Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

PIP-II: overview, status and challenges

Arkadiy Klebaner

1st Muon Community Meeting

20 May 2021

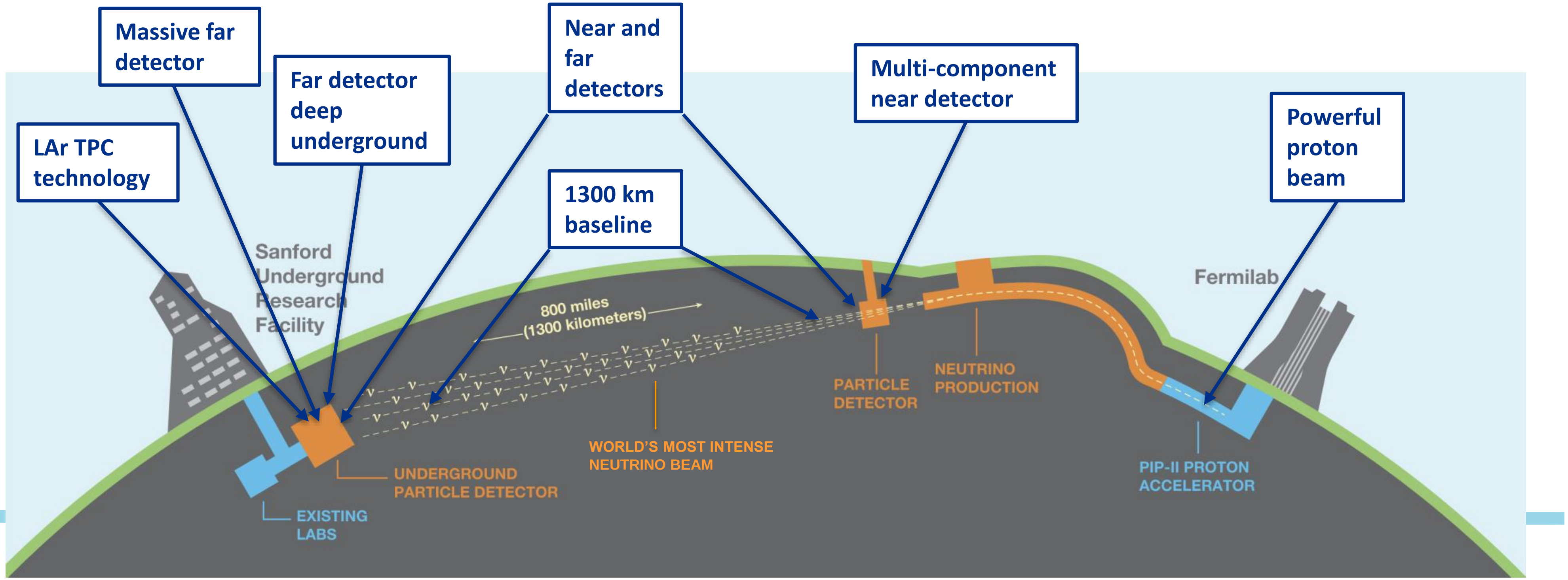
A Partnership of:
- US/DOE
- India/DAE
- Italy/INFN
- UK/UKRI-STFC
- France/CEA, CNRS/IN2P3
- Poland/WUST

Outline

- Project Status
- Technical Designs overview
- Challenges
- Summary

International Neutrino Program ➔ PIP-II / LBNF / DUNE

- 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



PIP-II….a new SRF accelerator to generate neutrinos

PIP-II Mission

***PIP-II** will enable the world's most intense beam of neutrinos to the international LBNF/DUNE project, and a broad physics research program, powering new discoveries for decades to come*.

PIP-II will provide:

Beam Power

- Meeting the needs for the start of DUNE (1.2 MW proton beam);
- Upgradeable to multi-MW capability;

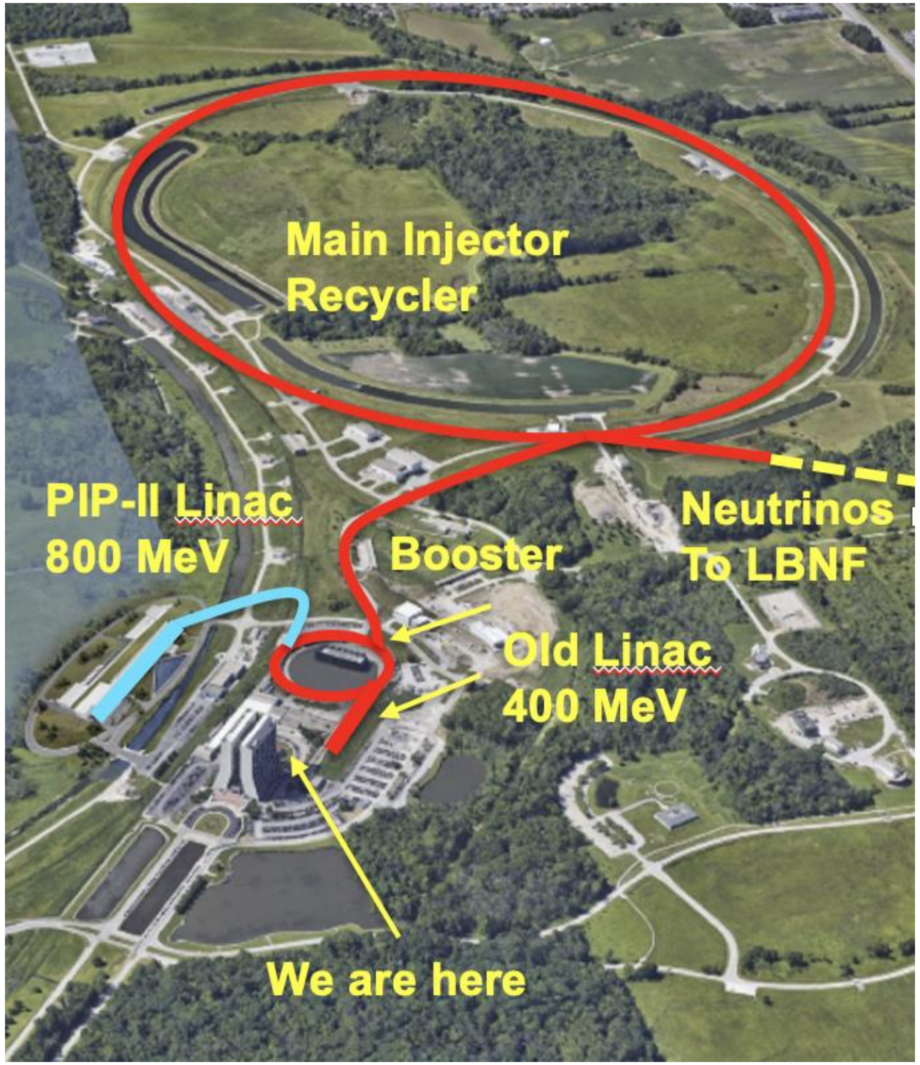
Flexibility

- Compatible with CW-operations which greatly increases the Linac's output;
- Customized beams for specific science needs;
- High-power beam to multiple users simultaneously;

Reliability

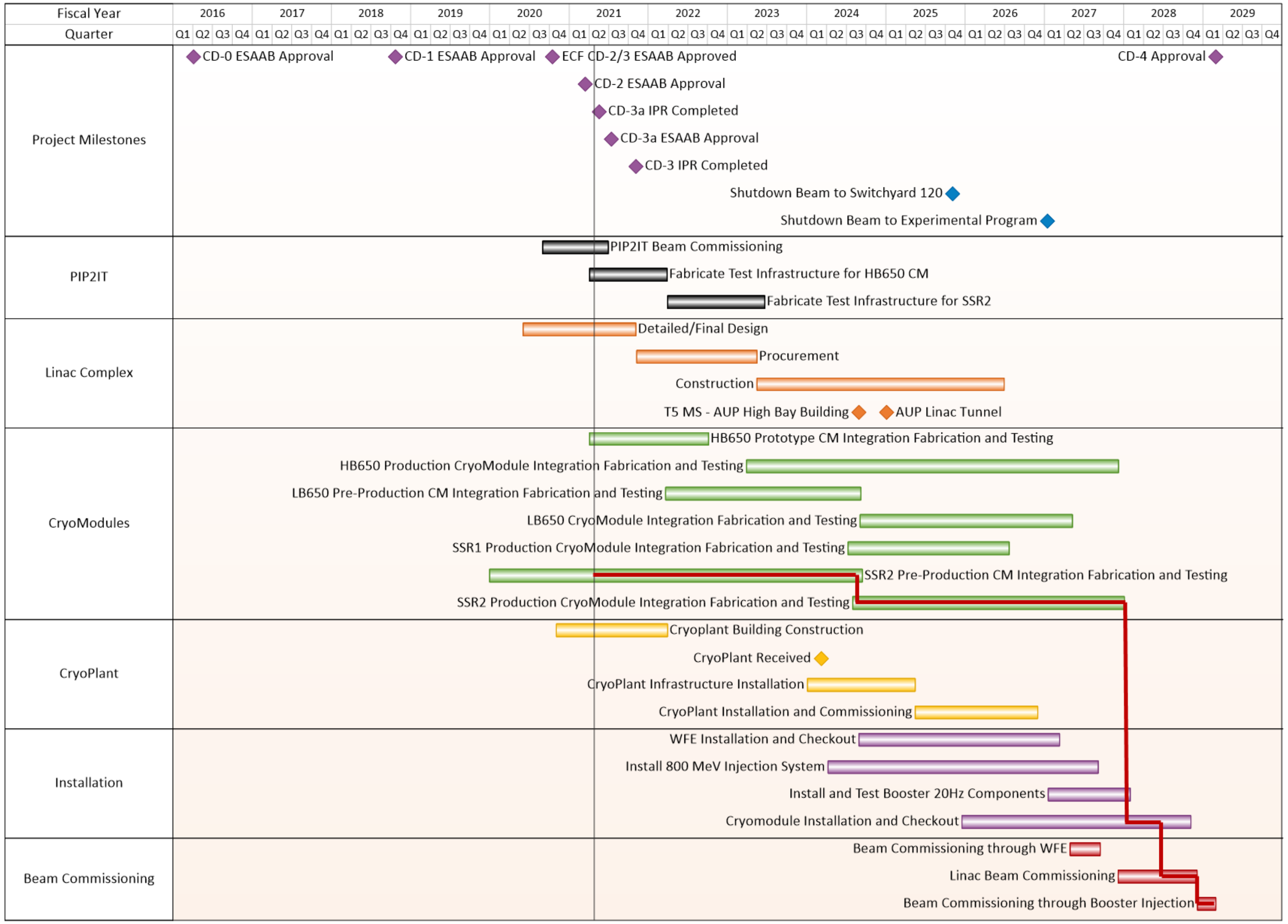
- Fully modernizing the front-end of the Fermilab accelerator complex.

