



Accelerator Capabilities Enhancement: Alignment to P5 and Challenges

Vladimir SHILTSEV

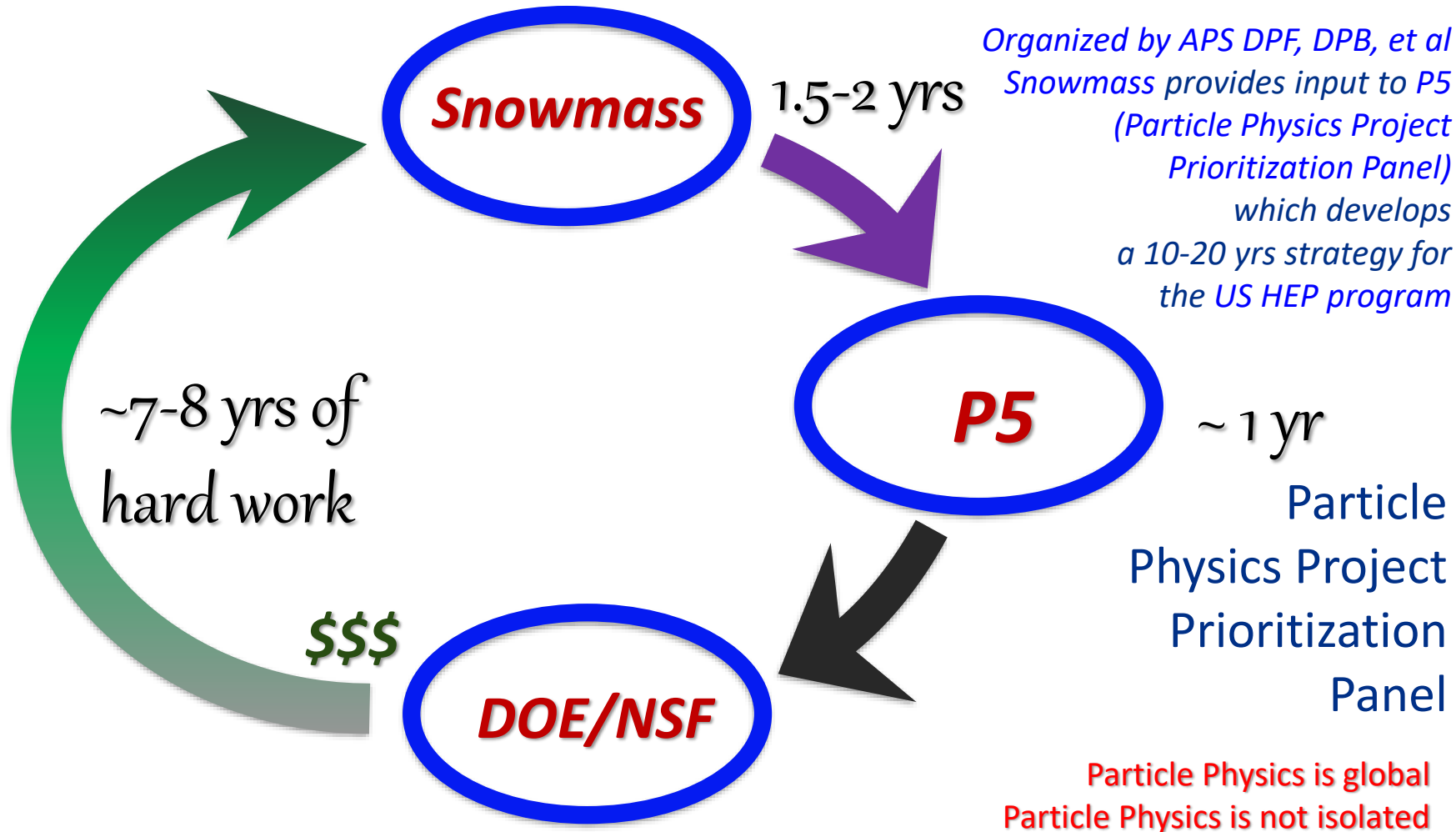
(with input from Cons, Mary, Sergey B. and Paul)

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'21

"a particle physics community strategic planning study"



<https://www.snowmass21.org/>

Snowmass'21 Accelerator Frontier Conveners



Steve Gourlay
(LBNL)



Tor Raubenheimer
(SLAC)



Vladimir Shiltsev
(FNAL)

(AF – one of 10 frontiers, incl. Neutrino, Rare Processes, 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

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
- $O(10 \text{ TeV/parton})$ 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

G. Arbanis, B. Assmann, C. Barf, M. Bai, S. Beharavayiti, S. Bernasconi, P. Blot, A. Brusa-Geslin, J. Caldeira, C. Gallas, G. Hellenic, M. Hogan, E. Huang, D. Li, S. Li, S. Li, R. Miller, P. Monetti, E. Nanni, M. Palmer, N. Papan, F. Pedersoli, E. Preys, Q. Qin, J. Power, T. Ruan, G. Saldá, D. Sotnikov, V. E. Sun, J. Tang, A. Valishev, B. Wang, F. Zimmermann, A.V. Zolotarev, R. Zou

For over half a century, high-energy accelerators have been a major enabling technology for particle and nuclear physics research as well as sources of X-rays for photon science research in material science, chemistry and biology. Particle accelerators for energy and intensity frontier research in high energy physics (HEP) continuously drive the accelerator community to invent ways to increase the energy and improve the performance of accelerators, reduce their cost, and make them more power efficient. Despite these past efforts, the increasing size, cost and demands required for modern and future accelerator-based HEP projects arguably distinguish them as the most challenging scientific research endeavors. In the meantime, the international accelerator community has demonstrated imagination and creativity in developing a plethora of future accelerator ideas and proposals.

Major developments since the last Snowmass/HEPAP P5 strategic planning exercise in 2013-2014 include start of the PIP-II proton beam construction for the LBNL/DUNE neutrino program in the US; emergence of the FCC/CEPC projects for Higgs/EW physics research at CERN and in China, respectively; a significant evolution of activity related to linear collider projects (ILC in Japan and CLIC at CERN); and, pseudocoincidentally, the end of the Muon Accelerator Program in the US and creation of the International Muon Collider Collaboration (IMCC) in Europe. The last decade saw several notable planning advancements, including the US DOE GARD Roadmap, European Strategy for Particle Physics and the Accelerator R&D Roadmap, EuPRAXIA, etc.

