PIP2IT Commissioning Report

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PIP2IT Commissioning Report

The PIP2IT Retreat held on May 6-7 was the compilation of the all the commissioning activities that occurred between July 2020 and April 2021. This document condenses all of the presentations into one final report about the commissioning activities, accomplishments, lessons learned, and recommendations for PIP-II. The PIP2IT Retreat presentations can be found on the FNAL Indico website PIP2IT Retreat / Mini-Workshop (6-May 7, 2021) · INDICO-FNAL (Indico) (https://indico.fnal.gov/event/48525/).

The presentations after PIP-II Project Director Lia Merminga's welcome were

Day 1

PIP2IT Run Overview - Eduard Pozdeyev

Operations Perspective – Darren Crawford

SRF, Performance and Lessons Learned - Joe Ozelis and Alexander Sukhanov

Cryoplant, Performance and Lessons Learned – Ben Hanson

Beam Commissioning Results and AP Perspective - Alexander Shemyakin

Accelerator Systems Overview - Elvin Harms

Accelerator Systems, LLRF - Brian Chase

Accelerator Systems, RFPI - Niral Patel

Accelerator Systems, Instrumentation - Vic Scarpine

Accelerator Systems, MPS - Arden Warner

Accelerator Systems, MagPS - Bruce Hanna

General Discussion and Summary of the Day - Darren Crawford

Day 2

Accelerator Systems, Controls - Dennis Nicklaus

Front End, Performance, Lessons Learned and Perspective - Lionel Prost

Installation, Lessons Learned – Curt Baffes

PIP2IT Infrastructure, Lessons Learned and Path Forward – Jerry Leibfritz

General Discussion and Summary of the Retreat - Eduard Pozdeyev

Closing Comments and Toast - Lia Merminga

The goals of the retreat were to: 1) to summarize and assess the performance of technical systems and their designs 2) to review experience with installation, integration testing, and operation of PIP2IT, 3) assess the impact of PIP2IT test results on the design of PIP-II systems and summarize required changes to address deficiencies and improve performance for PIP2IT CM test stand and PIP-II, and 4) identify lessons learned with a goal of applying them to PIP2IT CM test stand and PIP-II to improve performance.

There are numerous acronyms associated with Fermilab and PIP2IT is no exception. Here is a list of the acronyms found within this report.

AC	Accelerator Complex
AD	Accelerator Division
AP	Accelerator Physics
ACCT	Alternating Current Current Transformer
BCM	Beam Current Monitor
BID	Beam Inhibit Device
BLM	Beam Loss Monitor
BPG	Beam Pattern Generator
BPM	Beam Position Monitor
CDS	Cryo Distribution System
CM	Cryomodule
CP	Cryoplant
DBCM	Differential Beam Current Monitor
DCCT	Direct Current Current Transformer
DPI	Differential Pumping Insert
EPICS	Experimental Physics and Industrial Control
FAV	Fast Acting Valve
FFC	Fast Faraday Cup
FTP	Fast Time Plot
GDR	Generator Driven Resonator
H-BCAM	HIE-ISOLDE Brandeis CCD Angle Monitor
HA	Hazard Analysis
HEBT	High Energy Beam Transport
HPRF	High Power RF
HTTS	High Temperature Thermal Shield
HWR	Half-wave Resonator
ICW	Industrial Chilled Water
IOC	Input Output Controller
IS	Ion Source
LBNF	Long Baseline Neutrino Facility
LCLS-II	Linear Coherent Light Source 2
LEBT	Low Energy Beam Transport
LL	Liquid Level
LLRF	Low Level RF
LOTO	Lock Out Tag Out
LTTS	Low Temperature Thermal Shield
MEBT	Medium Energy Beam Transport
MOA	Memorandum of Agreement
MP	Multi-Pactor
MPS	Machine Protection System
PCB	Printed Circuit Board
PIP-II	Proton Improvement Plan 2
PIP2IT	Proton Improvement Plan 2 Injector Test
RF	Radio Frequency
RFPI	RF Protection Interlocks
RFQ	Radio Frequency Quadrupole
RWCM	Resistive Wall Current Monitor
SRF	Superconducting RF
SSR1	Single Spoke Resonator 1
ToF	Time of Flight
TRS	Technical Requirements Specification
WFE	Warm Front End

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PIP2IT Run Overview

PIP2IT commissioning was completed in two stages. Stage 1 was from 2013 through 2018. During this stage the design, acquisition, installation and commissioning of the ion source, RFQ, and MEBT systems with a final energy of 2.1 MeV to the beam dump was accomplished. After Stage 1 was complete, the PIP2IT enclosure was extended to include the HWR and SSR1 cryomodule. After installation the beam dump was moved to the downstream end of SSR1. The CMTF CP, utilized for LCLS-II cryomodule testing, was modified to provide liquid helium to HWR and SSR1. The MEBT was adjusted to include a kicker and its own absorber.

Stage 2 commissioning activities included re-establishing beam through the MEBT with similar parameters as Stage 1, testing the newly installed kicker system with the beam pattern generator, and sending kicked beam to the MEBT Absorber. This staged also included new activities such as conditioning HWR and SSR1 CM cavities, establishing beam through to the HEBT and beam dump. The design beam energy to the dump with all 16 SRF cavities available was 22 MeV. The PIP2IT Stage 2 Run commissioning goals were to:

1. Test systems on the PIP-II critical technology roadmap,
2. Validate designs and implement findings in the design of the technical systems to address deficiencies and improve performance,
3. Accelerate beam in the SRF CMs, validate beam optics, quantify beam parameters, and confirm results of numerical simulations,
4. Gain experience with installation, integrated testing and operation of PIP2IT equipment while developing and validating processes and procedures,
5. Document and implement lessons learned into the design of technical systems and operational procedures for PIP-II.

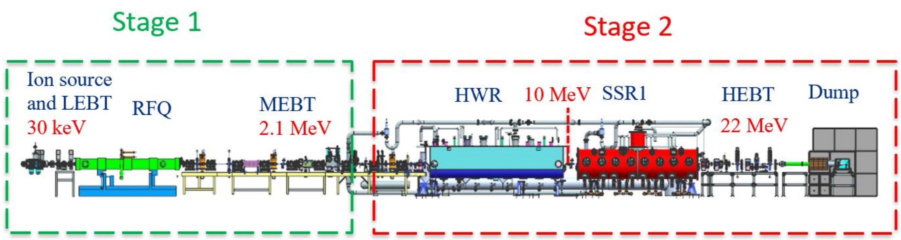


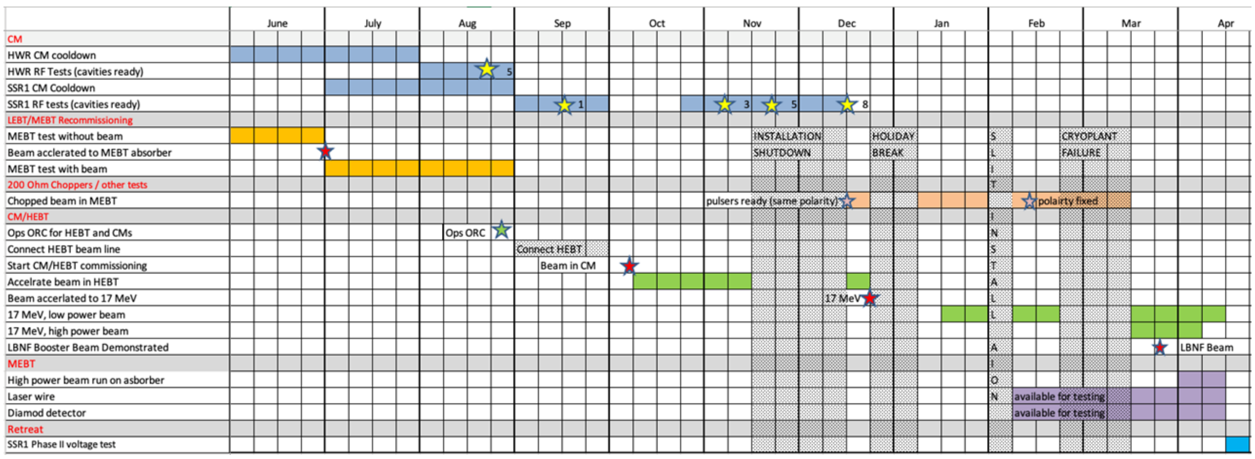
Figure 1-1. PIP2IT beamline layout.

The scope of the Stage 2 commissioning activities were:

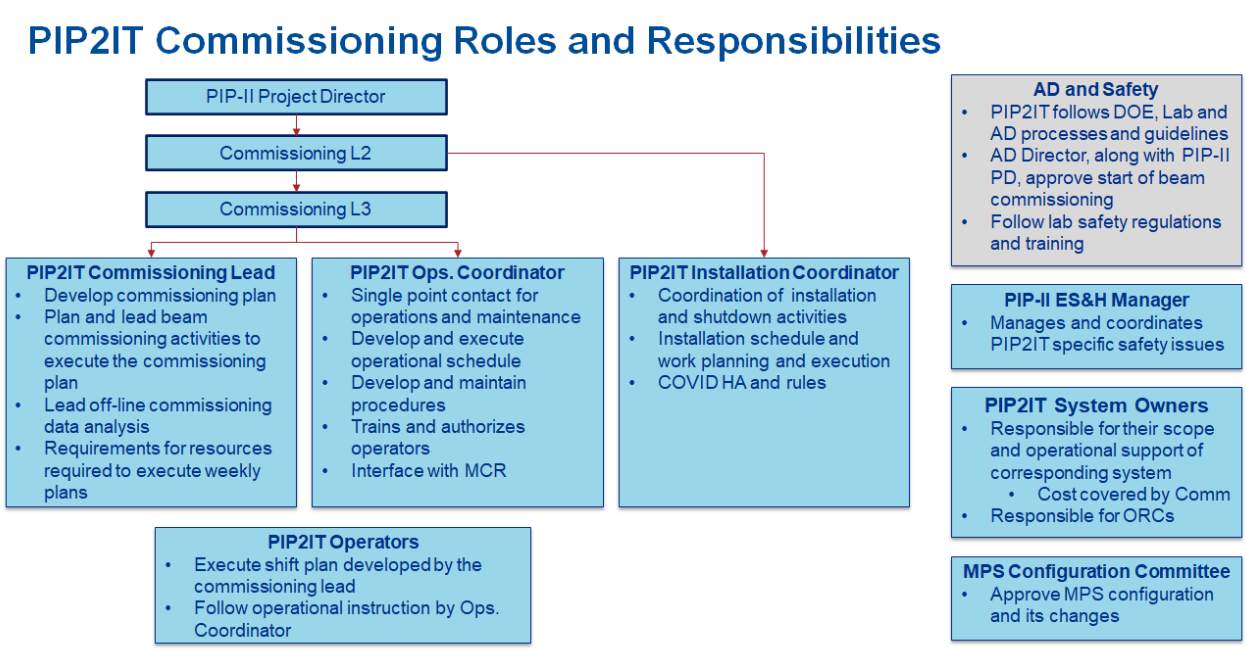
- Beam commissioning and studies
- Test HWR and SSR1 Cryomodules, with and without beam
- Test HWR and SSR1 amplifiers (in-kind), and distribution system
- LLRF, including resonance control - HWR, SSR1, MEBT bunchers
- RFPI for SRF cavities
- Second 200 Ohm kicker and new absorber
- Instrumentation - Laser wire, BPMs (cold and warm), HEBT Slits
- MPS - New hardware and algorithms, DBCM, diamond detector
- Power supplies for CM solenoids and correctors

- Controls, test EPICS
- New HEBT beamline and dump, including vacuum system
- Cryogenics: distribution for CMs, new Kinney pumps

PIP2IT was classified as a Radiation Generating Device. It was exempt from DOE O 420.2C Accelerator Safety Order and managed under FESHM and FRCM. The PIP2IT commissioning was conducted from the local PIP2IT or FAST/IOTA control rooms. The beam commissioning of Stage 2 started in June of 2020. Originally, PIP2IT commissioning activities were to cease on January 31, 2021 but the run was extended due to shutdowns for required equipment installations and the late delivery of SSR1 amplifiers. The commissioning run ended April 16, 2021. The commissioning schedule can be seen below.



The PIP2IT commissioning roles and responsibilities are outlined in the diagram below.



The following personnel were assigned to the aforementioned roles:

- PIP-II Project Director: Lia Merminga
- Installation and Commissioning L2 Manager: Jerry Leibfritz
- Commissioning L3 Manager: Eduard Pozdeyev
- PIP2IT Commissioning Lead: Alexander Shemyakin
- PIP2IT Operations Coordinator: Darren Crawford
- PIP2IT Installation Coordinator: Curtis Baffes

An MPS Configuration Committee was created to review proposed changes within the system configuration and, if approved, recommend implementation to the Commissioning L3 Manager. The committee members were system level managers that were responsible for inputs to the MPS and the committee chair was the PIP-II Operations Coordinator.

A set of technical deliverables was developed for PIP2IT technical systems and beam tests by corresponding system owners and documented in PIP-II DocDB 5044. The deliverables defined the required test condition, impact on the PIP-II scope, definition of success, and summary of test results. The deliverables also provided input to commissioning team to facilitate planning for beam tests. The table below summarizes the status of the deliverables at the end of PIP2IT commissioning. The overall completion status of PIP2IT run deliverables was 92%. The remaining 8% were related to beam commissioning measurements. Table 1-1 outlines the completed, partially completed, and uncompleted deliverables.

Table 1-1 PIP2IT Deliverables.

System	No. of Deliverables	Completed	Partially Completed	Not completed
SRF HWR	6	6		
SRF SSR1	6	6		
Beam Comm.	11	4	3	4
Front End	2	2		
MPS	7	7		
HPRF	4	4		
LLRF	5	5		
Mag/PS	2	2		
Vacuum	2	2		
Controls	1	1		
Instrumentation	4	4		
Total	**50**	**43 (86%)**	**3 (6%)**	**4 (8%)**

The specific deliverables not completed were:

1. Measure 4D distribution in the HEBT
2. Measure correlations between transverse and longitudinal planes in the HEBT
3. Emittance dilution due to chopping measured in the HEBT by the slit-slit emittance scanner
4. 24-hour PIP2IT beam reliability run

The main reason for the first three items was due to the late delivery of the HEBT slit scanners. The 24-hour reliability run was not completed due to other higher priority deliverables that took precedence at the end of the run.

There were many issues that hindered progress and led to lessons learned. They included project personnel and priority, late delivery of hardware and systems, and insufficient testing of systems prior to installation.

Fermilab personnel were involved in many projects and activities simultaneously across the lab (e.g., AD Ops, R&D projects, PIP-II, etc.). This resulted in hardware and systems delivered at the last moment or, in some cases, late. Some hardware systems were not tested thoroughly or at all, and thus operable issues and interferences were discovered post-installation. This ultimately required additional shutdowns to remove, repair, and reinstall components. A total of 1.5 months of additional shutdowns were accumulated for equipment removal and reinstallation.

The lessons learned were:

1. PIP2IT was not managed as part of the PIP-II project until later stages, causing significant lapses in implementation of formal requirements, interfaces, engineering documentation, and engineering processes. The PIP-II project is managed more formally, implements changes in the project culture, and relies on processes approved by DOE.
2. For PIP-II, the project personnel need to focus on delivery of their systems and scope through the whole development cycle, including testing and debugging of hardware prior to delivery for integration.
3. System owners must plan for early testing of equipment using test stands and mockups.
4. System owners, along with Linac Installation, and Commissioning teams, need to plan for integrated testing and acceptance of beam line equipment. A set of technical (not only safety) acceptance requirements must be developed that those systems have to meet before being approved for operations.

There were other issues that hindered PIP2IT progress, and some contributed to lessons learned.

1. The emergence of COVID-19 had a major impact on the schedule and caused several systems to be delayed. The availability of personnel directly affected the PIP2IT commissioning timeline.
2. The first three cavities in the HWR CM were not capable of accelerating beam. Cavities 1 and 2 were far off from the proper frequency and cavity 3 developed a short in the coupler bias due to an RFPI failure.
3. CMTF infrastructure, utilities, and CP were not ready to support year-long operations with a high level of availability. Testing of nearby LCLS-II CMs impacted PIP2IT operations due to limited plant capacity.
4. Low reliability of some technical systems affected PIP2IT operations. Antiquated LLRF hardware in the WFE delayed or prolonged beam startup operations.

In summary, the PIP2IT Stage 2 run met all main goals and most of its extended goals. All accelerator systems were tested with beam and the test results will be used to advance the design of technical systems. The beam parameters were deemed suitable for injection into Booster. The PIP2IT team went above and beyond to meet the PIP2IT goals, especially during a worldwide COVID-19 pandemic.

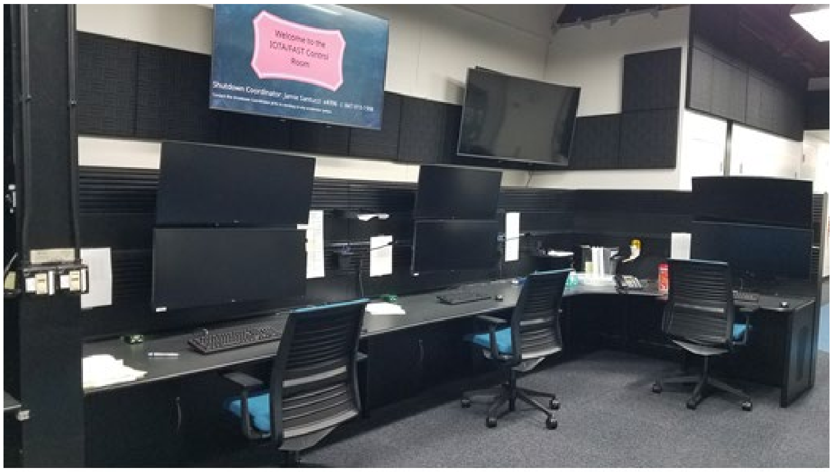
PIP2IT Operations Summary

PIP2IT work planning was carried out through various meetings. These weekly meetings set the long-term schedule for coordinating installation and commissioning activities, setting near-term priorities, and planning shifts. The weekly meeting schedule is seen in Figure 1-4.

- 08:30 M, Th – Operations Meeting
    - Short meeting to coordinate ops activities and adjust plans if necessary
    - Attended by ~40 stakeholders
- 13:15 T – PIP2IT Coordination Meeting
    - Coordination of activities, discuss progress and issues
    - Attended by ~50 stakeholders
- 13:00 Th – Operations/Commissioning Planning Meeting
    - Plan the schedule for the next week
    - Attended by ~10 stakeholders
- 09:00 M, W, F - AD Scheduling Meeting
    - Representatives from several divisions and system departments
    - Necessary utility and system outages are scheduled
    - Attended by ~100 people

Figure 1-4. Weekly meeting schedule.

The COVID-19 pandemic required changes to the commissioning strategy. The CMTF COVID-19 HA limited the control room occupancy to a maximum of 5 people for commissioning tasks. This meant WFE and HWR commission activities could not occur simultaneously. The solution was the creation of an MOA with the FAST Facility Department for use of their control room; a building geographically close to CMTF. WFE commissioning shifts were scheduled for the FAST control room and SRF shifts for the CMTF control room. The MOA allowed for the installation of specialized PIP2IT programs on FAST control room consoles.



