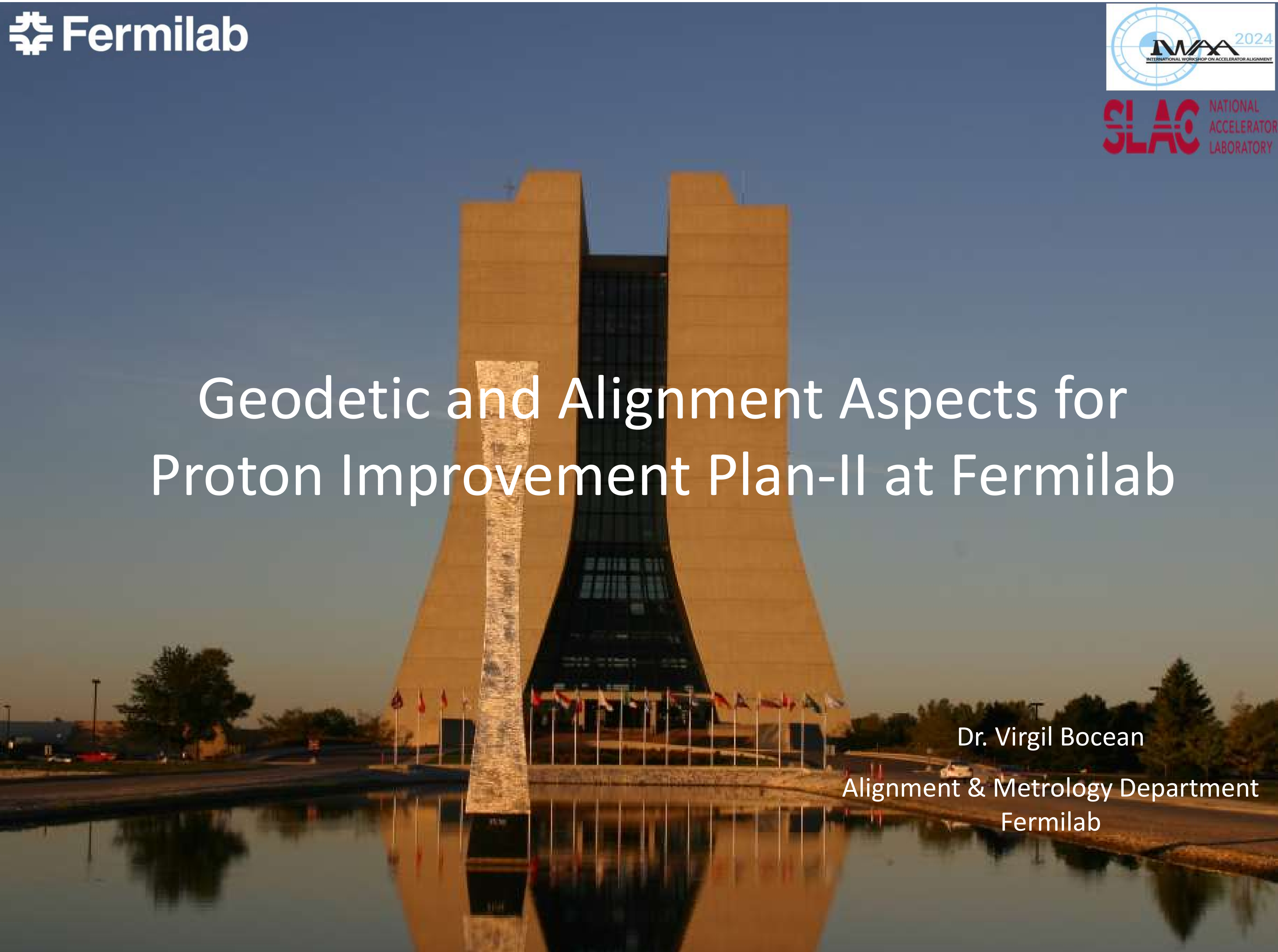

Geodetic and Alignment Aspects for Proton Improvement Plan-II at Fermilab

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Alignment & Metrology Department
Fermilab

Proton Improvement Plan-II (PIP-II) Goals

- **Proton Improvement Plan-II (PIP-II)** is Fermilab's plan for upgrading the accelerator complex
- PIP-II goal is to support long-term physics research objectives as outlined in the P5 plan, by delivering world-leading beam power to the U.S. neutrino program and providing a platform for the future:
  - ✓ Deliver >1 MW of proton beam power from the Main Injector over the energy range 60 – 120 GeV, at the start of LBNF operations
  - ✓ Support the ongoing 8 GeV program including Mu2e, g-2, and short-baseline neutrinos
  - ✓ Provide an upgrade path for Mu2e
  - ✓ Provide a platform for extension of beam power to LBNF to >2 MW
  - ✓ Provide a platform for extension of capability to high duty factor/higher beam power operations
- Proposed schedule : Start operations in newly-configured complex in 2029

PIP-II Technical Approach

- Construct a modern 800-MeV superconducting linac, of continuous waveform CW-capable components, operated initially in pulsed mode
  - Increase Booster/Recycler/Main Injector per pulse intensity by ~50%
- Increase Booster repetition rate to 20 Hz
  - Maintain 1 MW down to 60 GeV **or**,
  - Provide factor of 2.5 increase in power to 8 GeV program
- Modest modifications to Booster/Recycler/Main Injector
  - Accommodate higher intensities and higher Booster injection energy
- This approach as described in the Reference Design Report:
  - ✓ Builds on significant existing infrastructure
  - ✓ Capitalizes on major investment in superconducting RF technologies
    - Fermilab is one of the leading SRF laboratories in the world
  - ✓ Existing linac removed from service upon completion of PIP-II
  - ✓ Siting is consistent with eventual replacement of the Booster as the source of protons for injection into Main Injector (PIP-III)

PIP-II Site Context

- Fermilab's accelerator complex supports a diverse program:

➢ Neutrinos
  - NuMI
  - BNB
  - LBNF

➢ Muons
  - g-2
  - Mu2e

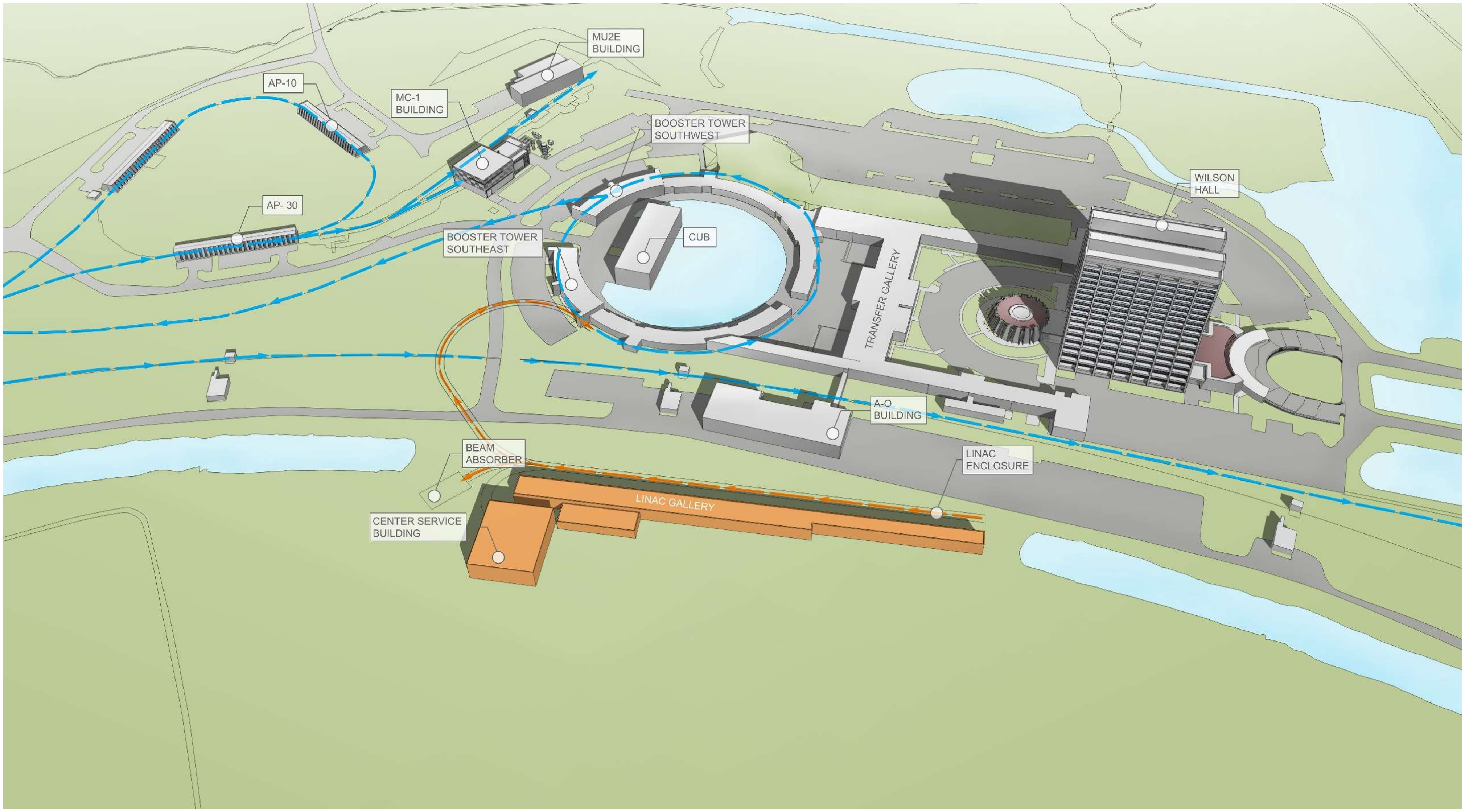
➢ Test Beams

➢ Fixed Target

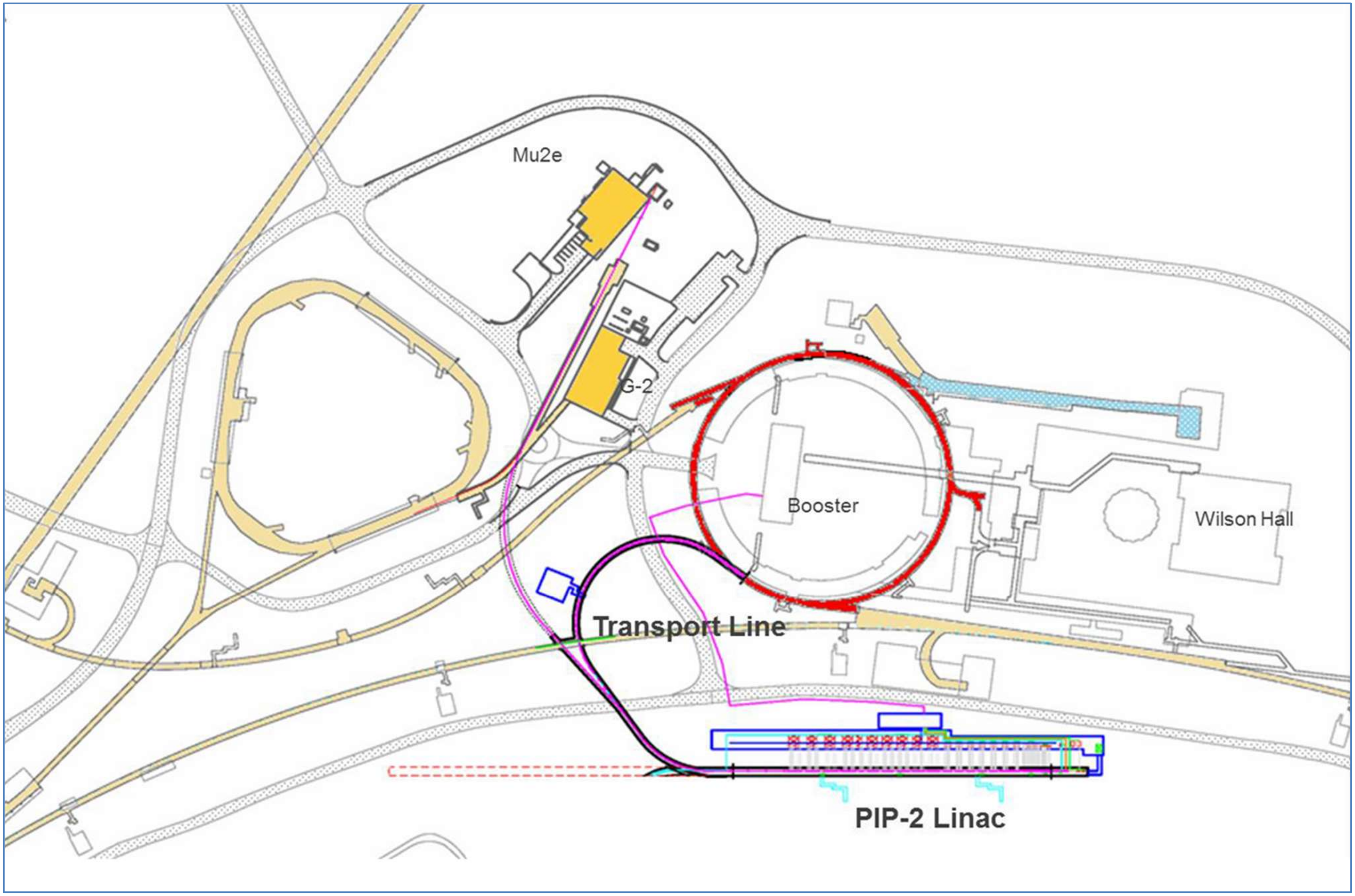
PIP-II Performance Goals

Performance Parameter	PIP-II	
Linac Beam Energy	800	MeV
Linac Beam Current	2	mA
Linac Beam Pulse Length	0.54	msec
Linac Pulse Repetition Rate	20	Hz
Linac Beam Power to Booster	17	kW
Linac Beam Power Capability (@>10% Duty Factor)	~200	kW
Mu2e Upgrade Potential (800 MeV)	>100	kW
Booster Protons per Pulse	6.5×10^{12}	
Booster Pulse Repetition Rate	20	Hz
Booster Beam Power @ 8 GeV	166	kW
Beam Power to 8 GeV Program (max)	83	kW
Main Injector Protons per Pulse	7.5×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	1.0-1.2	MW
LBNF Upgrade Potential @ 60-120 GeV	>2	MW

PIP-II Site Layout

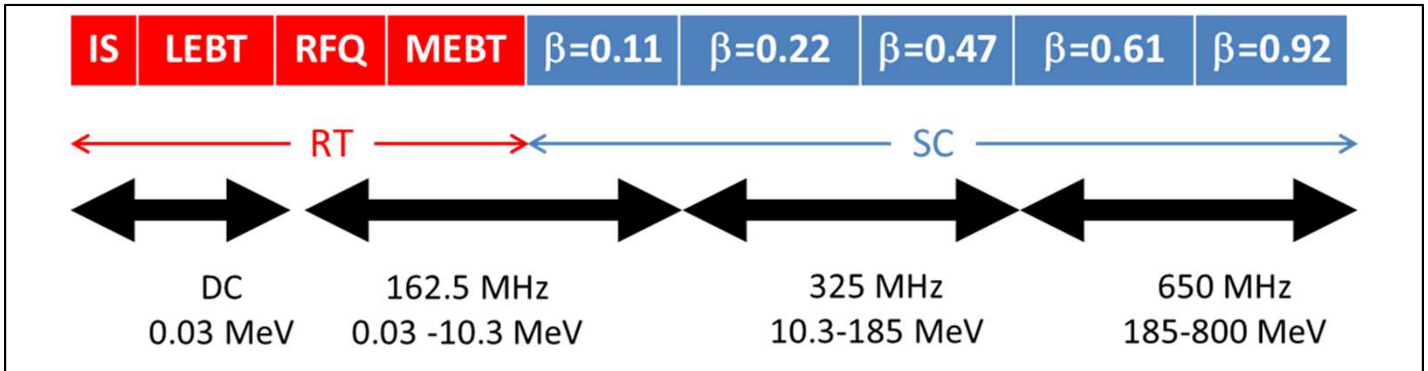


PIP-II connection to Booster and Muon Campus



PIP-II 800 MeV Linac

- The 800 MeV linac will be located in an underground 210 m long tunnel
- It will use superconducting RF accelerating cavities at three different frequencies
- Beam focusing is provided by quadrupoles and solenoids
- A 300 m long transfer line connects to the Booster



