Overview of US Accelerator R&D after P5

Mark Palmer
Chair, Accelerator Science & Technology Department
2023 P5 Member

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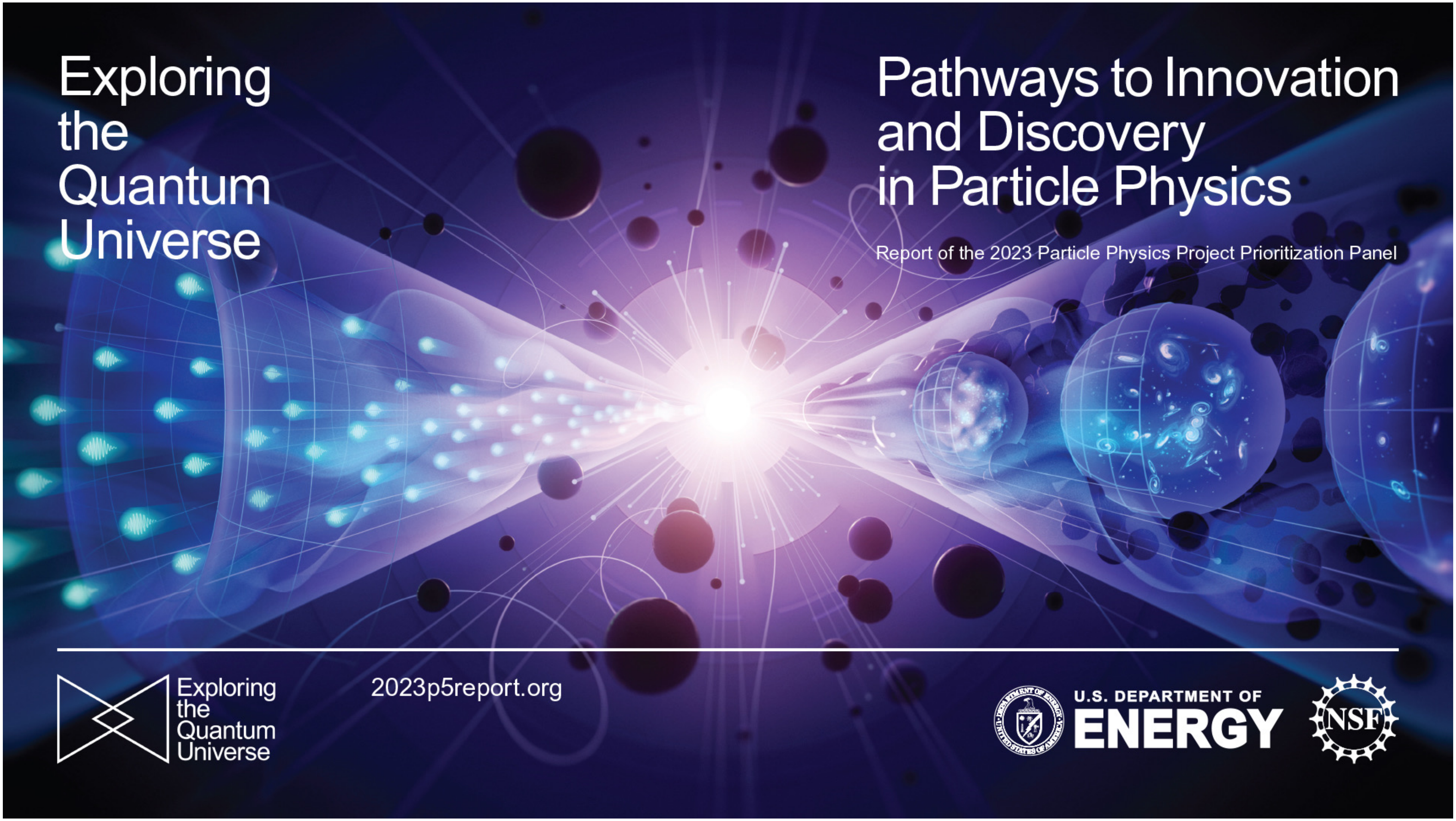
@BrookhavenLab



Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

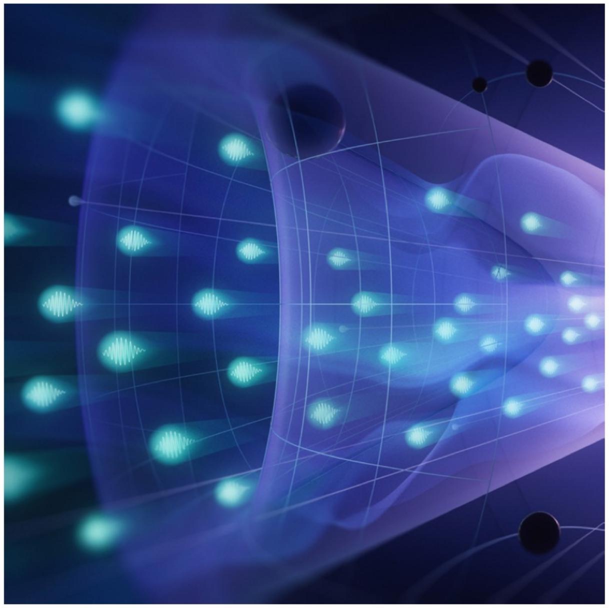
Report of the 2023 Particle Physics Project Prioritization Panel

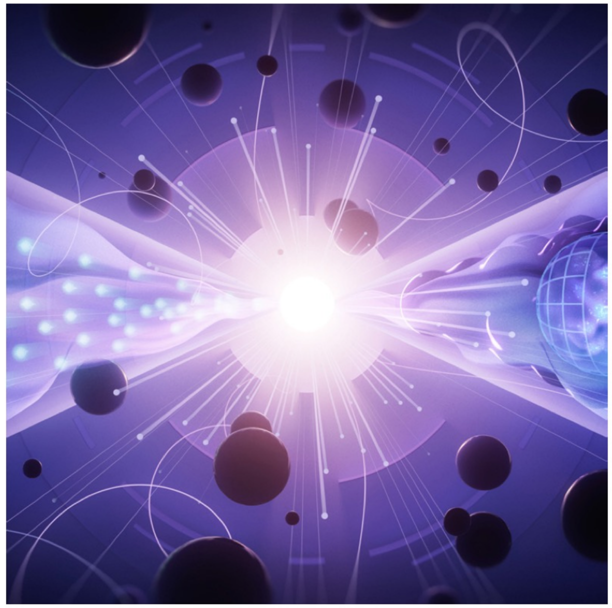
Exploring the Quantum Universe

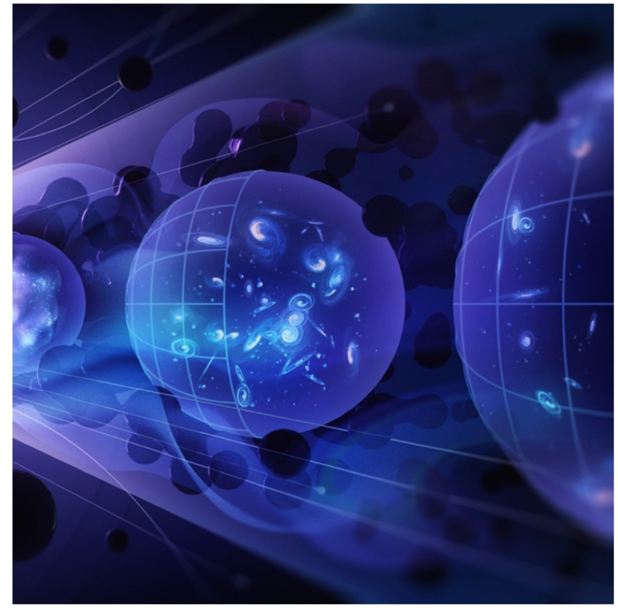
2023p5report.org

U.S. DEPARTMENT OF ENERGY

NSF







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

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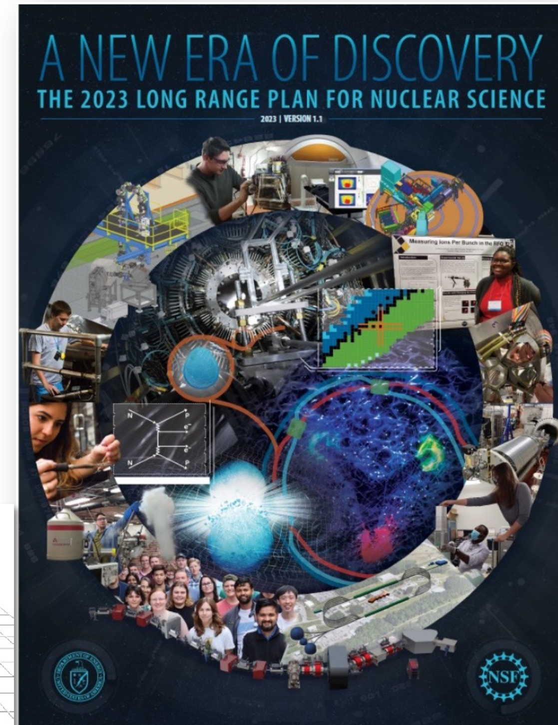
Overview & Vision (Sect. 1.1)

