Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

PIP-II SRF Cryomodules

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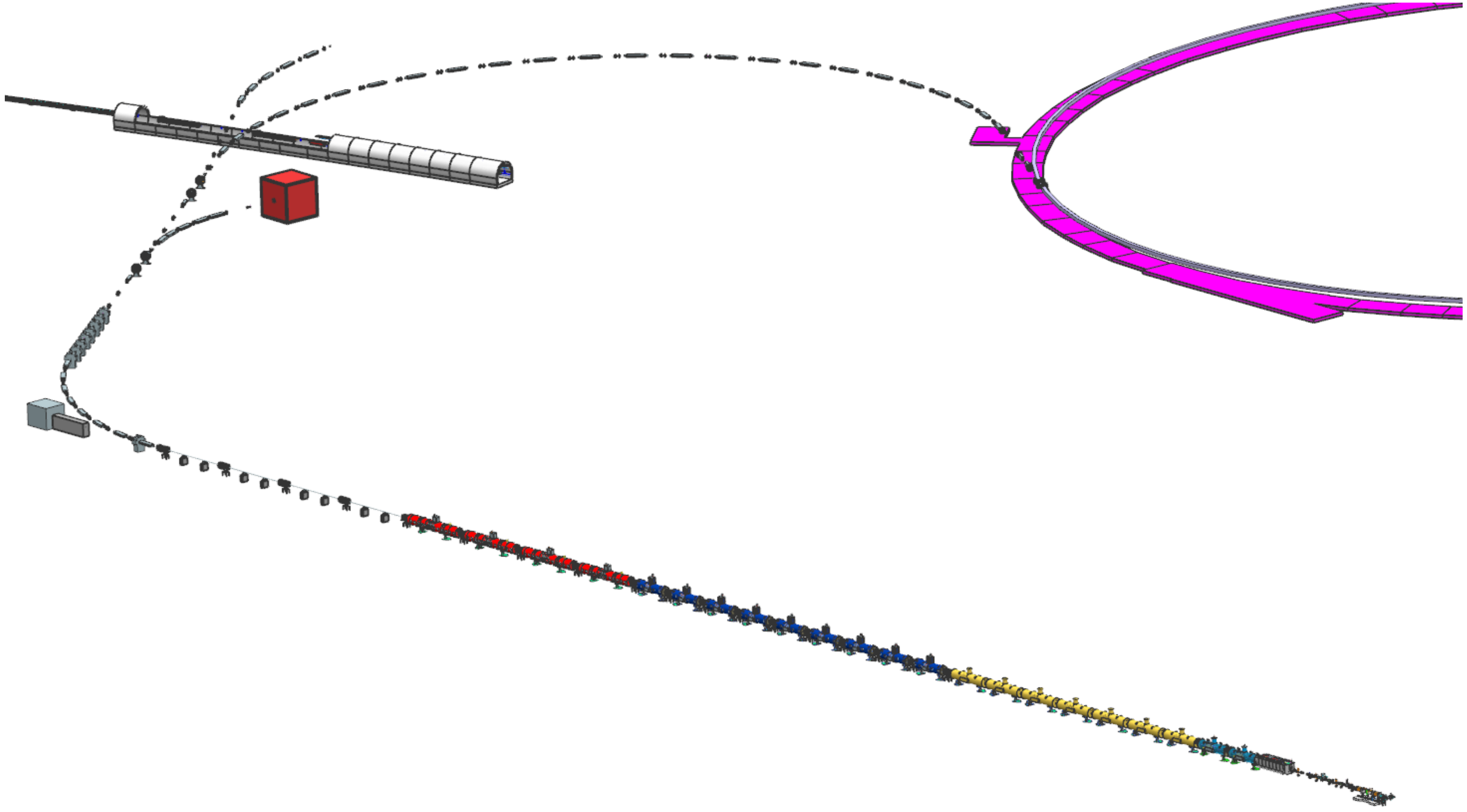
Americas Workshop on Linear Colliders 2020

