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MEBT beam line overview

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PIP-II MEBT FDR

March 16, 2023

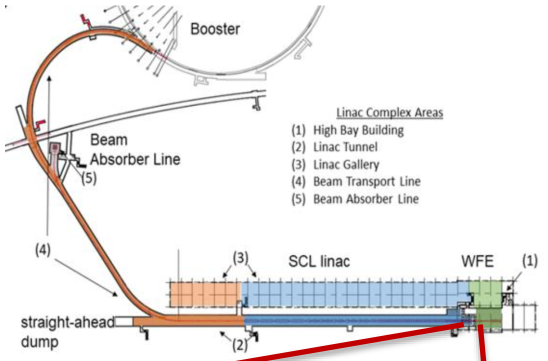
PIP-II is a partnership of:
- US/DOE
- India/DAE
- Italy/INFN
- UK/STFC-UKRI
- France/CEA, CNRS/IN2P3
- Poland/WUST

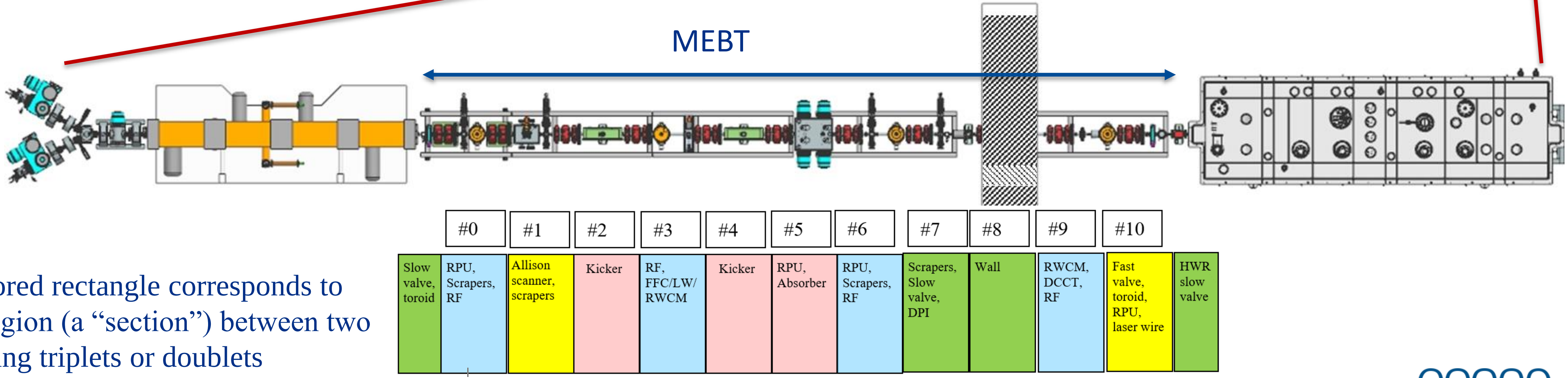
Outline

- Introduction
- PIP-II MEBT configuration
- Experience with PIP2IT MEBT
- PIP-II MEBT commissioning
- Summary

Introduction

- MEBT: 13 m section between RFQ and cold linac
  - The concept was tested at PIP2IT
- Main functions
  - Beam transport and matching; diagnostics
  - Chopping
  - Collimation; protection
  - Vacuum management





Each colored rectangle corresponds to MEBT region (a "section") between two neighboring triplets or doublets

PIP-II

PIP-II MEBT peculiarities

	#0	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	
Slow valve, toroid	RPU, Scrapers, RF	Allison scanner, scrapers	Kicker	RF, FFC/LW/ RWCM	Kicker	RPU, Absorber	RPU, Scrapers, RF	Scrapers, Slow valve, DPI	Wall	RWCM, DCCT, RF	Fast valve, toroid, RPU, laser wire	HWR slow valve

- Bunch-by-bunch chopping system
  - Two kickers and absorber: 3 sections
- MEBT is right upstream of SRF linac
  - Need to transition from high-vacuum of RFQ to ultra-high vacuum, particle-free sections near the HWR cryomodule. ~ 1 section (Differential Pumping Insert, DPI).
- Decided to include a radiation wall shielding the High-Bay Building from the linac
  - 1 section
- Need to protect the kickers and the cold linac from errant beam and beam tails
  - Included 4 scraper “stations” with 4 independent scraper plates in each
- Each addition comes with “overhead” of additional focusing
  - 4 bunching cavities; 45% of the MEBT length is occupied by magnets
- Total length 13 m
- The concept of the MEBT was tested at PIP2IT

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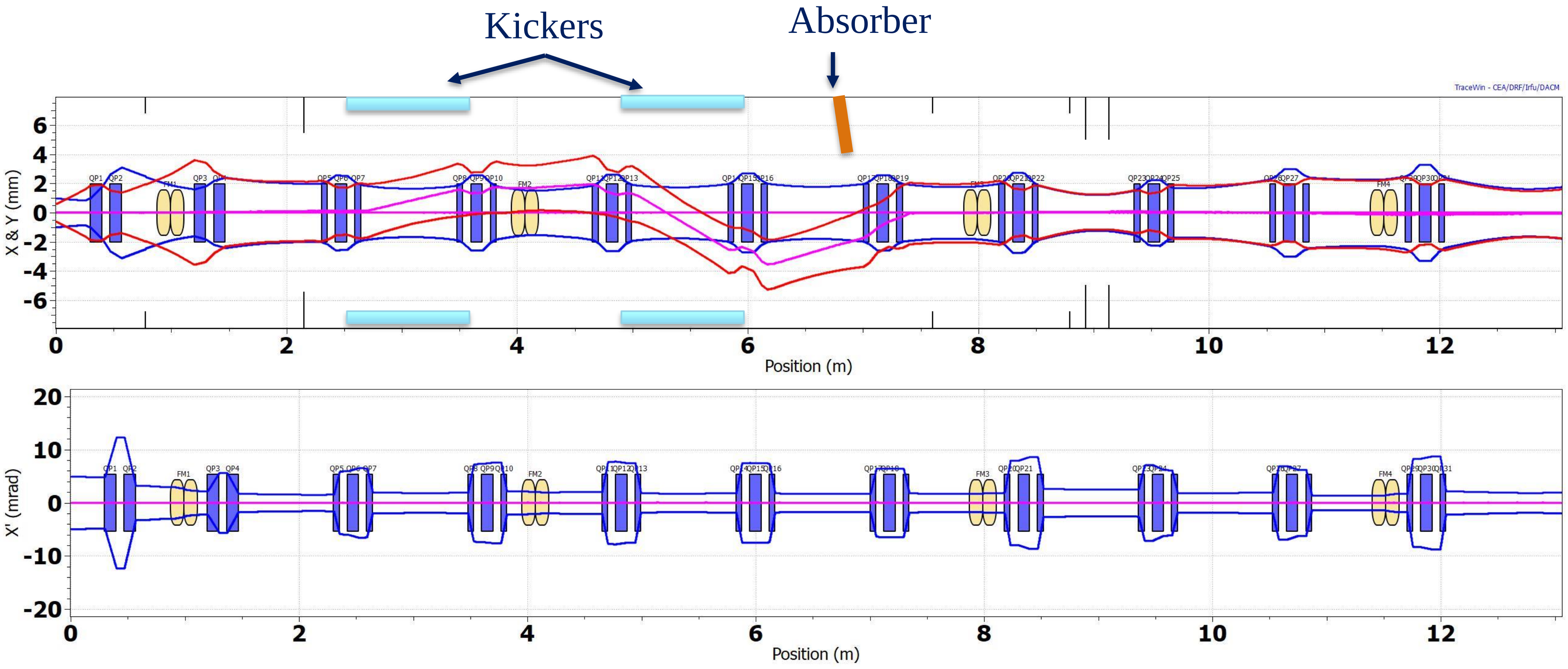
Beam in PIP-II MEBT

