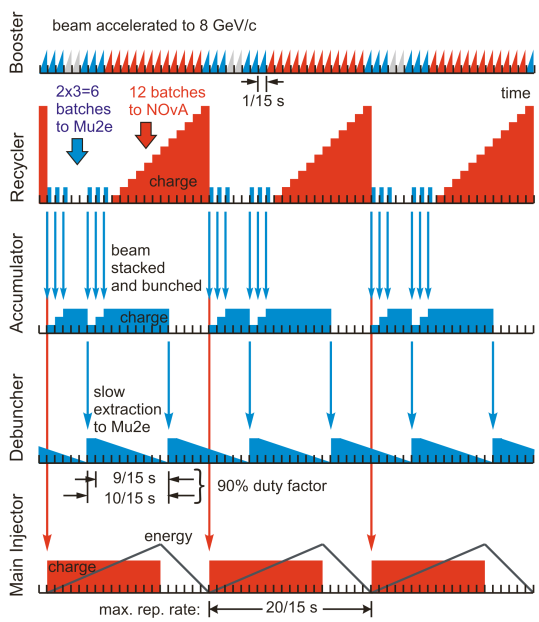


FIGURE 2. Proposed timing scheme for Mu2e.

ment used for antiproton production which will be removed to generate less aperture restrictions for the high intensity operations of any future 8 GeV experimental program.

Particle losses in the Booster currently limit the beam delivered by this synchrotron to about 1.6×10^{17} protons/hour. Comparatively, 15 Hz operation at 4 Tp per pulse would produce roughly 2.2×10^{17} protons per hour.

It is expected that the new magnetic corrector system [3], the installation of which was recently completed, will allow for this increased intensity under 15 Hz operation. Measures will need be taken to improve the environmental impact of the new uses of the antiproton source storage rings under these new high intensity conditions.

Beam Preparation and Delivery

For Mu2e, an 8 GeV proton beam must be injected from the MI-8 transport line into the Recycler, and extracted from the Recycler into the P1 transport line. The injection line is part of the NOνA project. The Mu2e experimental scenario described above only requires beam to circulate part-way around the Recycler. Thus, either (a) an extraction kicker similar to that used for injection can be arranged for extraction as well, or (b) a pulsed dipole magnet can be turned on during the Booster cycles from which beam passes through the Recycler.

Once out of the Recycler and into the P1 line, the beam is transported to the Accumulator ring in the same manner as is done presently for so-called "reverse proton" operation (used during tune up of the antiproton source). Naturally, hardware to transfer beam between the Accumulator and the Debuncher also exist and are used routinely.

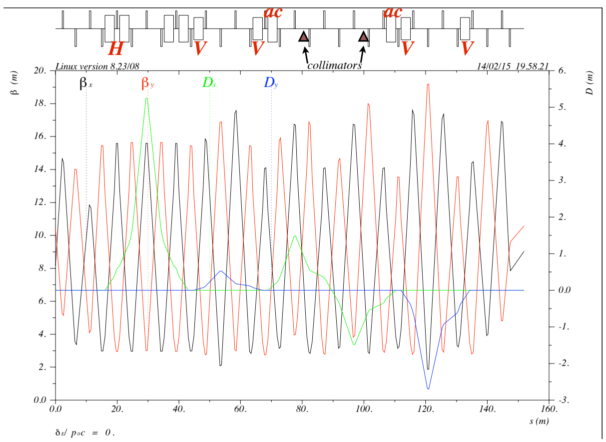


FIGURE 3. Schematic of beam line transporting 8.9 GeV/c beam from the Debuncher to the Mu2e production target. "H" and "V" in this preliminary design denote the locations of horizontal and vertical bending elements, and "ac" indicates possible locations of the AC dipole magnets used in the extinction process, with collimators located in between.

Mu2e Beam Line

Design effort for the extraction line leading toward the experiment has been started. The length of the extraction line, using the layout depicted in Figure 1, will be approximately 150-200 m and its cost and complexity roughly can be scaled from the many other 8 GeV beam lines built at Fermilab over the past decades. While a final design for the beam line elements is not in place, it will be conceptually similar to other 8 GeV transport systems, for example the miniBooNE beam line at Fermilab. One exceptional feature of the line is the extinction insert, discussed separately below. Otherwise the line will contain on the scale of 20-30 quadrupoles, a few minor bend centers, and standard cooling, powering, and instrumentation requirements. A schematic of an early beam line design showing possible betatron optical functions is provided in Figure 3.[5]

