The Booster Replacement study: plans for the machine and physics potential

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Physics Advisory Committee Meeting

9 December 2020

HEP Working group: Greg Bock, Angela Fava, Laura Fields, Alex Friedland, Andrei Gaponenko, Stefania Gori, RH (chair), Gordan Krnjaic, Maxim Pospelov, Luciano Ristori, Nhan Tran, Matthew Toups, Richard Van de Water

Accelerator Working group: Mike Syphers (chair), Jonathan Jarvis, Alexander Valishev, Eduard Pozdeyev, Sam Posen, Jeff Eldred, Ioanis Kourbanis, Valeri A Lebedev, Bob Zwaska.

Outline

- Physics opportunities
  - Reminder about the goals on Booster Replacement
  - Status of the Physics opportunities study
  - Global contexts (details in addendum)
  - Appendix on beyond main injector study

- Comments on accelerator design studies

Booster Replacement

Preamble

- P5 recommendation is for 2.4MW to DUNE
- 2.4 MW requires 1.5×10^{14} particles from MI @ 120 GeV
- 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 and possible upgrades of the MI.*

***Booster Replacement Mission**:*

- Deliver 2.4 MW @ 60-120 GeV from the Main Injector to the LBNF beam line 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 CW @ 800 MeV (or more) to support a second generation Mu2e
- Exploit the capabilities of CW SRF PIP-II linac **to enable other physics opportunities**

Physics Opportunities

- **The goal of the physics working group was to inform the accelerator design about potential physics opportunities. Solicit input from the community (May 19 workshop).**

- We are interested in concrete ideas and near term opportunities, but also a long-term and inclusive approach:
  - The Fermilab Booster was designed ~50 years ago. Its replacement will be with us for decades.
  - We cannot foresee what will be motivated decades ahead.
  - Hope to enable exciting physics experiments and leave door open to pursue others.
  - Plan the accelerators as well as the gaps between them.

Physics Opportunities - Heuristic Map

- Heuristically, we want to identify physics goal on or “near” the path from PIP II to 2.4 MW.
- Small detours on this map can have a high impact:

Physics

Physics

PIP II **2.4MW**

Physics

Physics

Physics

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Physics

Physics

PIP II

2.4MW

Physics

Physics

Physics

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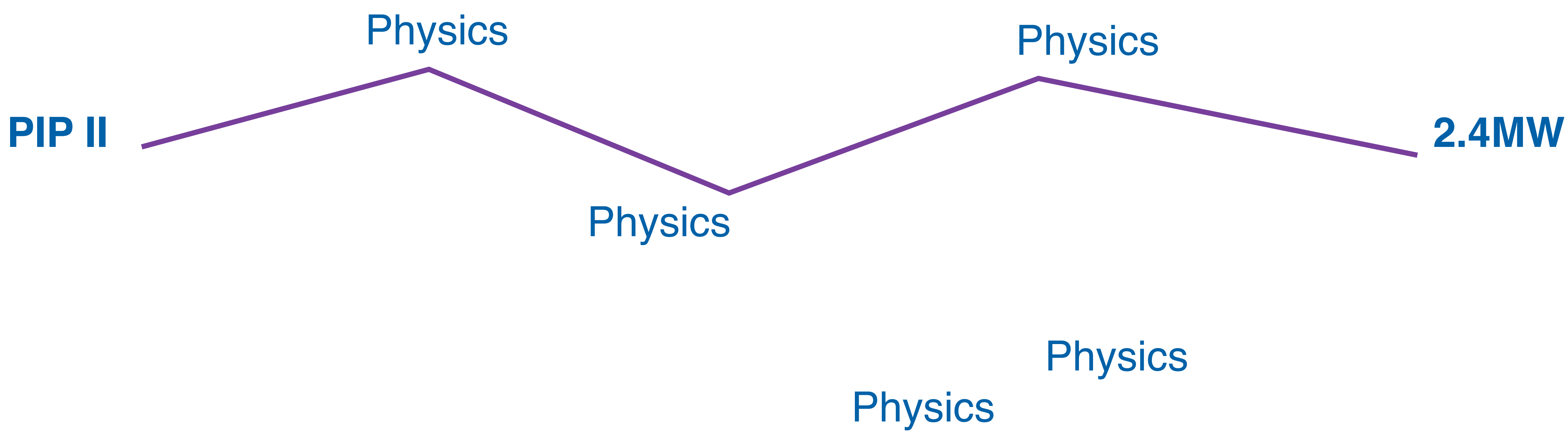

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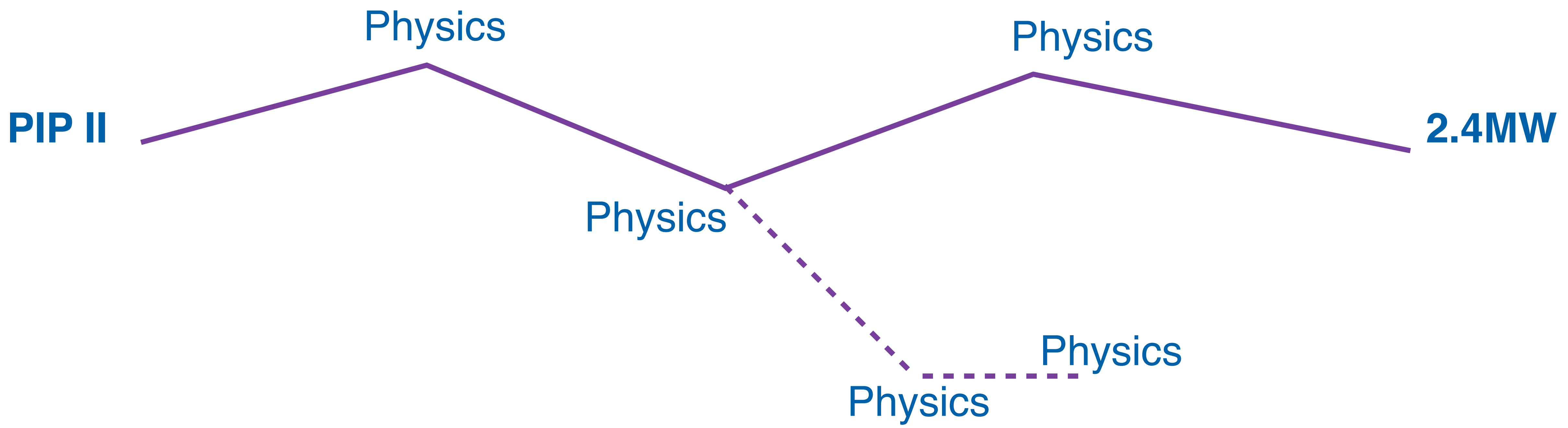

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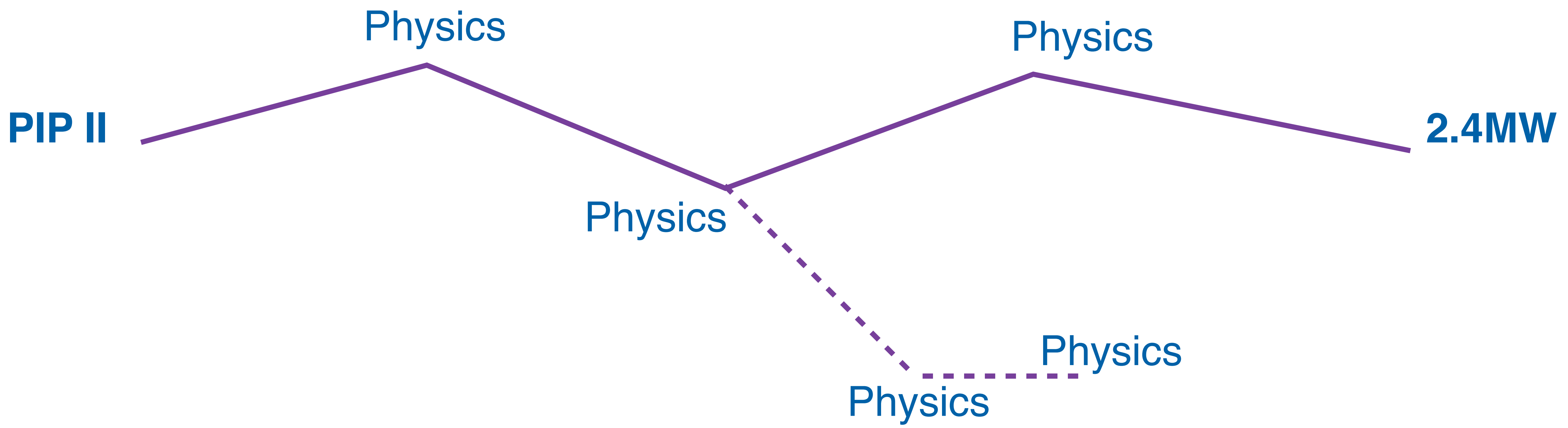


In the conceptual design that mike will present, most opportunities can be enabled to a large degree.

Roughly: proton and muon based experiments are “on the way” to 2.4. Electron based experiments require further infrastructure.

Document Preview:

Physics Opportunities for the Fermilab Booster Replacement

Physics task force

November 27, 2020

Abstract

This is a menu of physics opportunities afforded by the Fermilab Booster Replacement and its various options. As in any self-respecting fancy restaurant, there are no prices in the menu.

https://www.overleaf.com/read/scgtzvbngfxr

A companion accelerator paper is being put together.

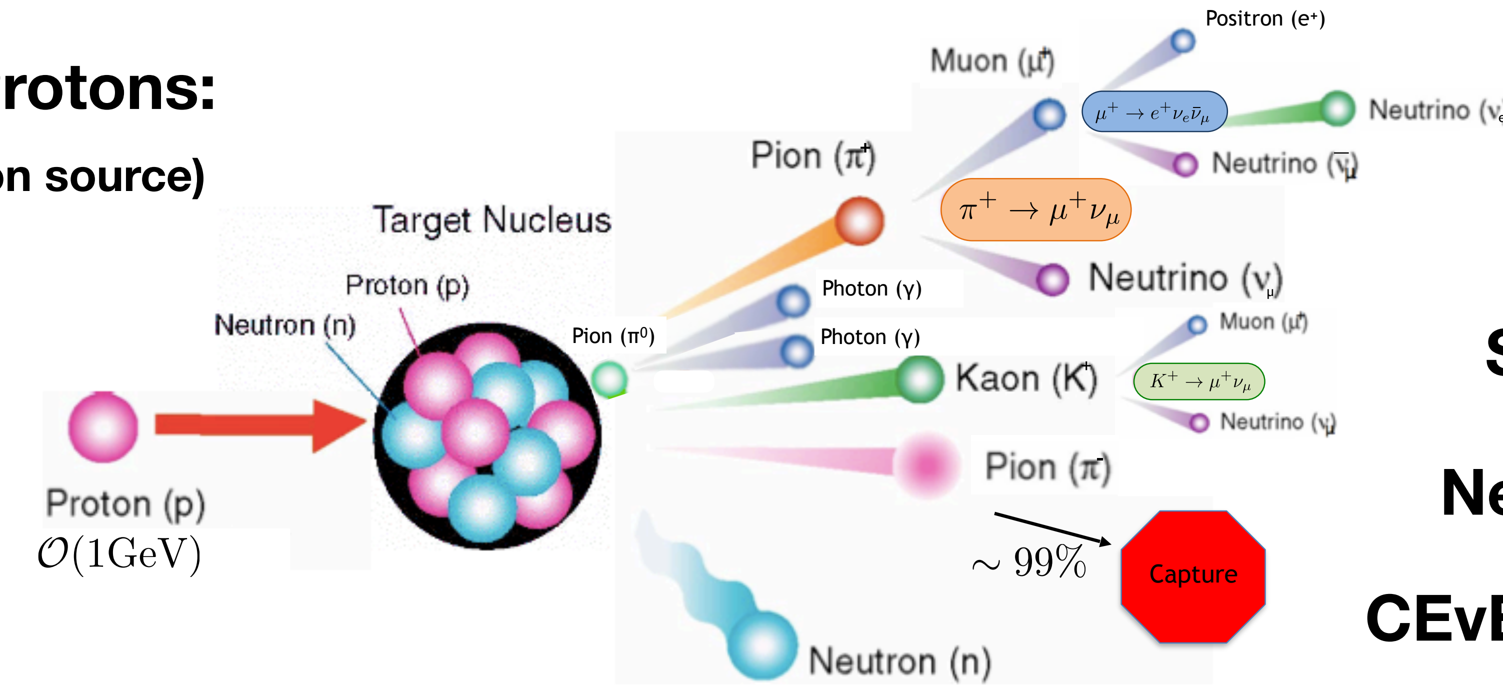
The two will be submitted to snowmass as a single white paper.

Contents

Dark sectors

~1 GeV Protons:

(stopped pion source)



π decay to light DM.

