Protons for Neutrinos: Mid-Term and Project-X

Bob Zwaska
Fermilab

Intensity Frontier Neutrino Working Group Meeting
October 24, 2011

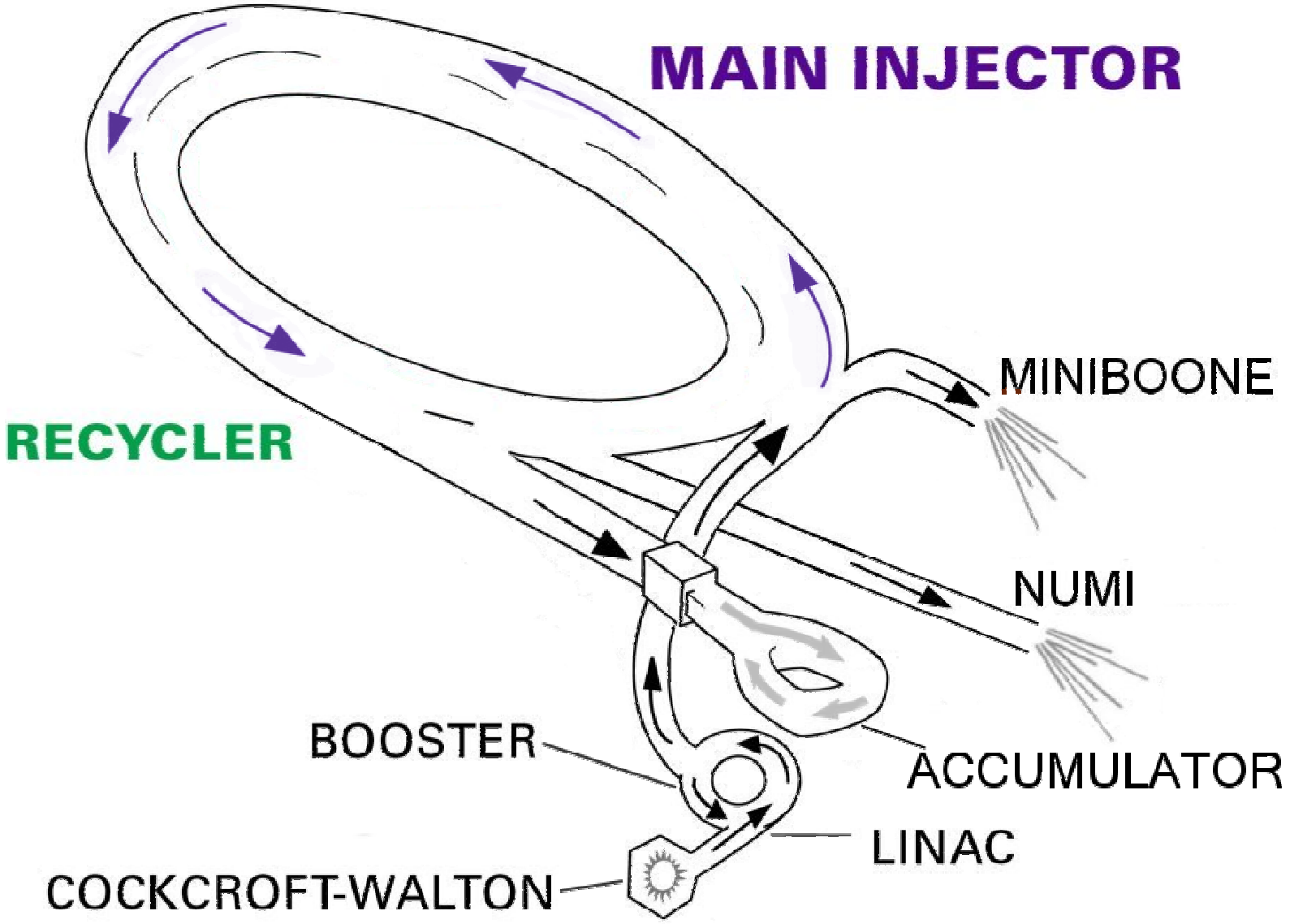
Introduction

- Recent, intense neutrino experiments at Fermilab have stressed proton production
  - Protons are the raw material to make neutrinos
  - NOvA requires proton exposure 3-6x that of MINOS, LBNE even more
  - Fermilab has several short-, mid-, and long-term initiatives to provide more protons

Outline

- Present Fermilab Accelerator Complex
  - Provides protons neutrino production (and other fixed-target applications)
  - 340 kW @ 120 GeV, another ~ 10 kW @ 8 GeV
- Programs to improve proton beam power
  1. Proton Improvement Plan $\Rightarrow$ in progress
  2. NOvA Upgrades (ANU) $\Rightarrow$ in progress
  3. Proton Driver / Project X $\Rightarrow$ in R&D

