EXPERIMENTAL STUDY OF BEAM DYNAMICS IN THE PIP-II MEBT PROTOTYPE

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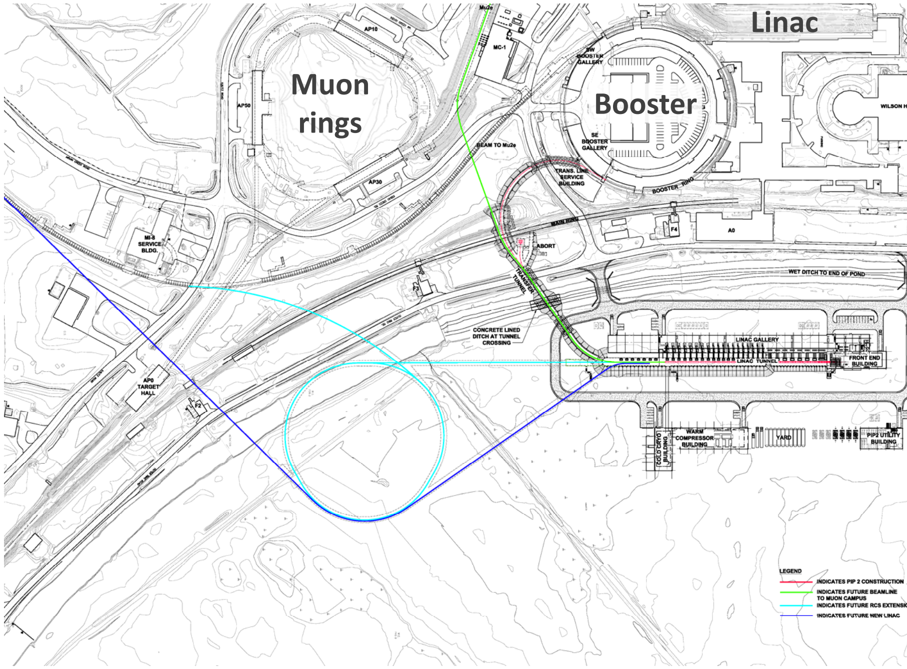
Outline

- Introduction: PIP-II and PIP2IT
- PIP2IT MEBT
- Transverse optics
  - Differential trajectories and envelope
  - Tuning; position jitter; tails
- Longitudinal optics
  - Cavities phasing and bunch length measurements
  - Transverse – longitudinal coupling
- Summary

Proton Improvement Plan – II (PIP-II)

- Upgrades for Fermilab Accelerator Complex
  - 800 MeV, 2 mA CW-compatible H^- Superconducting Linac and beam line to Booster. Goal is to deliver the beam in 2026.
    - Present warm Linac: 400 MeV, 30 mA, 40μs x 15 Hz
  - Upgrades to Booster, MI, and RR
  - The immediate goal is to provide >1 MW to neutrino experiments
- Platform for future upgrades
  - Higher MI power; multiple experiments



Layout of PIP-II and its possible future upgrades

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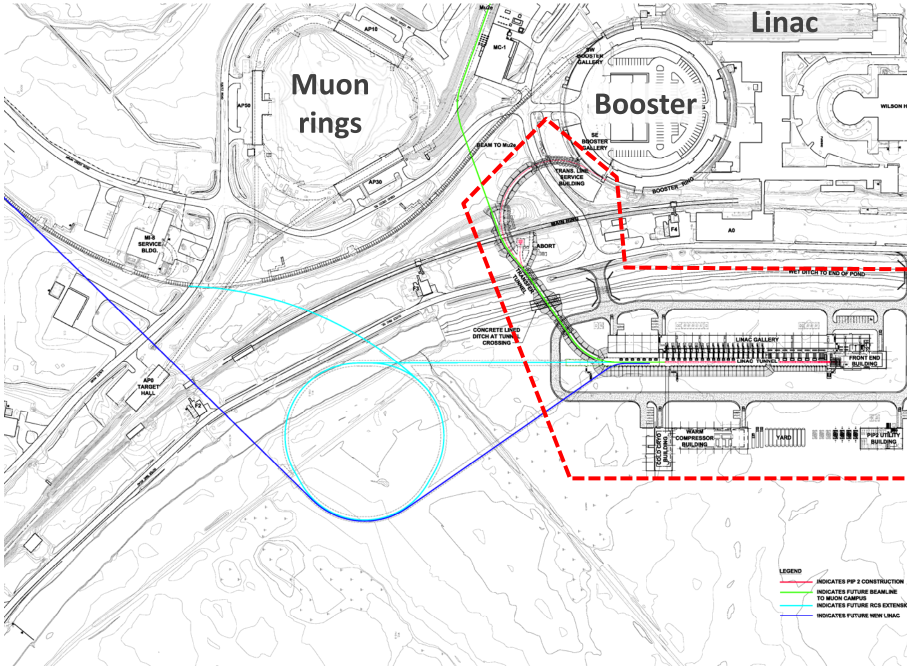

