Accelerators for Intensity Frontier Research

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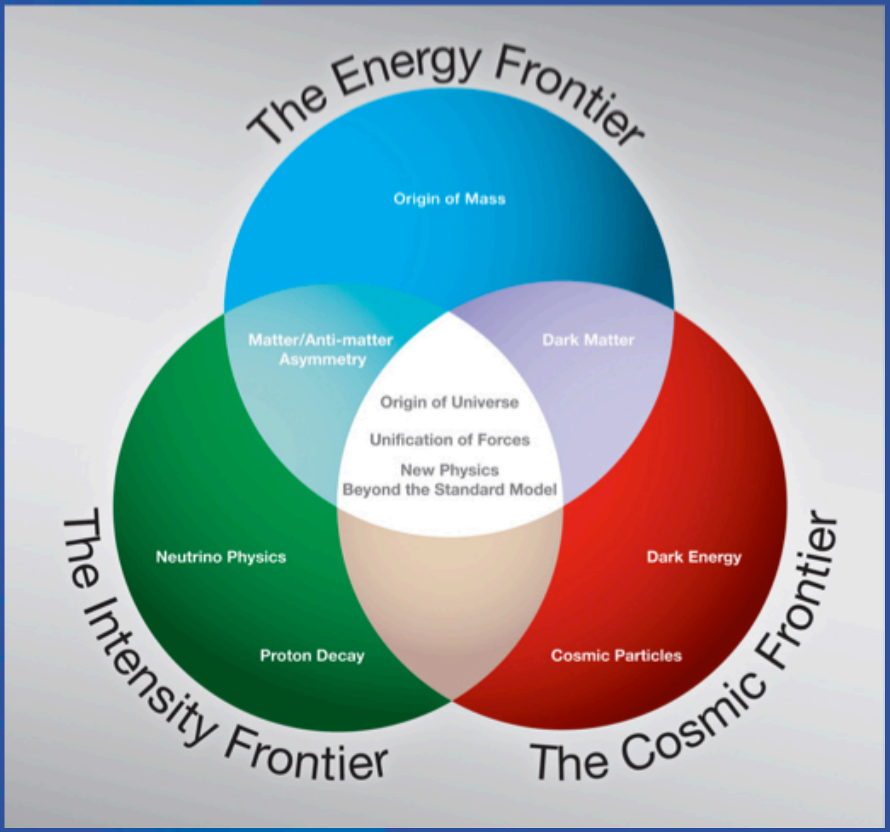
May 21-25, 2012

U.S. DEPARTMENT OF ENERGY

Fermilab

The Intensity Frontier



- In the fall of 2007, HEPAP commissioned a panel for the purpose of developing a plan for US particle physics for the coming decade:
  - Particle Physics Project Prioritization Panel : P5
- Designated three frontiers:
  - Energy: Tevatron & LHC
  - Intensity: Neutrinos and Rare Decays
  - Cosmic: Dark Energy & Matter

From the P5 report,
http://www.er.doe.gov/hep/files/pdfs/P5_Report%2006022008.pdf

The Intensity Frontier

- At the Intensity Frontier, scientists use accelerators to create intense beams of trillions of particles for neutrino experiments and measurements of ultra-rare processes in nature. Measurements of the mass and other properties of the neutrinos are key to the understanding of new physics beyond today's models and have critical implications for the evolution of the universe. Precise observations of rare processes provide a way to explore high energies, providing an alternate, powerful window to the nature of fundamental interactions.

- Present @ Fermilab:
  - MINOS, MINERvA, MiniBoone, ArgoNeut
- Future @ Fermilab:
  - NOvA, MicroBoone, long baseline ν experiment, Mu2e, g-2, ORKA

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The Worldwide Intensity Frontier

Presentations in plenaries at IPAC'12

- J-PARC: neutrinos
  - S. Nagayima, Status of the J-PARC Facility TUXA01
- B Factories: bottom quark
  - M.E. Biagini, Overview of B Factories WEYA03
- BEPCII: charm quark
  - Q. Qin, Performance and Prospects of BEPCII, TUYA03
- Project X: many aspects
  - R. Tschirhart, Project X: The High Intensity Horizon at Fermilab WEXA01
- Many other programs around the world

- Focus on the Fermilab program

Fermilab’s role: intensity frontier

- Advance the understanding of neutrinos and the observation of rare decays coupled to new physics processes
- Fermilab strategy: develop the most powerful set of facilities in the world for the study of neutrinos and rare processes, well beyond the present state of the art.
- Will define the role of US facilities in the world’s program.

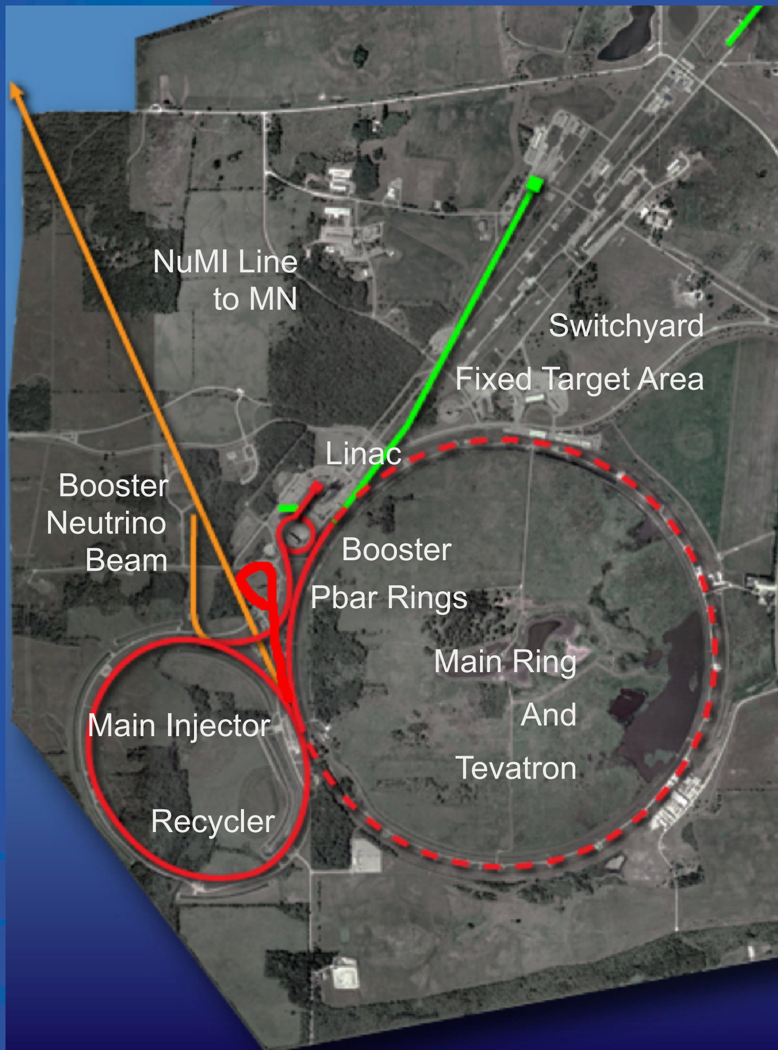
Near Term Program

- In the near term, a series of world-class experiments exploiting the present complex:
  - NOvA: ν vs. $\bar{\nu}$, next step in oscillation parameters
  - MicroBooNE: follow MiniBooNE anomaly; LAr TPC
  - MINERvA: ν nuclear cross sections/nuclear structure
  - MINOS+ : ν vs. ν; anomalous interactions
  - LBNE (700 kW): neutrino oscillations, neutrino mass spectrum, matter-antimatter symmetry, proton decay, SN burst – in flux at this moment in time!
  - ORKA : K -> $\pi\nu\nu$, 1000 event samples
  - g-2: anomalous magnetic moment of the muon
  - Mu2e: direct muon to electron conversion
  - SeaQuest: nuclear physics Drell-Yan process
- Usually about power, also about packaging

Power and Packaging

- Fermilab program harkens back to its birth
  - Fixed target program
  - Neutrinos
    - Oscillation physics, generally all about beam power
    - Single turn extraction, as many protons as possible
  - Kaons
    - Rare decay K -> $\pi\nu\nu$ using stopped K
    - Slow spill, bunch spacing to match K lifetime (~10-50 nsec)
  - Muons
    - Muon to electron conversion with atomic capture
    - Slow spill, bunch spacing to match μ lifetime (~900 nsec)
    - Anomalous magnetic moment
    - Single turn extraction, spacing to match μ lifetime (64 μsec at 3.09 GeV/c)

