Vision and Plans for Fermilab's Next 10-20 Years

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Snowmass Community Summer Study
University of Washington, Seattle
25 July 2022

This is an exciting time for Particle Physics

- Profound science questions and discovery potential
  - Higgs boson
  - Neutrinos
  - Dark matter
  - Dark energy and inflation
  - Exploring the unknown

- Significant advances in technology and other enabling drivers
  - Accelerator science & technology
  - Detectors & Microelectronics
  - Computing, AI/ML
  - Quantum science & technology
  - Theory

This is a defining moment for Fermilab

- With the successful completion of LBNF/DUNE/PIP-II, Fermilab will become host to the first internationally conceived, constructed, and operated mega-science experiment on U.S. soil
  - US/Fermilab is universally acknowledged as the world leader in neutrino science

- As it enters its next 50 years, Fermilab remains America's premier Particle Physics and Accelerator Laboratory, delivering groundbreaking science and technology innovation, underpinned by a world-class and diverse workforce, excellence in business and operations, a renewed and sustainable campus and strong and lasting regional, national and international partnerships

Over the next decade, Fermilab plans to:

- Continuously deliver groundbreaking discovery science and technology innovation
  - Addressing the 2014 P5 science drivers *and* science priorities informed by the next P5 report
  - NOvA, SBN; LHC; Muon g-2; LSST-DESC, ….
- Successfully complete the 2014 P5 plan, begin scientific exploitation consistent with P5 timeline
  - LBNF/DUNE; PIP-II; HL-LHC; Mu2e; CMB-S4
  - Host Lab for DUNE
- In collaboration and coordination with the US community and international partners, ensure the success and impact of the new P5 strategic plan
  - Booster Replacement (BR), DUNE Phase II
  - Lay the groundwork for the next major facility onsite, as an international project, conceived and executed as a global endeavor
- Pursue accelerator and detector R&D
  - BR, DUNE Phase II, FCC @CERN, next major facility @Fermilab
  - As sciences in their own right
- Advance emerging science & technology capabilities → further enhancing lab's core mission
  - Quantum Information Science & SQMS Center
  - Artificial Intelligence / Machine Learning
  - Microelectronics

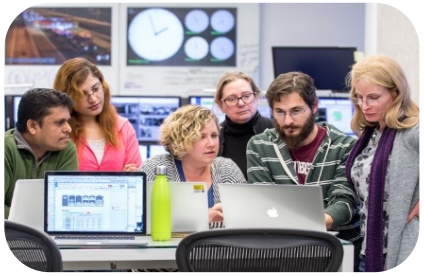
Over the next decade, Fermilab also plans to:

- Diversify and empower our workforce
  - Develop and execute a workforce and diversity strategic plan
  - Foster a culture of respect, inclusion, transparency, integrity and excellence that is essential to ground-breaking science
  - Partner with Chicagoland and nationwide colleges and universities, including minority serving institutions, to host upwards of 100s of students and advanced degree programs
- Achieve excellence in business & operations, and renew our campus infrastructure with sustainability goals, integrated with science vision
- Forge strong regional, national, international partnerships: with University of Chicago, Argonne, Universities Research Association and other national and international institutions
- Launch a strategic plan for Fermilab's next 20 years

Strategic Thrusts: Pillars of our vision for Fermilab

Deliver groundbreaking science and technology innovation

Building for Discovery: Project Execution



Diversify and empower our workforce

Transform business systems & operations, execute sustainable campus strategy integrated with science vision

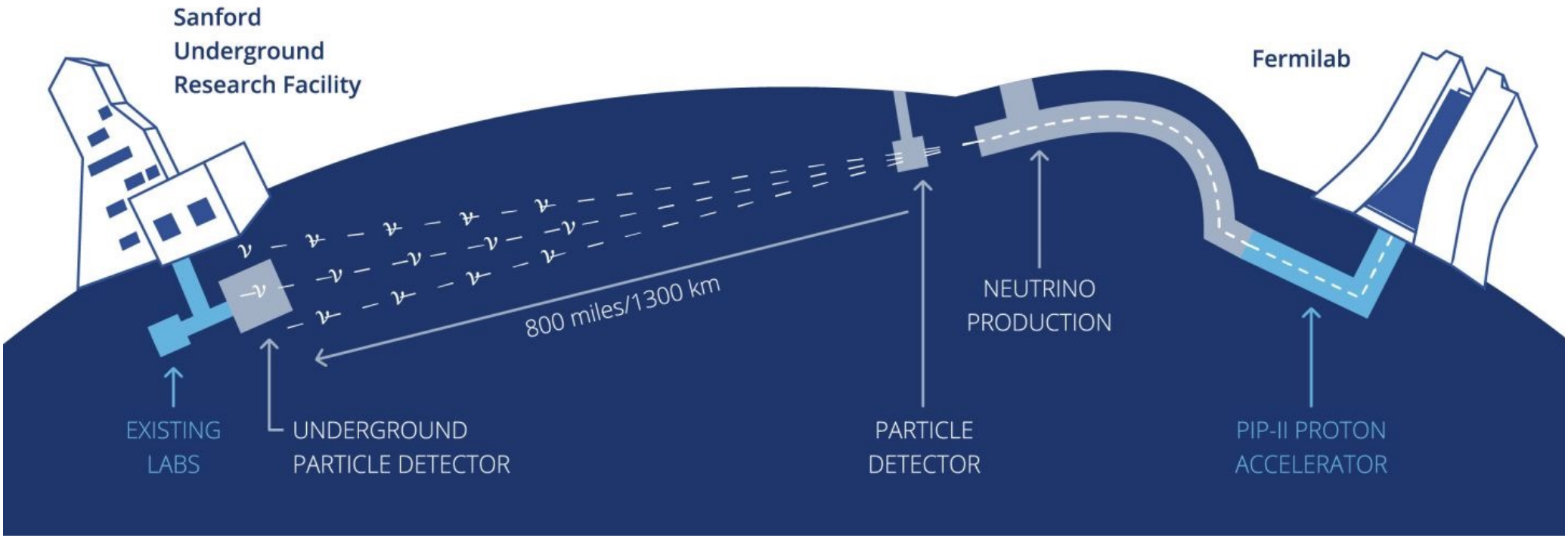
Forge strong alliances with UChicago, ANL, URA and other national/international institutions

