Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

PIP-II and proton opportunities

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MUSE Network General Meeting

24 October 2018

“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, 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*
  - Focus on a high energy neutrino program to determine the mass hierarchy and measure CP violation.
    - Will ultimately require a “multi-megawatt” beam at 60-120 GeV
  - Continue at least R&D toward a future linear e^+e^- collider (ILC)

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Fermilab Program Goals

Fermilab's goal is to construct & operate the foremost facility in the world for particle physics research utilizing intense beams.

- Neutrinos
  - MINOS+, NOvA @700 kW
  - LBNF @ multi-MW
  - Short Baseline Neutrino @ 10's kW
- Muons
  - Muon g-2 @ 17-25 kW
  - Mu2e @ 8-100 kW
- Longer term opportunities

⇒ ***This requires more protons!***

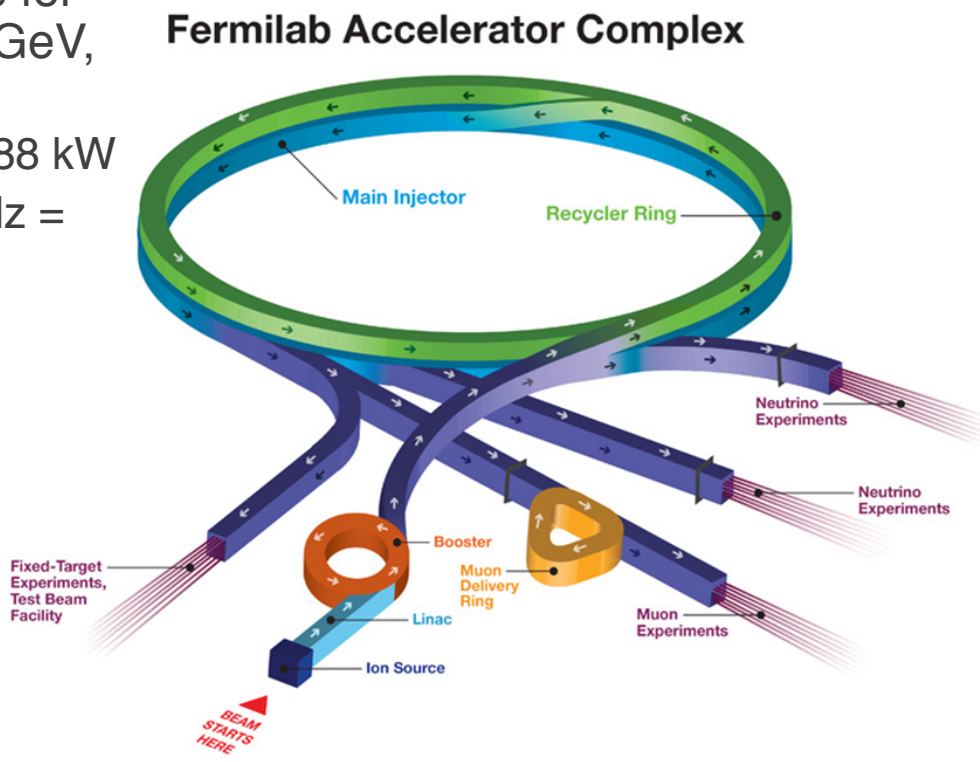
(and this statement tends to be time invariant)

"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 the first operation of the new long-baseline neutrino facility" – Recommendation 14, P5 report

The Fermilab Accelerator Complex Today

- The Fermilab complex delivers protons for neutrino production at both 8 and 120 GeV, with a present capability:
  - 8 GeV: 4.6×10^{12} protons @ 15 Hz = 88 kW
  - 120 GeV: 5.0×10^{13} protons @ 0.75 Hz = 715 kW

- Present limitations
  - Booster pulses per second
    - The Booster magnet/power supply system operates at 15 Hz
  - Rings Beam Loss
    - Higher Power operation is all about controlling beam loss
  - Target systems capacity
    - Limited to ~800 kW



Experimental Program

- At 8 GeV
  - Neutrinos (Booster)
    - ANNIE
    - MicroBooNE
    - MiniBooNE
    - MITPC
    - SciBath
    - ICARUS (future)
    - SBND (future)
  - Muons (Recycler & Muon Rings)
    - g-2
    - Mu2e (future)
- At 120 GeV
  - Neutrinos
    - MINOS+
    - MINERvA
    - NOvA
    - DUNE (future)
  - Fixed Target
    - SeaQuest
    - LArIAT
    - Test Beam Facility

Strategy for the next ~10 years
Proton Improvement Plan (PIP)