π, K decay to mediators
(e.g. axion-like particles, dark photons)

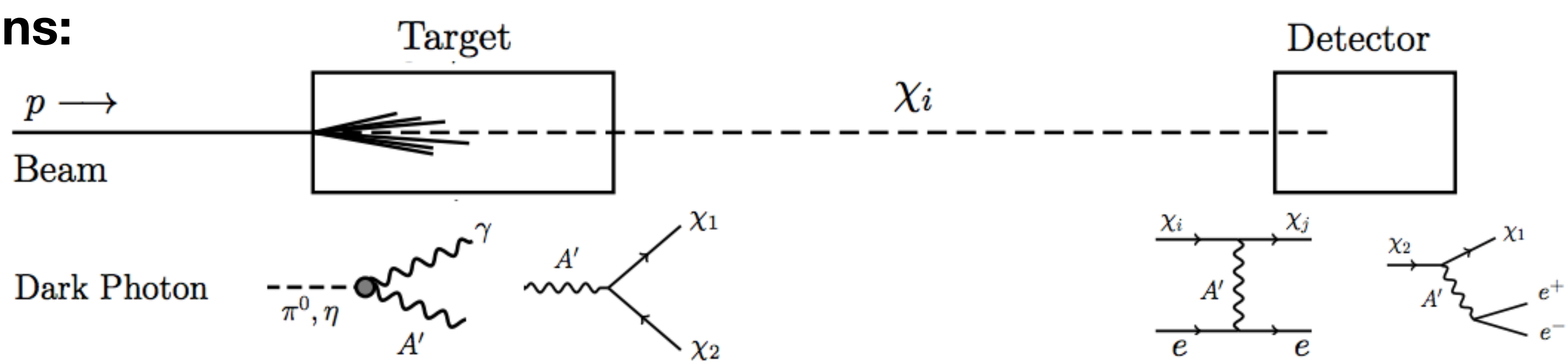
Sterile ν via oscillation.

Neutrino NSI.

CEvENS (requires low duty factor)

ν cross section and SN neutrinos

~10 GeV Protons:



Dark matter searches

see talk by M. Toups at workshop.

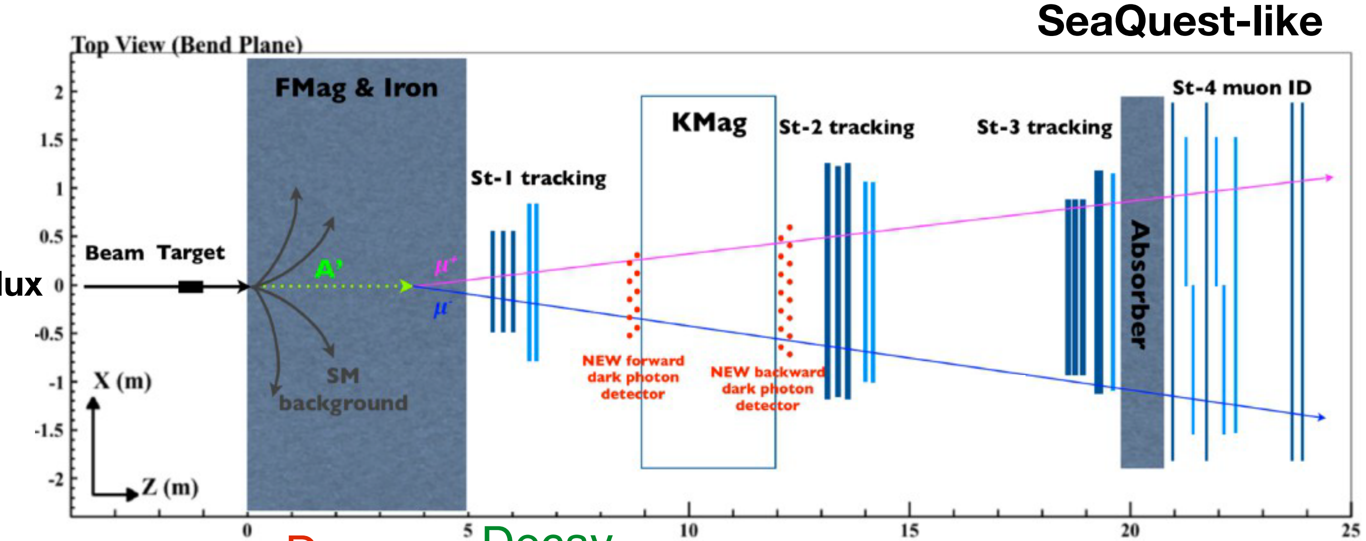
see talk by Gori

Highlights - Dark sectors

~100 GeV Protons:
("compact" beam dump)

say, 5% of LBNF flux

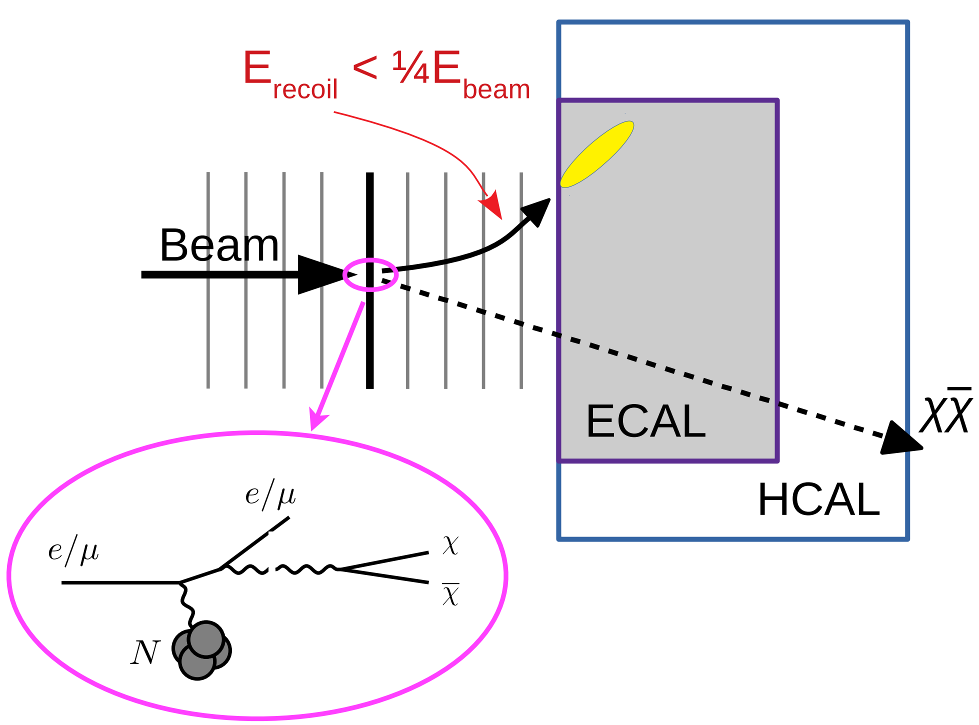
SeaQuest-like



Searches for displace decays. Mediators.

~Electrons (few GeV):

electron missing momentum

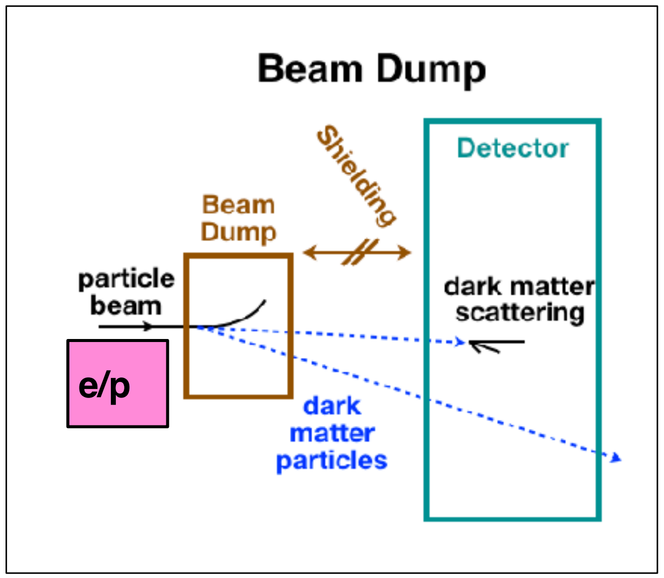


DM searches

Dark sectors

e-N scattering for ν cross sections

electron beam dump



DM + mediator searches

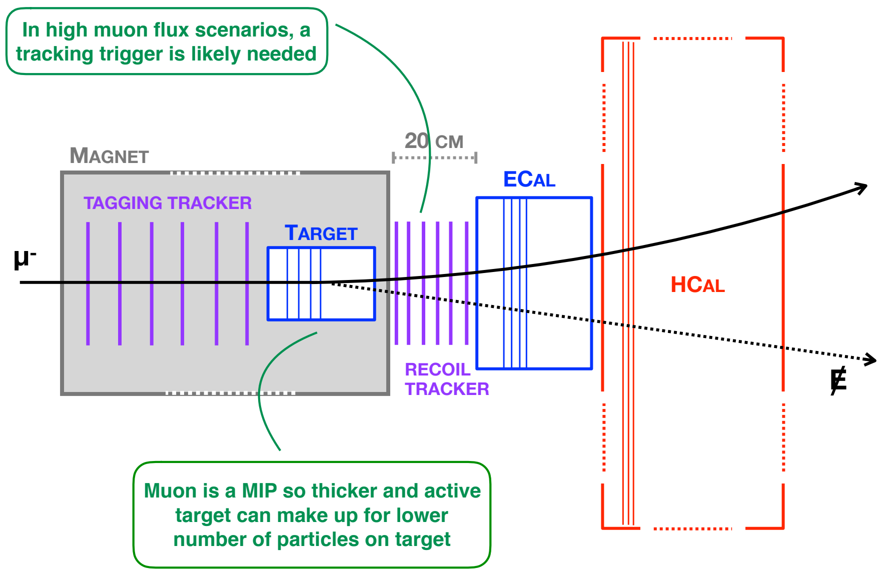
see talk by Krnjaic

Muons

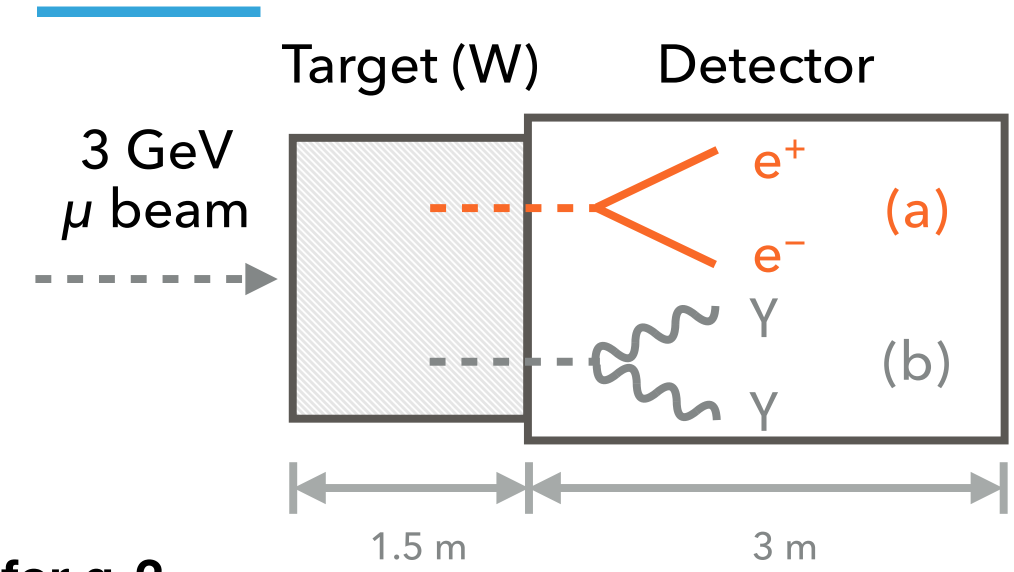
see talk by Krnjaic

Muon missing momentum

μ's (10+ GeV)



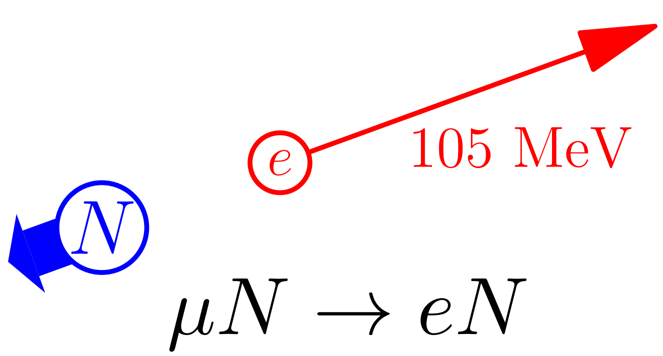
Muon beam dump

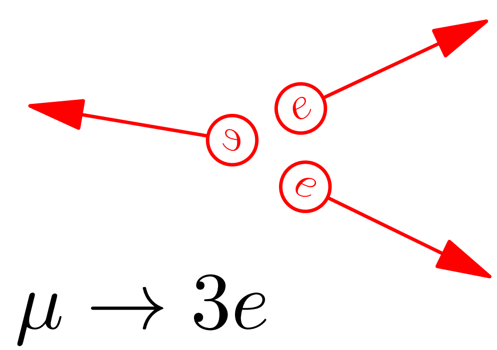


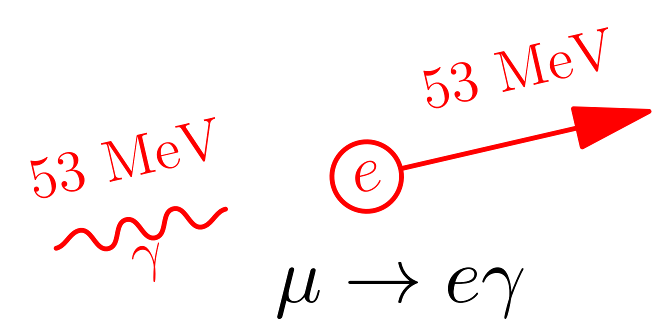
Mu-philic DM, models for g-2

Flavor Violating Muon:

Exploring opportunities to bring all world leading μ CLFV channels to FNAL



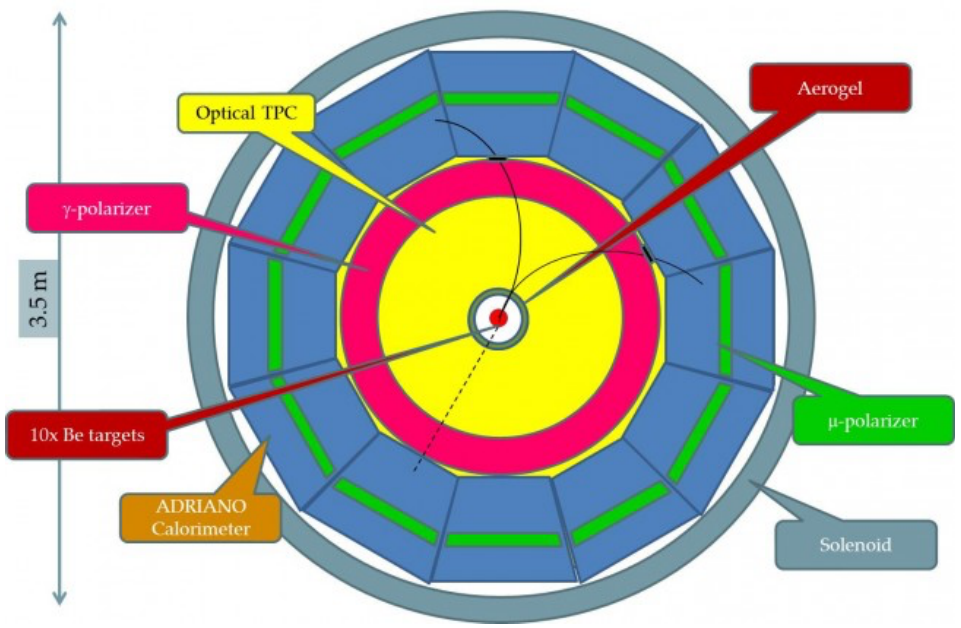




see talk by Gaponenko

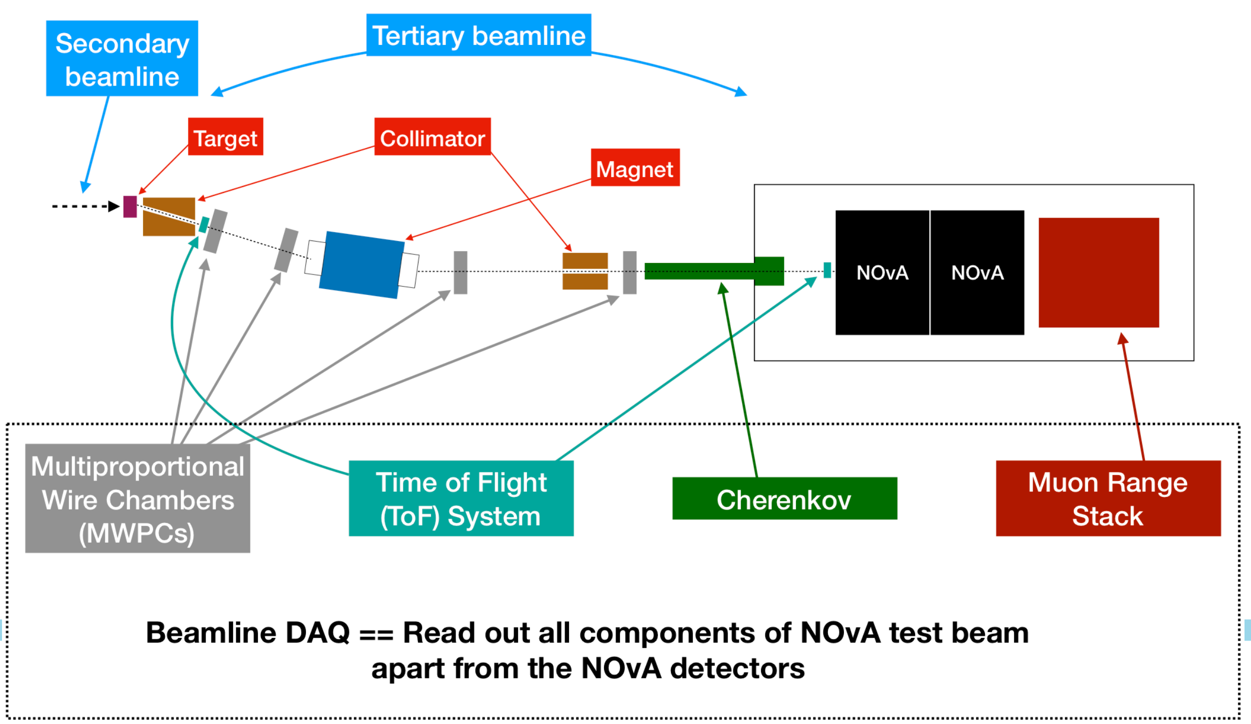
Hadrons

REDTOP - Rare eta decays and dark searches



Lead: Anna Mazzakane

R&D infrastructure: Test beam facility and proton irradiation



Lead: Petra Merkel

		Dark Sectors	ν Physics	CLFV	Precision tests	R&D
	Charged lepton flavor violation: muon to electron conversion			■		
	Charged lepton flavor violation with muon decays	■		■		
	Stopped Pion Source	■	■			
	Kaons Decay at Rest	■	■			
	DM searches with Intermediate Energy Protons	■	■			
	High Energy Proton Fixed Target	■				
electron exp.	Electron missing momentum	■	■			
electron exp.	Nucleon Electromagnetic Form Factors from Lepton Scattering		■		■	
electron exp.	Electron beam dumps	■				
	Muon Missing Momentum	■	■			
	N-Nbar oscillations				■	
	Muon Collider R&D and Neutrino Factories		■			■
	Tau Neutrinos		■			
	Rare Decays of Light Mesons	■			■	
	Proton Irradiation Facility					■
	Proton Storage Ring: EDM and Axion Searches	■			■	
	Test-beam Facility					■
	Physics with Muonium	■			■	
	Muon Beam Dump	■				

Global Efforts

The PAC commented that "In evaluating potential experiments, it will be important to consider the capabilities of existing other planned facilities, along with other experiments and facilities that are being developed".

- We have asked various proponents to address this in the write-up. The response obviously varies. (**see addendum at end of slides for a selection**).

Global Efforts - continued

Major actors in the field:

On a similar timescale envisioned for this program (mid-to-late 2020's), the **Spallation Neutron Source at Oak Ridge National Lab** will likely achieve a >2~MW, 1.3 GeV proton beam, along with a second target station.

The **Lujan Center at Los Alamos National Lab**, the **J-PARC Material and Life Science Experimental Facility**, and the **European Spallation Source (ESS)** are three additional spallation neutron sources providing 100 kW, 800 MeV proton beams, 1 MW, 3 GeV proton beams, and 5 MW, 2 GeV proton beams, respectively.

Experiments based on the **CERN SPS** at 400 GeV may also probe dark sectors. NA62 is the primary effort in this category (and SHIP in the future?). There is, however complementarity in reach (compared to a SeaQuest-based setup) due to the different beamlines. LHC based experiments (FASER, LHCB, Codex-B,…) are also active in this arena in a complementary way.

SLAC and **JLab** operate few GeV electron beams. Pursuing HEP goals often competes with other needs. LDMX may be making headway. A HEP-owned electron beam?

PSI is a major actor in muon experiments, as is **J-PARC** (COMMET). Fermilab has the capability to dominate this area.

Global Efforts - continued

- A common themes from the various experiments:
  - PIP CW and the upgrades booster will provide a unique combination of power and beam structure for physics.
  - There are current or future facilities that may be able to pursue a particular science goal. However, doing so often requires: further upgrades, R&D, space, beam time, effort, and/or will. This affects the physics reach and/or the probability of the experiment being pursued. In some cases there is a need for multiple facilities due to oversubscription(e.g. a test beam).
- Caution in interpreting:
  The goal of this document is not to evaluate the experiments and prioritize for the near term. Rather to identify opportunities and inform a design which may be around for ~50 years. The current snapshot of plans and aspirations may change on this time scale.
- We agree that this is valuable input when a more formal evaluation/selection is done. See slides with specific experiment info.

Appendix: Beyond the Main Injector

Questions that arose in discussion -

- After the booster is replaced, should one consider a future replacement to the main injector?
- LBNF energy was chosen with MI as a constrain. What happens if this is relaxed?

- Laura Field performed a GLoBES based study of this question, using sensitivity to CP and mass hirarchy in DUNE as figures of merit.
- Results are interesting. (Lower energy protons reduce the neutrino energy, also reduce “wrong sign” backgrounds.)

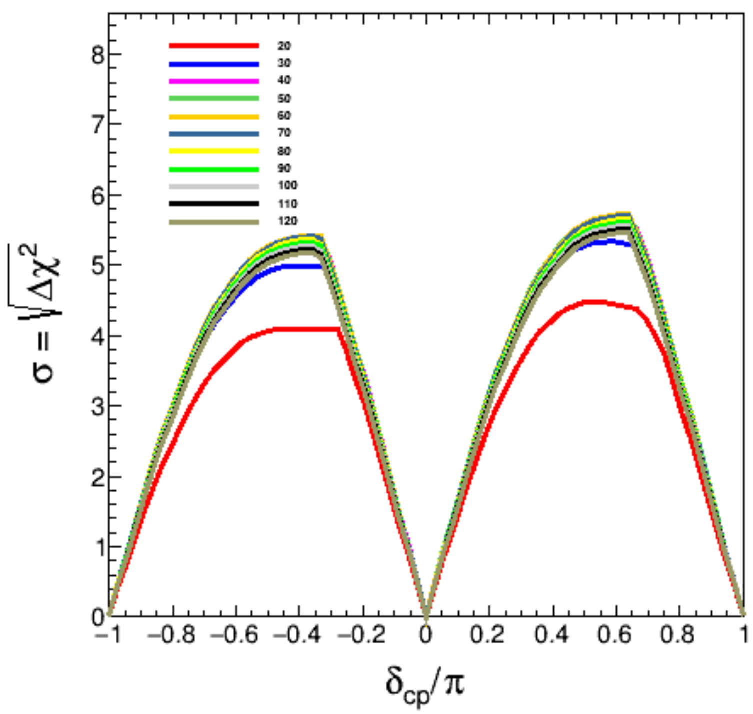
- This is added to the working group’s document as an appendix.

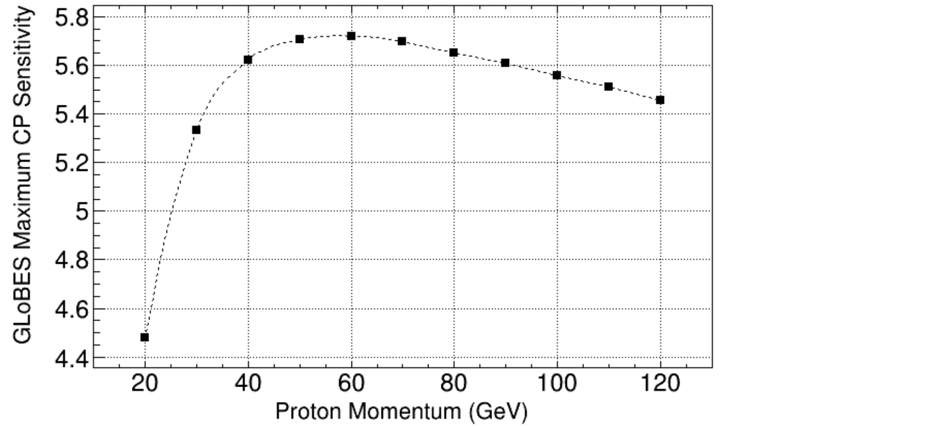
https://www.overleaf.com/read/scgtzvbngfxr

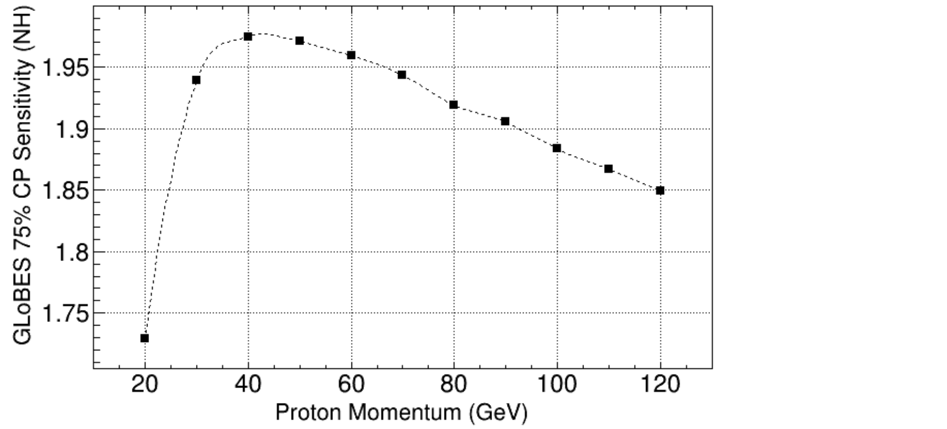
(Laura Fields)

Appendix: Beyond the Main Injector

The “flat” power assumption: power is independent of beam energy.