PIP-II Scope



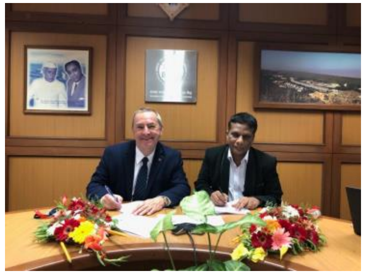
- An 800-MeV superconducting H^- Linac
- Beam transport of 800-MeV H^- from the SRF Linac to the Booster
  – A new injection area in the Booster
- Modifications to the Booster, Main Injector, and Recycler Ring to enable >1MW power on LBNF target for 60-120 GeV
- Associated conventional facilities. The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

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




Main Injector
PIP-II
Transfer Line
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)

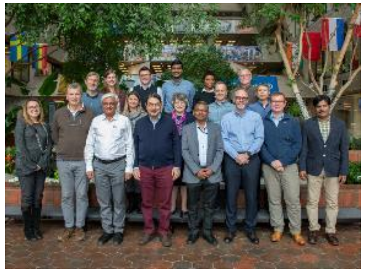
Internationally recognized leader in superconducting RF technologies
SRF cavity and cryomodule fabrication for XFEL; SRF cavities for ESS

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

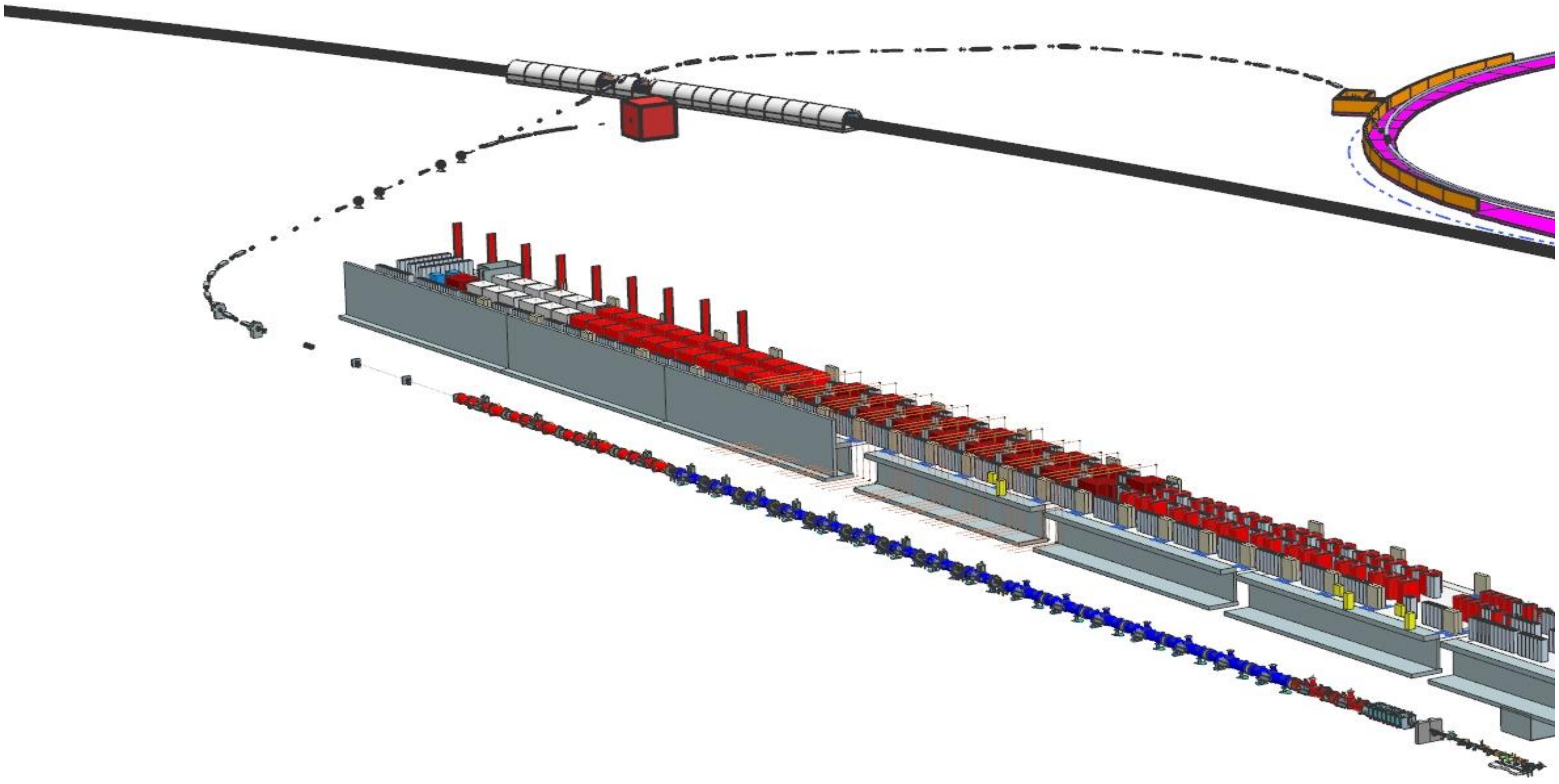


Poland, WUST, WUT, TUL (started 2018)

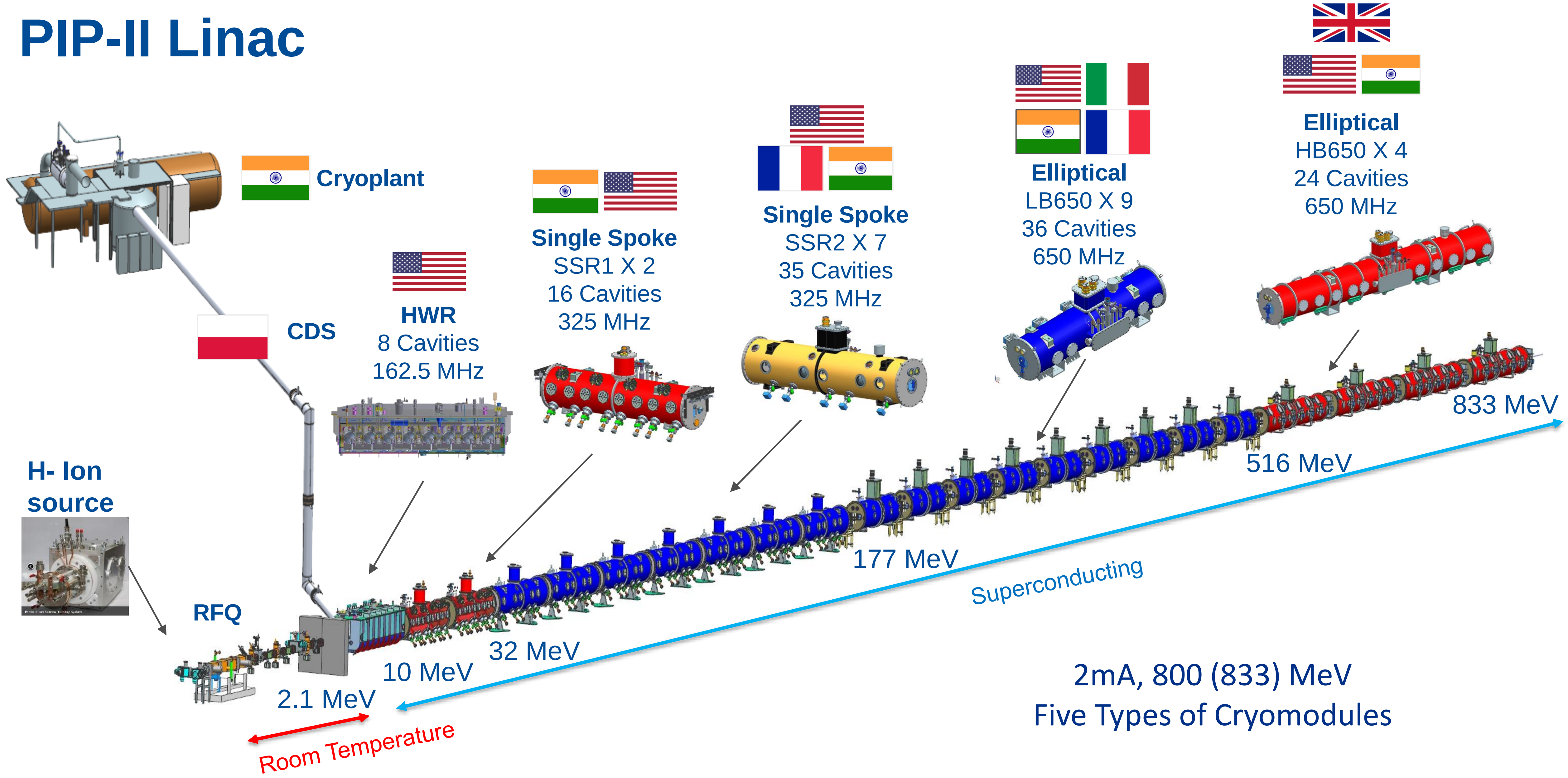
Substantial engineering / manufacturing experience; CDS, LLRF, QC for XFEL, ESS