In addition, since the last Snowmass meeting that took place in 2013 was shortly after the confirmation of the Higgs, the goals for the Energy Frontier have changed as a result of the LHC measurements. While a Higgs/EW factory at 250 to 300 GeV is still the highest priority for the next large accelerator project, the motivation for a TeV or few TeV e^+e^- collider has diminished. Instead, the community is focused on a 99+ TeV (parton e^+e^-) discovery collider that would follow the Higgs/EW Factory. This is an important change that will reflect some of the accelerator R&D programs.

The technical maturity of proposed facilities ranges from show-ready to those that are still largely conceptual. Over 100 contributed papers have been submitted to the Accelerator Frontier of the US particle physics broad community planning exercise, Snowmass2021. These papers cover a broad spectrum of topics: beam physics and accelerator education; accelerators for neutrinos, colliders for Electroweak/Higgs studies and multi-TeV energies; accelerators for μ gaseous CERN and rare processes; advanced accelerator concepts; and accelerator technology for Radio Frequency cavities (RF), magnets, targets, and sources.

Future facilities: The accelerator community in the US and globally has a broad array of accelerator technologies and expertise that will be needed to design and construct any of the near-term HEP accelerator projects. P5 will need to prioritize what option(s) should be developed. Planning of accelerator development and research should be aligned with the strategic planning for particle physics and should be part of the P5 prioritization process. Accelerator experts can contribute to the US and international projects under consideration by providing top-down metrics for expected cost-scales and technology/maturity evolution, following the ITF findings.

Among possible actively discussed future facilities options are:

- A multi-MW beam power upgrade of the Fermilab proton accelerator complex that seems to be the highest priority for the neutrino program in the 2030s; corresponding accelerator technology and beam physics studies are needed to identify the most cost- and power-efficient solution that could be timely implemented leading to breakthrough results of the DUNE neutrino program.
- Several beam facilities for dark and Dark Matter (DM) searches are shown to have great potential for construction in the 2030s in terms of scientific output, cost and timeline, including PAR (a 1 GeV, 100 MW PIP-II Accelerator Ring); in general, we should efficiently utilize existing and upcoming facilities to explore dedicated or parallel opportunities for rare process measurements - examples are the SLAC SRF electron beam, MWs of proton beam power potentially available after construction of the PIP-II SRF line, upgrades of the future multi-MW FNAL complex upgrade, and at CERN, a Forward Physics Facility at the LHC, etc.
- In the area of future colliders - several approaches are identified as both promising and potentially feasible, and call for further exploration and support: in the Higgs/EW sector - there is growing support for the FCCs at CERN and proposals of somewhat more advanced linear colliders in the US or elsewhere, such as C³ and HELEN;
- At the energy frontier, the discovery machines such as $O(30 \text{ TeV } e^+e^-)$ muon colliders have rapidly gained significant momentum. To be in a position for making decisions on collider projects viable for construction in the 2040s and beyond at the time of the next Snowmass/P5, these concepts could be explored technically and documented in pre-CDR level reports by the end of this decade.

The US HEP accelerator R&D portfolio presently contains an collider-specific focus. This creates a gap in our knowledge-base and accelerator/technology capabilities. It also limits our national reputation for a leadership role in particle physics in that the US cannot lead or even contribute to proposals for accelerator-based HEP facilities. To address the gap, the community has proposed that the US establish a national integrated R&D program on future colliders in the DOE Office of High Energy Physics (OHEP) to carry-out technology R&D and accelerator design for future collider concepts. This program would aim to create synergistic engagement in projects proposed abroad (e.g. FCC, ILC, IMCC). It would support the development of design reports on collider options by the time of the next Snowmass and P5 (2025-2030), particularly for options that can feasibly be hosted in the US, and to create R&D plans for the decade past 2030. Without such a program there may be few accelerator-based proposals for a future P5 to evaluate.

- Science Drivers (6 pages)
- (Brief) Frontier Summaries (~40 pages)
- (Brief) Cross-Frontier Topics (~10 pages)
- High-Level Conclusions (4 pages)

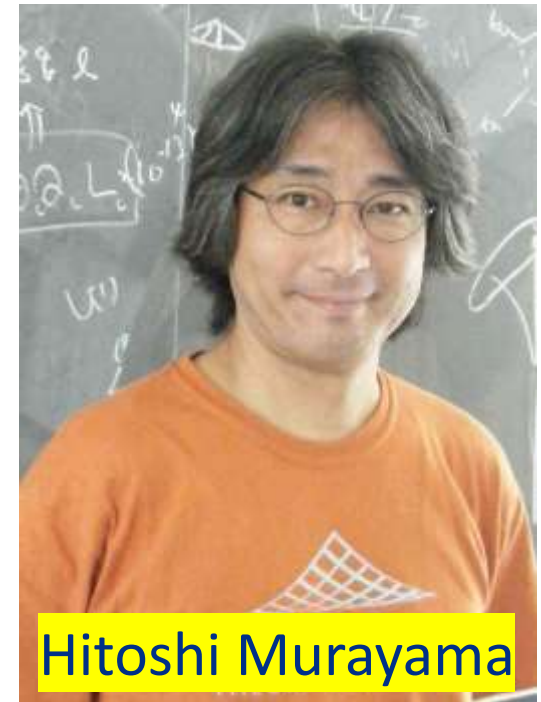


Frontier/Decade	Coming Decade (2025 - 2035)	Next Decade (2035 -2045)
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		Higgs Factory Construction
Neutrino Frontier	LBNF/DUNE Phase I & PIP- II	DUNE Phase II (incl. proton injector)
Cosmic Frontier	Cosmic 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



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 Flaughter

Report from the Fermilab Proton Intensity Upgrade Central Design Group

Robert Ainsworth¹, Giorgio Apollinari¹, Tug T Arkan¹, Sergey Belomestnykh¹, Pushpalatha C Bhat¹, S.J. Brice¹, Brian Chase¹, Mary E Convery¹, Steven J Dixon¹, Jeff Eldred¹, Grigory Ereemeev¹, Brenna Flaughter¹, Jonathan D. Jarvis¹, David Johnson¹, Jonathan Lewis¹, Richard Marcum¹, Sergei Nagaitsev¹, David Neuffer¹, Donato Passarelli¹, Frederique Pellemoine¹, William A Pellico¹, Sam Posen¹, Eduard Pozdeyev¹, Alexander Romanenko¹, Arun Saini¹, Kiyomi Seiya¹, Vladimir Shiltsev¹, Nikolay Solyak¹, James M Steimel¹, Diktys Stratakis¹, Alexander A Valishev¹, Mayling L Wong-Squires¹, Slava Yakovlev¹, and Robert Zwaska¹

