Commissioning and Integrated Test of PIP-II Injector Test Facility (PIP2IT)

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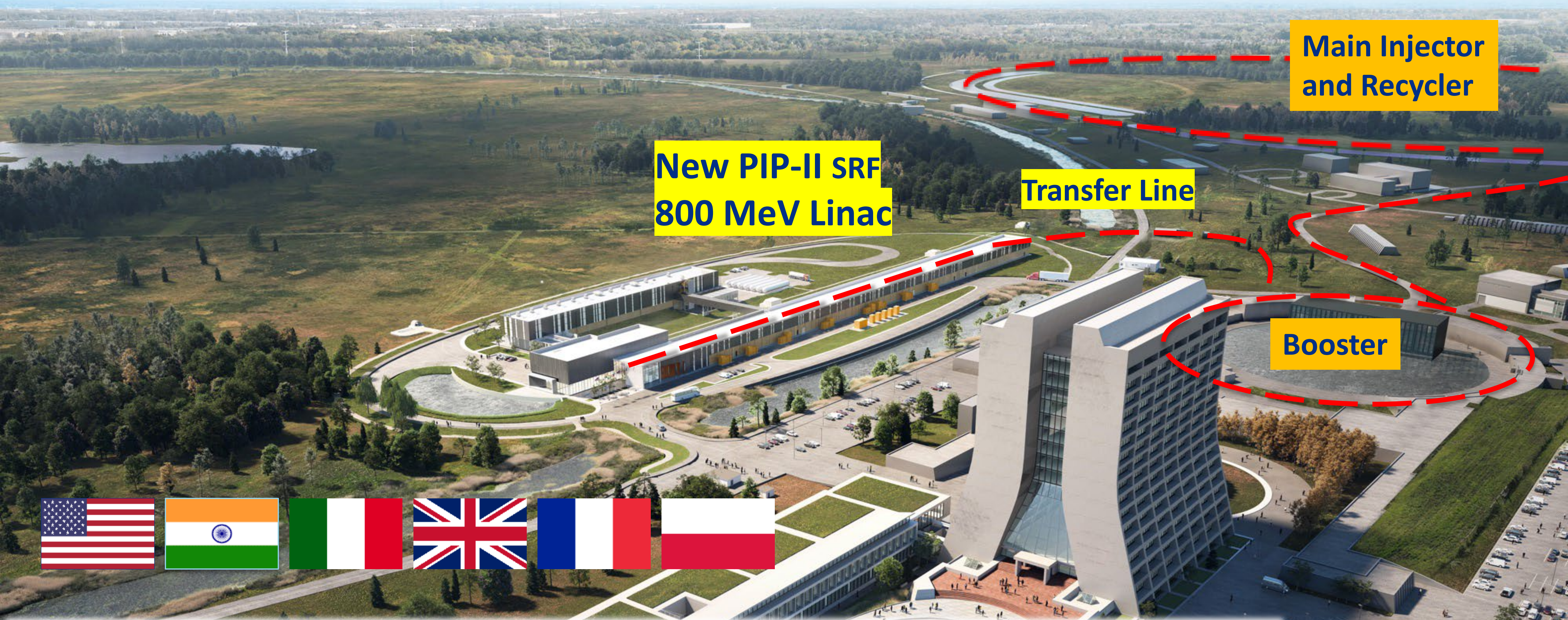
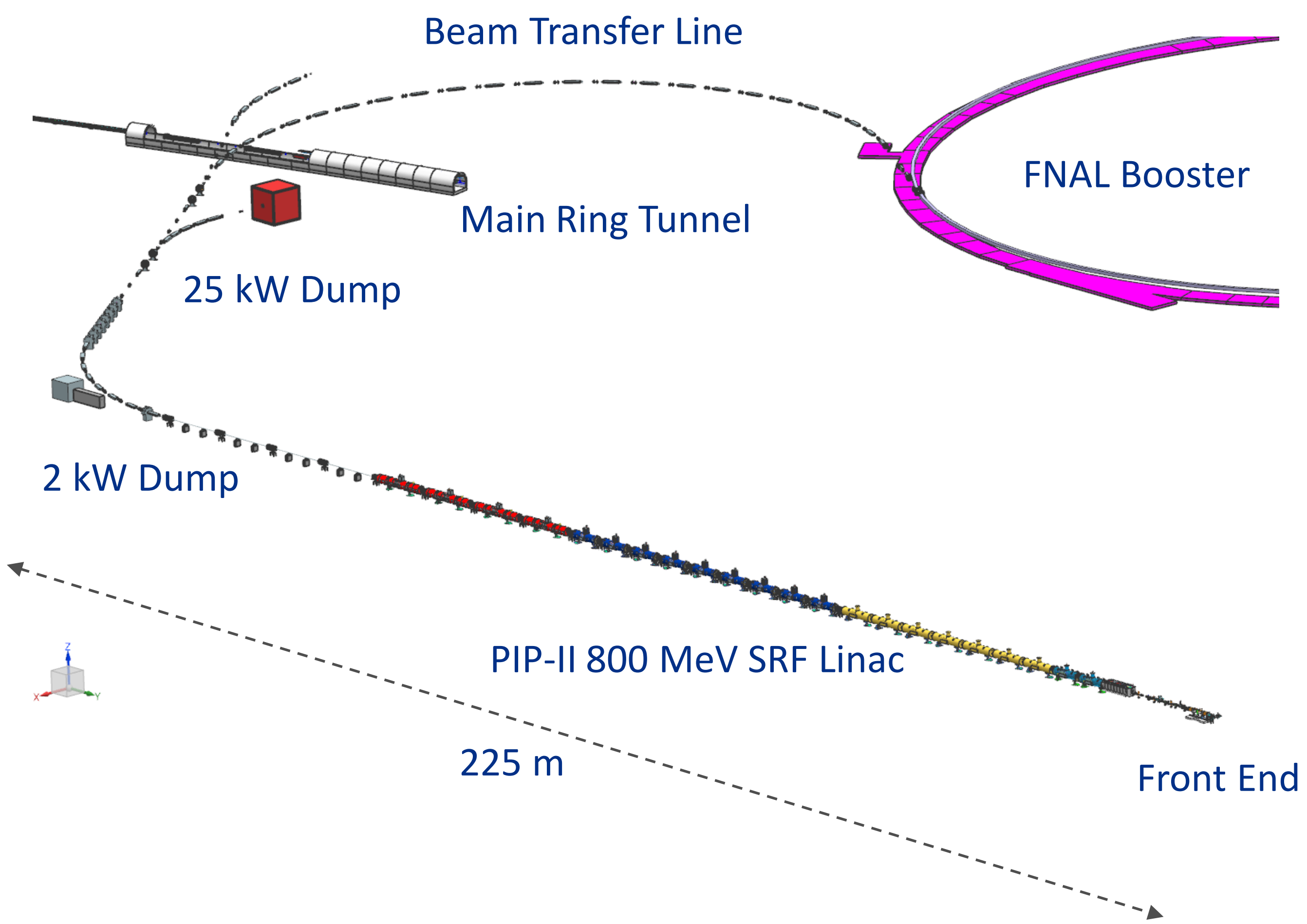
A Partnership of:
- US/DOE
- India/DAE
- Italy/INFN
- UK/STFC-UKRI
- France/CEA, CNRS/IN2P3
- Poland/WUST

