DESIGN OF 162-MHZ CW BUNCH-BY-BUNCH CHOPPER AND PROTOTYPE TESTING RESULTS

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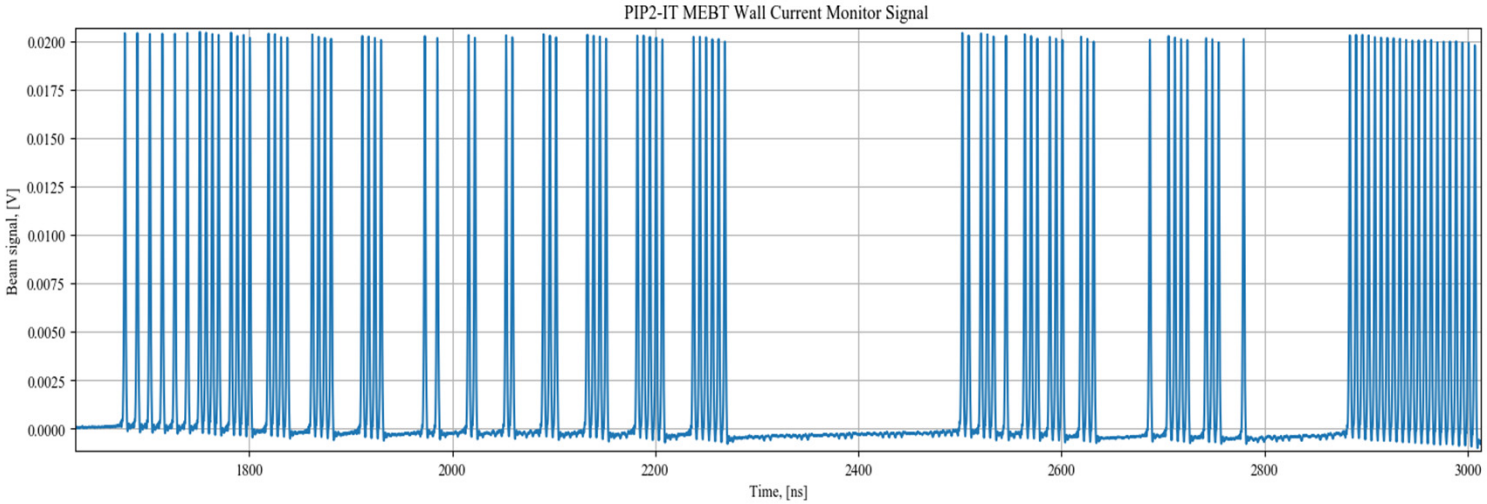
Outline

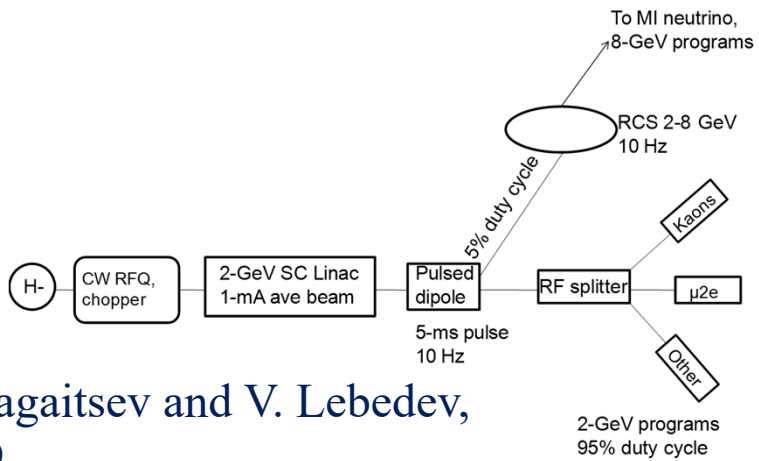
- Introduction
  - Origin and the concept of a bunch-by-bunch chopper
- Prototypes of the components
- Beam tests
- Summary



Randomly generated bunch pattern recorded with RWCM.

Introduction

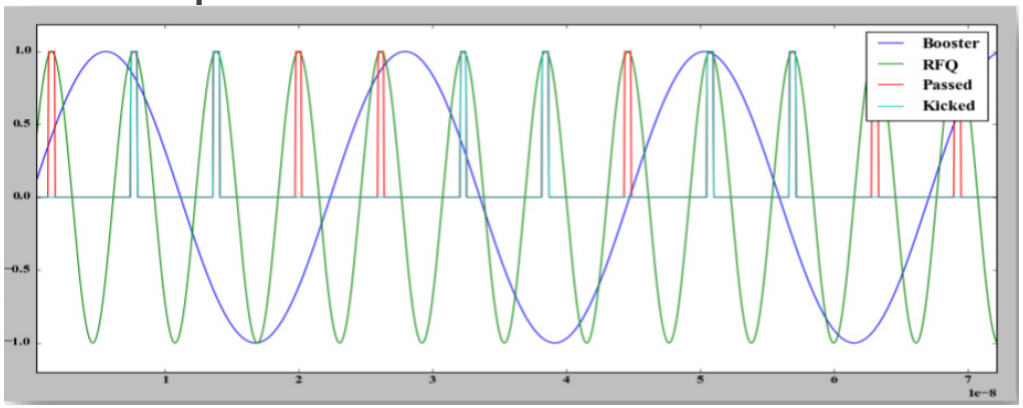
- What should replace 50-years old Fermilab Linac?
  - PIP-II: 800 MeV, 2 mA CW-compatible H^- SRF linac
  - Should be flexible enough to serve for another ~50 years
  - Capability to deliver different bunch structure to different users is a potential big plus
- "Project-X" scheme
  - RF-splitter downstream of the linac, spreading the beam between experiments
  - A fast chopper in the MEBT removes the bunches that do not fit into the sum of the experiments' request
    - Start of chopper R&D



