PROTON IMPROVEMENT PLAN-II (PIP-II): AN OVERVIEW

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Users Meeting-2023

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PIP-II is a partnership of:

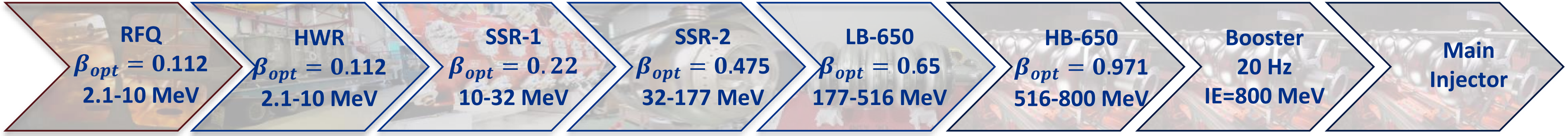
- US-DOE
- India-DAE
- Italy-INFN
- UK-STFC-UKRI
- France-CEA, CNRS/IN2P3
- Poland-WUST, WUT, TUL

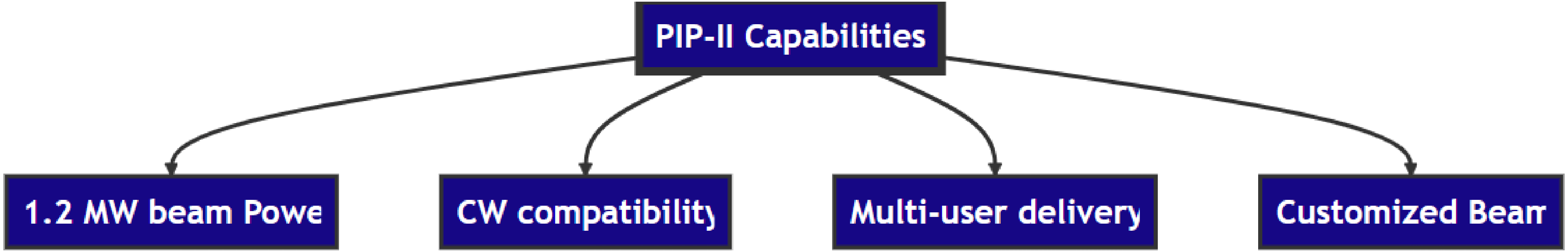
Outline

1. PIP-II Mission & Scope
2. International Confluence
3. Design
4. Status
5. Schedule

PIP-II MISSION & SCOPE

The Fermilab's PIP-II project is a key upgrade that's constructing a superconducting Linac, powering future experiments, enabling the world's strongest neutrino beam for LBNF/DUNE, and nurturing extensive physics research for decades ahead.





PIP-II MISSION & SCOPE

The Fermilab's PIP-II project is a key upgrade that's constructing a superconducting Linac, powering future experiments, enabling the world's strongest neutrino beam for LBNF/DUNE, and nurturing extensive physics research for decades ahead.

- **RFQ** — $\beta_{opt} = 0.112$ — 2.1-10 MeV
- **HWR** — $\beta_{opt} = 0.112$ — 2.1-10 MeV
- **SSR-1** — $\beta_{opt} = 0.22$ — 10-32 MeV
- **SSR-2** — $\beta_{opt} = 0.475$ — 32-177 MeV
- **LB-650** — $\beta_{opt} = 0.65$ — 177-516 MeV
- **HB-650** — $\beta_{opt} = 0.971$ — 516-800 MeV
- **Booster** — 20 Hz — IE=800 MeV
- **Main Injector**