Develop Strategic Plan for Fermilab's next 20 Years

S&T

DUNE: The world's most capable neutrino experiment, driven by LBNF and PIP-II

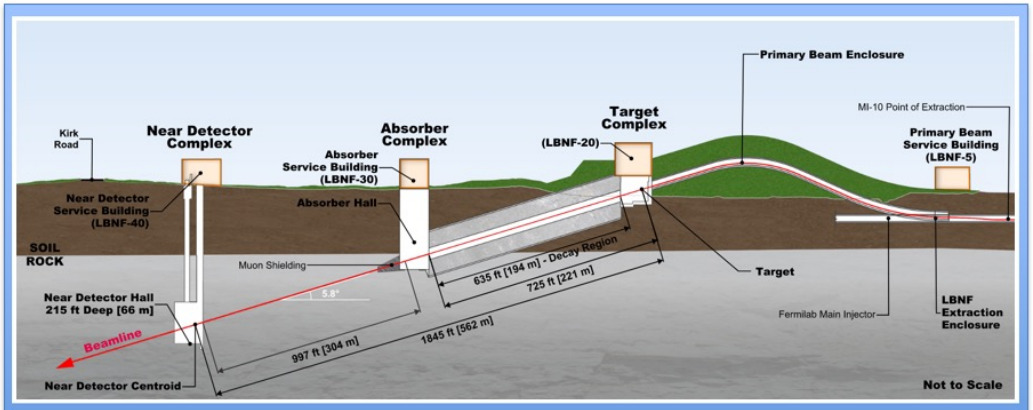
Delivering on LBNF/DUNE is Fermilab's highest priority



Proton Improvement Plan – II (PIP-II)

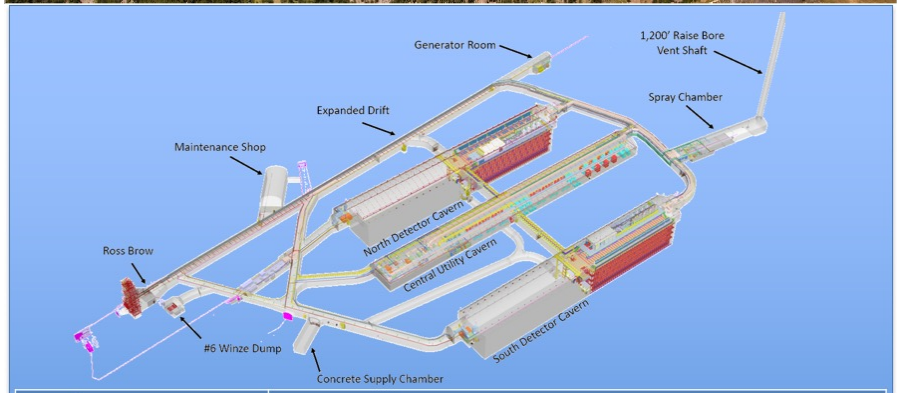
LBNF/DUNE-US Project Scope

Near Site – Batavia, IL



WBS/Subproject	Scope
131.NSCFB/NSCF + Beamline	1.2MW primary and neutrino beam, upgradable to 2.4MW; facility to support 1.2MW upgradable beamline and ND Complex
131.ND/Near Detector	DUNE-US contributions to Phase 1 Near Detector; LAr and LHe systems to support ND; installation and integration for detector and cryogenic systems.

