Beam to Muon g-2 and Mu2e Experiments from Recycler

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DRAFT

Abstract

This note describes how to deliver beam to the Muon g-2 and Mu2e experiments from the Fermilab Recycler. Initially, Booster proton beam will be used, but the concept assumes that in the future, the 8 GeV protons will come from Project X and the same beam structuring will be used.

Introduction

At present it is envisioned that both the Muon g-2 and the Mu2e experiment will get beam initially prepared in the Recycler. The initial incarnation of the Mu2e experiment at Fermilab is based on 8 GeV Booster beam. The experiment is designed for 3.4×10^7 protons on target per micro-bunch. The micro-bunches are each ≈200 ns long, with one micro-bunch every ≈1.7 μs. So the aim should be to reproduce approximately this time structure in the Recycler. One way of achieving this goal is to break the Booster beam into seven ~170 ns proton trains and equally distribute them around the Recycler. Once the beam is arranged in this way, extraction can be used to transfer beam to the Debuncher as a single train or momentum stack up to seven trains and slowly extract to the Mu2e target; the details are not relevant to this discussion. For the Muon g-2 experiment, seven trains can additionally be shortened using 2.5MHz RF system and extracted on the target every ~10ms, one at a time. Many of the ideas presented here are described in note DocDB 3974 [1].

Injection into Booster

At present, 400 MeV H^- beam from the linac is injected into the Booster using H^- stripping and multi-turn injection. The beam in the Booster is initially DC beam, and it takes ~500 μs for the RF system to adiabatically bunch the beam and capture it in 37 MHz buckets. Just before the acceleration starts, an extraction gap is formed by kicking out three Booster bunches. The extraction gap is ≈60 ns wide and is used to allow extraction kickers to rise to full voltage without losing any additional beam. Figure 1 shows the notch-creating kicker magnet connected to the switch tube (Thyratron) and pulse-forming network (PFN). The PFN is slowly charged with a high-impedance (Z1) power supply. A square pulse is created when the switch is closed and the PFN is discharged into the kicker magnet. The pulse has half of the PFN charged voltage and duration equal to twice the PFN electrical length. In principle, to create seven notches equally spaced, this system can be charged and fired seven times. However, because the thyratrons take ~1 ms to recover and charging the PFN is a slow process, this approach does not look practical.

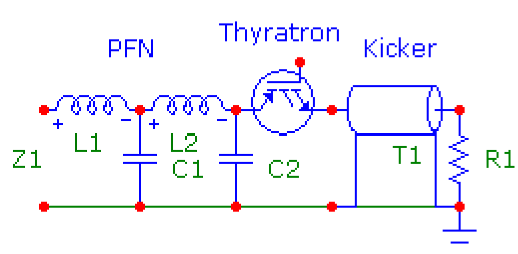

Figure 1. Booster Notcher system.

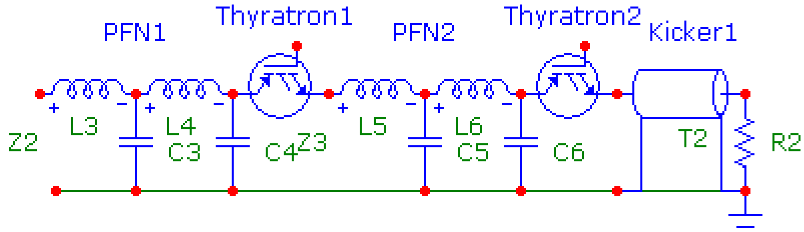

Figure 2. Two-PFN notcher example.

Another option is to combine more than one thyratron/PFN system and fire them one at a time with appropriate delay during one or several Booster turns. Figure 2 shows a two-stage system. Although this is technically doable right now, creating seven notches even at injection energy creates additional losses that should be avoided. At present there is an attempt to develop a 750 keV notcher in the linac for the RFQ-based front end.

Extraction from Booster

Once the seven notches are created, this beam is accelerated to 8 GeV and extracted to the Recycler. The present kicker system extracts the full Booster beam in one turn. The kicker system takes ≈40 ns to produce full voltage in the kicker magnet, and its firing is synchronized with the notch gap in the beam.