PIP-II Scope

- 800 MeV, 2 MA H- Beam
- Beam Transfer Line
- Complex Upgrade

PIP-II : BEAM PARAMETERS

Position	Current, mA	Beam Energy (MeV)	Velocity $\beta = v/c$	Emittance, H/V, norm (µm)		Emittance, Long.,norm, (µm)		Beam Size, H/V,Trans., typ., mm	Beam length, deg@162.5 MHz	Energy spread, (%)
				rms	99.99%	rms	99.99%	rms	rms	rms
LEBT	5.2	0.03	0.008	0.18	1.2	NA	NA	5	NA	NA
RFQ Exit	5	2.1	0.067	0.21/0.21	3.87/4.0	0.34	6.0	1/0.5	7.1	0.4
MEBT output	2	2.1	0.067	0.21/0.2	2.95/2.68	0.35	7.35	1.89/1.84	7.71	0.6
HWR output	2	10	0.145	0.24/0.24	6.06/6.15	0.33	8.0	1.31/1.23	1.93	0.3
SSR1 output	2	32	0.256	0.25/0.25	4.91/4.43	0.33	11.12	1.65/1.61	1.07	0.18
SSR2 output	2	177	0.541	0.23/0.27	5.23/6.61	0.33	12.13	1.64/1.72	0.61	0.06
LB650 output	2	516	0.764	0.24/0.27	6.54/6.73	0.32	12.89	1.68/2.17	0.3	0.04
HB650 output	2	833*	0.848	0.24/0.27	6.49/7.02	0.32	12.18	1.56/2.09	0.25	0.03
BTL	2	800*	0.842	0.24/27	6.49/7.02	0.32	12.18	1.3/1.3	4.5	0.03

PIP-II will provide a highly capable, reliable, upgradeable and expandable scientific infrastructure with significant savings to DOE

A CONFLUENCE OF INTERNATIONAL EXPERTISE AND CAPABILITIES

India, Department of Atomic Energy (DAE) (started 2009) BARC, RRCAT, VECC; and IUAC

Substantial engineering / manufacturing experience; Superconducting magnets for LHC; 2 GeV synch light source

Italy, INFN (started 2016)

Internationally recognized leader in superconducting RF technologies
SRF cavity and cryomodule fabrication for XFEL; SRF cavities for ESS

UK, STFC UKRI (started 2017)

Substantial engineering and manufacturing experience; Construction, operation of synch light & neutron sources SRF cavity processing and testing for ESS

France, CEA, CNRS/IN2P3 (started 2017)

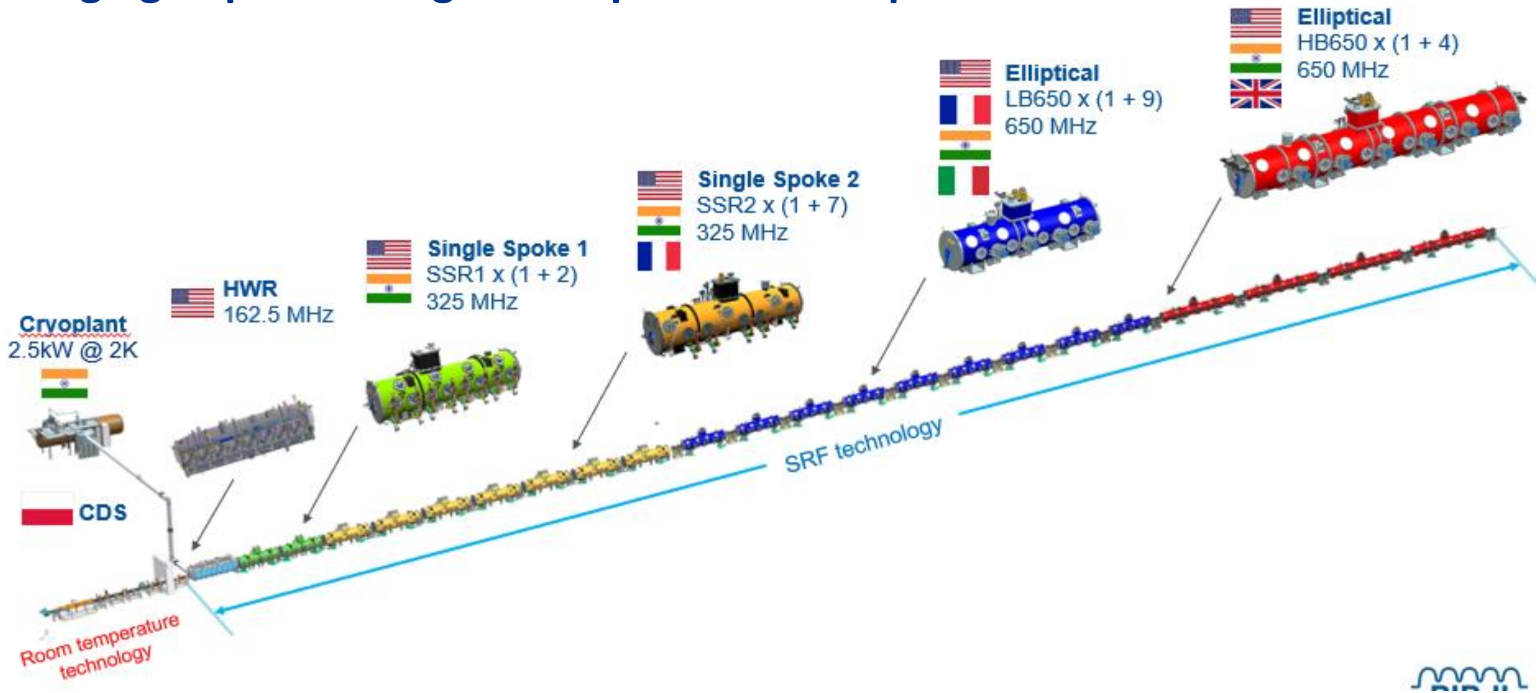
Internationally recognized leader in large-scale CM assembly
CM assembly for European XFEL and ESS; SSR2 cavities and couplers for ESS