October 20, 2020

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

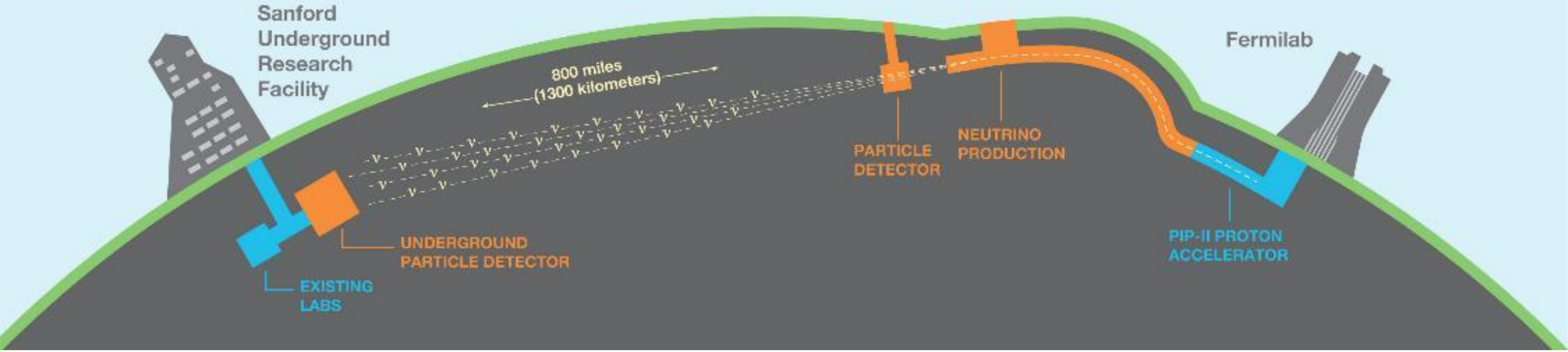
Outline

- Introduction
- Design Overview
- Recent progress
- Summary



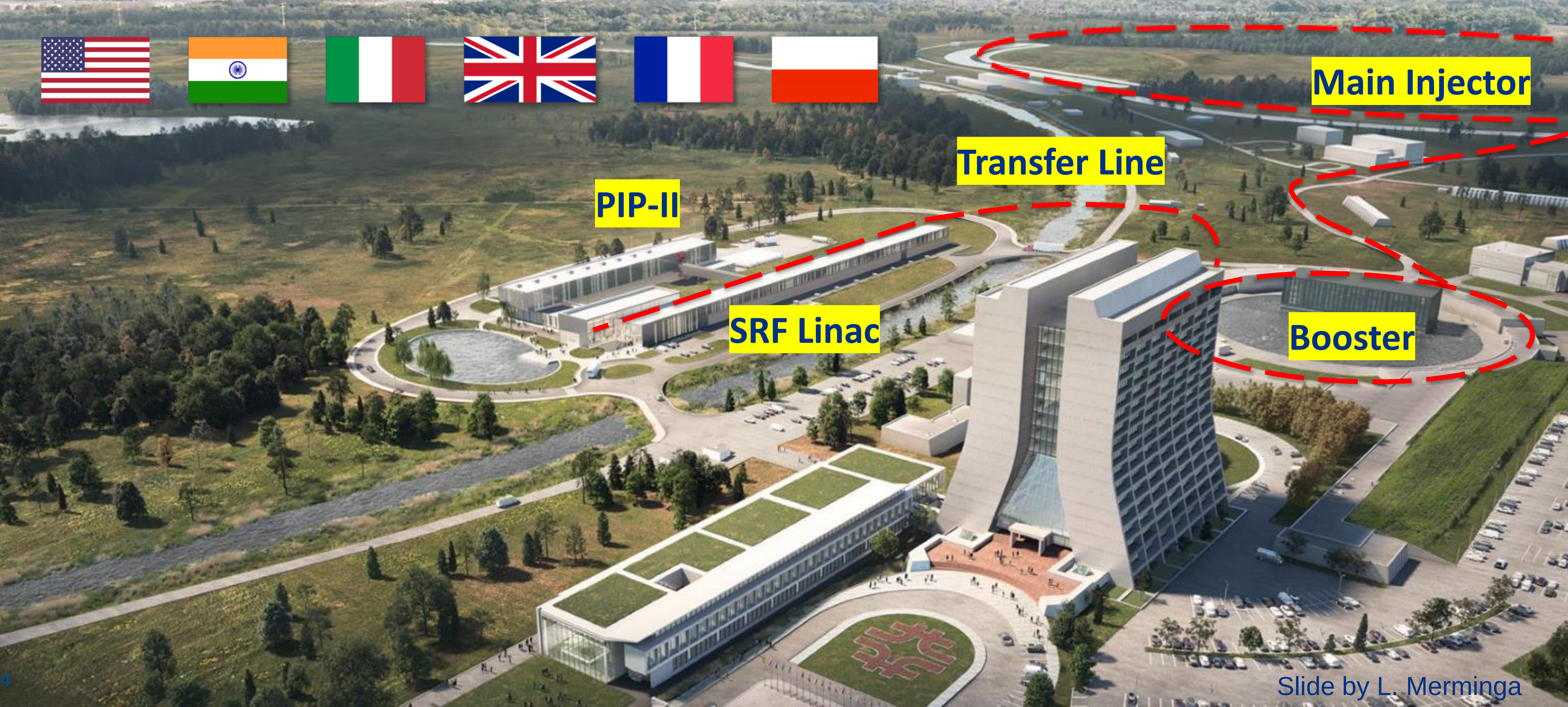
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Currently: 1,214 collaborators from 202 institutions in 33 countries (including CERN)



- **Origin of matter.** Investigate leptonic CP violation. Are neutrinos the reason the universe is made of matter?
- **Neutron star and black hole formation.** Ability to observe neutrinos from supernovae events and perhaps watch formation of black holes in real time.
- **Unification of forces.** Investigate nucleon decay.

Proton Improvement Plan – II (PIP-II)



Slide by L. Merminga

PIP-II Mission

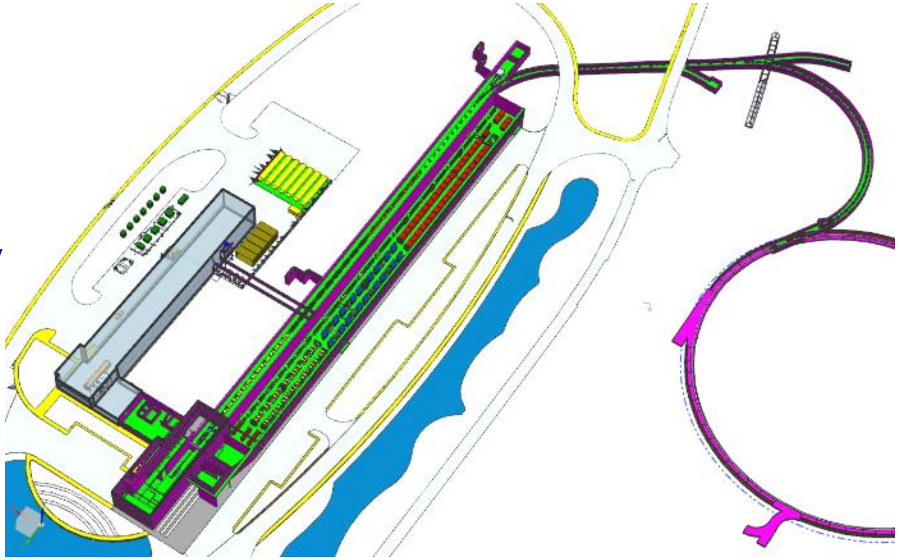
PIP-II will enable the world's most intense beam of neutrinos to the international LBNF/DUNE project, and a broad physics research program, powering new discoveries for decades to come.

PIP-II Linac capabilities

Beam Power
- 1.2 MW proton beam
- Upgradeable to multi-MW

Flexibility and multi-user capability
- Compatible w/ CW-operations
- Customized beams
- Multi-user delivery