We envision a new era of scientific leadership, centered on decoding the quantum realm, unveiling the hidden universe, and exploring novel paradigms. Balancing current and future large- and mid-scale projects with the agility of small projects is crucial to our vision. We emphasize the importance of investing in a highly skilled scientific workforce and enhancing computational and technological infrastructure. Acknowledging the global nature of particle physics, we recognize the importance of international cooperation and sustainability in project planning. We seek to open pathways to innovation and discovery that offer new insights into the mysteries of the quantum universe.

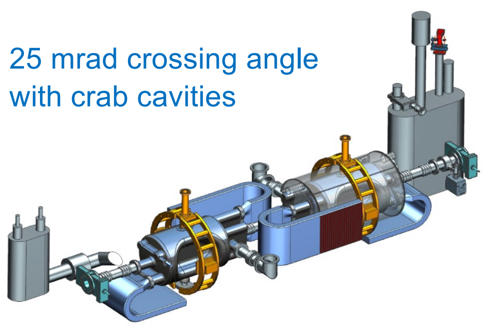
Also, the Nuclear Physics Long-Range Plan

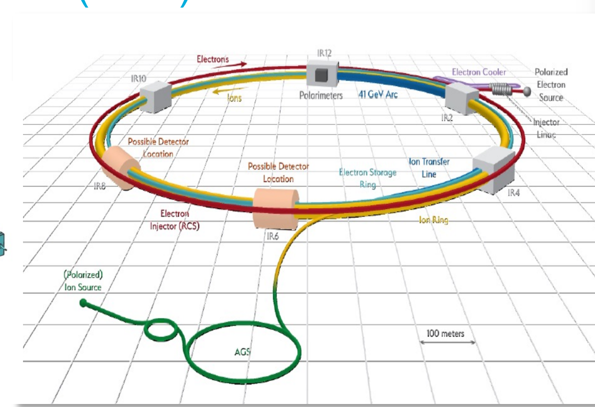
Outlines an ambitious set of goals for Nuclear Physics in the next decade

- Drives the only current US-sited collider effort
  - ⇨ Electron-Ion Collider at BNL
    led by a joint BNL-JLAB project team
    - 40-275 GeV Hadron Storage Ring
    - 18 GeV Electron Storage Ring
    - Electron Rapid Cycling Synchrotron (1 Hz)
    - High Luminosity IR



25 mrad crossing angle
with crab cavities





Accelerator Efforts in the P5 Report

- US accelerator efforts will drive scientific discovery via the projects and experiments that are currently underway
  - Includes PIP-II

- US accelerator efforts are critical for the new projects that are *(we hope)* launching within this decade (captured in Recommendation 2)
  - ACE-MIRT to support a re-envisioned DUNE Phase II
  - An *off-shore* Higgs Factory

- A robust US accelerator R&D program is the foundation for future discovery and leadership in the field (captured in Recommendation 4)
  - "Support vigorous R&D toward a cost-effective 10 TeV pCM collider…"
  - "Expand the General Accelerator R&D (GARD) program within HEP…"
  - "Develop plans for improving the Fermilab accelerator complex…"

