Fermilab

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Accelerator Complex Evolution at Fermilab

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U.S. DEPARTMENT of ENERGY
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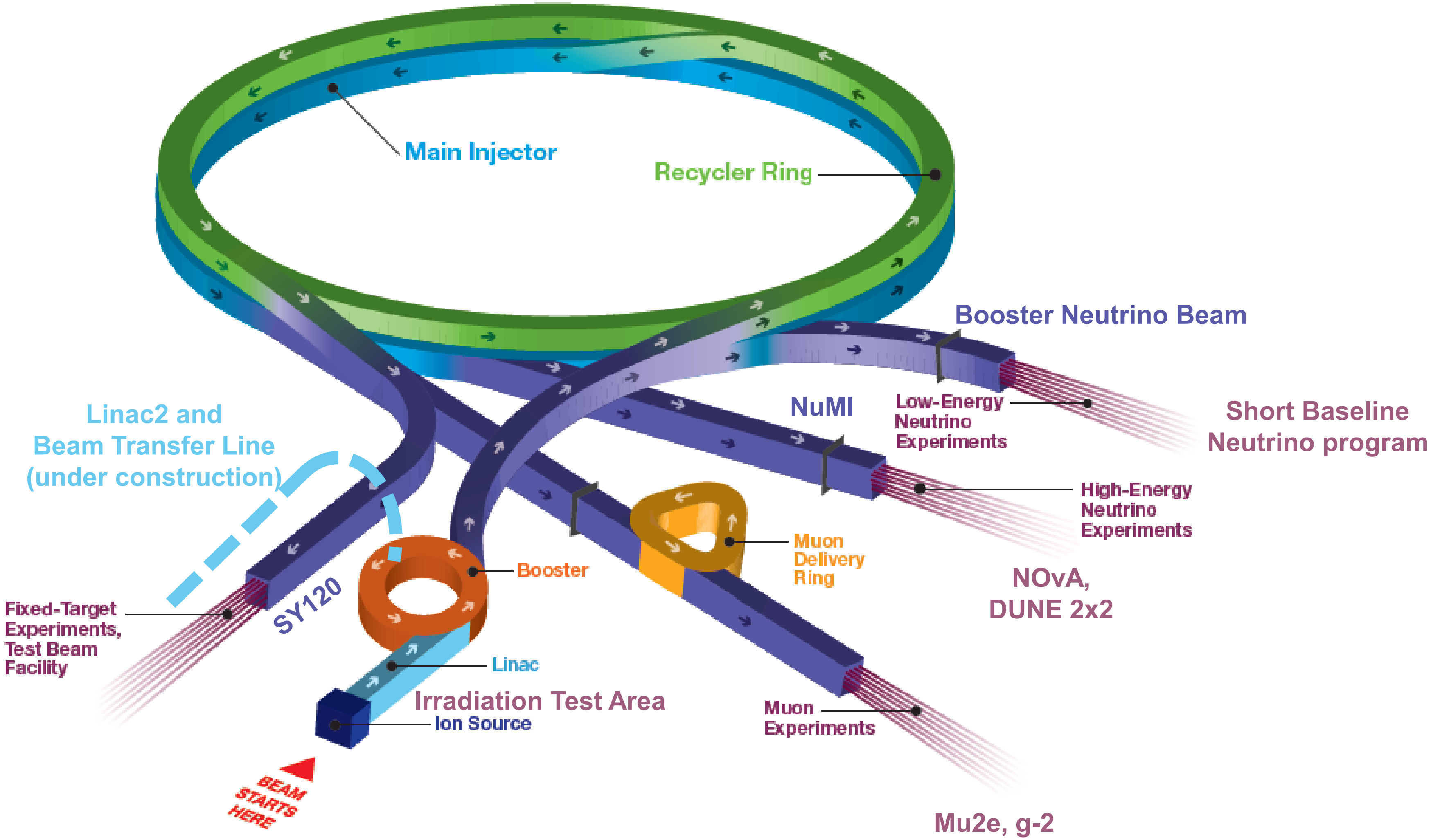
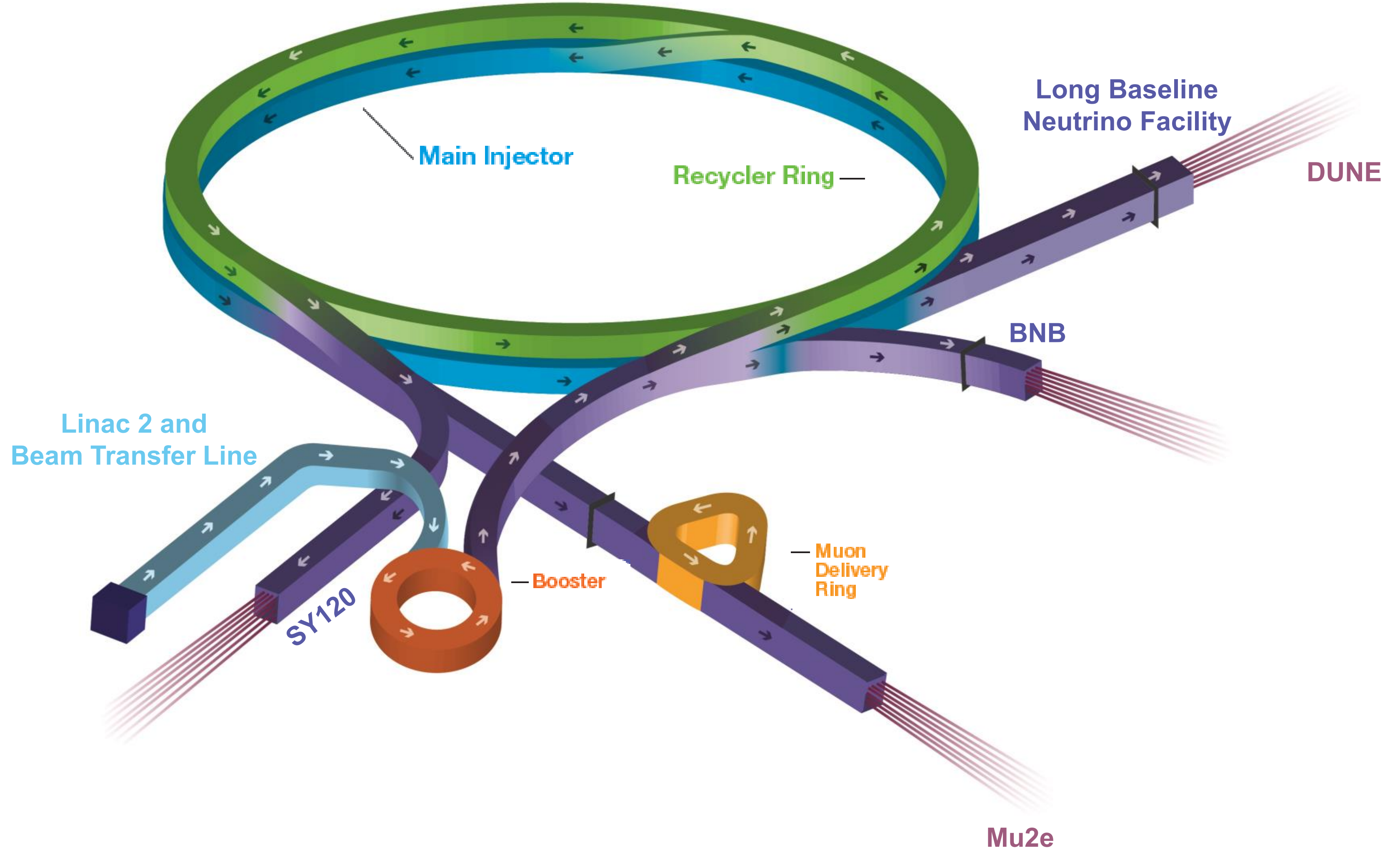
Outline

- Introduction
- Status of the Fermilab accelerator complex
- Transition to the Linac2, LBNF/DUNE era
- Accelerator Complex Evolution program
  - Accelerator Infrastructure Readiness
  - PIP-II Integration
  - Main Injector Ramp and Targetry
- Accelerator controls modernization
- Summary