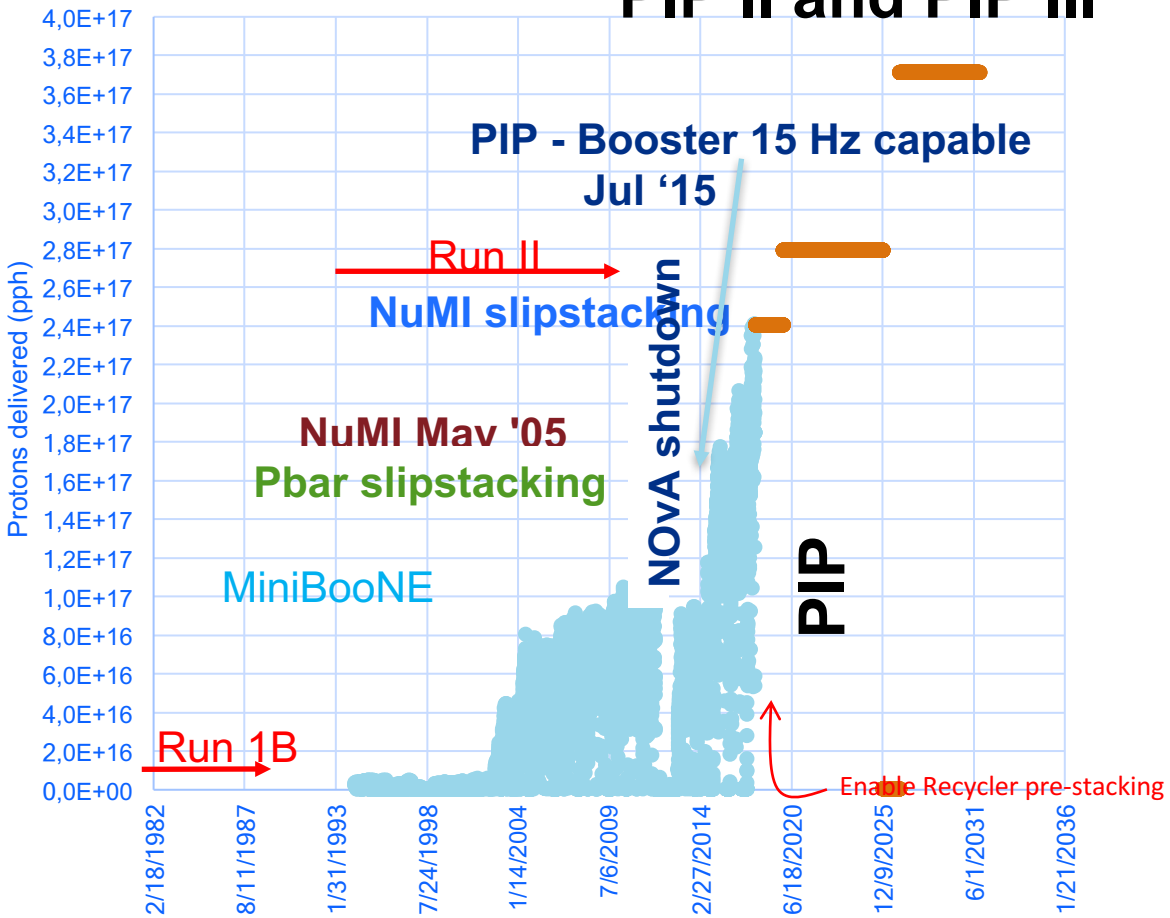
The near-term goal is to double the Booster beam repetition rate to 15 Hz, while addressing reliability concerns

- Required for simultaneous operations of NOvA, g-2, Mu2e, SBN
- 700 kW to NOvA: 4.9e13 @ 120 GeV @ 0.75 Hz

- Design Criteria
  - 15 Hz beam operations at 4.2×10^{12} protons per pulse (80 kW)
  - Linac/Booster availability > 85%
  - Residual activation at acceptable levels
  - Useful operating life for the Linac through 2023 and the Booster through 2030
- Scope
  - 15 Hz Capability:
    - RF upgrades, cavity refurbishment
    - Power and water distribution
  - Reliability: >85% uptime, reduce operational risk
    - Drift Tube Linac RF replacement ⇒200 MHz klystrons/modulators
    - Additional Booster RF cavities
    - Power and water distribution
  - Beam Quality and Losses: RFQ, dampers, collimators/absorbers
    - To maintain activation at current levels or lower
- Execute over the years 2011 – 2019

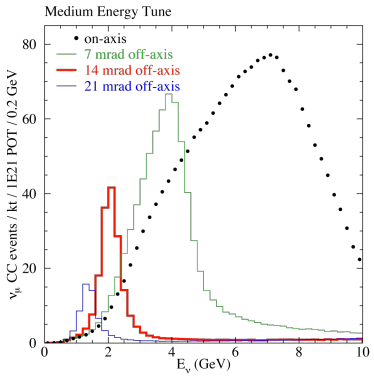
PIP II and PIP III

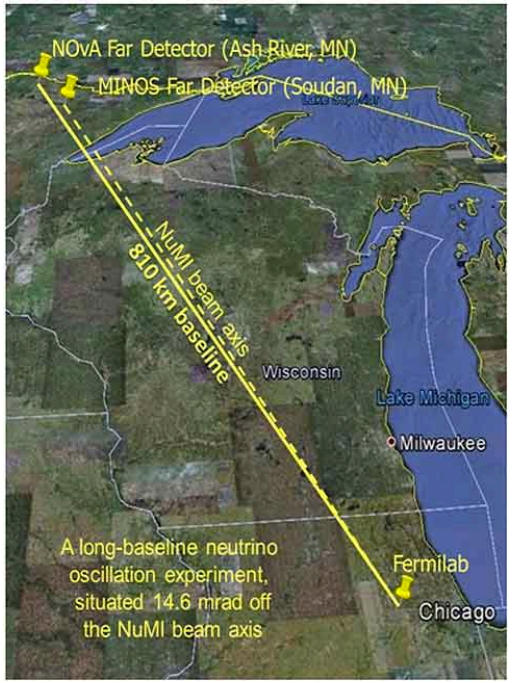
Progress: Beam through Booster



Current ν Program: NuMI➔MINOS+NOνA

- 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 in the Soudan Mine in Minnesota
  - NOνA: 810 km away in Ash River, Minnesota, 14.6 mrad off axis
    - Produces narrower energy spread



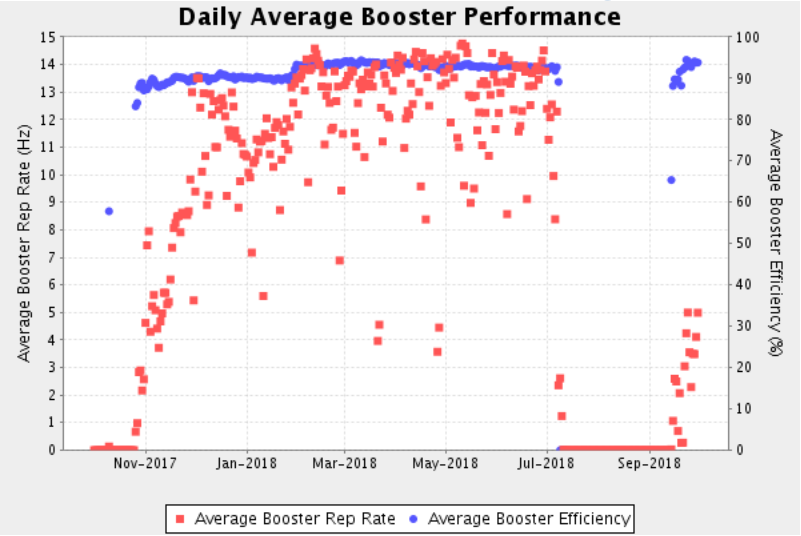


Current Program: g-2, Mu2e

- g-2 :
  - 4 Booster batches (4e12 at 8 GeV) every 1.4 seconds to Recycler
  - Adiabatically rebunch 53 MHz to 2.5 MHz
    - ~125 nsec width
  - 16 extractions of protons -> 3.094 GeV muons to Delivery Ring
  - Circulate 5 turns (protons & muons separate in time), then to g-2 ring
  - 15 kW