Proton Improvement Plan Phase II (PIP-II)



- Reduce the time required for LBNF/DUNE to achieve goals
  - Deliver 1.2 MW of beam power on LBNF/DUNE target at 120 GeV
  - Provide path for future multi-MW upgrade
- Sustain high-reliability, multi-user operations of the Fermilab complex

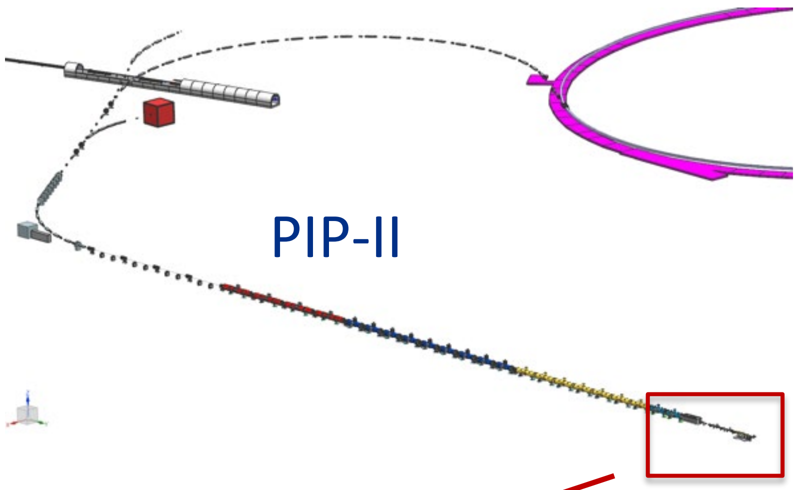
PIP-II SRF Linac and Front End

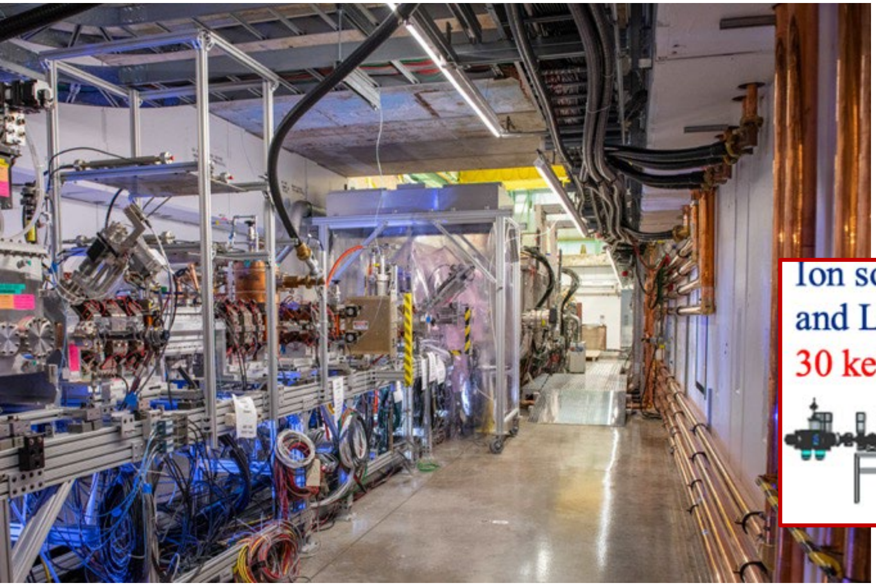


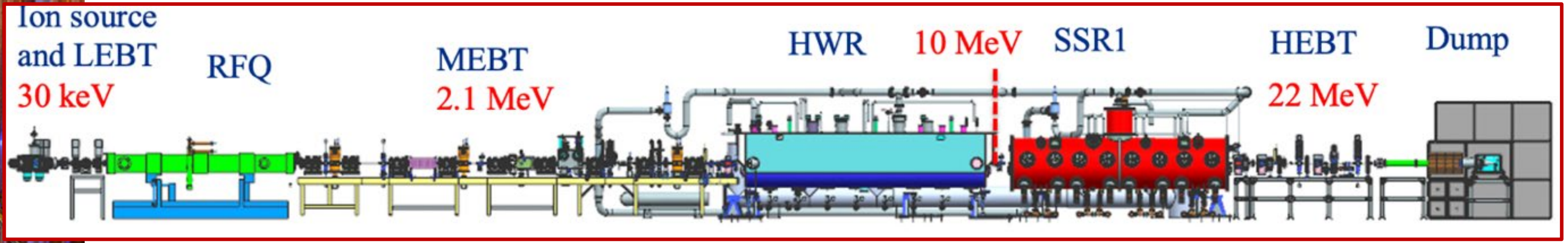
- 800 MeV, 2 mA H− SRF Linac
  - Energy 800 MeV
  - Beam current 2 mA
  - CW-compatible
  - Capable of 1.6 MW CW beam
- Front End plays critical role
  - Generates bunched beam
  - Defines beam quality
  - Generates bunch pattern for Booster injection and users

