Fermilab
Proton Improvement Plan-II

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

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PIP-II PROJECT PROGRESS AND CHALLENGES

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U.S. DEPARTMENT of ENERGY
Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

FERMI NATIONAL ACCELERATOR LABORATORY

Outline

1. PIP-II Design Goals
2. The PIP-II Facility
3. Status of Construction
4. Challenges
5. PIP-II Facility Upgrades
6. Conclusion

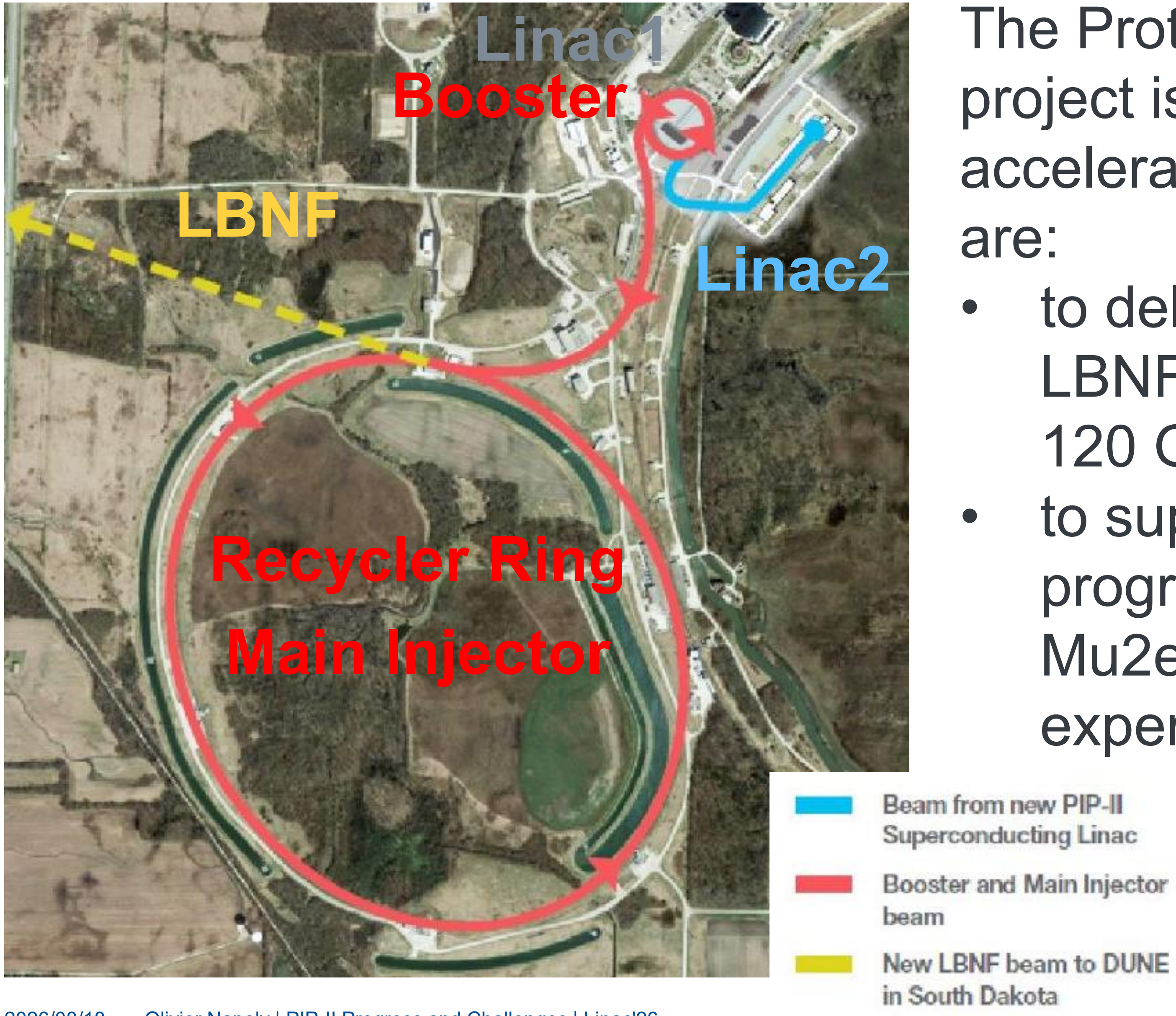
PIP-II Design Goals

The Proton Improvement Plan-II (PIP-II) project is an upgrade of the Fermilab accelerator complex whose main goals are:

- to deliver 1.2 MW power on the LBNF target from a beam of 120 GeV protons,
- to support the current 8 GeV program at Fermilab including the Mu2e and short baseline neutrinos experiments.

It will be the first accelerator project built in the US including major In-Kind Contributions for foreign institutes: DAE (India), INFN (Italy), UKRI (UK), CEA and CNRS (France), WUT, WUST and TUL (Poland)

PIP-II Design Goals



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PIP-II Design Goals

The LBNF beam line will extract protons from the Main Injector (MI) RCS at 1.2 s cycle period, which includes:

- MI ramp-down: accumulation and storage of 12 batches of 8-GeV protons from Booster RCS cycled at 20 Hz in the Recycler Ring (RR)
- transfer from RR to MI
- MI ramp-up: acceleration to 120 GeV energy and 1.2 MW beam power.

In parallel with the MI ramp-up, RR accumulates another 12 Booster batches for various 8 GeV neutrino and muon campus experiments.

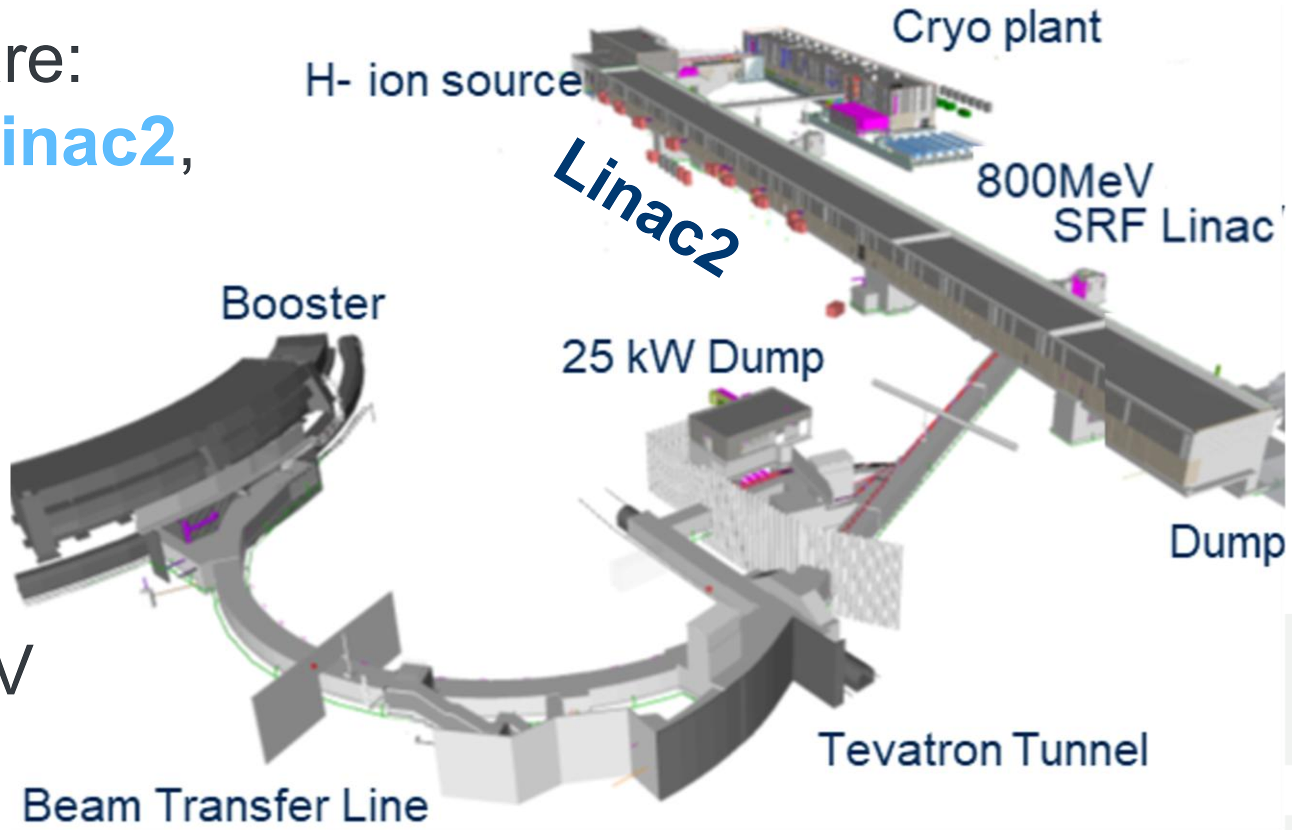
The total beam power delivered by the Booster will be in excess of 160 kW corresponding to **6.5×10^{12} protons per 20 Hz pulse**.