CP sensitivity versus delta_{CP}$with a 7 year exposure and a 40 kTon detector with 1.2 MW.

Important to note:

Delivering a high powered, >2.4 MW beam based off 30-40 GeV protons introduces new challenges, particularly for targeted and horns.

A 30 GeV proton beam may come with a different time structure. If more CW-like, the affects on DUNE physics should be studied (BSM exotic searches are likely to be affected).

Accelerator design effort

Accelerator Conceptual Studies

Using the present Main Injector infrastructure to attain 2.4 MW (and perhaps beyond) for DUNE, present Booster synchrotron creates a bottleneck

If the Booster were replaced in order to meet the desired increased power for DUNE, could a new system better address the science just outlined?

- Primary goals of present accelerator study:
  - Create straightforward path toward 2.4+ MW at 120 GeV with Main Injector
  - Optimize a new injector system to meet this goal, as well as meeting as much as possible the science objectives presented earlier
  - Enable future growth of higher-power, lower-energy accelerator complex, as well as ties to Main Injector and any future higher-energy accelerator systems
  - Identify necessary accelerator R&D, if any, for implementing the chosen scheme
  - Identify necessary target and beam line infrastructure needs and R&D required for new experimental site(s)

- Team of ~ dozen Fermilab experts meeting regularly since last Spring

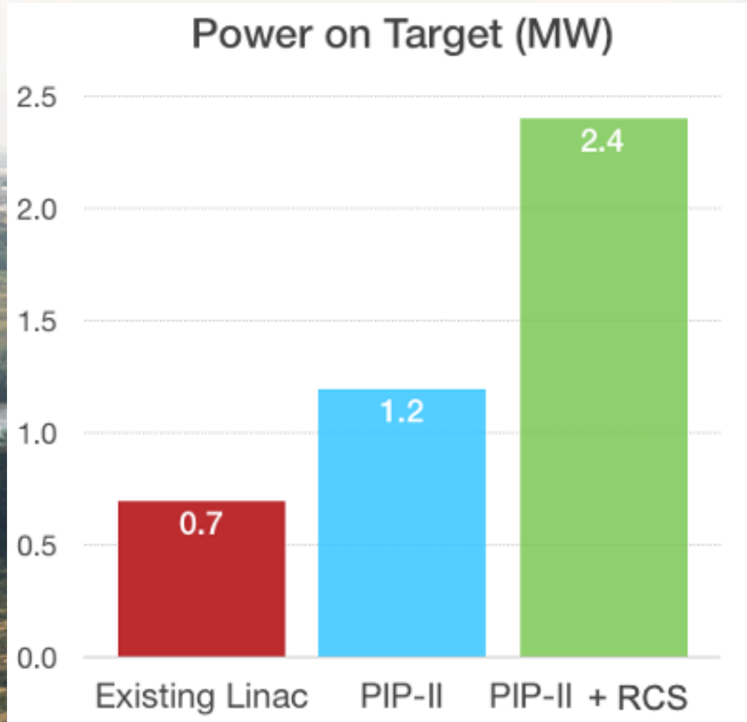
Highlights of the Scenario To-Date:

- Central to the scheme: new Rapid Cycling Synchrotron (RCS) system to replace existing Booster.
  - 8 GeV, to minimize the impact on existing Main Injector systems such as injection
  - higher repetition rate to reduce the fill time into the Main Injector (30 Hz, from 20 Hz)
  - optimize for high-intensity operation
  - make compatible with potential technology upgrades (i.e., nonlinear focusing, *etc.*)
  - include storage ring at injection energy for particle accumulation, charge exchange, bunch formation prior to delivery to actual RCS
- Extend PIP-II linac to 2 GeV
  - higher injection energy into the RCS system to mitigate space charge effects
  - energy chosen in coordination with lower-energy science opportunities
- Inject directly into Main Injector from RCS
  - slip-stacking operations in Recycler no longer required, simplifying the operation
- Enable path toward higher beam power beyond 2.4 MW
  - MI power supply improvements to reduce overall cycle time —> up to ~4 MW to DUNE
- Target Station R&D being identified to enable higher power operations

High-Level Parameters of Possible Upgrade Scheme

Parameter	Value	Unit	(PIP-II)
Linac Output Energy	2	GeV	0.8
Linac Beam Current (CW)	2	mA	2
RCS Output Energy	8	GeV	8
RCS Intensity	3.7	10^{13}	0.5
RCS Repetition Rate	30	Hz	20
RCS batches to Main Injector	5		12
Main Injector Intensity	1.9	10^{14}	0.8
Main Injector Cycle Time	1.5	s	1.2
Main Injector Beam Power	2.4	MW	1.2
Ultimate Main Injector Beam Power	4	MW	1.2

PIP-II Will Fuel Scientific Discovery at Fermilab



PIP-II SRF linac will enable

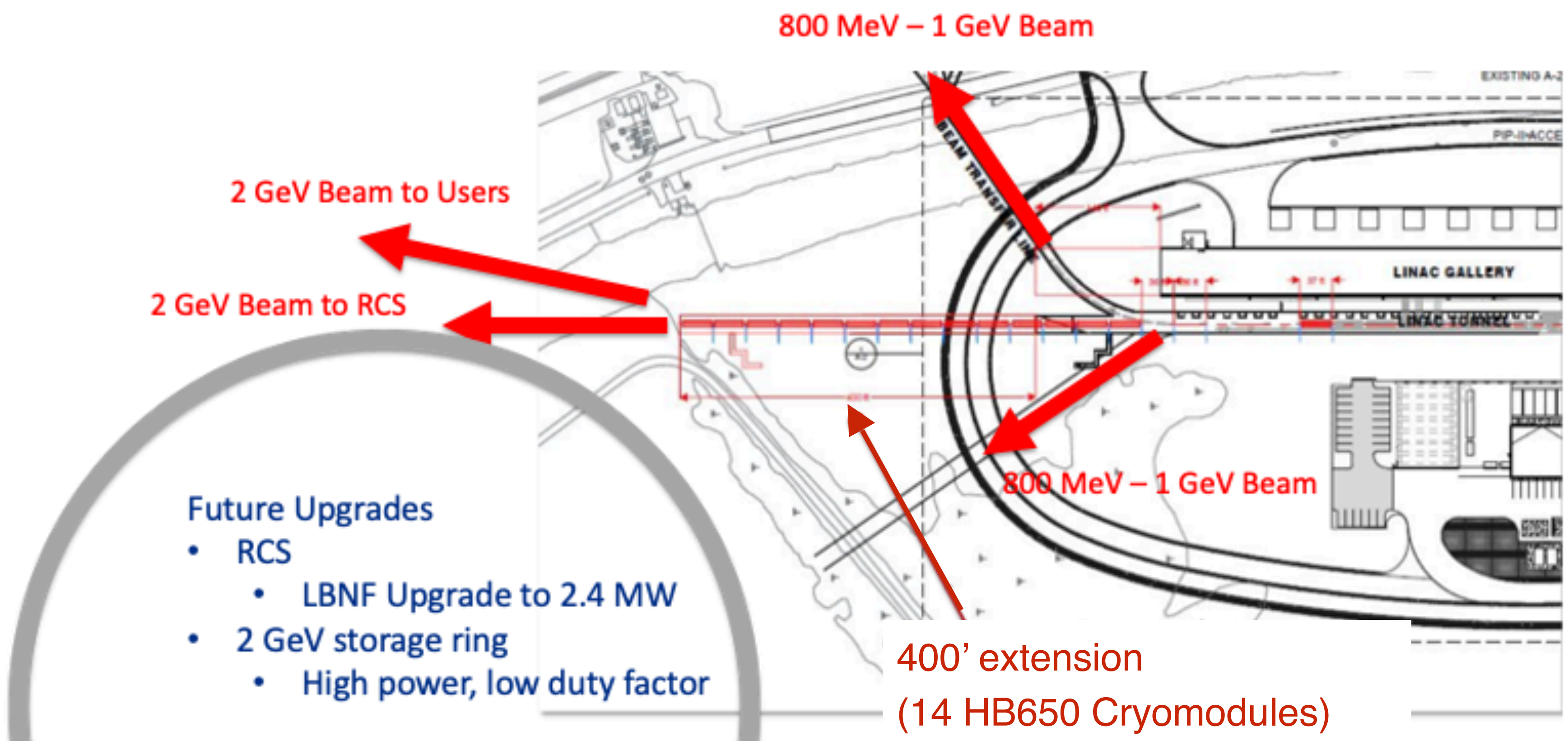
- Beam power upgrades
- Continuous beam mode
- Broader scientific reach
- Multi-user operations
- Upgradability

PIP-II Linac – Flexible, Extensible Proton Driver Compatible with Science Driven Upgrades

Linac Parameters	*PIP-II Multi-users*	*with 2 GeV Upgrade*	
Beam Energy	*0.8*	*2.0*	*GeV*
Ave. Beam Current	*2*	*2**	*mA*
Bunch Length	*4*	*4*	*ps*
Min. Bunch Spacing	*6.2*	*6.2*	*ns*
Max. H- per bunch	*4*	*4*	*10^8*
Beam Power	*1.6*	*4**	*MW*

- 2 GeV Energy Upgrade – 400' linac extension and additional 14 HB650 Cryomodules
- Multi-user capability provided by RF separators and fast switching magnets
- PIP-II will deliver customized beam patterns and intensities to users concurrently
- Can deliver H- and proton beams simultaneously

* - Average beam intensity can be increased if more powerful RF amplifiers are installed



Rapid Cycling Synchrotron (RCS)

- Replace present Booster with a modern RCS, with no transition-crossing and higher injection energy.
  - idea existed since Proton Driver 2 (2003), and Project X ICD-2 (2010)
  - major technical issues well-considered; now a question of design requirements and optimization strategy
- At 2 GeV injection energy, space-charge is manageable for ~3.7×10^{13} protons, removes need for slip-stacking in Recycler to reach 2.4 MW
- Injection time becomes an issue for high-intensity, fast-ramping RCS
  - Solution 1: Retrofit PIP-II linac for 5-10 mA pulses, 0.3-0.6 ms injection
    - This strategy has strong precedents at other facilities
  - Solution 2: Create 2 GeV storage ring for injection, transfer to RCS
    - With laser stripping, opportunity for ~ MW pulsed 2 GeV proton program
- RCS design capable of extracting 8 GeV every 30 Hz or 12 GeV at 20 Hz
  - 8 GeV makes transfer to MI straightforward (*present baseline design*)
  - 12 GeV might help with MI space-charge / beam-quality

Fermilab RCS upgrade Snowmass LOI AF2 092

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Rapid Cycling Synchrotron (RCS)

The RCS would operate at 30 Hz and accelerate from 2 to 8 GeV

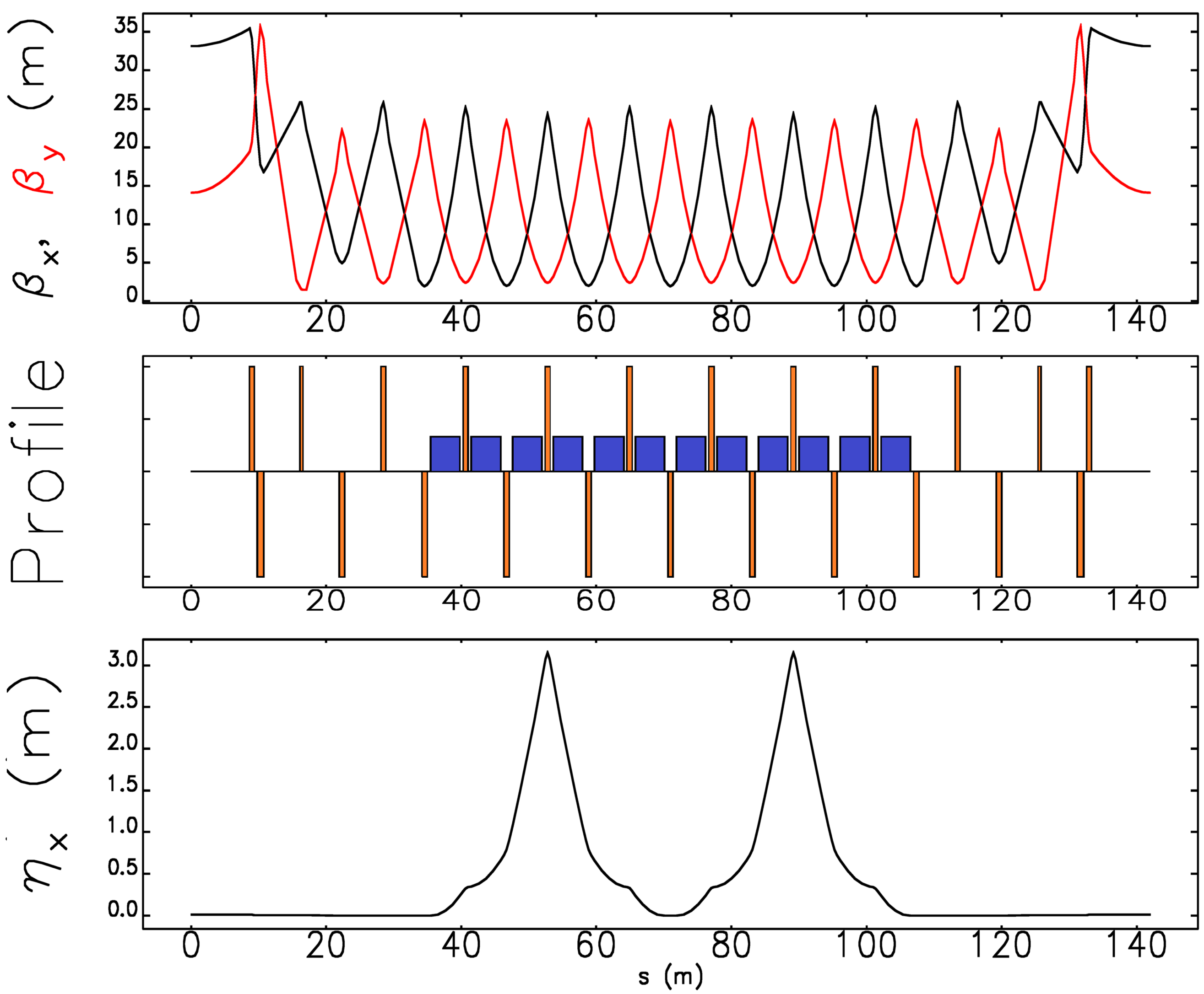
A second ring operating at 2 GeV is proposed to be located above the RCS and used to accumulate charge from the upgraded linac, improving the high-current beam injection and bunch formation before single-turn extraction into the RCS itself