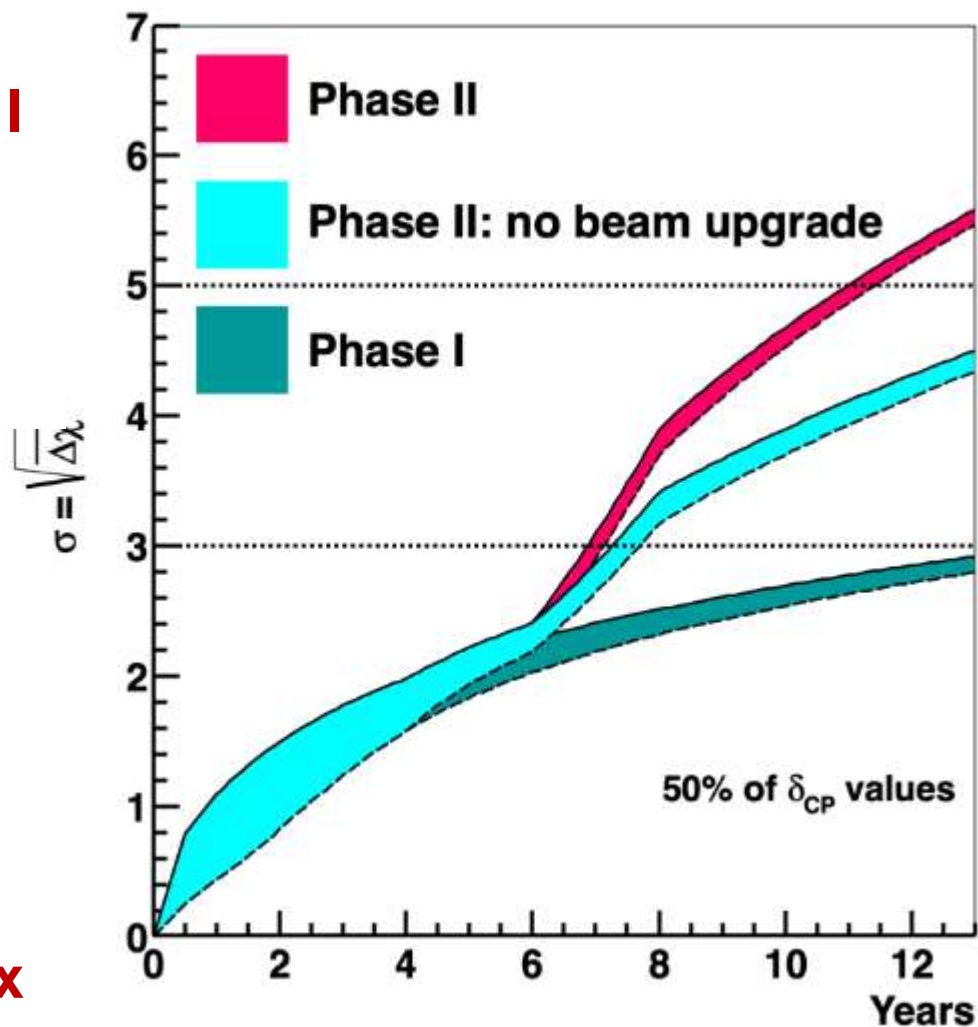
¹Fermi National Accelerator Laboratory

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)