Reducing the MI cycling time to 0.7 s will provide a path to LBNF power up to 2 MW with the identical Booster batch input and dropping the proton yield to the 8 GeV physics program.

The PIP-II Facility

The main elements of this upgrade are:

- an 800 MeV SRF linac, named **Linac2**, accelerating 6.7×10^{12} H- at 20 Hz repetition rate, and
- a beam transfer line (BTL) to a new Booster injection region.



The nominal beam power at 800 MeV is 17.6 kW

This new facility will **double the injected proton energy and intensity** in comparison with the present 400 MeV room-temperature injector, aiming at a yield of 3.3×10^{21} protons/year, assuming 76% uptime (44 weeks at 90% reliability)

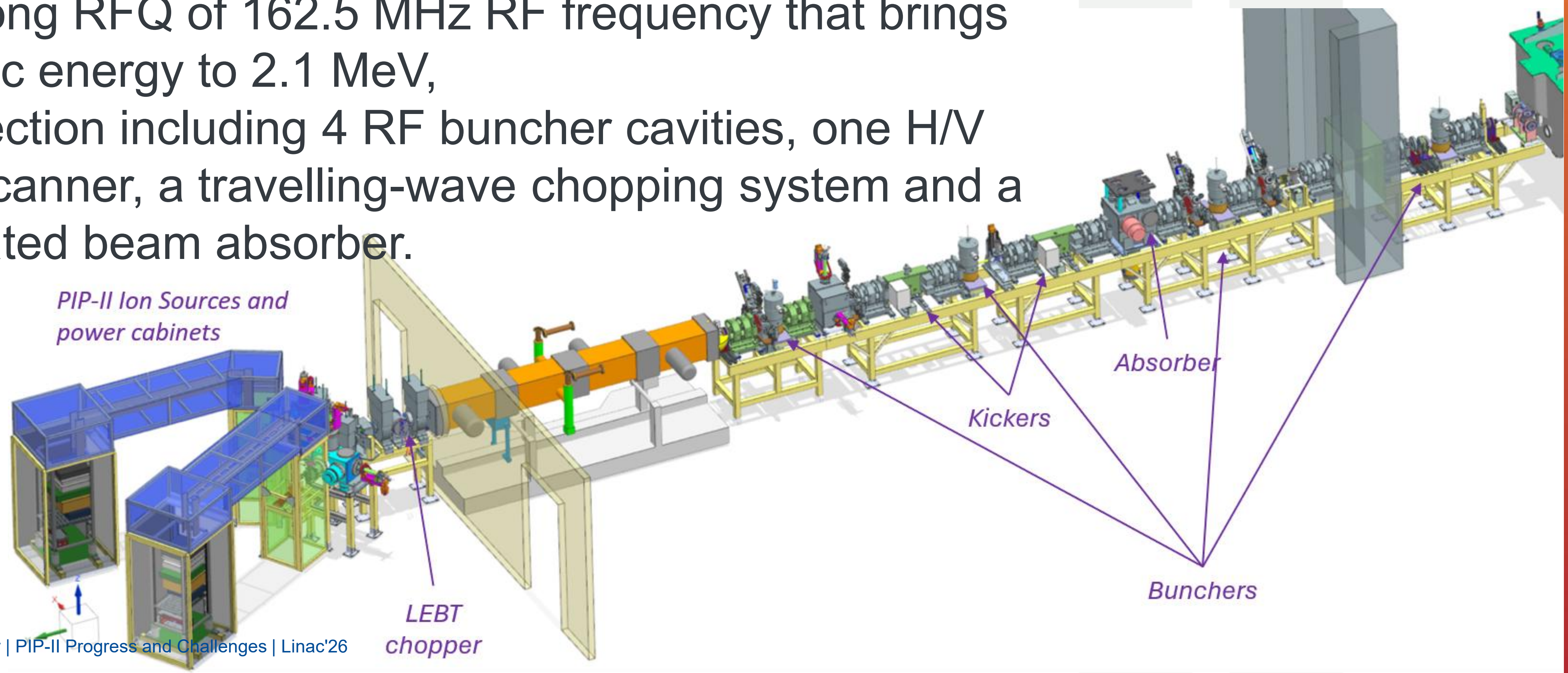
The PIP-II Facility Main Parameters

Linac Parameters	
Beam energy	800 MeV
Beam pulse length	550 µs
Repetition rate	20 Hz
Pulse average current	2 mA
Fundamental RF frequency	162.5 MHz
Cryogenic power	2.5 kW @ 2 K
Beam duty factor	1.1 %
RF duty factor	100 %
Linac/BTL length	267/308 m

