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Long Term Plans to Increase Fermilab's Proton Intensity to Meet the Needs of the Long Baseline Neutrino Program

Eric Prebys
Accelerator Division/Accelerator Physics Center
Fermilab, USA*

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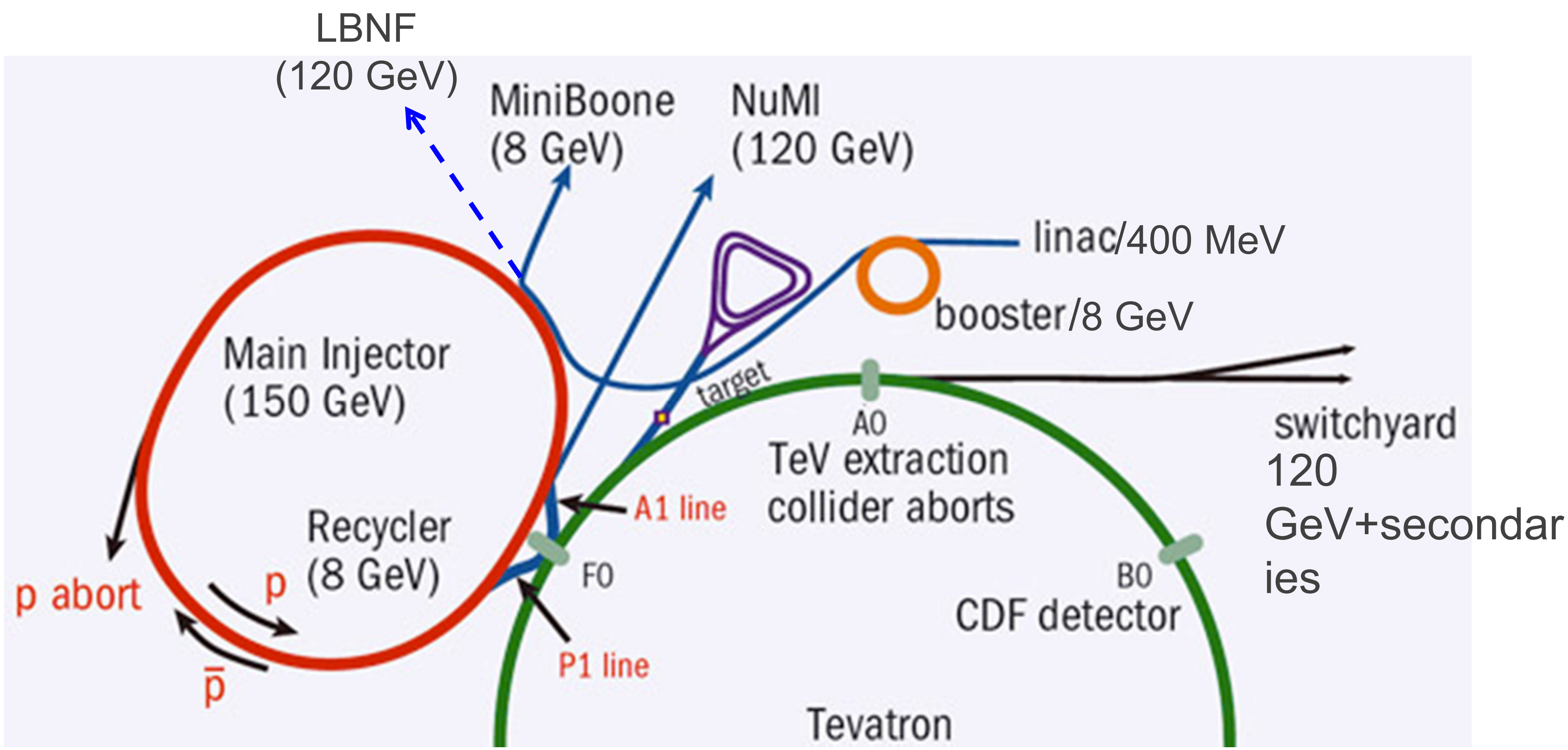
Fermilab's Priorities ("P5 Report")

- The Particle Physics Project Prioritization Panel (P5) advises the US Department of Energy (DOE) Office of High Energy Physics on research funding priorities in high energy physics
- After a lengthy process involving the entire HEP community, the panel released a report in May, 2014. Top priorities for Fermilab:
  - Support the LHC and its planned luminosity upgrades
  - Pursue the g-2 and Mu2e muon programs
  - Continue at least R&D toward a future linear e^+e^- collider (ILC)
  - Focus on a high energy neutrino program to determine the mass hierarchy and measure CP violation.
    - "Flagship" activity for the next 20-30 years!
    - Will ultimately require a "multi-megawatt" beam at 60-120 GeV