PIP-II Injector Test (PIP2IT) – Testbed for PIP-II Technologies [1]

- PIP2IT was developed to test PIP-II critical technologies and reduce project technical risks
- PIP2IT was commissioned in two phases
  - Phase 1 (2015 – 2018): Ion source, RFQ, MEBT (2.1 MEV)
  - Phase 2 (2020 – 2021): HWR, SSR1, HEBT, Dump (22 MeV)
- PIP-II components moved to storage, will be installed at PIP-II.
- The test cave converted to cryomodule test stand

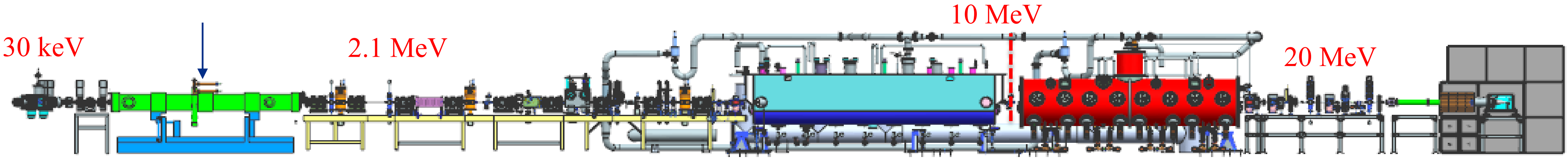






PIP-II Injector Test (PIP2IT) – Testbed for PIP-II Technologies [2]

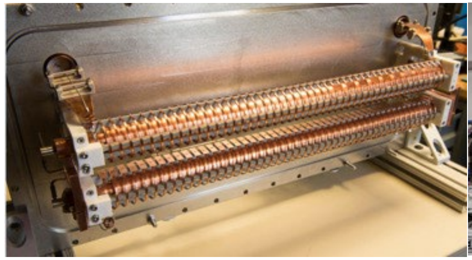
- PIP2IT was a full-fledged SRF accelerator with all systems required to operate the machine
- PIP2IT included all PIP-II Front End critical components

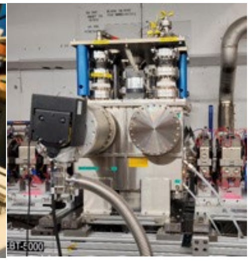


10 mA H^- Source

CW RFQ, 162.5 MHz

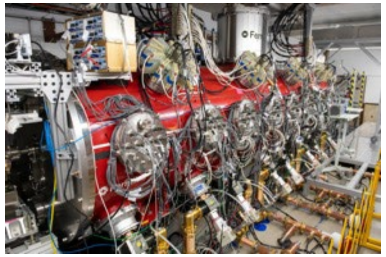
Bunch-by-bunch MEBT Chopper





HWR CM

Spoke Resonator CM

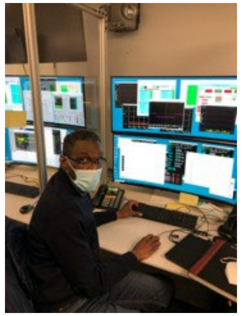


PIP2IT Goals and Deliverables

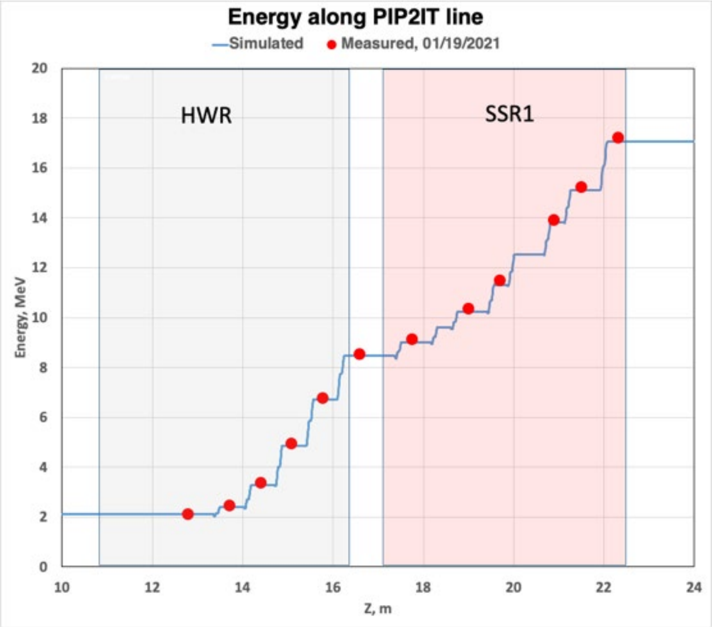
- Reduce PIP-II technical risks and provide commissioning experience that will be used later to shorten commissioning of PIP-II
- Demonstrate beam with LBNF/DUNE parameters at the end of SSR1-1, including chopping pattern required for Booster injection
- Validate beam optics and quantify beam parameters. Test beam tuning procedures
- Test PIP-II technical systems to validate designs and inform design decisions
- Gain experience with installation, testing, and operation of PIP2IT equipment
- Integrate in-kind contributions
- Include lessons learned in the design of technical systems and operational procedures

