A Proton Source for a Muon Collider ?

MAP → ACE

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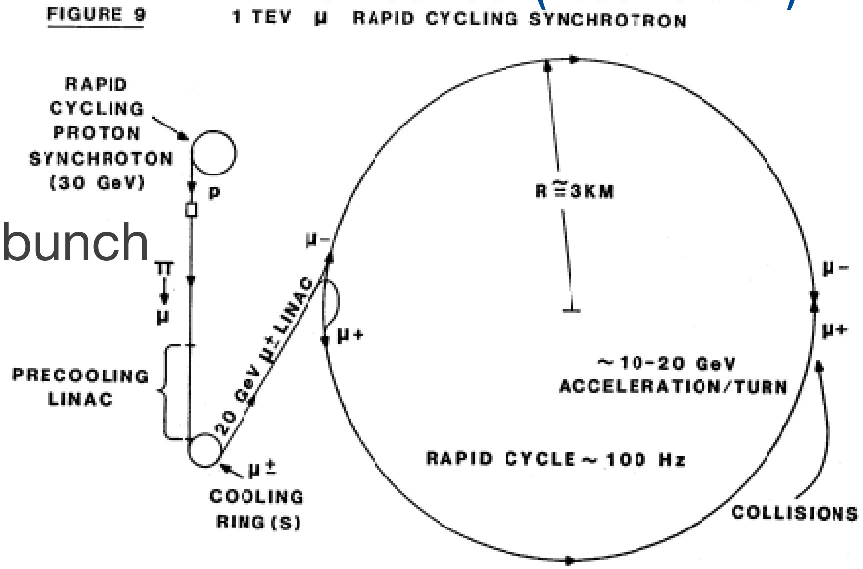
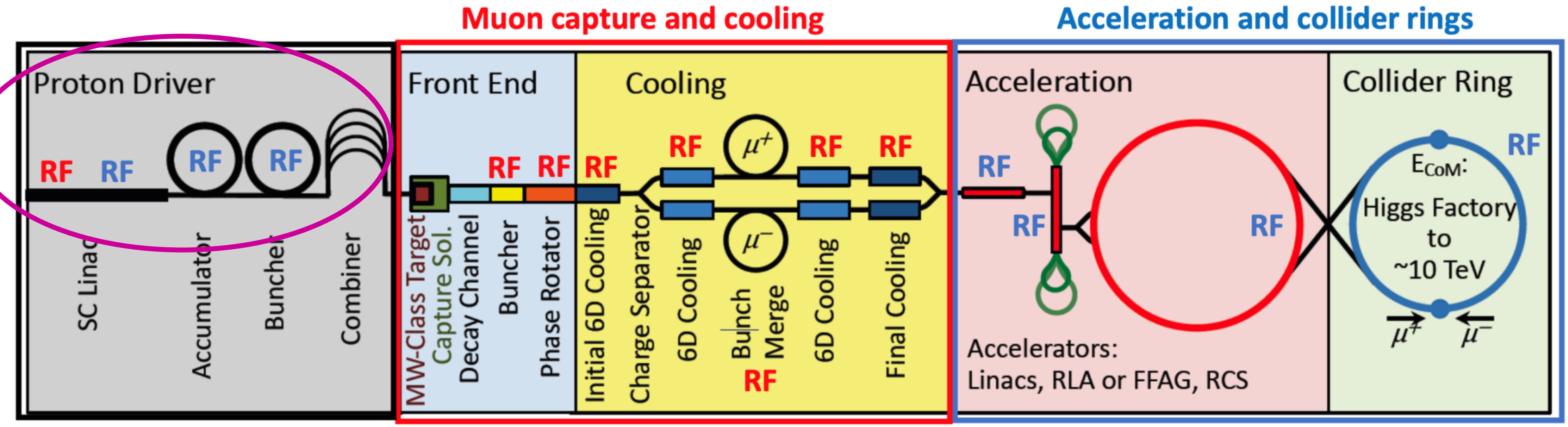
Outline

- **Muon Collider –**
  - Site filler - Muon Collider ?
    - "energy frontier"
- **Muon Collider Components**
  - **Proton source**
    - ~10^{14} proton source in ~1m bunch
  - Muon source and cooling
  - Accelerator
    - Fast-cycling
  - Collider Ring
- **Parameters**
  - Up to ~10 TeV Muon collider "site-filler"

2 TeV Collider (1983 version)



MAP Proton Driver ~2013



Muon Collider Parameters					
		Higgs	Multi-TeV		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
b*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, e_{TN}	p mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1.5	70	70	70
Bunch Length, s_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