Reliability



PIP-II Scope

800 MeV H− linac
- Warm Front End & SRF section

Linac-to-Booster transfer line
- 3-way beam split

Upgraded Booster
- 20 Hz, 800 MeV injection
- New injection area

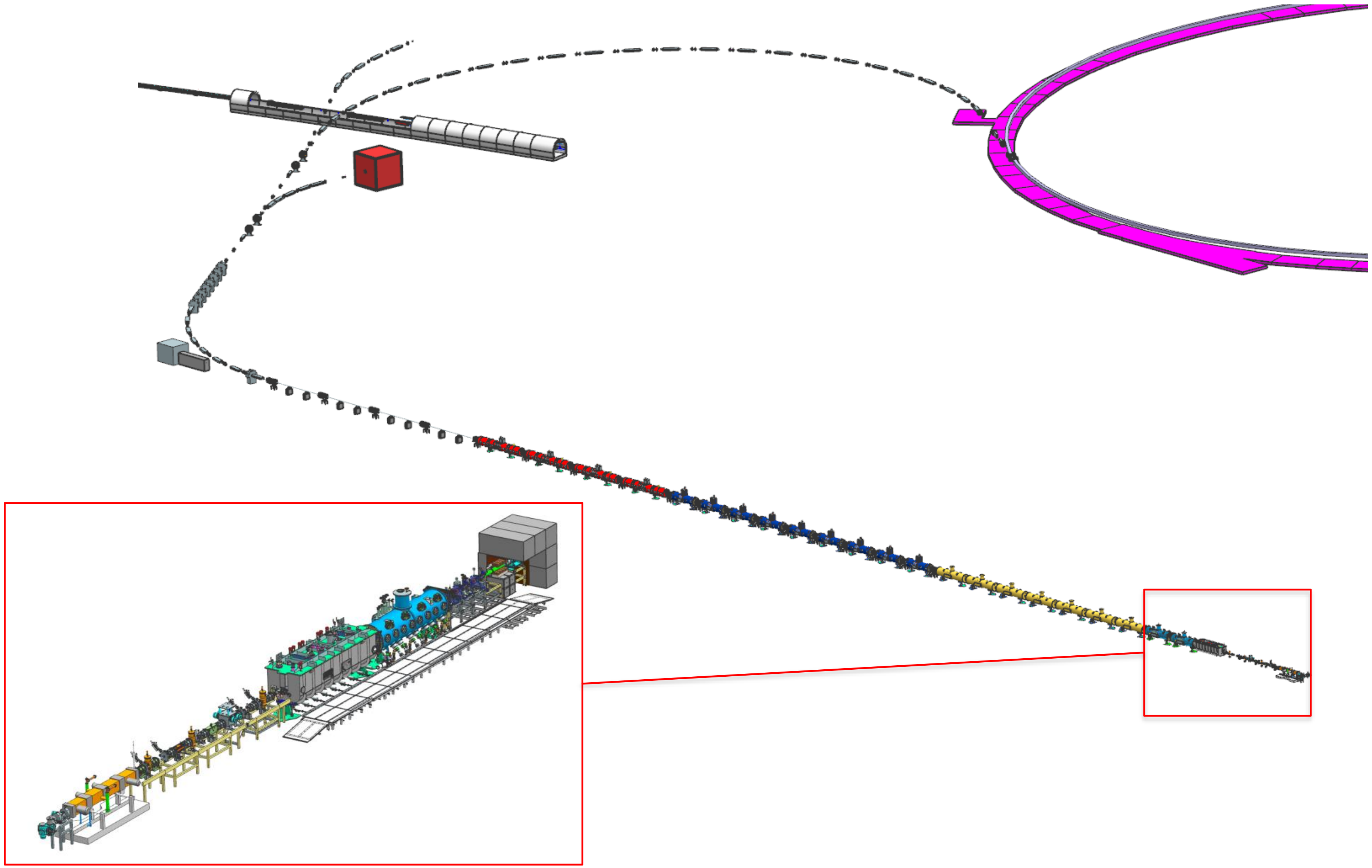
Upgraded Recycler, Main Injector
- RF in both rings

Conventional facilities, incl.
- Site preparation
- Cryoplant Building
- Linac Complex
- Booster Connection

The PIP-II scope enables the accelerator complex to reach 1.2 MW proton beam on LBNF target.

Slide by L. Merminga

PIP-II Front-End and Injector Test Facility



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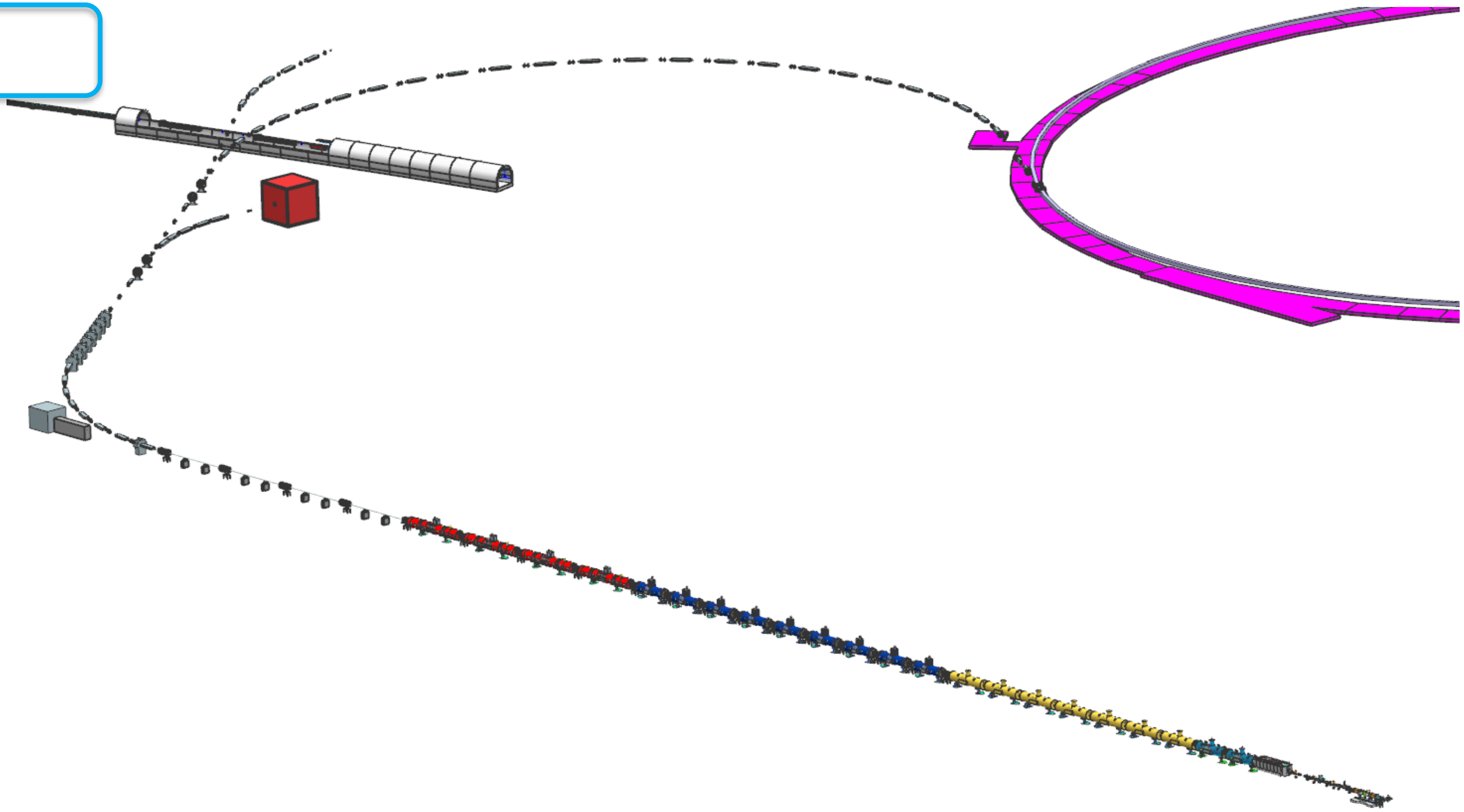
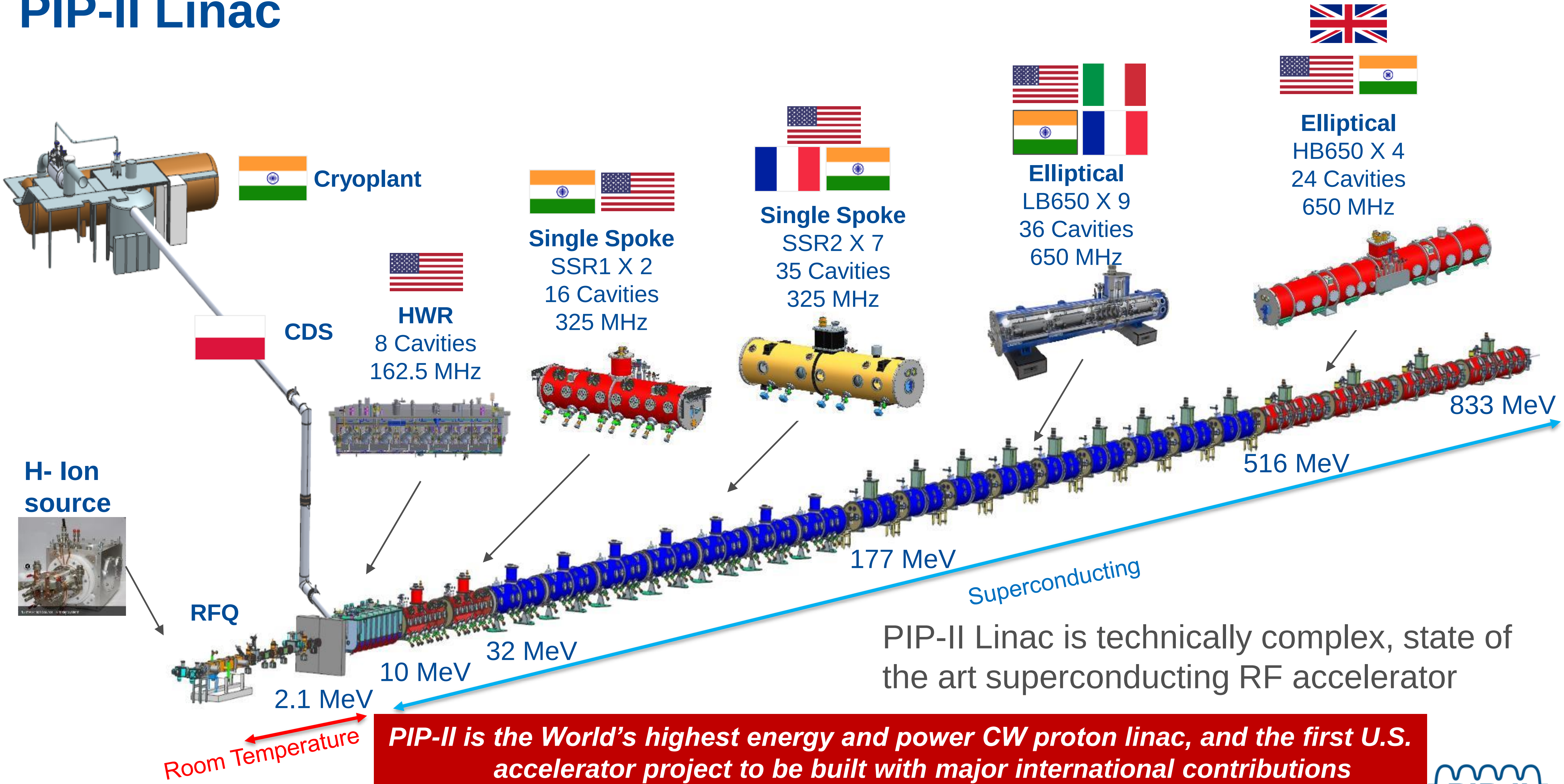


