Beams-doc-3558
Mu2e-doc-787

Status of Mu2e Operating Scenario

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A viable operating scenario for the Mu2e experiment has emerged and continues to develop. Now that the experiment has received CD-0 from the Department of Energy, and with a goal of reaching CD-1 in the next 12-18 months, work is focusing toward the eventual generation of a Conceptual Design Report. The purpose of the present document is to provide a short overview of the status of the operational concepts for Mu2e and the accelerator issues being addressed in an effort to help guide the work toward the Accelerator chapter of the CDR.

1 Experiment Requirements

The Mu2e experiment needs bursts of protons delivered on target within a time window of about 200 ns every $\sim 1.7\ \mu$s, corresponding to the revolution time of the Debuncher ring. The total number of protons to be delivered on target for the experiment is $\sim 4 \times 10^{20}$ each year for two years.

In the original experimental proposal[1], three Booster batches of 4×10^{12} (4 Tp) are delivered twice each NOνA cycle of 1.333 s. The average rate is thus 18 Tp/s corresponding to about 25 kW on target. The experiment has requested as high a duty factor as practical – 90% in the proposal. The average instantaneous rate on target under these conditions is about 34 Mp every 1.7 μs burst.

2 Present Plans for Mu2e Operation

To meet the requirements of the experiment, the 8 GeV Accumulator and Debuncher storage rings are employed. Three Booster batches are to be momentum stacked into the Accumulator on consecutive Booster cycles, for a total of about 12 Tp. The stored beam is then bunched into 4

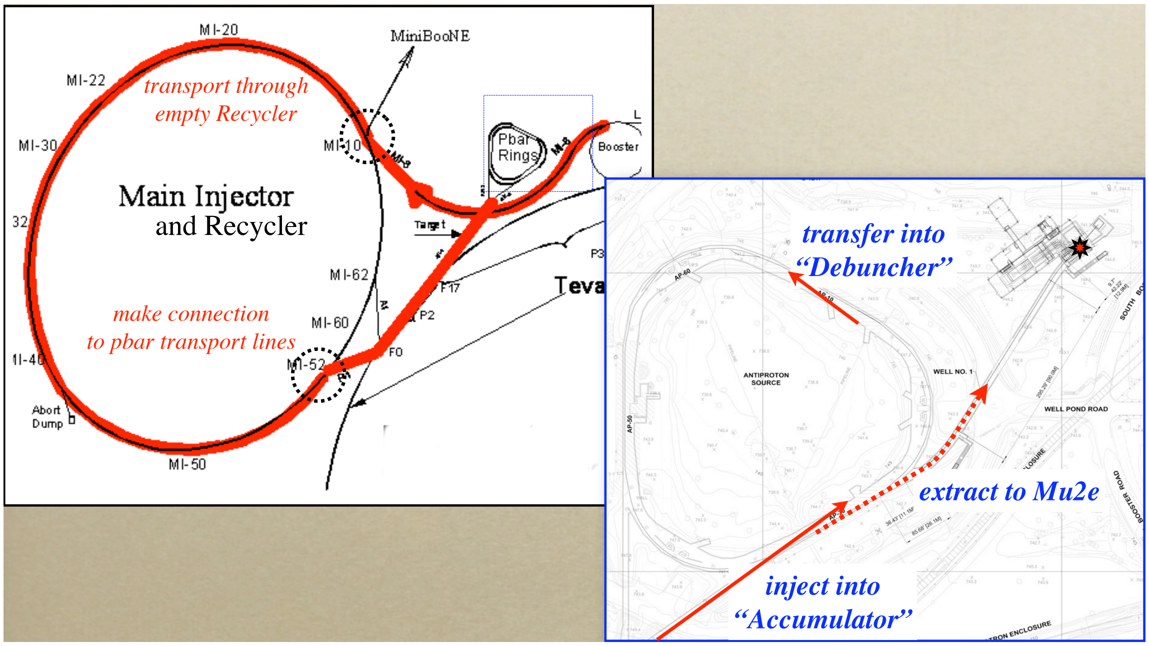

Figure 1: Beam transport from Booster to Accumulator through the Recycler for Mu2e.

bunches of 3 Tp each using an h=4, 2.5 MHz RF system, with voltage to produce a total bunch length of $\lesssim$200 ns. At this intensity and bunching factor, the space charge tune shift is on the order of 0.025 or less. Then, one-by-one, each bunch is transferred to the Debuncher ring and extracted out to the experiment using resonant extraction with spill times of approximately 150 ms. This process is repeated twice during the Main Injector cycle to be used for NOνA.

