Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

MC Proton Driver parameters: US siting

FNAL from DUNE-era to MC-era

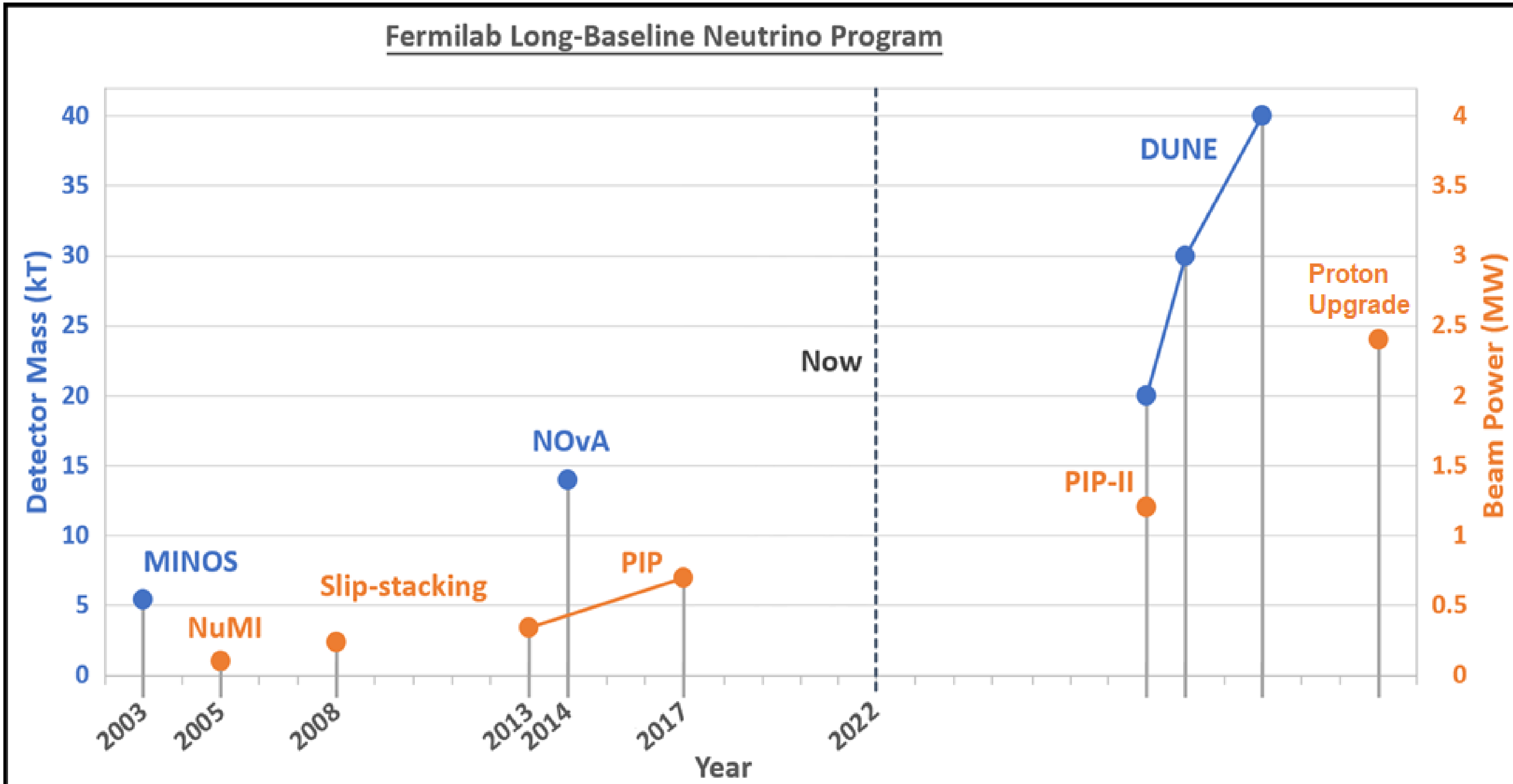
Jeffrey Eldred

Muon Collider Collaboration Meeting

October 12th, 2022

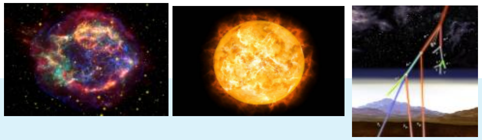
Neutrinos: Beam Power and Detector Size

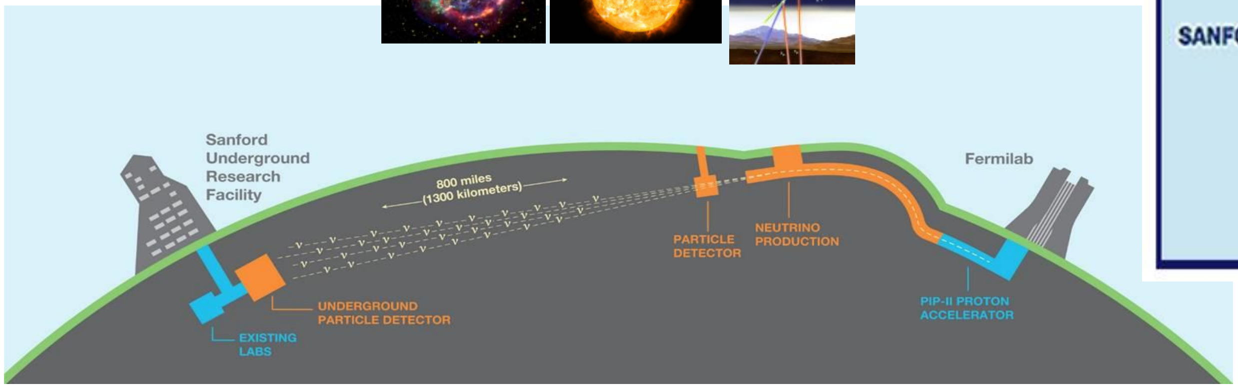
DUNE long-baseline neutrino program calls for **2.4 MW**



J. Eldred, JINST 2019

DUNE physics program





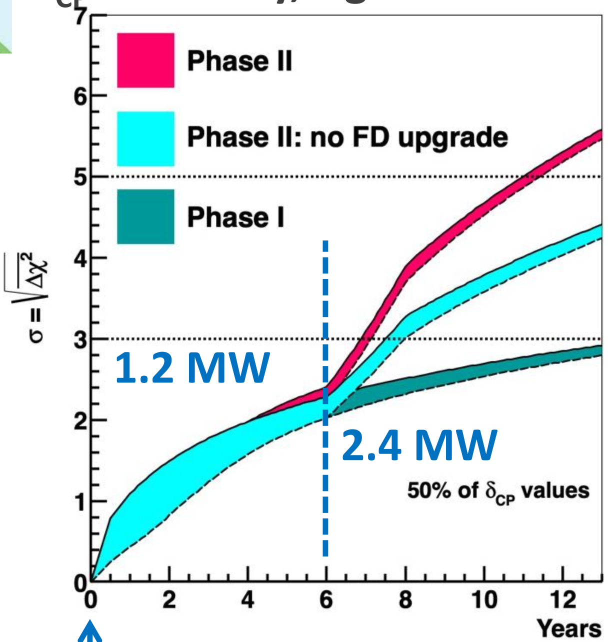
Unambiguous, high precision measurements of Δm^2_{32}, δ_{CP}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ in a single experiment

Discovery sensitivity to CP violation, mass ordering, θ_{23} octant over a wide range of parameter values

Sensitivity to MeV-scale neutrinos, such as from a galactic supernova burst

Low backgrounds for sensitivity to BSM physics including baryon number violation

δ_{CP} Discovery, sigmas over time



starts ~2032 -> ~2048

Proton Intensity Upgrade (PIU)

(aka DUNE/LBNF Phase II driver, aka Booster Replacement, aka PIP-III, aka 2.4 MW Upgrade, Arguably aka Project X)

