Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Beam Physics Research in Context – Community Priorities

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IOTA/FAST Collaboration Meeting
14 March 2024

Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

2023p5report.org

US Process for Future Planning

Community

“Snowmass” Community Study

Organized by APS / DPF

Snowmass 2021

Particle Physics Project Prioritization Panel (P5)

Organized by HEPAP

Charge
Budget scenario

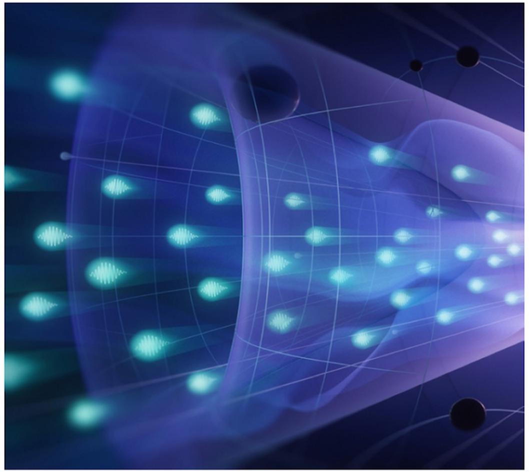
DOE HEP
NSF PHYS

DOE HEP
NSF PHYS

OMB
OSTP
Congress

Science Drivers

Exploring the Quantum Universe



Decipher the Quantum Realm

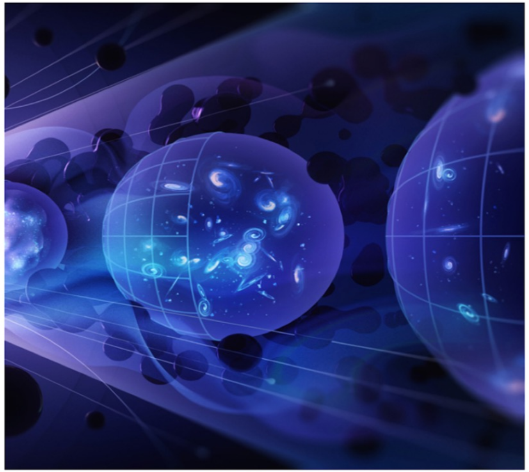
Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena



Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

Prioritization Principles

Overall program should **enable US leadership in core areas of particle physics**
It should leverage **unique US facilities and capabilities**
Engage with **core national initiatives** to develop key technologies,
Develop a **skilled workforce** for the future that draws on US talent
Effective **engagement and leadership in international endeavors** were also considerations

P5 also **considered the uncertainties in the costs, risks, and schedule** as part of our prioritization exercise. The prioritized project portfolios were chosen to **fit within a few percent of the budget scenarios** and to ensure a reasonable outlook for continuation into the second decade, even though that is beyond the purview of this panel.

Balance of program in terms of

- Size and time scale of projects
- On-shore vs off-shore
- Project vs Research
- Current vs future investment