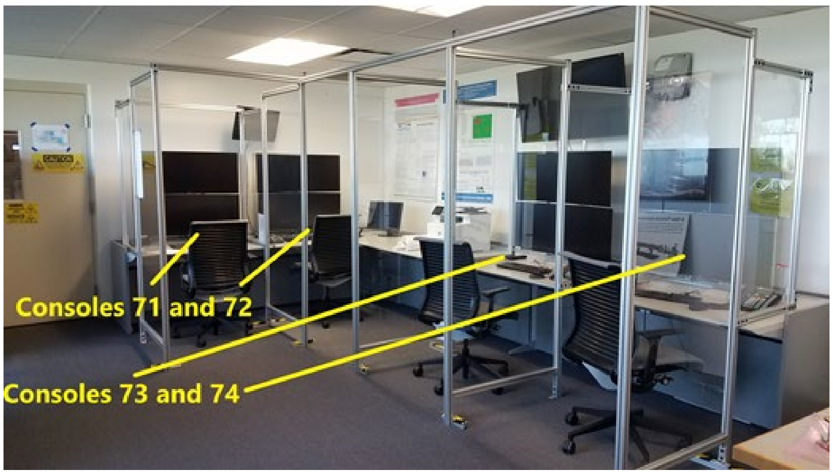


Figure 1-5. The top image shows the portion of the FAST/IOTA control room utilized for WFE commissioning per the MOA with the FAST Facility Department. The bottom picture shows the CMTF control room with COVID-19 mitigation barriers between controls consoles.

Stage 2 PIP2IT commissioning began on June 22, 2020 and concluded April 16, 2021. The total scheduled beam commissioning time was 1249 hours over 43 weeks. From June to September 2020, the enclosure was in Supervised Access mode from 07:00-14:00 and utilized for CM and HEBT installation and checkout activities. The enclosure was then turned over to PIP2IT operations for search and secure. Commissioning studies occurred from 14:30 to 18:00. The PIP2IT beam commissioning shift hours per week is seen in Figure 1-6.

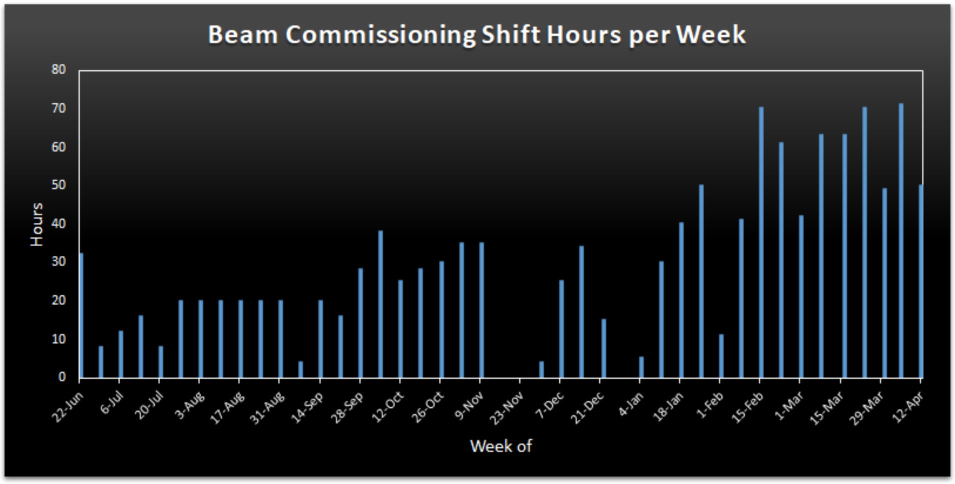


Figure 1-6. Beam commissioning scheduled shift hours over the course of the run.

In September 2020, installation activities required less time, so the enclosure was turned over to PIP2IT operations at 12:00 for search and secure. Installation activities concluded in October 2020 and PIP2IT operations moved to 2 shifts per day, 08:00-13:00 and 13:00-18:00. At this point, any accesses into the PIP2IT enclosure were scheduled by the PIP-II Operations Coordinator and those accesses were performed under Controlled Access conditions.

The month of November 2020 was spent in shutdown to allow for the HEBT slit scanners and MEBT kicker system installation. The HEBT slit stations were removed prior to the end of the shutdown due to mechanical issues in both vacuum chambers. Beam commissioning operations resumed in early December 2020. After the winter holiday break, issues with the HEBT slit scanners were rectified and another shutdown occurred to install the stations. Concurrently, Laser Wire issues were repaired in the MEBT.

Once the aforementioned installations were completed in February 2020, the schedule was modified so that each commissioning shift was 7 hours, 08:00-15:00 and 15:00-22:00. Commissioning operations was expanded to weekends but only on a volunteer basis. This was the schedule for the remainder of the run.

There were 2 PIP2IT operators scheduled for each shift during the stage 2 run. PIP2IT operators were responsible for communicating with the MCR at the beginning and end of their shift, performing search and secures of the enclosure if needed, and approving enclosure accesses pertinent to the shift study. A list of the PIP2IT operators is below.

Beam Commissioning Operators

- Sasha Shemyakin
- Lionel Prost
- Bruce Hanna
- Jean-Paul Carneiro
- Arun Saini
- Michael Geelhoed
- Darren Crawford

Daily operations required the PIP2IT operator to know multiple platforms for controlling devices inside and outside of the enclosure. PIP2IT operators utilized all of the programs/platforms below.

Controls Programs Utilized

- ACNET
- Java
- Synoptic
- EPICS
- LabVIEW
- Remote desktop

ACNET is the AD accepted accelerator controls network for the AC. It allows operators to open parameter pages, launch FTPs, run sequencer aggregates, and monitor parameter alarms. Specialized Java programs allowed operators to save, control and plot ACNET parameters while also writing data to the console local and network disk drives. Synoptic displays are GUIs that display and plot ACNET parameters. Digital control and status readback are allowed with synoptic displays.

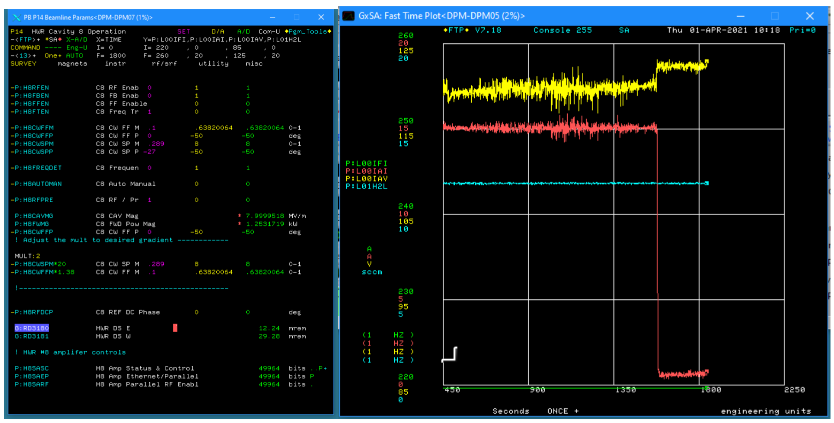


Figure 1-7. The left image is of an ACNET parameter page and the right plot is an ACNET FTP displaying parameter data over time.

EPICS is the new control system AD is moving towards and PIP2IT was a test bed for certain subsystems. IOCs were developed that interfaced to the SSR1 amplifiers and LLRF resonance controller. PIP2IT operators learned to interface with each IOC.

Figure 1-8. An EPICS IOC was tested for SSR1 amplifier control, status, and readback.

PIP2IT operators used LabVIEW for establishing RF power to the RFQ, Bunchers 1-3, HWR, and SSR1. For room temperature RF structures, the ACNET sequencer aggregates established the gradients, whereas operators were manually instructed via aggregate to establish the SRF cavity gradients with LabVIEW.

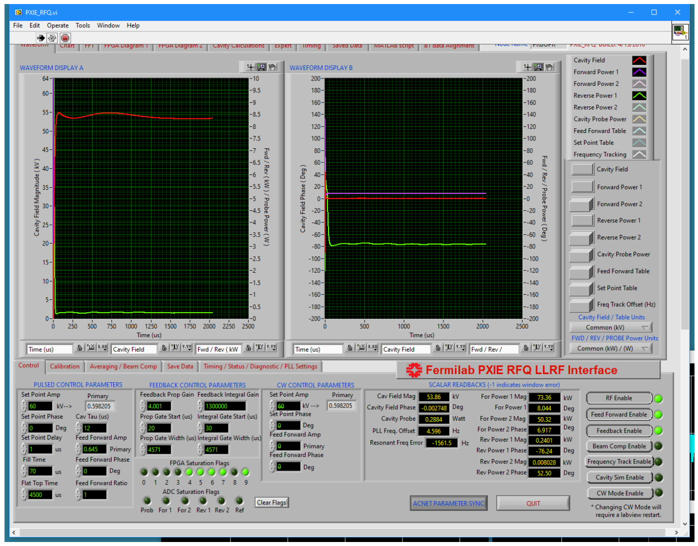


Figure 1-9. PIP2IT LLRF control programs utilized LabVIEW, for example this image of the RFQ control page.

Remote login was utilized for the Allison scanner and the BPG since their respective computers were located in the CMTF gallery. Usage allowed operators to execute commands in proprietary software and FNAL written Controls programs.

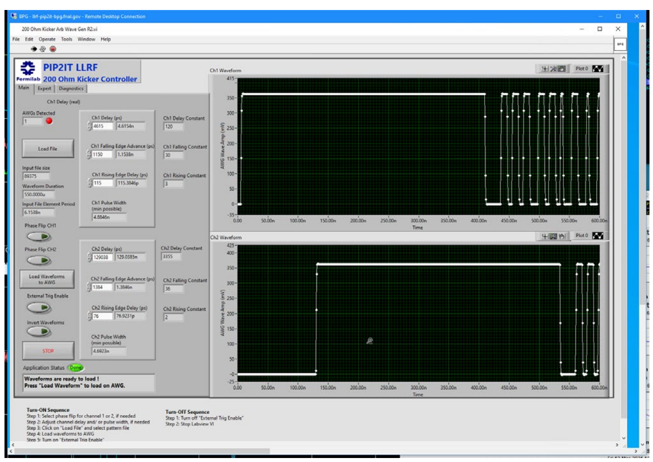


Figure 1-10. Loading BPG files required the operator to remote login into the program's computer.

Controls programs and platforms used by PIP2IT operators can be seen in Figure 1-11.

	Ion Source	RFQ	B1	B2	B3	HWR	SSR1	MPS	Kickers	Save/Set	Instr.
ACNET	X	X	X	X	X	X	X	X	X		X
JAVA										X	X
Synoptic						X	X	X			
EPICS							X				
Labview		X	X	X	X	X	X				
Remote Desktop									X		X

Figure 1-11. Operators had to utilize a wide range of programs for controlling the PIP2IT accelerator.

The PIP2IT turn-on process was developed and then streamlined to minimize the total time spent in establishing beam to either the MEBT absorber or HEBT dump. The sequencer aggregates for the RFQ and Bunchers developed during stage 1 commissioning activities in 2018 were condensed into one aggregate. Personnel from APS-TD and AD RF directly involved with commissioning HWR and SSR1 communicated the steps-to-operation which were then written into sequencer aggregates. The list of operations, with associated ACNET sequencer page number, required to establish beam to the HEBT dump can be seen in Figure 1-12.

PIP2IT Turn-on Process

1. Ion Source sequencer P135
2. RFQ sequencer P137
3. Bunchers sequencer P137
    - B1 Pulsed mode
    - B2 CW mode
    - B3 CW mode
    - Labview monitor
4. HWR 4-8 sequencer P136
    - Labview commands
    - RFPI reset
5. SSR1 1-8 sequencer P135
    - Labview commands
    - RFPI reset
    - EPICS resonance control
6. MPS mode setting sequencer P135
7. MPS synoptic reset

Figure 1-12. ACNET Sequencer turn-on process operators used to establish beam to the HEBT dump.

PIP2IT operators worked in parallel to efficiently establish beam to the HEBT absorber. One operator turned on the ion source, RFQ, and Bunchers while the other operator established gradients to the SRF cavities. Once field was established to the CMs, operators phased in each cavity. The entire turn-on process was typically completed in 1.5 hours.

The most reliable systems during the Stage 2 commissioning run were:

1. LCW system
2. Controls Network
3. CMTF electrical infrastructure
4. Ion source
5. HWR amplifiers
6. Magnet power supplies

The most notable downtimes during the run are outlined in Figure 1-13.

System	Cumulative downtime during run (hours)
SSR1 amplifiers	83
Cryoplant purification	244
Cryoplant Kinney vacuum skid	262
RFQ IGBT	73
Cryogenics breaker incident	32
Enclosure VIP tours	108

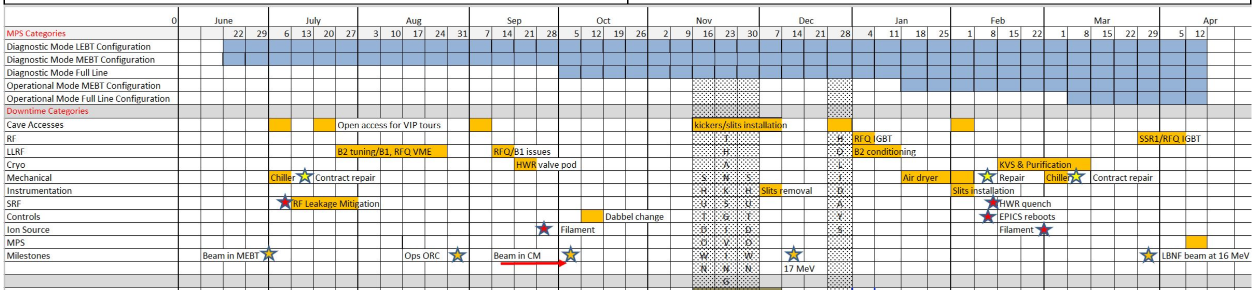


Figure 1-13. The most notable downtimes encountered are indicated in the top table. The downtime categories and major events over the course of Stage 2 commissioning are called out in the calendar.

There were lessons learned from the Stage 2 commissioning run that were documented in iTrack and HPI. There was one unexpected outcome during the run.

- **iTrack Lessons Learned**
  - # 104417 **-** Communication of ODH conditions to those in control rooms
  - # 104096 – RF power leakage interfering with ODH monitors
- **HPI**
  - # 284 – Modification of Controls programs during beam operation
  - # 281 – MEBT 200 Ohm kicker – driver directional issue
  - # 276 – PIP2IT key issued to individual with improper training credentials
  - # 287 – PIP2IT MPS management practices
- **Unexpected outcome**
  - Cryo breakers accidentally turned off by technician during LOTO removal

Over the course of the commissioning run there were three operational lessons learned:

1. Keep RFQ and Bunchers RF high voltage on when not in use
2. Place HWR into standby mode (1 MV/m) when not in use
3. Keep SSR1 amplifiers on, with RF disabled, when not in use

These were all related to the RF systems and should be highly considered for PIP-II operations. If these are not adhered to then the cost will be extensive downtime to those systems.

The following recommendations were made for PIP-II:

1. No service contracts, ownership should go to Fluids Group for the:
   - LCW chiller
   - Air compressor system
   - Ion Source chiller

2. A Cryo 24-hour operations group should be formed, akin to Tevatron era Cryo operations
3. The ICW system should be designed such that it will deter silt build up in KVS
4. Vacuum gauge controllers should be outside of the Cave so accesses aren't required to reset
5. RF test station should be created for controls testing prior to upgrade rollout
6. Vendor quality control testing for amplifiers is needed prior to acceptance
7. An MPS operational file comparison program is required for periodic configuration verification
8. Instrumentation hardware testing and verification is needed prior to acceptance for installation
9. A LLRF upgrade to RFQ/Buncher 1 system is needed to replace the antiquated hardware
10. A PID regulation loop is needed for Buncher RF resonance control
11. Ion Source filament lifetime requires a second standby-ready ion source for minimal impact to operations
12. Accelerator controls programs are needed on one platform
13. AD Operations involvement during commissioning is required for Transfer-to-Operations

Cryomodule Testing at PIP2IT

Cryomodule testing for HWR and SSR1 was performed by APS-TD and AD RF personnel.

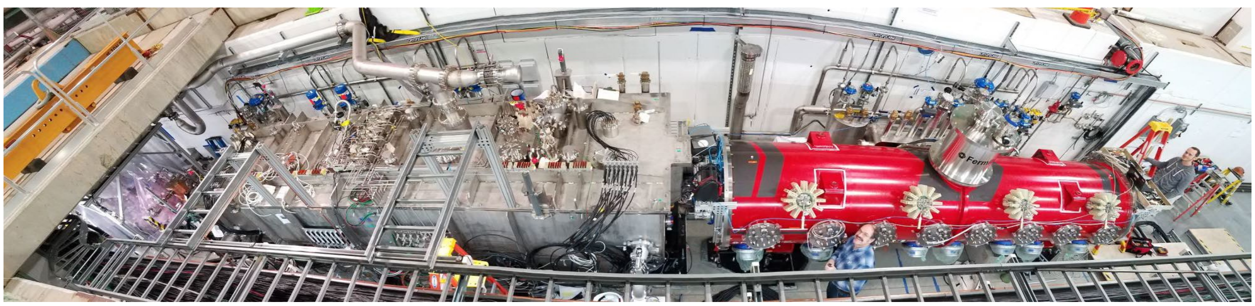


Figure 1-14. Fisheye lens view of HWR and SSR1 CMs from above.

HWR

ANL was responsible for the HWR design, procurement, subcomponent testing, assembly, and final leak check at ANL. The HWR CM was designed to operate at CW with a beam current of 2 mA and accelerate the beam from 2.1 MeV to 10 MeV.

Prior to shipment to FNAL, a leak was found in the lower thermal shield 40 K circuit. The decision was made to address the leak at FNAL, so the CM was delivered to APS-TD, partially disassembled, leak checked but no leak was found in vacuum or pressure test modes. Suspected equipment was replaced and HWR CM passed further leak checks.

The HWR CM was shipped to PIP2IT, installed, and the 40 K circuit leak returned. At this point, the decision was made to operate the CM with only the top shield since the additional heat load at 2 K ranged from 8 W to 20 W. Cryo personnel determined the CMTF CP could support the additional load.

A test plan was created that started with verifying signal integrity of instrumentation and ended with full operation of the CM. The test plan is shown below.

HWR Test Plan

- Warm Pre-Test Checkout
  - Instrumentation,
  - signal integrity,
  - beamtube and insulating vacuum,
  - cavity & tuner "health",
  - component alignment
- Cooldown to 4K
- Cooldown to 2K
  - Achieve stable cryo operation,
  - control loops,
  - LL control
- Individual Cavity RF Testing @ 2K
  - Gradient,
  - FE/MP,
  - cavity frequency,
  - coupler Q_{ext},
  - tuner range
- Magnet Testing at 2K
  - Full field operation of solenoids and X/Y correctors
- Ensemble Cavity Testing @ 2K
  - Total 2K heat loads,
  - average Q_0 (individual cavity 2K heat loads were too small to measure)
- LLRF Control @ 2K, Microphonics
  - Simultaneously operate cavities in GDR mode,
  - demonstrate control with microphonics

HWR CM was ready for cooldown by late January 2020. The 40 K top shield cooldown started on February 25, 2020 and was followed by the 5 K circuit cooldown 2 days later. Cavities and solenoids were at 2 K by March 9, 2020 once the LL and Joule-Thompson valve controls were optimized.

There were some notable issues during the cooldown process. LCLS-II CM testing interfered with CP availability due to limited capacity to support both test areas. HWR cooldown issues were:

- Bayonet relief valve settings too low
- Balancing flow to 5 K strongback circuit and 5 K cold mass circuit
- Some interference with LCLS-II CM
- Strongback flow stagnated until proper valve opened
- Uncertainty about target liquid level
- PID loop tuning less than optimal initially

The established parameter set for stable 2 K operation revealed issues within the HWR CM. The 2nd LL probe 91% value indicated the cavities were fully immersed in liquid He. The 1st LL probe 100% setpoint regulation didn't provide the appropriate cavity immersion. The difference between the LL probes suggested a slight vertical tilt to the 2 K header – about 1.2" between the 1st and 8th cavities.

