PIP-II: A state of the art accelerator powering the next generation neutrino experiment DUNE

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Fermilab Neutrino Seminar
18 March 2021

A Partnership of:
- US/DOE
- India/DAE
- Italy/INFN
- UK/UKRI-STFC
- France/CEA, CNRS/IN2P3
- Poland/WUST

Outline

- LBNF/DUNE/PIP-II: Context and Scientific Objectives
- PIP-II Technical Design and Challenges
- Status & Schedule
- Summary

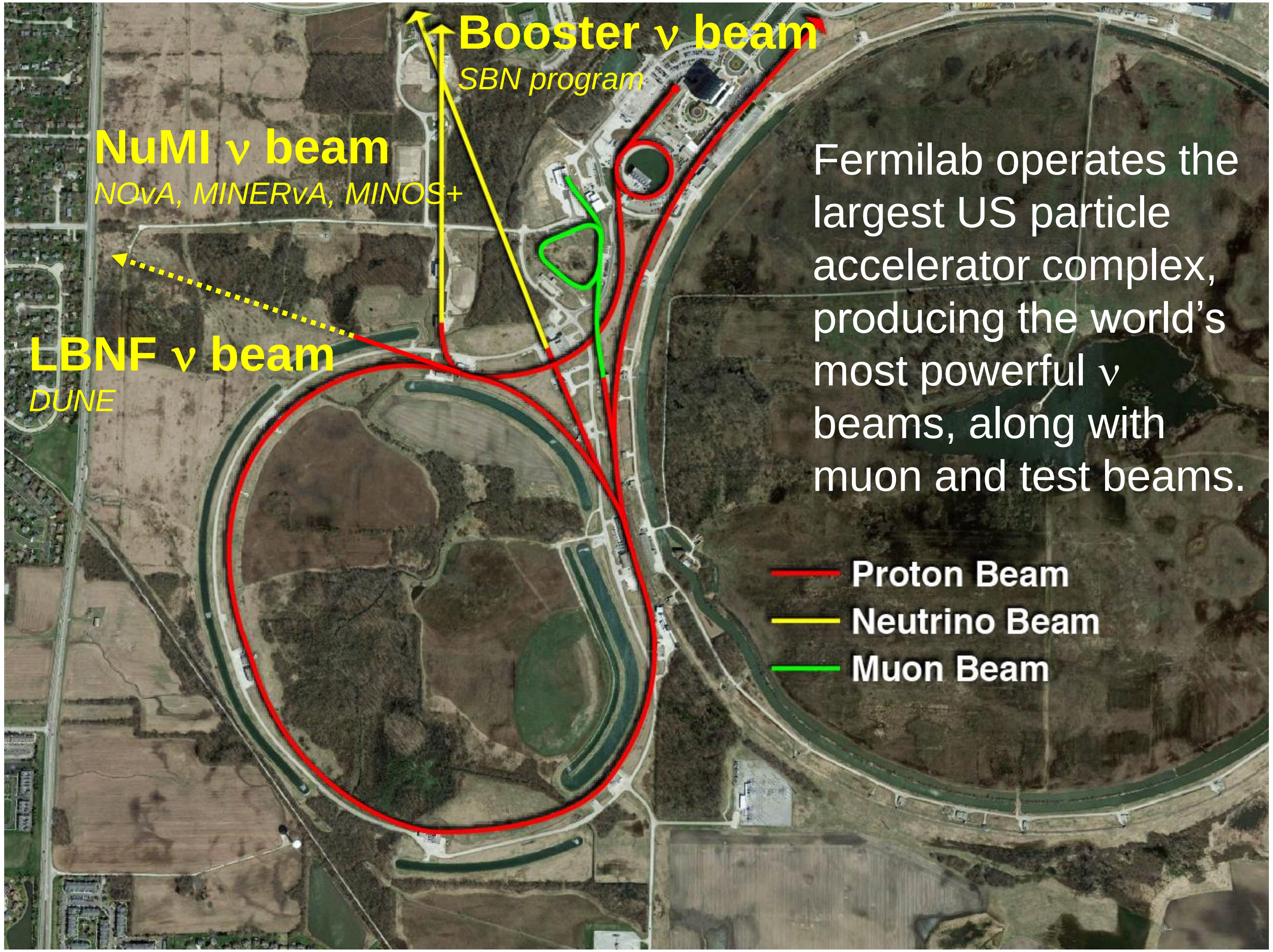
Fermilab at a Glance

America's particle physics and accelerator laboratory

- ~1,800 staff
- 6,800 acres of federal land
- 4,000 scientists from >50 countries use Fermilab facilities

As we move into the next 50 years,
our vision remains to solve the mysteries of
matter, energy, space, and time
for the benefit of all.

Fermilab accelerator complex: operates at >800kW; enables diverse Particle Physics Program with a Flagship



Neutrinos to Minnesota… NOνA:
Fermilab's present flagship neutrino experiment
Neutrinos to South Dakota… DUNE:
International neutrino experiment hosted by Fermilab

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

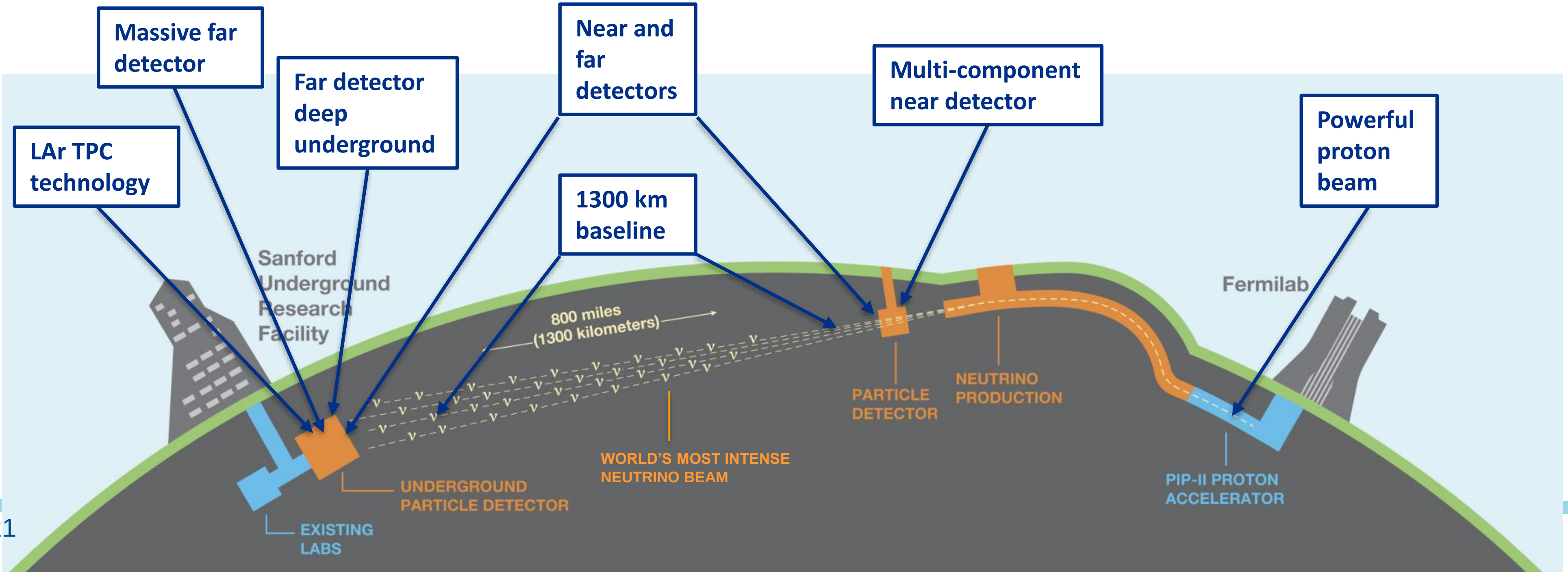
- Build a world-class neutrino program
- Host it as a global project
- Upgrade Fermilab accelerator complex to provide >1 MW proton beam

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest priority large project in its timeframe.

Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

PIP-II / LBNF / DUNE meets P5 requirements

- Powerful proton beams (**PIP-II**)
  - 1.2 MW upgradable to multi-MW in energy range of 60-120 GeV to enable world's most intense neutrino beam
- Dual-site detector facilities (**LBNF**)
  - Deep underground caverns (1.5 km) to support 4 x 17 kt liquid argon volume detectors
  - A long baseline (1300 km) neutrino beam, with wideband capability
- Deep Underground Neutrino Experiment (**DUNE**)
  - The next-generation neutrino experiment



DUNE – A Global Collaboration

~1,214 collaborators

202 institutions

33 countries (including CERN)

DUNE Science Objectives

Neutrinos – most ubiquitous matter particle in the universe, yet the least understood.
Opportunities for game changing physics discoveries:

- **Origin of matter**
  Investigate leptonic CP violation, mass hierarchy, precision oscillation physics
  - ➢ Discover what happened after the big bang: Are neutrinos the reason the universe is made of matter?

- **Neutron Star and Black hole formation**
  Ability to observe supernovae events
  - ➢ Use neutrinos to look into the cosmos and watch the formation of neutron stars and black holes in real time

- **Unification of forces**
  Investigate nucleon decay targeting SUSY-favored modes
  - ➢ Move closer to realizing Einstein's dream of a unified theory of matter and energy

PIP-II….a new accelerator to generate neutrinos

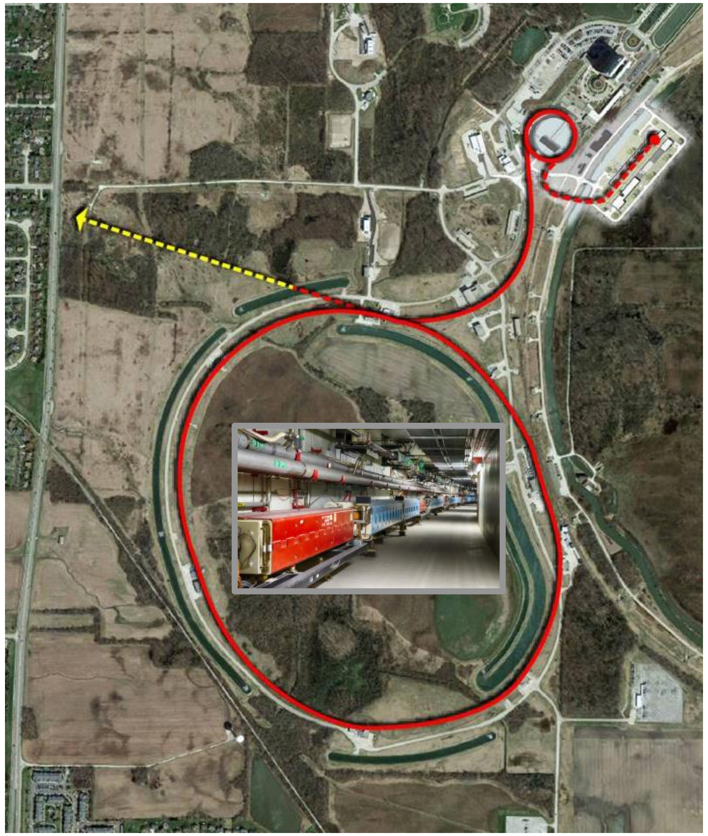
Global Requirements Define Scope, Performance Requirements

Performance requirements for PIP-II are established based on the P5 report and the approved DOE Mission Need Statement

Deliver >1 MW of proton beam power from the Main Injector over the energy range 60 – 120 GeV and 1.2 MW at 120 GeV
Support the current 8-GeV program at Fermilab including the Mu2e, g-2, and short-baseline neutrinos experiments
Provide a platform for extension of beam power to LBNF to >2 MW
Provide a path to increase the beam power to the Mu2e experiment to ~100 kW at 800 MeV, with a duty factor of up to 100%
Provide a platform for extension of capability to flexible bunch pattern, high duty factor/higher beam power operations to multiple experiments simultaneously.
The above capabilities should be provided in a cost-effective manner.

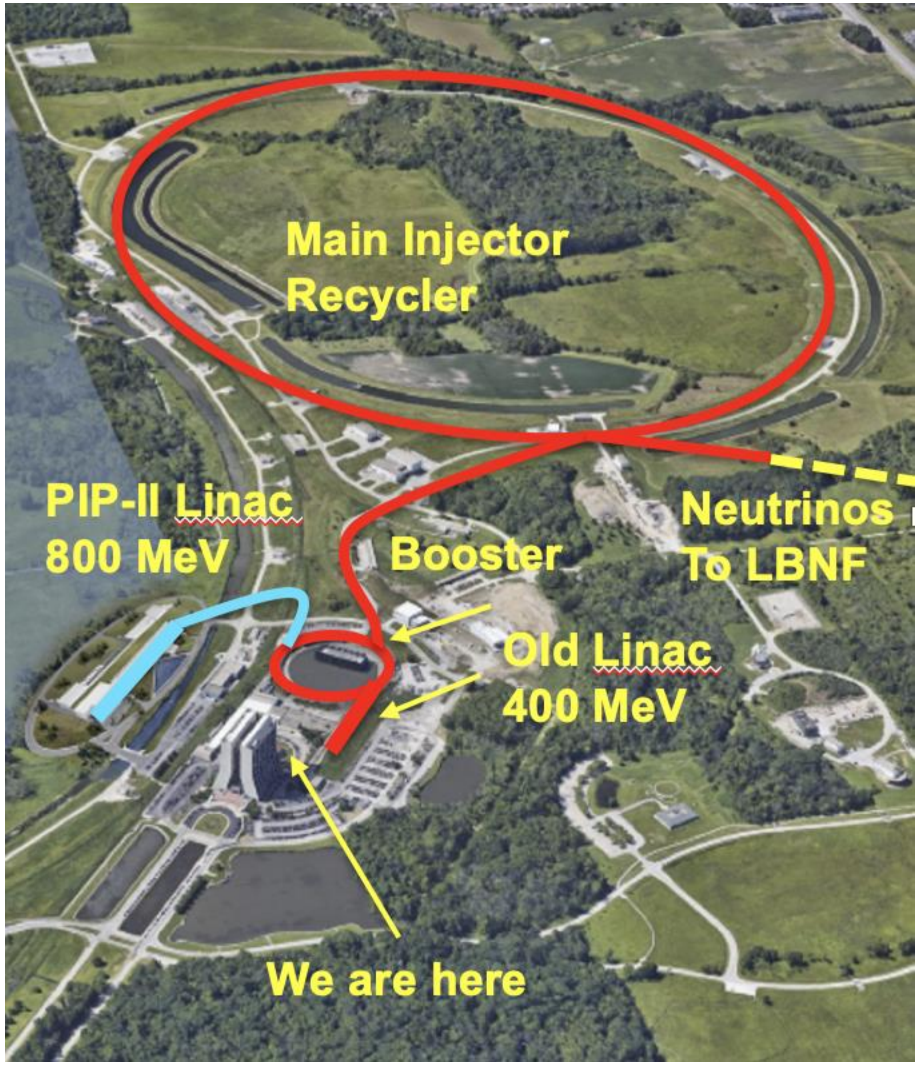
Path to 1.2 MW on LBNF Target

- Increase the number of protons per extracted Booster pulse:
  $4.3 \times 10^{12} \rightarrow 6.3 \times 10^{12}$
- Reduce Main Injector cycle:
  1.33 s → 1.2 s
- Increase Booster rep. rate:
  15 Hz → 20 Hz



- New 800 MeV superconducting linac as Booster injector
- Upgrades to Booster, Recycler Ring (RR), and Main Injector (MI).

