



# PIP-II Injector Test Warm Front End: Commissioning Update

Lionel Prost

9<sup>th</sup> International Particle Accelerator  
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*Designates co-authors*

# Outline

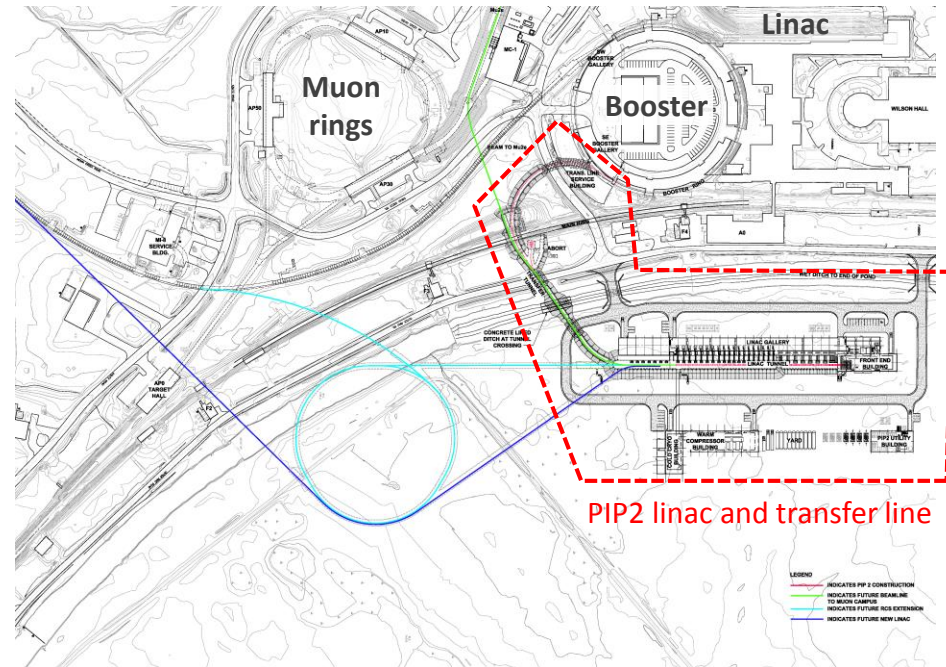
- Proton Improvement Plan II (PIP-II) & PIP-II Injector Test (PIP2IT)
  - Introduction, scope & goals for the Warm Front End (WFE)
- PIP2IT WFE commissioning status
  - Focus on Medium Energy Beam Transfer (MEBT) line
- Plans for high-power operation
  - 10+ kW
- Conclusion

# Proton Improvement Plan-II (PIP-II)

S. Nagaitsev's talk (MOYGB3)

- Upgrades to Fermilab's accelerator complex
  - Central part: 800 MeV, 2 mA (average over  $\sim \mu\text{s}$ ) **CW-compatible**
  - H<sup>-</sup> Superconducting Linac and transfer line to Booster
    - Present 'warm' Linac: 400 MeV, 30 mA,  $40 \mu\text{s} \times 15 \text{ Hz}$
  - **MW-class accelerator with multi-user operation capability**

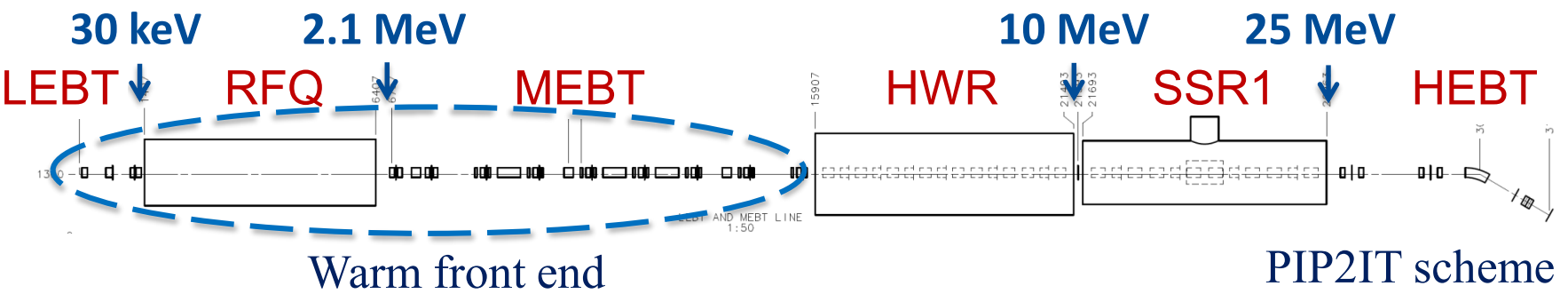
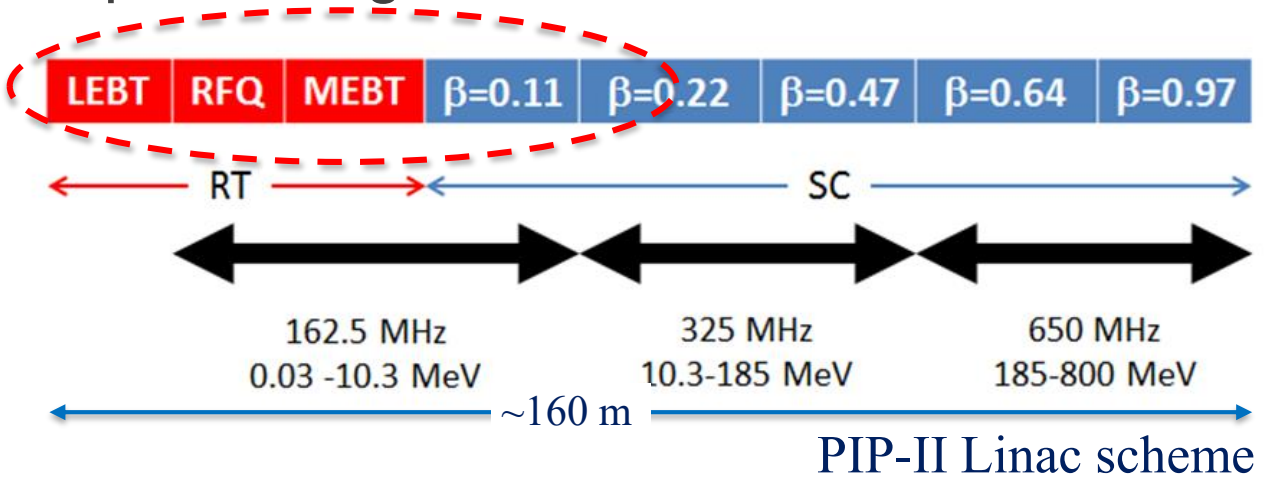
- Platform for future upgrades
  - Higher Main Injector power, multiple experiments simultaneously