As previously stated, the additional 2 K heat load from the loss of the lower thermal shield was estimated at 8-20 W. The additional heat load was measured to be 14 W. The lower thermal shield will be repaired prior to HWR CM installation into PIP-II and the static heat load is expected to 30 W.

Cavity frequencies were measured as a function of temperature. The expected frequency shift of +200 kHz behavior was observed for all cavities, but cavities 1 and 2, which were prototypes, pre-tuned differently at ANL and, unfortunately, could not be used during the PIP2IT commissioning run due to landing at the wrong frequency. The +200 kHz behavior can be seen in Figure 1-15.

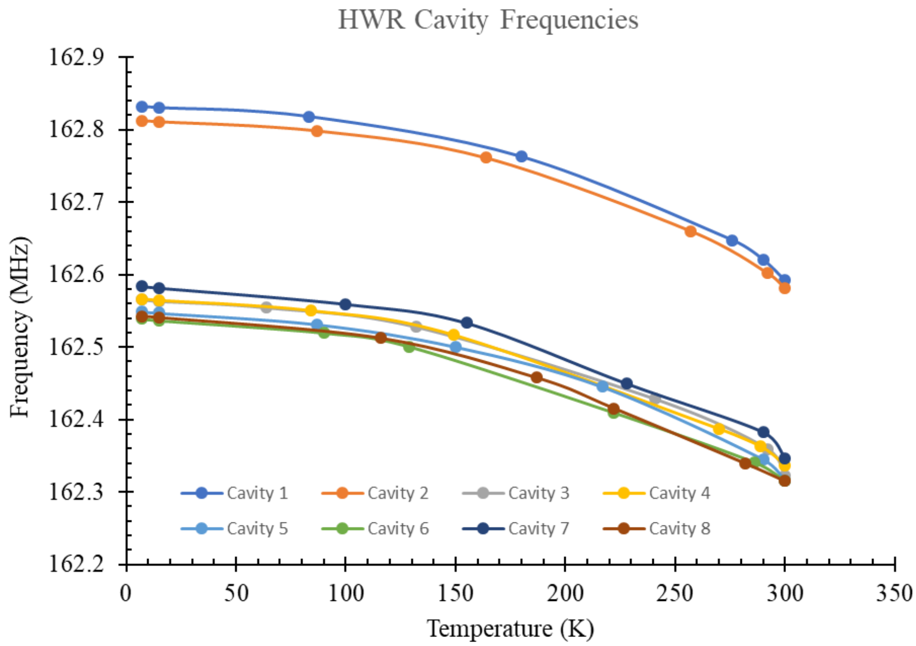


Figure 1-15. Observed cooldown frequency shift from room temperature to 2 K.

The Q_{ext} of cavity input couplers were measured as a function of temperature. The cavity couplers were then adjusted to achieve the 2.3×10^6 nominal value. Coupler 3 was the exception, achieving a Q_{ext} of 1.1×10^6 while still within the amplifier power margin. The tuner operating range was verified to be >100 kHz.

HWR CM Frequencies and Couplings RF/QC

	Cavity, #	1	2	3	4	5	6	7	8
FPC Tuning, RT, Tuner: 15 psia	F0, MHz	162.615	162.601	162.341	162.359	162.334	162.332	162.363	162.333
	Q_EXT	2.40E+06	2.35E+06	8.50E+05	2.40E+06	2.30E+06	2.35E+06	2.40E+06	2.20E+06
CM Cold, 2K, Tuner: 15 psia	F0, MHz	162.812	162.785	162.553	162.543	162.527	162.521	162.578	162.526
	dF, RT to 2K, MHz	0.197	0.184	0.212	0.184	0.193	0.189	0.215	0.193
	Q_EXT	3.27E+06	3.42E+06	7.52E+05	2.44E+06	3.39E+06	3.32E+06	3.59E+06	3.33E+06
CM Cold, 2K, Tuner: 75 psia	F0, MHz	162.621	162.591	162.374	162.342	162.351	162.361	162.412	162.365
	Q_EXT	3.57E+06	3.45E+06	7.36E+05	3.39E+06	3.14E+06	3.43E+06	3.46E+06	3.40E+06
	Tuner range , MHz	0.191	0.194	0.179	0.201	0.176	0.160	0.165	0.161
	Operating pressure, psia	**113**	**103**	**33**	**28**	**24**	**23**	**43**	**25**
CM Cold, 2K	F0, MHz	162.743	162.789	162.555	162.544	162.528	162.520	162.418	162.369
	Q_EXT	2.30E+06	2.30E+06	1.00E+06	3.50E+06	2.40E+06	2.30E+06	3.60E+06	3.40E+06
	Tuner pressure, psia	40	15	15	15	15	15	75	75
	FPC antenna shift, mm	+2.5	+2.5	-2.0	0.0	+2.5	+2.2	0.0	0.0
CM Cold, 2K	F0, MHz	162.776	162.755	162.525	162.512	162.498	162.492	162.539	162.524
	Q_EXT	2.30E+06	2.40E+06	1.10E+06	2.36E+06	2.30E+06	2.30E+06	2.35E+06	2.35E+06
	Tuner pressure, psia	25	25	25	25	25	25	25	25
	FPC antenna shift, mm	+2.5	+2.5	-2.0	+2.0	+2.5	+2.2	+2.0	+2.0

Figure 1-16. Coupler and tuner data with Q_{ext} calculated values for each cavity.

HWR cavities were individually tested in SEL mode. The power was increased until the gradient administrative limit of 11.2 MV/m was achieved. Any FE or MP encountered during conditioning was processed away. There was a MP barrier at 3.5-4.5 MV/m in some of the cavities. No quenches occurred during the cavity testing.

Cavity 3 had a coupler HV bias failure at 6 MV/m which was traced to a faulty cable. The RFPI system did not catch the bias failure, allowing MP activity at a power of >2 kW for several seconds. This resulted in a high ohmage short, likely due to sputtering over the warm window, preventing usage of the bias supply. Thus, cavity 3 was not available for the PIP2IT commissioning run. The RFPI system was modified to detect cable faults.

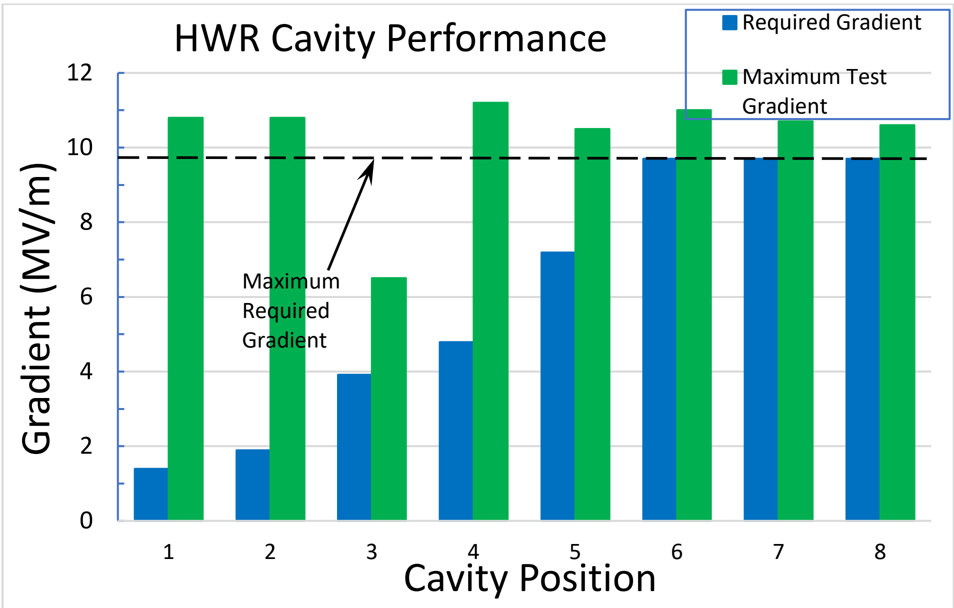


Figure 1-17. HWR cavity field performance. Although cavities 1 and 2 met the maximum gradient required, they could not be used for beam acceleration due to their resonant frequency shift.

HWR solenoids and corrector coils were ramped individually and then as an entire unit. Solenoids were powered to 60 A and correctors to ±10 A. No quenches were observed for any of the magnets. All magnet packages were run simultaneously for hours and no noticeable heat load was detected. Then, all magnets and the 7 cavities were run at maximum nominal currents and maximum operating gradient of 9.7 MV/m for several hours.

Cavity 2 K heat load was measured calorimetrically, using the 2 K return mass flow. Individual cavity heat loads were not a reliable measurement since the static sensitivity is 0.4-0.6 W and the dynamic sensitivity is 0.8 W, therefore the cavities were measured as an ensemble. Once the static heat load was measured, all 7 cavities were set to 9.7 MV/m and the dynamic heat load was determined from the change in mass flow. The static heat load was then remeasured once the cavity amplifiers were turned off.

Static Heat Load (average) = 1.92 g/sec

Static + Dynamic heat load = 2.21 g/sec

Dynamic Heat Load = 0.29 ± 0.04 g/sec

After accounting for the vapor fraction of mass flow through the J-T valve, the Dynamic Heat Load is calculated to be 8.1 ± 0.8 W (1.16 W/cavity). Considering HWR cavity parameters (L_{eff}=0.207 m, R/Q=271 Ω, and E_{avg}=9.69 MV/m), the average Q_0 is calculated to be 1.3 ±0.1x10^{10}. ANL measured the average HWR Q_0 to be 1.5x10^{10}.

In summary, HWR

- Operated all available cavities to the full nominal field (9.7 MV/m) and at least 10% above the nominal maximum gradient for extended time
- No residual FE, soft MP barriers at 3.5-5 MV/m (processed within minutes)
- Average Quality Factors exceeded specification of 8.5 x 10^9 (measured as an ensemble)
- Solenoids all met specification and exceeded operational requirements
- Tuner ranges exceeded requirements
- Demonstrated all cavities (except #3, untested) operated in GDR mode (LLRF control)
- Alignment of cold mass and warm/cold shift was within specifications

Cavity Position	Cavity S/N	Nominal Required Gradient (MV/m)	Maximum Test Gradient (MV/m)	Notes
1	P1	1.39	10.8	No residual FE or MP
2	P2	1.89	10.9	No residual FE or MP
3	2	3.91	6.5	Cplr HV Bias failure, test aborted
4	3	4.79	11.2	No residual FE or MP
5	4	7.19	10.5	No residual FE or MP
6	5	9.70	11.0	No residual FE or MP
7	7	9.70	10.7	No residual FE or MP
8	8	9.70	10.6	No residual FE or MP

Figure 1-18. Required and maximum gradients of HWR cavities.

Besides the lower thermal shield leak, Cavity 1 and 2 off frequency, and Cavity 3 coupler incident, other operational issues developed during the commissioning run. Spurious ODH alarms were attributed to RF leakage from the HV bias signal box and DC block assembly. The signal box was redesigned for better shielding and filtering. Additional antennae were added to the RFPI.

An iceball formed on the CM top plate cooldown valve assembly which caused an O-ring seal to fail due to the low temperature. A fan was added to mitigate the ice formation.

The helium pneumatic tuner valves appeared to “stick” when unused over a long time. A LabVIEW procedure was developed for moving the tuners a large distance which would then allow finite step pressure control.

A spontaneous quench in Cavity 8 led to increased FE. While ramping the cavity to 9.7 MV/m, the cavity quenched at 8 MV/m and the forward power railed to 7 kW. After the recovery, strong FE saturated the radiation detectors positioned in the enclosure with readings >250 mR/hr at 6 MV/m, as seen in Figure 1-19. The FE could not be fully processed out, so the operating gradient was reduced to 8 MV/m.

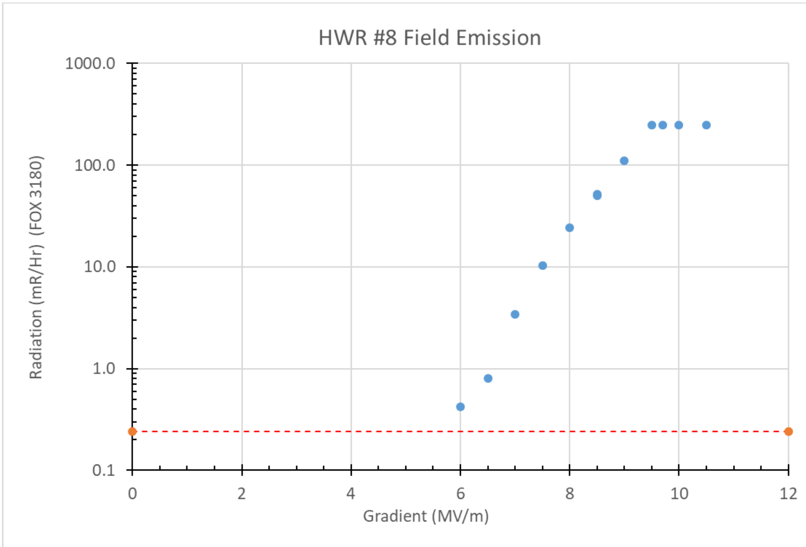


Figure 1-19. Field emission from HWR cavity 8 after a quench.

After a CP recovery from shutdown and thermocycle later in the commissioning run, all cavities were requalified. Cavity 7 showed the onset of FE at 5.5 MV/m and the cavity was limited to an operating gradient of 8.0 MV/m. Cavity 8 quenched at 8.5 MV/m with FE present. Once Cavity 8 was recovered it did not have FE. The operating gradient for Cavity 8 was then deemed to be 9.3 MV/m due to frequent HV bias current trips. The field emission plots can be seen in Figure 1-20.

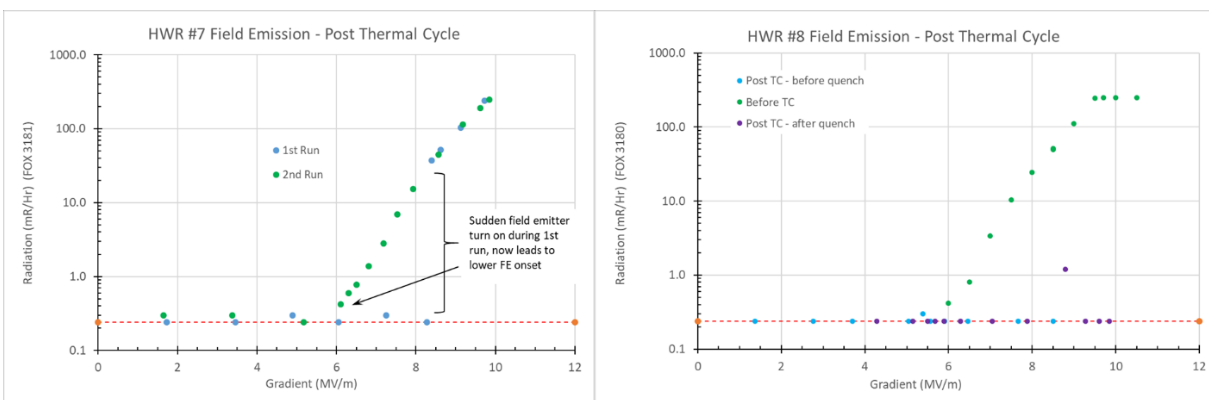


Figure 1-20. The right plot shows the field emission from cavity 7 after the CP thermal cycle. The left plot shows the post quench field emission of cavity 8 and the response after the CP thermal cycle.

There were many recommendations for future HWR modifications based on PIP2IT commissioning.

1. Modify thermal shield piping interface to eliminate soldering stainless steel tube to copper blocks – replace existing cooling circuits.
2. Re-tune Cavities 1 & 2 warm to match others
3. Replace Cavity 3 coupler warm window
4. Rectify limit on adjustment of Cavity 3 coupler, to achieve nominal Q_{ext}.
5. Re-design cooldown valve pod to eliminate Ice-ball formation
6. Re-consider cold mass element target spacing
7. Re-design 2 K/2-phase manifold heater installation and heater wiring

8. Consider coupler adjustment mechanism re-design to eliminate issue found on Cavity 3 coupler
9. Coupler HV Bias signal box redesign to eliminate RF leakage
10. DC Block re-design to eliminate RF leakage
11. Re-design vertical transport restraints to eliminate top plate lifting for removal
12. Add exhaust port for coupler airflow
13. Replace electronic WEKA valves with pneumatic
14. Improve warm window braze/weld method
15. Bring tuner He circuit into code compliance
16. Re-design of 2 K header to eliminate miter joints
17. Eliminate cold VCR fittings, use welds

SSR1

The goal of testing the SSR1 prototype CM at PIP2IT was to demonstrate acceleration of H- beam with the parameters required for the PIP-II physics program.

- Demonstrate achievement of critical parameters:
  - E_{acc} and Q_0 correspond to project requirements
  - Magnets provide required parameters
  - Cavities and magnets are aligned according to specifications
  - RF coupler can sustain full power
  - Tuners provide required range, resolution; cavities are tunable to 325.000 MHz
  - pCM do not exceed designed static and dynamic heat loads
  - Microphonics level within specifications
- Phased approach for cavity qualification: for 1st and 2nd CM slot in PIP-II Linac

Figure 1-21. SSR1 testing goals at PIP2IT.

Phase I/II requirements: Accelerating Field and Q0

Phase 1 (CM1)					Phase 2 (CM2)				
Cavity ID	Operating condition		Acceptance Criteria		Cavity ID	Operating condition		Acceptance Criteria	
	E_{acc}, MV/m	Q_0, x10^9	E_{acc}, MV/m	Q_0, x10^9		E_{acc}, MV/m	Q_0, x10^9	E_{acc}, MV/m	Q_0, x10^9
SSR1_1_1	4.88	8.2	5.61	8.2	SSR1_2_1	10.00	8.2	11.50	8.2
SSR1_1_2	4.63	8.2	5.32	8.2	SSR1_2_2	8.78	8.2	10.10	8.2
SSR1_1_3	4.78	8.2	5.50	8.2	SSR1_2_3	8.05	8.2	9.26	8.2
SSR1_1_4	7.32	8.2	8.42	8.2	SSR1_2_4	10.00	8.2	11.50	8.2
SSR1_1_5	7.80	8.2	8.97	8.2	SSR1_2_5	9.76	8.2	11.22	8.2
SSR1_1_6	7.56	8.2	8.69	8.2	SSR1_2_6	10.00	8.2	11.50	8.2
SSR1_1_7	7.32	8.2	8.42	8.2	SSR1_2_7	8.54	8.2	9.82	8.2
SSR1_1_8	10.00	8.2	11.50	8.2	SSR1_2_8	10.00	8.2	11.50	8.2

Figure 1-22. Phase 1 gradients were used for beam acceleration and Phase 2 gradients were tested once beam commissioning activities were complete.

The test plan outline was similar to the one for the HWR CM.

- Warm Pre-Test Checkout
    - Instrumentation,
    - signal integrity,
    - beamtube and insulating vacuum,
    - cavity & tuner “health”,
    - alignment
- Cooldown to 4K
    - Thermal shield (dT < 50K) and strongback (T > 283K, dT < 5K)
    - Coupler warm window (T > 275K)
- Cooldown to 2K
    - Achieve stable cryo operation,
    - control loops,
    - LL control
- Individual Cavity RF Testing @ 2K
    - Gradient,
    - FE/MP, cavity
    - frequency,
    - coupler Q_{ext},
    - tuner range
- Magnet Testing at 2K
    - Full field operation of solenoids and X/Y correctors
- Ensemble Cavity Testing @ 2K
    - Total 2K heat loads,
    - average Q_0 (individual cavity 2K heat loads were too small to measure)
- LLRF Control @ 2K, Microphonics
    - Simultaneously operate cavities in GDR mode,
    - demonstrate control with microphonics

The cooldown of SSR1 CM started in July 2020. A leak at the solenoid feedthroughs developed when the 50 K shield temperature went below 100 K and was determined to be caused by an interference between the shield and the current leads. To mitigate the issue, the shield was kept at around 140K, causing an additional 15-25 W heat load on the 2 K circuit. Cooldown of the 50 K shield was achieved on July 20, 2020, followed by the 5 K circuit eight days later. SSR1 CM 2 K stable operation was established on July 30, 2020 with the strongback thermal gradient < 1 K.