PIP2IT Successfully Commissioned With Beam

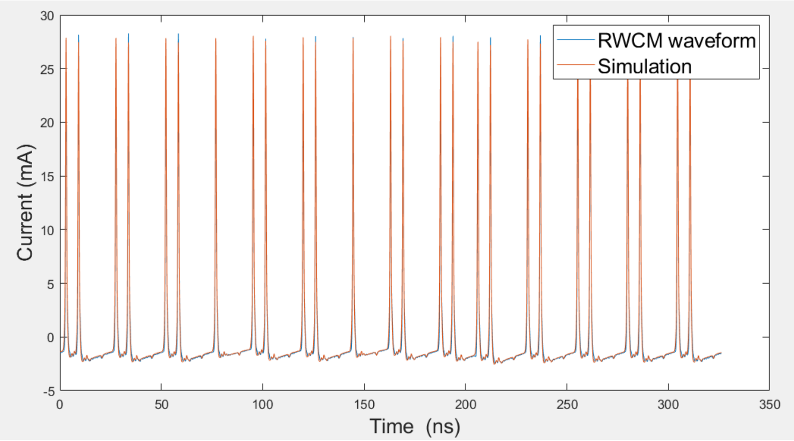
- Beam with PIP-II design parameters demonstrated
  - Energy = 16 MeV
  - Pulse beam current = 2 mA
  - Pulse length = 550 μs
  - Pulse rep. rate = 20 Hz
  - Beam power = 350 W
  - Chopped with the Booster pattern



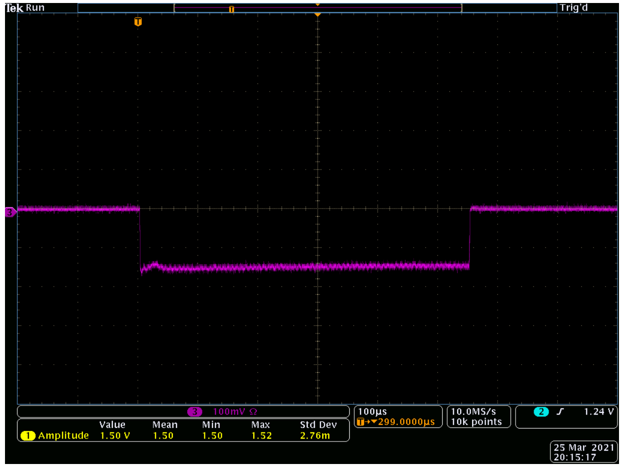
Measured beam energy matches simulated energy profile



”Booster” chopped bunch patter at 16 MeV
Minimum bunch separation is 6.15 ns



550 μs-long, 2 mA beam pulse at 16 MeV

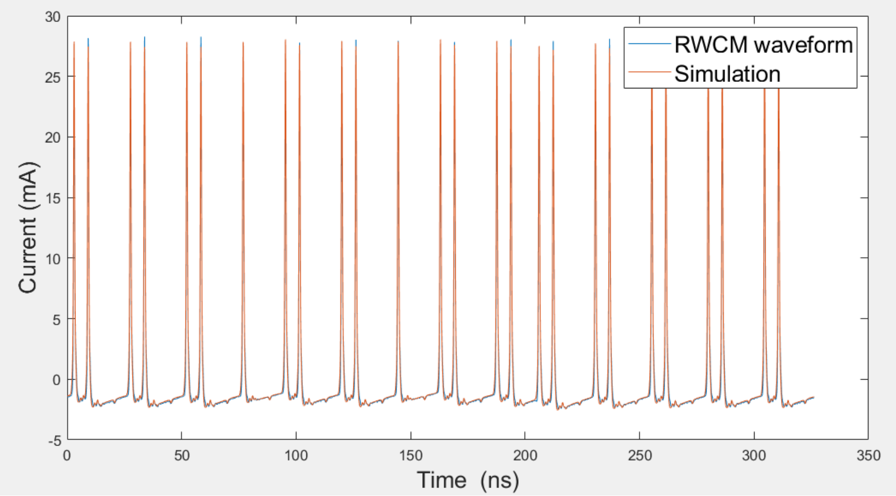


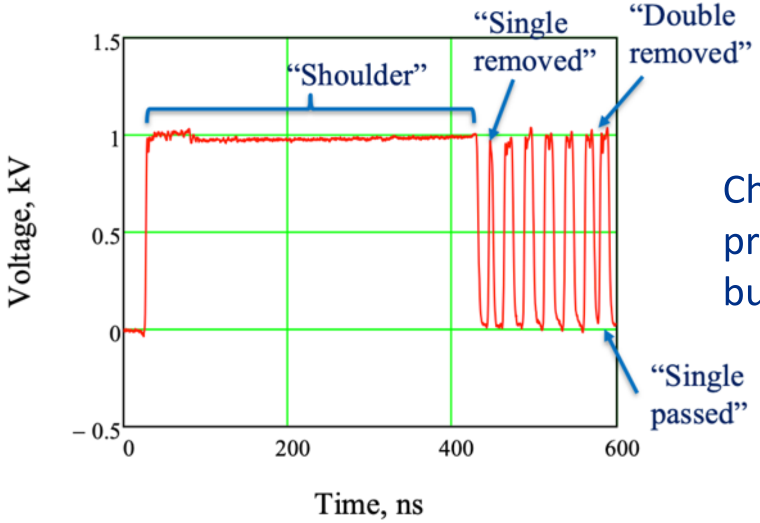
Bunch-by-Bunch Chopper Met Operational Requirements

- MEBT chopper can remove individual bunches at 162.5 MHz
- Goal to remove bunches missing Booster buckets and create required beam patterns for users

	Requirement	Measurement
Extinction Factor	10^{-3}	$< 5 \cdot 10^{-4}$

Bunch pattern measured at 16 MeV at the end of PIP2IT. The pulses are bunches passed by the chopper. Min. separation is 6.15 ns