- Mu2e:
  - 2 Booster batches (4e12 at 8 GeV) every 1.4 seconds to Recycler
  - Adiabatically rebunch 53 MHz to 2.5 MHz
  - 8 Extractions of protons
    - Slow spill from Delivery Ring
    - 7.3 kW

Previous Year Delivery



Regular operation at 15 Hz

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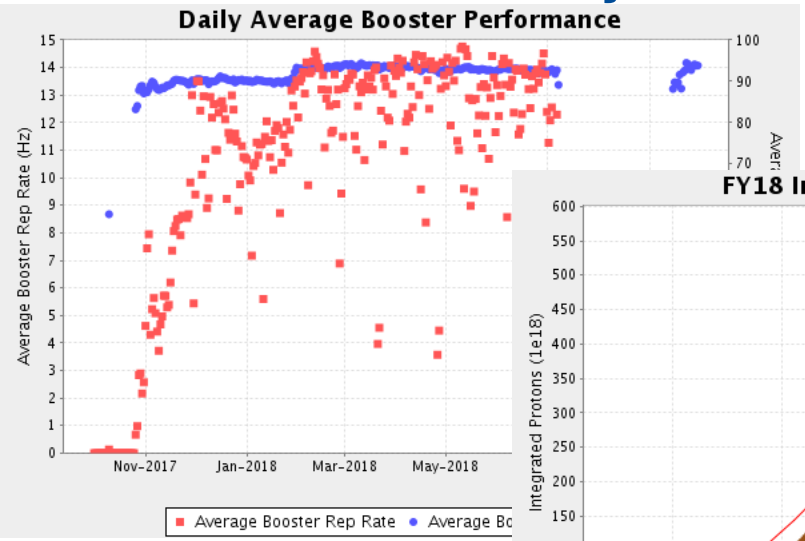
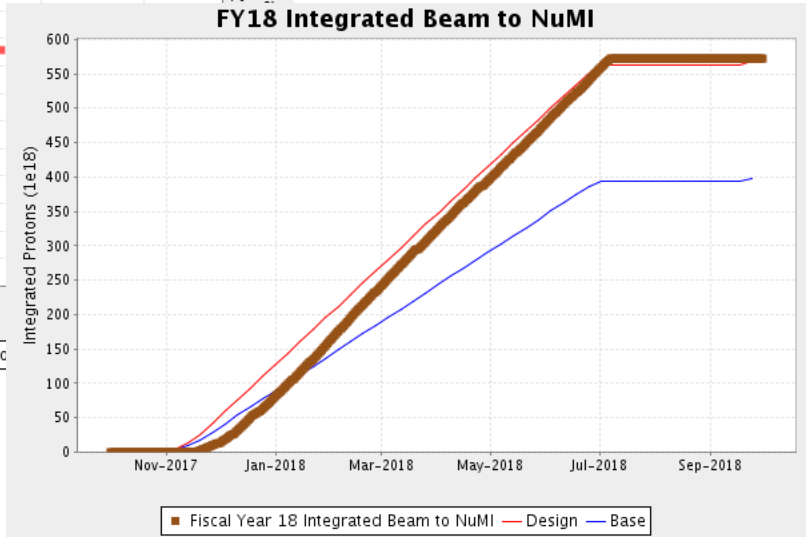
Previous Year Delivery





