Muon Cooling Demonstrator Siting at Fermilab

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International Muon Collider Collaboration: Demonstrator Workshop

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Fermilab Proton Accelerator Near-term Upgrade Plans

Some Highlights of Fermilab Neutrino Program in P5 Report

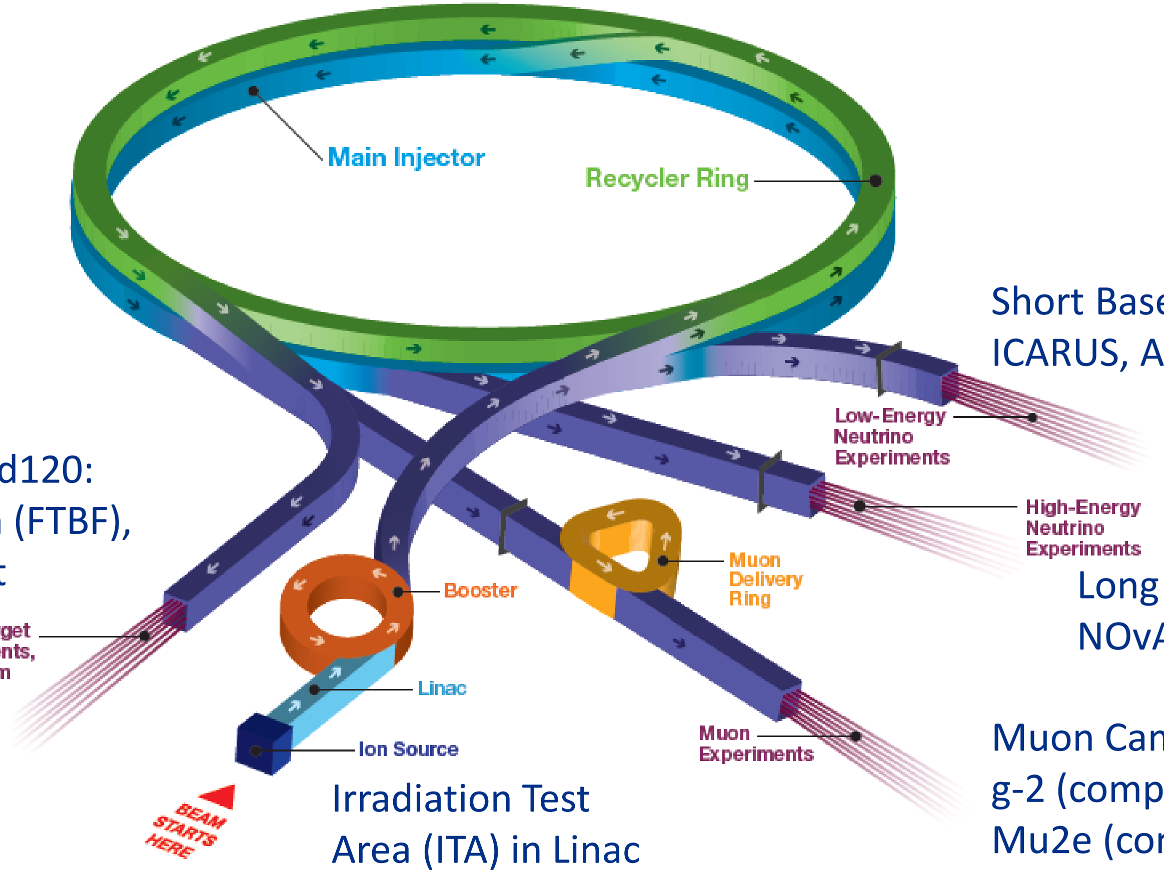
2023 P5 Report Recommendations

R1b: "Highest Priority… The **first phase of DUNE** and **PIP-II** …"
R1d: "Highest Priority… **NOvA, SBN**, T2K and IceCube …"
R2b: "Plan and start…order of priority… A re-envisioned **second phase of DUNE** with an early implementation of an enhanced 2.1 MW beam—**ACE-MIRT**—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind."

R4g/R6/AR12: "Form…a **strategic 20-year plan** for the Fermilab accelerator complex within the next five years…consistent with the long-term vision of this report including **neutrinos, flavor, and a 10 TeV pCM collider**"

AR13: "**Assess the booster synchrotron** and related systems for **reliability risks** through the first decade of DUNE operation, and **take measures** to preemptively address these risks."

Accelerator Complex



Short Baseline Neutrino:
ICARUS, ANNIE, SBND

SwitchYard120:
test beam (FTBF),
SpinQuest

Long Baseline Neutrino:
NOvA

Muon Campus:
g-2 (completes this year),
Mu2e (commissioning)

Irradiation Test
Area (ITA) in Linac

Introduction to Fermilab accelerators

H^- linac (1970, 1993, 2012)

- 400 MeV linac ~20mA

Booster synchrotron (1970)

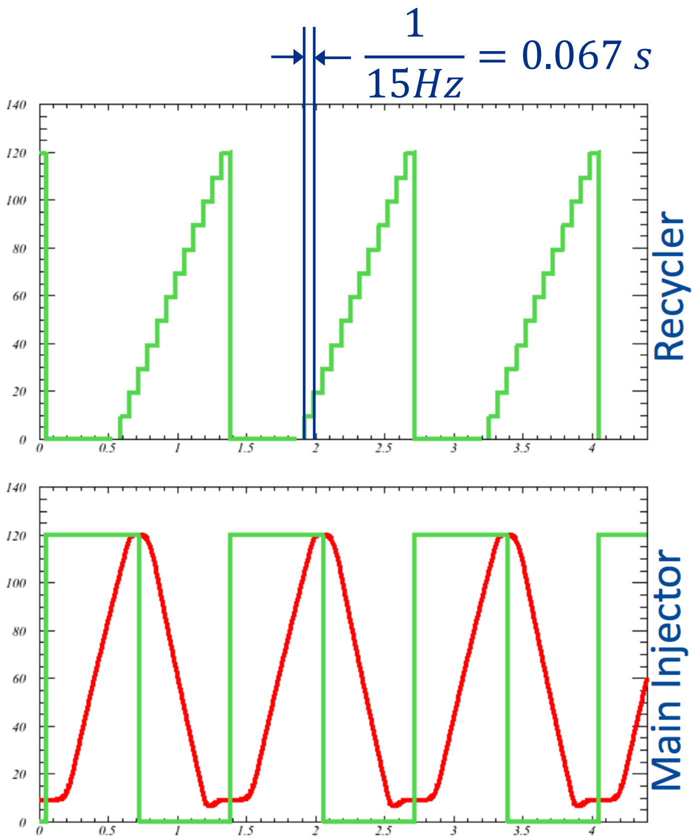
- H^- stripping injection (1978)
  16 turns to ~4.7×10^{12} p per pulse
- Ramp from 0.4 to 8 GeV at 15 Hz