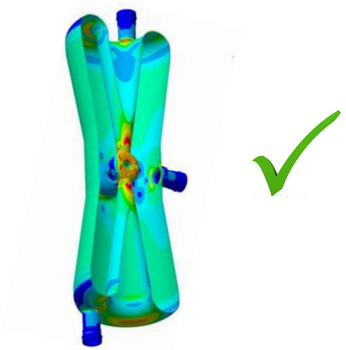
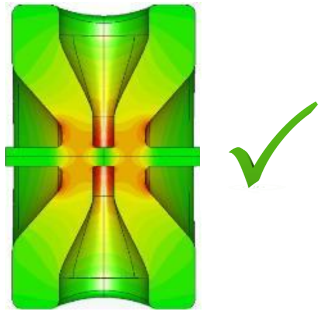
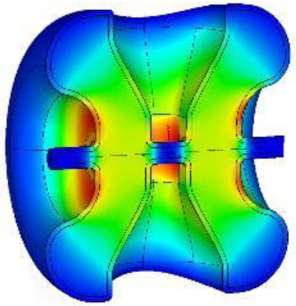
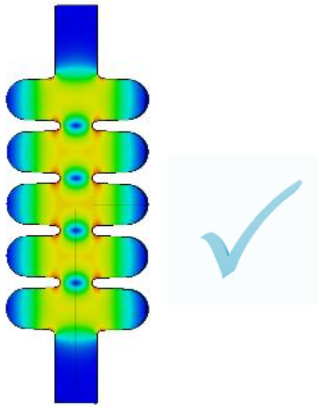
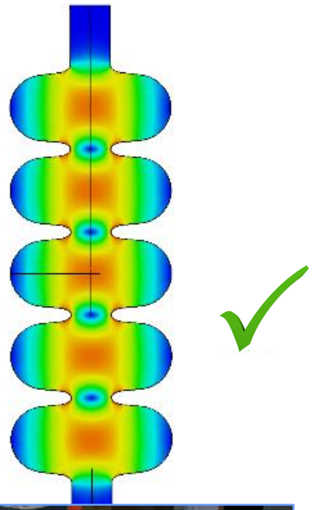
PIP-II Linac

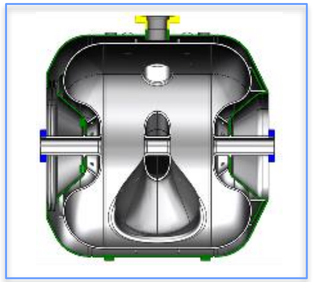


PIP-II Linac is technically complex, state of the art superconducting RF accelerator

PIP-II is the World's highest energy and power CW proton linac, and the first U.S. accelerator project to be built with major international contributions

PIP-II Cavities

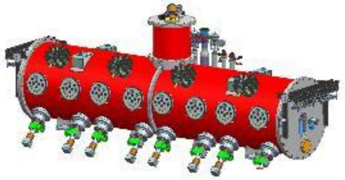



Cavity	β	Frequency [MHz]	Aperture [mm]	Effective Length [cm]	Accelerating Gradient* [MV/m]	E_{peak} [MV/m]	B_{peak} [mT]	R/Q [Ω]	G [Ω]
HWR	0.11	162.5	33	20.7	9.7	44.9	48.3	272	48
SSR1	0.22	325	30	20.5	10.0	38.4	58.1	242	84
SSR2	0.47	325	40	43.6	11.5	40.3	77.4	305	115
LB650	0.61	650	88	70.4	16.8	40.2	75.0	340	193
HB650	0.92	650	118	106.1	18.7	38.8	72.8	610	260

