Beam Commissioning of PIP-II Injector Test (PIP2IT) H- linac

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for PIP2IT commissioning team

Workshop "Experiences During Hadron LINAC Commissioning"

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

Outline

- PIP2IT
  - Introduction, parameters, status
- List of diagnostics
- Beam commissioning
  - Beamline configurations
  - Cavities phasing
  - Energy measurements
- BPMs performance
  - Beam jitter vs electronics noise
- Other tools
- Plans and summary

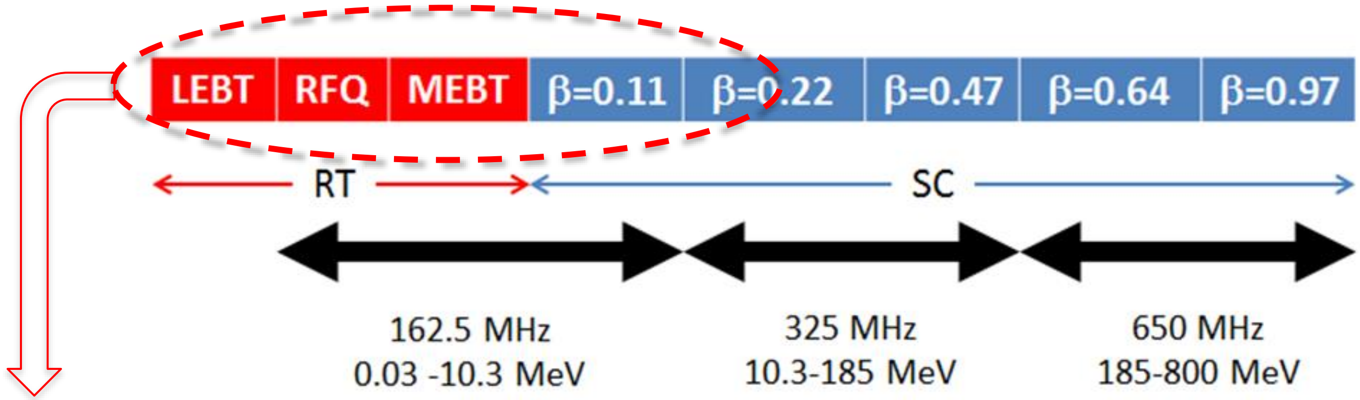
Proton Improvement Plan – II (PIP-II)

- Upgrades for Fermilab Accelerator Complex
  - The main component: 800 MeV, 2 mA CW-compatible H^- Superconducting Linac. Goal: beam in 2028
  - Platform for future upgrades

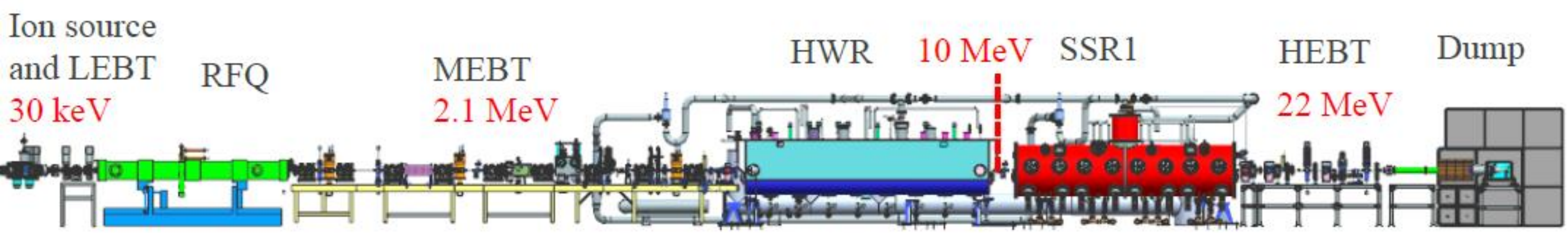
PIP-II Injector Test (PIP2IT)

- PIP2IT: a test accelerator representing the PIP-II front end
  - Acceleration in SRF from 2 MeV
  - Bunch-by-bunch chopper in MEBT

PIP-II Linac scheme



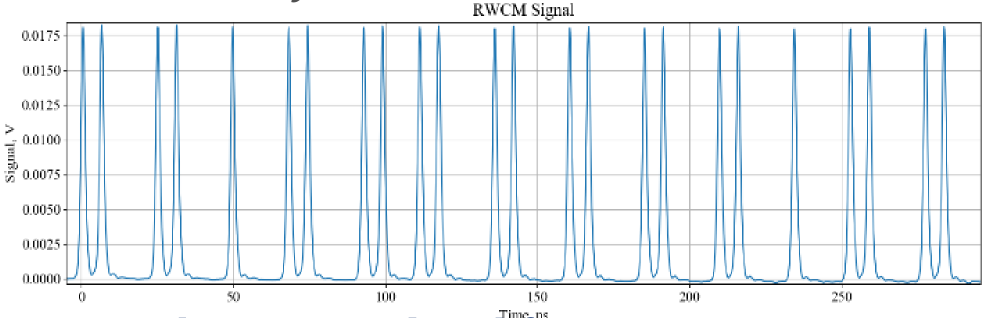
Collaboration:
RFQ (LBNL)
MEBT magnets (BARC, India)
HWR (ANL)
SSR1 PAs (BARC)
SSR1-8 cavity (BARC)