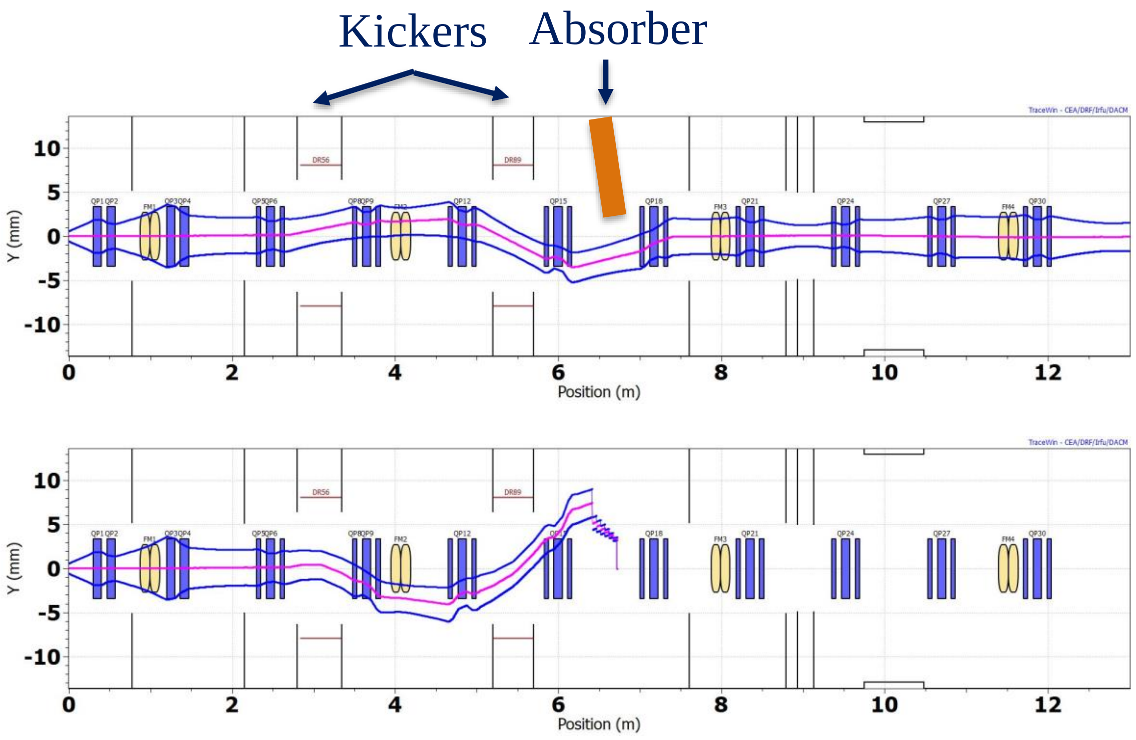
- Focusing with quadrupole doublets and triplets transversely and with 4 bunching cavities longitudinally.
  - Smooth envelopes. Designed for CW operation.



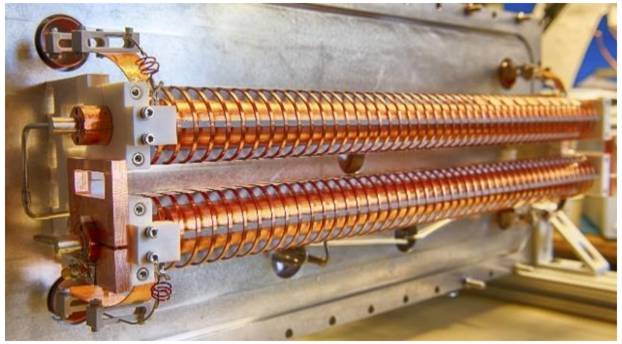
Simulated rms envelopes in PIP-II MEBT. Z=0 corresponds to the end of RFQ. Upper – transverse (blue-X, red-Y), lower- longitudinal. The envelopes are shown for “5 mA” bunches. A. Pathak.

Chopping system (= 2 kickers + absorber + optics)

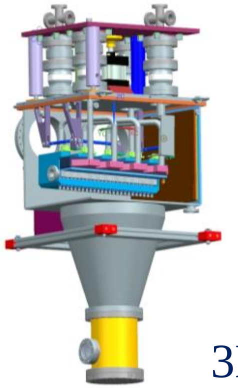
- Two travelling – wave kickers operating in sync direct the beam to absorber
  - 180º phase advance between kickers
  - 90º between last kicker and absorber
- ~6σ_y separation at the absorber
- Any bunch from initially CW sequence can be either removed or passed
  - Maximum average switching frequency is 500 kHz



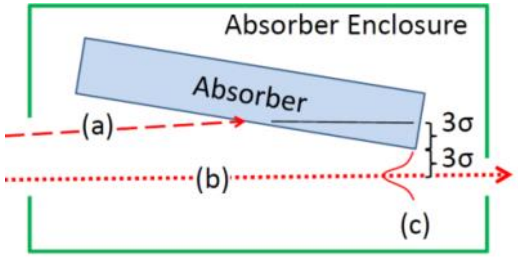
Rms vertical envelopes in PIP-II MEBT. Top – passing bunches, bottom- removed bunches. A. Pathak.



Fully assembled kicker’s two-helix structure.

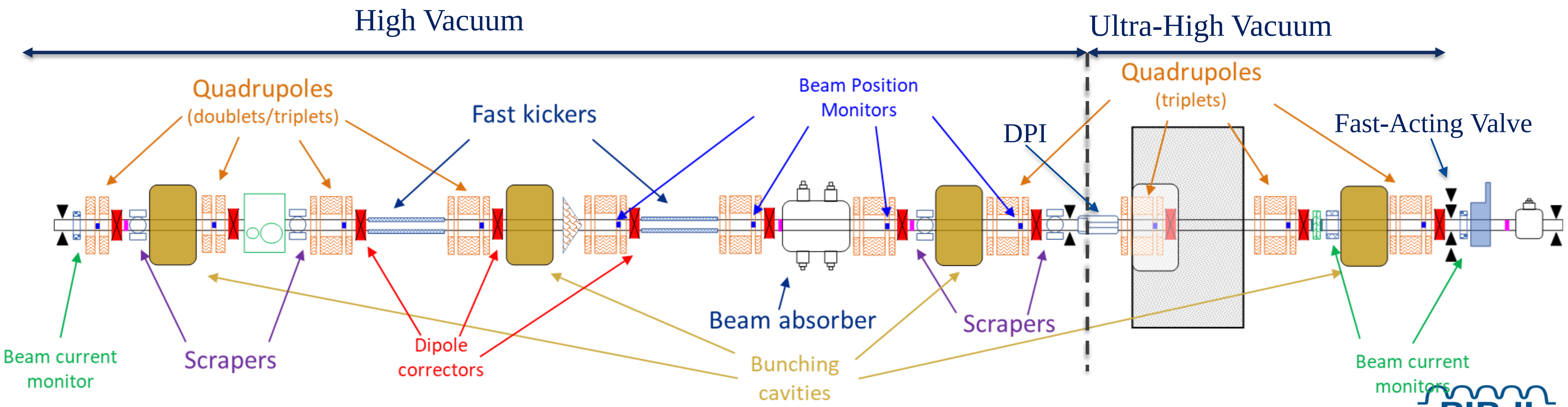


3D model of absorber. 20 kW rating.