S. Nagaitsev and V. Lebedev, 2009

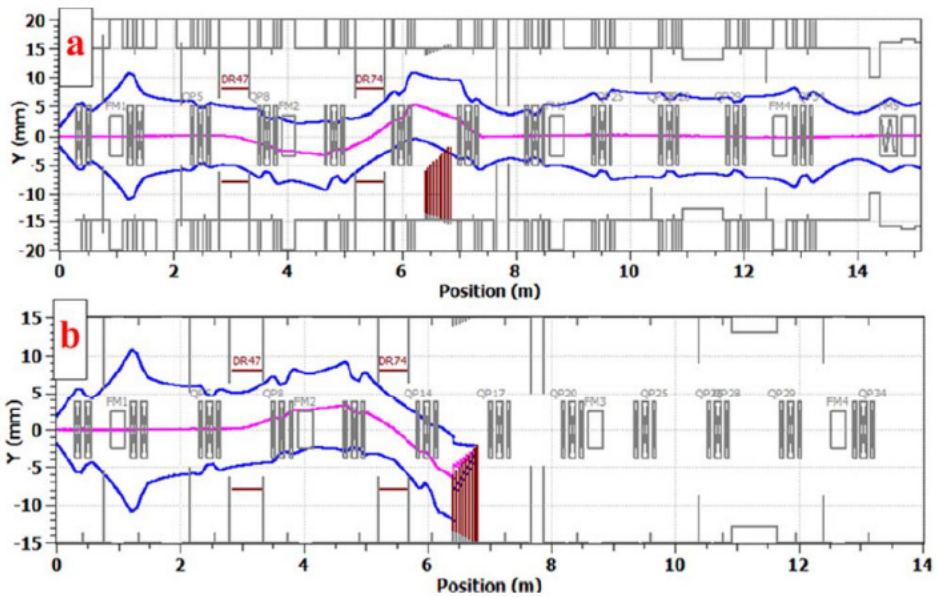
Booster injection scheme

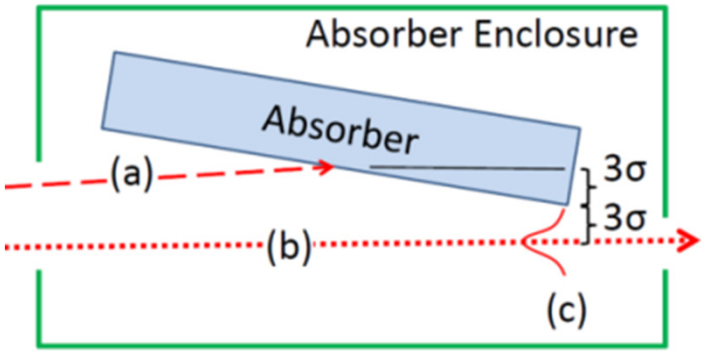
- Presently, PIP-II is concentrated on the initial stage, when a pulsed beam is injected into the Booster
  - Linac's 162.5 MHz x N and Booster's 44.7 MHz are not harmonically related
  - Optimum bucket-to-bucket injection requires removal of bunches that would come to edges of separatrix
    - Also, create a gap for the extraction kicker
  - Need a bunch-by-bunch chopper capable of creating an aperiodic bunch structure from a CW train



Chopper concept

- Two travelling – wave kickers deflecting in sync
  - 180º phase advance between kickers
  - 90º between last kicker and absorber
- $6\sigma_y$ separation at the absorber





3σ vertical envelopes in PIP-II MEBT

Some of chopper elements specifications

- Mode: initially CW; presently reduced to 0.55 ms x 20 Hz

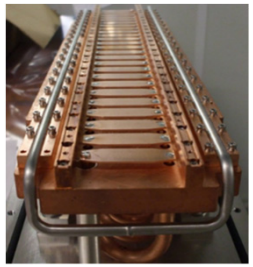
Parameter	Value	Units
Kicker deflection angle*	7.4	mrad
Gap between kicker plates	16	mm
Gap in the kicker protection electrode**	13	mm
Kicker plate length	500	mm
Maximum power from beam loss, CW	40	W
Maximum accidental beam loss	20	J
Absorber surface length	500	mm
Maximum power at absorber, CW	21	kW

*Defined as the angle between passed and removed trajectories created by one kicker
** Kicker protection electrodes are installed on both sides

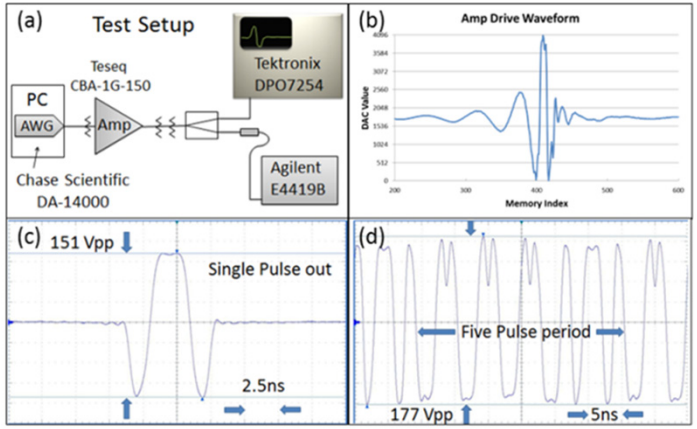
- Two kicker versions were developed in parallel
  - Named according to their impedance, 50 Ohm and 200 Ohm

50 Ohm kicker design

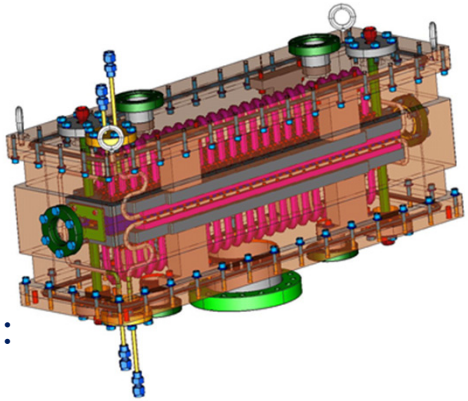
- Travelling wave structure:
  - with 25 plates connected in vacuum by coaxial cables with the length determined by necessary delays
  - Large bandwidth (>1 GHz)
  - Thermal tests at x1.5 of nominal power dissipation