Layout of PIP-II and its possible future upgrades

# PIP-II Injector Test (PIP2IT)

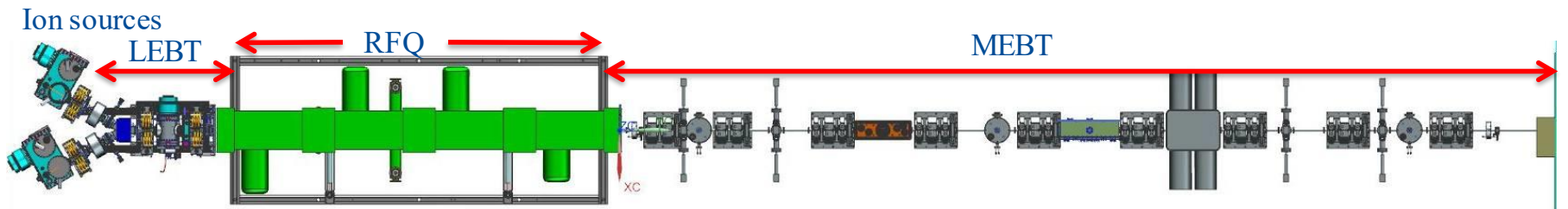
- A test accelerator representing the PIP-II front end



*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*

# Warm Front End scope

- The **Warm Front End** (WFE) prepares a H<sup>-</sup> beam optimized for injection into the Booster and provides capabilities for future **CW operation**
- It is composed of:
  - Two Ion Sources (IS) and a Low Energy Beam Transport (LEBT)
    - **DC/long pulse operation**
  - RFQ
    - **CW operation (RF)**
    - 30 keV ⇒ 2.1 MeV
  - Medium Energy Beam Transport (MEBT)
    - Nominal output current: 2 mA averaged over ~μs (from μs to **CW operation**)
    - **Bunch-by-bunch chopping capability**

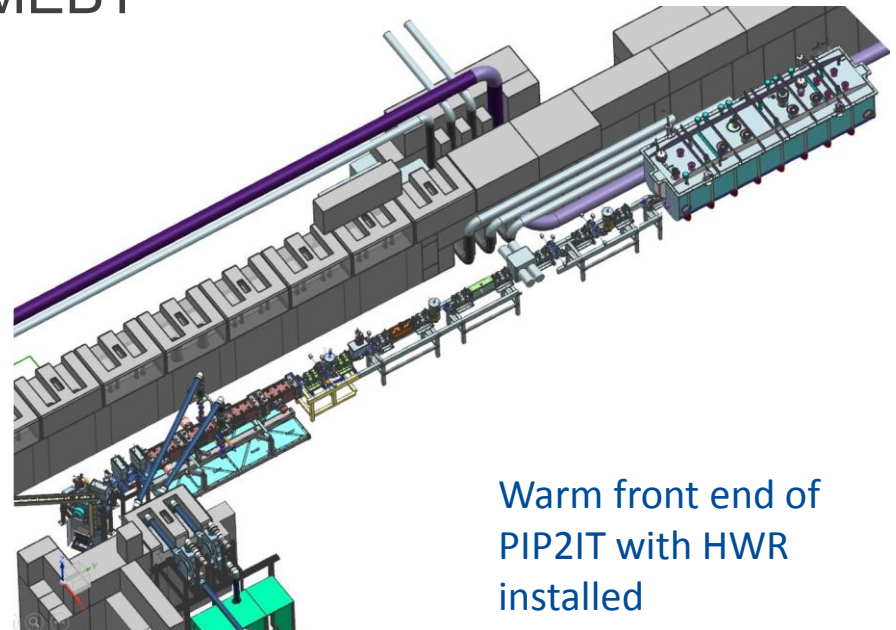


# PIP2IT WFE main goals

- Address all critical issues:

- LEBT with low emittance growth compatible with chopping
  - Vacuum management in the LEBT/RFQ region
- Reliable CW RFQ, including couplers<sup>\*</sup>
- Bunch-by-bunch selection in MEBT
  - Bunch extinction, effective emittance growth
- Compatibility of high-power deposition in MEBT absorber with SRF downstream
  - Absorber reliability & lifetime

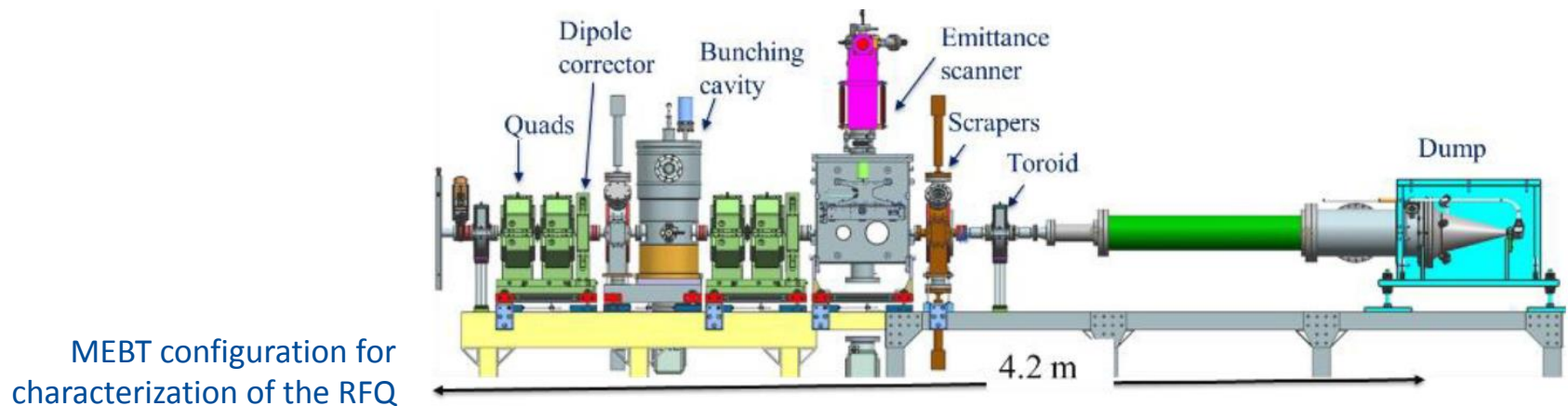
Reported previously



Warm front end of PIP2IT with HWR installed

# LEBT and RFQ performance highlights

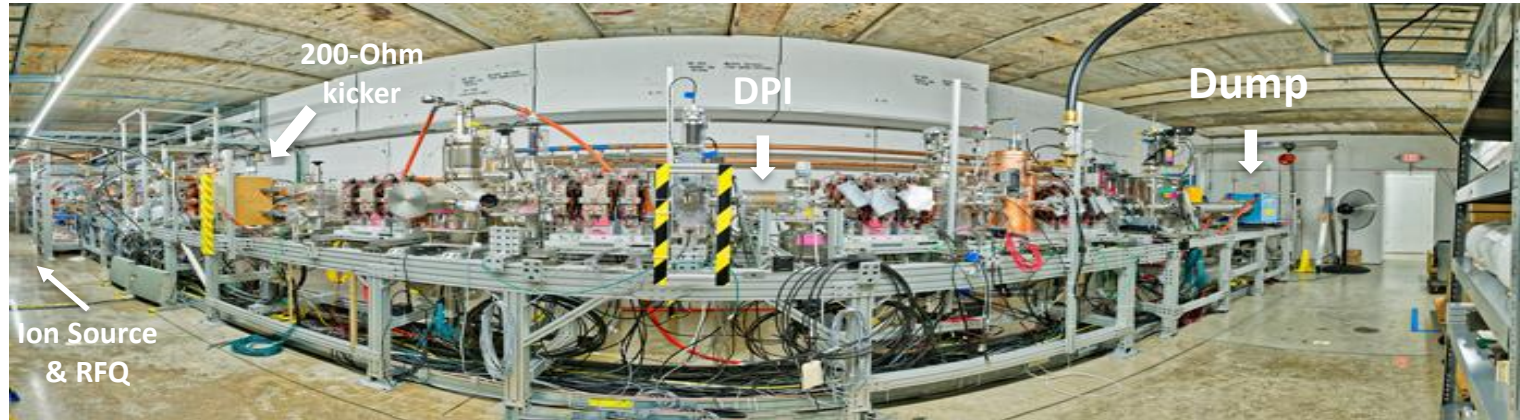
- LEBT delivers up to 10 mA, 10 $\mu$ s-dc, 20 Hz
  - $\epsilon_{n,rms} = 0.13$  mm mrad (for  $\leq 5$  mA)
- RFQ operated pulsed (up to 5 ms) or CW, 162.5 MHz, 60 kV
  - Time of Flight measurements  $\rightarrow 2.11 \pm 0.006$  MeV
  - $98 \pm 2\%$  transmission efficiency at 5 mA (pulsed beam)
    - Up to 10 mA with low losses
  - $\epsilon_{n,rms} < 0.2$  mm mrad (for  $< 5$  mA, nominal)