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

Technical Designs



PIP-II Linac

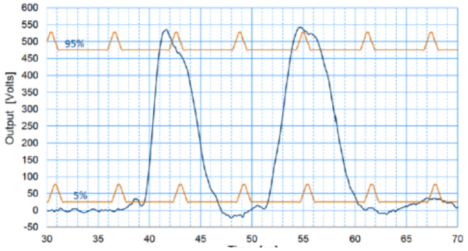


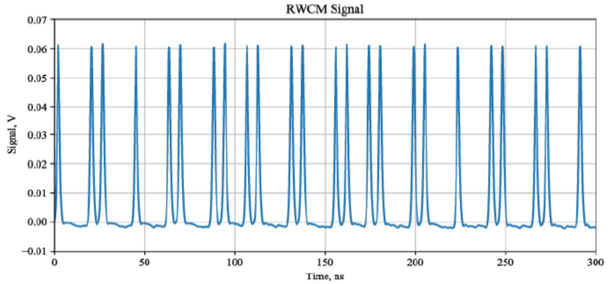
2mA, 800 (833) MeV

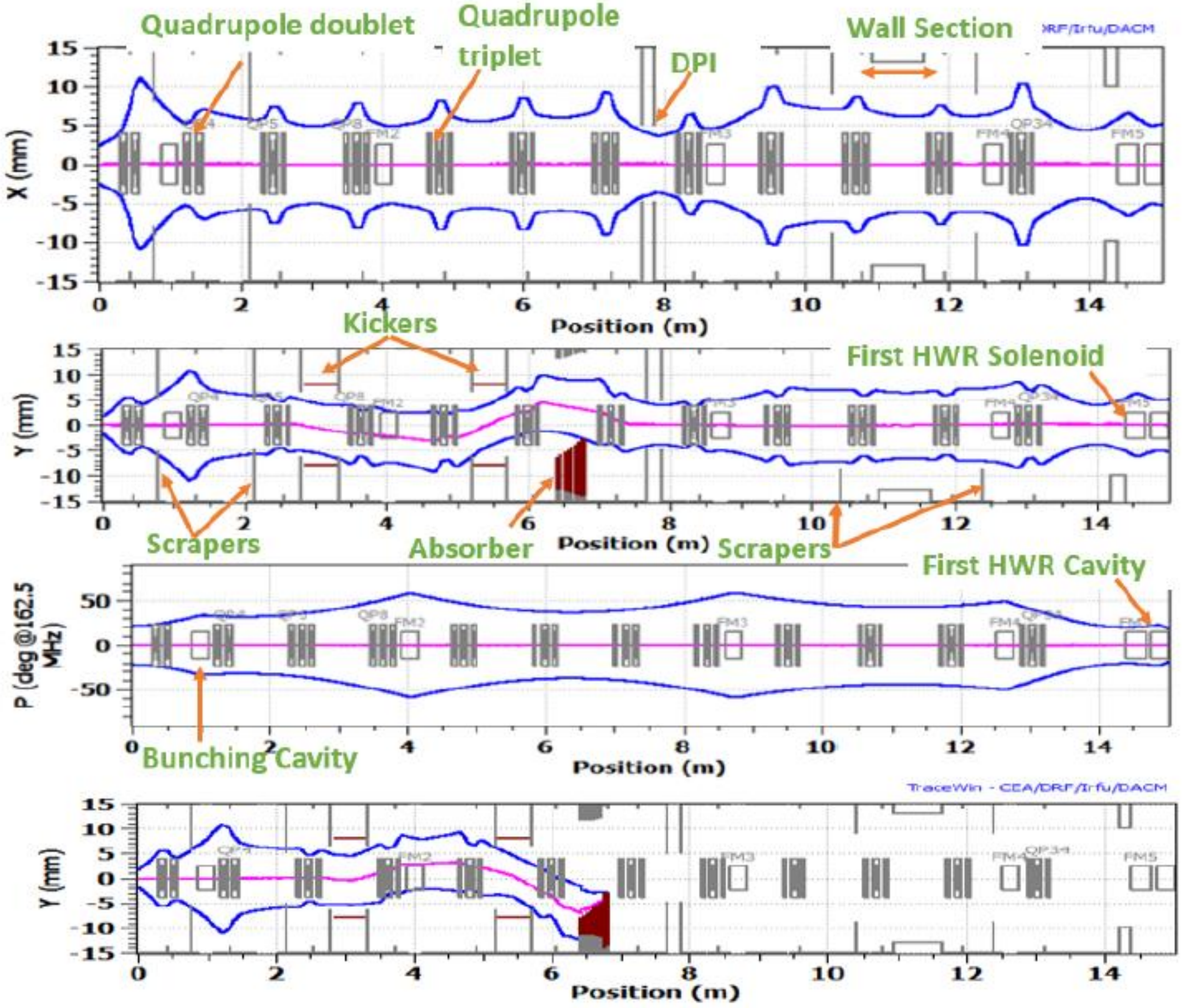
Five Types of Cryomodules

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.



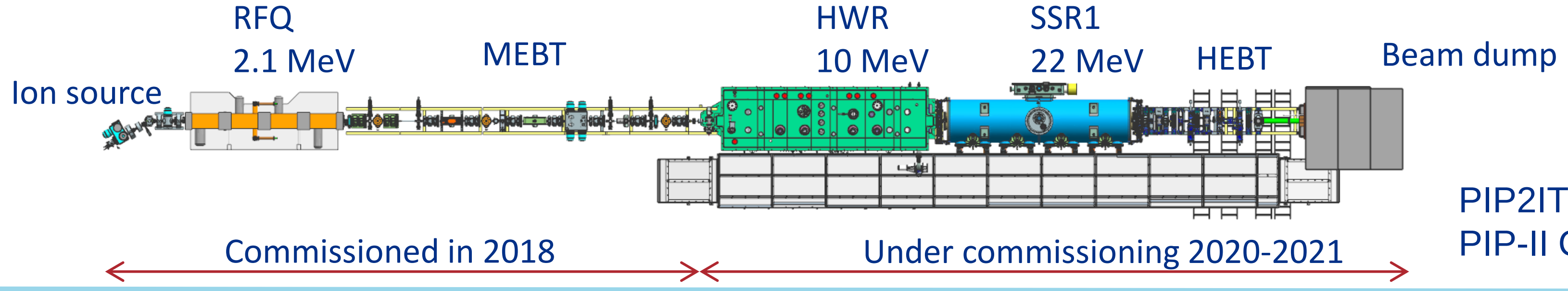




Bunch-by-bunch chopper removes undesired bunches leaving beam current at up to 2 mA.

PIP-II Warm Front End and Critical Systems were tested at PIP2IT

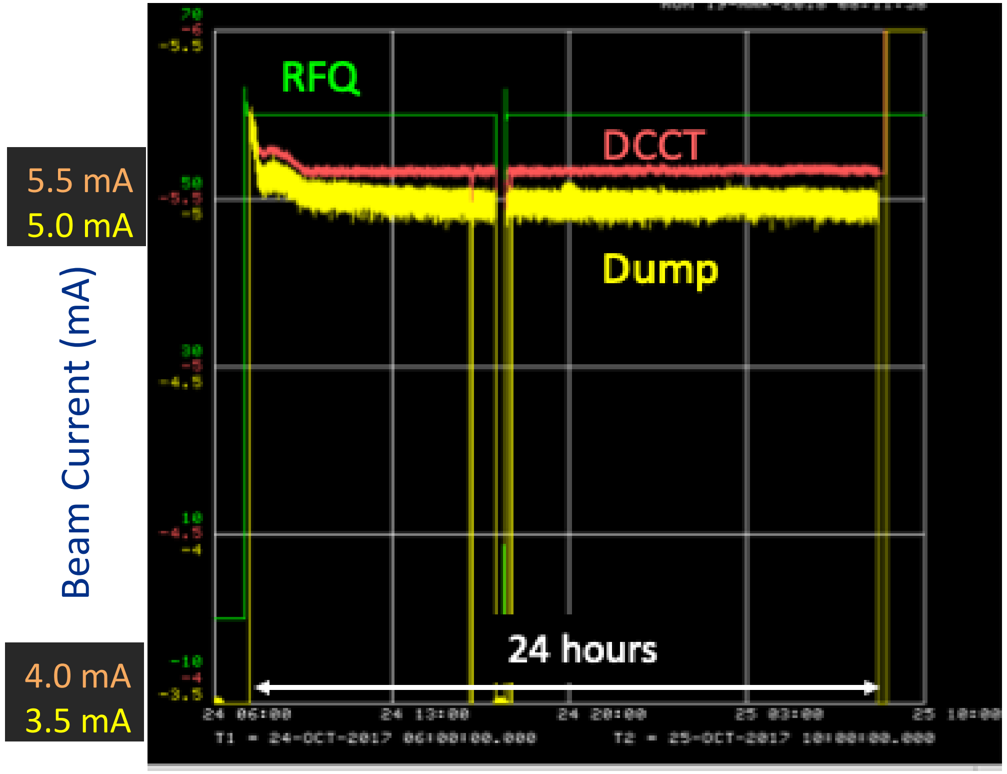
- ✓ Ion source
- ✓ RFQ, 2.1 MeV
- ✓ Chopper/Absorber to produce bunch pattern for injection into Booster
- ✓ Beam dynamics agrees with design
- ✓ Cryomodule/Cavity test
- ✓ LLRF and resonance control test
- ✓ Instrumentation
- ✓ EPICs early development