0.8 GeV PIP-II Linac (ops 2028)

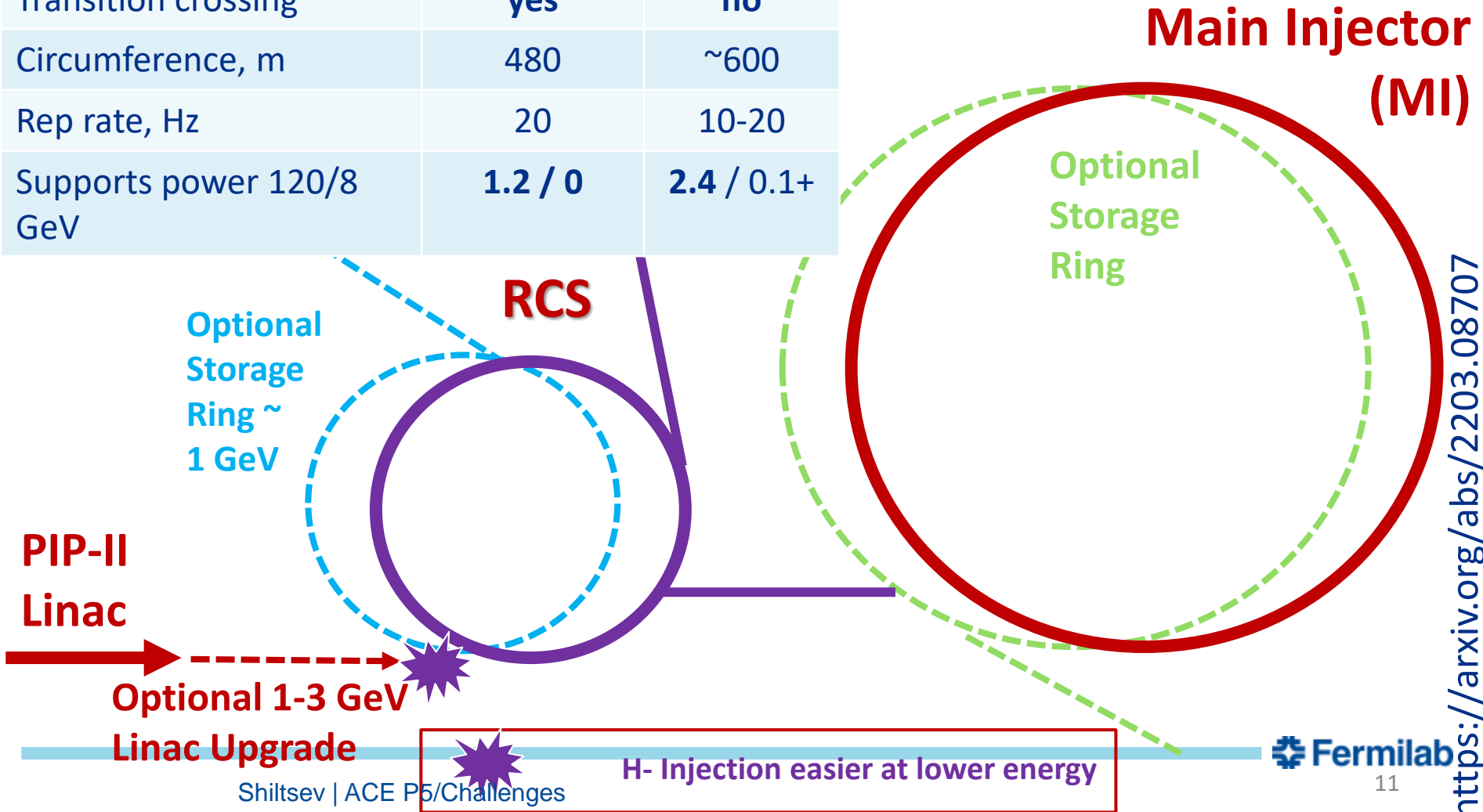


$$\text{"MW years"} = \frac{eN_{ppp}E_{beam}}{T_{cycle}} \times \text{Ops Time}$$

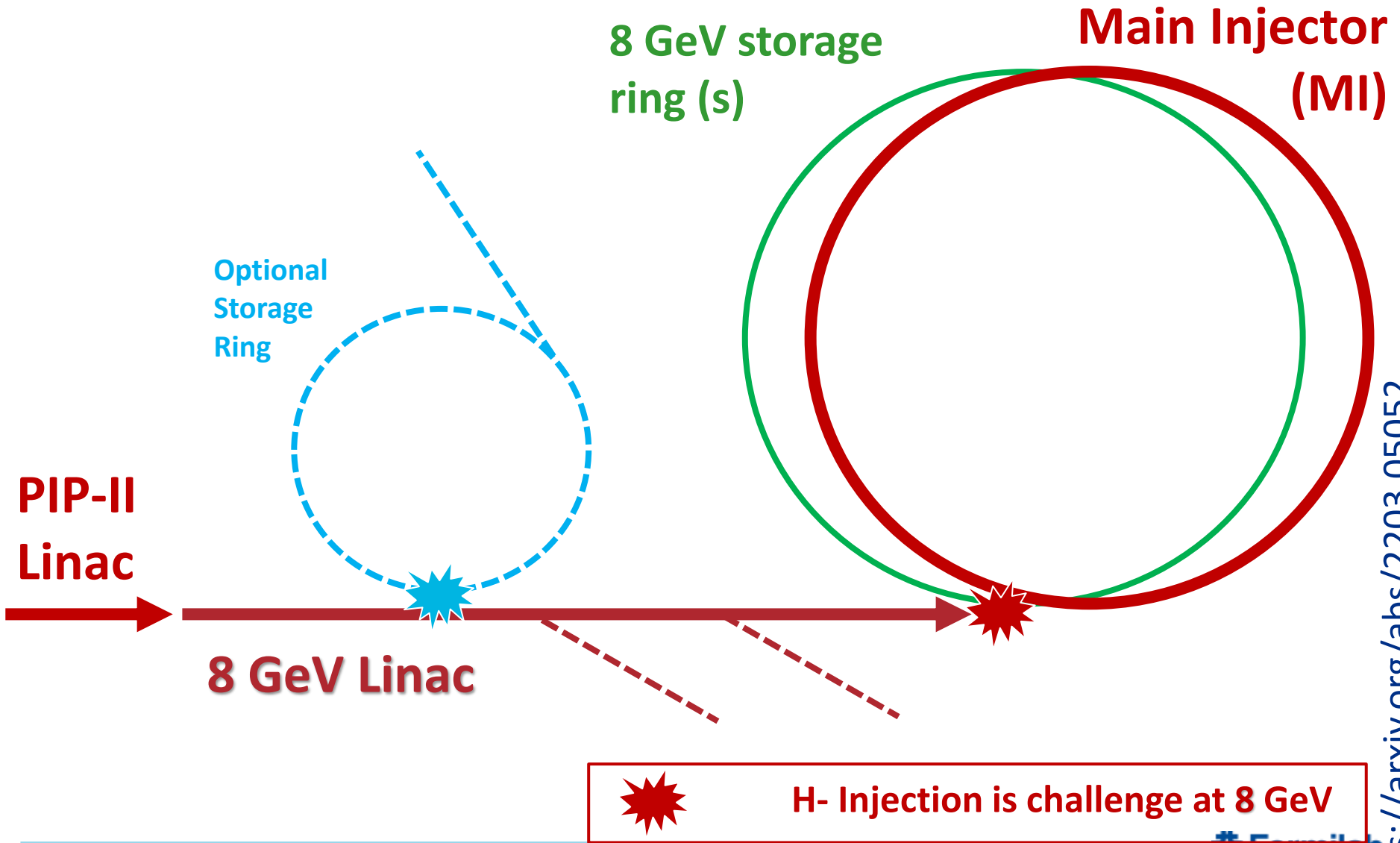
- Replace 8 GeV Booster to increase pulse intensity N_{ppp}
 - 8 GeV Synchrotron (~500m ring) **Option A**
 - 8 GeV Linac + accumulator ring **Option B**
- Reduce cycle time T_{cycle}
 - 120 GeV MI ramp **1.33/1.2s** → **0.6-0.7s** **Option 0**
- Increase **operations time**
 - # of years vs race with 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+