RCS Parameters

RCS Circumference	*570*	*m*	*Min/max Dipole Field*	*0.31 — 1*	*T*
RCS Repetition Rate	*30*	*Hz*	*Min/max Quadrupole Gradient*	*4.2 — 14*	*T/m*
RCS Output Energy	*8*	*GeV*	*Dipoles per superperiod*	*8*	
RCS Intensity	*3.7*	10^{13}	*RF Frequency Range*	*50.326 — 52.812*	*MHz*
RCS pulses to fill Main Injector	*5*		*Total RF Voltage*	*1.9*	
Average Beam Current	*3*	*A*	*No. RF Cavities (@ 60 kV)*	*32*	
Superperiodicity	*8*		*Max. Available Beam Power*	*1.2*	*MW*

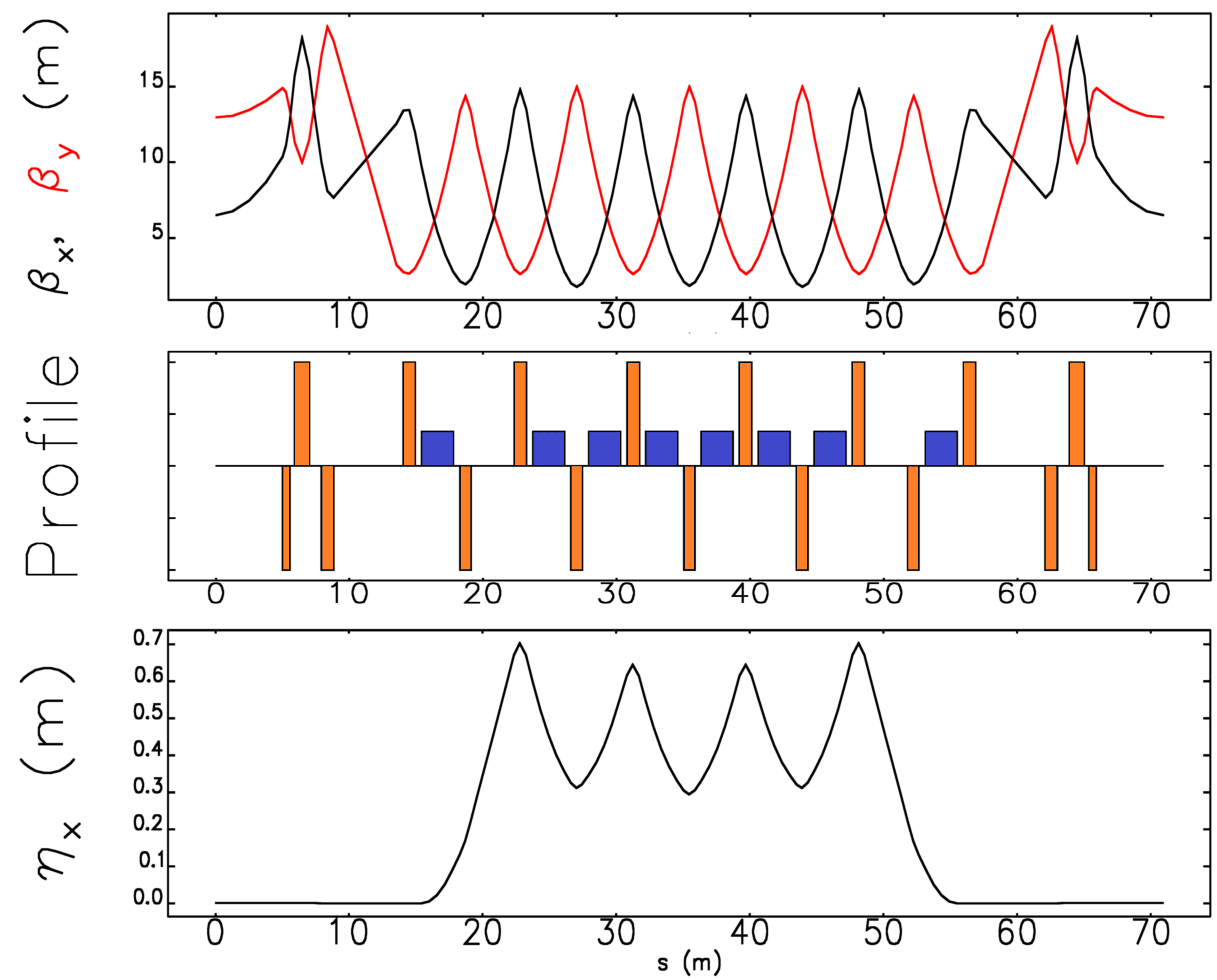
Preliminary RCS Lattice Configurations

2 GeV Injection Ring



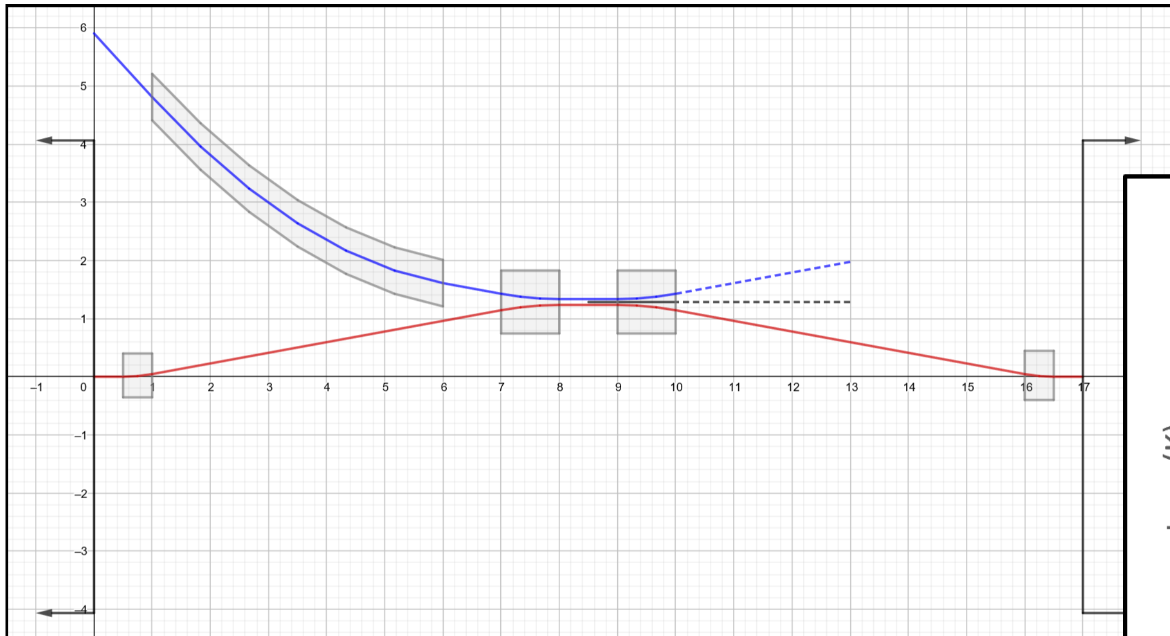
2 GeV Ring Optimized for Injection

2 - 8 GeV RCS Ring

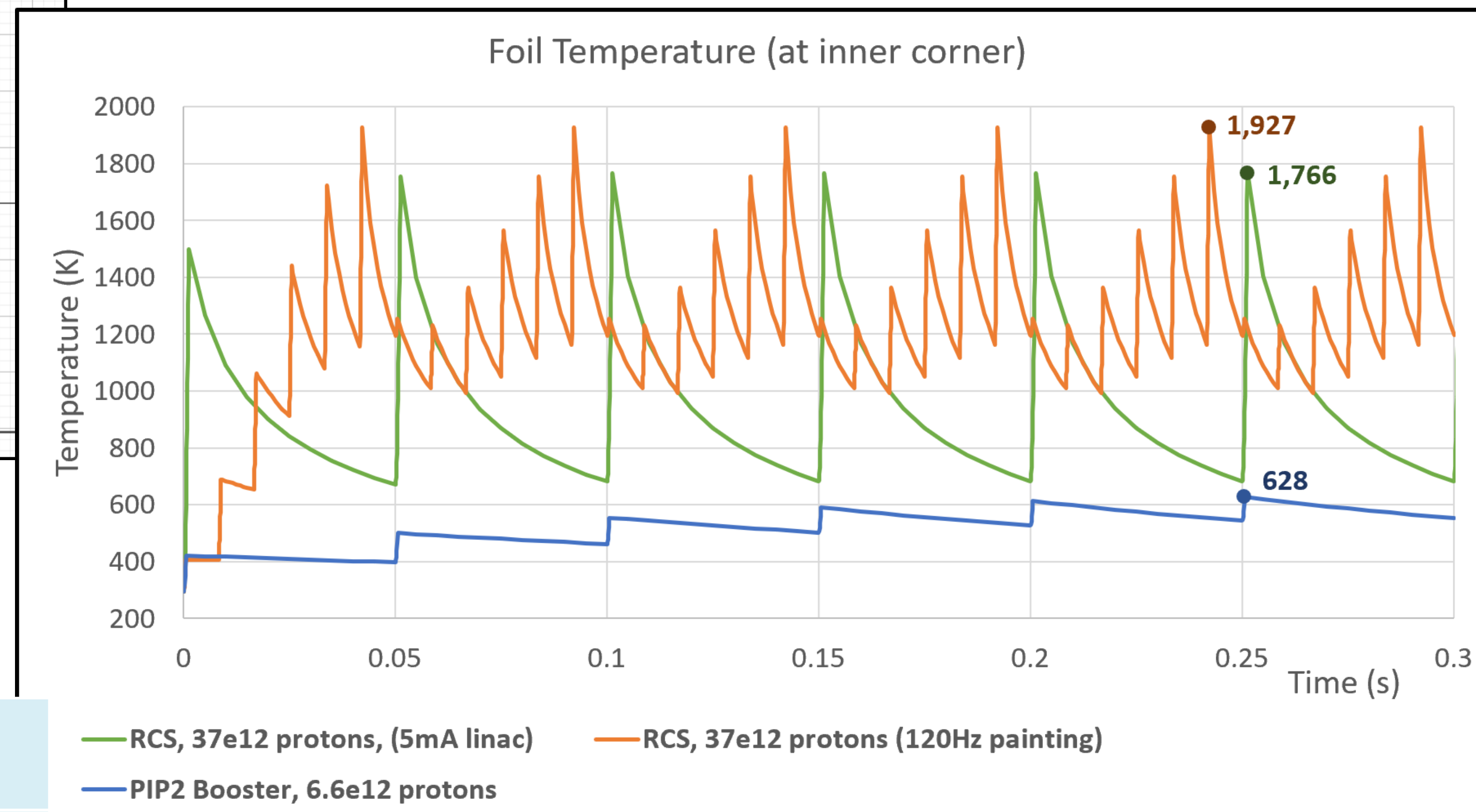


8 GeV Ring Optimized for Acceleration

Beam Accumulation and Charge Exchange in a Storage Ring



H- Charge-Exchange
Injection Straight Section

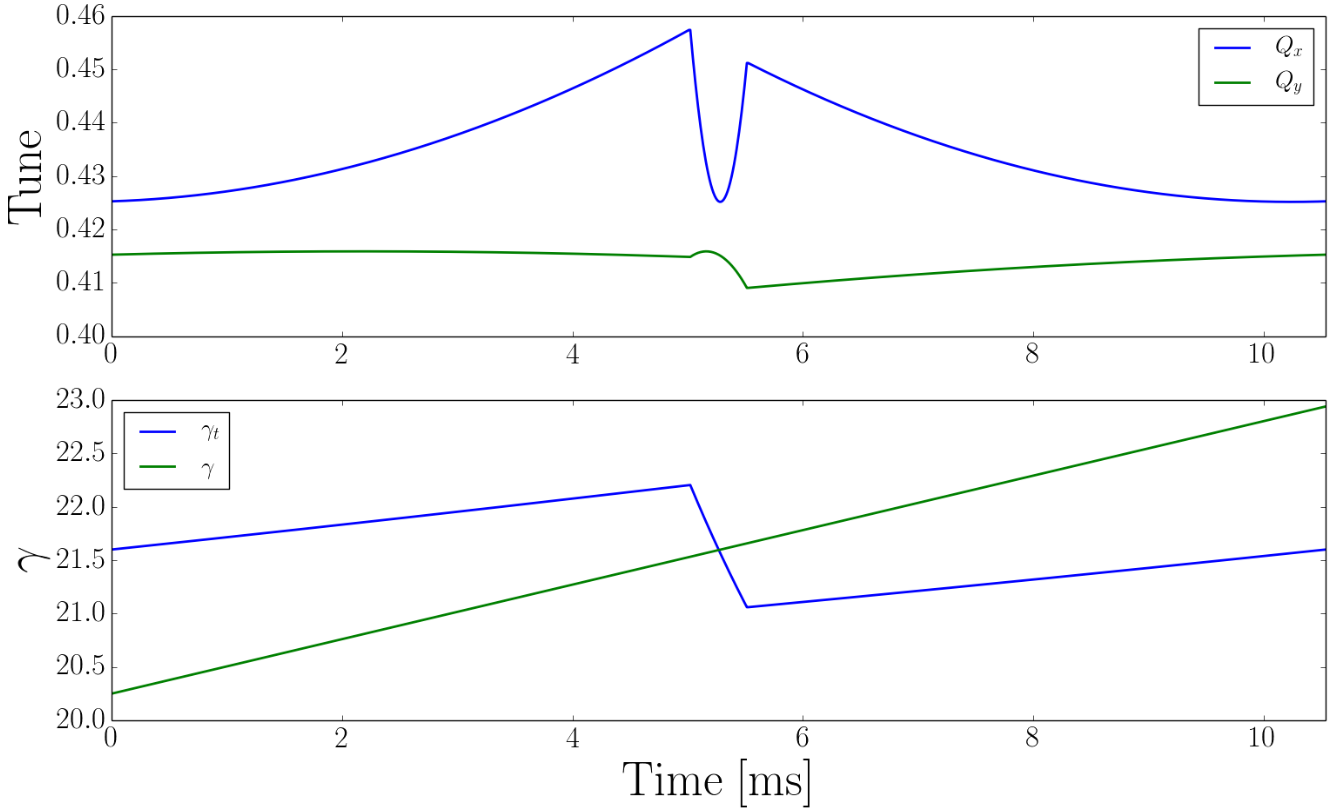


SR Circumference	***570***	***m***
SR Energy	***2***	***GeV***
Superperiodicity	***4***	
Injection Insertion Length	***12***	***m***
Dipoles per Superperiod	***12***	
Dipole Strength	***<0.5***	***T***

Perform H^- injection into storage ring, strip off electrons to produce pure proton beam; accumulate charge, and single-turn inject into RCS

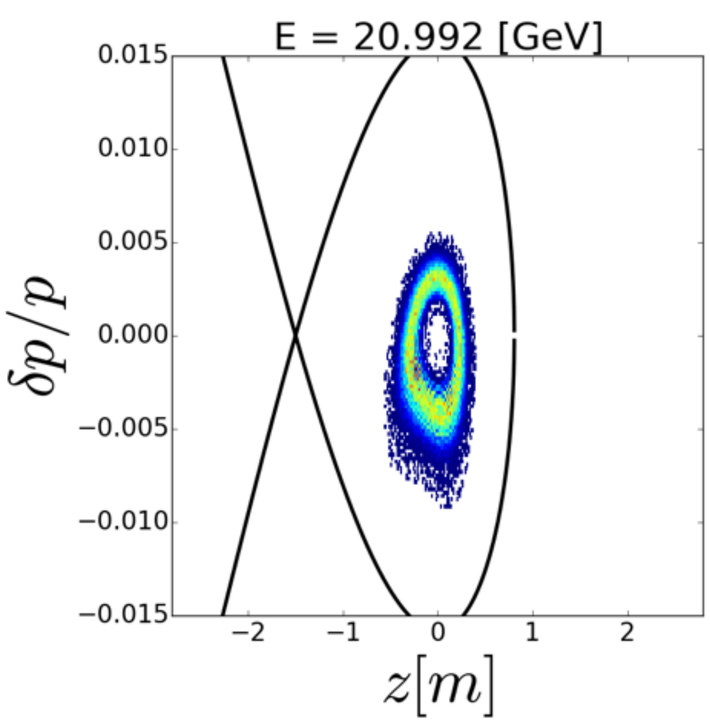
Main Injector Operations