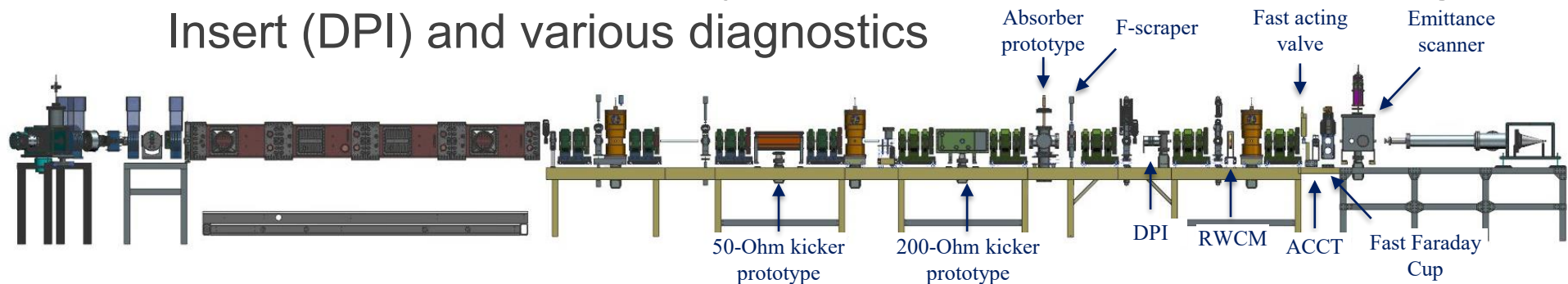


# PIP2IT beam line configuration

- Full length MEBT has been installed at the CryoModule Test Facility (CMTF) followed by a high-power dump

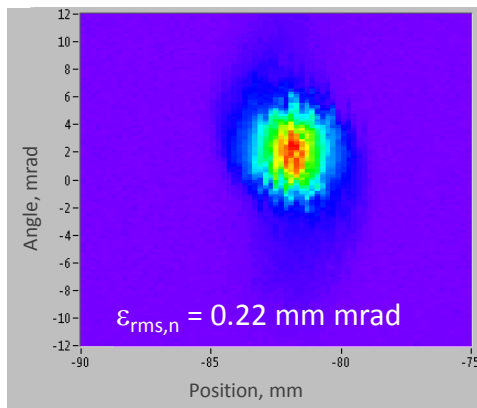


- Includes two different prototype kickers (50-Ohm & 200-Ohm), all scraper paddles, prototype absorber, Differential Pumping Insert (DPI) and various diagnostics

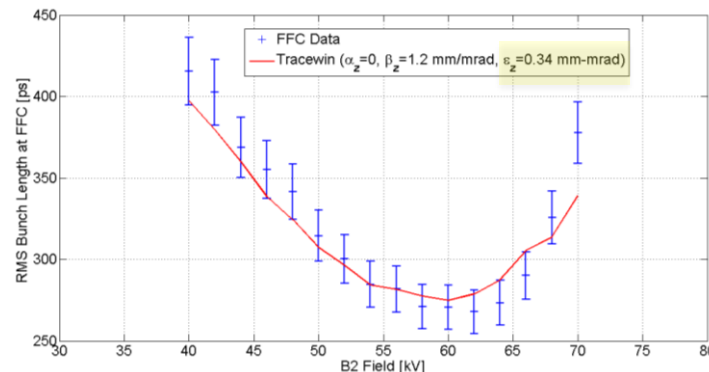


# Beam transport

- Demonstrated 96% availability (over 24 hours) for beam with nominal MEBT parameters
  - $5 \text{ mA} \times 0.55 \text{ ms} \times 2.1 \text{ MeV} \times 20 \text{ Hz} = 115 \text{ W}$  with appropriate bunch pattern for Booster injection
- Up to 10 mA to the dump with negligible **uncontrolled** losses
  - Dedicated distributed scraping system removes  $\sim 2\%$  (halo)
- Measured beam emittances near the end of the MEBT
  - **0.22/0.34** mm mrad (rms, n) **Transverse/Longitudinal**



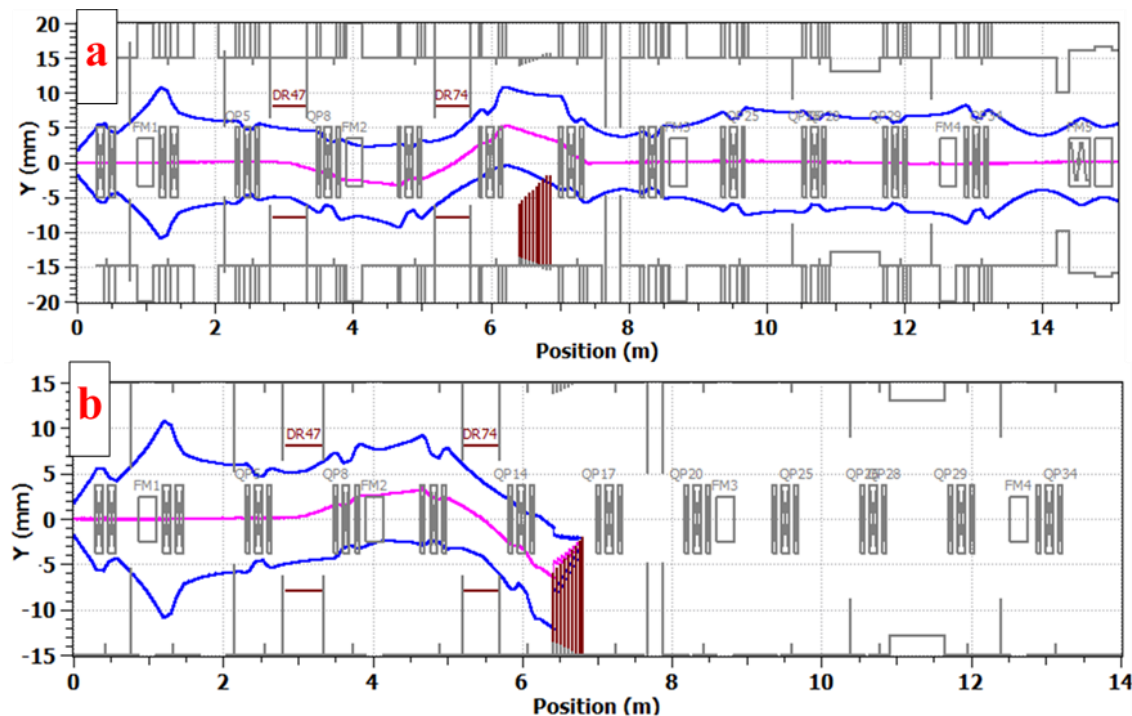
Vertical phase-space with Allison scanner (5 mA, 10  $\mu$ s pulse)