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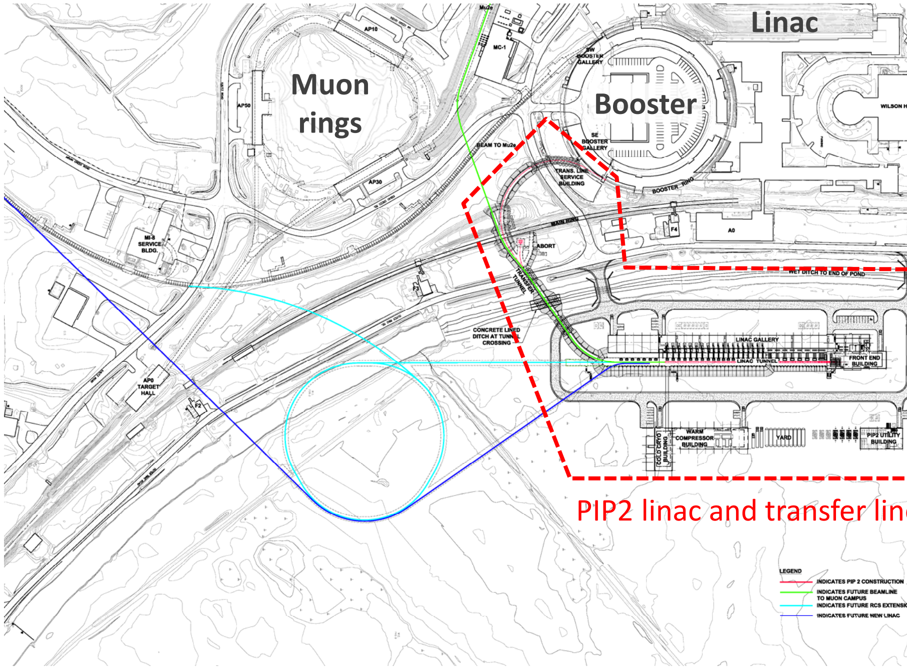
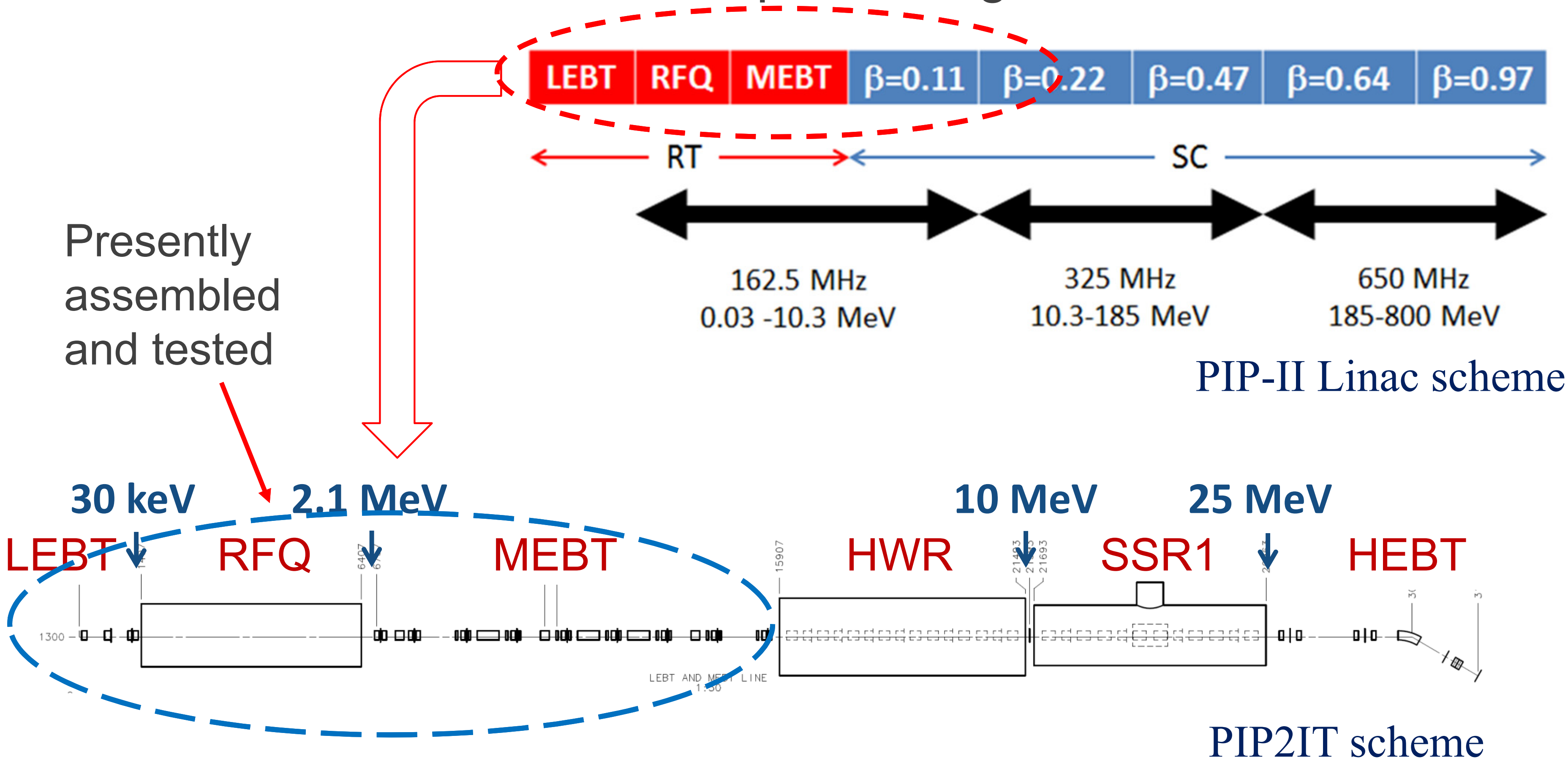


Layout of PIP-II and its possible future upgrades

PIP-II Injector Test (PIP2IT)

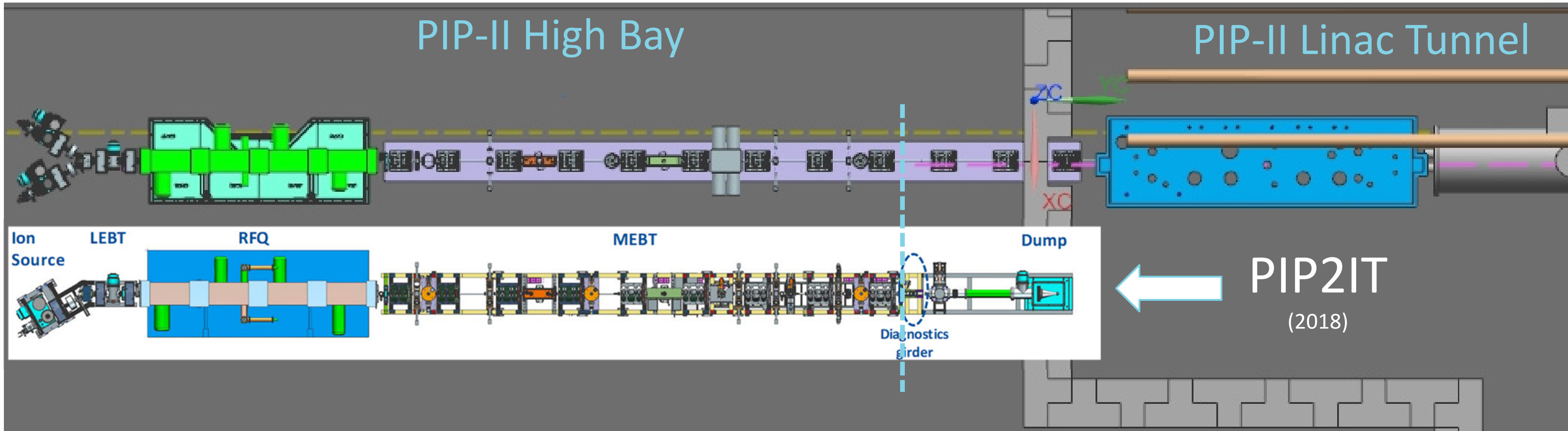
- PIP2IT: a test accelerator representing the PIP-II front end