FERMILAB'S PROTON COMPLEX



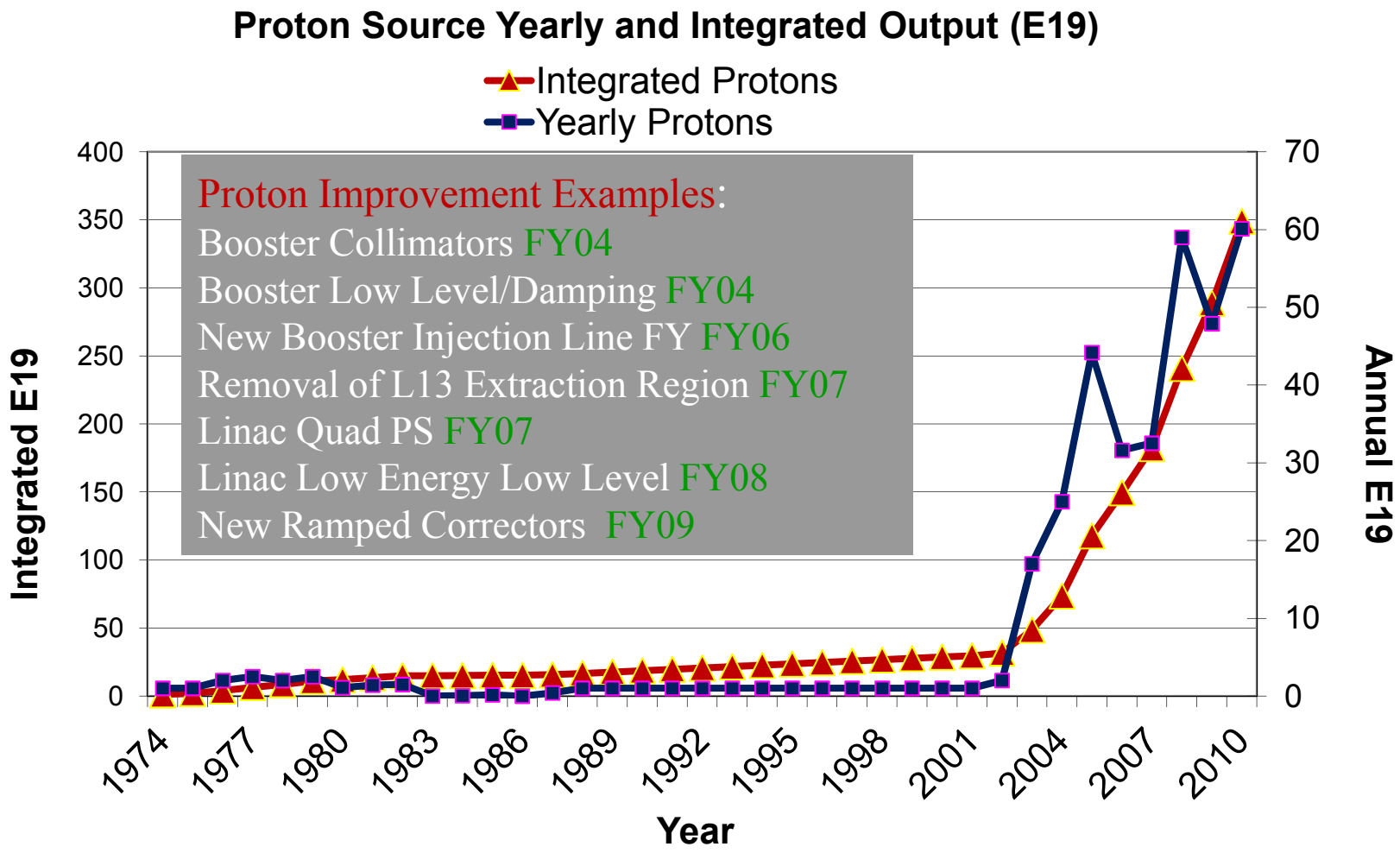
Present Proton Production

- Linac produces 400 MeV H^-
  - Bunched at 200 MHz
  - 35 mA for up to 40 us at up to 15 Hz
- Booster produces 8 GeV protons (MiniBooNE, etc.)
  - Bunched at 53 MHz
  - Up to 5e12 (typically 4.3e12) in 1.5 us
  - Operates up to ~ 7 Hz (40 kW)
- Main Injector produces 120 GeV protons (NuMI)
  - Bunched at 53 MHz
  - Up to 4e13 (typically 3.7e13) in 9.7 us
  - Operates as quickly as 2.2 s (350 kW)
  - Almost all is for neutrino production, but ~ 20% was for antiprotons until recently

