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Mission Need for PIP-II

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DOE Independent Project Review of PIP-II

16 June 2015

Outline

- Mission Need : P5 + DOE Strategic Plan
- Physics goals and requirements for beams and detectors
- Present capability of accelerator complex ➔ capability gap
- Proposed solution : a new/upgraded facility

P5 Science Drivers

- Use the Higgs Boson as a New Tool for Discovery
- Pursue the Physics Associated with Neutrino Mass
- Identify the New Physics of Dark Matter
- Understand Cosmic Acceleration : Dark Energy and Inflation
- Explore the Unknown : New Particles, Interactions, and Physical Principles

Recommendations from May 2014 P5 Report

- Recommendation 12: In collaboration with international partners, develop **a coherent short- and long-baseline neutrino program** hosted at Fermilab.

- Recommendation 13: Form a new international collaboration to design and execute a **highly capable Long-Baseline Neutrino Facility (LBNF)** hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

- Recommendation14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP- II) should proceed immediately, followed by construction, to provide **proton beams of >1 MW** by the time of first operation of the new long-baseline neutrino facility.

Mission Need : DOE Strategic Plan 2014 - 2018

- Strategic Objective 3 : *Deliver the scientific discoveries and major scientific tools that transform our understanding of nature and strengthen the connection between advances in fundamental science and technology innovation.*
- Strategies to achieve this objective :
  - *Conduct discovery-focused research to increase our understanding of matter, materials and their properties through partnerships with universities, national laboratories, and industry;*
  - *Provide the nation's researchers with world-class scientific user facilities that enable mission-focused research and advance scientific discovery;*
  - *Use the national laboratory system and leverage partnerships with universities and industry to conduct mission-focused research.*

PIP-II at Fermilab will deliver science + technology

Mission Need : Understanding Neutrinos

- Neutrinos are the most ubiquitous and puzzling of known particles
- Menu of a discovery program :
  - Determine if neutrinos violate leptonic CP and by how much
  - Extract multiple detailed properties of neutrinos in a single experiment to test the current 3-flavor paradigm
  - Look for surprises
  - Search for nucleon decay (because we need very large detectors)
  - Detect thousands of neutrinos from galactic supernova explosions
  - And more

Mission Need : Understanding Neutrinos

- **FNAL currently operating** two neutrino beams : NuMI and BNB
  - NuMI : 120GeV, 3e20 POT/yr ➔ >6e20 POT/yr (@700kW)
  - BNB : 8 GeV, ~1 – 2 e20 POT/yr (depends on rate to NuMI)
- Collecting **DATA** from NOvA, Minerva, MINOS+ and soon MicroBooNE!
- **PHYSICS**
  - neutrino mass and mixing, mass hierarchy
  - cross-sections
  - sterile neutrinos
  - resolve anomalies
- At this time, the U.S. has a unique opportunity to host a flagship global program : LBNF/DUNE to study and possibly discover CP violation in the leptonic sector
  - LBNF is a natural progression from NUMI/MINOS and NOvA, and the expertise exists at Fermilab to host this facility
  - DUNE is a highly motivated, experienced and well organized international team that has assembled quickly and is anxious to begin

Next Generation Long Baseline Neutrino Experiment : DUNE

- DUNE will be a world-class accelerator-based neutrino experiment for CP violation searches and more!
  - **Baseline** of 1300 km
    - For the determination of the mass hierarchy AND measuring the CP violating phase
  - **Wide-band neutrino beam** of 0.5 – 5GeV
    - Enough statistics to fit event spectra for both neutrinos AND anti-neutrinos
  - **Underground Liquid Argon Detector** of ~40kT mass
    - Excellent signal efficiency and background rejection
  - **High Resolution Near Detector**
- The combination of these components make LBNE a very effective way to get to neutrino CP-violation physics
- Underground leads to extended physics capabilities (supernova, proton decay, ….)

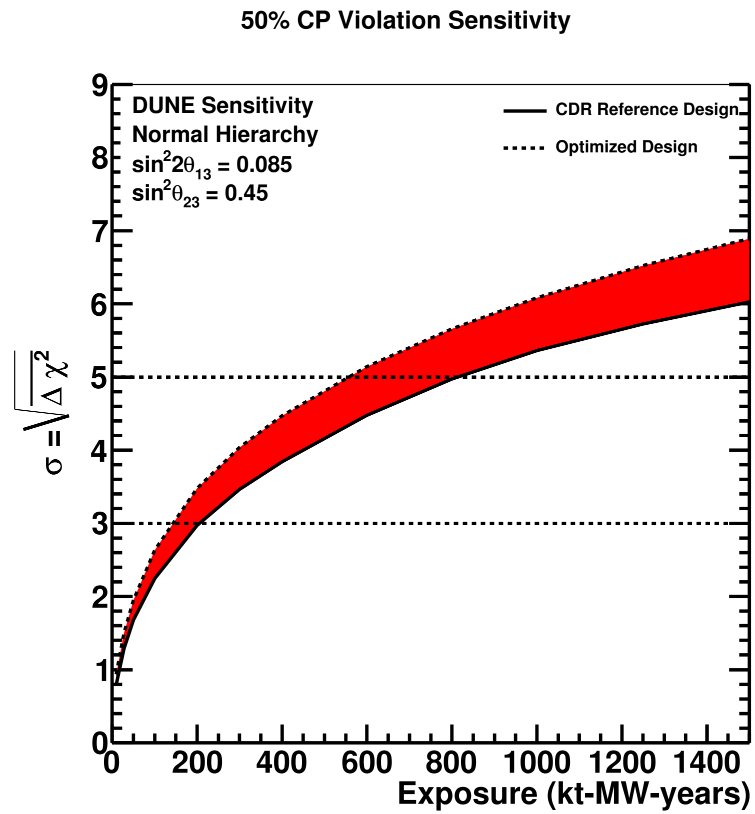
Full scope may need to be achieved in stages

From P5 report

- For a long-baseline oscillation experiment, based on the science drivers and what is practically achievable in a major step forward, we set as the goal a mean sensitivity to CP violation of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δCP.
  - By current estimates, this corresponds to an exposure of **600kt*MW*y** assuming systematic uncertainties of 1% and 5% for the signal and background, respectively. With a wideband neutrino beam produced by a proton beam with power of 1.2 MW, this implies a far detector with fiducal mass of more than 40 kilotons (kt) of liquid argon (LAr) and a suitable near detector.
- The minimum requirements to proceed are the identified capability to reach an exposure of at least **120 kt*MW*yr** by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power.

Neutrino Experiments Need : Mass * Power * Time

From DUNE CDR – May 2015



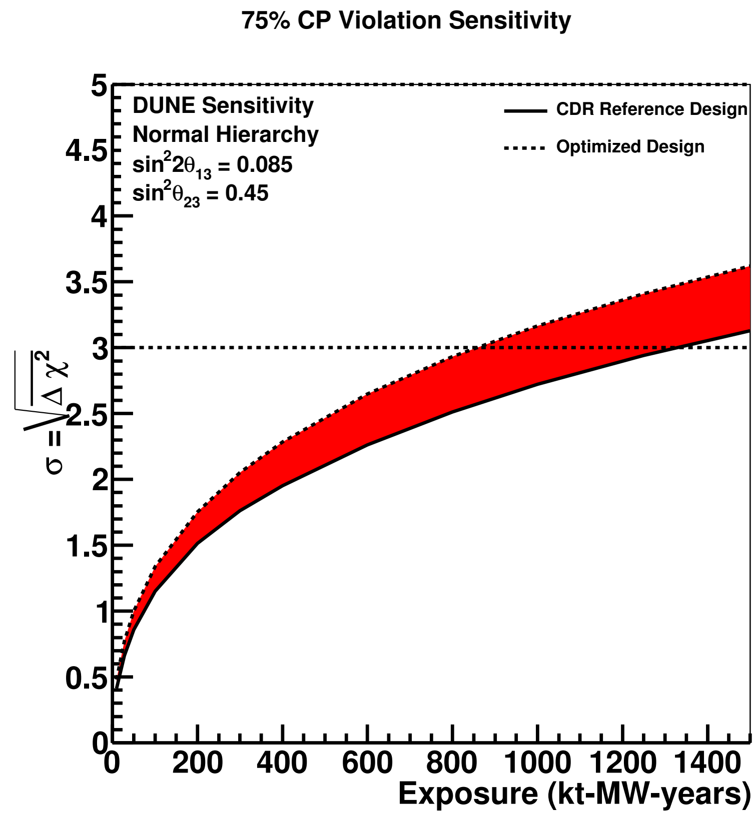


Figure 3.17: The significance with which CP violation can be determined for 50% (left) or 75% (right) of $\delta_{\rm CP}$ values as a function of exposure. The shaded region represents the range in sensitivity due to potential variations in the beam design. This plot assumes normal mass hierarchy.