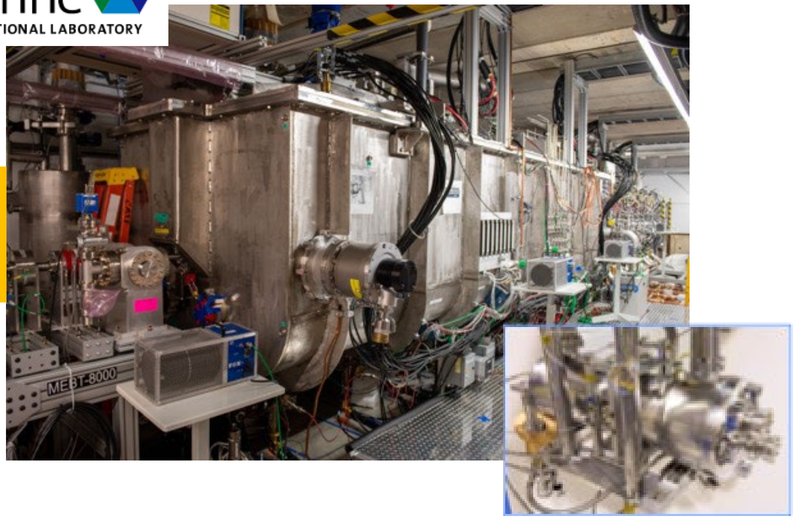


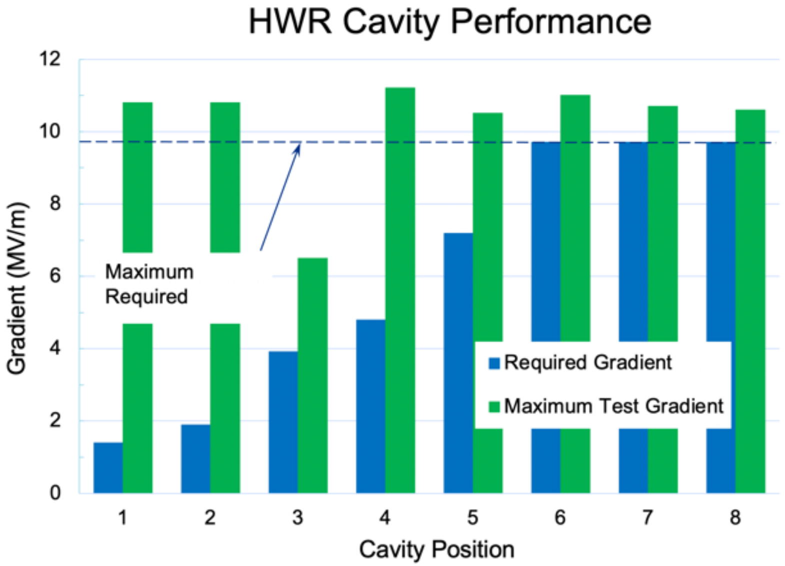
Chopper generates pre-programmed bunch patterns

SRF Cavities and Cryomodules Successfully Tested

Argonne NATIONAL LABORATORY

HWR Cryomodule



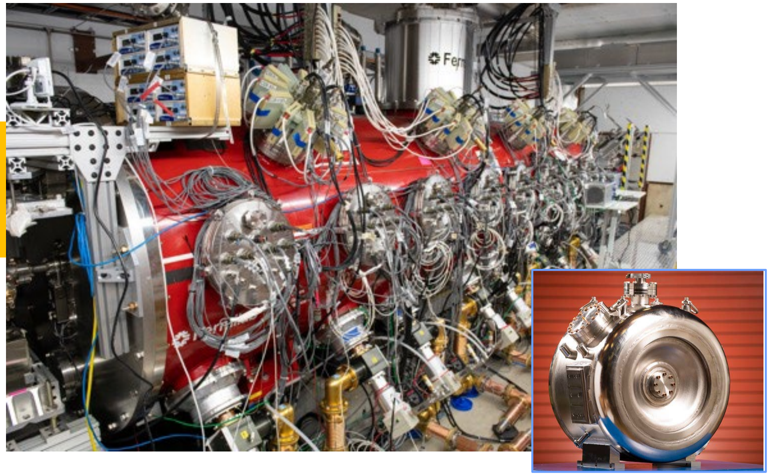


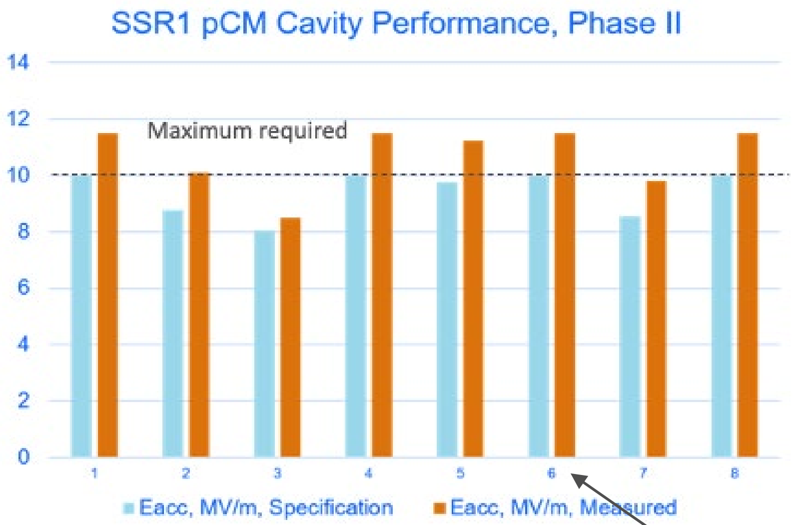
Requirement
$Q_{0(avg)}$= 0.85 x 10^{10}

Measured at Argonne
$Q_{0(avg)}$= 1.5 x 10^{10}

Measured at PIP2IT
$Q_{0(avg)}$= 1.3 ± 0.1 x 10^{10}

SSR1 Prototype Cryomodule





Requirement
$Q_{0(avg)}$= 0.82 x 10^{10}

Measured at PIP2IT
$Q_{0(avg)}$= 0.35 x 10^{10}

Lower Q_0 correlated with measured residual field inside the cryomodule.

