Warm Front End and PIP2IT Status

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DOE Independent Project Review of PIP-II

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- Accelerator physicist for 35 years
- PhD from BINP, Novosibirsk – 1990
- At Fermilab since 1998
  - ECOOL project – responsible for electron beam
- With PIP-II project since 2011
  - PIP2IT warm front end manager
  - Responsible for MEBT

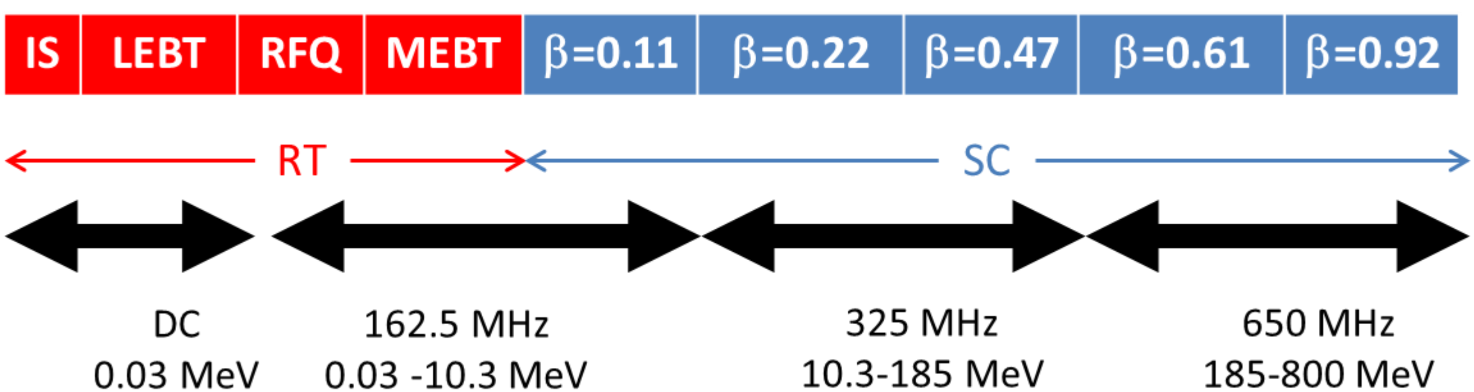
Outline

Charge Item: #1
P. Derwent

- PIP-II warm front end concept
- R&D Goals and PIP2IT
- Status of warm front end of PIP2IT
- Schedule
- Summary

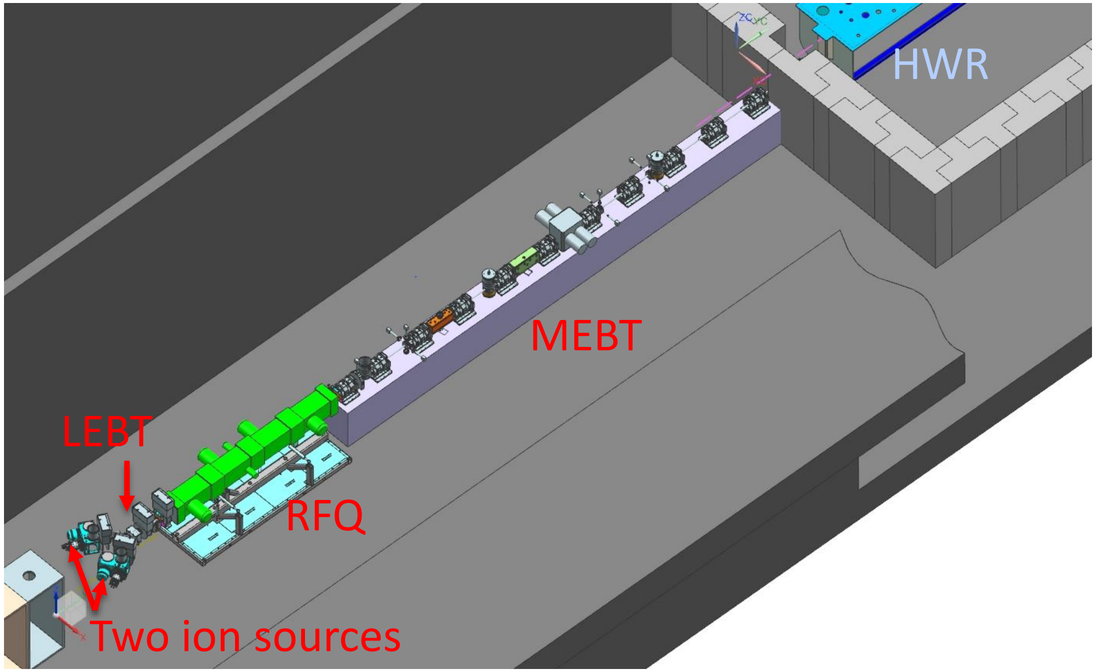
PIP-II warm front end

- The warm front end prepares H- beam optimized for Booster injection and provides capabilities for future CW operation
  - Ion Source (IS) and Low Energy Beam Transport (LEBT)
  - Radio Frequency Quadrupole (RFQ)
  - Medium Energy Transport (MEBT)
- Output parameters: 2.1 MeV, $\varepsilon_\perp$<0.23 µm, ε_L<0.31 µm
  - Nominal current 2 mA averaged over ~µs (from µs to CW)
  - Bunch-by-bunch selection capability