STATISTICS in Neutrino Experiments

Neutrino Events/Unit Time =

Neutrino Flux x ← **BEAM = Protons/year + Target/horns, Beam Energy**

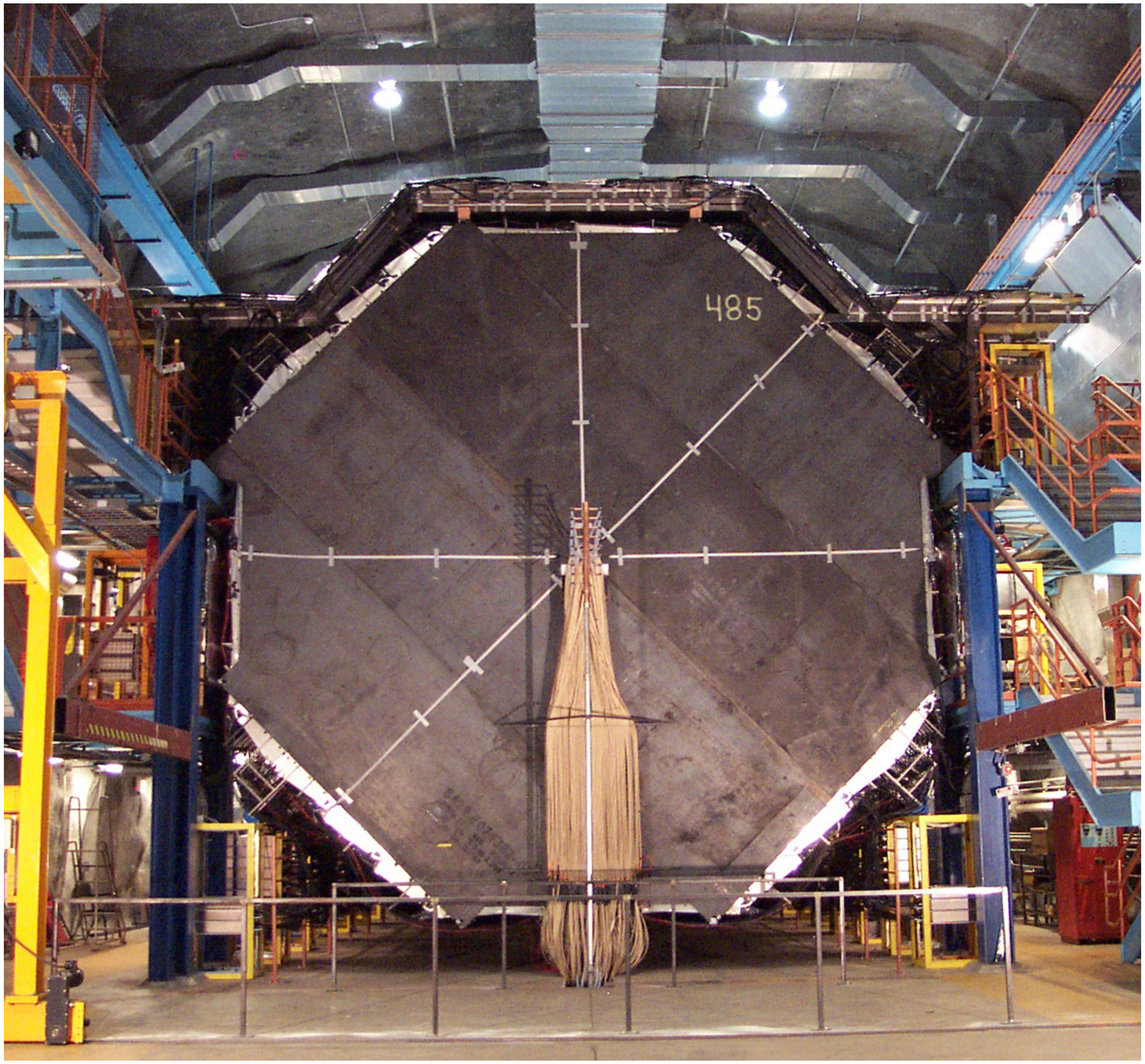
Neutrino Cross-section/Nucleon x ← PHYSICS!

Number of Nucleons ← **Detector = Mass + Efficiency**

Neutrino Experiments Need : Mass * Power * Time

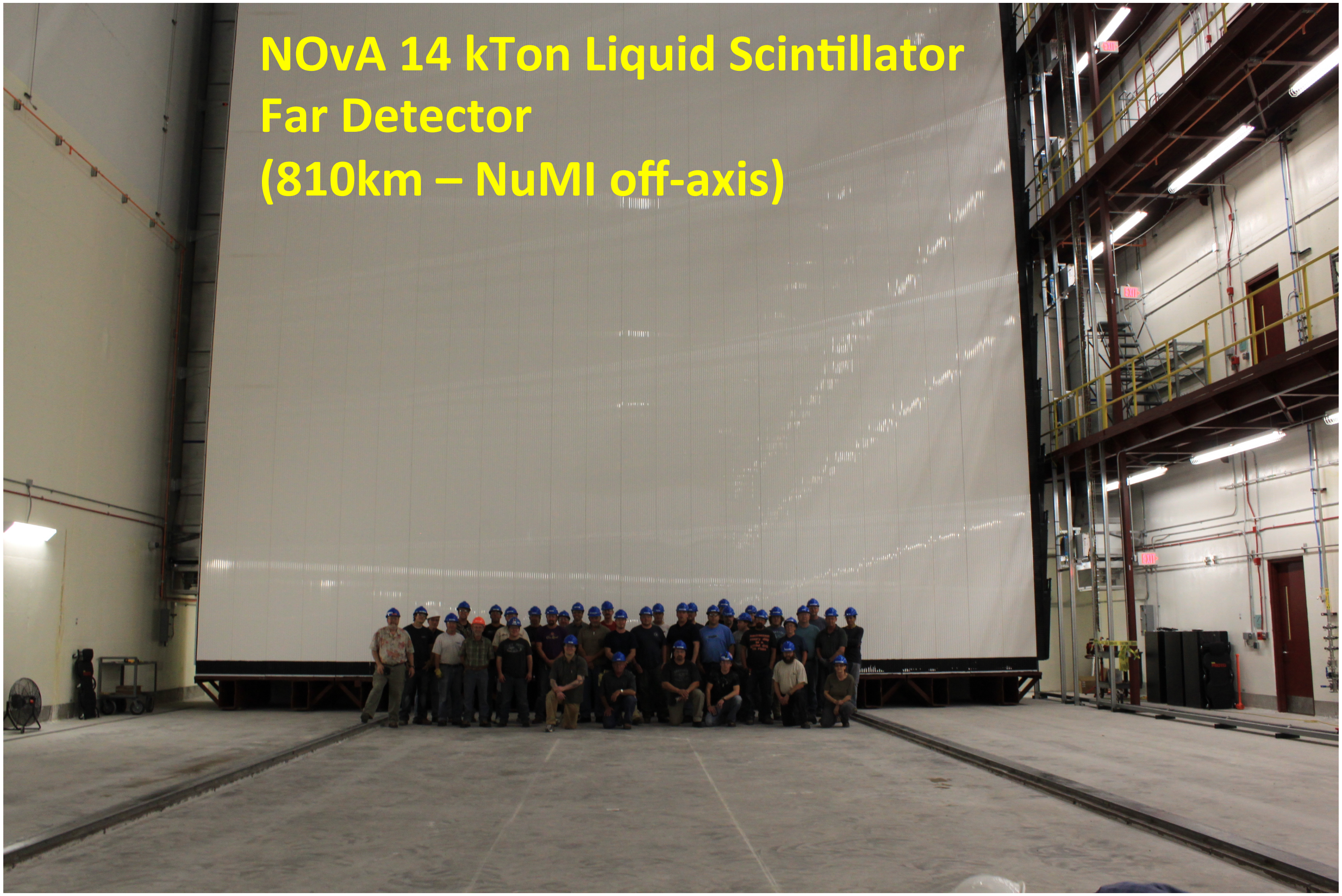
We want to achieve our physics goals in a timely manner!

Mass : Neutrino Detectors are large!



MINOS Far Detector :
5kTon Fe-Scintillator
(NuMI on-axis @ 735km)

And getting larger ….