- Keep 8 GeV injection into MI, re-using portions of Recycler as injection line
- Removing slip stacking operation (Recycler) creates lower momentum spread in MI; helps to alleviate issues at crossing of transition energy



"Transition": energy where revolution frequency is independent of momentum

Special optics manipulation at the transition energy (left; part of PIP-II) and smaller momentum spread provide adequate phase space through transition:



transition energy in
Main Injector (γ = 21.5)

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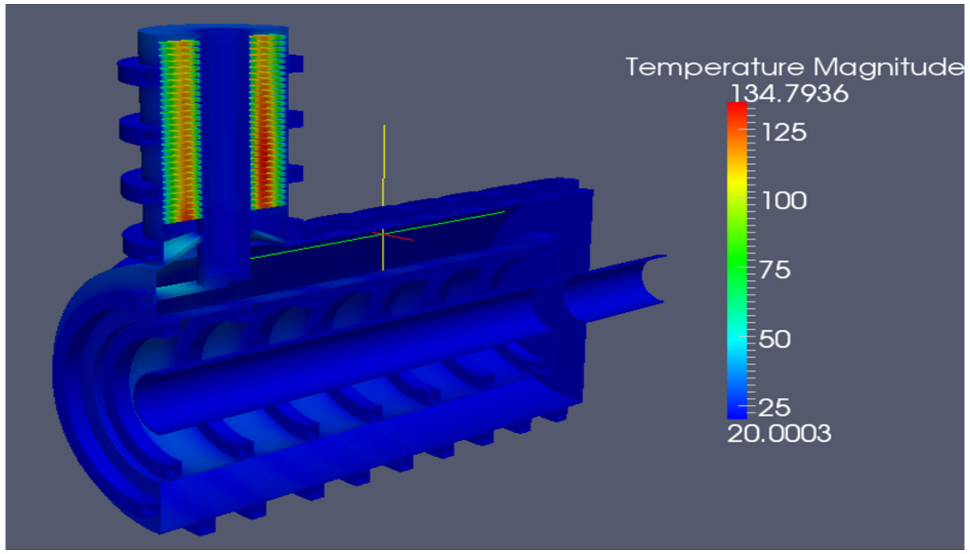
Main Injector RF System

- MI RF system would be upgraded with new modern RF cavity system
  - increases RF power to meet final intensity requirements
  - also enables increased ramp rate to achieve higher overall beam power above 2.4 MW

RF System Specifications		
Frequency	*52.617 — 53.104*	*MHz*
Max. Acceleration Rate	*240*	*GeV/s*
Acceleration Voltage	*2.7*	*MV*
Peak Beam Power	*7.1*	*MW*
Average Beam Power	*3.6*	*MW*
Peak Voltage	*4.8*	*MV*
Average Beam Current	*2.7*	*A*
Fundamental RF Current	*4.6-5.2*	*A*
No. RF Stations required	*31*	



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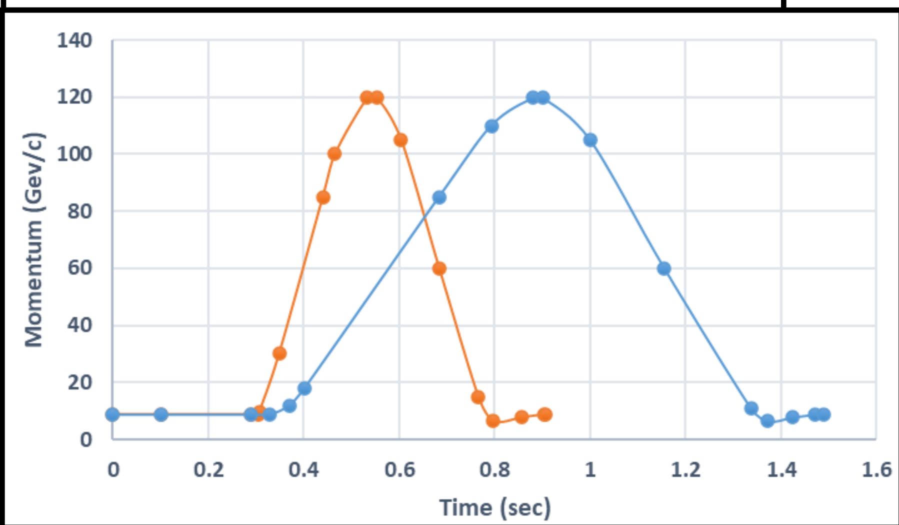
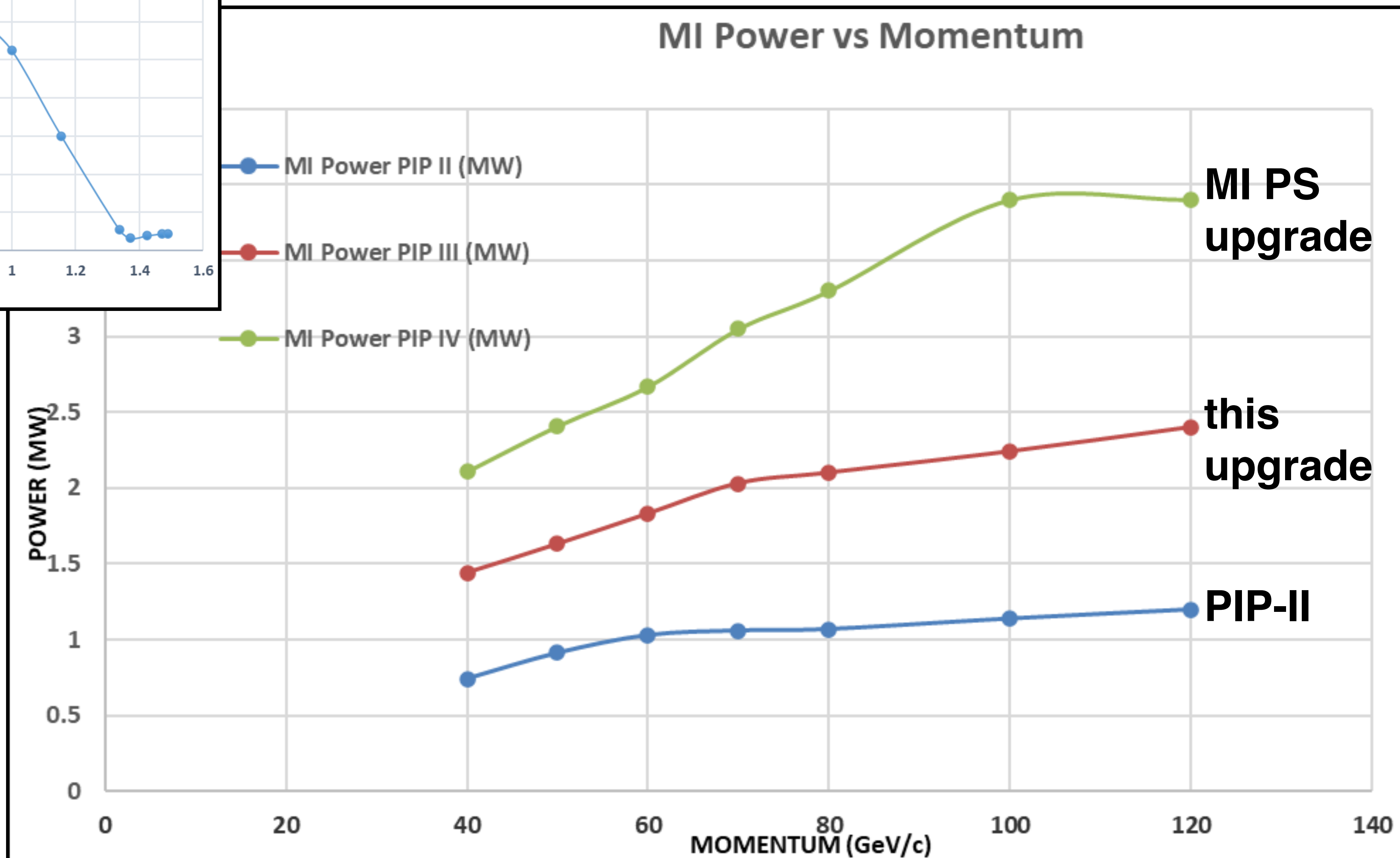
Possible MI Upgrade for Higher Power Beyond 2.4 MW