MAP Proton Source Requirements

Want high intensity of protons in a short pulse to put on target

Followed by Muon collection, cooling, acceleration

~2-4 MW – 10 Hz -> 5Hz

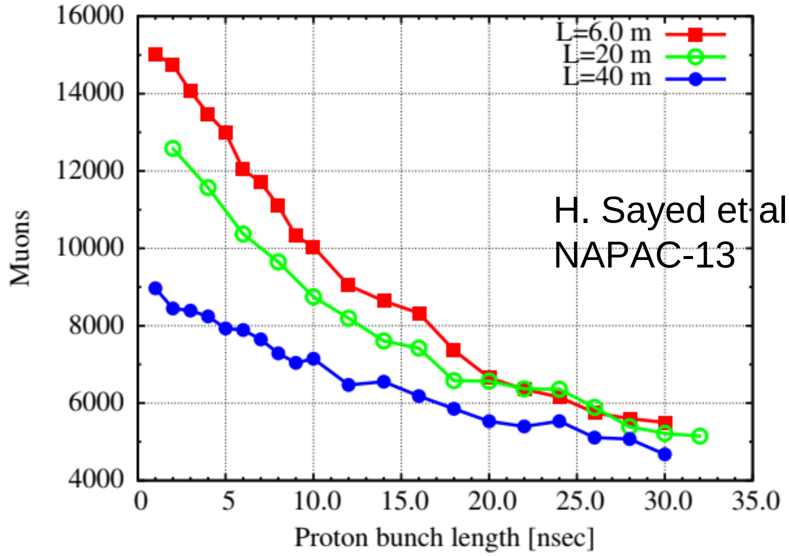
200 kJ / pulse -> 400 kJ

1.6 10^{14}p → 3.1 10^{14} (8 GeV)

Bunch Length ~1-3 ns (rms)

0.3-1m rms

Lose a factor of 2 when L = 10 m

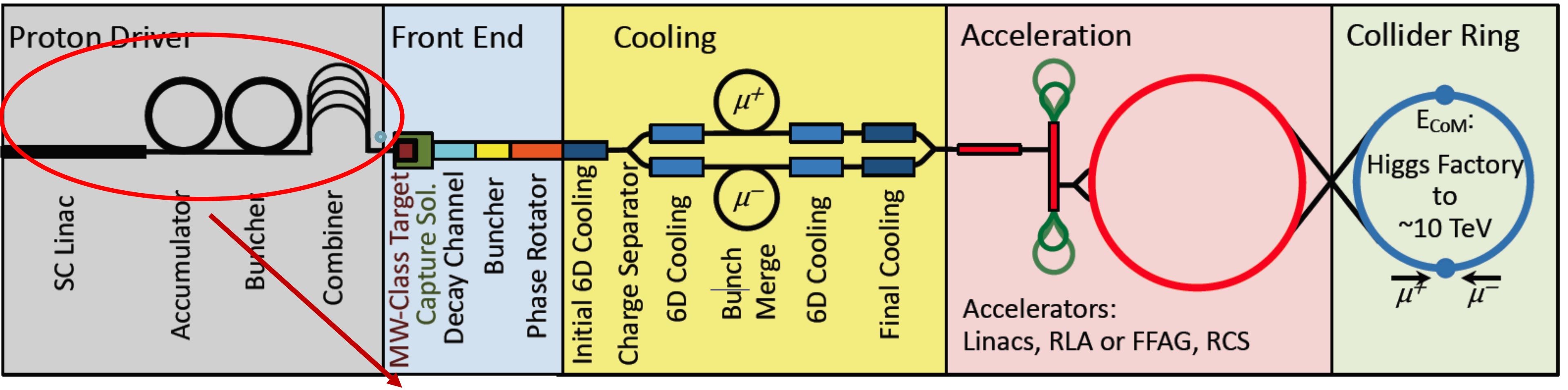


Dependence of stored μ's on proton bunch length

and B-field taper length

~ non-adiabatic preferred

MAP proton source



- **Based on Fermilab project X – 8 GeV Linac**
  - With Accumulator ring and Buncher
    - ~10^{14} protons in 4 compressed bunches
  - Extracted into Combiner transport lines that converge into
  - ~1m bunch length on the target (~15 Hz)