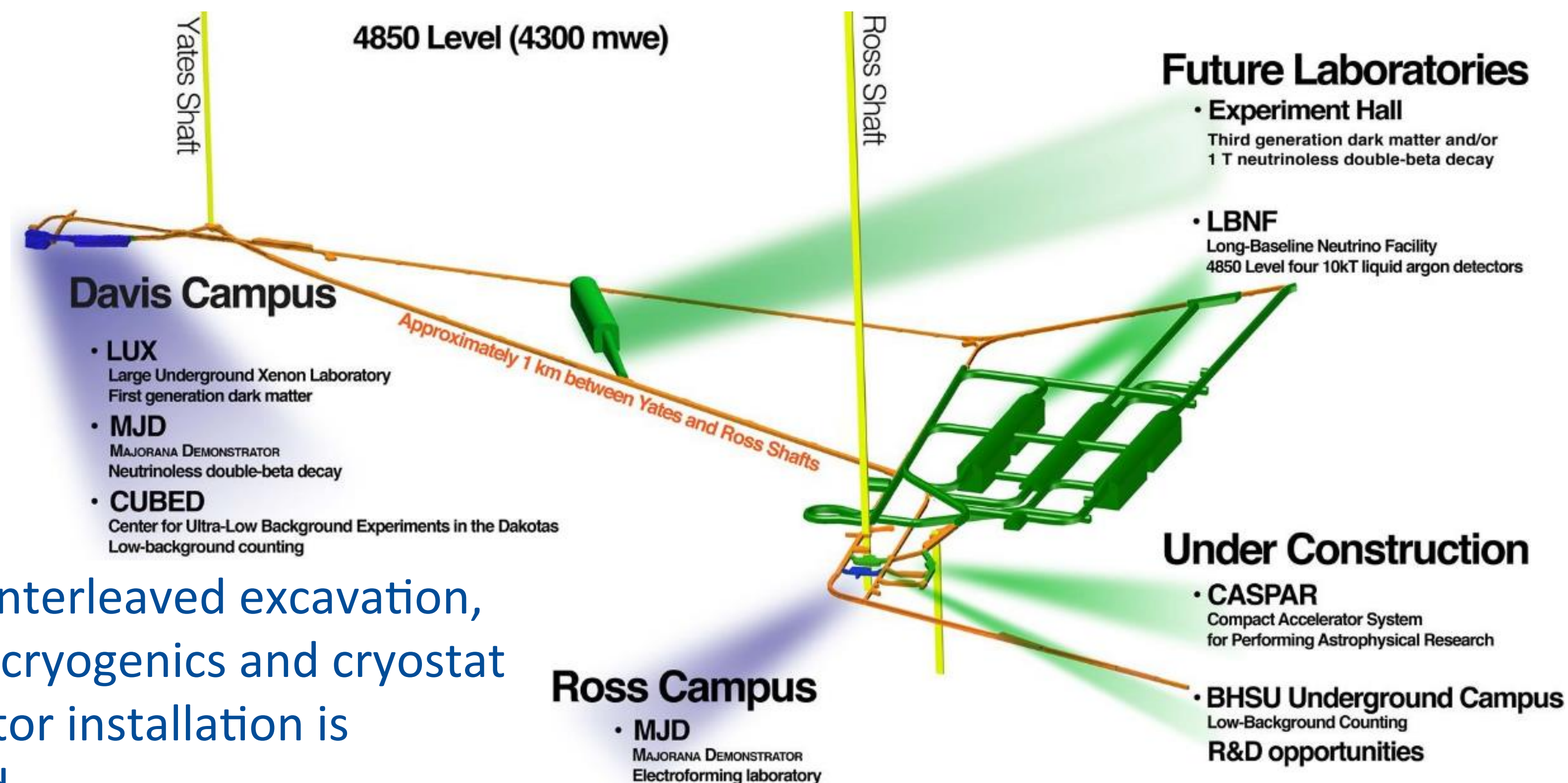
A 10kT fiducial mass detector

Size of a single 10kT detector

Plan is to build 4 of them 1 mile underground

Reference design:

- Rectangular caverns
- 4 caverns, each to hold a 10 kt fiducial mass detector
- Central utility cavern to house cryogenic equipment and common utilities



- Potential interleaved excavation, outfitting, cryogenics and cryostat and detector installation is envisioned.

Power : Current high power operation and plans for NuMI

- The MI has been delivering 2.4E13 ppp every 1.333 sec by using the Recycler as a proton stacker (6 batches, no slip stacking).
  - 350 KW beam power (315 KW with SY120)
- On March 5th, 2015 it switched to 2+6 operation, currently delivering ~420 KW of beam power.
  - 453 KW new MI Beam Power record (running without SY120) achieved on March 25th, 2015.
- Plan to demonstrate 4+6 operation in June 2015, before the summer shutdown.
- Achieve 575 KW with 4+6 operation-November 2015 (19 re-furbished Booster RF stations, 7.5 Hz operation).
- Achieve 700 KW with 6+6 operation-Feb. 2016 (20 re-furbished Booster RF stations, 9 Hz operation).

Time : Neutrino experiments take time

- Consider several options for how one could reach the P5 goals
- We see that the existing 700kW capability, even when paired with the full detector mass leads to an unrealistic time line for achieving the physics goals
- Given the size and complexity – it is difficult to imagine more mass (at least at this time)

Detector Fiducial Mass (kton)	Proton Beam Power (MW)	YEARS to reach 120kT.MW.yr	YEARS to reach 600kT.MW.yr	YEARS to reach 900kT.MW.yr
10	0.7	17	86	129
20	0.7	9	43	64
30	0.7	6	29	43
40	0.7	4	21	32
10	1.2	10	50	75
20	1.2	5	25	38
40	1.2	3	13	19
20	2.4	3	13	19
40	2.4	1	6	9

Time : Neutrino experiments take time

- Consider several options for how one could reach the P5 goals
- We see that the existing 700kW capability, even when paired with the full detector mass leads to an unrealistic time line for achieving the physics goals
- Given the size and complexity – it is difficult to imagine more mass (at least at this time) **40kT with 1.2 MW is a 20 year program**

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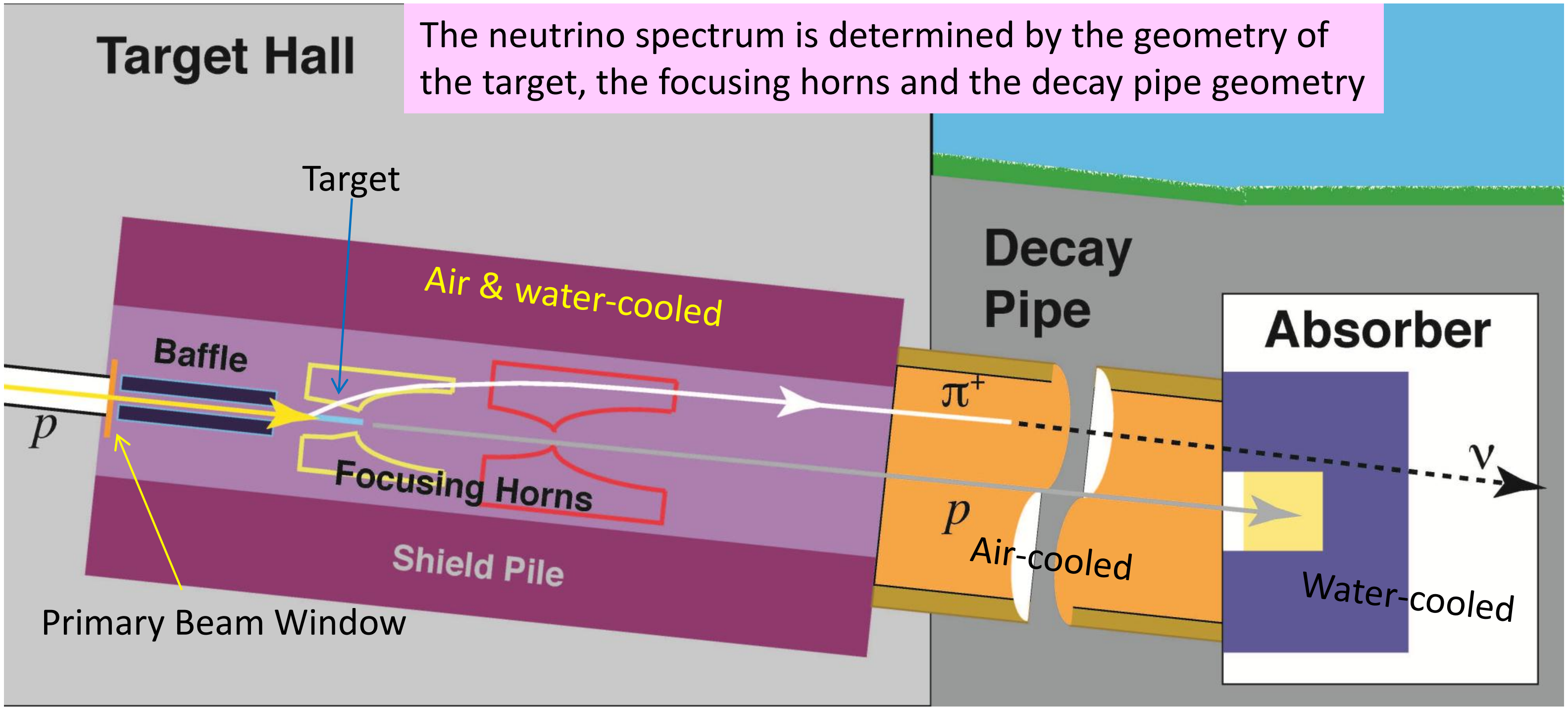
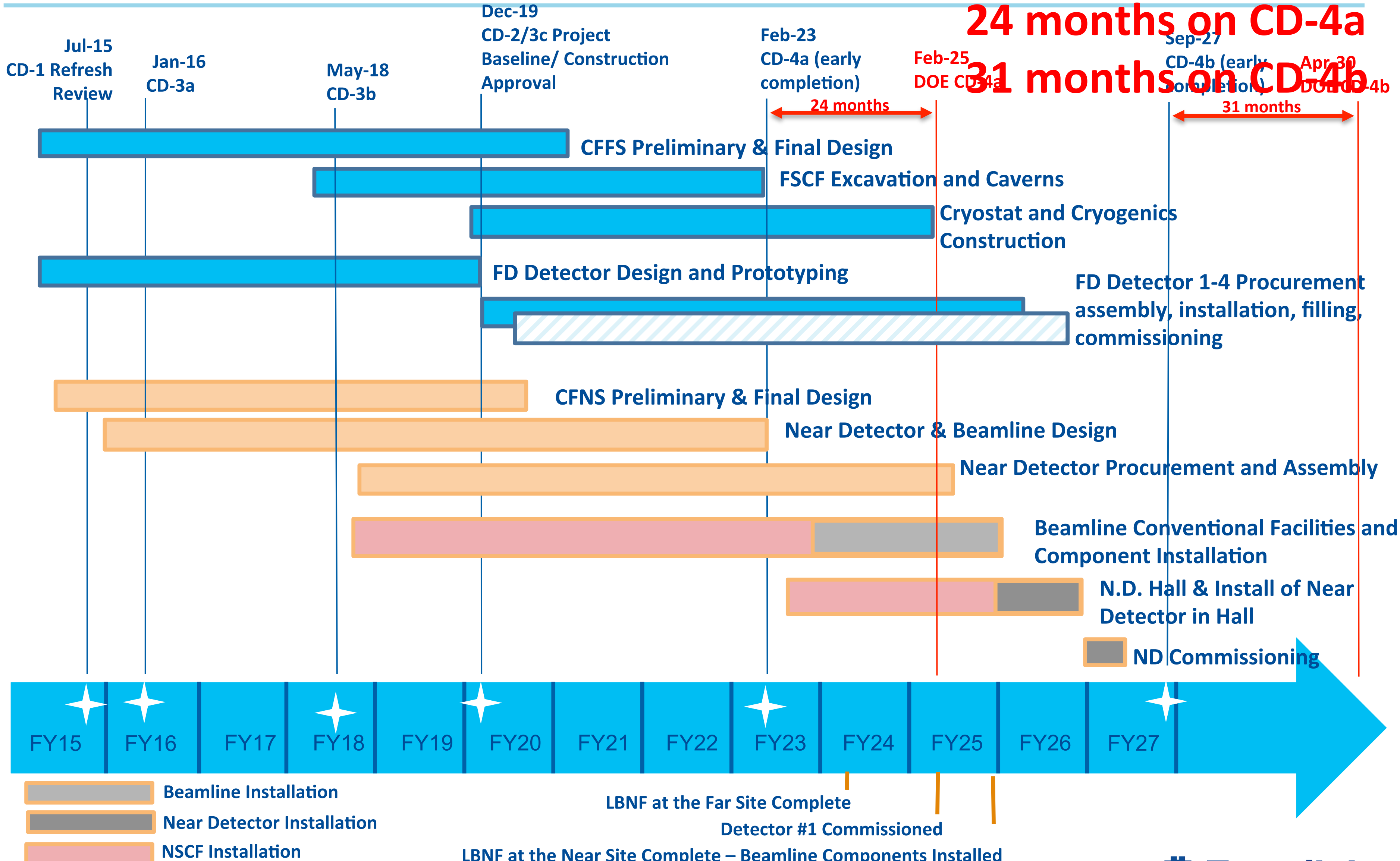
Protons ➔ Neutrino Flux