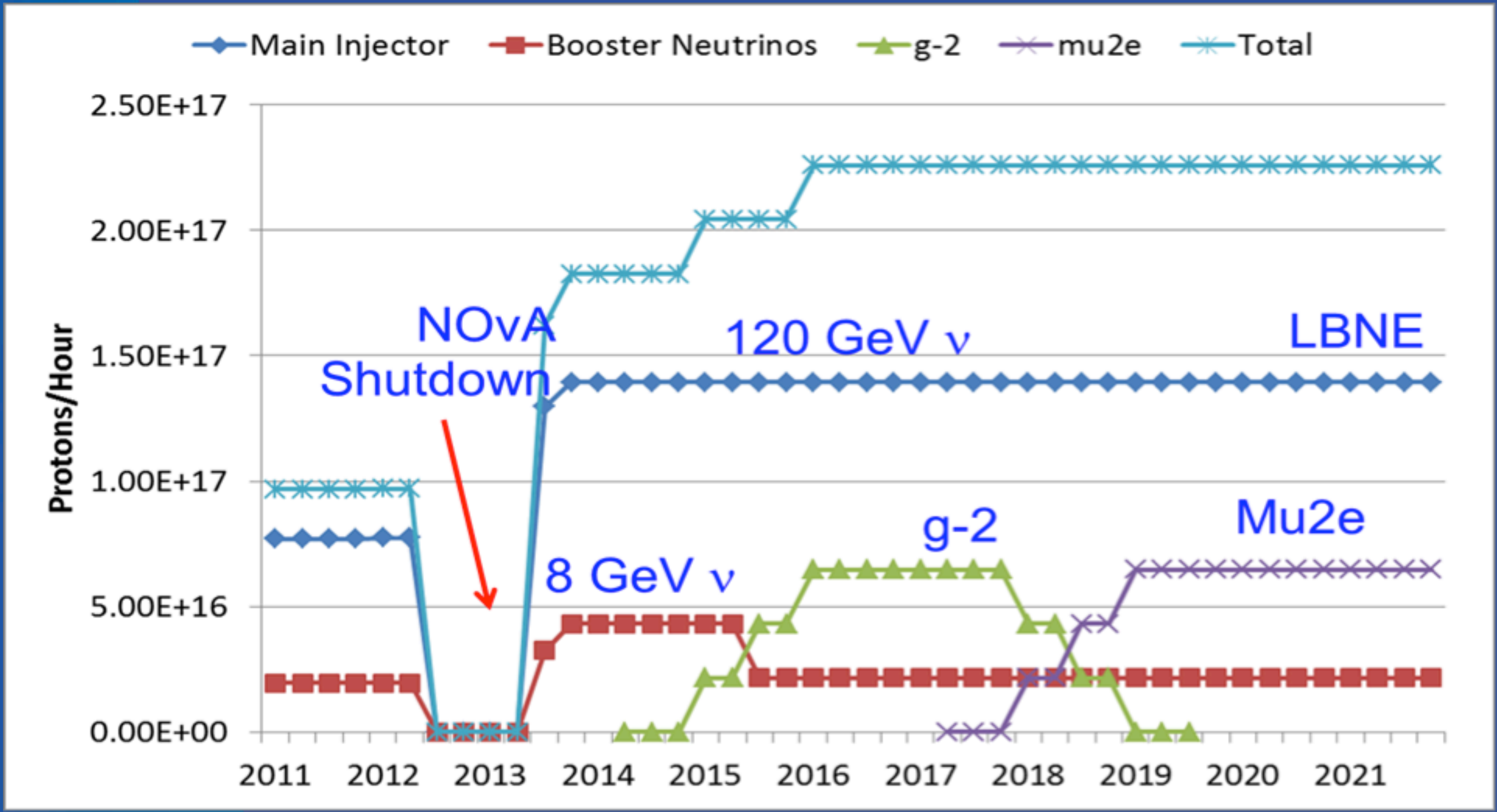
The Accelerator Complex at Fermilab



- Linac: H^-, 400 MeV, 35 mA
- Booster: 15 Hz, Charge Exchange Injection, 8 GeV, 5e12 protons/pulse
- Recycler: Permanent Magnet, 8 GeV, 7x Booster Circumference
- Main Injector: Fast Cycling, 120 GeV, 7x Booster
- Pbar Rings: Debuncher 8 GeV, 1x Booster

Experiment	Energy	Proton Request	Lifetime	
MicroBoone	8 GeV	2 Hz, 5e12 ppp (Booster)	4 years	
NOvA (Minos +, a lbne?)	120 GeV	9 Hz, 4.5e12 ppp(Booster) 0.75 Hz, 4.9e13 ppp (MI)	6 years	700 kW
Mu2e	8 GeV	1.5 Hz, 5e12 ppp (Booster)	3 years	54 msec spill, 10^{-10} extinction
g-2	8 GeV	4.5 Hz, 5e12 ppp (Booster)	1.5 years	2.5 MHz rebunching, delivery ring
ORKA	95 GeV	4.8e13 protons/spill, 4.4 sec spill	4 years	44% duty factor, 20 nsec spacing, low loss spill
SeaQuest	120 GeV	1e13 protons/spill, 4 sec spill	2 year	10% duty factor, low loss

Proton Requests



- Peak intensity: ORKA would take away from 120 GeV ν program

8 GeV experimental program

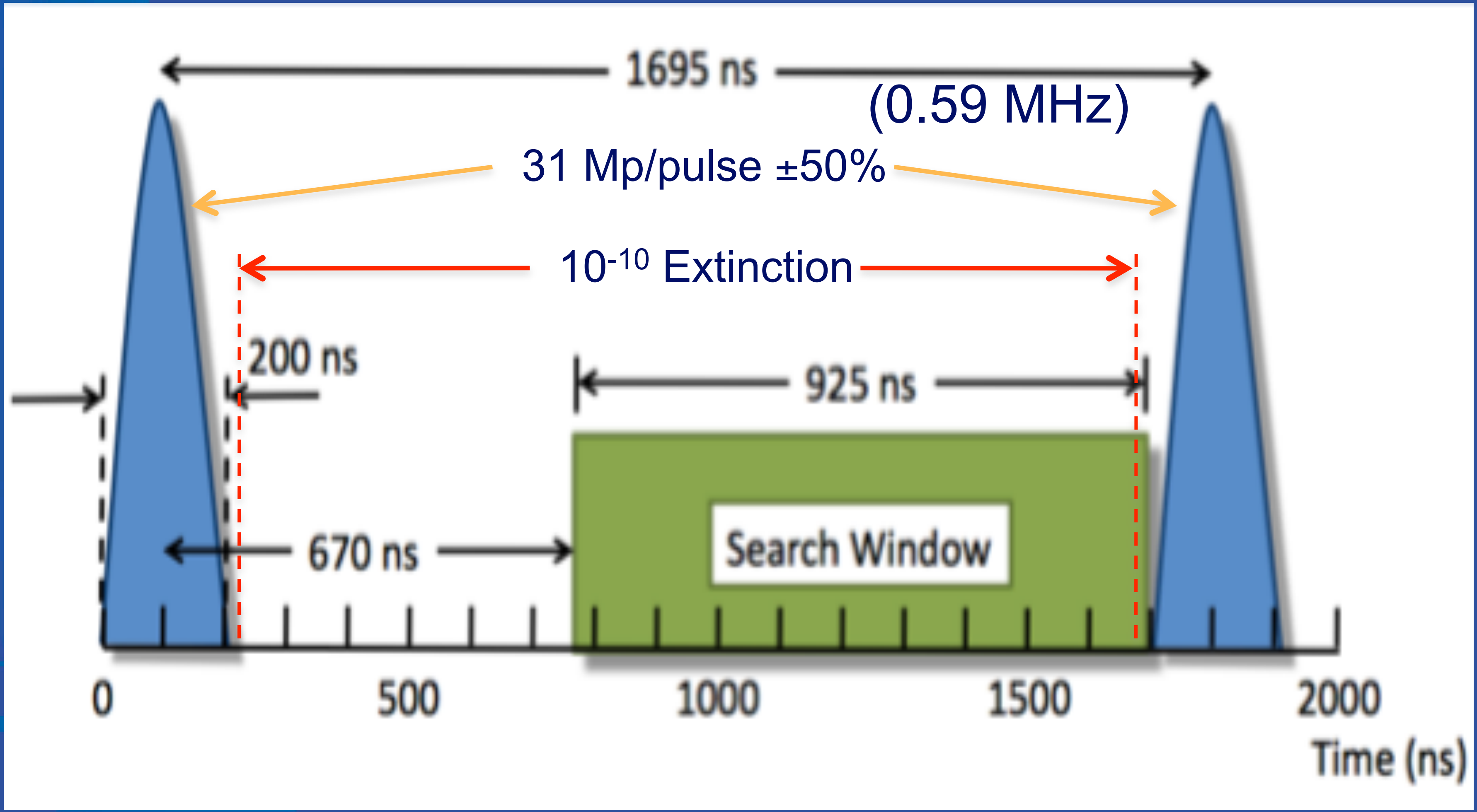
- Booster Neutrino Beam
  - Supports experiments in short baseline neutrino oscillation physics
  - As many protons as possible
  - Single turn from booster (1.6 μsec) 5e12 ppp
  - MicroBoone: continue LSND and MiniBoone anomalies
  - 4e20 POT