Recommendations

6 High-Level Recommendations

R1: Present Program

R2: Recommended Program

R3: Balancing the Program

R4: Program Elements for the Future

R5: The Workforce

R6: Mid-Course Correction

20 Area Recommendations

Theory

Small Projects – ASTAE

Instrumentation

Accelerator R&D

Collider R&D

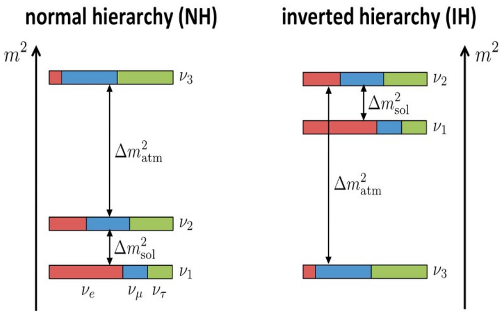
Facilities & Infrastructure

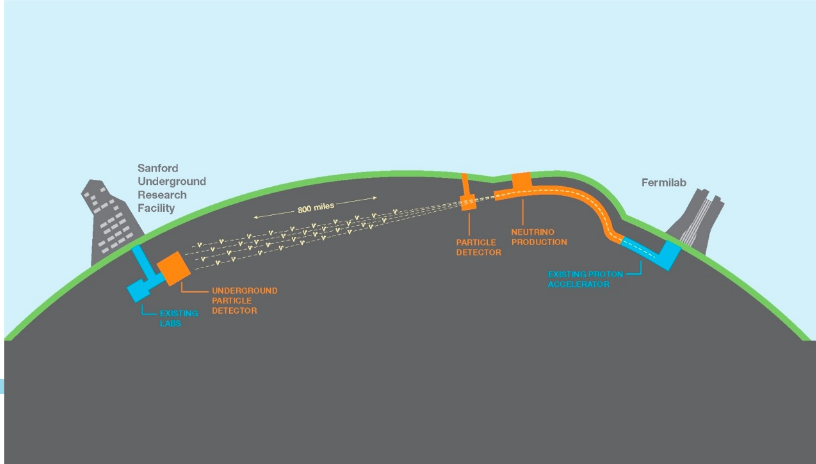
Software, Computing, & Cyberinfrastructure

Sustainability

2023 P5 – Top Priority: Complete LBNF/DUNE Phase I

- Two **10 kt LArTPCs** at Sanford Underground Research Facilities (SURF)
- A **near detector facility**, illuminated by the **world's brightest neutrino beam**
- The **PIP-II accelerator upgrade** under construction, which will enable a **1.2 MW proton beam**
- First goal? **Mass ordering**, with some sensitivity to the CP-violating phase
- Also, sensitivity to electron neutrino component of a **supernova burst**!



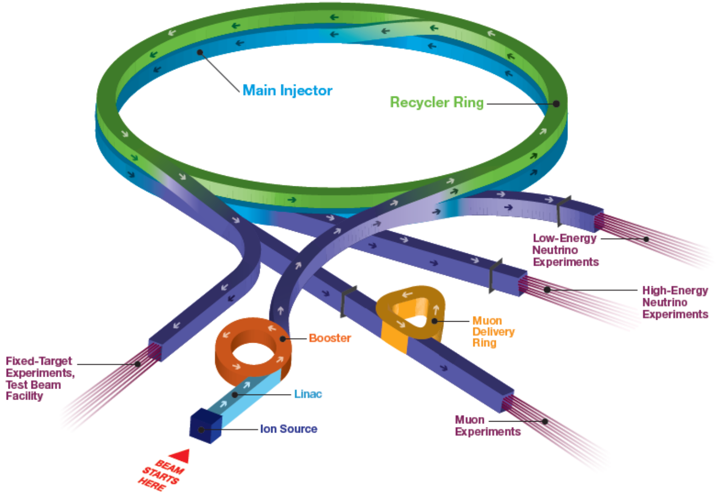


2023 P5 – Major project this decade: reimagined DUNE Phase II

- Include an **early implementation of ACE-MIRT** with the enhanced **2.1-MW beam**
- A **third** far detector at SURF
- An upgraded **near detector complex** to aid in controlling systematics and search for **BSM physics**

Science goals:

- Most precise measurement of the **CP phase** across a range of possible CP phase space
- Search for signatures of **unexpected neutrino interactions**
- Study direct appearance of **tau neutrinos**



2023 P5

“These projects have the potential to transcend and transform our current paradigms. They inspire collaboration and international cooperation in advancing the frontiers of human knowledge…

Plan and start the following major initiatives in order of priority from highest to lowest: a) CMB-S4; b) ACE-MIRT. …

Early implementation of the accelerator upgrade ACE-MIRT advances the DUNE program significantly, hastening the definite discovery of the neutrino mass ordering. This upgrade in conjunction with the deployment of the third far detector and a more capable near detector are indispensable components of the re-envisioned next phase of DUNE.”