Acknowledgements & White Papers

Snowmass White papers related to DUNE/LBNF PIU upgrades

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

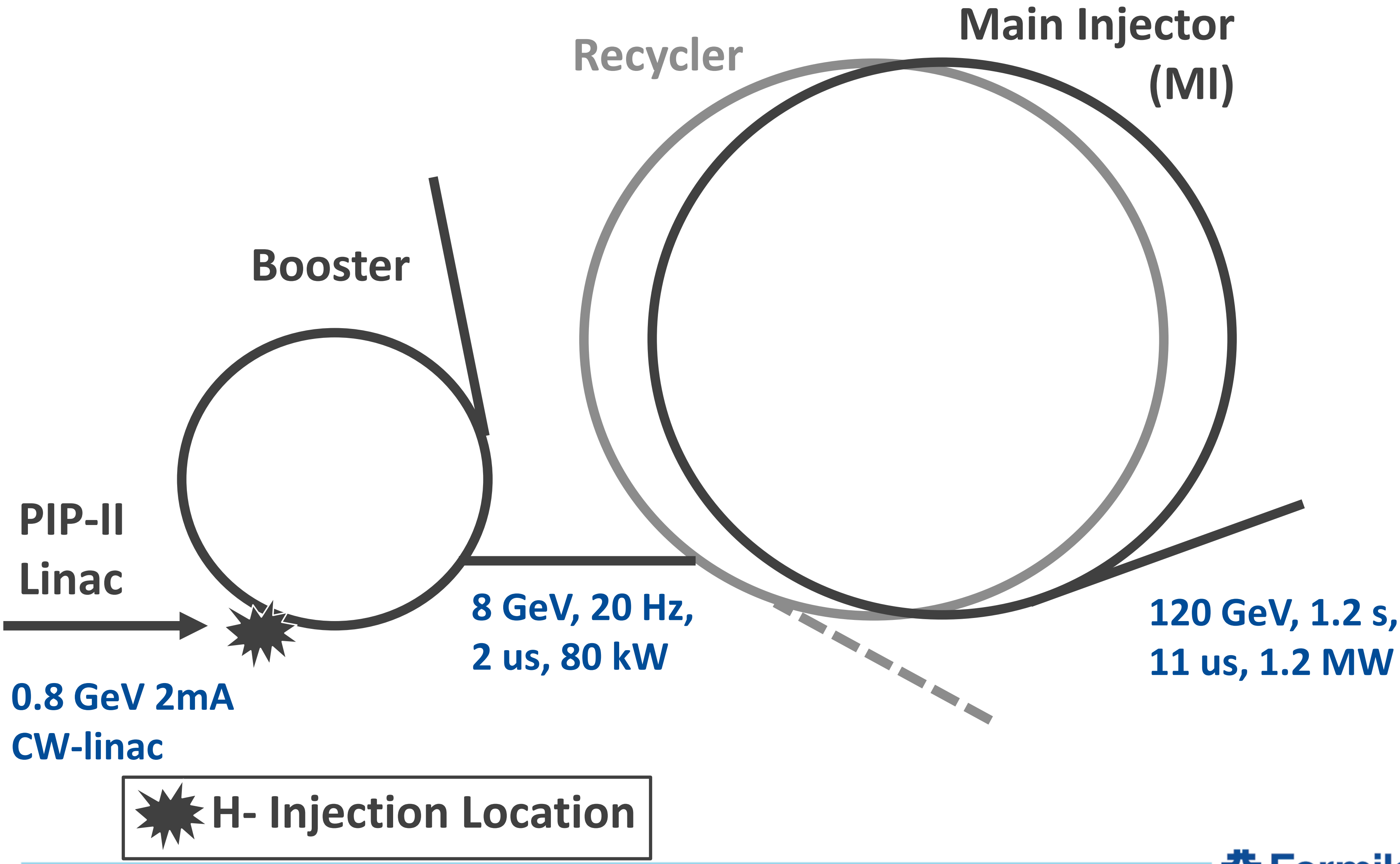
"An Upgrade Path for the Fermilab Accelerator Complex"
Rob Ainsworth, Joe Dey, Jeff Eldred, Roni Harnik, Jonathan Jarvis, Dave Johnson, Ioanis Kourbanis, David Neuffer, Eduard Pozdeyev, Mike Syphers, Sasha Valishev, Vyacheslav Yakovlev and Bob Zwaska

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

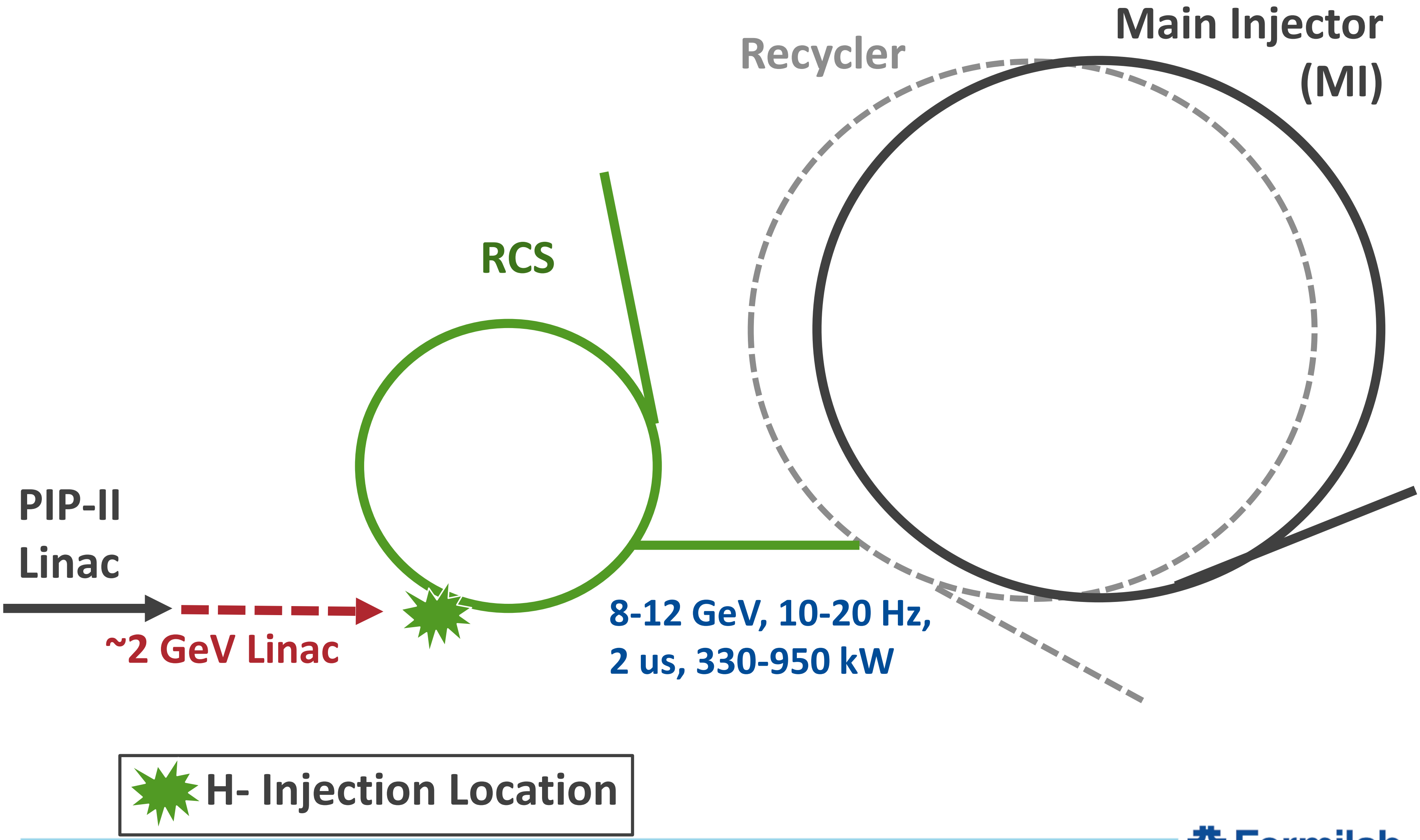
"An 8 GeV Linac as the Booster Replacement in the Fermilab Power Upgrade"
Sergey Belomestnykh, Mattia Checchin, David Johnson, David Neuffer, Hasan Padamsee, Sam Posen, Eduard Pozdeyev, Vitaly Pronskikh, Nikolay Solyak, Vyacheslav Yakovlev

PIU-MC Group Pushpa Bhat, Jeff Eldred, Sergo Jindariani, Sergei Nagaitsev, David Neuffer, Sam Posen, Vladimir Shiltsev, Diktys Stratakis, Katsuya Yonehara,