Power and Uptime to meet Proton on Target goals

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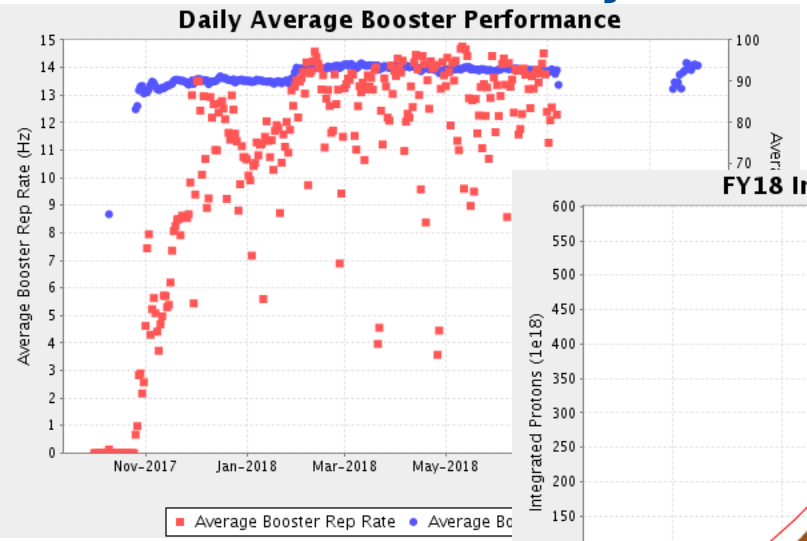
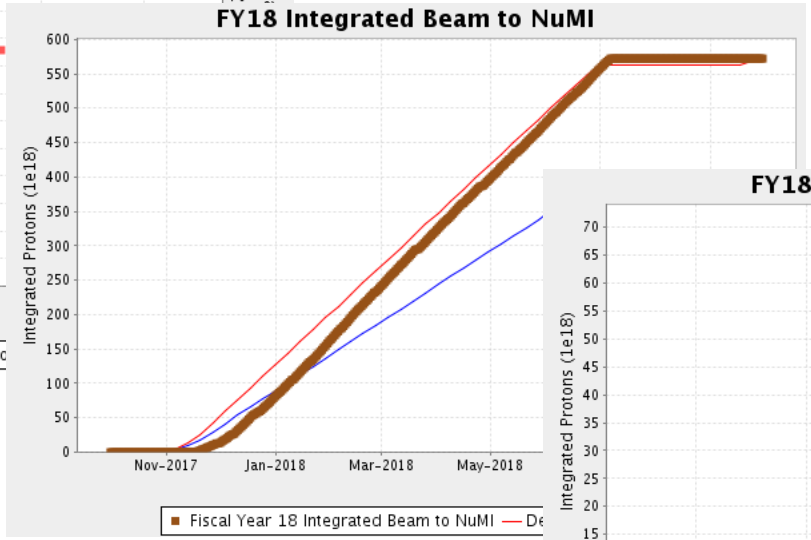
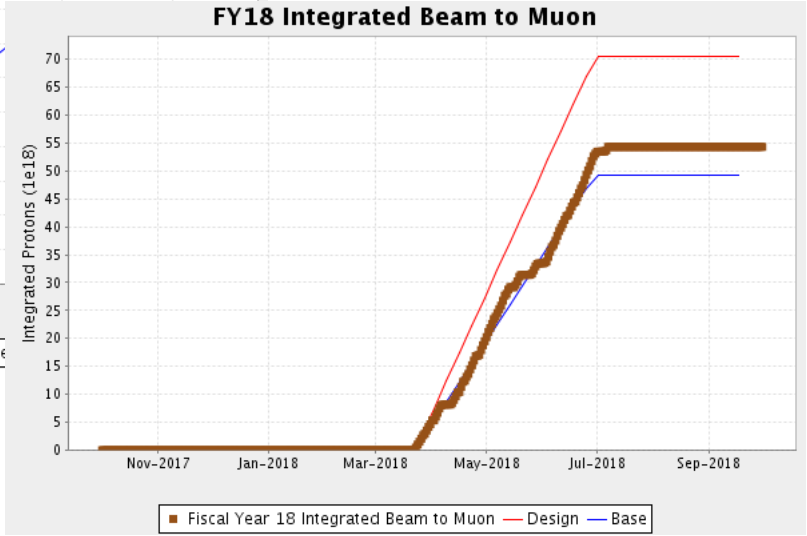
Previous Year Delivery







g-2 has approached total positrons from BNL operation

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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!

From DUNE CDR – May 2015

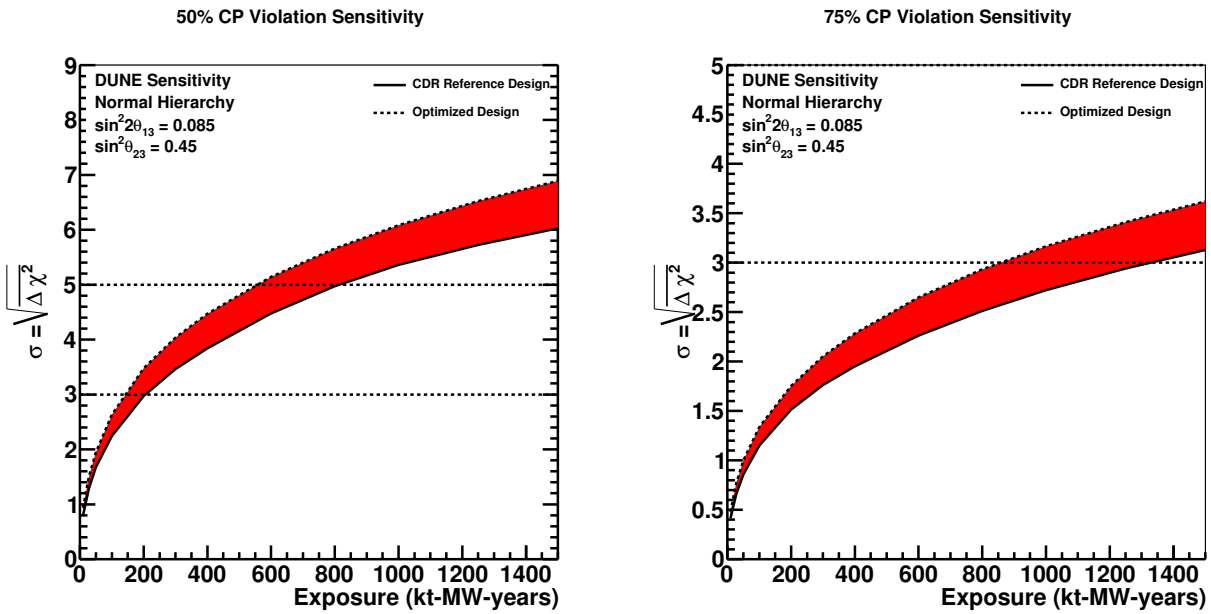


Figure 3.17: The significance with which CP violation can be determined for 50% (left) or 75% (right) of δ_{CP} values as a function of exposure. The shaded region represents the range in sensitivity due to potential variations in the beam design. This plot assumes normal mass hierarchy.