Recycler (1998)

- 3.3 km permanent magnet 8 GeV ring
- Slip-stacking 12 Booster batches, ~56×10^{12} p
- Also re-bunches beam for Muon Campus

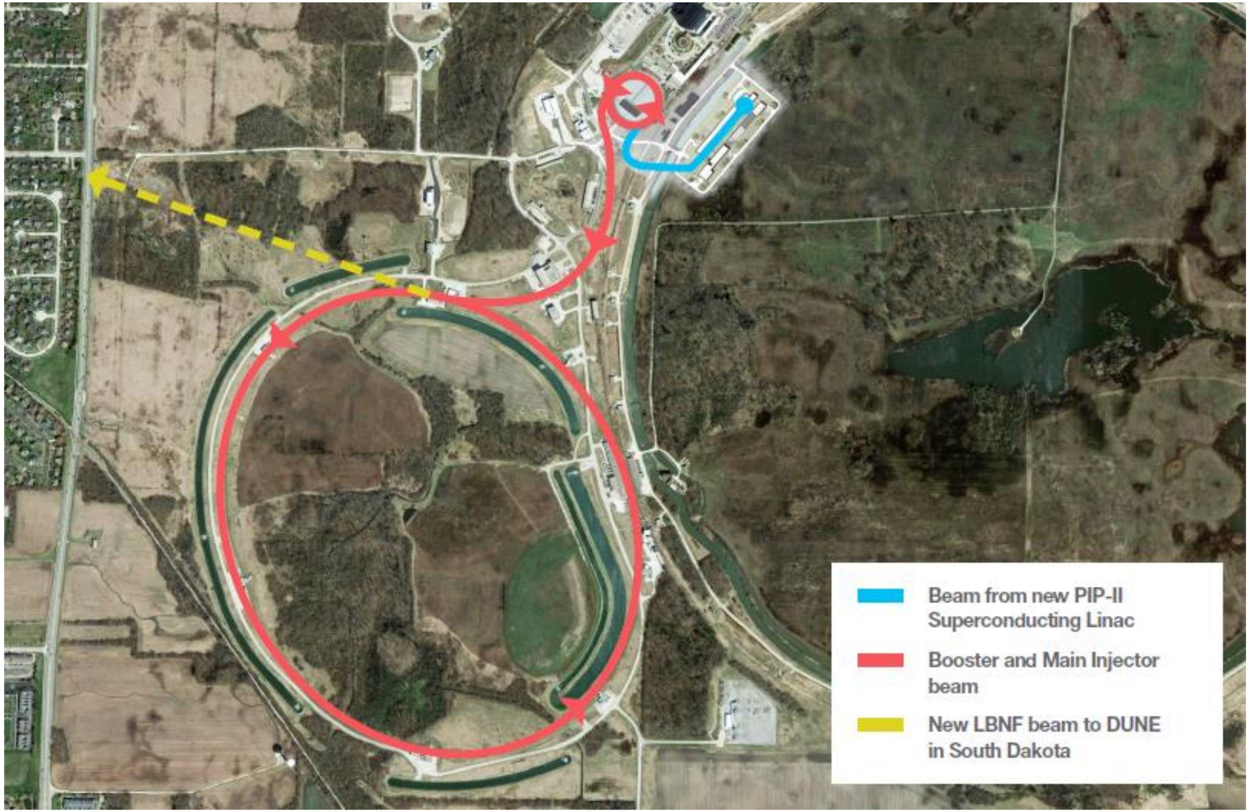
Main Injector (1998)

8 to 120 GeV ramp, cycle time 1.2-1.4 s



1.33s cycle shown

Accelerator Complex in PIP-II / LBNF era (pre ACE plan)



Accelerator Complex in PIP-II / LBNF era (pre ACE plan)

PIP-II Project provides

- New SRF linac for injection into Booster at 800 MeV (present 400 MeV).
- Booster cycle rate upgraded to 20 Hz from 15 Hz.
- Increased proton beam intensity for 1.2 MW beam power from MI.

		PIP-II Booster	
Operation scenario	**Nominal**	**PIP-II**	**units**
MI 120 GeV ramp rate	**1.333**	**1.2**	s
Booster intensity	**4.5**	**6.5**	10^{12} p
Booster ramp rate	15	**20**	Hz
Number of Booster batches	12	12	
MI power	0.75	**1.2**	MW
cycles for 8 GeV	6	12	
Available 8 GeV power	29	**83**	kW