- g-2 anomalous magnetic moment of the muon
  - 8 GeV protons to target, collect 3.1 GeV secondaries
  - Muons transported to special purpose decay ring at 3.09 GeV/c and measure the difference between the cyclotron frequency and the spin precession frequency by looking at electrons from V-A decays, which give modulation in the decay rate
  - Long transport line to minimize pion contamination in beam (backgrounds to electron identification)
  - Goal: (g-2)/2 to 0.14 ppm
    - 20x improvement in statistics, 3x reduction in systematics

8 GeV Experimental Program

- Mu2e Conversion
  - Low energy muons are captured in orbit around Al nucleus and decay
  - Lifetime 864 nsec in stopping target
  - Conversion electrons have E ~ 105 MeV vs ~53 MeV from decay
  - Pulsed beam ~2 μsec spacing, 100 nsec RMS width
  - Beam backgrounds important
  - Beam Extinction between pulses 10^{-10}
  - 10^{18} stopped muons to reach 2 x 10^{-17} sensitivity

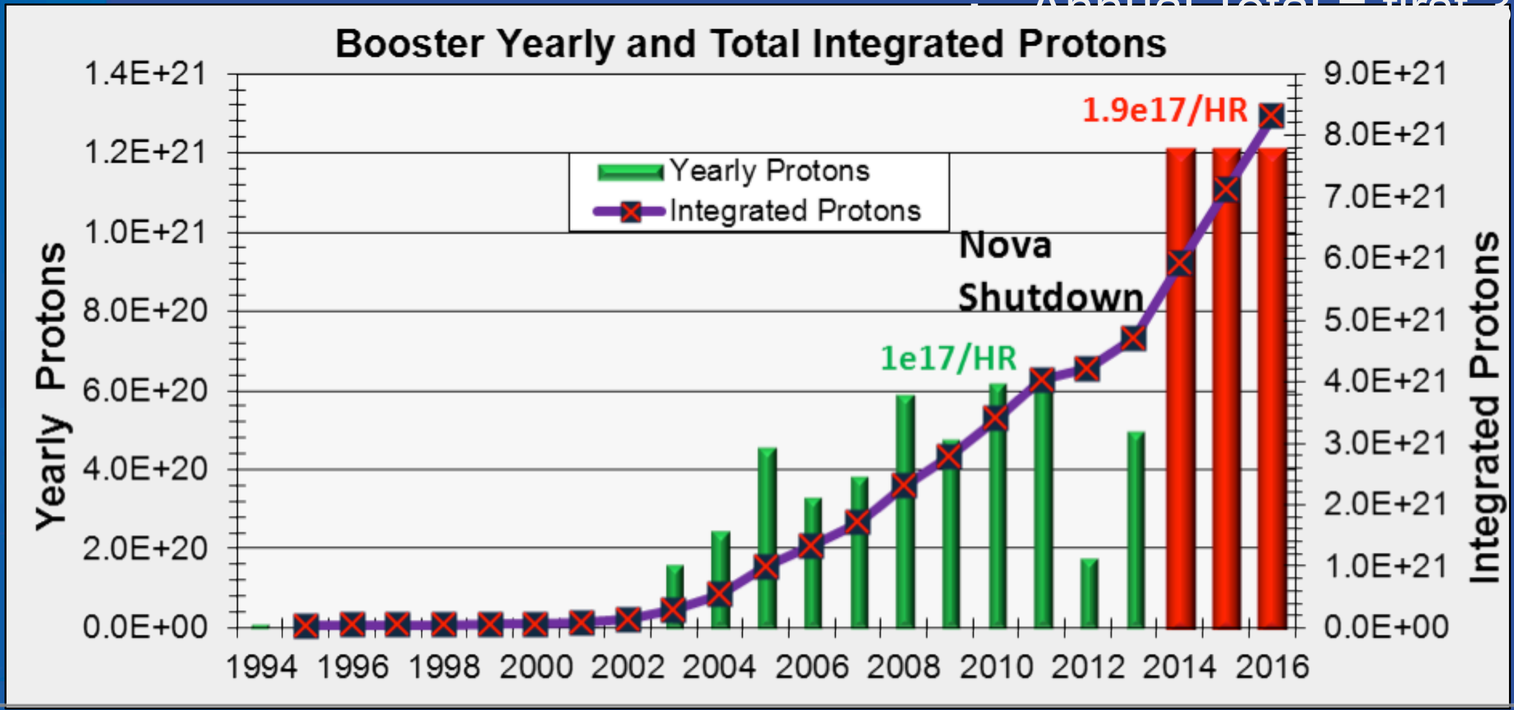
Mu2e beam delivery request



8 GeV performance

- Booster:
  - ~7 Hz
  - Limited by RF cavity cooling
  - 5e12 peak
  - Limited by beam loss

- 2003, 2004, 2005
  - ~Doubled previous total flux
  - Doubling yearly flux to meet program goals
  - Annual Total = first 35 years



Proton Improvement Plan

- Recognizing the future demands on the Linac and Booster, developed a plan to:
  - Increase the beam repetition rate from ~7 Hz to 15 Hz
  - Eliminate major reliability vulnerabilities and maintain reliability at present levels (>85%) at the full repetition rate
  - Eliminate major obsolescence issues
  - Increase the proton source throughput with a goal of reaching > 2e17 protons/hour
  - Ensure a useful operating life of the proton source through at least 2025

- Capability of delivering 1.8e17 protons/hour (at 12 Hz) May 2013
- Capability of delivering 2.2e17 protons/hour (at 15 Hz) January 2016

Proton Improvement Plan

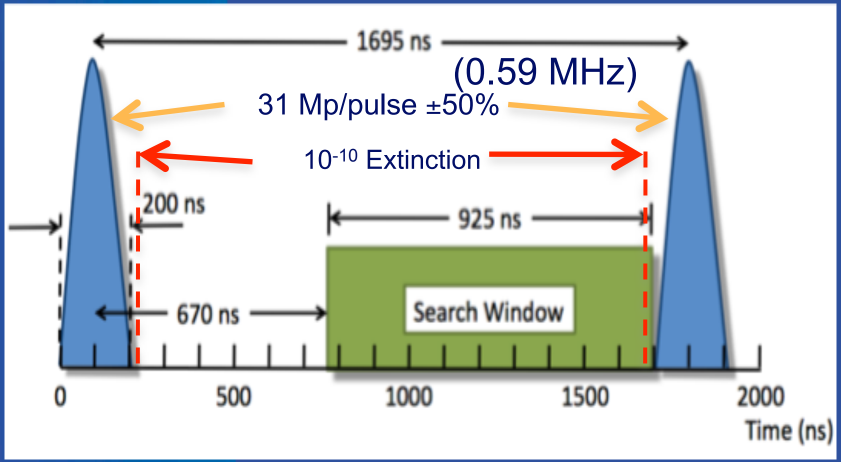
- Started in 2011, a 5 year plan with 3 major components:
  - Reliability: water, RF power, magnet power, vacuum system, magnet spares
  - Beam physics: improvements in aperture, orbit control, dynamics
  - System upgrades:
    - Ion source & RFQ
      - Similar to the BNL linac
    - Solid State RF Power amplifiers & Modulators
      - Identical to FNAL Main Injector systems
    - RF Cavity refurbishments
      - Cooling, Tuners

Muon Program Upgrades

- Delivery ring: repurpose the Debuncher Ring
  - g-2: utilize as beam line
  - Mu2e: slow extraction
  - New injection and Extraction areas
    - Dual energy 3.1 GeV and 8 GeV
  - 2.4 MHz RF for Mu2e
  - Common transport to split to separate experimental areas

- Mu2e: Extinction challenge
  - Ring RF : 10^{-5}
  - AC Dipole in extraction line :10^{-5}
    - Dipole phase locked to Ring RF
    - Sweep into collimator but pass bunch
    - Develop instrumentation to measure as well!