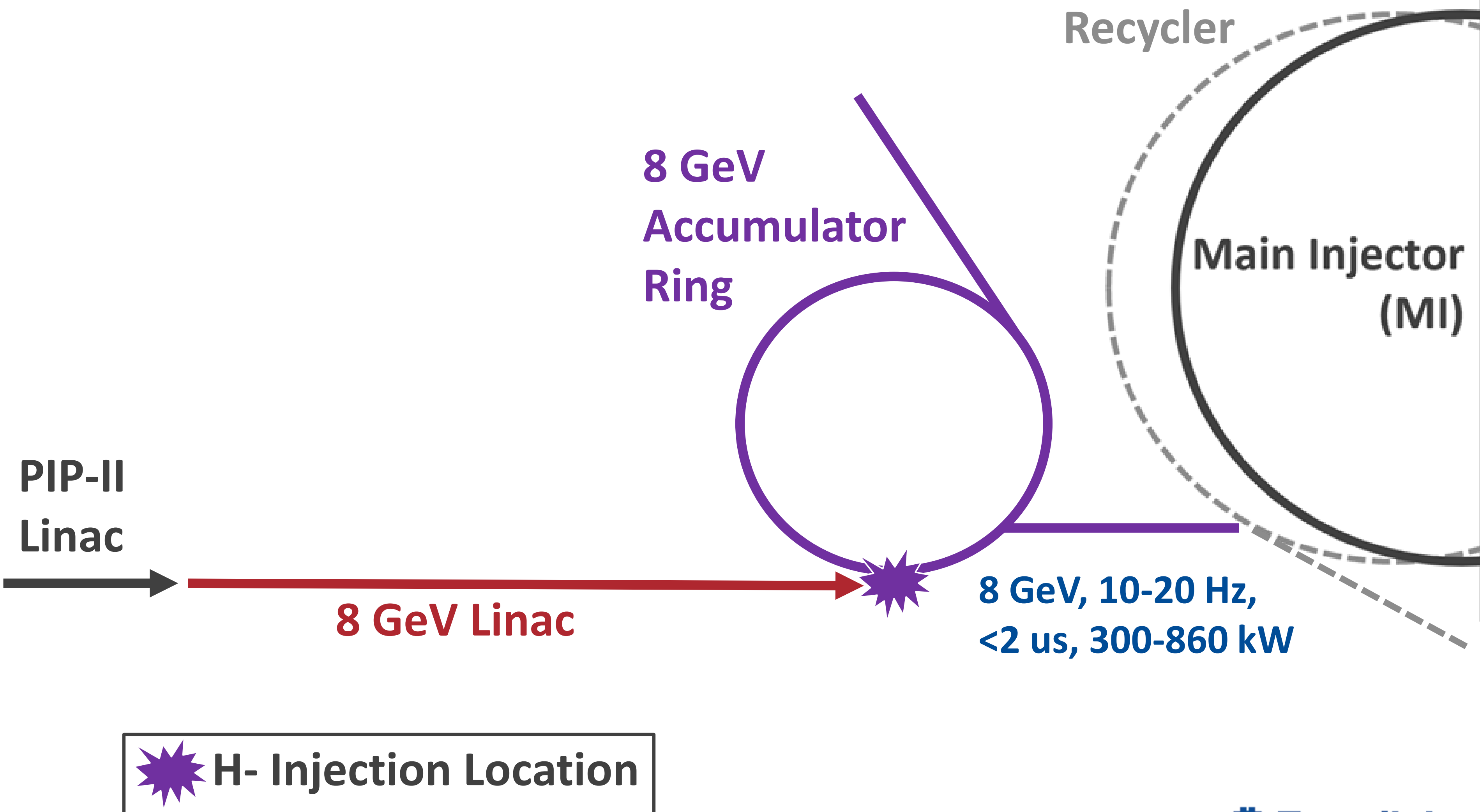
Fermilab PIP-II Era



Fermilab PIU – “RCS” Option



Fermilab PIU – "Linac" Option



PIU Parameter Tables

Five versions of PIU have different implications for 8 GeV program.

Parameter	PIP-II	PIU: "RCS"		PIU: "Linac"		
Parameter	Booster	v1	v2	v1	v2	v3
Linac Energy	0.8 GeV	2 GeV	2 GeV	8 GeV	8 GeV	8 GeV
Minimum Linac Current	2 mA	2 mA	5 mA	2.5 mA	2.5 mA	5 mA
Rep. Rate	20 Hz	10 Hz	20 Hz	10 Hz	20 Hz	10 Hz
Ring Energy Inj-Ext	0.8-8 GeV	2-8 GeV	2-8 GeV	8 GeV	8 GeV	8 GeV
Ring Intensity	6.5 e12	26 e12	37 e12	25 e12	34 e12	31 e12
Number of batches	12	6	5	6	6	6
H^- Linac Injected Power	17 kW	83 kW	240 kW	320 kW	860 kW	800 kW
8 GeV Beam Power from Ring*	160 kW	330 kW	950 kW	320 kW	860 kW	800 kW
120 GeV Beam Power in MI**	1.2 MW	2.4 MW	2.8 MW	2.4 MW	3.1 MW	2.8 MW

*** Total 8-GeV Beam Power, (2.4 MW MI program uses 160 kW)**

- ~2 μs pulses either from RCS or an 8 GeV Accumulator Ring.

**** DUNE/LBNF beam power strictly limited to 2.4 MW.**

- all PIU scenarios deliver 2.4 MW for DUNE/LBNF.

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Minimal versions of PIU have about 320 kW at 8 GeV, roughly half of which is sent to the MI program.

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120 GeV Beam Power in MI**	1.2 MW	2.4 MW	2.8 MW	2.4 MW	3.1 MW	2.8 MW

800-950 kW at 8 GeV available for only a small marginal cost.

These scenarios provide a clear path to Muon Colider Proton Driver.

From PIU to
MC Proton Driver (MCPD)

High Level FNAL MCPD Parameters

Parameter	PIU Scenarios	MCPD Scenarios
Energy	8 GeV	8-16 GeV
Rep. Rate	10-20 Hz	5-20 Hz
Power	0.3-0.9 MW	1-4 MW
Proton Structure	25-40 e12 over 2 μs ring	40-120 e12 in four 1-3 ns bunches

MCPD Energy: 8-16 GeV

- Starting from FNAL-PIU, doing less than 8 GeV doesn't make sense.
- Muons / MW and other production/capture design aspects appear to be relatively insensitive to changes in energy.
- Proton compression is a challenging aspect, energy helps space-charge.
- Energy can be a convenient way to boost beam power.

High Level FNAL MCPD Parameters

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Energy	8 GeV	8-16 GeV
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Rep. Rate 5-20 Hz

- For a 10 TeV collider, the muon lifetime is ~0.1s. Luminosity will be heavily front-loaded for a 5-20 Hz repetition rate.

- The RCS/Linac beam would either be used directly or be reconfigured for lower repetition rate.

High Level FNAL MCPD Parameters

Parameter	PIU Scenarios	MCPD Scenarios
Energy	8 GeV	8-16 GeV
Rep. Rate	10-20 Hz	5-20 Hz
Power	0.3-0.9 MW	1-4 MW
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Power 1-4 MW
Proton Structure 40-120 e12 in four 1-3 ns bunches

- Intense ns-scale bunches maximize initial phase-space of muon beams.
    - Assume four bunches will converge on target.
- Parameters targeting 2 e35 $cm^{-2}s^{-1}$ luminosity for 10 TeV collider.
- Parameters achievable from proton driver perspective
    - Proton compressor ring is used to adapt PIU to MC PD pulses.
    - Preliminary assessment for space-charge and machine performance.