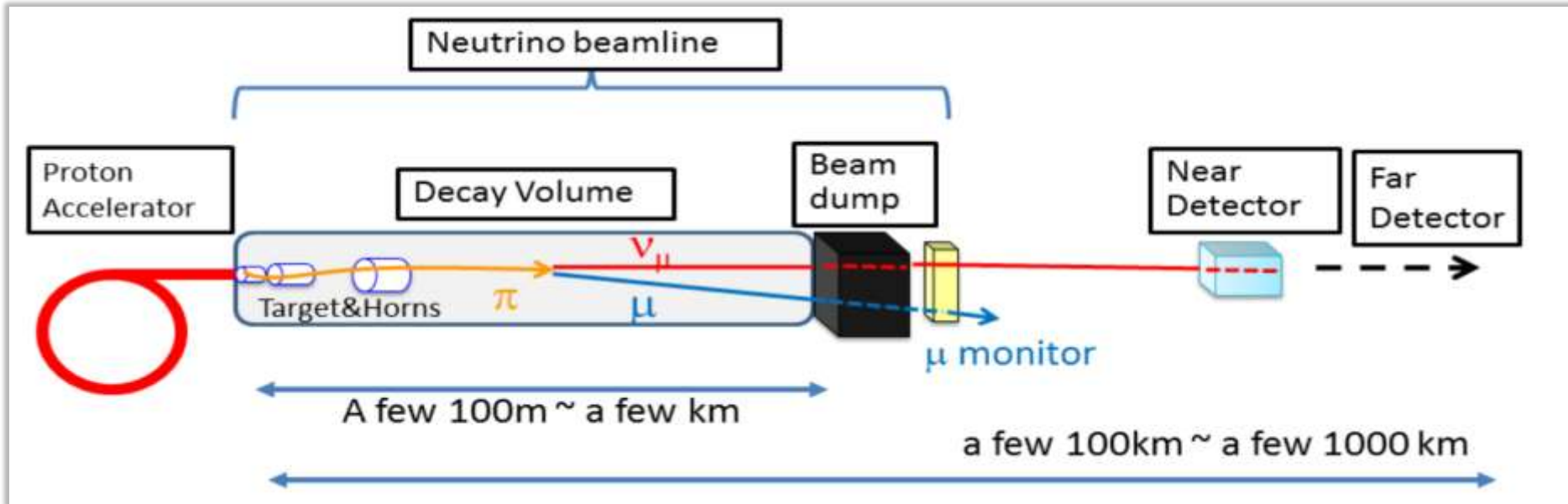


Option B: 8 GeV SRF Linac (and AR?)



<https://arxiv.org/abs/2203.05052>

Neutrino Superbeams Rivalry



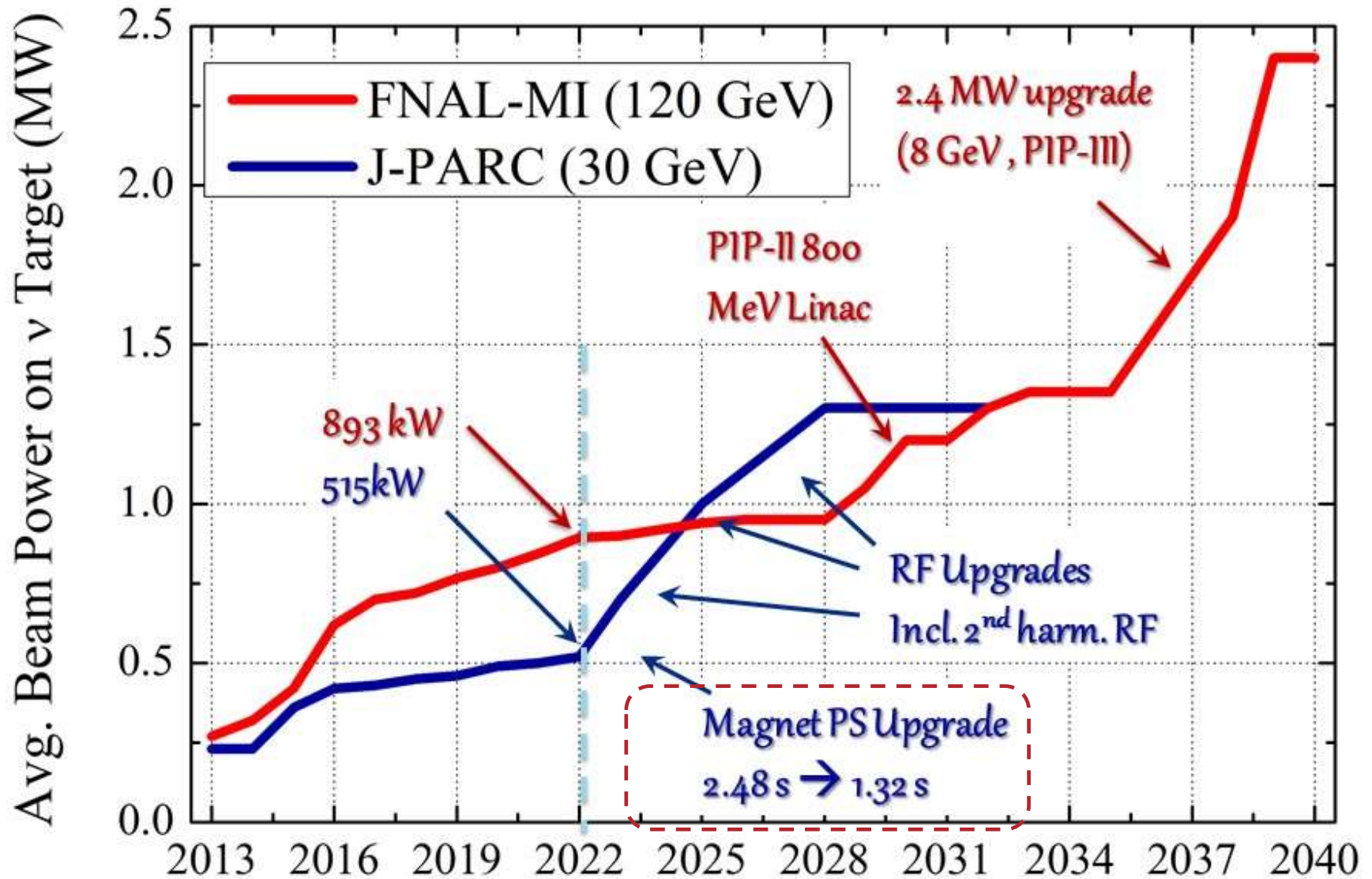
Japan Proton Accelerator Research Complex – 3/30 GeV (295 km to SuperK)