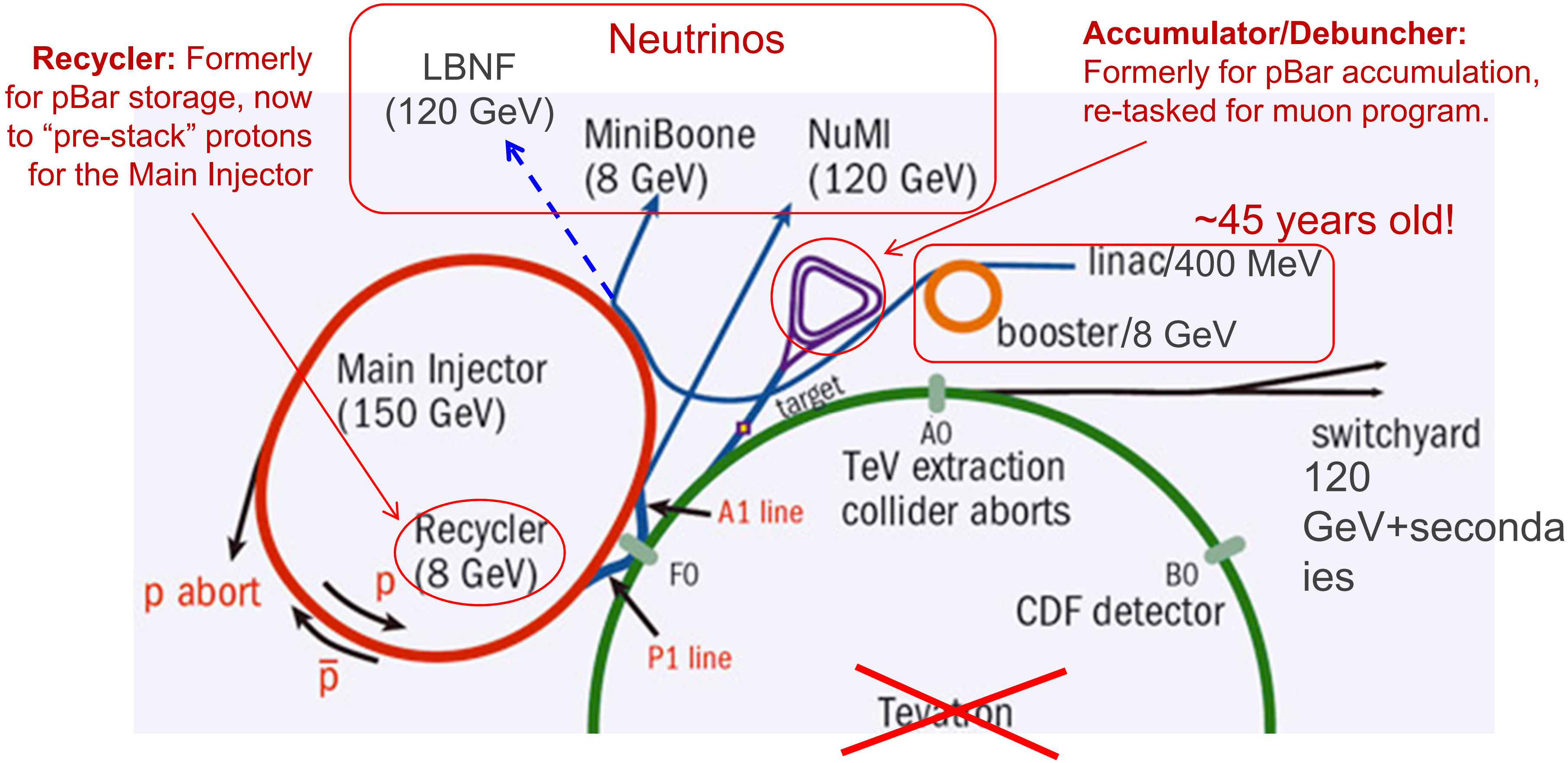
This talk

Orientation: Accelerator Complex



Orientation: Accelerator Complex

- Following the LHC turn-on, FNAL has transitioned to an intensity based program



- Intensities are limited by the 8 GeV proton source, which is still largely original.