- Conventional Neutrino Beam = target + focusing horns + decay volume
  - Design choices made to optimize the flux and provide reliable operation
  - Lot’s of design effort, not an additional factor of two to be found

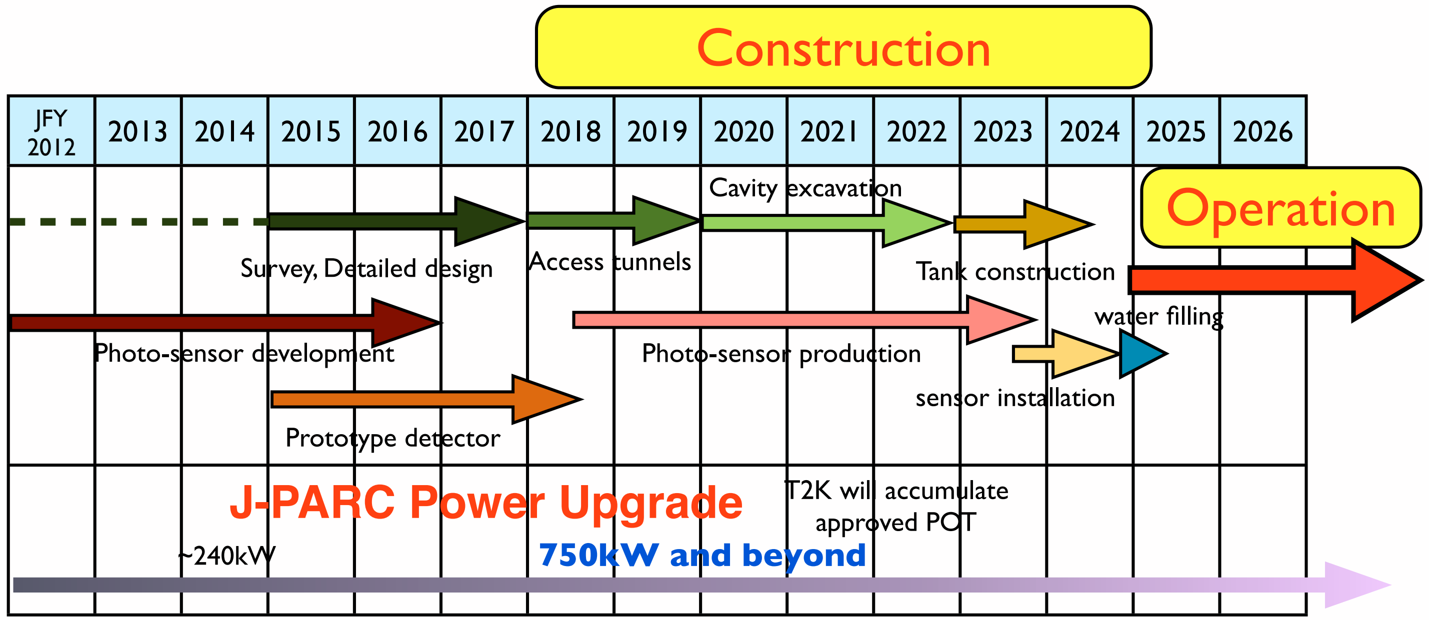
LBNF/ DUNE Schedule Summary Overview

SCHEDULE CONTINGENCY:
24 months on CD-4a
31 months on CD-4b



Timeliness is important

Target Schedule



-2018 Construction starts
-2025 Data taking start
  -2028 Discovery of Neutrino CP violation ?
  -2030 Discovery of Proton Decay ?
  -20xx Detection of supernova neutrinos
  -20xx Discovery of new phenomena

Strategic Risk of Not Filling the Capability Gap

- The Fermilab complex, when fully operational at 700kW does not allow for a timely execution of the neutrino science program that is proposed (LBNF/DUNE)
  - Additionally, by 2021 the accelerator complex will be 50 years old
- The proposed Hyper-K experiment in Japan is complimentary to the DUNE experiment, and execution of both would provide an outstanding attack on the open neutrino questions.
- If a timely solution to the proton power problem is not realized, the DUNE experiment risks missing the opportunity for significant scientific discovery