Bunch length vs. bunching cavity #2 voltage (5 mA, 10  $\mu$ s pulse) and 'fit' with Tracewin

# Chopping system concept

- 2 identical kickers in sync and a beam absorber
  - Two broadband travelling-wave kickers separate bunches by  $6\sigma$
  - Absorber is rated for 21 kW (i.e. full max. beam power)
    - Beam comes at 29 mrad to decrease power density to  $<17 \text{ W/mm}^2$



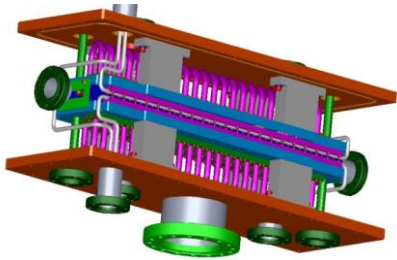
$3\sigma$  envelopes of the transmitted (a) and chopped-out (b) bunches simulated with TraceWin.

# Kickers development

- Two versions developed in parallel  $\Rightarrow$  1 of each prototype installed at PIP2IT

## “50-Ohm”

- 24 electrodes per plate connected in vacuum by 50 Ohm cables
- Driver: commercially available linear amplifier
  - Concept tested with similar lower-power amplified



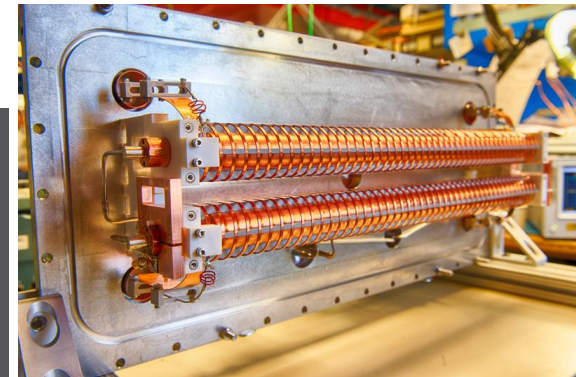
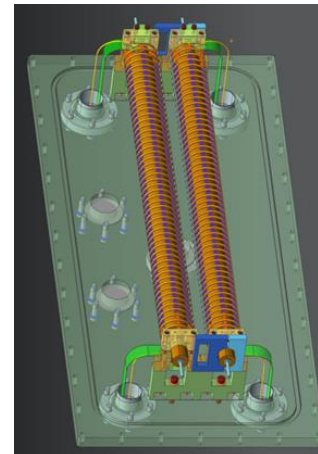
*D. Sun  
A. Chen*



## “200-Ohm”

- Helix as a travelling-wave structure
- Driver developed at Fermilab
  - Broadband, DC-coupled switches in push-pull configuration

*A. Chen  
G. Saewert*

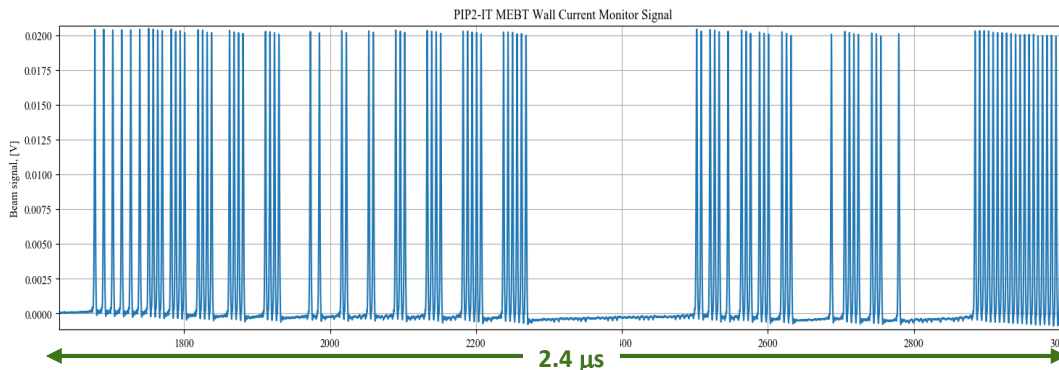
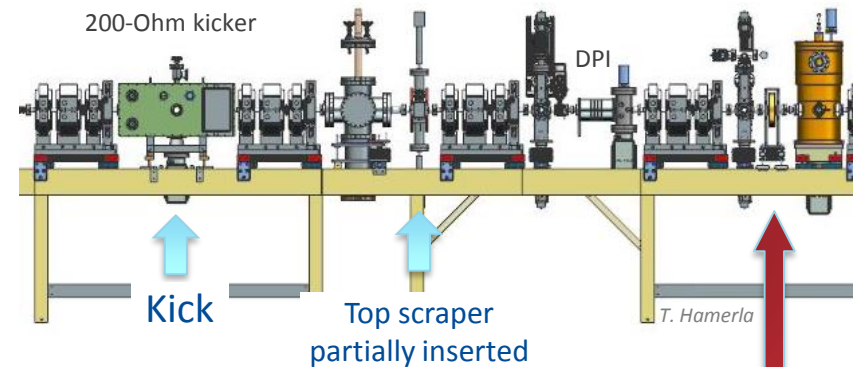