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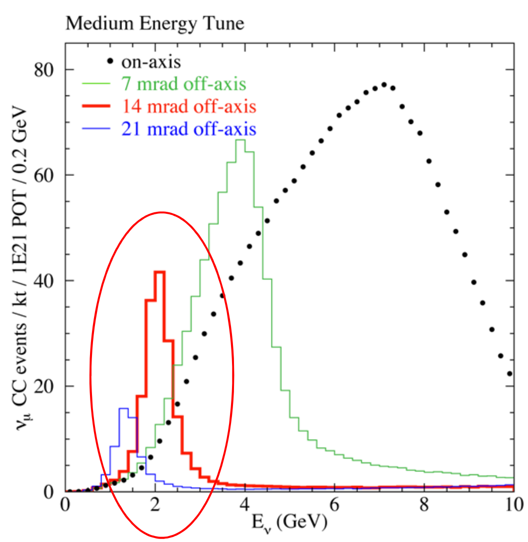
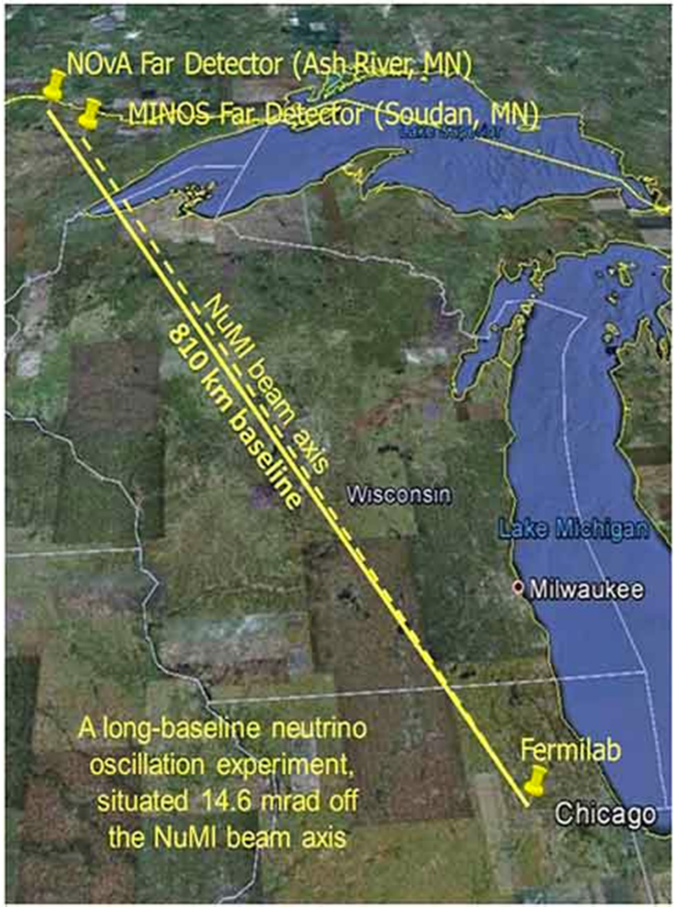
Current Long Baseline ν Program

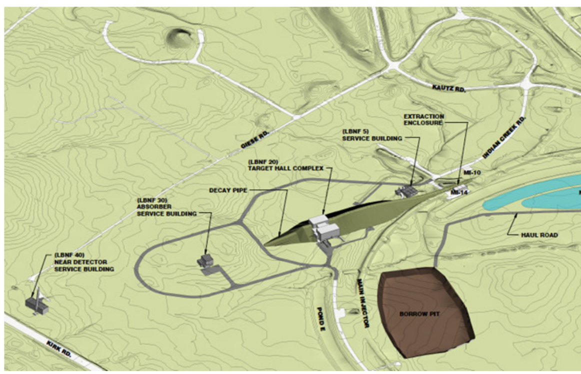
- The "Neutrinos from the Main Injector" (NuMI) line uses 120 GeV neutrinos from the Main Injector to produce neutrinos, which are detected in
  - MINOS: 725 km away
  - NOνA: 810 km, 14.6 mrad off axis
    - Produces narrower energy spread, which is important for physics goals

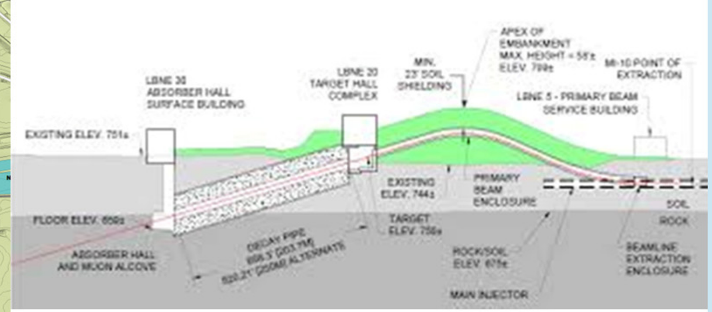




Future ν Program: LBNF→DUNE

- Fermilab will construct a new new “Long Baseline Neutrino Facility” (LBNF) beam line to produce neutrinos for the “Deep Underground Neutrino Experiment” (DUNE), located at the “Sanford Underground Research Facility” (SURF) in Lead, SD, 1300 km away.





- Truly international effort, including 150 institutions in 27 countries.
- Physics program extends 20-30 years.

Long Term Goals

- P5 Recommendation:

  "[…] , we set as the goal a mean sensitivity to CP violation of better than 3σ […] over more than 75% of the range of possible values of the unknown CP-violating phase δCP"

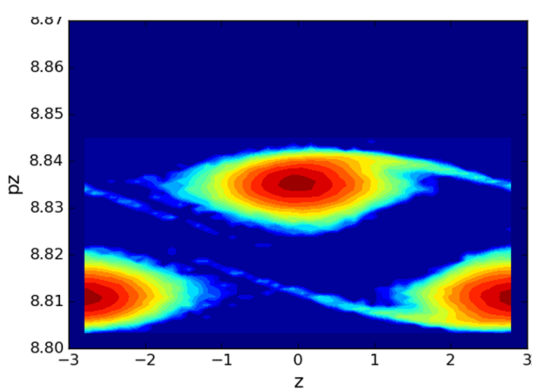
- Assuming a Liquid Argon detector and an optimized beam line, this corresponds to ~900 kt•MW•y*
  - >50 years with 40 kt detector at the 400 kW intensity when the plan was first conceived.
- Tentative plan for the Long Baseline Neutrino Facility (LBNF):
  - ~10 years to build
  - 5 years at 1.2 MW (near-term upgrades)
  - Many years at "multi-megawatts"