LEBT = Low Energy Beam Transport; RFQ= Radio Frequency Quadrupole; MEBT= Medium Energy Beam Transport; HWR = Half-Wave Resonator; SSR1=Single Spoke Resonator; HEBT = High Energy Beam Transport

PIP2IT parameters and history

- PIP2IT goal: demonstrate parameters suitable for PIP-II
  - 22 MeV x 2 mA x 0.55 ms x 20 Hz
    - Base design: SRF works in CW
  - Pulse-average 2 mA is prepared from RFQ's 5 mA beam by removing bunches that would not fit into Booster's longitudinal acceptance with the MEBT chopper
- Warm Front End was built and commissioned in 2015-2018
  - Ion source; LEBT; 2.1 MeV, 162.5 MHz CW RFQ; MEBT
  - Required emittances at 5 mA ($\varepsilon_x \approx \varepsilon_y \le 0.23\ \mu m$; $\varepsilon_z \le 0.3\ \mu m$)
  - Max power 2.1 MeV x 5 mA x 25 ms x 20 Hz
  - Prototypes of fast MEBT kickers and an absorber were tested



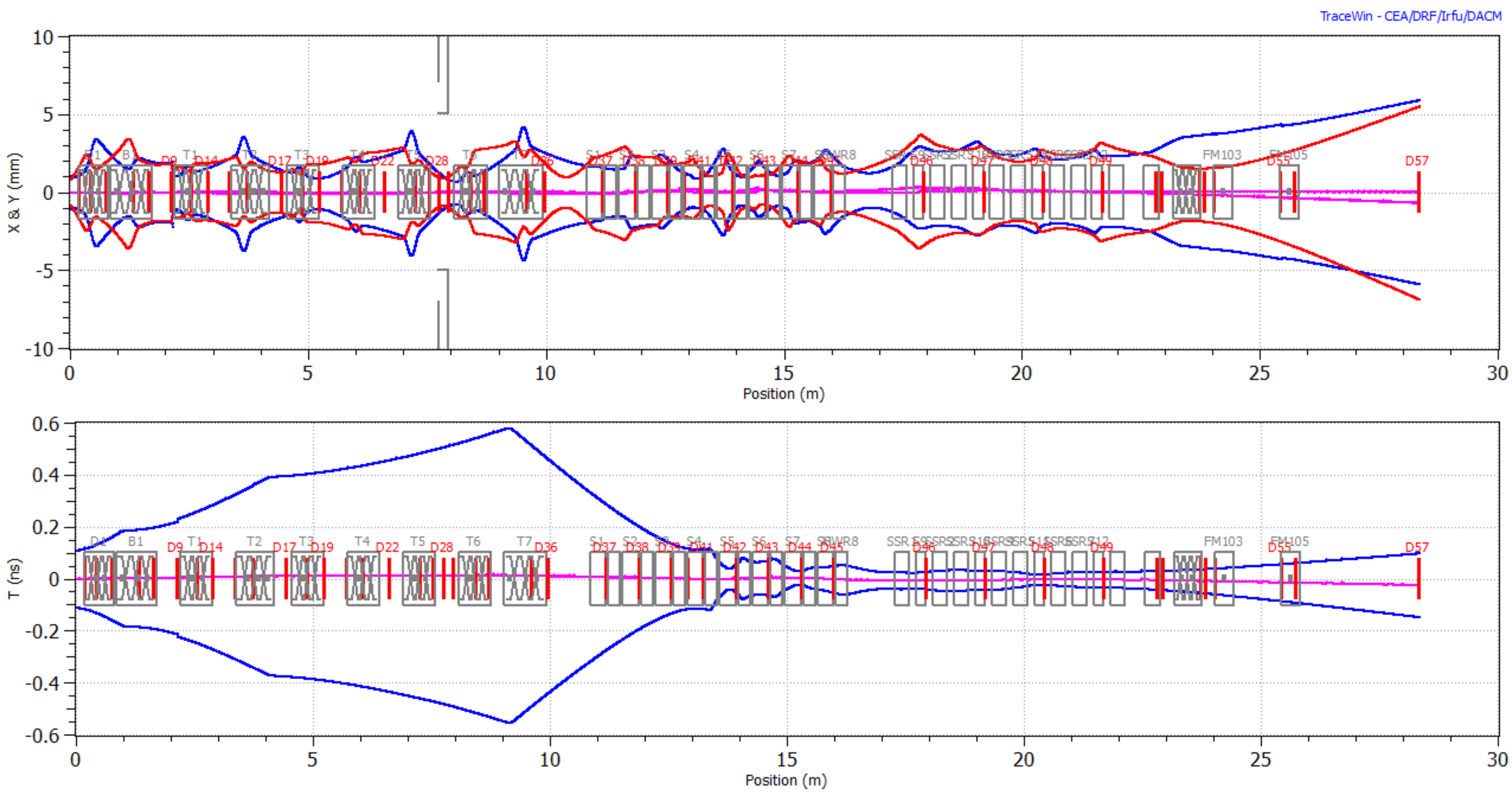
Bunch pattern tailored for Booster injection. Recorded with RWCM.

