Accelerator Capabilities Enhancement:

Alignment to P5 and Challenges

Vladimir SHILTSEV

(with input from Cons, Mary, Sergey B. and Paul)

Fermilab ACE Workshop, Jan. 30-31, 2023

1. Snowmass'21 and P5 (2023)

2. LBNF/DUNE Phase I → II

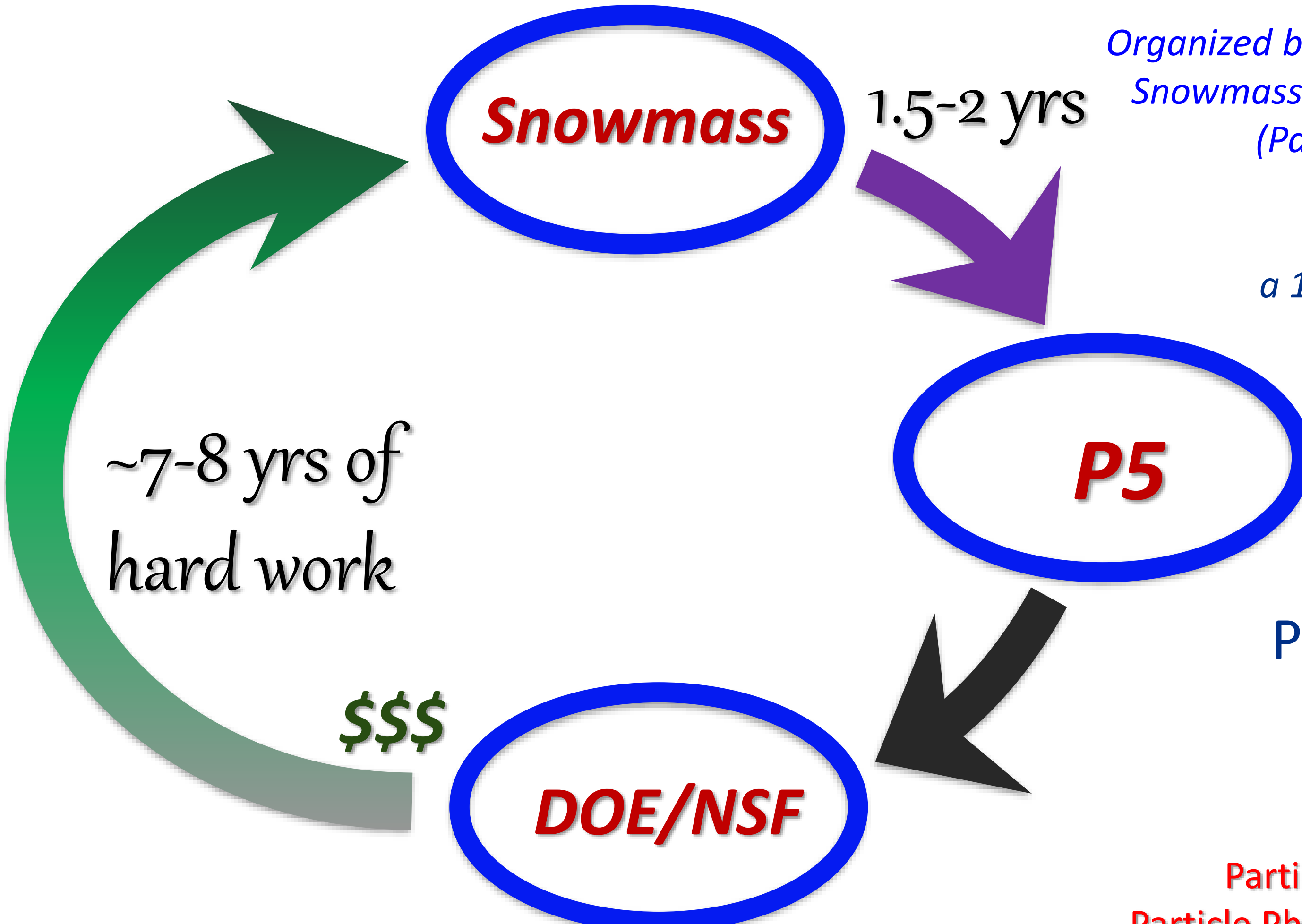
3. Accelerator Options → ACE

4. Challenges (performance, reliability, timeline)

Snowmass 2021

Snowmass'21

"a particle physics community strategic planning study"



Organized by APS DPF, DPB, et al
Snowmass provides input to P5
(Particle Physics Project
Prioritization Panel)
which develops
a 10-20 yrs strategy for
the US HEP program

~ 1 yr

Particle
Physics Project
Prioritization
Panel

Particle Physics is global
Particle Physics is not isolated

https://www.snowmass21.org/

Snowmass'21 Accelerator Frontier Conveners

Snowmass 2021

Steve Gourlay
(LBNL)

Tor Raubenheimer
(SLAC)

Vladimir Shiltsev
(FNAL)

(AF – one of 10 frontiers, incl. Neutrino, Rare Priocesses, Energy, etc)

Focus:

- Understand the most important questions for the field of *Accelerator Science and Technology*
- Identify promising opportunities and tools to address them
- Consider a mix of large, mid, and small scale accelerators as well as R&D
- ➤ **Provide information to P5 to help develop a strategy for the US HEP**

AF Report: Executive Summary

Snowmass 2021

arxiv:2209.14136

"Intro":

- Since last P5, this Snowmass'21 process

"Future Facilities":

- *TBD by P5* – accelerator/people need to be part of P5; ITF analysis can greatly help
- *Multi-MW FNAL complex upgrade* will be priority for NF in 2030 (AccFrontier is ready)
- Many opportunities for Rare Processes (AF ready), incl. *PAR and utilize what we have*
- Several Higgs/EW factories are feasible: *FCCee, C3 and HELEN* to be explored
- *O*(10 TeV/parton) needed for >2040's, *muon colliders* to be explored/ pre-CDR by 2030
- Need an *Integrated Future Colliders R&D program* in OHEP to provide design reports by next Snowmass/P5'2030 and engage internationally (FCC, ILC, IMCC)

Accelerator Frontier

S. Gourlay, T. Raubenheimer, V. Shiltsev

(Top Level) Snowmass Summary

Snowmass 2021

arxiv:2301.06581

SLAC-PUB-17717
January 2023

Report of the 2021 U.S. Community Study
on the Future of Particle Physics
(Snowmass 2021)

Summary Chapter

2021 – 2022 Snowmass Steering Group

Joel N. Butler, R. Sekhar Chivukula,
André de Gouvêa, Tao Han, Young-Kee Kim,
Priscilla Cushman (APS Division of Particles and Fields),
Glennys R. Farrar (APS Division of Astrophysics),
Yury G. Kolomensky (APS Division of Nuclear Physics),
Sergei Nagaitsev (APS Division of Physics of Beams),
Nicolás Yunes (APS Division of Gravitational Physics)