Vacuum

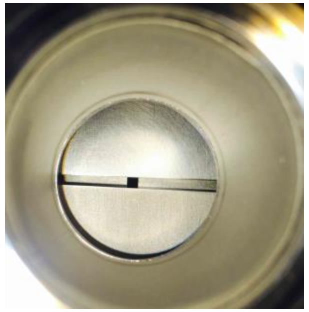
- The most downstream MEBT sections are particle-free, UHV (< 10^{-8} Torr)
- The upstream sections are High Vacuum (<10^{-6} Torr)
- Separated by Differential Pumping Insert (DPI)
  - 200 mm long, 10 mm ID pipe. One of the restrictions in beam optics.
  - Suppresses flow of hydrogen from the absorber for the case of a high-power beam
  - Delays the shock wave in a case of a vacuum accident upstream



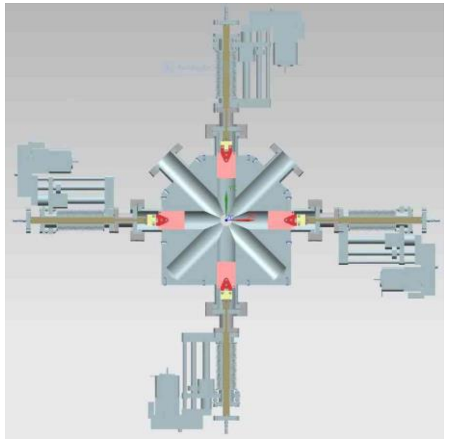
Scraping system

- 4 MEBT locations with 4 plates in each can
  - Independently movable, radiation –cooled. Rating: 75 W/plate, 200 W/can
- Usage
  - Decrease losses downstream
  - Protect from beam focusing and position errors
    - When kept near the beam boundary for high-power operation
  - Create a pencil beam for commissioning
  - Used for measuring the beam transverse size

Mounted scraper plate



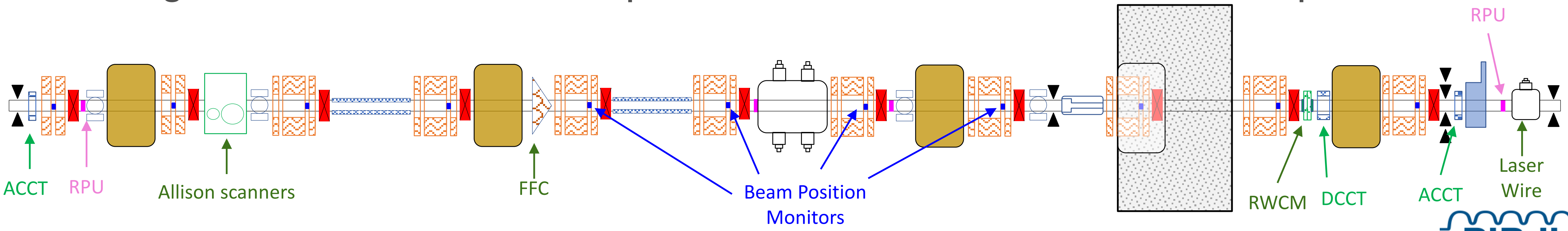
Scraper plates in the positions to create a pencil beam



Cartoon of scraper can with mounted plates

Diagnostics

- 11 BPMs: X/Y positions and phase in each
- Beam Current Monitors: 2 ACCT, 1 DCCT
- 2 Allison scanners (X and Y): transverse density distribution in phase space
- Resistive Wall Current Monitor: analysis of the bunch pattern and extinction
- 4 Wire Scanners (in each scraper can): transverse distribution
- Fast Faraday Cup: bunch length
- Laser Wire: non-interceptive measurement of bunch parameters
- 4 Ring Pickups (RPU): monitoring relative changes in beam current for MPS
- Reading of currents from kicker protection electrodes, DPI, and scrapers



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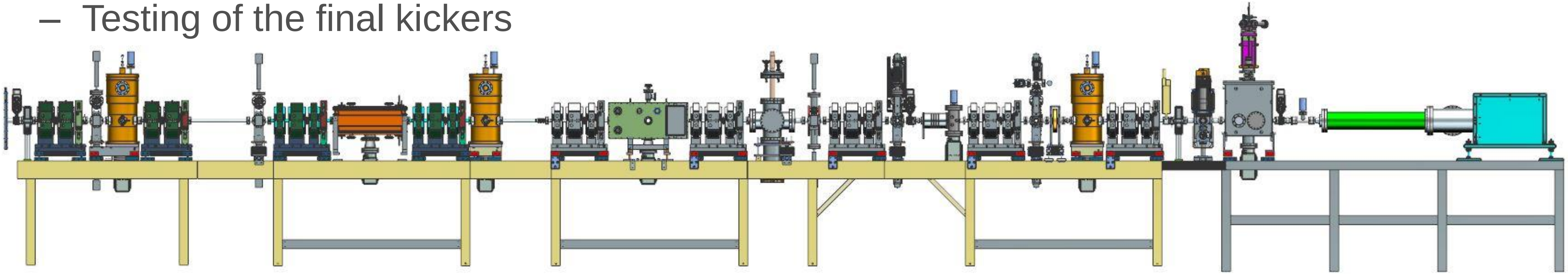
PIP2IT MEBT: testing all solutions

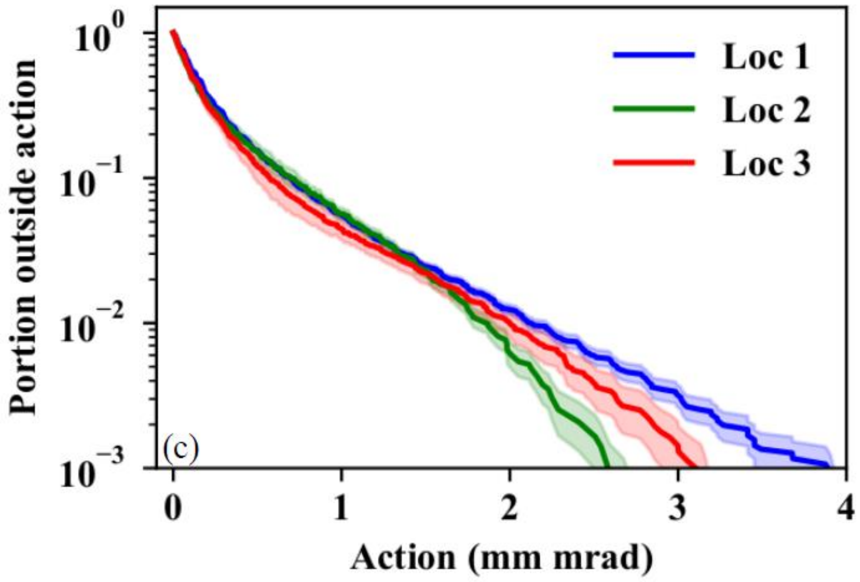
- PIP2IT MEBT was assembled in several steps in 2016 – 2018
  - In the final configuration, it had all main features of future PIP-II MEBT
  - The beam properties were measured at the end of the beamline
    - Main characterization of the MEBT solutions
- Run 2020 – 2021
  - beam operation was interleaved with assembly and RF commissioning
  - Mostly providing the beam to SRF linac
  - Testing of the final kickers



PIP2IT MEBT in 2018 configuration.