Alignment of SSR1 was performed with 4 H-BCAMs and 12 target setups. The deviation of the cavities and solenoids from room temperature to 2 K was monitored. The horizontal and vertical displacement can be seen in the Figure 1-23 below.

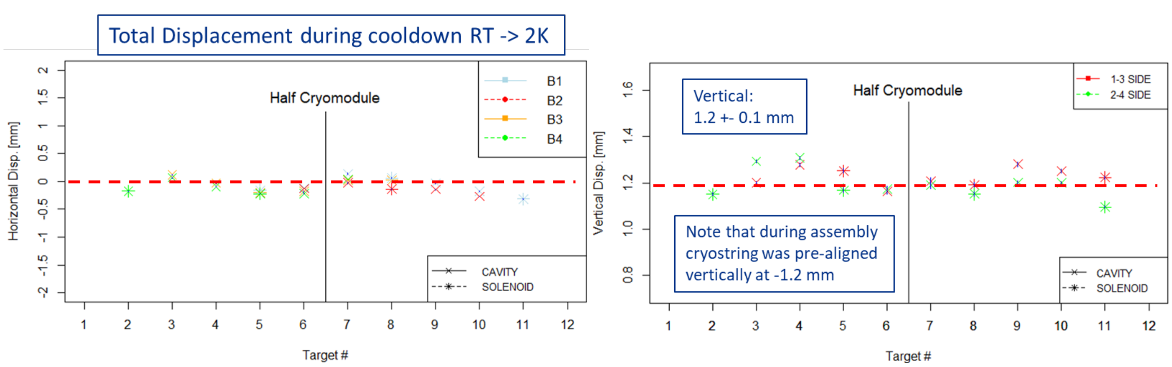


Figure 1-23. Horizontal and vertical alignment data from the H-BCAMs.

The cavities were placed onto their resonance frequencies. The couplers and tuners performed within specifications. Microphonics were measured to be better than 10 Hz.

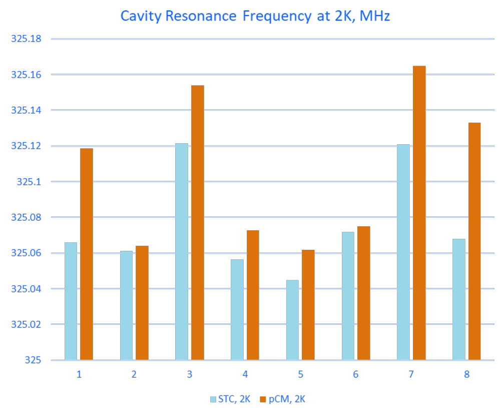


Figure 1-24. SSR1 cavity resonance at 2 K as measured at the STC and in PIP2IT.

All 4 magnet packages within the cryomodule were tested individually and then as a whole unit. Solenoids were powered to 47 A and correctors were powered to ±30 A. No quenches occurred and there was no noticeable heat load on the 2 K circuit.

After LLRF calibrations the cavities were conditioned with RF. There were 3 strong MP barriers between 4 - 7.5 MV/m. Field emission was monitored as each cavity field was slowly increased to full gradient. Cavity 4 had mild field emission, measured by radiation detectors positioned in the enclosure, at 2-3 mR/h. The average time to condition an SSR1 cavity was 16 hours. All 8 cavities achieved nominal Phase 1 gradient + 15%.

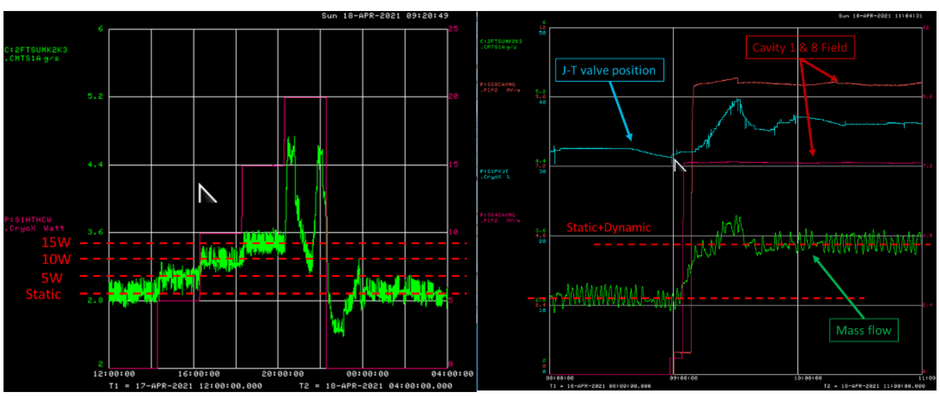


Figure 1-25. Static and Dynamic heat load test plots.

Static and Dynamic heat load studies were performed with Phase I gradients. The method was identical to that used for the HWR CM.

Static	Static + Dynamic	Ploss
2.888 g/s	3.518 g/s	15.2 W

Figure 1-26. Measured Static and Dynamic heat loads of SSR1.

The measured $\langle Q_0 \rangle$ of the CM was then calculated to be 4.5 x 10^9.

Following the completion of beam commissioning activities and the in-situ repair of the HTTS at PIP2IT, SSR1 cavities were conditioned to Phase II fields. All cavities, except 3 and 4, reached the Phase II administrative limit. Cavities 5 and 6 showed no field emission while cavities 1, 2, 7, and 8 exhibited mild local radiation between 0.6 – 0.9 mR/h. Cavity 3 had the onset of field emission at 5 MV/m and a soft quench above 8 MV/m. Cavity 4 demonstrated the onset of field emission at 7.5 MV/m.

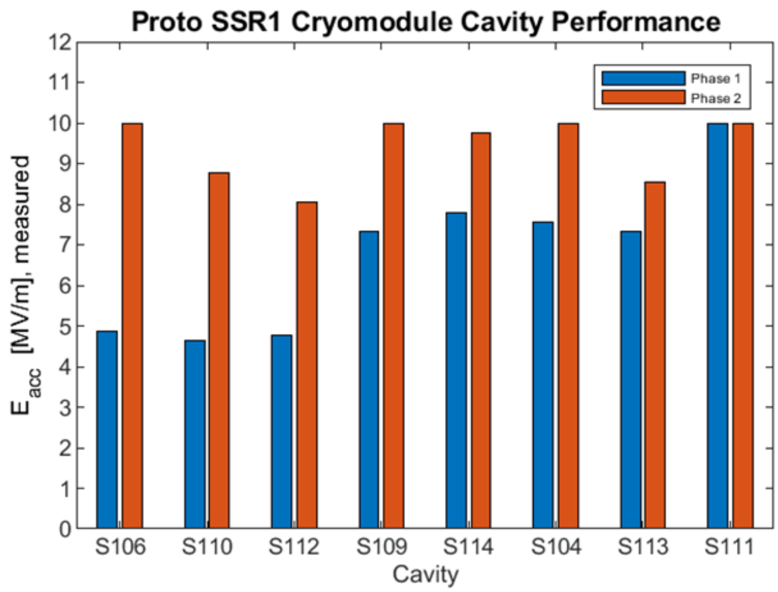


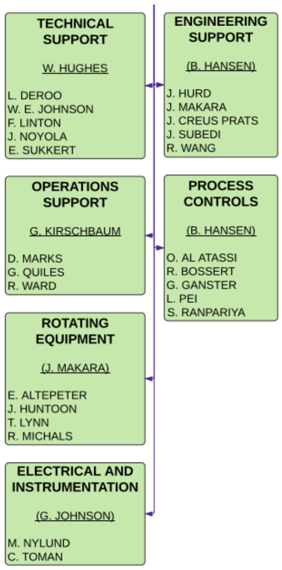
Figure 1-27 SSR1 Phase I gradients were attained and used for beam commissioning. Phase II administrative gradients were reached, except for cavities 3 and 4 due to >200 mR/h field emission. The horizontal axis indicates the cavity serial number for SSR1 cavities 1 to 8.

Parameters	Nominal Condition	Run I		Run II	
		Estimated	Measured	Estimated	Measured
Hight Temperature Thermal Shield	50-80 K		100-130 K		50-80 K
CM Static Heat Load	26 W	40-50 W	37 W	26 W	33 W
CM Dynamic Heat Load (Phase 1)	9 W	9 W	15 W	9 W	12.8
CM Dynamic Heat Load (Phase 2)	15 W	15 W	38 W	15 W	35.5 W

Figure 1-28. After the HTTS was repaired, static and dynamic heat load measurements were repeated. The Run II values in the table reflect the new measurements.

Cryoplant Performance

A CMTF cryogenic operations team was responsible for maintaining the CP. The team was comprised of a spokesperson and 3 weekly rotating teams. The spokesperson was the direct point of contact for all CP issues. The spokesperson, teams, and support groups are shown in Figure 1-29.



CMTF Spokesperson: Jerry Makara

Weekly Rotating Teams:

- Renzhuo Wang (Lead), Sergey Koshelev, Jun Dong
- Jerry Makara (Lead), Joaquim Creus Prats, Omar Al Atassi
- Mike White (Lead), Jeewan Subedi, Greg Tatkowski

Figure 1-29. Cryo support personnel for CP operation.

There were a total of 4 Coldbox trips during the stage 2 commissioning run. Two of the trips were the result of human error. One trip was the result of an instrument air system outage and another was due to a faulty instrumentation readback. Each trip caused 1-2 days of downtime for PIP2IT.

There were two scheduled Coldbox shutdowns during the run. One was for integrating Kinney vacuum skids 2 and 3 into the CP and the other was for decontamination of the CP for recovery of helium capacity. CP events are outlined in Figure 1-30.

Date	Event
24-Feb-2020	HWR Cooldown
15-July-2020	**Coldbox Trip** Loss of instrument air (1 day)
20-July-2020	SSR1 Cooldown
17-Sep-2020	**Coldbox Trip** False high LL on 3 kL Dewar (1 day)
13-Oct-2020	Beam through HWR
17-Nov-2020	**Coldbox Shutdown** (during Planned November Shutdown)
22-Dec-2020	**Coldbox trip** LOTO incident (1 day)
02-Mar-2021	**Coldbox Shutdown** Decontamination of Coldbox (2 days)
18-Mar-2021	**Coldbox Trip** Instrument air e-switch bump (1 day)

Figure 1-30. PIP2IT CP events.

There were 2 cryogenic permits for each CM to operate Magnets and RF. The RF permit was a logical AND gate and required LL LL704H > 90%, pressure PT704H < 30 torr, and temperature TX730 < 2.1 K. The Magnet permit required LL LL705H > 90%, pressure PT705H < 20 psia, and temperature TX730H < 4.6 K. The primary contributors to permit downtime are listed in Figure 1-31.

Primary Contributions to downtime:

Kinney Pump Failure:…………………………..528 hrs, 13%
Coldbox Shutdowns:……………………………120 hrs, 3%
November Shutdown:…………………………..312 hrs, 8%
Winter Break (Affected HWR SRF):………264 hrs, 6%
F1.3-06a Fast Cooldown Interruptions:..144 hrs, 3.5%

	CRYO Permits	Permit hours	No permit hours	Permit Availability	Adjusted
SSR1	**Magnet**	3208	875	79%	**88%**
	RF	2928	1155	72%	**81%**
HWR	**Magnet**	3264	818	80%	**90%**
	RF	2688	1395	66%	**80%**
	Kinney pump	3432	662	**84%**	

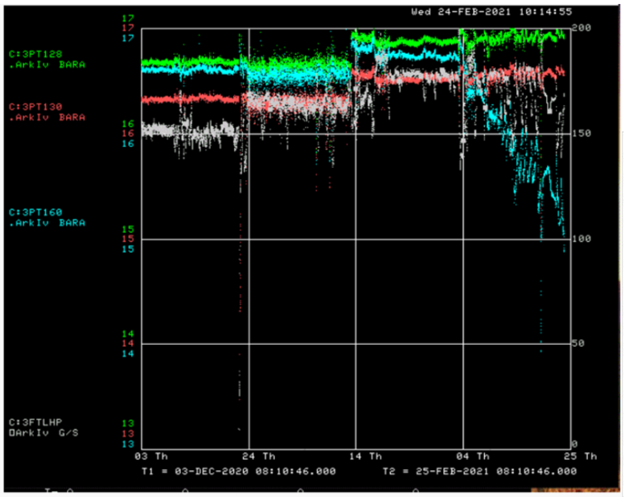
Figure 1-31. The top list is of the major CP downtimes and causes. The bottom table shows the HWR and SSR1 RF and Magnet permit availability.

On February 19, 2021, KVS1 had a booster pump failure due to an injection of silt from the ICW system, which was correlated to a switchover of water sources. The silt clogged the flow indicator on the bearing cooling line. This failure led to many improvements of KVS1 such as:

1. Booster ICW flow indicators were replaced with full flow orifices
2. Hardwired water flow switch was installed
3. Gearbox oil temperature software interlock was added
4. Reduced booster pump current trip software interlock was added

The booster pump was replaced with an on-hand spare and KVS1 was operating by March 12, 2021. As a side note, the Cryogenics Department operated KVS systems for 15 years without any silt issues in the past.

Capacity from the CP dropped off significantly in February 2021. A change in pressure across Turbine 3 filter indicated there was a contamination buildup corresponding to a drop in isentropic efficiency. A 1-day warmup was initiated to decontaminate and recover the CP system capacity. The potential sources of the contamination were likely due to “make up” gas, maintenance activities, helium leaks with back diffusion of air into the system, or sub-atmospheric operation. The CP LN_2 precooler failed in May 2018 so internal full-flow adsorbers could not be used. Long term use of the system without the precooler allowed for the accumulation of contaminants.



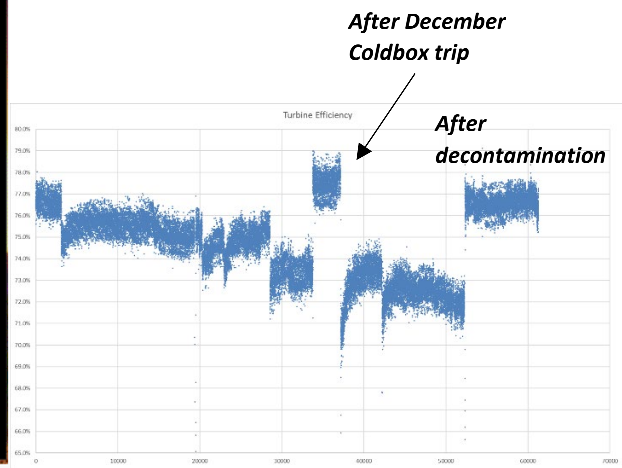


Figure 1-32. The left plot shows the effect of contamination on the CP. The right plot shows the Coldbox efficiency jumps after the December trip and the CP decontamination procedure.

Without the LN_2 precooler, liquefaction was greatly reduced to 11 g/s and support for 3 CM operation at CMTF was challenging. Operation of PIP2IT CMs was limited during some CMTS1 testing modes and representatives from both experiments carefully coordinated the interruptions.

Description	W/ LN_2 Precooler (measured)	No LN_2 Precooler (calculated)	HB650	SSR2	LCLS-II 1.3 GHz	LCLS-II HE (TBD)
Liquefaction	**25 g/s**	**11 g/s**	**~7 g/s (130 W)**	**~3.2 g/s (60 W)**	**~8.0 g/s (80 W)**	**~14 g/s (140 W)**
5K Shield	120 W	75 W	27 W	15 W	10 W	10 W
40K Shield	750 W	400 W	151 W	280 W	80 W	80 W

Figure 1-33. Liquefaction rates with and without the LN_2 precooler.

Improvements to the CP to combat capacity degradation would be to:

1. Repair the LN_2 precooler and run the internal adsorber
2. Operate with a 20 K adsorber
3. Add a parameters and alarms in the Controls system that monitors the Turbine isentropic efficiency
4. Schedule periodic decontamination cycles of the Coldbox.

Two pumps, KVS2 and 3, were brought online near the end of the commissioning run and greatly improved cryo pumping capacity from 11 g/s to 18.5 g/s. The addition of the two skids provided a level of redundancy to the CP and reduced LL excursions for the PIP2IT CMs during high CMTS1 CM operation.

	Pumping Capacity (g/s)
KVS1 (g/s)	11
KVS2 and KVS3 (g/s)	7.5
Total Capacity (g/s)	**18.5**

Figure 1-34. Pumping capacity of the KVS1 and KVS2 and 3 skids.

The PIP2IT enclosure will be converted into a HB650 Test Stand area. Currently, the LTTS and HTTS shield heat loads cannot be accurately measured due to the lack of a flow meter. Fast cooldowns that require > 40 g/s are not possible because of flow restrictions. The PIP2IT CDS will be modified to include a large cooldown valve attached to the relief stack which will eliminate any flow restrictions. A thermal flow meter will be added to the cooldown compressor suction return header that will enable LTTS/HTTS heat load measurements for PIP2IT.

Beam Commissioning Results and the Accelerator Physics Perspective

The beam commissioning team activities included: testing new systems; establishing and improving beam transmission; attaining established goals of energy, current, power, and bunch structure; and studying the beamline optics.

The incorrect landing frequency of the first two HWR cavities and the failure of the coupler of the third cavity rendered those cavities unusable for PIP2IT beam commissioning. Based on the results of beam dynamics simulations, a decision to proceed with PIP-II beam commissioning instead of repairing the cavities was made. Not having the first three cavities significantly affected the beam quality and reduced the final energy to 17.2 MeV but allowed the PIP2IT team to complete all hardware test and most of beam tests. Alternatively, a decision to repair the cryomodule would have caused a significant delay in the commissioning of PIP2IT and made a significant negative impact on readiness of PIP-II systems.

Originally, the PIP2IT optics was expected to be close to the PIP-II design. The failure of the first three cavities forced a significant deviation from the optimum design. To get beam to HWR cavity 4, Buncher 2 had to be over-focused and the bunch length in Buncher 3 had to be increased. In simulations, the RMS emittances grew by 10%-20% of the optimal design and the bunch length was increased at HWR cavity 4.

SRF beam commissioning started with 10 μs beam pulses sent to the HEBT dump without acceleration. This pulse length was enforced by the MPS and deemed safe even if the beam was fully lost. The beam went through on the first shot without significant loss of beam intensity, indicating good alignment of solenoids. Once the trajectory and transmission of the coasting beam was improved, the cavity voltage and phase were set for each cavity.