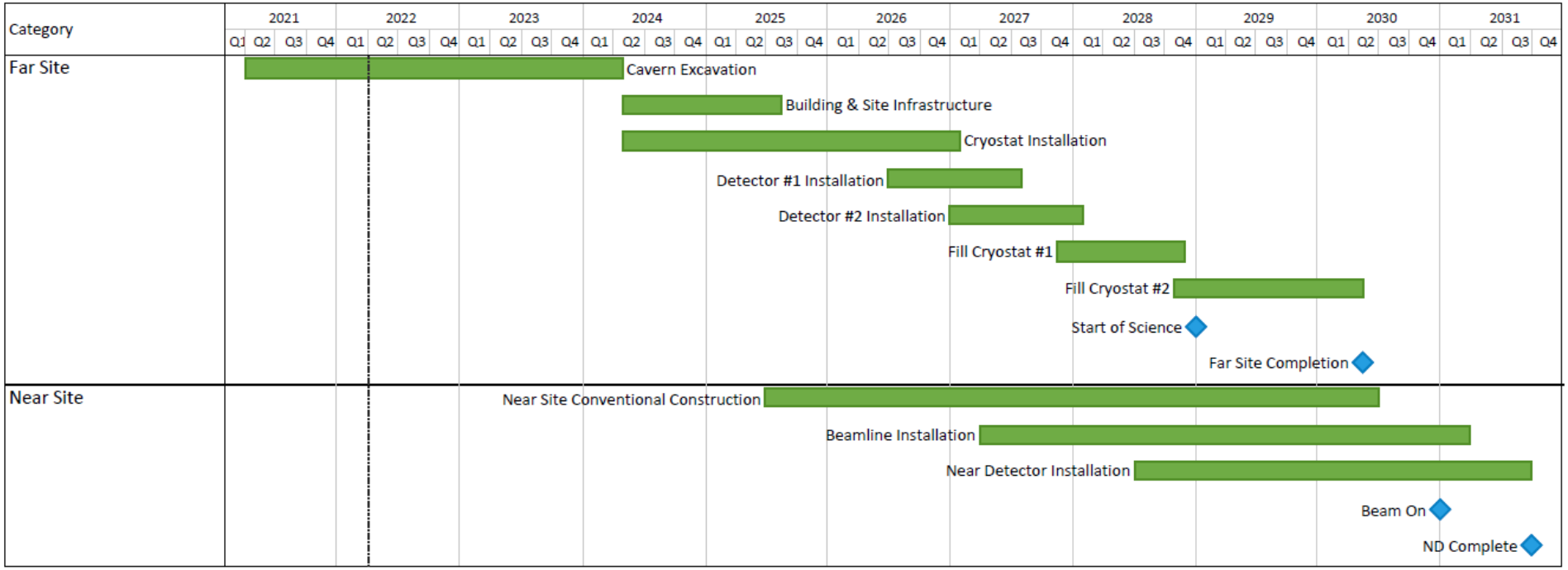
Far Site – SURF, Lead, SD



WBS/Subproject	Scope
131.FSCFEXC/FSCF-Excavation	Project management, preliminary and final design, reliability/infrastructure upgrades, pre-excavation systems, and excavation work to support 4 detector modules.
131.FSCFBSI/FSCF-Building & Site Infrastructure	Project management, preliminary and final design, and construction of surface and underground utilities, and infrastructure outfitting of spaces for detector modules.
131.FDC/Far Detectors and Far Site Cryogenic Infrastructure	DUNE-US contributions to two DUNE detector modules; two cryostats & associated liquid argon; cryogenic systems to support two detector modules; installation and integration for two detector modules and cryogenic infrastructure

Over 50% of scope is at final design maturity

LBNF DUNE Summary Schedule



Definition of Phases

- Originally envisioned in the 2014 P5 plan
- **Phase I**
  - Accomplished with PIP-II, LBNF/DUNE-US, and DUNE International Partners
  - Meets P5 minimum requirements to proceed by 2035 timeframe
  - **Same project scope as proposed at CD-1R in July 2015**
- **Phase II**
  - Increased mass at Far Detector
  - More Capable Near Detector (MCND)
  - Increased beam power by Booster replacement

Capability Description	LBNF/DUNE-US Project + DUNE Int'l Project: Phase I	Phase II
Beamline		
1.2MW (includes 2.4MW infrastructure)	X	
2.4MW		X[1]
Far Detectors		
FD1 – 17 kton	X	
FD2 – 17 kton	X	
FD3		X
FD4		X
Near Detectors[2]		
ND LAr	X	
TMS	X	
SAND	X	
MCND (ND GAr)		X

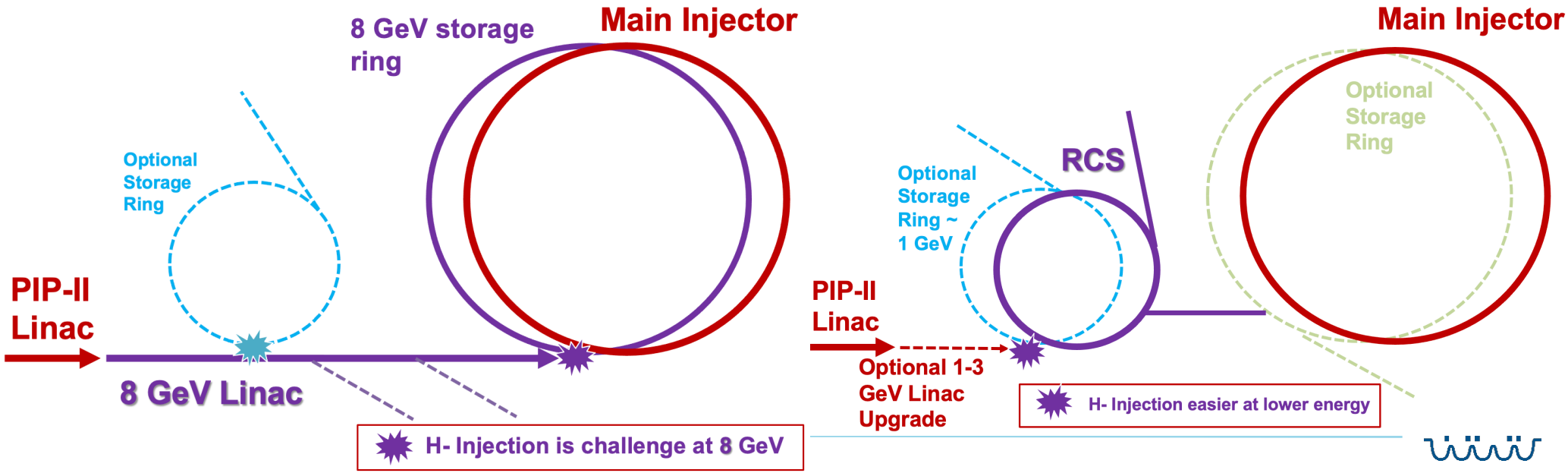
Note 1: requires upgrades to LBNF neutrino target and upgrades to Fermilab accelerator complex. The LBNF facility is built to support 2.4MW in Phase I.
Note 2: Near Detector Subproject threshold scope provides "day 1" requirements to start the DUNE experiment