PIP2IT to be converted to PIP-II Cryomodule Test Facility

MEBT Meets Design Performance Requirements

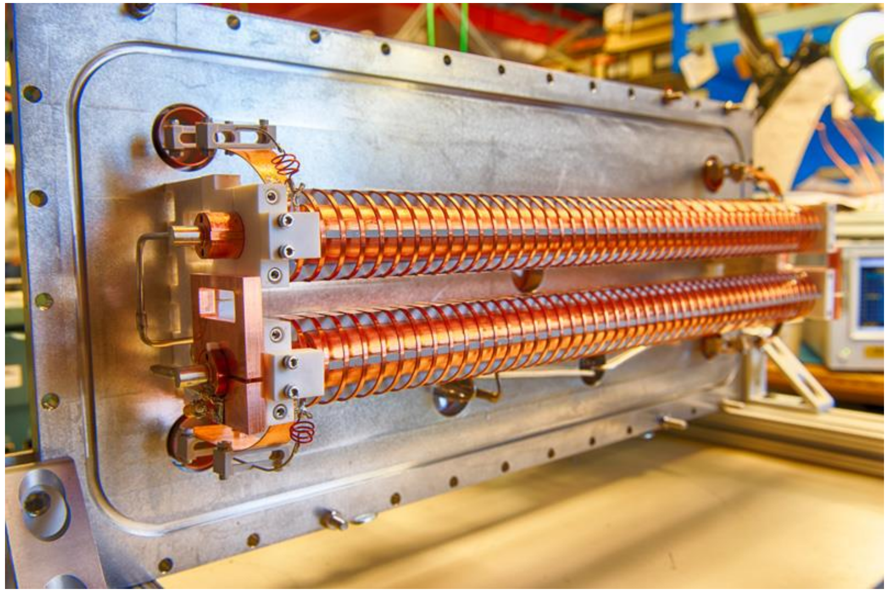
Demonstrated transporting 'LBNF beam' through PIP2IT MEBT for 24 hours, meeting design performance requirements:
5 mA ×0.55 ms×20 Hz×2.1 MeV



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

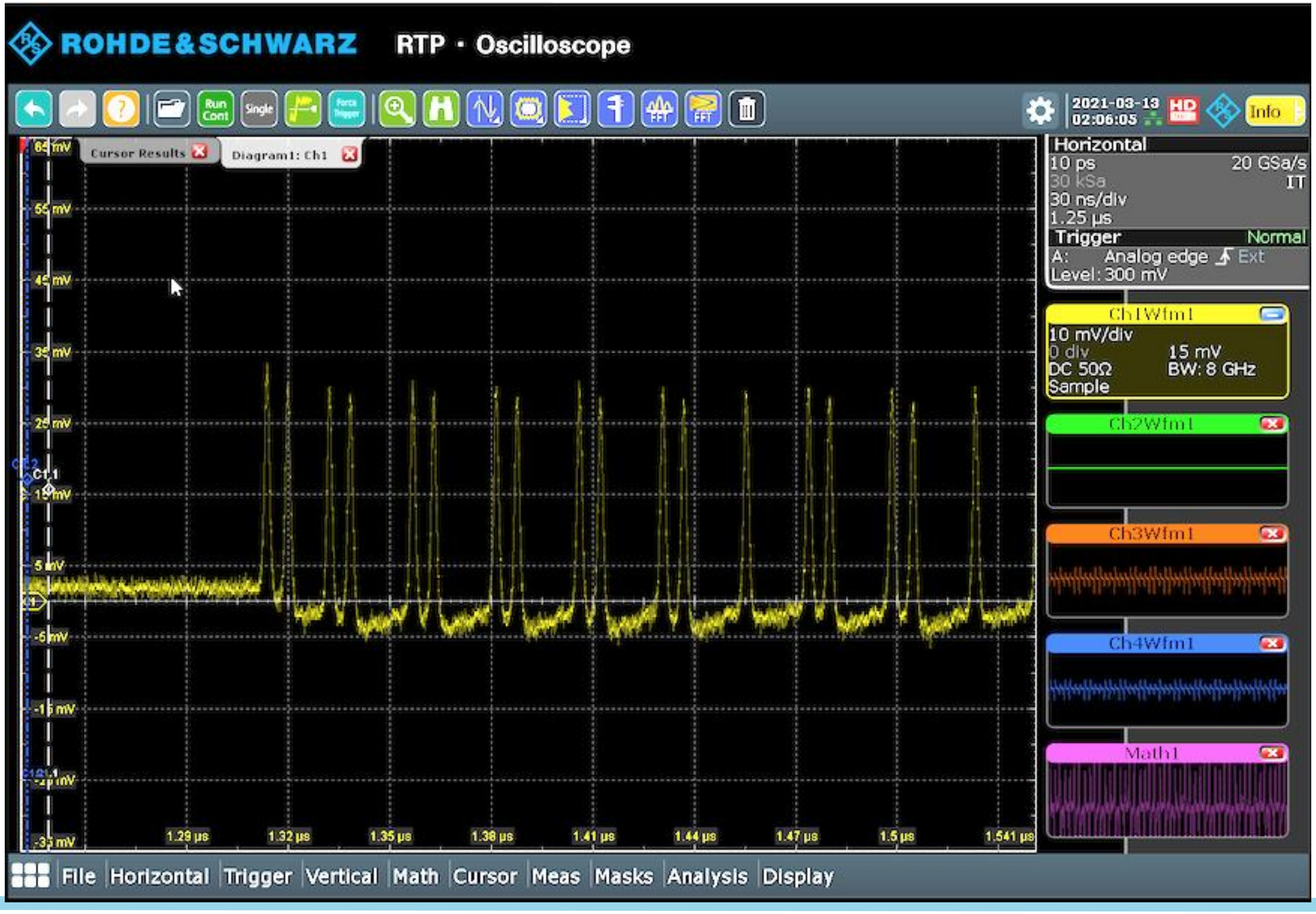
Bunch-by-bunch chopper offers arbitrary bunch pattern capability

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



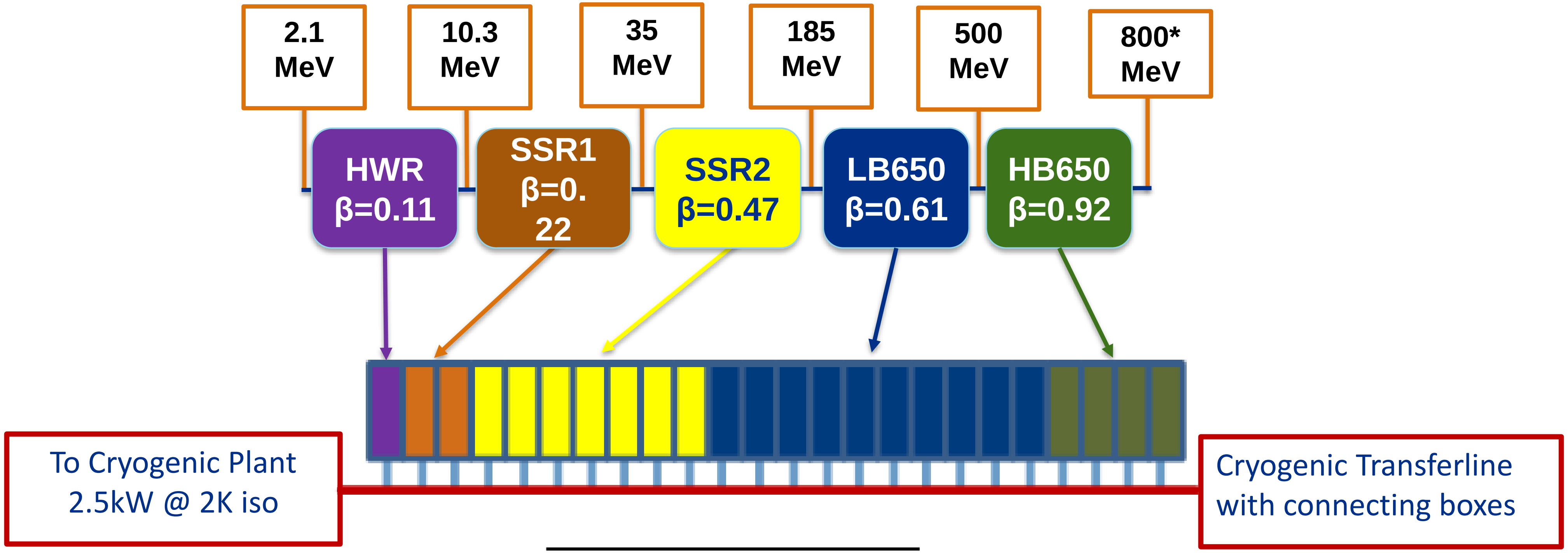
MEBT Chopper Is Fully Operational

- 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

Superconducting Section

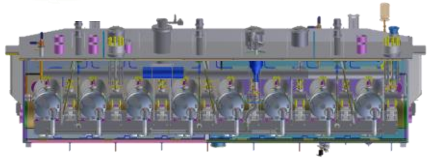


CM name	Number of Cryomodules	Cavities per CM
HWR	1	8
SSR1	2	8
SSR2	7	5
LB650	9	4
HB650	4	6