Demonstrated

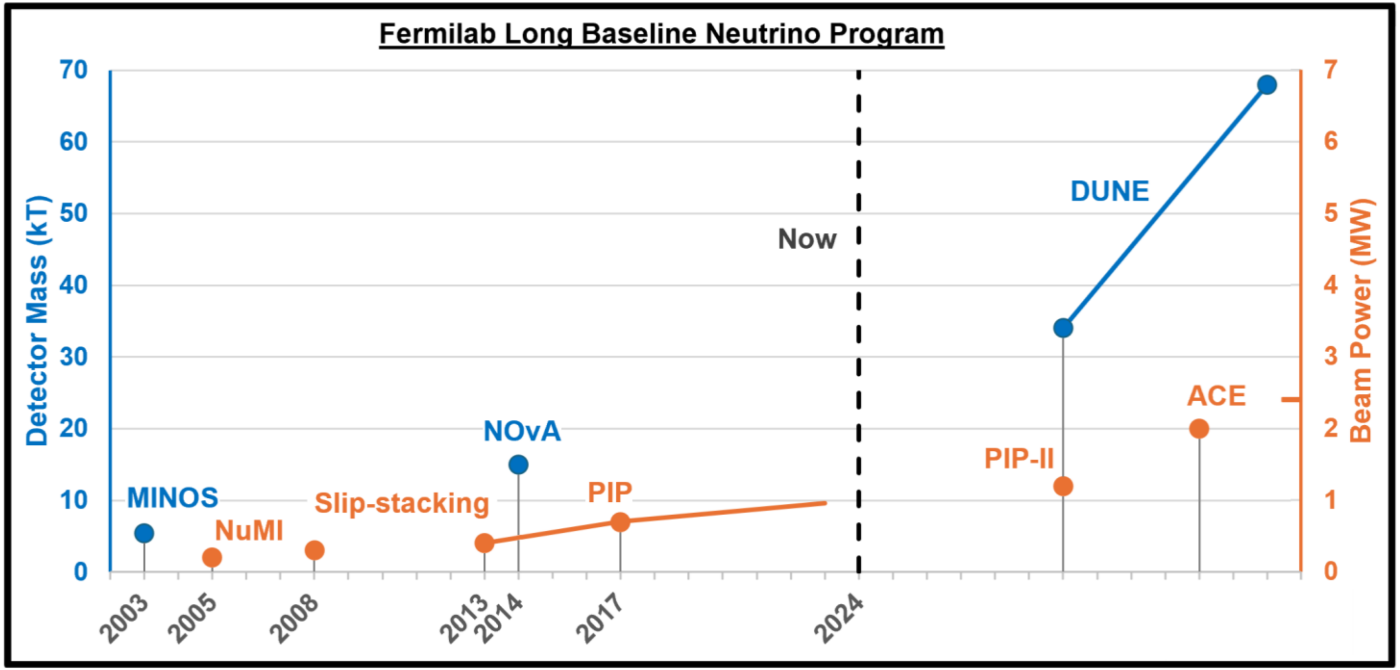
1.067-1.133 s

4.7-4.9 e12

0.96 MW

Fermilab

Past & Future Long Baseline Neutrino Program (with ACE)



PIP-II upgrade will provide proton power of 1.2 MW (at most 1.35 MW).

Upgrade to 2-2.4 MW will make best use of the full DUNE detector.

Accelerator Complex Evolution (ACE) Main Injector Ramp & Targetry (MIRT)

ACE-MIRT proposed to reduce Main Injector cycler to ~0.65s to increase beam power

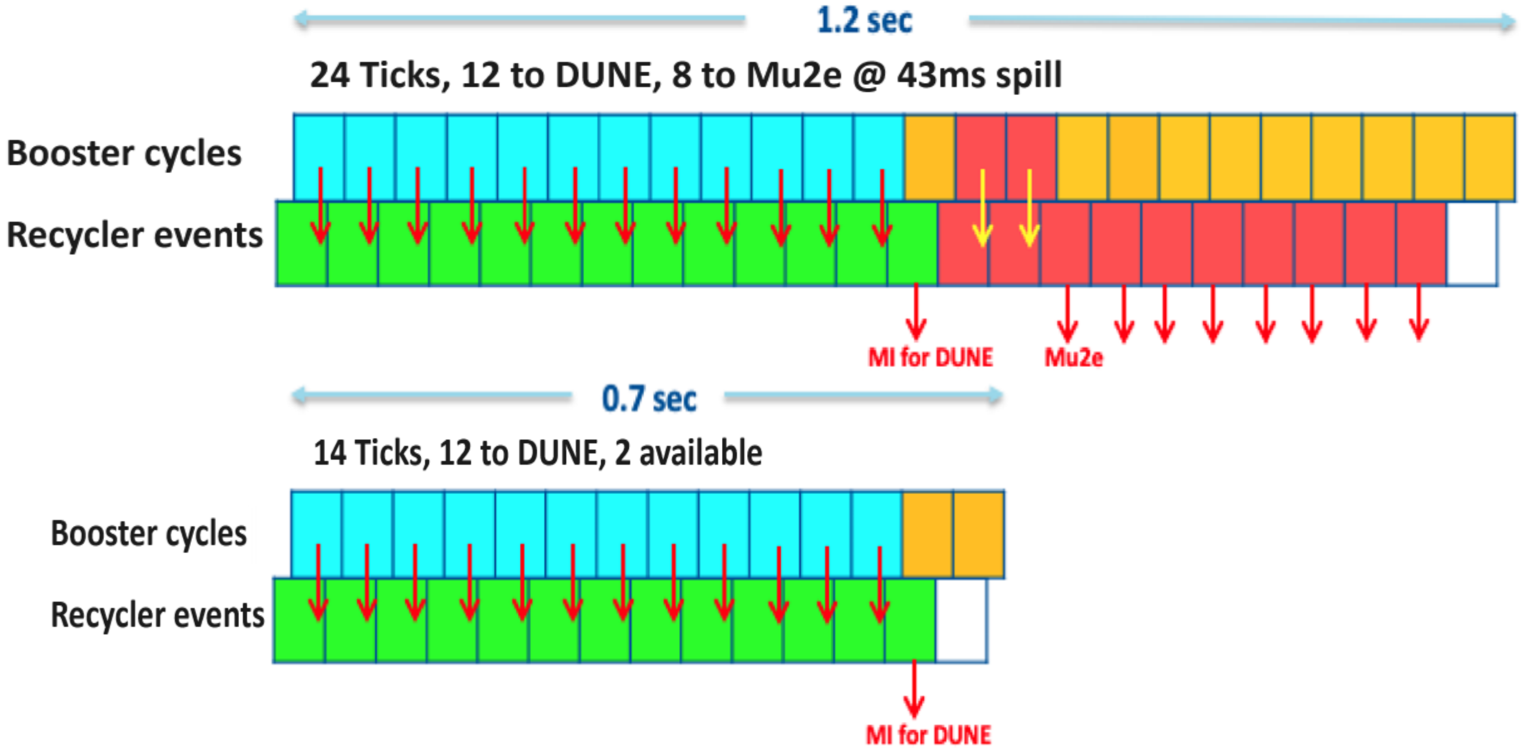
- Requires x2 RF acceleration and x2 magnet power supplies
- Emphasis on reliability and infrastructure modernization upgraes.