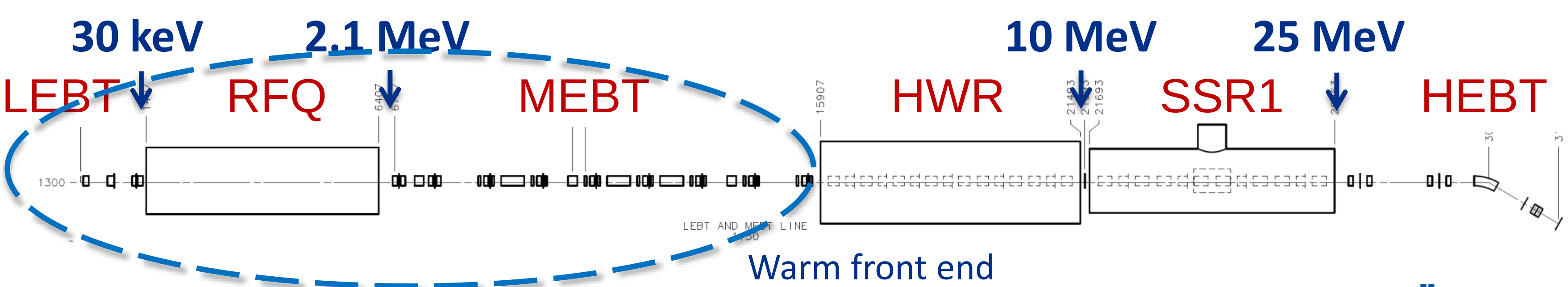
Present conceptual design

- Two ion sources with switching magnet (30 keV, 10 mA DC)
- 2-m long LEBT with partial neutralization
- RFQ: 4.4-m, 2.1 MeV, 162.5 MHz CW, 4-vane
- MEBT: 14-m, bunch-by-bunch chopping system; radiation protection wall; differential pumping after absorber



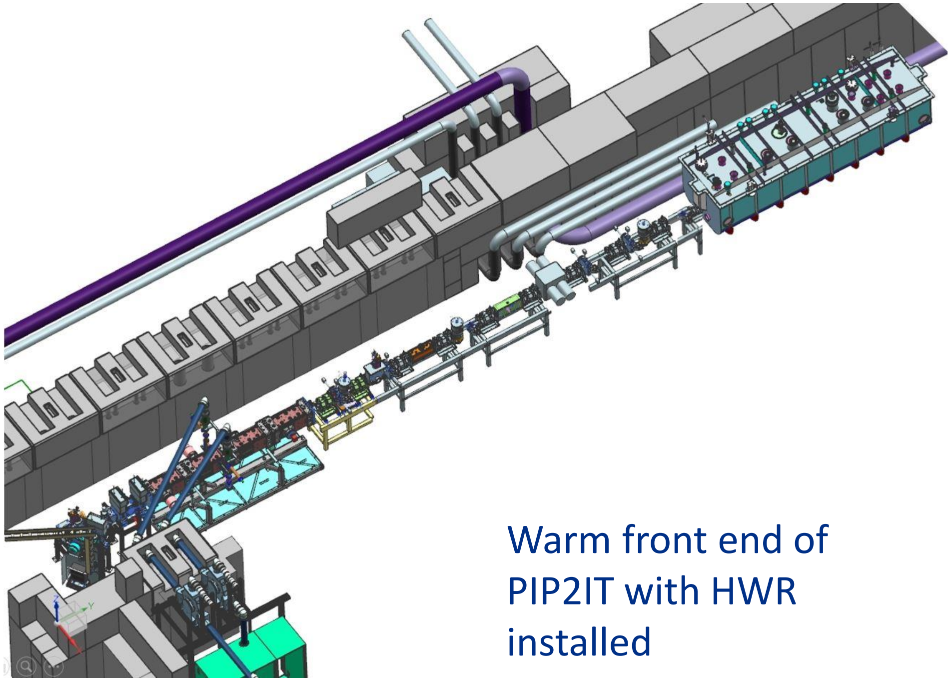
R&D goals

- R&D will mitigate risks associated with the front end for PIP-II and speed up commissioning
- The most important R&D issues
  - LEBT with low emittance growth compatible with chopping ✓
  - Reliable CW RFQ, including couplers (partially ✓)
  - Bunch-by-bunch selection in MEBT
  - Compatibility of high-power deposition in MEBT absorber with SRF downstream
- Are being addressed by PIP-II Injector Test (PIP2IT)



Warm front end of PIP2IT

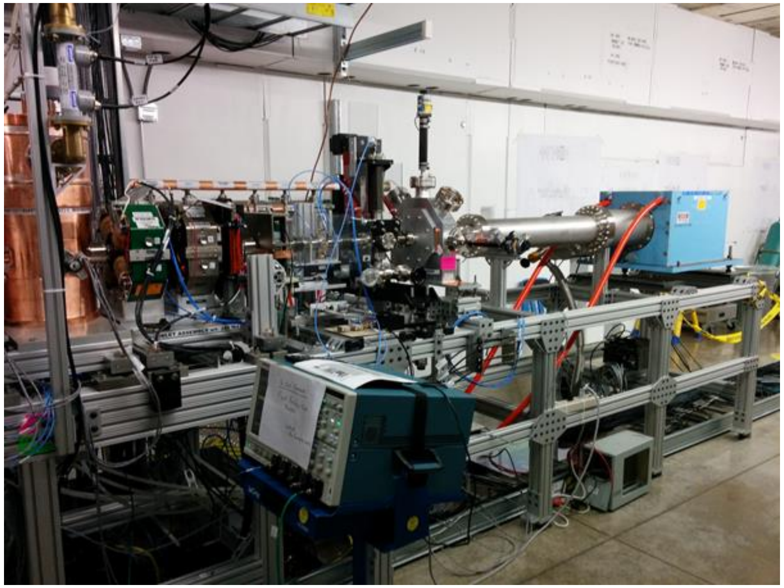
- Warm front end of PIP2IT represents as close as possible the PIP-II front end as it is envisioned now
  - Same ion source (only one); same LEBT and RFQ
  - Same MEBT chopping system
  - Slightly shorter MEBT to fit into CMTF building
    - By ~3.5 m, 3 triplets, one bunching cavity
    - No wall across MEBT
    - Less effective protection from vacuum accidents
- Addresses all critical issues of PIP-II front end
  - Almost all parts will be used at PIP-II