Booster Replacement

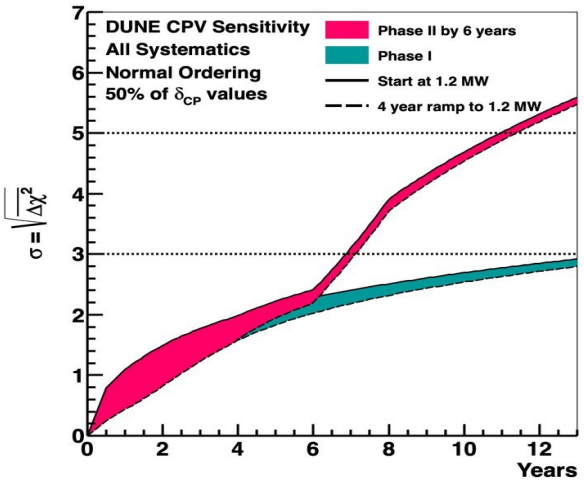
PIP-II provides a platform for extended physics program and future facility upgrades.

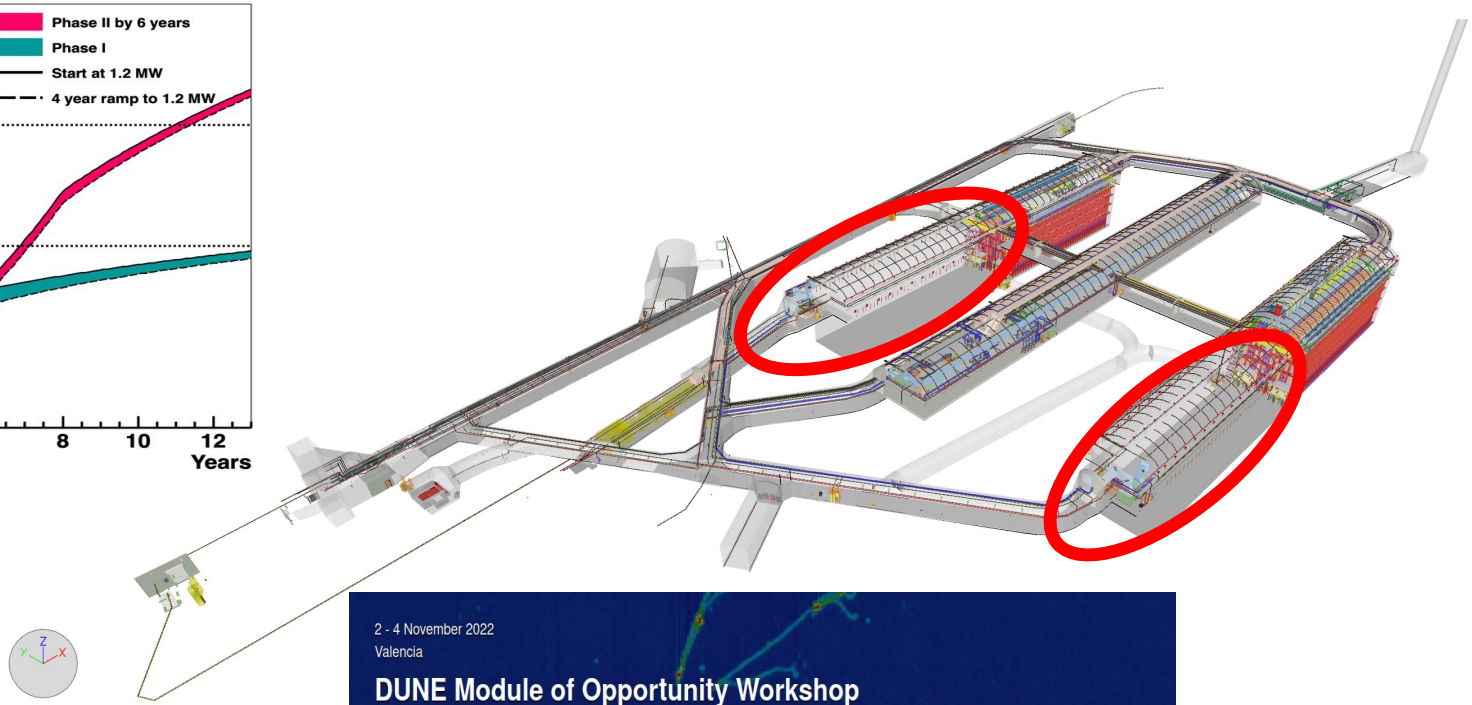
Booster replacement scenarios are developed informed by input from Snowmass/P5

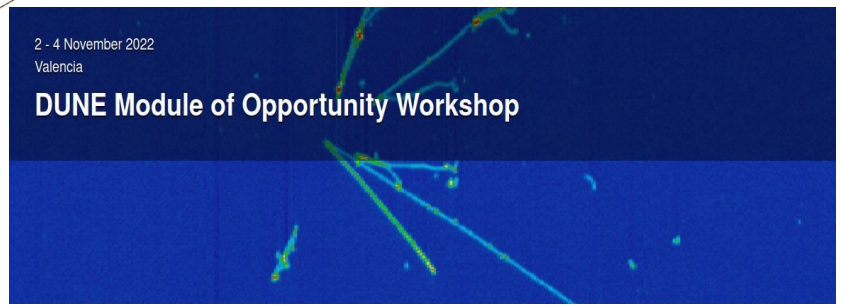
- Cost-effective and fastest path to increased power to 2.4MW for LBNF.
- Capture options for additional medium and small-scale experiments.
- Enable long-term vision.