Snowmass 2021 Frontier Conveners

Editor: Michael E. Peskin

Science Drivers (6 pages)

(Brief) Frontier Summaries (~40 pages)

(Brief) Cross-Frontier Topics (~10 pages)

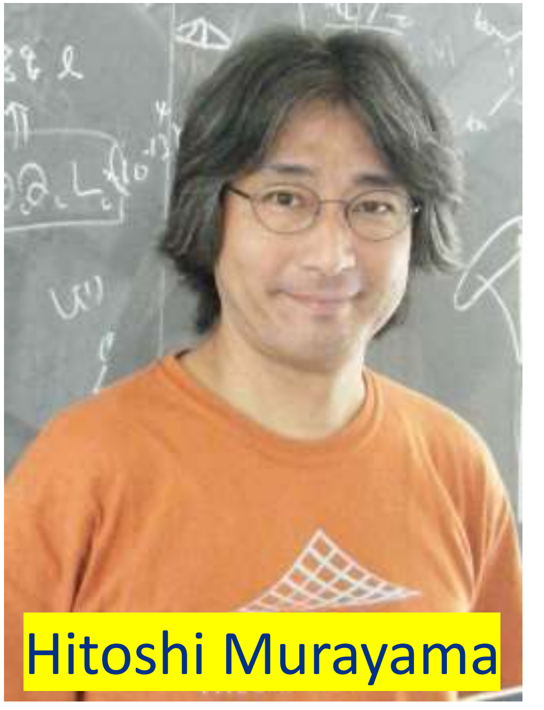
High-Level Conclusions (4 pages)

10 The Future of U.S. Particle Physics: Summary of Snowmass 2021

Frontier/Decade	Coming Decade (2025 - 2035)	Next Decade (2035 -2045)
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		Higgs Factory Construction
Neutrino Frontier	LBNF/DUNE Phase I & PIP- II	DUNE Phase II (incl. proton injector)
Cosmic Frontier	Cosmic Microwave Background - S4	Next Gen. Grav. Wave Observatory*
	Spectroscopic Survey - S5*	Line Intensity Mapping*
	Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		Advanced Muon Facility

Table 1-1. *Large-scale projects or programs (total projected costs of $500M or larger) endorsed by one or more of the Snowmass Frontiers to address the essential scientific goals for the coming and next decades. Projects were not prioritized, nor examined in the context of budgetary scenarios. In the observational Cosmic program, project funding may come from sources other than HEP, as denoted by an asterisk.*

…and Now It's All to P5



- **Chaired by Hitoshi Murayama**
- **Web site: http://hitoshi.berkeley.edu/P5/**
- **Charge**
- **Composition: 29 total, 4 from accelerators, 2 from Fermilab**
- **"Town Halls":**
  - **Week of March 20, 2023 :** Fermilab/Argonne, *Neutrino, Rare Processes and Precision Frontier, High-Energy Astrophysics*
  - **Early Career (virtual) townhalls:**
    - week of May 15
    - week of June 5
    - week of June 26


Petra Merkel


Bob Zwaska

Fermilab PIU Group

- **Proton Intensity Upgrade Central Design Group**
- **By request of the FNAL Director…** ***"our message to P5 (on 2+MW upgr.)"***
- **Members from AD, TD, PPD, ND, LBNF/DUNE, …**
- **Report: in progress, ~50+ pages, options, risks, R&D, timeline, etc**
- **Steve Brice seminar**
  - **(soon, tbd)**
- **Presentation to P5 (tbd)**

Steve Brice

Brenna Flaugher

Report from the Fermilab Proton Intensity Upgrade Central Design Group

Robert Ainsworth[1], Giorgio Apollinari[1], Tug T Arkan[1], Sergey Belomestnykh[1], Pushpalatha C Bhat[1], S.J. Brice[1], Brian Chase[1], Mary E Convery[1], Steven J Dixon[1], Jeff Eldred[1], Grigory Eremeev[1], Brenna Flaugher[1], Jonathan D. Jarvis[1], David Johnson[1], Jonathan Lewis[1], Richard Marcum[1], Sergei Nagaitsev[1], David Neuffer[1], Donato Passarelli[1], Frederique Pellemoine[1], William A Pellico[1], Sam Posen[1], Eduard Pozdeyev[1], Alexander Romanenko[1], Arun Saini[1], Kiyomi Seiya[1], Vladimir Shiltsev[1], Nikolay Solyak[1], James M Steimel[1], Diktys Stratakis[1], Alexander A Valishev[1], Mayling L Wong-Squires[1], Slava Yakovlev[1], and Robert Zwaska[1]

[1]Fermi National Accelerator Laboratory

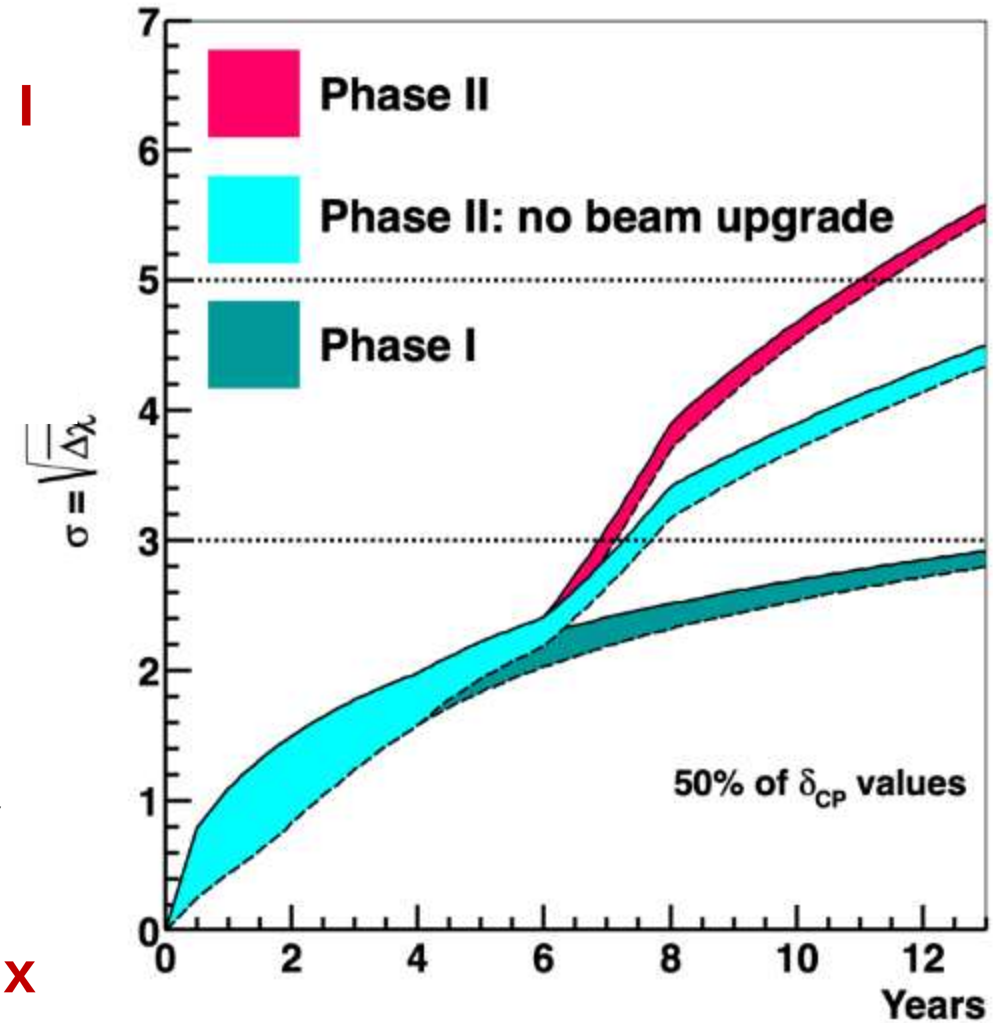
January 20, 2023

Serving Neutrino Physics (LBNF/DUNE Phases)