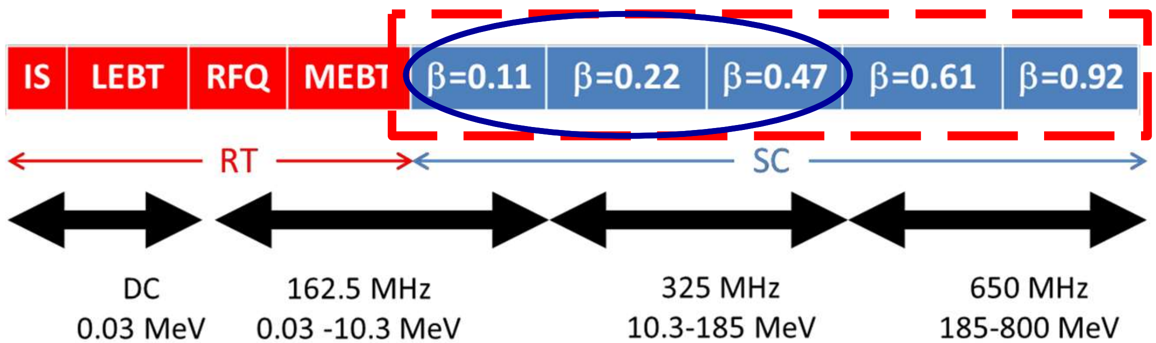
Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-10.3	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	10.3-35	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.47)	325	35-185	35/21/7	SSR, solenoid
LB 650 (β_g=0.61)	650	185-500	33/22/11	5-cell elliptical, doublet*
HB 650 (β_g=0.92)	650	500-800	24/8/4	5-cell elliptical, doublet*

*Warm doublets external to cryomodules

All components CW-capable

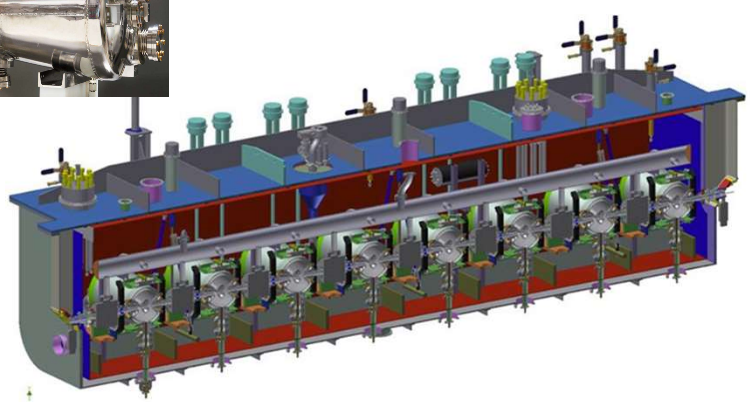
PIP-II Linac SRF Section

- The PIP-II superconducting section will occupy ~150 m of the linac enclosure with:
  - 1 CM (8 cavities) HWR @ 162.5 MHz => at ANL
    - Cryomodule built in FY17 and used in PIP2IT
  - 9 CM (51 cavities) SSR1 & SSR2 @ 325 MHz => at Fermilab
    - One SSR1 Cryomodule built in FY17 and used in PIP2IT



HWR Cavity

SSR Cavities



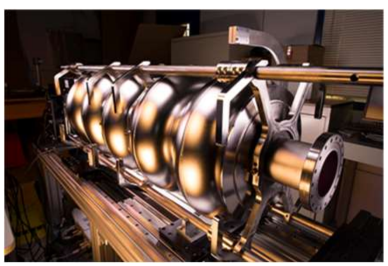
Half-Wave Resonator (HWR) Cryomodule

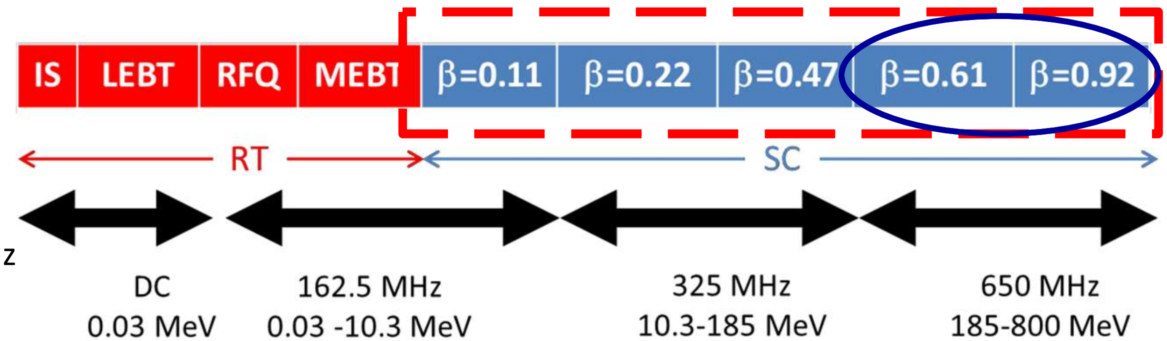
Single Spoke Resonator (SSR) 1-2 Cryomodules

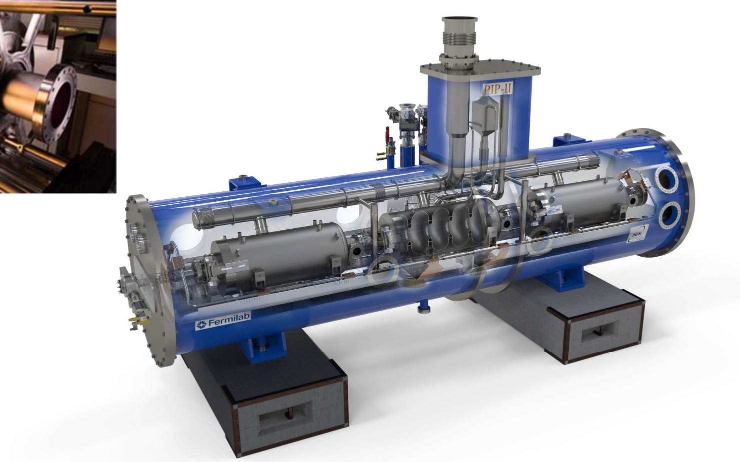
PIP-II Linac SRF Section

- The PIP-II superconducting section will occupy ~150 m of the linac enclosure with:
  - 15 CM (57 cavities) LB & HB @ 650 MHz
    - The prototype HB650 cryomodule was built in 2022 and tested at PIP2IT test stand

