Letter of Interest: Bunch Compressor for the PIP-II Linac

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Introduction

The PIP-II linac at Fermilab will provide dramatically increased proton intensity for the long term Fermilab neutrino program. PIP-II will create more protons than needed for the neutrino program at 800 MeV and those protons will then be available for other research.

Unfortunately, the bunch structure of the Linac is not well matched to all experiments. For example, it is not practical for a future muon-to-electron conversion experiment based on an FFA, in the style of the proposed PRISM/PRIME experiment at J-PARC[1, 2]. Such an experiment would need bunch sizes of roughly 1×10^{12} protons with lengths of less than 30 ns.

We therefore propose a small "compressor" ring to produce more intense bunches. We will use bunch requirements of the PRISM FFA as our nominal target in this document, although specifications might change based on the needs of other experiments.

PIP-II Beam

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			
ϵ_L [ns-keV,RMS]	1.1			
σ_E [keV]	275			ϵ_L/σ_t
Max. Ave. Bunch Size	0.8×10^8			2 mA
Peak Bunch Size	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 PIP-II Linac is described in detail elsewhere[3], but the important beam parameters are shown in Table 1. A key feature of the PIP-II Linac is an injection chopper that can generate an arbitrary bunch pattern up to a maximum bunch rate of 162.5 MHz. The high energy ($\geq$ 8 GeV) physics program is limited by the maximum batch size and repetition rate of the Fermilab Booster to about 1% of the available linac beam, so a great deal of beam will be available to other experiments.

Many options are being considered for delivering the excess beam to users, but a popular scenario is that it will be switched to a line containing a 40.625 MHz RF separator, which can supply beam to up to three users. Individual lines will be selected by producing bunches with the appropriate phase relative to the separator RF. The central "node" line will therefore get bunches at up to a maximum rate of 81.25 MHz, while each of the two "side" (anti-node) lines will get bunch rates of up to 40.625 MHz each. We will see that the latter frequency is well suited to our needs.

Compressor Ring Parameters

An 800 MeV proton beam has rigidity of about 5 T-m. Assuming bend dipoles of about 1 T and a fill factor of about 2/3 the corresponding ring has a $\sim$ 46 m circumference. This is close to the 49.7 m circumference that would be harmonic 8 for 40.625 MHz, and we therefore use that as a reference. A schematic of the ring is shown in Figure 1.

The ring would use charge exchange injection to inject over many revolutions, painting to uniformly fill the available emittance acceptance. Since the Linac bunch intensity is 1.5×10^8, it will require 6667 turns to reach 10^{12} protons/bunch. With the 182 ns period of the ring, this will take 1.3 ms. Note that this time is independent of how many bunches we decide to populate.

To mitigate space charge tune shift effects, it is important to slighly detune the local RF with respect to the Linac RF to make the accumulated bunch as long as possible. We assume that we the bunch length will grow to fill half the bunch spacing, or 12.1 ns. This would only leave 12.1 ns between bunches, which is likely insufficient for the extraction kicker, and we therefore assume that we only populate four bunches.

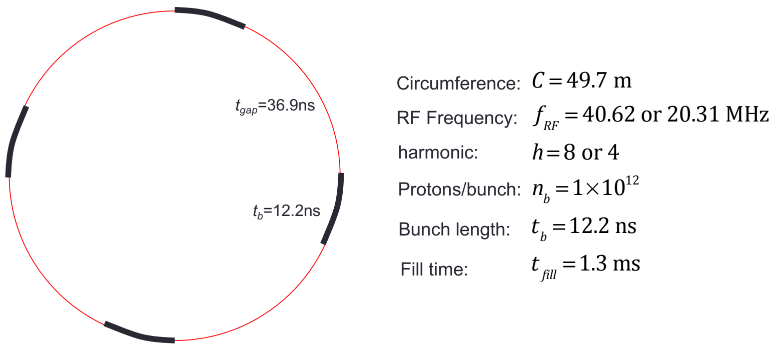

Figure 1: Schematic view of the PIP-II Bunch Compressor ring.

Space Charge

With a 12.1 ns bunch, if we want to keep the tune shift below about 0.2, the normalized RMS emittance will have to be greater than 3.4 mm-mr, or slightly more than the present Fermilab Booster; this is not particularly challenging.

The energy RMS energy spread coming out of the Linac is 275 keV. The velocity spread is the about $\Delta\beta/\beta = 6.5 \times 10^{-5}$, yielding a time shear of about 65 ns/ms, requiring an RF system to keep the beam bunched.

We can approximate the longitudinal beta function by $\beta_L \approx t_b/2/\sigma E$, which would require a single modest RF voltage of only about 350 V at 40.625 MHz.

Reference Performance

The performance of the parameters discussed is shown in Table 2.

Table 2: Reference performance of the Compressor Ring, assuming 4 bunches/fill.

Parameter	Value	Comment
Bunches	4	Assumed
Bunch Size	10^{12}	Target
Fill Time [ms]	1.3	$6667 \times \tau$
Extraction Rate [Hz]	100	Assumed
Average Power [kW]	12.8	

This power is too low for some proposed experiments. Upgraded muon-to-electron conversion experiments, for exmaple (([2]), would prefer beam power $\geq$ 100 kW and as much as 1 MW. Increasing the power from the parameters discussed here would require increasing the bunch size and/or the extraction repetition rate. These two are coupled: increasing the bunch size will increase the required aperture, which then increases the complexity of the extraction kicker. Different experiments might also favor different trade-offs between bunch size and repetition rate.

This is an area that needs more discussion and R&D; we hope the Snowmass process will help launch a systematic investigation of the design.

References

[1] R. Barlow, "The PRISM/PRIME project," *Nucl. Phys. B Proc. Suppl.*, vol. 218, pp. 44–49, 2011.

[2] R. H. Bernstein *et al.*, "A New Charged Lepton Flavor Violation Program at Fermilab," 2020, Snowmass 2021 LOI RF5-RF0-AF5-AF0-009.

[3] V. Lebedev and PIP-Collaboration, "The PIP-II Reference Design Report," FNAL, Tech. Rep., 6 2015, FERMILAB-DESIGN-2015-01.