https://arxiv.org/abs/2203.06100

- Figure-of-Merit "kt-MW-years"
  - **120 kt-MW-yrs for Phase I** (ca 2036)
  - **600-1000 for Phase II** (ASAP)

- Phase II is a complex plan:
  - **New near detector** (ca 2036)
  - **Double up DUNE LAr volume** (20kt → 40 kt, by ~2036)
  - **Double up the proton flux** (POTs per year, by ~2036)



Serving Neutrino Physics (2)

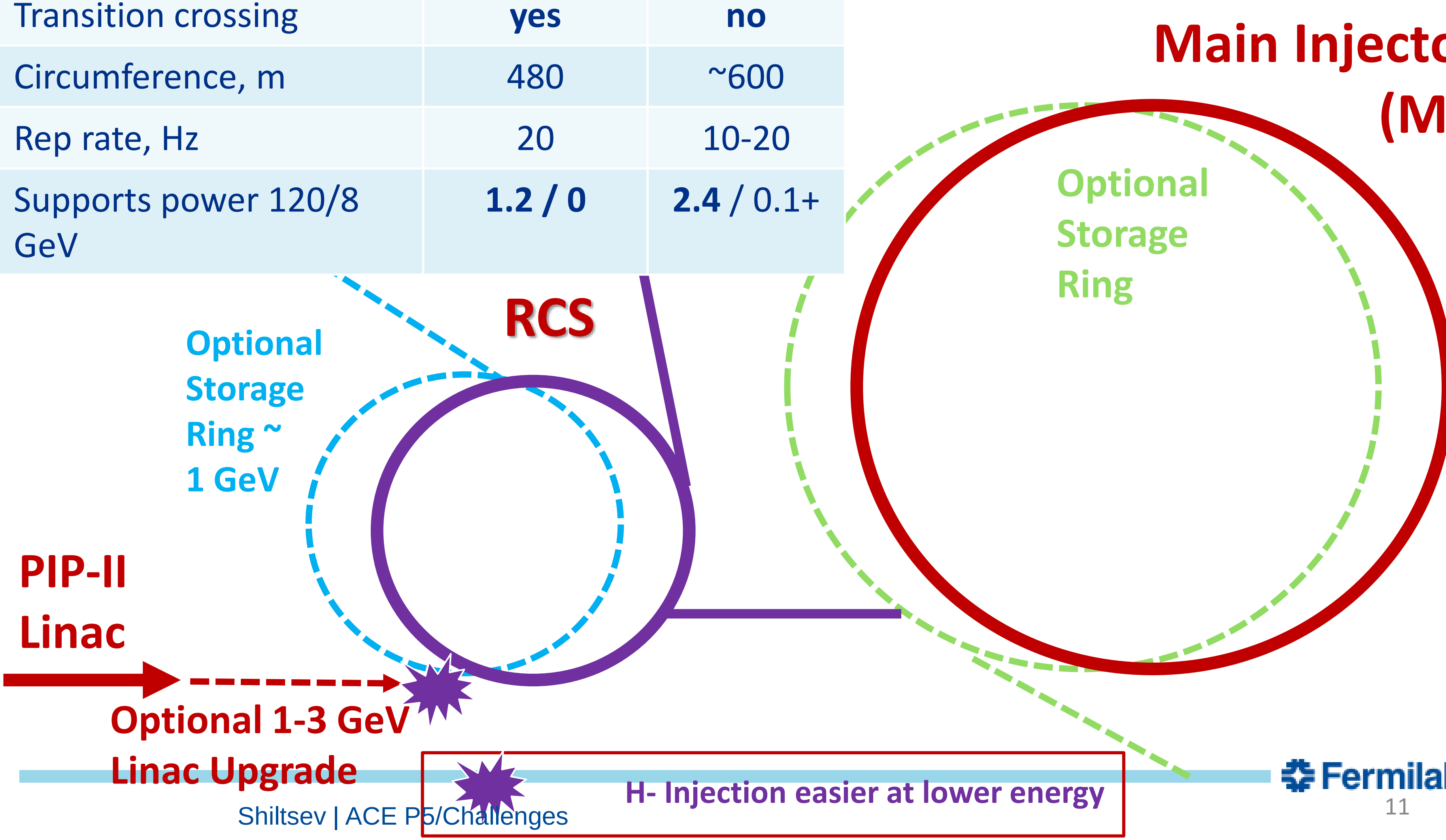
- DUNE/LBNF Phase I assumes:
  - PIP-II constructed and commissioned
  - **1.1e21 POTs/yr** in 2031-2036
- Accelerator Phase II Options (PIU)

$$\text{"MW years"} = \frac{e N_{ppp} E_{beam}}{T_{cycle}} \times Ops\ Time$$

- Replace 8 GeV Booster to increase pulse intensity ***N_ppp***
  - 8 GeV Synchrotron (~500m ring) **Option A**
  - 8 GeV Linac + accumulator ring **Option B**
- Reduce cycle time ***T_cycle***
  - 120 GeV MI ramp 1.33/1.2s→0.6-0.7s **Option 0**
- Increase **operations time**
  - # of years vs race with Hyper-K
  - Annual operational efficiency