RF Requirements

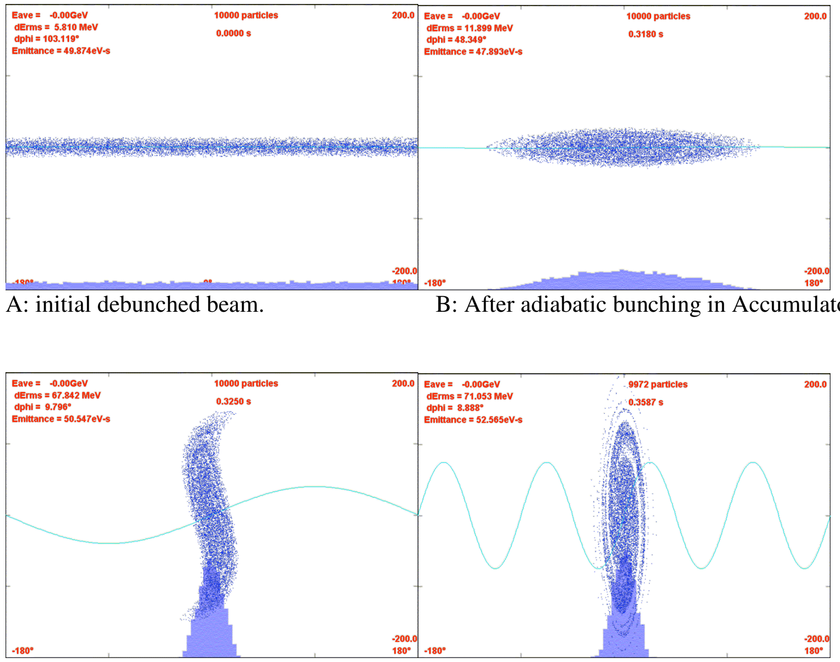
As noted earlier, the major beam preparation for the Mu2e experiment is performed in the Accumulator and Debuncher rings. The Accumulator with its large aperture and momentum stacking system is well suited for accumulating pulses of protons from the Booster (*via* the Recycler) and stacked three at a time. Protons enter the Accumulator onto an "outer" orbit, are captured with 53 MHz RF and decelerated toward the "core" orbit where they merge with already circulating particles. Should the present system require more total voltage to enable three consecutive batches from the Booster to be accumulated, the Debuncher's 53 MHz system, not needed in the new scenario, can be relocated to the Accumulator. Once three Booster batches have been accumulated in this way, the present scheme ([4]) uses an $h = 1$ RF system that is turned on adiabatically to 4 kV, capturing the beam into a single bunch. This allows enough time for an extraction kicker to fire sending the beam to the Debuncher ring. Once in the Debuncher, a similar $h = 1$ system running at 40 kV will cause the bunch to rotate in phase space, generating larger momentum spread but shorter bunch length. After $\sim$7 msec the bunch rotates 90° at which time it is captured by an $h = 4$ RF system running at 250 kV. This system keeps the beam bunched with an rms length of 38 nsec and energy spread of $\pm$200 MeV. Figure 4 displays the evolution of the longitudinal phase space through the process.

The Accumulator and Debuncher rings at present contain $h = 1$ and $h = 4$ RF systems, but are run at much lower voltages (< 2 kV). Thus, upgrades to these systems will be in order, including additional cavity hardware and high level RF amplifiers. Details of the beam transfer process between rings (proper orbits and RF frequency matching) require further refinement.

Slow Extraction

Resonant extraction is a technique for slowly and relatively evenly removing particles from a synchrotron, and has a long history at Fermilab. The original Main Ring, the Tevatron, and the Main Injector have all used, or are using, half-integer resonant extraction for producing slow spill particle beams for targeting. In these cases, the non-integral part of the betatron tune resides near one half, and a fast quadrupole magnet system with feedback circuitry is used to carefully ease the tune toward the half-integer. Due to nonlinear magnetic fields inherent in any real magnet system, which can be further enhanced by the introduction of tunable octupole magnets, particles with larger betatron oscillation amplitudes will have tunes that go on-resonance first, increasing their amplitudes even further, and these particles can be directed into an extraction channel leaving the synchrotron. As the tune slowly approaches 0.5, the higher amplitude particles are "peeled off" from the distribution, generating a smooth stream of particles leaving the ring.

The Debuncher, with its three-fold symmetry and a design tune near a third of an integer, makes the use of third-integer extraction a possibly attractive option for the Mu2e application. Here, sextupole magnets are used to enhance the resonance at a tune of 1/3 generating a dynamic aperture (or stable phase space area) that is proportional to the difference of the tune from 1/3. As the tune adiabatically approaches 1/3, particles that suddenly find themselves outside the dynamic aperture



A: initial debunched beam.
B: After adiabatic bunching in Accumulator.
C: After ϕ-E rotation in Debuncher
D: After h=4 bunching in Debuncher.

FIGURE 4. Particle distributions in phase (horizontal, $\pm 180°$ or $\sim \pm 0.85$ μsec) and energy (vertical, ± 200 MeV) phase space, with histograms shown along the bottom edge, for stages of Mu2e bunch preparation. Curves indicate the RF wave forms used.

stream away from unstable fixed points in a well defined pattern and, as in the half-integer case, will eventually wander to the other side of a septum to be directed out of the synchrotron.