Accelerator Complex Evolution (ACE) plan – beyond 1.2MW

Our vision is centered on the ACE plan that has two components

2MW

The Main Injector reliability improvements, cycle time shortening, and target systems upgrade to be carried out through the 2020's called **ACE-MIRT (Main Injector Ramp and Targets)**

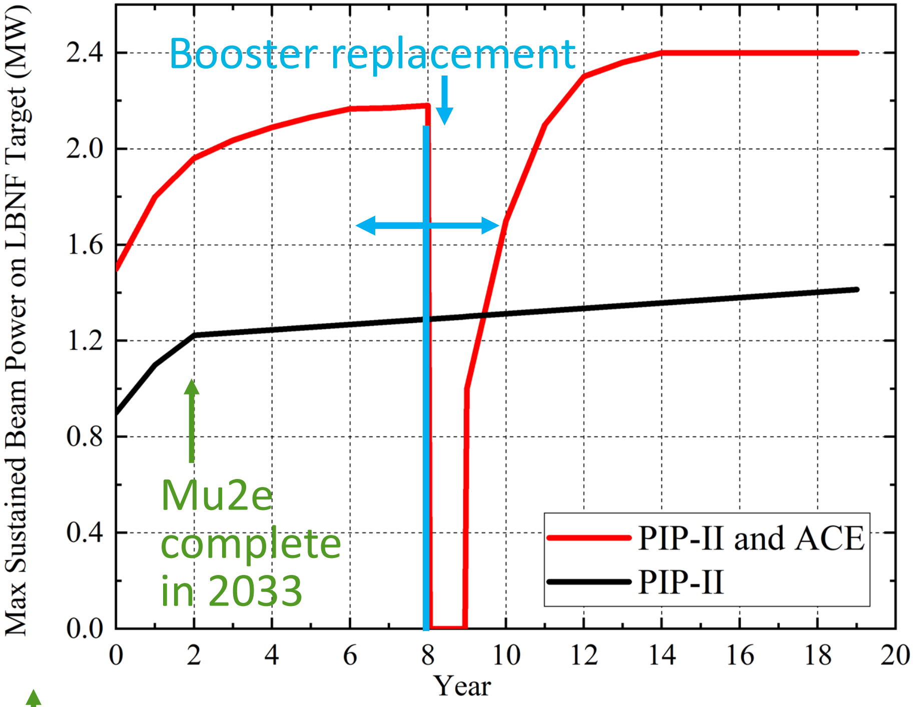
- Will accelerate the achievement of the DUNE science goals with respect to the original PIP-II plan
- Improve reliability and safety of the key machines for the future of accelerator complex