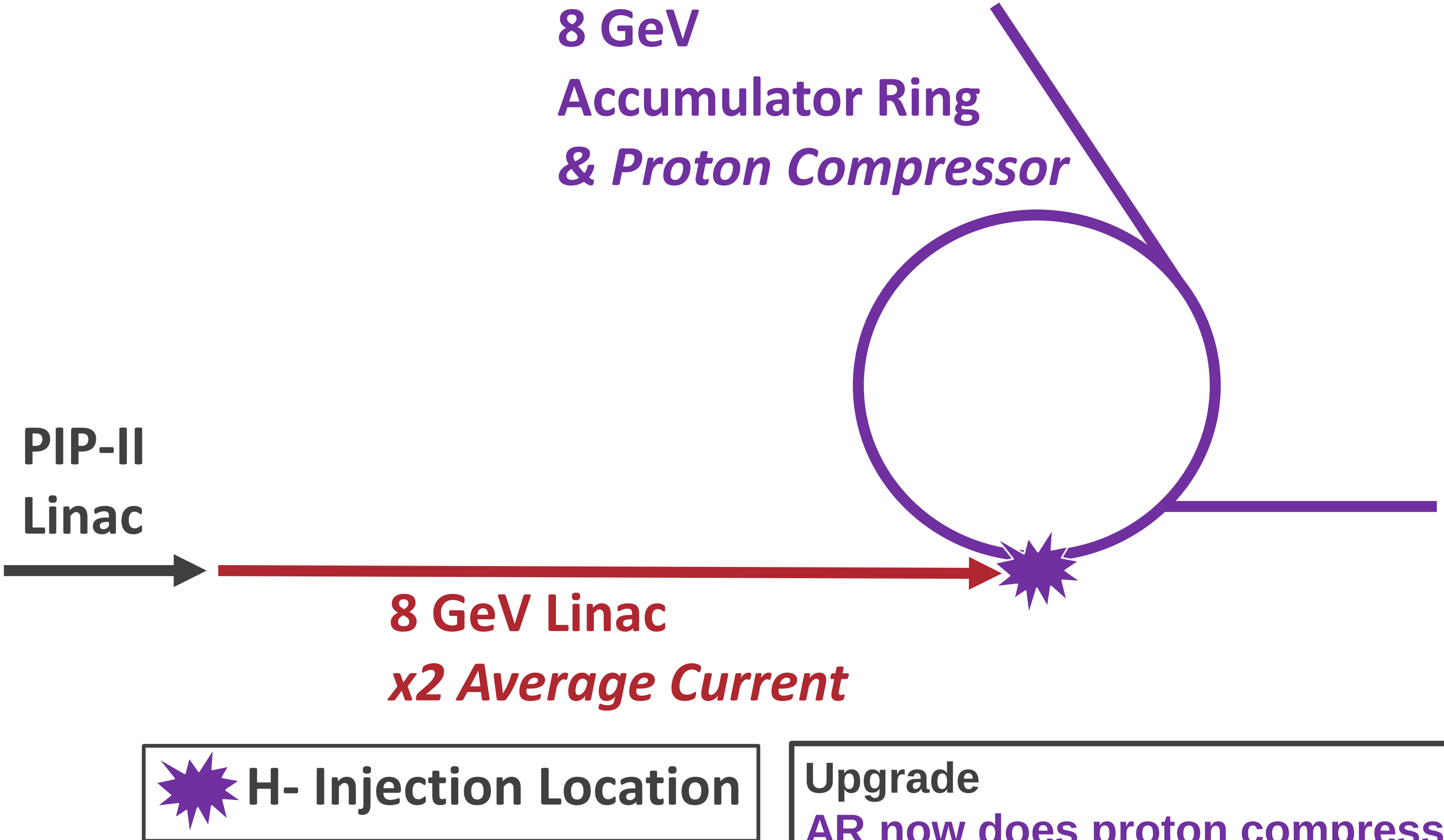
PIU-to-MCPD Scenarios

		MCPD 1	MCPD 2	MCPD 3
MCPD Parameters	Energy	8 GeV	12 GeV	16 GeV
	Pulse Intensity	60 e12	40 e12	120 e12
	Rep rate	20 Hz	20 Hz	5-10 Hz
	Power	1.5 MW	1.5 MW	1.5-3 MW
Linac-PIU Scenarios	Linac rep rate	**20 Hz**	20 Hz	**10 Hz**
	Linac proton rate	**12 e14/s**	8 e14/s	**6 e14/s**
	AR upgraded for acceleration?	**No**	Yes	**Yes**
	New PC ring?	**No**	12 GeV	**16 GeV**
RCS-PIU Scenarios	RCS upgrade/replacement	Upgrade	**Upgrade**	Replacement
	Example RCS normalized emit	40 mm mrad	**24 mm mrad**	80 mm mrad
	New PC ring?	8 GeV	**12 GeV**	16 GeV

Many paths between PIU and MCPD, but a few to examine closely:

MCPD1 – Close to Linac-PIU scenario already.

Fermilab PIU-Linac to MCPD 1



Upgrade
AR now does proton compression.
Linac peak current or rep rate doubles.

PIU-to-MCPD Scenarios

		MCPD 1	MCPD 2	MCPD 3
MCPD Parameters	Energy	8 GeV	12 GeV	16 GeV
	Pulse Intensity	60 e12	40 e12	120 e12
	Rep rate	20 Hz	20 Hz	5-10 Hz
	Power	1.5 MW	1.5 MW	1.5-3 MW
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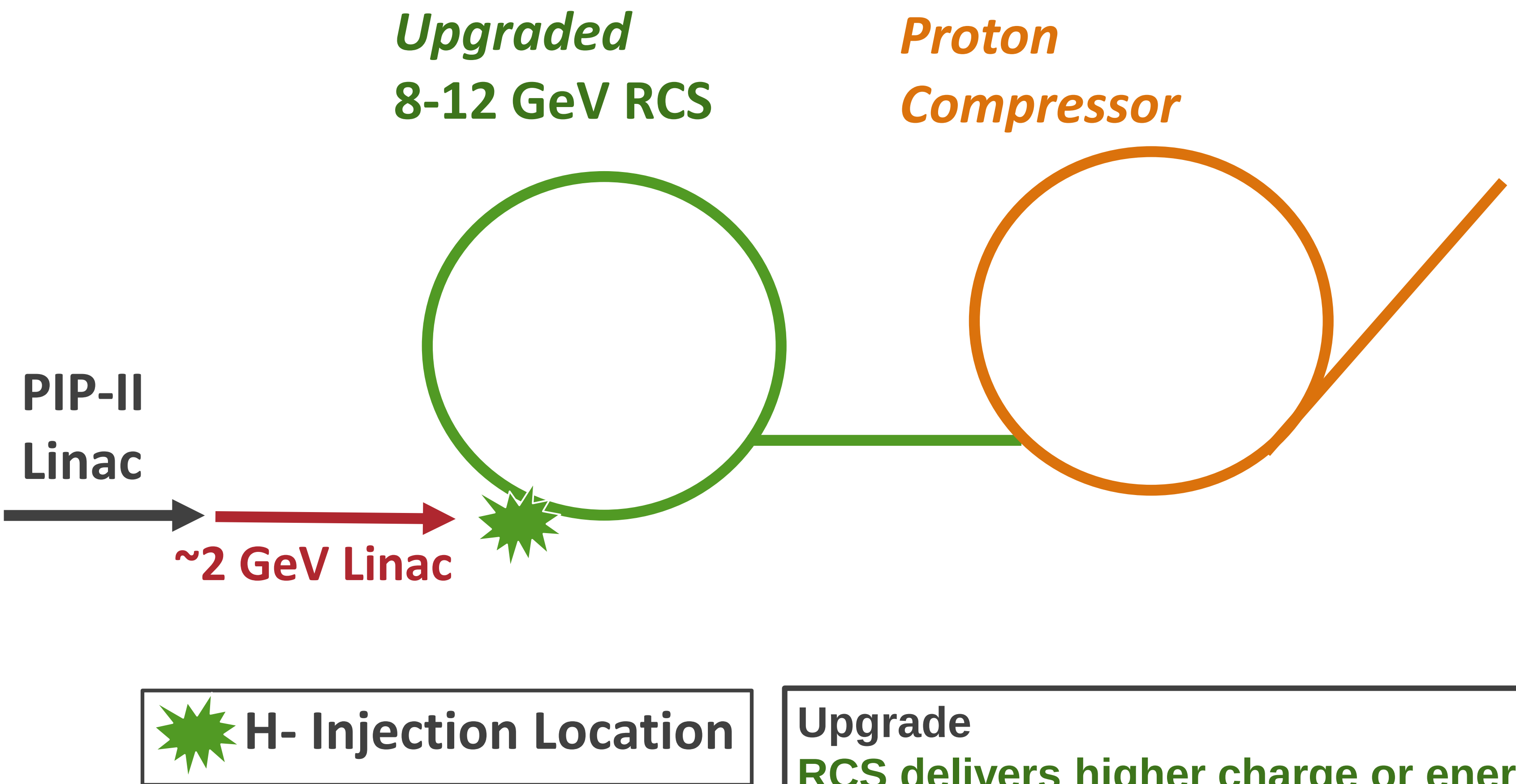
	New PC ring?	**No**	12 GeV	**16 GeV**
RCS-PIU Scenarios	RCS upgrade/replacement	Upgrade	**Upgrade**	Replacement
	Example RCS normalized emit	40 mm mrad	**24 mm mrad**	80 mm mrad
	New PC ring?	8 GeV	**12 GeV**	16 GeV