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MAP – Project X Linac

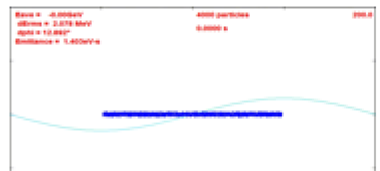
- 8 GeV Linac – 1300 MHz SRF

- Add Accumulator Ring
  - Captures (H^- stripping) and bunches beam
    - 15 Hz, 2×10^{14} p, h=4

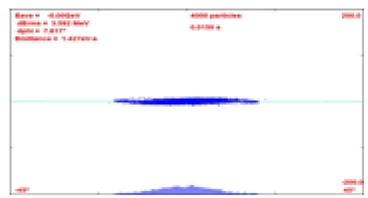
- Compressor: ¼ phase rotat to short bunches
  - Combine onto target for MC
  - Trombone transports

- Many design details …..
  - Space charge, instabilities

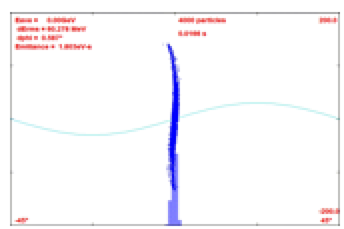
- Probably could combine Accumulator Compressor



From Linac: σ = 11m



Accumulator: σ = 6.5m



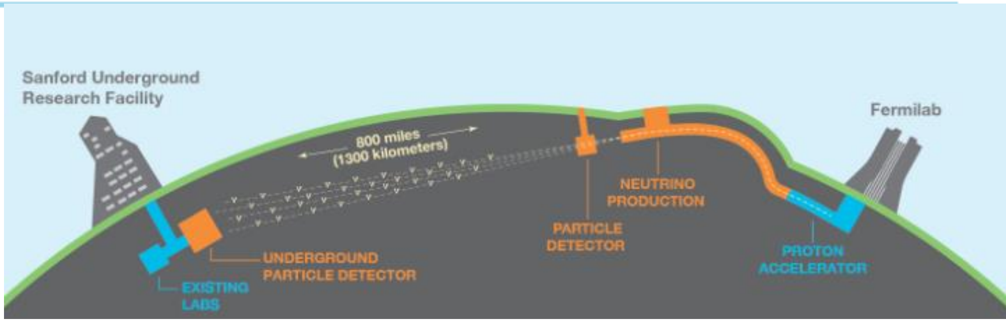
Compressor: σ = 0.5m

FMC versions (Y. Alexahin)

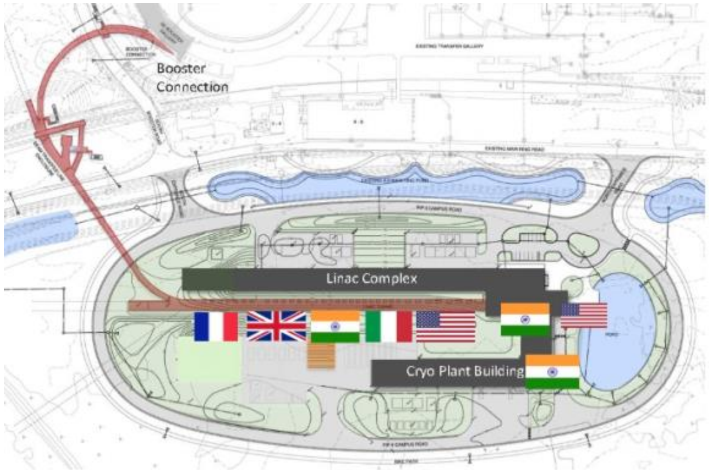
Parameter	AR	CR
Circumference, m	308.23	308.23
Momentum compaction	-0.052	0.001
Slippage factor	-0.063	-0.01
RF frequency, MHz	3.87	3.87
RF voltage, kV	10	240
Synchrotron tune	$2.1\cdot10^{-4}$	$4.2\cdot10^{-4}$
Peak current, A	100	1040
Final r.m.s. bunch length, ns	29.2	3.2
Final r.m.s. energy spread	$5.2\cdot10^{-4}$	$6.9\cdot10^{-3}$
Threshold impedance, Ohm	20	$3 \rightarrow 53$
R.m.s. emittance, μm	5	5
Space charge tuneshift, h/v (Gaussian distribution)	0.02/0.02	0.14/0.16
Betatron tunes, h/v	7.94/6.91	6.76/8.44

2014 Snowmass P5 results

- **DUNE neutrino experiment is highest priority**



- **Project X 8 GeV Linac →**
- **PIP-II 800 MeV Linac**
  - **Construction initiated**