		PIP-II Booster			
Operation scenario	**Nominal**	**PIP-II**	**A**	**B**	**units**
MI 120 GeV ramp rate	**1.333**	**1.2**	0.9	**0.7**	s
Booster intensity	**4.5**			**6.5**	10^{12} p
Booster ramp rate	15			**20**	Hz
Number of batches	12		12		
MI power	0.75	**1.2**	1.7	**2.14**	MW
cycles for 8 GeV	6	12	6	2	
Available 8 GeV power	29	**83**	56	**24**	kW

Impact of shortened cycle on other experiments

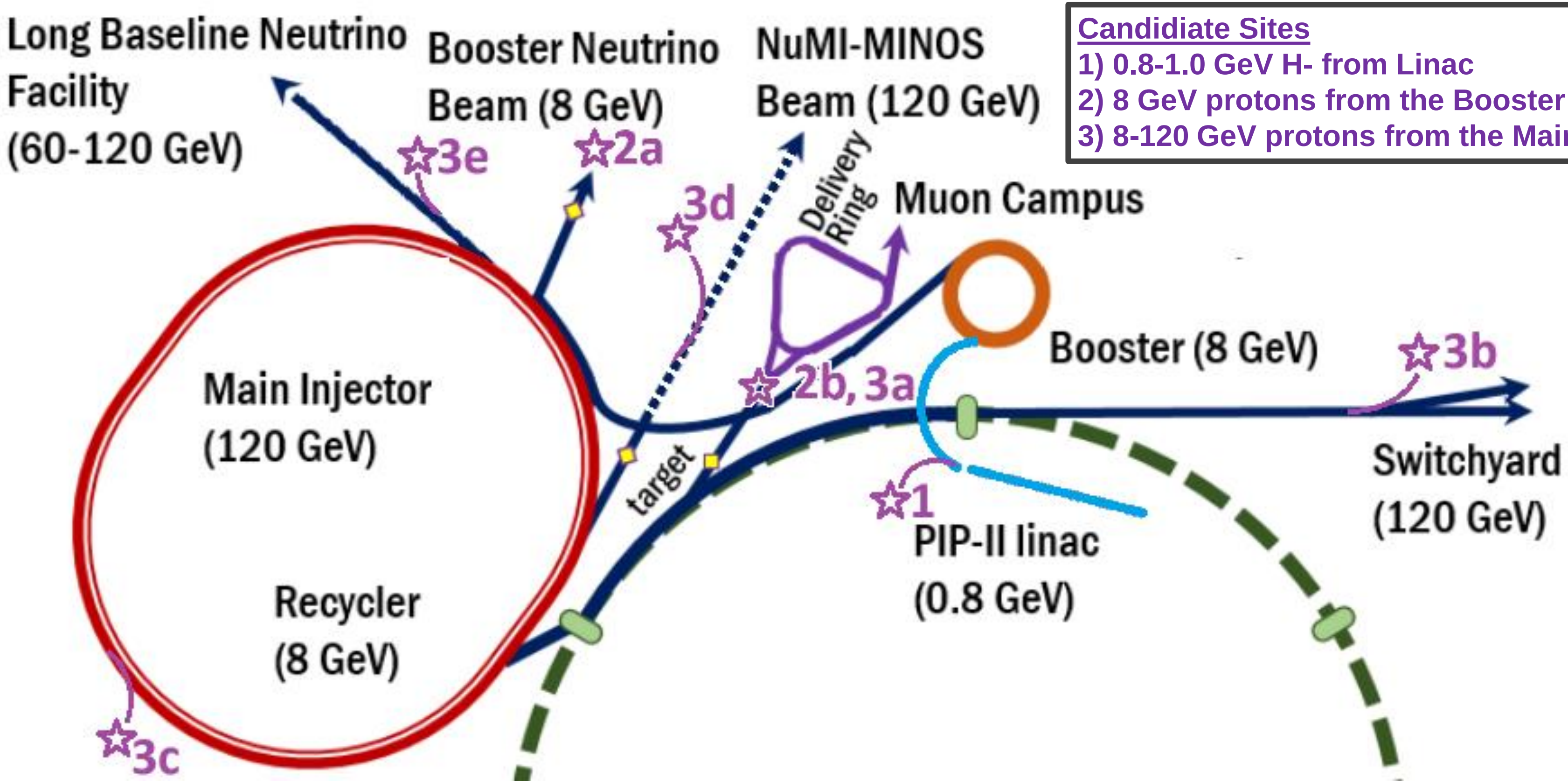
PIP-II Era MI Cycle:

ACE-MIRT MI Cycle:



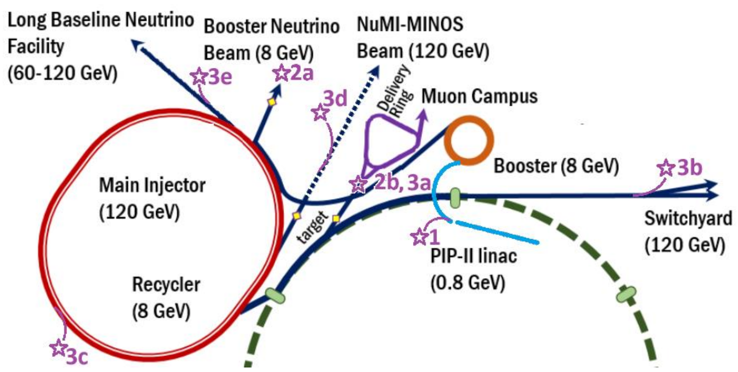
Muon Ionization Cooling Technology Demonstrator Candidate Sites at Fermilab

Demonstrator Candidate Sites



Candidiate Sites
1) 0.8-1.0 GeV H- from Linac
2) 8 GeV protons from the Booster
3) 8-120 GeV protons from the Main Injector