* - Design is 833 MeV

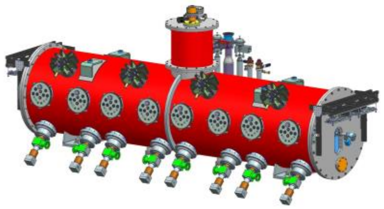
The state-of-the-art PIP-II Superconducting RF Systems

✓



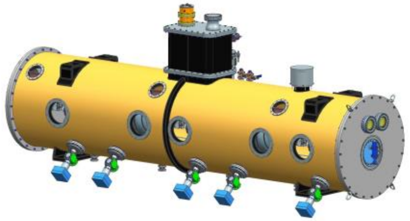
5.9 m

✓



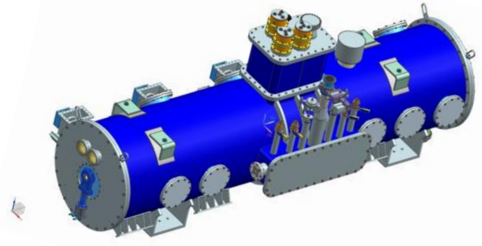
5.3 m

2023



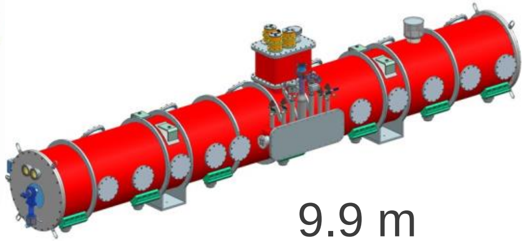
6.5 m

2023



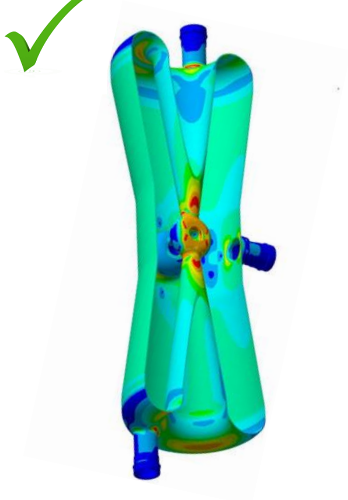
5.5 m

2021-22



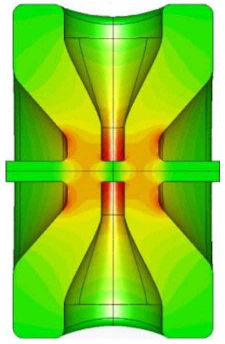
9.9 m

✓



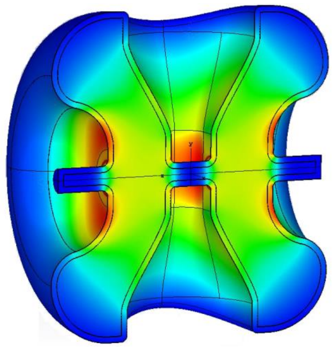
Half Wave Resonator
β=0.11 Q_0=0.85x10^{10}

✓



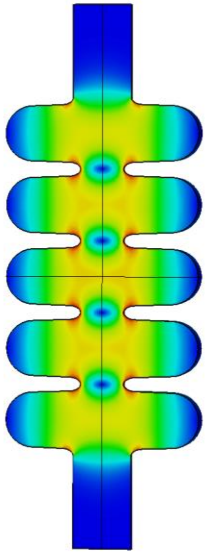
Single Spoke
SSR1
β=0.22 Q_0=0.82x10^{10}

2022



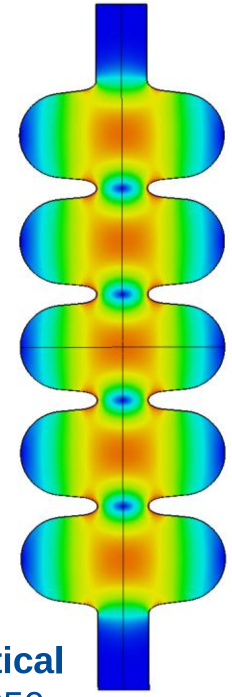
Single Spoke
SSR2
β=0.47 *Q_0=0.82x10^{10}