PIP-II Scope Meets Performance Requirements



- An 800-MeV superconducting H^-, CW-compatible Linac
- Beam transport of 800-MeV H^- from the SRF Linac to the Booster
- A new injection area in the Booster
- Modifications to the Booster, Main Injector, and Recycler Ring to enable >1MW power on LBNF target for 60-120 GeV
- Associated conventional facilities. The linac enclosure is compatible with upgrades.
  - Site preparation
  - Cryoplant Building
  - Linac Complex
  - Booster Connection


Main Injector
Transfer Line
PIP-II
SRF Linac
Booster

PIP-II International Partners, Expertise and Capabilities

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

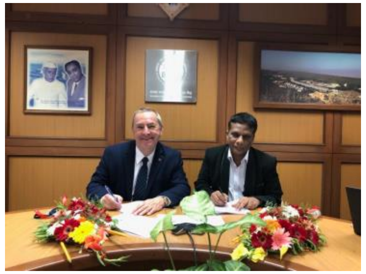
Substantial engineering and manufacturing experience; Construction, operation of synch light & neutron sources SRF cavity processing and testing for ESS

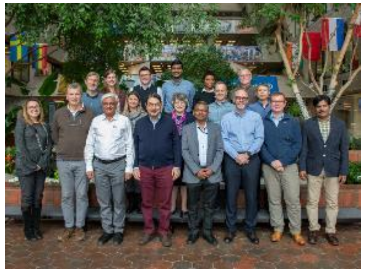
France, CEA, CNRS/IN2P3 (started 2017)

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





PIP-II is the U.S. first accelerator project to be built with major international contributions; benefits from world-leading expertise, capabilities.

Parameters and Performance Requirements for Technical Systems Established

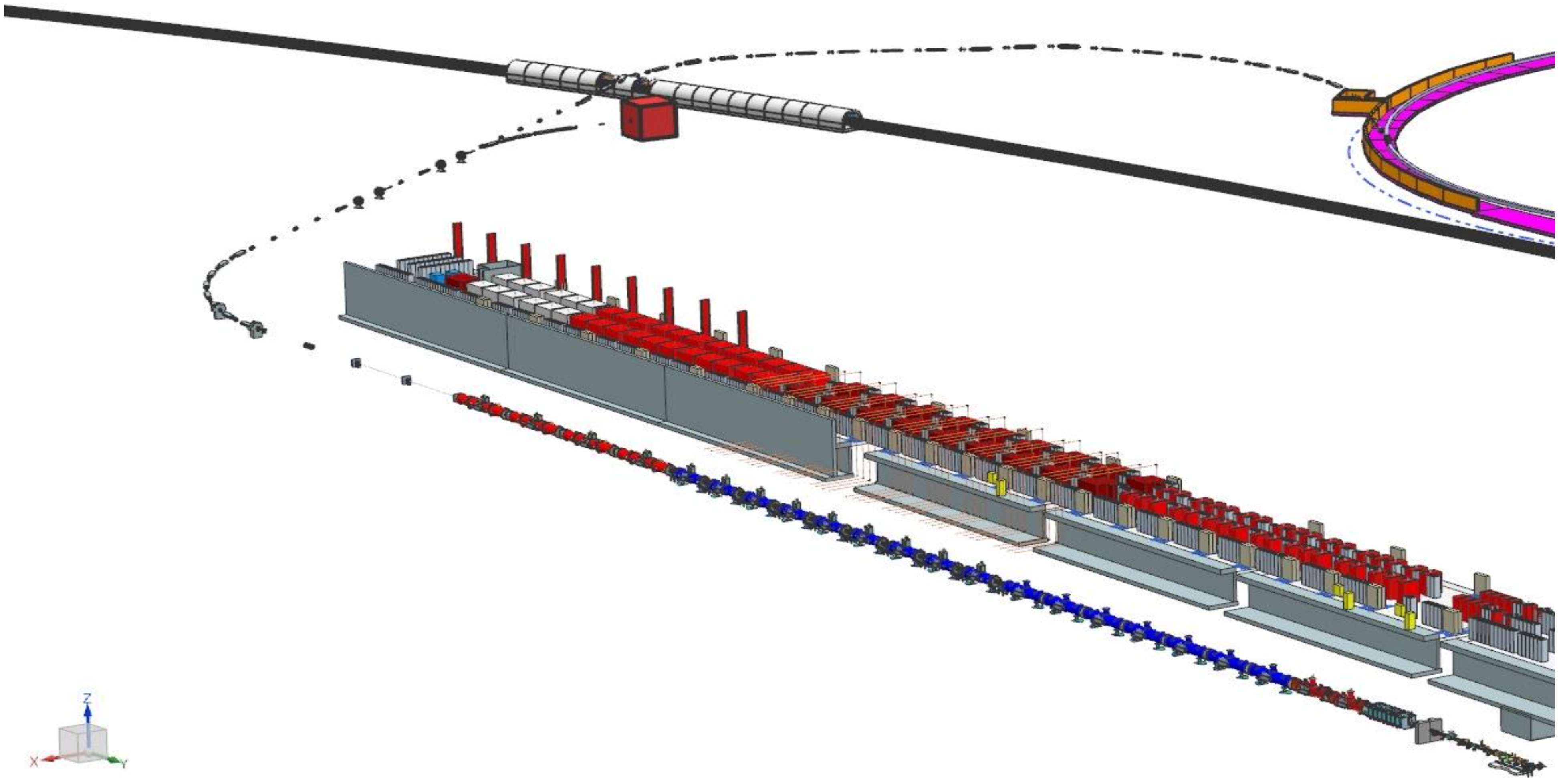
Beam parameters are optimized to meet requirements and maximize value.

Injection into Booster	PIP-II	Current Performance
Delivered H- Beam Energy	800 MeV	400 MeV
Particles per Pulse	6.7×10^{12}	4.7×10^{12}
Average Beam Current in Pulse	2 mA	25 mA
Pulse Length	550 μs	30 μs
Pulse Repetition Rate	20 Hz	15 Hz

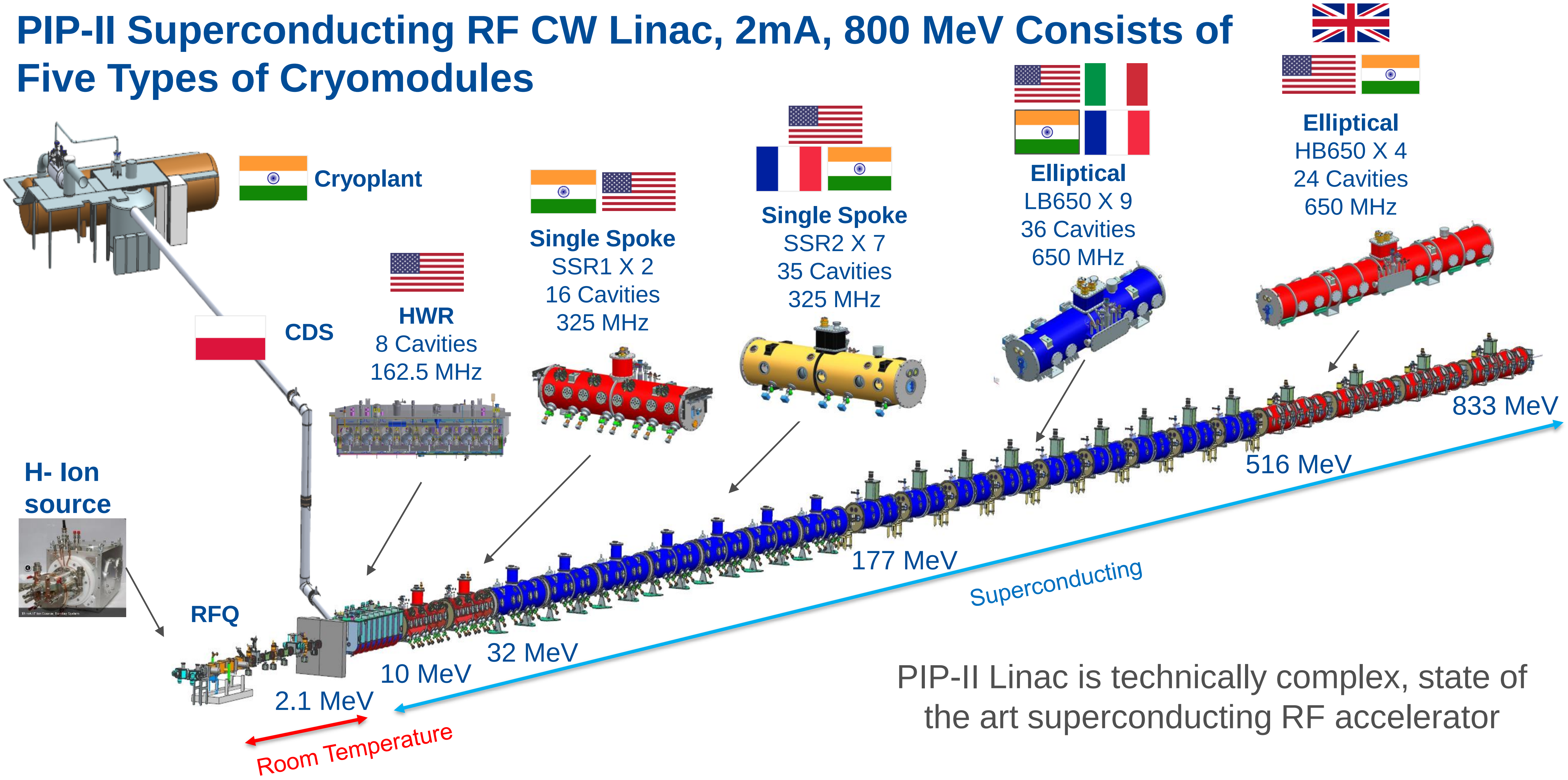
Main Injector	PIP-II	Current Performance
Beam Energy	60-120 GeV	120 GeV
Cycle time	1.2 sec	1.33 sec
Beam Power (60 - 120 GeV)	1.1 - 1.2 MW	0.75 MW (@120 GeV)

Potential Upgrades		
Upgrade potential	2.4 MW	

Technical Design & Challenges



PIP-II Superconducting RF CW Linac, 2mA, 800 MeV Consists of Five Types of Cryomodules



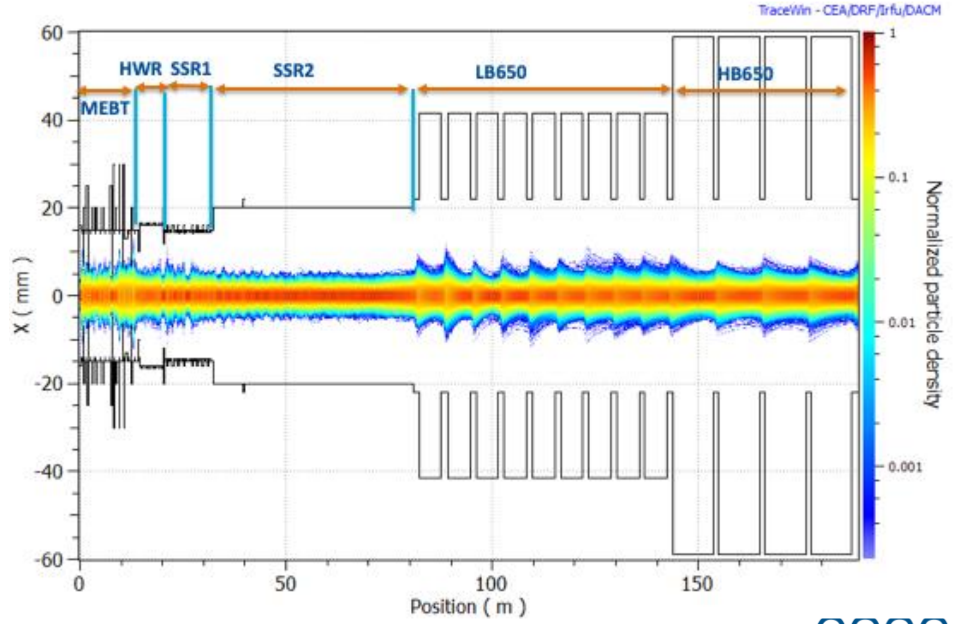
PIP-II Linac is technically complex, state of the art superconducting RF accelerator

PIP-II is the world's highest energy and highest power CW proton linac.

Linac Design Meets Requirements, Robust, Flexible, Fault-Tolerant

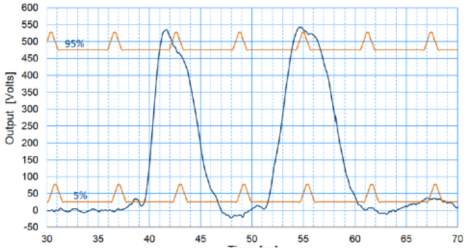
- Design provides energy margin
- Design is flexible and fault tolerant
  - Arbitrary, programmable bunch patterns, including gaps and reduced frequency
  - Linac can tolerate failure of any single element
  - Linac can operate if cavities of one single type underperform by 20%
- High quality, low halo beam
  - Losses typically are less than 0.1 W/m in CW regime

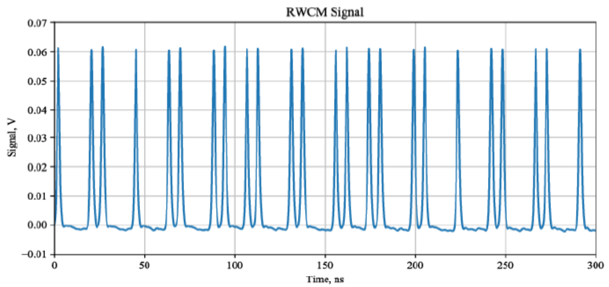
Beam energy	833 MeV
Beam current, average	2 mA