Limits to Proton Throughput

- Linac/Booster (Proton Source)
  - Losses in the Booster accelerator limit power
  - Not initially intended as high duty factor machines
  - Proton Improvement plan is to more than double throughput (goal of 2.5e16/hr, or 90 KW)
- Main Injector
  - Losses and cycle time limit power
  - More modern machine – designed for high duty factor
  - NOvA accelerator upgrades will reduce the cycle time, pushing MI power to near 700 kW
- Target Stations
  - Generally, the target stations to produce beams can limit how many protons can be delivered to them
  - Issues become significant in the 10s of kW and severe in the 100s of kW – MW will be above and beyond
  - Beyond scope of this talk – but an important issue for any planned application

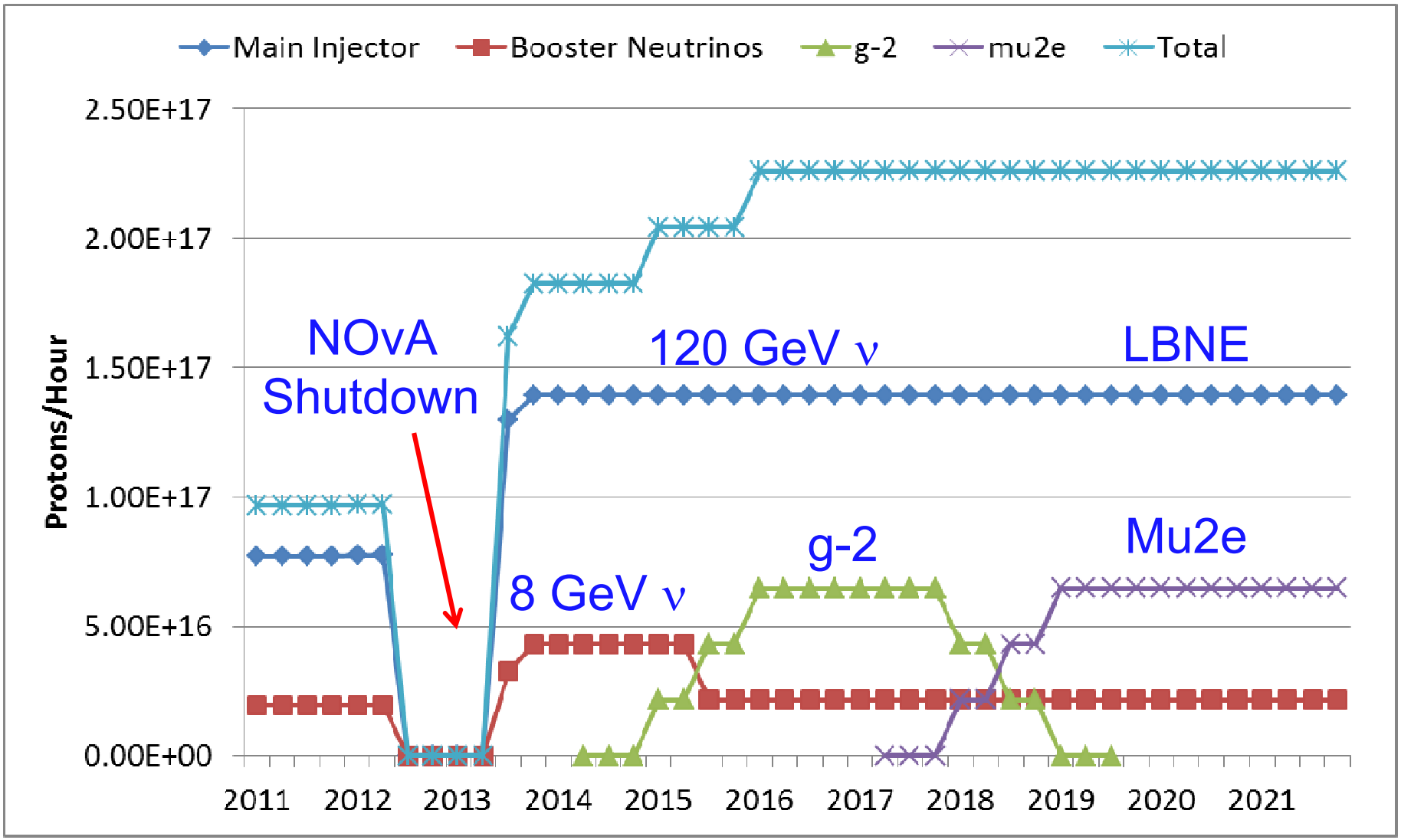
Booster - Historical Performance



PIP – Proton Improvement Plan

- A recognition that, until the Project-X linear accelerator is operational, the entire domestic accelerator-based high-energy physics program is powered by the 40+ year old Proton Source.
- Despite age-related issues of reliability and availability of spare components, demands on the Proton Source continue to increase.
- Experiments that have received Fermilab PAC approval or are in the DOE CD-process expect a factor of two increase of the current proton delivery rate within the coming decade.