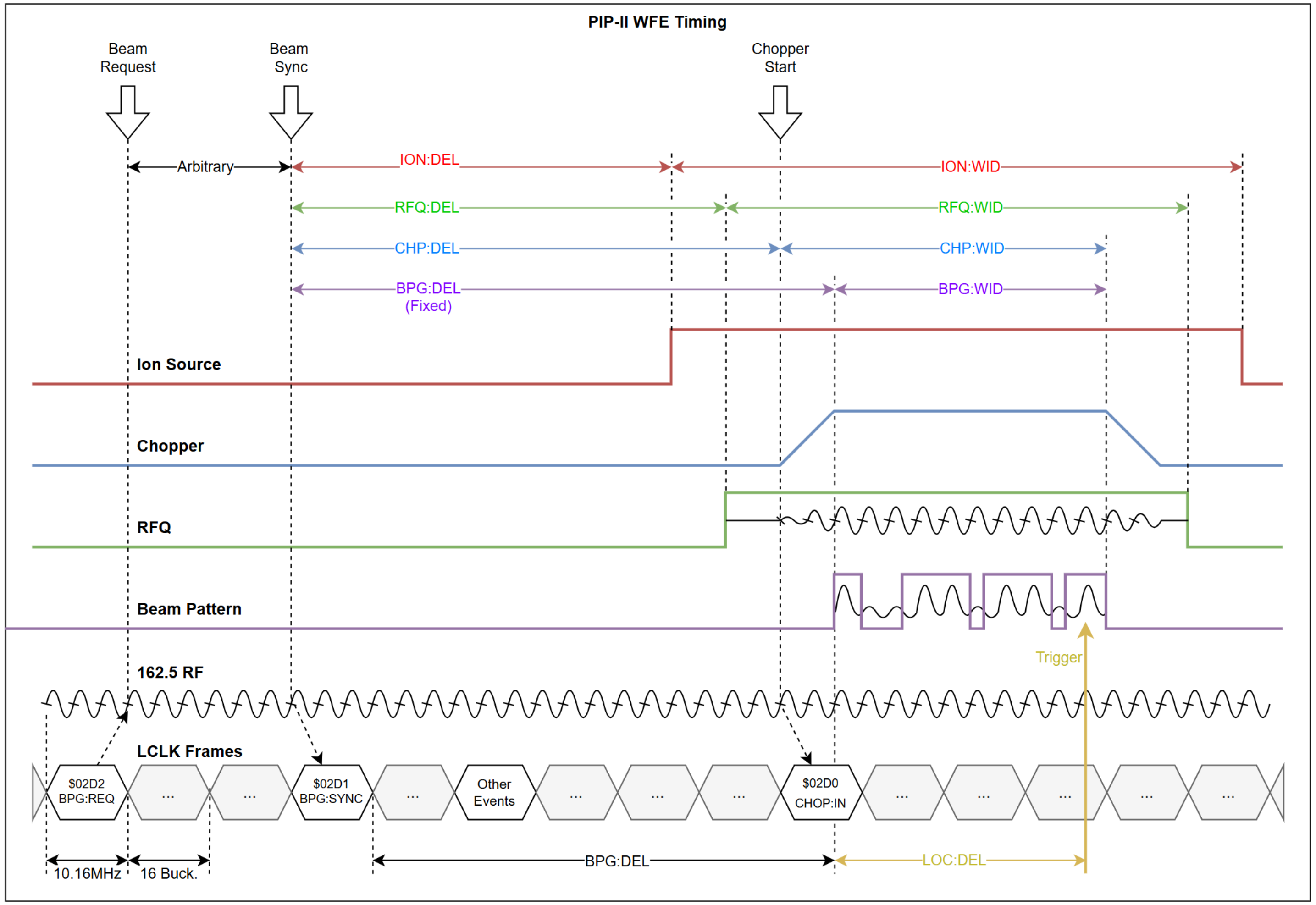
The PIP-II Facility: the Warm Font End

WFE includes:

- two 30 kV H- ion sources generating up to 15 mA current,
- LEBT including a ±30° dipole which selects the beam from either of the two H- sources, one H/V Allison scanner and a DC chopping system,
- 4.43 m long RFQ of 162.5 MHz RF frequency that brings the kinetic energy to 2.1 MeV,
- MEBT section including 4 RF buncher cavities, one H/V Allison scanner, a travelling-wave chopping system and a 21 kW-rated beam absorber.



The PIP-II Facility: the Warm Font End



WFE timing system interaction with the beam.

Ion source modulator and LEBT chopper HV are fast the critical devices used by Machine Protection System and activated at any beam interruption request,

Beam commissioning of WFE to start in November 2027 for 12-month duration.

The PIP-II Facility: the SRF Linac

5 flavors of SRF cavities and cryomodules

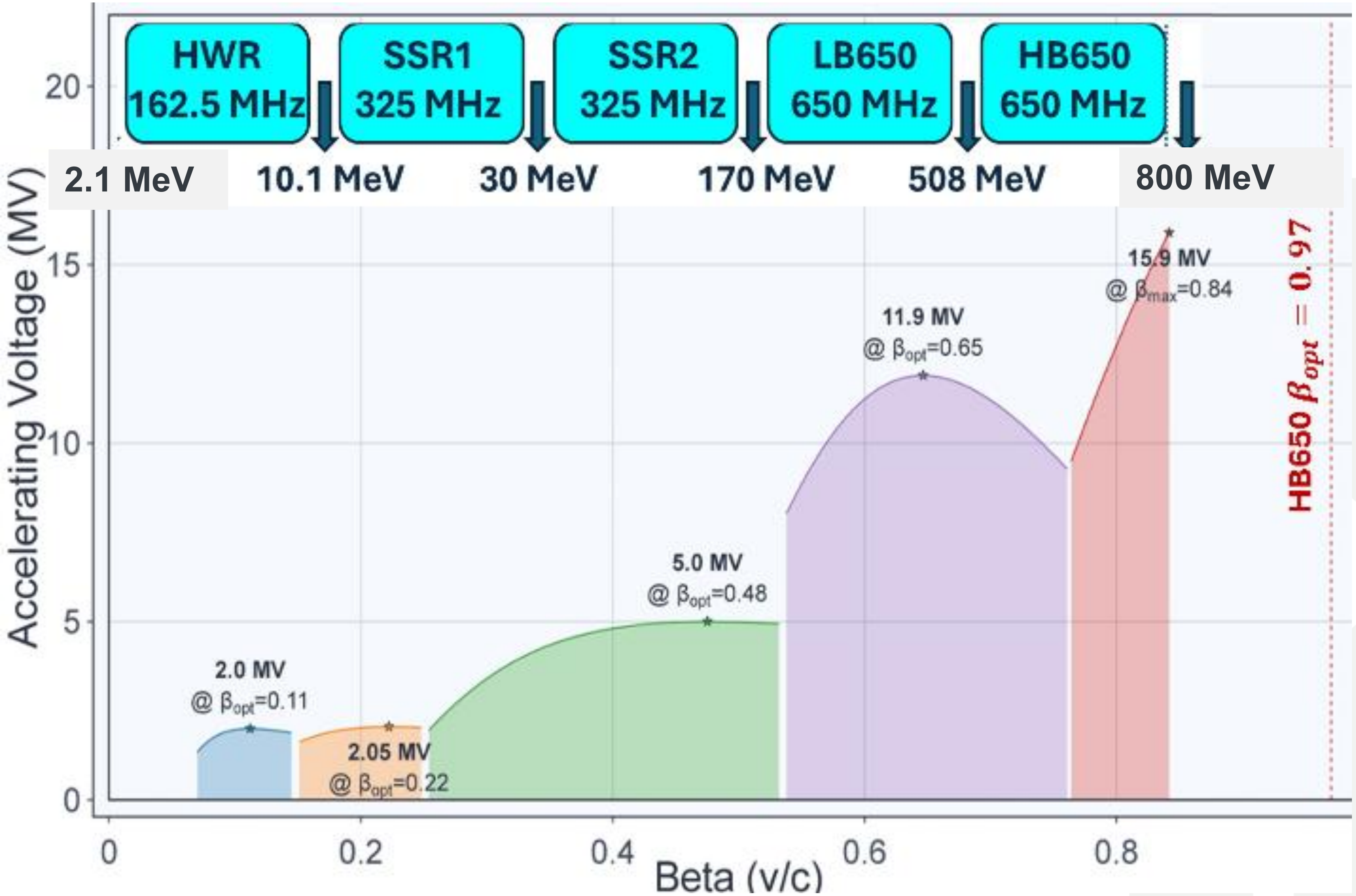




Name (Qty.)	**HWR (8)**	**SSR1 (2×8)**	**SSR2 (7×5)**	**LB650 (9×4)**	**HB650 (4×6)**	Units
Type	Half-Wave	Single Spoke	Single Spoke	Elliptical	Elliptical	-
β	0.11	0.22	0.47	0.61	0.92	-
Frequency	162.5	325	325	650	650	MHz
Q_0	8.5×10^9	8.2×10^9	8.2×10^9	2.4×10^{10}	3.3×10^{10}	-
Gradient	9.7	10	11.5	16.9	18.8	MV/m
Doped	No	No	No	Mid-T bake	Yes	-
Status	-	Production	Production	Production	Production	-