- Envisioned driver: two 0.05–1 GHz, 1 kW linear amplifiers



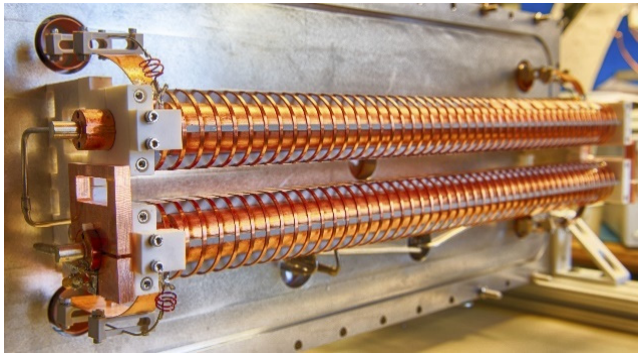
  - Plate voltage changes from +250 V to -250 V
  - AC-coupled



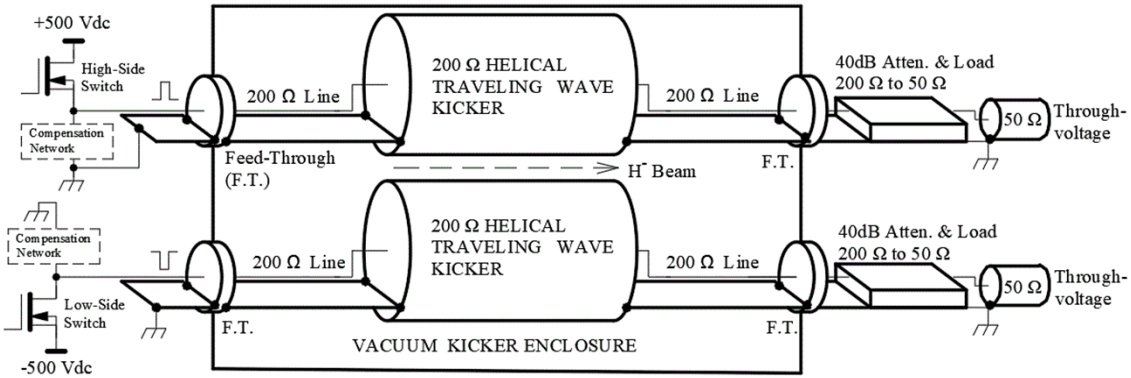
IPAC'12, WEPPD078. Proof-of-principle tests with 150W PA (2012):
- Bipolar pulse with zero integral over 6.15 ns period
- Effects of PA's non-linearity of the PA are corrected by pre-distorting the driving signal

200 Ohm kicker design

- Travelling wave structure:
  - two helices each with 47 welded plates
  - Bandwidth up to 500 MHz
  - Thermal tests: 40 W to emulate heating by the beam
- Driver: a fast switch developed at Fermilab
  - DC – coupled; 4 ns from 0 to 500 V
  - Max switching rate 81.25 MHz

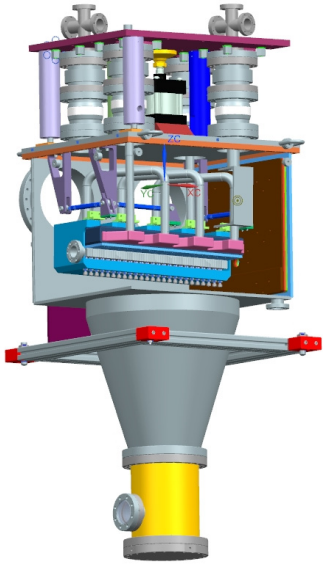


Fully assembled 200 Ohm kicker's two-helix structure.

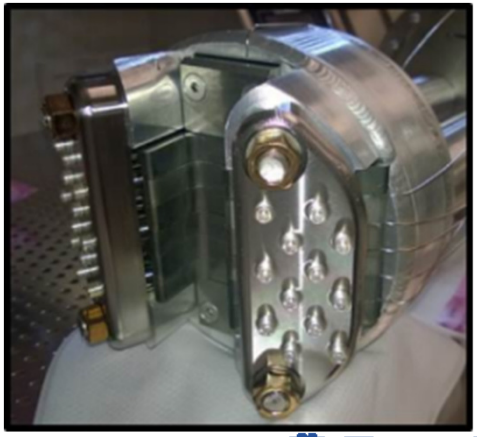


- Presently, average switching rate is 500 kHz
  - Determined by transistors' cooling

Absorber

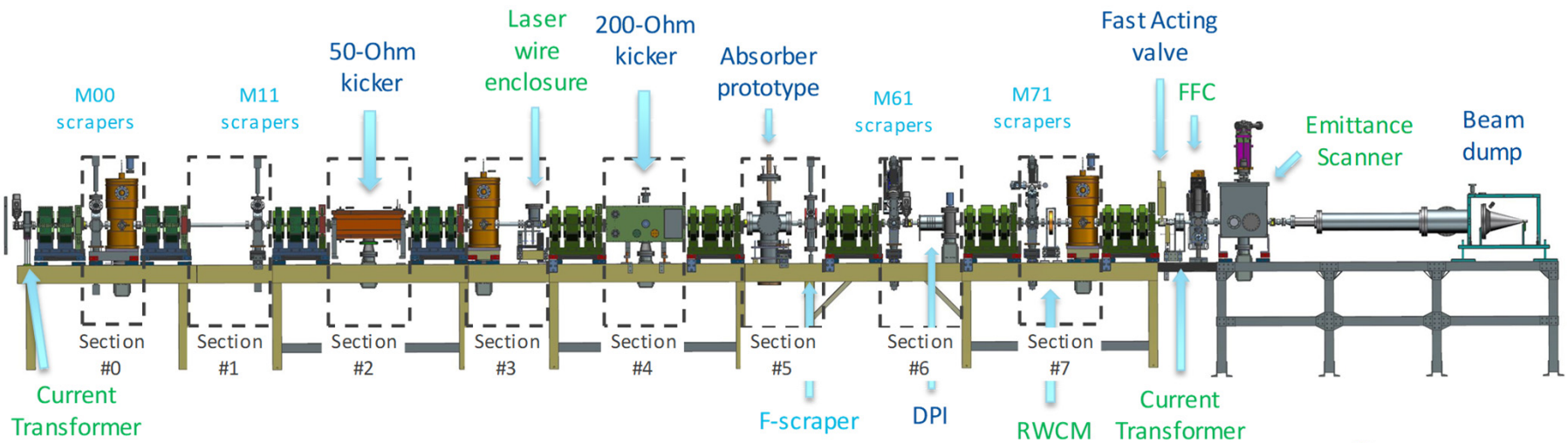


- Features of the concept
  - grazing angle of 29 mrad to decrease the surface power density to 17 W/mm^2
  - longitudinal segmentation to relieve thermally-induced stresses
  - absorbing surface: separate molybdenum alloy TZM bricks
- ¼-length prototype was tested with an electron beam
  - At power density up to 20 W/mm^2
  - More than 10^4 of “30s on- 30s off” cycles
- The prototype is installed at PIP2IT