Proton Source Throughput Goals



Goals for the Proton Improvement Plan

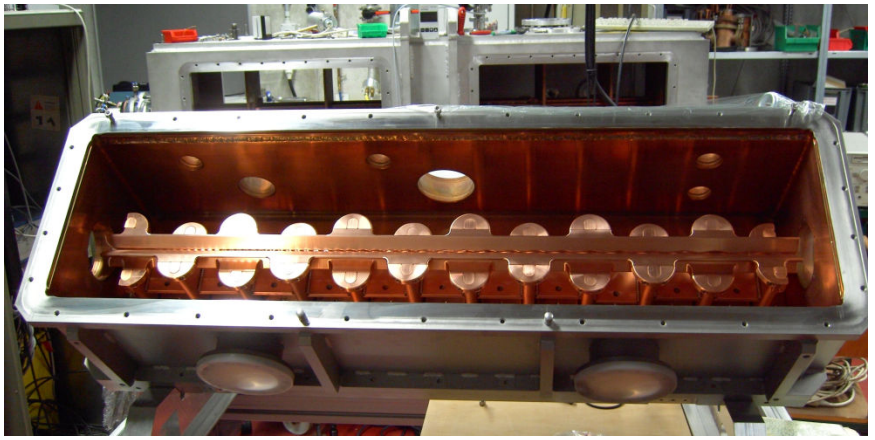
- The ***Proton Improvement Plan*** should enable Linac/Booster operation capable of
  - delivering 2.25E17 protons/hour (at 15 Hz) in 2016

  while
  - maintaining Linac/Booster availability > 85%, and
  - maintaining residual activation at acceptable levels

  and also ensuring a useful operating life of the proton source through 2025.
- The scope of the ***Proton Improvement Plan*** includes
  - Upgrading (or replacing) components to increase the Booster repetition rate
  - Replacing components that have (or will have) poor reliability
  - Replacing components that are (or will soon become) obsolete
  - Studying beam dynamics to diagnose performance limitations
  - Implementing operational changes to reduce beam loss
- Several important activities are well underway (e.g. RFQ replacement, Booster solid-state RF replacement)

PIP

- Plan is underway, though just organized formally in the last year
- Advanced items
  - Source/RFQ replacement
  - Solid State RF upgrade
- Utilities work
  - Aging water, electrical, vacuum systems
- Items in planning
  - Linac RF replacement
  - Booster cavity rework
  - Loss reduction and control
  - Numerous small items
- Installation of all work to be complete by 2016, gains realized along the way as commissioning occurs

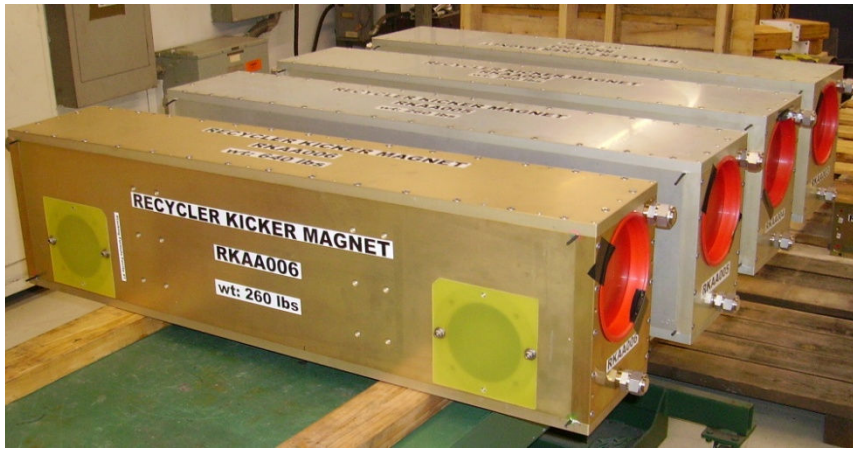


NOvA Upgrades: Recycler as an 8 GeV Proton Pre-injector

- Recycler had been an antiproton storage ring in MI tunnel
  - Use the Recycler to accumulate protons from the Booster while MI is running
    - Time needed to inject multiple Booster batches
    - Save 0.8 s for 12 Booster batches injected
- Recycler momentum aperture is large enough to allow slip-stacking operation in Recycler, for up to 12 Booster batches
  - 4.9×10^{13} ppp at 120 GeV every 1.333 s $\Rightarrow$ 700 kW
  - New Kicker and Collimator system to control losses
  - Kickers force stray beam in injection and extraction gaps to the abort
  - Collimators collect beam that is not captured and spirals inward