G. Saewert's poster (WEPML021)

# Kickers characterization

- Both kickers (50-Ohm and 200-Ohm) meet specs
  - For  $\Delta V = 500$  V (nominal), angle of deflection at the end of either kicker is  $> 7$  mrad (specs)
- Demonstrated arbitrary bunch structure
  - Kicked bunches intercepted with a scraper  $\rightarrow$  passing bunches recorded with Resistive Wall Current Monitor (RWCM)

*D. Sun  
G. Saewert  
A. Chen  
B. Chase  
V. Lebedev*



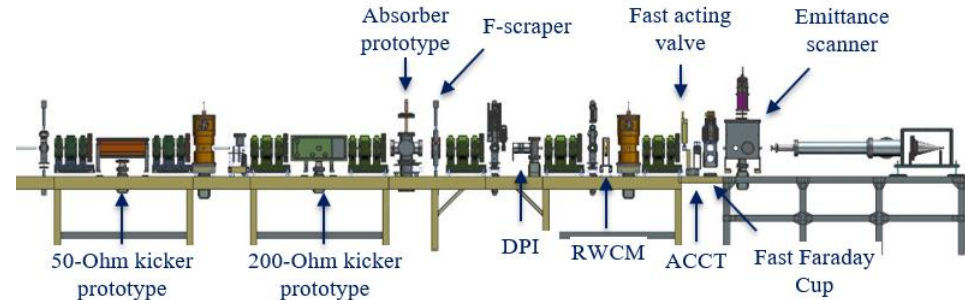
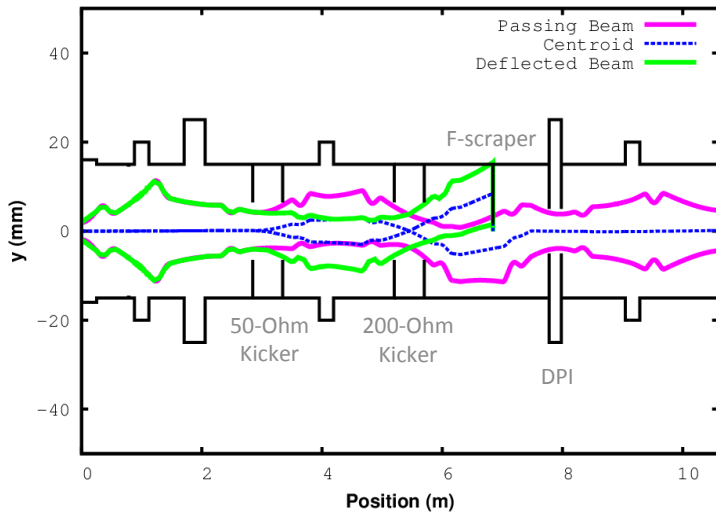
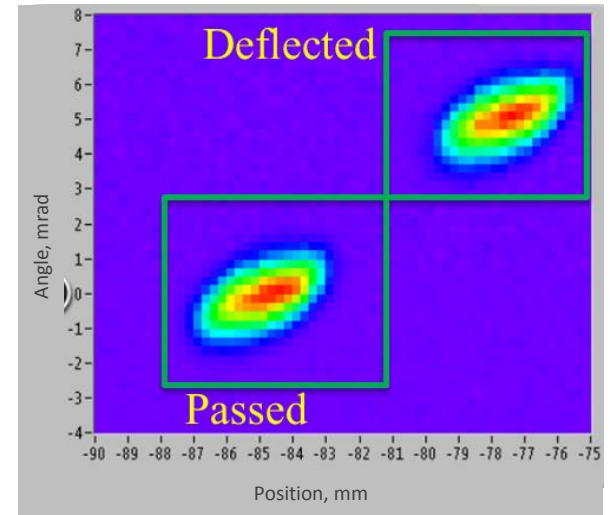
**RWCM**

*F. Frolov  
G. Saewert  
J. Simmons*

# Kickers characterization(cont')

- Kickers do not significantly deteriorate the transverse emittance of the beam
- Kickers were successfully operated together in sync

5 mA beam collimated to 1.5 mA and deflected by the 200-Ohm kicker



$3\sigma$  vertical envelope simulated with Tracewin showing both the passing and the deflected bunches in the configuration with both kickers used in sync.