✓



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

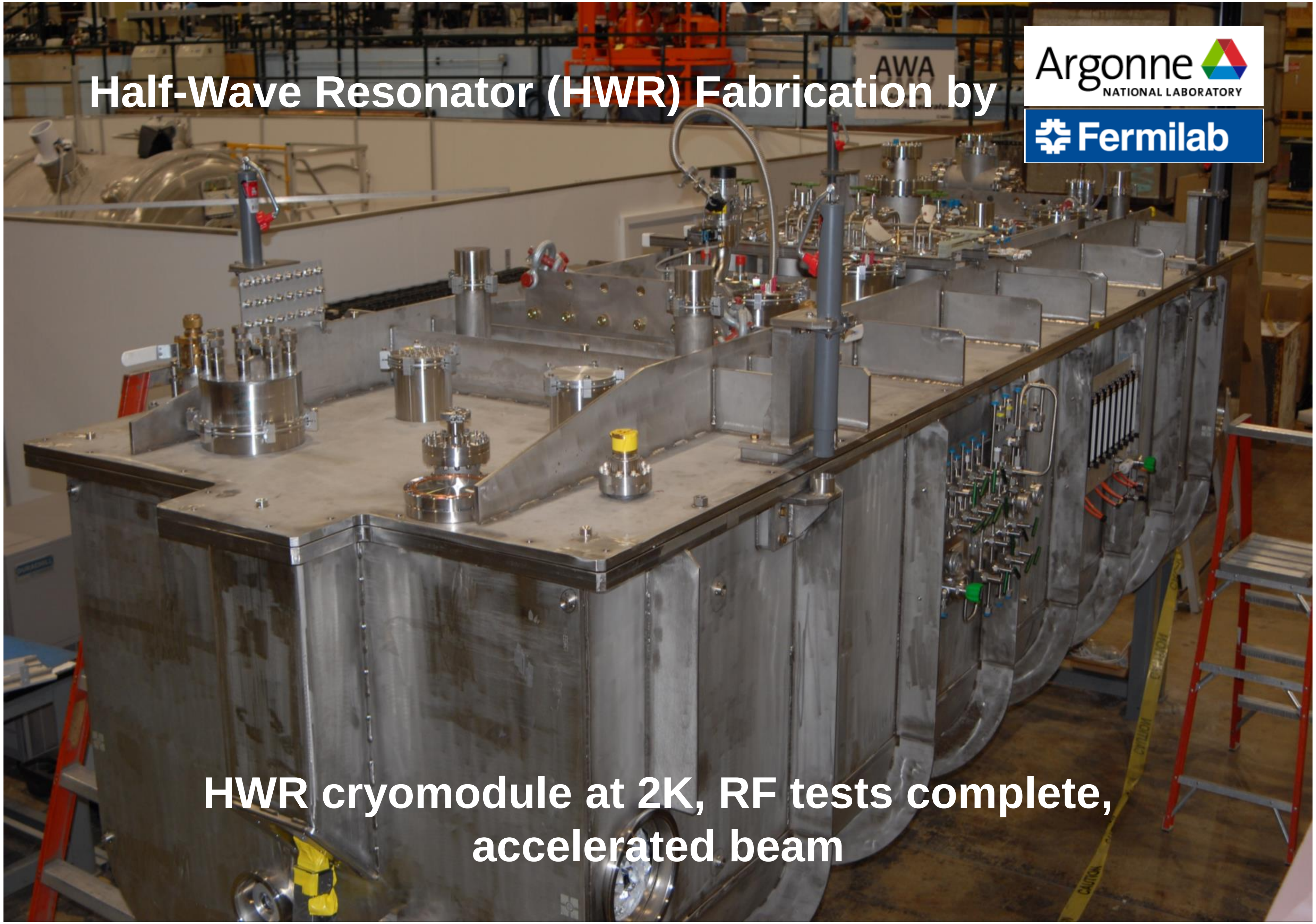
✓

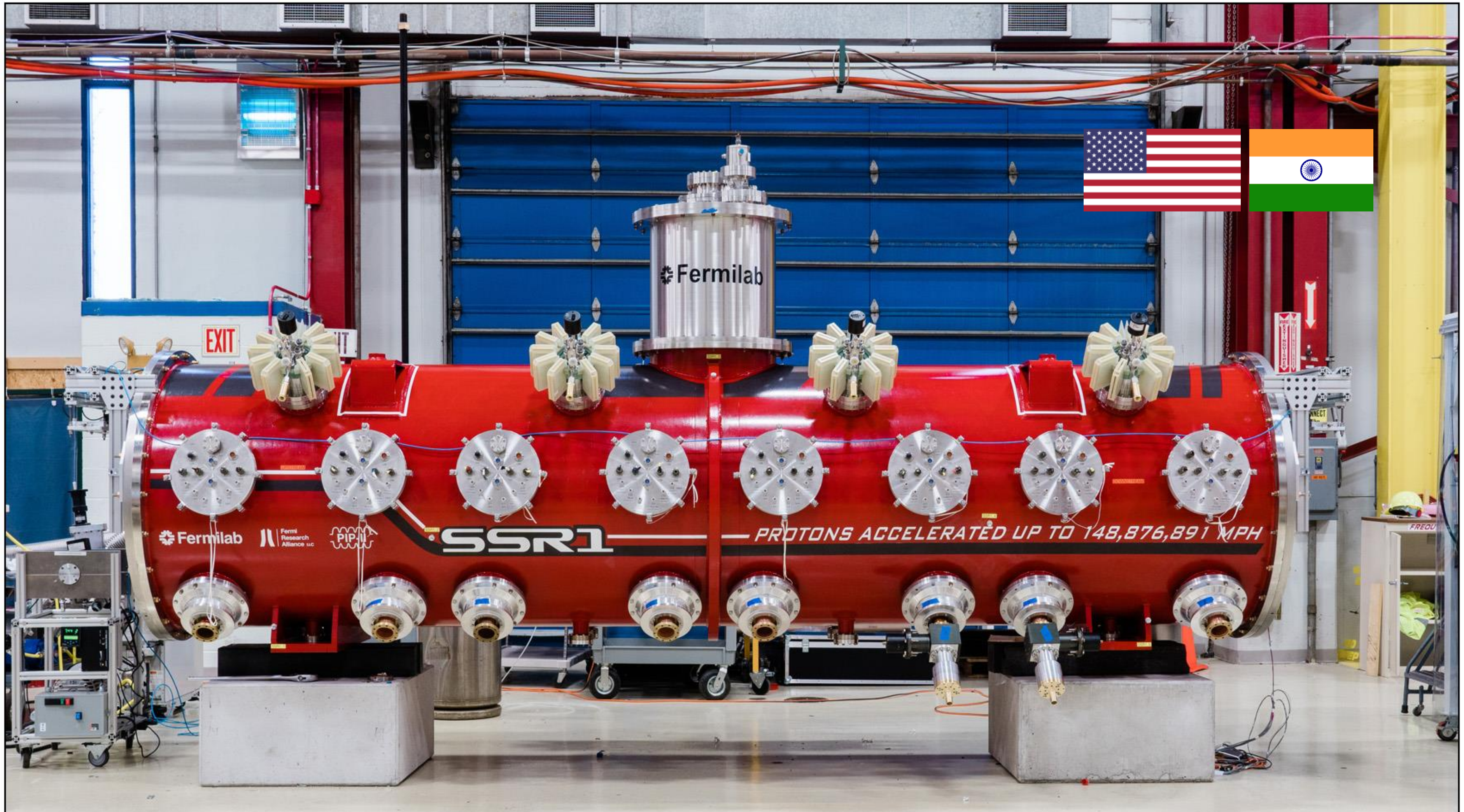


Elliptical
HB650
β=0.92 *Q_0=3.3x10^{10}

✓ Performance validated ✓ Testing in progress Dates: component built

*state-of-the-art performance requirement

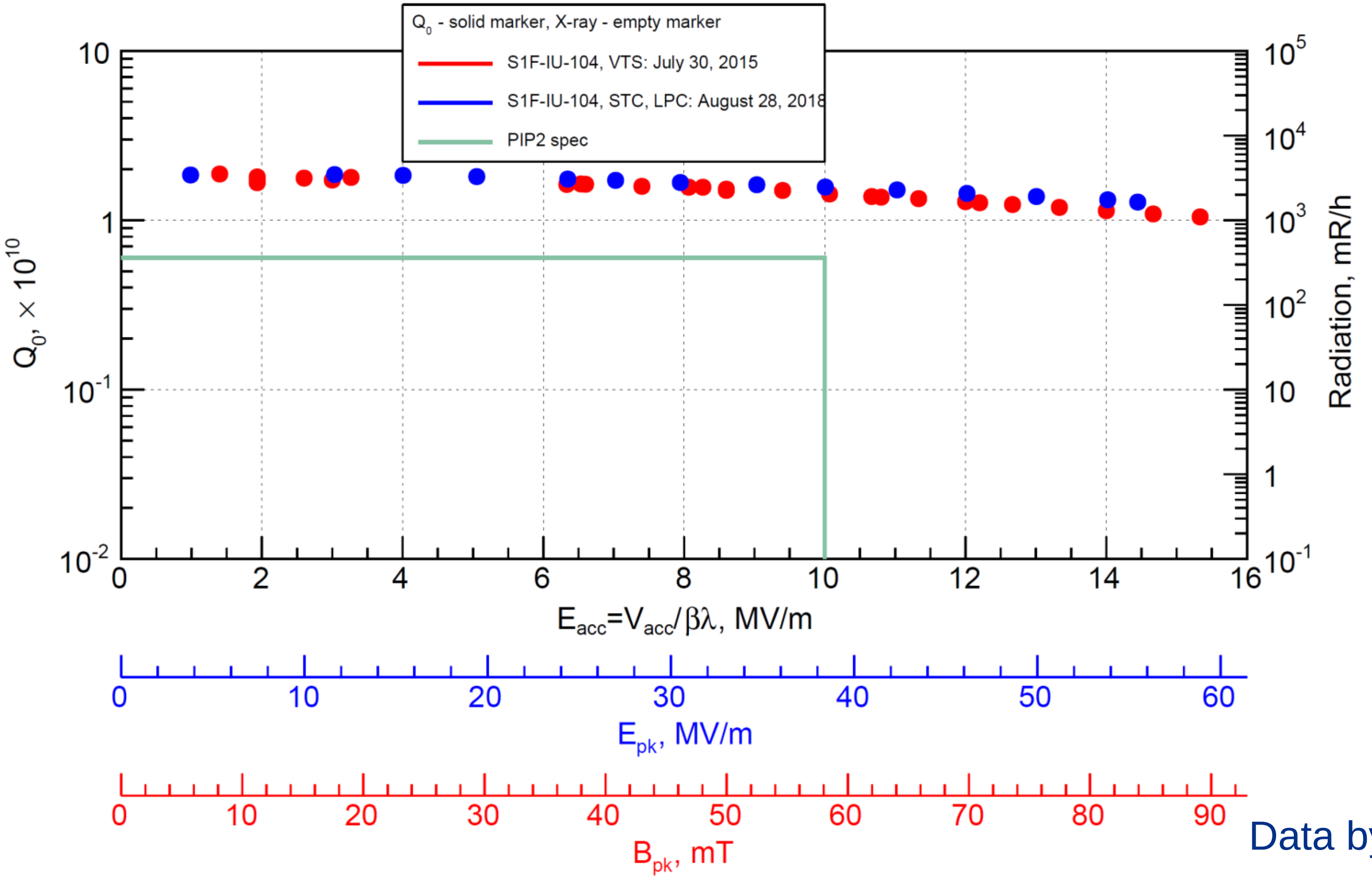

Half-Wave Resonator (HWR) Fabrication by
Argonne NATIONAL LABORATORY
Fermilab
AWA
HWR cryomodule at 2K, RF tests complete,
accelerated beam



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

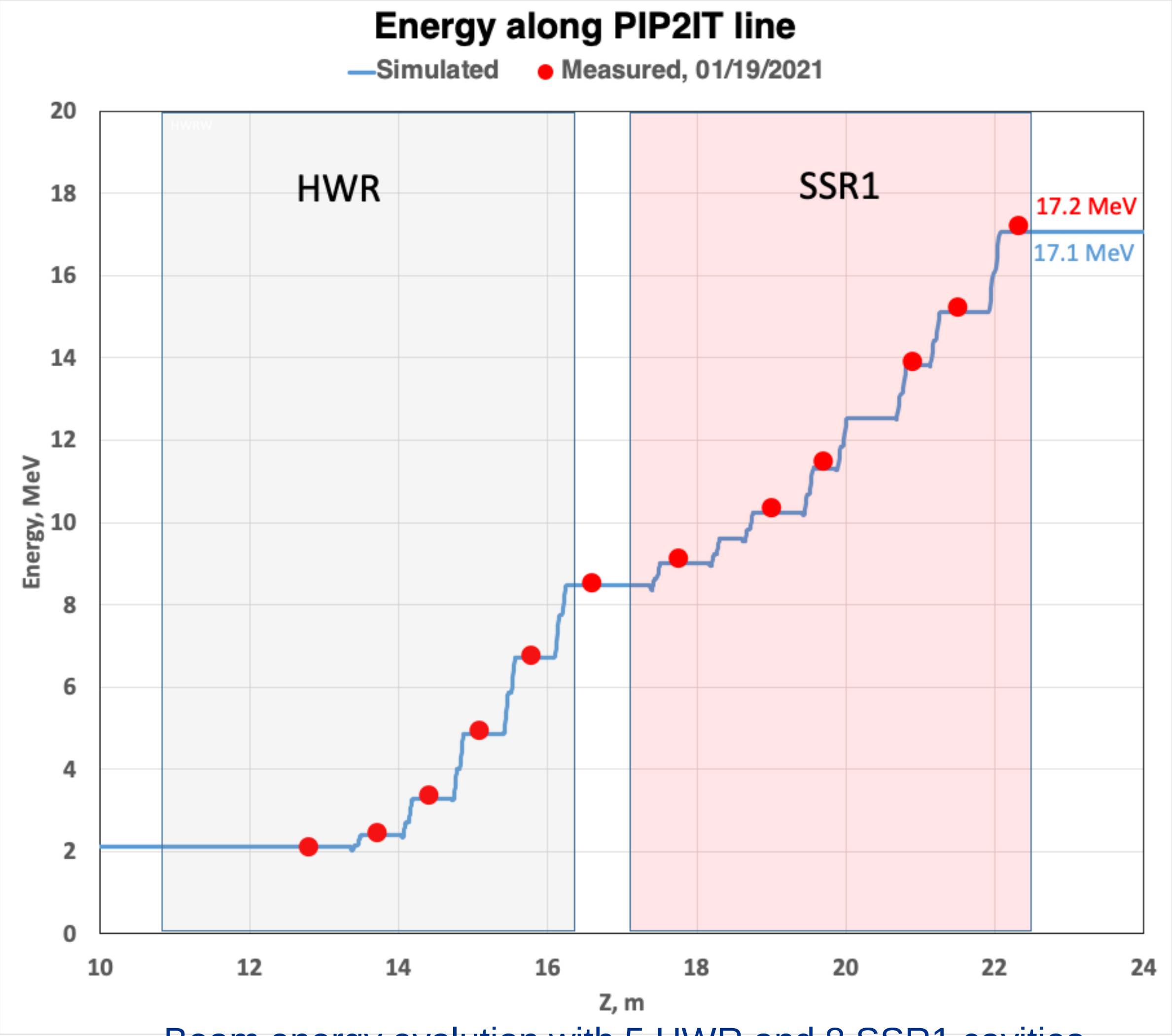
*STC= Spoke Test Cryostat

DAE Solid-State Amplifiers

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

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

PIP-II Cryomodules Accelerate Beam to 17 MeV!