*Highest gradient in a cryomodule

PIP-II SRF Cryomodules

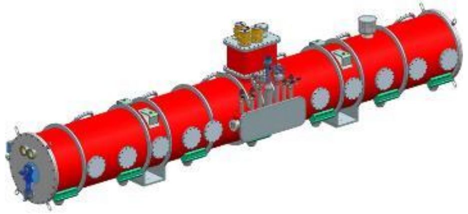
HWR



SSR1

SSR2

LB650



HB650

Cryomodule	CM #	Cavity #	String Assy.	CM Length [m]	Q_0 @ 2K	R_s [Ω]	Q_L [x10^6]
HWR	1	8	8 x (SC)	5.93	8.5E9	5.6	2.3
SSR1	2	8	4 x (CSC)	5.3	8.2E9	10.2	3.0
SSR2	7	5	SCCSCCSC	6.5	8.2E9	14.0	5.1
LB650	9	4	CCCC	5.52	2.4E10	8.0	10.4
HB650	4	6	CCCCCC	9.92	3.3E10	7.9	9.9

C = Cavity, S = Solenoid

23 Cryomodules + 4 Prototypes, 14 Cryomodules will be transported between Europe and US

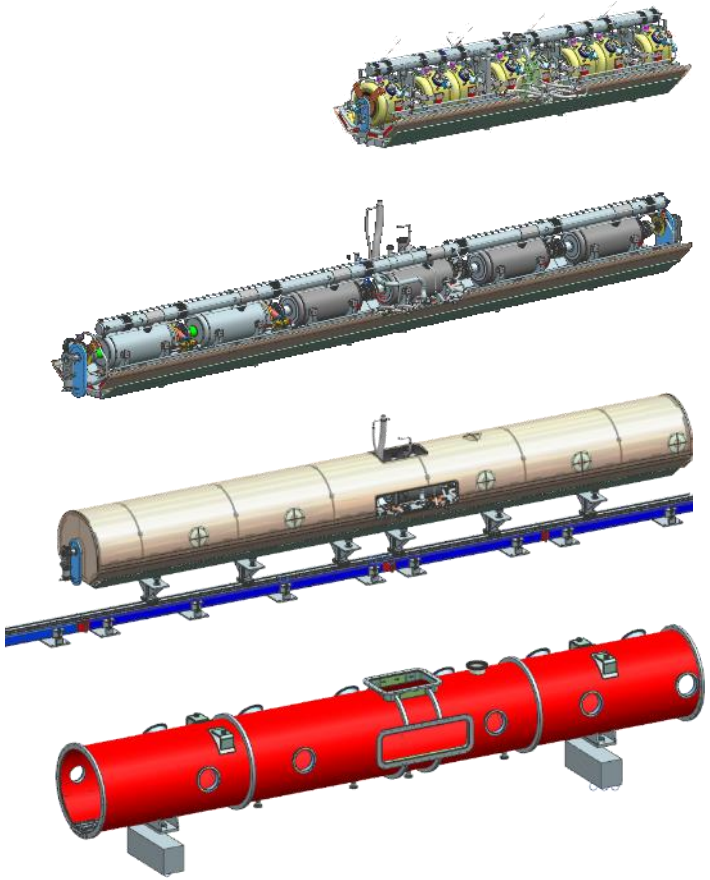
Total Linac 2K nominal heat load is 1.7 kW

Cryomodules Standardization

Except HWR

- All cryomodules have cavities supported by room temperature strong back.
- Same size of thermal shield, support post and vacuum vessel.
- Same tooling and assembly procedure.

- SSR1/SSR2 common design and components
- LB650/HB650 common design and components



Strongback cryomodule design

- Ease of assembly and tooling
- Less assembly footprint
- Predictable alignment
- Favorable vibration isolation