To minimize beam line costs beam is transferred from the Booster to the Accumulator via the MI-8 line, Recycler, and P1-P2-AP1-AP3 beam lines, as indicated in Figure 1. The MI-8 line is to be connected to the Recycler for the NOνA Project. Thus, for Mu2e, connection of the Recycler to the P-1 line at MI-52 is required including appropriate extraction kicker magnets for the transfer.

In order to achieve high duty factor yet lower final bunch charge, the slow spill from the Debuncher is divided into 8 spills per Main Injector NOνA cycle (1.333 s). To spread out the two sets of transfers from the Booster to the Accumulator, a scheme has been developed in which beam destined to Mu2e can be transported through the Recycler while beam destined for NOνA is circulating.[2] This “beam threading” allows for a situation in which the experiment receives their desired flux with high duty factor, while maintaining a space charge tune shift well below 0.05. The Mu2e time line is illustrated in Figure 2.

Under this scenario, the experiment can have essentially 100% duty factor (not including “end effects” of the slow spill operation) and the final bunch preparation in the Accumulator can take place in approximately one-half of a Booster cycle ($\sim$33 ms). With the help of Figure 3 it can be shown that a bunch formation time, f, of between 0.5 and 1 Booster cycle ($= b$) reduces the ideal duty factor from 100% to 93%. Present estimates lie at $0.5 \leq f \lesssim 0.65$. An overall duty factor of $\gtrsim$90% should be feasible.

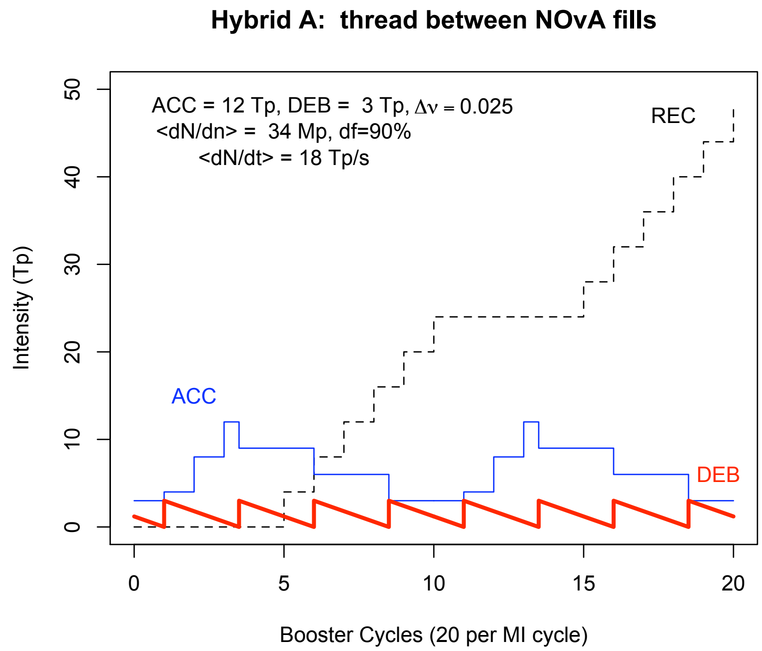

Figure 2: Illustration of beam intensities in the Recycler, Accumulator, and Debuncher rings during the two Mu2e cycles within one NOνA cycle.