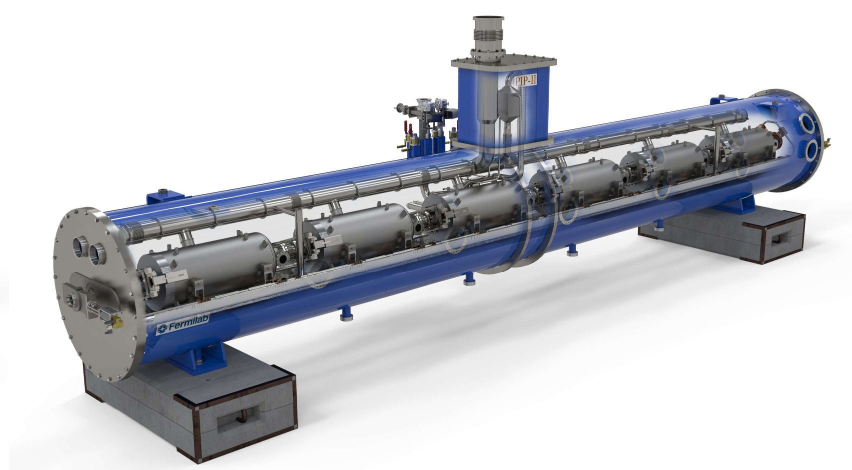
Elliptical Cavity LB/HB 650 MHz







Low Beta 650 (LB 650) Cryomodules

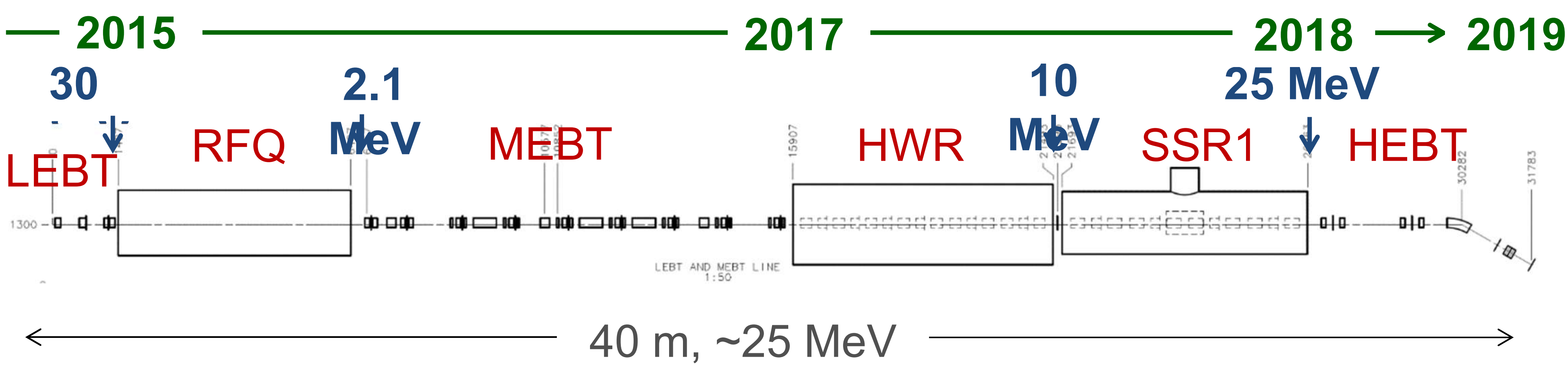


High Beta 650 (HB 650) Cryomodules

PIP-II R&D: PIP-II Injector Test

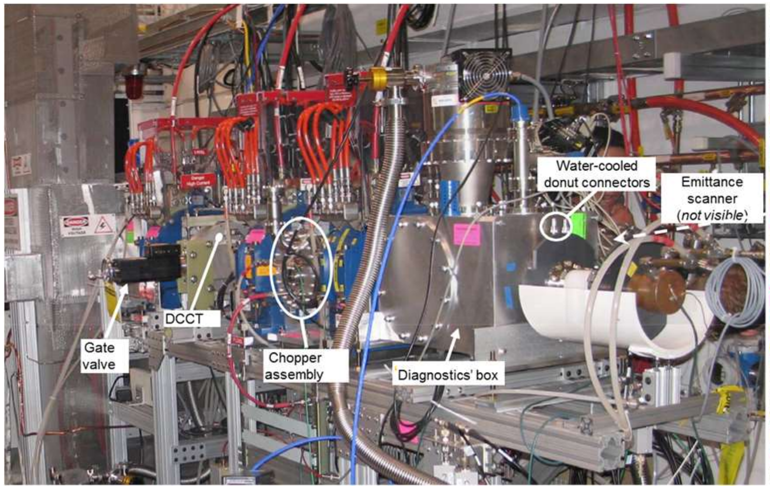
- PIP2IT was installed and run at the CM Test Facility (CMTF) building
- demonstrated the front end of the PIP-II linac by accelerating H- ions up to 25 MeV in about 40 m length
  - ✓ H- ion source: 30 kV, 10 mA
  - ✓ LEBT - pre-chopping
  - ✓ RFQ - 2.1 MeV, CW mode
  - ✓ MEBT – bunch-by-bunch chopper with beam absorber, vacuum management
  - ✓ Operation of HWR in close proximity to 10 kW absorber
  - ✓ Operation of SSR1 with beam - CW and pulsed, resonance control and LFD compensation in pulse mode

Collaborators
- ANL: HWR
- LBNL:LEBT, RFQ
- SNS: LEBT
- BARC: MEBT
- IUAC: SSR1

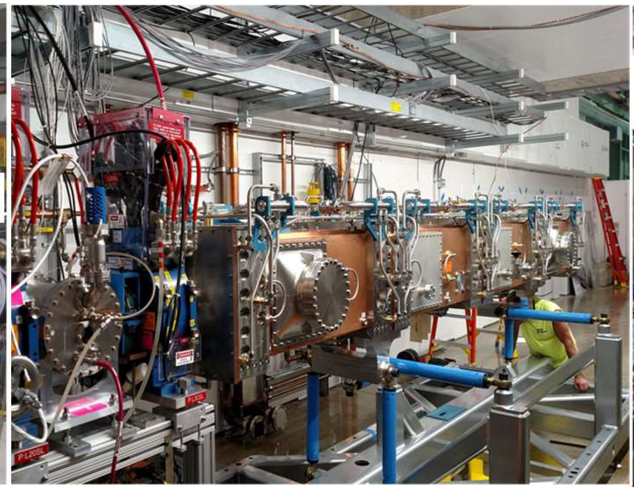


PIP-II R&D: PIP-II Injector Test

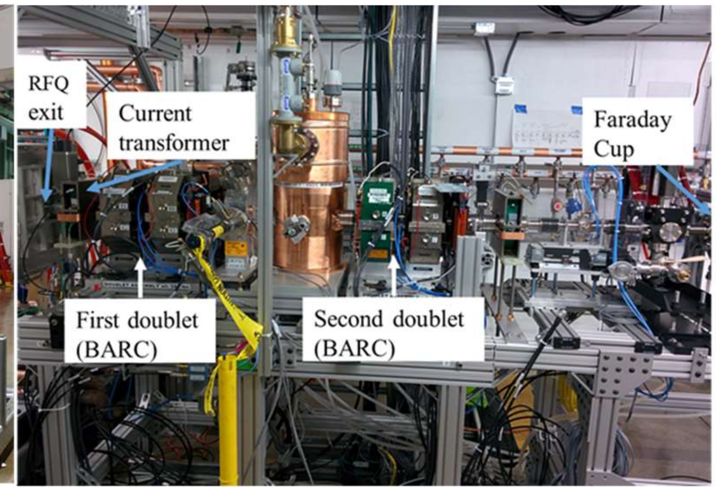
Low Energy Beam Transport (LEBT)