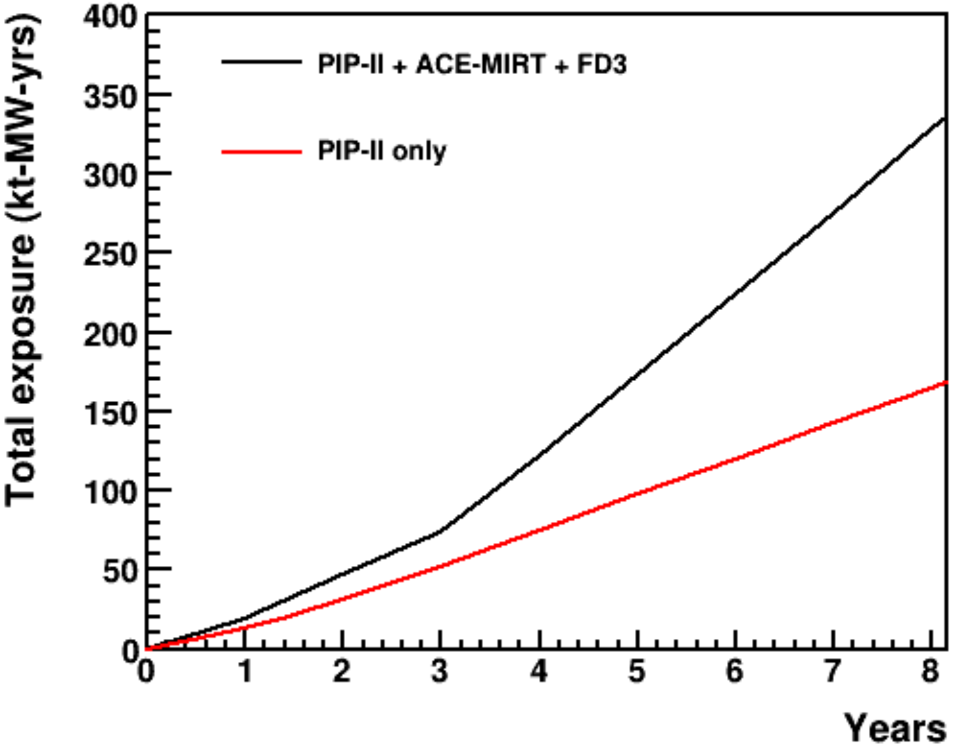
2.4MW

Further, a project would be established to build Booster Replacement. The implementation of **ACE-BR** would

- **Reliably deliver even more beam power to LBNF** to ensure CP Violation measurement in DUNE Phase II
- **Considerably enhance beam capabilities for a broader physics program**
- **Provide a robust and reliable platform for the future evolution of the Fermilab accelerator complex**, possibly including a proton source for multi-TeV accelerator research

DUNE power and POT/Exposure implications





(Mu2e restarts 2029)

Recommendation 4

Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

Investing in the future of the field to fulfill this vision requires the following:

Recommendation 4

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a. Support **vigorous R&D toward a cost-effective 10 TeV pCM collider** based on proton, muon, or possible wakefield technologies, including an evaluation of options for US siting of such a machine, with a goal of being ready to build **major test facilities and demonstrator facilities within the next 10 years** (sections 3.2, 5.1, 6.5, and Recommendation 6).

b. Enhance research in **theory** to propel innovation, maximize scientific impact of investments in experiments, and expand our understanding of the universe (section 6.1).

c. Expand the **General Accelerator R&D (GARD)** program within HEP, including stewardship (section 6.4).

d. Invest in R&D in **instrumentation** to develop innovative scientific tools (section 6.3).

e. Conduct **R&D** efforts to define and enable new projects in the next decade, including detectors for an e^+e^- Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping (sections 3.1, 3.2, 4.2, 5.1, 5.2, and 6.3).

f. Support key **cyberinfrastructure** components such as shared software tools and a sustained R&D effort in computing, to fully exploit emerging technologies for projects. Prioritize **computing and novel data analysis techniques** for maximizing science across the entire field (section 6.7).

g. Develop plans for improving the **Fermilab accelerator complex** that are consistent with the long-term vision of this report, including neutrinos, flavor, and a 10 TeV pCM collider (section 6.6).