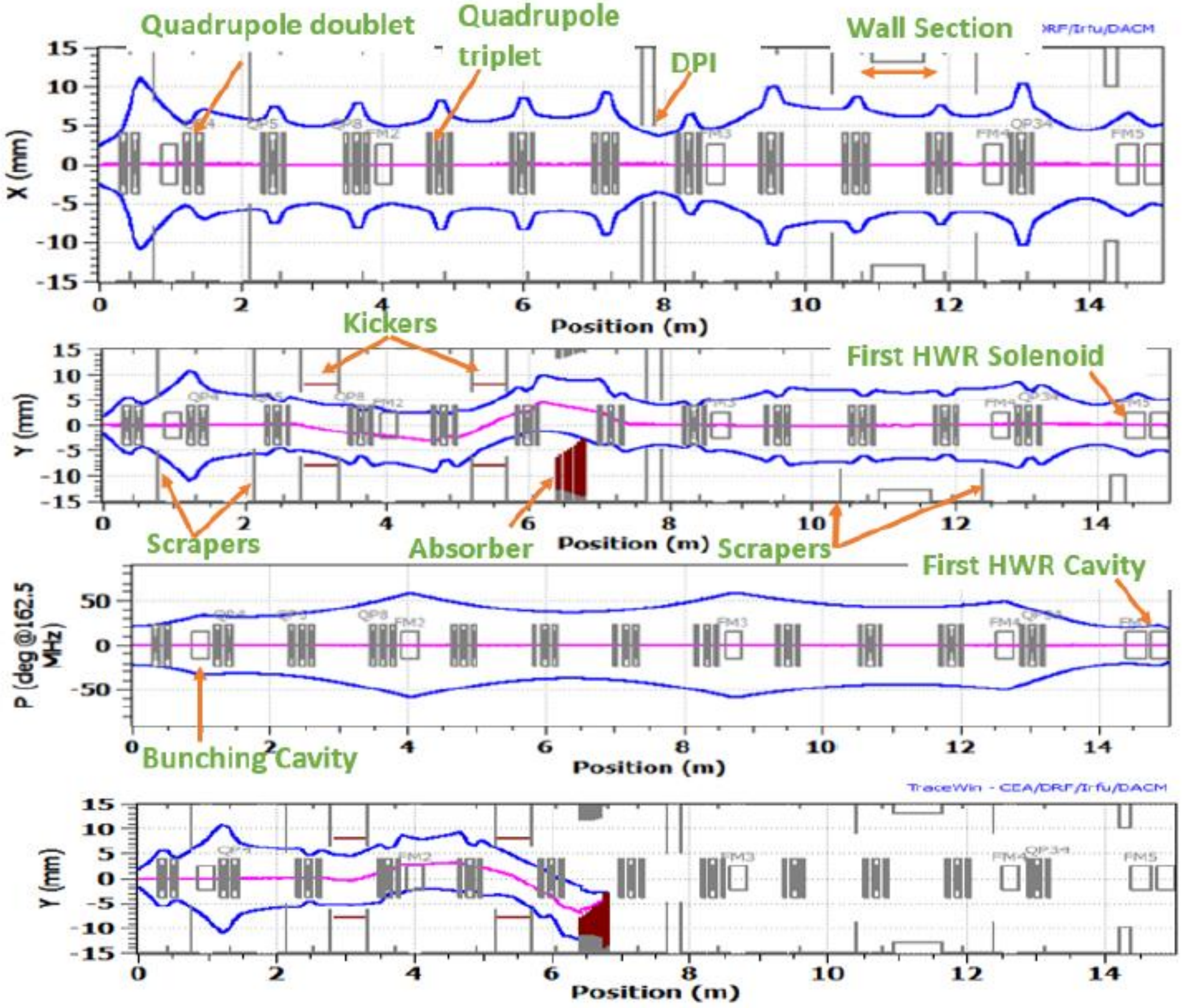


Warm Front End

- 15 mA, 30 kV ion source
- 2 m LEBT ('slow' chopper, diff. pumping, envelope match to RFQ)
- 2.1 MeV, 162.5 MHz RFQ, 5mA
- 14 m MEBT (bunch-by-bunch chopper, shielding wall, envelope match)
- Successful integration of magnets from DAE/BARC.

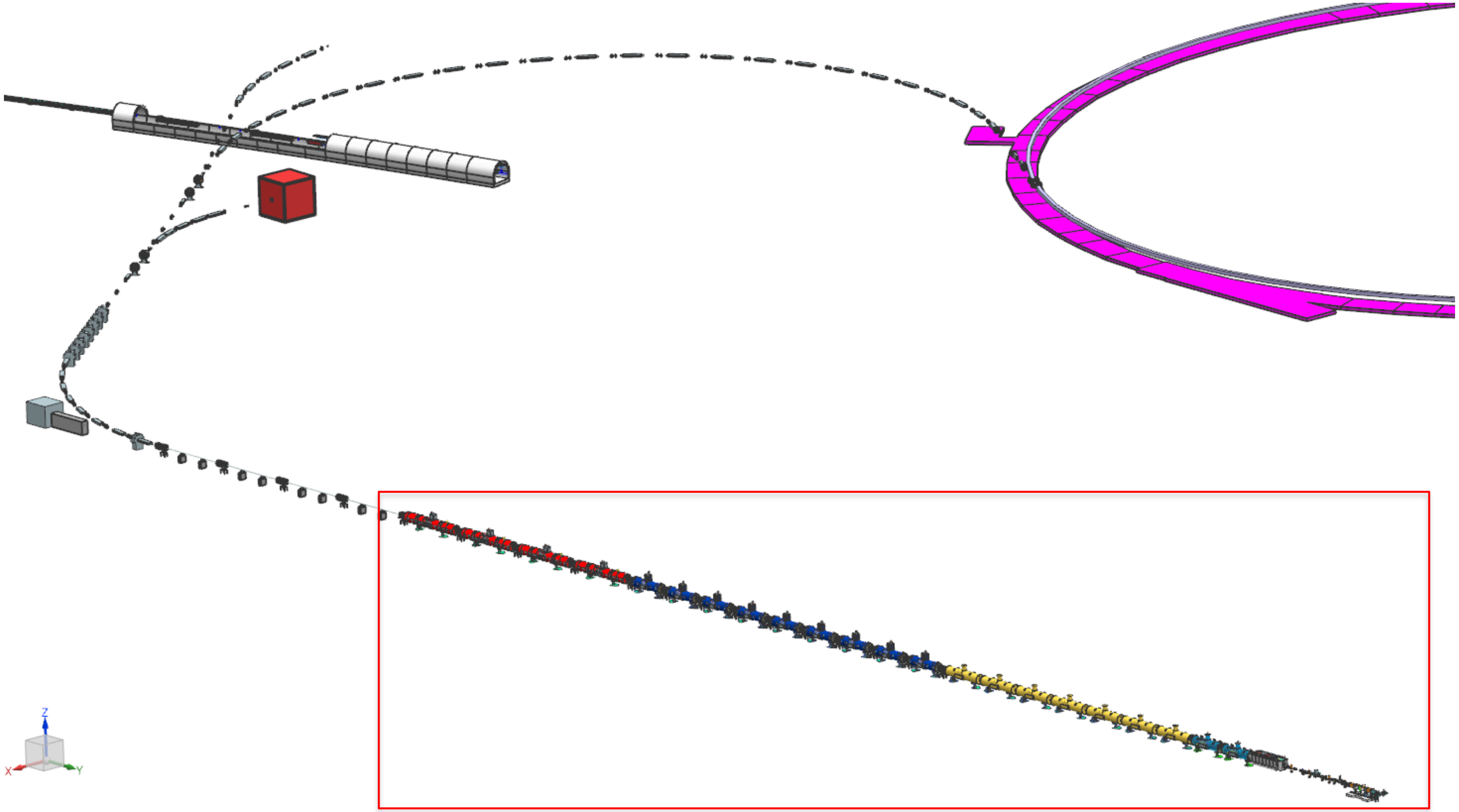




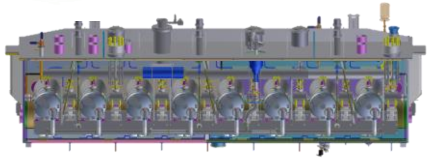


Bunch-by-bunch chopper removes undesired bunches leaving beam current at up to 2 mA.