Many paths between PIU and MCPD, but a few to examine closely:

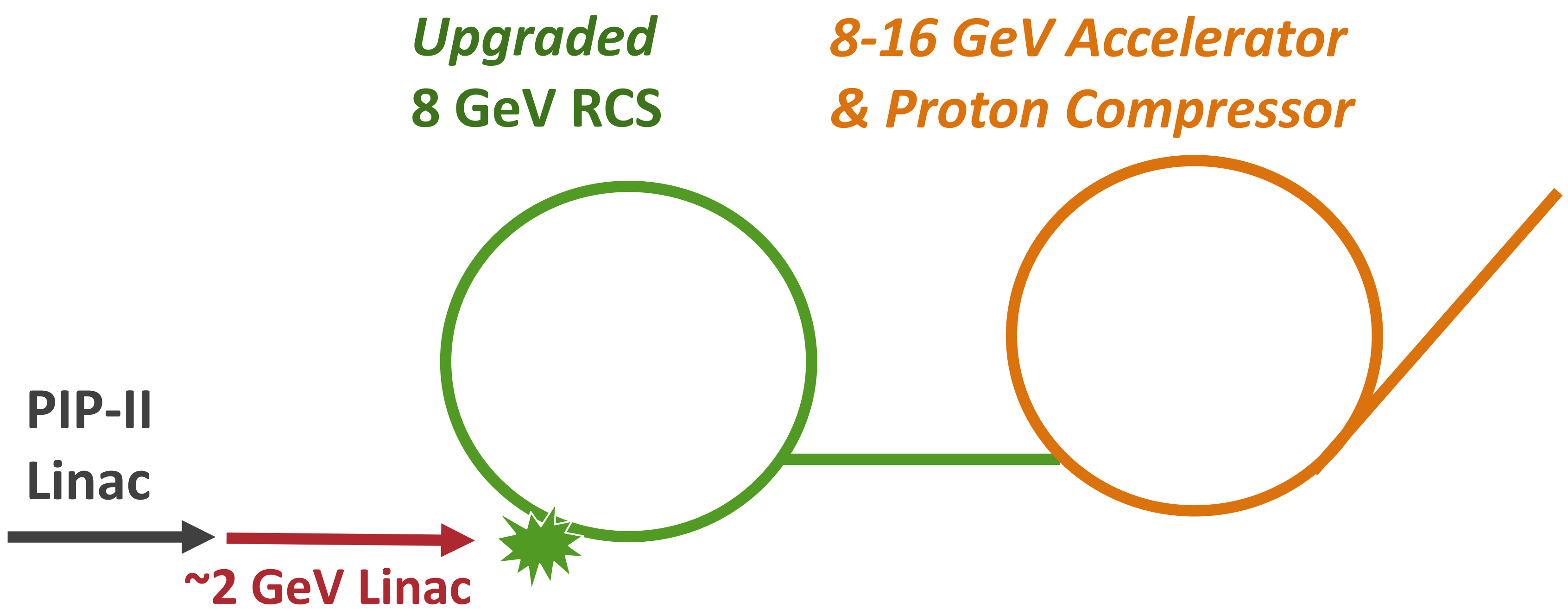
MCPD2 – Overdesign or upgrade of RCS, plus a new compressor ring

Fermilab PIU-RCS to MCPD 1-2



Upgrade
RCS delivers higher charge or energy
Build
Proton Compressor

Fermilab PIU-RCS to MCPD 2-3



H- Injection Location

Upgrade
RCS used directly or delivers more charge.
Build
Proton Compressor, also accelerates.

PIU-to-MCPD Scenarios

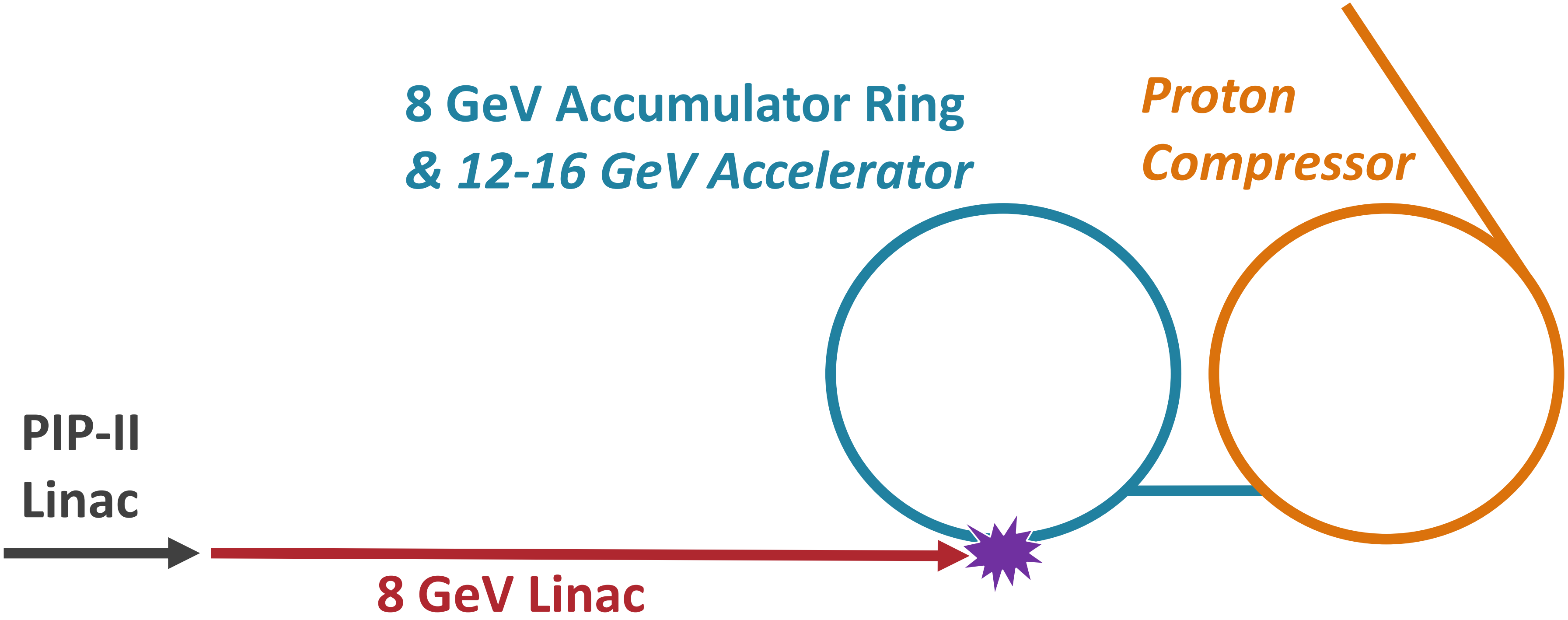
		MCPD 1	MCPD 2	MCPD 3
MCPD Parameters	Energy	8 GeV	12 GeV	16 GeV
	Pulse Intensity	60 e12	40 e12	120 e12
	Rep rate	20 Hz	20 Hz	5-10 Hz
	Power	1.5 MW	1.5 MW	1.5-3 MW
Linac-PIU Scenarios	Linac rep rate	**20 Hz**	20 Hz	**10 Hz**
	Linac proton rate	**12 e14/s**	8 e14/s	**6 e14/s**
	AR upgraded for acceleration?	**No**	Yes	**Yes**
	New PC ring?	**No**	12 GeV	**16 GeV**
RCS-PIU Scenarios	RCS upgrade/replacement	Upgrade	**Upgrade**	Replacement
	Example RCS normalized emit	40 mm mrad	**24 mm mrad**	80 mm mrad
	New PC ring?	8 GeV	**12 GeV**	16 GeV

Many paths between PIU and MCPD, but a few to examine closely:

MCPD3 – At high energy, more intense pulses are possible. Will require some linac acceleration, some ring acceleration, and a pulse compressor.

Any of these PIU scenarios can go to any of these MCPD scenarios.