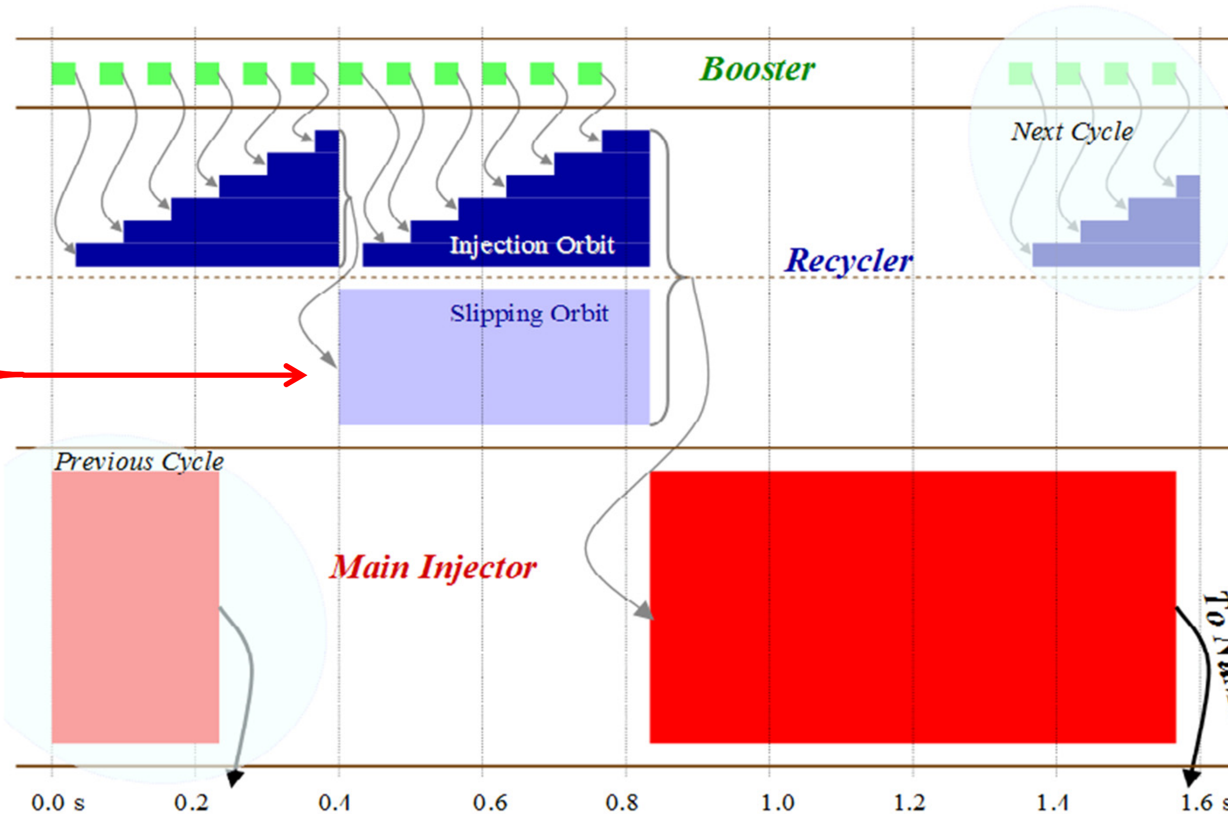
*P5 Report specifies 600 kt•MW•y, but more accurate simulations revised this up to 900 (see G. Rameika, PIP-II Project Review)

NuMI/NOνA Accelerator Cycle

- The 15 Hz Booster injects 12 “batches” into the Recycler
- These are then transferred to the Main Injector, which accelerates and extracts them as the loading process repeats in the Recycler

“slip-stacking” cleverly gets around limits on Booster batch size by allowing two batches to “slip” together, doubling the number of protons in each MI cycle