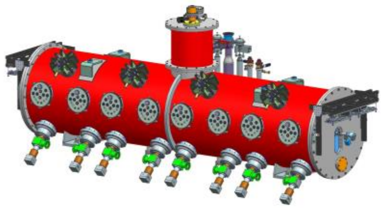
PIP-II Superconducting Linac



The state-of-the-art PIP-II Superconducting RF Systems

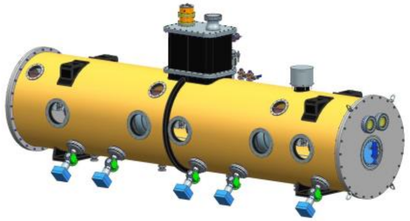


5.9 m



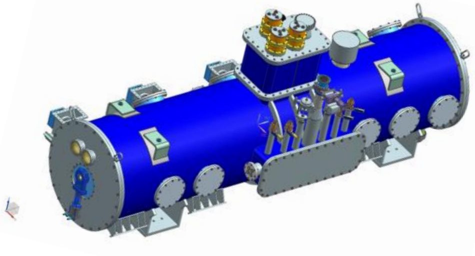
5.3 m

2023



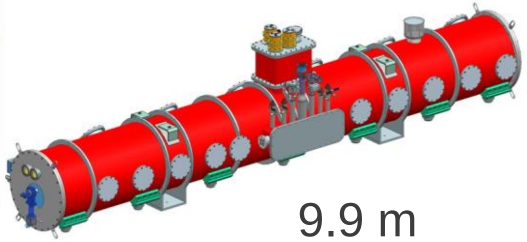
6.5 m

2023

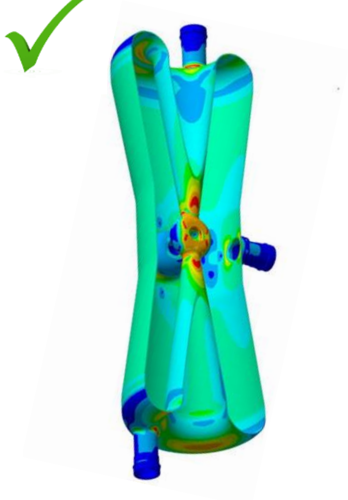


5.5 m

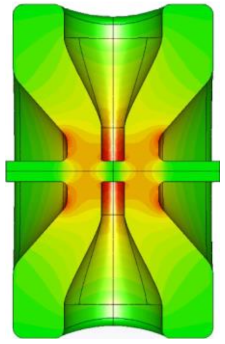
2021-22



9.9 m

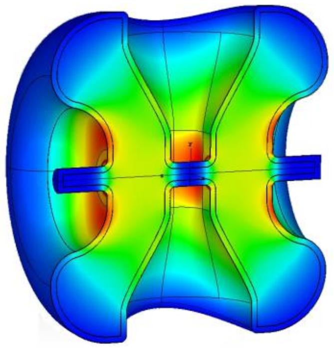


Half Wave Resonator
β=0.11 Q_0 =0.85x10^{10}

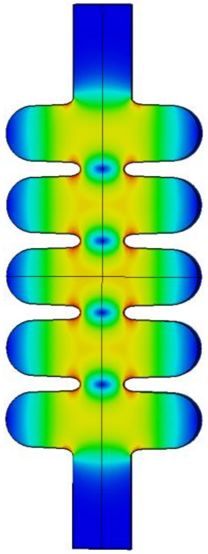


Single Spoke
SSR1
β=0.22 Q_0 =0.82x10^{10}

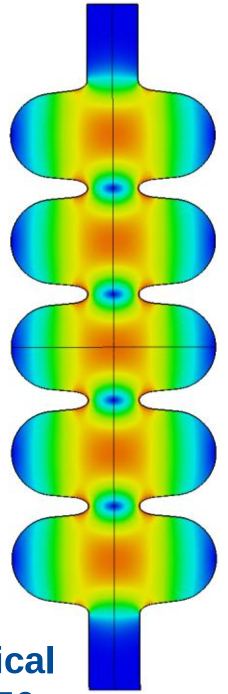
2022



Single Spoke
SSR2
β=0.47 *Q_0 =0.82x10^{10}



Elliptical
LB650
β=0.61 *Q_0 =2.4x10^{10}

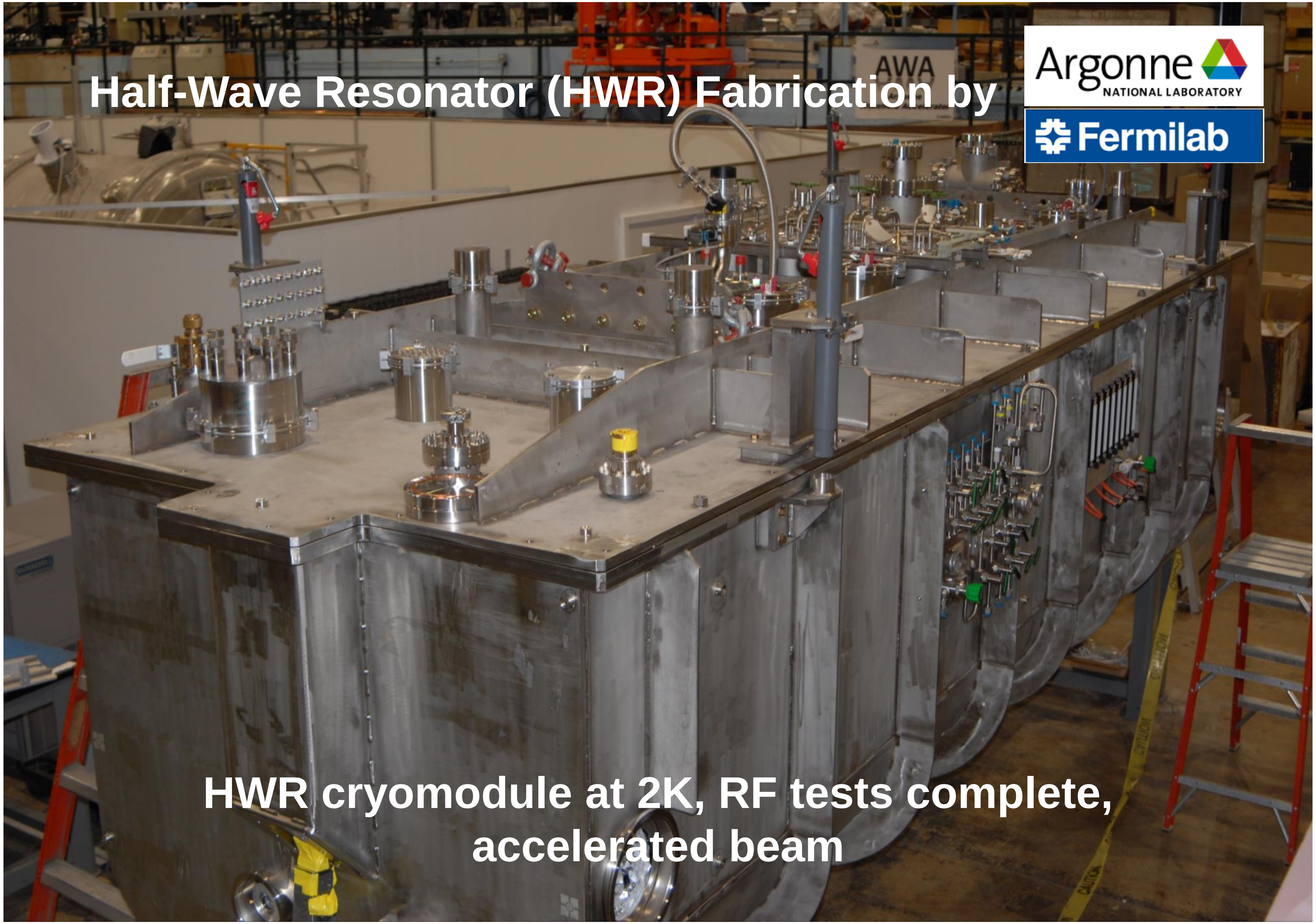


Elliptical
HB650
β=0.92 *Q_0 =3.3x10^{10}

✓ Performance validated ✓ Testing in progress Dates: component built

*state-of-the-art performance requirement

Half-Wave Resonator (HWR) Fabrication by Argonne National Laboratory / Fermilab

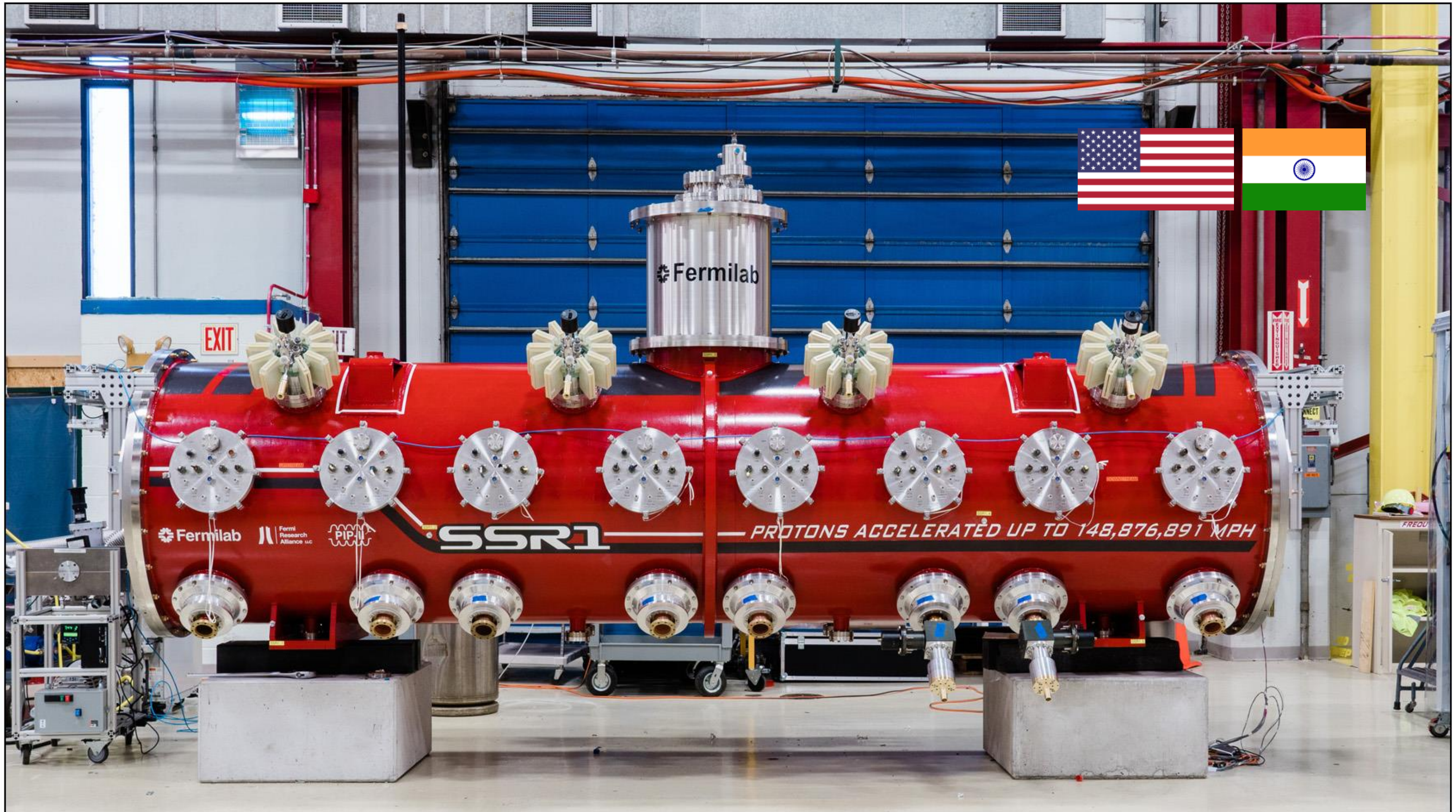


HWR cryomodule at 2K, RF tests complete, accelerated beam

HWR Cryomodule Tests

- Operated all cavities to the full nominal field (9.7 MV/m) and at least 10% above the nominal maximum gradient for extended time.
- Average Quality Factors exceeded specification of 8.5e9 (measured as an ensemble).
- Solenoids all met specification, exceed operational requirements
- All cavities (except 3, untested) operated in GDR mode (LLRF control demonstrated)

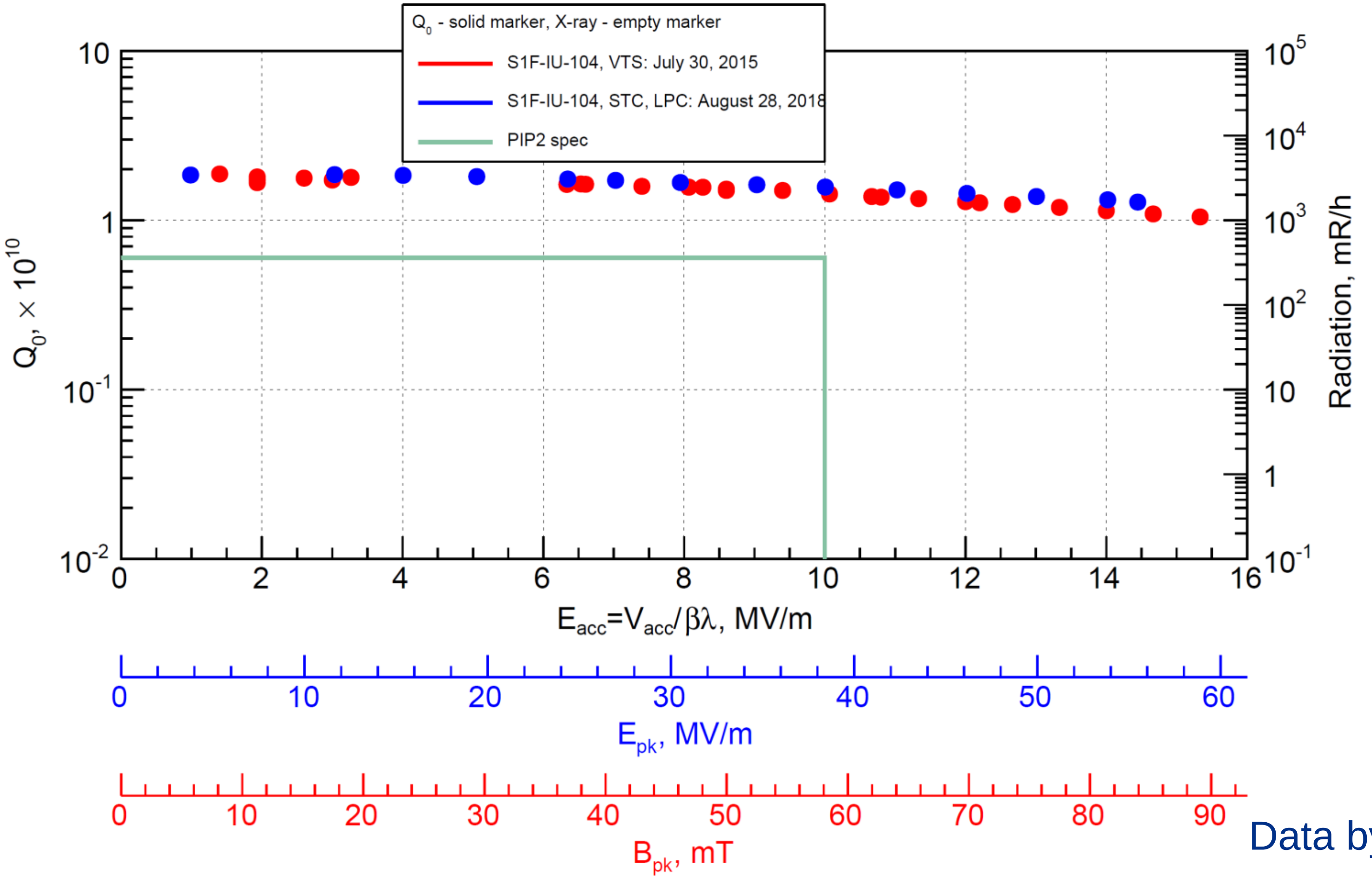
Cavity Position	Cavity Serial #	Nominal gradient required (MV/m)	Maximum gradient (MV/m)	Cavity Q_0	Note
CAV1	#P1	1.6	10.6	>1.4e10	No FE, no MP
CAV2	#P2	2.5	10.9	>1.4e10	No FE, no MP
CAV3	#2	3.5	6.5		Need to replace warm window
CAV4	#3	4.8	11.2	>1.4e10	No FE, no MP
CAV5	#4	6.5	10.5	>1.4e10	No FE, no MP
CAV6	#5	8.7	11.0		No FE, no MP
CAV7	#7	9.4	10.7	>1.4e10	No FE, no MP
CAV8	#1	9.7	10.8	>1.4e10	No FE, no MP



Single Spoke prototype cryomodule fabricated by Fermilab; installed at PIP2IT; 2K RF tests complete; successfully accelerated beam

SSR1 – Indian Cavity Performance

STC* test with low power coupler



Data by A. Sukhanov

High Q at high gradient and field emission free
IUAC/BARC cavity has the best cavity Q performance up to date

*STC= Spoke Test Cryostat

SSR1 Prototype Cryomodule Tests: Phase 1 Gradients achieved

- All eight SSR1 cavity gradients measured, exceed Phase 1 requirements.
  - Phase 2 test, Qo measurements in March.
- Completed first heat load measurement with all cavities and solenoids at nominal field/current.

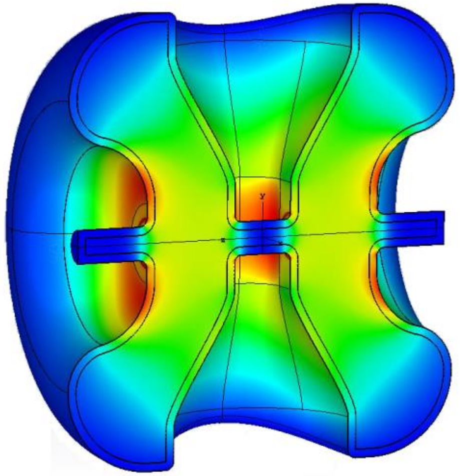
Cavity Position	Cavity Serial #	Phase 1 gradient required (MV/m)	Phase 2 gradient required (MV/m)	Cavity gradient measured (MV/m)	Notes
CAV1	S1H-NR-106	**4.88**	10.00	**11.5**	Phase 2 admin limit, FE onset 10.5 MV/m.
CAV2	S1H-NR-110	**4.63**	8.78	**5.3**	Phase 1 admin limit
CAV3	S1H-NR-112	**4.78**	8.05	**5.5**	Phase 1 admin limit
CAV4	S1H-NR-109	**7.32**	10.00	**8.4**	Phase 1 admin limit, FE onset 5.5 MV/m
CAV5	S1H-NR-114	**7.80**	9.76	**9.0**	Phase 1 admin limit
 **CAV6**	S1F-IU-104	**7.56**	10.00	**8.7**	Phase 1 admin limit
CAV7	S1H-NR-113	**7.32**	8.54	**8.4**	Phase 1 admin limit
CAV8	S1H-NR-111	**10.00**	10.00	**11.0**	Phase 1 admin limit, FE onset 10.5 MV/m.

Phase 1: first SSR1 slot; Phase 2: second SSR1 slot

SSR2 Cavities, Pre-Production Cryomodule

Cavity

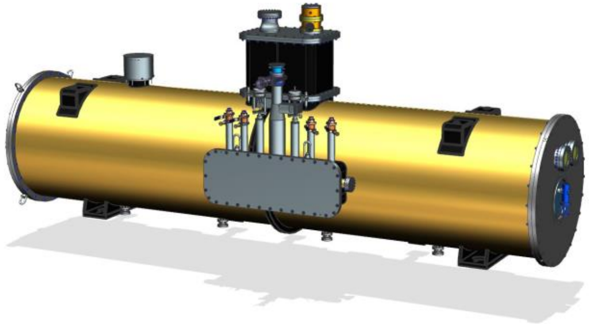
- Integrated design team: Fermilab, IN2P3 and DAE
- Niobium production at vendor completed
- Prototype jacketed cavity procurement in progress
- Coupler procurement in progress

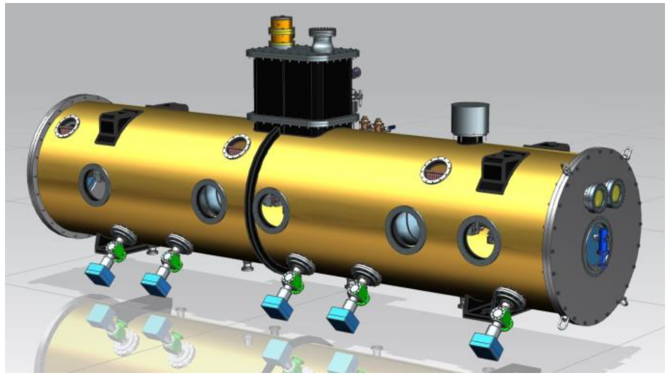


Parameters	SSR2 v 3.1
Optimal beta β_{opt}	0.472
Aperture [mm]	40
Frequency [MHz]	325
Effective length $2\beta_{opt}\lambda/2$ [m]	0.436
E_{peak}/E_{acc}	3.51
B_{peak}/E_{acc} [mT/(MV/m)]	6.75
G [Ohm]	115
R/Q [Ohm]	305.2
E_{peak} [MV/m] @ 5 MeV	40.2
B_{peak} [mT] @ 5 MeV	77.4
Max energy gain [MeV]	5.0
Max gradient [MV/m]	11.47