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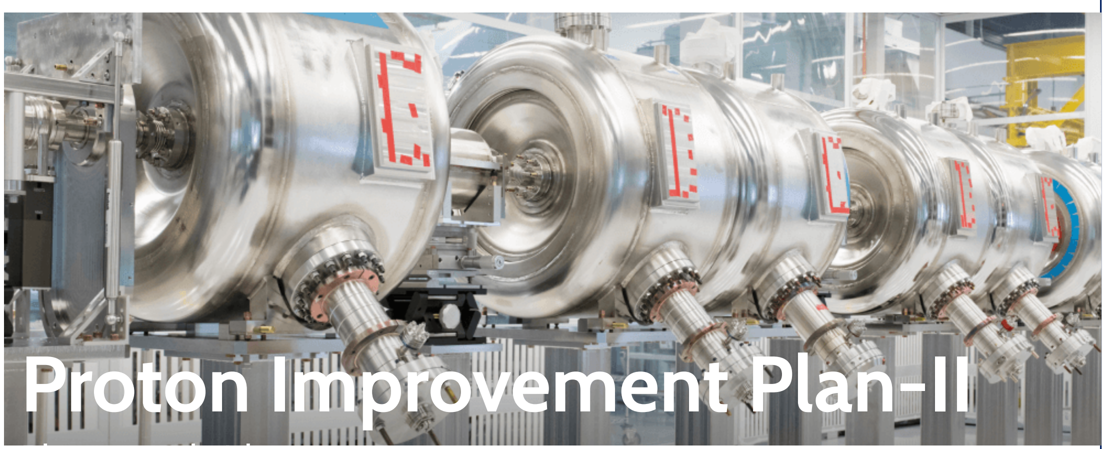
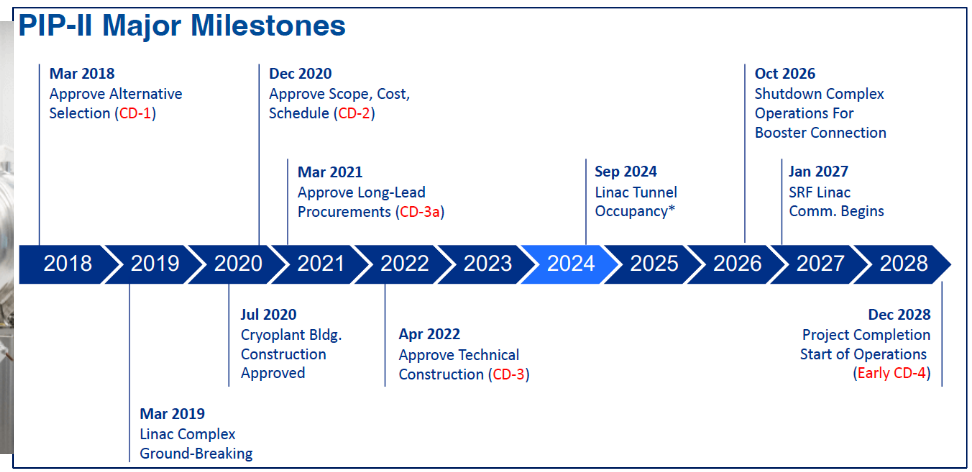
Accelerators To Support Ongoing Projects

Elements of Recommendation 1:

- HL-LHC Program [Rec 1a]
  - Delivery of the hardware required for ATLAS, CMS, and AUP
    - *The 1st US Nb_3Sn Quadrupole Magnet delivered to CERN*
- DUNE Phase I and PIP-II [Rec 1b]