Warm front end of PIP2IT with HWR installed

Status of PIP2IT - outlook

- LEBT has been fully commissioned in straight configuration
- RFQ is RF commissioned in both pulse and CW modes
- Parameters of the beam out of RFQ are partially measured
- MEBT in two- doublets configuration is characterized
- Preparations are underway for CW beam test
- Assembly of a longer MEBT will start soon
  - LEBT bend will be installed at the same time
- Full – length MEBT is being designed

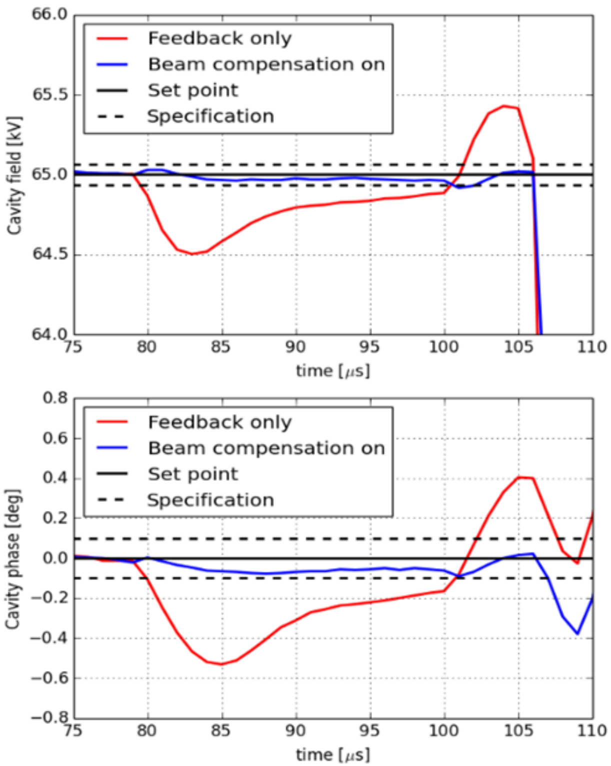


DAE contribution: MEBT magnets

- All MEBT magnets are produced by BARC, India
- FY15 – prototype magnets (two doublets and two dipoles)
  - Used in the present version of the MEBT
- FY16 – all 15 dipole correctors delivered
- FY17- all serial quadrupoles will be delivered
  - Total 36 quadrupoles and frames
    - PIP2IT MEBT, HEBT, spares

RFQ RF

- RFQ was installed and commissioned
  - Inter-vane voltage checked with X-ray detector
  - Initial conditioning took a day (pulsed)/several days (CW)
  - The resonant frequency is regulated by water temperature to vanes and walls
- Operate mainly in pulse mode
  - Typical RF pulse is 0.1 – 5 ms at 10 Hz
  - Extra level of protection from un-requested long- pulse or CW beam
  - Lower power consumption
  - Better reliability
  - LLRF keeps the flat top amplitude within 0.1% and phase $\pm 0.1^{o}$
    - FF, FB, and beam compensation on

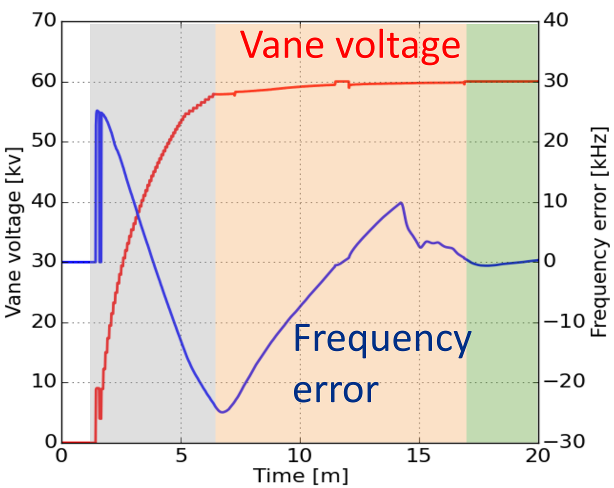


Fermilab PIP-II

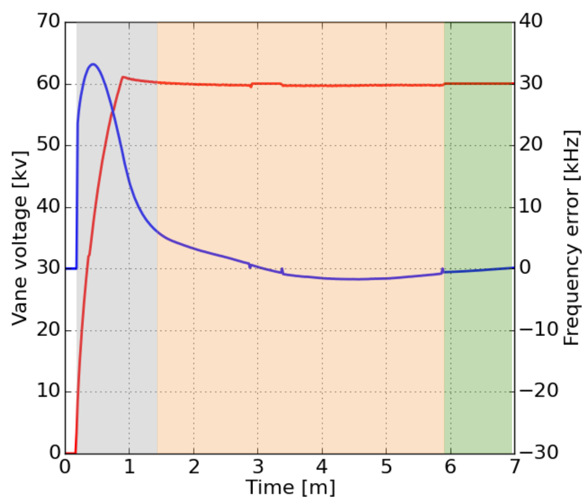
RFQ RF operation

- Applications were written to switch the RFQ on/off in both CW and pulsed modes and automatically recover from trips
  - Resonance control switches from fixed frequency (GDR) to self-excited loop (SEL) if the resonance frequency error is too large
  - Cold start takes 20-30 min from turn on to nominal frequency
  - Trip recovery in CW takes from seconds to several minutes
    - depending on whether the vane voltage restores immediately