- **Further Proton Source upgrade deferred …**

- **Discussion of Muon Collider forbidden**

Recent Ideas on Fermilab upgrade after PIP-II

- **8 GeV RCS, C=~500-600**

With 2 GeV Linac

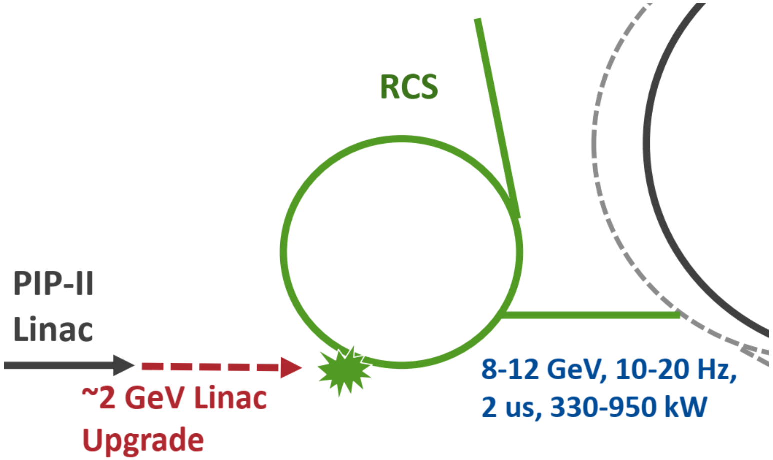
- **8 GeV Linac**

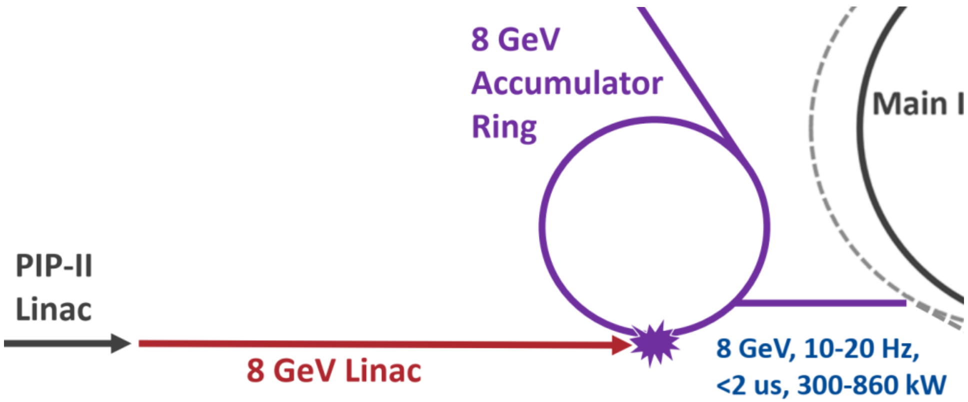
With 8 GeV Accumulator Ring

Beam is in 53 MHz bunches
Matched to Main Injector

Would need upgrade to Muon Collider parameters

- **Higher intensity**
- **Small number of bunches**





ACE –Fermilab Accelerator Complex Evolution

- **Fermilab accelerator upgrade plan**
  - **After PIP-II and DUNE initiation**
- **Priority goal: increase beam to DUNE ASAP**
  - **Modernize and improve Fermilab Complex for the future**