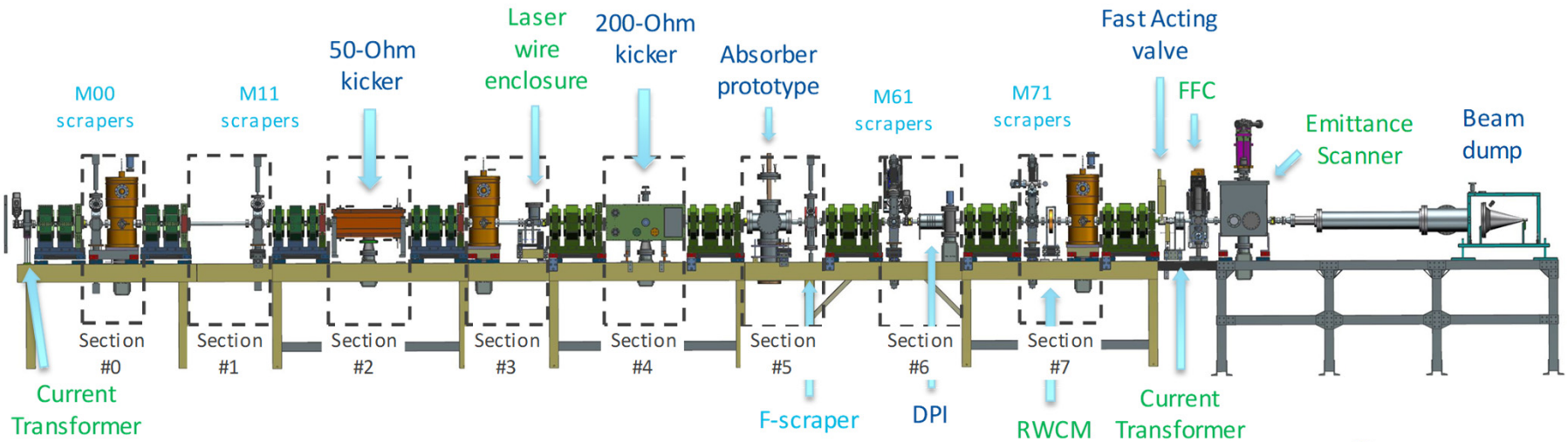
PIP2IT MEBT

- 2 doublets + 7 triplets; 3 bunching cavities (see MOP1WB03)
  - BPM in each doublet/triplet and pair of dipole correctors after
- Prototypes of two kickers and absorber
- Instrumentation:
  - 2 current transformers (ACCT) and dump; Allison scanner; Fast Faraday Cup (FFC); Resistive Wall Current Monitor (RWCM)



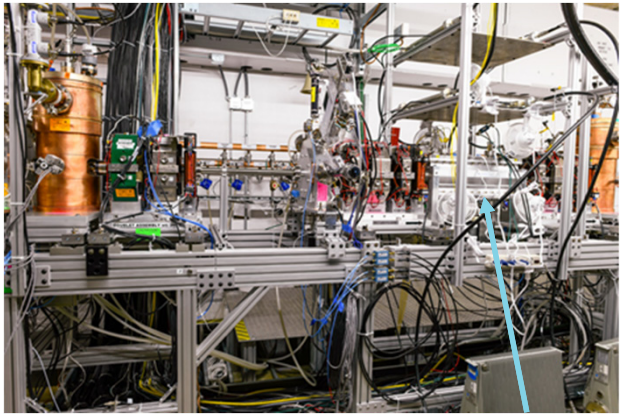
Tuning

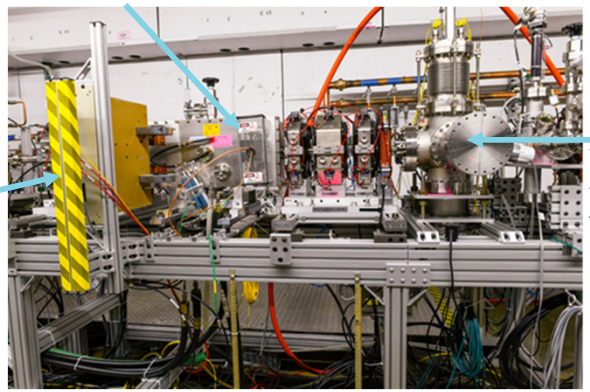
- All tuning is at 10μs x 20Hz x 5mA; separate high-power runs
- 4 sets of 4 scrapers each + 2-plates “F”-scraper
  - In part, used for scraping and beam size measurements
- “Flat beam” for kickers tuning: heavy scraping with 4 vertical upstream scrapers
- Most of kickers tests were made before installation of DPI
  - DPI= Differential Pumping Insert: pipe 10 mm ID x 200 mm L