Far Detector Modules 3 and 4

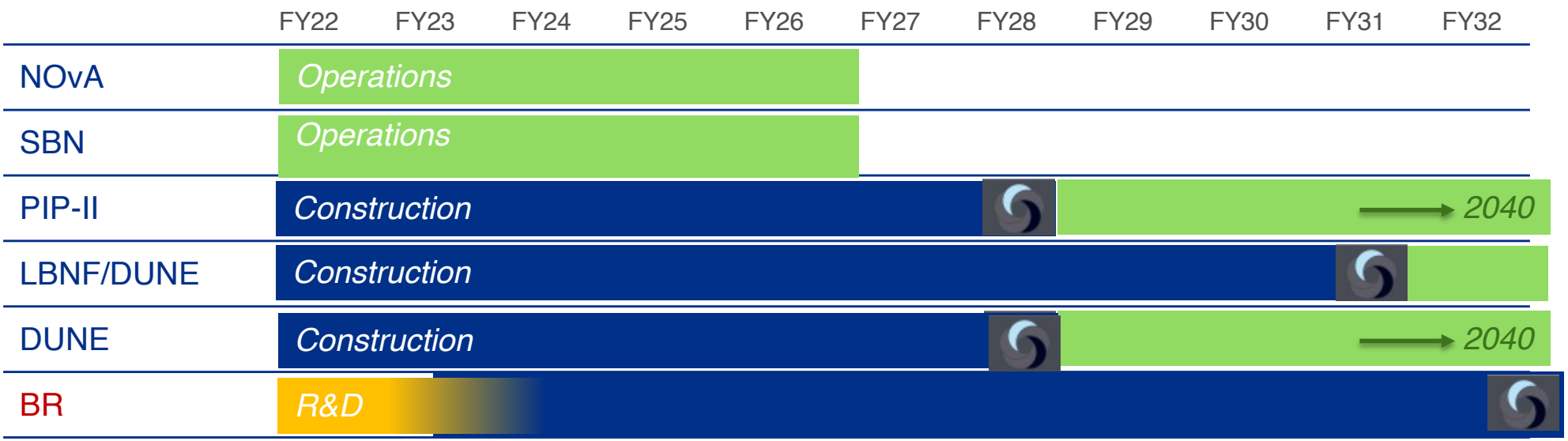






Neutrino Science

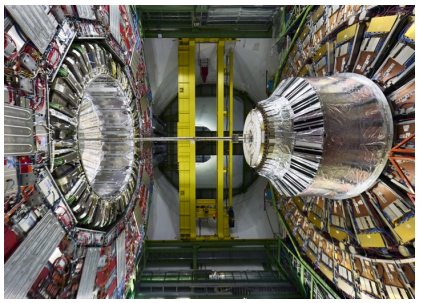
Vision: US/Fermilab is universally acknowledged as the world leader in neutrino science for decades to come



S&T Collider Science

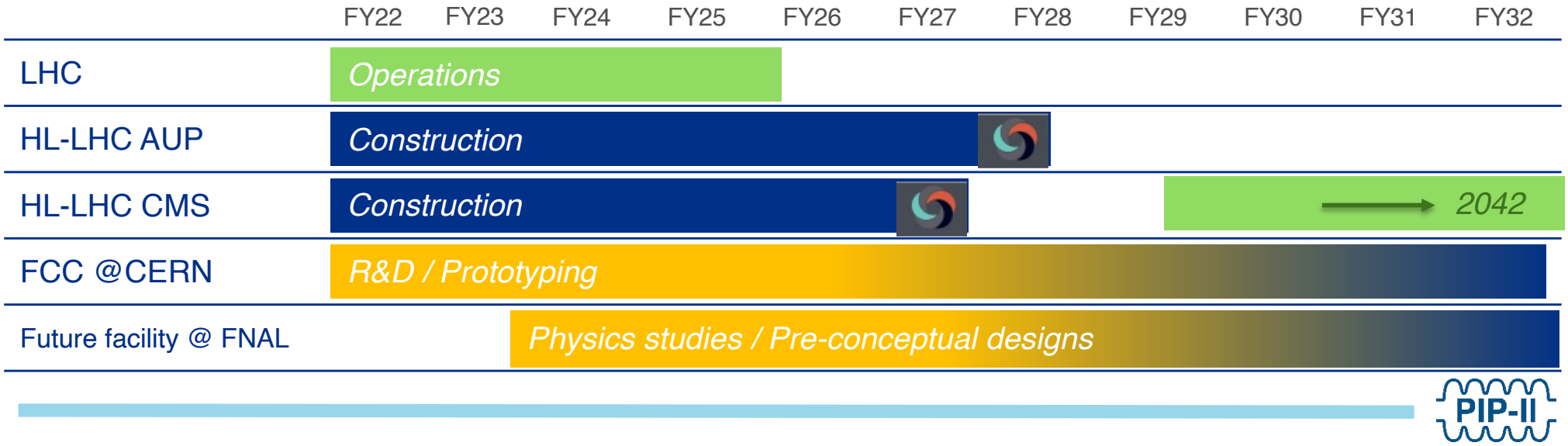
Vision: Fermilab continues to be the leading U.S. center for CMS and second leading center in the world after our partner CERN

