FNAL Booster Storage Ring

William Pellico, Jeff Eldred, Kiyomi Seiya, CY Tan, C. M. Bhat, Matthew Toups[1], Takahiro Watanabe [2], Richard Van De Water [3], and Chamseddine Benabderrahmane[4]

[1]Fermi National Accelerator Laboratory
[2]RIKEN SPring-8 Center, Japan
[3]Los Alamos National Laboratory
[4]European Synchrotron

Abstract

The FNAL accelerator complex is poised to reach MW neutrino beams on target, explore the dark sector physics space, cw linac operations and a rare physics program with beam intensities not seen before [1, 2]. The ambitious beam program relies on high-power H^- injection into delivery rings with intense space-charge, first into the PIP-II Booster and then either a new rapid-cycling synchrotron or the Main Injector directly. There are many challenging accelerator engineering items already known and many that will be discovered. This LOI proposal calls for an intermediate step, one that will facilitate operation of the PIP-II Booster and gain operational experience associated with high-power injection rings. This LOI is to investigate the design, construction and installation of a 0.8 GeV storage ring (upgradeable to 1 GeV) to be located in the Booster enclosure. The storage ring will be primarily designed around permanent magnet technology with an aperture to accommodate the desired high intensity 0.8 GeV proton physics program.

1 Design Concept

Permanent magnet storage rings are being built or in use in many accelerator facilities, because of the advantages of lower power consumption, higher reliability, and assembly cost when compared to powered magnet rings.The FNAL Recycler which uses permanent magnets [3] has proven itself to be a critical component of our success during the collider physics program and now in our high intensity neutrino and rare decay programs. The permanent magnet storage ring is an economical platform to manipulate beams for loading a rapid cycling accelerator without the accompanying time constraints or lattice constraints. The FNAL Booster does not accommodate long straight sections[1] and long beam fill times ideal for injection. This LOI highlights just a few of the critical areas that a Booster storage ring will address and how it can make an impact to our HEP program within this decade and help ensure the success of Fermilab upgrade plans.

The proposed storage ring will be located on the outside wall of the Booster where there is sufficient space. The PIP-II injection into the storage ring would be located in a large area of the Booster adjacent to the old Booster beam dump. This would allow for a easier injection girder design that reduces beam loss. The RF sections will be located at the present Linac to Booster injection region where space and access to penetrations can accommodate the storage ring needs. The locking of the storage ring to the PIP-II Linac will be be much simpler with greatly reduced field error variations. Once beam is accumulated in the storage ring, it will be transferred to the Booster via single turn extraction and then accelerated immediately in the Booster. The Booster will expect to see reduced losses and improved reliability when compared to the current PIP-II injection process. After commissioning beam to Booster, the storage ring can then be connected to a new 0.8-1 GeV extraction line down the existing 8 GeV line to the Booster Neutrino Beam complex[4] without building new enclosures. The power available for the new extraction line will depend upon shielding and hardware pulse limitations. The initial estimates is for a 100 kW baseline.

2 Magnets and Hardware

A Rapid Cycling Synchrotron (RCS) like the Booster, uses resonant-circuit magnets and therefore has no true flat energy during injection or extraction. This makes loading any RCS especially challenging because the beam orbit can move horizontally by several millimetres if injection takes more than 10 μs.[5]

Table 1: Expected parameters of Booster storage ring.

Accelerator	Aperture	Circumference	B Field
Booster Storage Ring	82 mm	∼500 m	.2 - .4 T

As can be been seen in Fig. 1, the bend field of the Booster is never flat, therefore a combination of incoming beam energy and bend field compensation with RF feedback manipulations have to be done to account for the long injection times ∼500 μs from the PIP-II Linac.

A storage ring alleviates this issue by accumulating beam before transferring it in a single turn to the Booster. This simpler process is more controllable because of reduced hardware complexity.

The required magnetic field for the permanent magnets will be around 0.2 T for a 3 inch gap. The magnets that will be investigated will be either Nd2Fe14B or Sm2Co17[6, 7, 8] because significant community effort have been invested in designs using these materials. However, we would like to consider the option of using a combo electro-permanent magnet design. This concept is not new but in this particular case will allow for a Booster storage ring to accommodate an increase in beam energy from the PIP-II Linac without adding more magnets.

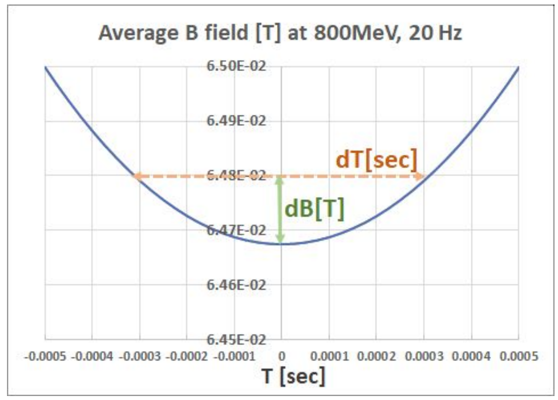

Figure 1: Booster bend field for 20 Hz 800 MeV injection cycle.

