PREPARATIONS FOR MUON EXPERIMENTS AT FERMILAB *

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Abstract

The use of existing Fermilab facilities to provide beams for two muon experiments — the Muon to Electron Conversion Experiment (Mu2e) and the New g-2 Experiment — is under consideration. Plans are being pursued to perform these experiments following the completion of the Tevatron Collider Run II, utilizing the beam lines and storage rings used today for antiproton accumulation without considerable reconfiguration.

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.

One experiment, the Muon to Electron Conversion Experiment (Mu2e), has been given relatively high priority by HEPAP and would take several years to construct. During the time period between when the Tevatron Run II program is concluded and Mu2e operation begins, much of the same facility components can be used to furnish beam to the other proposed experiment, the New g-2 Experiment (g-2) which would be relocated from Brookhaven National Laboratory.

Beam will be transported directly from the Booster to the Recycler ring, an operation also required (and funded) for the NOνA project. Mu2e and g-2 would also require extraction from the Recycler into the existing P1 beam line for transport toward the existing antiproton storage rings. These rings, the Debuncher and Accumulator, as well as the Recycler ring are involved in current scenarios for these experiments, and stochastic cooling (and, in the Recycler, electron cooling) equipment will be removed to generate less aperture restrictions for the high intensity operations of any future 8 GeV experimental program.

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Particle losses in the Booster currently limit the beam delivered by the 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 [2], the installation of which will be completed in 2009, will allow for this increased intensity under 15 Hz operation. In each of these two programs the antiproton source storage rings are utilized and measures must be taken to improve the environmental impact of the new uses of these facilities.

MUON TO ELECTRON CONVERSION

The Mu2e experiment [3] 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

For Mu2e, Booster beam would be sent through the Recycler and directly injected into the Accumulator (see Fig. 1.), where several Booster batches would be momentum stacked. Thus no new beam lines are required, and all magnetic elements operate at their present-day field strengths. Six of the eight free Booster cycles are used to feed 4 Tp per pulse to the Mu2e experiment, three

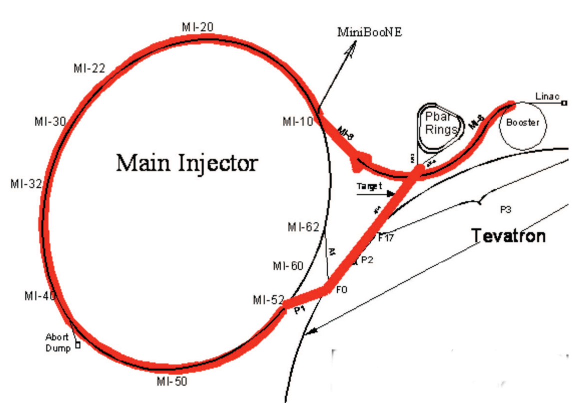

Figure 1: Beam transport scheme for Mu2e operation.

batches at a time. 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 ∼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, to be 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. 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} POT per year.

Beam Preparation and Delivery

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 and fast extracted toward the Debuncher ring. Once in the Debuncher, a similar $h = 1$ system running at 40 kV will bunch rotate 90° after ∼7 msec and 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 ±200 MeV. Figure 2 displays the evolution of the longitudinal phase space through the process.

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. Half-integer resonant extraction is also being explored, that would allow for the complete removal of the particles from the synchrotron to the experiment. A design for the extraction line leading toward the experiment is underway, with total length of ∼200 m.

Extinction

One exceptional feature of the beam line is the extinction insert at its downstream end. This portion of the transport system will utilize a set of rapid cycling dipole magnets (AC dipoles) on either side of a focusing channel the middle of which contains collimators. The dipole magnets cycle at half the burst frequency (∼300 kHz) and kick the unwanted beam well into the collimator iron. [5] Various hardware options for these magnets, as well as instrumentation for measuring and monitoring the level of extinction are being explored. [6]

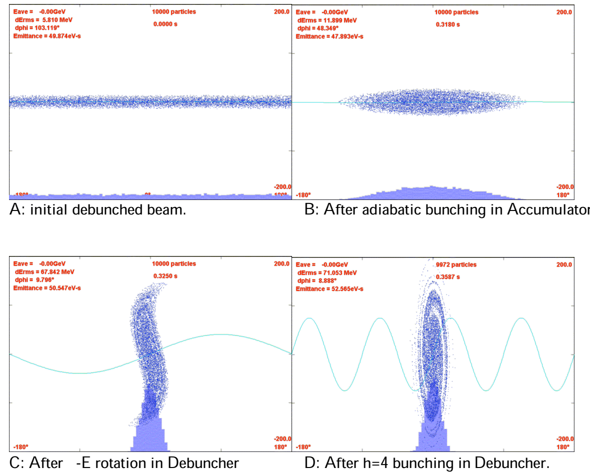

Figure 2: Bunched beam preparation for the Mu2e experiment. The dots are particle distributions in phase (horizontal, $\pm 180^\circ$ or $\sim\ \pm 0.85$ μsec) and energy (vertical, ±200 MeV) phase space, with histograms shown along the bottom edge. See [4] for details.