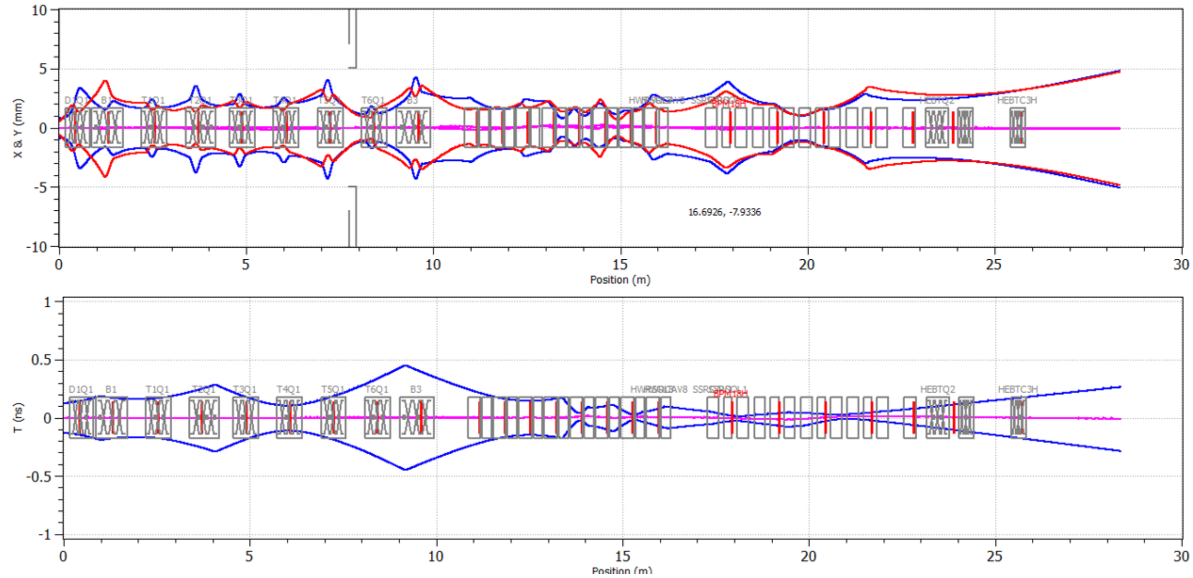


Figure 1-35. TraceWin simulations showing the bunch size in the PIP2IT MEBT. The longitudinal beam size had to be increased at the last MEBT buncher significantly to focus the beam at the fourth HEBT cavity. Still no good longitudinal match can be achieved. The bunch length at the location of the chopper had to be kept small to allow for an effective transverse kick.

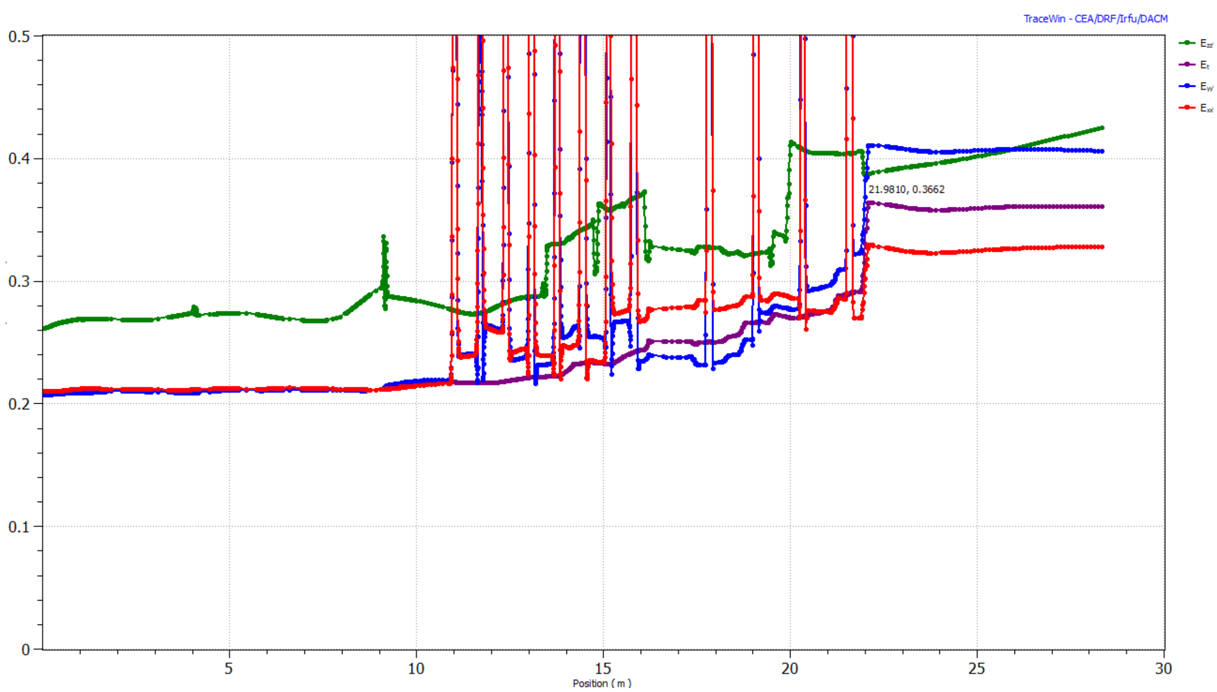


Figure 1-36. TraceWin simulations of the beam emittance along the machine. The simulations showed noticeable degradation of the beam quality due the inability to fully rematch beam at the HWR Cavity 4.

The cavity phase was determined by a standard phasing procedure for each cavity sequentially starting from the RFQ energy. In this procedure, the beam phase was measured by several BPMs versus the cavity set phase. The data was fit with a cosine curve. The phase corresponding to the maximum acceleration was designated as zero phase. The statistical error with this method can be <1°.

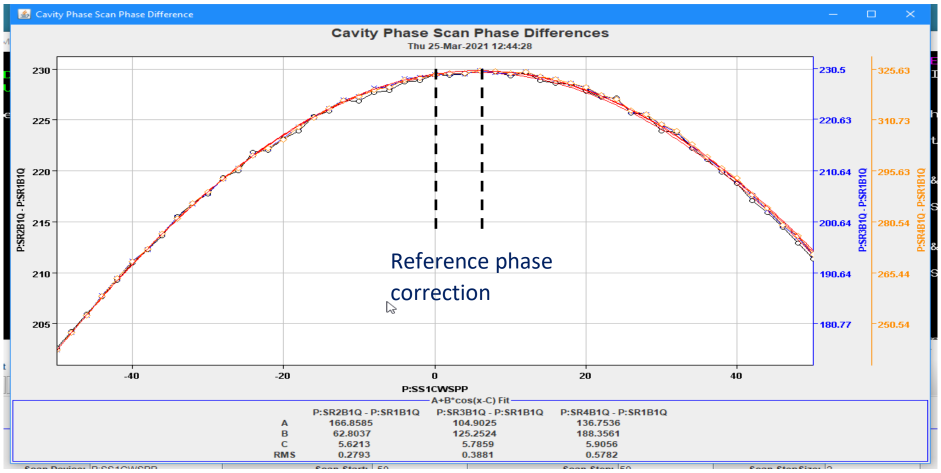


Figure 1-37. This plot is an example of a good phase scan of SSR1-1. The red curve is a cosine fit to the data.

Cavity voltage calibration was conducted for each cavity at 2.1 MeV. The voltage was calibrated by measuring a change in the beam energy in response to a cavity phase scan. It was found that the cavity voltage deviated from the SRF calibration typically less than +10% but in a few cases as much 20%.

Once the cavity voltage and phase were set, 10 us long beam pulses were accelerated to 17.2 MeV. The beam was used to test accelerator systems and improve the beam optics. Once the beam chopper came online, the beam was chopped with the Booster pattern. After the MPS was tested and validated with short pulses, the beam pulse length and average intensity were gradually increased.

The main goal of the PIP2IT beam test was the demonstration of the beam suitable for injection in to the Fermilab Booster in the PIP-II era. Stable acceleration of the beam with the Booster pattern was demonstrated in the end of March 2021. The following beam parameters were reliably demonstrated for several hours:

- Beam energy 16.5 MeV
- Beam pulse current 2 mA
- Beam pulse length 550 μs
- Pulse repetition rate 20 Hz
- Bunch pattern required for injection into the Booster with the extinction factor of $<10^{-3}$
- Beam loss in the cryomodules ~1%.

Figure 1-38 shows the measured beam energy along PIP2IT. The energy profile was re-constructed by adding the energy gain produced by each cavity, measured locally using BPMs nearest to the cavity. The pulse length measured after the SSR1 cryomodule is shown in Figure 1-39. The chopped bunch pattern measured by a RWCM after the SSR1 cryomodule is shown in Figure 1-40.

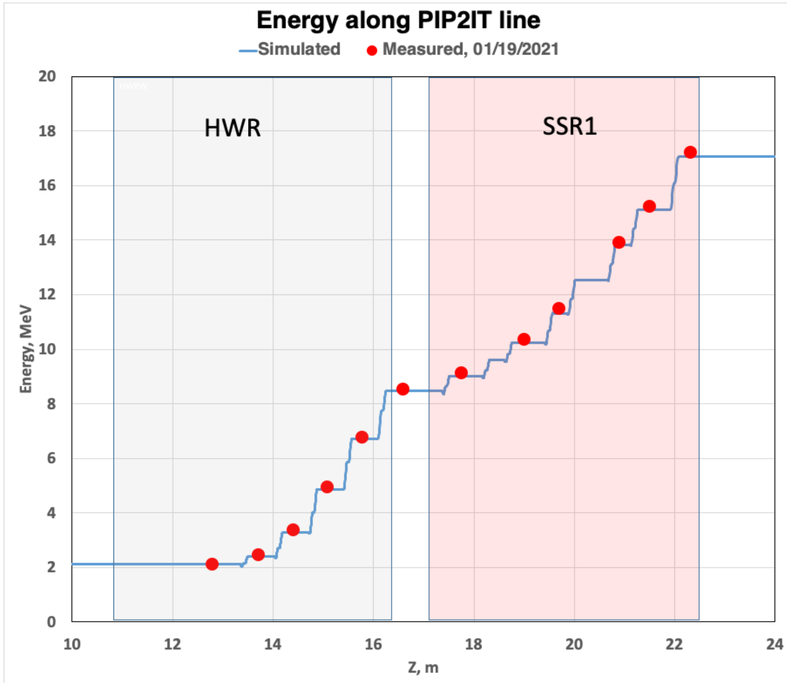


Figure 1-38. Comparison of beam energy measured (red) and simulated (blue). The maximum achieved energy was 17.2 MeV.

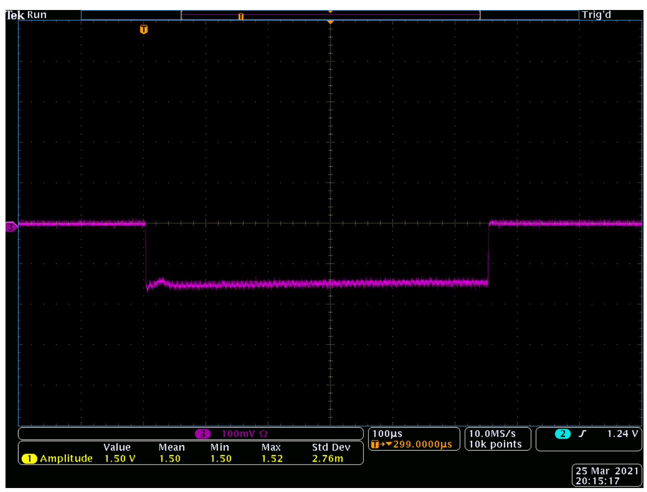


Figure 1-39. 16 MeV, 550 µs-long beam pulse

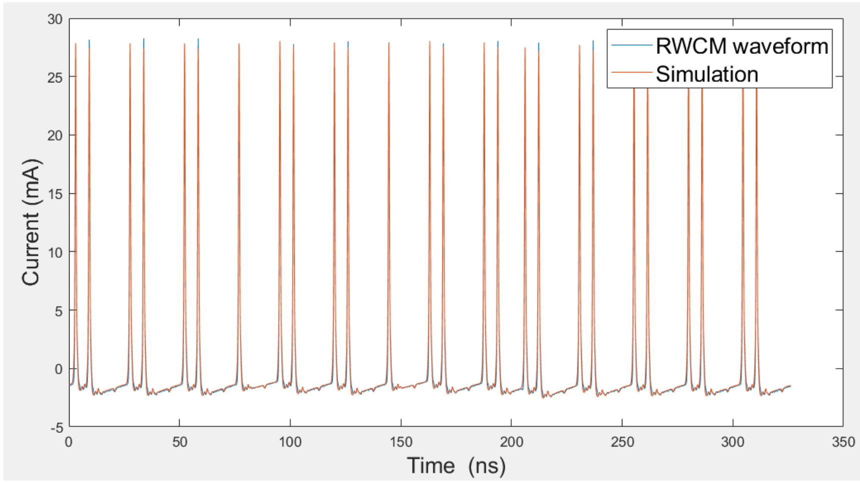


Figure 1-40. Bunch pattern chopped for injection into the Booster. Beam Energy is 16 MeV.

There were 4 different types of optics measurements: longitudinal; transverse; bunch centroid motion; and beam distributions. Longitudinal centroid motion was measured with the BPM phases and transverse centroid motion was measured with the BPM positions. Longitudinal beam distribution was determined by the FFC, RWCM, and Laser Wire while transverse beam distribution was measured with the Allison scanners, scrapers, wire scanners, and slit stations.

The PIP2IT beamline did not contain a spectrometer magnet to do a direct measurement of the H^- energy. Stationary BPMs installed along the accelerator and a ToF BPM system in the HEBT were utilized to measure the beam energy. The ToF BPM, a BPM physically moving along the longitudinal axis for 1 inch, demonstrated poor consistency of measurements and a strong dependence on the beam parameters in HEBT, frequently giving errors of the order of a few to ten percent. Stationary BPMs in the CMs did not require long beam transport and provided significantly better accuracy. Because the absolute calibration of the BPM phase was not implemented, only energy gain per cavity was measured. This method assumed the RFQ output energy was 2.12 MeV. The energy measurements and simulations were in good agreement, by <1%.

Significant variations in the beam phase at the first HWR cavity (#4) were observed during operations. The changes were observed after hardware power cycles and manifested themselves as a shift of the beam arrival time to the first HWR cavity, sometimes, as large as 70 degrees. These were caused by small variations (a few keV) in the beam energy magnified by the long MEBT. Although the source of the energy variation in the MEBT was not determined, likely suspects were changes in either the energy of the ion source or performance of the RFQ LLRF. The whole PIP2IT linac had to be re-tuned to compensate the phase shift due to a lack of a better recovery mechanism available at the time, requiring several hours of the tuning effort. Based on this experience, feedback to correct the arrival phase to a specific cavity using two preceding cavities will be implemented for PIP-II. Such feedback will keep the beam phase and energy profiles constant along the PIP-II Linac.

A RWCM and FFC were used to measure the longitudinal beam profile in the HEBT. The high-resolution FFC was suitable for the measurement of the longitudinal emittance in the HEBT. A 0.8 mm diaphragm cut the beam and the temporal data were measured with a scope in the CMTF gallery. The scope signal was fit to a Gaussian distribution to determine the bunch length. The bunch length was then measured as a function of the SSR1-8 phase and voltage.

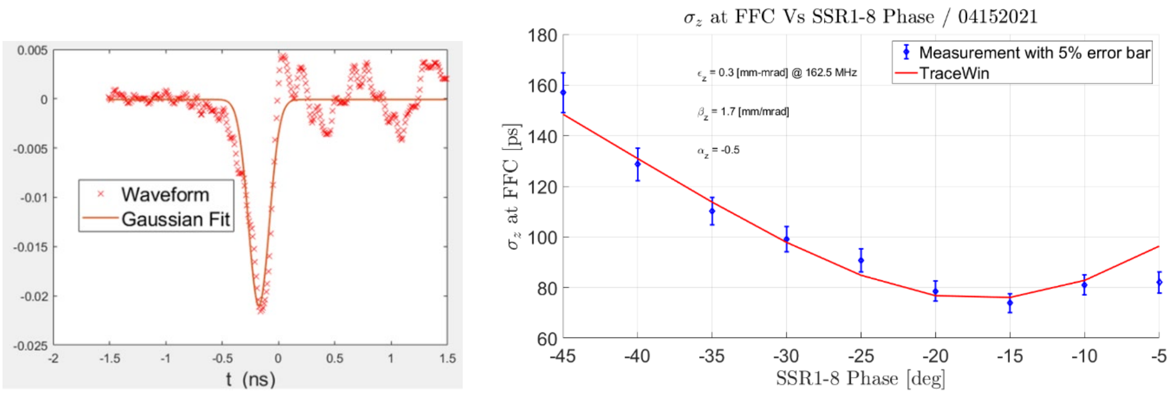


Figure 1-40. The left image is an example of the FFC signal with SSR1-8 at 25° and 10 MV/m. The right plot is the fit to the phase scan.

Bayesian Optimization with Gaussian Processes, a Machine Learning algorithm, was successfully applied to tuning the beam trajectory in the cryomodules. The convergency of the method demonstrates that the trajectory in the cryomodules can be tuned in a few minutes. As a separate effort, the simplex algorithm was applied successfully to the trajectory correction.

Hysteresis-like behavior was discovered in the cryo magnet dipole correctors. A systematic study of HWR dipole correctors confirmed the beam position would not return to its original position after adjusting a corrector current and then bringing it back to nominal. The SSR1 correctors were determined to have the same issue. A demagnetization procedure was developed to minimize the residual displacement caused by hysteresis in the correctors. Changes in the trajectory position after cycling SC solenoids also indicated that the magnetic field of solenoids exhibited hysteresis-like behavior; although, no accurate studies were conducted to confirm this hypothesis. The source of this hysteresis behavior will be investigated further and, if it is possible, mitigated in PIP-II.

Transverse distribution of the beam was measured in the HEBT with wire scanners and slits. There were 2 methods for determining the beam emittance. The first method was with a quadrupole scan that utilized a wire scanner. The quadrupole was adjusted to create a beam waist and then the wire scanned the beam profile. The data were fit to a Gaussian to calculate the RMS normalized emittance in both planes. The results were ε_x=0.29 mm-mrad and ε_y=0.27 mm-mrad.

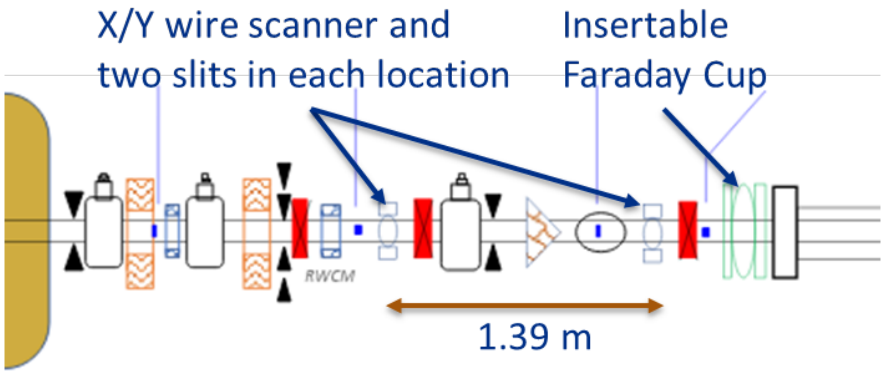


Figure 1-41. HEBT schematic layout indicating locations of wire scanners, slits, and Faraday Cup.

The HEBT slits were also used for measuring the beam emittance. The slits, which measured 0.3 mm, were shared with the wire scanner stations. The front station slit defined the position and moves in 1 mm steps while the back slit defined the angle and continuously scanned the beam profile. The Faraday Cup located downstream of the last slit provided the beam current profile during the scan. The RMS normalized emittances were calculated to be ε_x=0.23-0.28 mm-mrad and ε_y=0.31-0.47 mm-mrad.