CERN is our European sister laboratory and our strong partner in many areas



Major decadal goals

- Maximize science from LHC Runs 2 and 3 data – ROC is back in Operations!
- Execute HL-LHC AUP and CMS Detector Upgrade Projects
- Advance R&D towards FCC @CERN

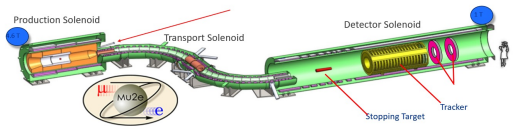


S&T Precision Science

Vision: Fermilab is a world center for accelerator-based Charged-lepton flavor violation (CLFV) and Dark Matter experiments, driven by intense particle beams and PIP-II/Booster Replacement

Major decadal goals

- Muon g-2: Complete data production, analysis, theory to achieve 5σ
- Complete Mu2e project and start science
- Design and build Mu2e-II, other upgrades



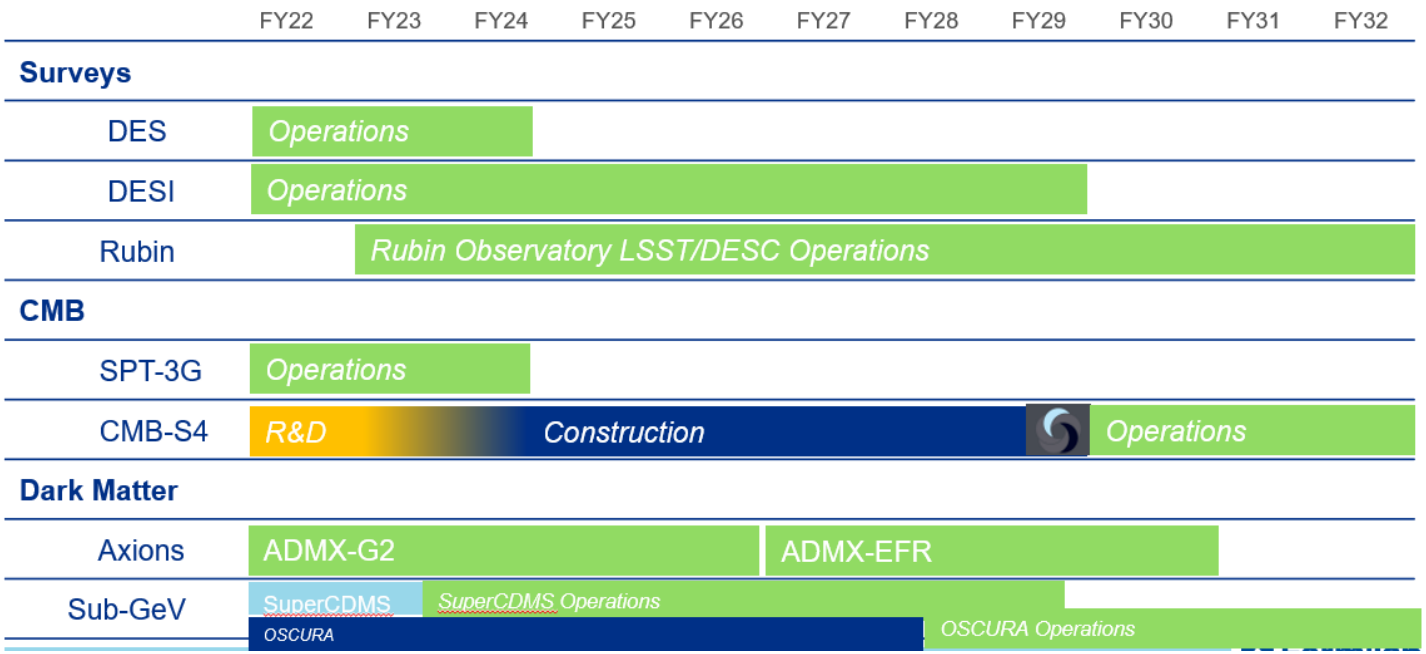
	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32
Muon g-2	*Operations/analysis*				*R&D*						
Mu2e	*Construction*				*Operations*						
Mu2e-II	*R&D*							*Construction*			

S&T Cosmic Science

Vision: Fermilab is an essential partner in world-leading cosmic science experiments and is contributing innovative R&D efforts toward future dark energy, dark matter, and cosmic microwave background (CMB) experiments and a coordinated campaign of experiments seeking to directly detect and study the properties of dark matter particles in the laboratory.

Major Decadal Goals

1. Cosmic Surveys → Transition from DES to DESI, LSST
2. Cosmic Microwave Background → Grow: Major role in CMB-S4
3. Dark Matter Detection → Consolidate: G2, Axions, Sub-GeV



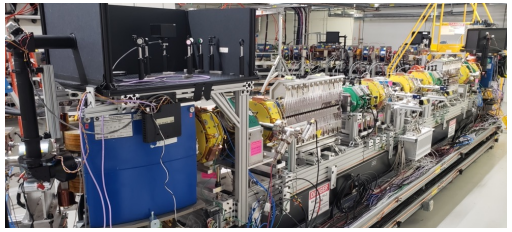
PIP-II

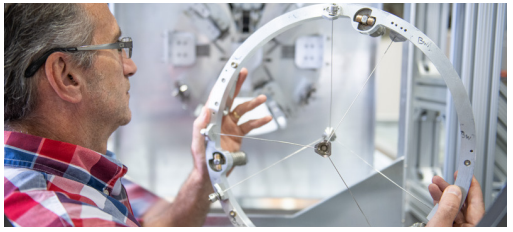
S&T Accelerator Science & Technology

Vision: Fermilab is a world-leader in Accelerator Science and Technology R&D that enables the next generation of particle accelerators and advances the HEP and Office of Science mission. Fermilab is an essential partner of choice for future large-scale accelerators.