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

Prototyping PIP-II warm front end at PIP2IT

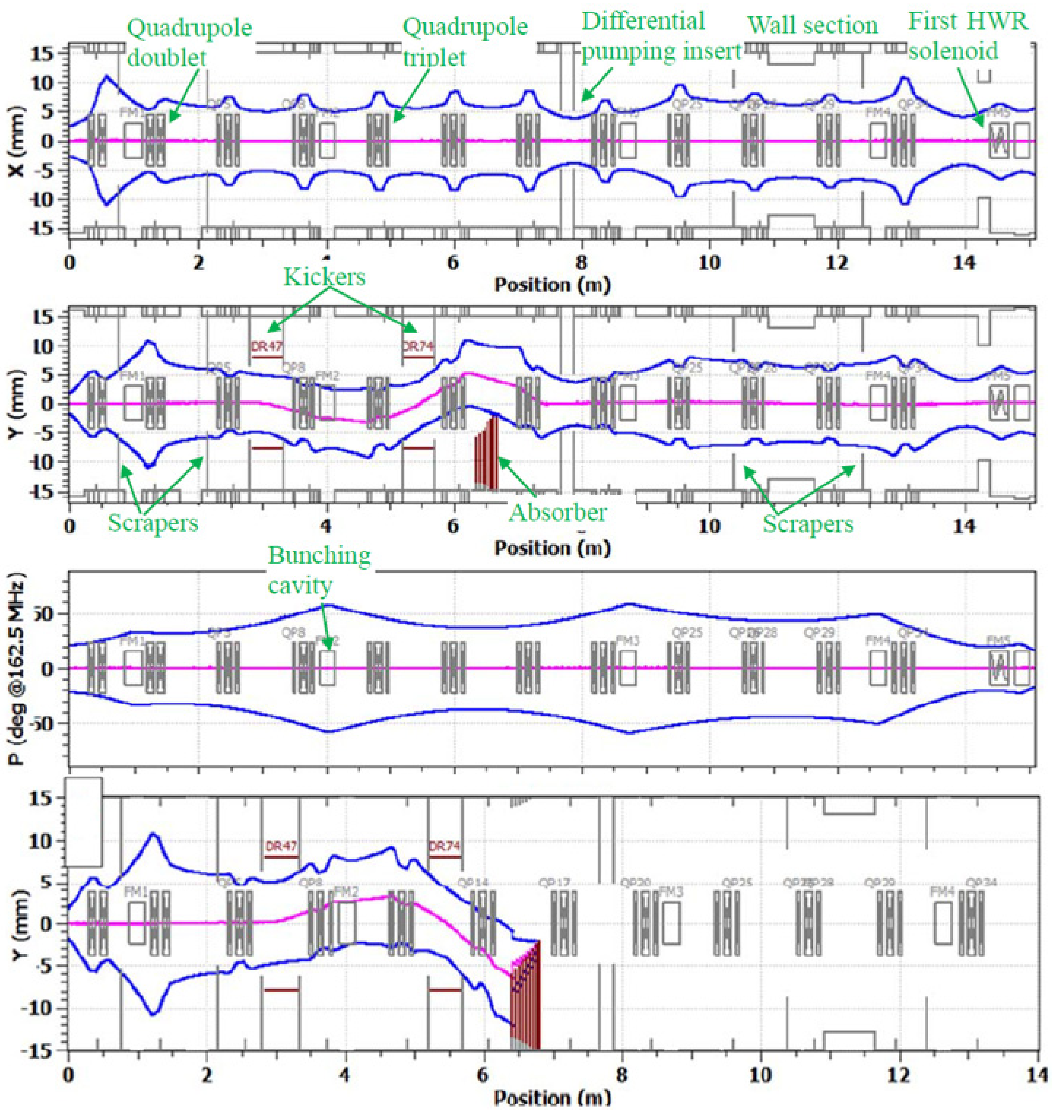
- PIP2IT warm front end is close to PIP-II's one
- Deviations:
  - one ion source instead of two
  - shorter MEBT; PIP-II has 3 more triplets and 1 bunching cavity
    - To accommodate a radiation wall and a better vacuum protection
- All specific features are represented



Main MEBT design parameters

- H^- energy - 2.1 MeV
- Beam current (average over µs scale)
  - Entrance (nominal/max) - 5/10 mA
  - Exit – 2 mA
- Output emittance X/Y/Z, µm rms n – 0.23/ 0.23/ 0.31
- Bunch structure
  - Entrance – 162.5 MHz CW
  - Exit – arbitrary pattern; unnecessary bunches are removed by the MEBT chopping system
- Macro-pulse
  - From 10 µs x 20 Hz to CW
    - Recent focus is on “Booster Injection” parameters, 0.55 ms x 20Hz

PIP-II MEBT optics

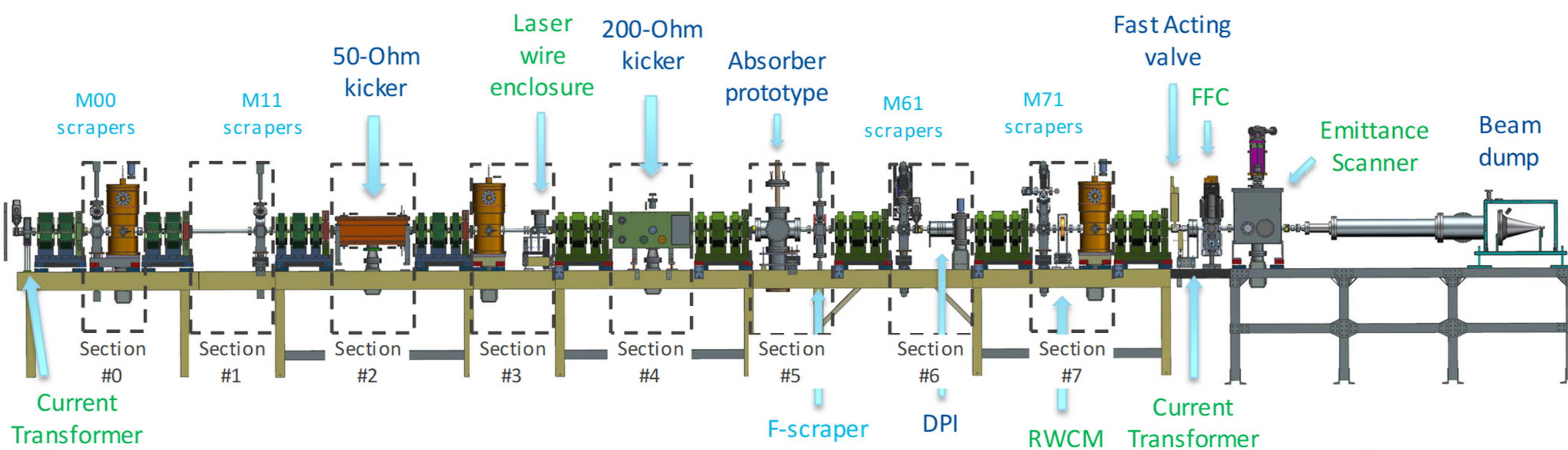


- Transverse focusing:
  - Two doublets and 10 triplets
- Longitudinal:
  - 4 bunching cavities
- Trajectories of passing and removed bunches are separated by two fast kickers

TraceWin simulation of 3σ X, Y, and Z envelopes. The lower plot is the Y envelope of removed bunches.

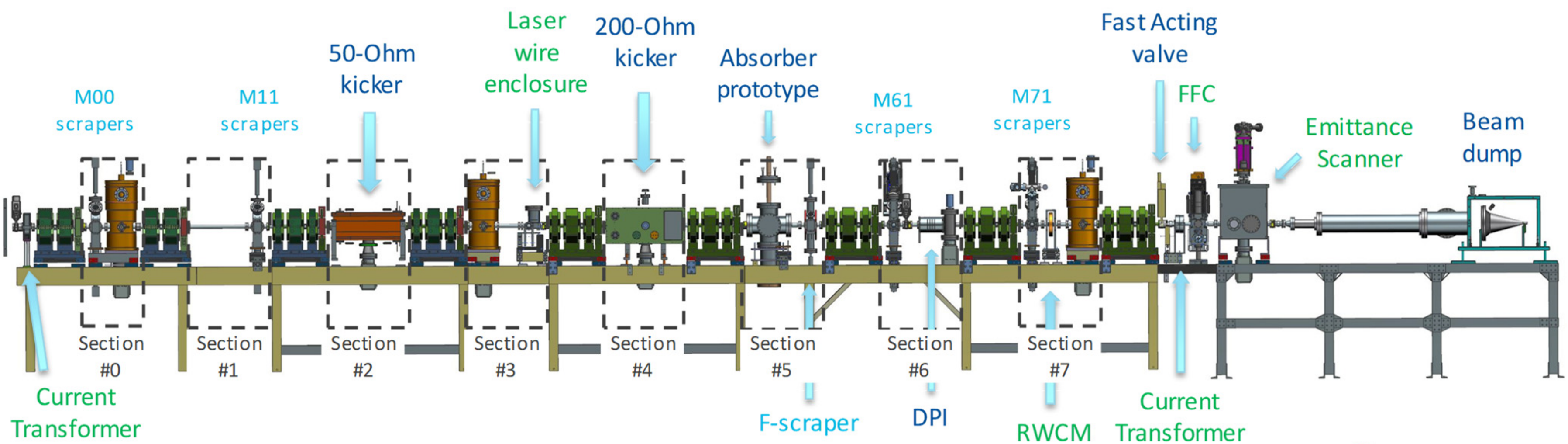
PIP2IT MEBT as presently assembled

- 2 doublets + 7 triplets; 3 bunching cavities
  - BPM in each doublet/triplet and pair of dipole correctors after
- Prototypes of two kickers and absorber (see THP1WC03)
- Differential Pumping Insert (DPI): 10 mm ID x 200 mm L
- 4 sets of 4 scrapers each + 2-plates “F”-scraper
  - The main tool for beam size measurements