For the needs of the Mu2e and Muon g-2 experiments, our aim is to extract Booster beam in seven steps and equally space it in the Recycler, as shown in Figure 3. The fastest way of doing this is to extract beam in seven consecutive Booster turns. This takes advantage of the fact that the Recycler circumference is seven times that of the Booster.

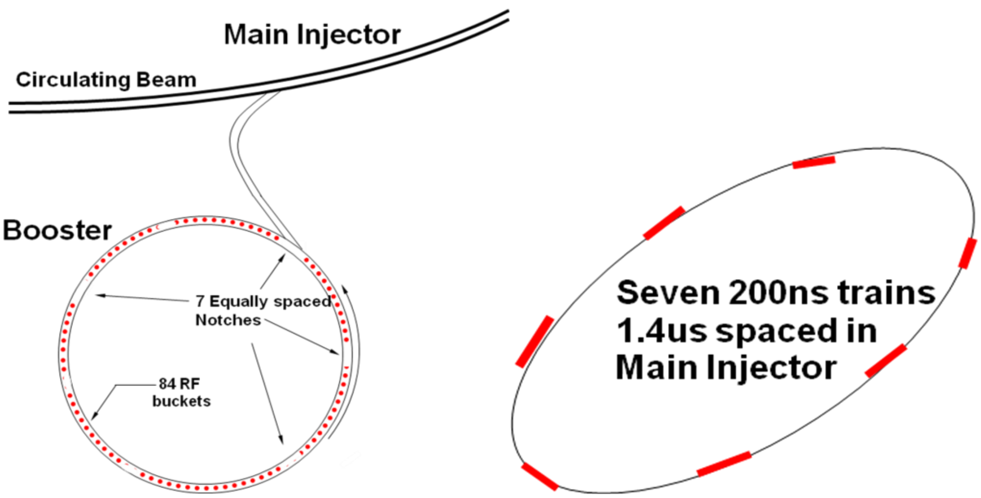

Figure 3. Illustration of the distribution of beam in the Booster and Main Injector desired for Mu2e.

The simplest way to achieve this is to use the existing kickers and replace the PFN system, which produces a 1.6 μs pulse, with one that produces a pulse 200 ns long. This will do single-train extraction. To do seven extractions in 11.2 μs as shown in Figure 3, we have to connect in series an additional six systems like the one shown in Figure 4.

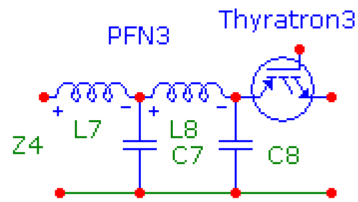

Figure 4. Single pulse-forming network and switch.

Assuming that the first PFN in this series system has a fall time shorter than 60 ns, which is expected based on the properties of the pulse from the 1.6 μs PFN, for the rest of the pulses, the beam gap will be sufficiently long to allow clean extraction.

Proton Rate for Mu2e

The Mu2e experiment was designed for 3.4×10^7 protons per micro-bunch at the time when the Accumulator and Debuncher were going to be used and the extraction spill was almost continuous. If that is the maximum tolerable instantaneous rate, then only 1.4×10^{12} protons per Booster period can be spilled onto the target. There are several possible operating conditions of the Booster that respect that limit. One extreme is to run the Booster with 5.6×10^{12} protons with a spill lasting four Booster periods; another is to run it at very low intensity, 1.4×10^{12} protons, with eight batches delivered per Main Injector cycle. In any case, under the assumption that the maximal number of protons is 3.4×10^7 protons per micro-bunch, Mu2e will get 8.4×10^{19} protons per year.

Recycler and Muon g-2 Beam

The proton beam for the Muon g-2 experiment needs to be less than about 100ns long, and targeting should be done not more often than every 10 ms. To meet these conditions, seven equally spaced trains, each ~170ns long, are injected from the Booster into 2.5MHz buckets in the Recycler. Each bunch train consists of nine consecutive Booster bunches. A preliminary ESME simulation shows that these beam trains can be made ~ 25ns long in less than 5ms. This allows for seven extractions from Recycler, 10ms apart, in the next 60ms. In that way the whole beam is extracted from Recycler in 66ms, and the process can be repeated on every Booster cycle that the Recycler is not needed to stack beam for the Main Injector.