Poland, WUST, WUT, TUL (started 2018)

Substantial engineering / manufacturing experience; CDS, LLRF, QC for XFEL, ESS

A CONFLUENCE OF INTERNATIONAL EXPERTISE AND CAPABILITIES

PIP-II represents the inaugural accelerator project within the United States that has been constructed with substantial international contributions, leveraging unparalleled global expertise and capabilities.



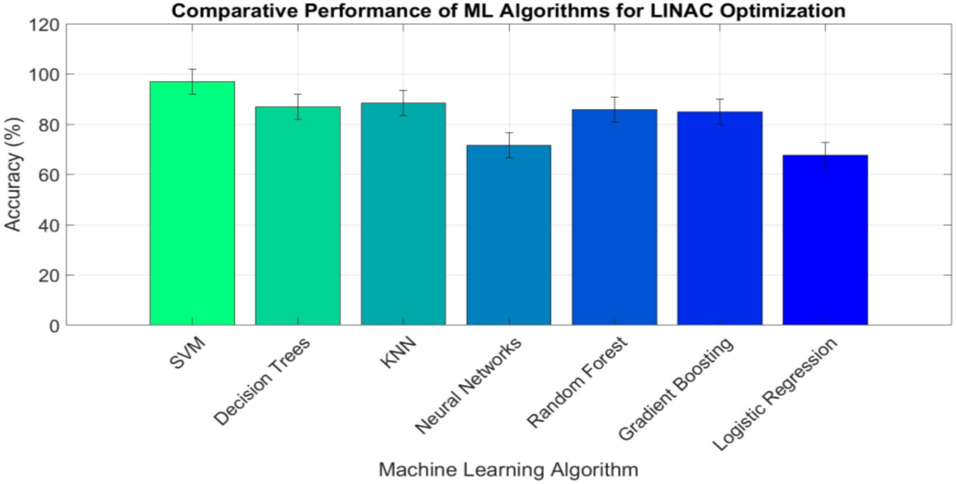
PIP-II : SC LINAC PHYSICS DESIGN

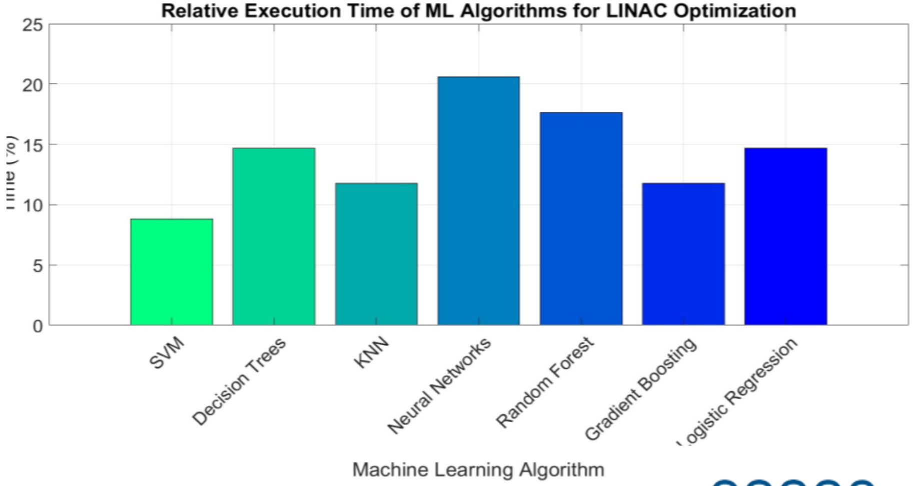
- **Performance Requirements Met**: Integrated PIP-II accelerator designs have been successfully completed.
- **Integrated Design**: Accelerator Physics (AP) is incorporated into PIP-II systems design.
- **Driven by Physics**: The design of accelerator systems, including Fermilab accelerator upgrades, is guided by physics requirements.
- **System Parameters**: Comprehensive studies (PIP2IT) have confirmed the selection of system parameters.
- **Continued Studies**: Synergistic studies are ongoing to improve the understanding of Fermilab accelerator complex performance in the PIP-II era.

ML FOR BEAM DYNAMICS & LINAC TUNING

•**Incorporation of Machine Learning**: An assortment of sophisticated Machine Learning methodologies has been judiciously applied and meticulously compared in an endeavor to accelerate beam dynamics simulations and enhance the efficiency of linac tuning procedures.