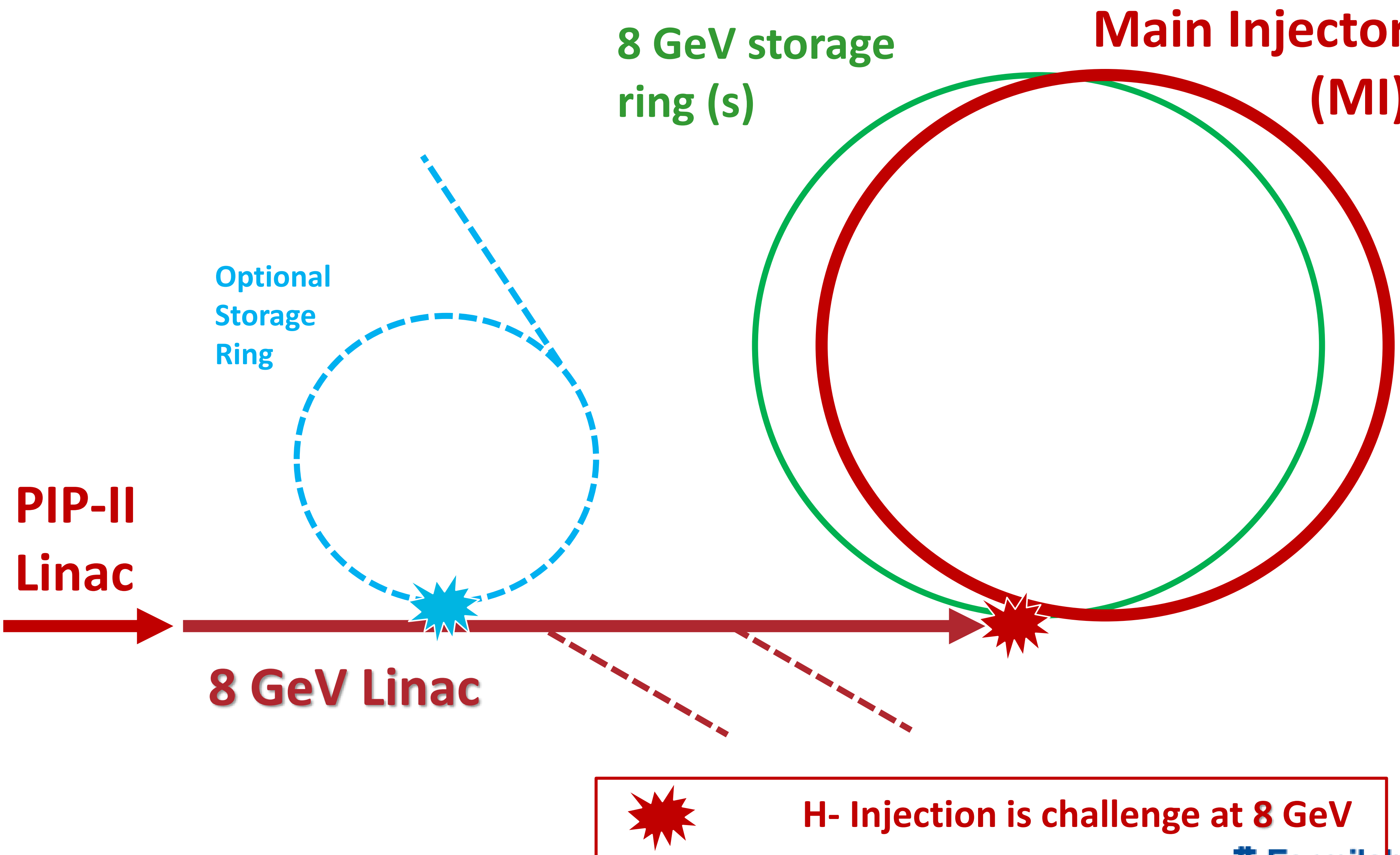
Option A: Rapid-Cycling Synchrotron (RCS)

	8 GeV Booster	8 GeV RCS
Injection energy, GeV	**0.8**	**1-3**
Transition crossing	**yes**	**no**
Circumference, m	480	~600
Rep rate, Hz	20	10-20
Supports power 120/8 GeV	**1.2 / 0**	**2.4** / 0.1+



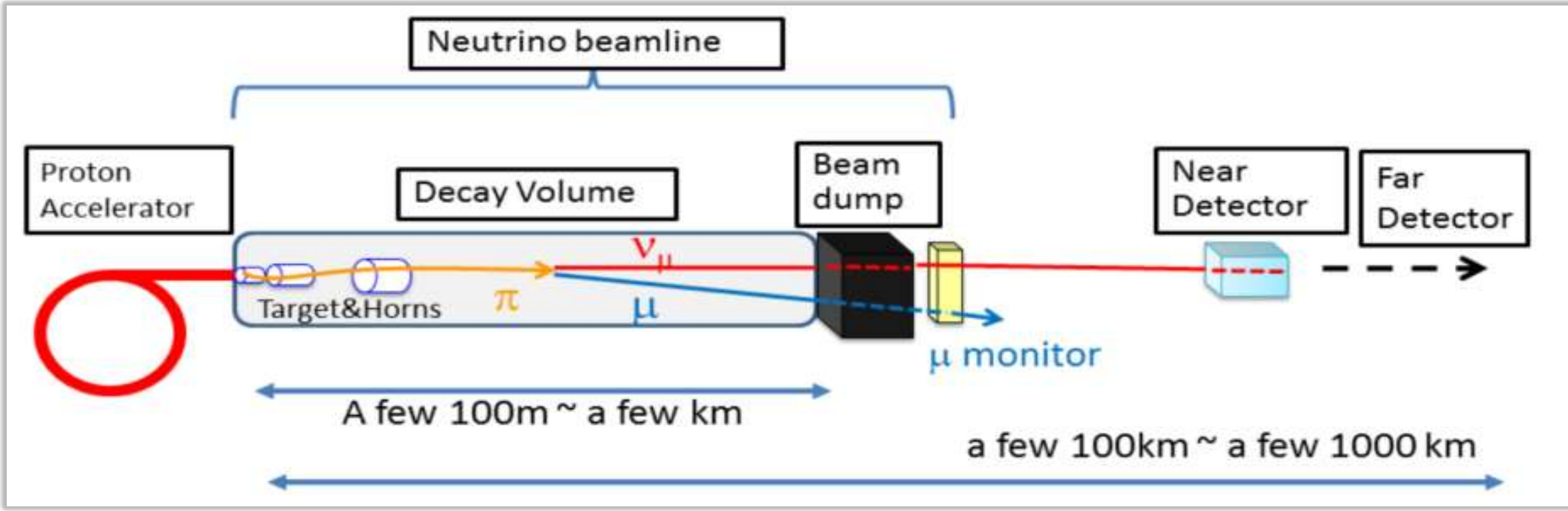
https://arxiv.org/abs/2203.08707

Option B: 8 GeV SRF Linac (and AR?)