Photo: Dan Svoboda, Fermilab



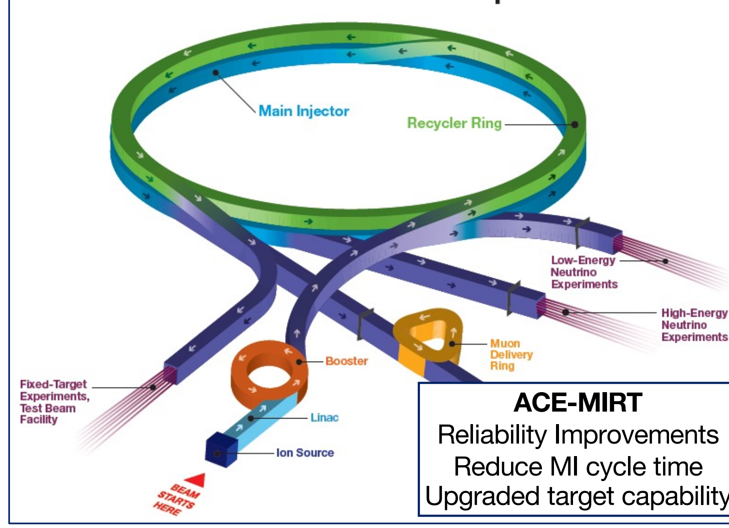


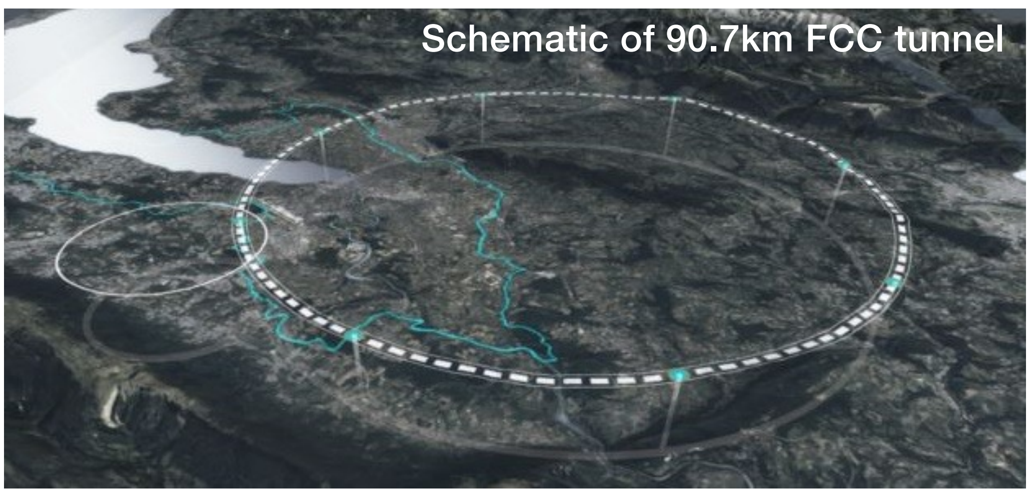
Accelerators To Support Next Efforts

Elements of Recommendation 2:

- A re-envisioned second phase of DUNE [Rec 2b]
  - *…with an early implementation of an enhanced 2.1 MW beam—**ACE-MIRT***
- An off-shore Higgs Factory [Rec 2c]
  - *"The current designs of FCC-ee and ILC meet our scientific requirements."*

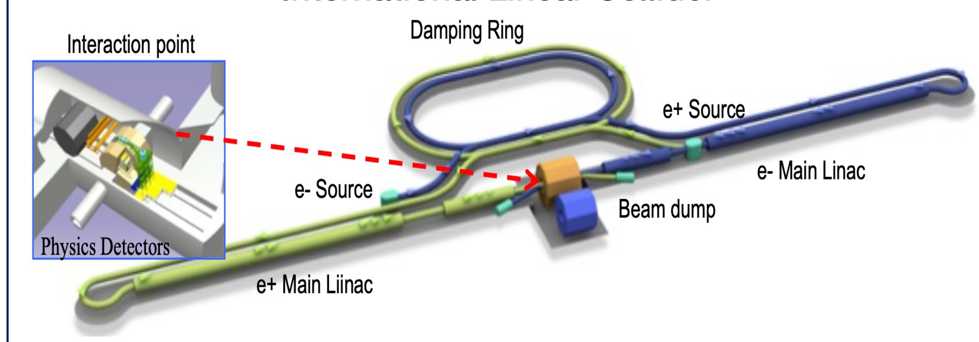
Fermilab Accelerator Complex





Schematic of 90.7km FCC tunnel

International Linear Collider



The Role of Accelerator R&D

Excerpt from Section 6.4

Particle accelerators play an essential role in high energy physics research. They deliver the unique beams that enable the majority of the P5 science drivers for the next decade (section 6.4.1). Physics goals beyond this decade place radical new demands on accelerator capabilities. ***To achieve these demanding performance requirements, while reducing costs and minimizing environmental impacts, requires focused investment in both generic R&D (section 6.4.2) and collider R&D (section 6.5) along with strategic investment in the existing accelerator complex at Fermilab (section 6.6.2).*** *In this context, DOE-HEP, in partnership with NSF and other Offices and agencies, has the opportunity to lead accelerator development into the future while simultaneously delivering broader benefits across science and society.*

The GARD Program

Recommendation 4 excerpt:

> "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.

Recommendation 4c:

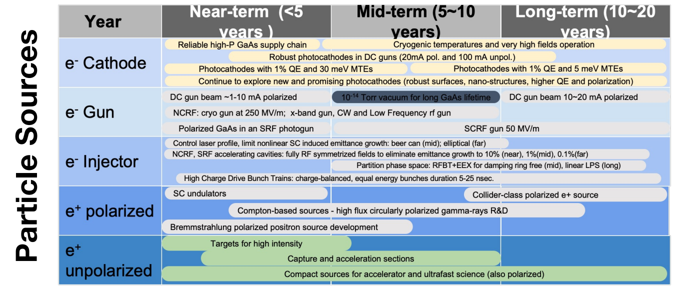
- Expand the **General Accelerator R&D (GARD)** program within HEP, including stewardship (section 6.4).