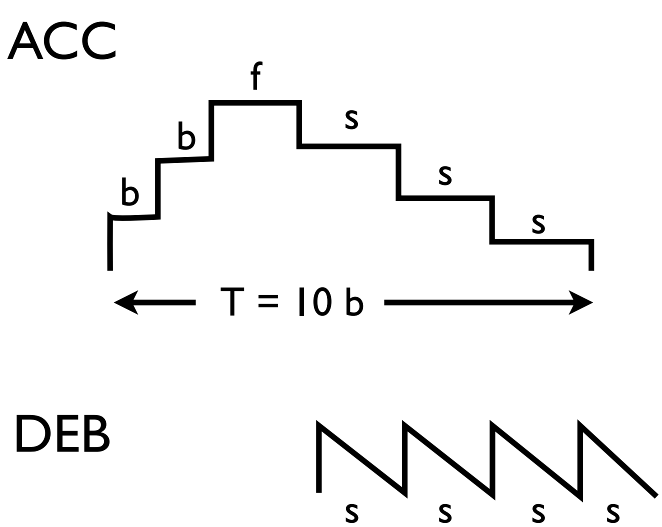

Figure 3: Time line diagram showing the relationships between the Booster cycle time, b, the bunch formation time, f (including the final momentum stacking operation), the slow spill time, s, and the total Mu2e cycle time, $T = 10b$. The final ideal duty factor to the experiment would be $df = 4s/T = (16 - 2f/b)/15$.

3 Recycler Systems

The NOνA project includes an injection system to the Recycler from the MI-8 line, which will also be used for Mu2e transfers. This system contains fast rise/fall-time kickers to allow for injection of the last six Booster batches (using slip stacking) while the first six are circulating. A similar, if not identical, set of kickers now will be required for the Mu2e transfers at a new MI-52 extraction point which will tie the Recycler to the P1 beam line. This connection requires design effort at this time.

For NOνA, the extraction kicker used to transfer beam from the Recycler to the Main Injector was specified assuming that no beam will remain in the ring until the next NOνA batch arrives from the Booster some 8 Booster cycles later. Thus, its fall time may not be consistent with an injection for Mu2e occurring only one Booster cycle later. While the Mu2e scenario only requires 6 batches, three at a time, this can be accommodated; however, it means that out of all 8 extra Booster pulses within an MI cycle, only 7 actually may be available for other uses without an upgrade to the NOνA extraction kicker.

4 Storage Ring Systems

The Accumulator and Debuncher storage rings will be reconfigured for use in Mu2e operations. Both synchrotrons will need h=4 ($\sim$2.5 MHz) RF. The Accumulator could be augmented with a broadband system in order to speed up the bunch formation process if required. The Debuncher RF system will be for holding a bunch formed in the Accumulator. The Accumulator will also require a 53 MHz system to be used for momentum stacking.

Kickers are required to inject beam into the Accumulator from the Recycler at a maximum 15 Hz rate, though with lower duty factor. Kickers for transfers between the two rings will need to operate at approximately 6-10 Hz average rate according to the spill time used. (To allow for flexibility in the time line, the higher rate capabilities are desirable.)

The beam lines directing particles from the Recycler to the Accumulator – P1, P2, AP1, AP3 – will likely require some aperture re-work to more efficiently transmit the much higher beam throughput.

Slow spill of beams with high space charge are an issue for the extraction process. Several scenarios, including half- and third-integer resonances, with and without resonant transverse kicks using RF systems, are being explored. Standard extraction devices are envisioned for this system, though new fast ramping corrector magnets and possibly an RF kicker may be required.

It is also important that the pulses of beam reaching the Mu2e experiment during the slow extraction process be distinct, with very low probability of out-of-time particles reaching the production target during the experiment's 900 ns measurement window. A system or set of systems in the Debuncher will be employed to render "extinct" any particles circulating outside the desired bunch window ($\lesssim$200 ns in total length).