•**Utilizing SVM for Precision Tuning**: The majority of our tuning endeavors exploit Support Vector Machine (SVM) algorithms owing to their superior performance and robustness in our domain-specific tasks.

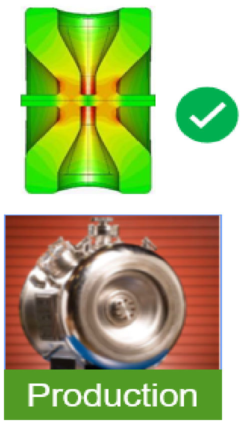


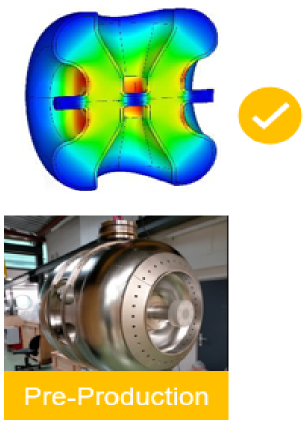


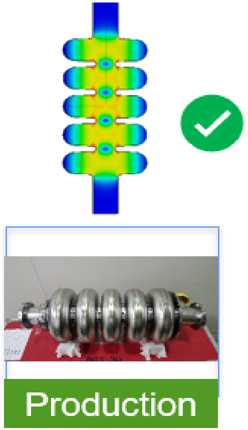
BEAM DYNAMICS IN BOOSTER

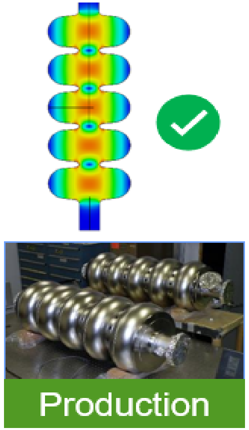
- **Modified Optics**: Booster 400 MeV optics were scaled to 800 MeV, with modifications made for PIP-II injection.
- **RFQ Tracking**: Realistic Linac beam distribution has been tracked from the RFQ.
- **Foil Model**: Foil model has been successfully integrated into simulations.
- **Intensity Limits and Losses**: PIP-II mitigates intensity limits and losses in Booster through:
  - **Space Charge Tune-shift Reduction**: This has been reduced by a factor of 2 – 4 at 800 MeV injection.
  - **Transverse Emittances**: These have met set requirements.
- **Electron Cloud**: The electron cloud has been simulated, showing a small impact at PIP-II intensity.
- **Beam Losses**: Beam losses are at the 2% level with 2-stage collimation in BTL and increased aperture extraction magnets.