Mu2e beam extinction

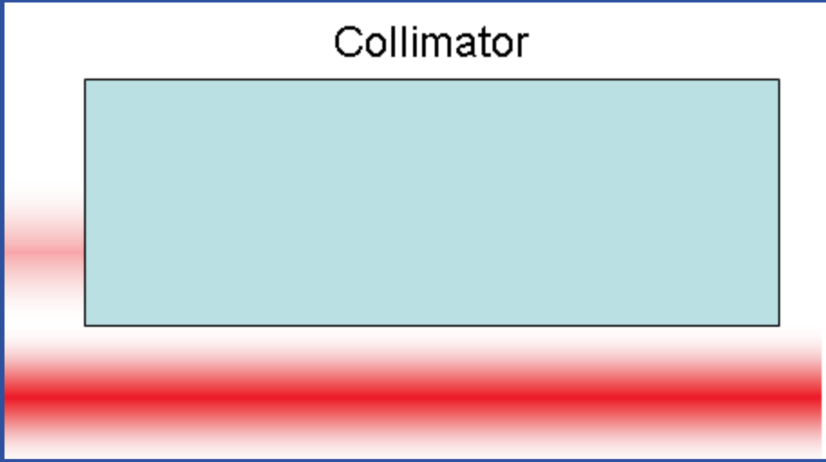


Kicker at ½ revolution frequency

Dual sided collimation

At collimator:

Beam fully extinguished when deflection equals *twice* full admittance (*A*) amplitude

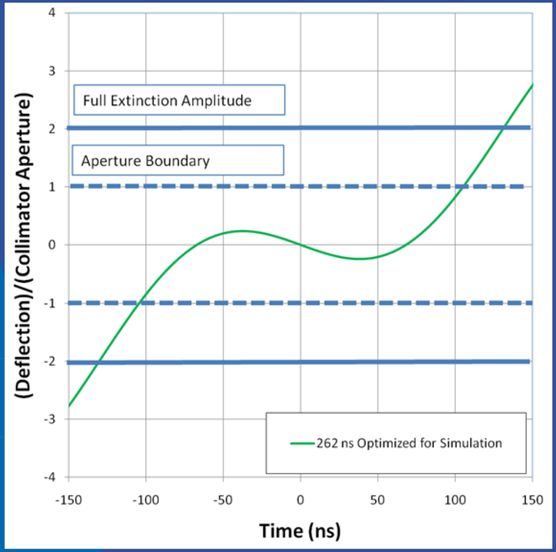


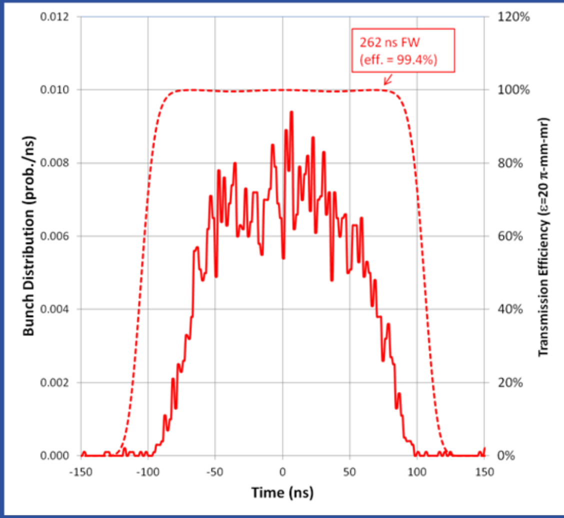
$$x = \sqrt{\frac{A\beta_c}{\beta\gamma}}$$

AC Dipole System

- System relies on two harmonic components
  - 300 kHz component to sweep beam past transmission channel
  - 3.8 MHz component to reduce slewing at transmission peak

Magnet	Frequency (kHz)	Length (cm)	Aperture		Peak B Field (Gauss)
			bend plane (cm)	non-bend (cm)	
A	300	300	7.8	1.2	120
B	3800	300	7.3	1.2	15



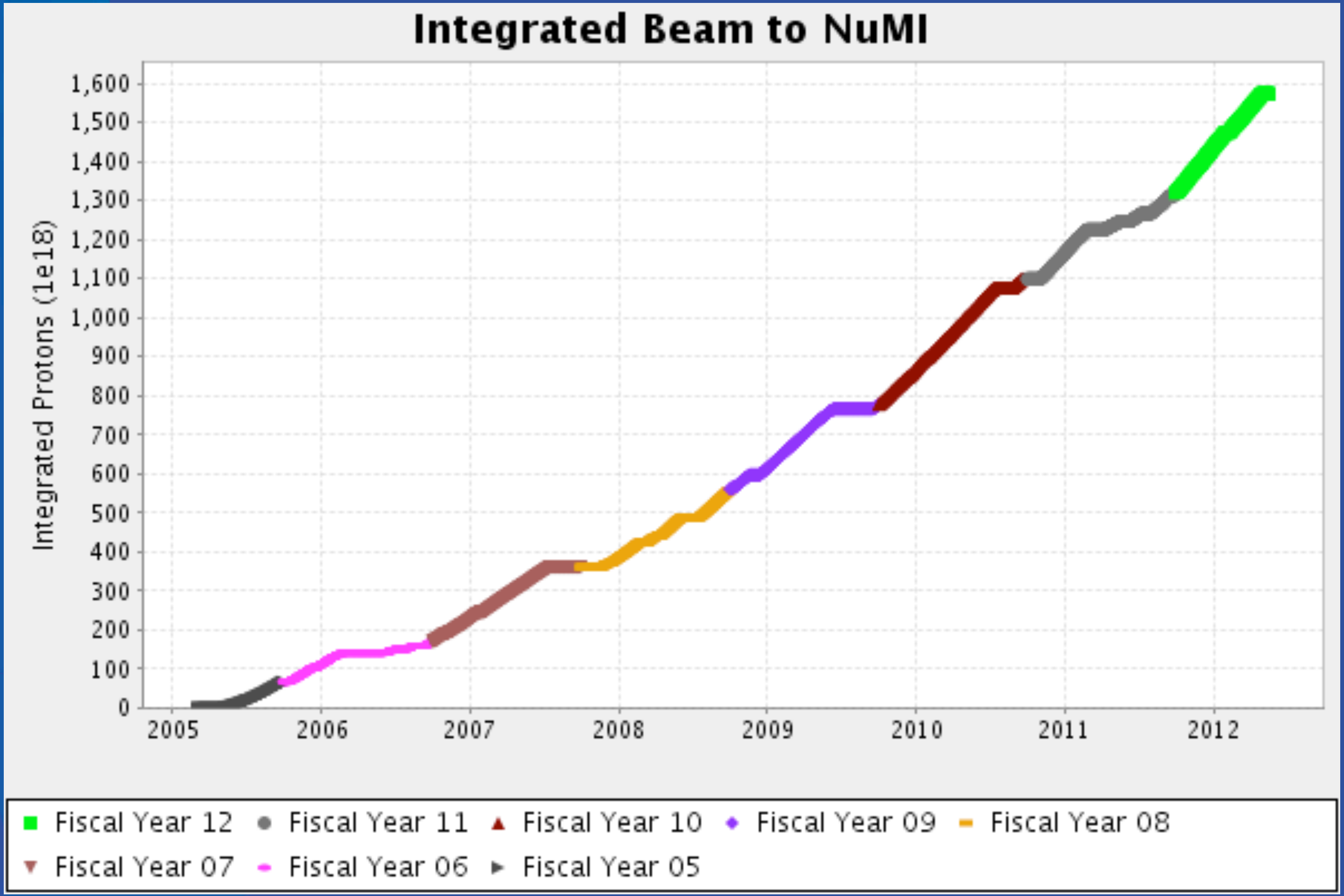


Main Injector Program

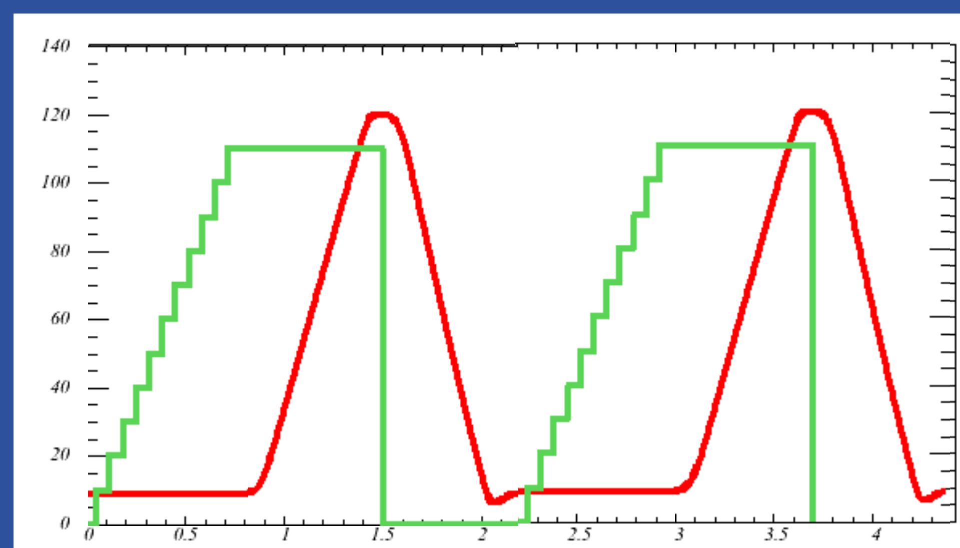
- Long Baseline Neutrino Experiments:
  - NOvA, Minos+, Minerva
  - Single turn from Main Injector (9.6 μsec) 4.9e13 ppp
  - 3.6e21 POT over 6 year period – NOvA goal