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



Fermilab and J-PARC Power Upgrades



Main Findings of the PIU Group

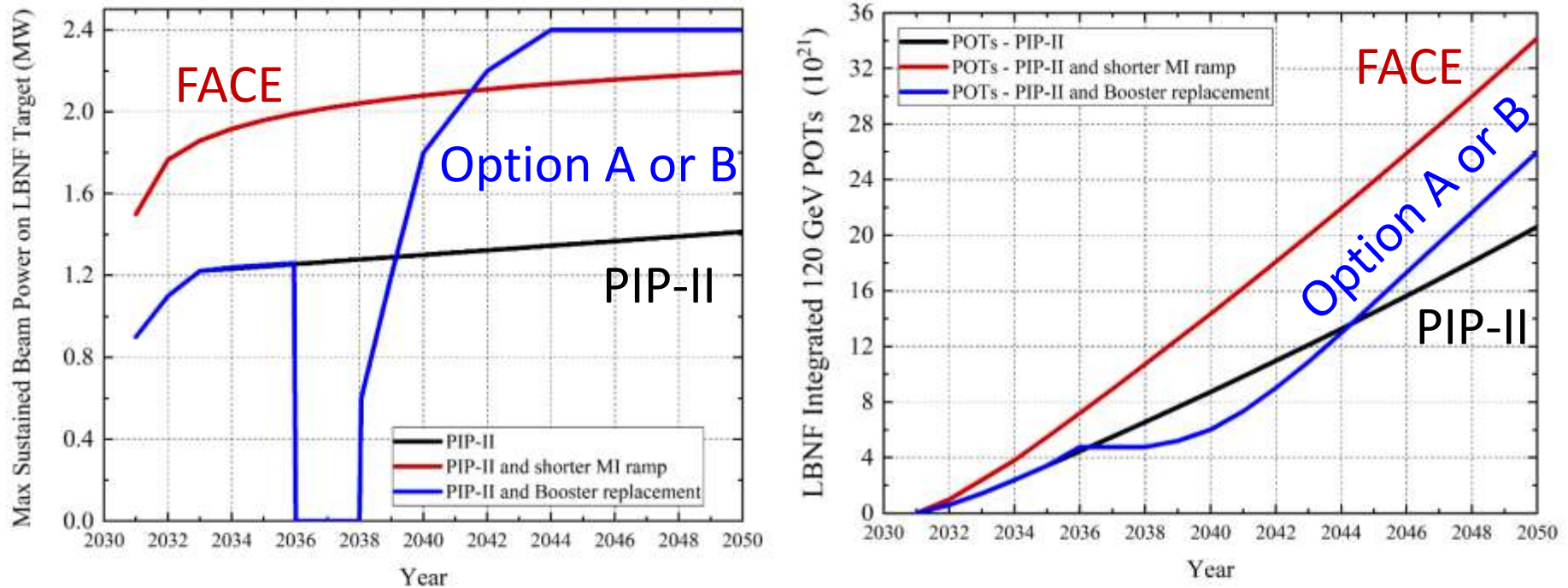


Figure 1: Maximum sustained beam power [left] and integrated number of 120 GeV protons on the LBNF neutrino target [POTs, right] under three scenarios: no upgrade beyond PIP-II (black line), PIP-II with Main Injector cycle time reduction (red), PIP-II with either an RCS or an SRF linac Booster replacement (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 \rightarrow 0.65s cycle)
- ❖ ~2.0 MW targetry (not yet exists \rightarrow 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)

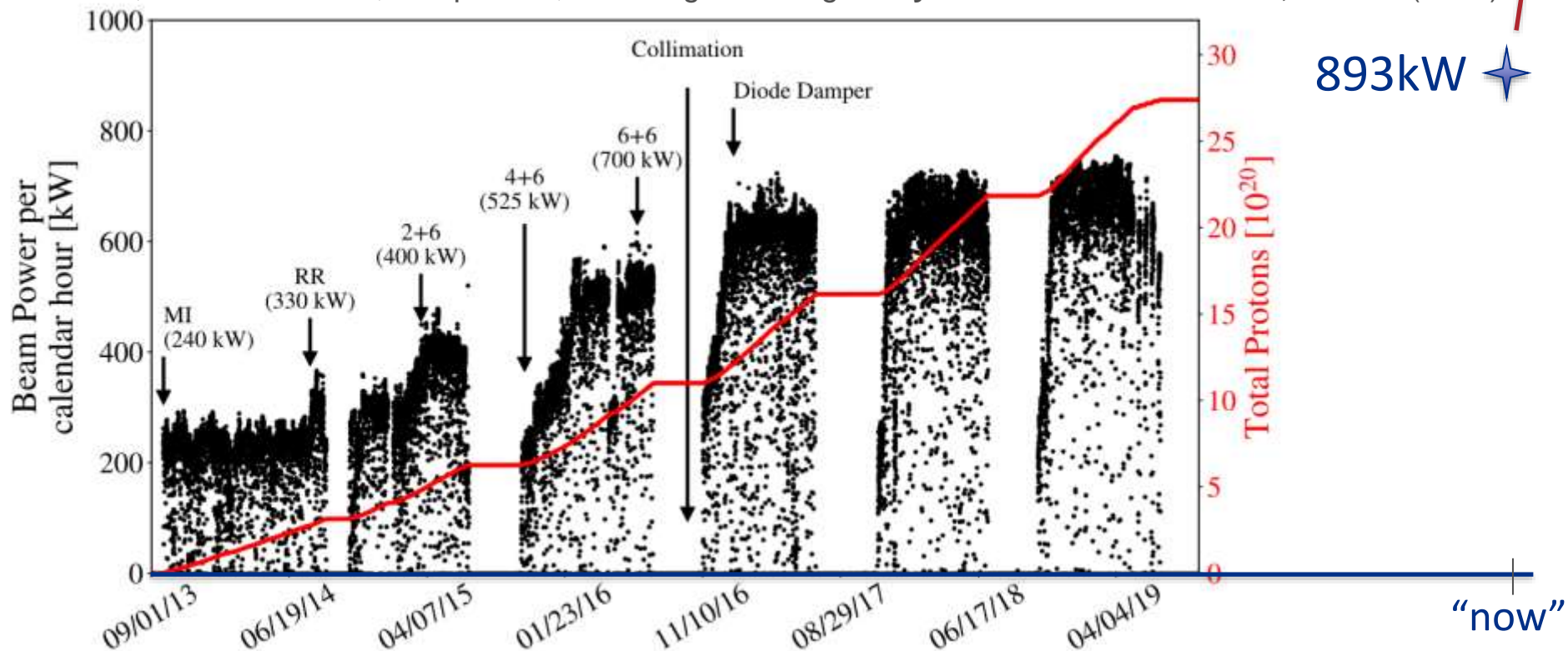


FIG. 4. The hourly beam power to NuMI and the total protons delivered since the end of the long shutdown in 2013. The beam power is initially limited to 240 kW when only the Main Injector is used. As slip-stacking in the Recycler is commissioned, the beam power is steadily increased until January 2017 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% decrease 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