Fermilab accelerator complex 2026



Fermilab accelerator complex 2031



PIP-II construction of Linac2

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PIP-II project and Linac2

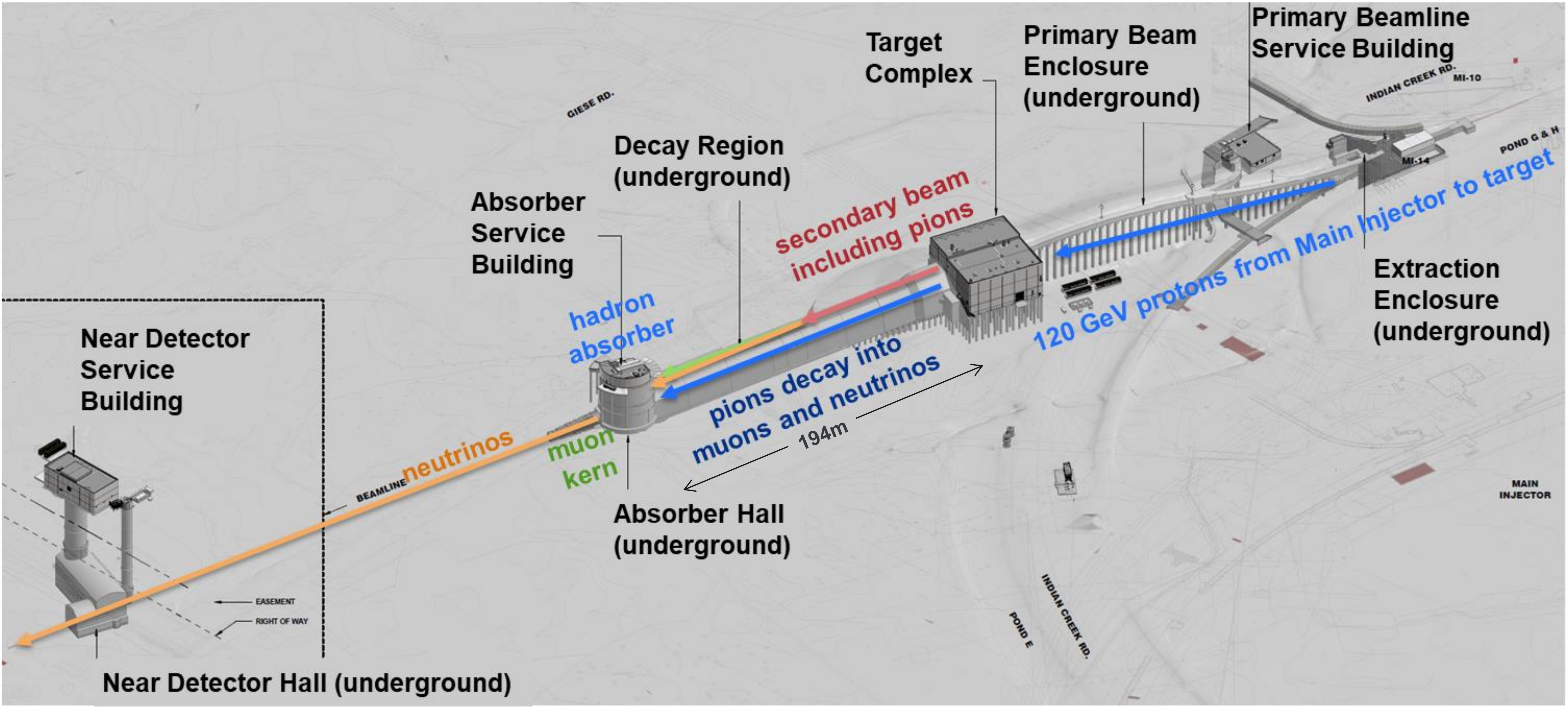
PIP-II provides an essential upgrade to the Fermilab accelerator complex to enable the world's most intense beam of neutrinos to LBNF/DUNE, and a broad physics research program for decades to come

- Linac2 is an 800 MeV H^- superconducting RF linac, compatible with CW operations and upgradeable to 1 GeV
- The project also provides upgrades of the Booster and Main Injector for 1.2MW beam

Key parameters	Linac	Linac2
Injection energy (MeV)	400	800
Current (mA)	30	2
Booster injection area	L1	L11
Pulse length (μs)	30	550
Booster intensity (protons per pulse)	4.7×10^{12}	6.7×10^{12}
Booster repetition rate (Hz)	15	20

Long Baseline Neutrino Facility (LBNF) beamline

Serving the Deep Underground Neutrino Experiment (DUNE) with far detector in South Dakota



Status of the Fermilab accelerator complex

Booster Neutrino Beam

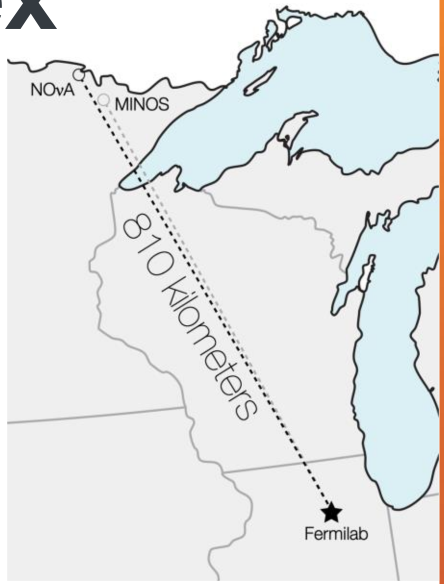
- 8 GeV protons from Booster, neutrinos to detectors on site
- Record yearly protons on target (POT) 3.7×10^{20} in 2025 run
- Met total beam request for the ICARUS and SBND experiments of 6.6×10^{20} POT in 2026

The Booster Neutrino Beam (BNB) Experiments

Status of the Fermilab accelerator complex

Neutrinos from Main Injector (NuMI)

- 120 GeV protons from Main Injector, neutrinos to NOvA detector in Minnesota
- Preparing to restart MI beam after 2024 electrical transformer failures



Electrical infrastructure

- Fermilab electrical system is owned and operated by the laboratory
- Two external 345kV transmission lines feed two electrical substations
- Each substation contains four high voltage power transformers that step down the incoming power to 13.8kV for local distribution throughout the site
- T88 caught fire, investigation showed others inoperable

Master Substation

- Built 1969, renovated 2015-2017
- Transformers
- T81 (1987) needs new bushings
- T82 (1972)
- T83 (1970)
- T84 (1970) needs new bushings

Kautz Road Substation

- Built in 1998 as part of the Main Injector facility
- Transformers
- T85 (1975) inoperable
- T86 (1996)
- T87 (2000) needs new bushings
- T88 (1987) inoperable due to fire

Fermilab electrical power infrastructure

Status of the Fermilab accelerator complex

Muon Campus

- 8 GeV protons re-bunched in Recycler
- Commissioning beam for the Mu2e experiment
  - Third-integer resonant extraction from the Delivery Ring – working to understand aperture and reduce losses
  - Improving spill regulation
  - Preparing to commission extinction using AC-dipole to remove remaining beam between spills