- Rare Kaon Decays
  - ORKA: K -> $\pi\nu\nu$
  - High intensity slow spill
  - High Duty Factor
  - Bunch spacing to match K lifetime ($K^{\pm}$ ~12 nsec, K^0_S ~ 1 nsec, K^0_L ~ 50 nsec)

Beam to NuMI Target



Increasing beam power

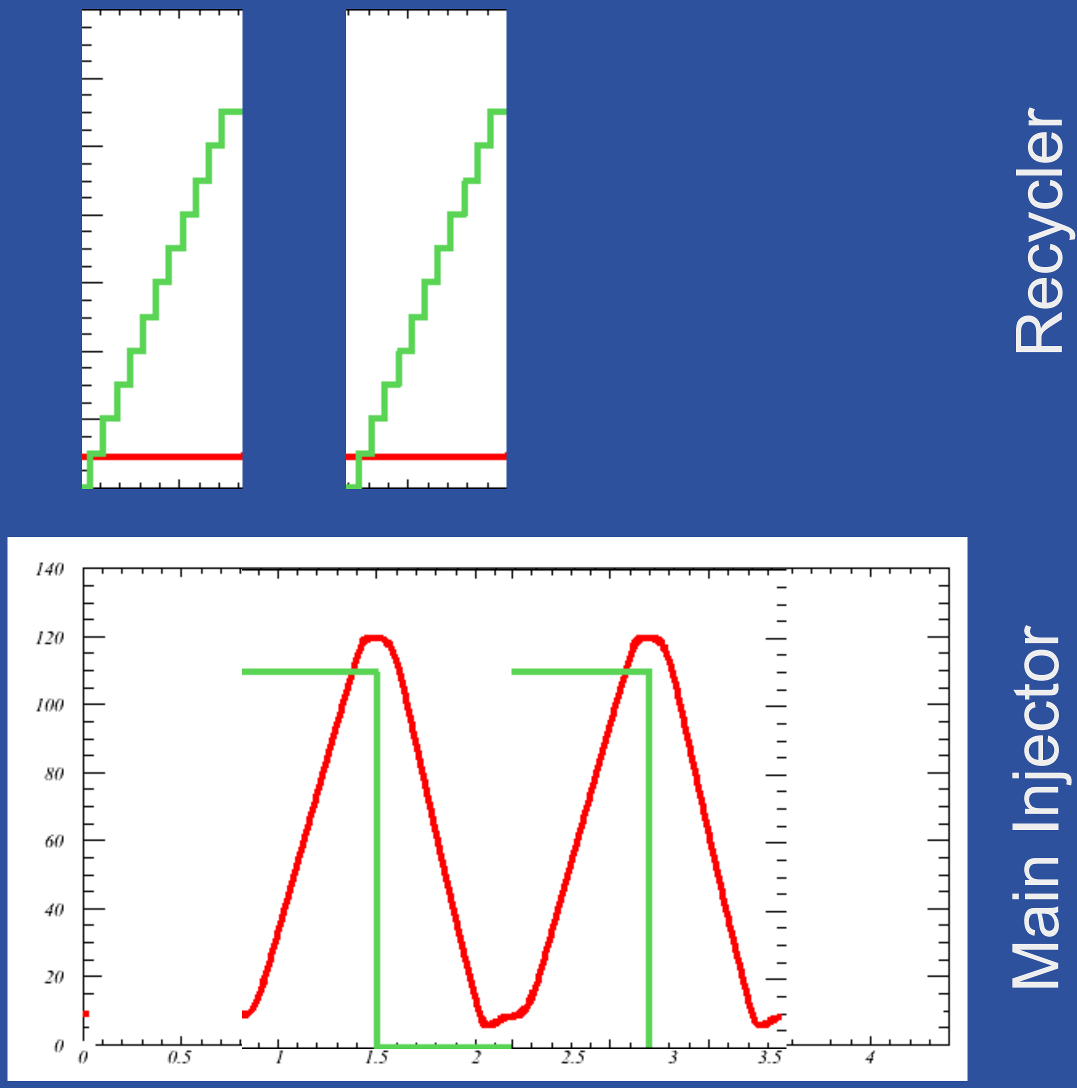


Recycler

Main Injector

Thanks to Phil Adamson for the animation

Increasing beam power

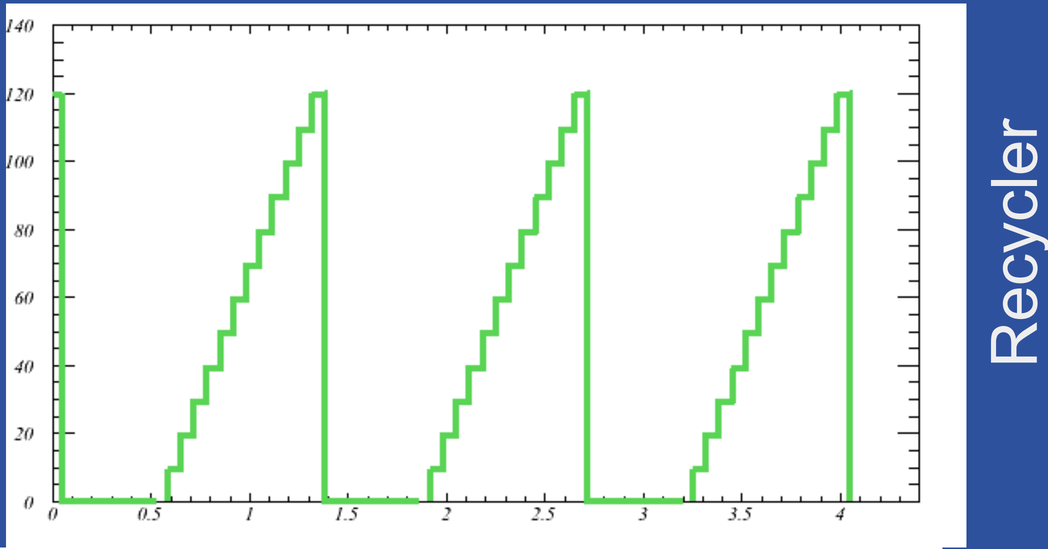


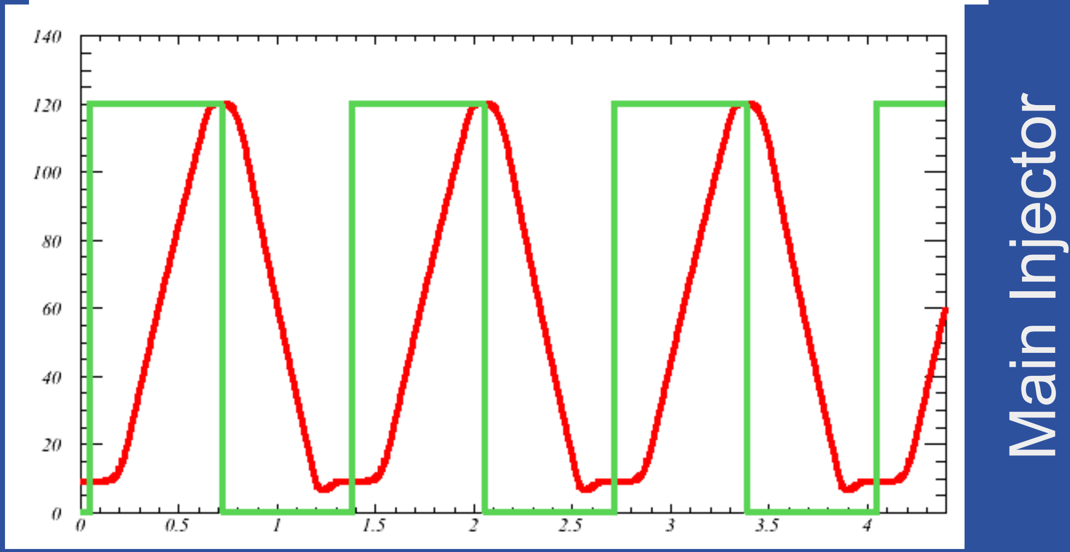
Thanks to Phil Adamson for the animation

22

Increasing beam power

- Move slip-stacking to recycler
- 11 batch -> 12 batch
- Increase Main Injector ramp rate (204 GeV/s -> 240 GeV/s)