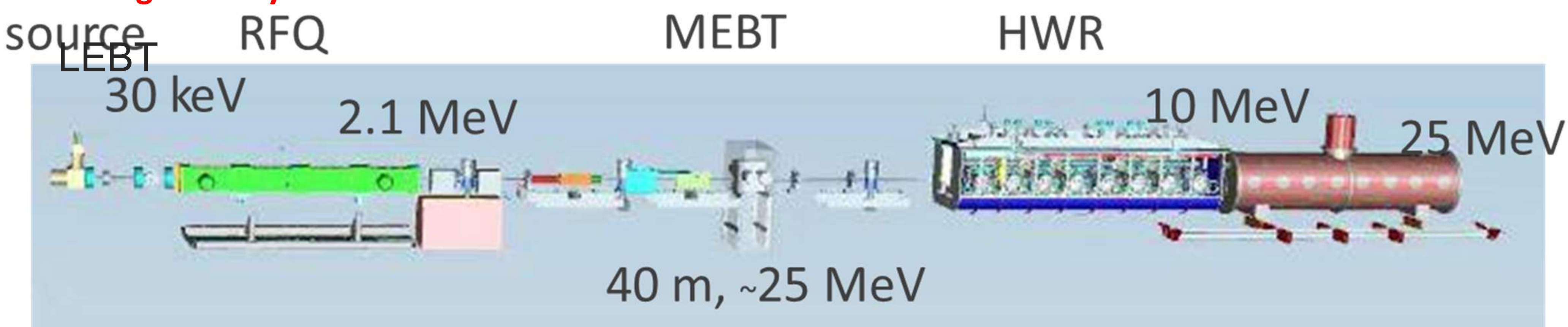
Radio frequency Quadrupole (RFQ)



Medium Energy Beam Transport (MEBT)



- LEBT, RFQ , MEBT and HEBT beamline components aligned < ± 0.25 mm
- PIP2IT completed various phases of installation and running test beam for physics
- **Successful conclusion of the PIP2IT commissioning in 2021 with beam at the designed energy through the cryomodules**



Alignment Tolerances

- Warm Components Tolerance Requirements

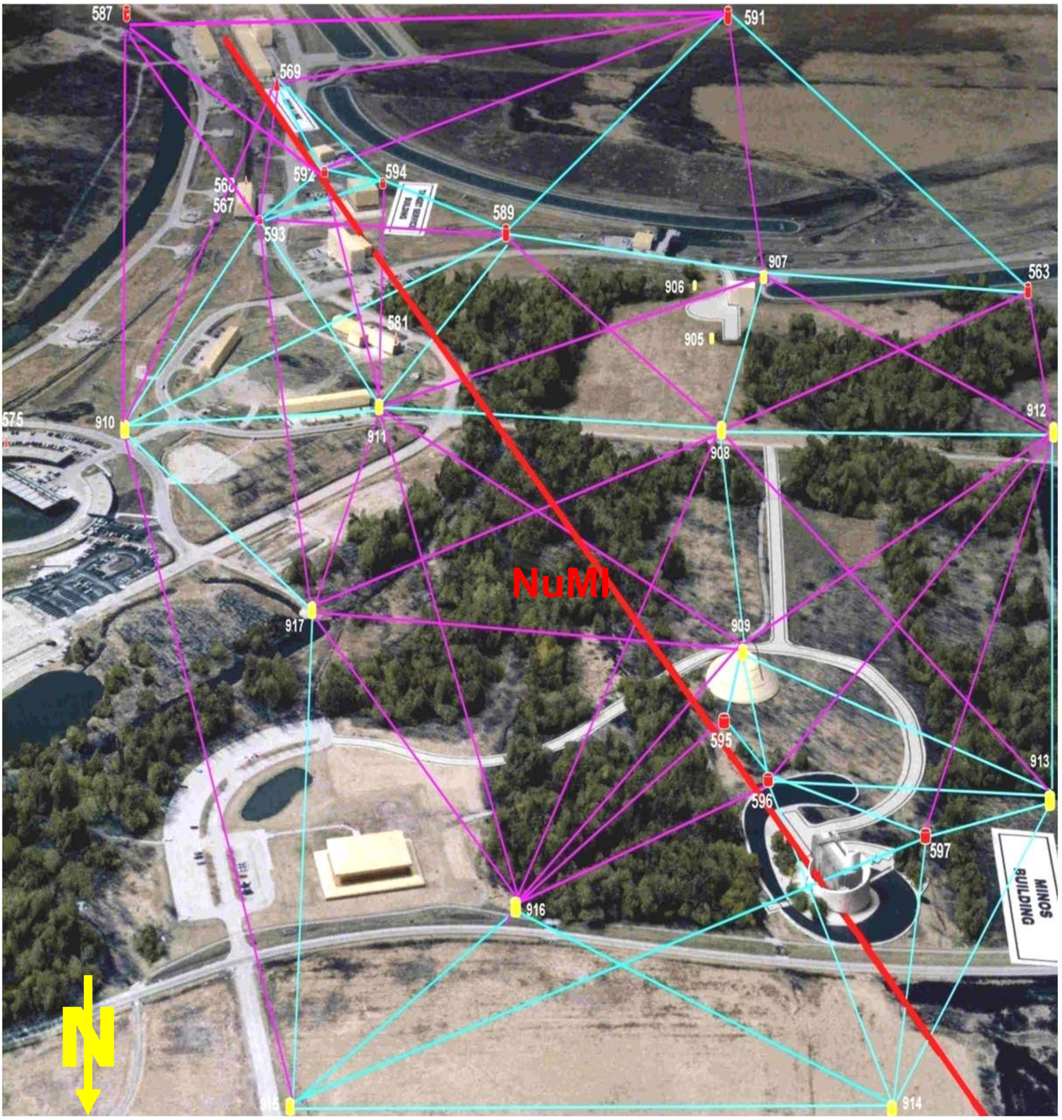
Beam Line Element	X-Offset (mm)	Y-Offset (mm)	Z-Offset (mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
Front End						
Ion source	0.25	0.25	5	*F*	*F*	*NR*
LEBT Solenoid	0.25	0.25	5	*F*	*F*	40
LEBT Dipole Magnet	0.25	0.25	5	*F*	*F*	*F*
LEBT Chopper	0.25	0.25	5	*F*	*F*	*NR*
RFQ entrance/exit	0.125	0.125	2	*F*	*F*	1
MEBT Quad	0.25	0.25	0.5	*F*	*F*	4
MEBT Corrector	1	1	0.5	*F*	*F*	4
Bunching cavities	0.175	0.175	1	*F*	*F*	*NR*
200 Ohm Kicker	0.25	0.05	0.25	*F*	*F*	*F*
MEBT Absorber	1	0.125	1.5	0.25	2	5
Differential Pumping Insert	0.25	0.25	5	1	1	*NR*
SRF Linac						
RT Linac Quad	0.25	0.25	0.5	*F*	*F*	3
RT Steering Dipole	1	1	1	10*	*F**	5
Straight Ahead Dump	1	1	5	5	5	*NR*

Alignment Tolerances

- Cold Components Tolerance Requirements

Beam Line Element	X-Offset (mm)	Y-Offset (mm)	Z-Offset (mm)	Pitch (mrad)	Yaw (mrad)	Roll (mrad)
Cavities						
HWR Cavity	0.5	0.5	1	3	3	*NR*
SSR1 Cavity	0.5	0.5	1	3	3	*NR*
SSR2 Cavity	0.5	0.5	1	3	3	*NR*
LB650 Cavity	0.5	0.5	1	2	2	*NR*
HB650 Cavity	0.5	0.5	1	1	1	*NR*
Solenoids						
Solenoid HWR*	0.5	0.5	1	1	1	5
Solenoid SSR1*	0.5	0.5	1	1	1	5
Solenoid SSR2*	0.5	0.5	1	1	1	5
Cold Instrumentation	**X-Offset (mm)**	**Y-Offset (mm)**	**Z-Offset (mm)**	**Pitch (mrad)**	**Yaw (mrad)**	**Roll (mrad)**
Cold BPMs	0.5	0.5	1	*F*	*F*	5*