Demonstrator Candidate Sites

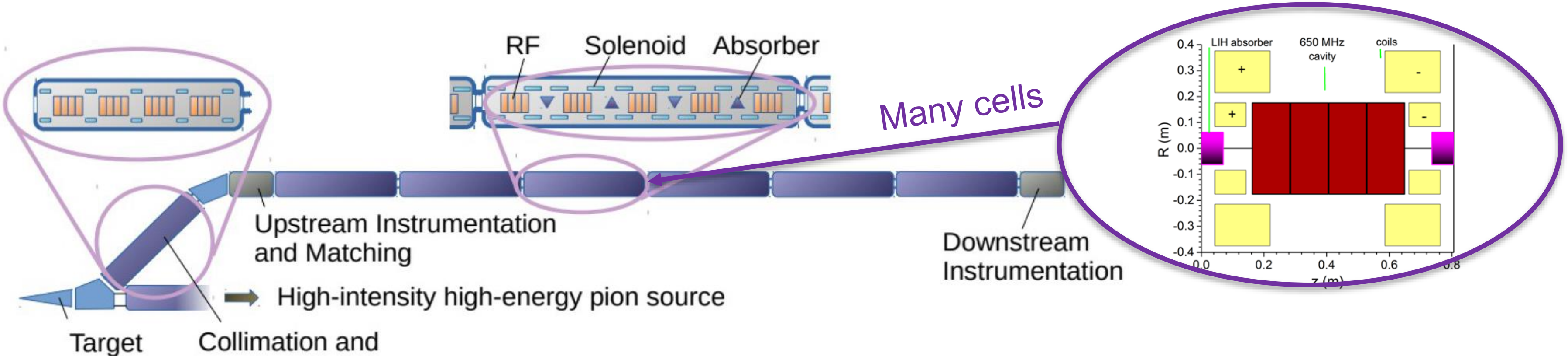


1) **0.8-1.0 GeV H-** particles from the PIP-II linac:
- **(1a)** Greenfield site in the Tevatron field
- **(1b)** Following the proposed mu2e-II line to muon campus.

2) **8 GeV protons** from the Booster:
- **(2a)** At the present day short-baseline neutrino
- **(2b)** At present day muon campus site.

3) **8-120 GeV protons** from the Main Injector:
- **(3a)** Split off P1 Muon Campus line.
- **(3b)** Split off P1 Meson line.
- **(3c)** Split off MI Abort beamline.
- **(3d)** At the present day NuMI beamline.
- **(3e)** Split off LBNF beamline.

Muon Ionization Cooling Technology Demonstrator



"A Demonstrator For Muon Ionisation Cooling" – C. Rogers ([here](#))

50m long, 7.2 T peak solenoid field, 704 MHz RF, LiH wedges

Evaluated for CERN PS (25 GeV) or SPS (450 GeV) beams.

Site Considerations

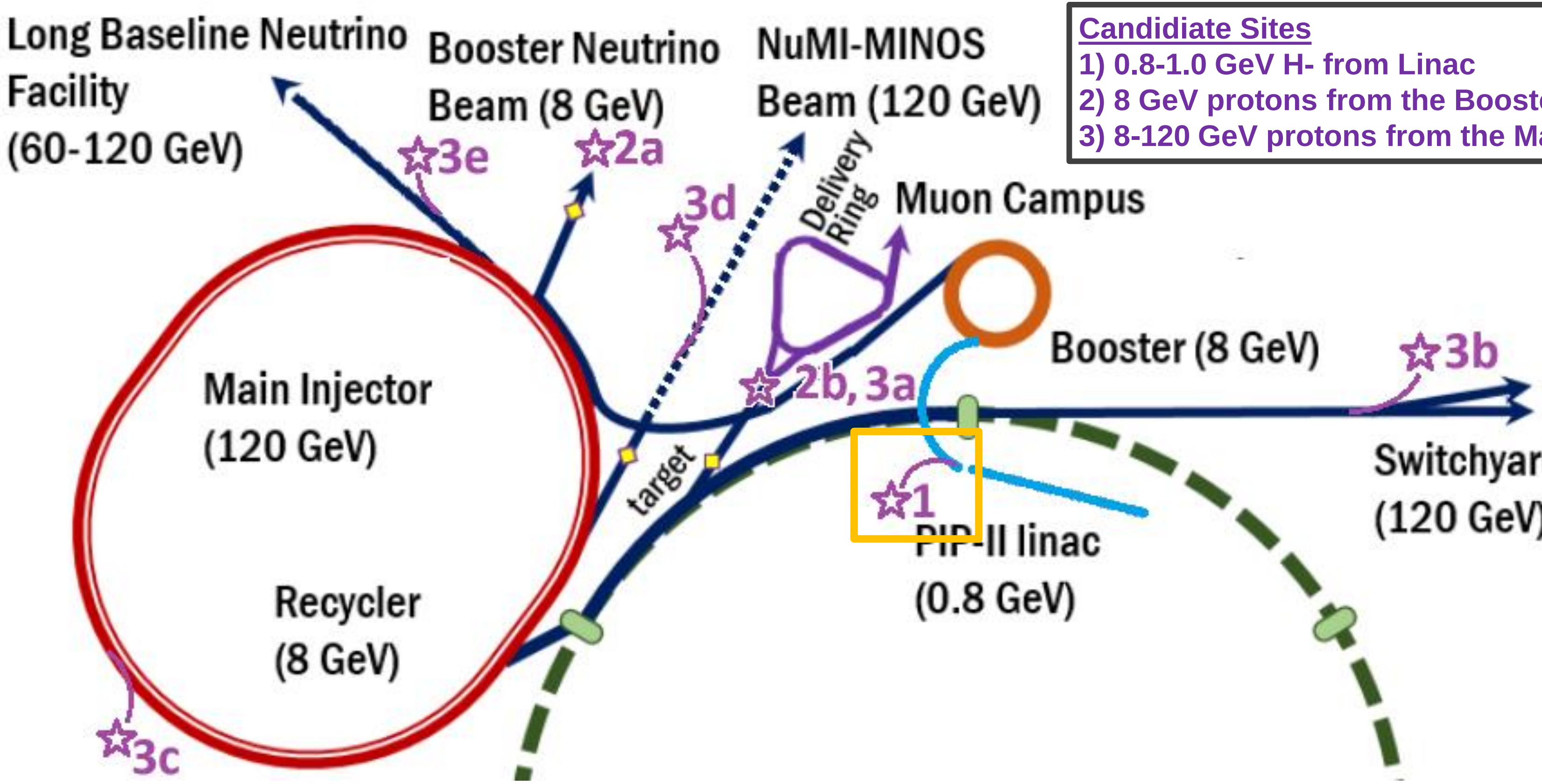
Regardless of proton energy, we intend to capture **190-210 MeV/c muons.**
- They would have different muon production yields and initial muon distributions.
- This will probably impact the target & capture system significiantly, but we will try to isolate the impact from ionization cooling demonstrator itself.
- We will also need to evaluate the impact on instrumentation and statistics.