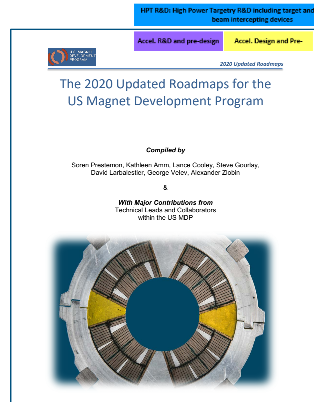
- NOTE: US Roadmaps for the GARD thrusts underwent extensive development as the US entered the Snowmass/P5 process
  - ***Now undergoing further evolution based on the P5 recommendations!***

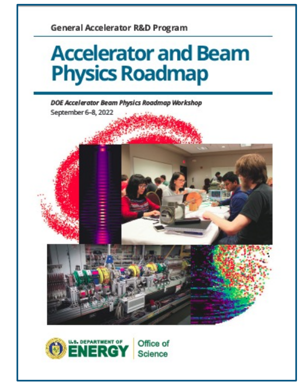
General Accelerator R&D

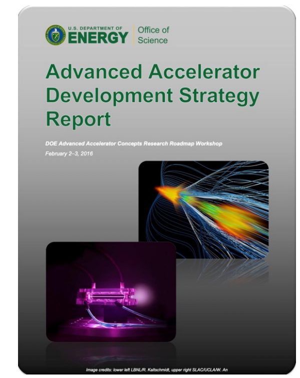
The DOE-HEP General Accelerator R&D (GARD) Program

- Broad ***accelerator technology*** *and* ***beam physics*** *effort to provide the foundation for future capabilities*
  - Accelerator and beam physics
    - Beam physics experiments, modeling, instrumentation, theory
  - Particle sources and targets
    - Photoinjectors, e+, high-power targetry
  - Advanced acceleration concepts
    - Beam-, laser-, and structure-based wakefields
  - RF acceleration technology
    - SRF, NCRF, high gradient research, and RF sources
  - High field superconducting magnets and materials
    - LTS and HTS









Collider R&D Program

The P5 Report strongly supports the implementation of a US Collider R&D Program:

> *"Targeted collider R&D is required to translate advancements in detector and accelerator technology into the experimental facilities that shape our understanding of the universe."* Section 6.5

Higgs Factory

- ILC
- FCC-ee
- Re-evaluate options at next P5 if these projects don't proceed

10 TeV pCM Collider

- FCC-hh
- Muon Collider
- Possibly Wakefield Technology

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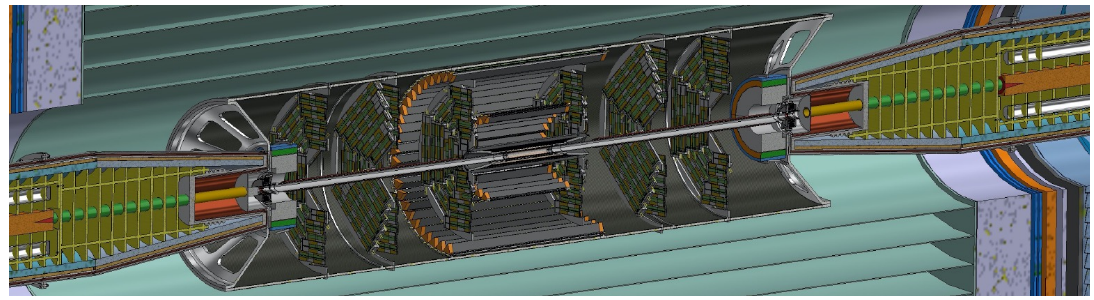
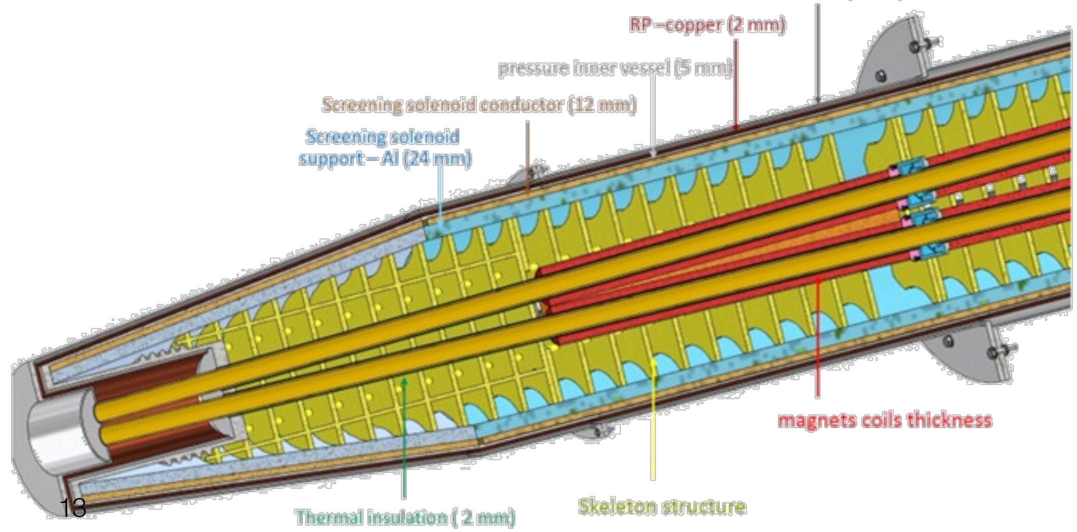
Collider R&D Program: Higgs Factory