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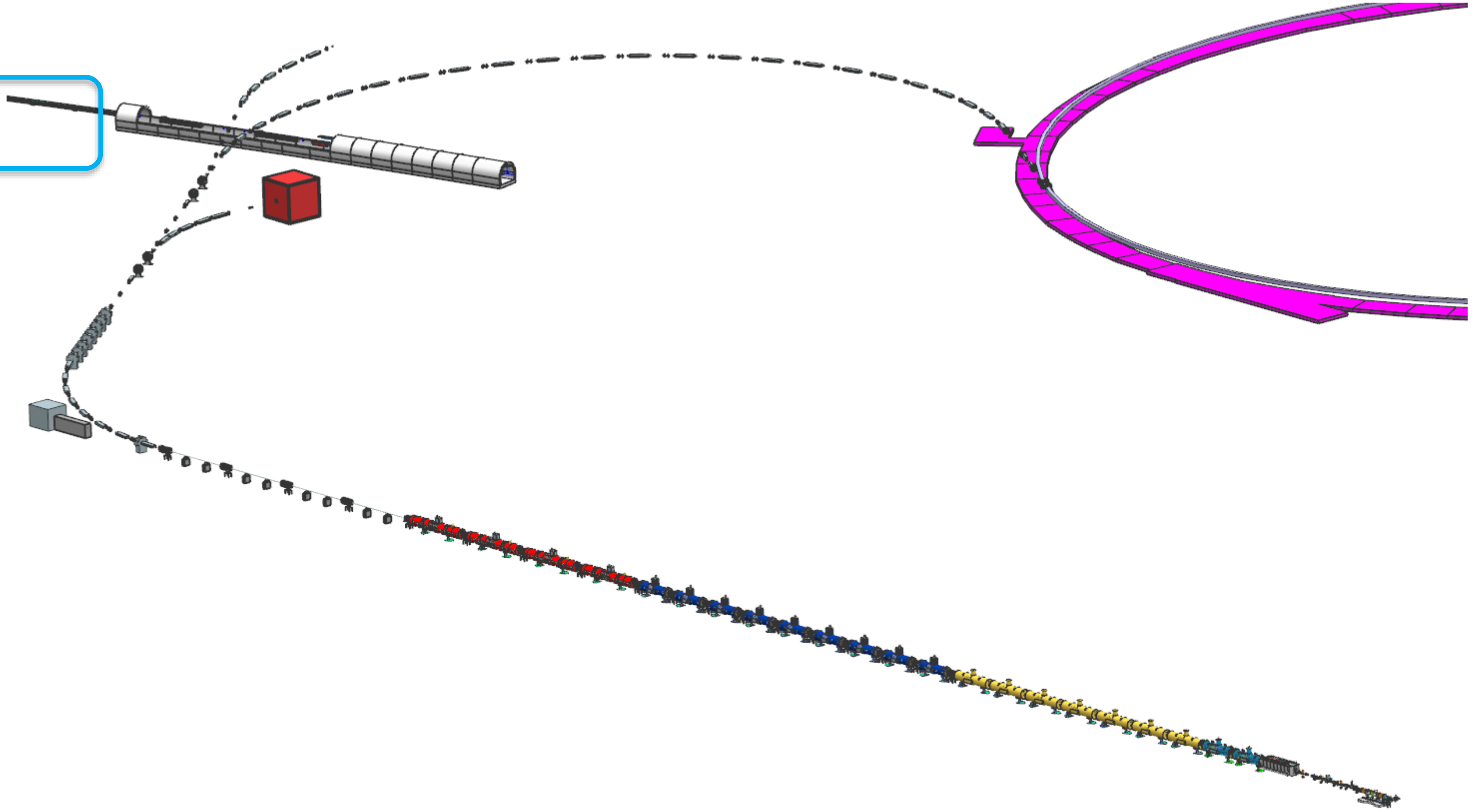
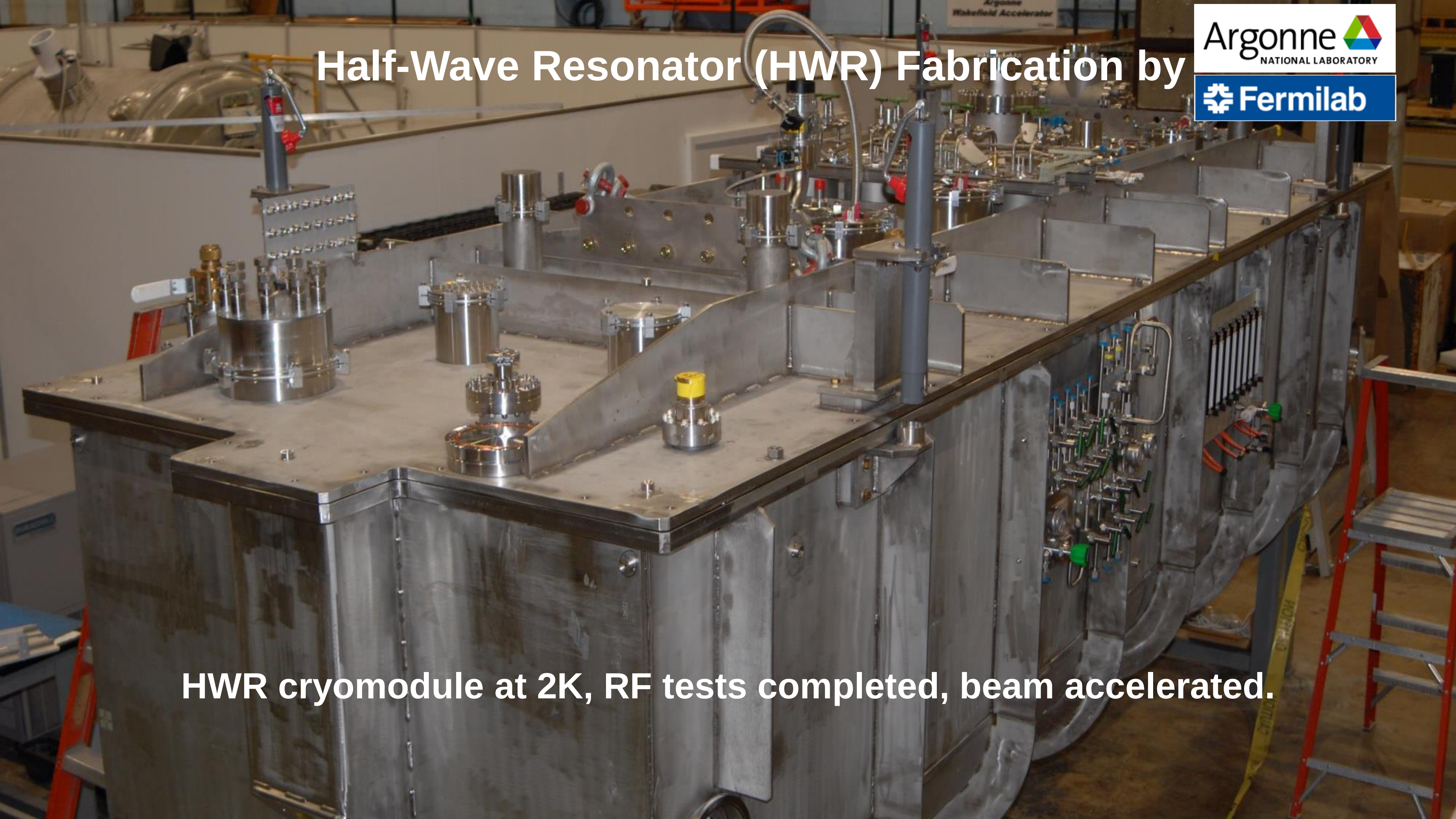