Different **beam powers** and **longitudinal structures** available at different energies.

All sites will need **infrastructure**:
- 50m of straight tunnel space (after 1m dogleg), appropriate civil construction.
- Electrical power (magnets and HLRF) & cryogenics.
- Appropriate shielding, tritium mitigation, ODH.

Some opportunities to re-use existing infrastructure or to construct a multipurpose facility.

Demonstrator Candidate Sites



Candidiate Sites
1) 0.8-1.0 GeV H- from Linac
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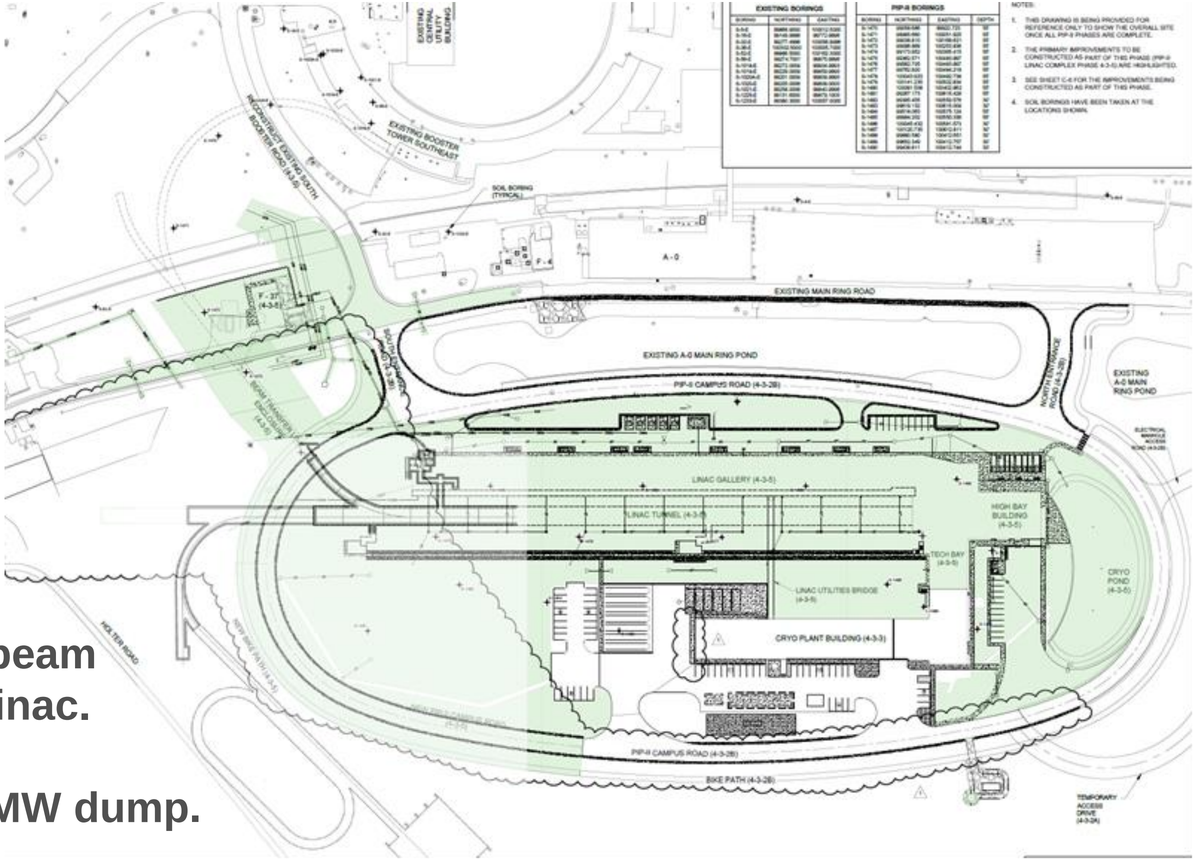
Proposed Facility at PIP-II Linac (from F2D2)



0.8-1 GeV CW beam split off PIP-II linac.

Optional ring, MW dump.

0.8-1.0 GeV H^- particles from PIP-II Linac

Excellent Proton Availability
CW operation of the PIP-II linac would supply 1.6 MW of beam power, only 1% of which is used for the Fermilab Booster – the rest is potentially available for experiment.
- Mu2e-II proposed targets challenging at 100 kW, we need less power or different target.