Main results from 2018

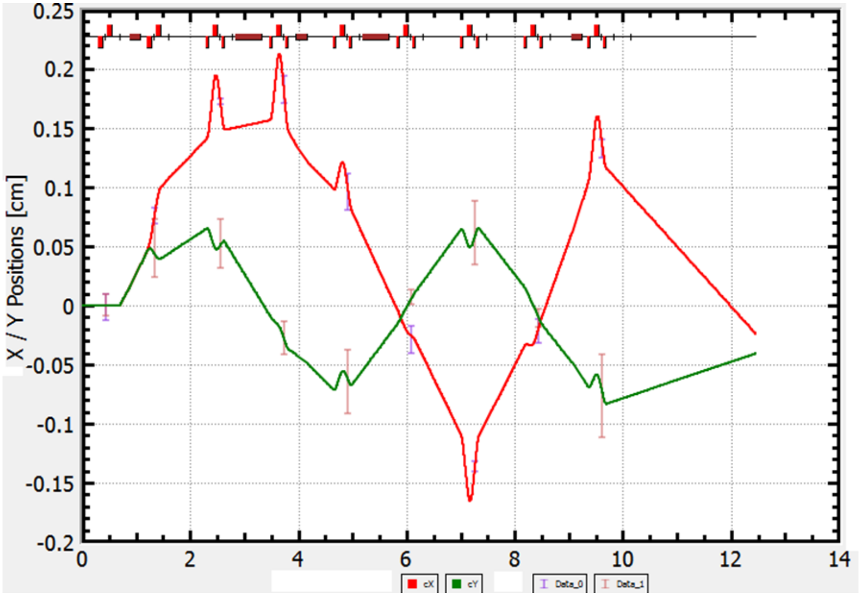
- All subsystems (or prototypes) were successfully tested
  - Optics, kickers, diagnostics, bunchers, magnets, vacuum, scraping, MPS
    - Some at prototype level
- No significant emittance growth through the MEBT
- Tuning procedures were developed
- High – power beam was transported with low losses
  - 1 min at 50% duty factor; 6 hrs without trips at 7%
    - no chopping
    - PIP-II needs 1.1%
- Tested fast-valve vacuum protection

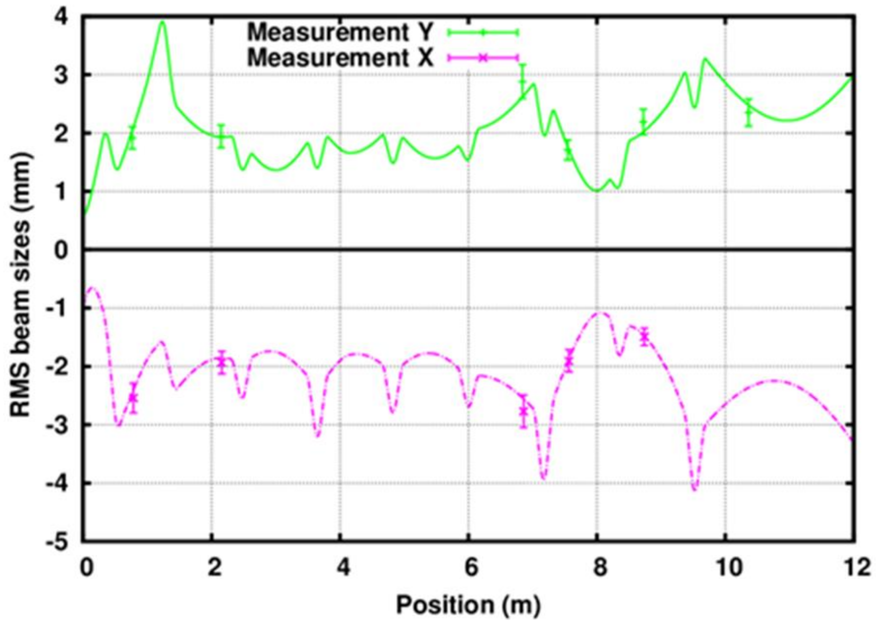


Phase distribution measured at the beginning of MEBT (Loc 1, ε_{rms_n}=0.20 µm), in the middle (Loc 2, 0.19 µm), and at the end (Loc 2, 0.22 µm). Pulse current is 5 mA; not chopped. ~1% of the beam is scraped. The beam is on axis.

Optics

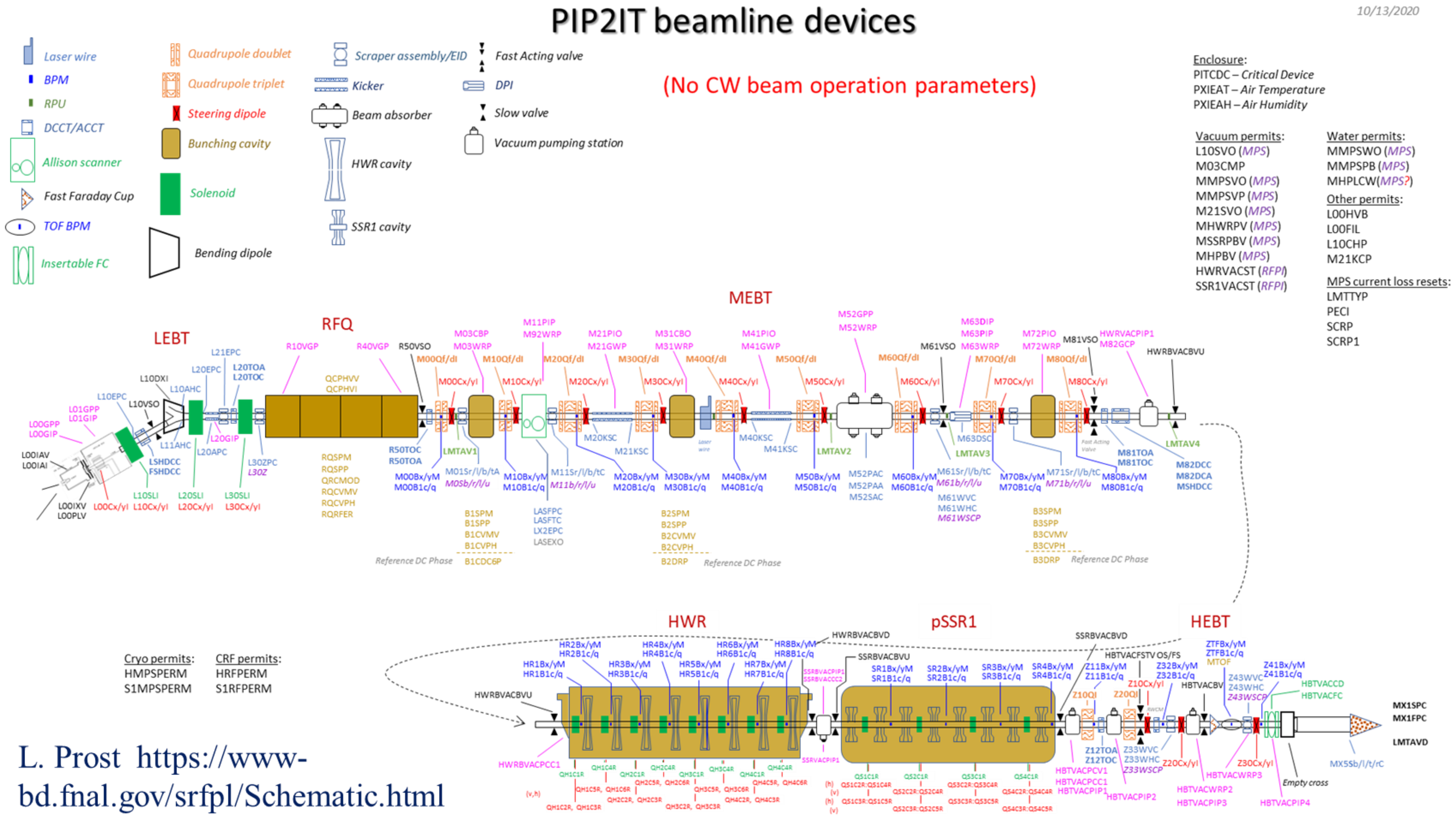
- Optical solutions were found satisfactory
- Good agreement of simulations with measurements
  - After resolving initial contradiction related to overlapping fields in triplets





Comparison of simulation and measurements for differential trajectories (top) and beam envelope (bottom). 2018 configuration.