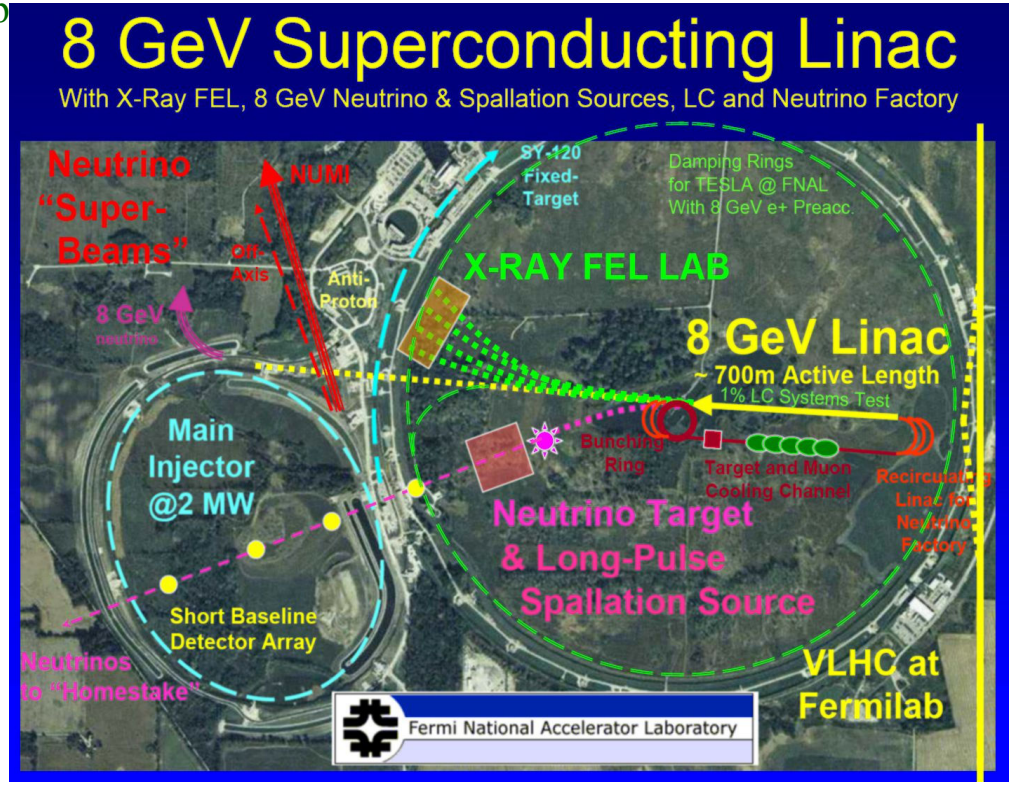
NOvA Progress

- Construction well underway
  - In planning since 2006
- Long shutdown planned to start next year
  - Add an injection line from Booster to Recycler
  - Add 53 MHz RF to Recycler
  - Add gap clearing kickers to Recycler
  - Add transfer line from Recycler to Main Injector
  - Improve Main Injector ramp and RF
  - Modify NuMI target station for higher energy and with more reliable target
- All upgrades to be finished by 2013, and high-power operations begin immediately



Proton Driver – an 8 GeV SC Linac

- Incorporated concepts from the ILC, the Spallation Neutron Source, RIA and APT.
  - Copy SNS, RIA, and J-PARC Linac design up to 1.3 GeV
  - Use ILC Cryomodules from 1.3 - 8 GeV
  - H^- Injection at 8 GeV in Main Injector
- "Super Beams" in Fermilab Main Injector:
  - 2 MW Beam power at both 8 GeV and 120 GeV
    - 150×10^{12} protons per cycle
  - Small emittances => Small losses in Main Injector
  - Minimum (1.5 sec) cycle time (or less)