- Engagement with pre-project R&D activities is encouraged
  - FCC Feasibility Study underway
  - US has multiple areas of relevant expertise and capability for FCC-ee
    - MDI & IR Magnets
      - Unique US Direct Wind capability
    - High performance SRF Cavities
      - Possible applications for Cold Copper technology
    - Beam Polarization
    - Collimation and Beam Loss



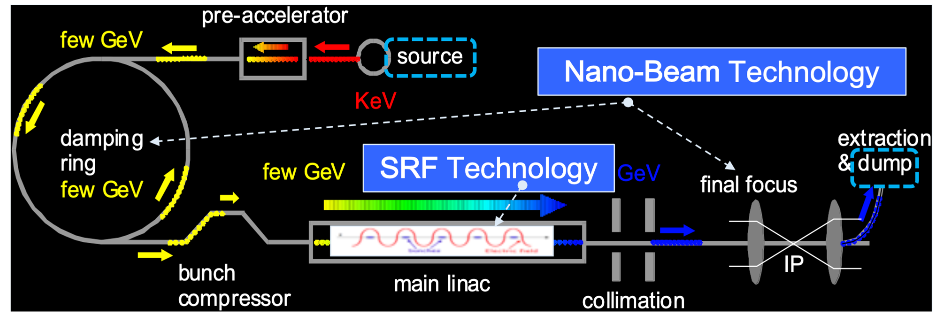
FCC-ee IR Design



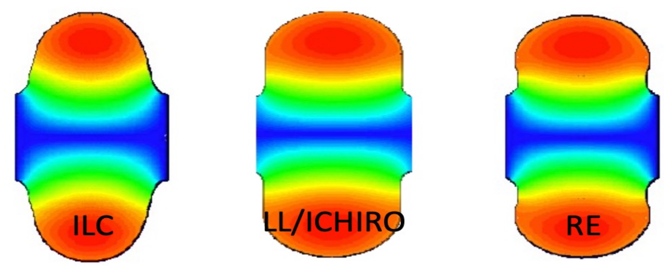
5 Cell Cavity Collaboration with JLab

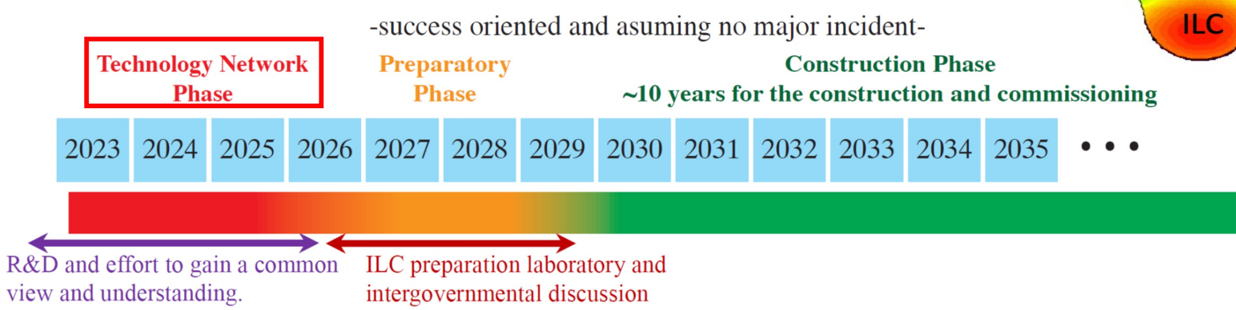
Collider R&D Program: Higgs Factory

- Engagement with pre-project R&D activities is encouraged
  - ILC Technology Network has been formed
  - US has broad expertise in ILC design and technologies
    - GARD-funded SRF R&D to improve gradients
    - Polarized e^- and e^+ source design
    - Damping Ring Design
    - IR magnet design and stability requirements