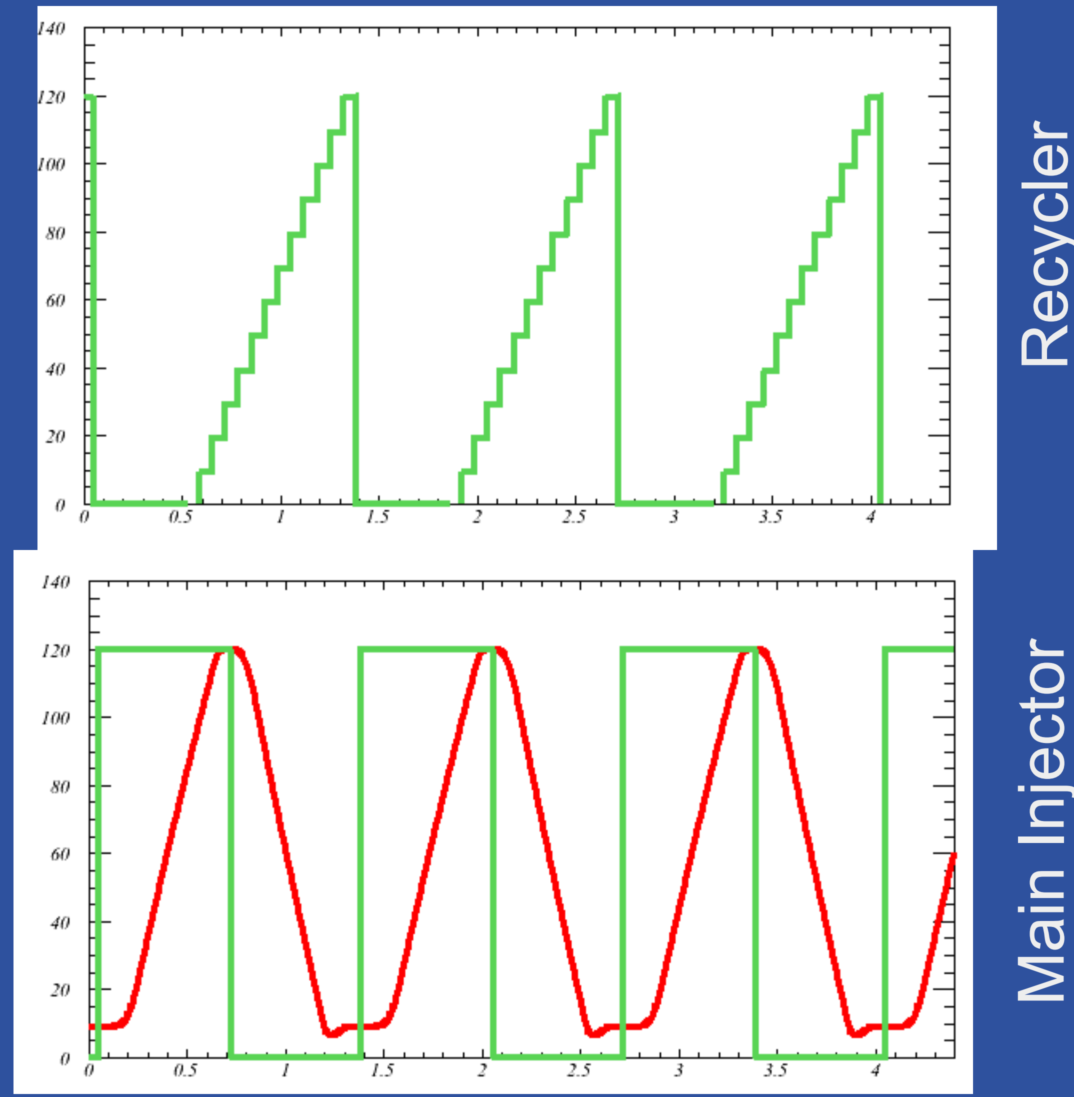




Thanks to Phil Adamson for the animation

Increasing beam power

- Move slip-stacking to recycler
- 11 batch -> 12 batch
- Increase Main Injector ramp rate (204 GeV/s -> 240 GeV/s)
- ~Double POT with only ~10% increase in per-pulse intensity



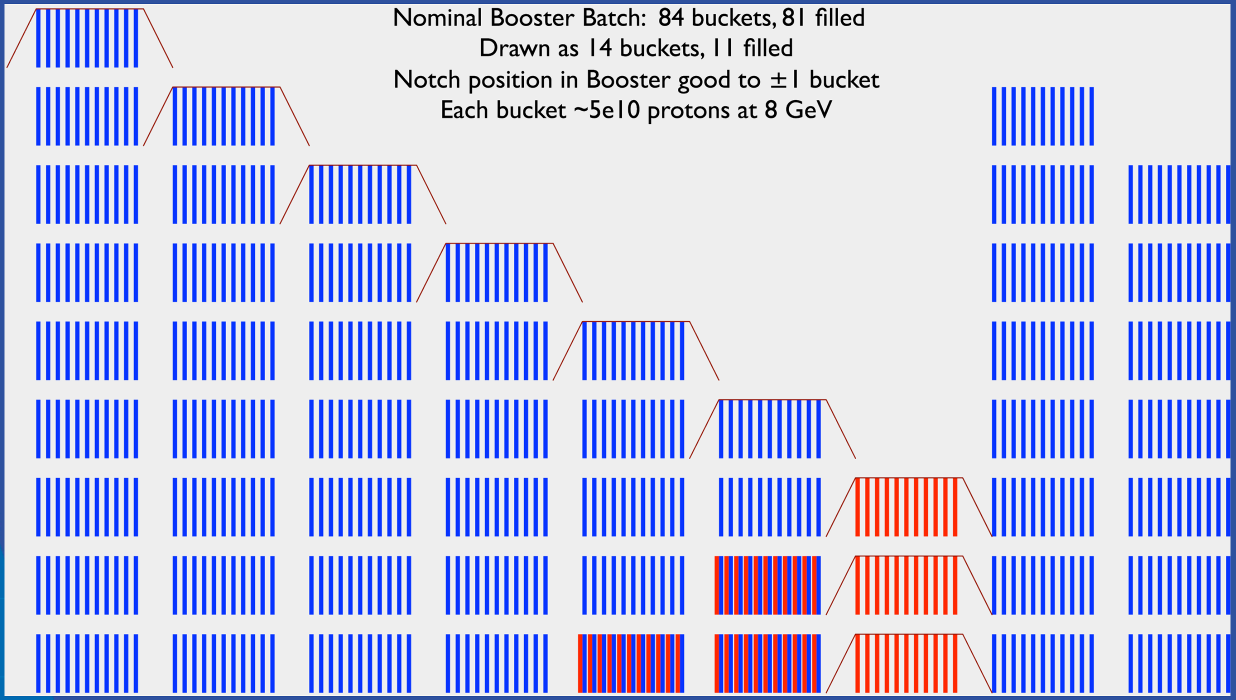
Thanks to Phil Adamson for the animation

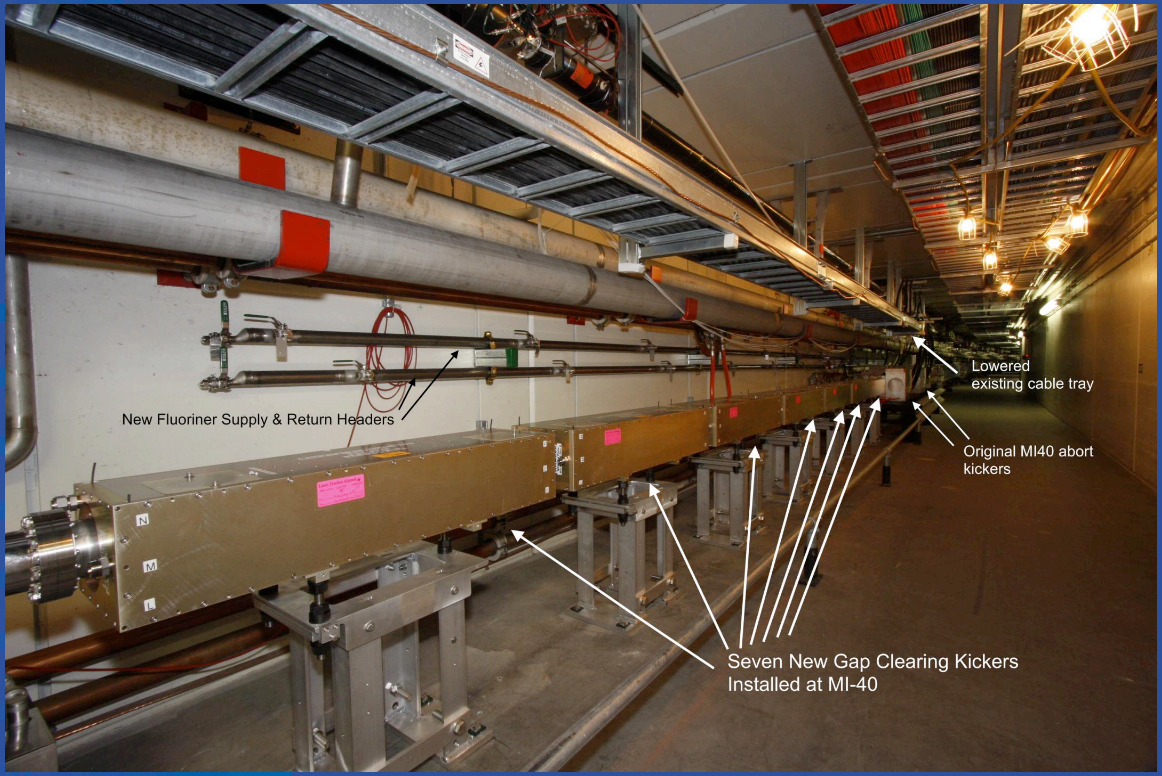
Upgrades in Support of NOvA

- Turn Recycler from pbar to proton ring
  - Injection and extraction lines
  - Associated kickers and instrumentation
  - 53 MHz RF
  - Decommission/remove pbar devices
- Shorten MI cycle to 1.33 seconds
  - RF upgrades
  - Power Supply upgrades
  - Decommission/remove pbar devices
- NuMI target station to 700 kW
  - Target & Horns to handle power
  - Configuration to maximize n flux
- Installation and Hardware commissioning