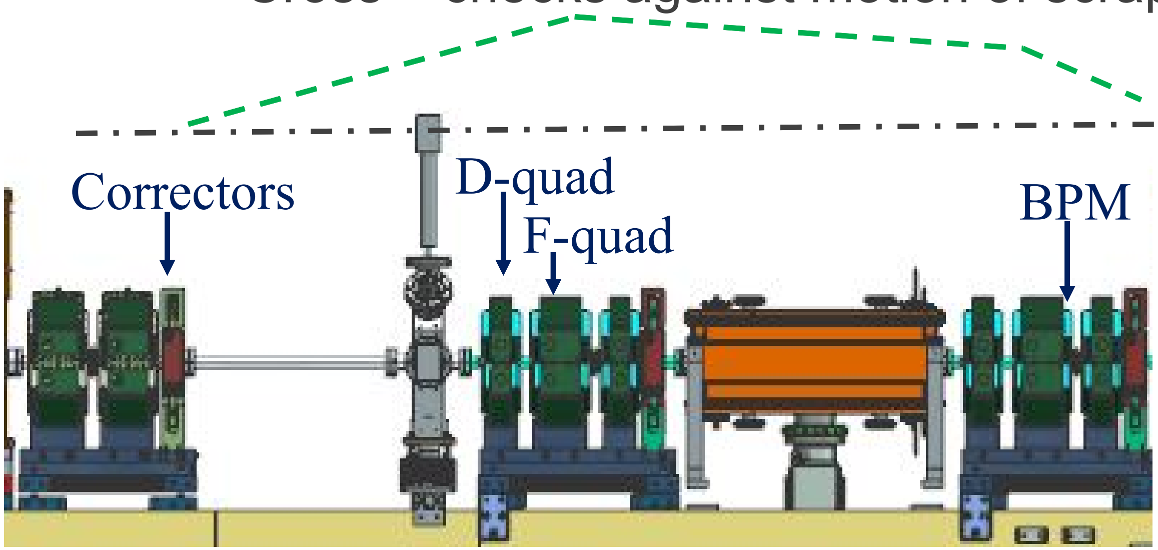
Additional instrumentation

- Beam current: 2 current transformers (ACCT) and dump
- Allison scanner; Fast Faraday Cup (FFC); Resistive Wall Current Monitor (RWCM)
- Most of measurements are performed at 10μs x 20Hz x 5mA
  - The “partially un-neutralized” LEBT scheme makes parameters nearly constant through the pulse => short-pulse measurements are representative



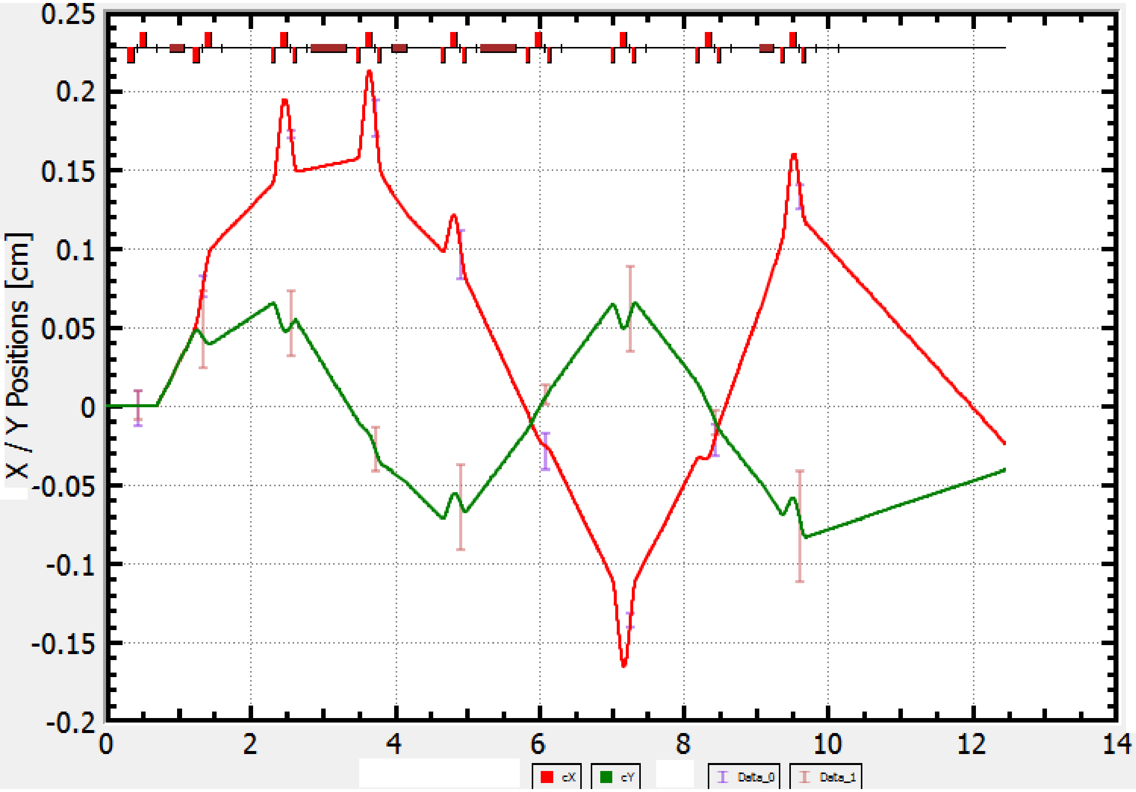
Transverse focusing calibration: differential trajectories

- The main tool to establish calibrations of magnetic elements
  - Change a dipole corrector; take the difference between BPMs readings before and after; compare with predictions of the optical model in the OptiM program; adjust calibrations
  - Repeat for all correctors
  - Rely on correctly measured distances and BPM calibrations
    - Cross – checks against motion of scrapers