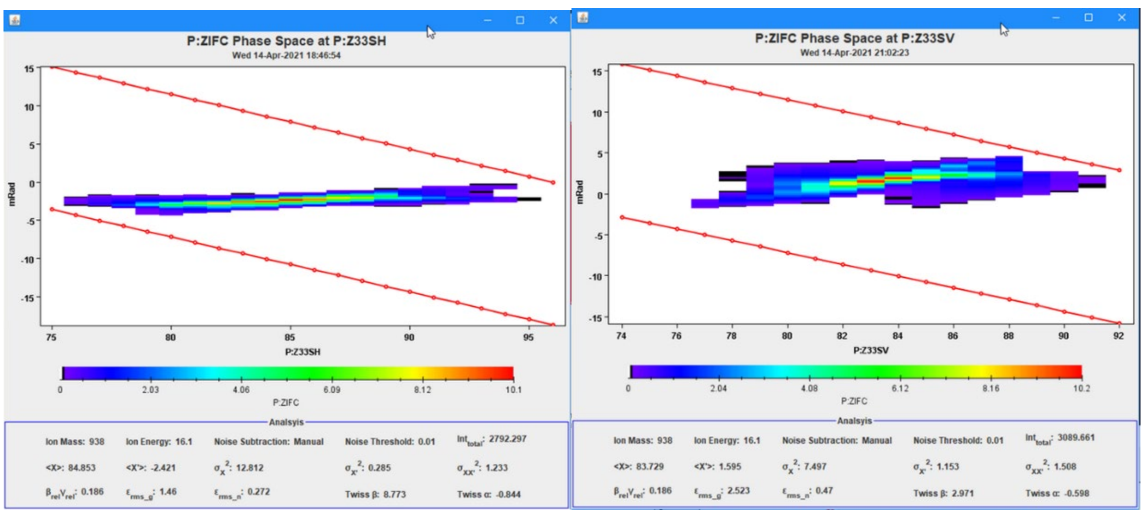


Figure 1-42. Examples of emittance scans with the slits. The horizontal emittance scan and calculation is seen on the left image and the vertical emittance data are on the right.

In summary, PIP2IT accelerated the beam that met PIP-II KPP parameters for the commissioned scope. The main beam core parameters were measured. The loss of 3 HWR cavities for beam acceleration created a deviation from the expected PIP-II layout. Thus, simulations were needed to construct the proper beam parameters so the PIPIT commissioning plan could move forward. Although the maximum beam energy of 17.2 MeV was below the 22 MeV goal, the ±2% accuracy of the measurement met specification. Transmission through the CMs was 99% and the 2 mA beam current met the set requirement. Table 1-2 summarizes the achieved results and compares them to the commissioning goals.

Table 1-2 Planned and achieved beam parameters at PIP2IT.

Parameter	Goal	Achieved	Comment
Energy, MeV	22	17.2 $\pm 1\%$	Three less HWR cavities
Pulse current, mA	2	2 $\pm 2\%$	
Transmission	99%	99% $\pm 2\%$	Through SRF cryomodules
Trans. Emittance (rms, norm), X/Y, μm	0.25/0.25	0.23, 0.25-0.4	Origin and validity of vertical tails are not clear
Long. Emittance (rms), μm	0.4	0.3 $\pm ?$	One measurement. Accuracy is difficult to estimate.
Bunch extinction	$5 \cdot 10^{-3}$	$< 1 \cdot 10^{-3}$	
Trans. Distr. resolution relative to max.	0.5%	0.01%	

Accelerator Systems

PIP2IT Accelerator Systems include HPRF, LLRF, RFPI, Beam Instrumentation, MPS, Cryo Magnet Power Supplies, and Controls. All of these systems required commissioning time throughout the run.

Overview

PIP2IT was a technical systems success. It validated beam properties, moved designs forward for PIP-II integration, and allowed for Fermilab's first EPICS platform programs to be developed and tested. The Traveler and ORC formalization was tested for PIP-II. COVID-19 brought remote operations to the forefront. Technical risks were mitigated in some systems while others were realized. Integration of systems demonstrated the successful completion of PIP2IT.

WBS / Ops Lab Activity : 121.3 Accelerator Systems (AccS) (16)

Risk Rank : 3 (High) (3)						
RT-121-03-001	AccS: Resonance control and field regulation do not meet requirements	50 %	1 -- 4 -- 12 months	100 -- 500 -- 3000 k$	600	2.8
RT-121-03-002	AccS: RF Power Amplifiers do not meet technical specifications	50 %	0 -- 3 months	20 -- 20 -- 600 k$	107	0.8
RT-121-03-031	AccS: Delay in Delivery of 650 MHz RF Amplifiers	25 %	1 -- 9 -- 15 months	0 k$	0	2.1
Risk Rank : 2 (Medium) (8)						
RT-121-03-005	AccS: Machine Protection System fails allowing a beam event	25 %	0.5 -- 6 months	30 -- 2000 k$	254	0.8
RT-121-03-032	AccS: Machine Protection System fails allowing a beam event during PIP2IT beam operation	25 %	0.5 -- 6 months	30 -- 2000 k$	254	0.8
RT-121-03-010	AccS: Integration of instrumentation into Machine Protection System	25 %	0 -- 12 months	0 -- 500 k$	63	1.5
RT-121-03-008	AccS: Preferred Laser profiling technology/transport mode does not work	25 %	0 -- 6 -- 12 months	0 -- 100 -- 500 k$	50	1.5
RT-121-03-014	AccS: Unforeseen issues with controls interface to existing accelerator complex	10 %	0 -- 12 months	0 -- 500 k$	25	0.6
RT-121-03-013	AccS: Magnetic measurement system or test stand is unavailable	10 %	5 -- 6 -- 7 months	90 -- 100 -- 110 k$	10	0.6
RT-121-03-030	AccS: Delay in Delivery of 325 MHz RF Amplifiers	15 %	1 -- 9 -- 15 months	0 k$	0	1.2
RO-121-03-002	AccS: PIP-II Beam Absorber Line Sweep Magnets	75 %	-3 months	-220 k$	-165	-2.3
Risk Rank : 1 (Low) (5)						
RT-121-03-033	AccS: Software issues with controls interface to existing accelerator complex	10 %	0 -- 6 months	0 -- 500 k$	25	0.3
RT-121-03-017	AccS: RF interlocks fail to protect SSA-Coupler-Cavity	10 %	2 -- 3 -- 5 months	90 -- 250 -- 340 k$	23	0.3
RT-121-03-018	AccS: Machine Protection System not allowing operation	25 %	1 -- 6 months	10 -- 150 k$	20	0.9
RT-121-03-028	AccS: Complex PIP-II bunch structure impacts instrumentation	5 %	0 -- 12 months	0 -- 200 k$	5	0.3
RT-121-03-020	AccS: SSR2 magnets require modifications to the QPMs	20 %	2 -- 6 months	10 -- 30 k$	4	0.8

Figure 1-43. Accelerator Systems risk registry.

The Accelerator Systems risks mitigated by PIP2IT were "LLRF resonance control and field regulation do not meet requirements", "MPS failure causes a beam event", "Integration of Instrumentation into the

MPS", and "Laser Wire profiling technology/transport mode does not work". The aforementioned risks should be reduced or retired in the risk register. The minimal risks realized were from the MPS and RFPI/SSA/cavity/coupler.

HPRF

The HPRF goals at PIP2IT were to test and qualify amplifiers, test and qualify the HPRF distribution systems, test the integrated RF system (LLRF, RFPI, HPRF, SRF, and Controls) with beam. The RF systems are shown in Figure 1-44.

System	Quantity	Power (kW)	Frequency (MHz)	Item	Manufacturer
RFQ	2	75	162.5	amplifier	Sigma Phi
RFQ	2	75		circulator	Ferrite
Bunchers	3	3	162.5	amplifier	Comark
Bunchers	3	7		circulator	McManus
HWR	8	7	162.5	amplifier	Tomco
HWR	8	7		circulator	McManus
SSR1	8	7	325	amplifier	DAE-ECIL
SSR1	8	28		circulator	McManus

Figure 1-44. PIP2IT RF systems.

The RFQ amplifiers had 3 separate DC power supply downtimes due to IGBT failures. These failures appeared to be an end-of-life issue and more investigation is warranted. A preventative maintenance schedule should be developed to address this common failure.

Corrosion on the RFQ can-bus caused controls issues so AD RF engineers were able to address this during the run. An upgrade to the Sigma Phi controls will be investigated and conducted after the amplifiers are relocated to the F0 service building. Roof blocks also trapped the directional coupler which made measurements precarious.

Buncher amplifier crosstalk remained a potential issue through the Stage 2 run. Some of the crosstalk was traced to faulty cables but the phenomenon remained.

HWR amplifiers were highly reliable throughout the run. Cavity 3 HV bias coupler failure that occurred during commissioning was investigated and a 3-fold protection scheme was instituted that included DC PS local trip at 2mA, PLC permit trip at 2 mA, and a RFPI fast current trip at 2 mA.

The HWR RF leak previously mentioned in the SRF section of this document was investigated and mitigated by RF personnel. Two antennas were installed at each CM and monitored by the RFPI system. RF leak checks on the HPRF system are a part of the ORC and documented in the travelers.

All SSR1 cavities were powered by DAE-ECIL amplifiers and an in-kind contribution from one of PIP-II's international partners. Each amplifier had a fuse failure at first power on. The issue was mitigated with replacement fuse holders and new fuses that were compliant with US electrical code.

In all, there were 15 SSR1 amplifier DC power supply failures. An electrical short on the internal power control board internal to the PS accounted for 12 of the failures. The other 3 failures remain under investigation. At the end of the run an RF slice failure occurred and remains under investigation. These issues and importance of their resolution were communicated to the partner providing the amplifiers.

Other issues that occurred pertained to water and RF leaks. Water leaks from the SSR1 power supplies occurred initially upon connection to the PIP2IT LCW. Internal water connection specifications were called out in a new TRS. RF leaks were found on the SSR1 RF distribution system. Anodized flanges on the coupler and HV bias tee mechanical issues were addressed to mitigate the leaks.

The ORC process was streamlined for SSR1 and will be adopted for the 650 CM Test Facility. The pre-ORC Traveler was utilized for verification of interlocks, connections, and acceptance tests. The Low Power Test Traveler was used for operating the RF system < 100 W for RFPI checkout, LLRF calibration, power interlock testing, and RF leak checking.

Each amplifier had two separate Controls paths, PLC and Ethernet. The PLC controls were essential for RF operation and Ethernet was required since each amplifier had a configurable IP address. EPICS control was integrated into SSR1.

The PIP2IT experience and commissioning results led to modification of the SSR1 amplifier technical specifications. The key changes are in reliability, maintainability, quality control, Controls, and electrical configuration.

LLRF

The FNAL LLRF team has been collaborating with groups from JLab, SLAC, and LBNL for more than 6 years on LCLS-II and now PIP-II. The successful results from LCLS-II were incorporated into PIP2IT LLRF development.

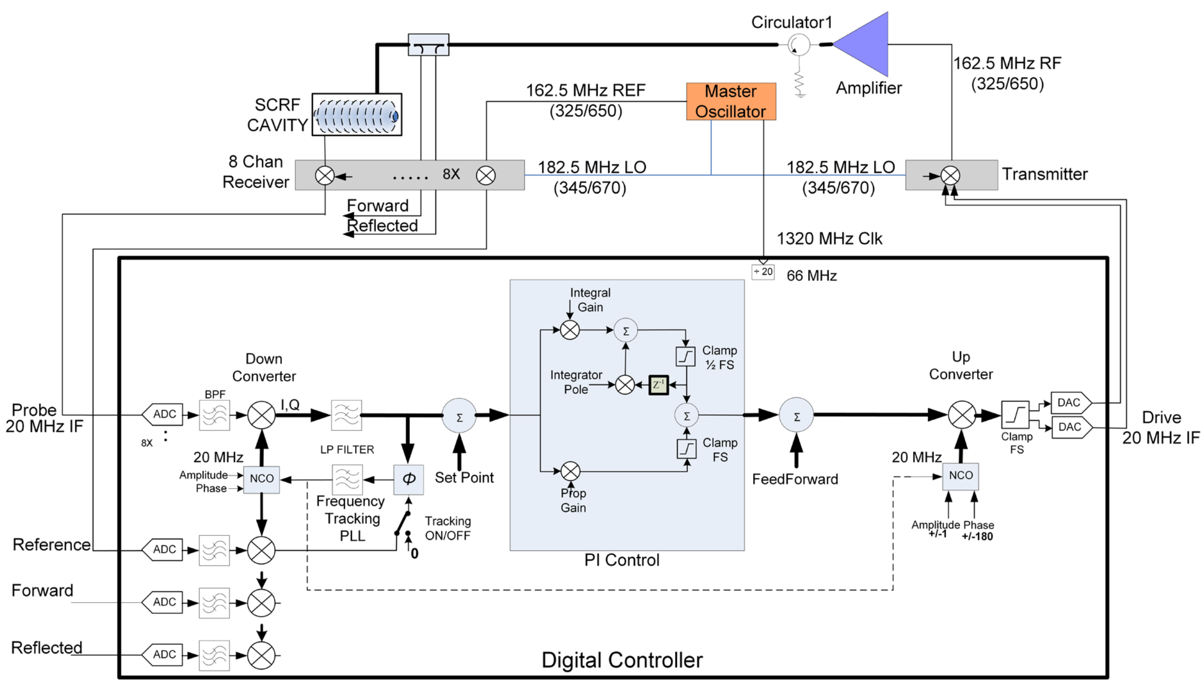


Figure 1-45. LLRF and RF system layout for PIP2IT.

One of the challenges during the commissioning run was with the HWR pneumatic control of the tuner pressure. The tuner bellows that set and changed the operating pressure would stick and drag. A procedure was developed to overcome this issue.

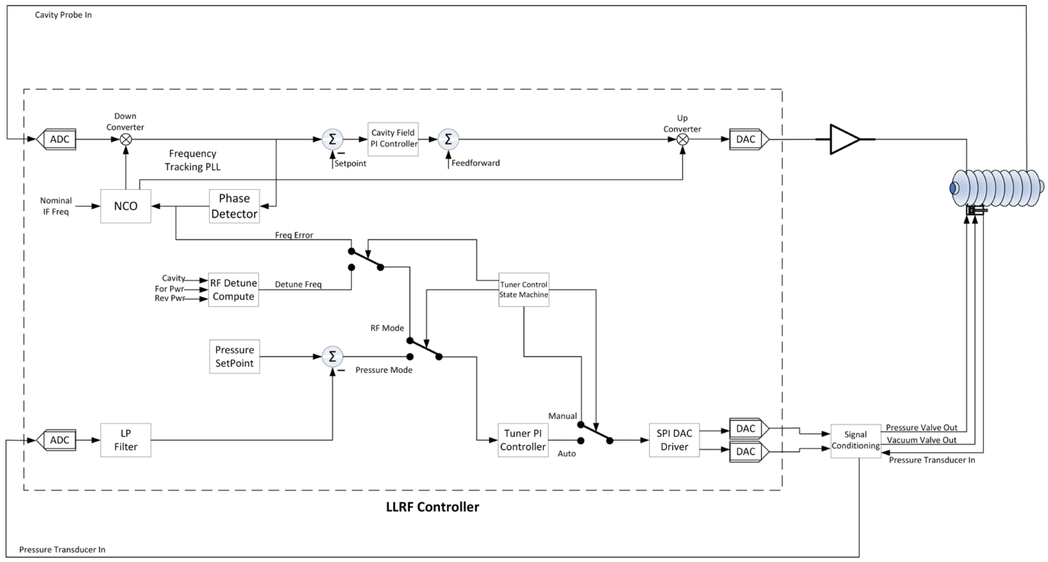


Figure 1-46. HWR tuner feedback loops.

The beam-bucket selection process was key technology developed for PIP-II that was tested at PIP2IT. The BPG was key component of this process and demonstrated the Booster bunch pattern to be used during the LBNF era.

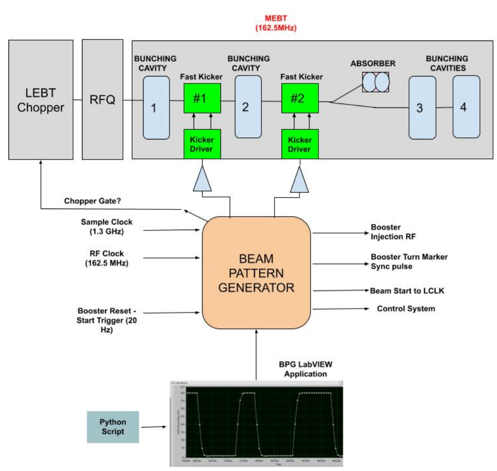


Figure 1-47. BPG system layout.

Buncher transient response and beam loading compensation worked well for all the operational SRF cavities. Beam loading compensation was verified for 10 μs pulse length unfortunately the Stage 2 commissioning run ended before longer pulse lengths could be tested.

The PIP-II specification for the stability of the cavity field amplitude and phase is 0.06% and 0.06°, respectively. The demonstrated stability of the field amplitude and phase was better than 0.0135% and 0.022° for all HWR cavities, easily meeting the requirements. The demonstrated stability of SSR1 cavities was better than 0.029% and 0.016° for the amplitude and phase respectively, meeting the requirements as well.

Resonance control performance for SSR1 was proven and understood with stepper motor and piezo control. LCLS-II resonance control chassis style worked without modification and utilized EPICS platform. Spectrogram were utilized to investigate both internal and external noise and vibration sources.

SSR1 microphonics identified vibration sources at 15 Hz, 30 Hz, and 55 Hz but the levels did not warrant investigation. The transfer function measurement induced a chirp to measure the detune frequency.

The fundamental goals for the LLRF and the RF systems were met. The Fermilab Field Control chassis were used during the PIP2IT run. Beam loading compensation was shown to work in the WFE and in HWR and SSR1 with feedback regulation. The Berkeley field control module was demonstrated. Resonance control on 4 RF structure types with different actuators was proven.

Quench detection was attempted but kept tripping on transient events. RF overdrive protection was not tested. Several systems needed a reboot or restart of the interface, inhibiting uptime operation. Studies with long beam pulse through the SRF section did not occur.

RFPI Systems

RFPI systems were built for HRW and SSR1 utilized similar platforms found in other accelerators at Fermilab. The initial plan was to use a system from one of the international collaborators but in order to meet the PIP2IT schedule it was decided to use Fermi based system and configure it for PIP2IT. Once fully commissioned, the RFPI system successfully met the project needs for protecting the RF system and CMs.

The HWR and SSR1 RFPI systems had many inputs, both analog and digital, and provided permits to the SSA, MPS, and LLRF systems. The monitored inputs and output permits for HWR and SSR1 can be seen in Figure 1-49.

Table 1: Make-up of RFPI Output Permits Based upon RFPI inputs for HWR

	Output Permits from RFPI		
Inputs to RFPI	**LLRF permit**	**SSA Permit**	**MPS**
RF antenna (gallery)	x	x	x
Safety Permit	x	x	x
Vacuum Status	x	x	x
Cryogenic Status	x	x	x
Temperature Sensors (RTD 1& 2)	x	x	x
Coupler Airflow Sensor	x	x	x
HV Coupler Bias voltage	x	x	x
HV Coupler Bias current	x	x	x
SSA Ready	x		x
RF Antenna (cave)*	x	x	x
RF Antenna 2 (cave)*	x	x	x
Forward Power **	x	x	x
Reflected Power**	x	x	x
Transmitted Power (for Cavity Quency)			

Table 2: Make-up of RFPI Output Permits Based upon RFPI inputs for SSR1

	Output Permits from RFPI			
Inputs to RFPI	**LLRF permit**	**SSA Permit**	**SSA_DC Permit**	**MPS**
FEP	x			x
RF antenna (gallery)	x	x		x
Safety Permit	x	x	x	x
Vacuum Status	x	x		x
Cryogenic Status	x	x		x
Temperature Sensors (RTD 1& 2)	x	x		x
Coupler Airflow Sensor	x	x		x
HV Coupler Bias voltage	x	x		x
HV Coupler Bias current	x	x		x
SSA Ready	x			x
RF Antenna (cave)*	x	x		x
RF Antenna 2 (cave)*	x	x		x
Forward Power **				
Reflected Power**	x	x		x
Transmitted Power (for Cavity Quency)				

Figure 1-48. RFPI inputs and output permits for HWR (left) and SSR1 (right).