DUNE Physics Goals

40kT with 1.2 MW is a 20 year program

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

Fermilab

Strategy for the next ~10 years
Proton Improvement Plan-II (PIP-II)

The longer-term goal is to increase the beam power delivered from the Main Injector by an additional 50% and to provide increased beam power to the 8 GeV program, while providing a platform for the future

- Strategy
  - Increase the Booster per pulse intensity by 50%
    - Requires increase in injection energy to ~800 MeV
  - Modest modifications to Booster/Recycler/MI
- Design Criteria
  - Deliver 1.2 MW of beam power at 120 GeV, approaching 1 MW down to 60 GeV, at the start of LBNF operations
  - Support the current 8 GeV program, including Mu2e, g-2, and the suite of short-baseline neutrino experiments
  - 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
  - At an affordable cost to DOE
- Execute over 2015 – 2026

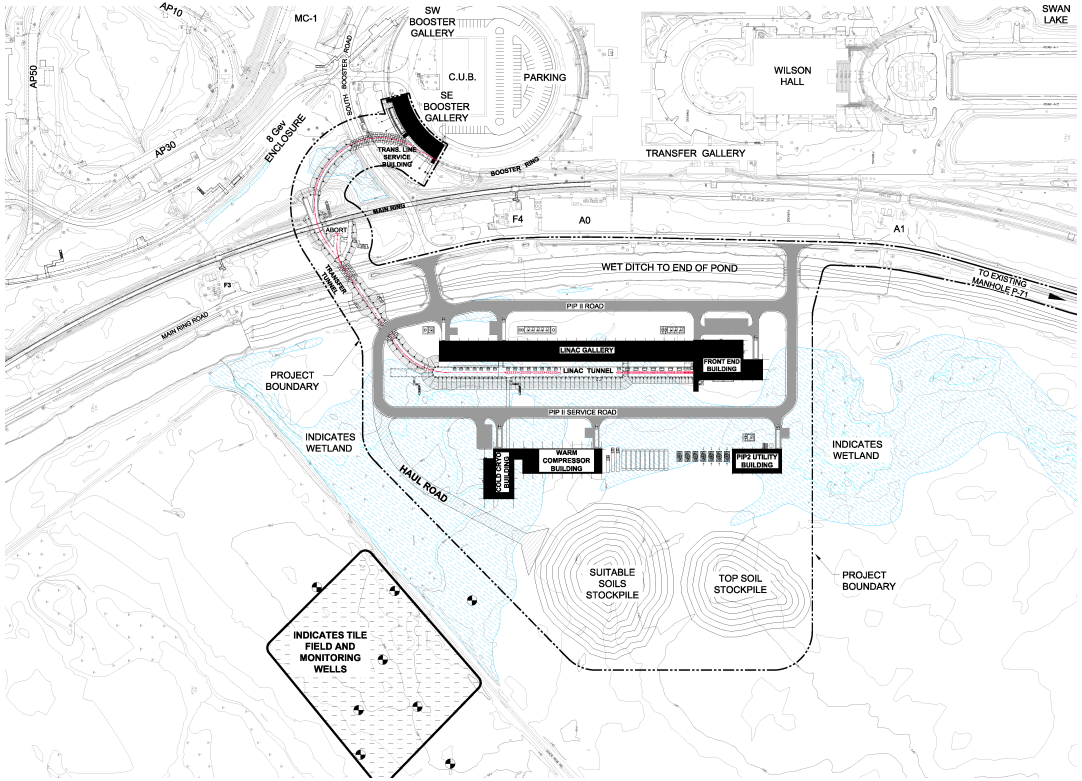
PIP-II Technical Approach

- Construct a modern 800-MeV superconducting linac, of Continous Wave (CW) RF components, operating initially in pulsed mode
  - Ameliorate space-charge forces at Booster injection, allowing an increase Booster/Recycler/Main Injector per pulse intensity of ~50%, while preserving transverse & longitudinal emittance at current levels
  - Allow for multiple destinations of SCL beam in addition to Booster / Long Baseline program
- Accompanied by modifications to Booster/Recycler/Main Injector to accommodate higher intensities and higher Booster injection energy
- Increase Booster repetition rate to 20 Hz
  - Maintain 1 MW down to 60 GeV or,
  - Provide factor of 2.5 increase in power to 8 GeV program
- Described in the Conceptual Design Report
  - http://pip2-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=113&filename=PIP-II_CDR_v.0.1.pdf&version=8

PIP-II

- Formal Department of Energy Project in the Office of High Energy Physics
  - Critical Decision 0: Mission Need Statement
    - Office of Science Approval October 2015
    - Energy Systems Acquisitions Advisory Board November 2015
  - Critical Decision 1: Selection of Alternative
    - Energy Systems Acquisitions Advisory Board July 2017
  - Preparing for Critical Decision 2: Approve Performance Baseline
    - FY19
  - Vigorous program to address technical, cost, and schedule risk underway
  - Anticipate construction start in 2020, with completion in 2026 time frame

PIP-II Technical Approach/Site Layout



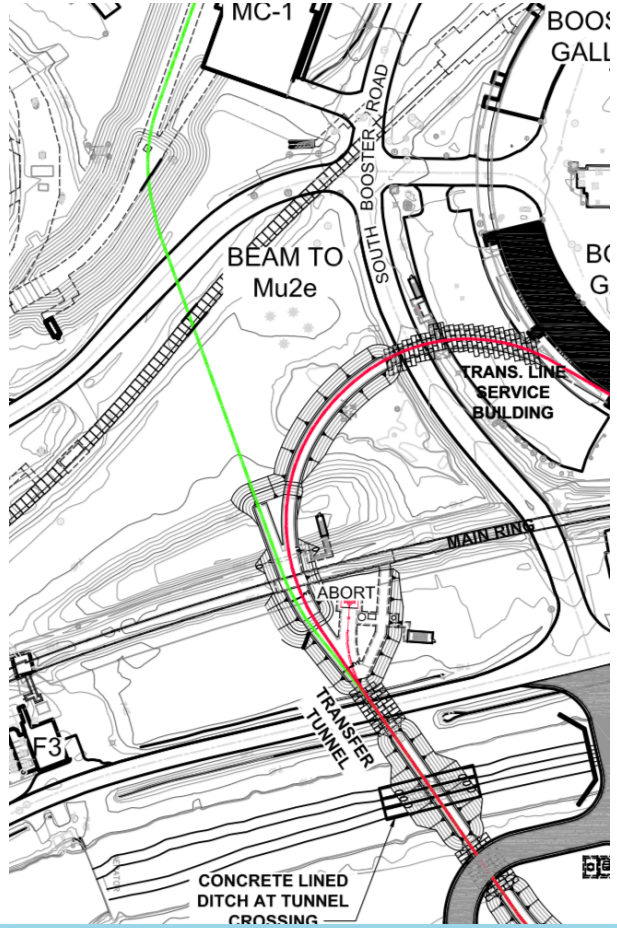
Performance Goals

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.54	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	17	kW
Linac Beam Power Capability (@>10% Duty Factor)	4	~200	kW
Mu2e Upgrade Potential (800 MeV)	NA	>100	kW
Booster Protons per Pulse	4.3×10^{12}	6.5×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	166	kW
Beam Power to 8 GeV Program (max)	32	83	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.5×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	1.33**	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	0.7**	1.0-1.2	MW
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