Cryomodule

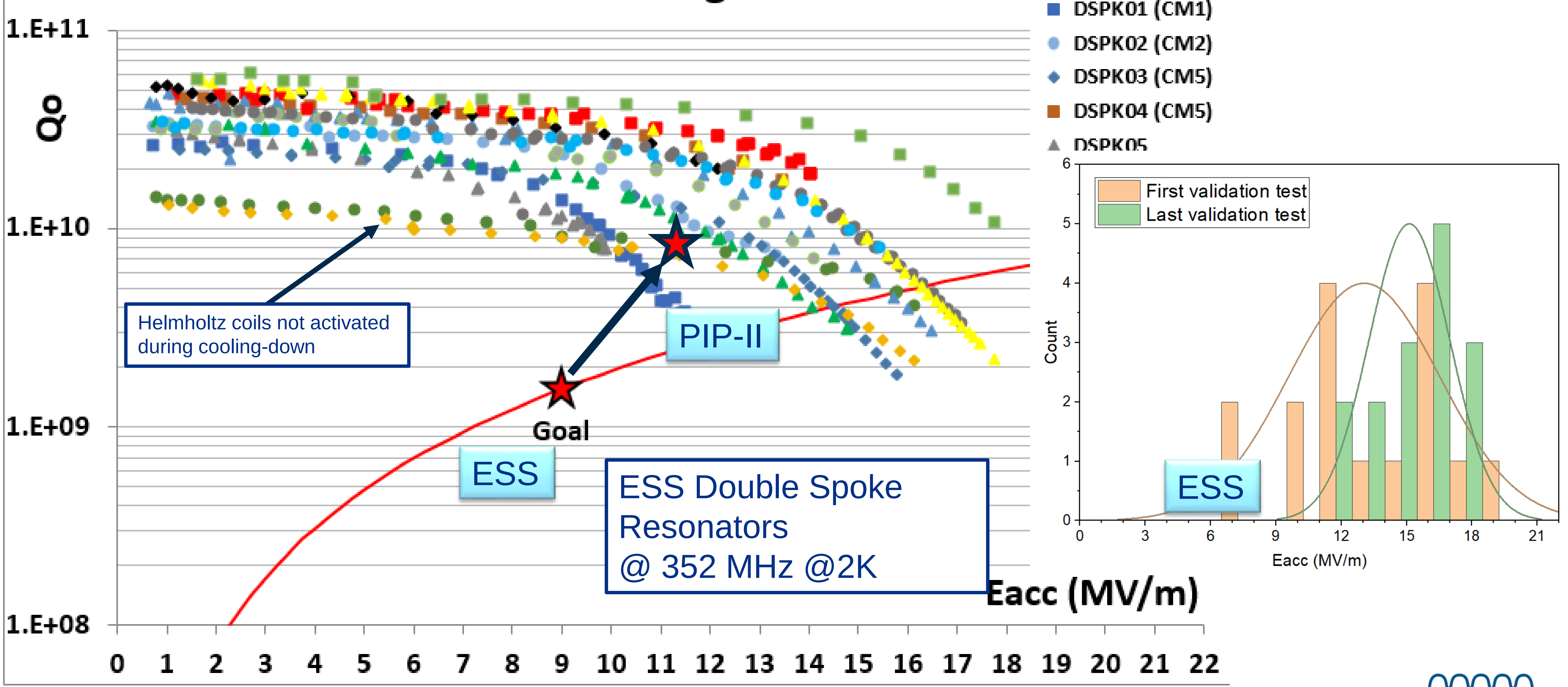
- Design in progress by Fermilab, DAE



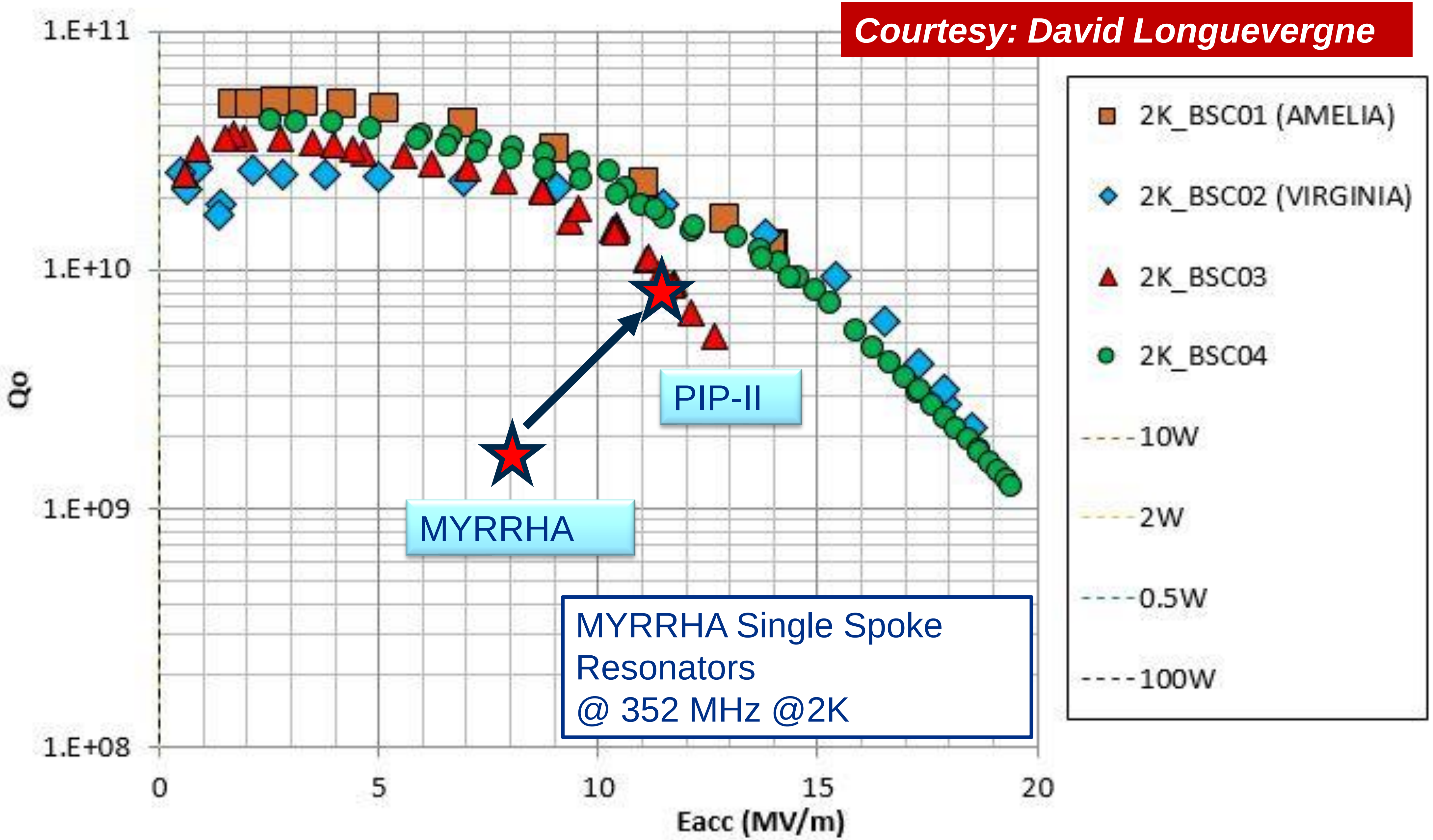


Double-Spoke OK for CM integration

Courtesy: David Longuevergne

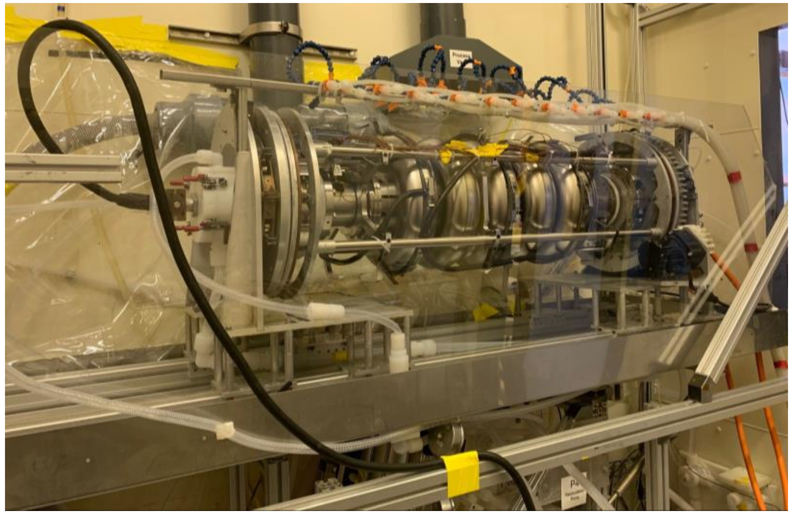


Courtesy: David Longuevergne

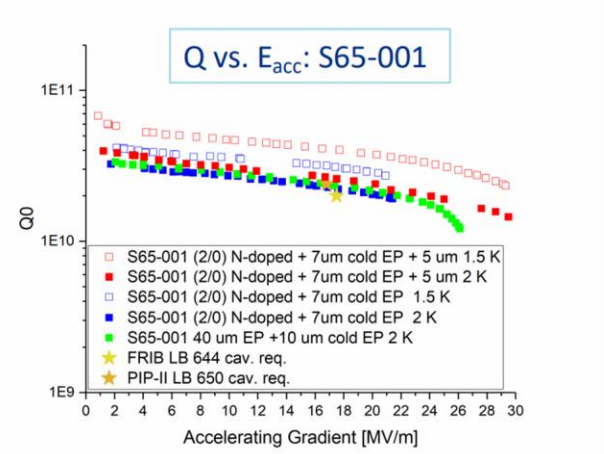

1.E+11
1.E+10
1.E+09
1.E+08
Qo
0
5
10
15
20
Eacc (MV/m)
2K_BSC01 (AMELIA)
2K_BSC02 (VIRGINIA)
2K_BSC03
2K_BSC04
10W
2W
0.5W
100W
PIP-II
MYRRHA
MYRRHA Single Spoke
Resonators
@ 352 MHz @2K

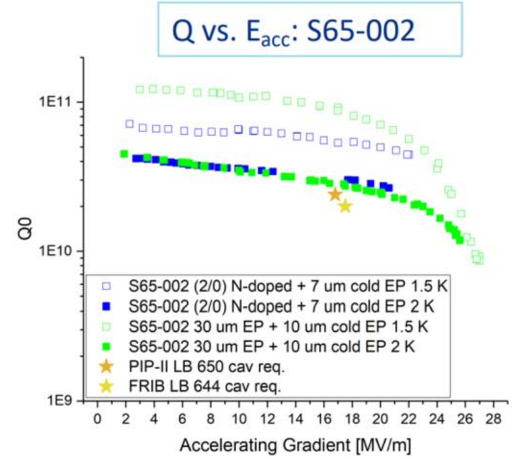
LB650 Cavities

- Q_0, Gradient → 2.4 x10^{10} and 16.8 MV/m - unprecedented for β <1
- Cavity RF design completed led by INFN
  - First prototype bare cavity INFN contribution arrived in May 2020
  - RF testing in progress
- MSU 644 MHz cavities tested, meet PIP-II Q_0, gradient specs



INFN cavity B61 on ANL EP stand





MSU cavities are directly scaled from PIP-II LB650 cavity design.
Courtesy: *Martina Martinello*

HB650 Prototype Cryomodule

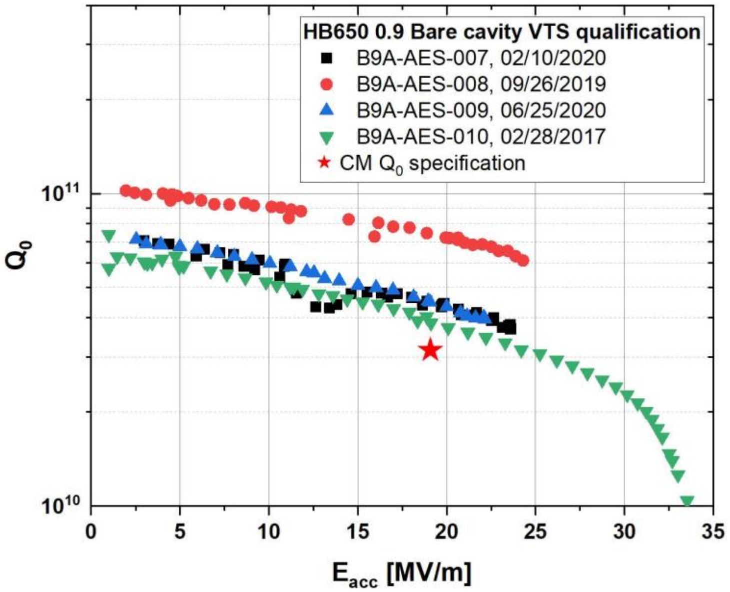
Fermilab | RRCAT | UKRI Science and Technology Facilities Council | cea

Cavity

- Q_0, Gradient → 3.3 x10^{10} and 18.7 MV/m - unprecedented for β<1
- Four HB650 Fermilab cavities exceeded cryomodule Q_0 spec
- RRCAT cavity reached max gradient 29 MV/m, met PIP-II specs
- Cavity, coupler procurement awarded

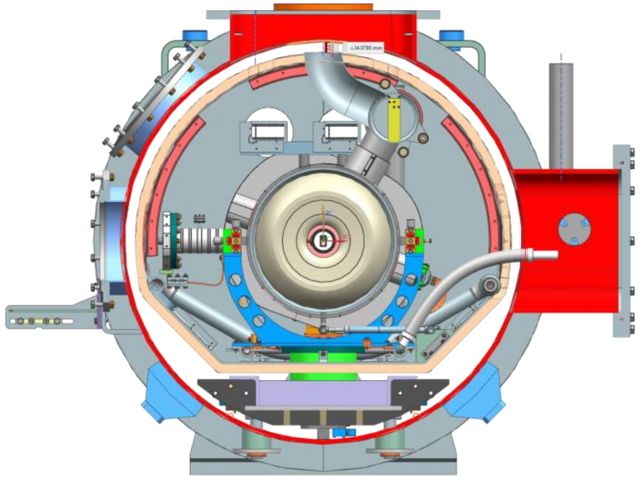
Cryomodule

- FDR was successfully completed in 7/29-31/2020
- Successful HB650 Transportation FDR on 9/22/2020 led by UKRI

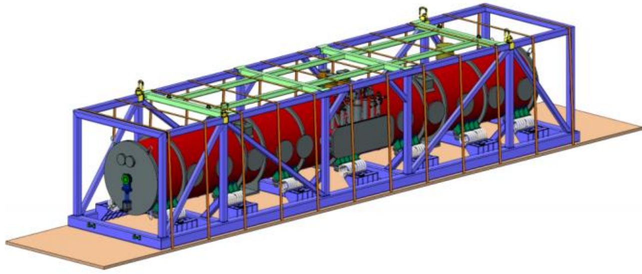


Bare HB650 Cavity

Jacketed HB650 Cavity in STC



HB650 proto cryomodule



HB650 Transportation Tooling

PIP-II

R&D Challenges in PIP-II SRF Systems

- High Q_0 and High Gradient → ~3 $x10^{10}$ and ~20 MV/m
  - N-doping optimization & fast cool down is required
  - Tests at 650 MHz show that additional doping optimization is desirable (relative to doping developed for 1.3 GHz)