A common issue with the RFPI for HWR and SSR1 were the requirements for the inputs. The RF antenna was initially regarded as unnecessary but early in commissioning it became a critical part of PIP2IT testing. The antenna trip settings were not initially defined. The HWR MPS permits for each of the 8 cavity-coupler systems were summed together which was undesirable since there were 3 unusable cavities.

The RFPI system failed to detect a short in the HV bias cable in the HWR Cavity 3, resulting in a damaging MP event at the initial stages of the RF cavity testing. The RFPI was designed to prevent such incidents, providing three layers of protection: (1) current limiting feature on the power supply unit, (2) tripping at the RFPI PLC, (3) tripping at the fast interlock cards on the RFPI VME system. However, the PLC had a logic error that was caught later, and the other two areas of protection did not have the limit set prior to powering up the system. The RFPI system did not interlock RF when the short developed, allowing multi-pacting, and the HV bias power supply went above 2 mA. Although the system was tested and approved for operation by the system owner prior to RF operations, insufficient testing of the RFPI system was the direct cause of failure to detect the power supply current. Additional root causes were identified and are mentioned in the following paragraph.

Integration and commissioning of both RFPI systems was challenging due to limited hardware availability, inadequate build instructions, and, importantly, personnel changes before the start of PIP2IT. Only 2 spare PCBs were produced therefore defective boards consumed many hours for diagnosis and repair which hindered beam commissioning. The time spent troubleshooting far exceeded the cost of purchasing additional PCBs. Initially, RFPI checkout was time consuming but as additional systems came online the turnaround time significantly decreased.

The key lessons learned from the RFPI commissioning were:

- A thorough plan is needed for handling non-ionizing radiation
- Calibration of trip point settings needed to be performed to maintain accuracy
- Redundancy in hardware for critical parameters was needed for minimization of system downtime
- An easy-to-use system user interface was needed prior to commissioning

Overall, the reliability of the RFPI systems was successful after initial problems were addressed. Neither system was plagued with false or missed trips. Some manufacturing defects in cable connectors and solder joints resulted in latent failures. In summary, the PIP2IT RFPI systems were successfully demonstrated with valuable lessons learned.

Beam Instrumentation

The scope of beam diagnostics was to provide the instrumentation systems necessary to successfully commission, characterize, and operate the PIP2IT accelerator. Key diagnostics were developed and tested at PIP2IT to reduce risks outlined by the PIP-II project.

Beam diagnostics instrumentation systems utilized in areas of the beamline are listed in Figure 1-50:

LEBT	**MEBT**	**HWR and SSR1**	**HEBT**
Allison scanner	Toroid	BPM electronics	ACCT

DCCT	ACCT		BPMs
Toroid	DCCT		Wire scanners
Electrical isolated electrodes	BPMs		ToF BPM
	Allison scanner		RWCM
	Prototype laser wire		Insertable Faraday cup
	RWCM		Fast Faraday cup
	Prototype wire scanner		Dump electronics
	Electrical isolated electrodes		BLM detectors

Figure 1-50. Instrumentation used throughout areas of PIP2IT beam line.

Beam Current Monitors

The PIP2IT beam current monitoring system consisted of many Bergoz style DCCTs and ACCTs. The list below shows the monitors and their function. Figure 1–51 details the location of the monitors in PIP2IT.

- DCCT-L measures and controls source current
- ACCT-L vs ACCT-M1 controls the loss in RFQ
- ACCT-M2 vs ACCT-H controls the loss in SRF
- ACCT-H vs Dump controls the loss in HEBT
- DCCT-M controls the average current (averaged over 50 ms) that goes into SRF
- ACCT-M2 controls the maximum charge over the pulse: 2mA x 0.55 ms

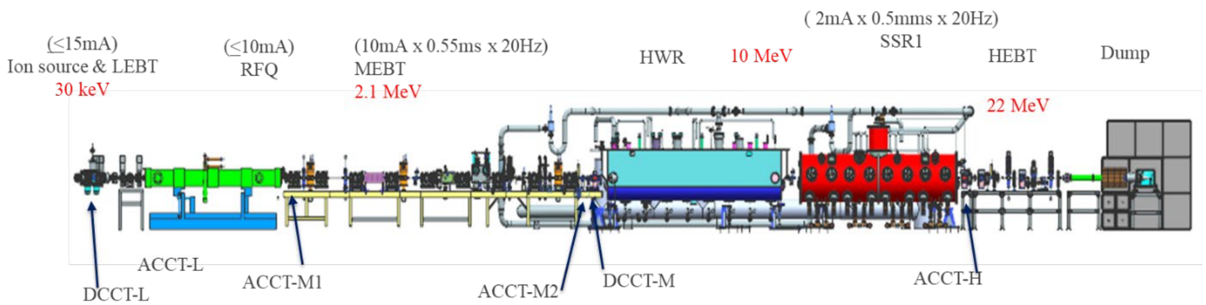


Figure 1-49. Beam current monitor layout in the PIP2IT beamline.

The DCCTs were able to provide current measurements up to 15 mA with a resolution of ±150 μA. The ACCTs provided current measurements for short and long pulses up to 10 mA. The monitors provided measurements up to a pulse width of 0.55 ms and a droop algorithm addressed errors for pulses >3 ms. Transition boards conditioned and distributed the signals between the digitizer, HRM, and MPS inputs.

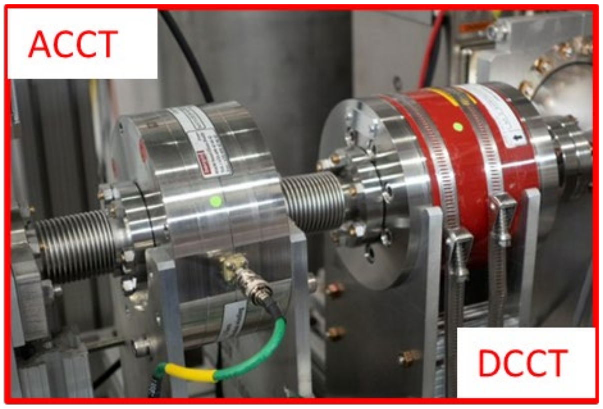


Figure 1-50. An ACCT and DCCT upstream of the HWR were used for monitoring the beam entering the CMs. The DCCT was a Bergoz in-flange model with magnetic shielding and a ceramic break.

BPMs

The BPM system consisted of 25 pickups each with 4 electrodes. In the warm area of the beamline there were 9 BPMs in the MEBT and 3 in the HEBT. The HEBT also contained the ToF BPM. For the CMs, HWR had 8 BPMs while there were 4 in SSR1. New electronics and DAQ system were designed and tested at PIP2IT. The typical VME readout was replaced by a 100 MB/s GigE readout with a transmission rate of 100 MB/s. A Linux server with 20 Xeon cores and 32 GB of RAM replaced the VME controller. New 16-bit, 250 MS/s ADC modules with GigE readouts were tested and provided signal processing for 1st and 3rd harmonic filtering. This will be the architecture used for PIP-II.

The ToF BPM was originally designed for the MEBT and tested during Stage 1 commissioning. The BPMs were HINS-style buttons, and the device had a longitudinal motion of 25 mm. It was relocated to the HEBT for Stage 2 commissioning.

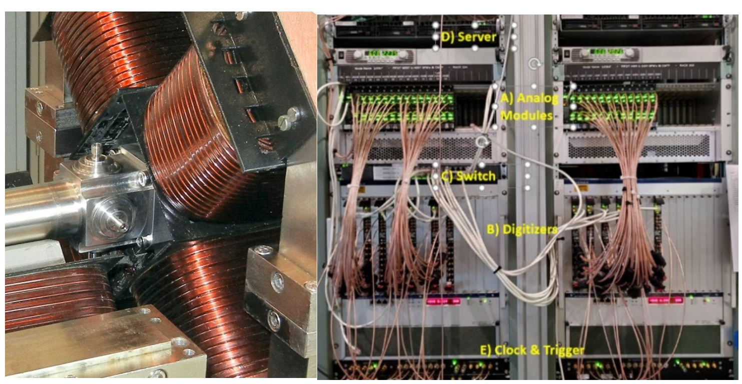


Figure 1-51. An installed BPM vacuum chamber (left) can be seen prior to cable connections. The BPM system electronics in the CMTF gallery (right) was spread over 2 relay racks.

Laser Wire

The Laser Wire system was tested with the primary goals of understanding signal-to-noise ratio, systematic issues, and DAQ techniques for a fiber-based laser profiler. The secondary goals were to acquire longitudinal and transverse beam profiles.

PIP-II was designed with a low H^- beam current per bunch so, with a photon interaction cross section of 3.5×10^{-17} cm^2 at 1.17 eV photon energy, the resulting Faraday Cup signal will be small. The laser power can be increased but the optical viewport has a damage threshold that limits the power. The direct current detection technique yielded a significant background of electrons even with the suppressor ring removing low energy electrons. The signal was obtained by averaging over many pulses as seen in Figure 1-54. The longitudinal bunch profile was then obtained by changing the phase of the laser relative to the beam (see Figure 1-55). A 2D XZ bunch distribution was obtained by scanning the beam with the laser beam transversely and in phase (see Figure 1-56).

Figure 1-52. With the laser off the background was measured to be 2 nA at the Faraday Cup. When the laser was on the signal went to 600 mV which corresponded to 6 nA at the Faraday Cup.

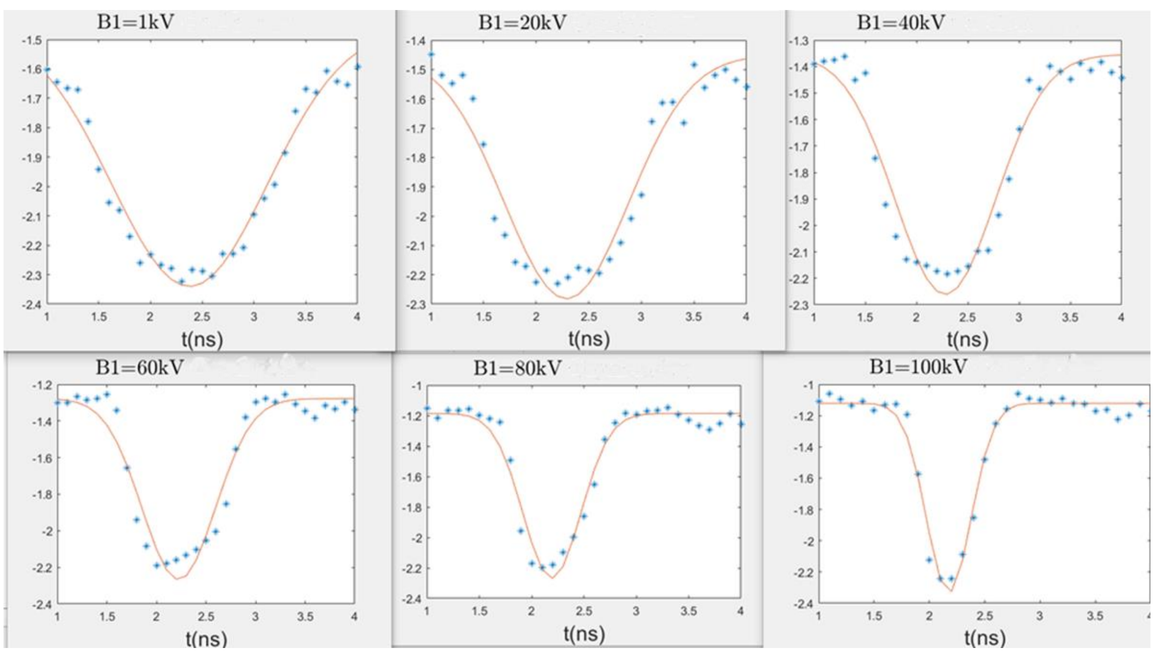


Figure 1-53. Bunch longitudinal profile measured with the laser wire for different settings of the MEBT Buncher 1.

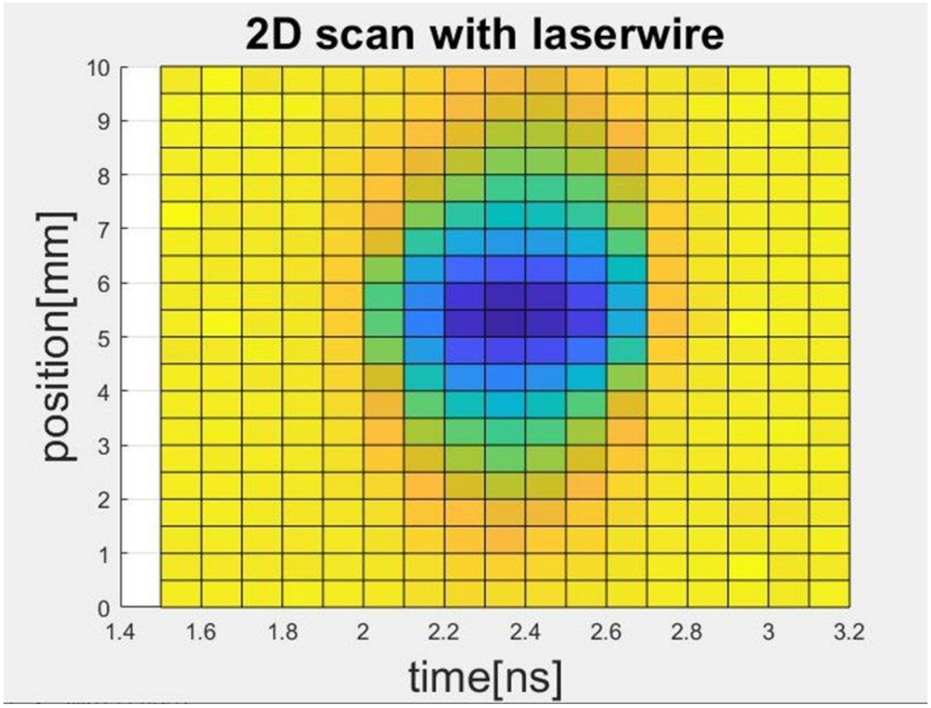


Figure 1-54. 2D XZ (transverse-longitudinal) distribution measured by the laser wire.

An amplitude modulation technique was developed where the laser repetition rate was locked to the PIP2IT RF and the modulated laser pulses were distributed to the fibers. The DAQ was locked to the modulation frequency which then allowed for the stitching together of multiple beam pulses from the Faraday cup. This technique eliminated the background electrons, but it was also sensitive to crosstalk effects.

MPS

The MPS architecture consisted of 3 layers: 1) Machine inputs, 2) Logic layer, and 3) Beam inhibit devices. All layers were tested and validated at PIP2IT. Machine inputs from various subsystems were sent to the FPGA Logic Unit which then established permits to beam enabling devices.

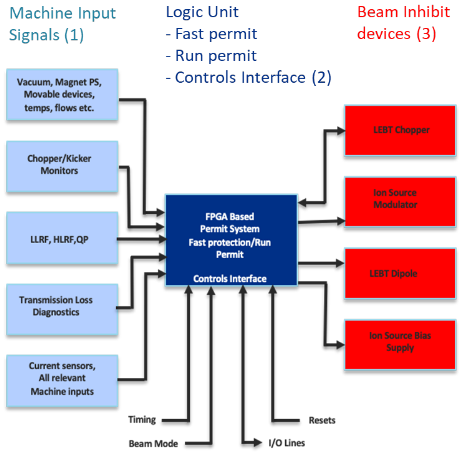


Figure 1-55. MPS architecture at PIP2IT.

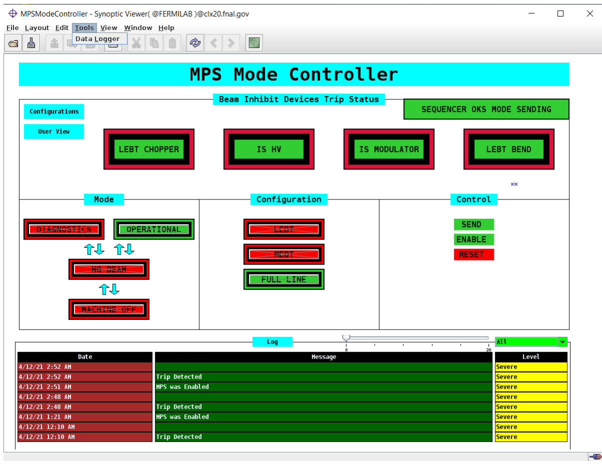
BIDs were arranged into 2 tiers for configuration and mode control development. Tier 1 was the LEBT Chopper and it added a layer of redundancy. Tier 2 devices were the IS Modulator, LEBT Bend Magnet, and IS HV. During commissioning, the decision was made to remove the IS HV from Tier 2 due to operational impact of restoring source output after an MPS permit trip. Abort concentrator units were added and tested as an upgrade for the HWR and SSR1 solenoid QPMs.

The fast beam interrupts were driven by serial communication between the LEBT Chopper and the MPS. The Chopper is a normally on device and there were 4 signals between the Chopper driver and the MPS. This scheme worked well and provided a redundancy and robustness to the MPS.

The MPS high-level functional requirements were achieved at PIP2IT. The system managed and monitored beam pulse widths within the jitter specification of < 1 ms and set the limits on various monitored devices. Beam modes and machine configurations were defined and verified. A post-mortem data collection process was developed and utilized for investigating permit trips. A comprehensive overview of the machine state, readiness, and permit status was validated and utilized by the operators on shift. The transition between configurations ran smoothly.

The 3 machine configurations for PIP2IT were LEBT, MEBT, and Full Line. These configurations defined the active input channels into the MPS. The LEBT configuration allowed for IS and LEBT tuning whereas the MEBT configuration allowed the operator to establish and tune beam to the MEBT absorber. The Full Line configuration allowed beam through the CMs and on to the HEBT dump.

Beam modes were created that characterized the machine's state. The operator executed an ACNET sequencer aggregate to transition between modes and established readiness to start beam operations via the Mode Controller program. The Diagnostic mode limited the pulse width to 10 μs and allowed instrumentation devices to intercept the beam, whereas the Operational mode allowed the pulse width to be extended to 550 μs and required all movable devices to be at their "out" limits.



Beam mode	Purpose
Machine Off	Default mode while starting or the last mode when shutting down.
No Beam	Default mode for full beam interruptions.
Diagnostic	Beam operation with short pulses. Pulse length and repetition rate may vary depending on what instrumentation is inserted.
Operational	Beam operation with average current up to maximum. Insertion devices (apart from the MEBT scrapers) cannot be moved from their 'parked' position.

Figure 1-56. The MPS beam modes are listed in the table (right). The left image is the Mode Controller synoptic GUI operators utilized for setting MPS mode and configuration.

The beam commissioning approach with the MPS was to gradually increase the intensity via the pulse length as system functions came online and were then verified. Initially, the maximum pulse length was 10 μs at 20 Hz repetition rate and 2 mA beam current. This was also defined as the Diagnostic mode parameters since 100% beam loss cannot damage machine components. Eventually, in the Operational mode the maximum pulse length was increased to 100 μs and then to 550 μs. The maximum pulse length was limited by the MPS.

New approved beam modes and machine configurations were added to the approved MPS configuration, allowing an incremental approach to the commissioning. Changes in the configuration of MPS, such as addition of new modes to the approved configuration and/or changes in the maximum beam pulse length, were reviewed by the PIP2IT MPS Configuration Committee, described earlier in the document. The committee made recommendations to the PIP2IT L3 Commissioning Manager.

Beam loss algorithms were integrated into the MPS and successfully tested. The MPS monitored beam loss with RPUs, kicker protection masks, toroids, DCCTs, and ACCTs. RPUs improved the stability of loss detection. MEBT kicker protection masks were tested down to a 6 μA loss. The differential pumping port beam loss protection was verified. The DBCM algorithm for CM protection was implemented and tested to better than 3% resolution.