5 The Mu2e Beam Line

The Mu2e experiment is being laid out to the west of the Antiproton Storage Rings, connected to the Debuncher with a new beam line requiring civil construction. The extraction will occur at the AP-30 straight section and sent out through the tunnel wall at or near the location of the old AP-4 beam line that connected the tunnel to the Booster enclosure. The layout is illustrated in Figure 4. The beam line is under design and will consist of the electrostatic and magnetic septa

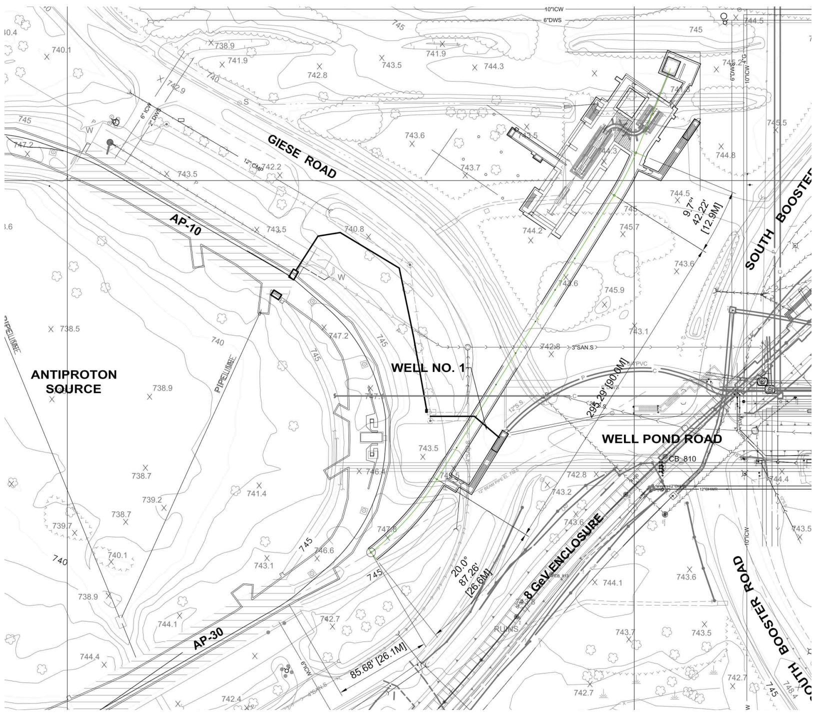

Figure 4: Location of new Mu2e beam line and experiment hall.

within the Debuncher ring, and new bending and focusing elements leading to a final focus system to focus the beam onto the Mu2e production target. A fair length of this beam line will contain optics, collimators, and time-varying magnetic elements to be used for a final "extinction" of unwanted protons between the spilled microbunches of particles.

The production target will be located within a graded solenoid field, into which the beam will enter at a large angle. Thus, the edge effects of the solenoid need to be taken into account in the design of the final optical and steering capabilities of the beam line.

6 Parameters Summary

A selection of parameters of the Mu2e operation are listed in Table 1 for consideration during further design efforts. Current lists of requirements and parameters can also be found at [3].

Table 1: Selection of Preliminary Parameters of Mu2e Accelerator Operations

Experiment cycle	10	BOO cycles
Exp. cycle time	666.7	ms
Spills per Exp. cycle	4	
Exp. cycles per NOνA cycle	2	
Bunch preparation time	33.3	ms
Spill time	150	ms
Duty factor	$\geq 75\%$	
BOO intensity	4	Tp
ACC intensity	12	Tp
DEB intensity	3	Tp
Microbunch intensity $\langle dp/dn \rangle$	34	Mp
Proton throughput $\langle dp/dt \rangle$	18	Tp/s
DEB Sp. Chg. tune shift	0.025	
ACC RF	h=84, 4	
DEB RF	h=4	
Kicker Rates (*prelim. specs*)		
REC out, max	15	Hz
REC out, ave	4.5	Hz
ACC in, max	15	Hz
ACC in, ave	4.5	Hz
ACC out, max	10	Hz
ACC out, ave	9	Hz
DEB in, max	10	Hz
DEB in, ave	9	Hz

References

[1] Mu2e Collaboration, "Proposal to Search for μ - $N \rightarrow e$ - N with a Single Event Sensitivity Below 10^{-16} ," FERMILAB-PROPOSAL-0973.

[2] M. Syphers, "On the Mu2e Operating Scenario," Fermilab Mu2e-doc-706.

[3] See Mu2e documents Mu2e-doc-48 and Mu2-doc-585 .