Sections #1 and 2

Final fit

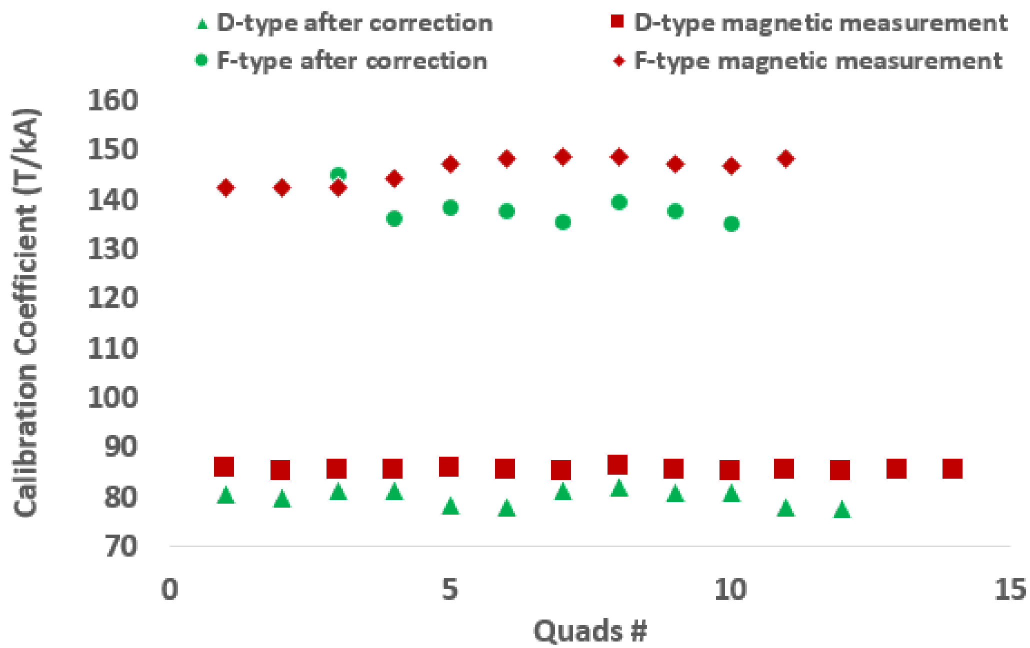


Differential trajectories due to the change of the first correctors by 0.4A. The measured data points are averages over 50 readings. The error bars are the rms scatter in these readings.

- After several iterations, the data for all trajectories fit reasonably the model.
  - Typical agreement is between rms and rms/$\sqrt{N}$

Quadrupole calibrations

- All magnets were measured at BARC, where they had been manufactured. Some of magnets were measured also at Fermilab with agreement < 1%
- Quadrupole coefficients found in beam measurements were almost always lower by 5 – 10% than in magnetic measurements
  - No explanation is found yet, but in further simulations, the beam – based calibrations are used



Comparison of calibrations found in magnetic and beam measurements

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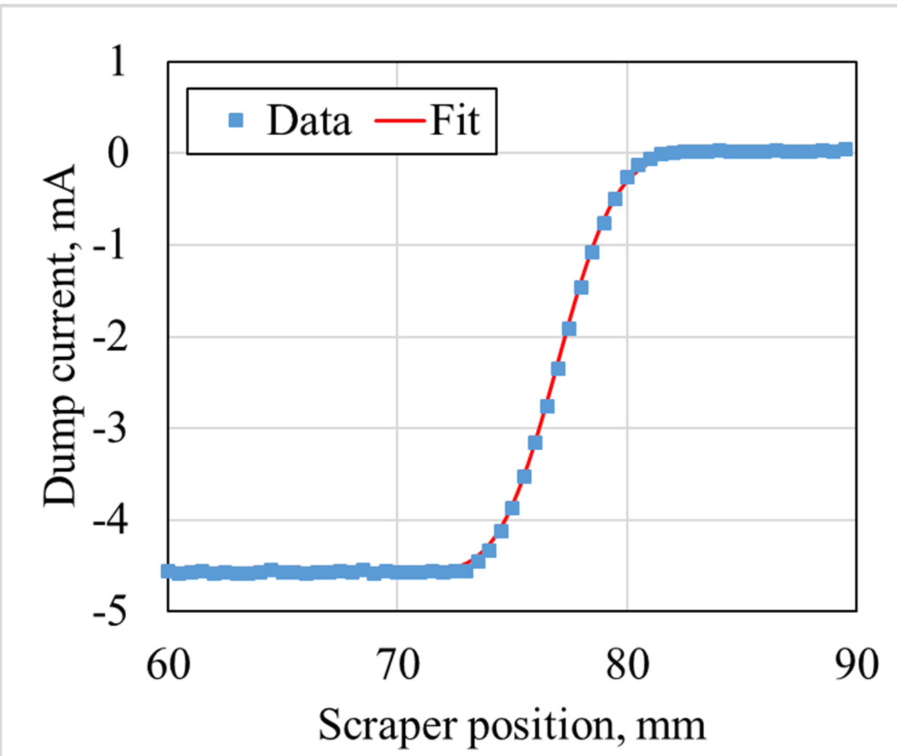
Beam size measurements

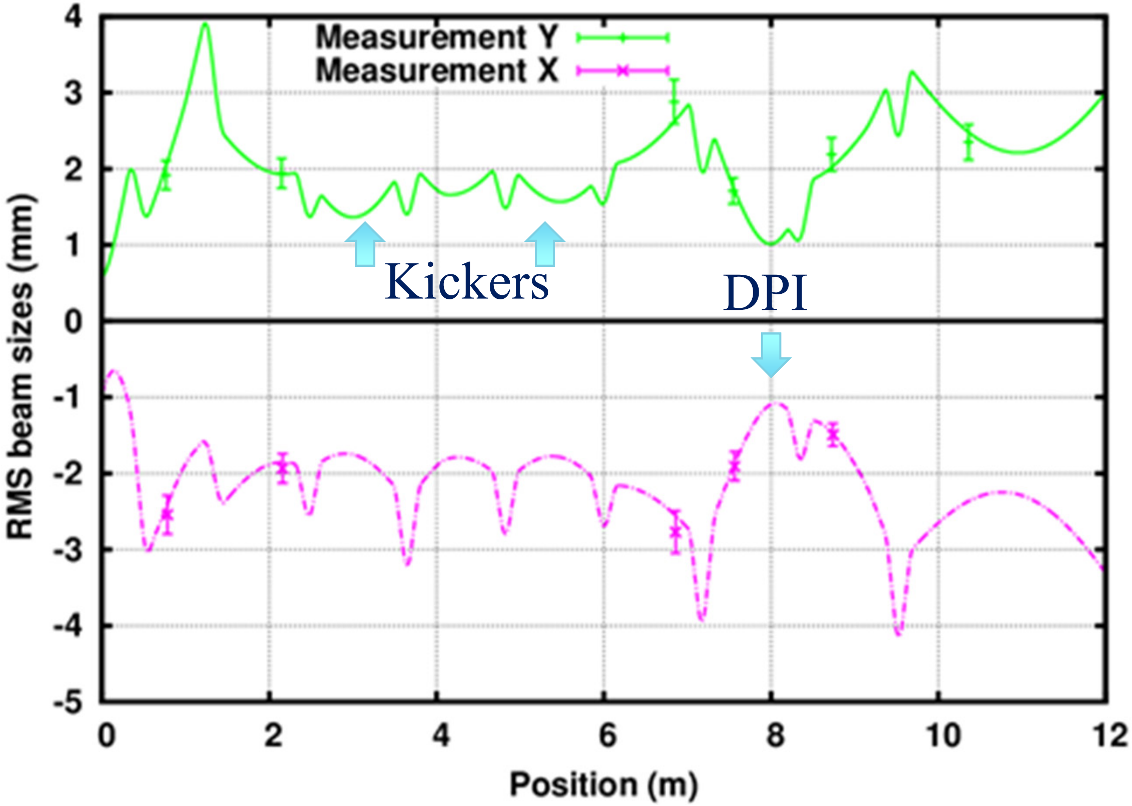
- The beam size is measured in 5 locations by scrapers (X and Y) and by Allison scanner in Y
  - The initial Twiss parameters are reconstructed to fit measurements in the first 3 scrapers
  - Simulated envelope goes through all measured points within 10%.