The accelerator complex supports a diverse program

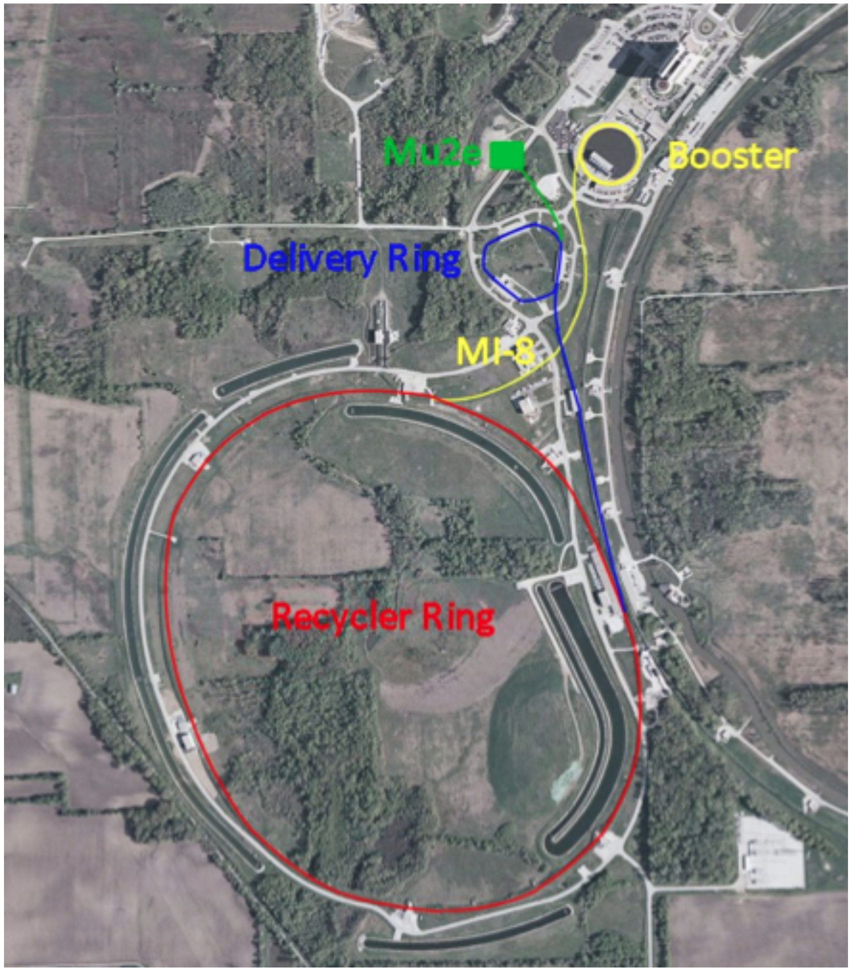
- Neutrinos
  - NuMI
  - BNB
- Muons
  - g-2
  - Mu2e
- Test beams
- Fixed Target

Short-baseline Neutrino Program

- **P5 Recommendation 12**: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

3 detector LArTPC program using the Booster Neutrino Beam

G-2 and Mu2e beamlines



- g-2 and Mu2e will use
  - 8 GeV protons from the Booster
  - Re-bunched in the Recycler
  - Slow-spill from Delivery Ring
- Do not run simultaneously
- Each can run simultaneously with BNB and NuMI
- g-2 would benefit from more protons
- Mu2e will benefit in long term with CW at 800MeV

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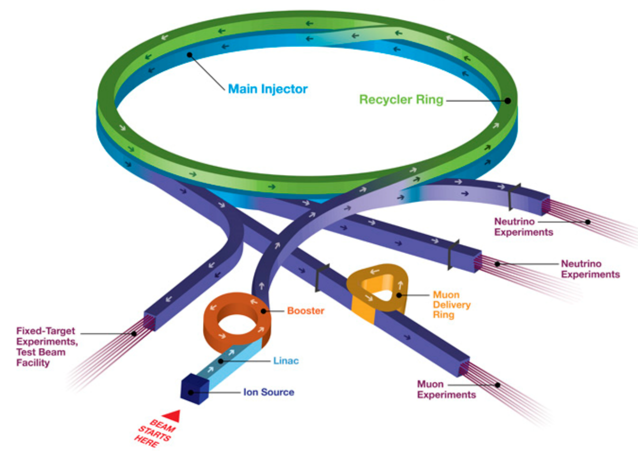
PIP Improvement

- The Fermilab complex will be capable (in 2016) of delivering protons at both 8 and 120 GeV, in support of the neutrino and muon programs:
  - Booster: 4.3×10^{12} protons @ 8 GeV @ 15 Hz = 80 kW
  - MI: 4.9×10^{13} protons @ 120 GeV @ 0.75 Hz = 700 kW

- Limitations
  - Booster pulses per second (15 Hz)
    - Total power available to 8 GeV program limited by the repetition rate
  - Booster protons per pulse
    - Limited by space-charge forces at Booster injection, i.e. the linac energy, and total beam loss
  - Reliability
    - Linac/Booster represent a non-negligible operational risk

Fermilab Accelerator Complex



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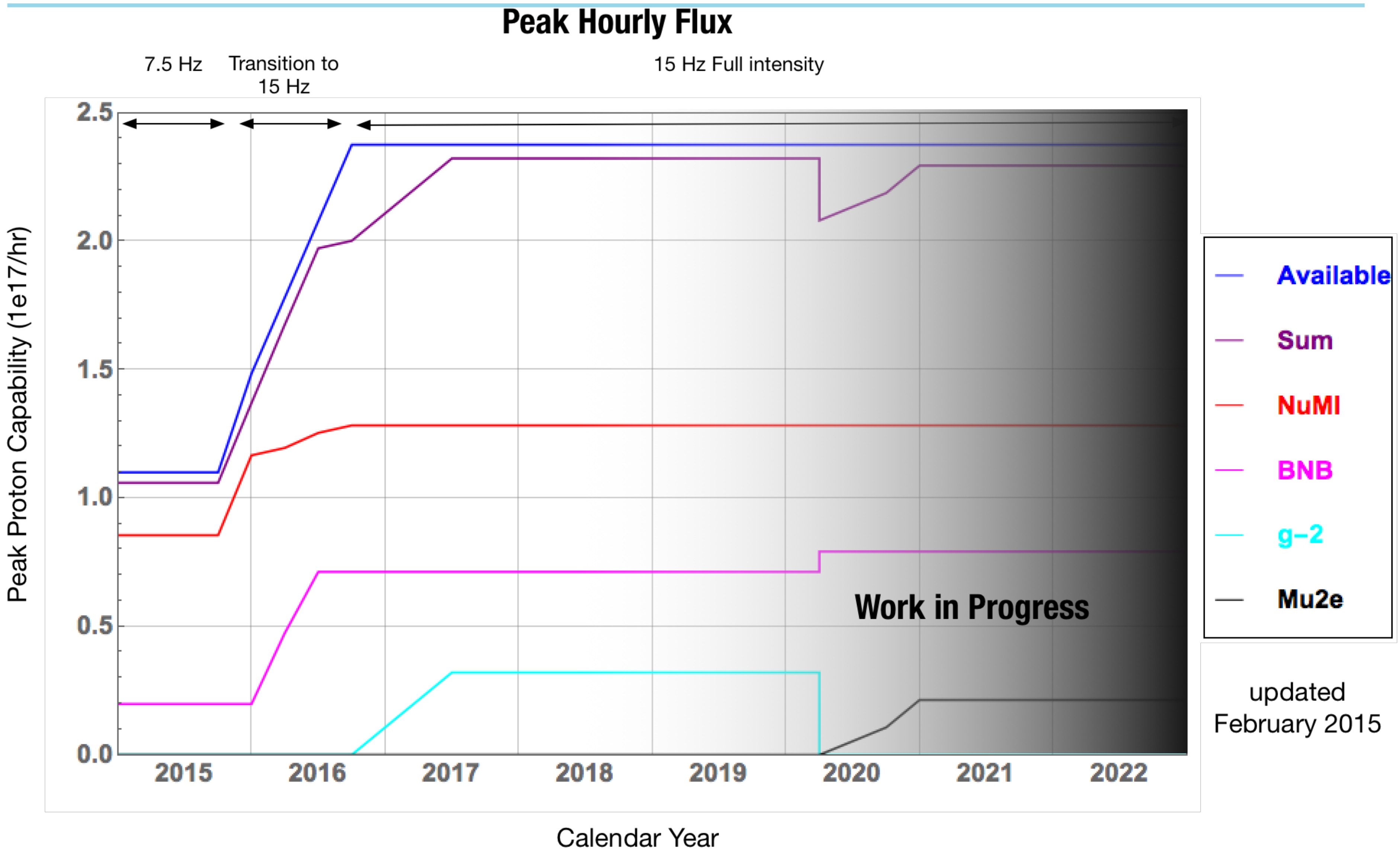
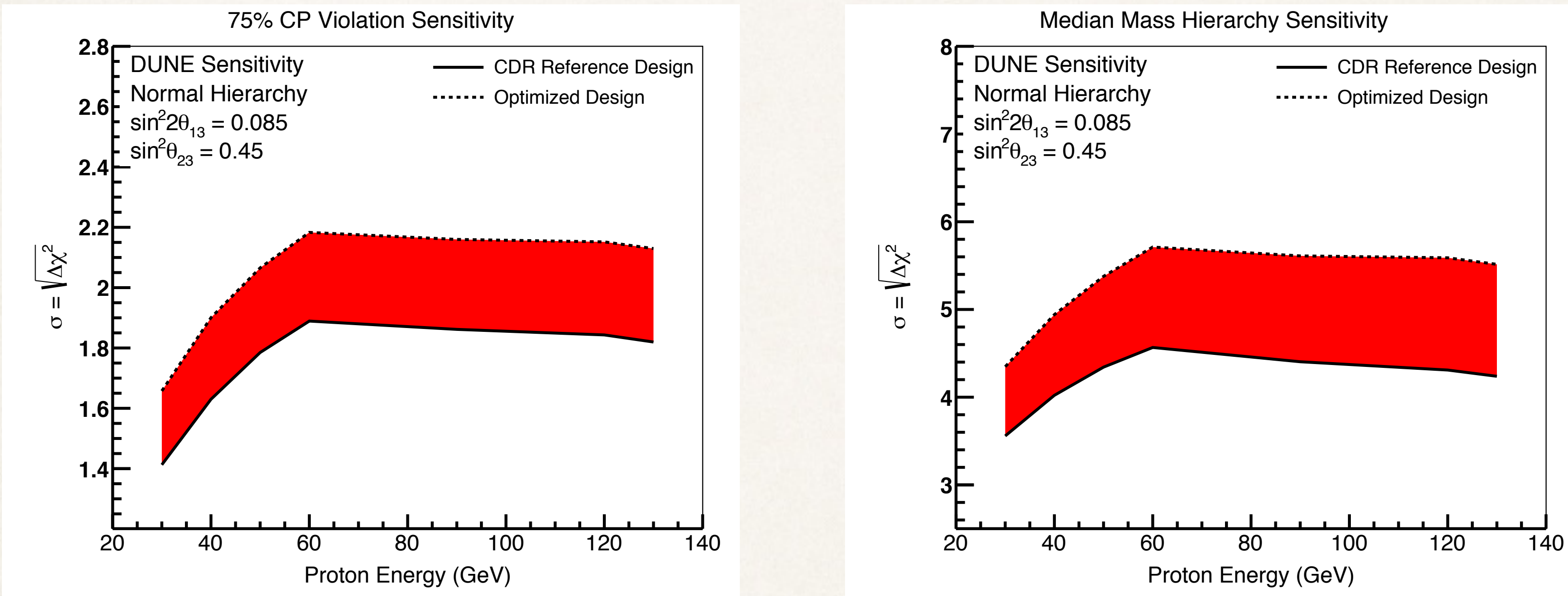
Proton Economics in the complex