# PIP2IT vs. PIP-II WFE beam parameters

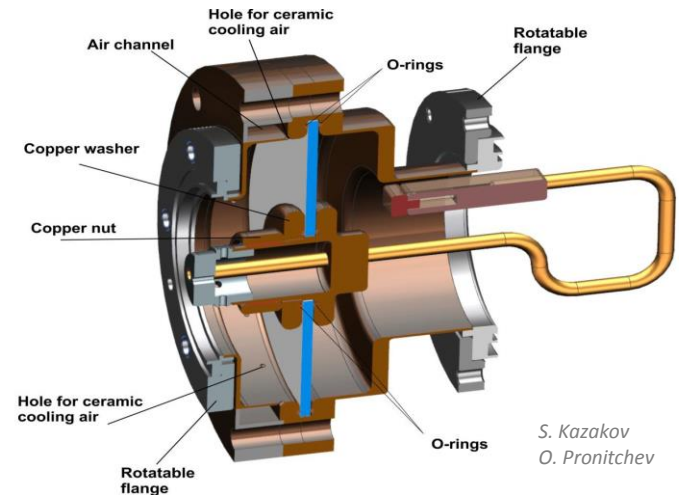
	PIP-II	Beyond PIP-II (cw)	PIP2IT (concurrently)	PIP2IT (max)
Beam energy, MeV	2.1	2.1	2.1	2.1
Bunch frequency, MHz	162.5	162.5	162.5	162.5
Peak current (RFQ exit), mA	5	5	5	10
Macro-pulse length, ms	0.55	-	0.55	4.8
Macro-pulse rep. rate, Hz	20	-	20	60
Bunch pattern	Booster inj.	Arb.	Booster inj.	Arb.*
Output current (averaged over $\sim\mu\text{s}$ ), mA	2	2	2	10
Average power, kW	0.1	10	0.1	5

\* Arbitrary patterns are currently limited to 0.6 ms bursts with average switching frequency of up to 45 MHz during the burst and 20 Hz bursts repetition rate

At PIP2IT, the bunch pattern for bucket-to-bucket injection into the Booster was demonstrated using *only 1 kicker* (2 are required to achieve nominal deflection)

# Path to high-power operation

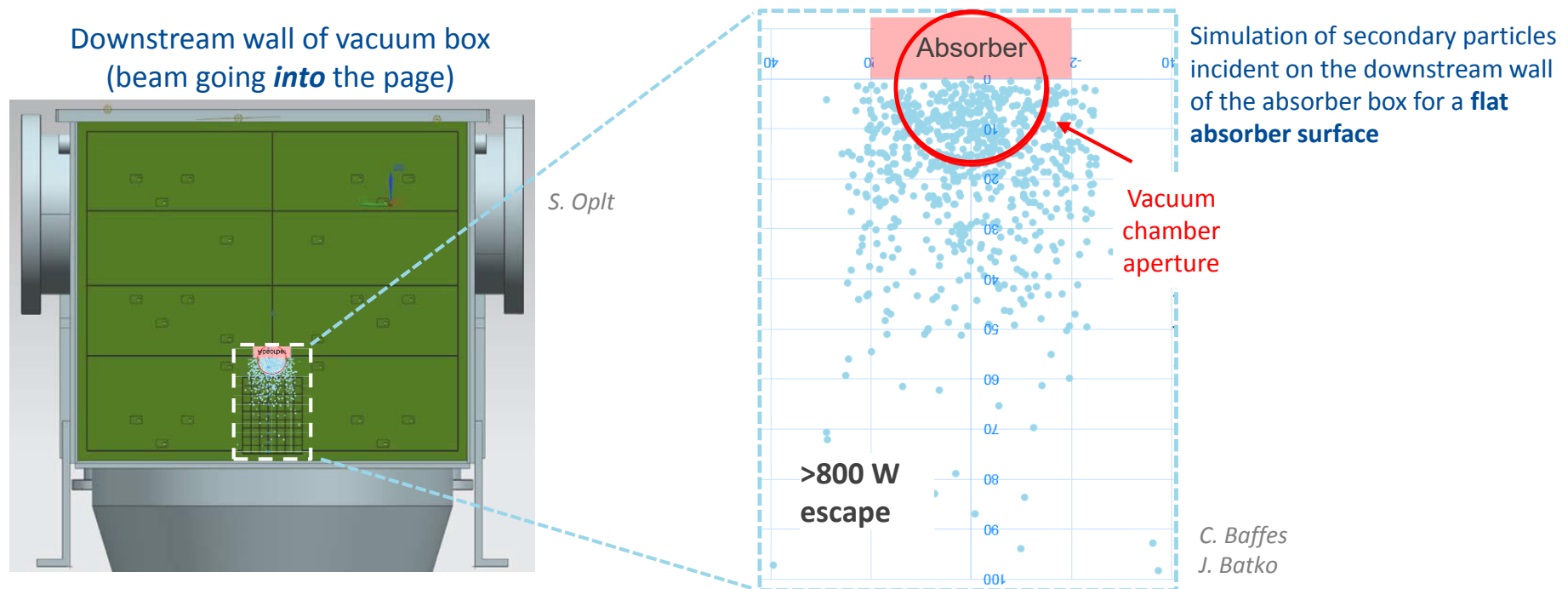
- RFQ consolidation
  - RFQ couplers were replaced with a new design where the ceramic window is sealed with Viton O-rings (instead of brazing)
- Identified solutions for the high-power absorber
- Machine Protection System (MPS)
  - Protection against unexpected and sudden beam loss is critical for going to higher beam power/duty factor
    - Compare current measurements along the beam line
      - Complications:
        - Beam is slightly scraped off on purpose
        - Beam current along the beam line varies by design