BARC

PIP-II

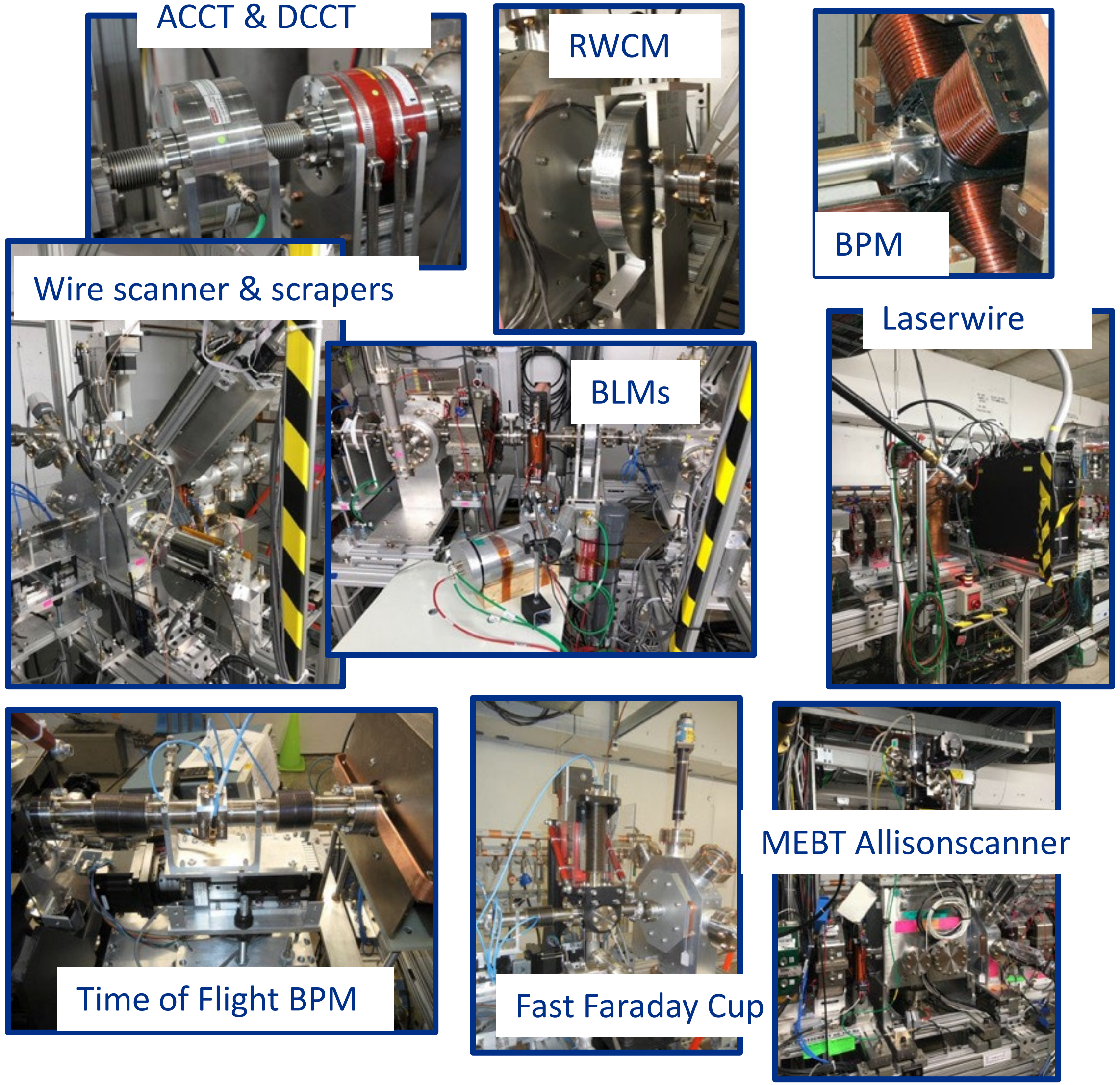
LLRF Performance Met Requirements

- Demonstrated phase and amplitude stability easily met requirements

Value	Requirement	HWR (mean)	SSR1 (mean)
Amplitude	0.06%	0.01%	0.02%
Phase	0.06°	0.009°	0.01°

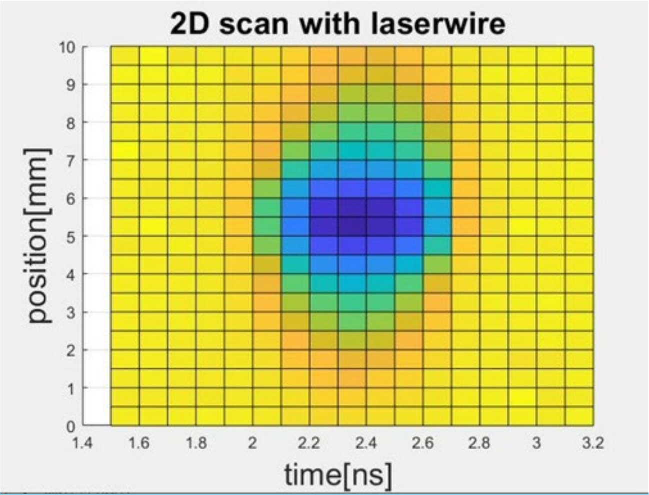
- 14 cavities out of 16 met the microphonics 20 Hz limit
  - Not a problem for PIP2IT and most PIP-II cavities due to sufficient RF power
  - Needs to be further investigated.
- Successful international collaboration

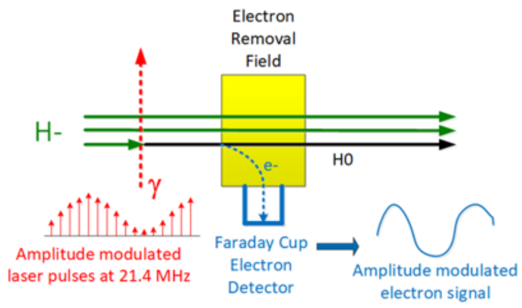
Beam Instrumentation – Multiple Systems Tested



Highlights

- BPMs are versatile diagnostics providing wealth of information about beam and accelerator
- Detailed characterization of the beam in the front end is a must
- Low energy CMs have large betatron phase advance but limited diagnostics
- Lower-power Laser Wire Monitor with fiber distribution successfully tested