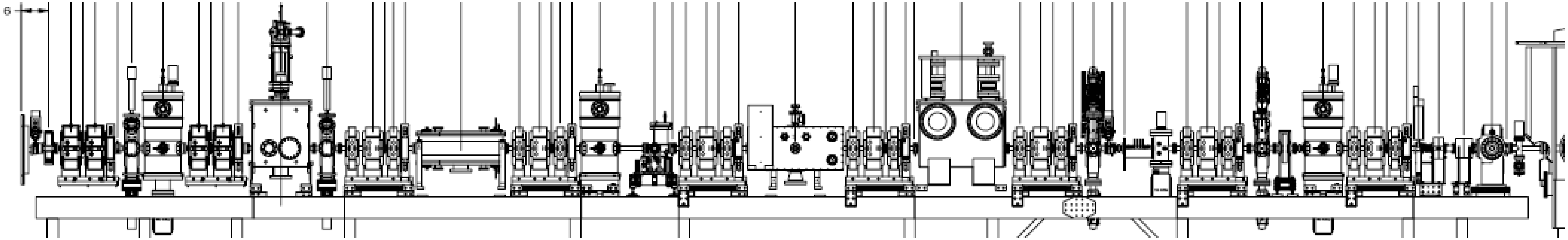
PIP2IT in 2021



L. Prost https://www-bd.fnal.gov/srfpl/Schematic.html

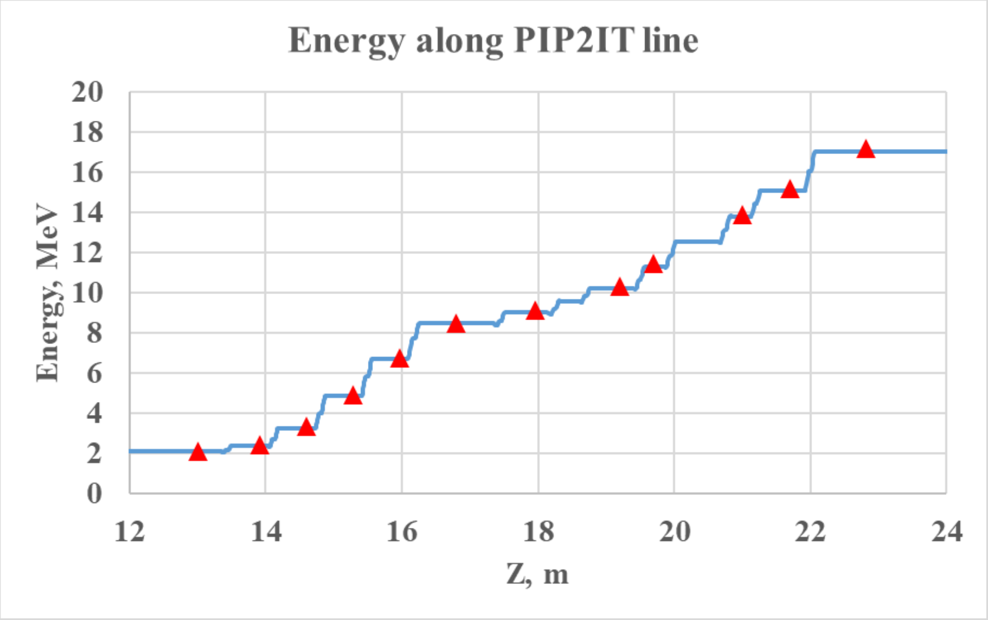
MEBT in 2021 run

- Main MEBT modifications from 2018
  - “Production” kickers and their drivers are installed
  - “Production” absorber instead of a prototype
    - Because of a manufacturing error, it was installed in a compromised configuration
      - Good for probably ~5 kW beam instead of specified 20 kW (need 100 W for PIP-II)
  - Transition section to cryomodules
  - New MPS, Laser wire, wire scanner, improved scrapers…
- Main emphasis: providing the beam into the cryomodules; kickers

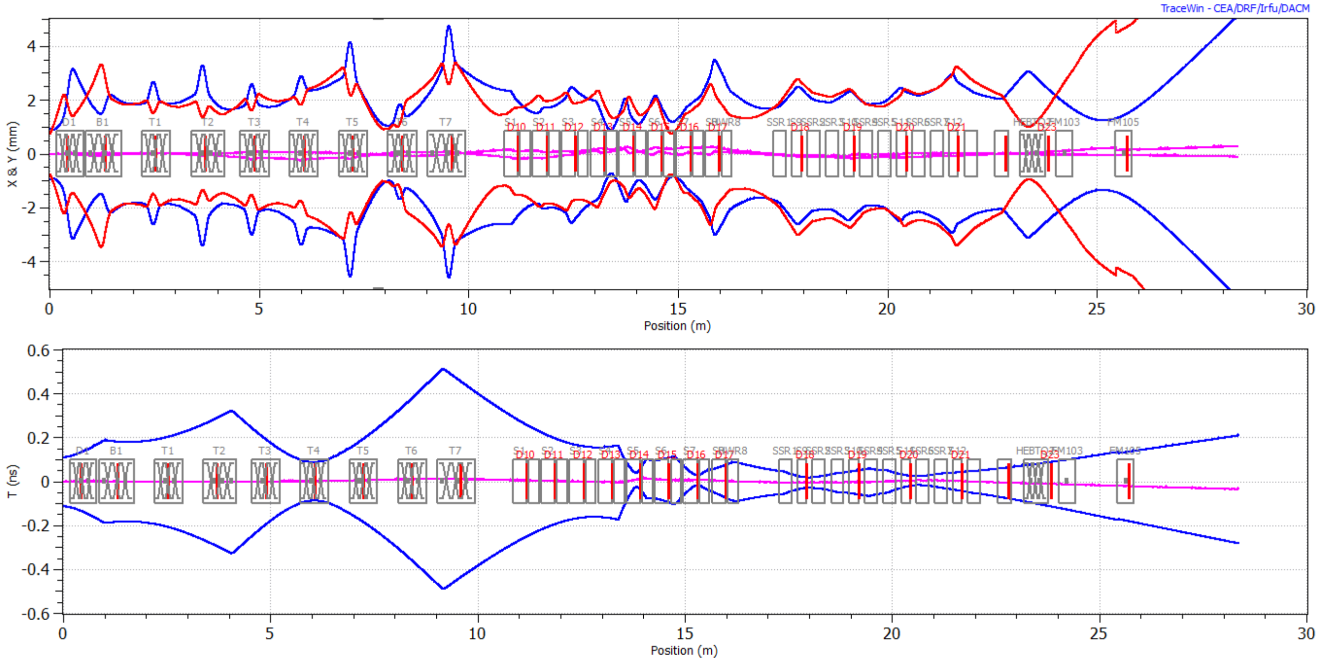


Peculiarity of 2021 run

- The first 3 HWR cavities were not operational
- With re-tuned MEBT, the beam was still accelerated through the cryomodules
    - To 16 MeV (vs initially expected 23 MeV)
  - The beam phase distributions were affected