Primary Surface Geodetic Network

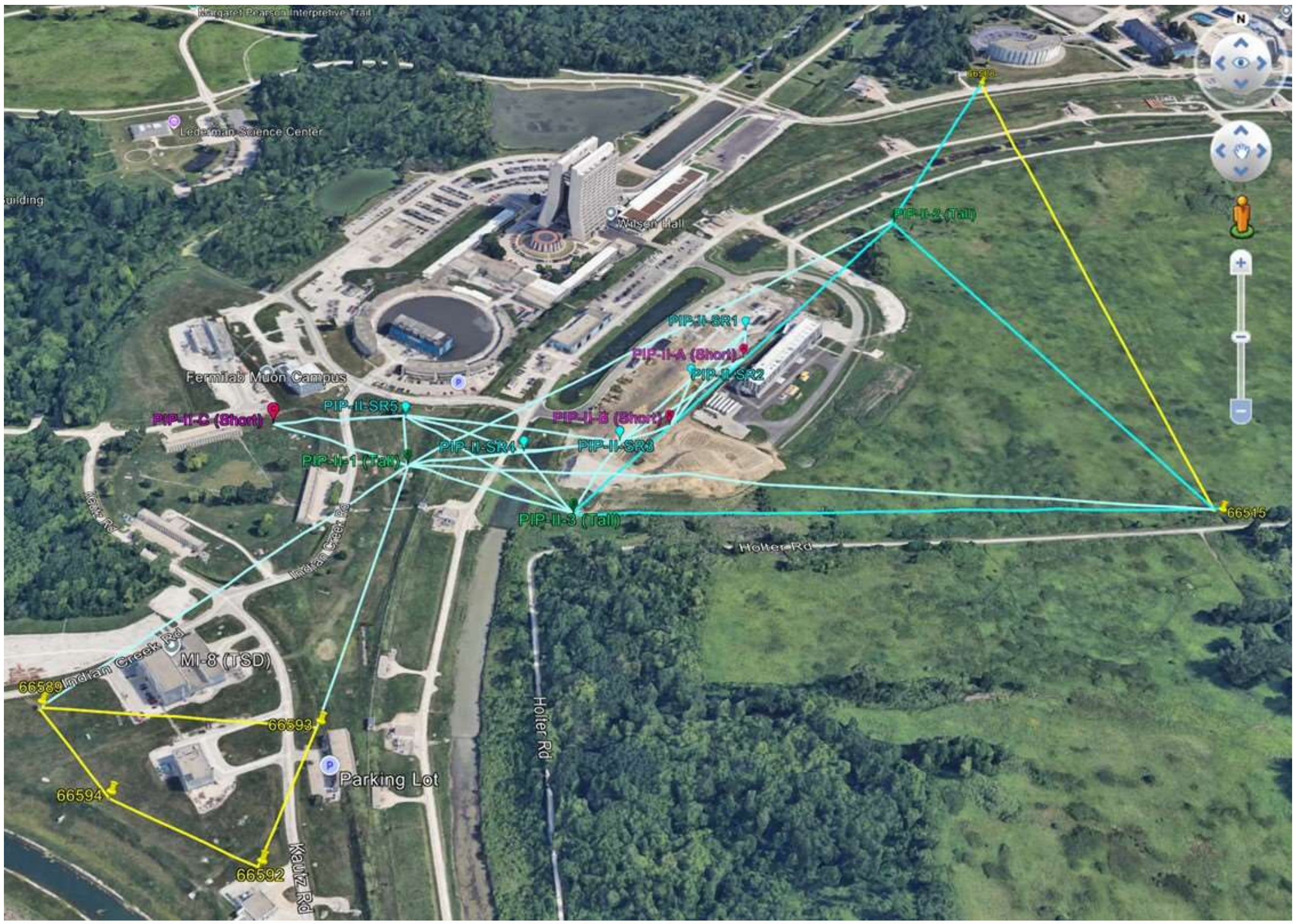


- Provides the basis for construction surveys and for the precision underground control networks
- Existing Fermilab control network (accuracy < 2 mm @ 95% confidence level)
  - horizontal geodetic datum = North American Datum of 1983 (NAD 83) based on the reference ellipsoid Geodetic Reference System 1980 (GRS-80)
  - vertical datum = North American Vertical Datum of 1988 (NAVD 88)
  - geoid model = NGS model Geoid12B
- Includes 4 monuments tied to CORS and IL HARN

•PIP-II surface network will have similar density and configuration as NuMI

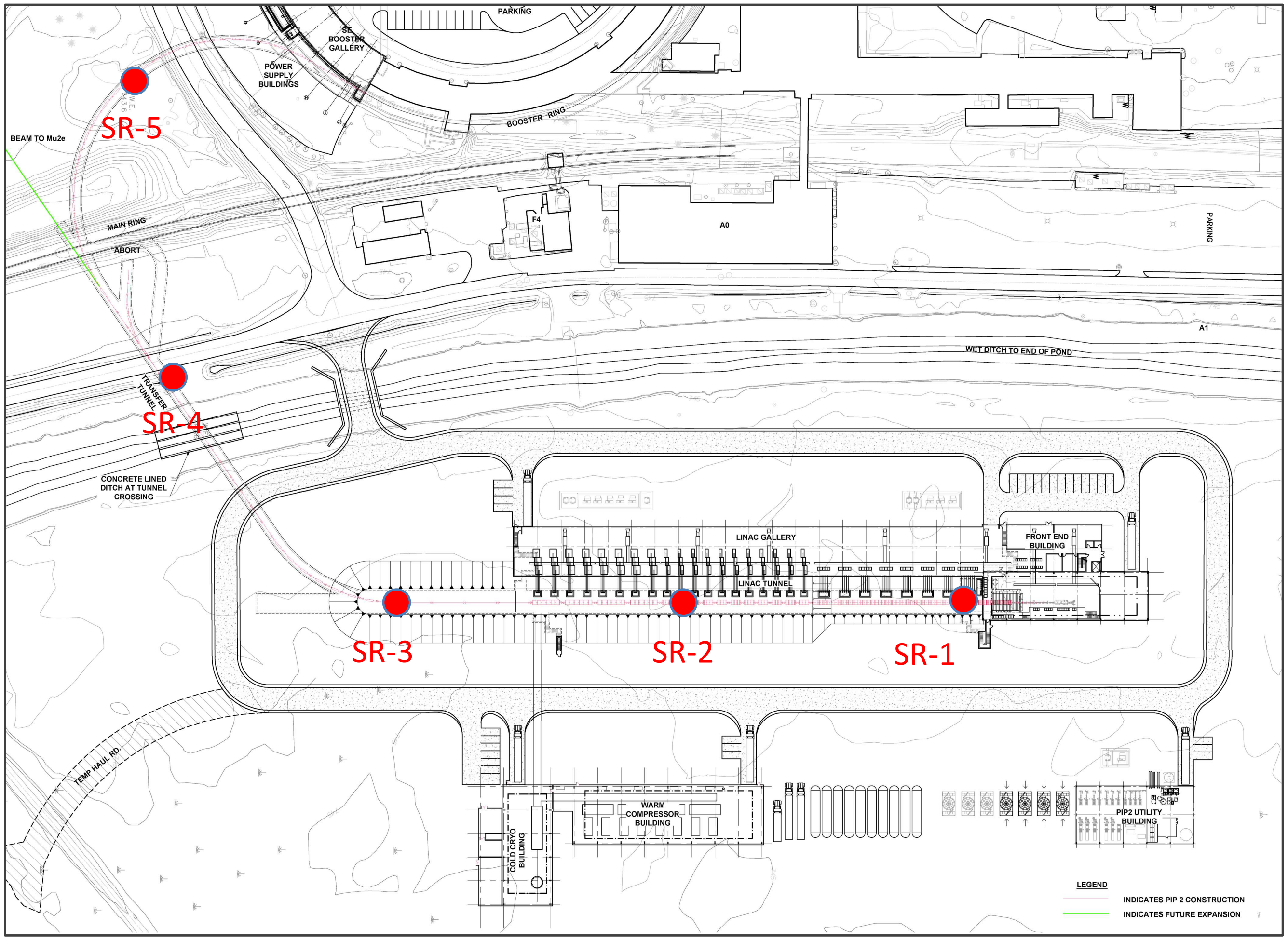
PIP-II Surface Geodetic Network

- Add 11 new geodetic monuments (densification around project site)
- ~400 GPS and terrestrial observations
- expected error ellipses average ±0.5 mm @ 95% confidence level