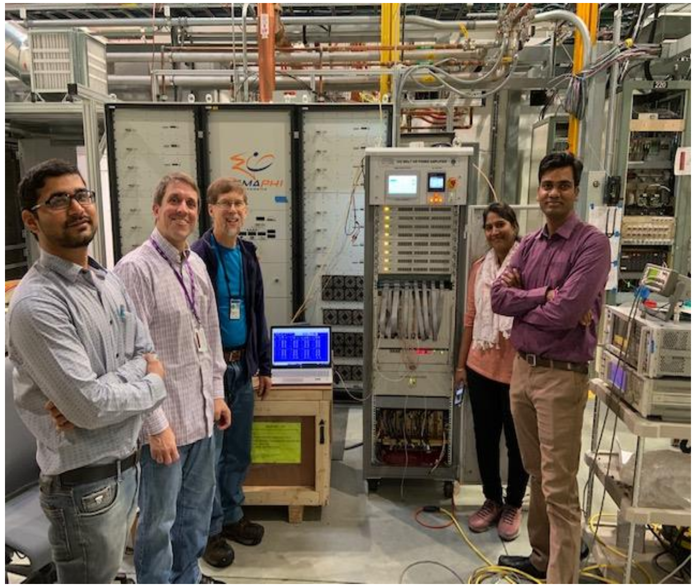
- Suppression of Microphonics noise
  - Maximum detuning < 20 Hz (σ<3 Hz)
    - Passive means
      - Cryomodule design
    - Active means
      - Adaptive Detuning Control Algorithm

Accelerator Systems

- Design, procurement, fabrication, and testing of various accelerator system hardware and software including:
  - Machine Protection Systems, High Power RF & RF distribution, Low Level RF, Magnets & Power Supplies; Vacuum; Controls; Safety Systems; Beam Instrumentation

- Focus:
  - PIP2IT support for beam operation and SRF testing
  - Maturing PIP-II technical designs

- Highlights:
  - LLRF/RFPI with resonance control operational in HWR, SSR1
  - Laser profile monitor installation complete
  - MPS focus on increasing beam pulse length up to 550 µs
    - Low energy loss detector (diamond detector) installed



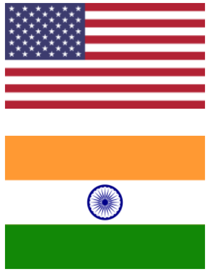
First ECIL/BARC 325 MHz, 7 kW RF amplifier at Fermilab – Feb 2020

DAE Solid-State Amplifiers

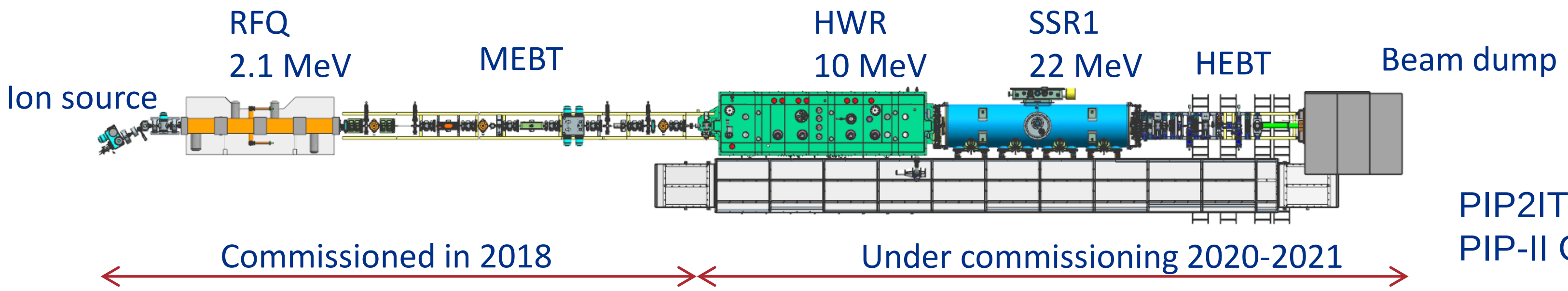
ECIL/BARC 7 kW 325 MHz amplifiers powering SSR1 cavities at PIP2IT

RRCAT 40 kW 650 MHz prototype amplifier just arrived, being assembled, in preparation for testing

PIP2IT Serves as Testbed for PIP-II Warm Front End and Critical Systems



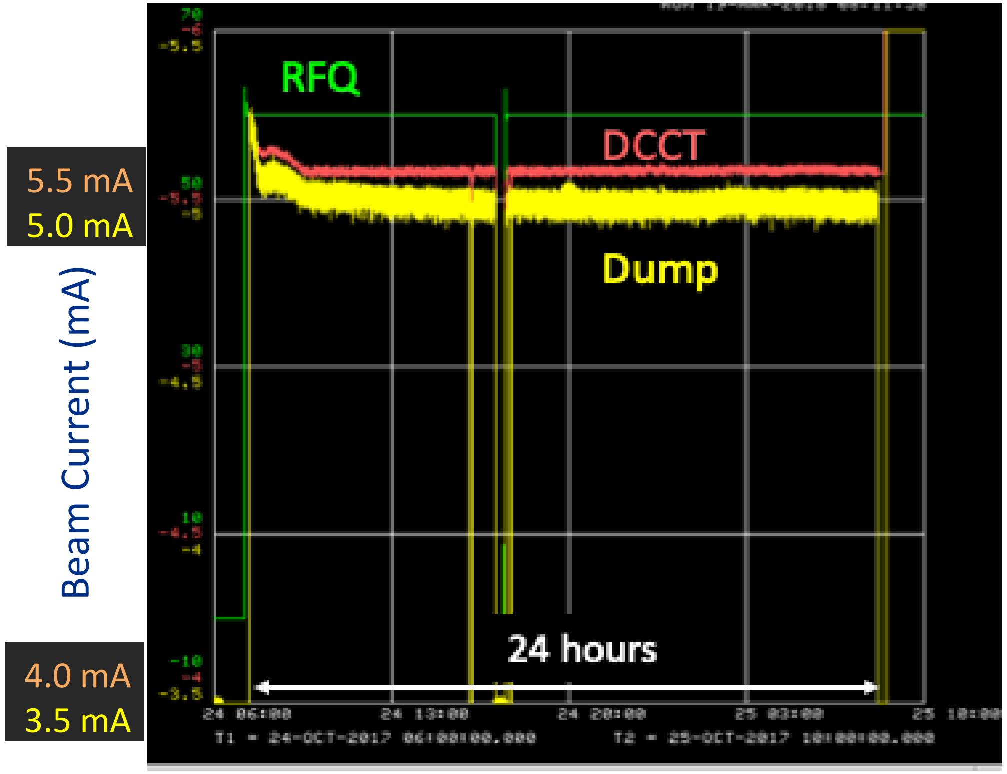
- ✓ Ion source
- ✓ RFQ, 2.1 MeV
- ✓ Chopper/Absorber to produce bunch pattern for injection into Booster
- ✓ Beam dynamics agrees with design
- ✓ Cryomodule/Cavity test
- ✓ LLRF and resonance control test
- ✓ Instrumentation
- EPICs early development



PIP2IT to be converted to PIP-II Cryomodule Test Facility

PIP2IT MEBT Meets Design Performance Requirements

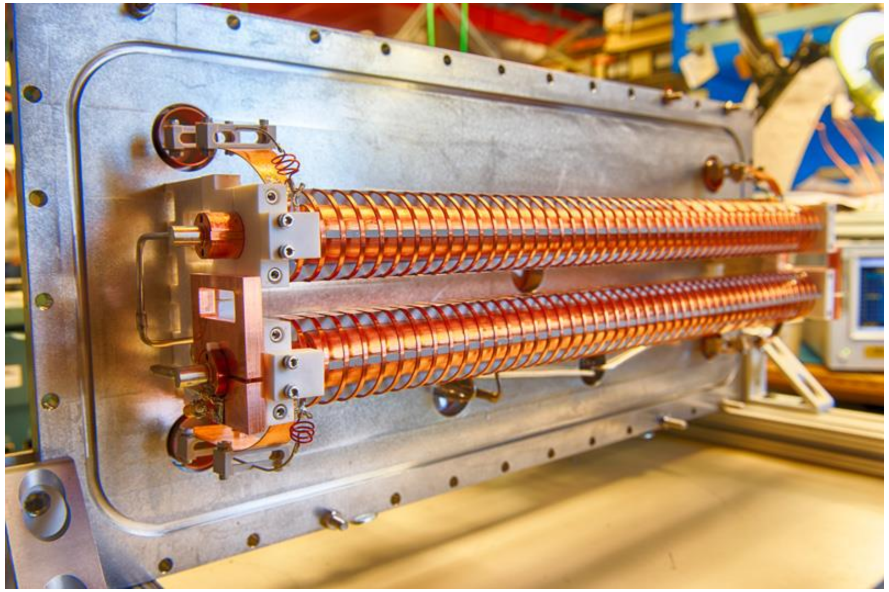
Demonstrated transporting 'LBNF beam' through PIP2IT MEBT for 24 hours, meeting design performance requirements:
5 mA ×0.55 ms×20 Hz×2.1 MeV



PIP2IT beam current measured by DCCT in LEBT and dump at the end of MEBT

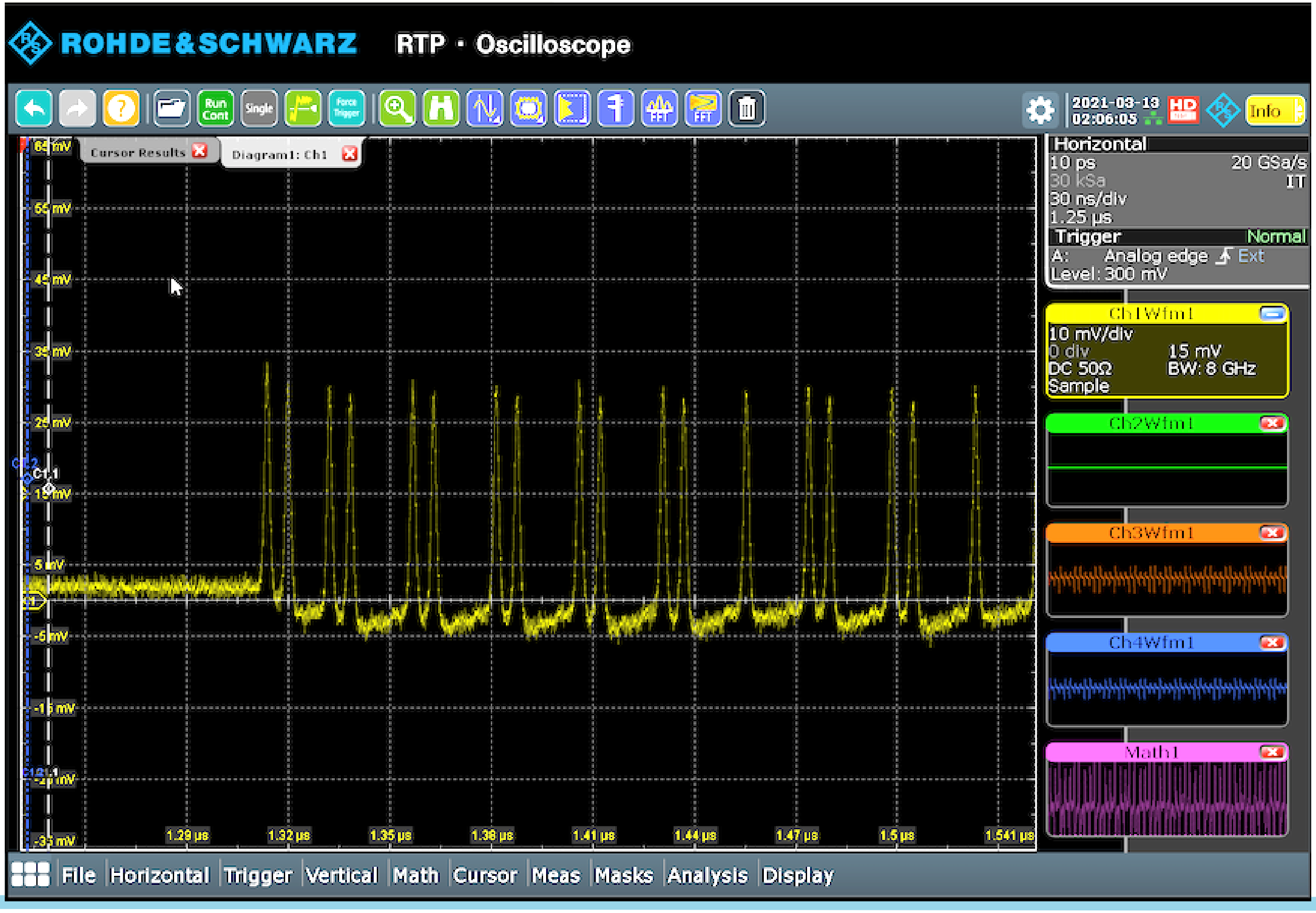
Bunch-by-bunch chopper offers arbitrary bunch pattern capability

- Kickers were successfully operated
- Kickers do not significantly deteriorate transverse beam emittance
- Down-selected 200-Ohm kicker as baseline



MEBT Chopper Is Fully Operational

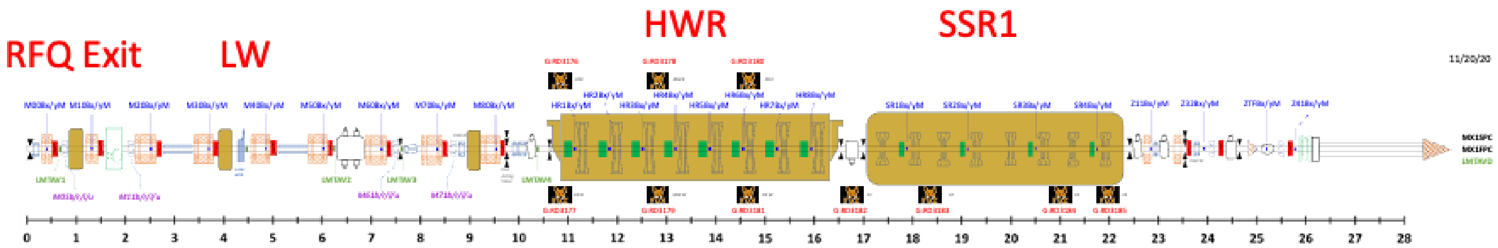
- Chopper generates LBNF bunch pattern for injection into Booster
- Chopped beam transported to HEBT Dump. Tuning with beam is ongoing.