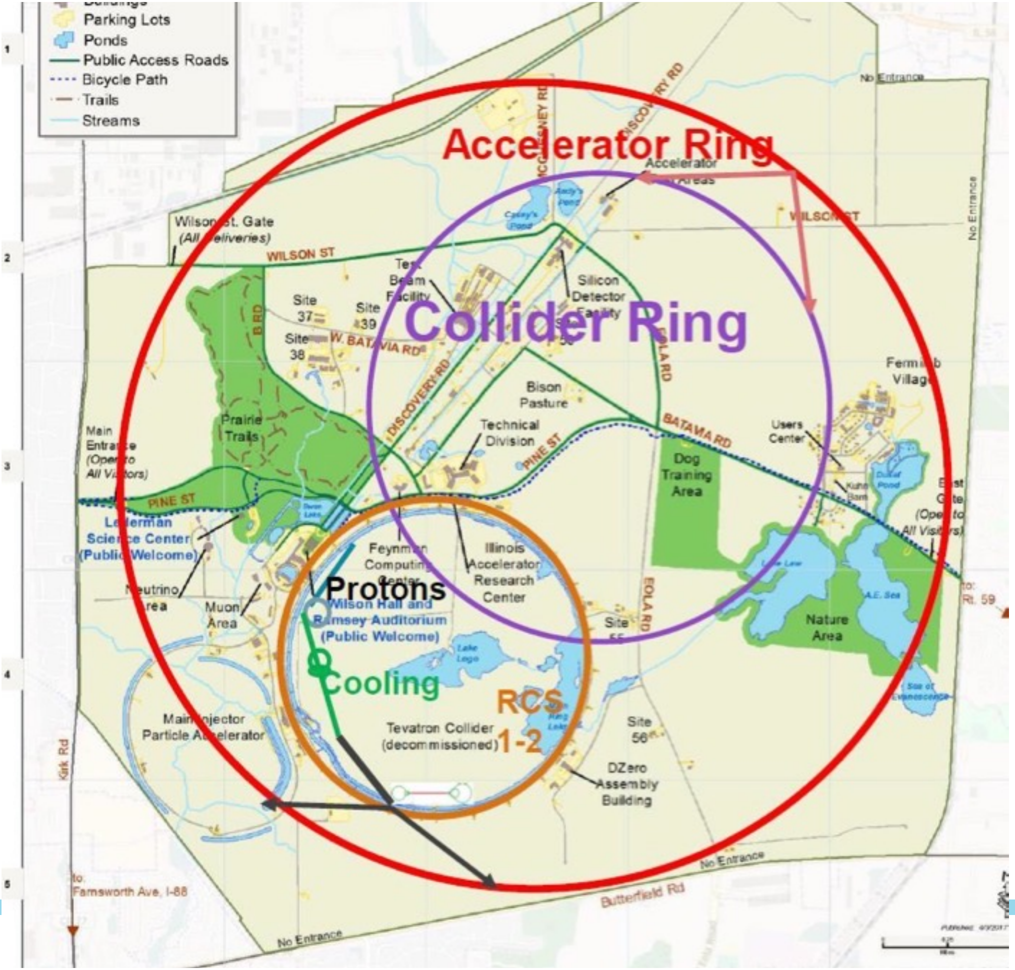
Recommendation 6

Convene a targeted panel with broad membership across particle physics later this decade that makes decisions on the US accelerator-based program at the time when major decisions concerning an off-shore Higgs factory are expected, and/or significant adjustments within the accelerator-based R&D portfolio are likely to be needed. A plan for the Fermilab accelerator complex consistent with the long-term vision in this report should also be reviewed.

The panel would consider the following:

1. The level and nature of US contribution in a specific Higgs factory including an evaluation of the associated schedule, budget, and risks once crucial information becomes available.
2. Mid- and large-scale test and demonstrator facilities in the accelerator and collider R&D portfolios
3. A plan for the evolution of the Fermilab accelerator complex consistent with the longterm vision in this report, which may commence construction in the event of a more favorable budget situation.

Potential scale of the 10 TeV Muon Collider complex at Fermilab



Fermilab

Fermilab Muon Campus – potential MC demonstrator facility

- Fermilab repurposed and rebuilt former Tevatron Antiproton Source beam lines and rings in an optimal and cost-effective manner for use with Muon Campus experiments, including Muon g-2 and Mu2e
- Mu2e to run into 2030s
- g-2 completed data taking
  - Muon production target is operational
  - MC-1 (g-2) building becomes available
  - Opportunity for R&D with muon beams

Area Recommendations

Exploring the Quantum Universe

Instrumentation

6. Increase the budget for generic Detector R&D by at least $4 million per year in 2023 dollars. This should be supplemented by additional funds for the collider R&D program

7. The detector R&D program should continue to leverage national initiatives such as QIS, microelectronics, and AI/ML.

General Accelerator R&D

8. **Increase annual funding to the General Accelerator R&D program by $10M** per year in 2023 dollars to ensure US leadership in key areas.

9. **Support generic accelerator R&D with the construction of small scale test facilities**. Initiate construction of larger test facilities based on project review, and informed by the collider R&D program.