From 30 MeV/m towards 90: shaping and new materials





Materials: T. Nakada, SLAC P5 Townhall

Collider R&D Program: 10 TeV pCM

3 accelerator technologies offer a potential pathway to the 10 TeV pCM scale:

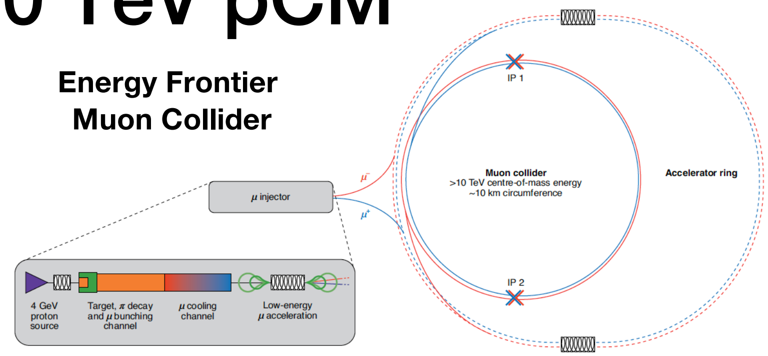
- 10 TeV muon collider
- ~100 TeV proton-proton collider
- Possibly a plasma wakefield collider

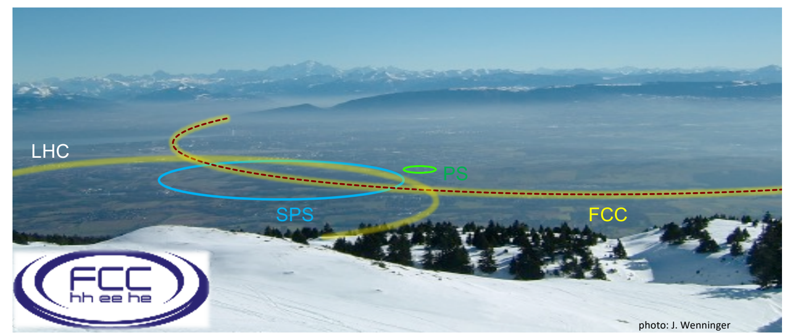
GARD-funded efforts help support specific technology elements of each of these options

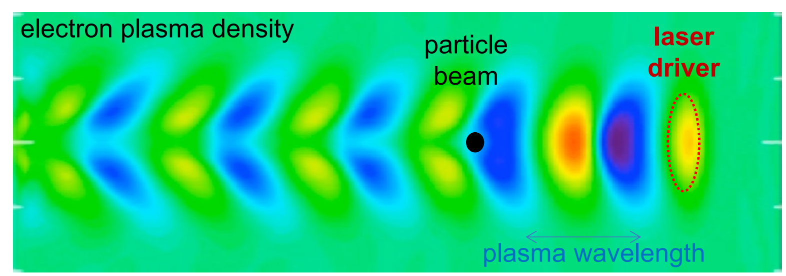
However, a *directed collider R&D program* is necessary to address the feasibility (both economic and technical) for each.

- *Establishment of a US Collider R&D Program will be critical to achieving our long-term aspirations for the Energy Frontier*

Energy Frontier Muon Collider







Plans for the Fermilab Complex

The P5 report states:

"Experimental particle physics in the US relies on strategic facilities and infrastructure that enable exploration of the unknown. Stewardship of these facilities through maintenance, planning, and development is central to the future efforts recommended in this report."

Recommendation 4g:

- 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).

Area Recommendation 12: Form a dedicated task force, to be led by Fermilab with broad community membership. This task force is to be charged with defining a roadmap for upgrade efforts and delivering a strategic 20-year plan for the Fermilab accelerator complex within the next five years for consideration… (Recommendation 6)...

Area Recommendation 13: Assess the Booster synchrotron and related systems for reliability risks through the first decade of DUNE operation and take measures to preemptively address these risks.

Closing Remarks
from Section 2.3: The Path to 10 TeV pCM

Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where decisions will be taken collectively from the outset by the partners. This differs from current and past international projects in particle physics, where individual laboratories started projects that were later joined by other laboratories. The proposed program aligns with **the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

…

In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

…

Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

Backups Follow

Brookhaven National Laboratory