PIP2IT status

- Added after 2018: two cryomodules, MEBT upgrade, HEBT
  - HWR (8 cavities, 162.5 MHz) and SSR1 (8 cavities, 325 MHz)
  - MEBT: “Final” chopping system, particle-free section
  - HEBT with diagnostics (partially moved from MEBT)
- Issue: the first 3 cavities in HWR are not operational
  - PIP2IT will operate at a decreased output energy
    - Acceleration in HWR to the energy suitable for injection into SSR1 may mean a compromise with emittance degradation
- In December 2021, all amplifiers were installed
  - Beam was accelerated to 17 MeV
    - 2 mA x 10 µs x 20 Hz; no chopping (scraped in MEBT from 5 mA)
- Present plan is to finish the run in Spring 2021

Bunch parameters

- 162.5 MHz, 5 mA => $1.9 \cdot 10^{8}$ H^{-} per bunch
- The bunches are mm - size, but vary through the beamline

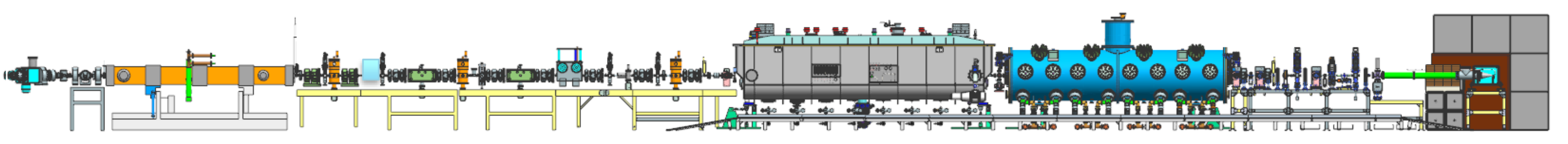


Beam 1-rms envelope in the scenario used for acceleration to 17 MeV. J.-P. Carneiro

List of beam diagnostics

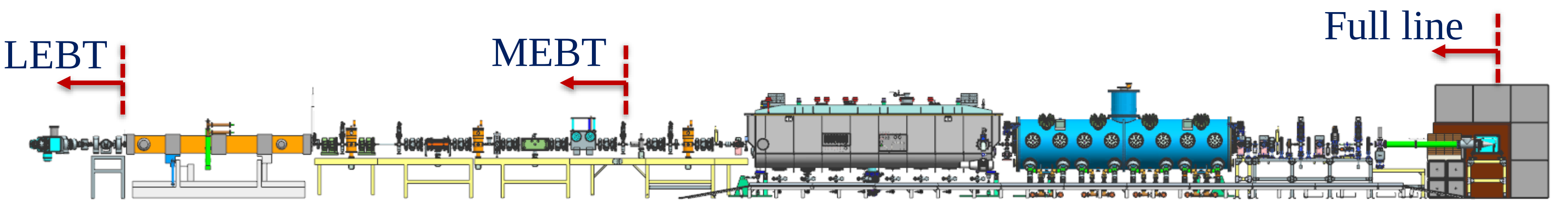
- So far, the main tools are BPMs and current diagnostics

Section	BPMs	Current/losses	Other
Ion source/ LEBT	0	DCCT, ACCT, 6 electrodes	Allison scanner, scraper
MEBT	9	2 ACCT, DCCT, 5 electrodes	Allison scanner, 4x4 scrapers, RWCM, 4 “ring pickups” for MPS, Laser wire, diamond detector
HWR	8		
SSR1	4		
HEBT	3 (+1)	ACCT, beam dump	ToF BPM, 2x2 slits + Faraday Cup, 2 wire scanners, RWCM, FFC