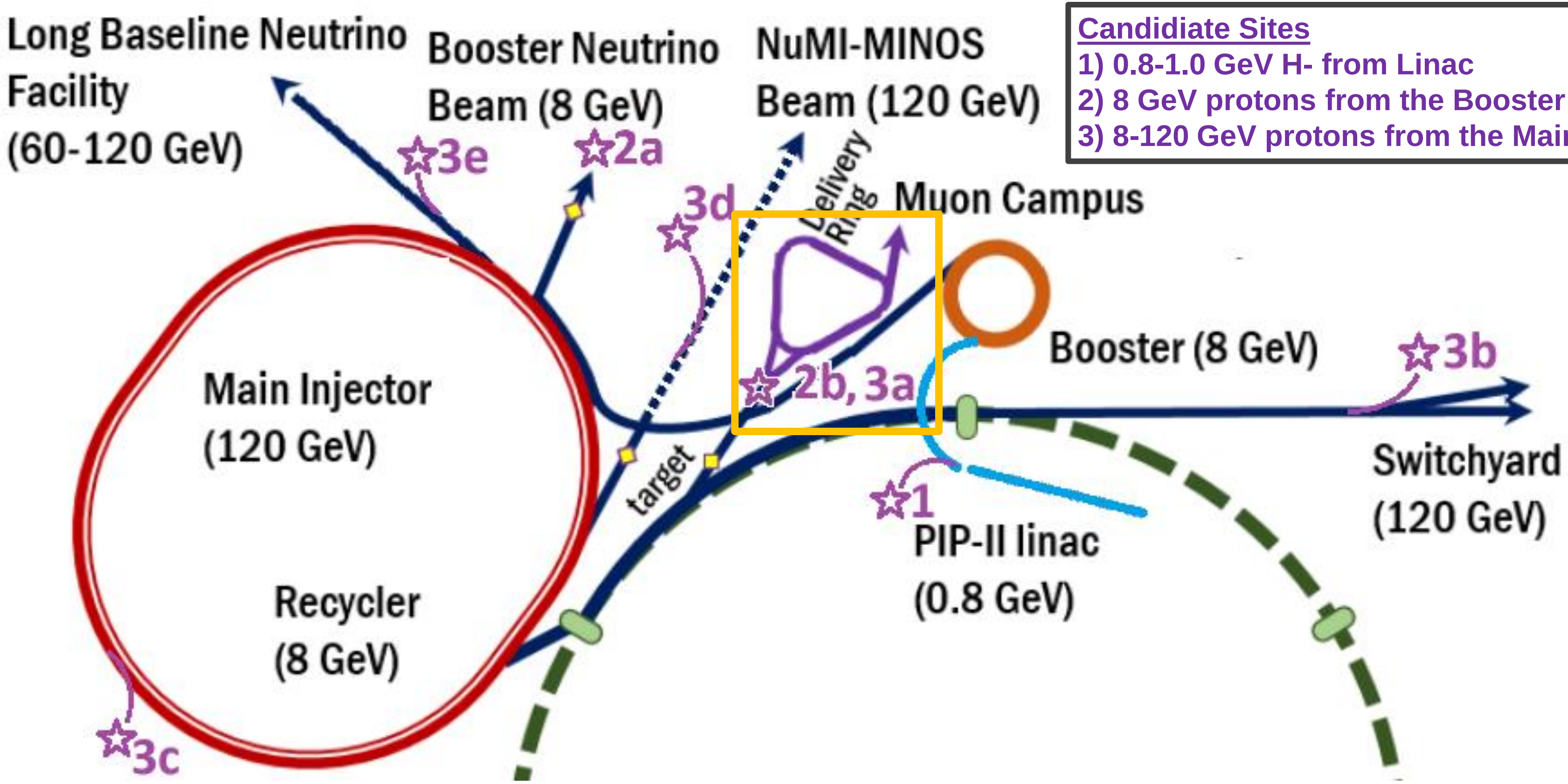
High-duty Macropulse Structure, 162.5 MHz Micropulse Structure
Beam arrives in ~1ns bunches arriving every 6-12ns averaging 2mA beam power.
Bunch-by-bunch chopping available to remove bunches further.

Greenfield Siting Near PIP-II
Abundant real-estate in the TeV field, proximity to PIP-II power/cryo.

Synergy with Other Proposed Programs
Proposed low-energy muon facility (muSR, muon HEP)
Proposed Fermilab Facility for Dark Discovery (F2D2) beam dump physics program
Proposed Co-location of 120-GeV test beam program.

Expect 0.8 GeV particles, but 1.0+ GeV scenarios can also be considered.

Demonstrator Candidate Sites



Candidiate Sites
1) 0.8-1.0 GeV H- from Linac
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8-GeV p / 3-GeV μ Muon Campus Delivery Ring Site

Fermilab

8 GeV protons from Fermilab Booster

Proton Energy Appropriate for Proton Driver

Fermilab proton driver scenarios envision ~8-GeV beams, so the muon production, capture, and selection systems are also being demonstrated (at much lower power of course.)

1.5us Macropulse, 53 MHz Micropulse Structure

81 bunches, each 1.2ns separated at 19ns intervals. 6.5e12 protons in 1.5us pulse.

Siting at Muon Campus M2/M3

Start after the end of mu2e program ~2033, take advantage of existing tunnel, cryo, power.
Transfer to the Muon Campus requires use of the Recycler, parasitic on LBNF program.

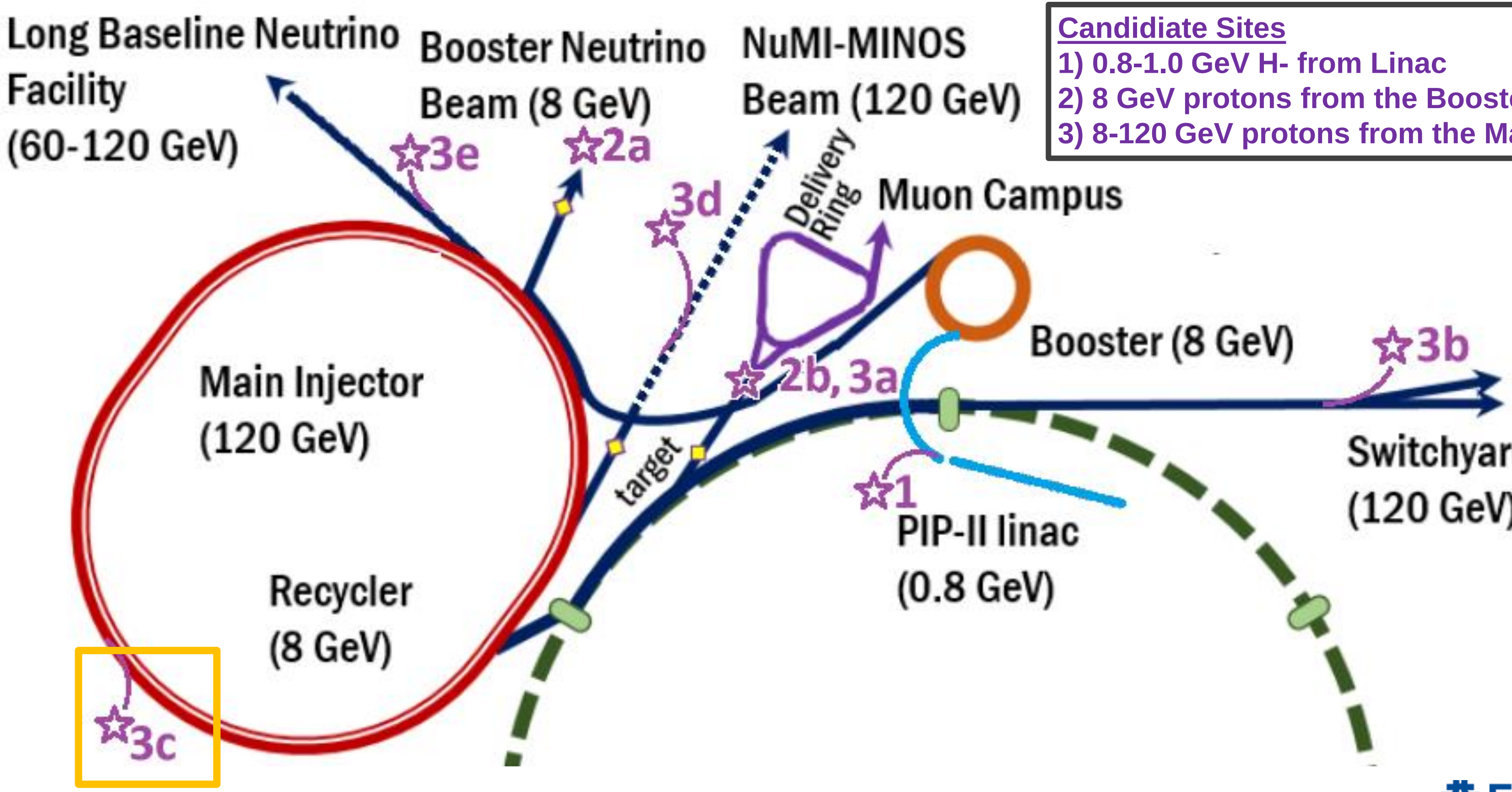
- A 7% reduction of LBNF 2.1 MW 120-GeV power for 10 kW at 8-GeV.
    - one 1.5us pulse every 0.7s MI cycle.
- Option to manipulate beam in Recycler before muon campus.

