Fermilab Main Injector and Recycler Operations in the Megawatt Era

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Fermilab Motivations: *Driving Increased Beam Power*

The Long Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) are Fermilab's scientific priorities in the coming decades[1]

Delivering a higher neutrino flux will bolster DUNE's oscillation-parameter sensitivity and measurement precision[2]

— **Achieved by increasing the beam power delivered from the Main Injector (MI)**

$P = |e|E \times {}^{N}/_{T}$, where N is particles per pulse and T is the MI ramp duration

Proton Improvement Plan II (PIP-II) will produce a new superconducting RF LINAC this decade to replace the original LINAC, commissioned in 1970[3]

— New system will have a cycle rate of 20 Hz, increased from 15 Hz

Will still feed the 8-GeV Booster synchrotron, which will also need to cycle at 20 Hz

Fermilab Accelerator Complex

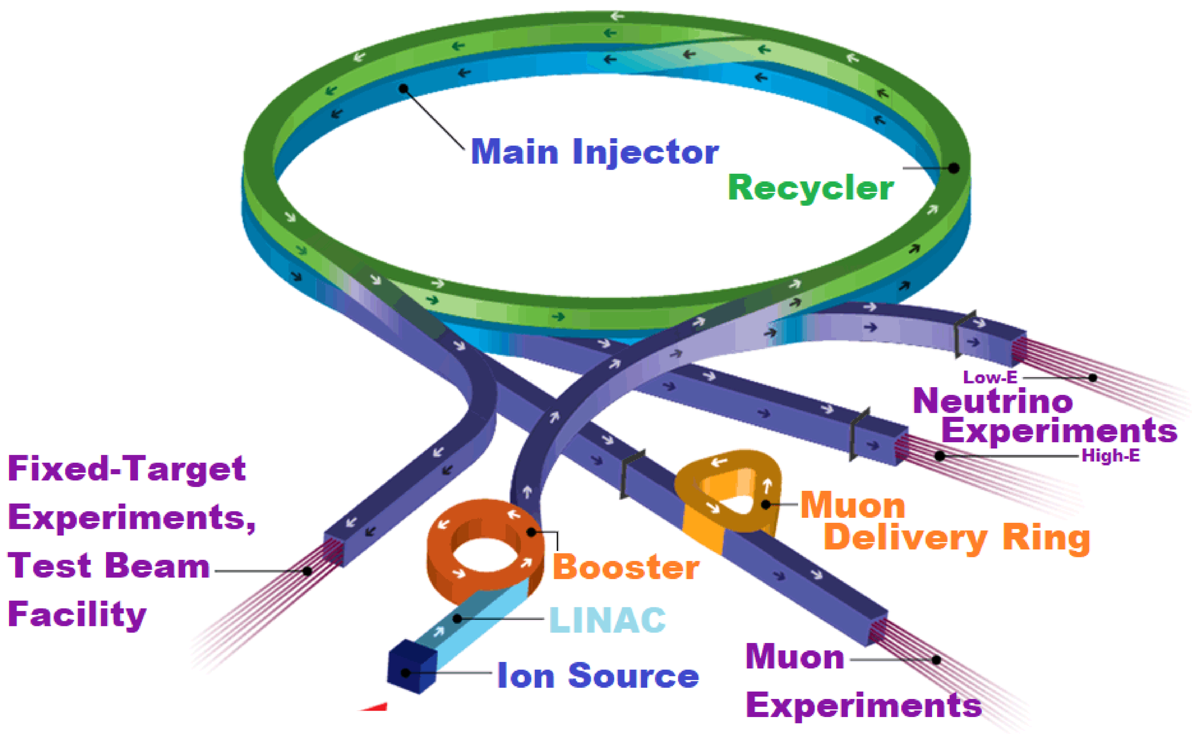


Illustration of the current Fermilab accelerator complex.