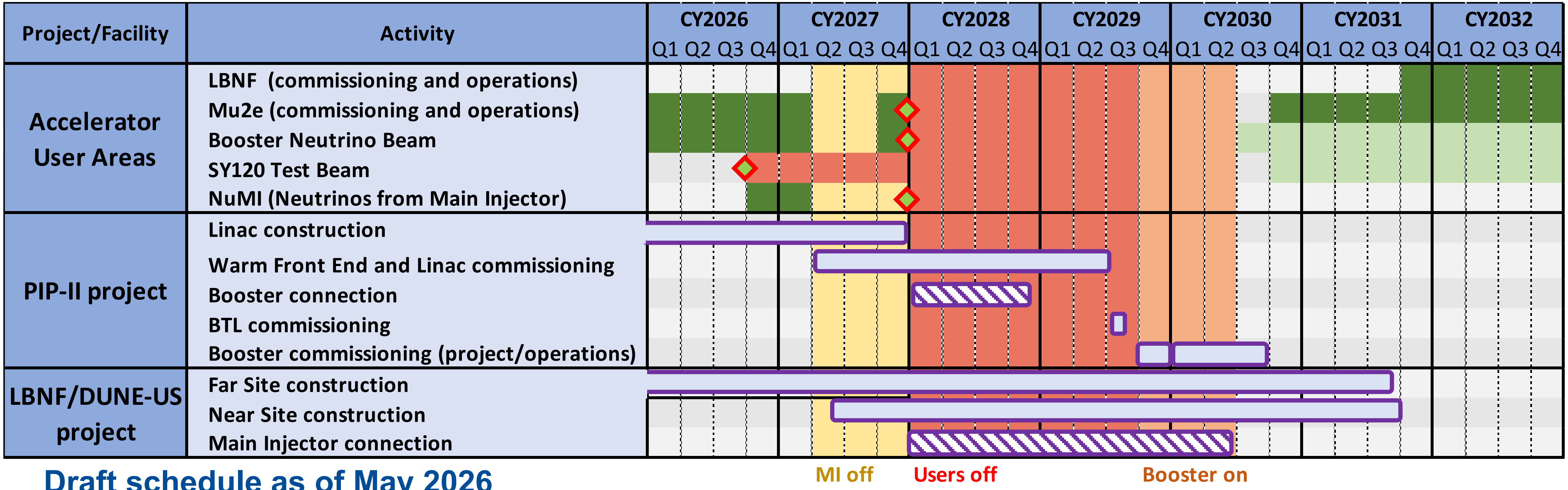
Status of the Fermilab accelerator complex

Fermilab test beam facility

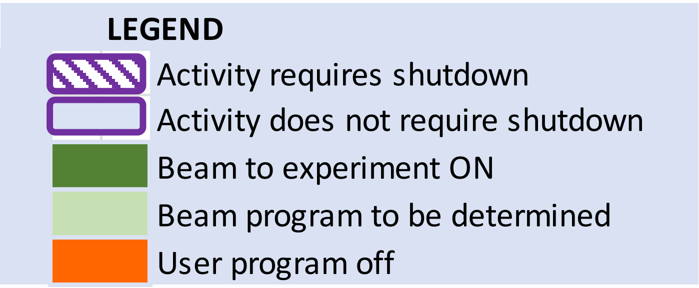
- 120 GeV protons via MI slow extraction
  - Electrical transformer failures prevent MI beam
  - Lab made decision to not resume operations of the 120-GeV test beam area next year due to rising infrastructure costs and other priorities

- Operating 400 MeV H^- ions from Linac to Irradiation Test Area

Timeline for transition to the Linac2, LBNF/DUNE era



Draft schedule as of May 2026



Accelerator program evolution

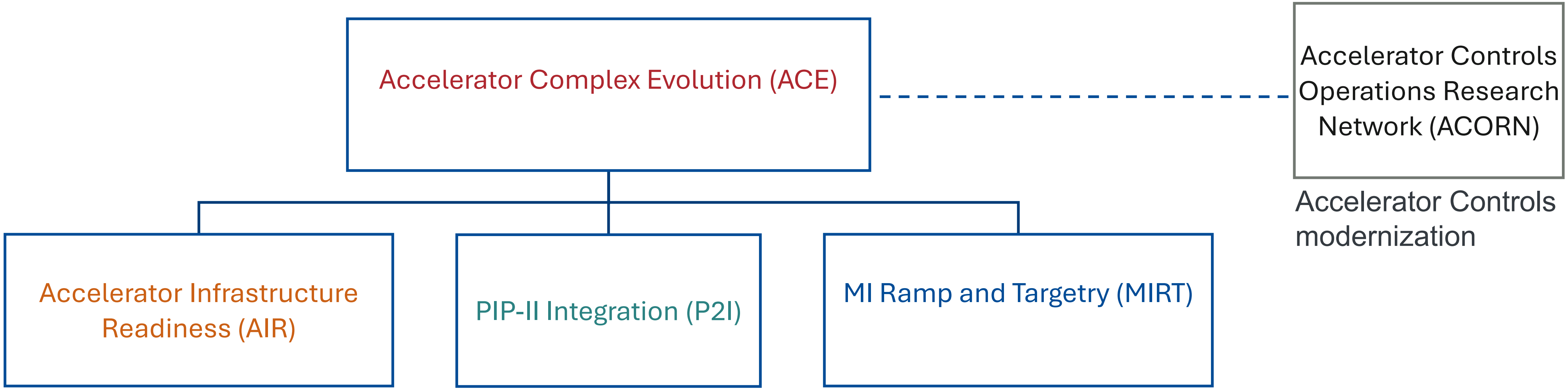
Status after the 2028-2029 "long shutdown"

- Operation of the current Linac and associated Irradiation Test Area ends
- Operation of NuMI (NOvA, DUNE 2x2) ends
- Future of the SY120 test beam program is to be determined
  - Task force considered options
- Booster commissioning with beam from the PIP-II linac uses the Booster Neutrino Beam facility which allows an experimental program if approved
- Operation of beam to Mu2e will resume
- Operation of LBNF beam to DUNE will begin in 2031

Long-term planning for reliability

- **Proton Improvement Plan** (PIP) addressed Booster reliability at 15Hz operations (2010's)
- **PIP-II** project began in 2011 to replace the ~60-year-old Linac with a new SRF accelerator
- **ACORN** project modernizes the accelerator controls system
- Booster reliability at 20Hz operations in the Linac2 era is considered by an ongoing internal **Accelerator Directorate (AD) / PIP-II task force** formed in 2020 to identify studies and improvements needed for operation of the Booster with the Linac2
- **Accelerator Complex Evolution** (ACE) program was presented to the US HEP Particle Physics Project Prioritization Panel (P5) committee in 2023
  - Reliability, MI Ramp and Targetry to reach 2MW w/o new Booster, eventual Booster Replacement (P5 deferred)
  - MI will be more than 30 years old when LBNF turns on, and its reliability was considered in multiple ACE workshops, with a comprehensive look at risks in the *AD Preparation for DUNE-PIPII Era Workshop* in 2024
- **Accelerator Infrastructure Readiness** (AIR) task force was charged in 2025 with identifying infrastructure required to support accelerator operations in support of LBNF/DUNE
  - Transformer fire brought to the forefront the backlog of deferred maintenance and end-of-life equipment
- Fermilab has charged a **test beam task force** with presenting options for the future
  - ACE is focused on beam to DUNE and excludes the test beam and Muon Campus

Accelerator Complex Evolution program



Infrastructure needed to keep the accelerator complex running

- Highest priority items need to be addressed before LBNF operations

Scope needed for operations in the Linac2 era, not required in the PIP-II project Key Performance Parameters

- Highest priority items need to be addressed before Booster operations with Linac2