MUON *G*-2

The New g-2 Experiment [7] requires 3.09 GeV/c muons injected into an existing muon storage ring that would be relocated from Brookhaven National Laboratory to Fermilab. The ring is 7 m in radius, giving a revolution time of 147 ns. To account for the injection kicker, the beam pulses need to have lengths of about 100 ns or less and separated by ∼10 ms for the muons to decay in the ring and data to be recorded prior to the next injection. To obtain a very pure muon beam, the decay channel should be several times longer than the pion decay length, which is $\sim$ 170 m at this momentum. The experiment requests a total of 2×10^{20} 8.9 GeV/c POT.

Beam Preparation and Targeting

Like for Mu2e, six Booster batches every MI cycle can be sent to the experiment for an average rate of 18 Tp/sec, yielding the required total protons on target in about a single year of running. Each batch of 53 Mhz bunches from the Booster would be sent to the Recycler and coalesced into four bunches for delivery to the experiment. The rebunching process takes approximately 30 ms, and the four bunches would then be delivered to the experiment every 12 ms. Thus, the last bunch is extracted just within the 66.7 ms Booster cycle. A broadband RF system, 2.5 MHz (max. V_{rf} = 60 kV) and 5 MHz (max. V_{rf} = 15 kV) RF systems that presently reside in the MI would be relocated to the Recycler. Upgrades to increase their maximum voltages by roughly 10-30% may be required. [8] Fig. 3 shows the resulting beam structure in the Recycler if the beam were not extracted. The plan would be to extract one pulse at a time, every 12 msec, when the bunches are at their narrowest time extent (4σ widths of 38-58 nsec). An appropriate extraction kicker system will also be required.

From the Recycler a bunch is sent toward the existing, though possibly modified, antiproton target station for $\sim$3.09 GeV/c pion production. A “boomerang” approach utilizes the Debuncher ring as a delay line allowing for pion-to-muon decay. The total length of the decay line would be $\sim$900 m, providing a large improvement over the original layout at BNL. After one partial pass through the Debuncher, beam is delivered to the AP0 target, and 3.09 GeV/c pions are collected into the AP2 line which is “retuned” to operate at 3.09 GeV/c. The g-2 ring would be located near the AP0 service building as indicated in Figure 4. As can be seen, little modifications are required of existing beam lines to perform the beam transport all the way from the Booster to the g-2 ring. Investigations of possible target station improvements are on-going. The end of the line and connection to the experimental ring requires design, but should be straightforward.

Experimental Facility

An experimental building approximately 80 ft $\times$ 80 ft with a full-span 40 ton bridge crane is being considered. The building must be large enough to enclose the g-2 ring as well as associated electronics and counting room. The cryogenic needs of the experiment can be met by the Tevatron accelerator cryogenics system with some modifications and additional transfer line work. The Tevatron is located only about 50 ft away from the AP0 service building, and is expected to be in 80°K standby mode during the time span of the experiment.

The exact location of the building south of AP0 will be determined by the final design of its connection with the beam transport line. The beam line will need to emerge vertically from the tunnel containing the AP3 line and make a roughly 90° horizontal bend into the experiment building.

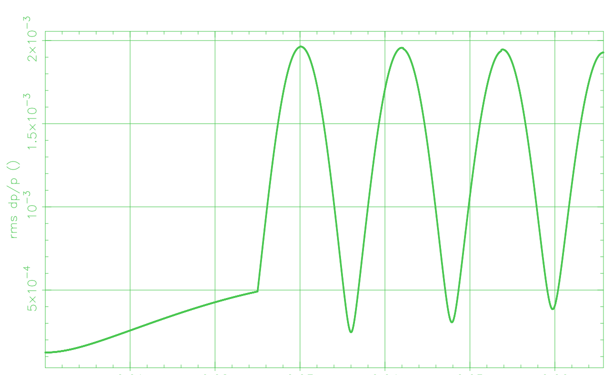

Figure 3: Resulting rms $\Delta p/p$ *vs.* time in seconds following Recycler injection. Beam is rotated and captured into four buckets. The half-rotation time is 12 msec allowing extraction one-by-one as the momentum spread reaches its peak (pulse length is at its shortest).

Figure 4: Proposed location (yellow) of the new g-2 hall.

GENERAL REMARKS

The Booster synchrotron needs to operate at its maximum rate of 15 Hz, and transfers into and out of the Recycler are required for both experiments. The g-2 operation requires kicker magnets as beam will circulate within the Recycler and the same devices could in principle be used for Mu2e as well.

Further refinements to the operational scenarios are being explored. The very high space charge in the Mu2e experiment has generated much discussion, and other beam delivery scenarios are being investigated. One example ([9]) uses the same bunch preparation scheme as in g-2, but single-turn transfers the four bunches into the Accumulator and then one-at-a-time delivers a bunch to the Debuncher for slow spill. This reduces the bunch intensities by a factor of 12, and potentially the momentum spread by a factor of 4 as well. It also uses the same bunch formation in the Recycler for the two experiments, which may have some benefits. Attempts will continue to integrate components for the two experimental scenarios where possible.

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