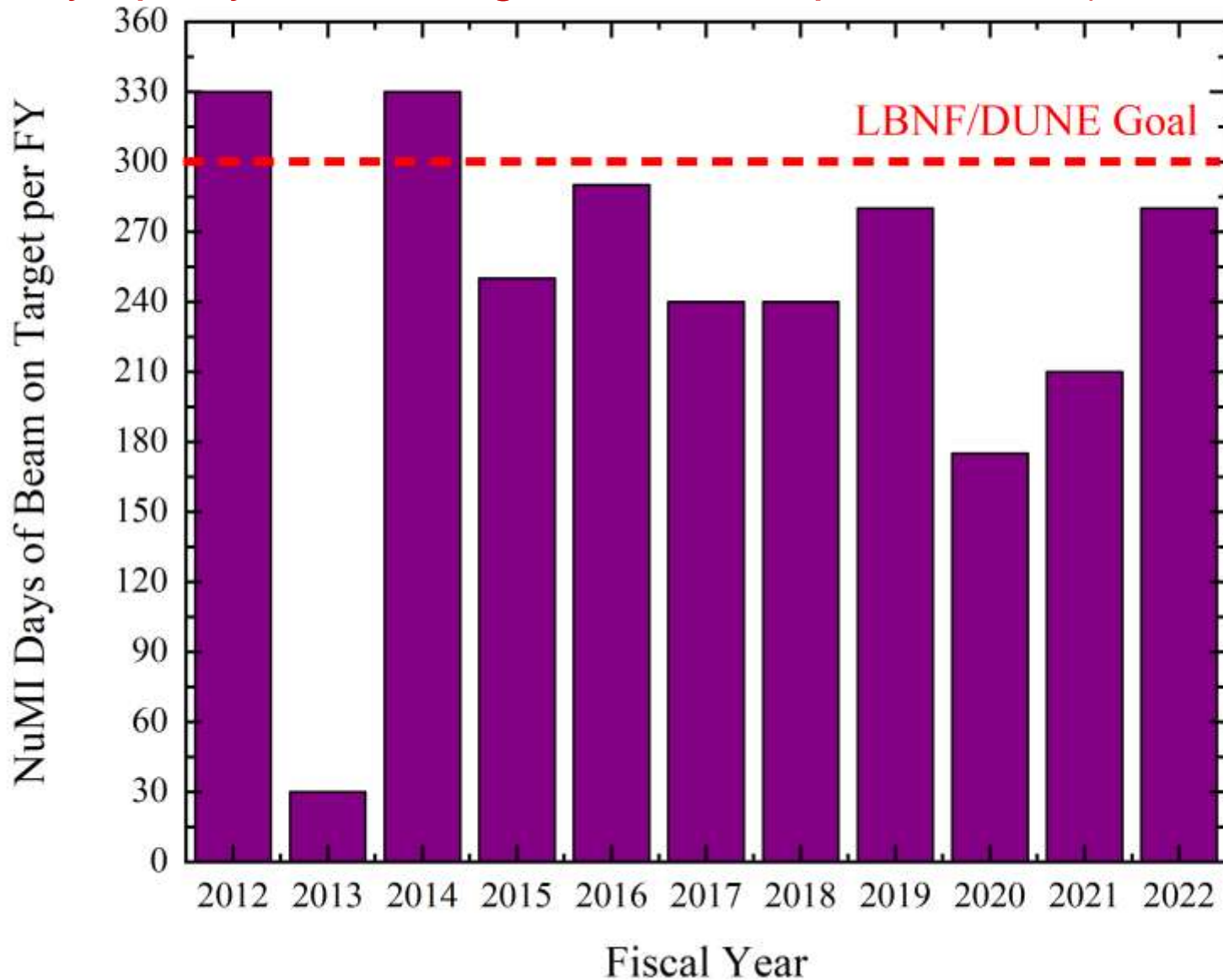
DUNE Phase I expects $1.12e21$ POTs/yr with 1.2MW maximum avg power and 44 weeks of operation (original PIP-II specs)

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

- less time (weeks/yr) \rightarrow need more efficiency if $P=\text{const}$
- less power \rightarrow 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