The exact system to be chosen requires further study. One of the major benefits of half-integer extraction is the fact that the entire phase space can be made unstable when the tune gets close enough to 0.5 (when the beam enters the half-integer stop-band gap). This allows for the complete removal of the particles from the synchrotron to the experiment, and is one of the primary reasons half-integer extraction was chosen for the three Fermilab synchrotrons mentioned above. The third-integer system will have particles remaining in the ring which will need to be aborted at the end of the slow spill. Also, when the particle beam has a large momentum spread, which will be true for either case with the Debuncher application (± 200 MeV/ 8.9 GeV = $\pm 2\%$), the chromaticity will need to be very finely controlled in coordination with other extraction parameters. A major concern is the tune spread due to space charge and its effect on the extraction process. All of these considerations are being actively investigated.

Extinction

As 34×10^6 protons on average should reach the production target every micropulse (every 1.7 μs) during the appropriate time window, an extinction at the level of 10^{-9} permits no more than 1 proton to reach the target during this time window every 30 micropulses. With this stringent of a requirement, several measures must be taken to ensure the appropriate level of extinction.

Internal Extinction

Measures will be taken within the rings during bunch formation to abate particles from being outside the ± 100 ns time window of the production micropulses. For example, tight rise and fall time requirements for the kicker magnets used in transferring the bunch from the Accumulator to the Debuncher will help. In the Debuncher ring itself, a gap-cleaning kicker system may be employed. Also, as the narrow bunch length will necessarily produce a bunch with large momentum spread, a collimator system at a large dispersion point in the ring can also be used to scrape away particles before they migrate between stable fixed points of the $h = 4$ RF system.

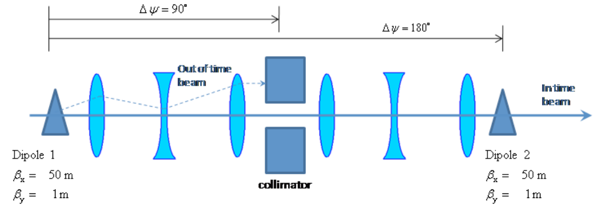


FIGURE 5. Schematic of extinction insert. Two AC dipoles steer the trajectory into collimators at an oscillation frequency of 300 kHz.

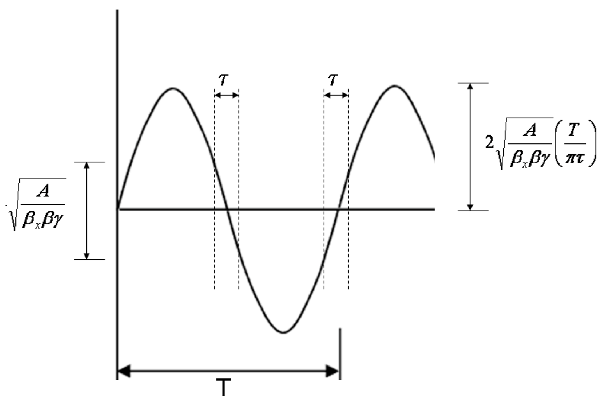


FIGURE 6. Relationships between dipole oscillation period, T, in-time window, τ, transverse admittance, A, and betatron amplitude function β_x at the location of the dipoles, for a two-dipole solution. See [6].

External Extinction

In addition to the above, the Mu2e beam line will include an "extinction insert" at its downstream end. This portion of the transport system, the "last resort" for the extinction process, will utilize a rapid cycling dipole magnet (AC dipole) or a set of dipoles on either side of a focusing channel to be used to steer beam into collimators. Were a single dipole magnet used, the frequency would need to be $\sim$600 kHz (the micropulse frequency). For a pair of bend centers, the dipole magnets would cycle at half the micropulse frequency ($\sim$300 kHz) and kick the unwanted beam well into the collimator iron. [6] The conceptual layout is shown schematically in Figure 5. Figure 6 indicates the extent of the in-time window relative to the micropulse period, T. By proper choice of frequency (or set of frequencies) and amplitude, the window for particles that arrive at the production target can be adjusted. Various hardware options for this magnet system are being explored. [7]

ALTERNATE OPERATING SCENARIOS

An inherent issue with the Baseline operating scenario described early in this document is the final bunch current in the Debuncher during the slow spill. With a total of 3 Booster cycles accumulated into a single 12 Tp bunch with rms bunch length of $\sim$38 ns, the space charge tune shift using expected transverse emittances is roughly $\Delta\nu \sim 0.1$. This large spread in betatron tunes, which will vary as the beam is slow spilled, will make difficulties in the resonant extraction process more pronounced. Additionally, the highest intensity stored in the Accumulator to date is under 3 Tp (antiprotons). An intensity higher by more than a factor of four, while not inherently impossible, will be challenging.

Alternative scenarios are being investigate which attempt to lower the bunch charge and total intensity in the rings while still providing a high duty factor to the experiment and a similar average rate of protons to target. One obvious step is to form four bunches in the Accumulator rather than one – reducing the space charge per bunch by a factor of four – and transferring one bunch at a time into the Debuncher for extraction. The spill time would be reduced from 600 ms to about 150 ms, occurring 8 times during a Main Injector cycle. The single-turn transfers from the Accumulator to the Debuncher will also help with the inter-bunch extinction. Several other scenarios similar to this are being investigated which have the potential to reduce the space charge even further, and may also add operational flexibility to the program.

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