The PIP-II Facility: the SRF Linac

SRF cavities accelerating voltage at nominal gradient



Status of Construction: Cryoplant

Conventional facilities are quite advanced with authorization of usage already delivered for the cryoplant building, the high-bay building (HBB) housing the WFE beamline and its services, the linac tunnel and gallery and the first part of the BTL tunnel, down to the crossing with the pre-existing Tevatron tunnel.

Status of Construction: High Bay Building

The high-bay building (HBB) with its shield door to the Linac tunnel is ready for WFE installation. The first accelerator component, the RFQ, has been lowered down and positioned. All WFE components are on site, for ongoing girder assembly.

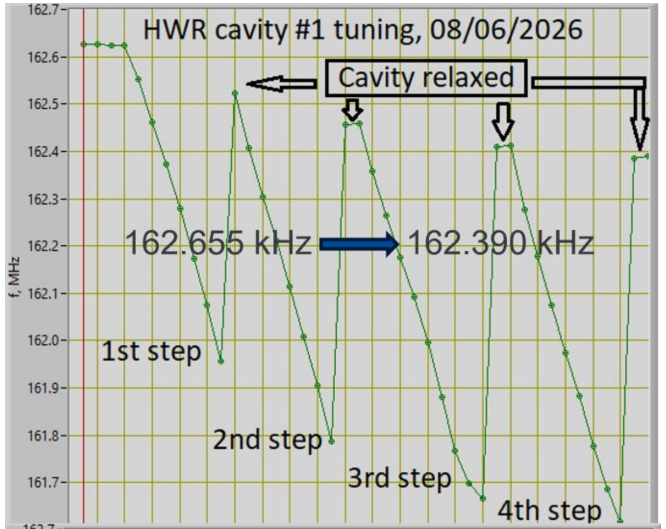
Status of Construction: Conventional Facility

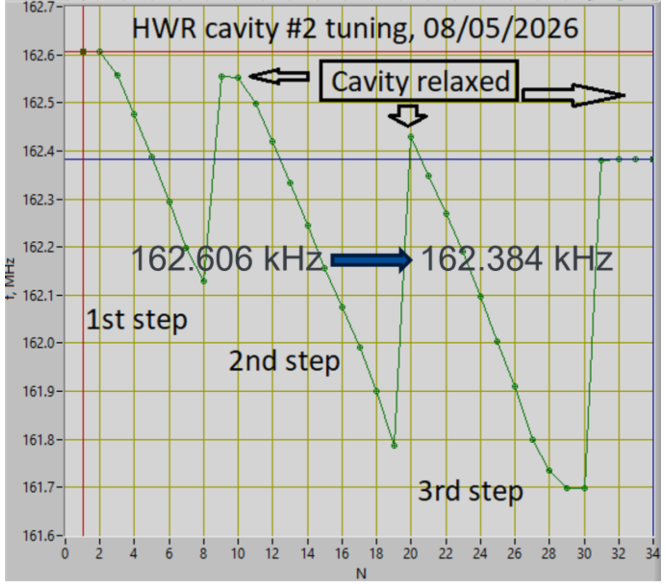
The PIP-II cryoplant building includes a compressor room, a cold box room, and a distribution valve box (DVB). The cold box with cooling capacity of 2.5 kW at 2 K, is an Indian in-kind contribution from the Department of Atomic Energy (DAE), supplemented with a 10,000 litres LHe dewar and a Helium purification and recovery system.

The cryoplant has received Operational Readiness Clearance.

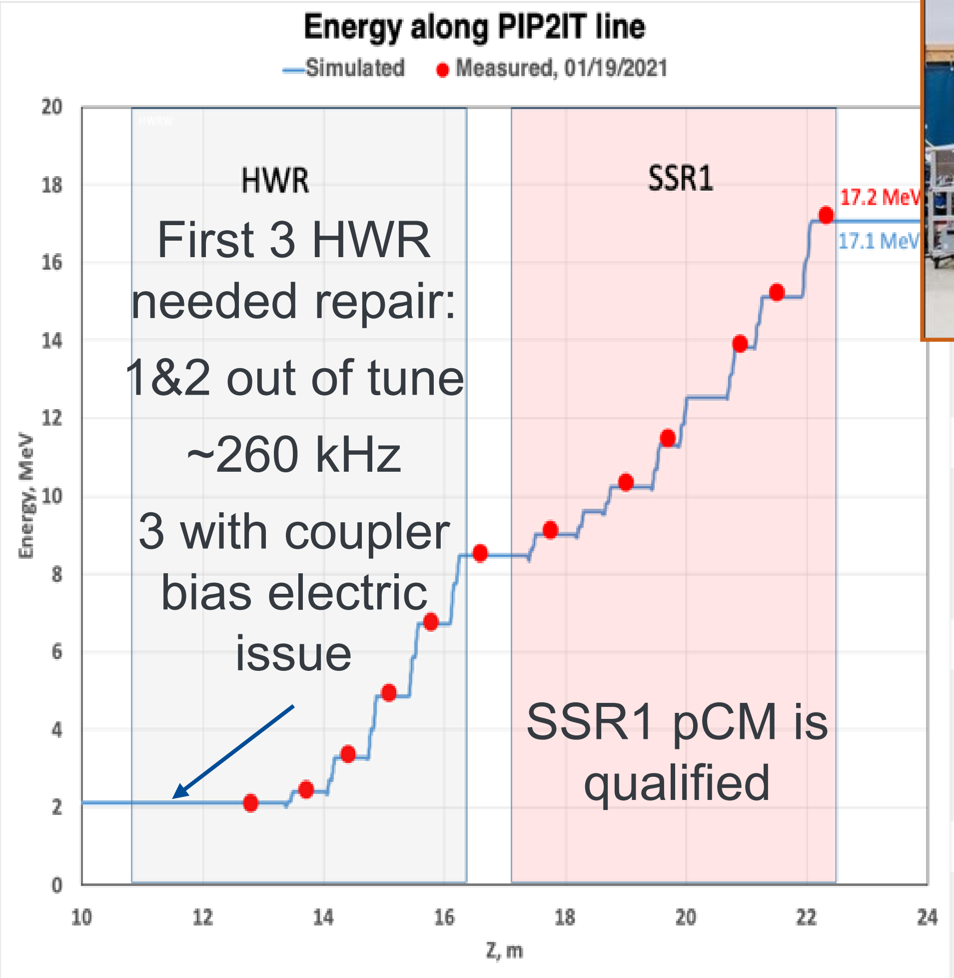
The completion of its commissioning is planned in spring 2027.