Main Injector Energy for LBNF/DUNE



Physics sensitivities for various primary proton momenta

Current estimates of efficiencies, backgrounds, smearing, etc indicate sensitivities to CP violation and the mass hierarchy are maximal with 60 GeV protons.

But relative different in sensitivity between 60 and 120 GeV is small. Optimal running energy should be reassessed as inputs are better understood.

Main Injector Energy for LBNF/DUNE

- What can we conclude from the sensitivity vs. energy study?
  - Two possible answers :
    - We should be sure to have the flexibility to lower the primary proton energy to 60 GeV
    - The energy dependence is small and therefore doesn't matter
- We recognize that the choice of primary beam energy for LBNF will has both technical and programmatic impacts

		Assuming a 15 Hz Booster			
Energy (GeV)	Intensity (1e13)	Cycle Time (seconds)	Power (MW)	Booster Demand (Hz)	Booster Remaining
120	7.50	1.2	1.20	10.0	5.0
110	7.50	1.133	1.17	10.6	4.4
100	7.50	1	1.20	12.0	3.0
90	7.50	0.933	1.16	12.9	2.1
80	7.50	0.866	1.11	13.9	1.1
70	7.50	0.8	1.05	15.0	0.0
60	7.50	0.8	0.90	15.0	0.0
50	7.50	0.8	0.75	15.0	0.0
40	7.50	0.8	0.60	15.0	0.0
30	7.50	0.8	0.45	15.0	0.0

15 ➔ 20 Hz in Booster Rep Rate

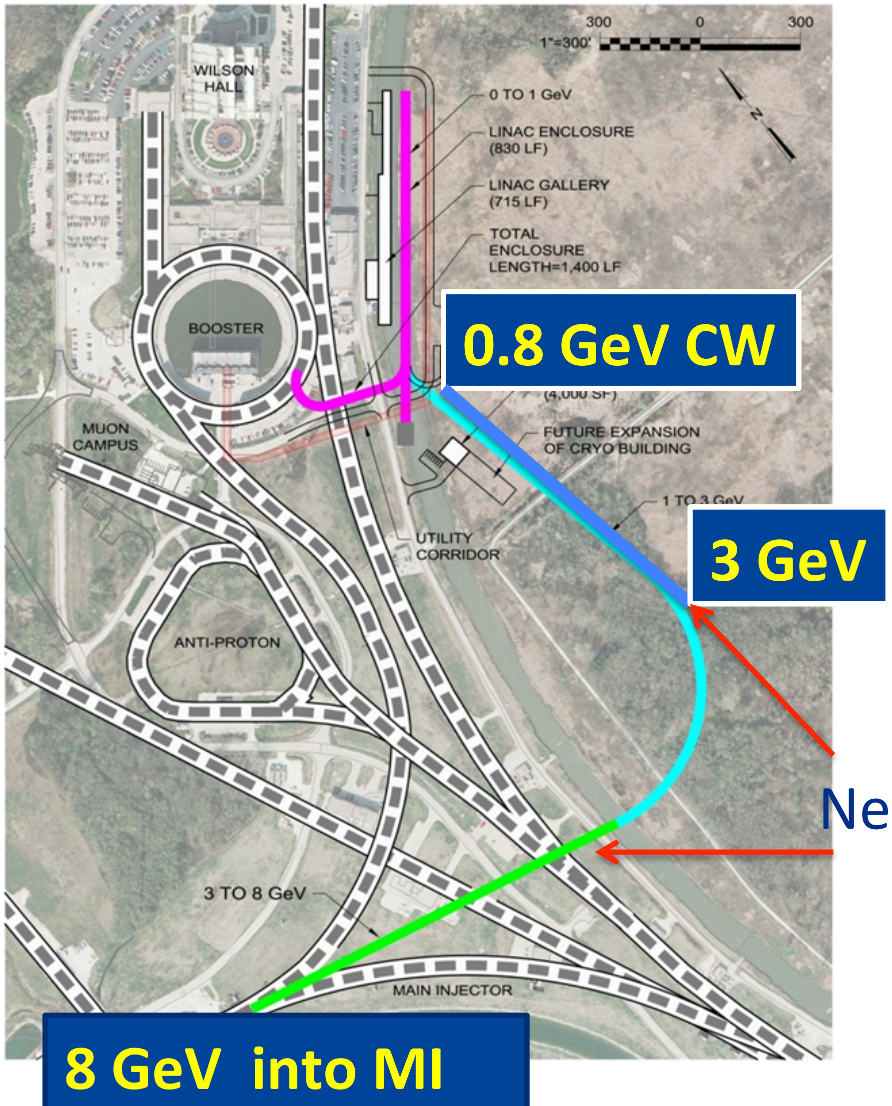
- Provides the capability to run the long- and short-baseline programs simultaneously

		Assuming a 20 Hz Booster			
Energy (GeV)	Intensity (1e13)	Cycle Time (seconds)	Power (MW)	Booster Demand (Hz)	Booster Remaining
120	7.50	1.2	1.20	10.0	10.0
110	7.50	1.1	1.20	10.9	9.1
100	7.50	1.05	1.14	11.4	8.6
90	7.50	0.95	1.14	12.6	7.4
80	7.50	0.9	1.07	13.3	6.7
70	7.50	0.8	1.05	15.0	5.0
60	7.50	0.7	1.03	17.1	2.9
50	7.50	0.65	0.92	18.5	1.5
40	7.50	0.6	0.80	20.0	0.0
30	7.50	0.6	0.60	20.0	0.0

P5 Looking forward

- Looking farther into the future, progress in precision physics and rare processes will be shaped partly by what particle physicists learn in the coming decade. Upgrades to the accelerator complex at Fermilab (PIP-II and additional improvements) will offer opportunities to further this program.
- For example, combined with modest upgrades to Mu2e, improvements in the Fermilab accelerator complex potentially could provide increased sensitivity (by a factor of ten) to muon-to-electron conversion and allow one to search for this very rare process in different nuclei. This will provide crucial clues on the nature of the new physics revealed in the event of an observation in the next-generation experiments.

Flexible Platform for the Future (PIP-III)



Addressing the capability gap : the PIP-II Program

- Deliver >1 MW of proton beam power from the Main Injector over the energy range 60 – 120 GeV, at the start of LBNF operations;
- Support the current 8 GeV program at Fermilab including Mu2e, g-2, and short-baseline neutrinos;
- Provide an upgrade path for Mu2e;
- Provide a platform for extension of beam power to LBNF to >2 MW;
- Provide a platform for extension of capability to high duty factor/higher beam power operations.