Cold start



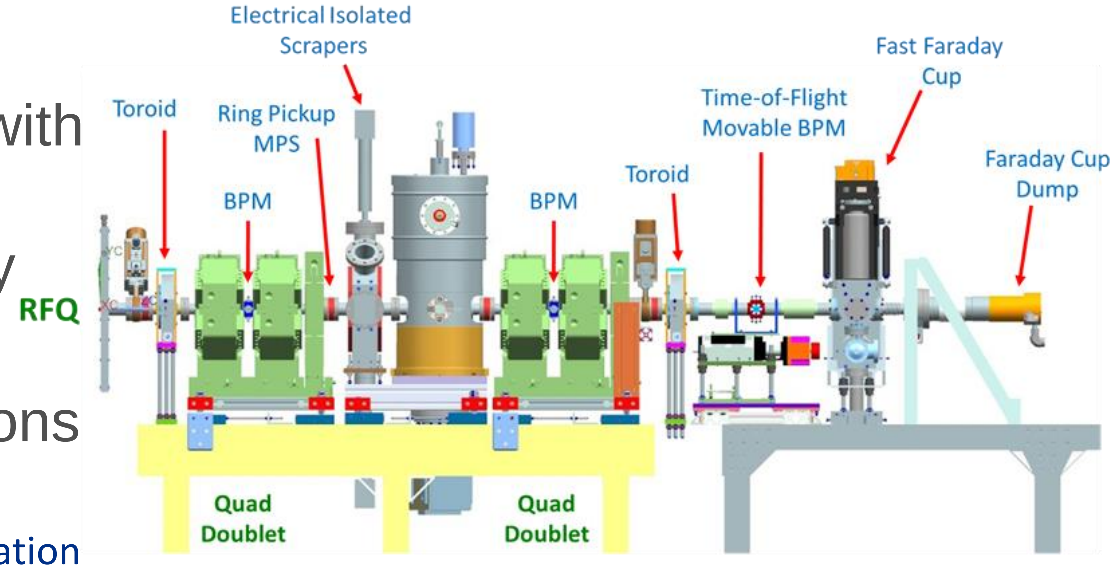
Trip recovery (after 10 sec delay)



Gray: RFQ power ramp; resonance control is idle; SEL
Orange: resonance control bringing RFQ to frequency; SEL
Green: RFQ is in GDR and LLRF feedback is active

RFQ beam in the short MEBT

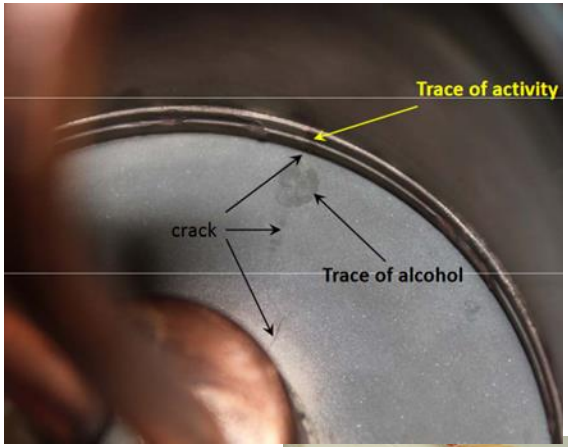
- Transmission: 98% ±2% (at 5 mA; the best result)
  - measured as ratio of beam current at entrance and exit of RFQ
- Energy: 2.11 MeV ±0.5% (measured with a movable pickup)
- Transverse parameters – estimated with quad scans/scrapers
  - Emittance ~ 0.2 μm at optimum conditions (probably ±20%)
  - No consistent numbers for Twiss functions yet
- Bunch length
  - Attempts to measure with two versions of Fast Faraday Cup were only partially successful
  - Considering modifications



MEBT-1.1 configuration

RFQ issues

- Coupler failure
  - One of couplers failed during conditioning in CW
    - Could be related to a known fabrication flaw, not-optimal conditioning procedure, or (unknown) design deficiency
    - Was replaced by a spare; changed operation procedures and improved cooling

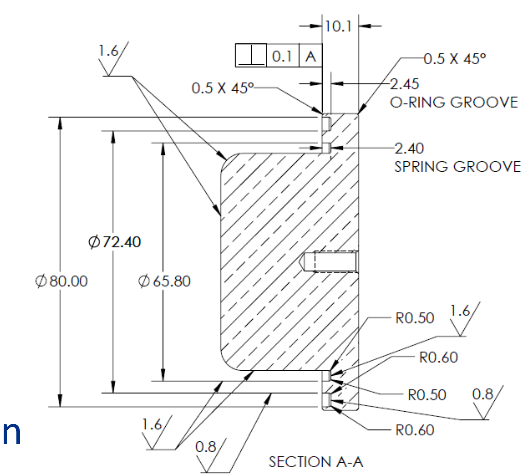


- Amplifier failures
  - Several "slices" during commissioning
    - Now have a good set of spares
  - wall power (480V) connection
  - intermittent controls issues