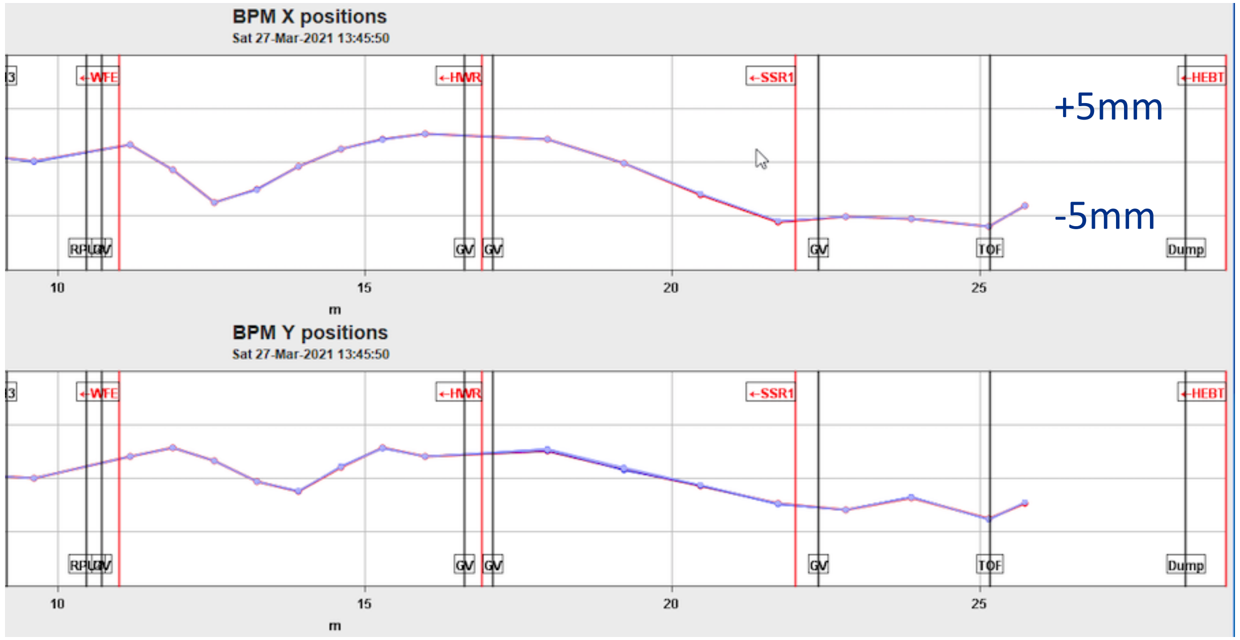
Machine Learning Software Tested With Beam

Bayesian Optimization with Gaussian Processes applied to optimize orbit in PIP2IT

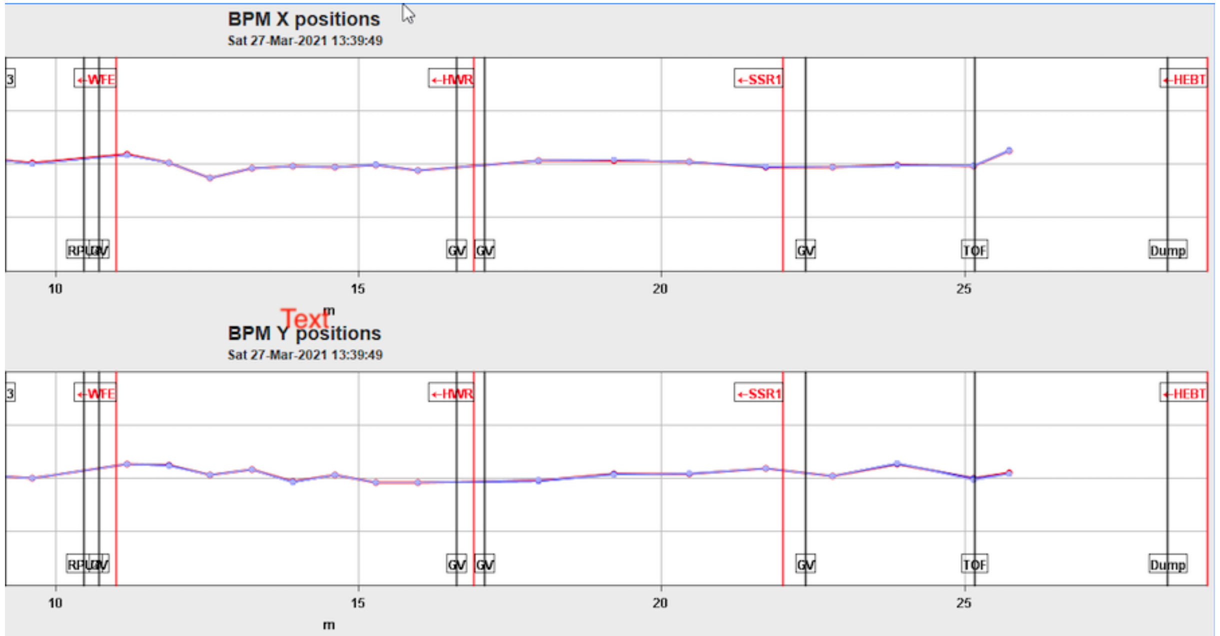
– Demonstrated convergence faster than Simplex

Results of orbit alignment in HWR and SSR1 Cryomodules using Bayesian Optimization

Before Correction



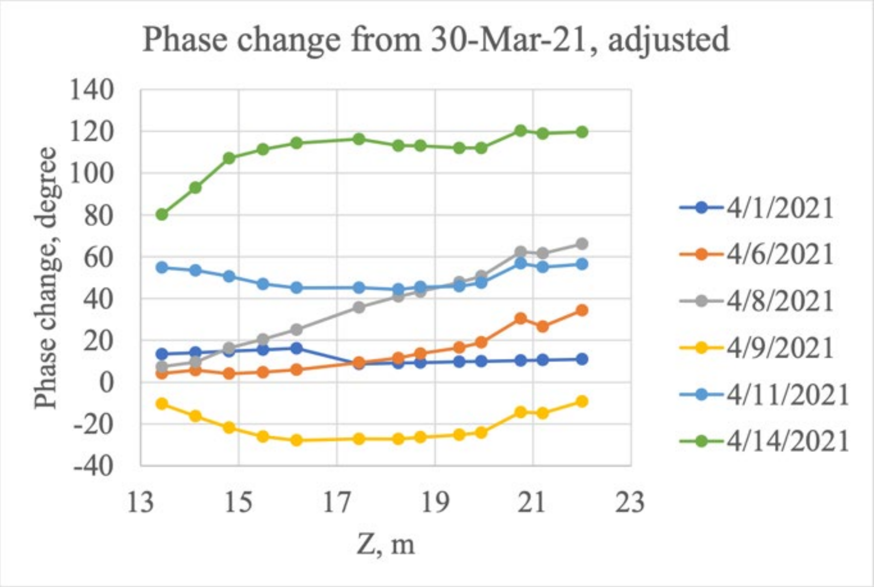
After Correction using Bayesian Optimization