Collider R&D

10. To enable targeted R&D before specific collider projects are established in the US, an investment in collider detector R&D funding at the level of $20M per year and **collider accelerator R&D** at the level of $35M per year in 2023 dollars is warranted.

Accelerator and Beam Physics Roadmap

Grand Challenge #1: Beam Intensity – How do we increase beam intensities by orders of magnitude?

- Beam intensities in existing accelerators are limited by collective effects and particle losses. A complete and robust understanding of these effects is necessary to help overcome the limits and increase beam intensities by orders of magnitude.

Grand Challenge #2: Beam Quality—"How do we increase the beam phase space density by orders of magnitude, towards the quantum-degeneracy limit?"

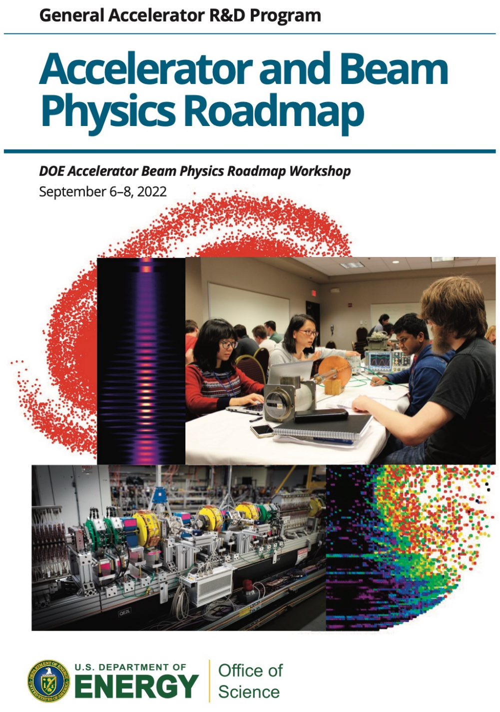
- Most applications of accelerators depend critically on the beam intensity and directionality (or beam emittance) in order to enable new capabilities or to optimize the signal-to-noise ratio. Addressing this grand challenge will yield unprecedented beam qualities that can revolutionize applications of particle accelerators.

Grand Challenge #3: Beam Control— "How do we measure and control the beam distribution down to the individual particle level?"

- An accelerator application benefits most when the beam distribution is specifically matched to that application. This challenge aims to replace traditional methods that use beams of limited shapes with new methods that generate tailored beams and also aims to provide new research opportunities, enabled by detecting and controlling individual particles in accelerators and storage rings.

Grand Challenge #4: Beam Prediction—"How do we develop predictive 'virtual particle accelerators'?"

- Developing virtual particle accelerators will provide predictive tools that enable fast computer modeling of particle beams and accelerators at unprecedented levels of accuracy and completeness. These tools will enable or speed up the realization of beams of extreme intensity and quality, as well as enabling much better control of the beam distribution, eventually reaching down to the level of individual particles.