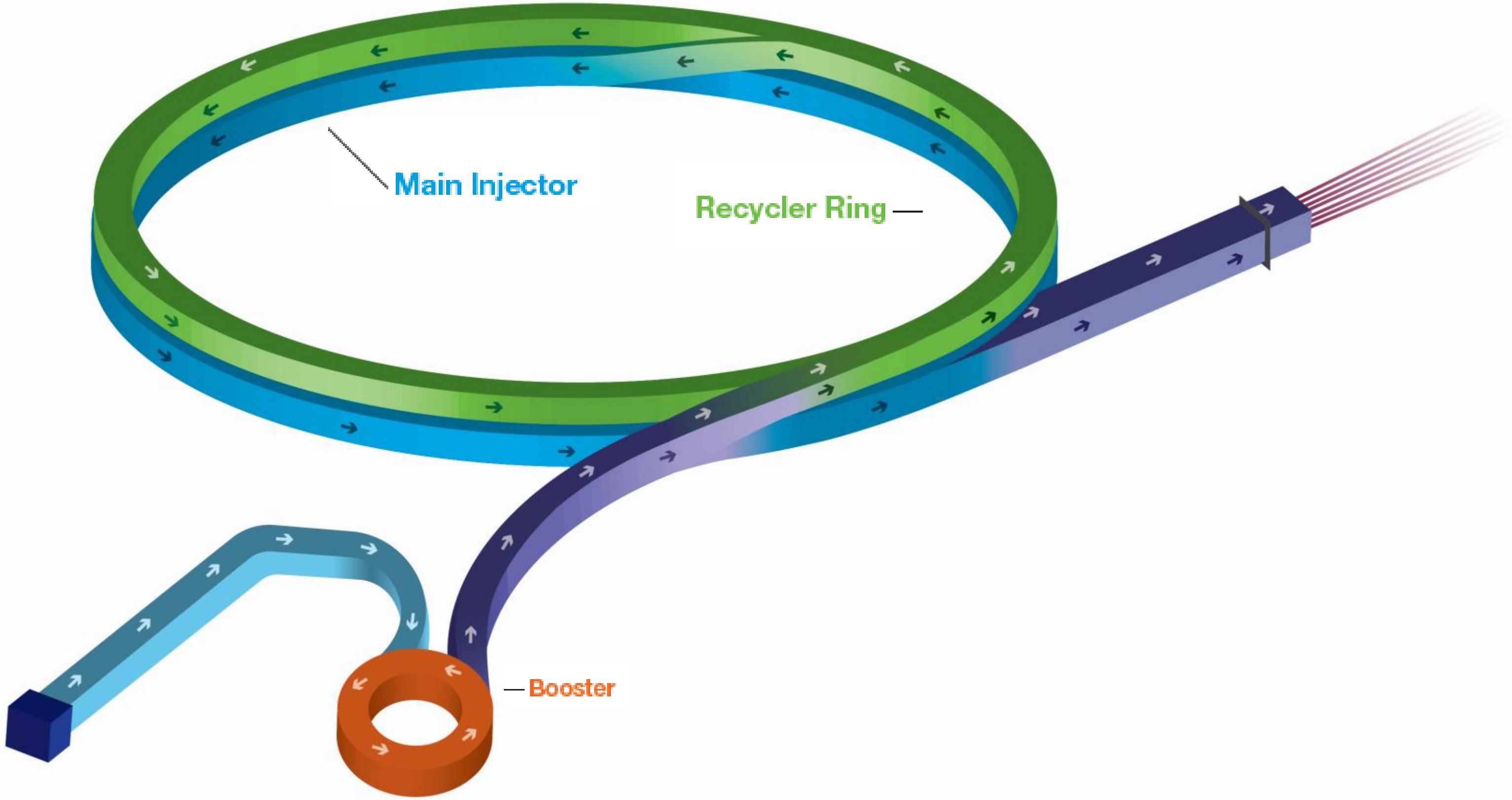
2MW-capable target

Increase beam power by shortening MI cycle rather than by increasing proton intensity

- Necessary to move beyond 1.2MW

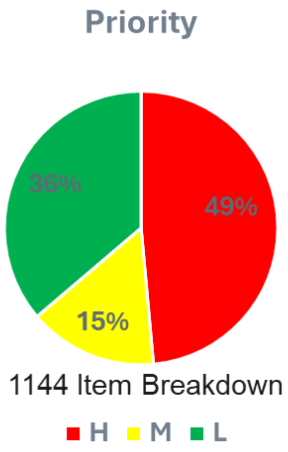
Accelerator Infrastructure Readiness

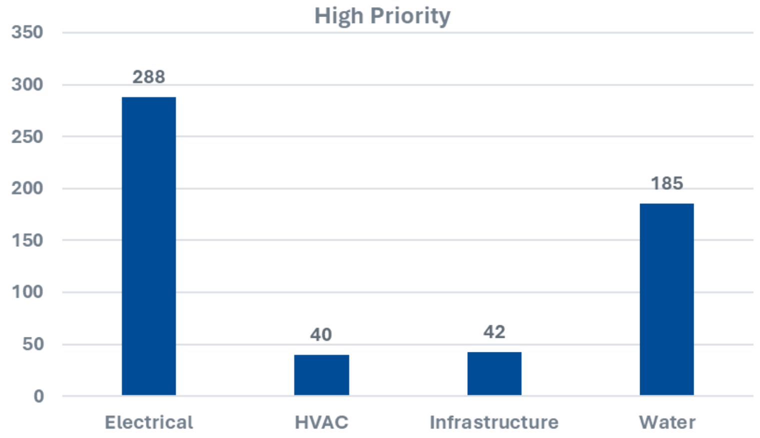
Focused on beam to DUNE



Accelerator Infrastructure Readiness

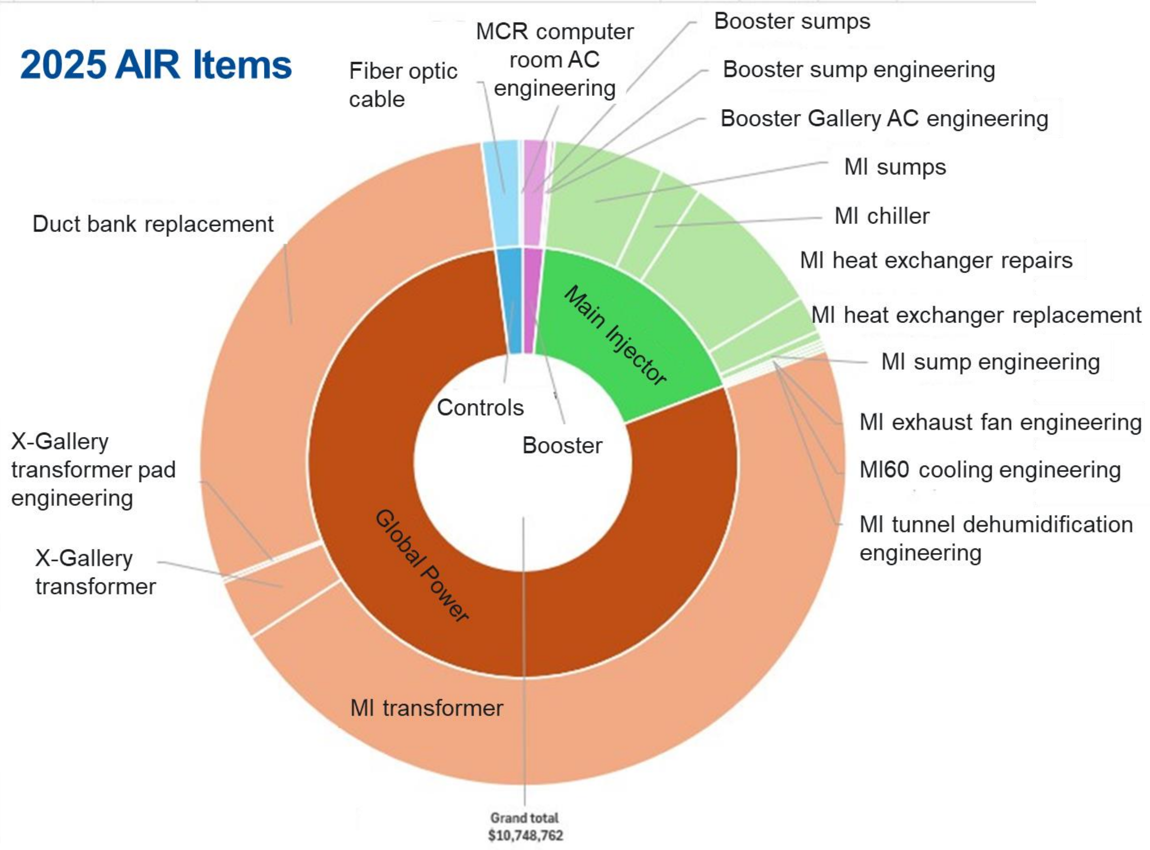
- Task force identified end-of-life infrastructure and ranked needs for replacement
  - 3,000+ items identified and categorized
  - 1144 items were deemed to impact beam operations
  - 555 items were determined to be of high priority, most electrical and water