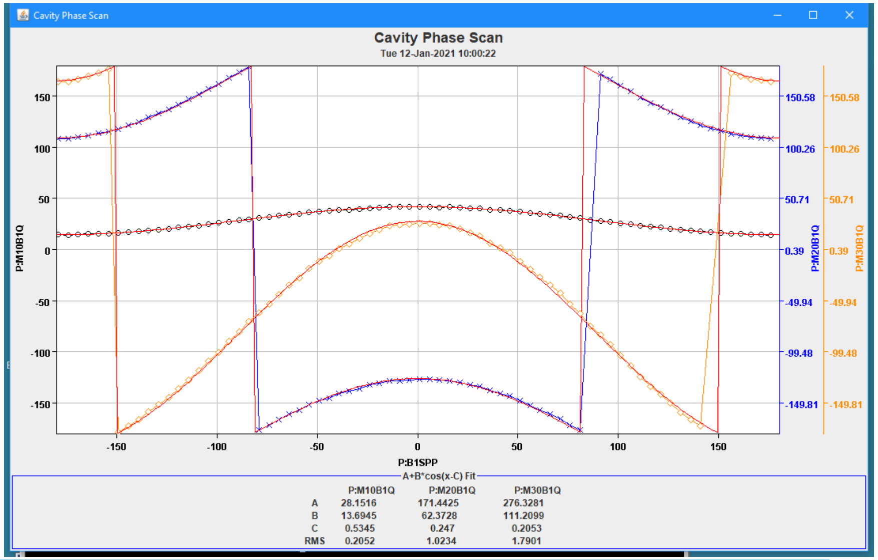
Beam commissioning modes in 2020/21 run

- 3 beamline configurations: LEBT, MEBT, Full Line
  - Beam propagation in LEBT and MEBT configurations is restricted by corresponding scrapers; vacuum valves are closed
    - 5 min to switch in a good case
- 2 beam modes
  - Diagnostic: 10 μs max, insertion devices allowed
  - Operation: up to 0.55 ms, insertion devices are parked
- Often, two or more parallel efforts
  - E.g. beam studies in MEBT, LLRF in HWR, SSR1 conditioning



Cavity phasing

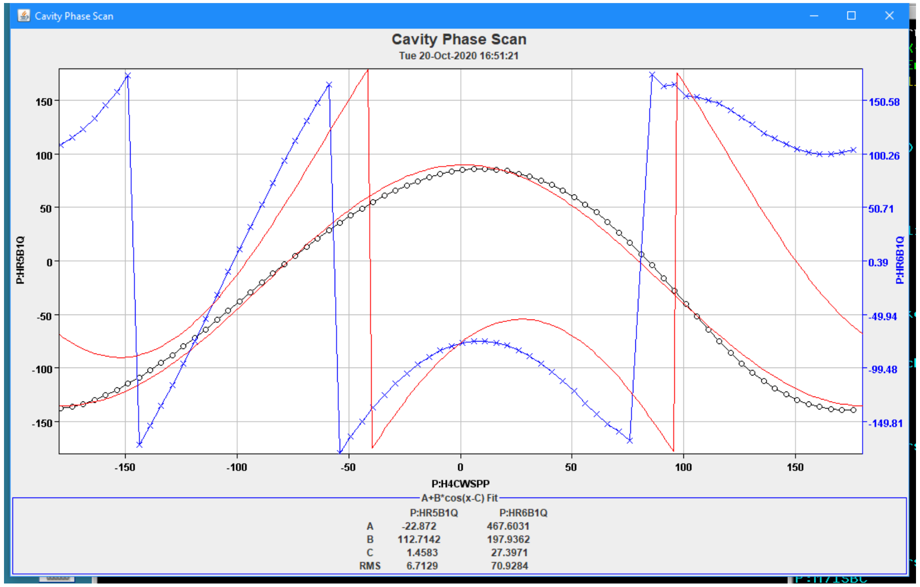
- Goal: set the cavity phases with respect to the beam as in the beam simulations with the TraceWin code
- Turn the cavities on, one by one; adjust the cavity reference phase in LLRF system so that zero phase corresponds to the maximum energy gain
  - Change the cavity phase while recording the beam phases in downstream BPMs. Fit cosine to the results.
  - Full 360º scan works well when the max energy change is << energy, e.g. with bunchers



Phases of 3 BPMs vs phase of the Buncher #1. Case of good phasing. Beam energy is 2.11 MeV. Maximum acceleration is 60 keV. For historical reasons, the reported BPM phases are inverted so that max of the curve corresponds to max energy.

Cavity phasing - SRF

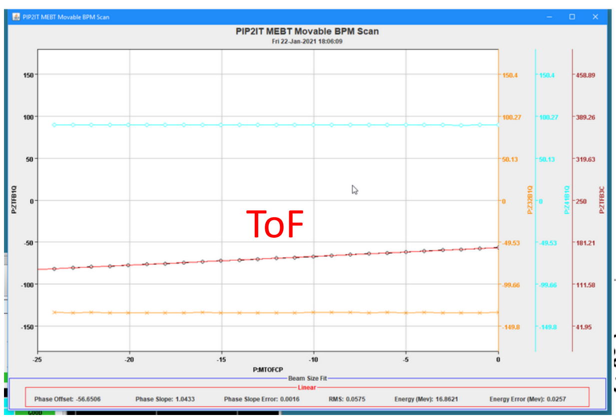
- Complication with SRF cavities comes from high gradients
  - Max energy gain in the first SRF cavities is comparable with the entrance energy
    - Phasing curves deviate from cosine; depend on cavity voltage
  - Strong longitudinal and transverse (de)focusing
    - Beam loss around -180º
    - Low BPM intensity at +90º
  - Preliminary phasing at low voltage and phasing at nominal voltage in smaller range (e.g. ±50º)