Major decadal goals:

1. Deliver 2.4 MW proton beam power to LBNF/DUNE
   - Design, develop Booster Replacement
   - Develop High Power Targetry capabilities
2. Advance R&D in high field magnets and Superconducting RF for FCC @CERN
3. Initiate physics studies and concepts towards next major facility on Fermilab site
4. Continue to advance accelerator science as science in its own right!
5. Continue to enable the mission of other Office of Science programs

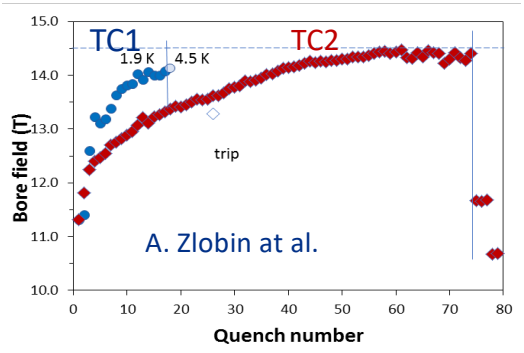





PIP-II

Fermilab Magnet and SRF Technology & FCC

- Fermilab accelerator technology R&D programs are highly synergistic with ambitious goals of FCC-ee and FCC-hh
- Fermilab magnet and SRF innovations can be leveraged for FCC:



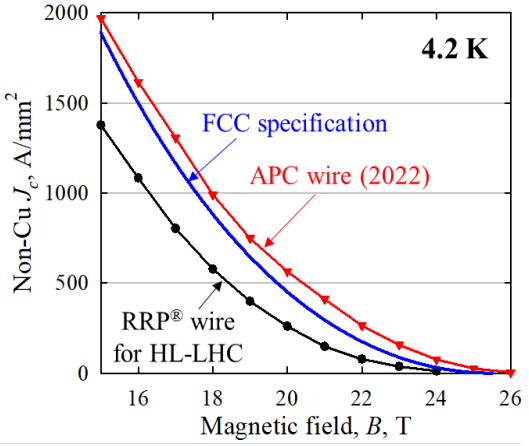
World record 14.5 T Nb_3Sn dipole magnet

Fermilab Nb_3Sn conductor with APCs exceeding FCC J_c spec for first time

Journal of Alloys and Compounds
Volume 857, 15 March 2021, 158270

The strong influence of Ti, Zr, Hf solutes and their oxidation on microstructure and performance of Nb_3Sn superconductors

X. Xu [a,*], X. Peng [b], J. Rochester [c], M.D. Sumption [c], J. Lee [a], G.A. Calderon Ortiz [c], J. Hwang [c]

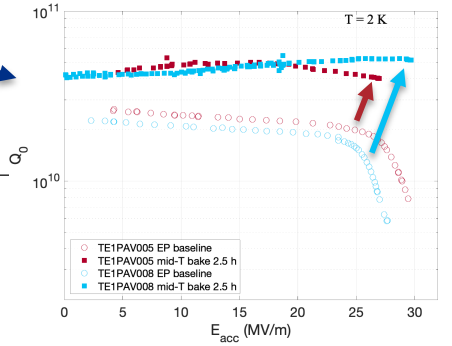


"mid-T bake" for high Q_0 SRF cavities at medium fields

PHYSICAL REVIEW APPLIED **13,** 014024 (2020)

Ultralow Surface Resistance via Vacuum Heat Treatment of Superconducting Radio-Frequency Cavities

S. Posen,* A. Romanenko, A. Grassellino, O.S. Melnychuk, and D.A. Sergatskov
Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA



Emerging Science & Technology Capabilities

Quantum Information Science & SQMS
Artificial Intelligence / Machine Learning
Microelectronics

S&T Quantum Information Science

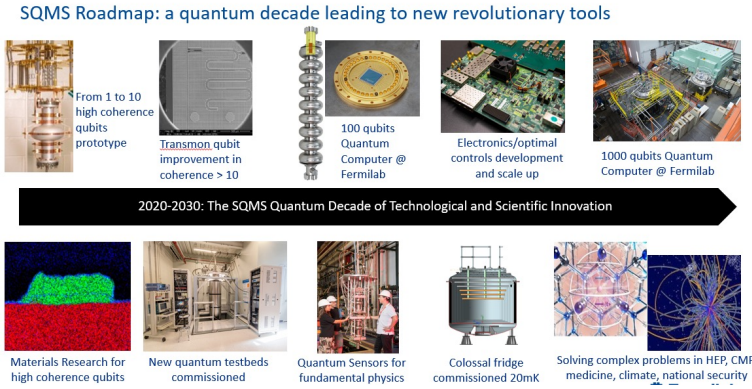
Vision: Fermilab, together with Chicagoland partners, is a major US quantum center; hosts national facilities for Quantum Science, developing innovative approaches that enable HEP discovery.