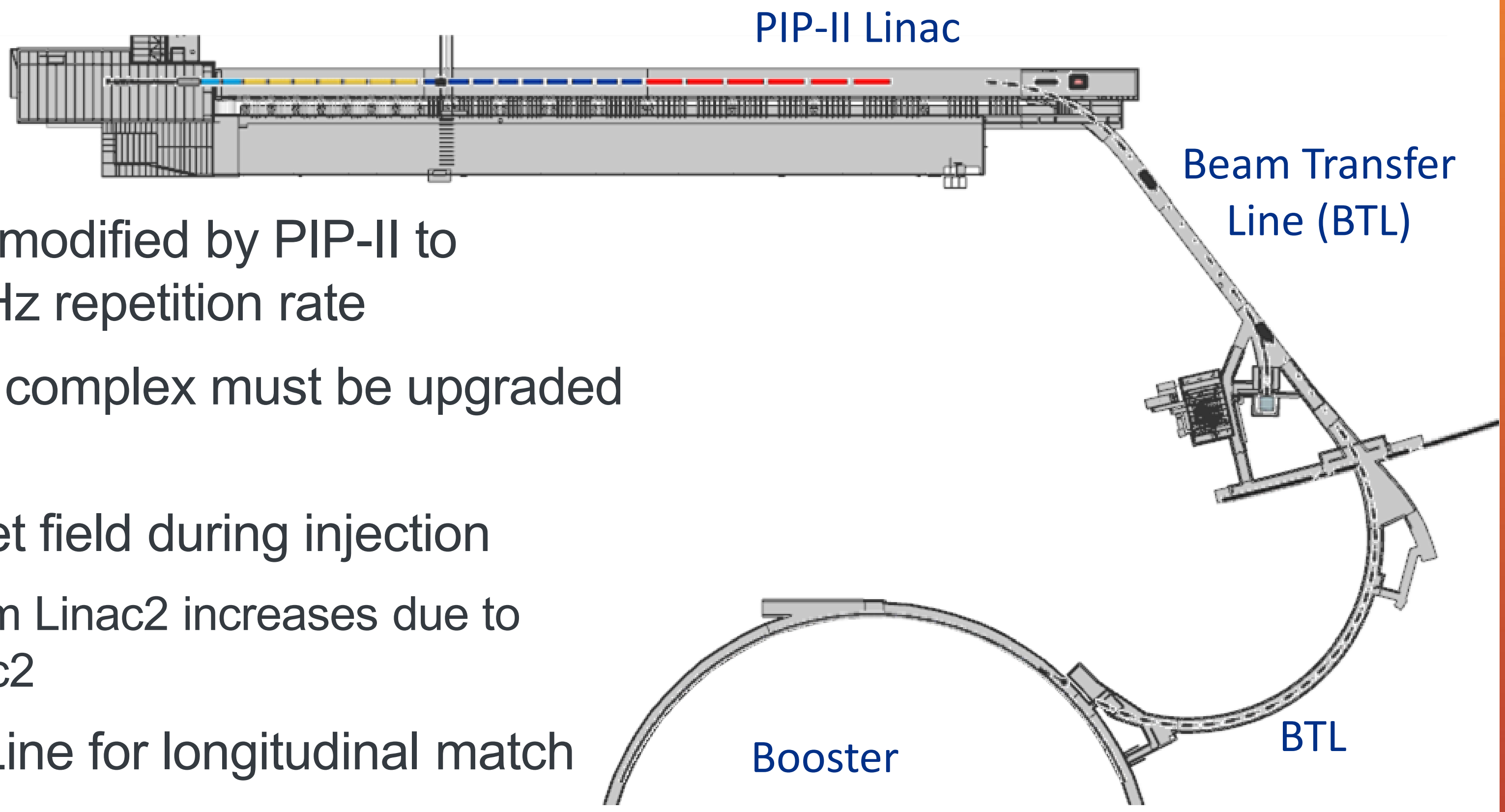
- Need lab-wide tool for tracking status of assets

- Developed a plan to address highest-priority items before LBNF is operational
  - Received and invested more than $10M in the last year



PIP-II Integration (P2I)

Operation of the accelerator complex with the Linac2 requires scope beyond that provided by the PIP-II project



- Booster magnet girders will be modified by PIP-II to upgrade from a 15 Hz to a 20-Hz repetition rate
- Instrumentation throughout the complex must be upgraded to read out at 20 Hz
- Flatten Booster gradient magnet field during injection
  - Injection time into Booster from Linac2 increases due to lower beam current from Linac2
- Add cavity in Beam Transport Line for longitudinal match into Booster
- Implement Booster γ_t jump for intensities > 5×10^{12} protons

S Krishnagopal poster

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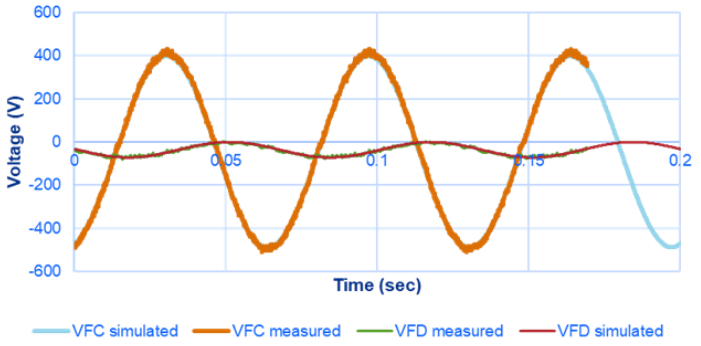
Booster magnets at 20 Hz

PIP-II Integration

- Concern that high-voltage isolation-to-ground of Booster gradient magnets could be insufficient for the expected voltage increase needed for the faster ramp cycle
  - Corona discharges could cause Booster magnets (60 years old) to fail over time
- Simulations and partial discharge measurements have shown that:
  - Some magnets are already experiencing some level of corona discharge at 15Hz operation
  - The voltage-to-ground expected when running at 20 Hz will not dramatically increase the severity of the discharges or the frequency at which they occur
  - Magnets which have been subjected to high integrated radiation do not necessarily present more severe corona discharges (or lower thresholds) than those which have never been in the beam line
- Based on measurements, modeling, and operational experience, we do not expect widespread magnet failures due to electrical discharges within the first few years of 20 Hz operations
- As mitigation, plan to fabricate new spares and continue investigations



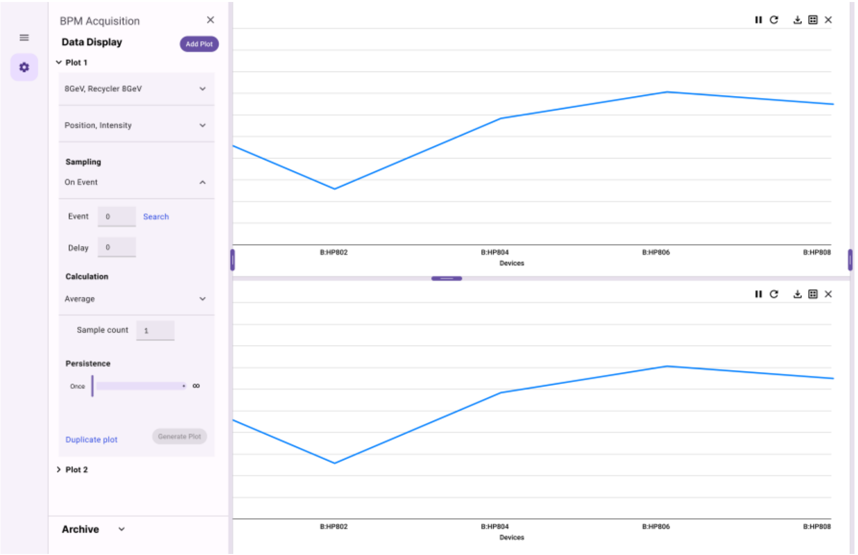
Instrumentation at 20 Hz

PIP-II Integration

- Beam Position Monitor (BPM) upgrade of readout electronics for 20-Hz operation in progress
  - Prototype crate installed, testing with beam
- Plan to use design to upgrade other BPM and Beam Loss Monitor systems in the complex