**NOvA operations at 120 GeV

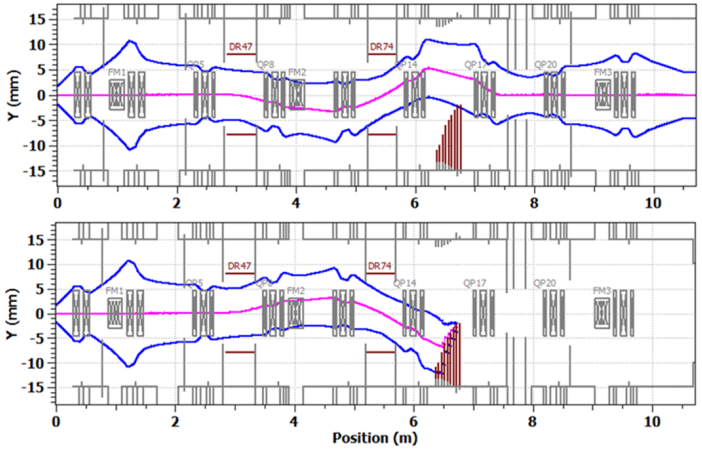
PIP-II Components

- Linac-to-Booster transfer line
  - 3-way beam split to: (1) Beam dump, (2) Booster & (3) Mu2e-II
  - Mu2e stub off enclosure
  - Design Optics to transport 800 MeV H- to M4



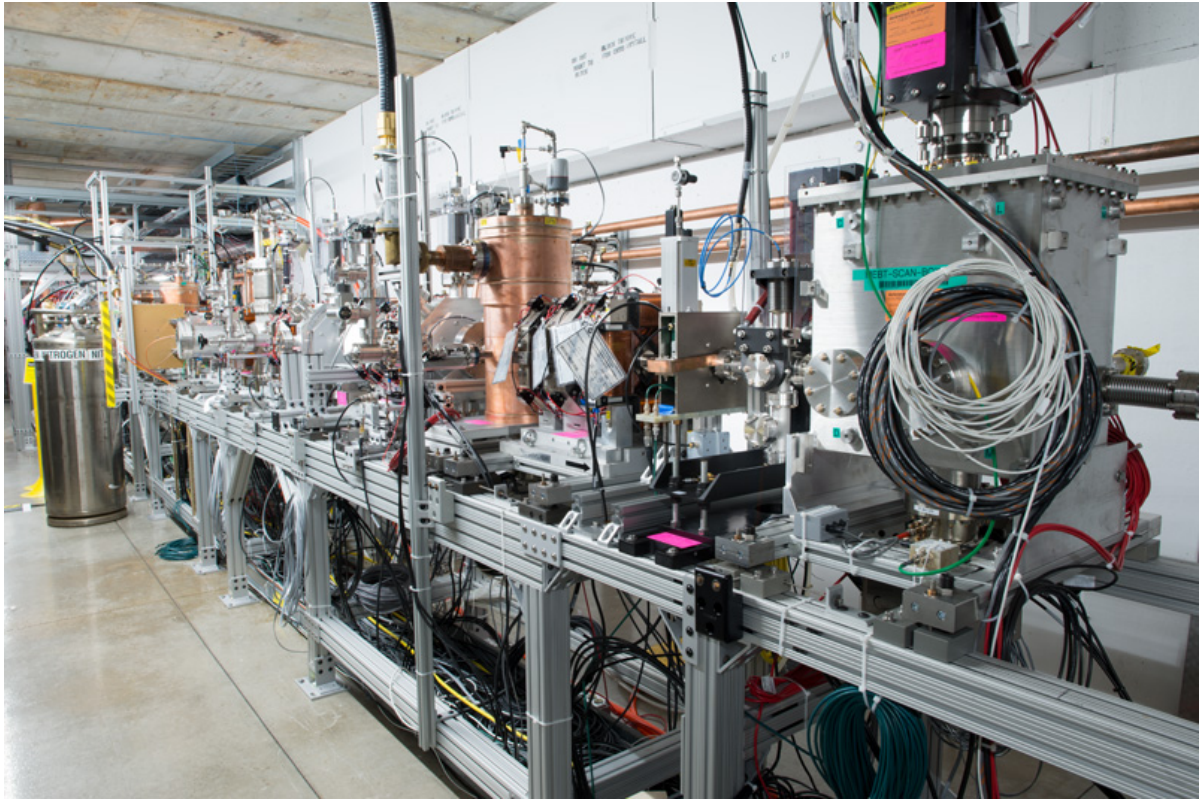
Unique feature of PIP-II: flexible bunch structure

- "Bunch-by-bunch selection" in MEBT allows removing un-wanted bunches
  - Effective injection into the Booster
  - With an RF separator at the end of the linac, possibility to deliver beam quasi-simultaneously to different users with very different time structure
- The selection scheme is being tested at PIP2IT
  - Chopping system: Two kickers working in sync and absorber.
  - 6σ separation at absorber



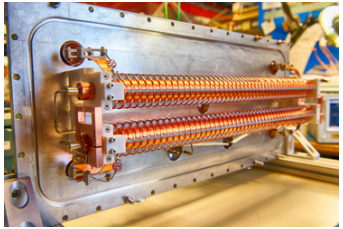
Simulated 3σ envelopes of passed (top) and removed (bottom) bunches – 99.9%