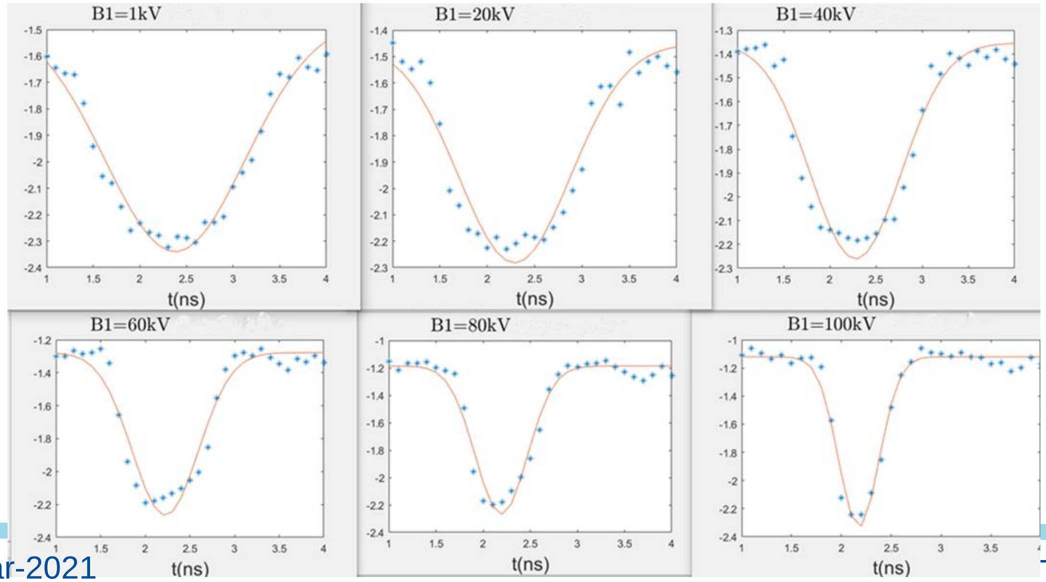
Chopped beam in HEBT at the end of PIP2IT

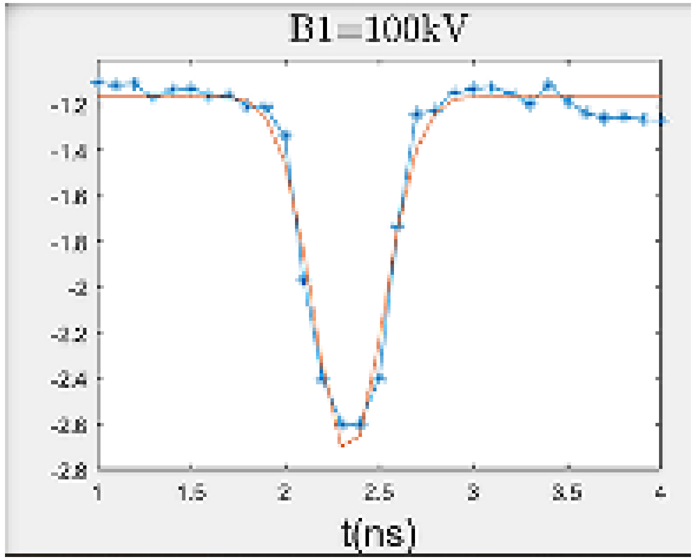
Laser Wire is Used for Beam Studies

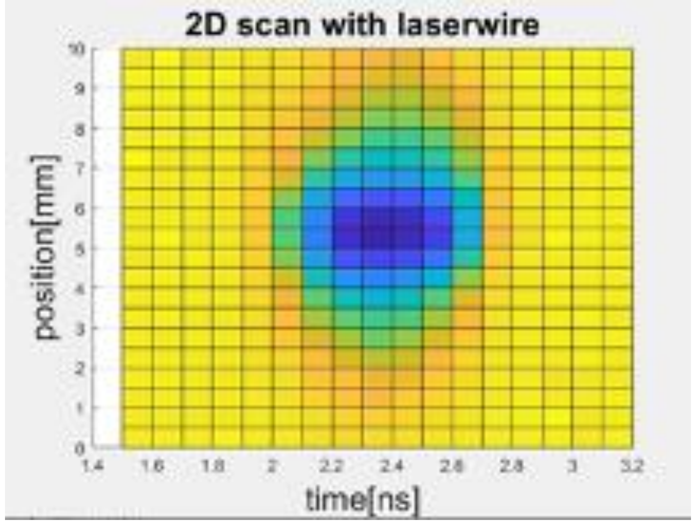
- Laser Profile Monitor measures transverse and longitudinal profiles by stripping electrons from H- with a laser and capturing stripped electrons.
- Used for transverse and longitudinal matching



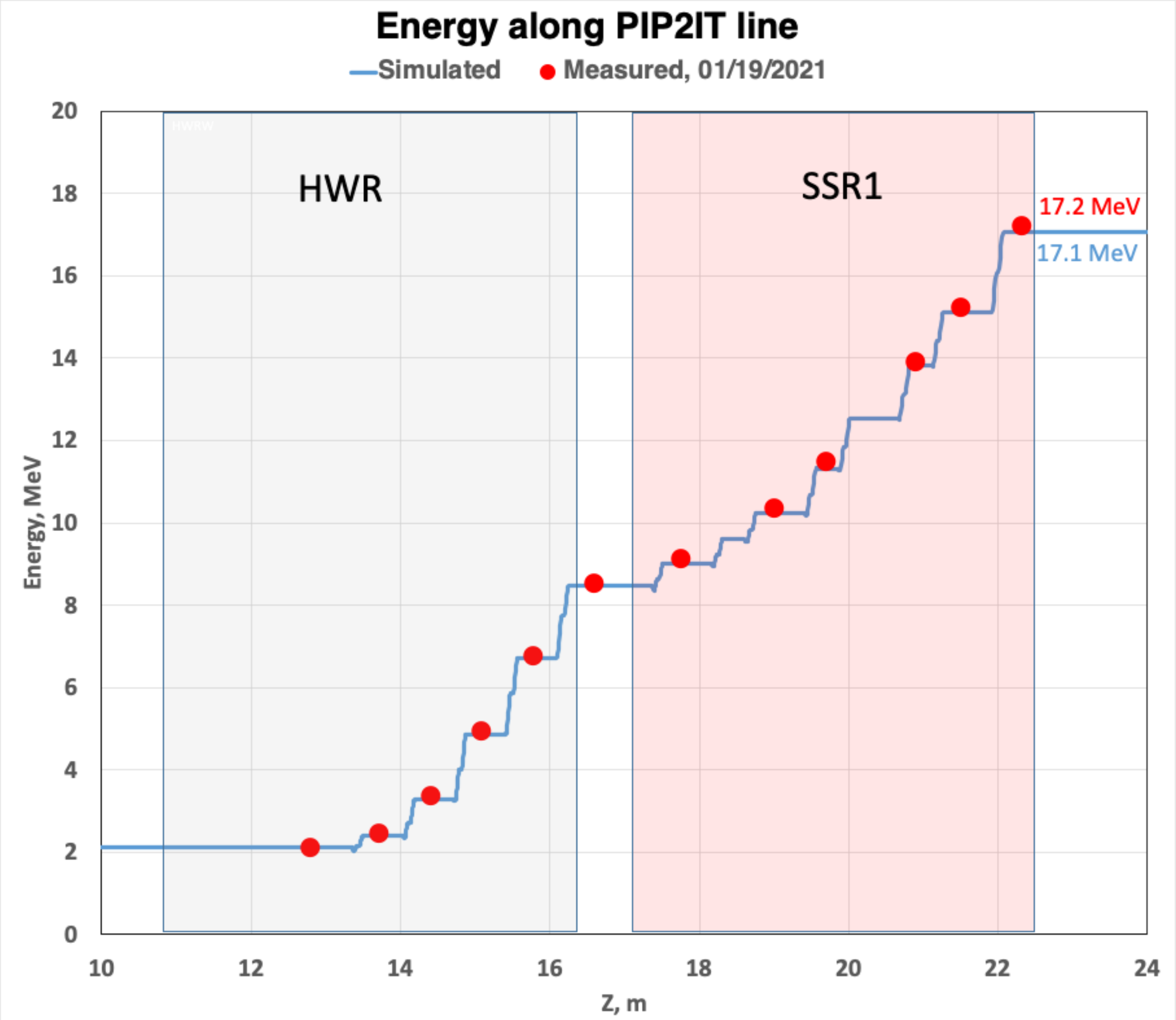
Longitudinal profiles for different MEBT Buncher 1 voltage settings







PIP-II Cryomodules Accelerate Beam to 17 MeV!



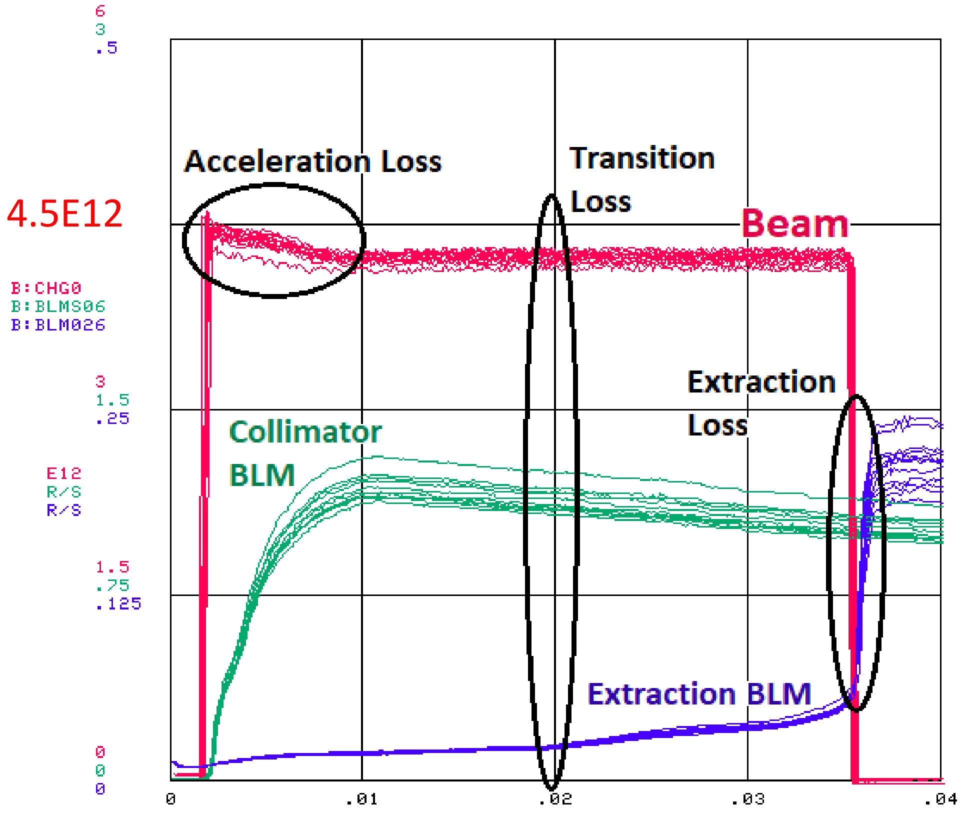
Beam energy evolution with 5 HWR and 8 SSR1 cavities

- Measured beam energy closely matches predicted value after cavity voltage calibrated with beam and beam quality improved.
- Goals of remaining test plan
  - Establish LBNF/Booster beam, long pulses, optics tuning
  - RF/LLRF with long pulses
  - Instrumentation and MPS

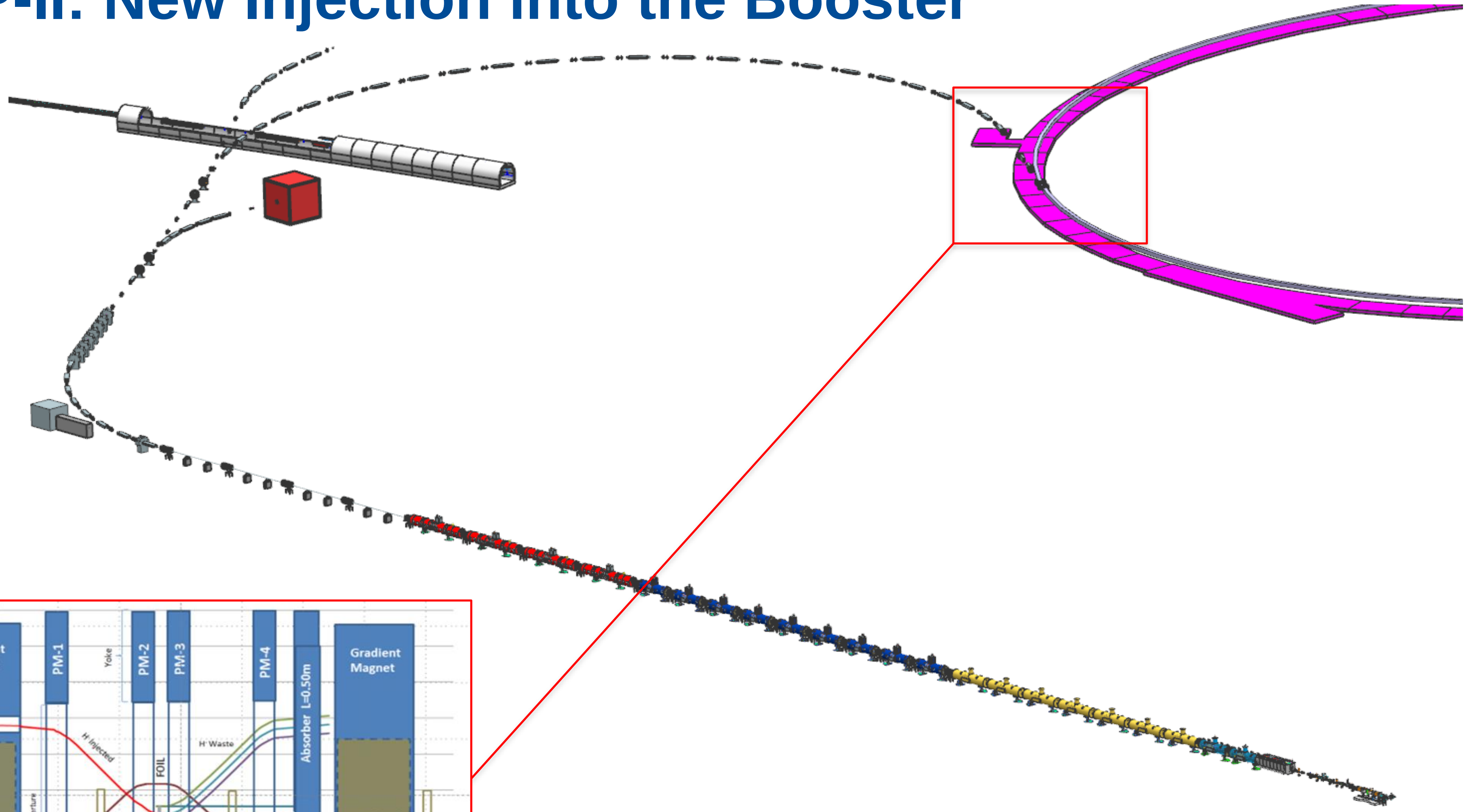
Significant Milestone: SRF cryomodules and battery of accelerator systems demonstrate solid performance; design requirements are being validated; international partners' deliverables seamlessly integrated. New era of SRF proton acceleration at Fermilab

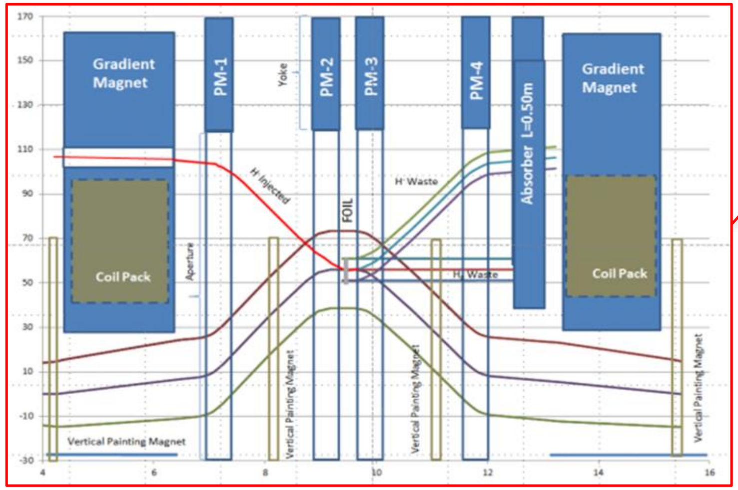
Presently, Losses in Booster Limit Accelerator Complex Performance