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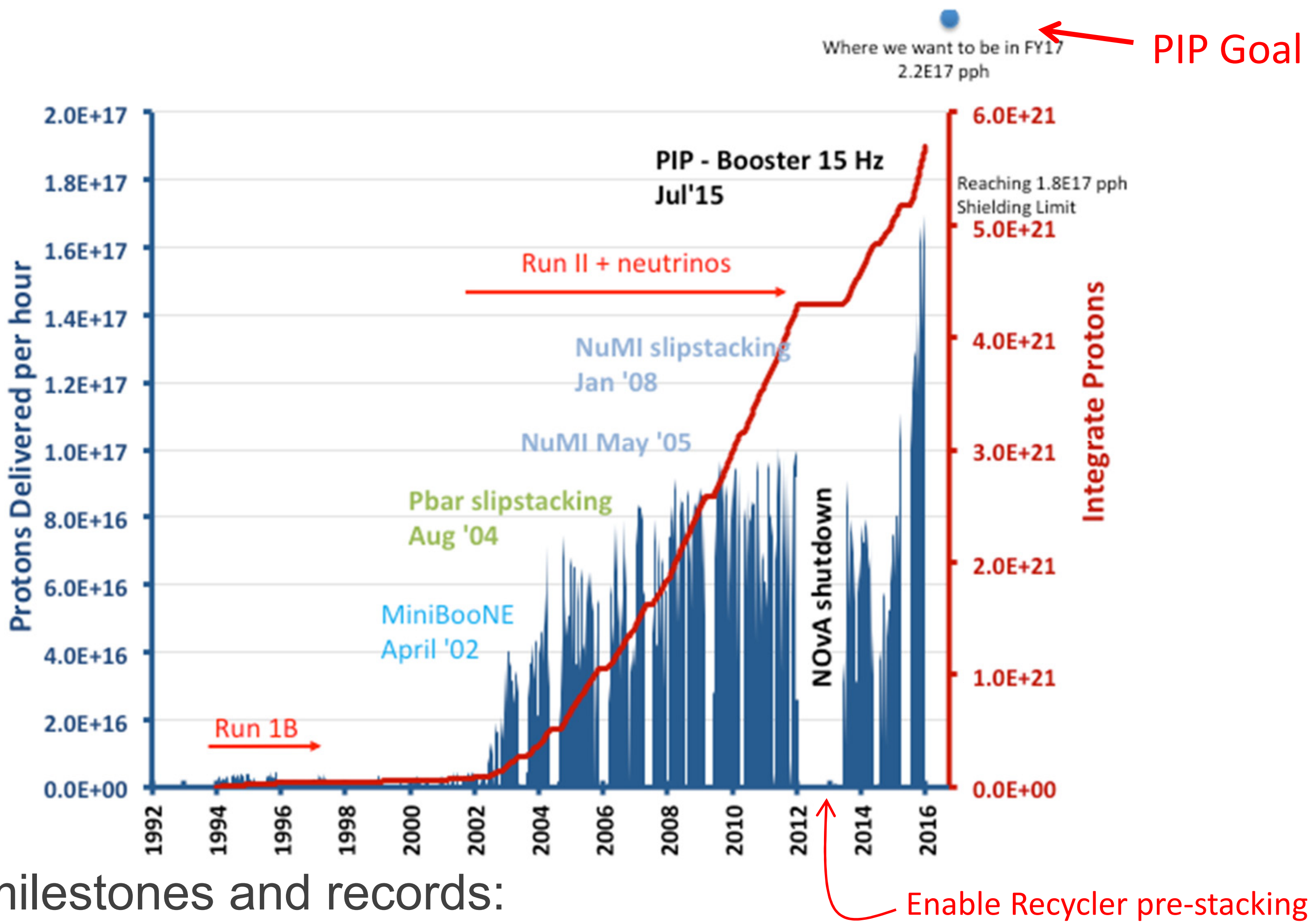
Staged Plan to Increase Intensity

- Ongoing "Proton Improvement Plan" (PIP)
  - Achieve full 15 Hz Booster operation (beam on all cycles)
    - Lattice elements run resonantly at 15 Hz, but historically pulsed elements and beam loss have prevented loading beam on all cycles.
  - Deliver 2.2e17 protons per hour from the Booster
  - These and other upgrades will deliver 700 kW to NuMI + 30 kW to 8 GeV program
- PIP-II (received preliminary approval in November, 2015)
  - Keep existing Booster, but increase cycle rate to 20 Hz
  - Continue to slip-stack in Recycler
  - **Replace existing 400 MeV linac with 800 MeV superconducting linac that has CW capability**
  - Deliver 1.2 MW to LBNF
  - Support 8 GeV program and 800 MeV programs
- Beyond PIP-II
  - Keep PIP-II linac
  - Replace Booster with "something"
  - Abandon slip-stacking (reducing losses)
  - Deliver multi-megawatts to LBNF/DUNE (+ ??)

Rapid Cycling Synchrotron (RCS) or pulsed linac?

Progress



- Recent milestones and records:
  - Full 15 Hz Booster operation
  - 615 kW for one hour to NuMI (Goal: 700 kW)

Beyond PIP: Space Charge Limit

- The maximum useful injected charge into the Booster is limited by the space charge tune-shift, which can drive harmonic instabilities.