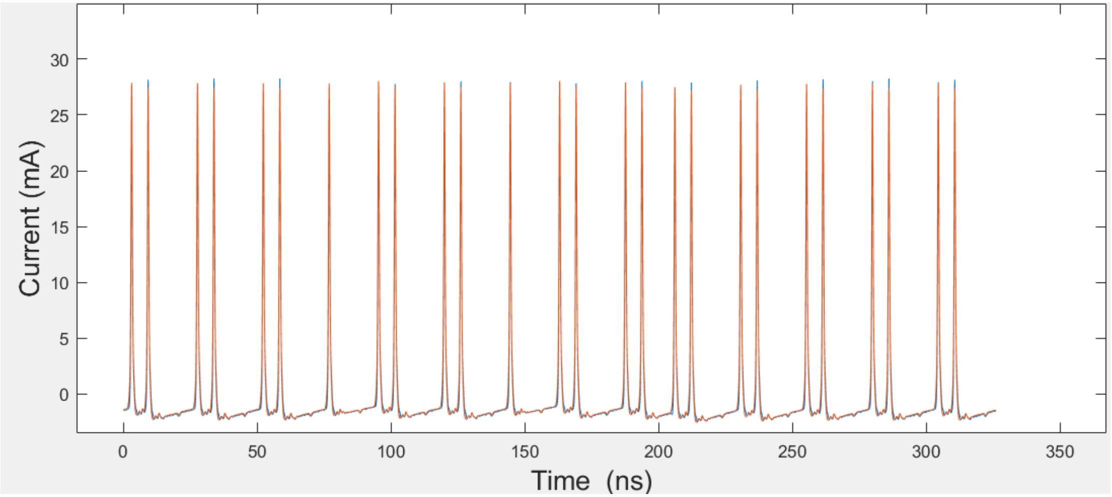
Comparison of beam energy measured (red) and simulated (blue).



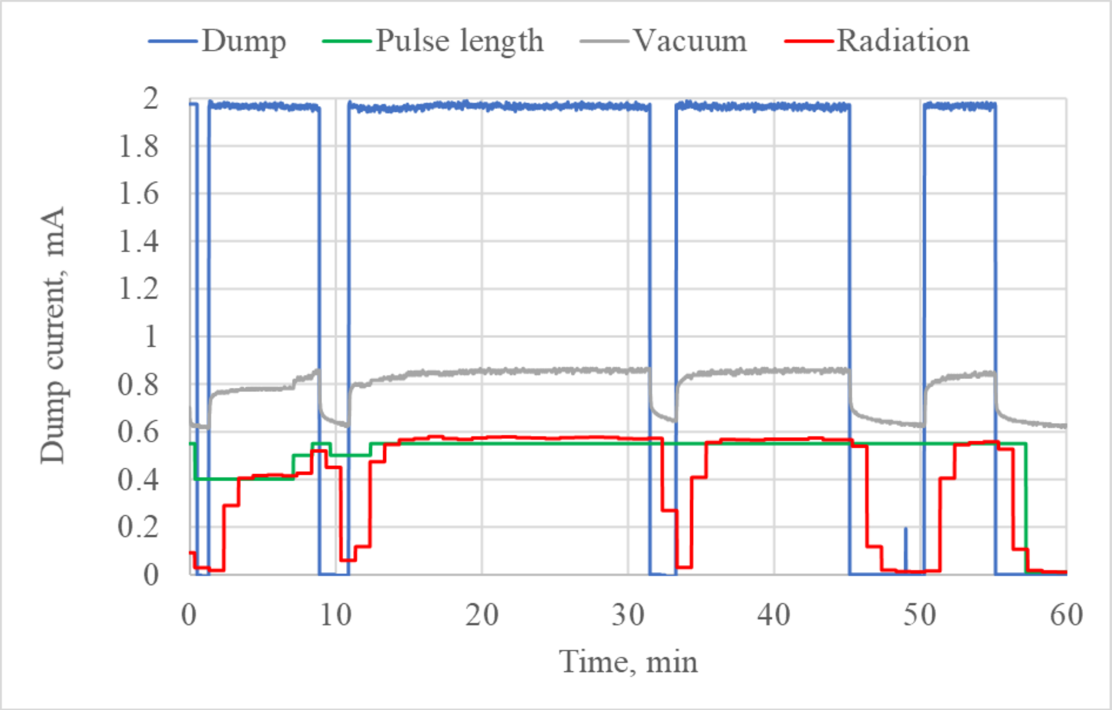
Simulated rms envelopes in PIP2IT. Z=0 corresponds to the end of RFQ. Upper – transverse (blue-X, red-Y), lower- longitudinal.

Main 2021 results (MEBT – related)

- MEBT optics was predictable; the beam was reliably delivered to cryomodules
- Kickers provided the pattern expected for PIP-II (Booster injection)
  - Bunch-by-bunch chopping



Bunch pattern of 16 MeV beam measured with HEBT RWCM. Residual population of the removed bunches is <0.1%.



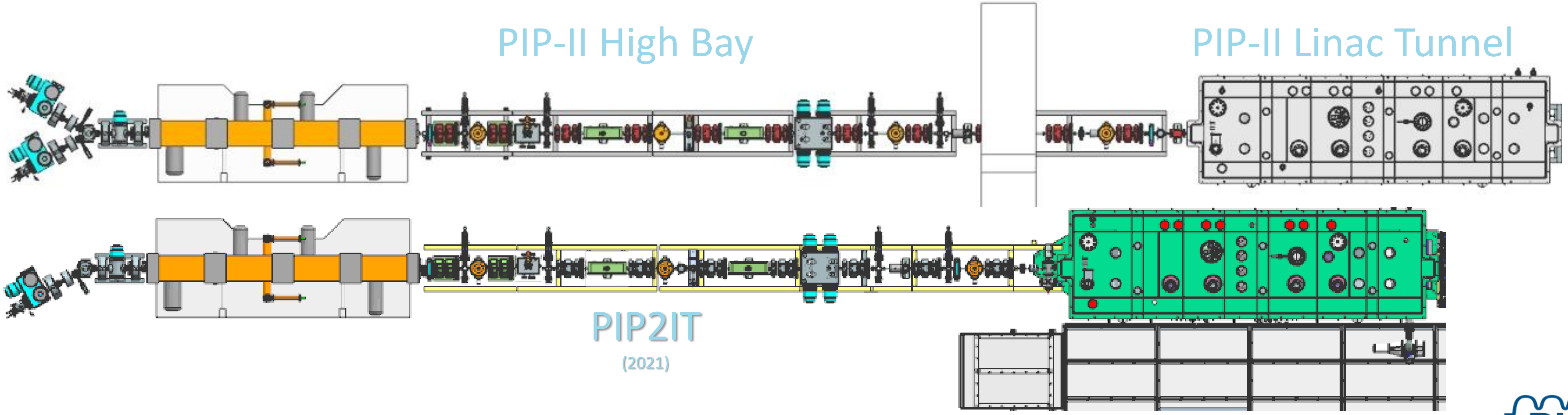
Parameters during one of the runs with "Booster injection" parameters. Blue – dump current (mA), green – pulse length (ms), gray – vacuum near the dump (in 10^{-7} Torr), red – radiation at the downstream end of SSR1 (in 100 mR/hr). 16 MeV beam.

Conclusion and lessons from PIP2IT (relevant to the talk)

- The main conclusion: in general, the MEBT design is sound and good for PIP-II
  - All subsystems performed reasonably well
- Lessons affected PIP-II MEBT design (from 2018)
  - Re-distribute the bunchers more evenly. Helps with emittance preservation.
  - Move all scraping out of the low-particulate area. Allows for more aggressive scraping.
  - The distance between fast-acting vacuum valve and HWR entrance can be shorter than envisioned originally. Ended up by shortening the PIP-II MEBT design by one section.
  - Beam size measurements with scrapers can't characterize tails. Add Wire scanners into the same vacuum cans.