Upgrade magnet power supply system to support higher ramp rate — reduce cycle time from ~1.5 s to about 0.9 s — factor of ~ 5/3

240 GeV/s —> 600 GeV/s



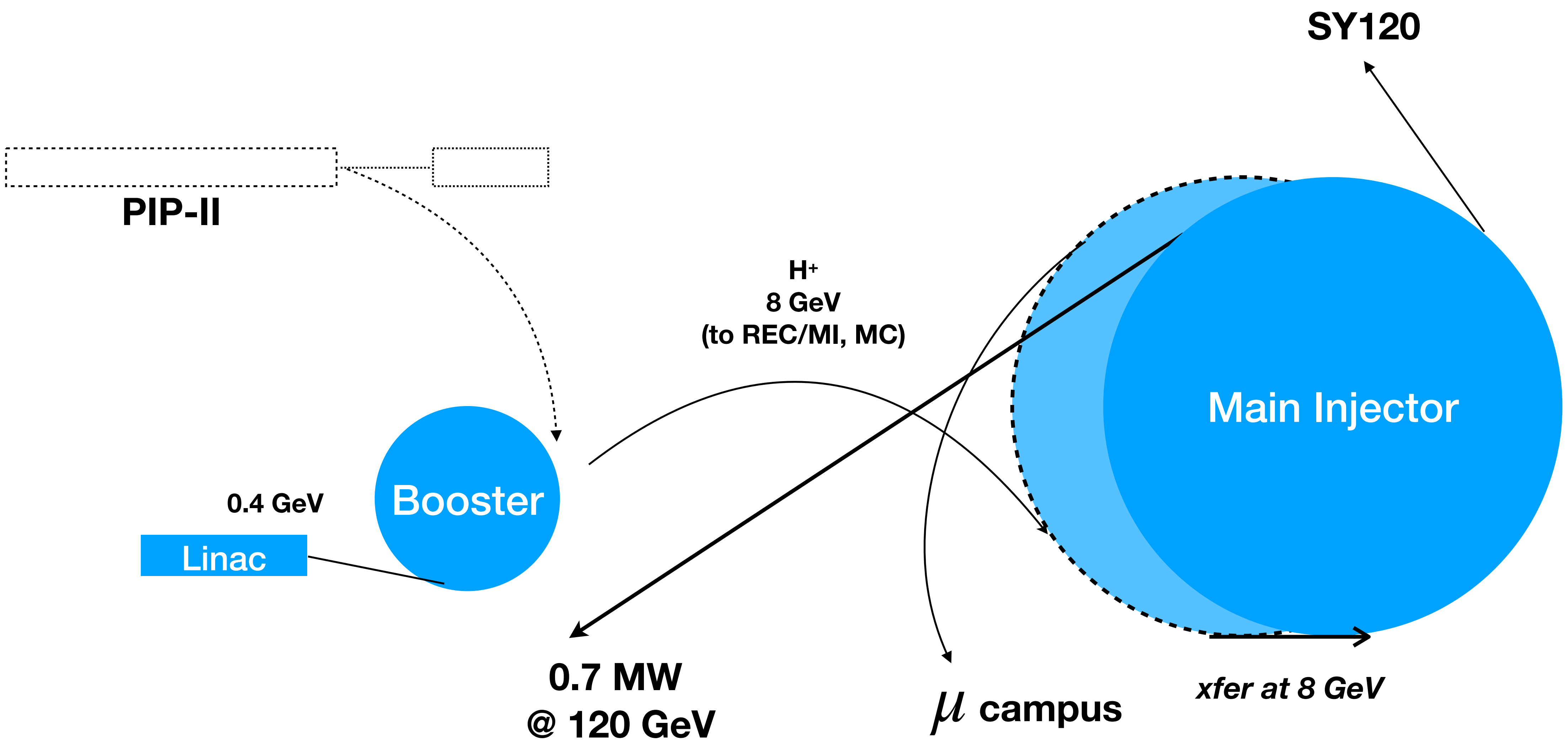


Schematic Only

Sketch of Upgrade Path

0.7 MW to DUNE

present-day

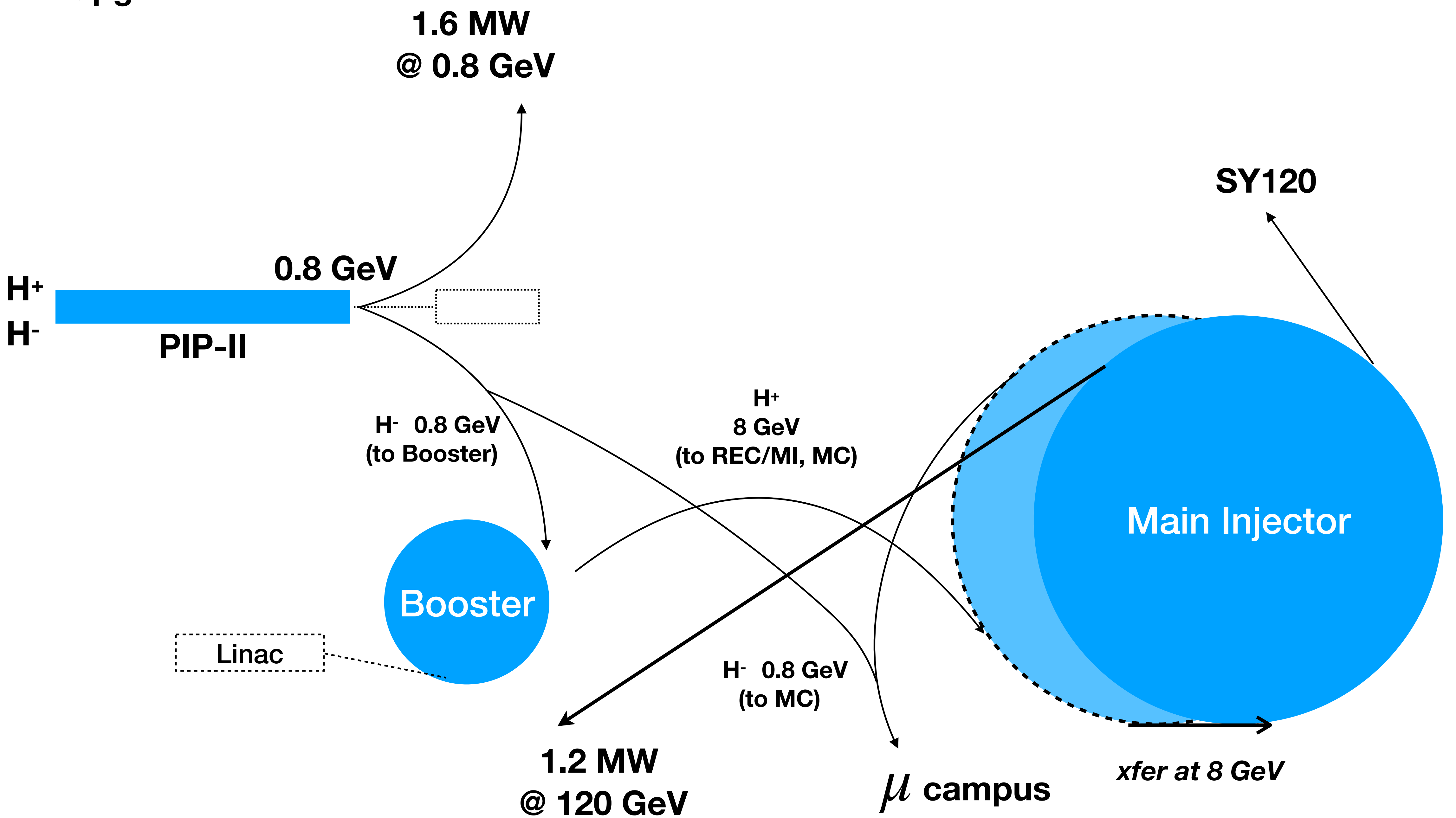


Schematic Only

Sketch of Upgrade Path

1.2 MW to DUNE + 1.6 MW @ 0.8 GeV

PIP-II Upgrade

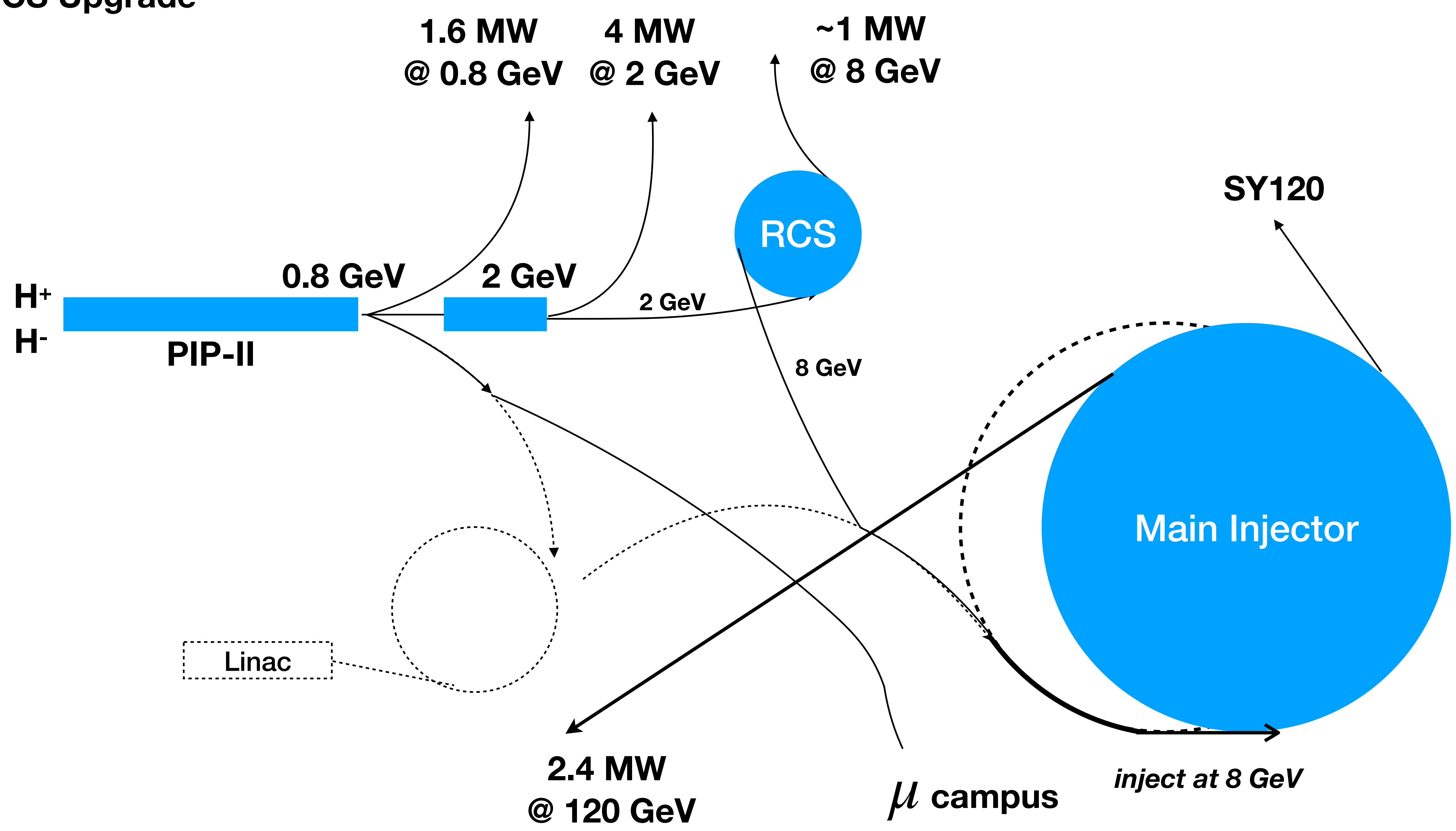


Schematic Only

Sketch of Upgrade Path

2.4 MW to DUNE + 1.6 MW @ 0.8 GeV &/or 4 MW @ 2 GeV &/or ~1 MW @ 8 GeV

RCS Upgrade



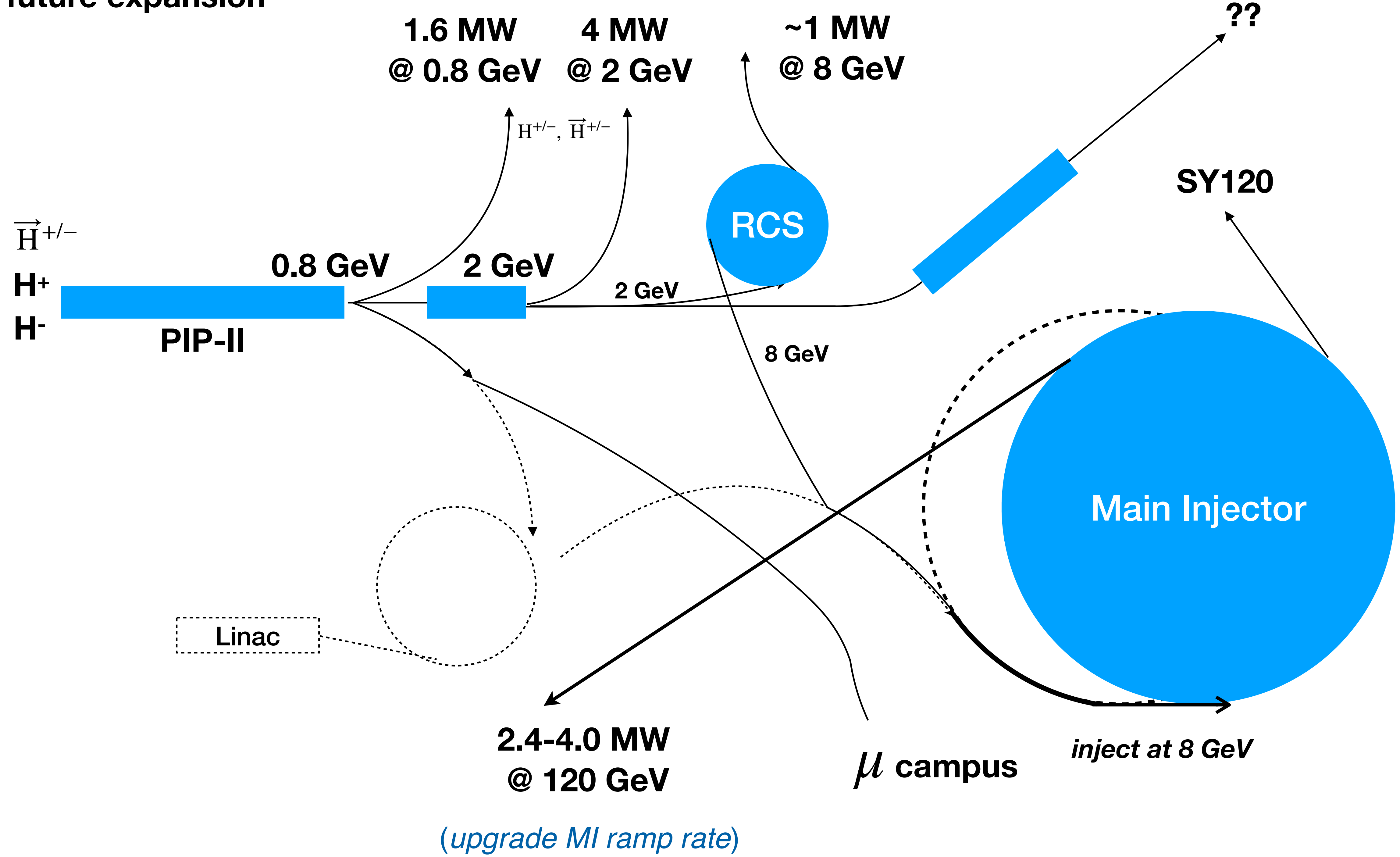
Fermilab

Schematic Only

Sketch of Upgrade Path

2.4 MW to DUNE + 1.6 MW @ 0.8 GeV &/or 4 MW @ 2 GeV &/or ~1 MW @ 8 GeV

+ future expansion



Fermilab

Addressing the Science

- 2 GeV CW-capable beam, 2mA
  - upgradeable to 4 MW shared with any pulsed 2 GeV program
- 2 GeV pulsed beam from SR, MW-scale
  - requires laser stripping and 2 GeV Storage Ring
  - 36-54 $\times 10^{12}$ at 60-120 Hz
  - investigating ~400 ns pulse compression
- 8 GeV RCS program, ~1 MW
  - 1 MW concurrent with 120 GeV program
  - upgradeable to ~2 MW with RCS ramp-rate and optics improvements
- 120 GeV DUNE/LBNF program, 2.4 MW
  - upgradeable to ~4 MW with MI ramp-rate
- 120 GeV Slow-Extraction program, 8×10^{12} over six seconds, once per min
  - loss-limited, may be highly upgradeable

Summary

- Science:
  - The BR science group, and the community, have provided a rich menu of physics opportunities to inform the design of the Booster Replacement.
  - Many of the opportunities will be best served by a HEP dedicated setting.
  - Informed thinking about beyond-main-injector facilities for DUNE.

- Accelerator Upgrade
  - Identifying plausible path to future accelerator upgrades that accommodates 2.4^{+} MW to DUNE, *and* creates opportunities for lower-energy high-flux science program
  - A large portion of the science opportunities can be enabled.
  - Presented here is a snapshot of current thinking, which continues to evolve and refine
  - Enables future upgrades beyond this one — higher rep rate in RCS, higher linac beam current, as examples
  - Targeting at such high power levels requires further R&D and careful consideration

- White Paper will outline the overall approach, and work will continue to pursue stated goals with input to/from upcoming Snowmass discussions

Back-Up Slides

Proposed Experiments (not exhaustive)

- 2 GeV CW-capable beam, 2mA
  - mu2e-like charged-lepton flavor violation experiment
  - Low energy muon experiments: CLFV decays, muon EDM, muonium
  - REDTOP run-II/run-III program (rare-decays)
  - polarized proton beams possible; pEDM
- 2 GeV pulsed beam from SR, MW-scale
  - stopped pion source experiments
  - dark matter search at GeV-scale
  - PRISM-like charged-lepton flavor violation experiments
  - neutron-antineutron oscillation experiments
- 8 GeV RCS program, ~1 MW
  - kaon decay-at-rest program
  - dark matter search from intermediate energy protons
  - proton irradiation facility
  - any successors to short-baseline neutrino program
  - NuSTORM and muon-collider R&D
  - Muon beam dump
- 120 GeV Slow-Extraction program, 8e12 over six second, once per min.
  - dark matter spectrometer experiment
  - muon missing-momentum experiment
  - test beam program

Addendum:
Global Perspectives on physics opportunities
(incomplete list: being populated)

Global perspectives:

Low energy stopped pion source:

There are 4 facilities that can support physics programs with some overlap with the program outlined here. On a similar timescale envisioned for this program (mid-to-late 2020's), the Spallation Neutron Source at Oak Ridge National Lab will likely achieve a >2~MW, 1.3 GeV proton beam, along with a second target station. Although the existing HEP experimental program in "Neutrino Alley" would not have sensitivities competitive with the Fermilab program laid out above, a scaled-up HEP program with dedicated space at the second target station would probe some of the same physics goals. The Lujan Center at Los Alamos National Lab, the J-PARC Material and Life Science Experimental Facility, and the European Spallation Source (ESS) are three additional spallation neutron sources providing 100 kW, 800 MeV proton beams, 1 MW, 3 GeV proton beams, and 5 MW, 2 GeV proton beams, respectively. While the ESS has a relatively large duty factor of 4\%, a proposed upgrade to the ESS would add a proton accumulator ring and provide 5 MW of 2 GeV protons for a decay-in-flight neutrino oscillation program with a much lower duty factor and has also been studied for its capability to support a beam dump physics program.

Global perspectives:

Muon program (Muon decays, Muonium, Muon Colliders)

As indicated in the table (from Snowmass LoI https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF0-AF0-007.pdf), PSI is currently the world leader in low-energy muon physics, with up to 9 x 10^8 muons/sec available. This capability is based on their megawatt 590 MeV sector-focused cyclotron. As shown in the attached figure (from https://indico.fnal.gov/event/45713/contributions/198278/attachments/135473/168006/Low-energy_Muon_Facility_Snowmass_2021_Townhall-final.pptx), 590 MeV is at the peak of surface muon production. Thus all recent low-energy muon physics experiments have been done at PSI.

Extending the reach of those experiments (including searches for mu–>e gamma, mu–>3e, and muonium–>antimuonium conversion and muonium spectroscopy and gravity measurements) will depend on future facility upgrades. Such an upgrade has been discussed at PSI, but the best way to do it has not yet been decided and the project is not currently proposed. There has also been discussion of creating a low-energy muon-physics facility at SNS at Oak Ridge, but such a project is not currently in the works.

PIP-II will be the world's most intense source of low-energy muons, both at Mu2e and possibly at a new facility to be proposed in the context of the Snowmass21 study.