1. **Increase MI rep rate (0.8 Hz > 1.5 Hz)**

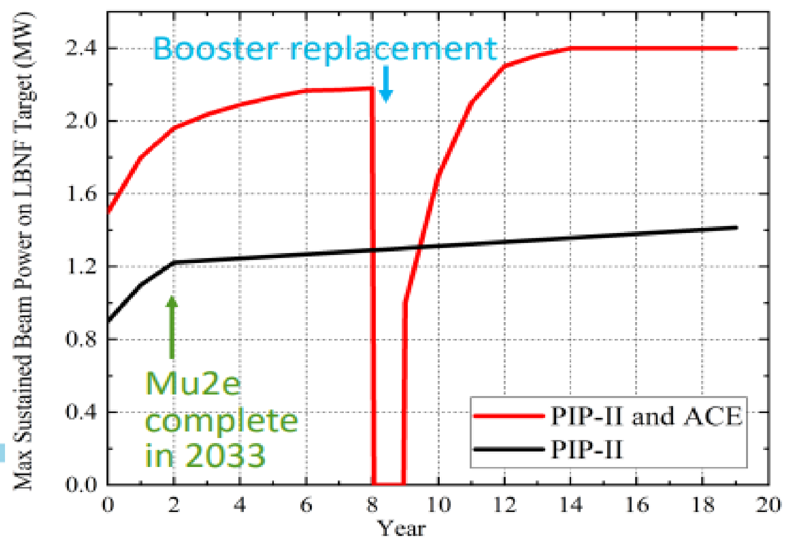
   1.2 MW → >2 MW

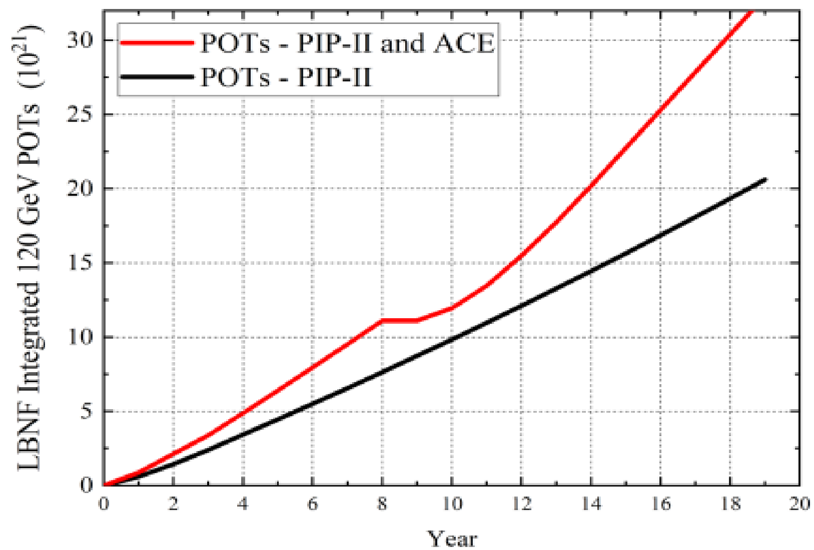
2. **Replace Booster with modern accelerator**

   ~8 GeV RCS or 8 GeV Linac

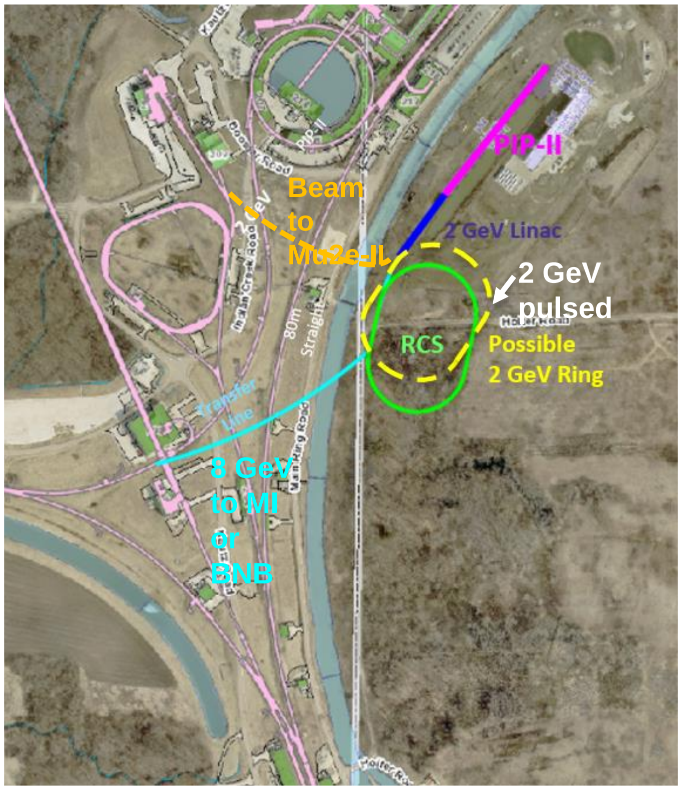
Increase beam on Dune and other Fermilab experiments