Beam energy evolution with 5 HWR and 8 SSR1 cavities

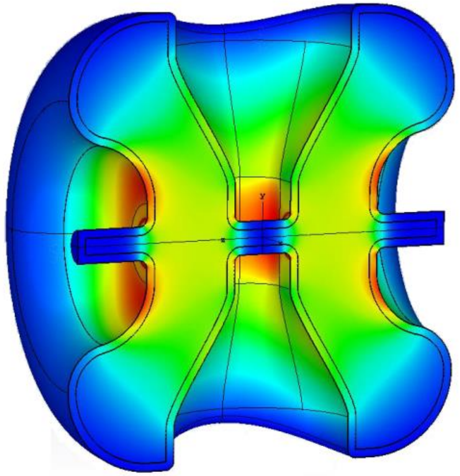
- Measured beam energy closely matches predicted
- Demonstrated LBNF/Booster beam pattern
- Validated RF/LLRF with long pulses, instrumentation and MPS

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

SSR2 Cavities, Pre-Production Cryomodule

Cavity

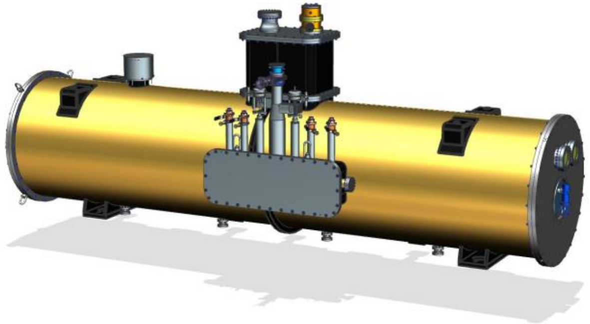
- Integrated design team: Fermilab, IN2P3 and DAE
- Niobium production at vendor completed
- Prototype jacketed cavity procurement in progress
- Coupler procurement in progress

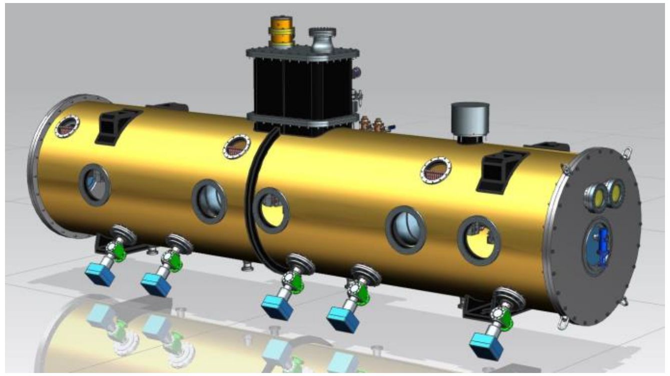


Parameters	SSR2 v 3.1
Optimal beta β_{opt}	0.472
Aperture [mm]	40
Frequency [MHz]	325
Effective length $2\beta_{opt}\lambda/2$ [m]	0.436
E_{peak}/E_{acc}	3.51
B_{peak}/E_{acc} [mT/(MV/m)]	6.75
G [Ohm]	115
R/Q [Ohm]	305.2
E_{peak} [MV/m] @ 5 MeV	40.2
B_{peak} [mT] @ 5 MeV	77.4
Max energy gain [MeV]	5.0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

Cryomodule

- Design in progress by Fermilab, DAE

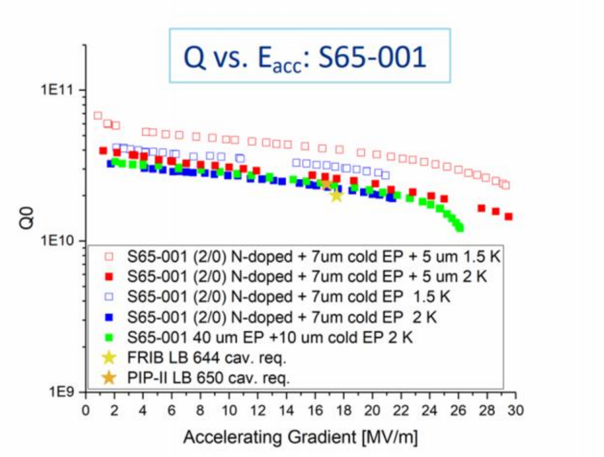


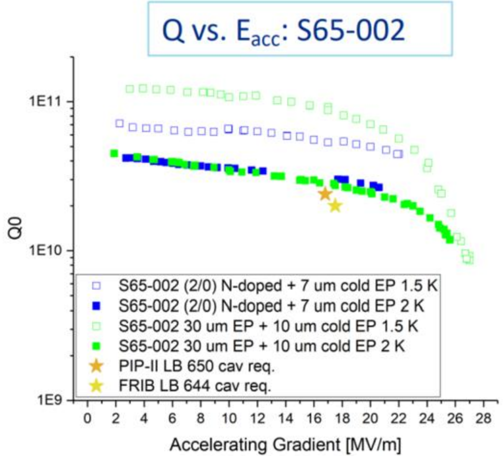


LB650 Cavities

- Q_0, Gradient → 2.4 x10^{10} and 16.8 MV/m – state-of-the-art for β <1
- Cavity RF design completed led by INFN
- MSU 644 MHz cavities tested, meet PIP-II Q_0, gradient specs

INFN cavity B61 on ANL EP stand





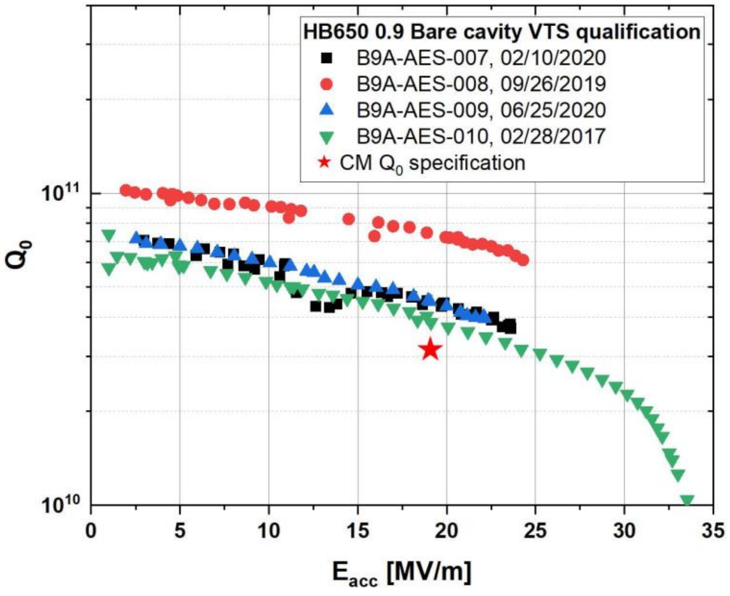
MSU cavities are directly scaled from PIP-II LB650 cavity design.
Courtesy: *Martina Martinello*

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 – state-of-the-art 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