PIP2IT at CMTF



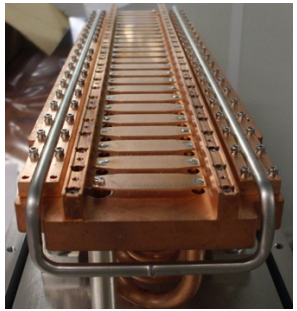
Chopping system

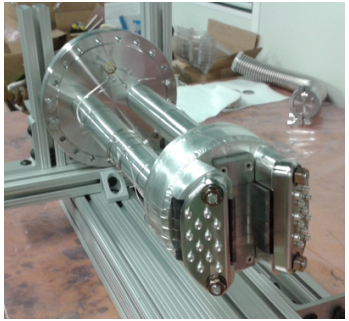
- Two kickers working in sync and absorber
- Since a CW-compatible kicker capable of providing an arbitrary pattern was beyond state-of-the-art, two kicker versions were developed, “200 Ohm” and “50 Ohm”
  - Both are installed and characterized with beam
- Absorber prototype has been developed and tested at full power density with an electron beam and at 7x CDR parameters at PIP2IT



200 Ohm kicker

50 Ohm kicker



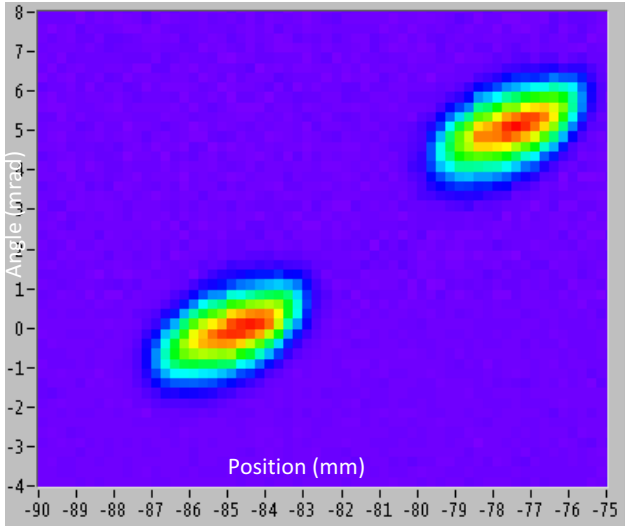


¼ length absorber prototype

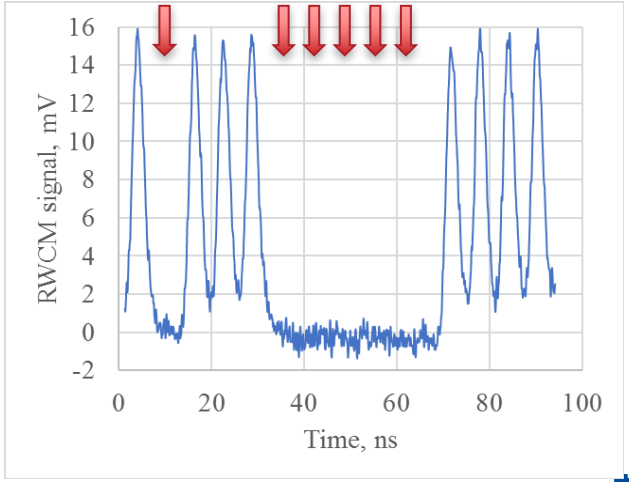
It does work!

- Single 200 Ω chopper:
  - See beam separation in transverse plane
  - Insert scraper, measure time structure with Resistive Wall Current Monitor
    - Understood at the 0.2% level (reflections, noise)
- For project, specification is only 10^{-4} extinction… we think it can do much better

Emittance Scanner

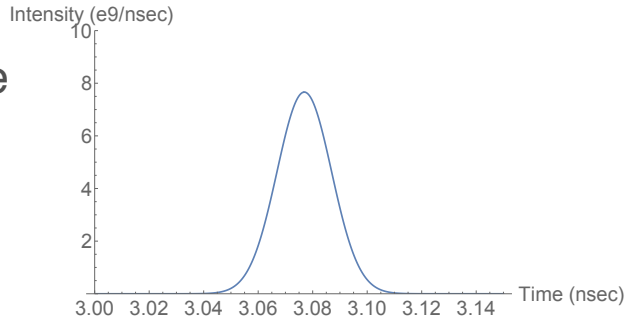


'Missing' bunches

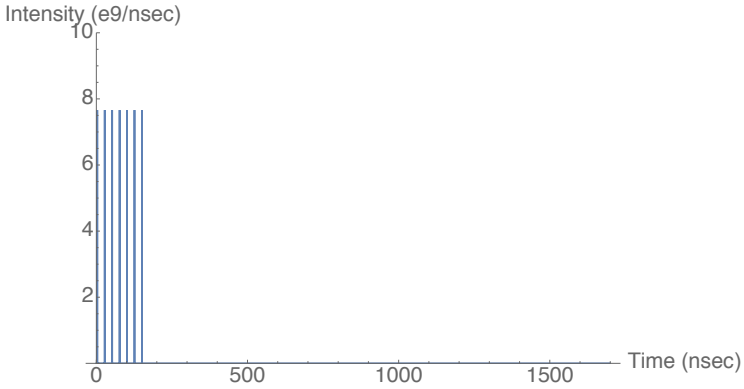


Time Structure for Mu2e

- Fundamental Time Structure set by 1st bunching device
  - 162.5 MHz Radio Frequency Quadrupole
  - 6.15385 nsec
  - <10 psec width at 800 MeV



- Select 162.5 MHz bunches : populated or empty
  - Populate: 1 every 4 (24.6 nsec) for 130 nsec – 1.15e9 H^-
  - Followed by 234 'empty'
  - 1.6923 μsec pulse spacing
- 20 Hz Booster program: DUNE/SBN
  - 1.1% duty factor
  - Mu2e-II can use other 98% duty factor
  - 6.6e15 H^- / second
  - 85 kW