BPM prototype crate

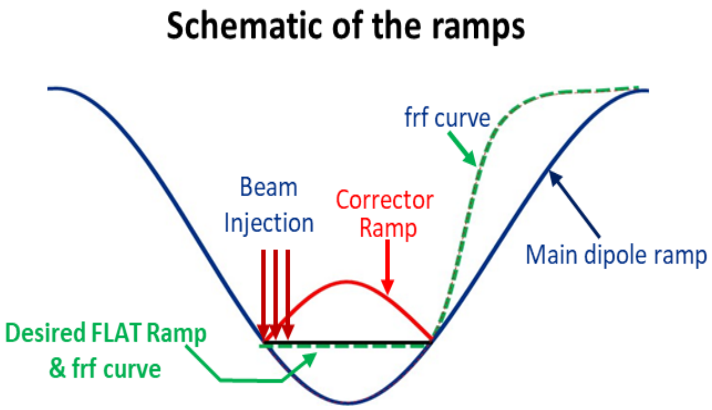
White Rabbit pulse per second signal



BPM client application user interface

Flat injection into Booster

PIP-II Integration



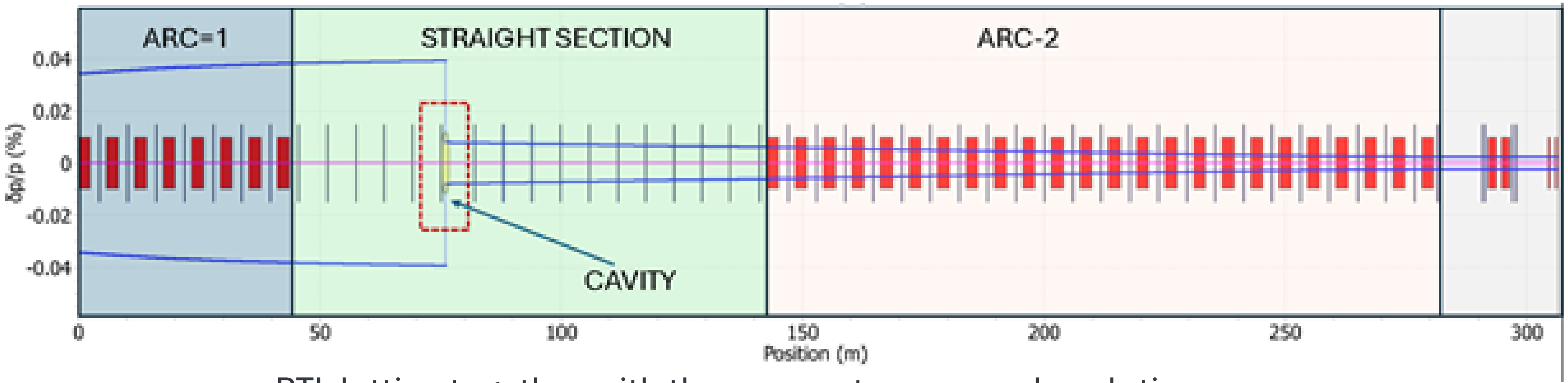
- Booster is a resonant synchrotron
- Gradient-magnet field changes significantly during longer injection time needed for Linac2 (2mA) relative to current Linac (>~20mA)
- Use corrector magnets to counteract the gradient magnet field
- Performed studies with the goal to establish a 400μs-long flat bottom during beam injection, characterize with beam position monitors, capture the beam and accelerate it to 8 GeV
- Implemented flat injection mode in Booster with a 400μs-long flattened front porch at 400 MeV with digital low-level RF in routine operations starting July 2025
- Currently developing strategy for operations with the Linac2 which needs
  - 800μs-long flat region (550μs for beam injection + 250μs for beam manipulation before beam acceleration)
  - Need to upgrade power supplies for corrector magnets

https://doi.org/10.18429/JACoW-IPAC2024-TUPC09

Beam Transfer Line cavity

PIP-II Integration

- Booster injection requires a momentum spread < 2×10^{-4} which simulations predict is ~half what is expected from Linac2
  - Needed to keep losses down at higher beam power
- BTL cavity can also decrease the energy scatter of the beam coming to the Booster
  - Compensate for failed cavities at beginning of Linac2
- Space has been located for RF cavities in the BTL and cavity design is in progress



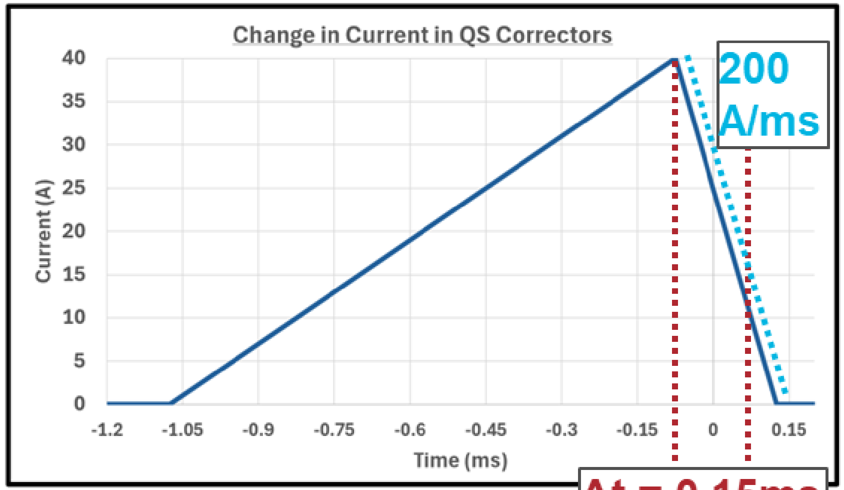
BTL lattice together with the momentum-spread evolution

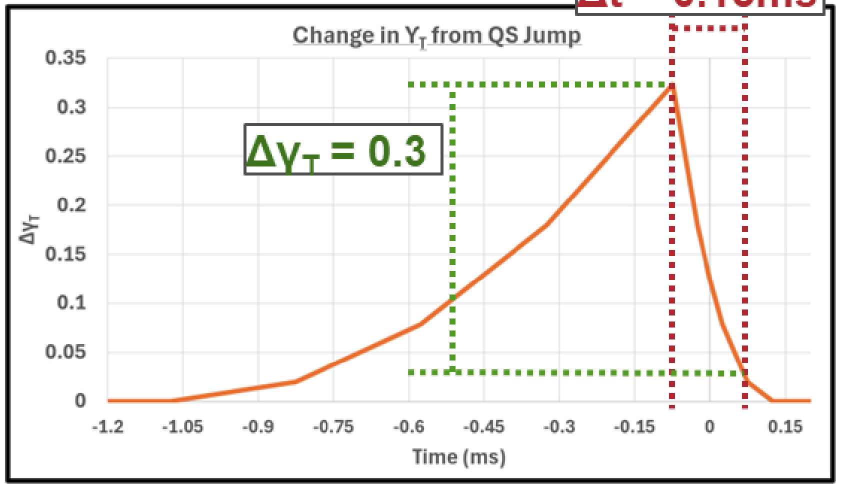
https://doi.org/10.18429/JACoW-IPAC2024-THPC22

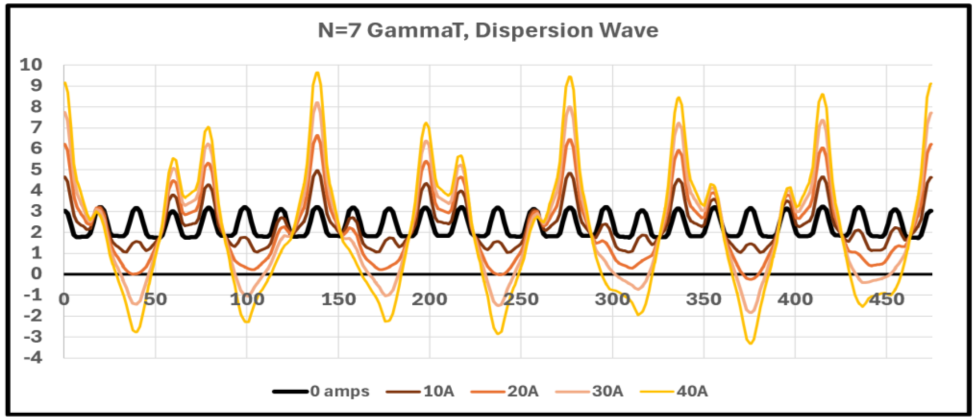
Booster gamma-t

PIP-II Integration

- Reduce losses at transition with a γ_t-jump system
- Plan to use existing quadrupole corrector magnets in 12 of 24 Booster short straight sections
- Upgrade power supplies
- Upgrading to inconel beampipe may also be needed in order to change the magnet field quickly enough
- Not required for commissioning with Linac2 but will be needed for full beam power to DUNE