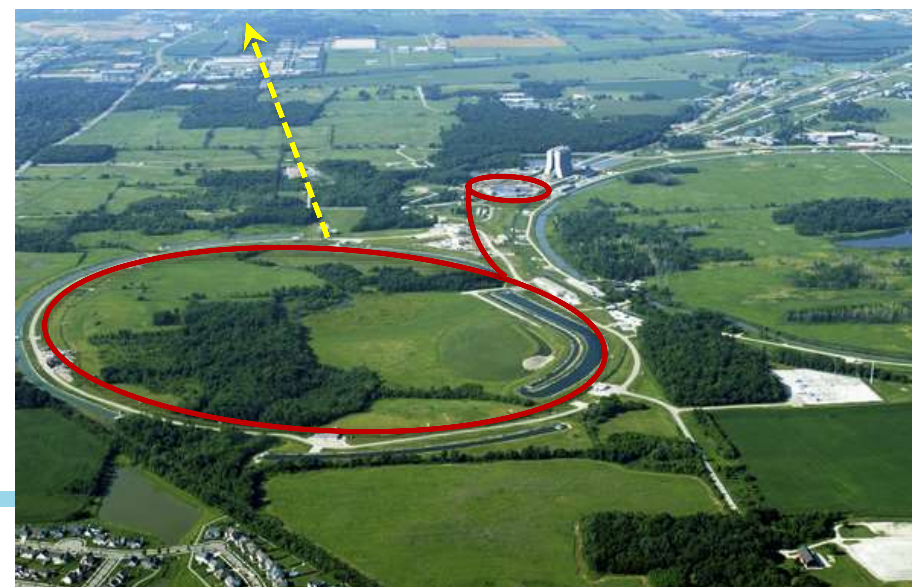
https://arxiv.org/abs/2203.05052

Neutrino Superbeams Rivalry

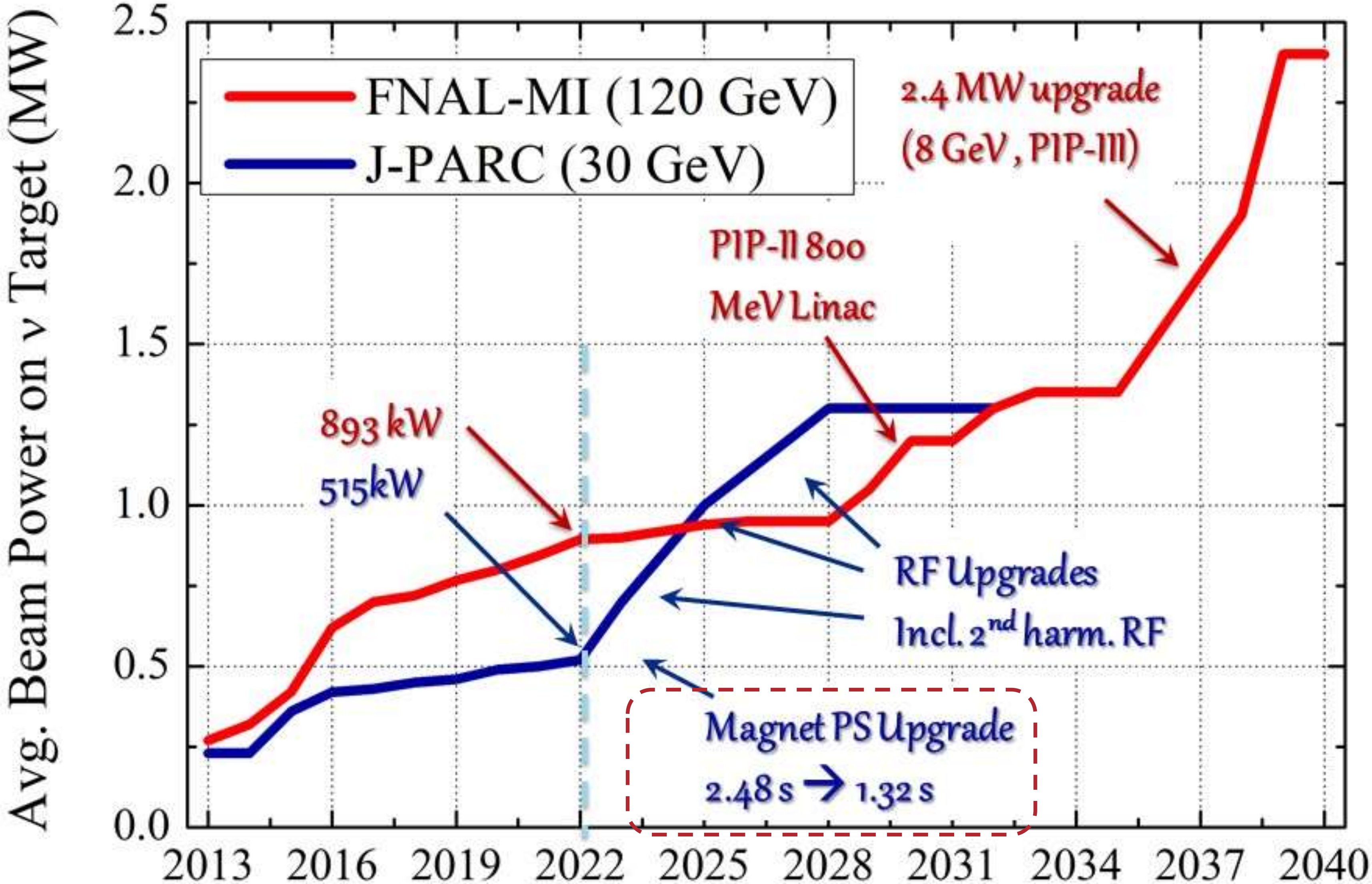


Japan Proton Accelerator Research Complex – *3/30 GeV (295 km to SuperK)*

Fermilab Proton Accelerator Complex – *8/120 GeV (810km to MINOS, 1300km to DUNE)*