Dump current as a function of the position of the horizontal scraper in the second set. Red- fit for Gaussian beam with rms width of 1.97 mm. Points are the average of ten 10-μs pulses.

Optimization of the beam envelope

- The beam envelope is optimized using the model
  - Smaller beam sizes in the kickers (Y) and in DPI (X, Y)
  - Phase advance between kickers and between scrapers

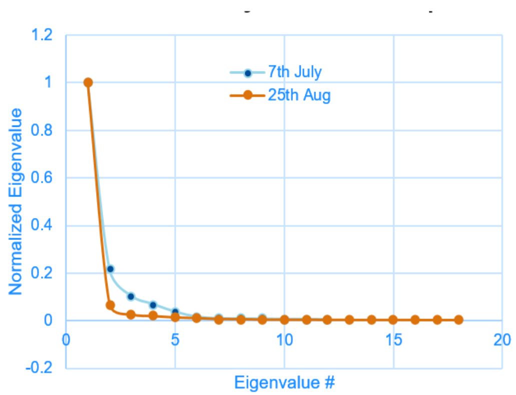


- Beam size in the dump is increased for high-power tests

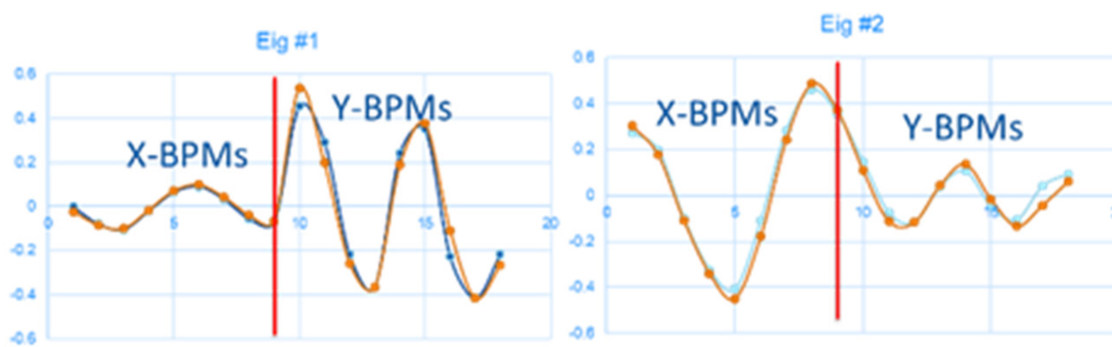
Simulated envelopes and beam size measurements. 5 mA, $\varepsilon_{x,y}$=0.2μm and ε_z= 0.28μm (rms n).

Beam position jitter in the MEBT

- Optics model helps to analyze the position jitter in the MEBT
  - A large set of BPMs data vs time is SVD-decomposed
  - The dominant spatial components are fit to the betatron modes

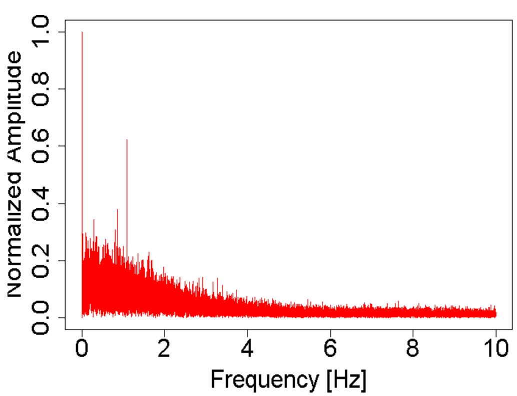


Eigenvalues (normalized by the largest one) of the SVD decomposition of matix (18 BPMs) x (20 Hz x 35 min). 7th July 2017 set is for 10 Hz x 10 min.



Fitting of the first two eigenvectors (orange) to betatron modes (blue).).

  - The jitter comes from upstream of the MEBT



Noise spectrum.

Tracing the source of the jitter

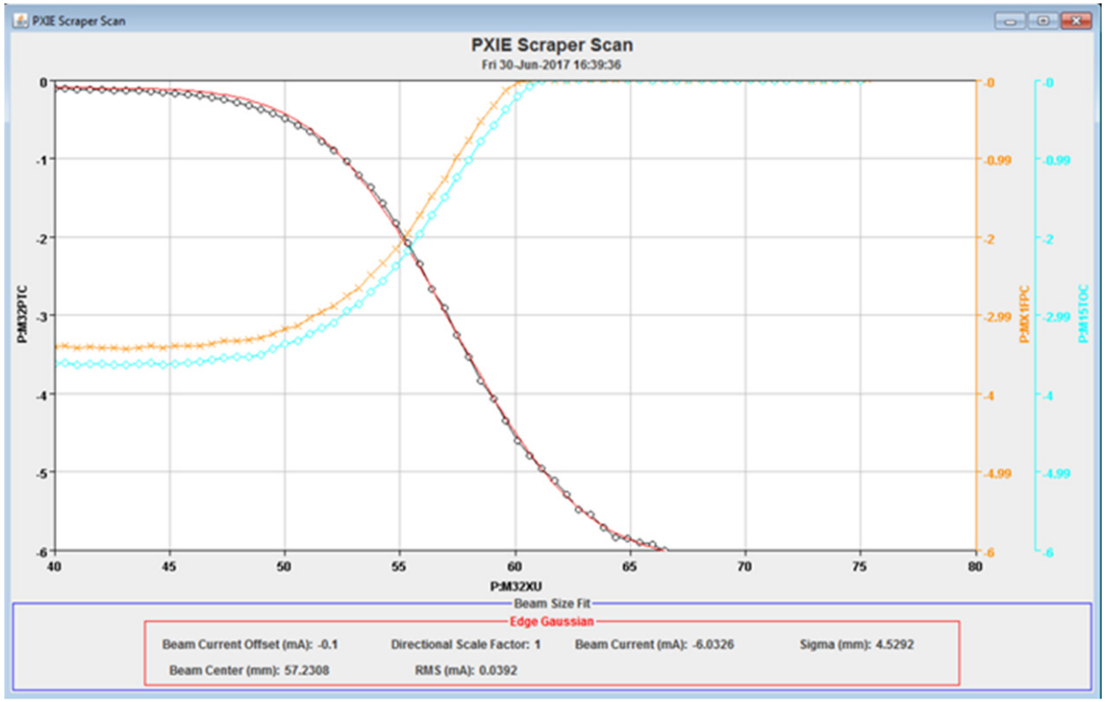
- RFQ, LEBT, or the ion source?
  - Found two more sets of currents in the last two LEBT solenoids providing a good RFQ transmission (>95%)
  - For each, analyzed the BPM noise.
    - Fitted the first eigenvector to betatron modes. From found "initial conditions" (x_0, x_0'), (y_0, y_0') and known Twiss function at the RFQ exit, calculated "actions" J_x, J_y. Calculated $\Theta = \mathrm{atan}(\sqrt{\frac{J_y}{J_x}})$
  - The jitter source appears to be upstream of the Solenoid #2