Beam current and losses in Booster over a Booster Ramp Cycle



PIP-II: New Injection into the Booster





PIP-II injection mitigates high intensity effects, reduces losses:

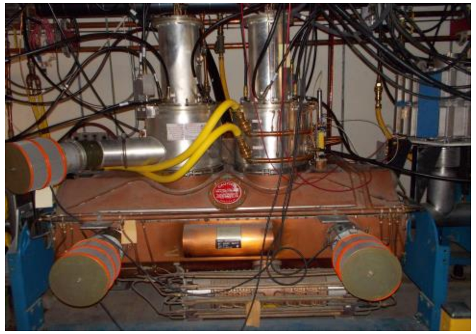
- Precision PIP-II linac beam allows 3D painting injection
- Increased energy & painting injection reduce space charge tune shift

PIP-II Mitigates Intensity Limits and Losses in Booster

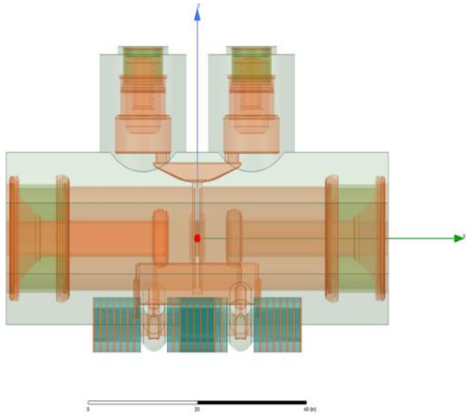
- **Increased injection energy and painting** reduce space charge tune shift by a factor of 2.5 comparatively to present Booster (equivalent to intensity $1.8x10^{12}$)
- **Improved single-unit, two-stage collimation** will reduce uncontrolled losses by a factor of ~2
- **Damper Upgrades** will reduce losses associated with transverse and longitudinal instabilities
- **New extraction magnets** with increased aperture will reduce losses at extraction
- **Direct bucket injection and the higher injection energy** (smaller slip factor) eliminate longitudinal losses associated with adiabatic capture and LLRF/RF noise

PIP-II Scope Includes Accelerator Upgrades Required to Achieve 1.2 MW

- Booster
  - New 800 MeV Booster Injection Area with ancillary systems
  - Booster modifications for 20 Hz operations
  - 5 new booster cavities, higher voltage, larger aperture to provide higher voltage (1.16 MV) required for 20 Hz and higher intensity
  - Collimators, Dampers to control losses in Booster
  - Two larger bore magnets to reduce losses at extraction
  - Advanced Booster Intensity Physics Studies
- Recycler Ring
  - 3 New Recycler cavities to support continuous operation mode
- Main Injector
  - Gamma_t jump to reduce losses at transition to address higher intensity and larger longitudinal beam emittance
  - 20 new RF amplifiers to provide additional RF power to enable acceleration of PIP-II beam



MI Cavity with two PAs



Scope Added in 2019 Removes Dependency On External AIPs

- Booster
  - New 800 MeV Booster Injection Area with ancillary systems
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  - Collimators, Dampers to control losses in Booster
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  - Gamma_t jump to reduce losses at transition to address higher intensity and larger longitudinal beam emittance
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Cryogenic Plant Building Groundbreaking – July 2020

PIP-II Cryogenic Plant Building – 17 March 2021

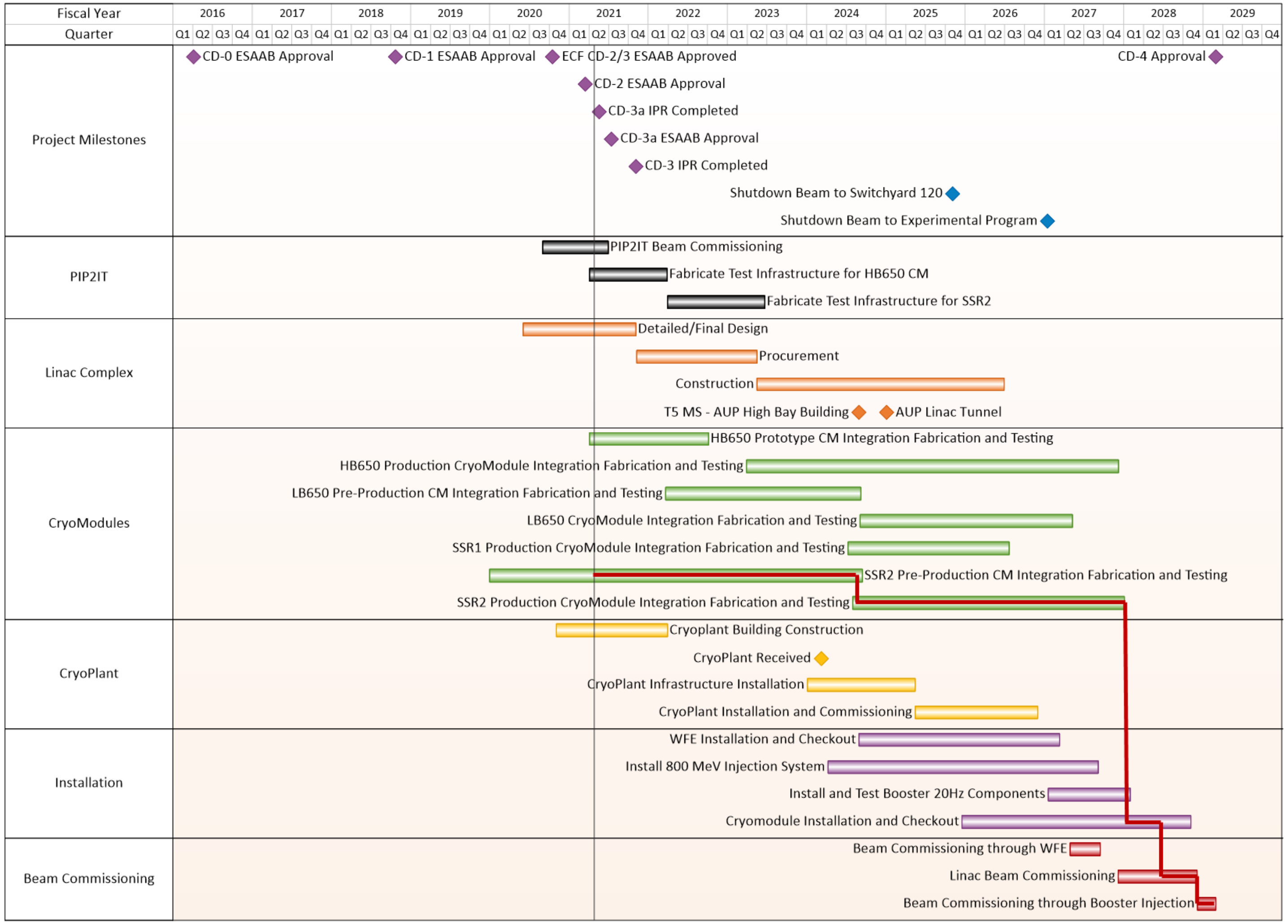
https://app.truelook.com/?u=fc1599677013#tl_live

https://app.truelook.com/?m=1600250083220556503647

Conventional Facilities

- Cryoplant Building Construction underway
  - Precast concrete wall panel installation completed in February 2021
  - Structural steel mostly completed
  - Completion ~ December 2021
- Site Work
  - DOE review April 21
- Linac Complex Design integrated with technical systems
  - Final design underway
    - 90% review completed in February
    - On track for 100% in April 2021
- Booster Connection
  - Start final design in April 2021

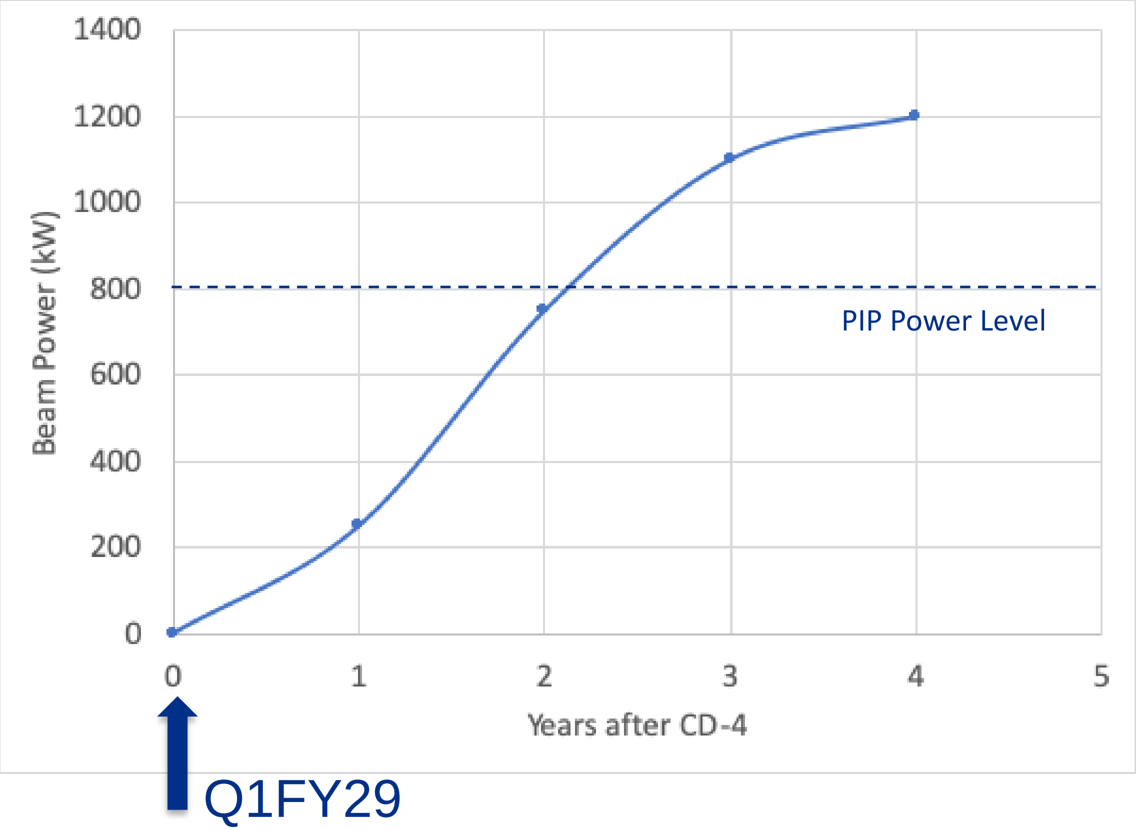
★ PIP-II baseline approved – 14 December 2020
★ PIP-II long-lead procurement approved – 16 March 2021



"This approval marks a significant milestone for the project and the start of a new era for Fermilab and the global HEP community. "

PIP-II

Preliminary Power Ramp Up Curve Developed

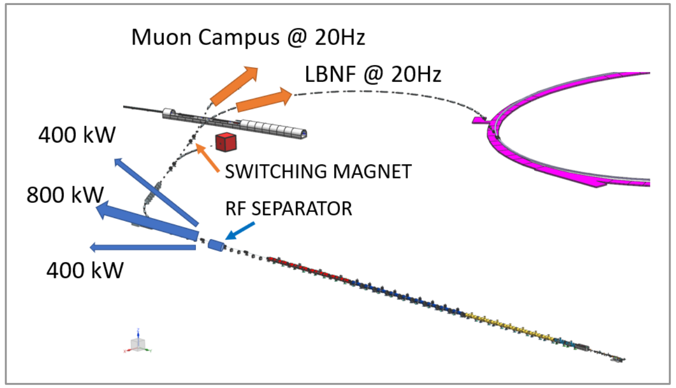


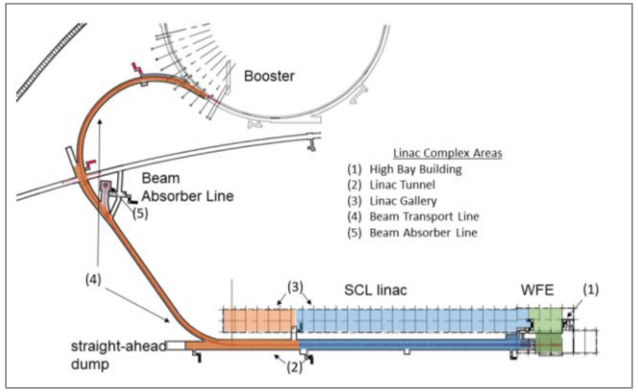
Year	P (kW)	P/1200
0	0	0
1	250	20%
2	750	63%
3	1100	92%
4	1200	100%

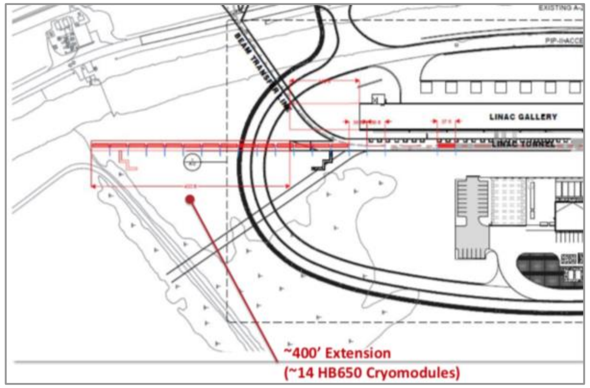
- Power ramp up begins after PIP-II CD-4 (Beam Circulated in Booster)
- Curve assumes LBNF target, the beam line, and MI are ready for beam.
- LBNF schedule is compatible with this assumption

PIP-II Design Is Compatible With Future Science-Driven Upgrades

- PIP-II is designed for >1 MW over 60 – 120 GeV and 1.2 MW at 120 GeV
- Provides platform for upgrade to >2 MW
- Linac beam power of 1.6 MW (CW), programmable bunch patterns
- Facility enables multi-user, simultaneous, high beam power operations
  - Switch yard to provide beams to Muon Campus in multiuser mode with LBNF
- Linac tunnel includes space and infrastructure to reach 1 GeV and space to add RF separator for beam sharing
- Tunnel extension (by 120 m) compatible with energy 2–2.5 GeV
- Beam current can be increased by a factor of a few by upgrading amplifiers







Summary

- PIP-II is a leading-edge SRF linear accelerator critical to the success of the LBNF/DUNE international neutrino program
- International partnerships are essential for the success of PIP-II
- Excellent, experienced project team and strongly committed partners ensure continued technical progress despite pandemic challenges
  - PIP-II baseline is approved
  - Cryoplant building construction is well underway
  - Beam has been accelerated by first two PIP-II cryomodules
- We are building a highly capable accelerator that will power the world’s best neutrino experiment!

We greatly appreciate the commitment and strong support from the neutrino community, DOE/SC, and our International Partners!

Thank you!