Fermilab and J-PARC Power Upgrades



https://arxiv.org/abs/2209.14136

Main Findings of the PIU Group

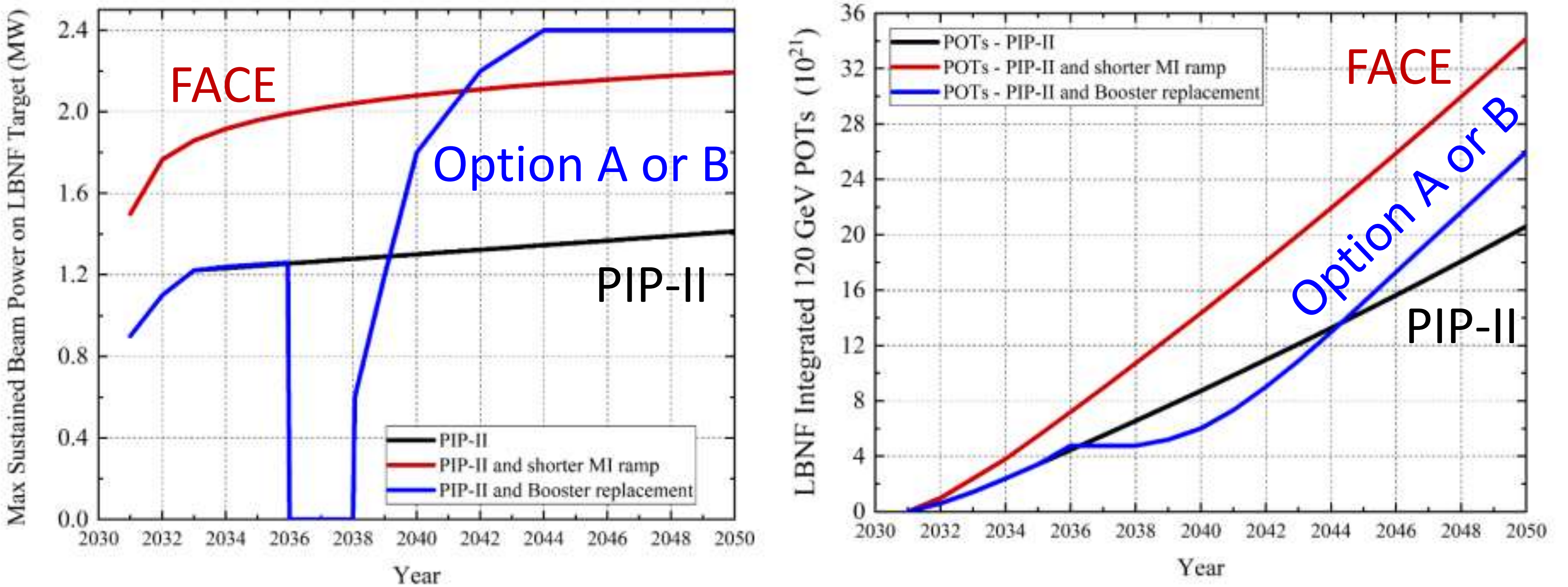


Figure 1: Maximum sustained beam power [left] and integrated number of 120 GeV protons on the LBNF neutrino target [POTs, right] under three scenarios: no upgrade beyond PIP-II (black line), PIP-II with Main Injector cycle time reduction (red), PIP-II with either an RCS or an SRF linac Booster replacement (blue). The integrated POTs number assumes 44 weeks of operation per year and expected machine commissioning progress, overall efficiency and availability of the Fermilab accelerator complex.

term. An additional appeal of the Main Injector cycle time option is that the cost is in the \$200M ballpark to be compared to the \$1B ballpark costs of the approaches involving a Booster replacement.

Challenges

2+ MW Upgrade: Challenges

- Programmatic challenges:
  - Will we win the race against the Hyper-K/JPARC?
  - Effect on other programs ($\mu 2e$? SY120? RPF MuC R&D?)
- Technical challenges (this Workshop)
  - Make PIP-II run up to the specs (current, 800 MeV, stability, etc)
  - Booster and RR run up to the specs (6.5e12 @ 8 GeV, 20 Hz)
  - MI and LBNF BL magnet PSs upgrade (1.2s → 0.65s cycle)
  - ~2.0 MW targetry (not yet exists → R&**D**)
- Performance risk:
  - PIP-II linac performance (92% as in the SNS?)
  - Booster: injection, transition, collimation, instabilities, e-cloud
  - RR: space-charge effects, instabilities/ecloud, losses?
  - MI: instabilities, losses, collimation, transition?
  - **All four machines + targetry : operational efficiency**

Q1: Power evolution - Can we make 1.5MW by '31?

A1: (see Con's analysis) 1 long shutdowns, 4 short but post-PIP-II power progress is not yet clear…

High intensity operation using proton stacking in the Fermilab Recycler to deliver 700 kW of 120 GeV proton beam // Robert Ainsworth, Philip Adamson, Bruce C. Brown, David Capista, Kyle Hazelwood, Ioanis Kourbanis, Denton K Morris, Meiqin Xiao, and Ming-Jen Yang // **Phys. Rev. Accel. Beams 23, 121002** (2020)

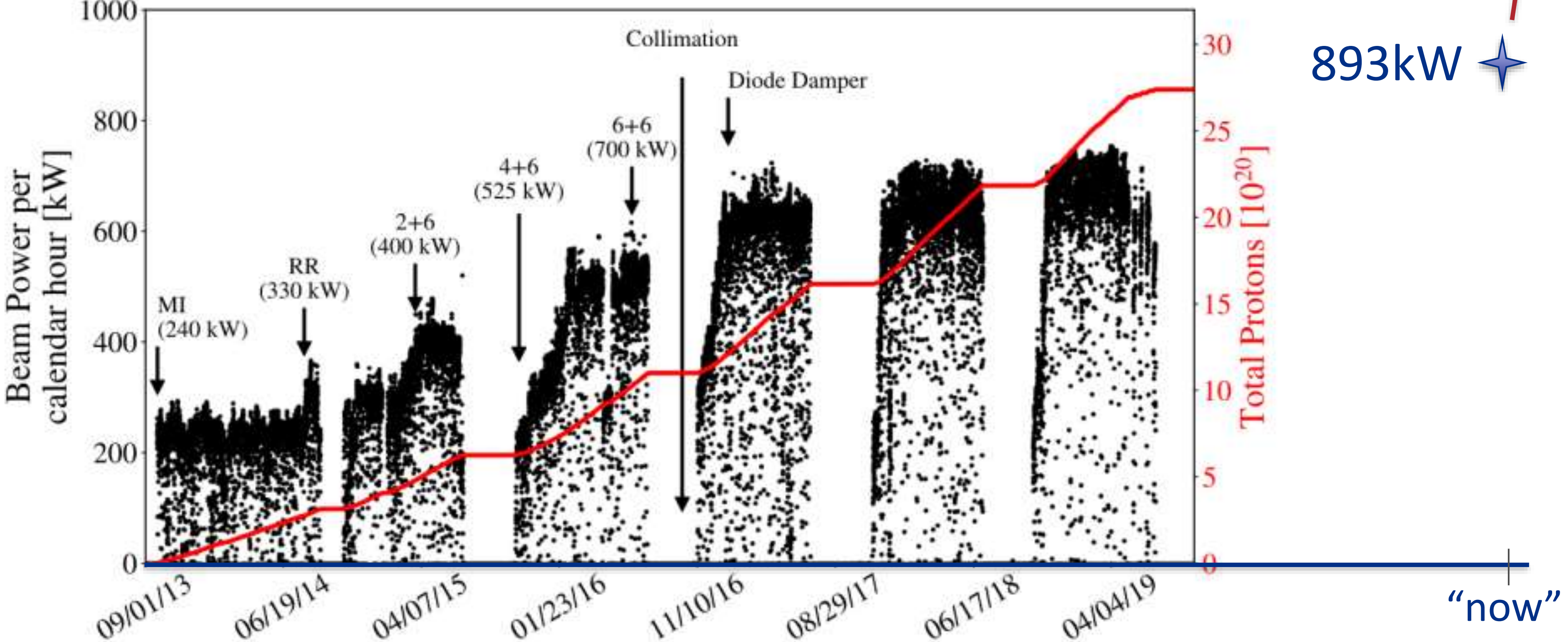


FIG. 4. The hourly beam power to NuMI and the total protons delivered since the end of the long shutdown in 2013. The beam power is initially limited to 240 kW when only the Main Injector is used. As slip-stacking in the Recycler is commissioned, the beam power is steadily increased until January 2017 when the beam power meets the design goal. If beam is also being delivered to Switchyard via resonant extraction in the Main Injector, NuMI will see a 10% decreases in beam power (630 kW).