Summary

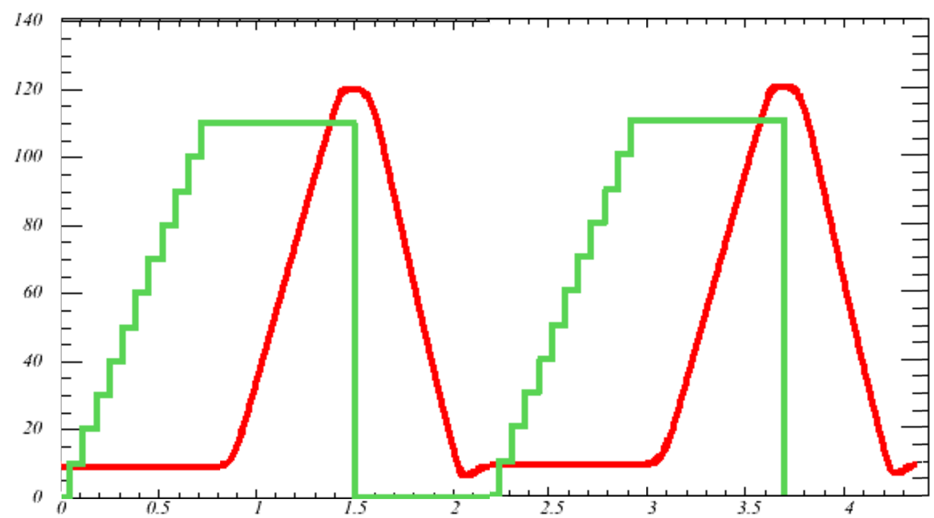
- **Mission Need : Science and Technology**
  - Fermilab's current and future science program includes experiments that require high intensity protons from the accelerator complex
  - Increasing the number of protons and reliability of the complex will be critical to the success of these experiments
- **Capability Gap : Limited protons and reliability**
  - Injection energy + intensity lead to space charge effects
  - 15 Hz operation limits the diversity of the physics program
  - Failures in the aging complex puts the physics program at risk
- **Proposed Solution : PIP-II Program**
  - PIP-II offers the opportunity for the future long-baseline neutrino program get to physics results as quickly as possible after construction completion (>1MW)
  - 20 Hz operation of the complex will allow diversity in the physics program
  - A new linac plus upgrades to the existing complex will increase reliability of operations
  - PIP-II builds a platform on which to expand the capability to > 2MW. (ultimate physics reach for LBNF/DUNE)

Backup

Power : the NuMI beam is powerful

- Operation for MINOS (2004 – 2014) : 400 kW
  - 11 batches in Main Injector
    - Slip Stacking in Main Injector
  - 2.2 sec cycle
    - 0.67 for injection

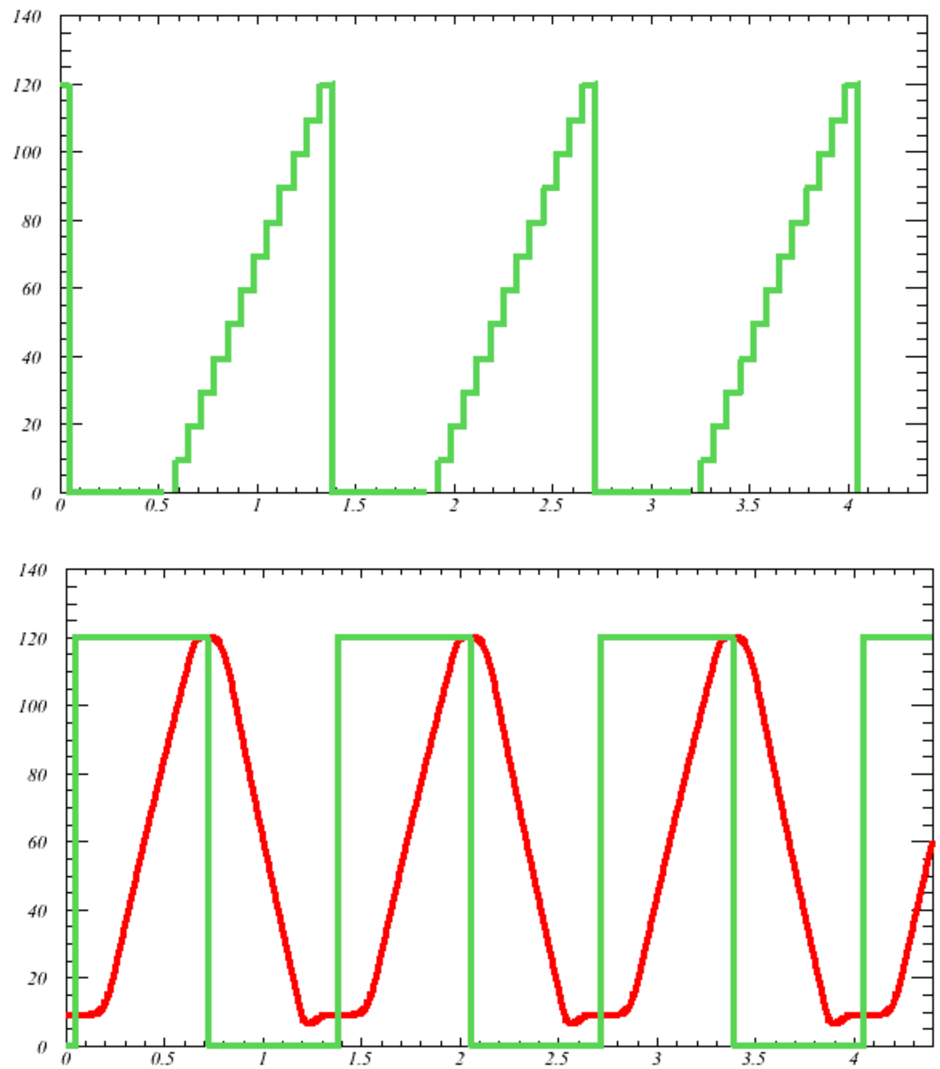
Recycler



Main Injector

And getting more powerful: from 400 kW to 700 kW for NOvA

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



Recycler

Main Injector

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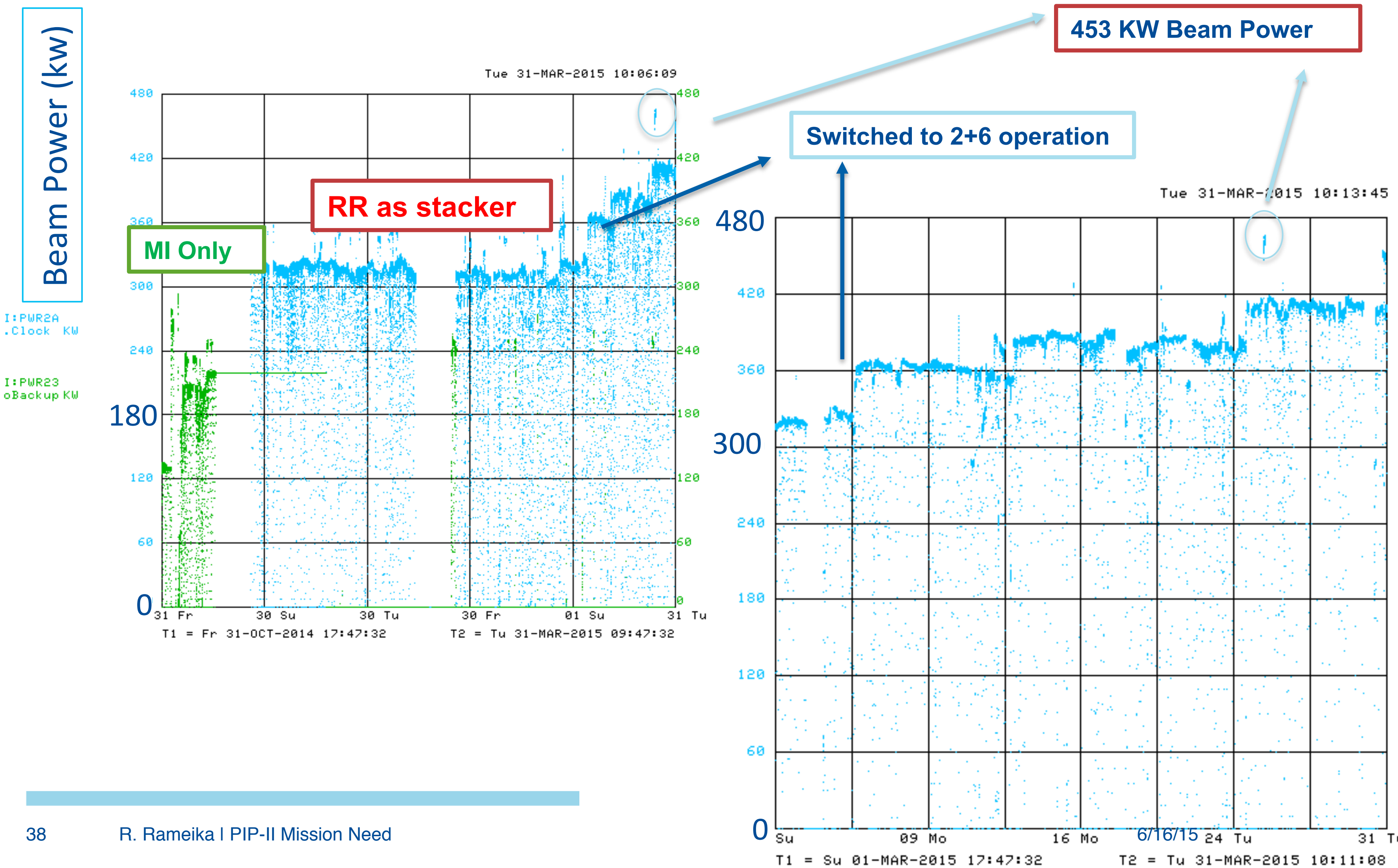
MI Beam Power since long shutdown and during March 2015