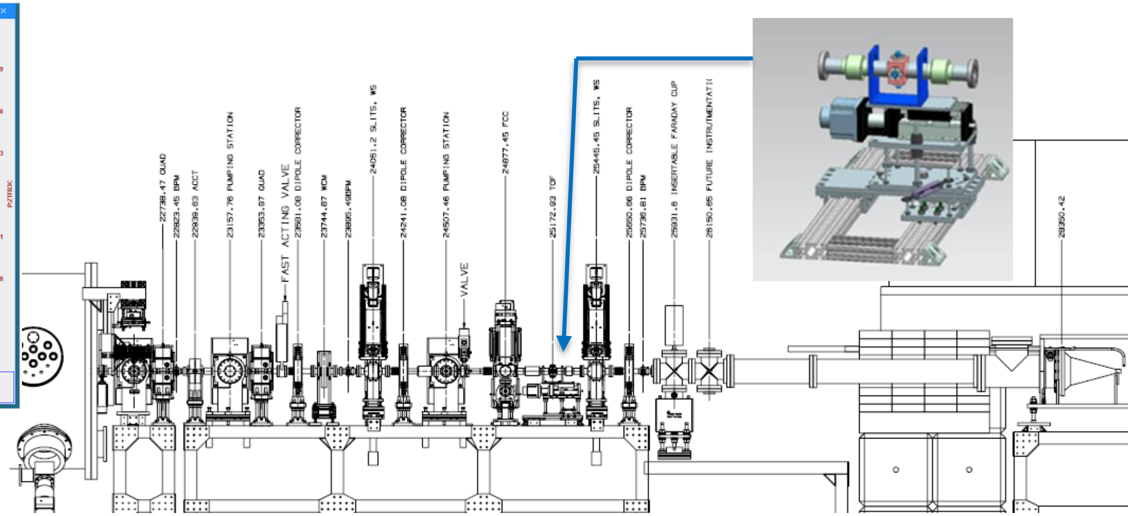
HWR#4 360ºphase rotation (don't do it anymore). Initial beam energy is 2.11 MeV. Maximum acceleration is 0.37 MeV. Orange curves are cosine fitting.

Energy measurements with ToF BPM

- “Time-of-Flight BPM”
  - 4-button pickup precisely movable longitudinally (by 25 mm)
  - Beam velocity is calculated from phase derivative $\frac{d\varphi}{dz} = \frac{\omega}{V}$
    - The idea came from A. Aleksandrov (SNS)
- “Good” scatter ~3%, but sometimes jumps up to >10%
  - Sensitive to RF noise, beam loss, low intensity, bunch shape
  - Absolute measurement

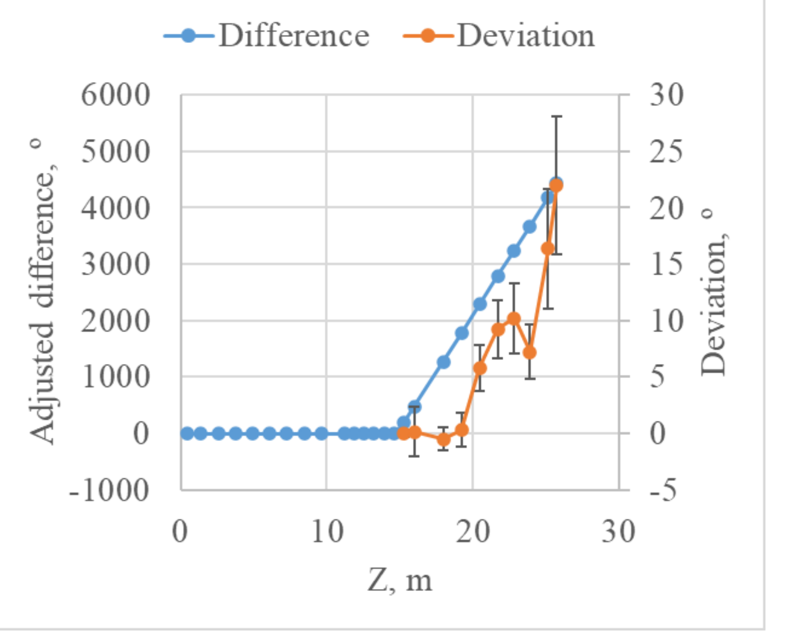


Example of ToF energy measurement at 17 MeV.