Major decadal goals:

1. Execute SQMS Center decadal roadmap:
   - Utilizing SRF technology to develop record coherence for 3D cavities in quantum regime demonstrated at FNAL ~ 2 seconds → Quantum computer → Solving complex problems in HEP, CMP, medicine, climate, national security

2. Quantum Networks towards a Quantum Internet:
   - Fermilab together with Chicagoland and other collaborators to deploy a multi-node, multi-user metropolitan scale quantum network in the greater Chicago area → Urbana → ORNL

3. Deep Cryogenic electronics for utility-scale Quantum Computers



AI/ML to accelerate discovery science

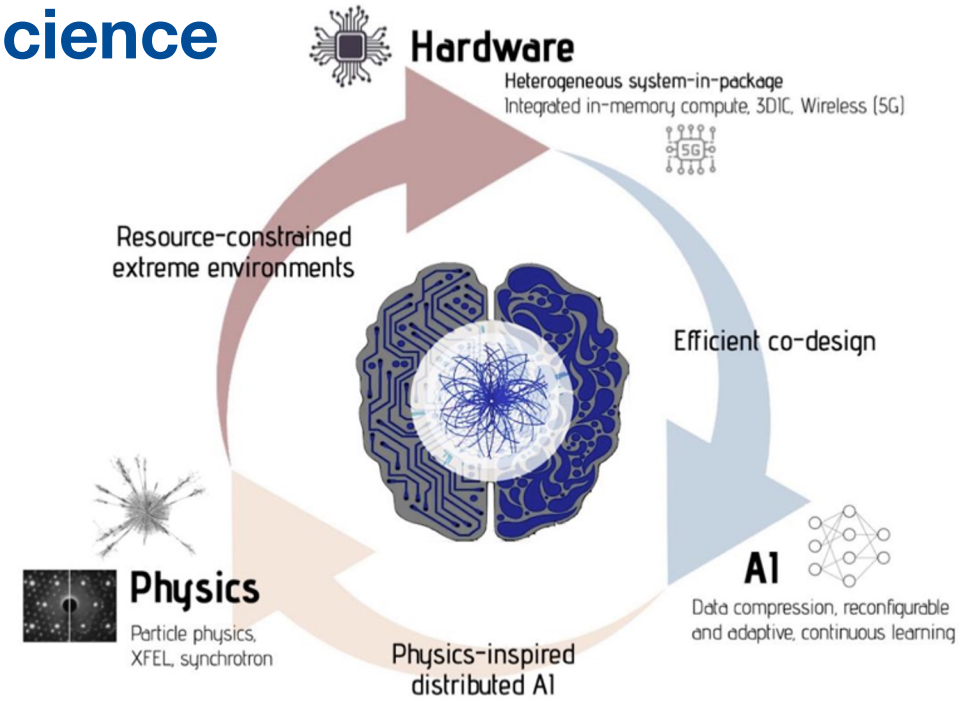
Vision:

Develop **powerful AI algorithms that are robust, interpretable, and explainable** for reconstruction, simulation, and operations

Optimized accelerator and experimental facilities with real-time, continuous learning control

Build software and hardware infrastructure to **support community AI computing needs** including open data, benchmarks, and training

Advance **world-leading capabilities in AI-on-chip for edge ML applications** – strong connections with smart sensing, internet-of-things, and novel microelectronics



ML advances foster a diverse AI-ready workforce with strong multi-disciplinary teams and collaborations

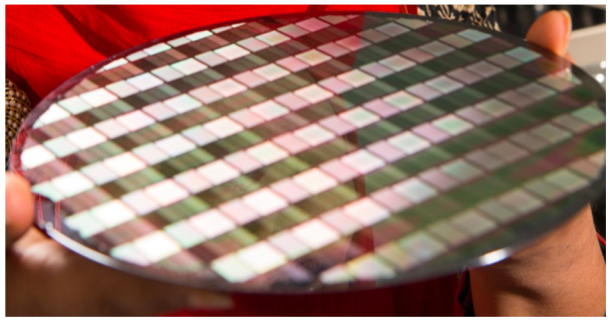
Microelectronics

Vision: Fermilab together with other national labs, academic and university partners establishes a major US Microelectronics Co-design center

Major decadal goals

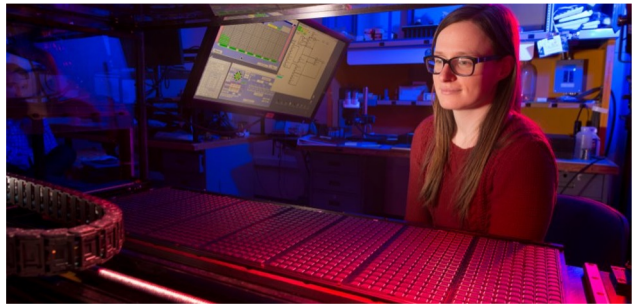
1. **Support the community for extreme environment microelectronic development**

- Enable lab-university-industry collaboration



1. **Maintain and grow expertise in state-of-the art integrated circuit design and testing to enable precision science measurements**

- Develop smart detectors with integrated sensing-edge computing - communication



1. **Engage with Industry on Heterogeneous Integration and Advanced packaging solutions**

- Leverage transformative technologies

Final Thoughts

- Particle physics is global! The evolving international context remains essential
- In this decade, Fermilab will complete the 2014 P5 strategic plan and follow the next P5 plan
  - DUNE Phase I will be realized, Phase II will be launched
- **Fermilab's role for the HEP Community is an integral part of the Fermilab mission**
  - as host of the USCMS and DUNE collaborations
  - as the nexus for US HEP, and the broader Snowmass Frontiers communities
  - as a resource for large-scale engineering, co-located expertise and capabilities, and intellectual vitality
  - as an International User Facility, dedicated to a diverse workforce and collaborative culture, and to enabling world-class scientific discovery

Thank you for your contributions to defining compelling future directions for our field!

Wilson Hall and IERC at dawn. The sloped roof on IERC is intended to mimic the curve of Wilson Hall rotated 90 degrees; this is especially evident when the image of IERC is doubled in the reflecting pond. Photo credit: Brian Rubik