Q2a: Can we deliver at least 1.12e21 POTs/yr btw 2031-2036 (Phase I post-PIP-II expectations)?
Q2b: Can we exceed the Phase I expectations and deliver upto 2.0e21 POTs/yr on the LBNF target?

A2a: Definitions : **1 year = 3.15e7 seconds**

1 MW at 120 GeV for 1 year = 1.64e21 POTs/yr

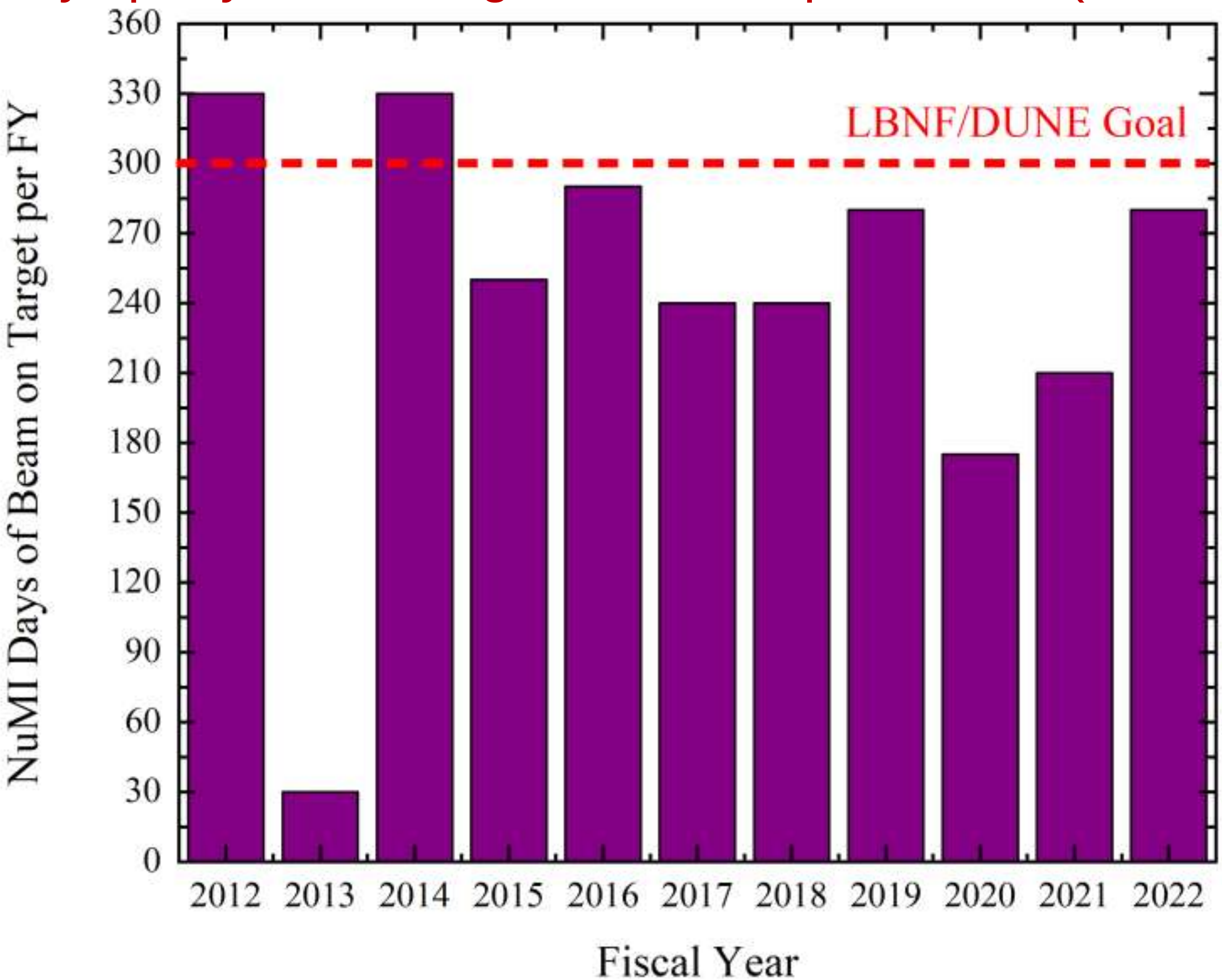
DUNE Phase I expects 1.12e21 POTs/yr with 1.2MW maximum avg power and 44 weeks of operation (original PIP-II specs)

That results in 57% total efficiency spec (1.12/1.64/1.2=0.57)

- less time (weeks/yr) → need more efficiency if *P*=const
- less power → need more efficiency to get 1.12e21 POTs

Days of Operation: NuMI Data FY12-22

LBNF/DUNE-Phase I target: 44 wks (308 days) of ops scheduled + 20 days per year for target or horn replacement (*not in shutdowns*)



Reality of NuMI FY2022 Operations

Integrated 0.58e21 POTs

(NB: DUNE-I assumes 1.12e21 POTs/yr)

Peak avg power 0.88MW

Total efficiency = 40%

0.58/1.64/0.88=0.40

Main reasons:

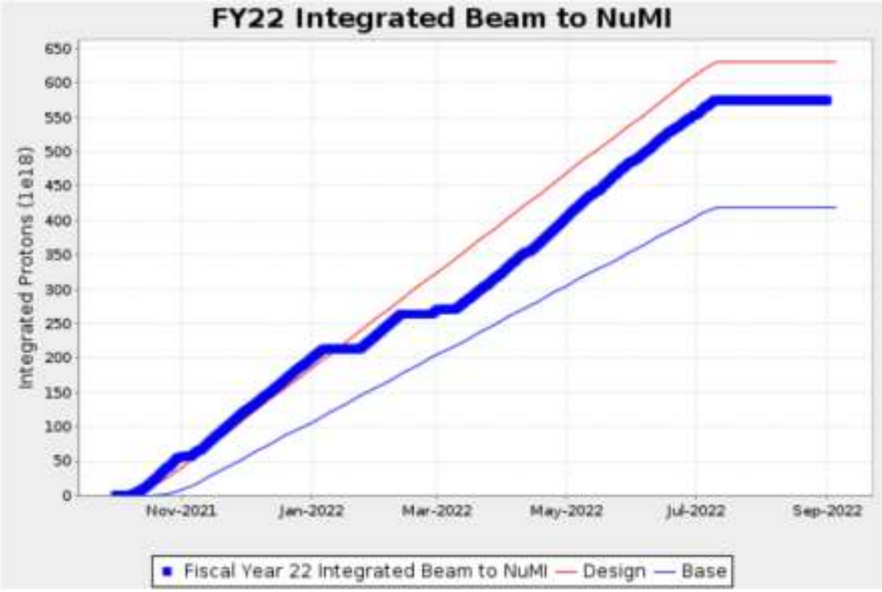
1) 282 days of operation (40 weeks, 77% CY)