From PIP2IT to PIP-II

- The scheme and most of elements are the same. Expect the same performance.
  - PIP-II MEBT is longer by 2 sections (radiation wall and extra bunching cavity)
  - Moving the DPI one section downstream so that there are no scrapers in UHV area
  - Shuffling and adding diagnostics, moving upstream 3rd bunching cavity, …
- See Lionel’s second talk for details



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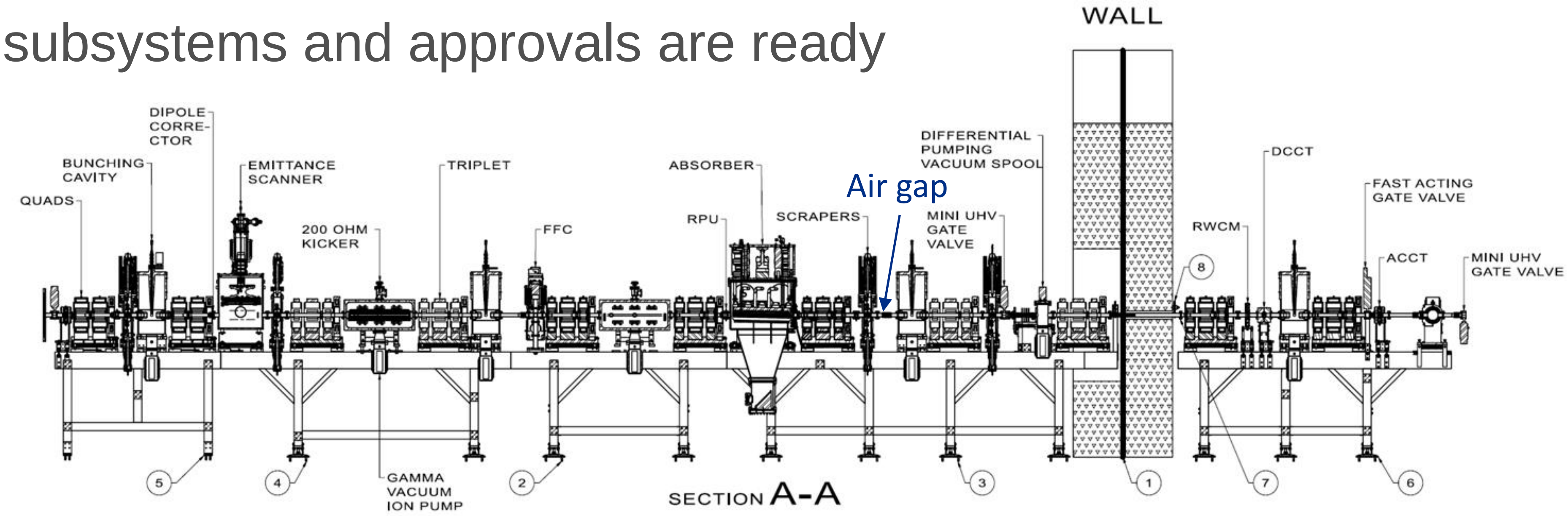
Commissioning of PIP-II MEBT: Prerequisites

- Configuration:
  - MEBT is fully assembled but with air gap instead of spool piece upstream of the Buncher 3
    - Safety requirement
  - If a temporary beam dump can be installed as well, it would be a big plus.
    - Under investigation.
- Ion source and LEBT are beam-commissioned. RFQ is RF – commissioned.
- All subsystems and approvals are ready



Beam modes

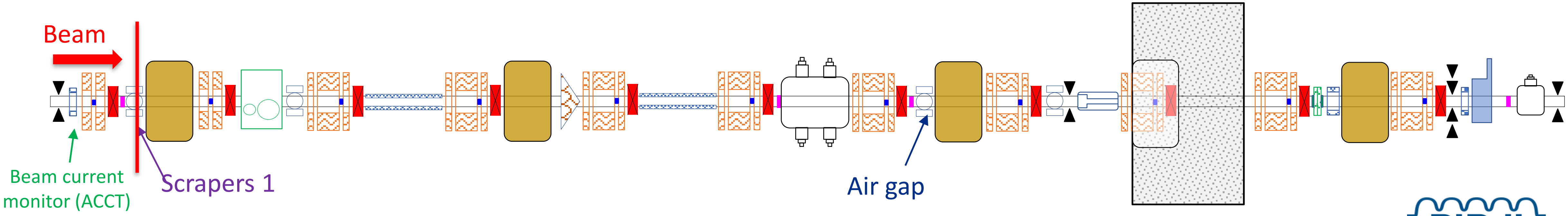
- Commissioning Plan (PIP-II DocDB# 5420) defines “beam modes”, the beam parameters that would be allowed by MPS in different situations
  - MEBT will be using the same mode definitions

Table 6 2: Beam power in Watts for different beam modes and energy locations. The table is provided for reference only. The peak beam current within a pulse is 2 mA for all modes for the SRF linac (33, 177, and 800 MeV) and 5 mA for the front end (2.1 MeV, marked *).

	Pulse length (μs)	Pulse rep. rate (Hz)	Beam Energy (MeV)			
			2.1	33	177	800
BM 1	10	1	0.1*	0.66	3.54	16
BM 2	10	20	2.1*	13.2	70.8	320
BM 3	550	1	5.8*	36.3	194.7	880
BM 4	550	20	116*	726	3894	17600
BM 5	CW	-	10500*	-	-	-

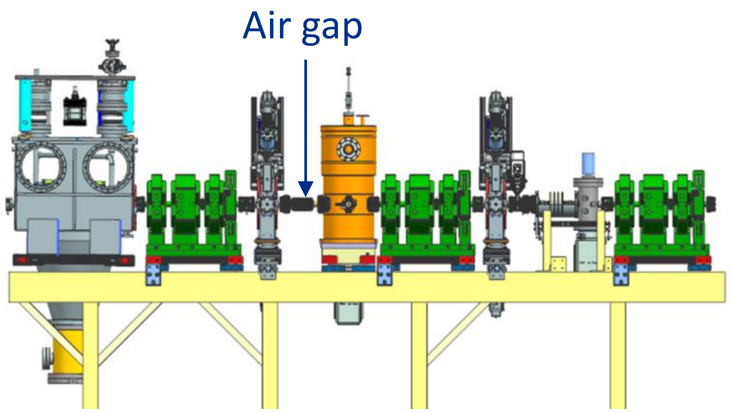
1st stage: RFQ beam commissioning

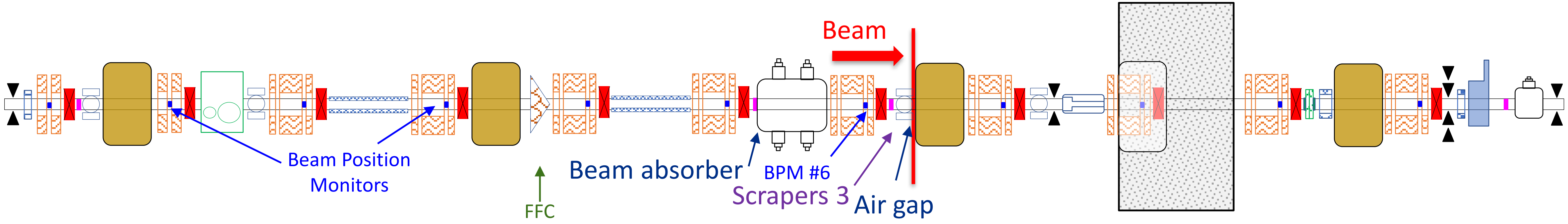
- First set of scrapers is closed; Mode 2 (10 µs x 20 Hz)
  - The beam is accelerated in RFQ. Observed by ACCT, BPM, Ring Pickup, scrapers.
  - Test MPS and controls
  - Tune transmission through RFQ; RFQ voltage calibration