Sol2, A	Sol3, A	Sol2+ Sol3, A	Rotation, deg	Δ, deg	Θ, deg	ΔΘ, deg
130.0	226.9	356.9	97.9	0	81.18	0
70.0	216.9	286.9	78.7	-19.2	64.11	-17.07
195.0	238.4	433.4	118.8	20.9	56.52	-24.66

- Likely in the ion source, where indications of 1.09 Hz line were observed
- Not found yet

Road to beam tail analysis: scrapers

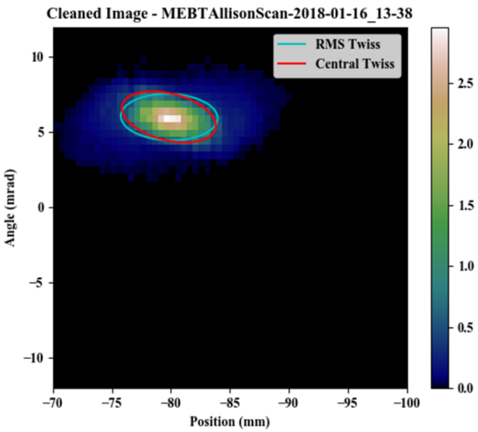
- Initial plan, to analyze the tails with the scrapers, did not work
  - Total beam current readings are too noisy to distinguish <1%
  - Scraper readings are too dependent on secondary particles
  - Plan to use a negatively biased wire scanner



Typical scraper profile. Beam current 3.5 mA. The scraper plate is biased by +100 V.

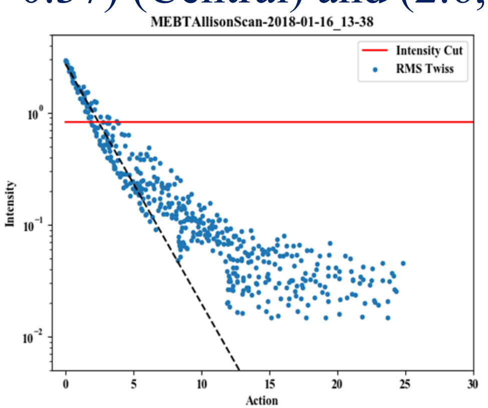
Phase portraits: preparations to treat tails

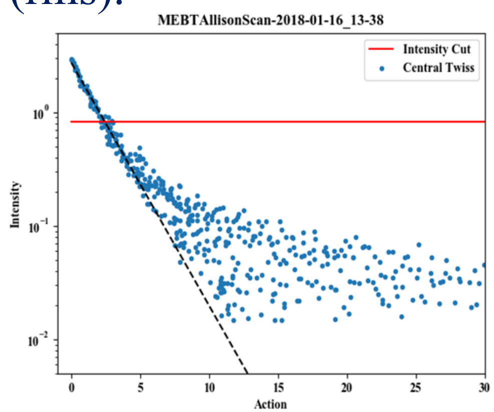
- Y phase portraits are recorded in with Allison scanner



  - Upgraded version of SNS/LBNL design; inherited LabView data taking/analysis program
  - Noise treatment: presently cut at 1% of max intensity
    - Python script: base the cut on the noise level
      - N*(rms noise); remove points without neighbors

5 mA; Max/cut ~200. Twiss: (β, α) = (2.5, -0.37) (Central) and (2.6, 0) (rms).

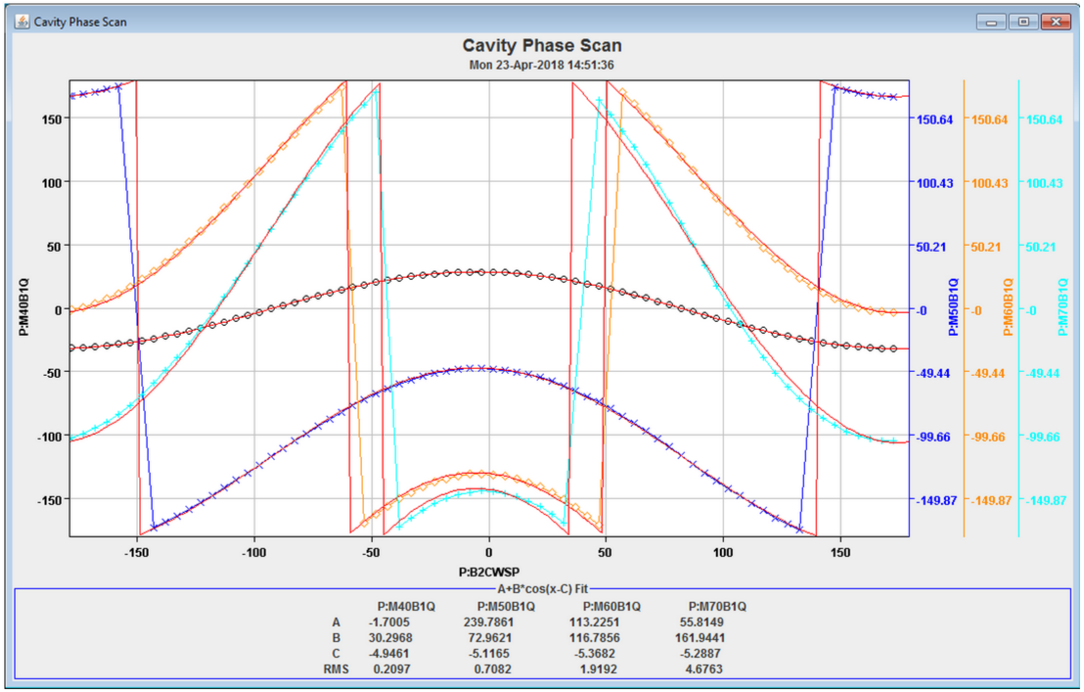




- "Central" Twiss parameters
  - Calculated using 50% of the beam with highest-intensity pixels. Do not change with scraping.
  - Core: pixels in the core with the same action have the same intensity

Left – actions calculated with rms Twiss, right – with "central".

Longitudinal motion: cavity phase rotation

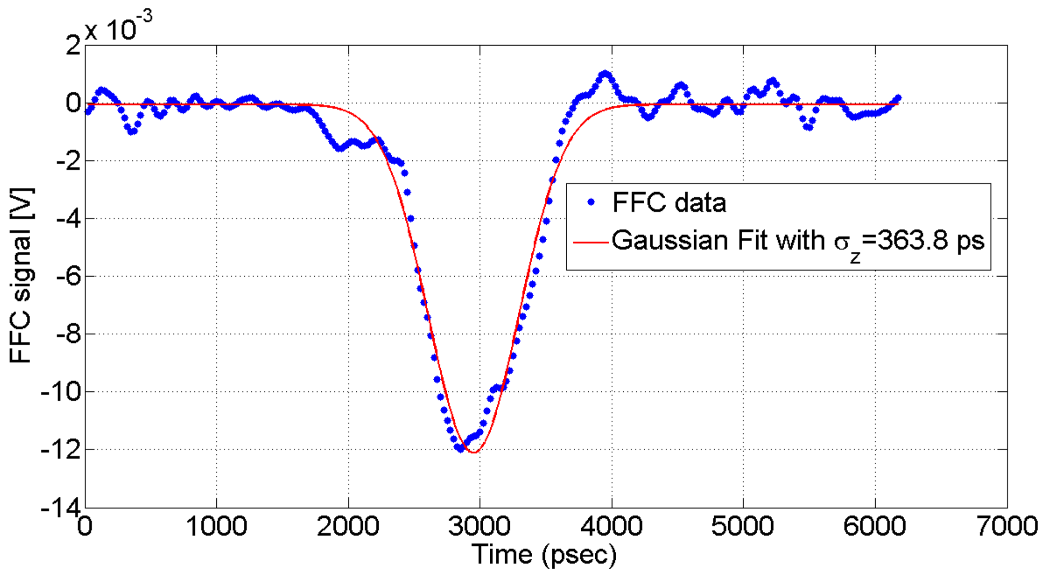


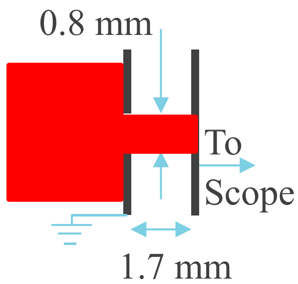
Screen shot of the cavity phasing program: phases of 4 BPMs vs the reference phase of cavity #2, set to 50 kV.