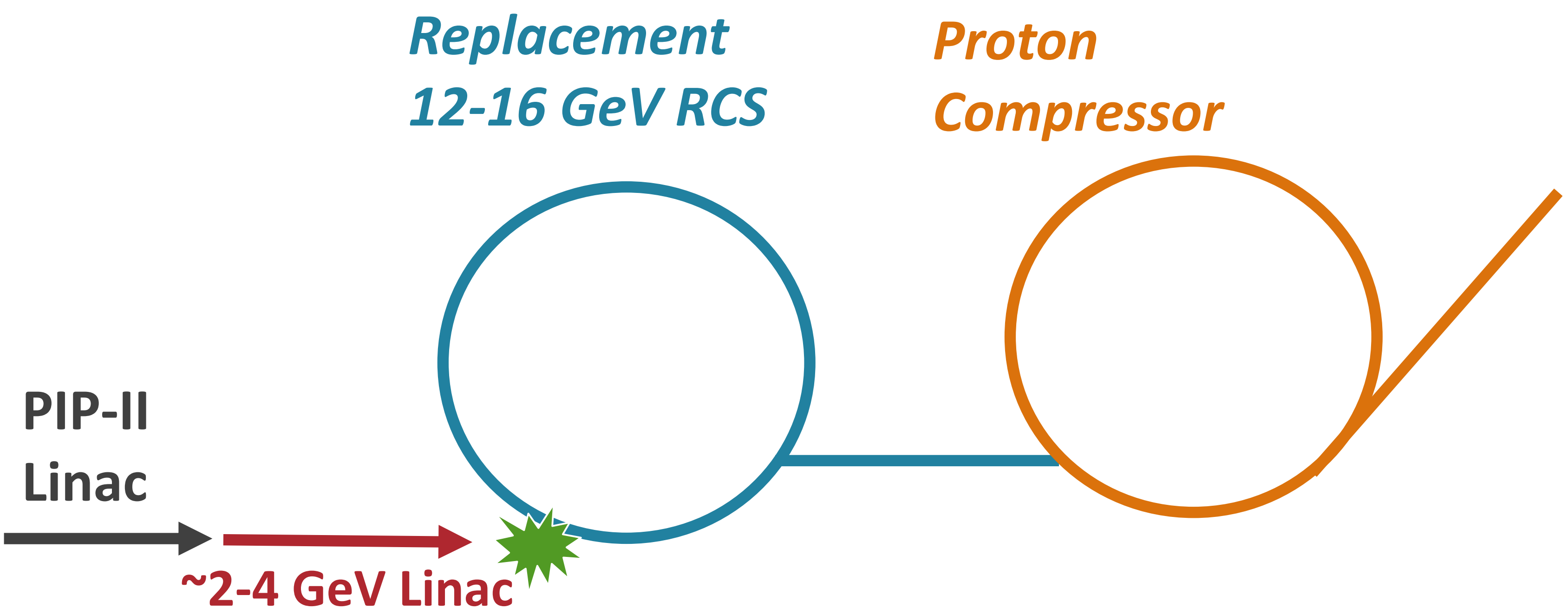
Fermilab PIU-Linac to MCPD 2-3



H- Injection Location

Upgrade
AR now accelerates
Build
Proton Compressor

Fermilab PIU-RCS to MCPD 2-3



H- Injection Location

Build
New RCS with higher energy and charge
Proton Compressor

PIU-to-MCPD Scenarios

		MCPD 1	MCPD 2	MCPD 3
MCPD Parameters	Energy	8 GeV	12 GeV	16 GeV
	Pulse Intensity	60 e12	40 e12	120 e12
	Rep rate	20 Hz	20 Hz	5-10 Hz
	Power	1.5 MW	1.5 MW	1.5-3 MW
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	Linac proton rate	**12 e14/s**	8 e14/s	**6 e14/s**
	AR upgraded for acceleration?	**No**	Yes	**Yes**
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RCS-PIU Scenarios	RCS upgrade/replacement	Upgrade	**Upgrade**	Replacement
	Example RCS normalized emit	40 mm mrad	**24 mm mrad**	80 mm mrad
	New PC ring?	8 GeV	**12 GeV**	16 GeV

Assumptions:

Accumulation // Acceleration // Compression

- Assume a ring can do any two out of three, but not all three.

Space-charge during injection dQsc < 0.2, compression dQsc < 0.6 .

Laser-stripping H- injection technology may be required to overcome limitations in H- injection foils (degradation and beam loss).

MC Proton Driver R&D Topics

1) H- Laser Stripping (especially Linac-PIU)
- SNS has demonstrated 95% efficiency over μs-scale with UV laser.
- Recommend laser demonstrator for IR wavelengths and ms-scale.

2) Muon Targetry & Cooling.
- A core design aspect, but areas for production/cooling optimization alongside proton driver optimization.

3) Pulse Compression Beam Dynamics.
- Simulations and experimental benchmarks.

4) Fast-ramping HTS Magnets (especially RCS-PIU)
- Needed on muon-side, but also benefits for proton RCS design.
    - aperture (5-20 cm), dipole field (1-4 T), ramping (60-600 T/s)

5) Extreme Space-charge (especially RCS-PIU)
- Muon Collider is at Energy Frontier and Intensity Frontier.
- SC during injection and proton compression stages.

Summary & Outlook

Fermilab is planning on upgrading beam power for DUNE/LBNF, but how should we do that upgrade to prepare for “what’s next?”

- Muon Collider provides a potentially compelling answer but what are we prepared to commit to in our near term planning?

Muon Collider Proton Driver scenarios 8-16 GeV seem quite achievable.

- H- Laser Stripping is a critical R&D area.
- Operational experience on proton compression schemes.
- That’s proton-side perspective, muon-side R&D even more critical.

Evaluation of proton scenarios for FNAL PIU are instructive for any MCPD.

Dave Neuffer’s talk tomorrow on muon-side at FNAL.

Bob Bernstein’s talk tomorrow on muon CLFV points to a possible synergy

- AMF envisioned for 1-2 GeV, but 8 GeV PIU can also power it.
- AMF parameters an intermediate point between Neutrino & MC.

Backup Slides

Rapid Cycling Synchrotron (RCS)

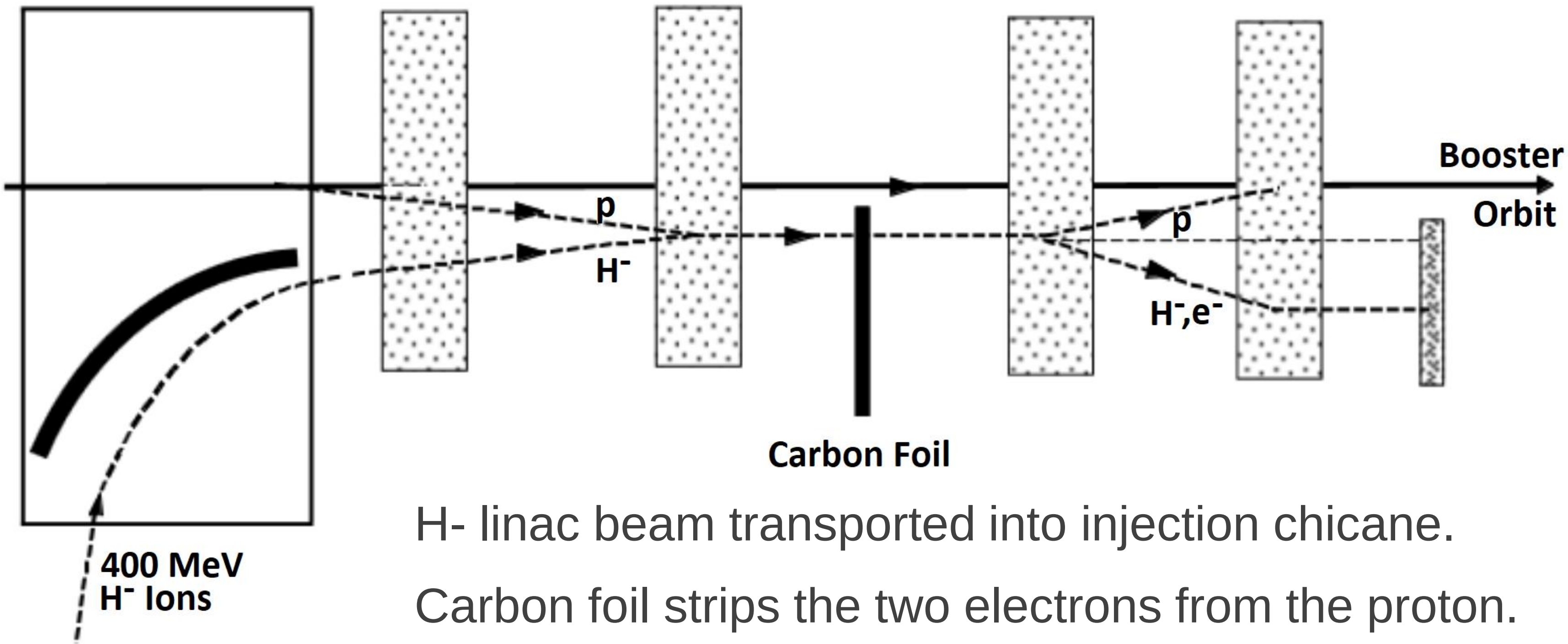
The 20 Hz RCS could be upgradeable to higher energy/rep.rate.