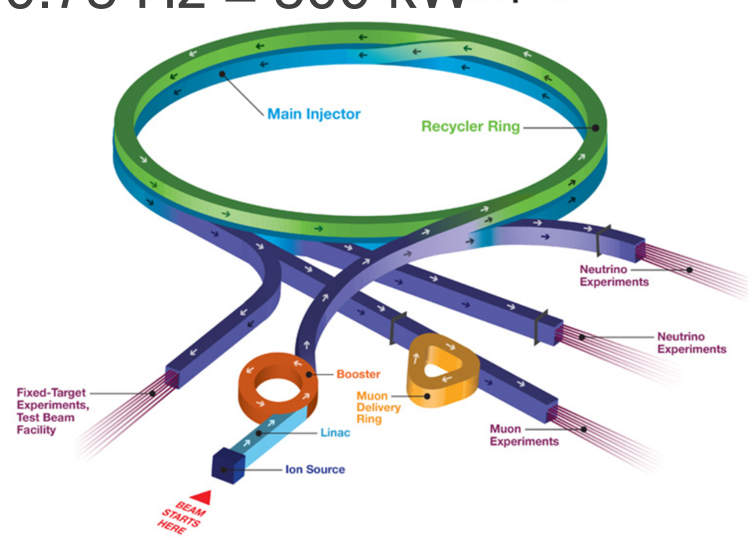
From the P5 report

- The PIP-II project at Fermilab is a necessary investment in physics capability, enabling the world's most intense neutrino beam, providing the wideband capability for LBNF, as well as high proton intensities for other opportunities, and it is also an investment in national accelerator laboratory infrastructure The project has already attracted interest from several potential international partners.
  - Recommendation 14 : Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP- II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

Present capability for delivered beam power

- In its current configuration, the Fermilab complex currently delivers protons for neutrino production at both 8 and 120 GeV, with a present capability :
  - Booster: 4.2×10^{12} protons @ 8 GeV @ 7.5 Hz = 40 kW
  - MI: 3.5×10^{13} protons @ 120 GeV @ 0.75 Hz = 500 kW

- Fundamental limitations
  - Booster pulses per second
    - The Booster magnet/power supply system operates at 15 Hz
    - RF system limited to 7.5 Hz
  - Booster protons per pulse
    - Limited by space-charge forces at the Booster injection energy, i.e. the linac energy



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8 GeV program in LBNE era

From PIP-II report, June 2014

subsequent sections of this document. Note that the concept presented here is capable of delivering 1.2 MW of beam power to LBNE at all energies between 80-120 GeV. For 120 GeV operations significant beam power is also available to support an 8 GeV program in parallel with LBNE. However, for LBNE operations at 80 GeV or below any beam power delivered to an 8 GeV program would come at the expense of beam power to LBNE. This situation could be

ameliorated by upgrading the Booster to 20 Hz operations, and while this possibility is currently under investigation it remains outside the purview of this report.

STATISTICS in Neutrino Experiments

Neutrino Events/Unit Time =

Neutrino Flux x

Neutrino Cross-section/Nucleon x

Number of Nucleons

STATISTICS in Neutrino Experiments

Neutrino Events/Unit Time =

Neutrino Flux x ← A really big number

Neutrino Cross-section/Nucleon x ← A really small number

Number of Nucleons ← A really big number

P5 Science Drivers

- Use the Higgs Boson as a New Tool for Discovery
- Pursue the Physics Associated with Neutrino Mass
- Identify the New Physics of Dark Matter
- Understand Cosmic Acceleration : Dark Energy and Inflation
- Explore the Unknown : New Particles, Interactions, and Physical Principles

Research Opportunities Afforded by PIP-II Beyond DUNE, SBN, and Mu2e-II

- **Next generation $\mu \rightarrow 3e$:**

Enabling technology is CW operation

- **Next generation $\mu^+ e^- \rightarrow e^+ \mu^-$:**

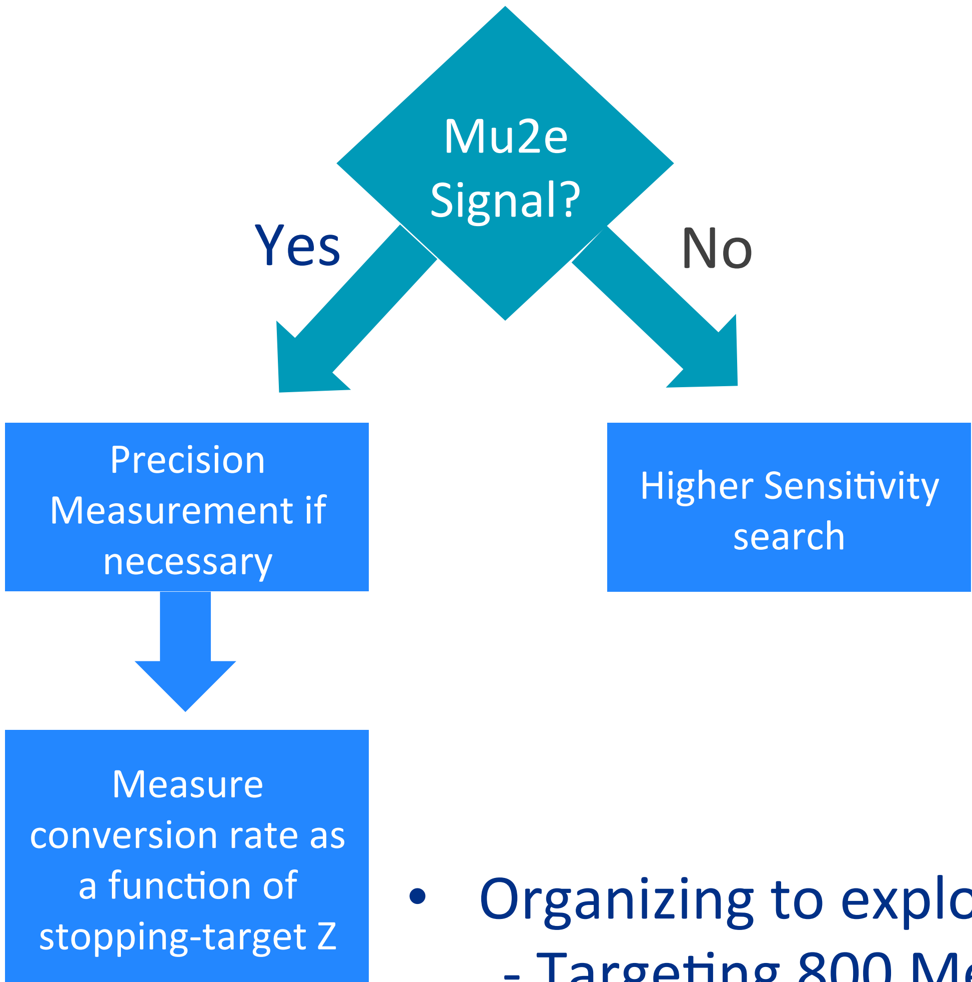
Enabling technology is high frequency pulsed beam, macro-CW operation

- **Proton edm experiment:**

Enabling technology is low emittance 236 MeV (T) polarized proton beam

- PIP-II can also drive other research opportunities that would require major facility enhancements such as a high-power spallation target for particle physics applications.

Mu2e-II : Next generation Mu2e experiment



- A next-generation Mu2e experiment makes sense in all scenarios
  - Push sensitivity (x10) or
  - Study underlying NP
  - Modest upgrade
  - Will require more protons
    (narrow pulses w/ 1-2 μs spacing, high duty factor, extinction $<10^{-11}$)
  - Snowmass White Paper, arXiv:1307.1168

- Organizing to explore pressing issues
  - Targeting 800 MeV p, accidental detector rates, radiation tolerance of Production Solenoid

Program Planning

- Mu2e and g-2 will not run together
- Booster Neutrino Beam CAN run with either
- BNB and Muons can run with NuMI and later LBNF, but limited by proton economics
- Schedules matter in trying to understand the proton economics issues in the short term
- Issues of beam structure, timing, etc. may be more important than just the # of POTs

Short Baseline Program in the Booster Neutrino Beam

- Two ways to increase neutrino flux :
  - Improve pion focusing efficiency : new target/horn configuration
  - Increase number of delivered protons
- Present BNB designed to handle maximum of 5 hz, limited by the horn power supply, and the horn structure itself
  - Typical operations over the
- During the past year we have done studies to see how we can improve the beam via new focusing with new target and new horns

Next generation Muon (g-2)

- Current Muon (g-2) uses μ^+
  - For 8 GeV protons, production $\pi^+ : \pi^- \sim 2.5 : 1$
- PIP-II would provide x2 protons to the Booster
  - Would enable a μ^- run over a reasonable timescale
  - Experimental sensitivity on a_μ would be comparable for μ^+ & μ^-
  - Uses baseline Muon (g-2) apparatus and detectors
  - Allows a sensitive test of CPT
- Instrumenting all calorimeters with trackers would additionally enable another x10 improvement in muon EDM