2nd stage: low-power beam commissioning

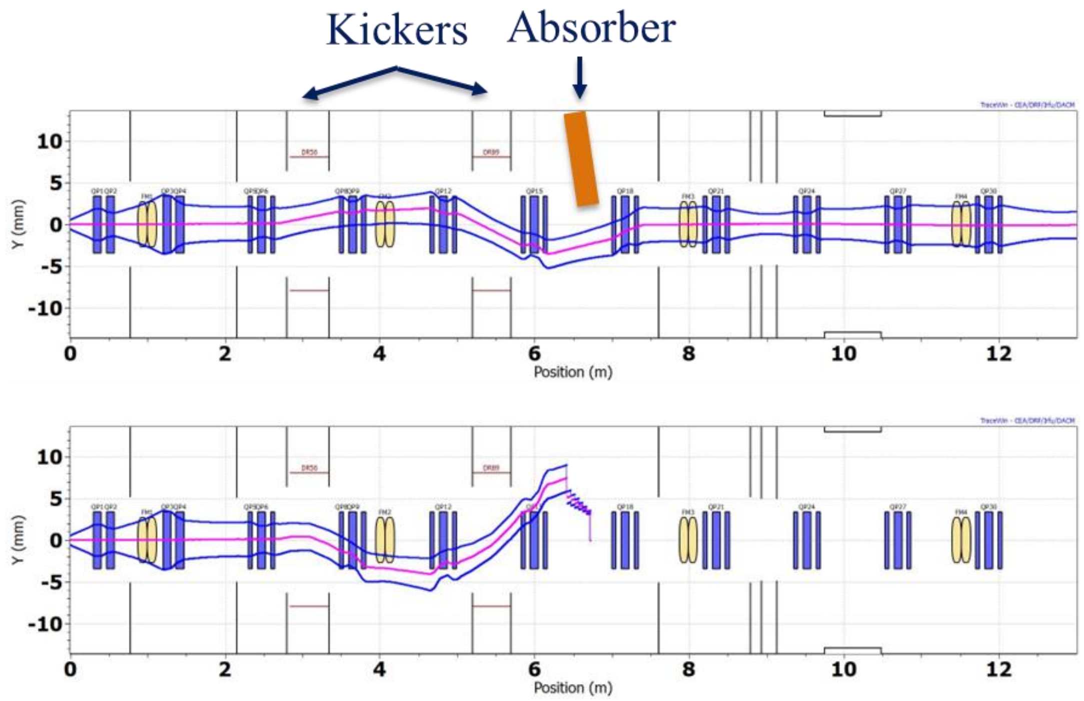
- The 3rd set of scrapers is closed; Mode 2 (10 µs x 20 Hz)
  - All other scrapers are retracted.
- With kickers off
  - Beam is transported on axis to the Scrapers 3
    - All inputs to MPS are checked with the beam
    - Transverse optics is verified by measuring the response matrix (correctors + BPMs).
    - Envelope is measured with Wire Scanners.
    - The bunchers are phased and calibrated. Bunch length is measured with Fast Faraday Cup.



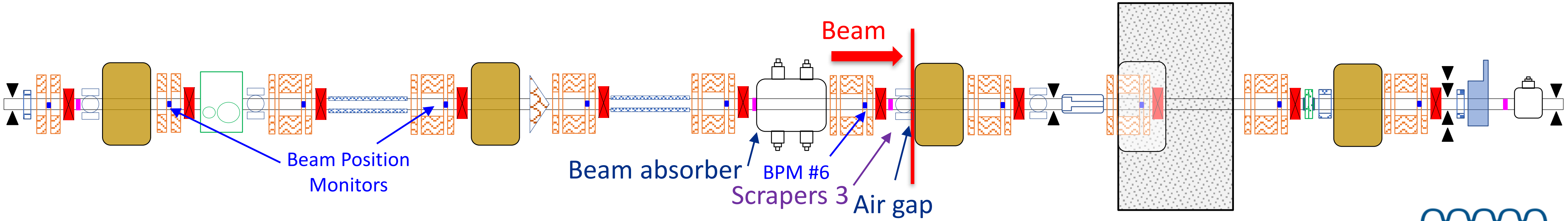


2nd stage: low-power beam commissioning with kickers

- Prepare trajectory for operation with kickers
  - Trajectory needs to be significantly perturbed with dipole correctors to pass the beam through narrow (13 mm) apertures of the kickers both with and without voltage at the kicker plates.
- Beam commissioning with kickers
  - Time with the pulse; phase with the bunches
- Verify kicker properties at 10 μs with BPMs
  - Deflection, pattern; estimation of extinction.



Rms vertical envelopes in PIP-II MEBT. Top – passing bunches, bottom- removed bunches. A. Pathak.



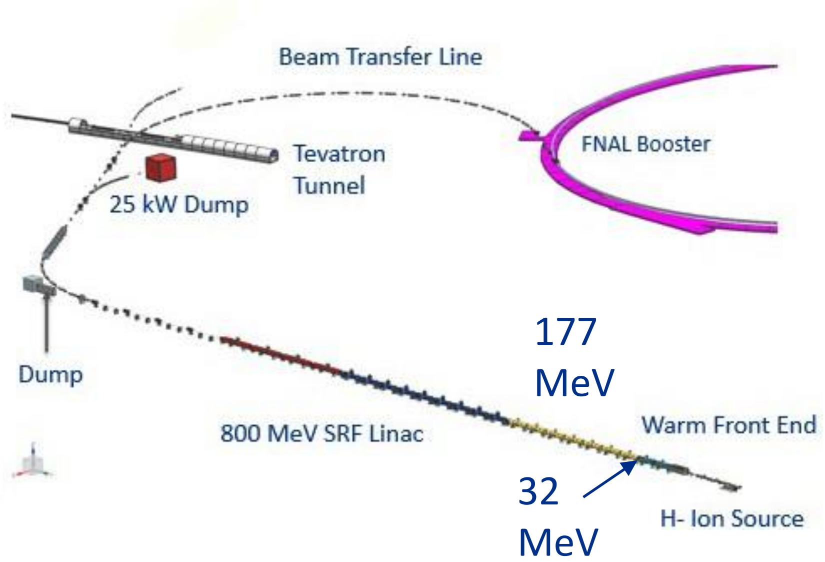
3rd stage: high-power beam commissioning

- Direct the beam to the absorber.
  - Scrapers 3 stay closed, and beam is interrupted if their current is too high. Kickers are off.
    - Such scenario was used at PIP2IT.
  - Increase the duty factor to 1.1%
  - If time allows, increase the duty factor, up to CW
- If the temporary 50 W beam dump is installed, will test the chopping system with the beam at 1.1% duty factor corresponding to Booster injection parameters
  - The next opportunity for that is when the beam reaches the BTL dump

- After MEBT commissioning, the air gap is removed
  - The portion of MEBT downstream of the air gap is beam commissioned together with HWR and SSR1

MEBT in PIP-II commissioning

- Stages after MEBT commissioning
  - Diagnostics cart at 32 MeV (after SSR1)
  - Diagnostics cart at 177 MeV (after SSR2)
  - Full linac to the straight-ahead dump (800 MeV)
  - BTL absorber
  - Beam to Booster



- The MEBT provides additional knobs for initial commissioning at each stage
  - “Pencil” beam can be prepared by heavy scraping with all MEBT scrapers
  - Variations of the bunch structure

Summary

- The present design of PIP-II MEBT has all components necessary for successful commissioning and operation of PIP-II
- The reports addresses the charge questions:
  - #2: Does the design support the various possible configurations of the beam line for beam commissioning?
  - #3: Have Lessons Learned from PIP2IT been taken into account and implemented (as deemed necessary)?

- We believe the answer to these questions is “yes”.