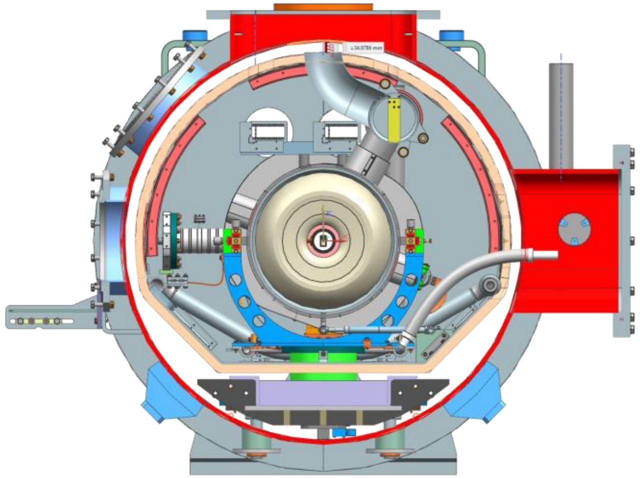


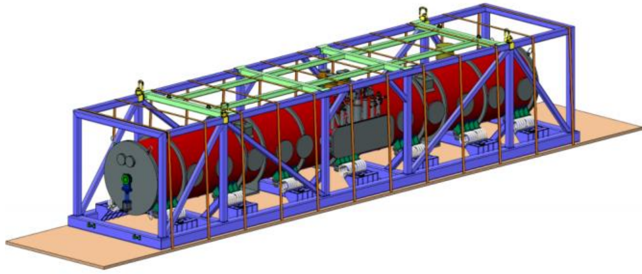
Cryomodule

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


Bare HB650 Cavity

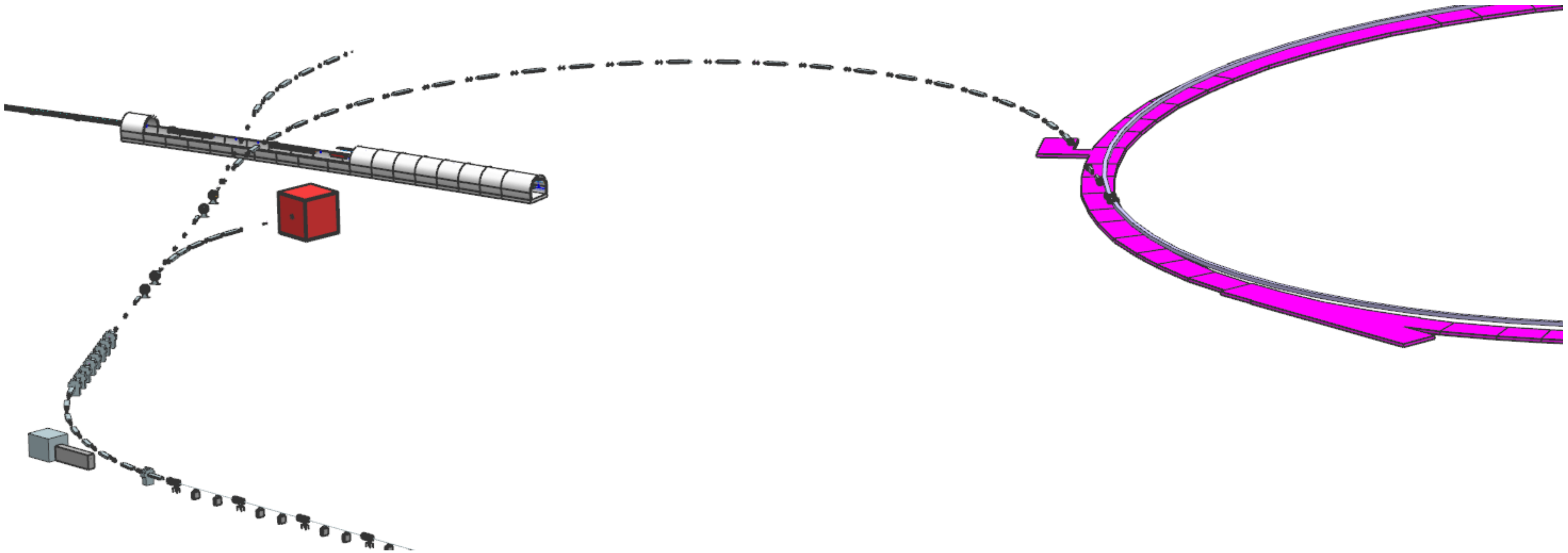

Jacketed HB650 Cavity in STC


HB650 proto cryomodule


HB650 Transportation Tooling

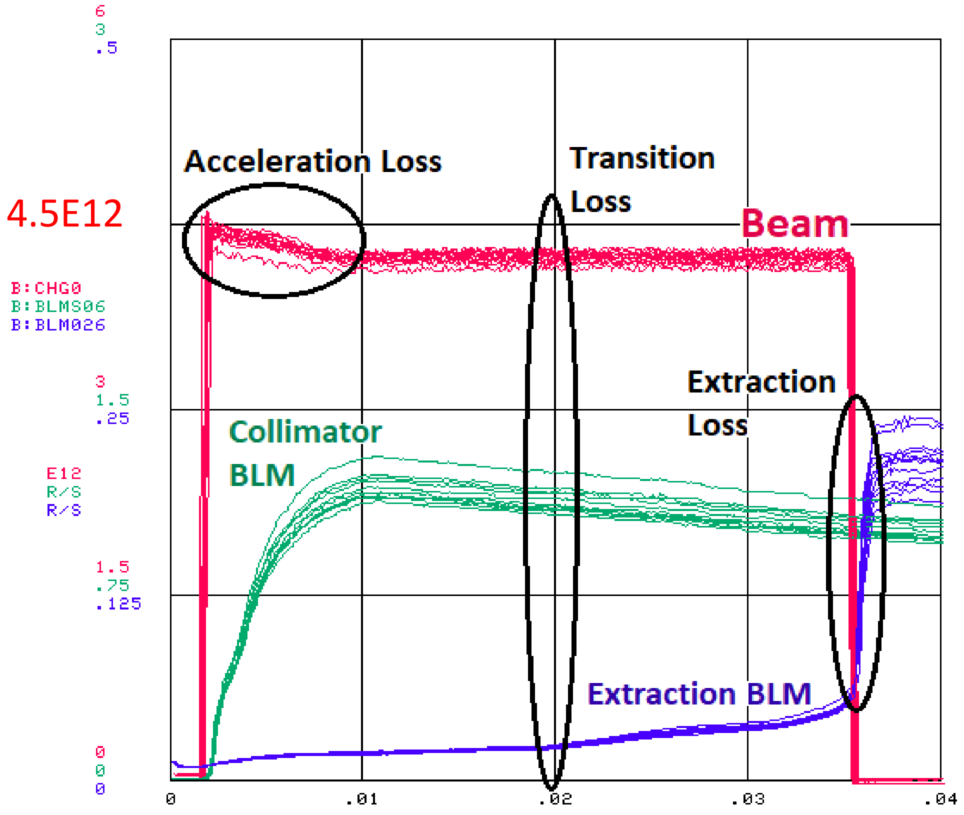
PIP-II

PIP-II: Booster Transferline



Presently, Losses in Booster Limit Accelerator Complex Performance

Beam current and losses in Booster over a Booster Ramp Cycle



PIP-II Mitigates Intensity Limits and Losses in Booster

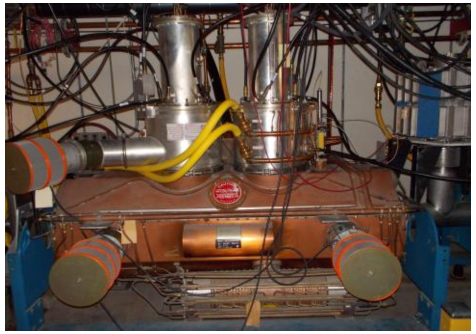
- **Increased injection energy and painting** reduce space charge tune shift by a factor of 2.5 comparatively to present Booster (equivalent to intensity $1.8x10^{12}$)
- **Improved single-unit, two-stage collimation** will reduce uncontrolled losses by a factor of ~2
- **Damper Upgrades** will reduce 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

Booster Injection

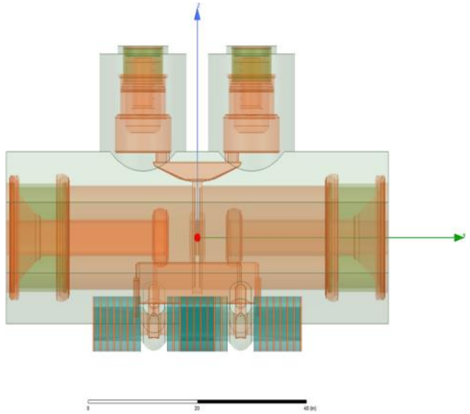
- **Injection parameters**
  - Injection energy increased from 400 MeV to 800 MeV
  - Injection beam intensity increased by 50%.
  - Booster rep rate increased from 15 Hz to 20 Hz
  - Injection time increased by a factor of 18
  - The length of the injection straight remained the same
- **New injection Girder**
  - New ORBUMP magnets and PS
  - Injection absorber
  - New injection foil
- **Booster gradient magnets**
  - New shorter magnets on each side of the girder

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
  - 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
  - Larger bore magnets to reduce losses at extraction
  - Advanced Booster Intensity Physics Studies
- Recycler Ring
  - 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
  - New RF amplifiers to provide additional RF power to enable acceleration of PIP-II beam



MI Cavity with two PAs



Some Challenges …

- Reliable, reproducible, and efficient beam tuning
  - *High sensitivity of beam dynamics to beam parameters and hardware performance in the low energy part (<30 MeV)*
  - *Changes in cavity performance require rephasing many cavities while precisely maintaining the linac energy*
  - *Requires accurate knowledge of the machine optics and comprehensive instrumentation*

- Control of beam quality and beam losses, for high power/CW operations
  - *Losses must be controlled down to ~1E-6/m* level

- Achieving and maintaining SRF cavities High Q0 and High Gradient
  - *Nitrogen doping & fast cool down are required*

More Challenges …

- Production of cryomodules reliably meeting performance requirements
  - *Supply chain management and quality control*
- Suppression of Microphonics noise
  - *Maximum detuning < 20 Hz (sigma < 3 Hz)*
    - *Passive means (Cryomodule design)*
    - *Active means(Adaptive Detuning Control Algorithm)*
- Rapid evolution of electronics
  - *Standardization of controls, electronics, etc.*

Even More Challenges …

- High efficiency of RF systems
  - *Reduction of power consumption*
  - *Improving power efficiency with a low Duty Factor beam through pulsed operations*
- Integration with existing Accelerator Complex
  - *Many critical booster components and infrastructure are aged*
- Operation of Booster with higher intensity
  - *50% higher intensity*
- Systems Integration
- …

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
- Challenges… we have some…

Thank you!