TABLE VII. RCS Ramp Parameters.

	8 GeV, 20 Hz	8 GeV, 30 Hz	12 GeV. 20 Hz	
Min. RCS Intensity for 2.4 MW	35	33.5	35	10^{12}
Available RCS Power*	0.75	1.2	1.1	MW
RF Frequency Range	50.326-52.812	50.326-52.812	50.326-52.965	MHz
Max RF Frequency Slew Rate	248	372	325	MHz/s
Total RF Voltage	1.2	1.9	2.1	MV
Required num. RF cavities (at 60kV)	20	32	35	
Max Acc. Rate	381	572	633	GeV/s
Max Dipole Field	1.0	1.0	1.4	T
Max Dipole Slew Rate	43	65	49	T/s
Max Quad Field	14	14	20	T/m

*concurrent with 120 GeV MI operations

H- Injection through Foil, Process



H- linac beam transported into injection chicane.

Carbon foil strips the two electrons from the proton.

Proton beam accumulates in the ring.

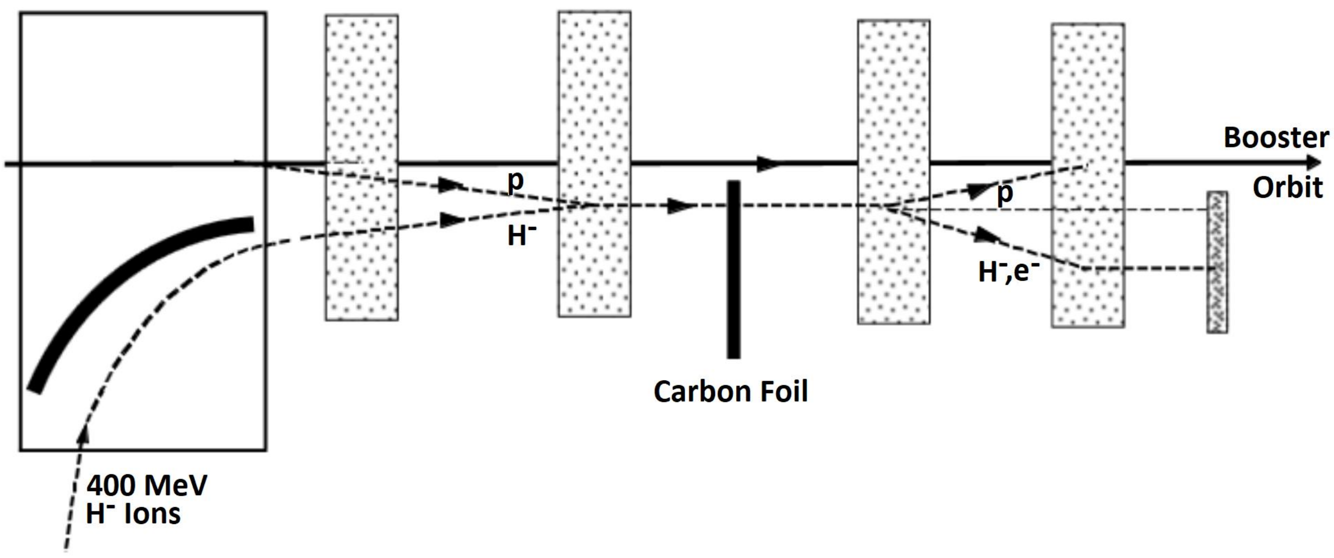
Unstripped H- ions are sent to an absorber.

Ring cheats Louiville’s theorem, concentrates beam current by x10-x1000!
Essential for long-baseline program and many experimental programs.

H- Injection through Foil, Challenges

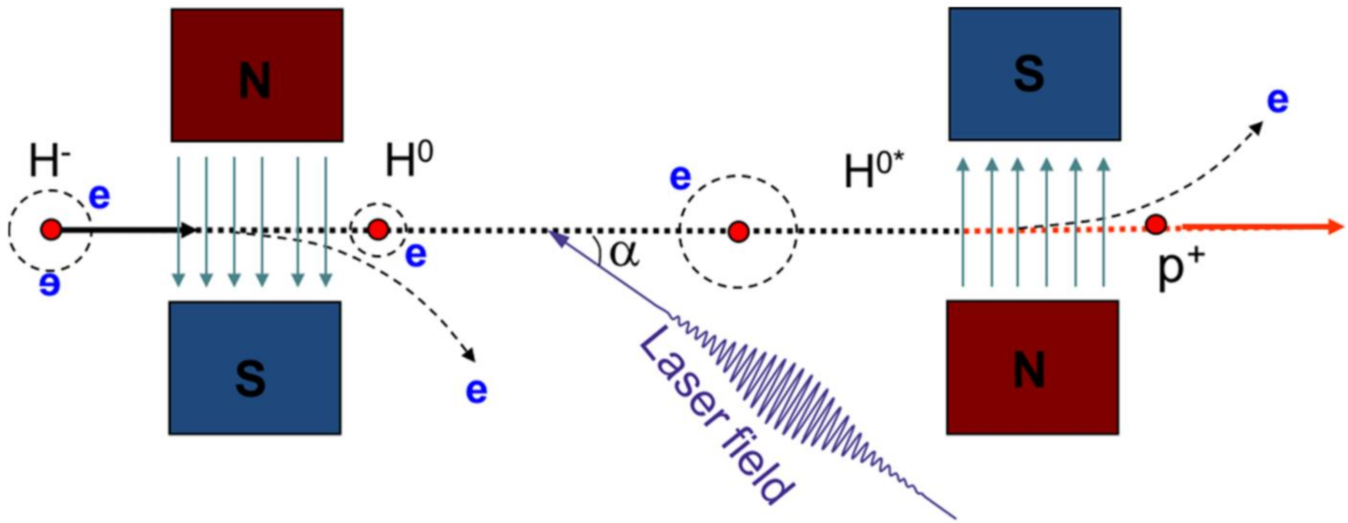
Challenges:

- Chicane magnets must be sufficiently long (weak) to avoid stripping H- beam while also inflecting the beam towards the stripping foil.
- Losses from protons scattering off injection foil, high radioactivation.
- Thin stripping foil degrades from radiation and extreme heat.
- Losses of unstriped H- particles, requires absorber or extraction line.
- Injection optics interfere with symmetric ring lattice, causing resonances.
- Beam orbit must be maintained precisely over duration of injection.



H- Injection through Laser

Laser-stripping technology R&D underway to eliminate many of these challenges....