- Cavity phasing: rotate the reference phase by 360º, fit the BPM phases to sinusoids, correct the offset by LLRF
- Amplitude of the sinusoid is proportional to the cavity voltage
  - Recently found a discrepancy with previous calibrations by ~10%

Bunch length measurements

- The bunch length is measured with a Fast Faraday Cup
  - Signal from 6 GHz scope is fitted with Gaussian curve
  - Output: rms width and integral
- Several locations along the beam line
  - The length is recorded vs cavity voltage at -90º to reconstruct the longitudinal emittance

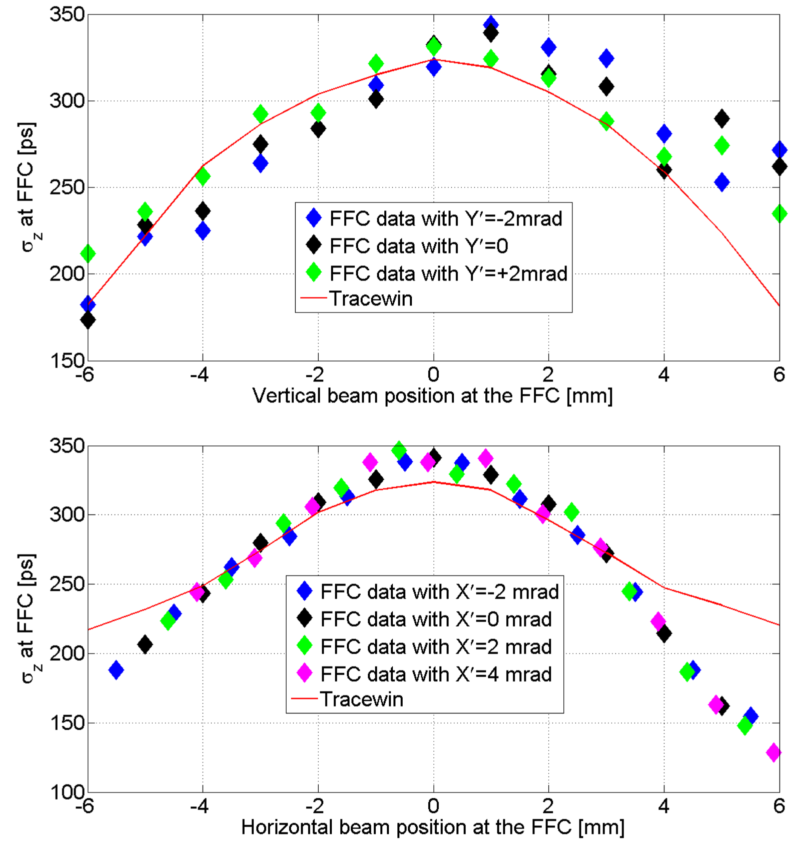




One period of the FFC signal (blue) and its Gaussian fit (red). The FFC is at the end of the beam line. Beam current is 9.3 mA

Longitudinal – transverse coupling

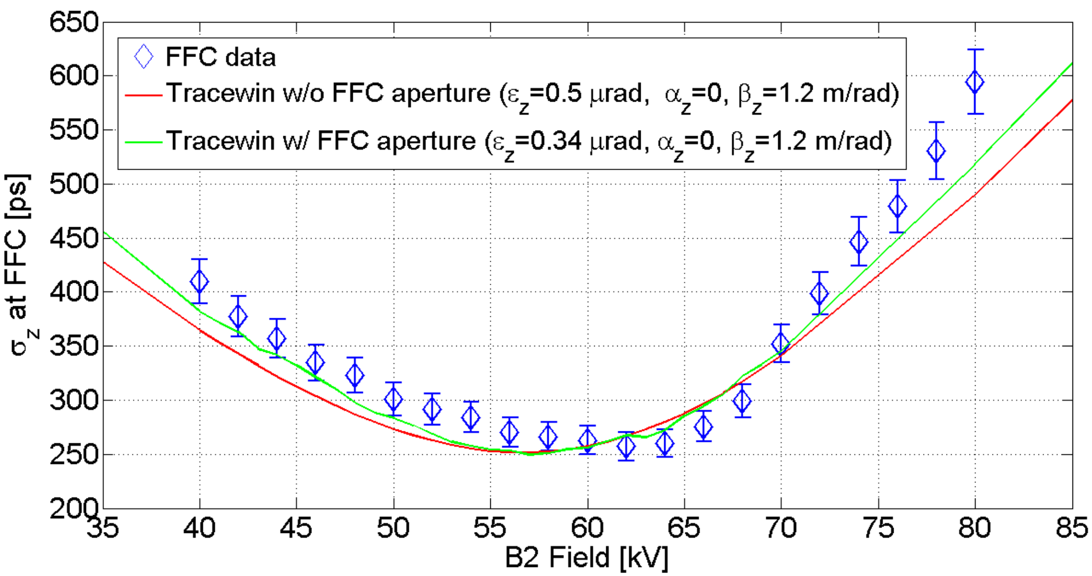
- The bunch length at the center of the beam and at its periphery differs significantly, up to ~2
  - Significantly affects emittance calculation
  - Is qualitatively reproduced in TraceWin simulations
    - Since simulation start with uncoupled 6D Gaussian beam, effect observed only with space charge and far into the beam line



Bunch length vs vertical and horizontal position across 5 mA beam. Red curves are simulations. Beam transverse rms size is 2.6 mm in X and 2.0 mm in Y.

Longitudinal emittance

- When FFC is in section #6, curve bunch length vs cavity voltage has minimum, which helps with emittance calculation.
  - Fitting: iterations with TraceWin simulations, where the FFC aperture is implemented, by adjusting emittance and Twiss parameters at the cavity location



Rms bunch length vs voltage of bunching cavity #2 (blue). FFC in section #6. Green – fit with 0.8 mm aperture, red – entire beam.

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Summary

- The transverse optics was re-constructed
  - magnets calibrations were adjusted by analyzing the beam dipole motion
  - Emittance and the initial Twiss parameters were set by fitting the beam sizes measured along the beam line.
  - Helps with beam tuning, e.g. allowing to predict the beam envelope within 10% or look for the source of position jitter.
- The longitudinal optics is defined as well
  - Cavity phasing and amplitudes are determined from analysis of the dipole motion (through BPM phases)
  - Emittance and initial Twiss parameters are from fitting to the rms bunch length, measured by FFC, vs cavity voltage.
  - significant coupling between the transverse and longitudinal beam distributions is found