Letter of Interest: Beam Delivery for Mu2e-II in the PIP-II Era

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The details of the Mu2e Experiment are described elsewhere[1]. The goal of the current experiment is to search for the conversion to an electron of a muon that has been captured by an aluminum nucleus, with a sensitivity four orders of magnitude better than the previous best experiment. Any signal will be unambiguous proof of physics beyond the Standard Model.

The PIP-II Linac[2], being constructed at Fermilab, will enable a follow up experiment, 'Mu2e-II', to collect an order of magnitude more statistics, either to increase the sensitivity of the search or to study any signal that has been observed by that point. A separate LoI has been submitted for the 2021 Snowmass conference outlining the Mu2e-II Experiment as a whole[3]. This note emphasizes some of the particular challenges associated with beam delivery from the PIP-II Linac to the Mu2e production target.

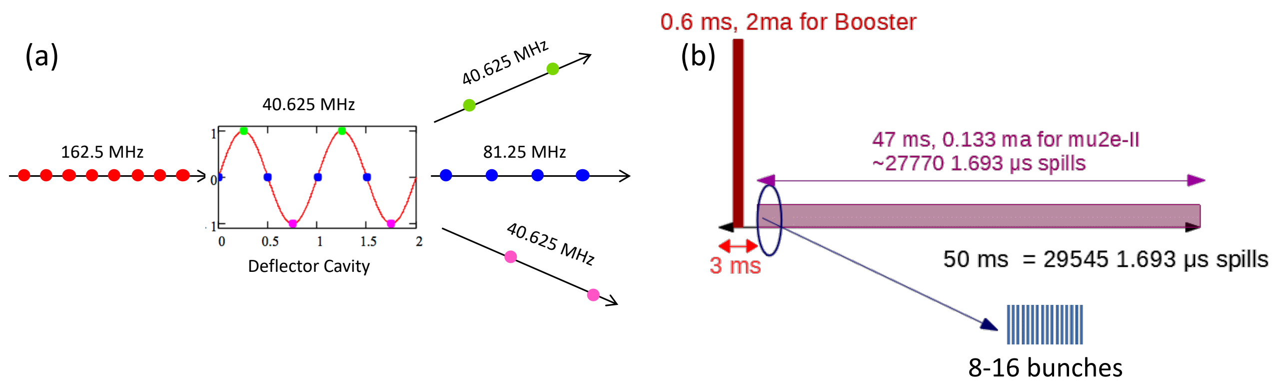

Figure 1: The PIP-II bunch splitter is shown in (a), and the proposed bunch structure for Mu2e-II is shown in (b).

Table 1: Beam Parameters for the PIP-II Linac. The third and fourth columns assume an RF splitter and give the beam available to the "central" and "side" users, respectively.

Parameter	Linac Output	Central Line	Side Lines	Comment
Energy [MeV]	800			
Bunch Length [ps]	4			
Max. Ave. H^-/Bunch	0.8×10^8			2 mA
Peak H^-/Bunch	2.0×10^8			5 mA
Bunch Frequency [MHz]	162.5	81.25	40.625	Maximum
Bunch Separation [ns]	6.2	12.3	24.6	Minimum

The key parameters of the PIP-II Linac are shown in Table 1. It will produce proton bunches at 800 MHz with a maximum frequency of 162.5 MHz. A proposed cryogenic upgrade will allow average currents of up to 2 mA, with peak bunch intensities of up to $2,0 \times 10^8$ protons (5 mA). A key feature of the linac will be a chopper in the Low Energy Beam Transport section that will allow arbitrary bunch patterns to be produced.

The high energy program will only use about 1% of the available beam pulses, limited by the 20 Hz repetition rate of the upgraded Fermilab Booster. Although a final decision has not been made regarding the distribution of the remaining beam, a leading concept involves a 40.625 MHz RF deflector to split the beam into three sub-lines, as shown in Figure 1(a). Individual lines are selected by populating RF bunches of the appropriate phase. We are assuming that Mu2e-II will have access to the central (node) line, and will therefore be able to receive bunches at up to 81.25 MHz.

Assuming the experiment is again run with an aluminum target, it will need short (<200 ns) bunches of protons, separated by about 1.7 μsec. In Mu2e, this structure will be fortuitously provided by slow extraction from the Fermilab Delivery Ring, which fortuitously has a 1.7 μsec period. In the Mu2e-II era, it will be provided by short bunch trains from the PIP-II Linac, as shown in Figure 1(b). Eight bunches of 2×10^8 each, every 1.7 μsec corresponds to 118 kW at 800 MeV - more than an order of magnitude increase over the first generation Mu2e.

Although there is still copious muon production at 800 MeV, changing the beam energy and increasing the power present a number of challenges:

Magnetic Stripping The beam from the PIP-II Linac will be H^- rather than protons, so magnetic fields must be limited during transport to prevent stripping. The transport lines are designed to stay well below the magnetic stripping threshold, but the high fields in the production solenoid would strip the outer electron before the particles hit the target. We must therefore include a stripping foil somewhere in the beam transport and design for the beam loss that it would produce.

Targeting The production solenoid is designed around the deflection of the 8 GeV beam. The field will perturb the path of the 800 MeV beam much more and the existing beam injection port and target orientation will not work. The heat and radiation shield (HRS) within the Mu2e production solenoid will intersect the 800 MeV beam path, and it also will not provide adequate shielding from the much higher beam intensity of Mu2e-II. The HRS must be redesigned and replaced. Correcting this will require significant modification to or replacement of the Production Solenoid, which will be complicated by the fact that it will be extremely radioactive by this time.

Beam Power and Beam Dump The initial Mu2e target is designed for lower beam power and is radiatively cooled. This will need to be redesigned for the increased beam power. The lower beam energy also means that the beam that goes through the target will not be correctly targeted at the beam dump. A separate LoI is being submitted regarding target issues.

Extinction The first generation Mu2e requires fractional out of time beam ("Extinction") of 10^{-10} or less[4]. We are relying on 10^{-5} from the bunch formation process, and are designing an active system of magnets and collimators to provide an additional 10^{-7}, providing a two order of magnitude safety margin[4]. The new experiment will need an order of magnitude more extinction, and at the moment the extinction of the beam out of the linac is only guaranteed to be 10^{-4}, so for the same safety margin, the active extinction system will have to provide 10^{-9} extinction. Luckily, both the reduced beam rigidity and dramatically lower beam emittance make this seem reasonable. In addition, the quoted extinction for the linac is very conservative and needs to be measured.

Extinction Monitoring

The Mu2e Extinction Monitor relies on a small acceptance spectrometer integrated into the beam dump target shielding[5]. It's designed to see approximately one ~ 4 GeV/c momentum scattered particle for every million protons on target. The entrance collimator of the spectrometer will not be pointed correctly for the lower energy particles produced by the 800 MeV beam. Reworking the extinction monitor for the 800 GeV beam will require significant R&D and effort, which will be complicated by the fact that the area will be extremely radioactive by that time.

References

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[5] E. Prebys, L. Bartoszek, A. Gaponenko, and P. Kasper, “Beam Extinction Monitoring in the Mu2e Experiment,” in *6th International Particle Accelerator Conference*, 2015, p. MOPWI017.