$$\Delta \nu \approx \frac{N r_0}{2\pi \epsilon_N \beta \gamma^2} F B \lesssim .3$$

total protons

"Bunch factor" = I_{peak}/I_{ave}
(Reduce with higher RF harmonics)

normalized emittance

= 3 for 95% Gaussian emittance
1 for 100% uniform (painted) emittance

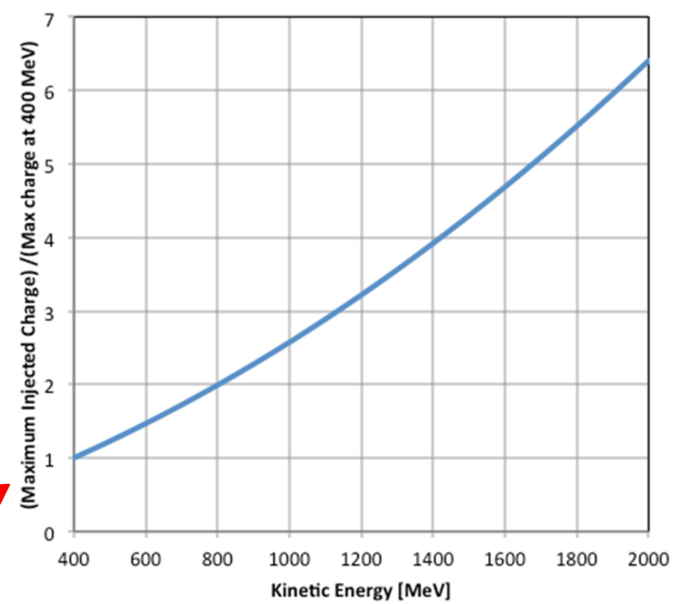
$$\epsilon_N = \epsilon \beta \gamma = \text{constant}$$

- So the maximum accelerated charge grows rapidly with increasing energy

$$N_{max} \propto \beta \gamma^2$$

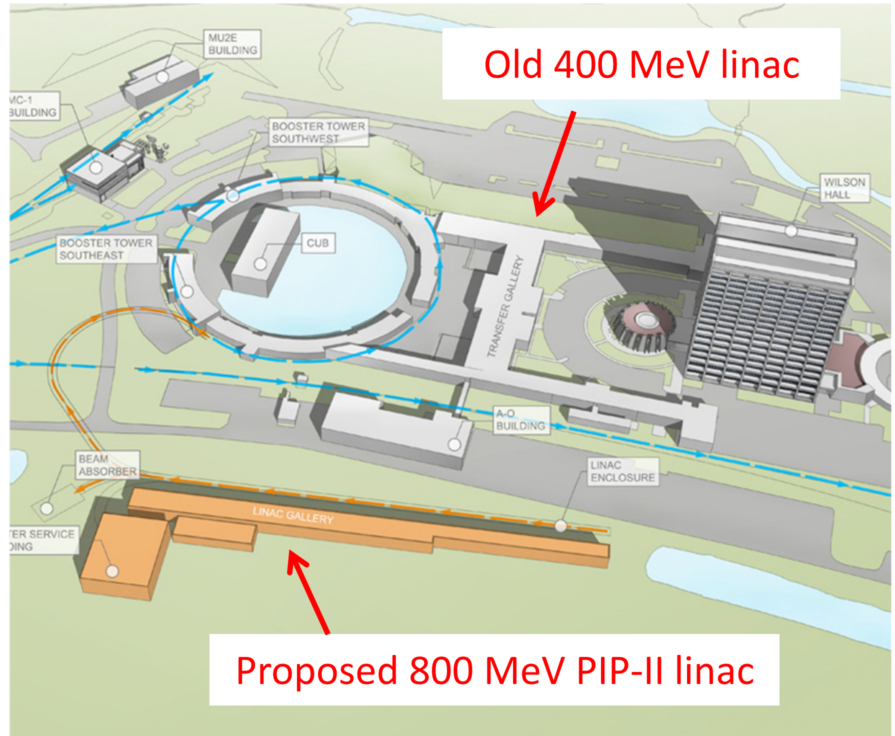
- Could gain an additional factor of βγ if we were not constrained by the MI admittance

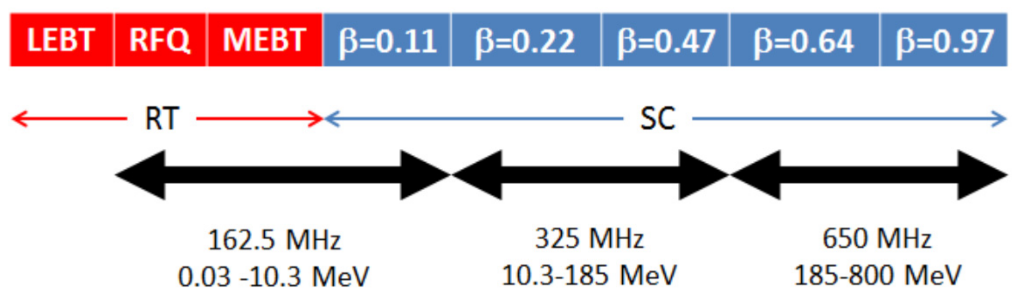
doesn't include improvement of going to uniform distribution with painting



PIP-II

- Key elements:
  - Replace existing 400 MeV linac with an 800 MeV linac capable of CW operation.
    - Higher energy + painting = more beam in Booster
  - Increase Booster rate to 20 Hz
  - “Modest” improvements to Recycler and MI
  - Significant contributions from India
- Goals:
  - 1.2 MW @ 120 GeV
  - Additional power:
    - 82 kW @ 8 GeV
      - Neutrinos (and kaons?)
    - Up to 1.6 MW @ 800 MeV
      - Arbitrary bunch structure
      - Looking for users