Status of Construction: HWR and SSR1 pCM





Beam measurements with WFE 2021

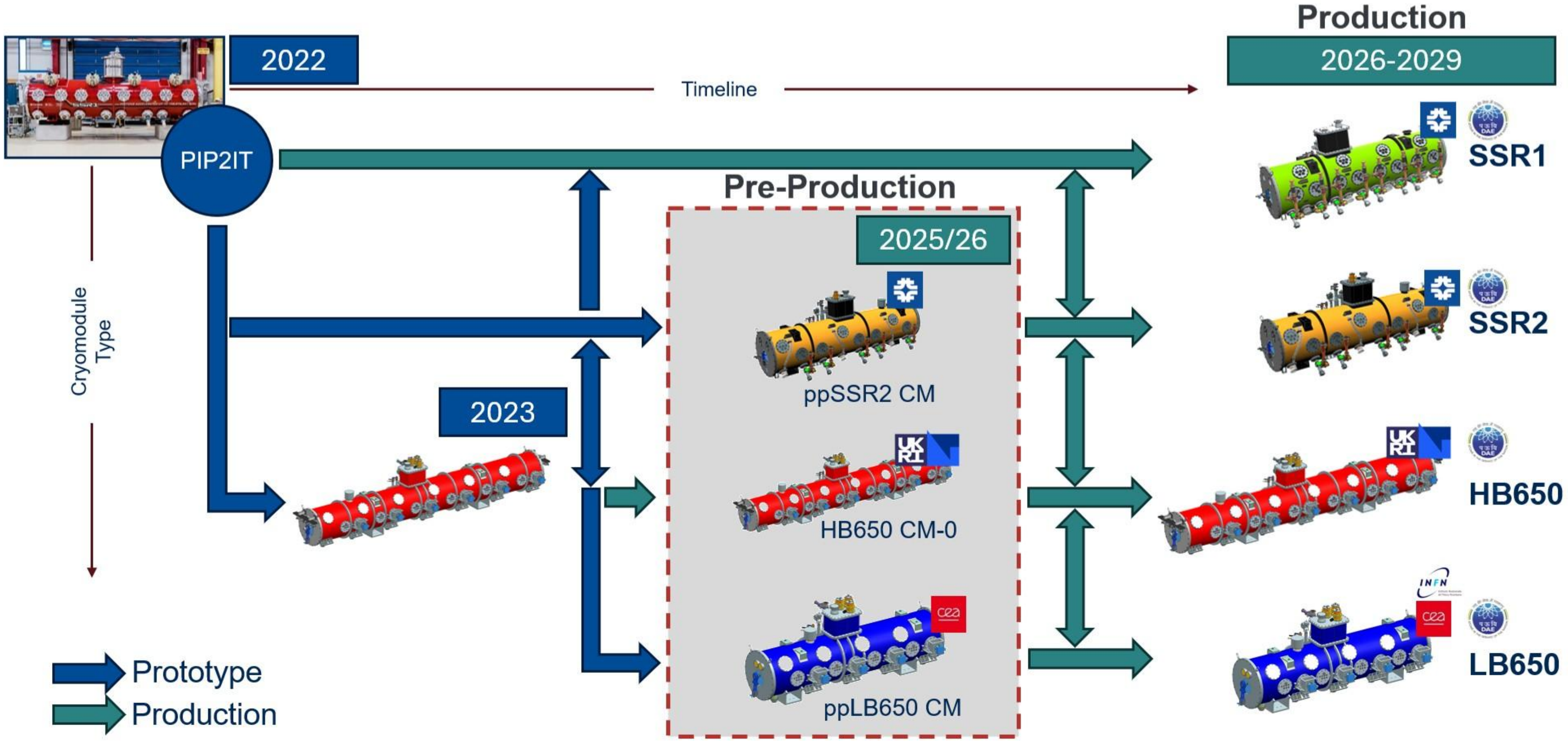


C1 and C2 tuned in the beamline, under vacuum.

The SSR1 cryomodule will be used at the first SSR1 slot of Linac2.

Interfaces are made compatible with the slightly different production SSR1 design.

Status of Construction: Cryomodules

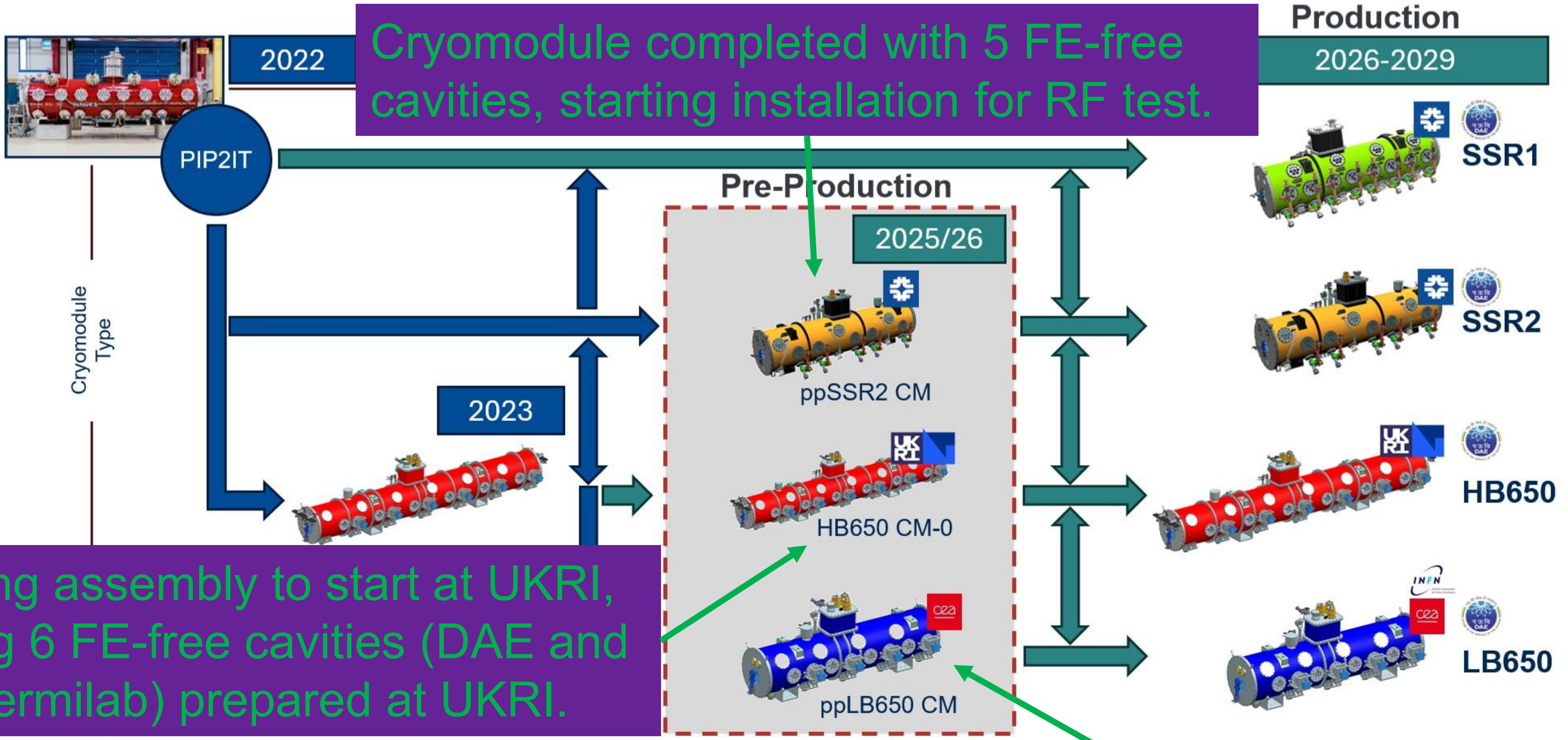


Cryomodule development plan, based on SSR1 RT-strongback technology.