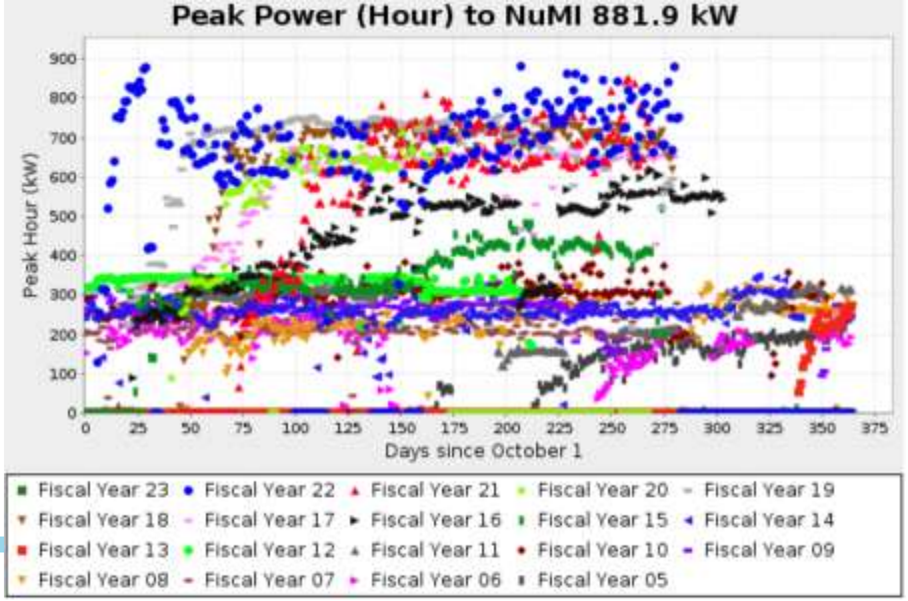
2) Timeline "tax" for SY120 (upto ~10%) or Muons (14%) or both

3) Machines' availabilities

4) Performance recovery

40% << 57%





FNAL Complex Unscheduled Downtime (from Cons)

	Linac	Booster	Recycler	MI	Total	Comments
FY17	236	92	46	357	731	CY17 stat.
FY18	250	116	32	203	601	+ studies
FY19	367	99	43	167	676	+ studies
FY20	319	71	28	88	506	+ studies
FY21	212	81	64	176	533	+ studies
FY22	149	123	61	274	607	+ studies
Average	256	97	41	211	609	incl.FY20

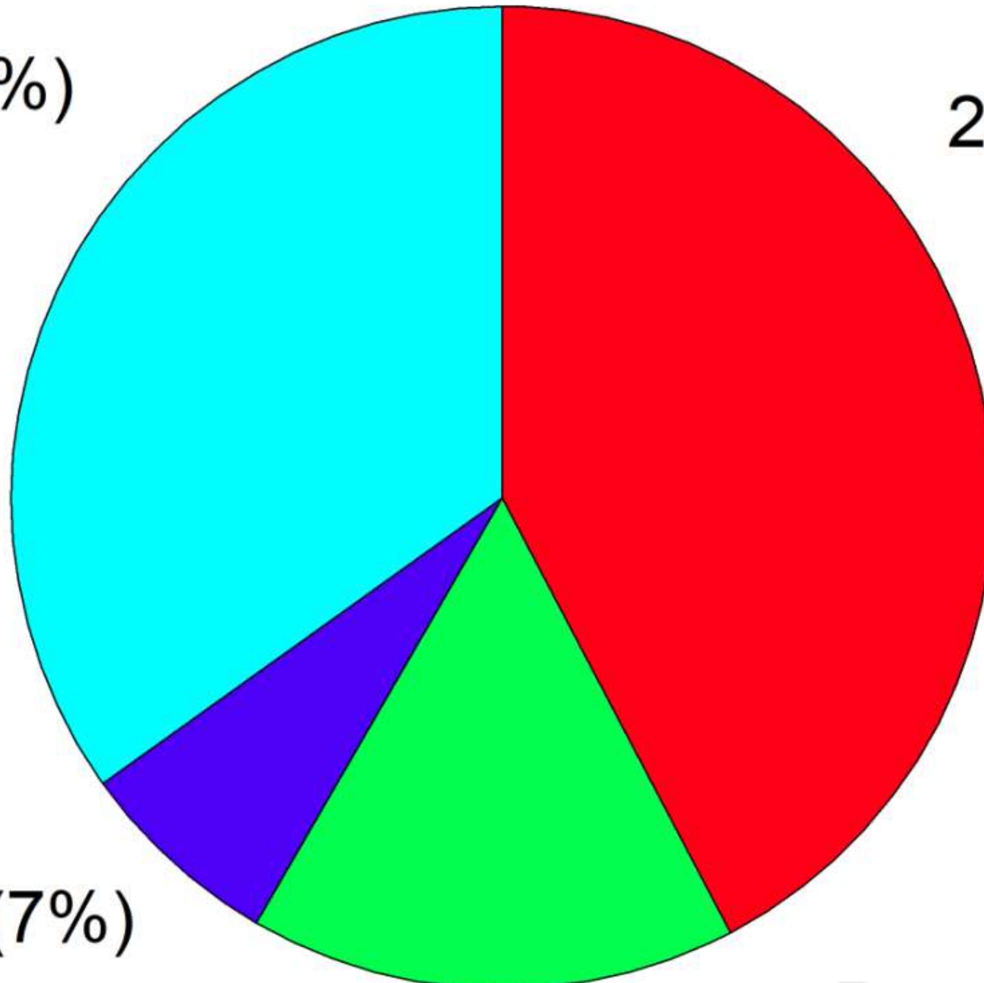
Of note :

i) On average ~610 hrs of downtime, or ~10% of scheduled time (~6800 hrs/yr)

ii) there is no statistically significant trend for any machine

iii) not yet adequately accounted yet is time used for beam studies and early start-up explorations, could be ~100 hrs/yr

What to Pay Attention To



Main Injector

- ¼ due to PSs
- 1/5 RF
- 1/10 magnets
- 1/10 water

Linac

- 3/5 due to RF

Recycler

- 1/2 due to PSs
- 1/3 RF

Booster

- 1/3 due to RF
- ¼ due to PSs

FACE Operations Challenges

- Ramp up and timeline:
  - Will we reach peak proton beam power level ~1.5MW in 2031 and >2MW in 2036?
  - Need to converge on the timeline "taxes" for SY and muon
  - Will extra time be needed for beam studies in the first years?
- By system:
  - PIP-II: availability is uncertain – compare with 2000 hrs early→ 200 hrs now in SNS (R.Geng, half of that SCL), or ~250 hrs of our Linac
  - Booster: now not bad, but with PIP-II 6.5e12 ppp? Need PAR?
  - Recycler: downtime is minimal now – how much will it increase with (2-3) x (current POTs per year)?
  - Main Injector: PSs, RF and magnets - how much worse will they be?
  - LBNF targets and horns: 20 unscheduled days per yr – is that reasonable estimate?

Thanks for your attention!

Questions?