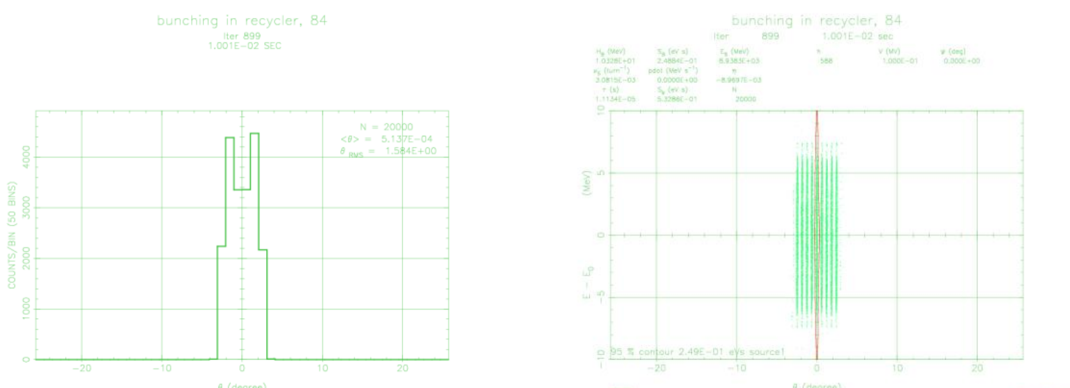

Figure 5. Nine Booster bunches injected in 80 kV 2.5MHz buckets. The bunch train is ~170ns long.
To simulate Booster beam in the Recycler, DC beam is adiabatically bunched with 53MHz system in Recycler in ten milliseconds. This process creates bunches with ~+/- 7MeV energy spread, as shown, like bunches coming from the Booster. At this point in the simulation, the 53MHz RF is turned off and the 2.5MHz system is set with a constant voltage of 80 kV. Tracking is continued for 5 ms as bunch rotation is completed, as shown in Figure 6.

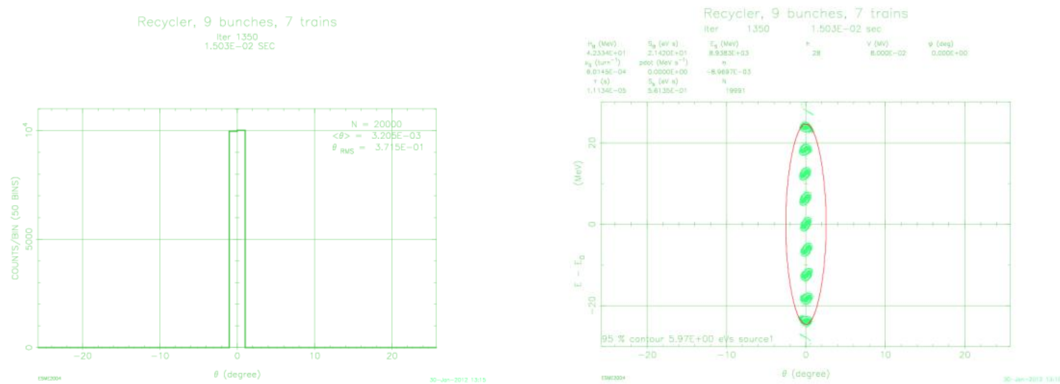

Figure 6. After ~5ms bunch train is rotated and it is ~25ns long

Conclusions

If the Mu2e experiment can accept three times more protons per micro-bunch, all available Booster beam left after NOVA can be used. In the scheme presented here, there will never be more than ~7eE11 protons in the Debuncher. This should be compared with record p-bar stores, ~3e12 p-bars when shielding of the tunnel is considered. The fact that the bunch trains are from the start ~170ns long and can be made ~25ns long in ~5ms in Recycler allows for the possibility of faster slow spill setup and cleaner extraction.
The very same scheme can also be used for the Muon g–2 experiment and will need less RF and a less-demanding extraction kicker system in Recycler.

References

1. http://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=3974