Tests

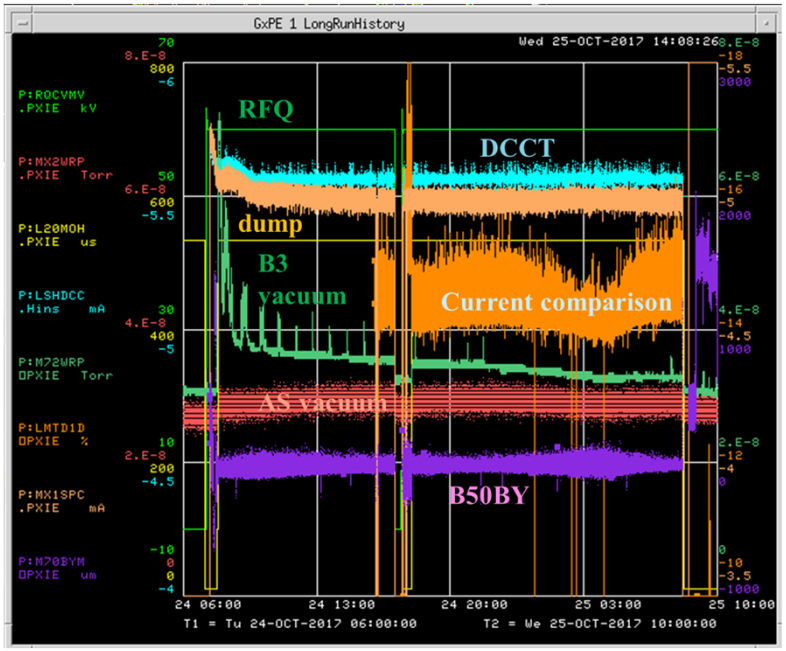
- Kickers: measured the deflection for each version
  - Because of budgetary constrains, the wide-band amplifiers were not purchased, and 50 Ohm kicker was tested with PAs operating at 81.25 MHz
- Additional tests with 200 Ohm kicker:
  - demonstration of bunch-by-bunch selection; sensitivity to H^- energy; perturbation of passing bunches
  - Also, two kickers working in sync
- Absorber was tested at 0.7 kW with the kickers off





Kickers survival test

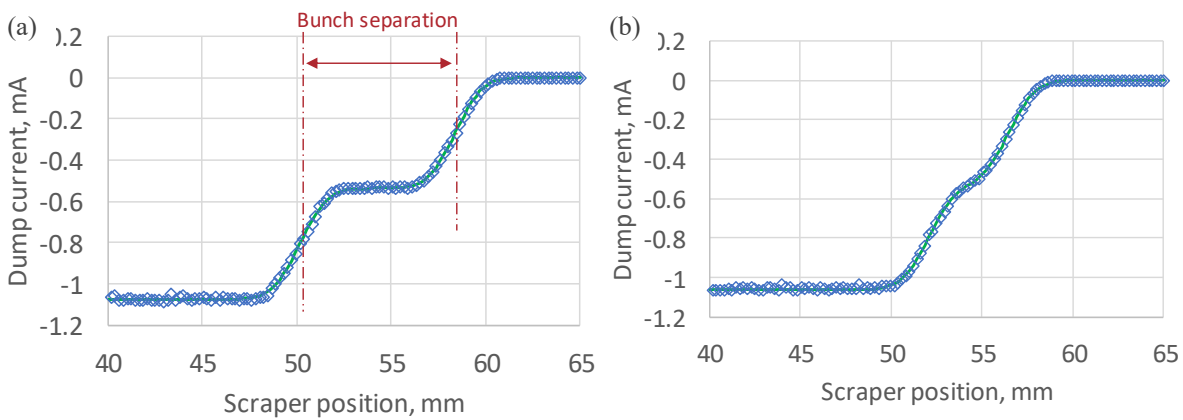
- Passed beam through non-pulsing kickers with the average power up to 5 kW (50% duty factor)
- “Booster injection” test – 24 hours
  - 200 Ohm kicker is pulsing with “Booster pattern”, 0.55 ms
  - 5 mA × 0.55 ms × 2.1 MeV × 20 Hz
- Machine Protection System protected the kickers effectively by monitoring of the kicker protection electrodes’ currents .



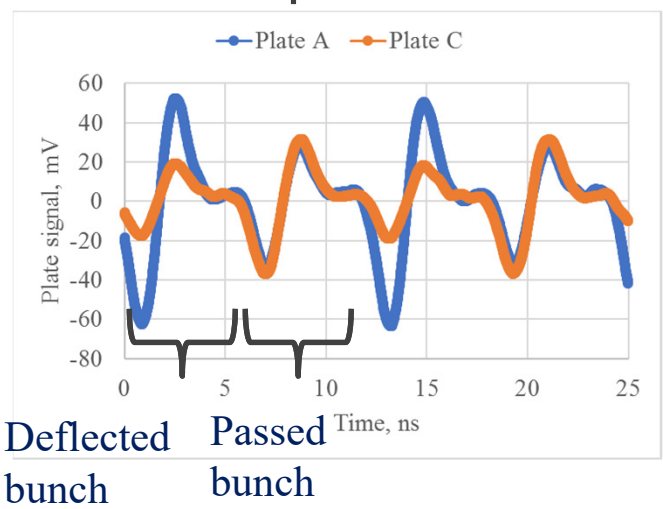
24-hrs run. 0.5 mA/div for currents; 2%/div for current comparison; 2.E-8 Torr/div for vacuum; 1 mm/div for BPM.

Deflection measurements procedure

- One kicker at a time, with the flat beam; mainly without DPI
  - with 81.25 MHz, deflecting every other bunch
  - Phasing by looking for the maximum separation
    - either with a BPM + scope or with a scraper
  - Measure the max separation with the F- scraper
  - Translate separation into deflection angle with the optical model



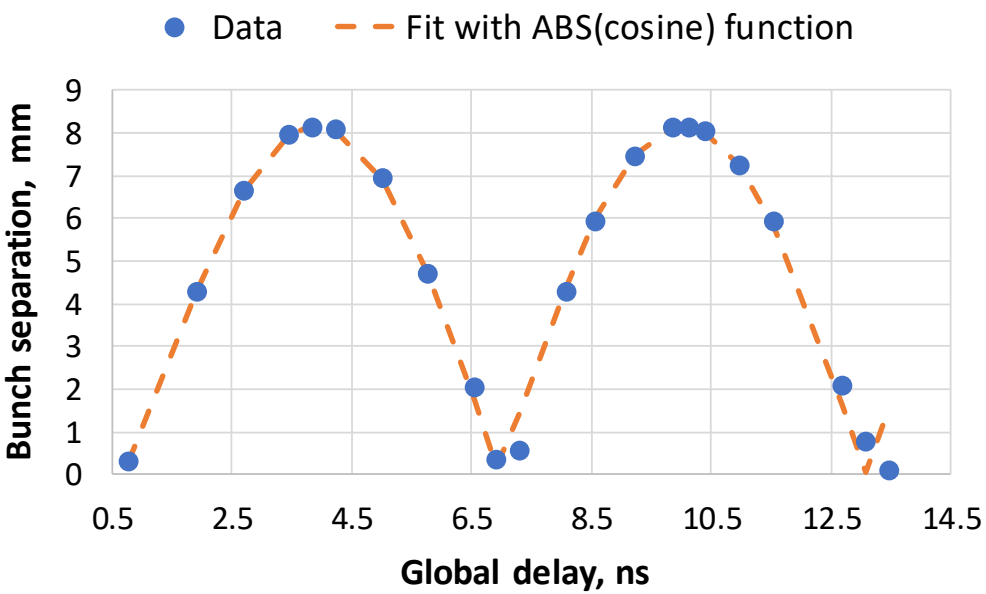
F-scraper profiles for optimum delay (a) and shifted by 1.73 ns (b). 50 Ohm kicker. The fitted rms beam size is 1.15 mm, and the bunch separation is 8.2 mm (a) and 4.4 mm (b).