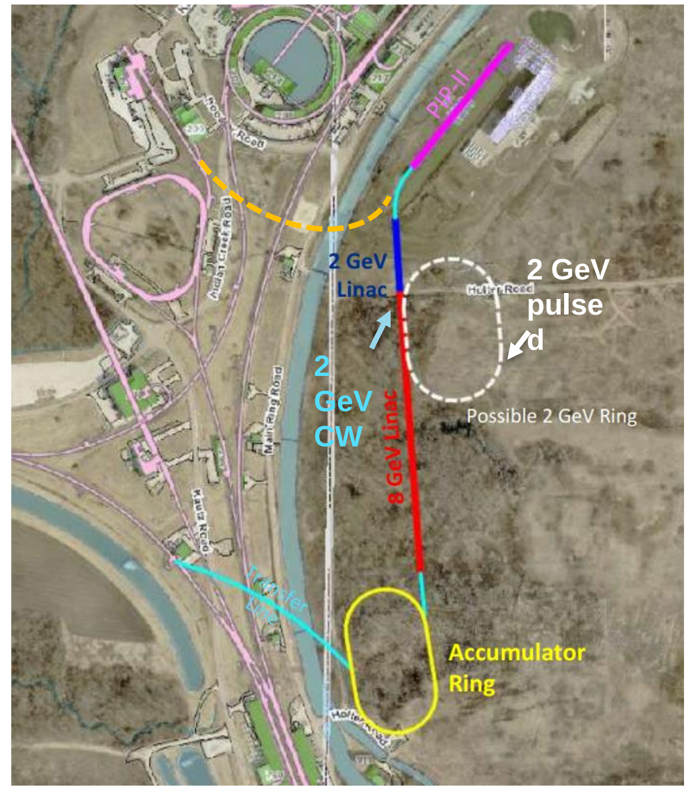
DUNE power and POT implications





Example Booster replacement options and possible add-ons





Booster replacement options

- Extend SRF Linac to higher energy or construct new Rapid-Cycling Synchrotron
- Looked at 3 representative options of each type
- All six configurations require an extension of the SRF Linac to 2 GeV
  - The RCS option will benefit from the reduced space charge at the increased energy
  - The high-energy linac option will need the beam with an approximate energy of 2 GeV to take advantage of higher frequency, β = 1, high-gradient cavities that can be grouped and fed from a single, high-power klystron.
- Parameters can be optimized based on outcome of this workshop

RCS

- C1a) 10 Hz: Metallic vacuum chamber
- C1b) 20 Hz: Ceramic vacuum chamber, larger aperture magnets, accumulator ring
- C1c) 20 Hz: (C1b) with high-current linac, no accumulator ring

SRF Linac and Accumulator Ring

- C2a) Basic: small increase in PIP-II current, using demonstrated XFEL RF
- C2b) High current (5mA) and some RF R&D
- C2c) High current and significant RF R&D