Precision underground control networks

- Provide vertical sight risers for transferring coordinates from the surface to the underground (better and more efficient for controlling error propagation in a weak geometry tunnel network)
- Network simulations => 5 locations for transferring coordinates from the surface
- Designed adequate procedure for precision transfer of surface coordinates underground

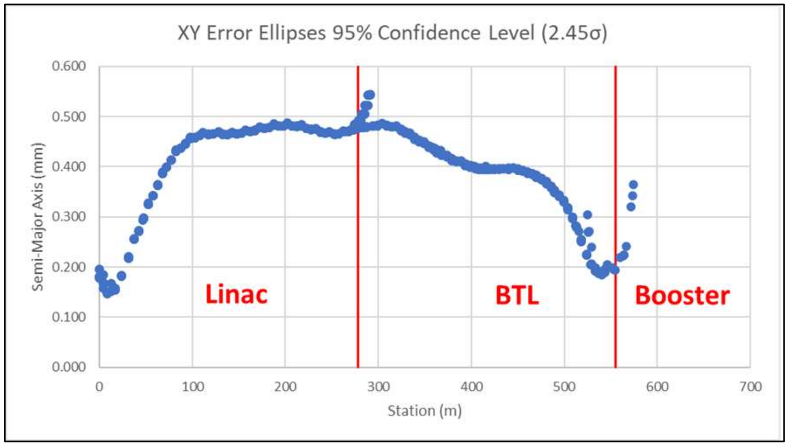


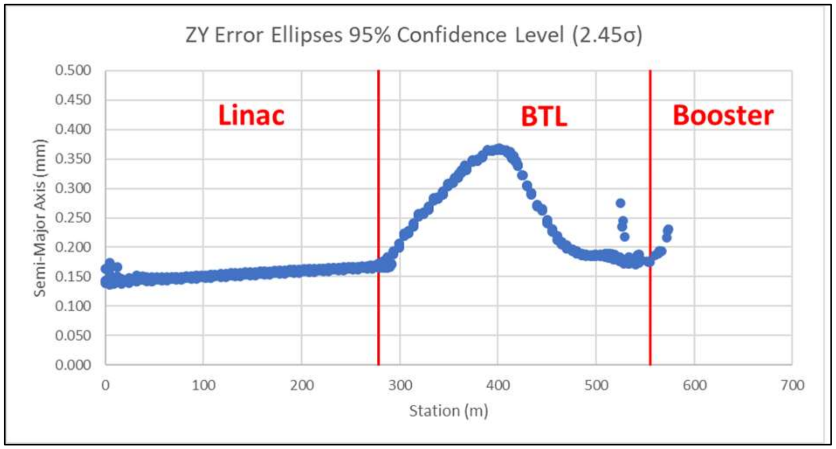
Precision underground control network for Linac and Transfer Line

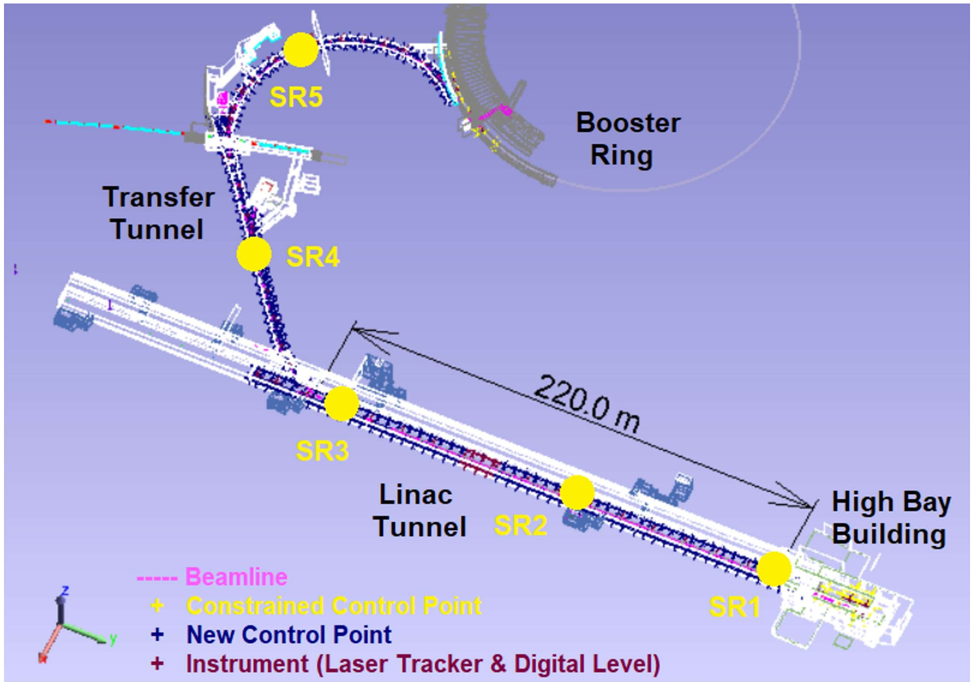
- Established to support the precision alignment of beamline components
- Components alignment wrt Linac and are very similar to MI and NuMI:
  - cryomodules, beam magnets and instrumentation aligned to ±0.25 mm
- Components alignment wrt CM and are similar to LCLS-II:
  - cavities and solenoids aligned to ±0.5 mm and 1- 0.5 mrad angular
- Error budget network requirements ±0.50 mm at 95% confidence level
- Network: continuous from Linac and Transfer Line to Booster
- Constraints at underground transfer points: 5 sight risers
- Network type: Laser Tracker and Precision Digital Level
- Additional Total Station angular and distance measurements to study and control network behaviour
- Beam trajectory Azimuth confirmed by precision Gyro ± 3 arcsec (0.015 mrad) between transfer points