Table 1: Comparison of Surface Muon Facilities and Mu2e

Facility	Max. (surface) μ rate (Hz)	Type	Comments
PSI [14]	9×10^8	CW	
TRIUMF [15]	2×10^6	CW	
MuSIC at Osaka [16]	10^8	CW	
J-PARC [17]	6×10^7	pulsed	
ISIS [17]	6×10^5	pulsed	
HIMB at PSI [13]	10^{10}	CW	(design goal)
Mu2e at Fermilab	10^{11}	pulsed	Not surface muons: $p_\mu \approx 40\,\mathrm{MeV}/c$
Mu2e with PIP-II	10^{12}	pulsed	Not surface muons: $p_\mu \approx 40\,\mathrm{MeV}/c$

Global perspectives:

CLFV - muon conversion:

Similar facilities: the COMET experiment in Japan is a competitor to Fermilab's present Mu2e. The author of the PRISM concept proposed constructing it in Japan \cite{Kuno:1997dr, Kuno:2000kd}, and an LOI has been submitted in 2003 \cite{2003-PRISM-LOI}. However it is not an officially approved project, and, for example, the 2019 roadmap report \cite{2019-KEK-roadmap} does not mention it. Fermilab is in a unique position to develop world leading muon physics program, which will include an evolution of Mu2e with the booster beam into Mu2e-II with PIP-II beam into a future muon conversion experiment using the infrastructure of the booster replacement accelerators.

CLFV - muon conversion:

Similar facilities: PSI conducts and active program of searches for LFV muon decays, and an upgrade of the muon beamline has been proposed. The upgrade plans to achieve the surface muon rate of the order of \$10^{10}\$ muons per second, by optimizing the pion production target and muon capture and delivery, but using the existing proton beam. The production target must be kept thin because the passing proton beam serves a spallation neutron facility. Muon production at Fermilab is free from such constraint, and higher rates should be achievable. Pursuing a program of LFV searches with muon decays at Fermilab in addition to the muon conversion searches will exploit synergies between positive and negative muon beams and grow the experimenter community.

Global perspectives:

REDTOP:

Although REDTOP could run in untagged mode in several laboratories (i.e Fermilab, BNL , ESS, etc.) , PIP-II is the only accelerator capable of providing the beam required to run in tagged mode and to produce the required luminosity for a discovery. Furthermore, the missing 4-momentum technique would make the experiment sensitive to long-lived dark particles. Similar to B-factories, but with x40,000 the yield.

Global perspectives:

10 GeV based dark sector searches:

There are no other similar facilities in the world currently or planned in the next five years that can directly probe for dark matter masses up to 1 GeV with a medium energy proton beam. This is a unique opportunity for FNAL to leverage existing SBN resources to lead the dark matter search and to directly probe relic density limits at the sub-GeV mass scale.

KDAR:

The best KDAR source in the world, J-PARC, currently operates at 600~kW. This will upgrade in the next couple of years to 1000~MW. Currently, JSNS^2 operates a 17~ton fiducial volume of liquid scintillator neutrino detector at 24~m from this source. So, the Booster replacement and/or associated detector(s) will need to best this in some way in order to be competitive.

N-Nbar:

The proposed source's integrated flux would be superior to all other operating or planned facilities (particularly for its integrated flux), with UCN sources currently operating at the Institut Laue-Langevin, the Paul Scherrer Insitute, Los Alamos National Laboratory and the Mainz Triga reactor, with sources under construction at the Petersburg Nuclear Physics Institute and TRIUMF. A conceptual analysis of a neutron-antineutron experiment at the PNPI source \cite{Fomin:2017} found possible improvements of 10 to 40 times current direct experimental limits, depending on the wall reflection model for their experimental geometry and expected source performance.

Global perspectives:

120 GeV Based Dark sector searchs:

Dark sector searches with the DarkQuest apparatus provide a unique opportunity, particularly in the near term. In general, the very short beam dump baseline ($\sim$5\,m) probes a challenging region of the lifetime/coupling phase space. The primary effort which is similar to DarkQuest is the NA62 experiment at CERN. However, the baseline of the experiment ($\sim$400\,m) for a similar beam energy means that the two efforts are quite complementary -- probing complementary regions of phase space. FASER at the LHC is another similar effort, though being at a colliding beam requires a longer time to integrate necessary statistics (over the life of the HL-LHC) to reach their planned sensitivity.

Electron Missing Momentum:

The LDMX is being primarily planned at SLAC, but that is not yet set in stone. There are no planned missing momentum/energy/mass searches in the world that have the sensitivity that LDMX has planned. NA64 at CERN is the nearest competitor sensitivity-wise and uses the missing energy technique. However, it doesn't not reach the sensitivity of LDMX (or an LDMX-like experiment) and will not reach all thermal relic density milestones for sub-GeV dark matter.

Global perspectives:

Test Beam

There is strong international demand for increased test beam resources. FTBF, CERN, DESY, and other test beams are heavily subscribed and subject to various operational limitations. A new facility at Fermilab would enable robust detector $R\&D$ across all frontiers looking forward.

Irradiation Facility

The current Fermilab Irradiation Test Area (ITA), which is under construction right now at the end of the LINAC, is designed for fluences needed for the HL-LHC detector upgrades. However, for future collider detectors doses up to two orders of magnitude higher are expected. It is paramount that detector elements under development can be tested for radiation hardness to these levels. Currently, there is no facility in the world, that would allow such tests at a reasonable timescale.