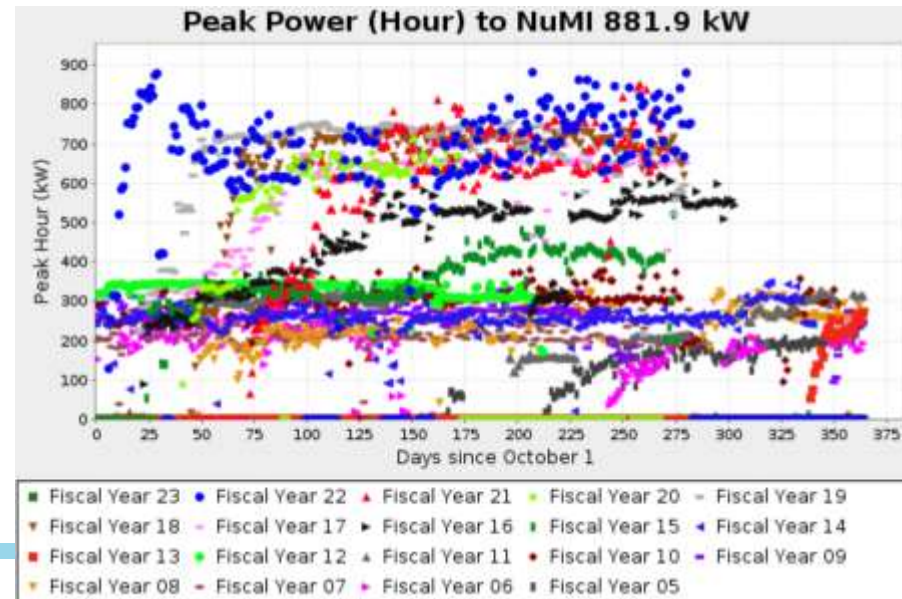
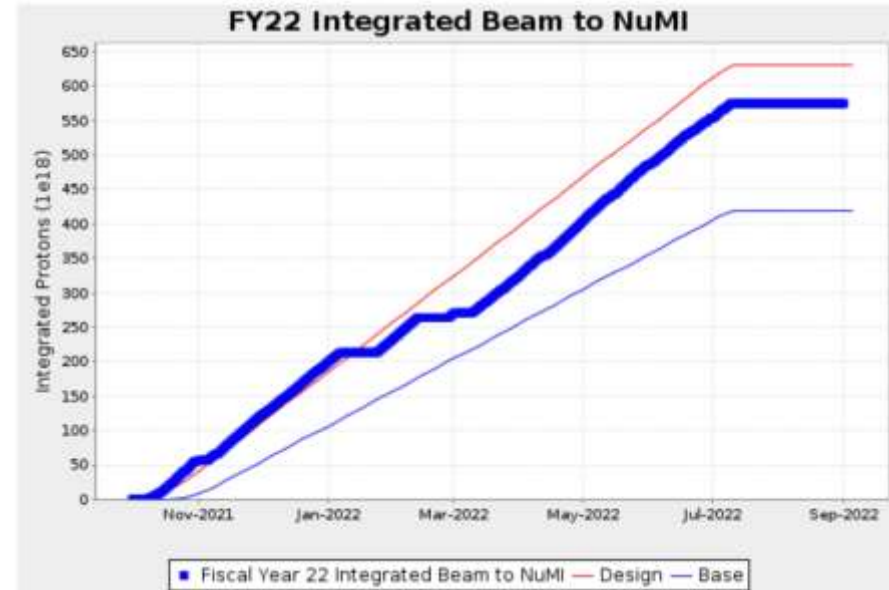
Total efficiency = 40%

$$0.58/1.64/0.88=0.40$$

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%



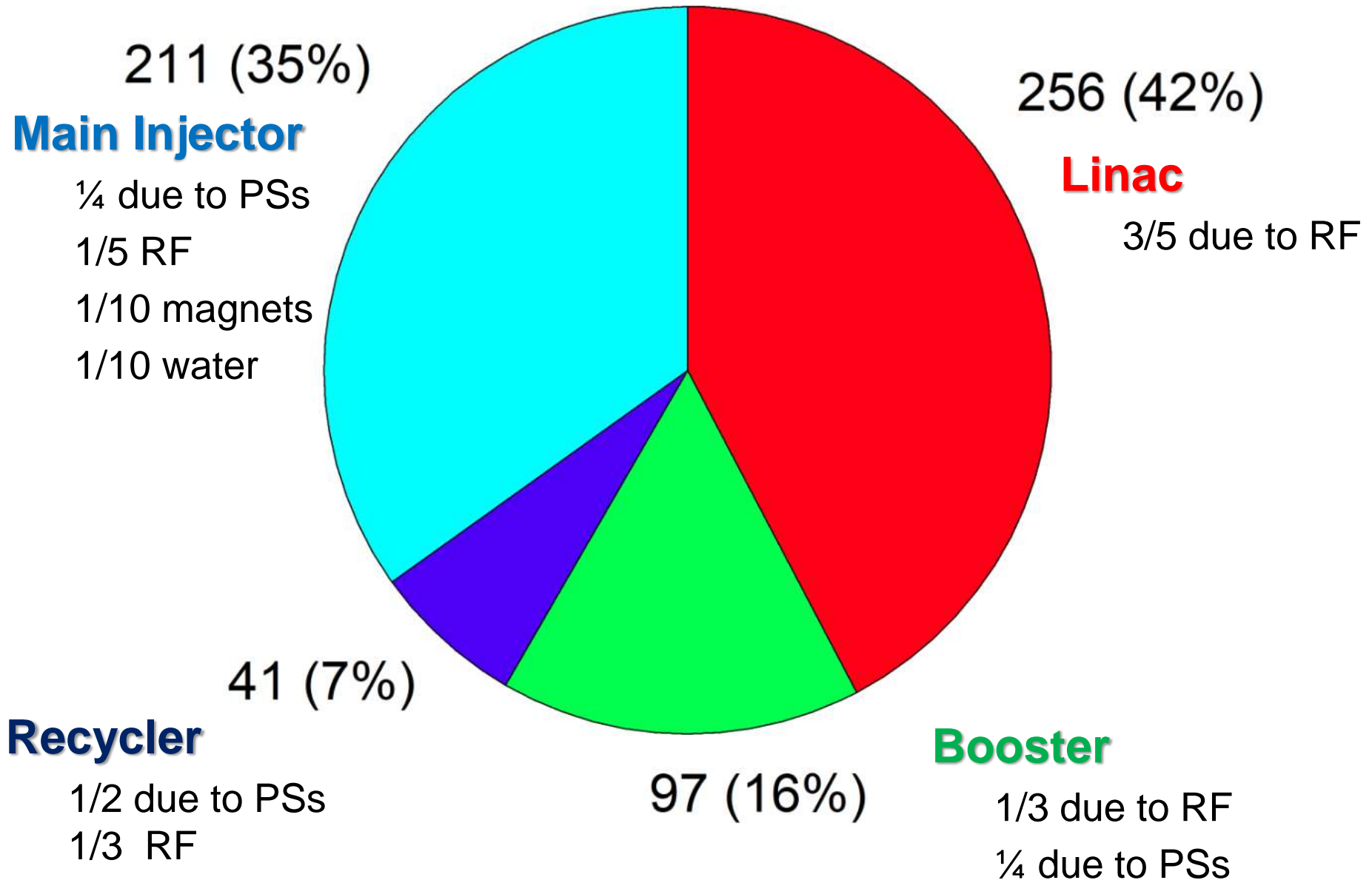
FNAL Complex Unscheduled Downtime (from Cons)

	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



FACE Operations Challenges

❖ Ramp up and timeline:

- ❖ Will we reach peak proton beam power level $\sim 1.5\text{MW}$ in 2031 and $>2\text{MW}$ 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 \rightarrow 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 $(2-3) \times$ (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?