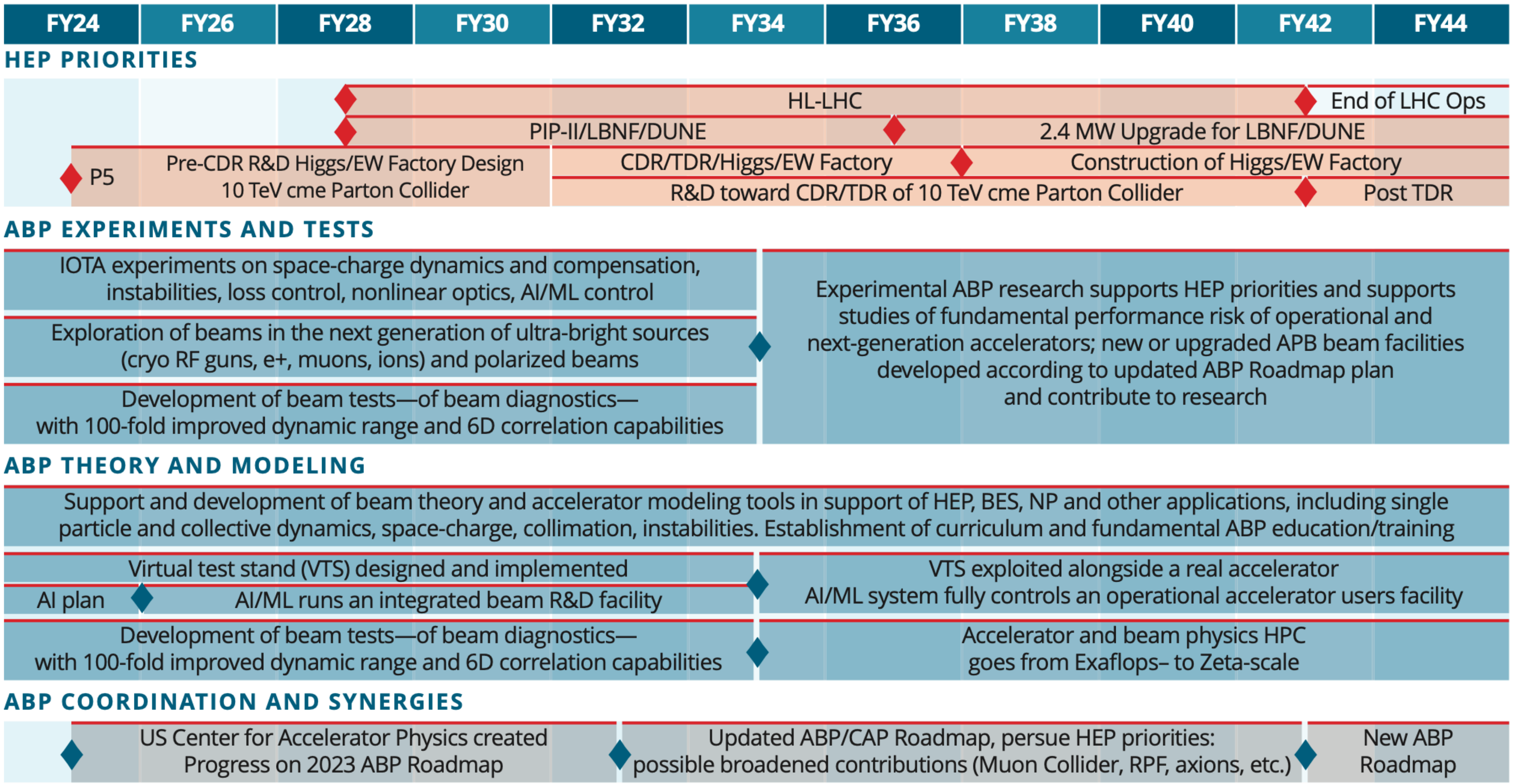


ABP context and connections

The ABP grand challenges must be considered in the context of important thrusts associated with the overall DOE HEP mission:

1. Advance the physics of accelerators and beams to enable future accelerators.
2. Develop conventional and advanced accelerator concepts and tools to disrupt existing costly technology paradigms in coordination with other GARD thrusts.
3. Guide and help to fully exploit science at the HEP GARD beam facilities and operational accelerators.
4. Educate and train future accelerator scientists and engineers.