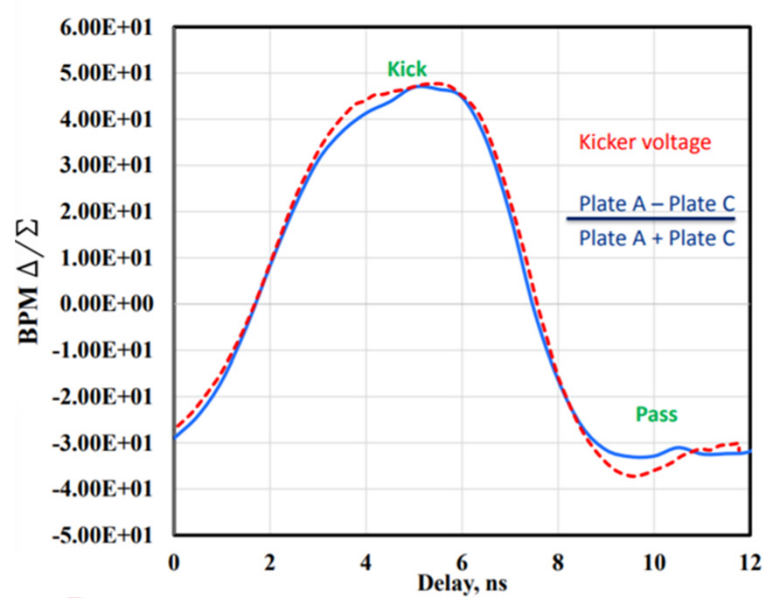
BPM signal.

Kicker phasing examples

- The phasing curve also contains information about the voltage pulse shape



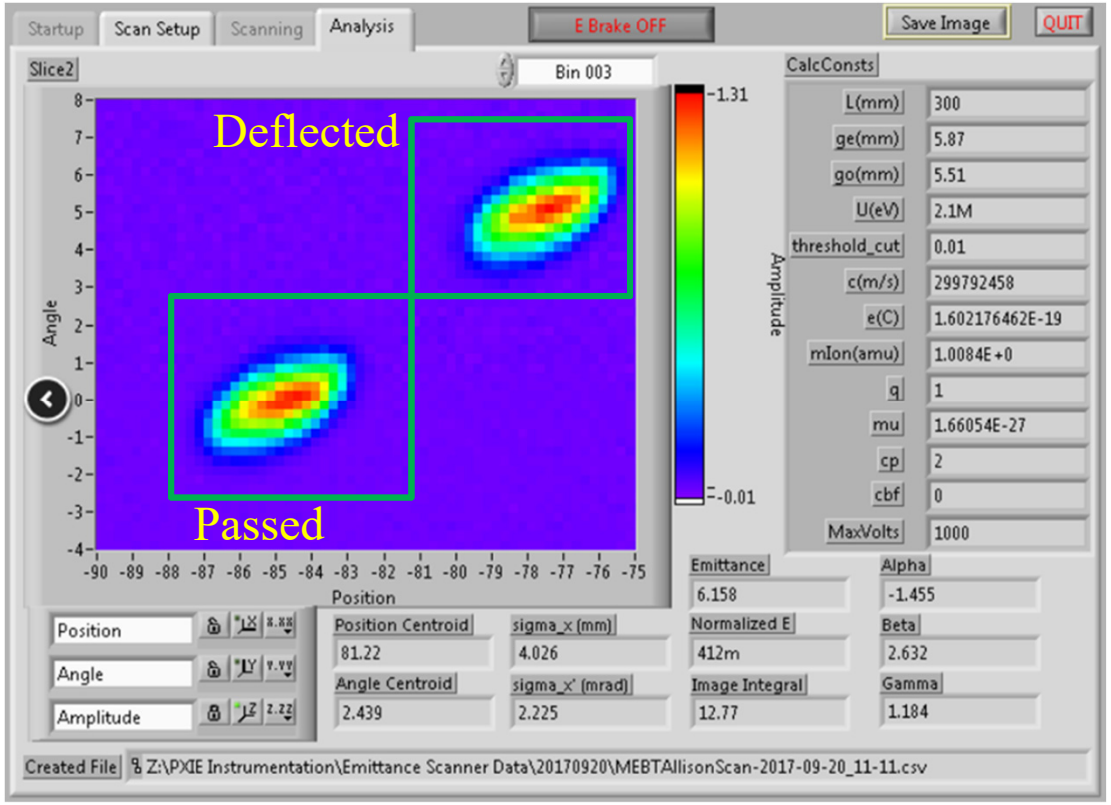
Phasing of the 50 Ohm kickers with scraper scans.



BPM signal for a given bunch vs the 200 Ohm kicker delay.