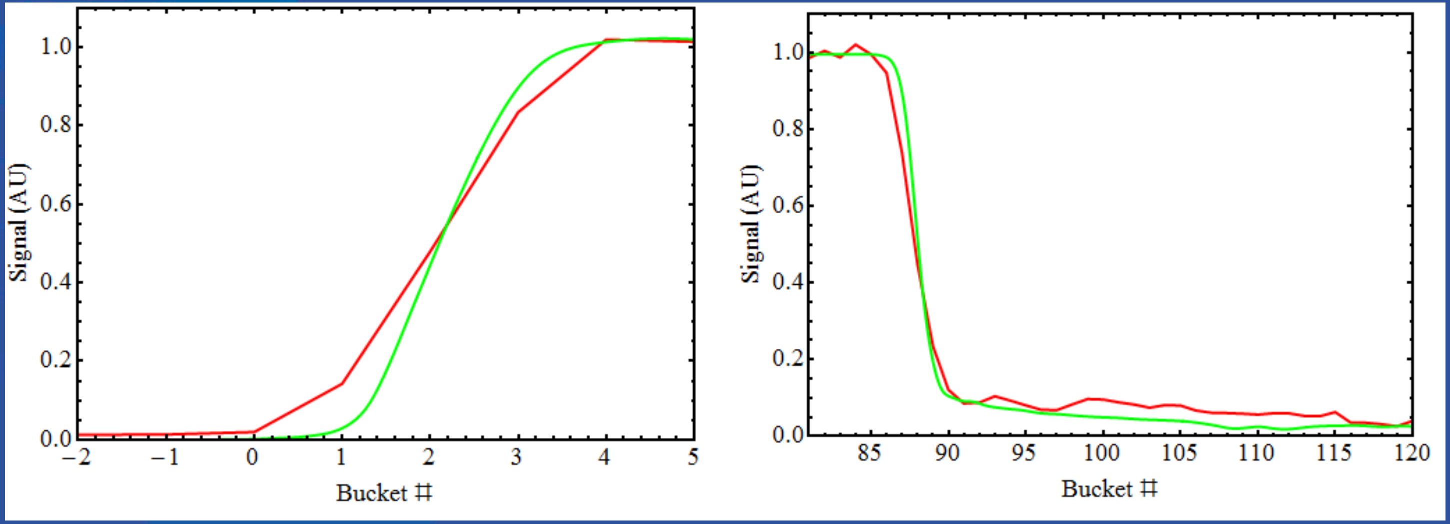
Upgrades for NOvA

- Most technically challenging component
  - Fast kicker to fit 12 Booster batches in 7 Recycler slots
  - 57 nsec rise, 1.59 μsec 50 kV 3% ripple flattop, 57 nsec fall, 3% tail





Fast Kickers installed in MI: Performance meets specifications



Comparison of Model (green) and beam measurements (red)

Additional bumper to cancel the long tail

120 GeV neutrino program parameters

	Current Operation	NOvA operation
Protons/Batch	4.3e12	4.3e12
Booster Batches	9	12
Booster Repetition Rate	4.3 Hz	9 Hz
# MI Injections	9	1
Cycle time	2.07 sec	1.33 sec
MI Efficiency	95%	95%
Controlled Loss	3.5%	3.7%
Uncontrolled Loss	1.5%	1.3%
Beam Intensity (Extraction)	3.7e13	4.9e13
Beam Power	323 kW	706 kW
Protons/hour	6.4e16	1.4e17

As of April 30, ~year long shutdown to implement all changes

Project X and the Intensity Frontier

- A broad program with megawatts of continuous beam, ideal to lead at the intensity frontier
  - Neutrinos, long/short base-lines, more than 2 MW
  - Kaons where the Standard Model backgrounds are minimal and we are sensitive to many models including supersymmetry
  - Rare muon decay with sensitivity to masses 1000 TeV
  - Symmetry violations through electric dipole moments in nuclei
  - Applications to transmutation, spallation targets, ADS

- 3 GeV CW linac feeding multiple programs
- 8 GeV pulsed linac feeding the Main Injector
- 2 MW available in range 60-120 GeV for ν physics

- The CW linac creates a unique facility, with performance that cannot be matched in a synchrotron based facility

- Key Accelerator Developments to reach this program
  - Project X Injector Experiment
  - Superconducting RF

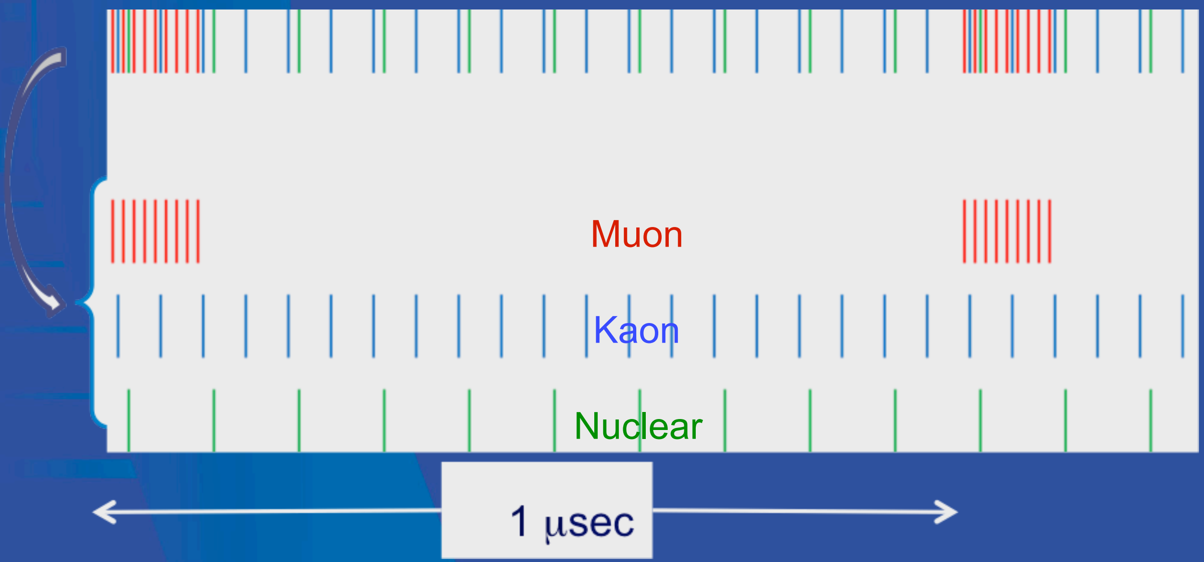
Operating Scenario
3 GeV Program

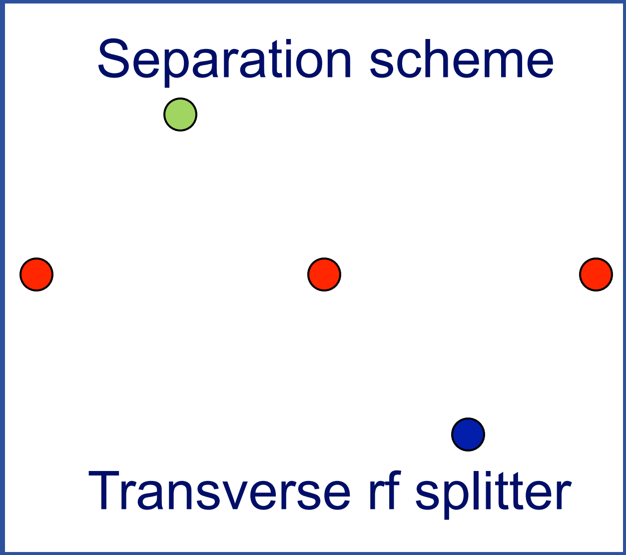
<u>1 μsec period at 3 GeV</u>

Muon pulses (12e7) 162.5 MHz, 80 nsec	700 kW
Kaon pulses (12e7) 27 MHz	1540 kW
Nuclear pulses (12e7) 13.5 MHz	770 kW