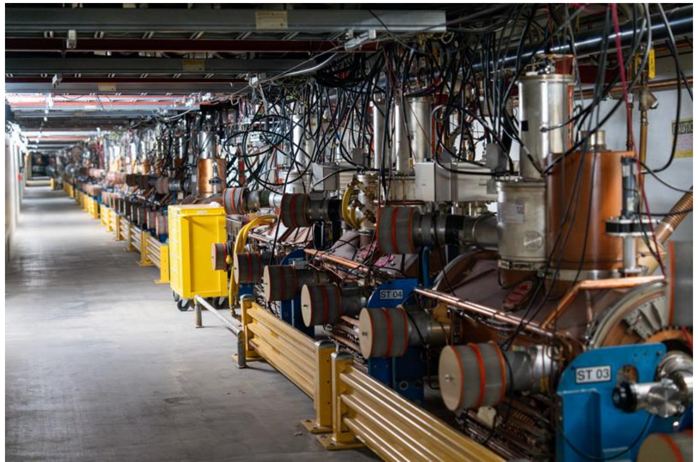


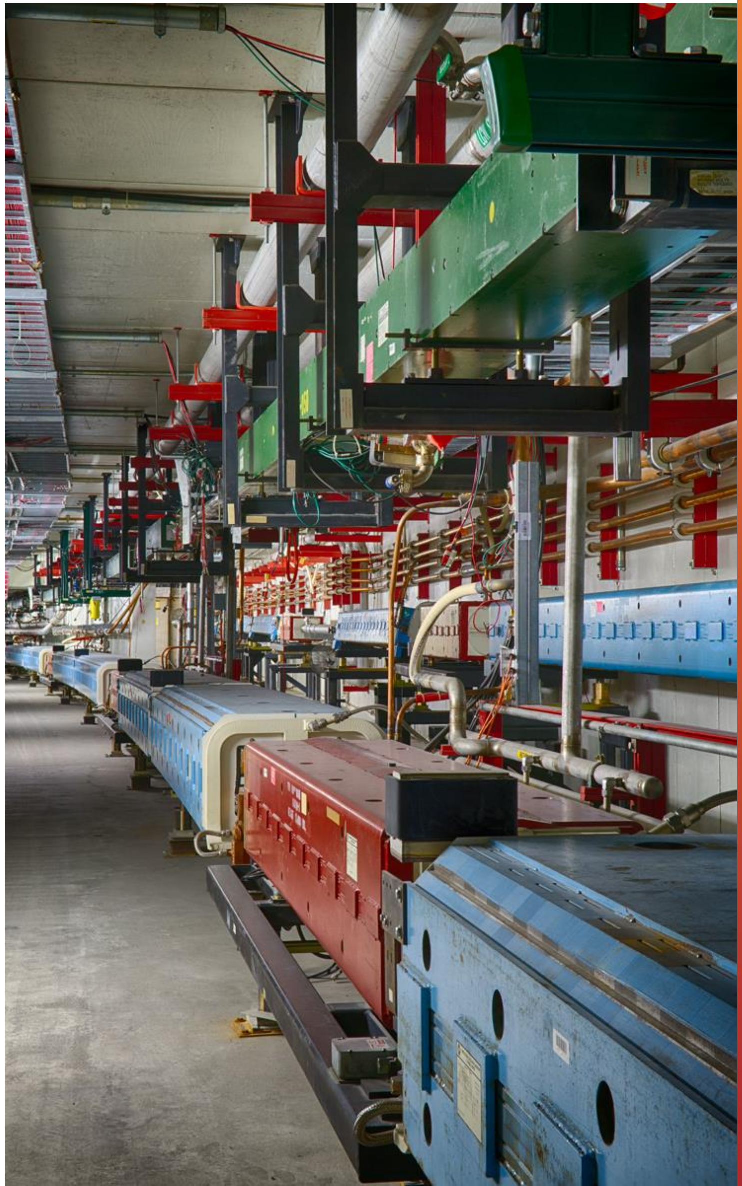
A high-intensity beam study demonstrated the large dispersion wave is contained within Booster apertures

Main Injector Ramp and Targetry

Increase beam power by shortening cycle time

- Reduce cycle time to reach ~2MW beam power to DUNE
  - 1.2 MW assumes 1.2s cycle time
  - May be able to reduce as low as 0.65s
  - Compared to increasing intensity:
    - Reduces likelihood of space charge effects and instabilities
    - Reduces impacts of limited aperture
    - Does not require replacing Booster!
  - Also mitigates risk of not meeting design intensity for 1.2MW
- Demonstrated 1.02 MW after reducing cycle to 1.067s