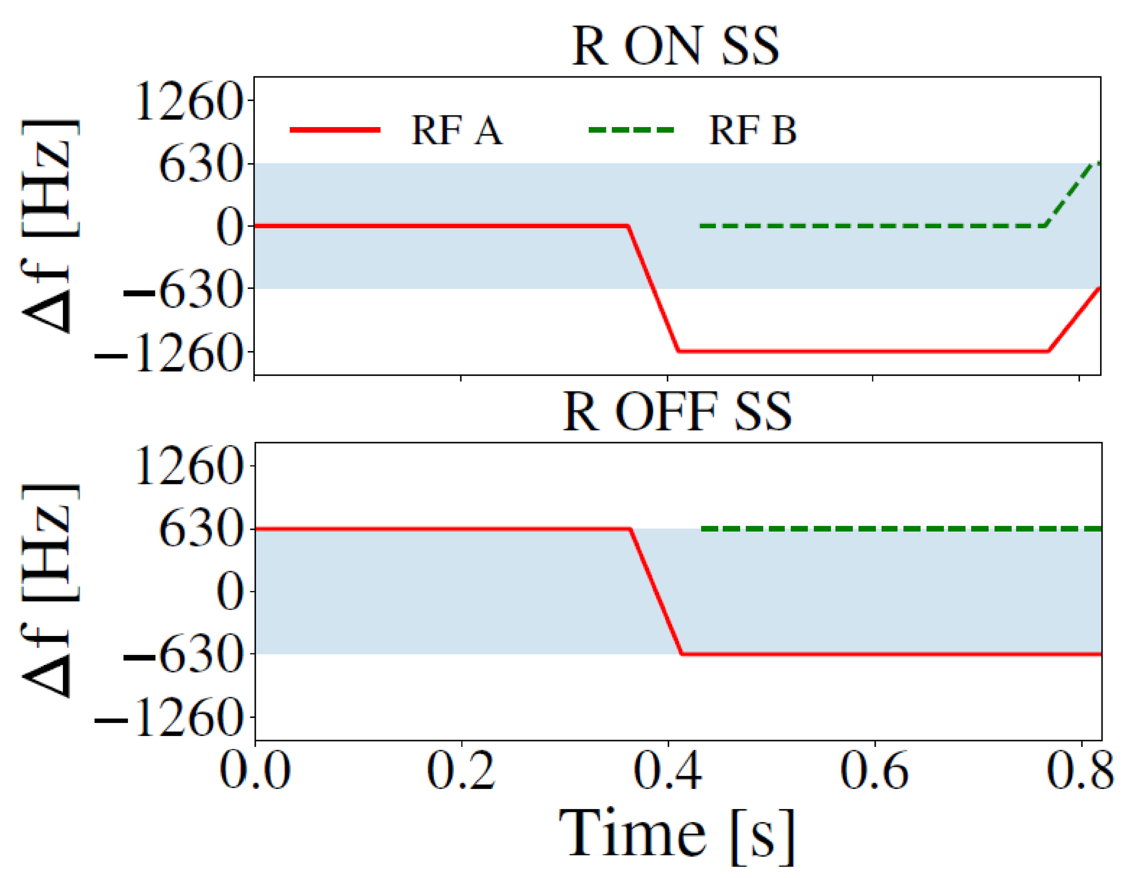
Recycler is now a proton stacker to double intensity, and new Radial Off-Center Slip-Stacking method reduced beam losses!

MI ramps to 120 GeV every 1.2 s at 5 x10^{13} protons on target; will yield 1.25 MW of beam power with a 20-Hz source

Intensity-driven approach to increasing beam power can produce beam instabilities and losses

Focusing on decreasing the MI ramp duration could yield substantial power improvements!

Radial Off-Center Slip-Stacking



Frequencies of the RF systems used during the Recycler slip-stacking methods. *Top:* R ON SS designates the original scheme. *Bottom:* R OFF SS depicts the Radial Off-Center approach. [4]

Recycler Ring accepts six batches of 84 bunches from Booster

— Booster encroaches intensity limitations

— Slip-stacking was introduced in Recycler to bypass those limitations

Original implementation: inject six batches on-frequency/on-center, decelerate by 1260 Hz as dictated by $\Delta f = h_b f_b$, where h_b is the Booster harmonic number (84) and f_b is the Booster cycle rate (15 Hz), inject 2nd set of six batches, wait for overlap, and accelerate by 630 Hz to impose radial symmetry

— 630-Hz reacceleration induced MI losses by producing DC beam

— 20-Hz rate will push needed momentum aperture to 2520 Hz (1680 Hz Δf)

Radial Off-Center Approach: inject first six batches 630 Hz above design frequency (off center in the machine), decelerate by 1260 Hz as before to make way for 2nd set of batches, inject 2nd set 630 Hz above design frequency, and extract at overlap

— Reduces momentum aperture requirement

— Reduces MI losses by 50%, significantly improving complex efficiency

Accelerator Complex Evolution (ACE) Plan — Goals for the Main Injector

Reducing ramp duration, the time-based approach to increasing power **avoids intensity instabilities** and **focuses efforts on one machine**

— Avoid e-cloud[5], transverse mode coupling[6], and convective instabilities

— Bypass systemic limitations in other machines that could hinder upgrades

Current ramp can be reduced from 1.2 s to 0.65 s through series of projects between 2024 and 2032

Increasing momentum ramp from 240 GeV/c/s to 500 GeV/c/s requires infrastructure upgrades and sufficient investigations that involve:

— Bend and quad magnet power supplies

— Low-conductivity water cooling ponds and evaporative towers

— Power substation upgrades, new transformers, feeders, and cables

— RF system capabilities and 17 new cavity installations

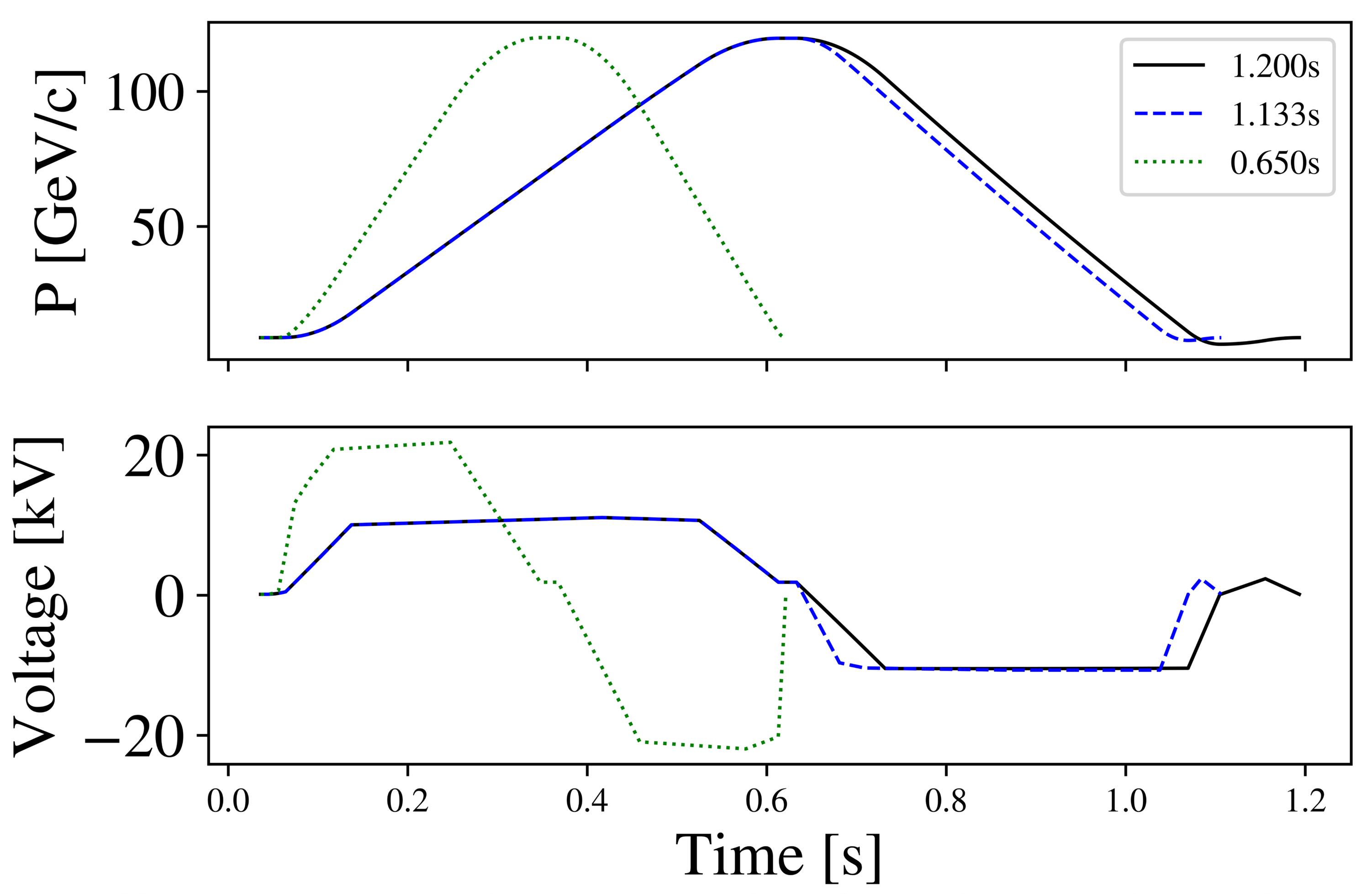
— Magnet limitations and spare availability

1.133-s ramp time set during FY23 to test feasibility and explore ACE Plan

New sustained power record of 959 kW set during test

1.067-s ramp test set for FY24, will surpass 1 MW

Fully realized, 0.65-s ramp would produce a 2.2-MW beam with 20-Hz source!



Momentum (*top*) and magnet supply voltage (*bottom*) given a 1.2-s (*solid*), 1.133-s (*dashed*), and 0.65-s (*dotted*) MI ramp time. The 1.2-s case represents nominal running. A 1.133-s ramp was reached during FY23, and the 0.65-s ramp is the optimal ACE consideration.

[1] A. Valishev, Fermilab Accelerator Capabilities Enhancement Workshop Introduction, *ACE Workshop*, Jan. 2023.
[2] B. Abi *et. al*, Deep Underground Neutrino Experiment (DUNE) Far Detector TDR, arXiv:2002.03005v1, Jan. 2020.
[3] M. Murphy, D. Morris, M. Wren, Fermilab Accelerator Complex Evolution: The Main Injector, *Workshop on Accelerator Operations 2023*, Sep. 2023.
[4] R. Ainsworth *et. al*, Improvements to the Recycler/Main Injector to Deliver 850 kW+, *NAPAC 2022*, Aug. 2022.
[5] A.P. Schreckenberger *et. al*, Electron Cloud Simulations in the Fermilab Recycler, *NAPAC 2022*, Aug. 2022.
[6] O. Mohsen, R. Ainsworth, Waker Experiments at Fermilab Recycler Ring, *NAPAC 2022*, Aug. 2022.
[7] V. Shiltsev, Alignment to P5 and other Considerations, *ACE Workshop*, Jan. 2023.

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