Siting at Short-Baseline Neutrino Target Hall

Start after the end of SBN program

- No impact on LBNF, 1-2 pulses every 0.65-0.7s corresponds to 13-24 kW at 8-GeV.

Demonstrator Candidate Sites



Candidiate Sites
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MI Abort / NuSTORM Site

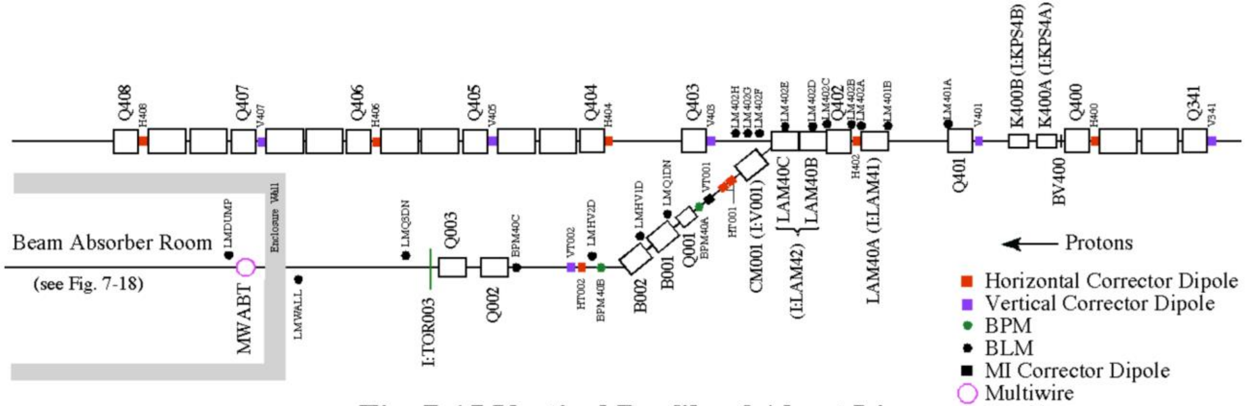
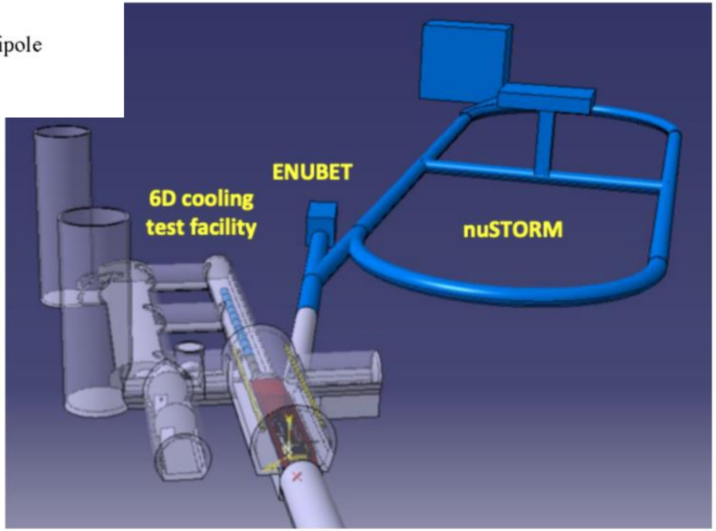


Fig. 7-15 Vertical Profile of Abort Line

MI-Abort + Dump



F. Esteban et. al.
NuSTORM Facility
at CERN

8-120 GeV protons from Main Injector / Recycler Ring

Low-duty Factor Intense Proton Pulse
972 bunches, each 2ns separated at 19ns intervals. 78e12 protons in 9us pulse.

Direct Extraction from Main Injector
Multiple beamline options, depending on real estate and infrastructure needs.
- MI Abort line was the planned site for NuSTORM.

Operations is Parasitic on LBNF program
- A 5% reduction in 2.1 MW LBNF power corresponds to 105 kW at 120 GeV.
- one 9us pulse every 13s or so.

8-120 GeV Tuneable Energy
Proton energy can be set by Demonstrator needs, option to vary energies.

Summary

P5 recommends that Fermilab prioritize DUNE/LBNF operations near-term, but also begin planning and preparations for a post-DUNE experimental program.

- Fermilab has a direct interest in establishing the feasibility of a Muon Collider.

Fermilab has opportunities at several energies for experimental programs to run alongside the DUNE/LBNF, and several candidate sites to host the program at each energy.

Operation at 8-GeV is the closest match to the proton driver case, and the siting opportunities initially appear to require the least beamline modifications.

Operation at 0.8 GeV could allow co-location synergies with other proposed physics programs.

Operation at 120 GeV enables higher power and higher energy.

Some Other Muon Collider Topics at Fermilab

Fermilab expertise and facilities for RF and superconducting magnets.

- S. Gourlay talk magnets and S. Belomestnykh talk RF.

Fermilab expertise and facilities for targets, muon production, capture, and instrumentation.

- M. Hedges talk targets and mu2e program at Fermilab.

Muon Collider proton driver scenario for Fermilab. (IPAC24 paper)

Proposed proton bunch compression experiment at IOTA. (IPAC24 paper)