Energy measurements with stationary BPMs

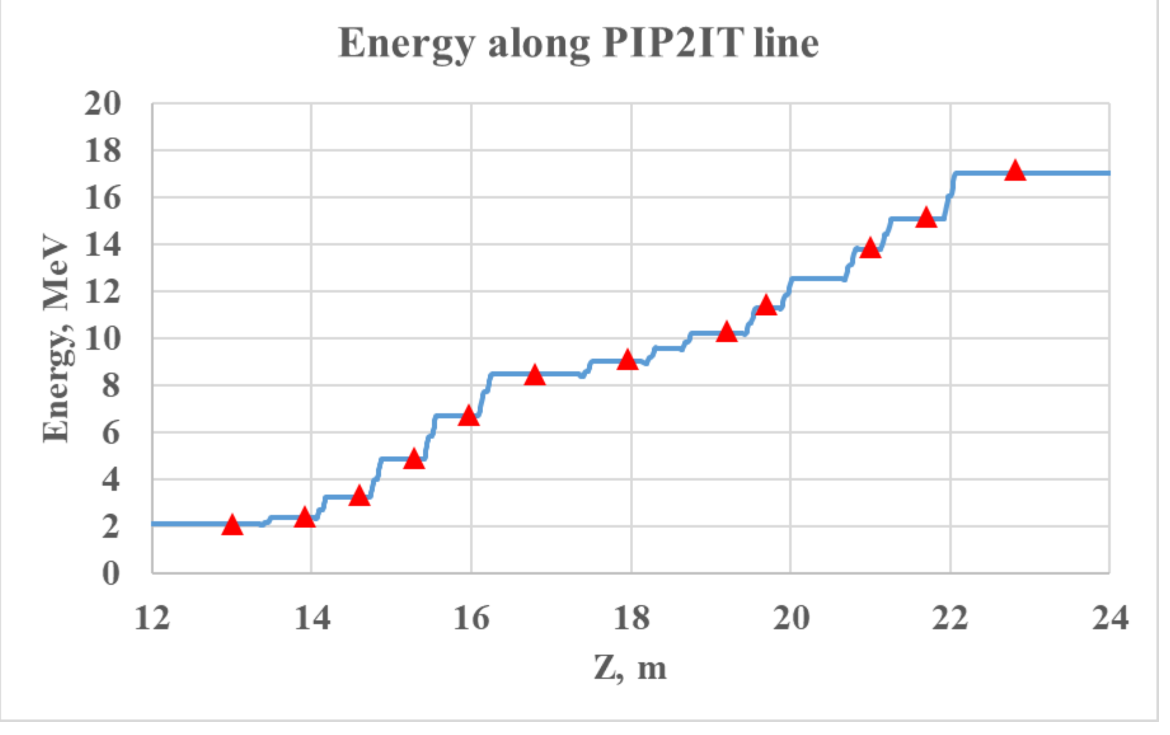
- Can use phases of "normal" BPMs for energy measurements
  - However, absolute phase offsets were not calibrated
- Procedure: make measurements step-by-step
  - Energy from the RFQ was well calibrated (2.12±0.3% MeV)
  - Measure the energy by comparing BPM phase readings before and after turning a cavities on
    - At low energies, need to resolve n·2π uncertainty by using un-equally spaced BPMs



Difference between BPM readings before and after setting cavity HWR#6 to nominal voltage (blue). The orange points indicate deviations from a linear fit using 4 points after the cavity. The error bars show the rms scatter in 100 BPM reading points. Relative error of the linear fit is $3 \cdot 10^{-4}$ (up to 2% in low-gain cavities). 3.28/4.87 MeV.

Energy measurements - results

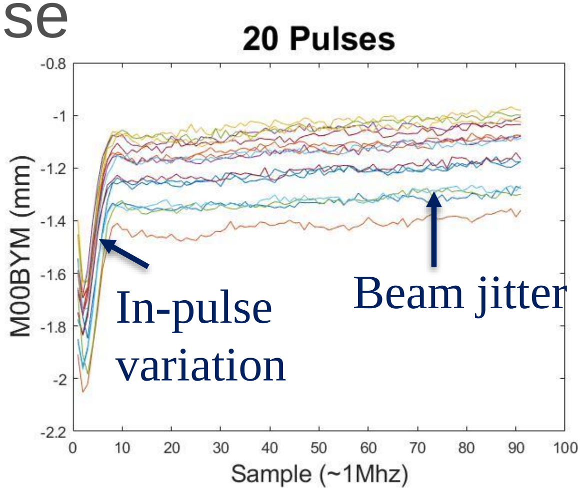
- The measured energy is a sum of all previous steps
    - Practically, updating from step to step the value of $\frac{d\varphi}{dz}$
  - At each step, can use 4-5 BPMs immediately downstream
  - Statistical error for the final energy is < 1%



Comparison of beam energy measured (red) and simulated (blue). 19-Jan-21.
Z=0 corresponds to the end of the RFQ.