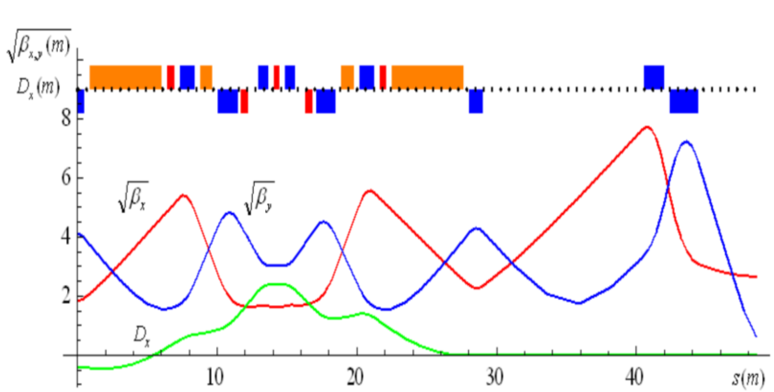
Cousineau et al. PRAB 2017

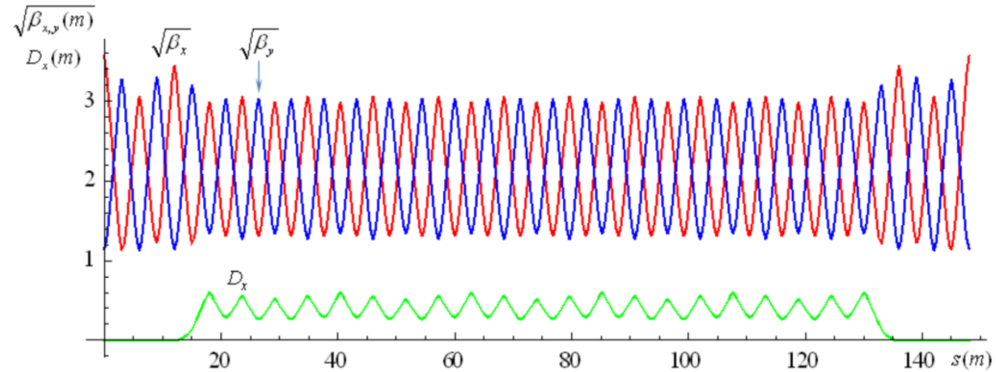
SNS demonstrated 95% stripping efficiency of a 1 GeV H^- beam with 10 μs macropulse duration using a UV laser at 1 MW peak power. However, millisecond duration with 99% efficiency is needed…

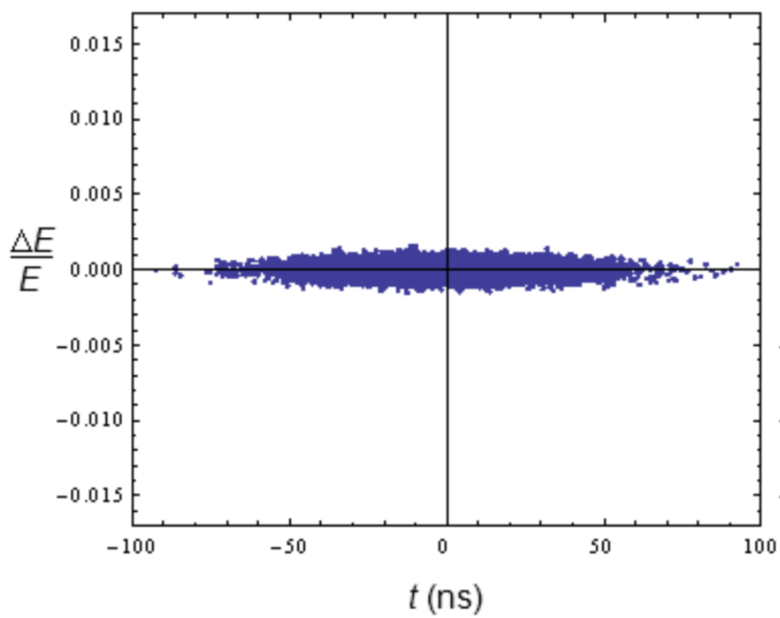
Present scenarios must proceed with a plan for H- foil injection (with laser-stripping as a subsequent retrofit).

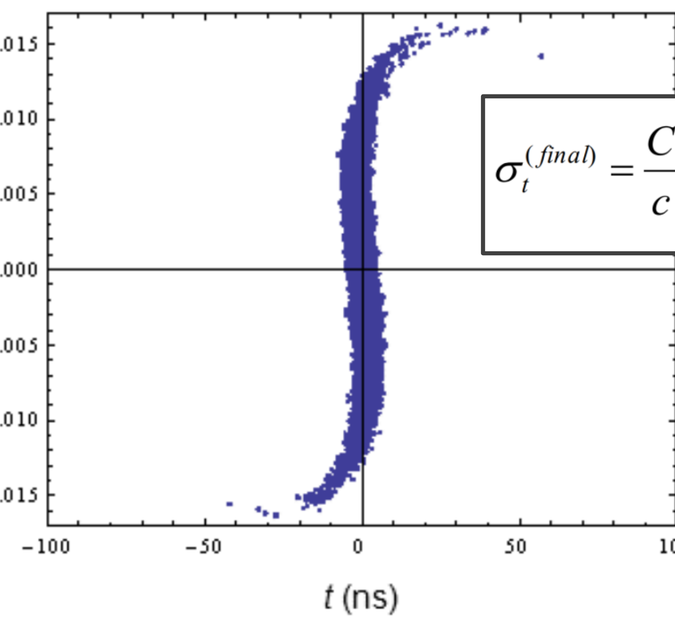
Example Pulse Compressor Ring Design

Alexahin, Jenner, Neuffer IPAC 2012



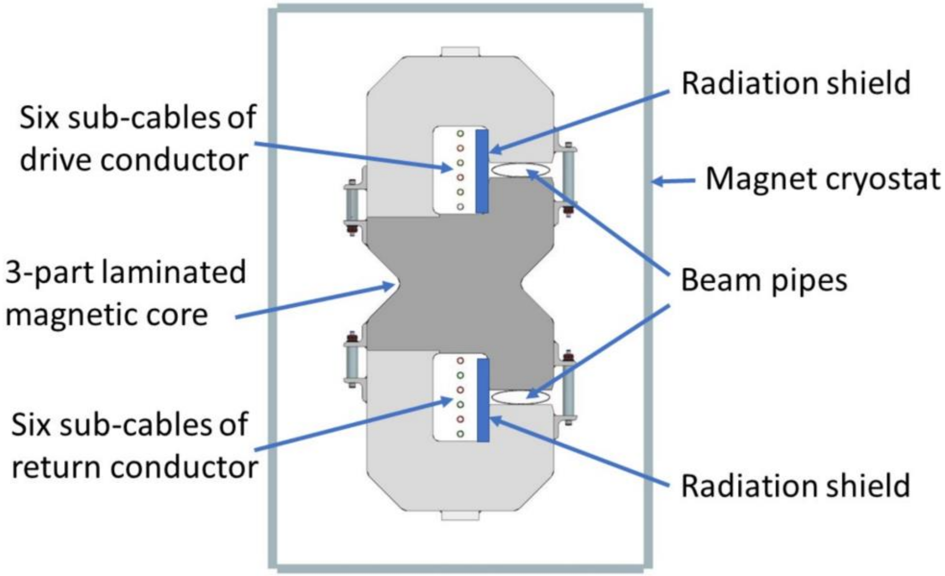


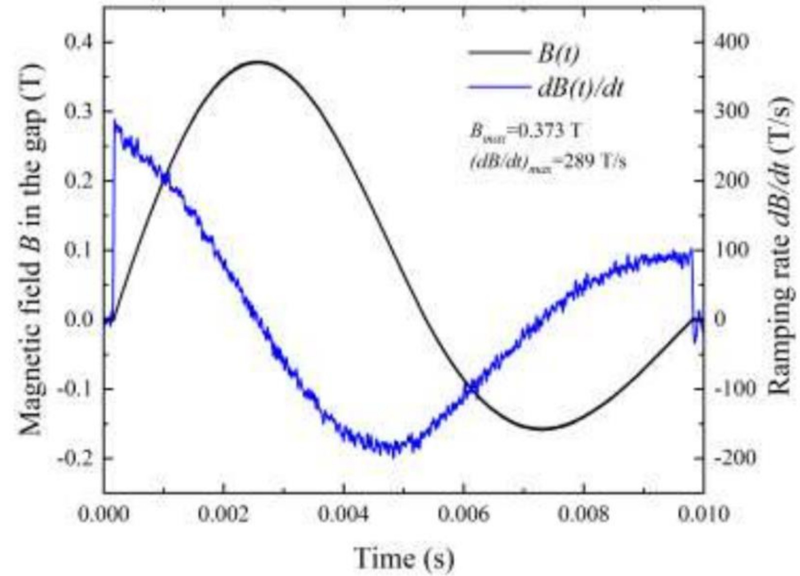




$$\sigma_t^{(final)} = \frac{C}{c}\sqrt{\frac{|\eta|\, E}{2\pi\, h\, eV}}\;\frac{\sigma_p^{(initial)}}{p}$$

Fast-ramping HTS Magnets





YBCO-based HTS super-ferric dipole demonstrated >300 T/s. **paper.**

Potential for a fast-ramping compact RCS:
- Higher field strength at circumference → higher energy beams.
- Less circumference for extraction energy → RF power more efficient.
- More aperture at required field strength → greater beam intensity.