M. Parise, TU1A005

Status of Construction: Cryomodules

Cryomodule completed with 5 FE-free cavities, starting installation for RF test.

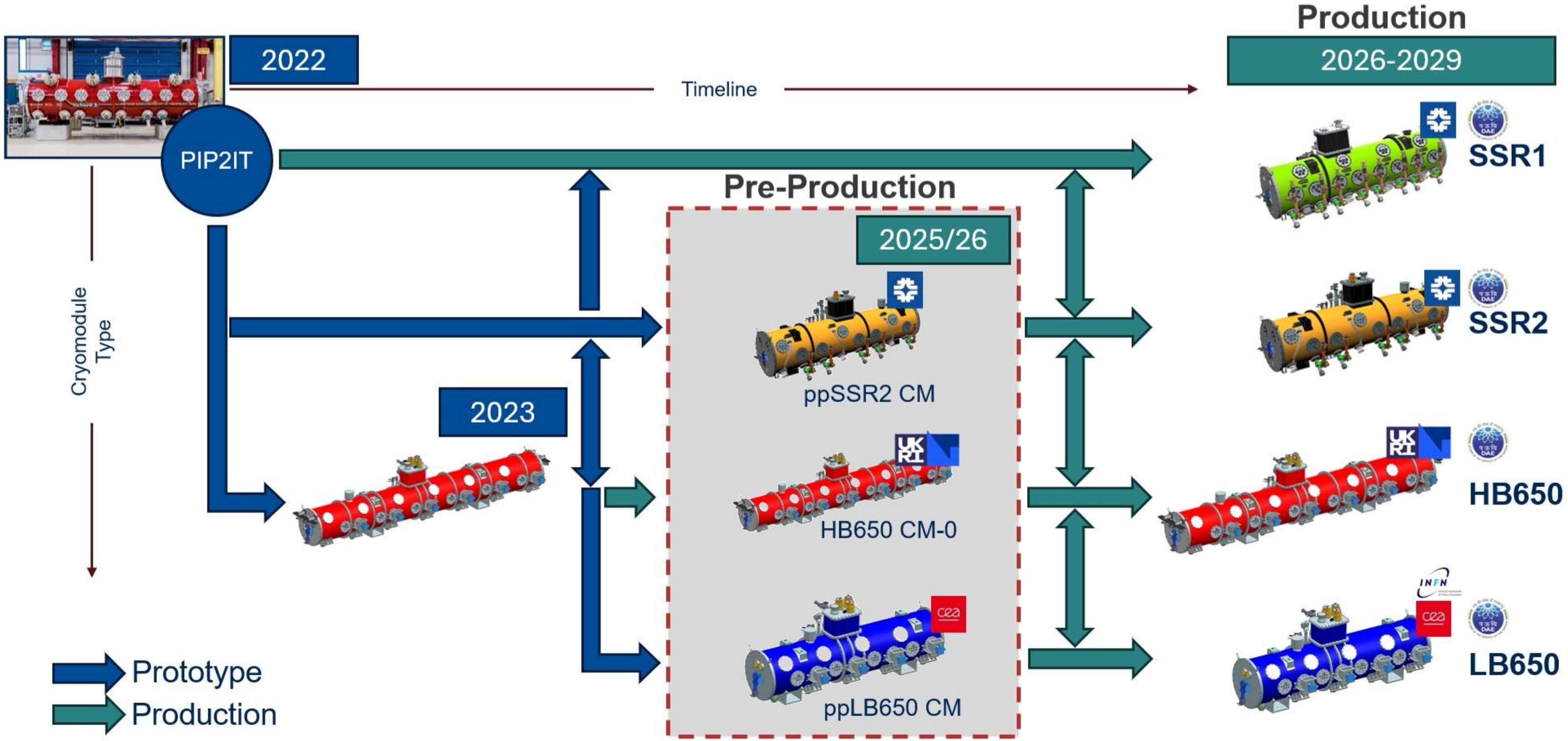


String assembly to start at UKRI, using 6 FE-free cavities (DAE and Fermilab) prepared at UKRI.

String assembly completed at CEA-Saclay, using four FE-free cavities from Fermilab

M. Parise, TU1A005

Status of Construction: Cryomodules



All pre-production CM SRF cavities are qualified for E_{acc} and Q_0, except one HB650 cavity quenching at < 18 MV/m.