Overall 8 GeV power must be increased to ~ 2 MW

53 MHz bunch structure must be recombined to fit proton pulse requirements

Or RF Replaced with low-frequency rf

Accumulator/Compressor

RCS or accumulator

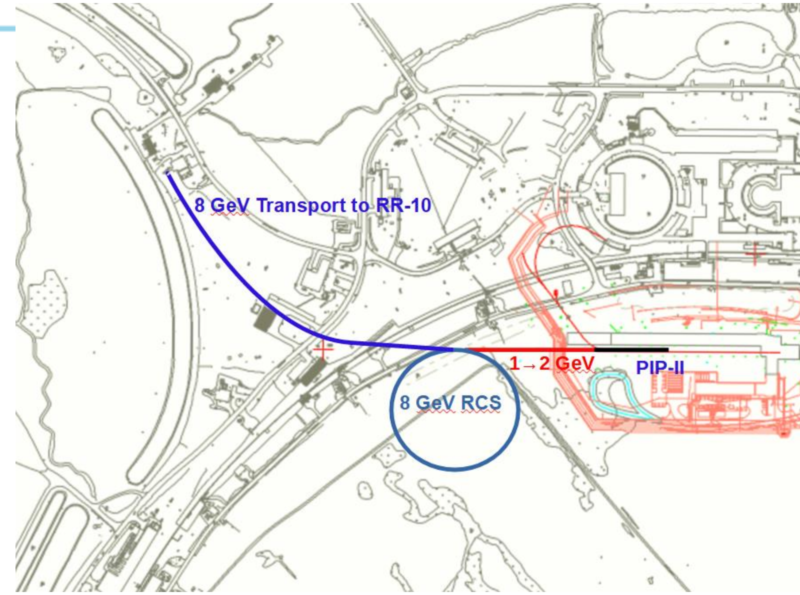
500-600 m circumference

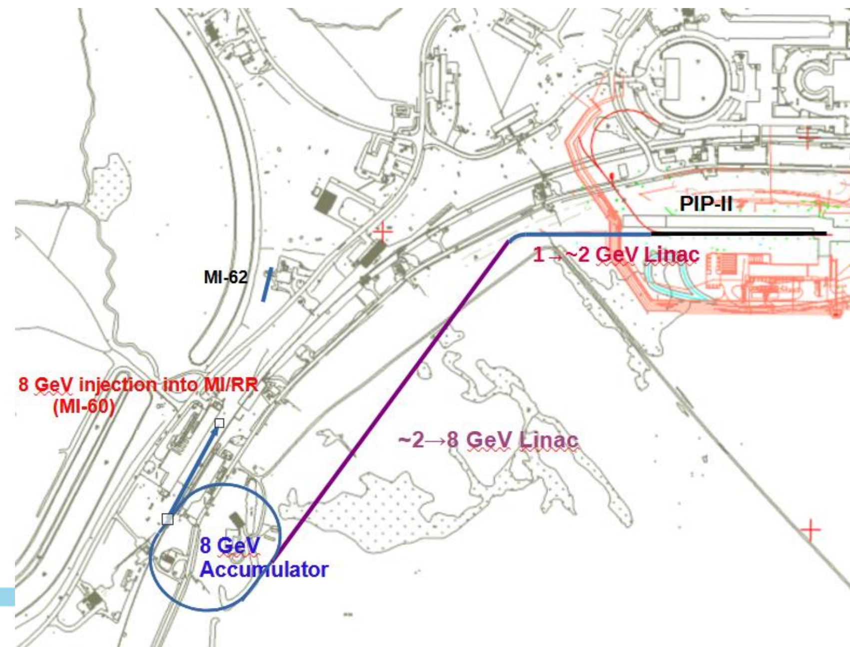
→ ?

Is a separate compressor ring needed ?

Accumulator/compressor focused on Muon Collider could be different.

S. Nagaitsev – ACE workshop

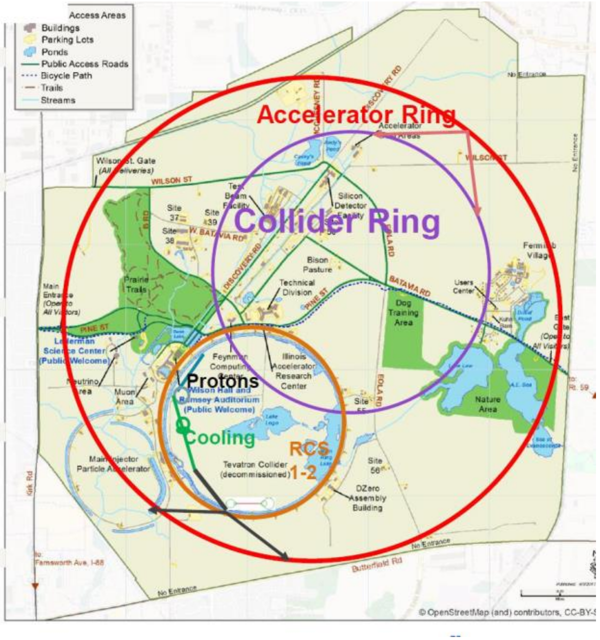




Muon Collider

Fermilab ACE program offers several synergies with Muon Collider R&D

The ACE Booster Replacement plan could provide a path for a Muon Collider front-end



Summary

- **Proton Source is a critical Muon Collider component**
  - 10^{14} protons in ~ 1m bunch
- **MAP program Proton source**
  - 8 GeV linac + Acc./Comp. Ring
- **Similar source possible in ACE program**
  - Post PIP-II Fermilab upgrades
- **Details of source are site-dependent**

  CERN, JPARC, ESS, …

Fermilab ACE program and 6—10 TeV Muon Collider are "difficult but perhaps not impossible"

DN, FN-319 (1979)

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Acknowledgements & White Papers

Snowmass White papers related to DUNE/LBNF proton driver upgrades

"Report from the Fermilab Proton Intensity Upgrade Central Design Group"
R. Ainsworth et al. FERMILAB-FN-1229-AD-CSAID-LBNF-ND-PIP2-PPD-TD

"A Cost-Effective Upgrade Path for the Fermilab Accelerator Complex"
Sergei Nagaitsev and Valeri Lebedev

"An Upgrade Path for the Fermilab Accelerator Complex"
Rob Ainsworth, Joe Dey, Jeff Eldred, Roni Harnik, Jonathan Jarvis, Dave Johnson, Ioanis Kourbanis, David Neuffer, Eduard Pozdeyev, Mike Syphers, Sasha Valishev, Vyacheslav Yakovlev and Bob Zwaska