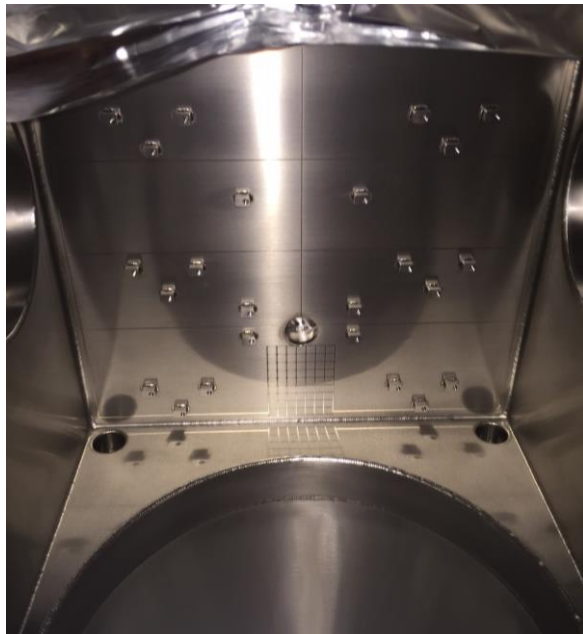
# Absorber: Main challenges

- Three major challenges
  - Dissipate high-power beam  $\Rightarrow$  Shallow angle of incidence
  - Significant amount of beam is reflected (~20%)
    - Limit propagation downstream
    - Manage power going to the walls of the vacuum box



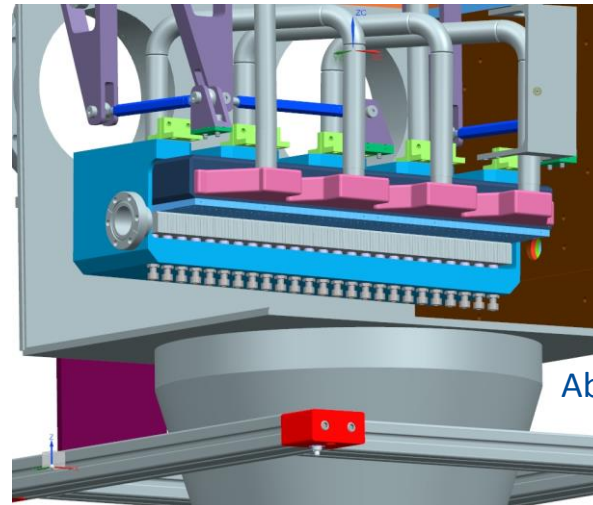
# Absorber fabrication status

- Baffling techniques have been used to limit transmission of secondary particles downstream
- Downstream wall was made with a grid pattern to localize thermal stress and includes multiple layers

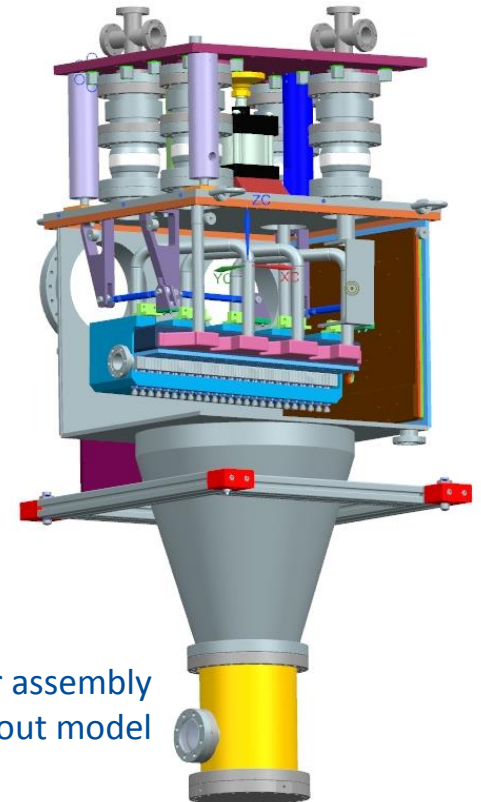


Downstream wall of vacuum box  
(beam going *into* the page)

- Design complete
  - Procurement has started



Absorber assembly  
cutout model



# Summary

- PIP-II Injector Test WFE works as an integrated system and demonstrated key technical aspects of the PIP-II WFE design, in particular for the MEBT:
  - Arbitrary bunch selection pattern
  - Two kickers working in sync
  - Beam to the dump at nominal parameters (5 mA, 0.55 ms, 20 Hz) with low losses and all aperture restrictions (kickers, DPI)
  - Most beam parameters within specs
- Most components have been tested with ~1 kW beam
  - Moving forward with demonstration of ~10 kW+ operation
    - Machine Protection System is key

# Plans

- Prepare for a ~2-year hiatus in the operation of PIP2IT with beam
  - For cryomodule installation and testing (RF)
- Then, proceed with final round of tests of the MEBT
  - Production kickers & absorber
    - Extinction measurements
  - Emphasis on vacuum management and protection of SRF from failures upstream

# Thank you for your attention