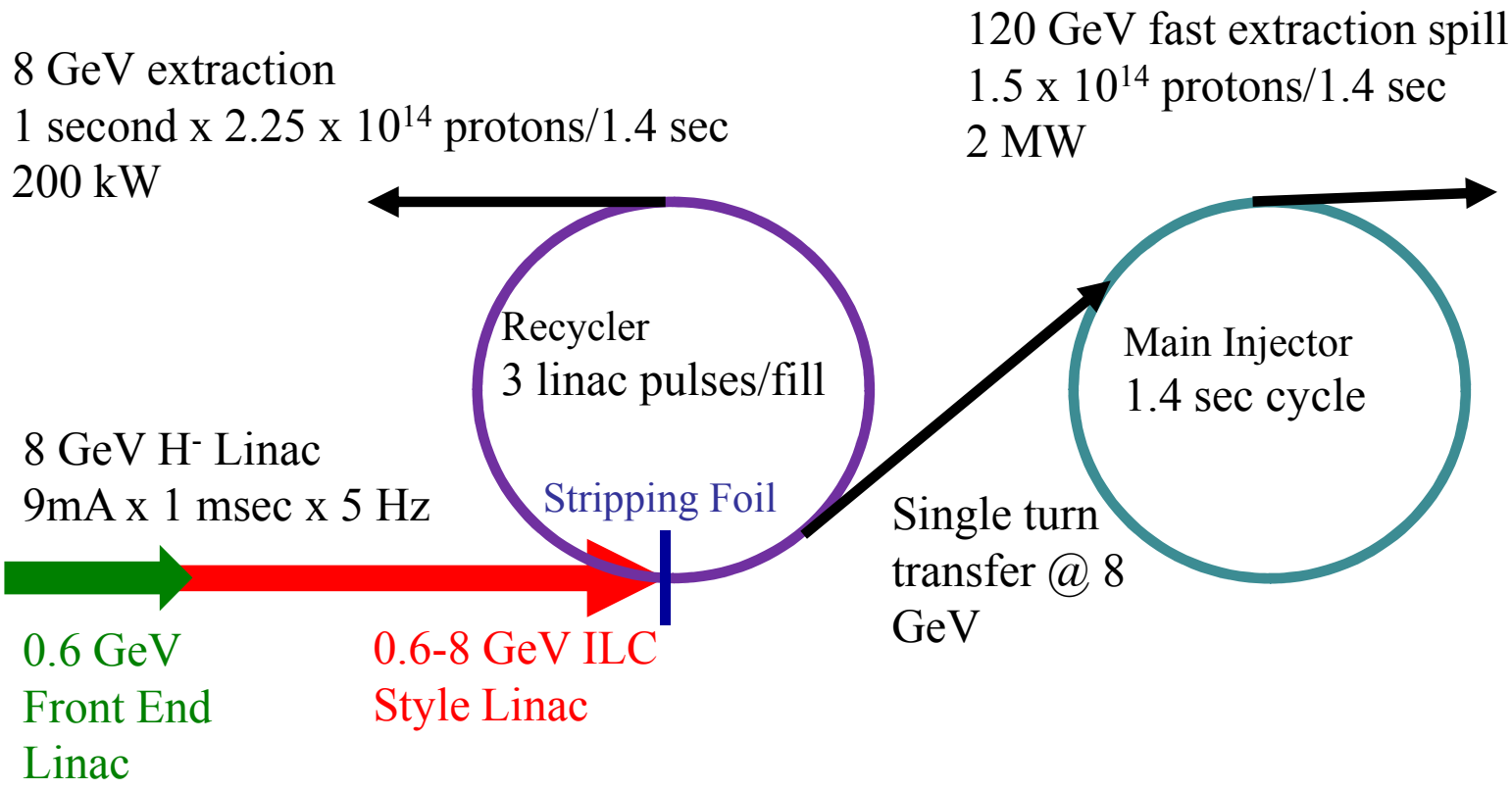


- **This was a great proposal for neutrino experiments, but didn't fit the broader mandate from P5**