"Design Considerations for Fermilab Multi-MW Proton Facility"
Jeff Eldred, Sergei Nagaitsev, Vladimir Shiltsev, Mike Syphers, Sasha Valishev, and Bob Zwaska

"An 8 GeV Linac as the Booster Replacement in the Fermilab Power Upgrade"
Sergey Belomestnykh, Mattia Checchin, David Johnson, David Neuffer, Hasan Padamsee, Sam Posen, Eduard Pozdeyev, Vitaly Pronskikh, Nikolay Solyak, Vyacheslav Yakovlev

References

Design of accumulator and compressor rings for the Project-X based proton driver, Y. Alexahin , D. Neuffer FNAL, Batavia, IL 60510 U.S.A Proc. IPAC 12, TUPPC043 (2012)

Design of a 2.2 GeV Accumulator and Compressor for a ν Factory, B. Autin et al. CERN–PS/2000–011 (AE) (2000)

Proton driver scenarios at CERN and Rutherford Appleton Laboratory, JWG Thomson et al. PRSTAB 16, 054801 (2013)

H.K. Sayed et al., Optimization of the Capture Section of a Staged Neutrino Factory, THPHO11, NA-PAC 13. (2013)

H.K. Sayed et al., Impact of the Proton Bunch Length on the Performance of the Muon Front End, TUPBA10, NA-PAC 13. (2013)

"A Muon Source at JPARC parameters, TUPMY005, IPAC 16 (2016)

"High Frequency Bunching and φ-δE Rotation for a Muon Source" D. Neuffer and A. Van Ginneken, Proceedings of PAC 2001, Chicago IL, p. 2029 (2001).

Hisham Kamal Sayed and J. Scott Berg, "Optimized Capture Section for a Muon Accelerator Front End" PhysRevSTAB 17, 070102 (2014)

Compact muon production and collection scheme for high-energy physic experiments D. Stratakis and D. Neuffer 2014 *J. Phys. G: Nucl. Part. Phys.* 41 125002

High intensity muon beam source for neutrino beam experiments, Nucl. Inst. and Meth. A 794 (2015) 193–199 Hisham Kamal Sayed

"Colliding Muon Beams at 90 GeV", FN-319 (1979)

"Principles and Applications of Muon Cooling", Paricle Accelerators 14, 75 (1983)

Thank you for your attention

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Feasibility: Has anyone done 200 kJ pulses in single bunches??

JPARC MR has ?
30 GeV 8 bunches

Demonstrates that Proton Driver is Possible

Could be upgraded to μ proton driver
0.3 Hz → 1 Hz
Add Compressor ??

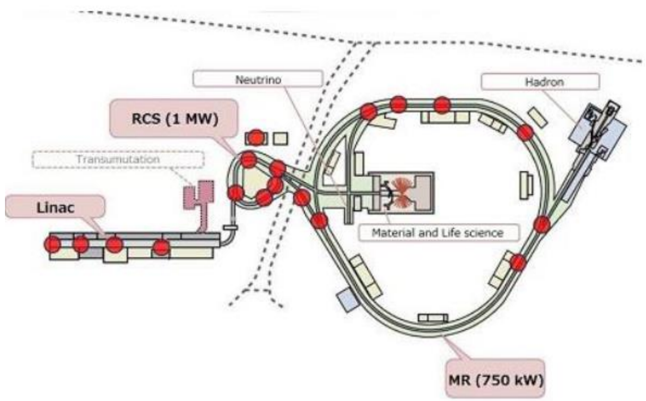

Table 2: Summary of proton drivers

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Parameter	**MAP→ACE**	**JPARC RCS**	**JPARC MR**
Injection E	8	0.4	3 GeV
Top Energy	8	3	30-50 GeV
Power	4MW	1MW	0.67-1.1 MW
Frequency	15	25	0.3 Hz
Emittance, 95%, N	30π	153π	153π mm-mrad
Admittance	50π	200π	300π
p/cycle	2.1×10^{14}	8.4×10^{13}	3.5×10^{14}
bunches	4→1	2	8
N/bunch	**5.2×10^{13}→ 2.1×10^{14}**	**4.2×10^{13}**	**4.2×10^{13}**
kJ/bunch	**67→268**	**20**	**200→320**
Circumference	308.2	348	1568m
Tune	7.94/6.91	6.7/6.3	22.3/22.3
γ_t	9.07	9.14	i31.7
Beam pipe R	5	12.5	6.5cm

IPAC16, TUPMY005