DUNE Physics Goals

40kT with 2.4 MW is a 10 year program

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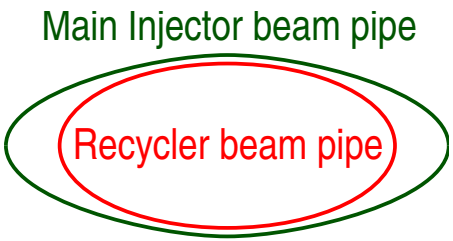
PIP-III (~203x)

- 2.4 MW requires 1.5×10^{14} particles from MI every 1.2 s @ 120 GeV
  - Every 0.6 sec @ 60 GeV
- Current model (Slip-stacking in Recycler) is not an option at these intensities
  - Need to box-car stack $6 \times 2.5\times10^{13}$ protons in less than 0.6 sec
  - >10 Hz rep-rate
  - Or inject a long (linac) pulse directly into Main Injector
- Booster is not capable of accelerating 2.5×10^{13} no matter what the injection energy, or how it is upgraded: many issues…
- ***Achieving 2+ MW will require replacement of the Booster with either a multi-GeV pulsed linac or a rapid cycling synchroton (RCS) fed by a ≥ 0.8 GeV linac***
- PIP-III: 20 Hz operations of a new RCS at ~2.5×10^{13} ppp
  - Deliver 2.4 MW @ 60-120 GeV from the Main Injector to the LBNF beamline in support of the DUNE experiment
  - Deliver up to 80 kW @ 8 GeV to support g-2, Mu2e, and short-baseline neutrinos
  - Deliver ~100 kW @ 800 MeV to support a second generation Mu2e

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:
    - Potential 8 GeV users want short bunches, so must keep Recycler, which complicates things and has worries about long term viability.
    - Charge stripping makes H^- injection at 8 GeV is a *very big* deal:
      - Weak magnets, extended optics in the beam transport
      - Even black body radiation stripping a problem -> cooled beam pipe
- 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.



Comparison of Parameters*

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

~6x record Booster ppp

~4x record Main Injector ppp

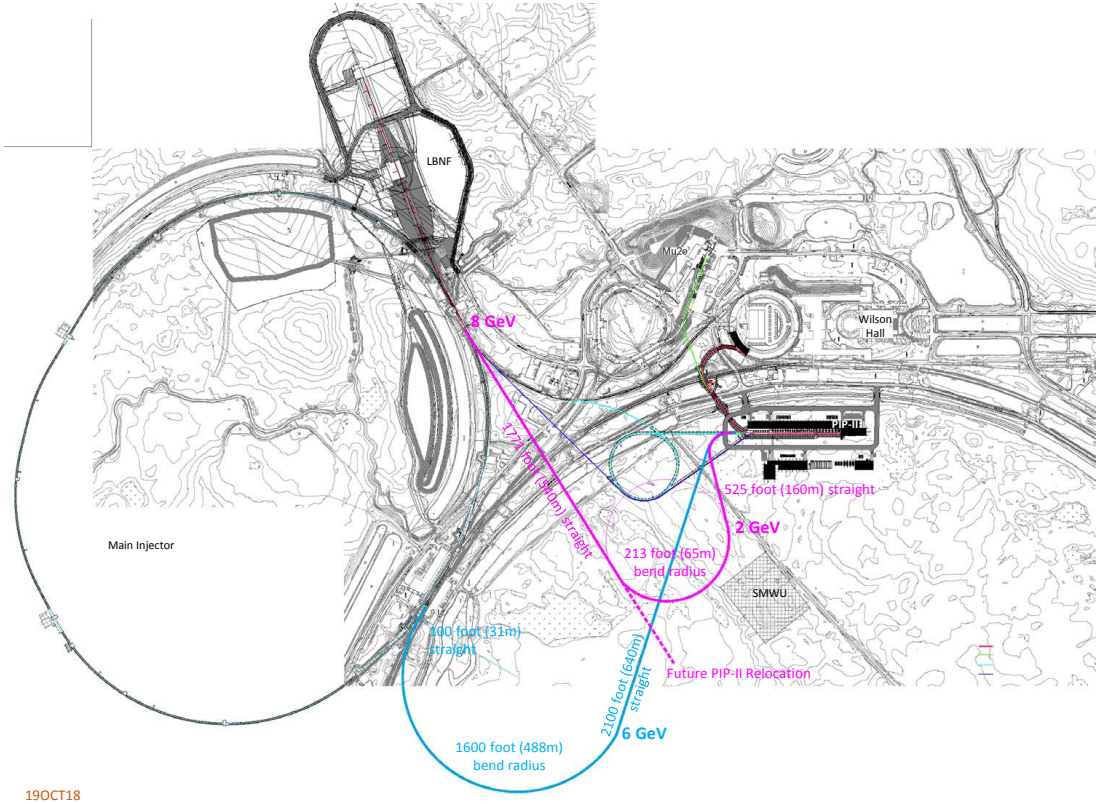
RCS Comparisons

	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

Too big for "ordinary" synchrotron

PIP-III (~203x)


LBNF
Muze
Wilson Hall
8 GeV
PIP-III
172 foot (640m) straight
525 foot (160m) straight
2 GeV
Main Injector
213 foot (65m) bend radius
SMWU
100 foot (31m) straight
2100 foot (640m) straight
Future PIP-II Relocation
6 GeV
1600 foot (488m) bend radius
19OCT18

Summary

Fermilab's goal is to construct & operate the foremost facility in the world for particle physics research utilizing intense beams.

- Neutrinos
  - NOvA @700+ kW
  - DUNE @ multi-MW
  - SBN @ 10's kW
- Muons
  - Muon g-2 @ 15-25 kW
  - Mu2e @ 8-100 kW
- Longer term opportunities

- Multi Stage Plan
  - PIP -> PIP-II -> PIP-III
  - 700 kW -> 1.2 MW -> 2+ MW Long Baseline Program
  - Continue to support Short Baseline and Muon Programs