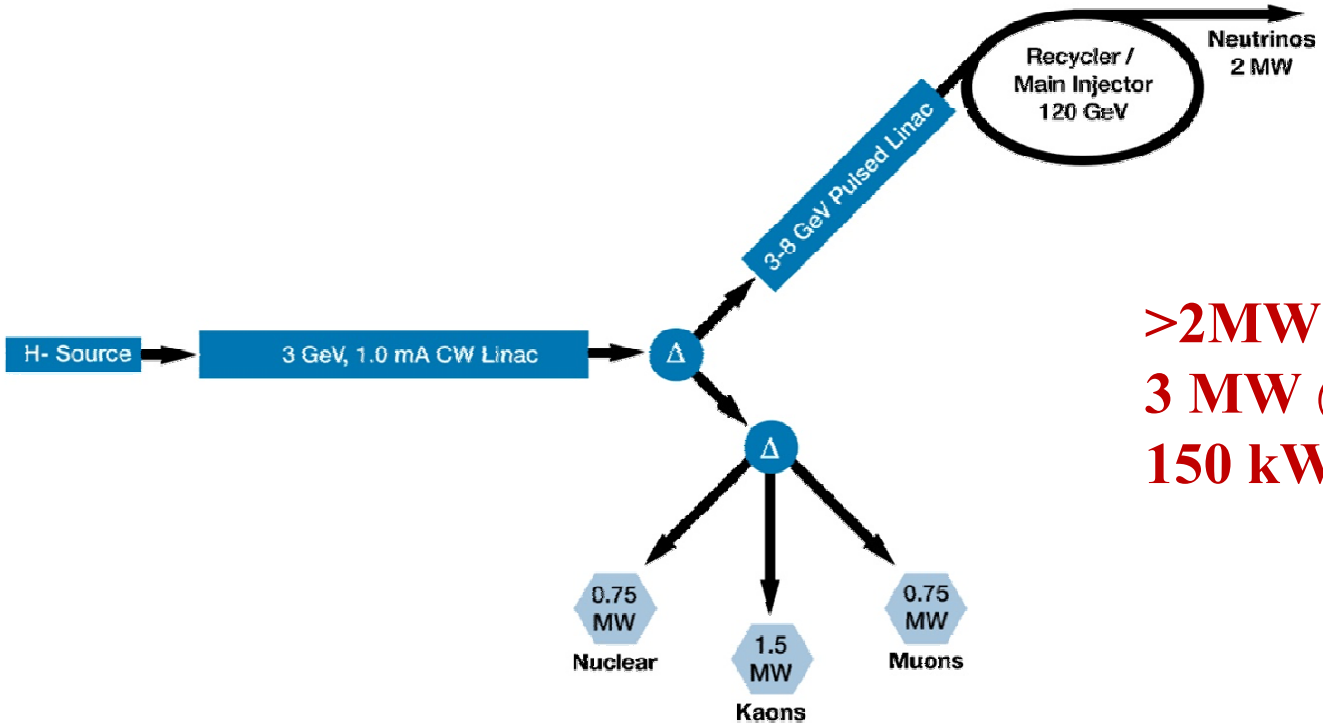
Proton Driver Evolution

- The P5 report identifies three physics goals for a new high intensity proton source at Fermilab which define the Project X mission need:
  - *"A neutrino beam for long baseline neutrino oscillation experiments..."*
  - *"Kaon-and muon-based precision experiments..."*
  - *"A path toward a muon source for a possible future neutrino factory, and, potentially, a muon collider at the Energy Frontier..."*
- The 8 GeV SC Linac was not optimized for the kaon and muon experiments
  - Need delivery of intermediate energy beam at a **high duty factor**

Project X – Mark I



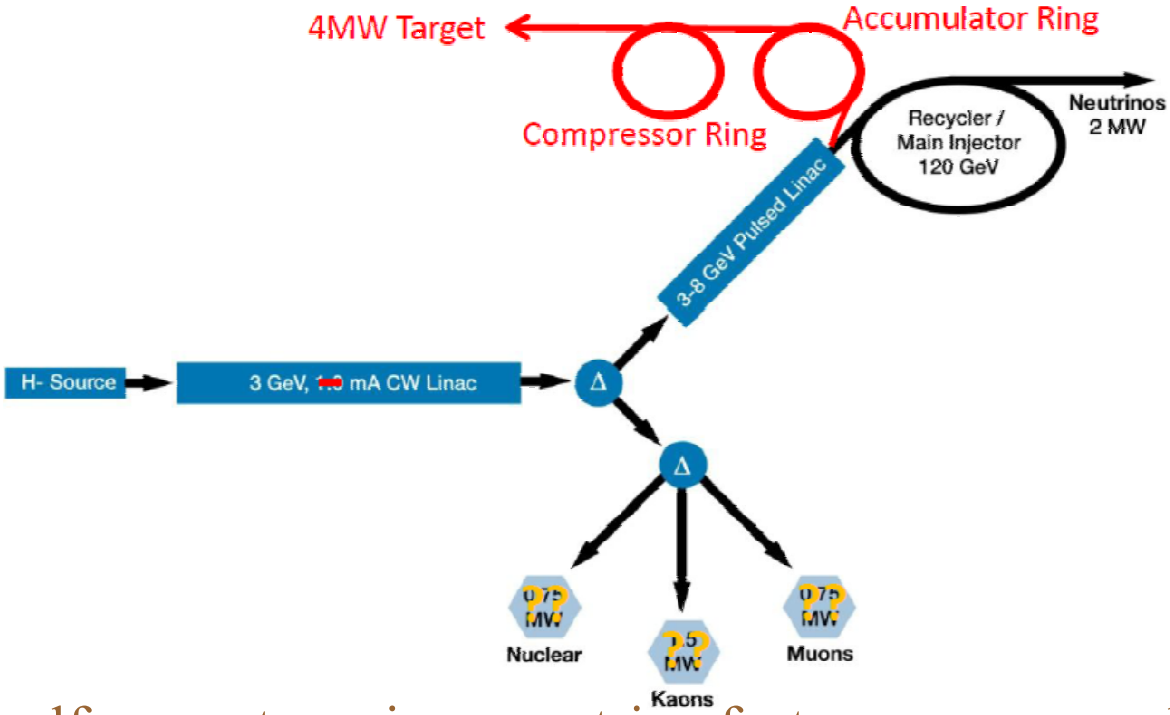
Project X Reference Design



>2MW @120 GeV
3 MW @ 3 GeV
150 kW @ 8 GeV

- CW technology emerged as the preferred choice
  - Slow extraction was deemed an insurmountable obstacle to high duty factor beams > 100 kW
- Still produces high-power beams for neutrinos, but in a more complicated way – more risky
  - Second linac/ring, long injection pulse, multiple injections, lower-energy injection …