Precision underground control network
Expected accuracy results

- Linac and Transfer Line Errors Ellipses: max ±0.5 mm @ 95% confidence level

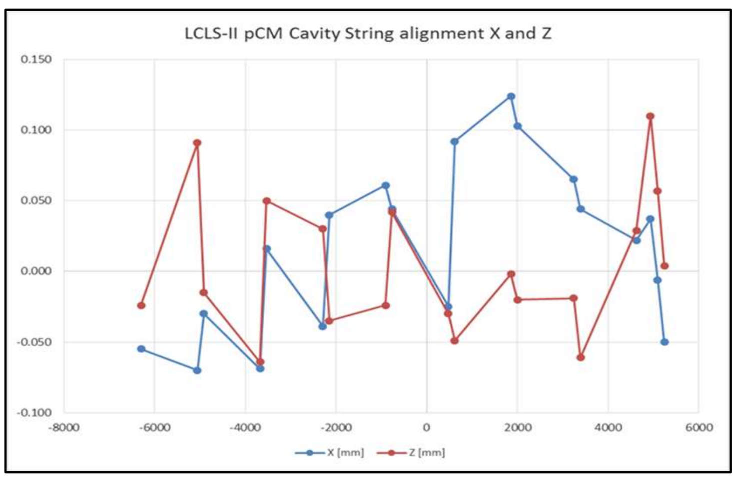


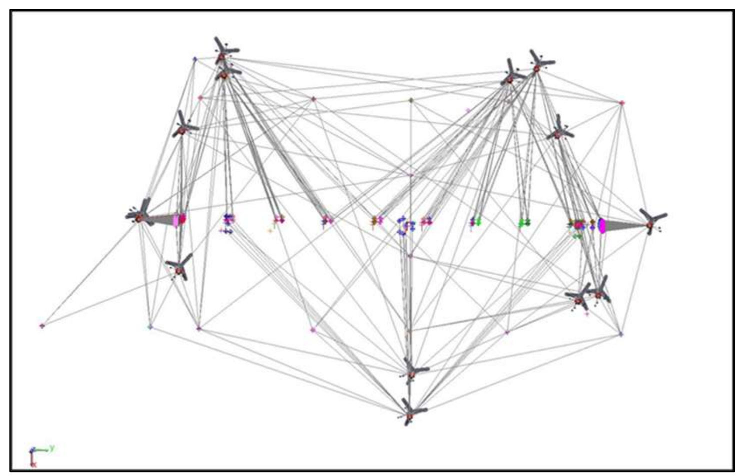




Cryomodules alignment

- Components alignment wrt CM and are similar to LCLS-II:
  - Cavities and solenoids aligned to ±0.5 mm transversal and 1-0.5 mrad angular
- The beam is mainly sensitive to the solenoids angle error: ±0.5 mrad => ± 0.15 mm pitch/yaw (1σ)
- Cryomodule error budget analysis (among others) < ± 0.5 mm
  - ➢ referencing of cavities/solenoids mechanical and magnetic axis < ±0.10 mm
  - ➢ cavity string alignment = ±0.15 mm
  - ➢ cold mas to vessel alignment and referencing to vessel = ± 0.2 mm
  - ➢ string misalignments due to transportation = ±0.2 mm
  - ➢ thermal cycling (warm up, cool down) = ±0.05 mm
- The FNAL cryomodules alignment procedure is well established and proven to achieve similar accuracy requirements as LCLS-II, well within PIP-II requirements
- Referenced and aligned 2 cryomodules for PIP2IT: the Half-Wave Resonator (HWR) and one SSR1





PIP-II current status

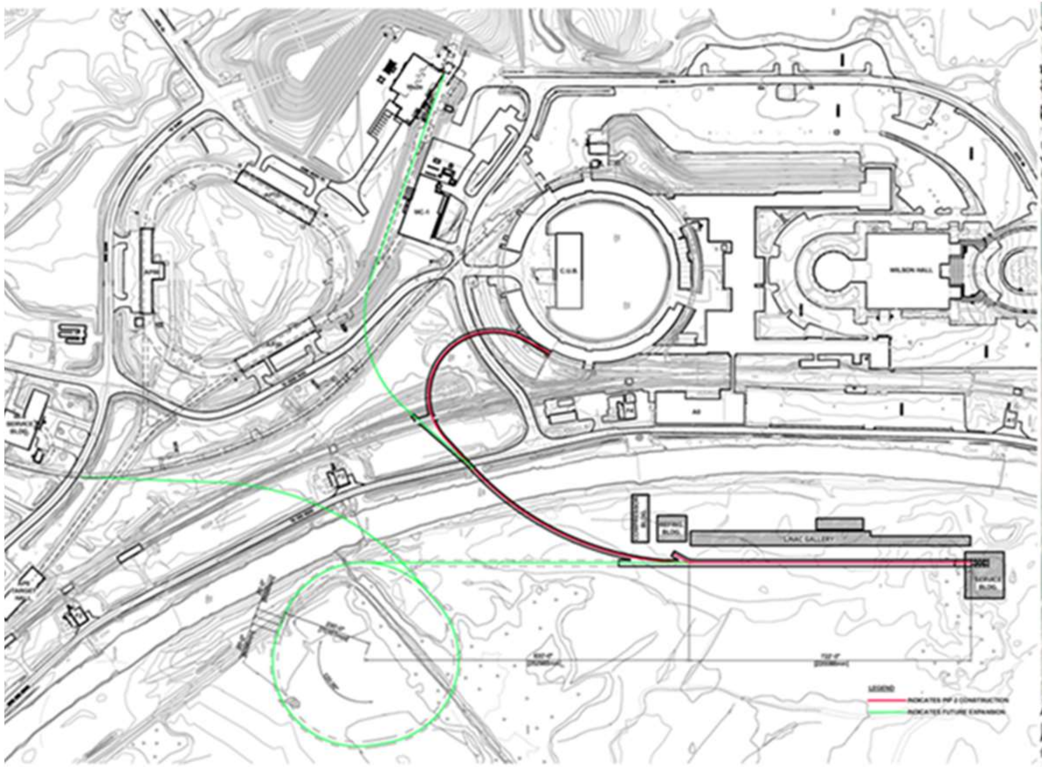
- Partners:

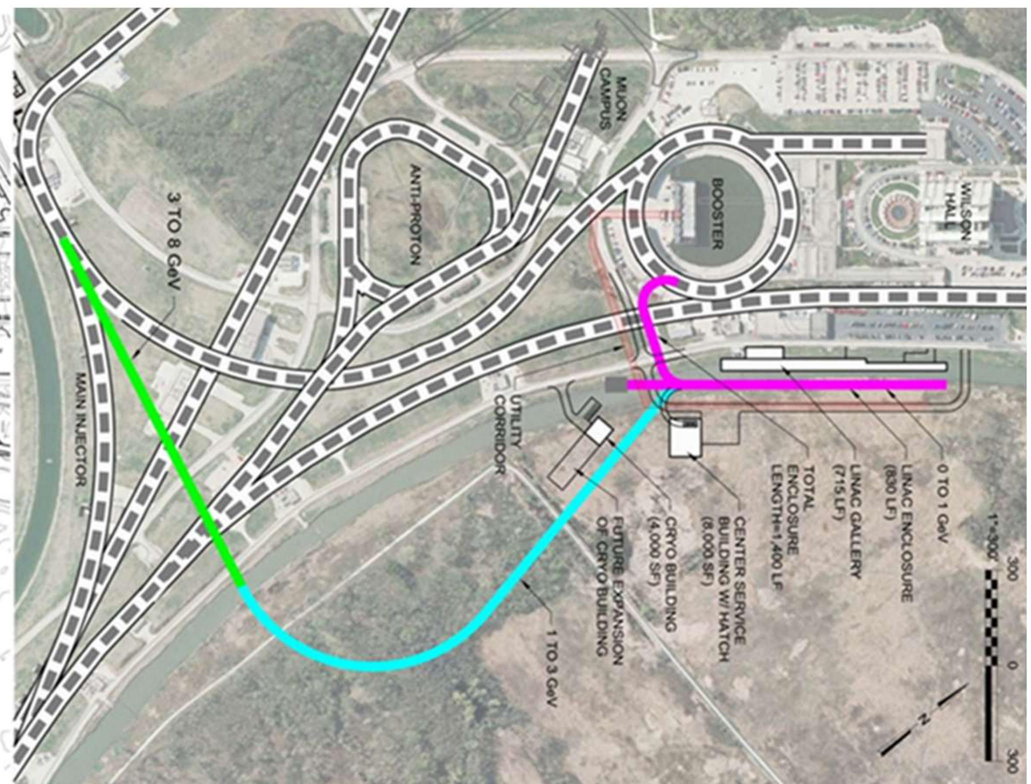
  - International: collaborations are formalized with institutions from India, France, Italy, United Kingdom and Poland
  - National: ANL, LBNL, SLAC most active

- PIP-II current status:
  - ✓ Critical Decision 3a (CD-3a) - the final PIP-II project design has been completed and approval to start construction was given February 2021. Currently, the project is in construction phase.

Future Directions: PIP-III

- The configuration and siting of the PIP-II linac are chosen to provide opportunities for future performance enhancements to the Fermilab proton complex
  - ➢ upgrading the PIP-II linac to CW operations and replacement of the Booster with higher performance accelerator (**PIP-III**)
  - ➢ PIP-III (booster replacement allows multi-MW beams) an essential part of the upgrade to 2.4 MW





S. Holmes

Summary

- PIP-II will allow Fermilab to maintain it's lead with the most powerful neutrino beam in the world, with >1 MW at startup
- Presents a challenge with respect to the detail and complexity of the geodetic and alignment aspects
- From the Alignment perspective the PIP-II is very similar with MI, NuMI, LCLS-II
- Past experience:
  - The absolute global tolerances have been achieved successfully
  - The relative alignment tolerances of beamline components have been also achieved successfully
- Similar geodetic and alignment concepts are proposed and used for PIP-II

Thank you

S. Holmes