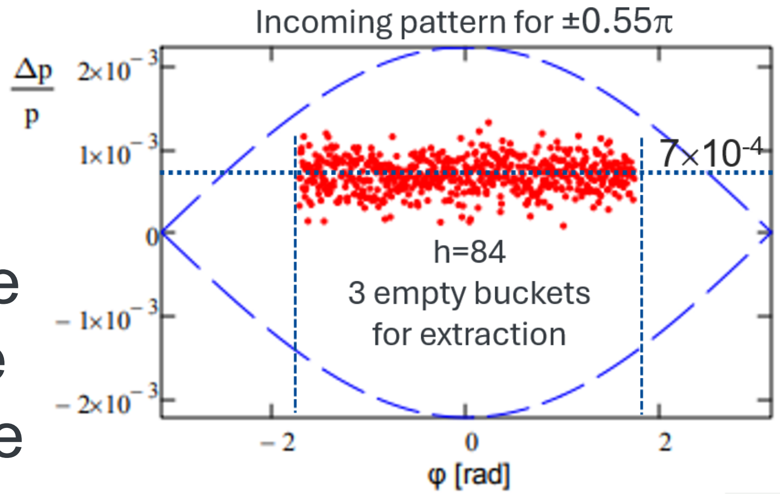
R. Sharankova,MOPO053

Challenges: Longitudinal Dynamics

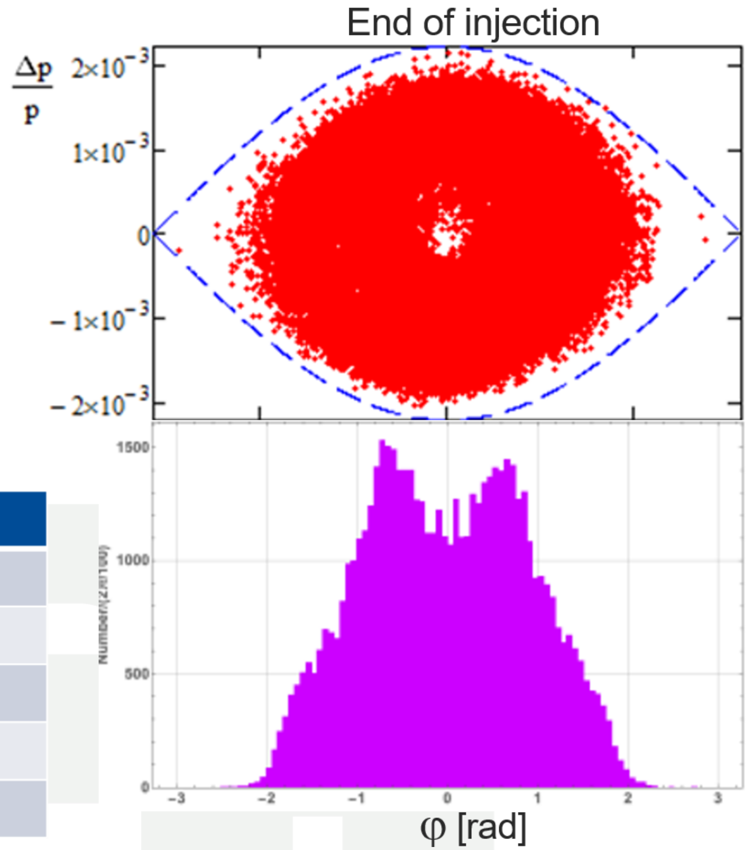
Linac2 will be the first SRF injector of an RCS: its 550 μs pulse spans ~300 turns.

- Bunches outside of the Booster longitudinal acceptance will be removed by the MEBT chopper, synchronized with the Booster RF system.
- Longitudinal painting requires small incoming momentum spread and jitter.

An RF buncher system has been designed to be installed in the BTL straight section, to re-tune the longitudinal emittance and compensate the twice too large momentum spread generated by the longitudinal space charge along the BTL.



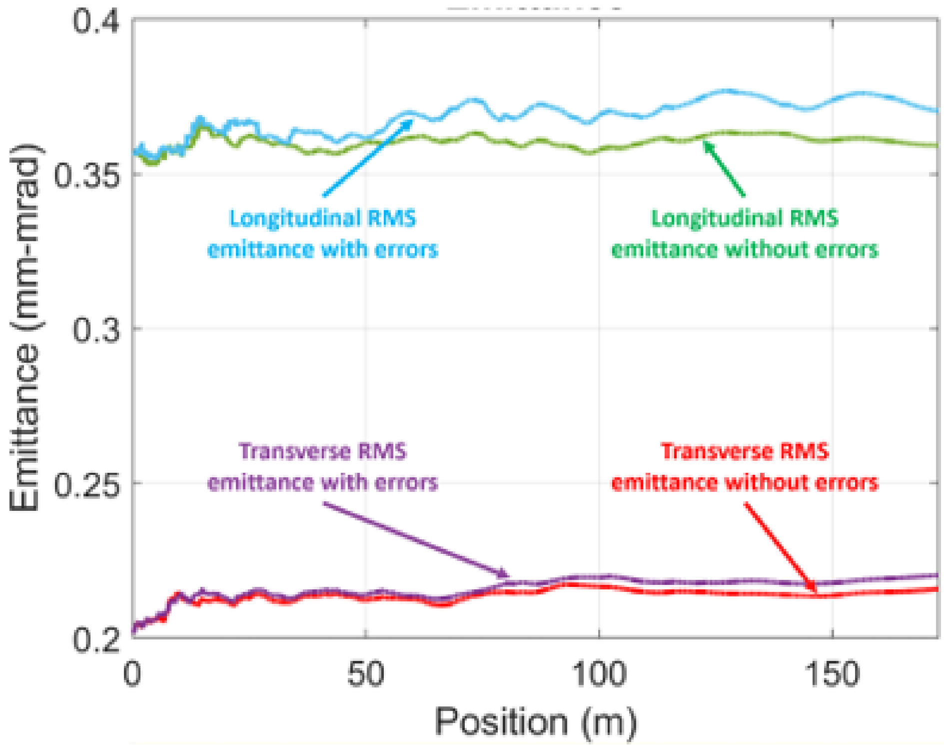
Linac current	2 mA
Booster acceptance	[$-0.55\ \pi$, $+0.55\ \pi$]
Booster bucket height	2.2×10^{-3}
Momentum offset	$+7\times10^{-4}$
Linac RMS momentum spread	2.1×10^{-4}
Linac momentum jitter	1×10^{-4}



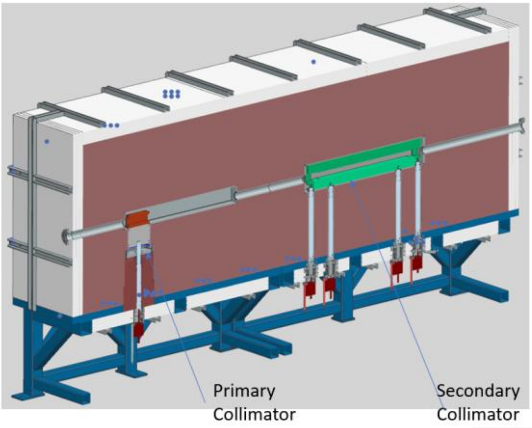
Challenges: Transverse Dynamics

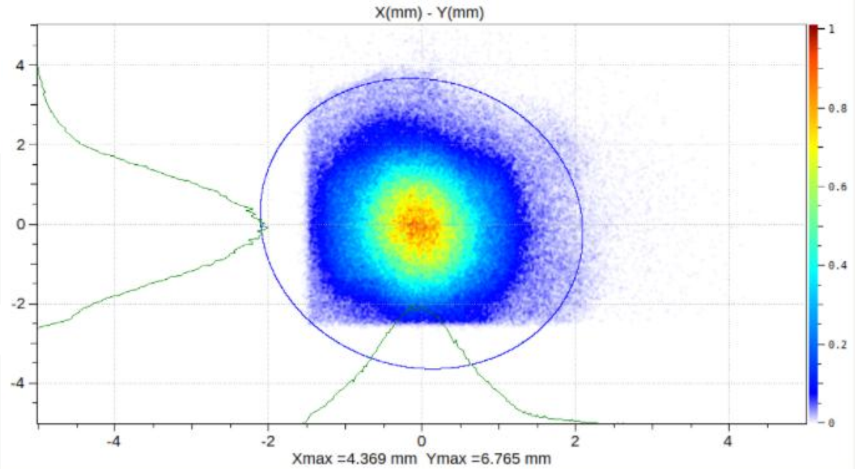
E. Chen, TUPO064
A. Pathak, TUPO062
A. Shemyakin, MOPO045

Linac2 lattice is optimized to decouple optics and preserve emittance in presence of space charge, RF focusing and errors using a new in-house code HELIX.