BPM signals

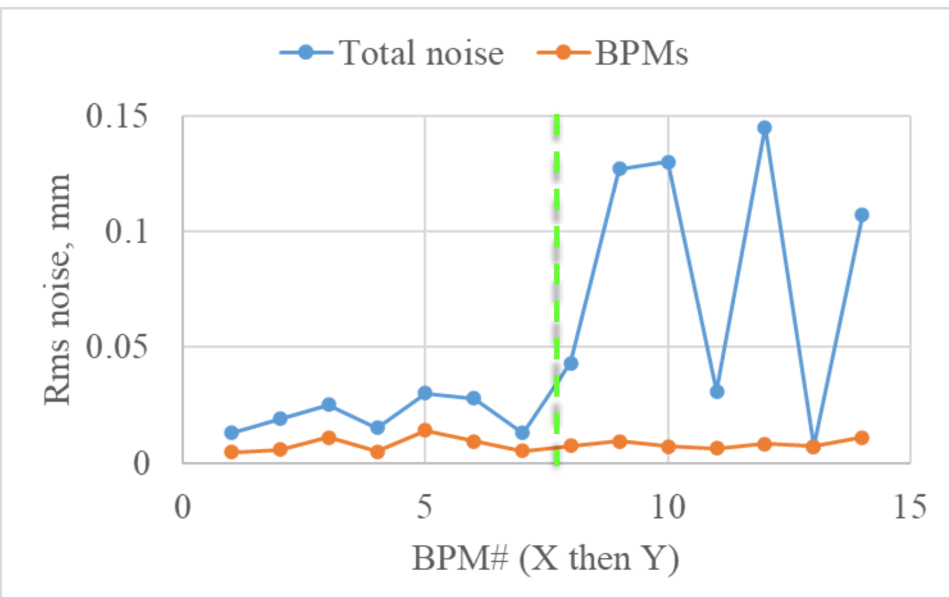
- All BPMs are 4 – buttons, operating at the first harmonic (162.5 MHz)
  - Pulse – average and in-pulse (~1 μs steps) data
- There is a significant scatter in readings within the pulse (not being discussed today) and from pulse to pulse
  - Both in positions and in phases
  - Analysis shows that it comes primarily from the beam motion
- Analysis of pulse-to-pulse scatter:
  - record data from BPMs
  - Singular Value Decomposition (SVD) of positions or phases
  - Comparison with response to changes in individual elements



Changes in vertical position in BPM M00BYM along 99 μs pulse. 5 mA beam. Measurements and plots by N. Eddy. 18-July-2020

BPM noise and beam position jitter

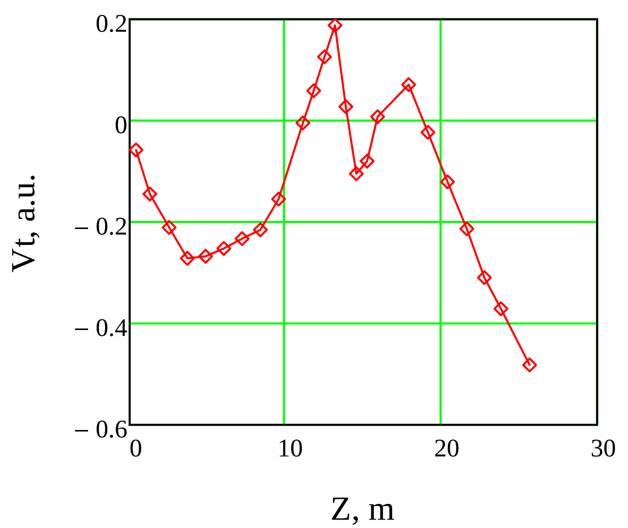
- The beam position jitter depends on location and plane
  - Analysis indicates that the jitter is determined mainly by the noise of the ion source high voltage (~60 V rms at 30 kV)
- After subtracting two main beam modes, the remaining component is 8 µm, likely associated with the true BPM noise