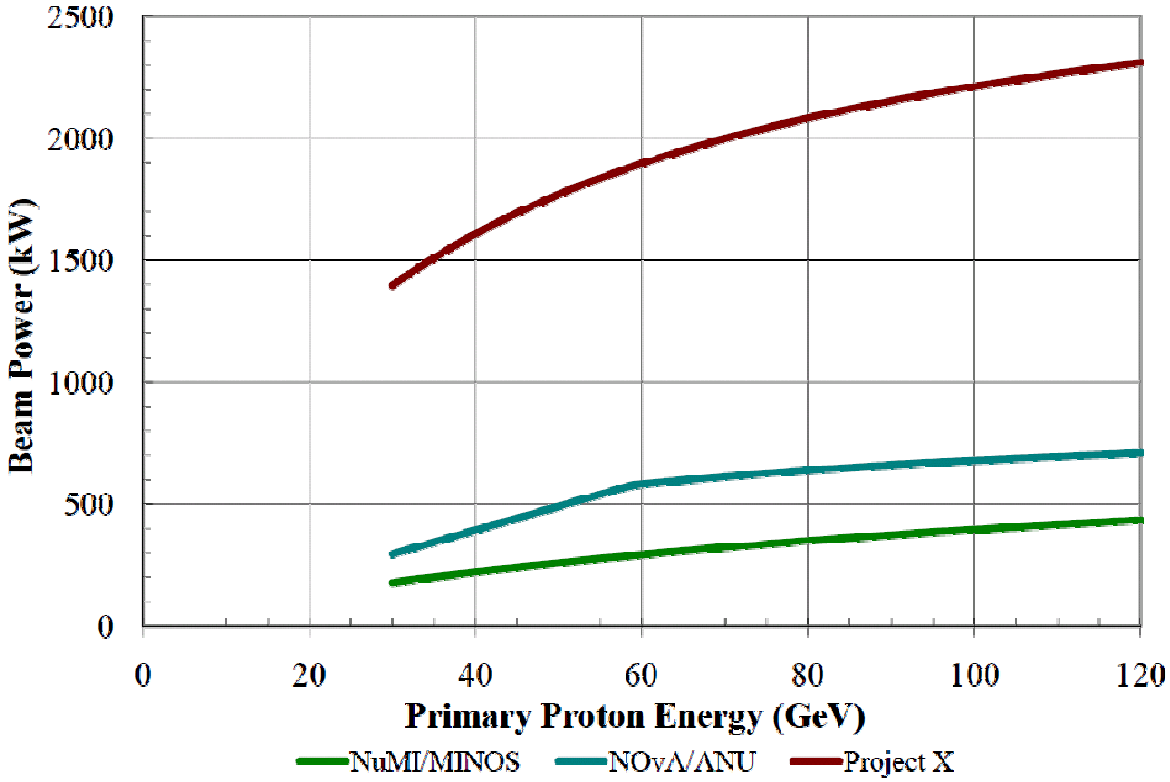
Project X Upgrades for a NF/MC



- Project X, itself, cannot service a neutrino factory or muon collider front end
- Additional rings to accumulate and combine low-current beam
  - For MC 10^7 linac microbunches must be combined into one
- Pulsed linac must be upgraded for higher current and duty factor

Options for Delivery

- Lower energy beams from the MI (8 GeV< E < 120 GeV)
  - More protons, but less power
  - Limited by fixed portions in the MI ramp
  - Limited by the availability of protons from the previous stage – greater consumption of 8 GeV beam



Summary

- Fermilab accelerators have vastly improved performance over the last decade
  - Prompted by MiniBooNE and MINOS experiments
- Performance will be enhanced by another factor of ~ 2 over the next several years
  - PIP for Linac & Booster produces ~ 90 kW @ 8 GeV
    - Completer by 2016
  - NOvA for MI / RR produces ~ 700 kW @ 120 GeV
    - Consuming 50 kW of the 8 GeV beam
    - Complete by 2013
- Present experiments account for all proton availability through the next decade (LBNE for another decade)
- Higher beam power requires a complete replacement of the proton source: Project X
  - 2 MW @ 60-120 GeV, 150 kW @ 8 GeV, 3 MW @ 8 GeV

References

- PIP (Proton Improvement Plan)
  - A Plan for Delivery of 8-GeV Protons through 2025, Beams-doc-3781, http://beamdocs.fnal.gov/ADpublic/DocDB/ShowDocument?docid=3781
  - Proton Source Task Force Report, Beams-doc-3660, http://beamdocs.fnal.gov/ADpublic/DocDB/ShowDocument?docid=3660
  - Proton Source December 2010 Workshop, http://beamdocs.fnal.gov/ADpublic/DocDB/DisplayMeeting?conferenceid=114
- NoVA Accelerator Upgrades
  - NOvA Technical Design Report, Chapter 8, http://www-nova.fnal.gov/nova_cd2_review/tdr_oct_23/tdr.htm
- Project X (nee Proton Driver)
  - Project X Functional Requirements Specification, http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=658
  - Project X Reference Design Report, http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=776

Protons for Neutrinos: Mid-Term and Project-X

Bob Zwaska
Fermilab

Intensity Frontier Neutrino Working Group Meeting
October 24, 2011