Ion source and RFQ operate at 4.4 mA

77% of bunches are chopped @ 2.1 MeV ⇒ maintain 1 mA over 1 μsec

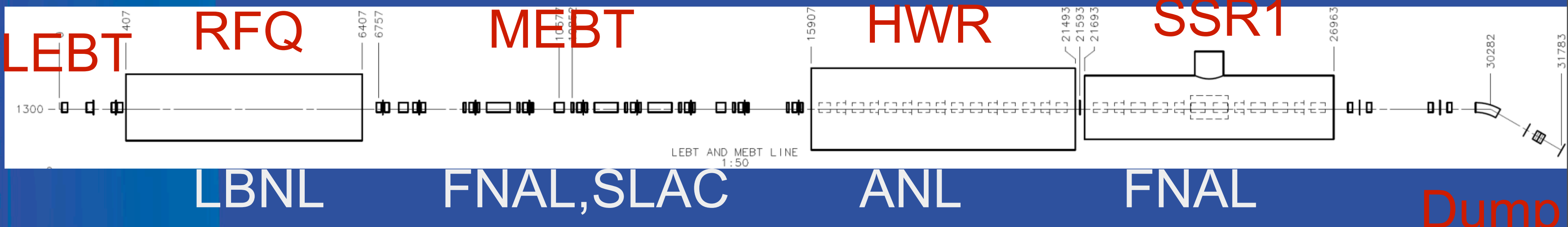




Project X Injector Experiment PXIE

- PXIE is the centerpiece of the Project X R&D program
  - Integrated systems test for Project X front end components
    - Validate the concept for the Project X front end, thereby minimizing the primary technical risk element within the Reference Design.
    - Operate at full Project X design parameters
- Systems test goals
  - 1 mA average current with 80% chopping of beam delivered from RFQ
  - Efficient acceleration with minimal emittance dilution through ~30 MeV
  - Achieve in 2016
- PXIE should utilize components constructed to PX specifications wherever possible
  - Opportunity to re-utilize selected pieces of PXIE in PX/Stage 1
- Collaboration between Fermilab, ANL, LBNL, SLAC, India

Project X Injector Experiment: PXIE



- CW H^- source delivering 5 mA at 30 keV
- LEBT with beam pre-chopping
- CW RFQ operating at 162.5 MHz and delivering 5 mA at 2.1 MeV
- MEBT with integrated wide-band chopper and beam absorbers capable of generating arbitrary bunch patterns at 162.5 MHz, and disposing of 4 mA average beam current
- Low beta superconducting cryomodules: 1 mA to 30 MeV
- Beam dump capable of accommodating 1.6 mA at 30 MeV (50 kW) for extended periods.
- Associated beam diagnostics, utilities and shielding

PXIE Goals

- Validate the Project X concept and eliminate technical risks
  - CW RFQ
  - Initial stage of acceleration in SC linac – never tested in experiment
    - Complications can be due to beam loss of RFQ tails in SC linac
  - Ion source lifetime
  - LEBT pre-chopping
  - Vacuum management in the LEBT/RFQ region
  - Validation of bunch by bunch chopper performance
    - Kicker extinction 10^{-4} level
  - Effectiveness of MEBT beam absorber
  - MEBT vacuum management
  - Operation of HWR in close proximity to 10 kW absorber
  - Operation of SSR with beam
  - Emittance preservation and beam halo formation through the front end
- Obtain experience in design and operation of SC proton linac
  - SSR1 cryomodule will be designed and build by Fermilab

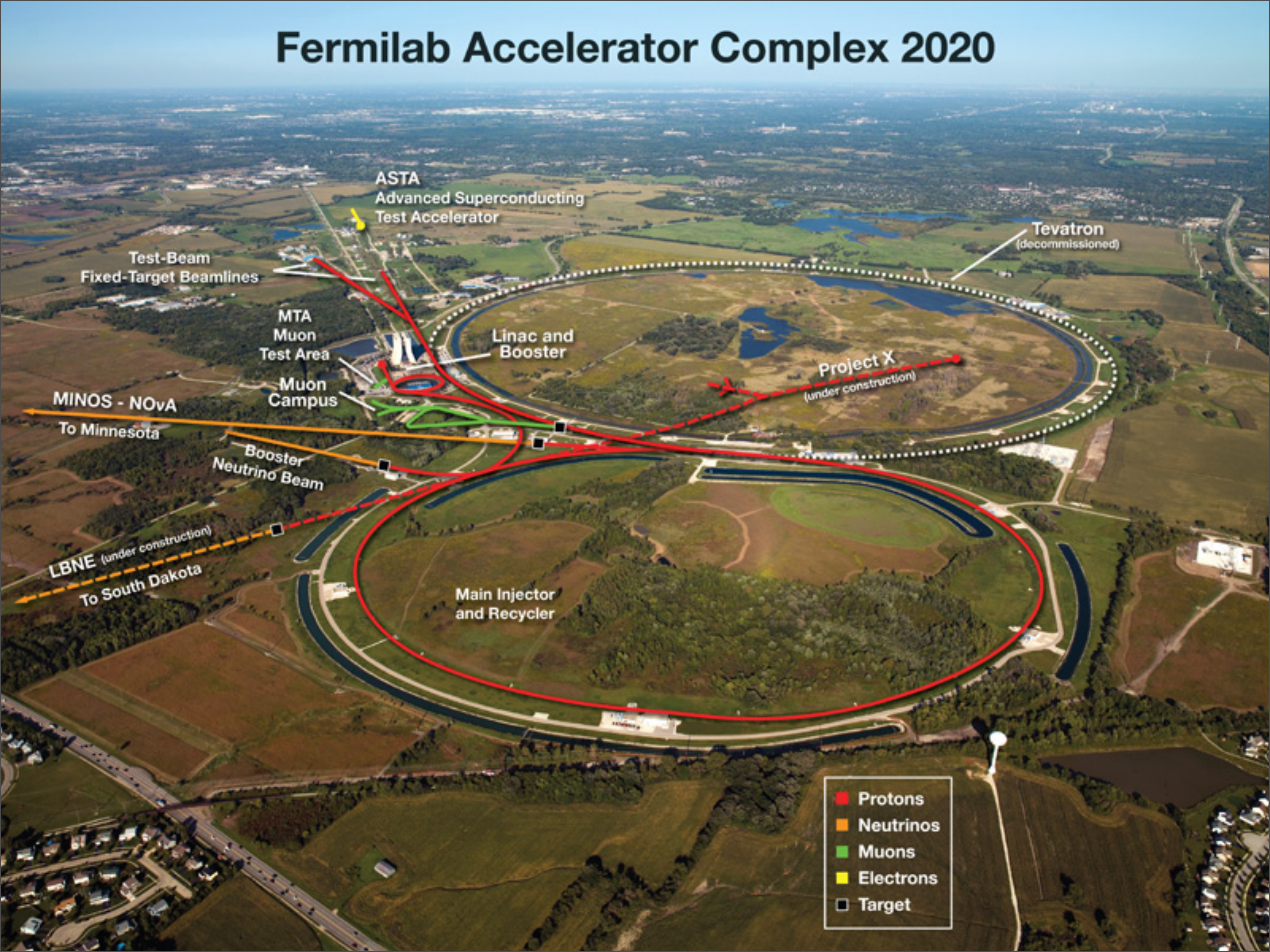
PXIE Timeline

- Jan 2012 Complete PXIE design layout and preliminary cost/ schedule estimates ✔
- Nov 2012 Complete RFQ design and begin fabrication
- Early 2013 Ion source and LEBT installation begins at Fermilab;
- Apr 2014 Start RFQ high-power testing without beam;
- Sep 2014 First beam through RFQ
- Nov 2015 Beam delivered to the end of MEBT with nearly final parameters (2.1 MeV, 1 mA CW, 80% arbitrary chopping) Begin installation of beta=0.1 and beta=0.2 CMs
- Oct 2016 Beam to 25 MeV with nearly final parameters (1 mA CW, 5 mA peak, arbitrary bunch chopping)

Fermilab and the Intensity Frontier

- Rich & varied near term program
  - 8 GeV
    - Short Baseline neutrino oscillations
    - Muon experiments
  - 120 GeV
    - Long Baseline neutrino oscillations
    - Kaon experiments
  - Accelerator upgrades to meet demands
    - Intensity
    - Beam Structure
  - Experiments to push accelerator development
    - PXIE

- Project X : the premier Intensity Frontier facility in the world


Fermilab Accelerator Complex 2020
ASTA
Advanced Superconducting
Test Accelerator
Tevatron
(decommissioned)
Test-Beam
Fixed-Target Beamlines
MTA
Muon
Test Area
Linac and
Booster
Project X
(under construction)
Muon
Campus
MINOS - NOvA
To Minnesota
Booster
Neutrino Beam
LBNE (under construction)
To South Dakota
Main Injector
and Recycler
Protons
Neutrinos
Muons
Electrons
Target