PIP2IT Operational Challenges

- HWR cavities 1 – 3 were not used to accelerate the beam
  - HWR Cavity 1 and 2 could not be tuned to 162.5 MHz without exceeding tuner specifications. Cavities tested in SEL
  - HWR cavity 3 coupler bias circuit developed a short
  - *Impact:* Design energy and beam quality cannot be achieved. High sensitivity to errors
  - Problems will be fixed before installation at PIP-II

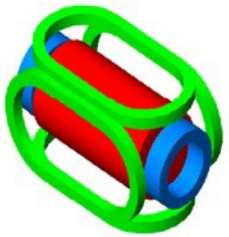
- Cavity phasing repeatability
  - Typically, jumps correlated with PIP2IT RF shutdowns
  - Can be caused by a small (~0.25%) variation in the beam energy in MEBT, Phase error is magnified by the long MEBT
  - Path forward for PIP-II:
    - Keep amplifiers and electronics running
    - Address the source of the energy change in MEBT
    - Implement feedback using two cavities and two BPMs



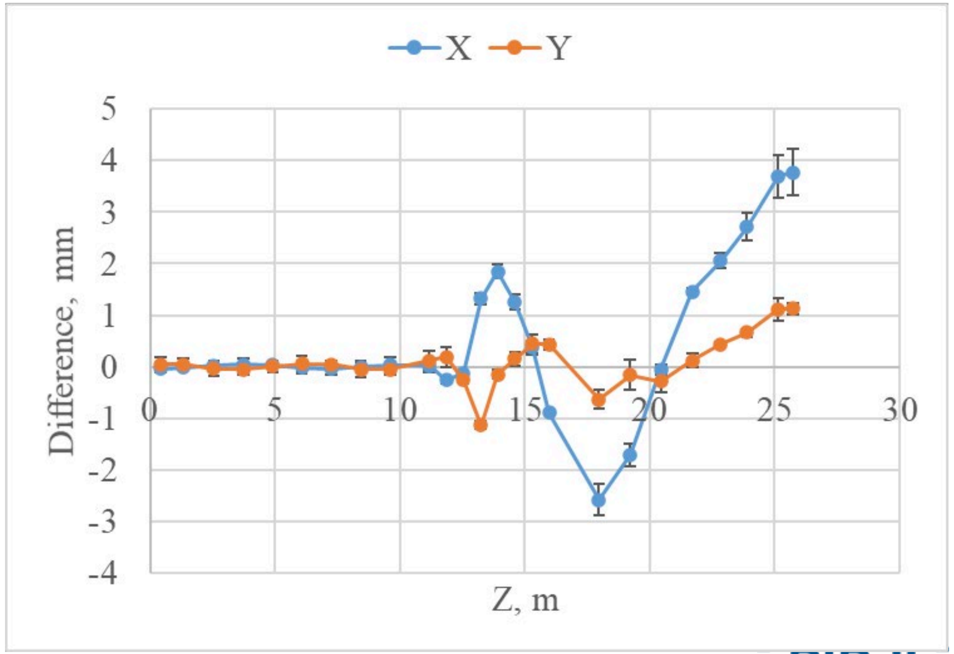
Hysteresis Behavior in SC Magnets

- Hysteresis behavior observed in superconducting correctors and solenoids
  - Observed in all magnets
  - Residual effect is a few percent of maximum field
  - No changes in the residual field over ~30 min
- Likely source is persistent current in the SC wire and its magnetization
- Effect can introduce discrepancy with the model and complicate tuning
- Effect can be mitigated with the degaussing procedure
- New SSR magnet package is wound with a wire with a smaller-size filament

HWR solenoid and corrector package



Difference in beam orbit trajectory at the same settings after variation of magnets in the HWR cryomodule.



Summary of Measured Beam Parameters

Beam Parameter	Units	Goal or Nominal Value	Achieved		Comment
Beam energy	MeV	22	17.1	✓	HWR cavities 1-3 not used for acceleration
Current	mA	2	2	✓	
Transmission through CMs	%	99%	>98%	✓	Likely due to increased long. emittance caused by HWR cavities 1-3 tuned off
Trans. emittance (rms. norm.)	μm	0.25	0.23	✓	Quad-scan measurements. Slit-slit results were inconclusive
Long. emittance (rms)	μm	0.4	0.3	✓	
Bunch extinction ratio		10^{-3}	$< 5 \times 10^{-4}$	✓	
Transverse distribution dynamics range	Ratio	200	10^4	✓	

International In-Kind Contributions Integrated and Operated

- PIP2IT provided opportunity to integrate and operate partner's contributions (DAE):
  - 7 kW amplifiers
  - SSR1 Cavity 6 – met operational requirements
  - MEBT magnets

Nine SSR1 7kW amplifiers

SSR1 Cav #6

RT Quadrupoles and correctors

DAE-ECIL

Summary

- Successful commissioning and test of PIP2IT/PIP-II systems reduces PIP-II technical risks
- Beam with parameters required for LBNF/DUNE operations has been demonstrated reliably
- Design of accelerator systems was validated with and without beam.
  - All 39 planned hardware tests were completed
- Partner's in-kind contributions were successfully integrated and operated at PIP2IT
- Test results and lessons learned guide development of PIP-II systems
- PIP2IT/Fermilab team and PIP-II Partners went above and beyond to meet the PIP2IT goals, overcoming new challenges and uncertainties presented by the worldwide COVID pandemic

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