D. Peterson

RFQ issues: frequency offset

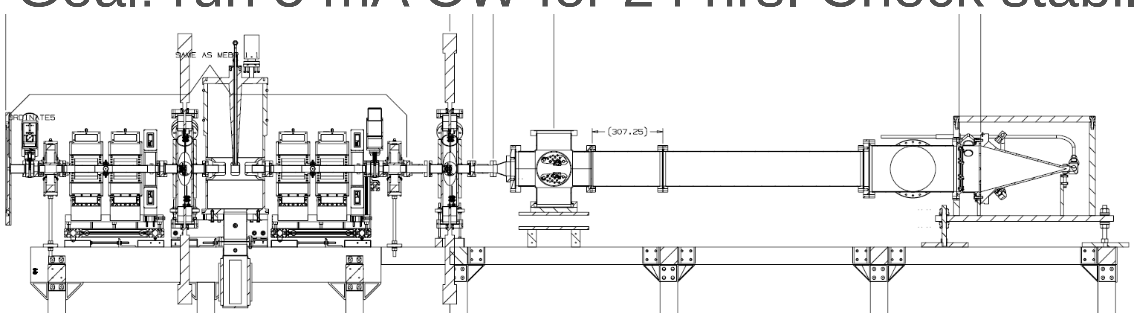
- Resonant frequency is found by 60 kHz lower than expected
    - Likely due to unforeseen mechanical deformations of RFQ body
- Difficult to compensate with wall- vane temperature difference
    - At the boundary of regulation in CW; ≥10 kHz in pulsed
        - -16.4 kHz/K vanes; +13.9 kHz/K walls; -2.5 kHz/K together
    - Now normally run at ~ -80 kHz offset
    - Is not a problem for present running but needs to be corrected before sending the beam into HWR
- Plan suggested by LBNL team: re-machine all 80 fixed plug tuners
    - Would not perturb field flatness
    - Discussing to do it in FY18



Existing tuners can be re-machined

Short MEBT

- Several setups (different in diagnostics)
  - Commissioning of diagnostics, development of procedures, beam-based checks and calibrations, beam properties
  - Up to 10 mA in pulse mode to the dump (losses < 3%)
- Radiation: higher than expected (prompt only)
  - Agrees with simulations by updated MARS code
  - Average current is limited to 0.25 mA until cave is interlocked
- Present configuration is optimized for a high-power run
  - Goal: run 5 mA CW for 24 hrs. Check stability of operation.



MEBT-1.2 configuration, optimized for high-power running

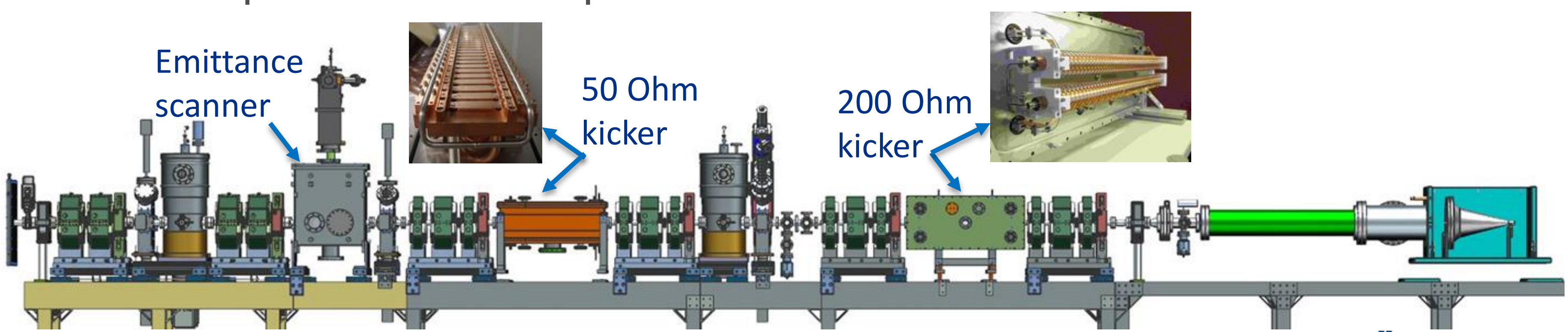
- Coming next: MEBT emittance scanner

Machine Protection

- Machine Protection System (MPS)
  - Plan to test a scheme envisioned for PIP-II
    - Two-tier list of MPS devices; inhibiting the beam primarily in LEBT; comparing beam current through the machine; shut-off time ~10μs
  - Exists now: protection from not-requested long pulses, poor vacuum, and RF trips; administrative measures
  - Coming: operational modes, current comparison, scrapers currents, loss monitors
- Protection of vacuum chamber and beam dump in CW run
  - Two 4 – plate scraper sets. Plates are placed at the beam boundary of an optimized envelope. Permit drops if a scraper current is too high or too low
  - Comparison of beam current measurements out of RFQ and in the dump