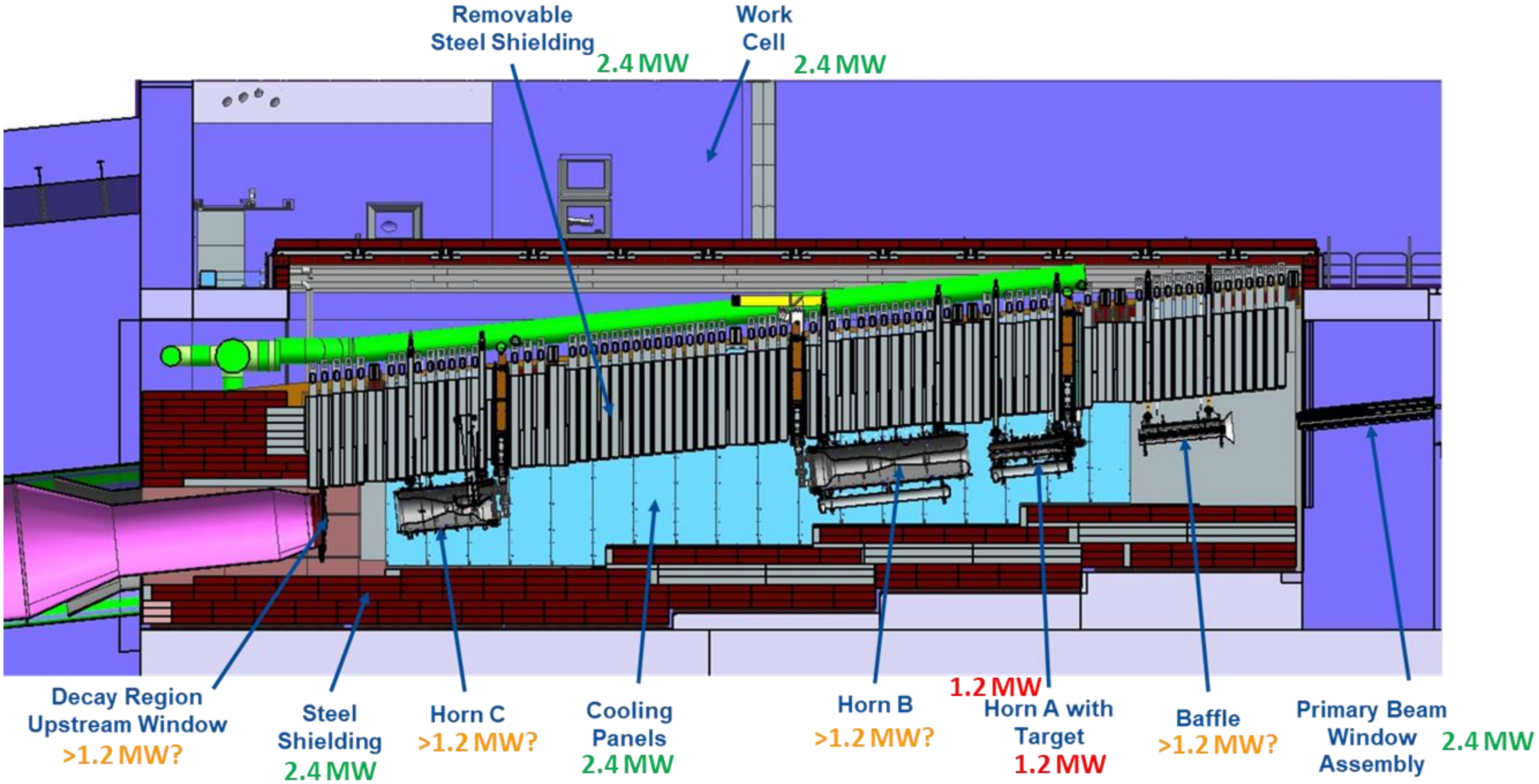




K Hazelwood poster

Main Injector Ramp and Targetry

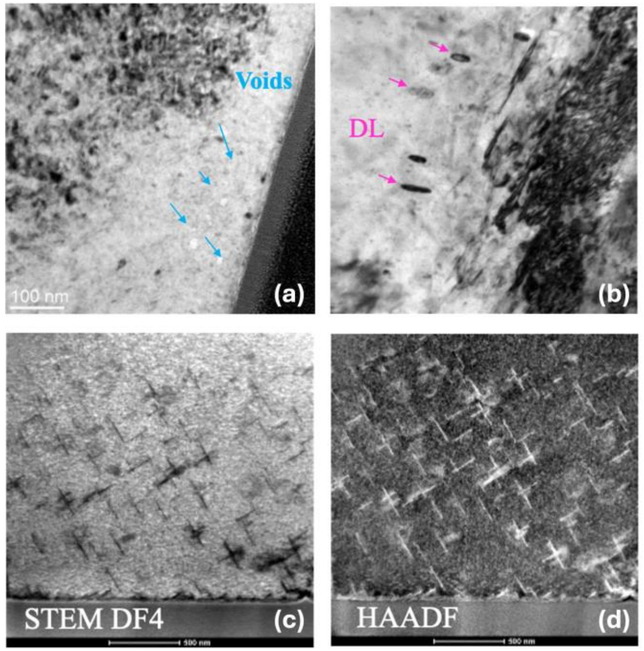
LBNF target systems designed for upgrade to 2.4MW



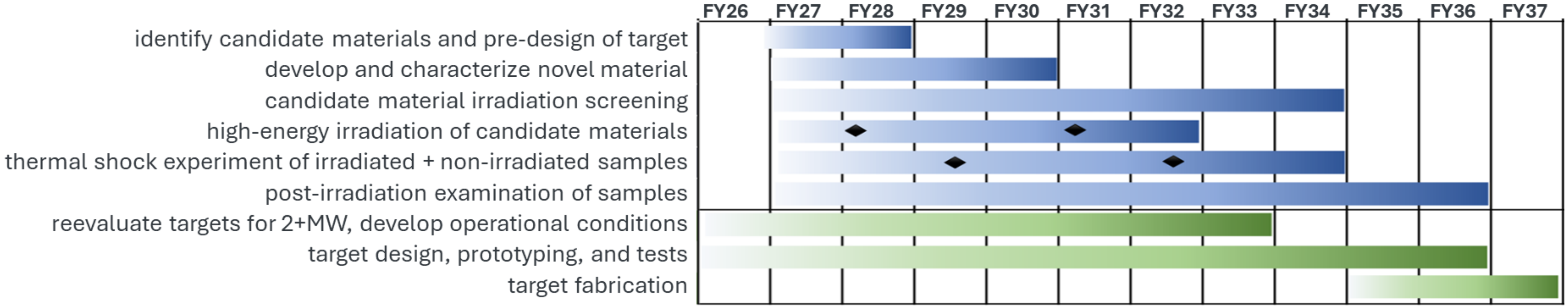
Main Injector Ramp and Targetry

Targetry

- Examining current design of LBNF target and horns to see limit of beam power they can withstand
- High-power target R&D is being conducted to find suitable materials for >1.2MW
- Executing a plan to develop a 2MW-capable target



Transmission Electron Microscopy images of irradiated high-entropy alloys
https://doi.org/10.18429/JACoW-IPAC2024-WECN2



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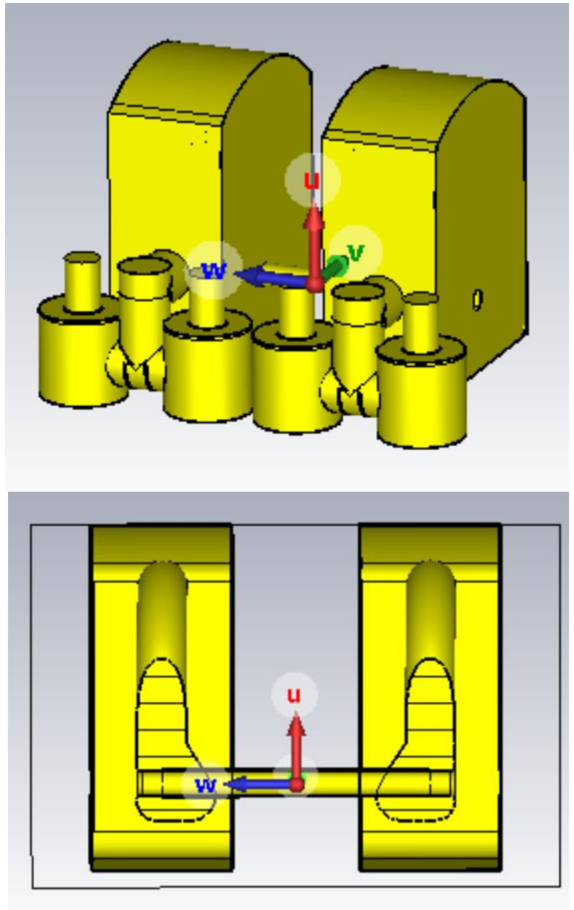
Main Injector Ramp and Targetry

Main Injector Ramp

- Conducted alternatives analysis for shortening the cycle time to increase beam power
  - Considered technical performance and reliability, schedule, and cost of implementation, maintenance, and operations
- Replacing magnet power supplies with a new design would allow added voltage without expanding or adding new service buildings
  - Modern power supplies are also more energy efficient
- Replacing a subset of RF cavities with a new 2nd harmonic design shows promise, and additional studies are in progress
- Tunable superconducting RF is also being explored
- Cost/benefit may be significantly better for 0.9s cycle where additional cavities of existing design can fit in available space



conceptual design for 2nd harmonic cavity

Accelerator Controls

ACORN

- ACORN (Accelerator Complex Operations Research Network) project will modernize the accelerator controls system
- Current accelerator controls system ACNET was developed for the Tevatron in the early 1980's based on a custom communication protocol and has become difficult to maintain
  - Old hardware (CAMAC, VME, MADC, custom), old software system, few experts remaining
- ACORN will allow using EPICS and leveraging experience from other US national labs
  - PIP-II has already introduced EPICS
- ACORN will also facilitate deployment of AI tools
- Staged plan will address components in order of priority based on obsolescence, need of long shutdown, etc
  - Will operate with a hybrid ACNET / EPICS system until resources allow us to fully modernize

Summary

- The Fermilab accelerator complex is undergoing an evolution to the LBNF/DUNE era, fueled by the new SRF Linac2 provided by the PIP-II project
- Updated infrastructure and a modern controls system will improve the reliability and efficiency of the complex
- New systems will be put into place to support operations with the Linac2 including scope needed due to the upgraded 20-Hz Booster repetition rate
- For the next phase of increasing beam power to DUNE from 1.2 MW to 2-2.4 MW, increasing the Main Injector ramp rate instead of increasing beam intensity seems to be a promising alternative that would not require constructing a new Booster

Thank you!

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