Deflection

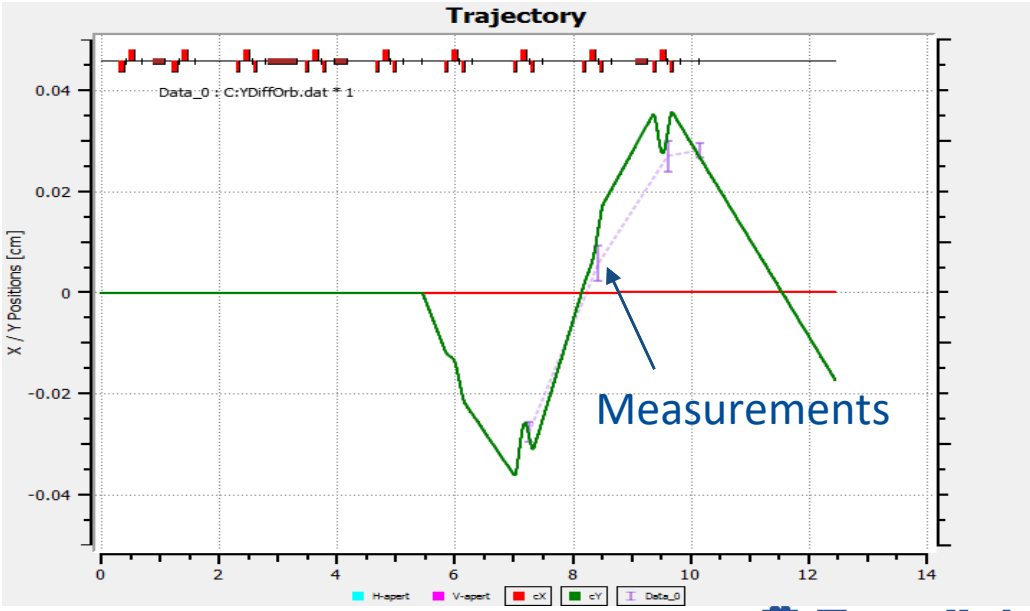
- Deflection was found at specification within 10%
  - Spec: 7.4 mrad per plate voltage change of 500 V
- Clear separation for the flat beam



Phase portrait with 200 Ohm kicker pulsing at 81.25 MHz. Scraping a 5.1 mA beam to the flat beam with 1.5 mA.

Perturbation of passing bunches (200 Ohm kicker)

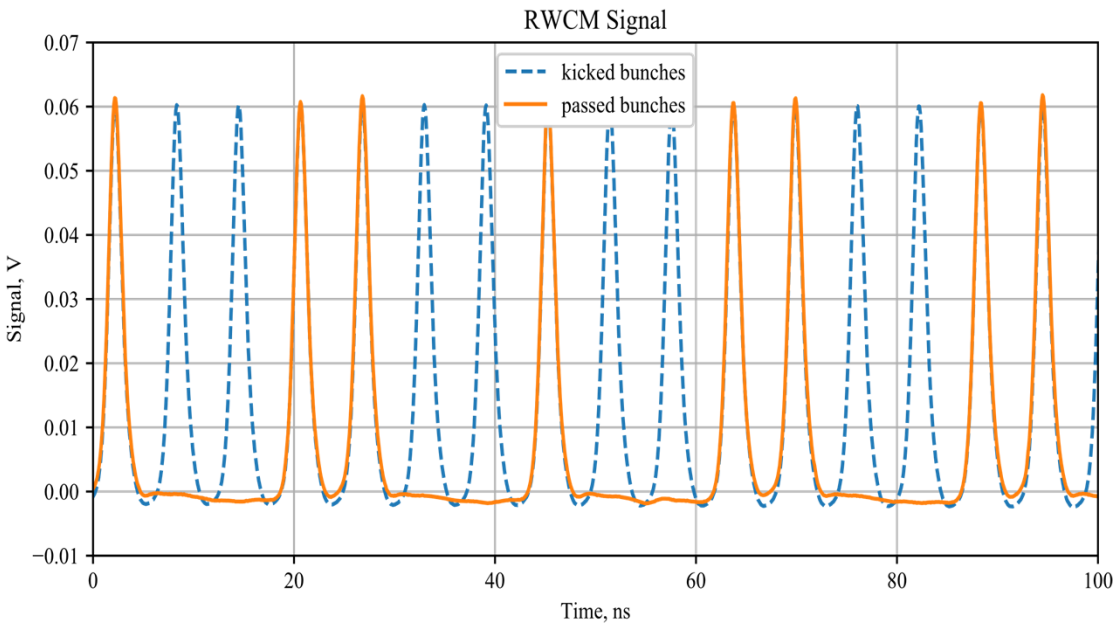
- The deflection of passing bunches results in an increase of effective emittance since it depends on the kicking pattern
  - Was measured with the flat beam by removing the deflected bunches and tracing the passed bunches with BPMs
- 0.3 mrad for 81.25 MHz pattern (the worst scenario)
  - Vs 7.7 mrad for deflected bunches
  - For the un-scraped beam, would give 2% emittance increase



Comparison of trajectory of passing bunches with OptiM. 81.25 MHz; flat beam.

Arbitrary waveforms

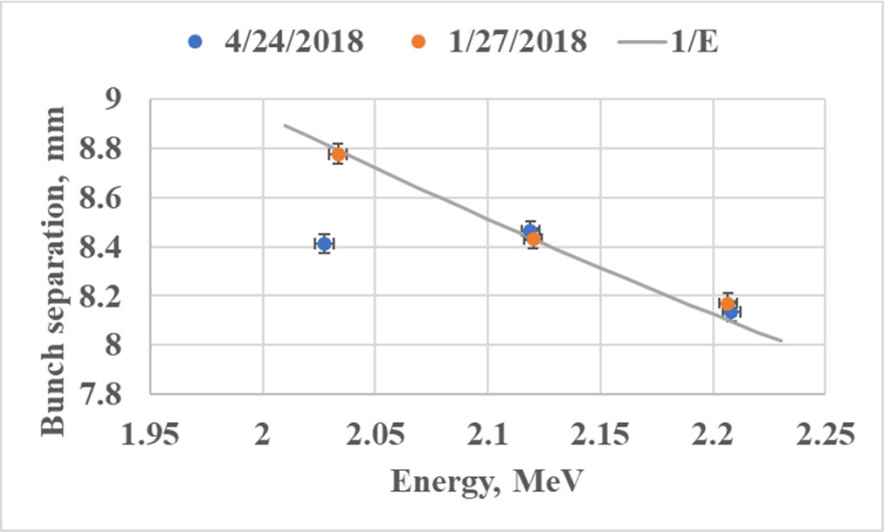
- 200 Ohm kicker can produce arbitrary bunch pattern
  - In combination with the flat beam and scraping of the deflected bunches
  - Examples: 81.25 MHz; “Booster injection pattern; “remove 10-pass 10”; randomly chosen sequence