Transverse coupling correction is critical for the image of the H-V collimator jaws to be mapped on the foil rectangular edges

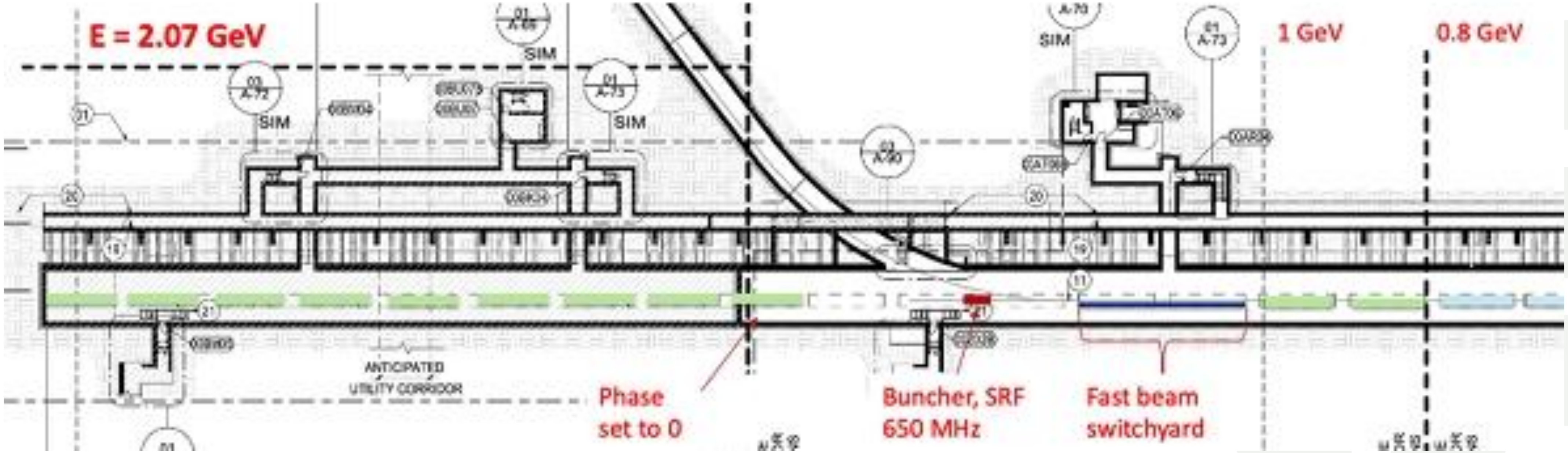




In preparation to Linac 2 commissioning, beam studies are conducted in the existing 400 MeV linac to test and validate beam tuning algorithms, and to develop and test in real conditions the high-level applications which will be used for PIP-II.

Future Upgrades: High Energy

A possible 2-GeV extension of Linac2 would include 11 HB650 cryomodules. The nominal acceleration voltage developed by the β=0.92 elliptical resonator reaches its maximum of 19.9 MV at 2.9 GeV energy compared to 15.9 MV at 800 MeV.



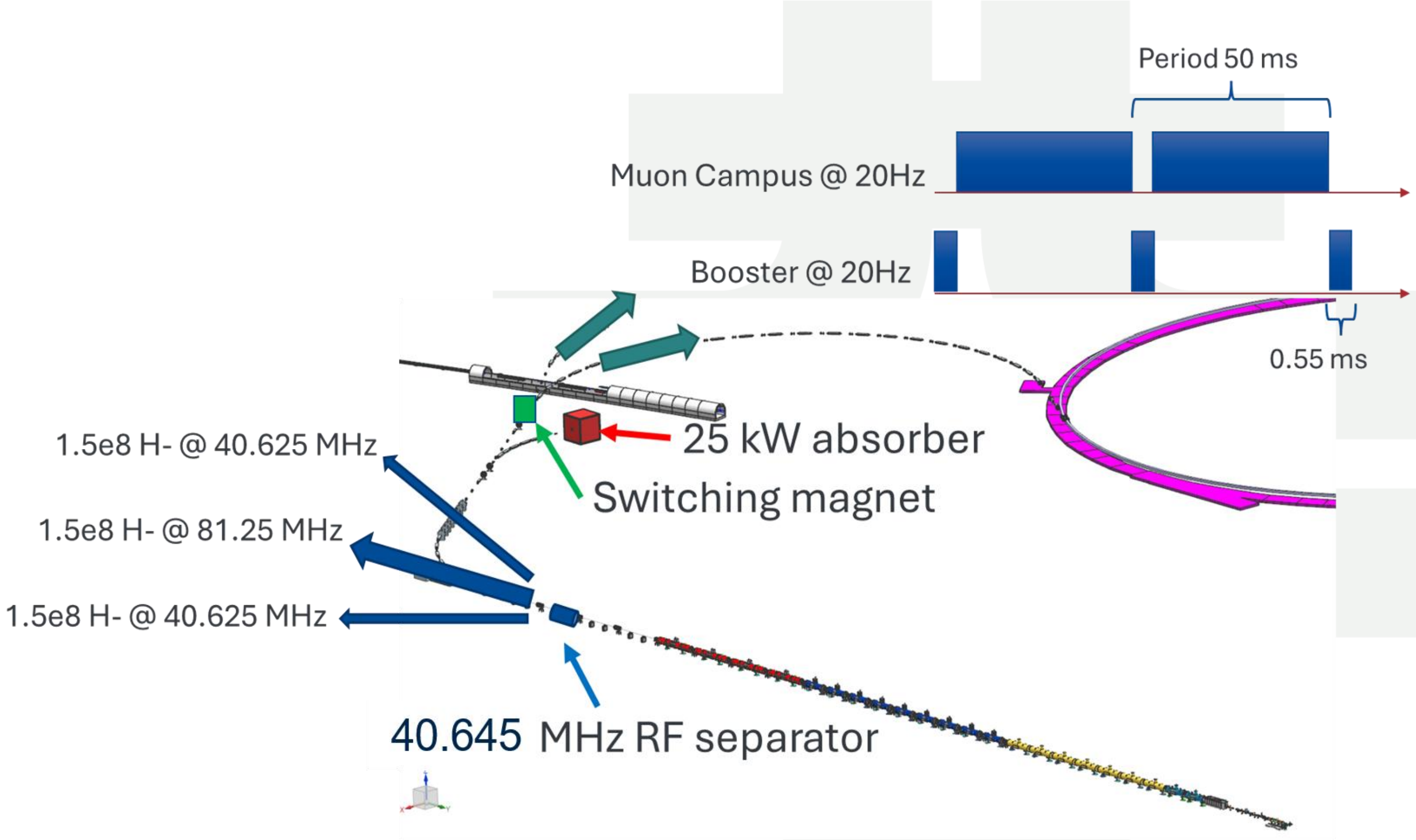
It could be used as the proton driver of the Main Injector either through a new 2-8 GeV Booster or further extended to an 8 GeV linac.

Future Upgrades: CW High Intensity

Linac2 is CW-compatible by design.
This means that all accelerator components can operate in CW mode (except some WFE components needing some upgrades) and that the only restriction to it is that no system is in place to dispose of a MW-range beam power.

CW operation would allow Linac2 to serve multiple beam lines delivering high intensity beam to different users, for example by using a 3-way switching system based on RF separators at ¼ of 162.5 MHz bunch repetition rate.

It could also serve as a multi-MW beam power facility.



Conclusion

- The PIP-II facility will enrich Fermilab with a modern, state-of-the-art SRF linac, now renamed Linac2, which will be the basis for the ambitious neutrino physics program of the LBNF/DUNE international experiment.
- Transition to Operation will occur gradually over the course of the 6 stages of beam commissioning, the last step expected in 2030.
- Attaining 1.2 MW on the LBNF target will be taken over by Fermilab Accelerator Directorate and will take several years.
- Linac2 is expected to operate over at least 40 years and will allow Fermilab to remain on the forefront of accelerator developments and physics programs for the next decades.

Acknowledgments

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PIP-II

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