PIP-II SRF CAVITIES









Name (Qty.)	**HWR (8)**	**SSR1 (16)**	**SSR2 (35)**	**LB650 (36)**	**HB650 (24)**	Units
Type	Half-Wave	Single Spoke	Single Spoke	Elliptical	Elliptical	-
β	0.11	0.22	0.47	0.61	0.92	-
Frequency	162.5	325	325	650	650	MHz
Q_0	$8.5 \cdot 10^9$	$8.2 \cdot 10^9$	$8.2 \cdot 10^9$	$2.4 \cdot 10^{10}$	$3.3 \cdot 10^{10}$	-
Gradient	9.7	10	11.5	16.8	18.7	MV/m
Doped	No	No	No	Mid-T bake	Yes	-

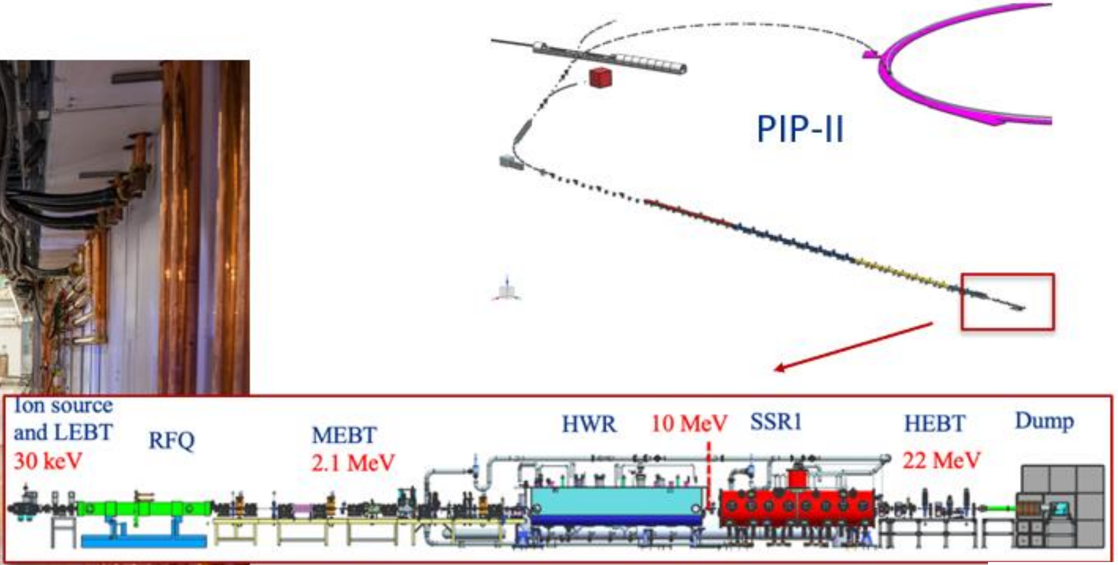
✓ *Prototypes validated* ✓ *Ongoing activities*

PIP-II: SRF CRYOMODULE FLAVOURS

Prototype designed · Prototype built · Prototypes validated

PIP2IT AS A TESTBED FOR PIP-II TECHNOLOGY

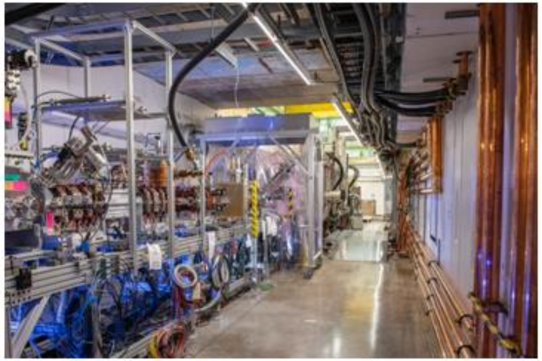
- PIP2IT successfully demonstrated LBNF beam parameter and full acceleration up to the first two linac cryomodules.