Half-Wave Resonator (HWR) Fabrication by

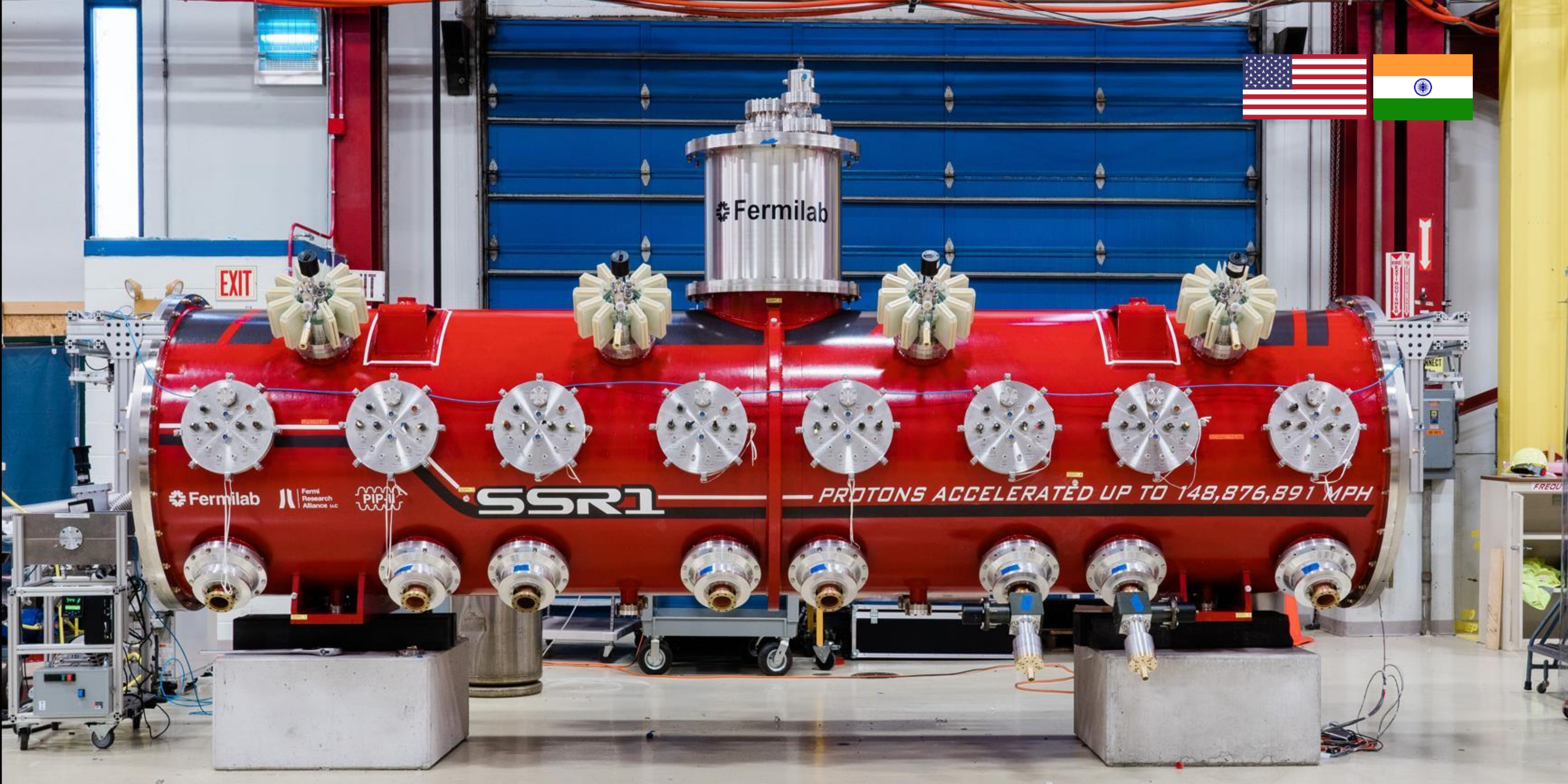


HWR cryomodule at 2K, RF tests completed, beam accelerated.

HWR Cryomodule Tests

- Operated all cavities to the full nominal field 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 tuner ranges exceed requirements.
- All cavities (except 3, untested) operated in GDR mode (LLRF control demonstrated)
- Five cavities were used to accelerate beams to >6 MeV

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 in progress

SSR1 Cryomodule Tests

- Two cavities exceed gradient specification required for PIP2IT beam test
- Both cavities have microphonics detuning ~15 Hz (< 20 Hz specification)
- RF amplifier used to power SSR1 cavities is a DAE deliverable; five more units are being installed.
- All solenoids tested and meet specification. Heat load tests are in progress.
- Strong back design validated preliminarily.

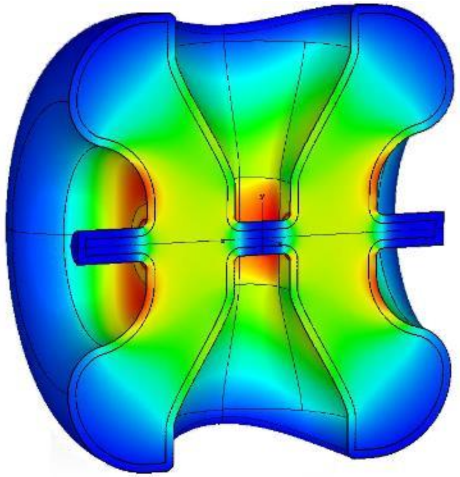
Cavity Position	Cavity Serial #	Nominal gradient required (MV/m)	Maximum gradient (MV/m)	Note
CAV1	S1H-NR-106	10.00	11.5*	No MP after conditioning FE onset 10.5 MV/m
CAV2	S1H-NR-110	8.78		
CAV3	S1H-NR-112	8.05		
CAV4	S1H-NR-109	10.00		
CAV5	S1H-NR-114	9.76		
CAV6	S1F-IU-104	10.00		
CAV7	S1H-NR-113	8.54		
CAV8	S1H-NR-111	10.00	11.0*	No MP after conditioning FE onset 10.5 MV/m

*Admin. limited

SSR2 Cryomodule

Cavity

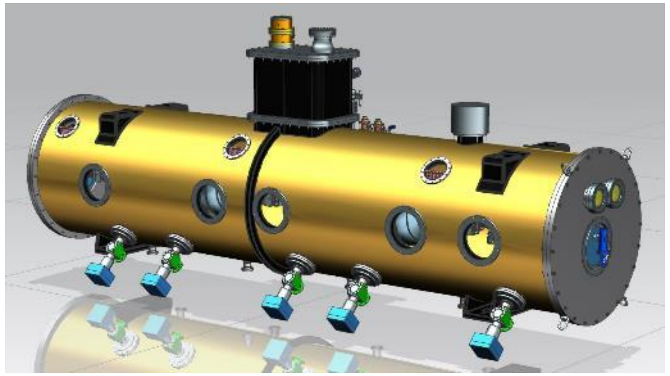
- Integrated design team: Fermilab, IN2P3 and DAE
- RF design optimized
  - Multipacting is dramatically minimized
- Niobium production at vendor completed
- Prototype jacketed cavity procurement in progress
- SSR1 Coupler power capability demonstrated at >20 kW;
  - procurement is in progress

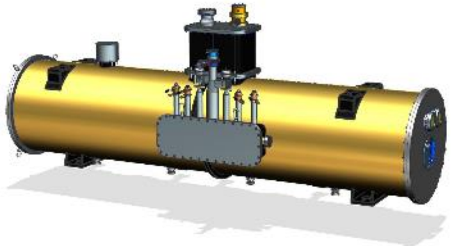


Parameters	SSR2 v 3.1
Optimal beta β_{opt}	0.472
Aperture [mm]	40
Frequency [MHz]	325
Effective length $2\beta_{opt}\lambda/2$ [m]	0.436
E_{peak}/E_{acc}	3.51
B_{peak}/E_{acc} [mT/(MV/m)]	6.75
G [Ohm]	115
R/Q [Ohm]	305.2
E_{peak} [MV/m] @ 5 MeV	40.2
B_{peak} [mT] @ 5 MeV	77.4
Max energy gain [MeV]	5.0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