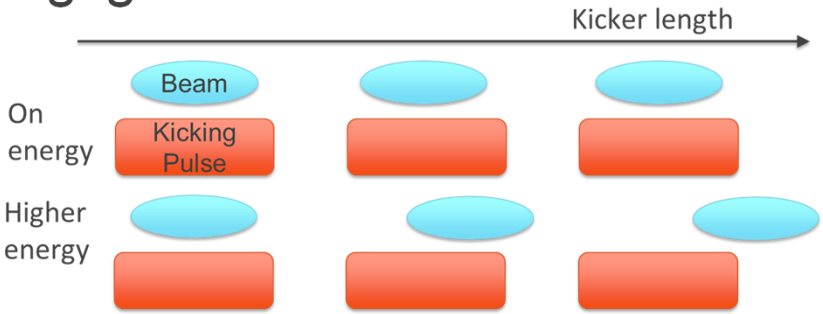


Part of the RWCM signal recording the 0.55 ms Booster injection sequence (orange), superimposed over the signal when the kicker is off (blue). 1.1 mA flat beam.

Verification of the phase velocity matching

- Compared the deflection at different beam energies
  - The energy was changed by ±86 keV using the bunching cavity upstream
  - The dominant effect is 1/E increase of the deflection for lower energy => velocity mismatch is negligible

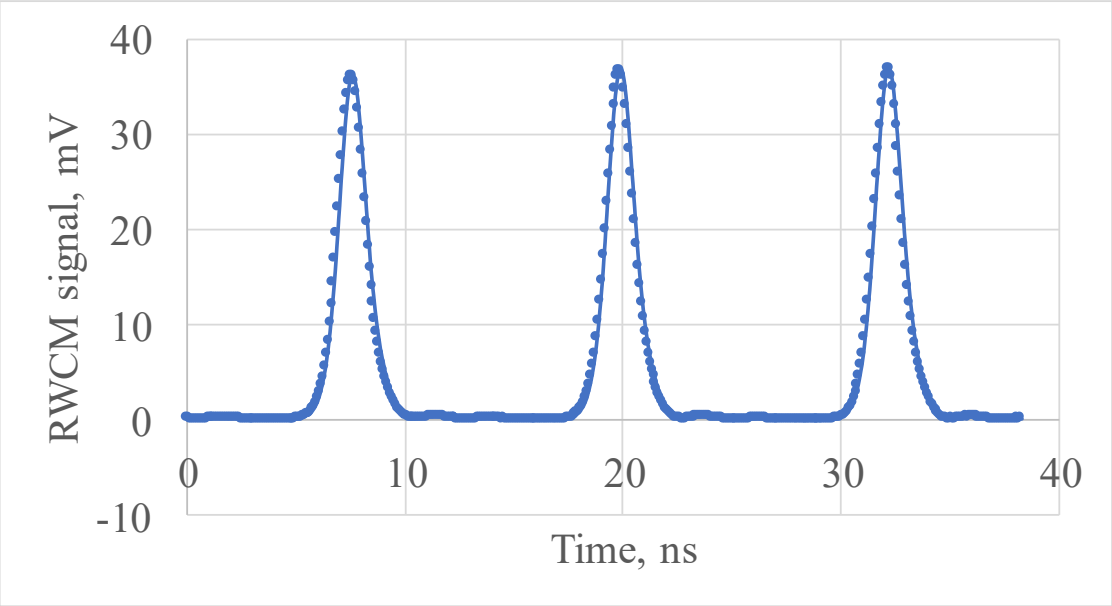




Bunch separation measured with the F-scraper vs beam energy. Two sets are measured at different voltage of the kicker plate power supply, with separation scaled to 500 V. The solid curve is 1/E dependence drawn through the point measured at the nominal energy.

Two kickers working in sync

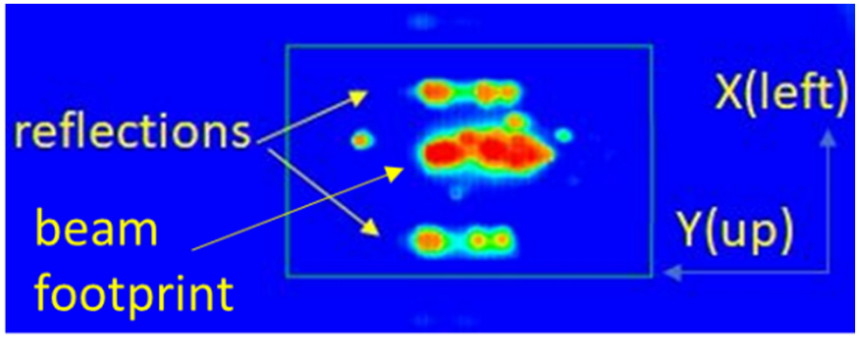
- Bunch separation with nominal 5 mA beam
  - In 81.25 MHz pattern, i.e. half of bunches deflected to F-scraper
  - “standard” scraping” at ~2% level with scrapers upstream of the chopper
  - Analysis with Resistive Wall Current Monitor: extinction is < 2%



RWCM signal of an initially 5 mA beam with two kickers operating synchronously at 81.25 MHz. .

Absorber prototype testing

- Test: irradiated for 36 hours with 98% beam up-time with 1.75 ms x 20 Hz x 10 mA x 2.1 MeV = 735 W (with the kickers off)
  - No damage or deterioration was observed.
- Tuning of the beam position at the absorber surface
  - Was expected and initially made using thermocouples squeezed between the bricks forming the absorbing surface
  - Surprise: a bright light clearly indicated the beam position
    - Observed with a camera in the visible spectrum
    - Surface was not hot enough for thermal radiation
    - OTR light should be too faint to be observed
    - Can be related to poor vacuum ($6 \cdot 10^{-6}$ Torr)?



Summary and plans

- Prototypes of two kicker versions and of the absorber were successfully tested with a 2.1 MeV H^- beam at PIP2IT.
  - The 200 Ohm kicker version demonstrated all capabilities required for PIP-II operation with bucket-to-bucket injection to Booster.
- Plans
  - A full–size absorber is being manufactured.
  - Production of two kickers and their drivers (200 Ohm version) is expected in 2019.
  - When PIP2IT operation resumes after installation of the cryomodules, the chopping system will demonstrate the ability to deliver a beam with nominal parameters chopped according to the Booster injection requirements.