The moveable device interface was tested and integrated into the MPS but took considerable time to implement. There were issues with initial conditions and positions were solved by setting hard limit registers in the FPGA.

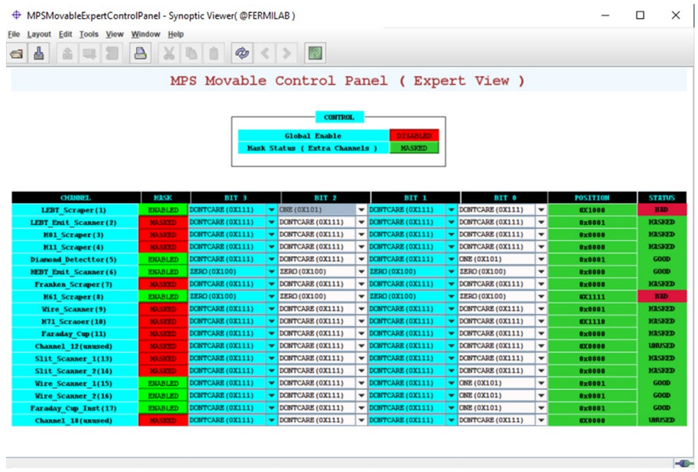


Figure 1-57. the movable devices control panel was integrated into the MPS.

On 4/11, the MPS failed to properly function, causing a beam incident. A false trip of a vacuum gauge in HEBT tripped the SSR1 RFPI and HPRF. The HWR cryomodule remained operational and accelerated the beam to ~8 MeV because the SSR1 RFPI did not affect the HWR HPRF. The wrong energy of the beam in the SSR1 CM caused ~75% beam loss in HEBT. In contradiction to the approved configuration, the MPS failed to

- React to SSR1 RFPI and SSR1 HPRF fault
- React to 75% beam loss in HEBT

Although this incident presented no danger to personnel and caused no hardware damage, it raised very serious concerns. All beam operations were stopped until further approval. High power operations with the pulse length longer than 10 µs ceased for the remainder of the PIP2IT run. A review of MPS Management Practices was launched. The committee found that the direct cause of the incident was misconfigured MPS. All the findings of the committee, including possible root causes, were documented in the review report. Committee recommendations are tracked in the iTrack system.

With the exception of the incident on 4/11, overall MPS architecture worked well and will be used for PIP-II. The algorithms developed will be optimized to newer hardware and platforms. Experience with PIP2IT allowed for system development. Software tool development will be integrated early into the PIP-II MPS in order to keep pace with systems brought online.

Cryo Magnet Power Supplies

AD Electrical Engineering Support Department designed and created the HWR and SSR1 magnet power supplies. Each CM has four 65 A switch modules, four capacitor banks, four QPMs, and two DC power supplies. The HWR has sixteen 10 A switchers for corrector magnets and SSR1 has sixteen 50 A switchers for corrector coils.

Figure 1-60. Layout of the Cryo magnet power supply relay racks at CMTF.

During the COVID-19 lab-wide shutdown the personnel who worked on the design and installation retired after the HWR power supply components were installed at CMTF. The SSR1 system was installed by a new set of technicians and thus there was a steep learning curve to fine tune the switchers to the load. Once operational, all power supplies were left on, with or without beam commissioning activities.

There was very little downtime associated with the cryo magnet power supplies. The majority of the downtime was attributed to the CM liquid level dropping below the threshold causing the QPM to issue a Cryo Permit trip.

Day-to-day trajectory variations led to demagnetization tests of all correctors. After demagnetization ramps were executed, trajectories were reproducible. This process was performed for both CM systems.

There was one HWR magnet quench during Stage 2 commissioning. HWR solenoid 7 quenched during beam studies. The QPM response time was 30 ms, faster than the 50 ms specification requirement. Diagnostic mode beam parameters at the time were 10 μs pulse width, 20 Hz repetition rate, and 2 mA beam current. Operators were varying the current on a vertical corrector magnet at HWR 5 and 6.

Power supply polarity connections were based on CM labeling but beam based studies determined some dipole corrector polarities were incorrect. QPM software changes were made to correct the issue. Also, QPM software was modified to allow for a single parameter of each SSR1 corrector magnet which allowed the operator easy adjustment during tuning.

Controls

AD Controls Department provided 48 trigger channels, 8 D/A channels, 169 A/D channels of which 62 were Sample & Hold, and 18 digital status and control channels. The operational issues encountered over the course of the commissioning run were:

1. One failed timer channel
2. Damaged MEBT HRM communication cable
3. One failed IS fiber clock receiver
4. A re-engineered grounding layout of the IS

PLC controls were provided for the entire LCW and vacuum systems. The PLC system provided analog readbacks, analog settings, digital control, and digital status information to ACNET. One D/A module for the H_2 flow regulation into the IS failed and was replaced.

Other issues experienced were feature creep and evolving-to-the-end requirements for systems like RFPI and MPS. A change to ACNET infrastructure resulted in substantial downtime to Bunchers 2 and 3. This did not allow the proper downloads to the LLRF for those two systems.

The EPICS platform was tested on SSR1 amplifiers and associated resonance control system. Readback, control, setting, and status were provided to the operator via an IOC. Collaborator contributions were integrated into those systems.

WFE Performance

The WFE delivered commissioning and normal operation beam parameters to the CMs. It demonstrated operational flexibility and was highly reliable. There were slow drifts of the IS output current once the plasma was established but this was only experienced after long shutdown periods.

The IS met the requirements of > 10 mA DC beam current, transverse emittance < 0.2 mm mrad (rms, normalized), kinetic energy stability of 0.5% at 30 keV, mean time between repairs > 350 hours, turn-on time < 10 min, and source filament replacement time < 8 hours.

The RFQ performance achieved a transmission > 95%, an output transverse emittance of < 0.25 mm mrad (rms, normalized), and an output longitudinal emittance of 0.9 eV μs. Near the end of the Stage 2 run, the RFQ output energy appeared to jump. Based on the trajectory change, the RFQ voltage jump was consistent with a 300 V increase. A post-PIP2IT investigation suggested the cause came from the LLRF system.

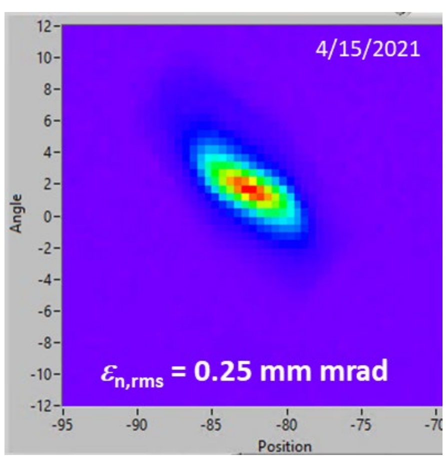


Figure 2-1. RFQ output emittance plot generated by the Allison scanner.

The MEBT demonstrated bunch-by-bunch chopping with no measurable emittance growth through its 10 m length and successfully delivered the kicked beam profile for LBNF Booster injection.

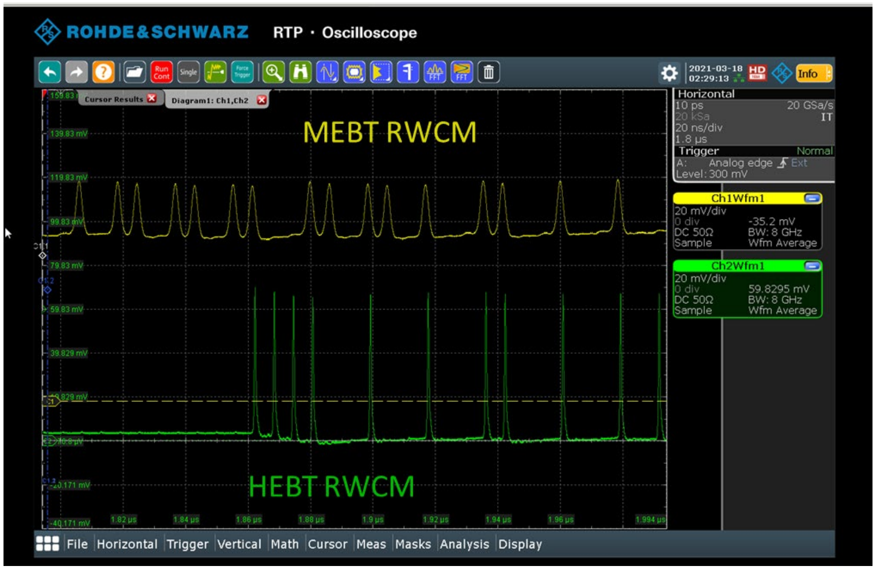


Figure 2-2. The kick pattern for Booster injection was verified with the MEBT and HEBT RWCMs.

The MEBT absorber was tested with a 4.4 ms pulse width and 4.5 mA beam current at 20 Hz repetition rate. The power level was 0.8 kW whereas the absorber was designed for 21 kW of beam power. The decision to limit the power was explained partially by a deficiency in the absorber assembly. The secondary absorber was not installed due to mechanical interference. The MEBT power level was not sufficient to fully validate the absorber design. The magnitude of the power reflection from the primary absorber surface was < 15%, which was smaller than the expected 25%. The distribution of the secondaries is more populated at shallow angles and less favorable than expected. This possibly can cause overheating of the beam pipe at a high average intensity. However, the current design of the absorber works well with the PIP-II baseline parameters and does not require modifications.

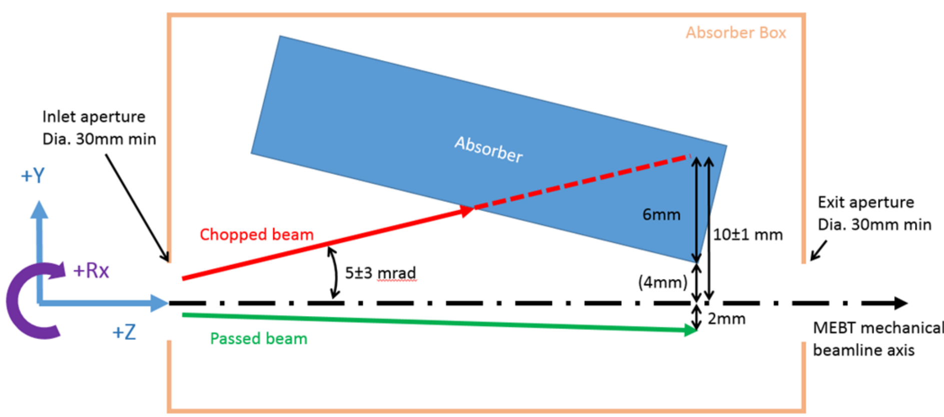


Figure 2-2. Absorber box layout for intercepting chopped beam.

The DPI provided 2-4 decades of vacuum isolation. In conjunction with the FAV it showed < 1.0 x 10^{-6} Torr liter of gas passed through the DPI, independent of the leak size.

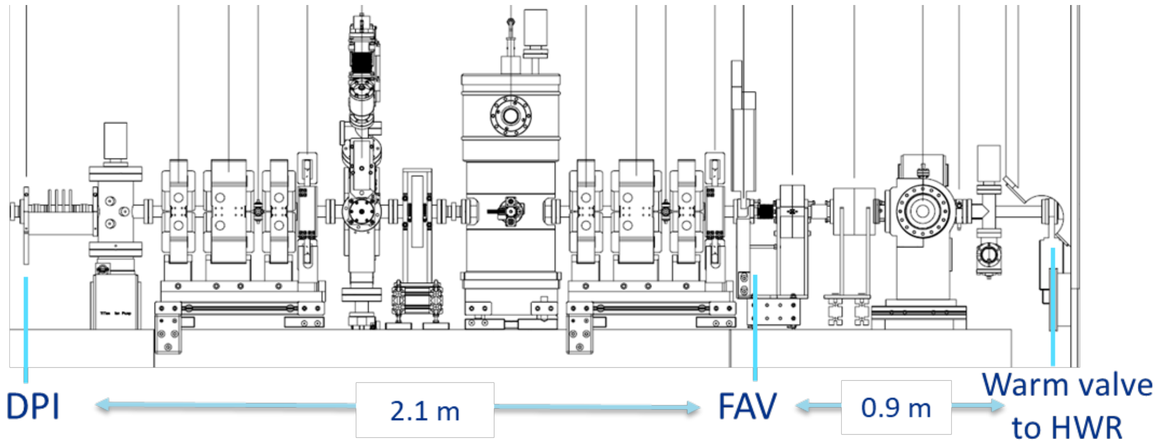


Figure 2-3. The DPI, upstream of the FAV, protects the HWR from an in-rush of gas during a vacuum leak.

As tested at PIP2IT, there was no cause to change the WFE design so it can be transferred to PIP-II as-is and reassembled once beneficial occupancy of the High Bay Building is attained. There will be an additional girder and buncher installed at the end of the PIP-II WFE. Completion of the production kicker driver final design remained at the end of PIP2IT commissioning. The IS HV cabinets will be redesigned for PIP-II.

Installation and Infrastructure

The L3 system managers were responsible for their equipment installations and managed the cost accounts for these devices. The Test Infrastructure group provided CAD, infrastructure, coordination, technician support, and partial mechanical engineering support. The PIP2IT equipment handoffs were not in the fashion planned for PIP-II.

PIP2IT was an early implementation of a very large NX CAD model. The MEBT went through many temporary configurations which were necessary to attain the program's goals but the various configurations became unmanageable in the CAD model. This led to a lessons learned that was incorporated into the PIP-II model and CAD design processes.

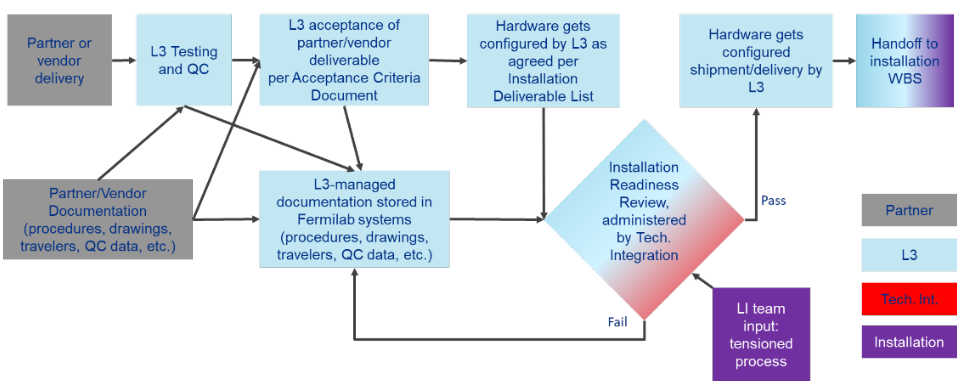


Figure 3-1. IRR tree for accepting hardware and handoff to installation team.

Documentation improved dramatically through the PIP2IT lifecycle. The Traveler framework was utilized but difficult to close out due to the scope being too large. Hazard analysis and Travelers were not tightly coupled. The ORC and Traveler processes were not well synchronized.

Mockups of critical installation tasks were successful. Small "glovebox" cleanrooms for CM vacuum work were successful. This is in contrast to the soft-wall cleanrooms that have been used in the past. PIP-II will need to make extensive use of glovebox cleanrooms for CM interfaces.

The CMTF primary infrastructure systems were LCW, Compressed Air, Nitrogen, ICW, and Electrical. The LCW system included 5 chillers, a pumping system, and 3 RFQ cooling skids. The compressed air system consisted of 2 air compressors and 1 dryer. The nitrogen system consisted of a tank outside CMTF and the subsequent piping to the cleanroom and enclosures. ICW was provided to CMTF either from Andy's pond or Casey's pond. The electrical system was distributed throughout CMTF and the adjacent compressor building.

Figure 3-2. RFQ water skids and piping are in the center of the image. The IS chiller system is to the right of the RFQ skids.

The COVID-19 pandemic played a role in the disruptive events that occurred during commissioning activities. The LCW and air compressor systems that tripped off were due to lack of regular maintenance since service technicians were not allowed on site during the pandemic. Other disruptive events included the IS chiller tripping off due to a failed capacitor and blown fuse, and an air temperature/dewpoint sensor failure on the air dryer which caused humidity to increase in the air lines and condense in instrumentation and SRF couplers.

Lessons learned from these occurrences were relevant to planning PIP-II future operations. In particular, the service contractors for CMTF were placed on the Lab's essential list in case another pandemic should occur. This practice will continue for PIP-II operations. Single point of failure systems were identified and redundancies are being planned for PIP-II.

Summary

PIP2IT was a successful test of the technologies and strategies for PIP-II. PIP2IT has accelerated beam with parameters required for the injection into the Booster. Completion of 92% of the outlined deliverables made PIP2IT a success. The operation of PIP2IT systems led to valuable experience and lessons learned that will be carried over to the final design. The majority of beam parameters for PIP-II were verified with PIP2IT. The loss of 3 HWR accelerating cavities did not provide the PIP-II design optics but simulations were utilized to adjust parameters for establishing H^- ions to the HEBT beam dump.

HWR CM operable cavities were commissioned with little or no MP. The cavities with MP were processed quickly. The cryo magnets were successfully tested and exceeded operational requirements. The couplers met all specifications and requirements. As an ensemble, the average Q_0 was measured at 1.3×10^{10}, which was greater than the requirement for HWR. Although there were issues with a spontaneous quench on cavity 8, SRF personnel quickly investigated and determined a best path forward for returning the CM to operation.

All SSR1 cavities were placed onto their resonance frequency without issue. Microphonics were measured to be < 10 Hz. All 4 magnet packages were tested without any issues and there was no measurable heat load detected when operated individually or as a whole unit. The in-kind amplifiers and resonance controllers were operated with the proposed new AD controls platform EPICS. All cavities operated at the required gradients for beam acceleration. Once beam commissioning activities had concluded, all SSR1 cavity gradients were increased to ascertain whether they could reach their administrative limits. Field emission and soft quench issues limited some of the cavities to the higher fields.

The CP operations team gained experience maintaining the plant with PIP2IT and LCLS-II CMs in simultaneous operation. Plant capacity became an issue during some of the CM functionality tests. Without the LN_2 precooler, liquefaction was constrained to 11 g/s and support for 3 CMs became challenging. KVS2 and 3 were brought online near the end of the Stage 2 commissioning run. This increased CP pumping capacity to 18.5 g/s and resolved the limited capacity issue.

The LLRF, HPRF, and RFPI systems for the CMs were commissioned and operated to specifications. HWR amplifiers were very reliable through the Stage 2 run. An RF leak from HWR was found at initial turn on and rectified quickly. The outcome was the establishment of antennae under the CMs with monitored RFPI inputs. The FNAL LLRF team collaboration with other national labs for LCLS-II led to the development and testing of the digital controllers and tuner feedback circuits for HWR and SSR1. The BPG technology successfully established the LBNF Booster injection pattern to the HEBT dump.

The MPS layered architecture was validated, and the established machine modes and configurations were tested at PIP2IT. Beam loss algorithms were verified with BIDs. The software developed for the MPS at PIP2IT will be optimized for the new hardware and Controls platform planned for PIP-II.

Numerous systems and technologies were successfully tested at PIP2IT and, as a result, many PIP-II risks were retired or reduced. The PIP2IT Stage 2 run met all main goals and most of the extended goals. All accelerator systems were tested with beam and the results will be used to advance the design of PIP-II technical systems. Beam parameters were deemed suitable for injection into Booster. The PIP2IT team went above and beyond to meet their goals, especially during a worldwide COVID-19 pandemic.

Acknowledgements

Thanks go out to all of those who contributed to the success of PIP2IT. Thank you to all who presented at the PIP2IT Retreat. A special thank you goes to Michael Geelhoed and Eduard Pozdeyev for taking to the time to edit and proof this document.