3 Injection

We evaluated the foil injection constraints associated with 100 kW beam power delivery to the proposed 0.8 GeV beamline concurrent with 20 Hz delivery to the PIP-II Booster. The heating of the injection foil by the circulating beam was calculated using the method outlined in [9]. Four out of five 100Hz pulses use parameters for the beamline program (9.5e12 protons and a 95% normalized emittance of 24 π mm mrad) and the remaining one out five pulses use nominal parameters for filling the PIP-II Booster (6.6e12 protons and emittance of 16 π mm mrad). The foil thickness of 600 μg/cm^2 and the product of β_x and β_y of 125 m^2 was retained from the PIP-II Booster injection scenario outlined in the CDR [1]. The result of the calculation is shown in Fig. 2 and compared to the scenario with Booster pulses only.

The hot-spot of the injection foil reaches a peak temperature of ∼1300 K, which is far below the temperature of 1800 K where foil sublimation begins to limit foil lifetime. Therefore, we do not anticipate any operational difficulties associated with an annually changed injection foil.

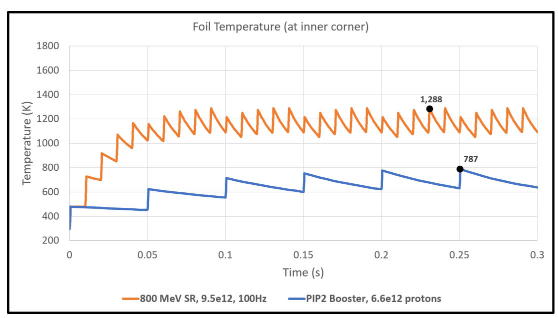

Figure 2: Projected injection foil heating for 0.8 GeV storage ring injection.

To accommodate the 800 MeV pulsed proton beamline at 100 kW, the beam power injected into the 800 MeV storage ring is a factor of 7 higher than the PIP-II Booster. Consequently injection absorbers for the unstripped H^- and H^0 ions as well as circulating protons scattered off the injection foil will have to be designed carefully.

The other important use of 0.8 GeV ring would be to support the newly proposed 0.8 GeV HEP programs: i) DS (dark energy sector) physics [10], ii) PRISM/PRIME type experiment [11] and iii) a charged lepton flavor violation program at Fermilab [12]. All these experiments demand 0.8 MeV intense short bunches of lengths in the range of 12 -500 nsec. We plan to conduct a systematic investigation on a possibility of using RF systems of the type being used at Fermilab RR at 2.5 MHz(h=4) rf system to bunches < 500 ns and use Fermilab Booster type rf system for short bunches. Furthermore, we also extend our studies on barrier rf systems used at Fermilab in the past to produce compressed bunches of variable bunch lengths as needed by the experimenters.

4 Conclusion

The implementation of a Booster storage ring offers significant benefits for the FNAL HEP program.

- Improved injection into Booster for PIP-II with a robust beam dump. Mitigates injection front porch challenges to PIP-II Booster and gives an option to increase beam intensity in the Booster beyond PIP-II design goal .
- Extremely cost effective because of no new enclosures and reduced Booster upgrade costs.
- Ability to adapt to changes in PIP-II energy with a simplified locking of the two machines.
- Streamlined PIP-II - DUNE power ramp up.
- A fast track to FNAL Dark Sector physics, PRISM type experimental and charged lepton violation programs with flexible bunch structures.
- Significant utilization of PIP-II capabilities from day 1.

Table 2: Accelerator Systems and Basic Parameters (for reference).

Accelerator *	**Rep Rate Hz**	**Beam Power MW**	**Injection E GeV**	**Extraction E**
Booster	15 - 20	.089 - .150	.4 - .8	8
PIP-II	20 - CW	2	.0012	.8 - 1
BSR	20 - 100	.1 - .2	.8 - 1	.8 - 1

*This list includes the new storage ring whose power output is not fully assessed.

References

[1] V. Lebedev et al. The PIP-II Conceptual Design Report V.0.3. *FERMILAB-TM-2649-AD-AIPC*, 2018.

[2] J. Eldred et al. Versatile Multi-MW Proton Facility with Synchrotron Upgrade of Fermilab Proton Complex. *Snowmass 2021 Letter of Interest*, 2020.

[3] James T Volk. Experiences with permanent magnets at the Fermilab Recycler ring. *Journal of Instrumentation*, 6(08):T08003–T08003, Aug 2011.

[4] BNB Neutrino Beamline. https://targets.fnal.gov/BNB_neutrino_beam.html.

[5] K. Seiya. Status of the flat injection beam studies. https://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=8043, February 2020.

[6] R. H. Kraus. The overview and history of permanent magnet devices in accelerator technology. *IEEE Transactions on Magnetics*, 30(4):1547–1554, 1994.

[7] P. A. Thonet. Use of permanent magnets in multiple projects at CERN. *IEEE Transactions on Applied Superconductivity*, 26(4):1–4, 2016.

[8] F. Bødker et al. Permanent magnets in accelerators can save energy, space and cost. In *Proceedings of the 4th International Particle Accelerator Conference, IPAC2013*, 2013.

[9] J. Eldred, V. Lebedev, and A. Valishev. Rapid-Cycling Synchrotron for Multi-Megawatt Proton Facility at Fermilab. *Journal of Instrumentation*, 14:P07021, 2019.

[10] M. Toups et al. Fixed-Target Searches for New Physics with $\mathcal{O}$(1 GeV) Proton Beams at Fermi National Accelerator Laboratory. *Snowmass 2021 Letter of Interest*, 2020.

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

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