Beyond PIP-II

- By the time PIP-II is realized, the Booster will be more than a half century old, and it's unrealistic to believe that it can be pushed further, in terms of performance:
  - No beam pipe in magnets! ➔ troublesome impedances from magnet laminations.
  - Presently the decelerating voltage (from impedance) at transition is above 100 kV/turn
    - Transition crossing with more than 50% intensity increase looks impossible without reducing impedance
    - No realistic way to do this.
- Further increases in power will require replacing the Booster. Options are:
  - A pulsed linac to go from the PIP-II linac to 8 GeV
    - Possibly increase the energy of the CW portion to 3 GeV?
  - Some sort of Rapid Cycling Synchrotron (RCS)
- Replacing the Booster is critical to going beyond PIP-II intensities.

Replacing the Booster: Linac or RCS?

- 8 GeV pulsed linac:
  - Pros:
    - Lots of power at 8 GeV and/or lower energies
      - Full Main Injector power at lower energies.
      - Short baseline neutrinos
      - Rare K decays, etc.
  - Cons:
    - Would need to continued to inject into the Recycler, or a new bunching ring, raising complexity and reliability issues.
      - No room to inject into MI
      - Might need more than one linac pulse to fill MI
      - Most 8 GeV users want short pulses
    - Charge stripping makes H^- injection at 8 GeV a *very big* deal:
      - Weak magnets, extended optics in the beam transport
      - Even black body radiation stripping a problem -> cooled beam pipe.

Linac or RCS? (cont'd)

- RCS
  - Pros:
    - Demonstrated performance (J-PARC)
    - Can eliminate Recycler (and associated risks and inefficiencies)
    - Option of increasing MI injection energy
  - Cons:
    - Limited protons at 8 GeV.
    - Main Injector power falls off at lower beam energies.

- We plan to determine the optimum configuration for both options

Comparison of Parameters*

		Current (Best)	PIP-II (Existing Booster)	New 8 GeV Lincac	New 8 GeV RCS	units
MI/Recycler						
	Beam Energy	120	120	120	120	GeV
	Cycle Time	0.615	1.2	1.2	1.45	sec
	Protons per pulse	3.8E+13	7.5E+13	1.6E+14	1.9E+14	ppp
	Beam Power	1.2	1.2	2.5	2.5	MW
Proton Source						
	Injection Energy (Kinetic)	0.4	0.8	0.8	0.8-2.0	GeV
	Extraction Energy (Kinetic)	8.0	8.0	8.0	8.0	GeV
	Protons per Pulse	3.3E+12	6.4E+12	1.6E+14	3.2E+13	
	Beam Power to Recycler/MI	38	82	168	168	kW
	Beam Power to 8 GeV Program	25	82	3872	645	kW

We've had bigger batches than this, but these have very low losses

Currently limited to less than this by losses

~6x record Booster ppp

~4x record Main Injector ppp

*P. Derwent

RCS Comparisons

	Booster (now)	Booster (PIP-II)	New RCS (800 MeV)	New RCS (2 GeV)	JPARC RCS
Circumference [m]	474	474	474	474	348
Injection Energy [MeV]	400	800	800	2000	400
Extraction Energy [MeV]	8000	8000	8000	8000	3000
Injection Current [mA]	30	4	5	5	50
RF Harmonic	84	84	84	84	2
Emittance (normalized) [pi-mm-mr]	15	15	20	20	102
Protons/batch [1e12]	4.2	6.6	32	32	84
Bunching Factor	3.0	3.0	3.0	3.0	2.0
Gaussian factor	3.0	1.0	1.0	1.0	1.0
Tune Shift Parameter	-0.43	-0.11	-0.41	-0.13	-0.28
Frequency [Hz]	15	20	20	20	25
Output power, max [kW]	81	169	819	819	1008

achieved

Probably an overestimate. Beam is not Gaussian. Plus, we lose a lot of beam.