Cryomodule

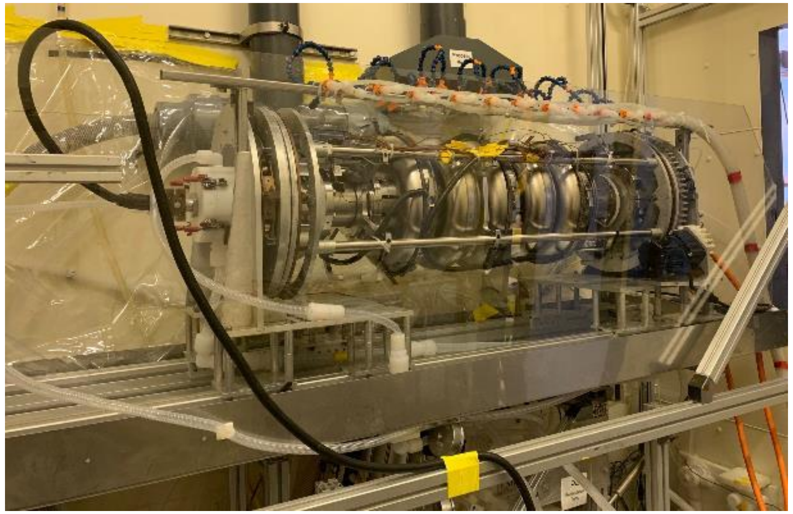
- Design in progress by Fermilab, DAE



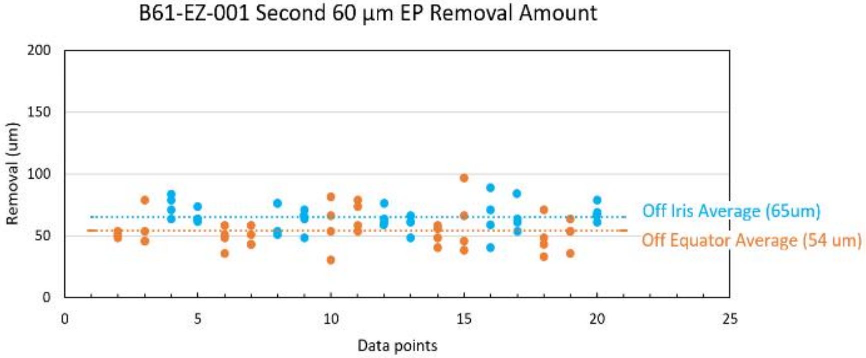


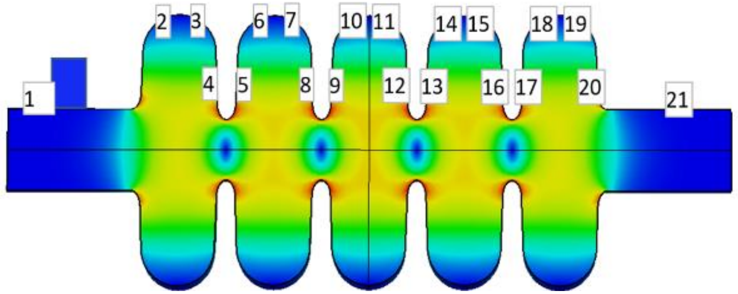
LB650 Cryomodule

- Cavity RF design completed
  - INFN led design of bare cavities
  - First prototype bare cavity INFN contribution arrived in May 2020
- Q_0, Gradient → 2.4 x10^{10} and 16.8 MV/m unprecedented for β <1
- Uniformity of electropolishing (EP) material removal is a prerequisite for N-doping
  - Low beta shape multi-cell cavity EP demonstrated promising uniformity
  - Testing in progress



B61-EZ-001 on ANL EP stand



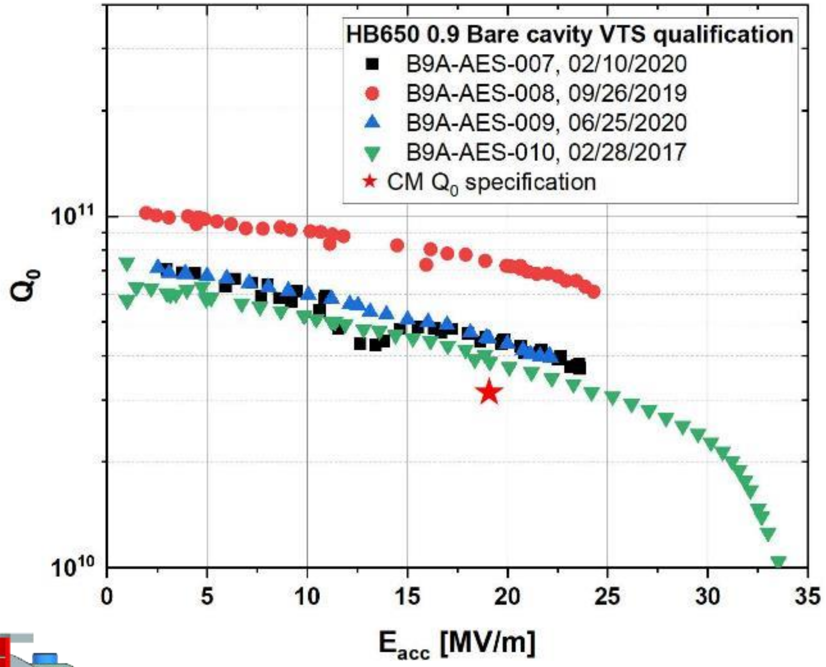


B61-EZ-001 EP uniformity

HB650 Cryomodule

Cavity

- Q_0, Gradient → 3.3 x10^{10} and 18.7 MV/m unprecedented for β <1
  - N-doping optimization is required
- All four HB650 Fermilab cavities exceeded cryomodule Q_0 spec
- RRCAT cavity testing in progress
- Cavity, coupler procurement in progress

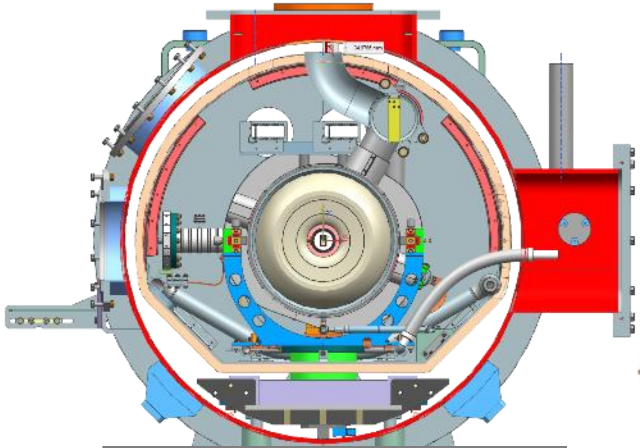


Cryomodule

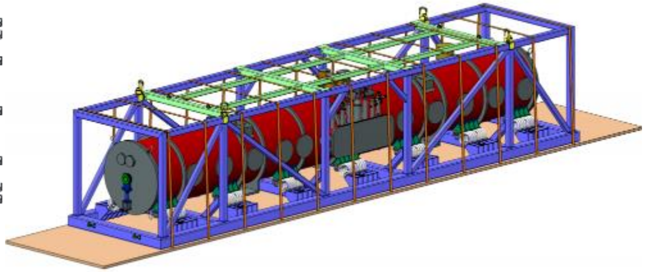
- FDR was completed successfully on 7/29-31
- Successful HB650 Transportation FDR on 9/22/2020 led by UKRI

Bare HB650 Cavity

Jacketed HB650 Cavity in STC



HB650 proto cryomodule



HB650 Transportation Tooling

Summary

- PIP-II SRF development is pushing the state of art to meet the needs of intensity frontier program at Fermilab.
  - PIP-II is the highest energy CW SRF Proton Linac in the world.
  - PIP-II has attracted interest from Partner labs for in-kind contributions.
- Significant progress has been made on all fronts.
  - HWR cryomodule demonstrated the beam acceleration.
  - SSR1 cold test is in progress.
    - Two cavities met specification.
    - Strongback design validated.
  - SSR2 and LB650 prototyping are in progress.
  - HB650 cryomodule design and cavity prototyping completed.
- We thank all the partner labs for their contributions !