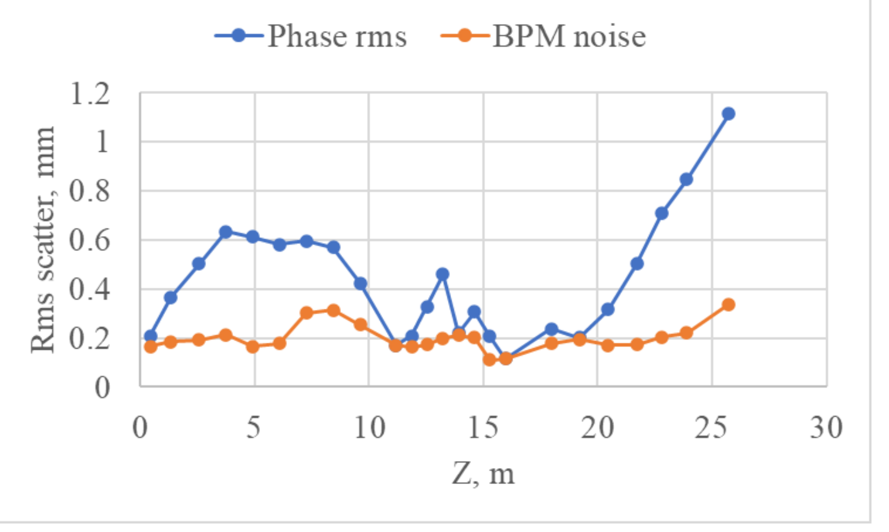


Rms of positions reported by 7 MEBT BPMs and rms of the signals after subtracting first two beam modes.
5 mA, 2.1 MeV beam, Signals are averaged over 10 µs pulse length.
22-Sep-2020.

Phase noise

- Scatter in BMP phase readings also depends on location
  – The main SVD mode points again to IS HV PS noise
    - Contributions from RF are significantly lower
  – Subtraction of beam-like modes gives ~0.1º for BPM noise

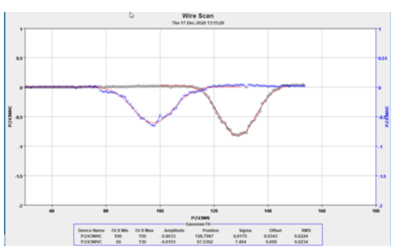




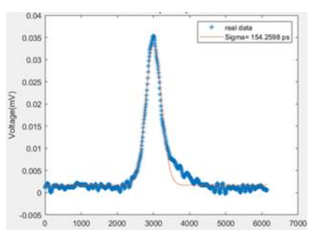
Scatter of BPM phases in PIP2IT. 11-Nov-2020. The beam is accelerated by 5 HWR and 3 SSR1 cavities to 10 MeV. 2 mA, 10 μs pulse x 20 Hz. Left – spacial distribution of the first SVD mode. Propagation in the free space corresponds to the rms energy scatter of $2 \cdot 10^{-4}$. Right – rms of BPM phase scatter. Blue – total, orange – after subtraction of the first mode.

Other tools (apart from BPMs)

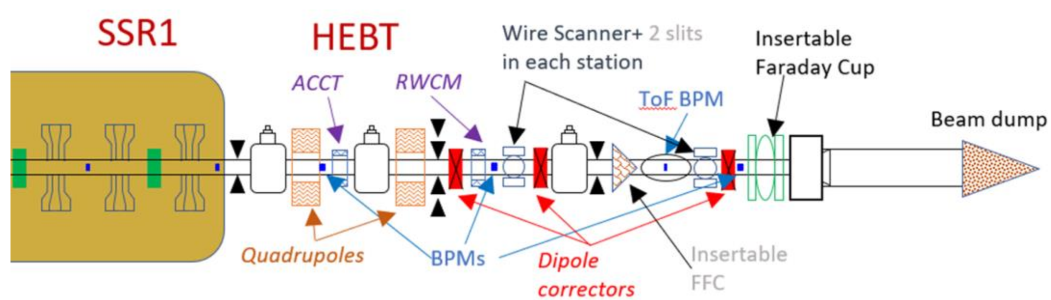
- Warm Front End instruments, commissioned in 2015-2018, are used extensively when something doesn't look right
  - 2 Allison scanners, 16 scrapers, electrically isolated electrodes
- ACCT on both sides of cryomodules to measure transmission
  - ACCT-to-dump comparison for HEBT transmission
- All other tools are in HEBT (starting to use)
  - Resistive Wall Current Monitor to observe bunch pattern
  - Two wire scanners to measure the beam profile
    - Slit-slit emittance scanner (2x2 slits + FC) are coming
  - Fast Faraday Cup to measure bunch length (not commissioned)



WS profiles



RWCM profile



Plans

- Commission the MEBT chopping system
    - Have already started commissioning of fast kickers
    - Have increased the pulse length to the new absorber to 0.1 ms
- Accelerate full-intensity bunches with the required aperiodic bunch pattern to full energy
- Commission all diagnostics, including the slit-slit scanner
- Analyze the beamline optics and measure the beam rms parameters in HEBT
    - Implementation of TraceWin Virtual Accelerator is underway
        - Collaboration with D. Uriot (CEA)
- Test new diagnostics (installed in MEBT)
    - Prototype Laser Wire
    - Diamond detector

Summary

- PIP2IT is fully assembled and will run for several months
- A short –pulse H- beam is accelerated to 17 MeV
  - The energy is measured with accuracy better than 1%
- Scatter in BPM readings is analyzed to distinguish the component related to the beam jitter. The remaining noise corresponds to 0.01 mm rms in transverse positions and 0.1º rms in phase.
- Commissioning of other diagnostics and of the bunch-by-bunch chopper has started