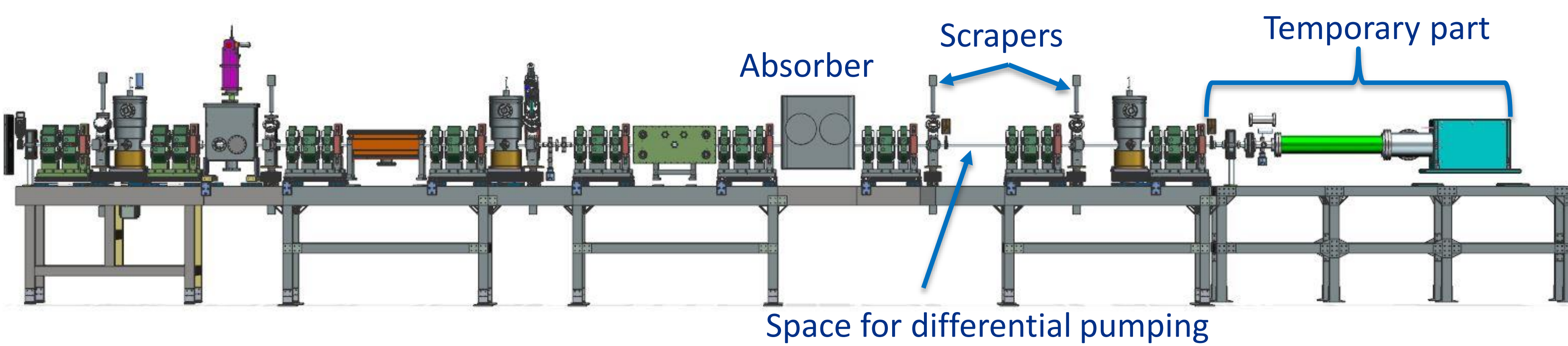
Longer MEBT: kickers' test

- Will be assembled after arrival of magnets for 4 triplets
  - One more bunching cavity, two kickers, BPM in each triplet
- Kickers' tests: electromagnetic performance and survival
  - 50 Ohm kicker: trajectory response to 81.25 MHz CW
    - Possible test with wide-band amplifiers on loan
  - 200 Ohm kicker: short bursts of arbitrary chosen "pass/remove" pattern, including ~10 μs of 81.25 MHz
  - The kick is measured by recording BPM signals with a scope
    - Optional: with scrapers



Full-length MEBT

- FY17: assemble when magnets for 3 more triplets arrive
  - Plus: bunching cavity, two scraper sets, differential pumping
- FY18 shutdown: MEBT in its final (for PIP2IT) state
  - Final chopping system: 21 kW absorber, two identical kickers
  - Full set of diagnostics
  - Complete MPS, fast vacuum valve and sensors
  - Particle – free sections downstream of absorber



R&D schedule for the PIP2IT warm front end

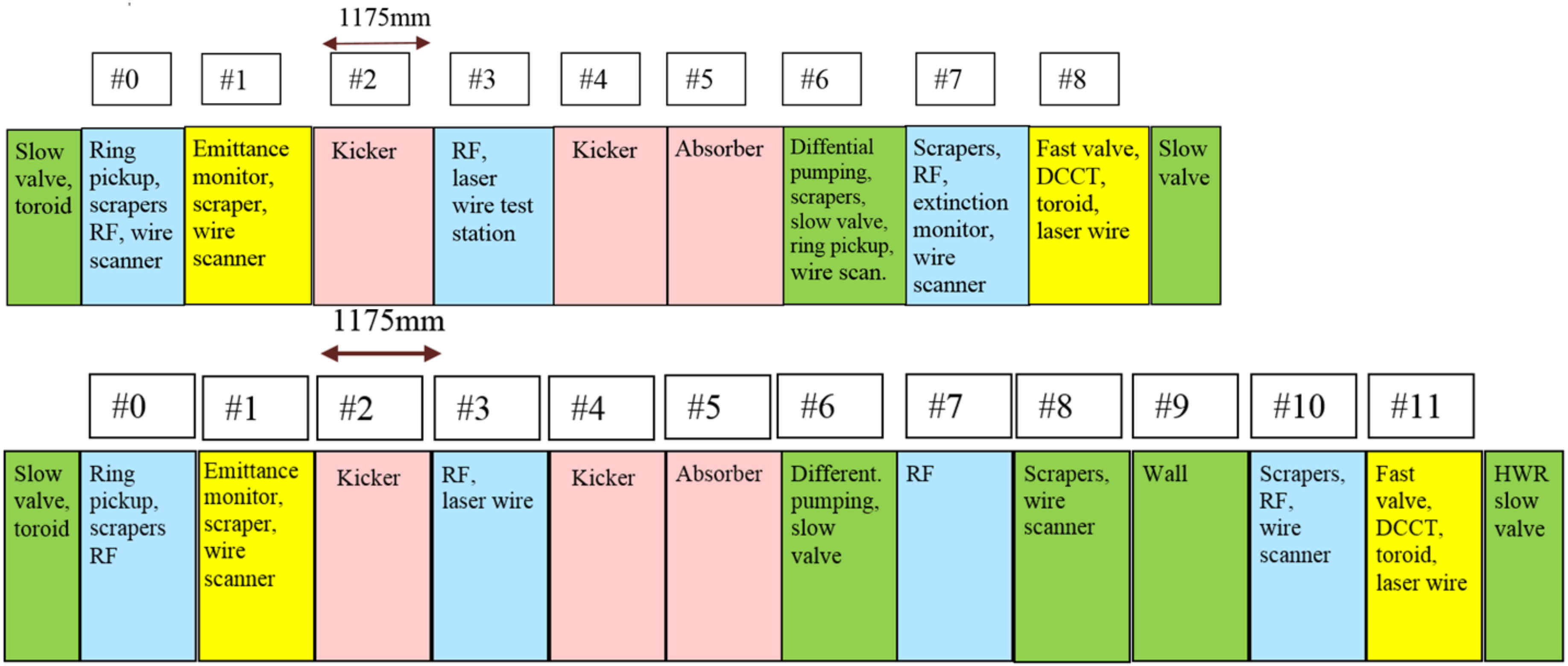
- FY17 – beam run in warm front end with SNS dump
  - Demonstrate high – power beam accelerated in RFQ
  - Assemble full – length MEBT
  - Measure electromagnetic response and survival of kickers
    - Choose the kicker version
- FY18 – shutdown to install cryo distribution system and HWR
  - Install final MEBT and connect to HWR
- FY19 - install and RF – commission both cryomodules
  - Commission the final MEBT in parallel
    - Full power to absorber, bunch-by-bunch selection in MEBT
    - Commission MPS, vacuum protection, diagnostics
- FY20 – beam through cryomodules
  - Supply the beam with final parameters