Too big for "ordinary" synchrotron

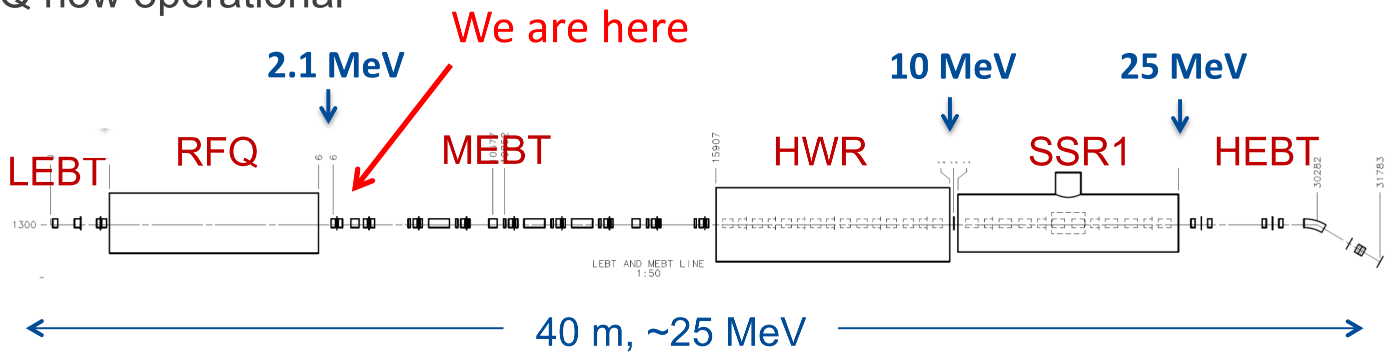
Novel Ways to Mitigate Space Charge

- Non-linear integrable optics
  - All synchrotrons ever built are based on linear optics (magnetic quadrupoles). Non-linearities are handled perturbatively, and eventually lead to instabilities.
  - Is has been shown* that non-linear magnetic fields that satisfy a very particular set of conditions can result in stable orbits, but without a unique tune
    - Extremely insensitive to harmonic instabilities
    - Stable up to space charge tune shifts of order unity!
- Electron lens
  - A beam of electrons can be used to cancel the space charge effects of the protons
  - Demonstrated in the Tevatron
  - Used operationally at RHIC

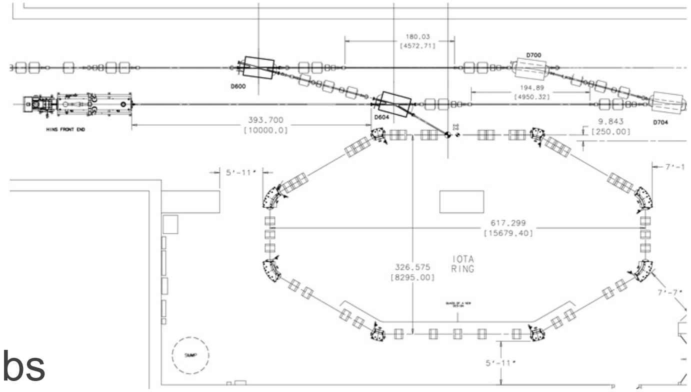
*Danilov, Nagaitsev, PRSTAB 2010

R&D Program

- SRF development for PIP-II
- PIP-II Injector Experiment (PXIE) will validate the front end of the PIP-II linac
  - Collaboration between US and India
  - Including novel bunch-by-bunch chopper
  - RFQ now operational



- The Integrable Optics Test Accelerator (IOTA) will test non-linear optics and other novel methods to mitigate space charge, allowing lower injection energy into a new RCS
  - Soliciting collaborators from universities and other labs



Key Questions beyond PIP-II

- Linac questions:
  - 8 GeV H^- injection design!
  - Optimum klystron power distribution?
  - Industrialization and other cost-saving measures
  - Cost vs. pulse rate parameterization.
- RCS questions:
  - Injection energy?
    - ie, do we need to increase the energy of the PIP-II linac beyond 800 MeV?
  - Circumference?
    - We've been assuming it's the same as the existing Booster, but might be better options.
  - Extraction energy?
    - Probably can't get above the 21 GeV transition energy of the Main Injector, but might be able to reduce cycle time.
- Main Injector questions:
  - What RF improvements will be necessary?

Acknowledgements and Related Posters

- In addition to the ongoing work of the PIP and PIP-II project teams, the following people have directly contributed to this talk:
  - Phil Adamson, Sam Childress, Paul Derwent, Steve Holmes, Ioanis Kourbanis, Valeri Lebedev, Bill Pellico, Alexander Romanov, Vladimir Shiltsev, Eric Stern, Alexander Valishev, Bob Zwaska

- The following IPAC16 posters are related to proton intensity upgrades at Fermilab
  - MOPOY010 Simulations and Measurements of Stopbands in the Fermilab Recycler
  - MOPOY012 Space Charge Simulations in the Fermilab Recycler for PIP-II
  - MOPMW027 Design of a Perpendicular Biased 2nd Harmonic Cavity for the Fermilab Booster
  - TUPMY042 Proton Injection into the Fermilab Integrable Optics Test Accelerator (IOTA)
  - WEPMR007 Electron Lens Construction for Integrable Optics Test Accelerator at Fermilab
  - WEPMR008 Mechanical Stability Study for Integrable Optics Test Accelerator at Fermilab
  - MOPOY049 The PXIE LEBT Design Choices
  - TUPMR033 Low Emittance Growth in a LEBT with Un-neutralized Section
  - TUPMR025 Design of the LBNF Beamline
  - MOPMW026 Resonant Control for Fermilab's PXIE RFQ
  - THPOY020 Machine Learning for Particle Accelerator Control Systems: Resonance Control of the PXIE RFQ at Fermilab with a Neural Network
  - MOPOY013 Modeling Longitudinal Dynamics in the Fermilab Booster Synchrotron