ABP roadmap for the next two decades reflecting HEP priorities

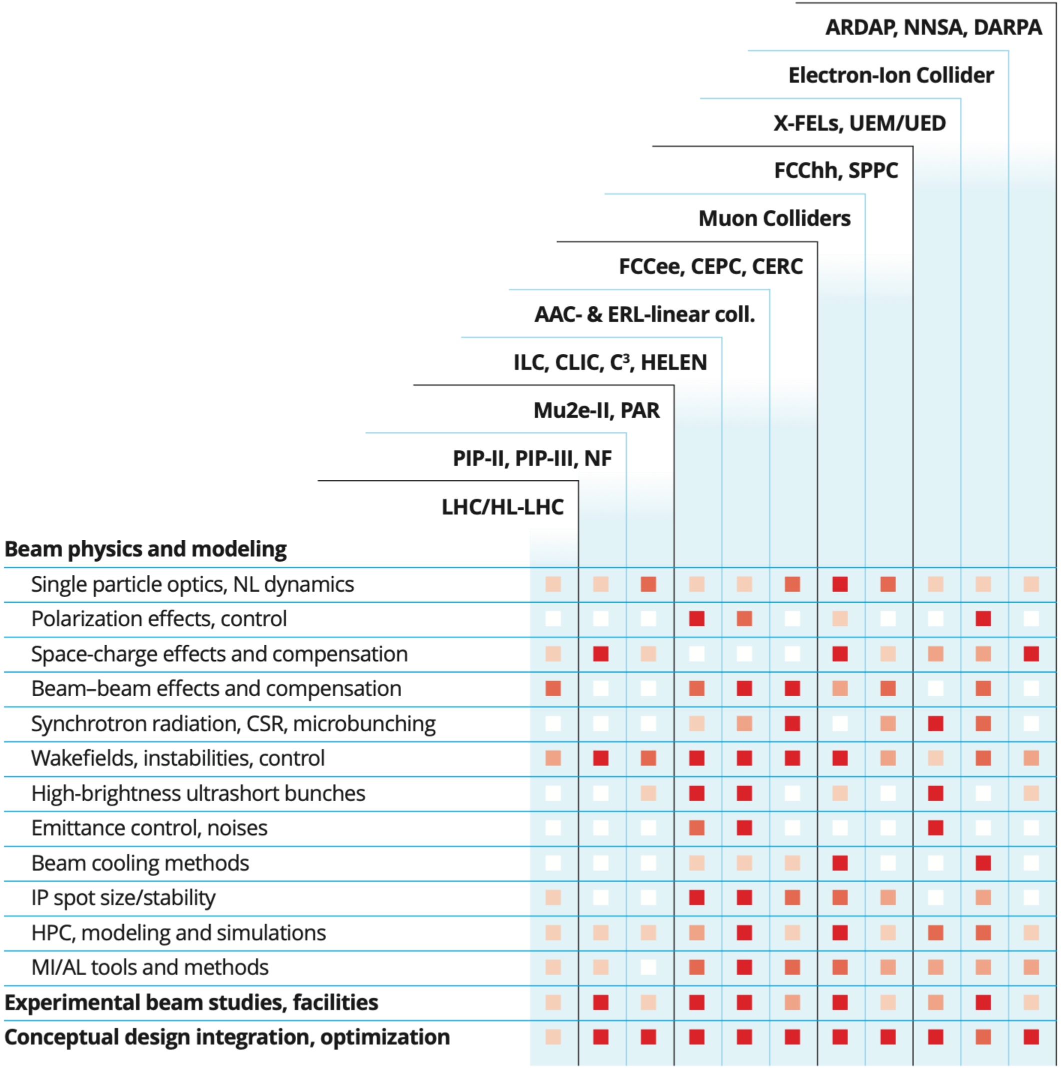


Synergies outside of HEP – Electron Ion Collider

Electron-Ion Collider design and construction requires many collider-related beam physics techniques and tools, with specific interests

- Theory and modeling
  - polarization production and control, orbit tuneup by AI/ML, electron-proton(ion) beam–beam effects in the presence of crossing angle, crab cavities, external noises, nonlinearities and dynamic aperture, collective effects in the electron storage ring, such as impedance and TMCI, **strong hadron cooling** poses a spectrum of issues depending on the scheme (microbunch cooling or e-cooling ring)
- Experimental studies/tests
  - understanding the localized impedance effects due to collimators as in SuperKEKB, demonstration of the coherent electron cooling using plasma cascade at RHIC, **analysis of the potential application of the optical stochastic cooling**, etc. One can also expect that shortly after (or even before) the end of the EIC construction integrated machine design studies will be started to understand possibilities for the collider luminosity upgrade.

ABP needs mapping to facilities



IOTA / FAST has a role in many of the ABP topics !!!