Summary

- Proposed warm front end concept satisfies PIP-II requirements both for Booster injection and for future CW operation
- Critical issues are being addressed at PIP2IT
  - Performance of LEBT and RFQ has been demonstrated
  - Preparations are under way to test elements of the chopping system
  - All R&D questions related to the warm front end will be answered by the end of PIP2IT run
- PIP2IT warm front end will be ready to inject the beam into HWR in the time of cryomodules installation to test performance of SRF with beam

- Backup slides

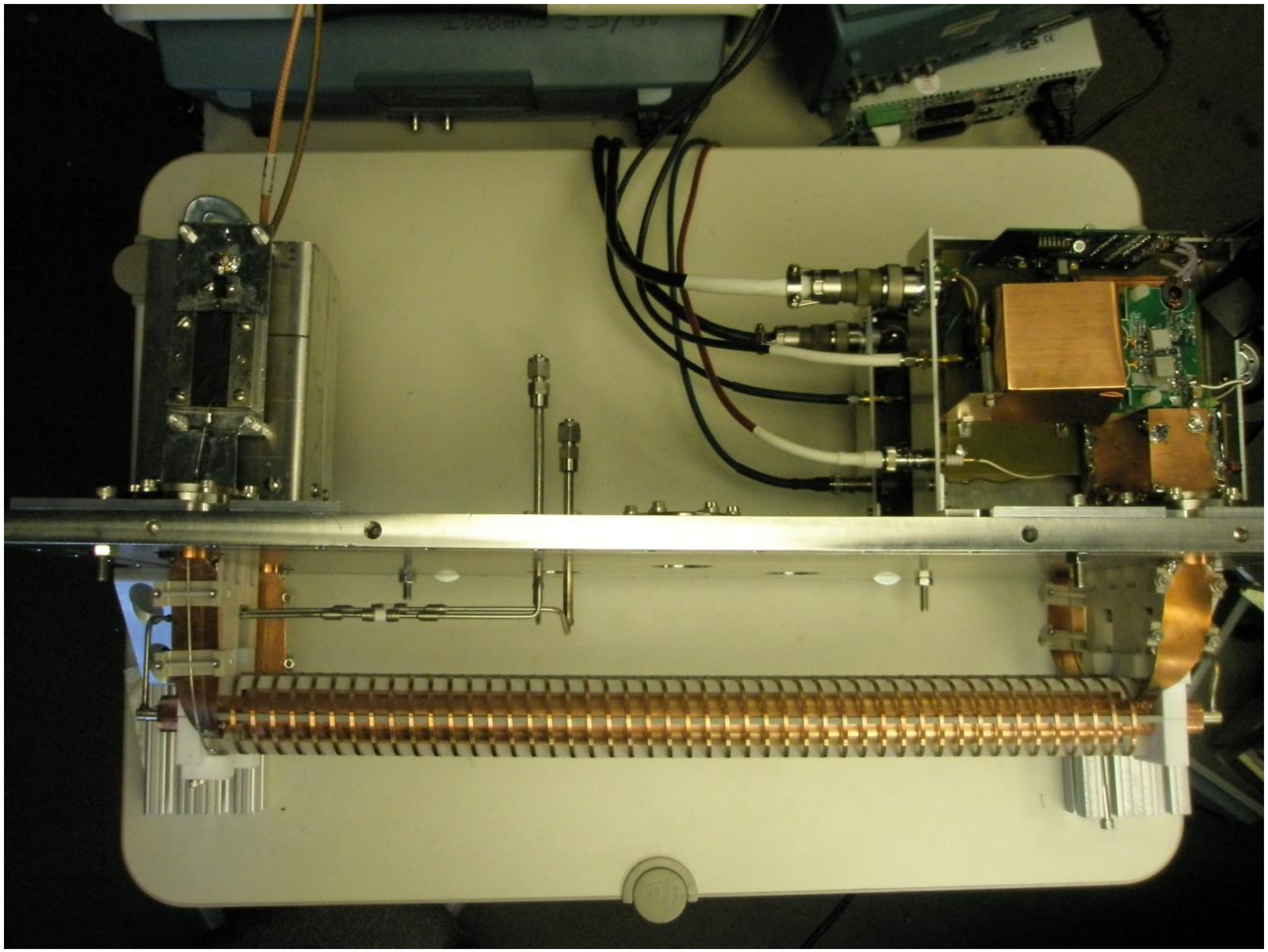
Comparison of PIP2IT and PIP-II MEBTs



- PIP2IT MEBT
  - Shorter by: ~3.5 m, 3 triplets, one bunching cavity;
  - No wall across MEBT
  - Less effective protection from vacuum accidents

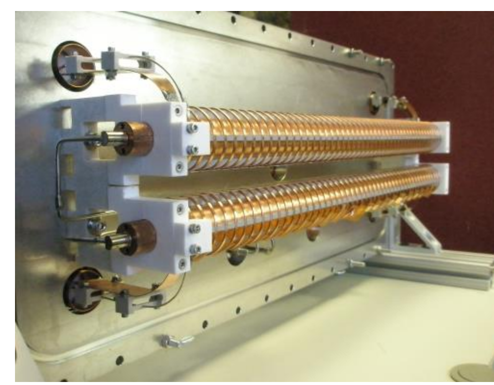
200 Ohm kicker

- Kicker is assembled with two drivers and is under RF testing



Top view of 200 Ohm kicker (without vacuum box). Two helixes and two drivers are assembled on the side panel of the vacuum box.