PIP-2IT TRANSITION TO CRYOMODULE TEST STAND

- PIP2IT accelerator was disassembled, and area converted into the 650 MHz and 325 MHz cryomodule test stands
  - Cold RF testing of prototype HB650 CM in progress

Evolution of PIP2IT Test Facility (same area shown in all images)



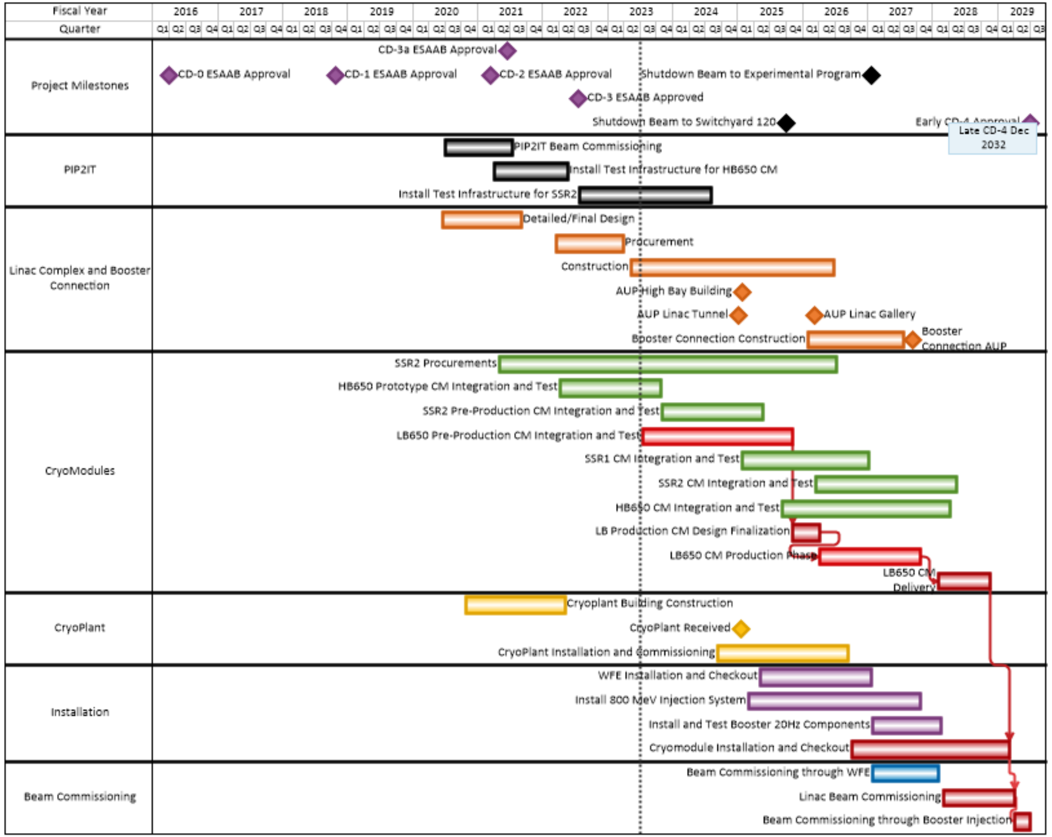
PIP2IT Test Accelerator (April 2021)

PIP2IT Test Stand infrastructure installed (Nov. 2022)

pHB650 Cryomodule installed at 650 Test Stand (Feb. 2023)

PIP-II

SCHEDULE SUMMARY – Early completion April 2029



SYNOPSIS

- **Enabling Intense Neutrino Beams**: PIP-II is poised to facilitate the world's most intense neutrino beam directed towards the LBNF/DUNE, thus modernizing Fermilab's accelerator complex and empowering scientific discoveries for many forthcoming decades.
- **Project Milestone**: PIP-II has successfully secured CD-3 approval, commencing the project execution phase and foreseeing delivery in the year 2028.
- **Innovative Collaborations**: PIP-II is pioneering unprecedented paths as the inaugural DOE/SC accelerator to be constructed with substantial international contributions.
- **International Partnerships**: Our international collaborations have been making commendable technical progress by finalizing designs, demonstrating pivotal technologies, and initiating project construction.
- **Broad Support**: The PIP-II project continues to receive robust support from a wide spectrum of entities including Fermilab, our partners, the physics community, the Office of Science, DOE, and Congress.

PIP-II

Thank You

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