Side view

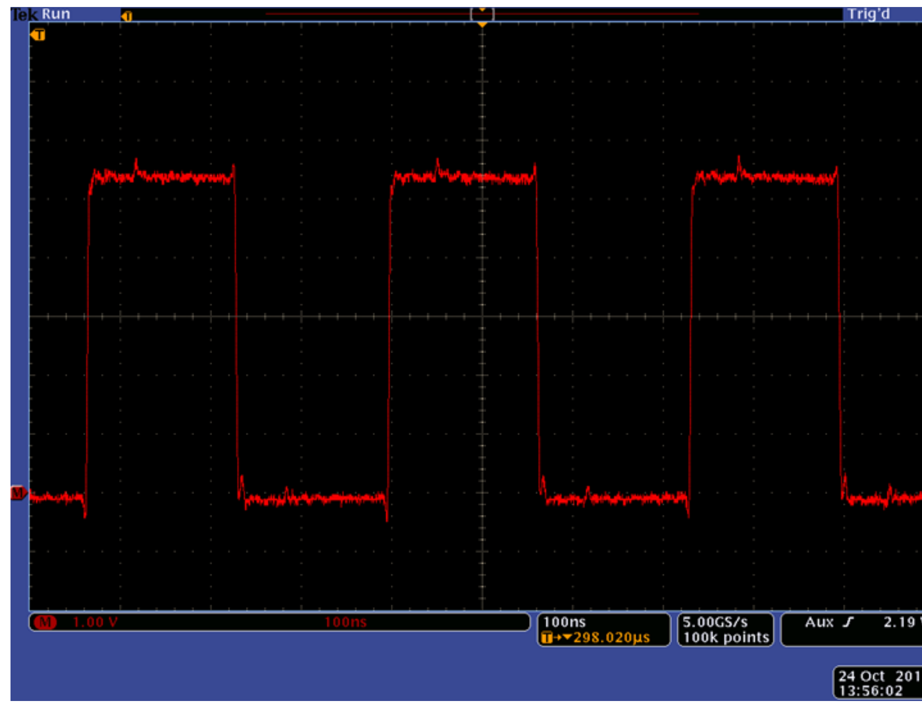


200 Ohm kicker driver

- Driver parameters are within specs for short bursts
  - Transition to CW requires adding of water cooling (doable)

Zoomed in example of wave forms formed by the drivers. Shown are differential signals measured between outputs of the helixes. Peak – peak voltage 1200 V.

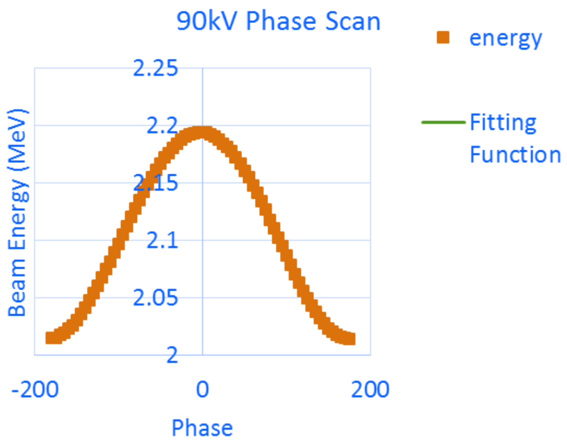
50 Hz, 40 µs, 81.25 MHz. Emulates removal of every other bunch of the 162.5 MHz train. 4 ns/div.

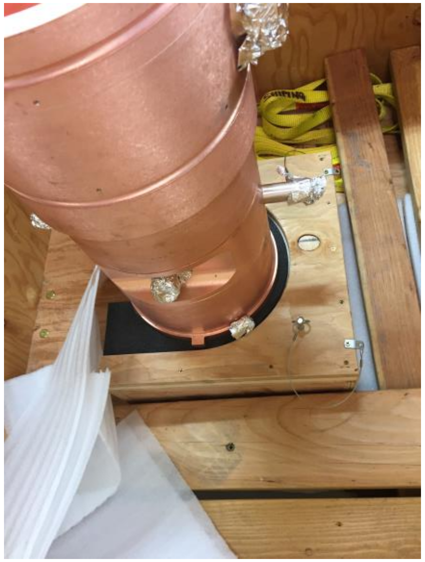


20 Hz, 0.6 ms, 3 MHz. Emulates removal of half of bunches in 300 ns batches. 100ns/div.

Bunching cavity

- Cavity prototype was built and fully commissioned; 3 cavities in production
- Calibration by measuring the beam energy with BPMs and a movable Time-of-Flight pickup
  - This calibration agrees with X-ray measurements
  - 100 kV requires 1.8 kW vs simulated 1.4 kW
- Delay with cavities production
  - Vacuum leaks and shape distortion after first brazing
  - Repairs will be attempted during following brazing





Body of the first "production" cavity after second brazing