Measurements of a 2.1-MeV H^- beam with an Allison scanner

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APT seminar

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Outline

- PIP-II and PIP2IT
- MEBT Allison scanner
  - Calibration and background removal
- Beam distribution: core and tails
- Selected measurements
  - Quadrupole scan
  - Distribution in different locations
  - Variations through the pulse
  - Scraping
  - Perturbation by the chopper
- Summary
- Discussion: how to use the results for simulations

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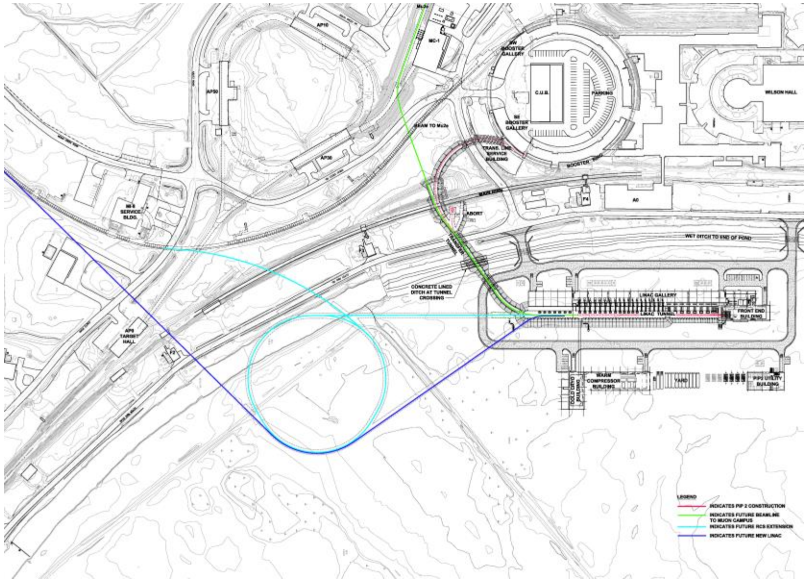
PIP-II and PIP2IT

- 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
  - Upgrades to Booster, MI, and RR
  - The immediate goal is to provide >1 MW to LBNF/DUNE
  - Platform for future upgrades
    - “PIP-III”: Higher MI power; multiple experiments
- PIP2IT: a test accelerator representing the PIP-II front end
  - To retire possible risks associated with PIP-II front end



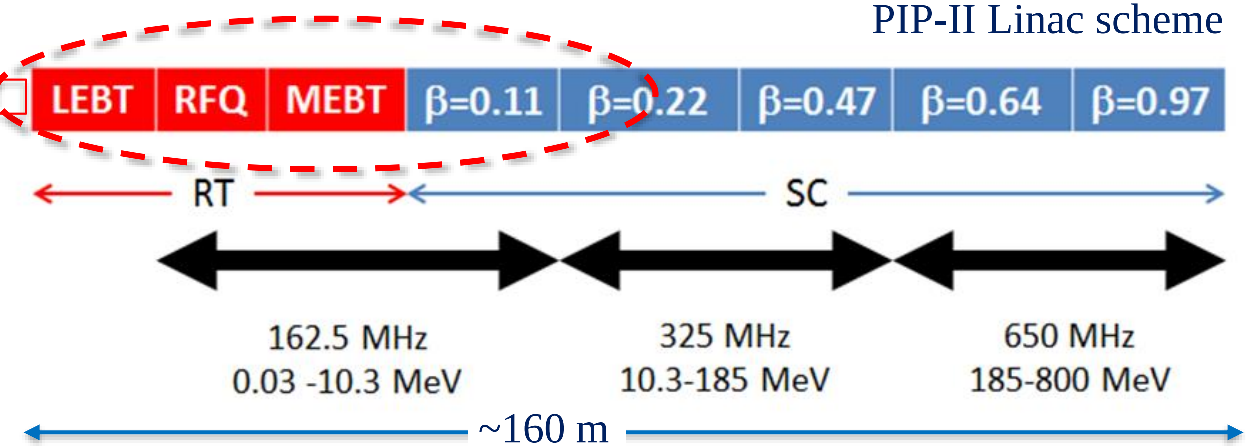
Layout of PIP-II and its possible future upgrades

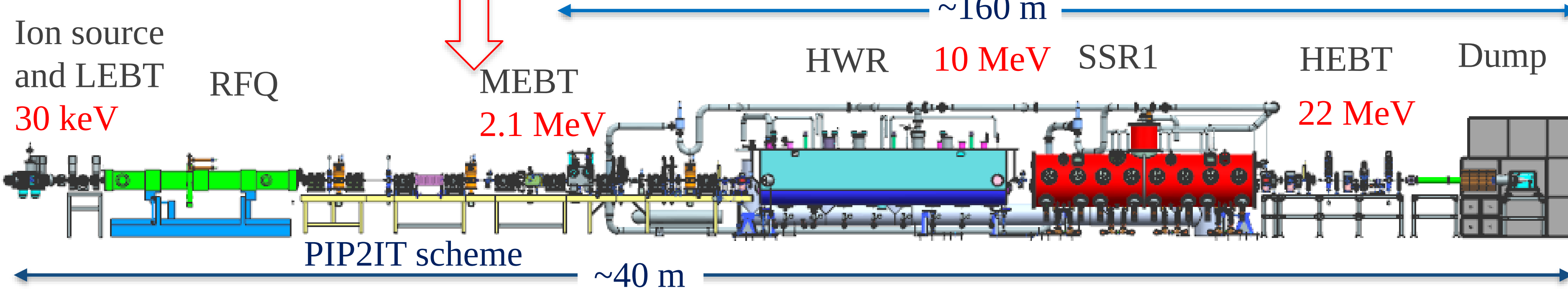
PIP-II Injector Test (PIP2IT)

- Presently, the warm front end is assembled and tested
  - Nominal 2.1 MeV x 5 mA x 20 Hz x 0.55 ms; up to 5 kW in tests
- This talk is about one-plane transverse distribution measurements performed in the MEBT with Allison scanner

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

PIP-II Linac scheme





PIP2IT scheme

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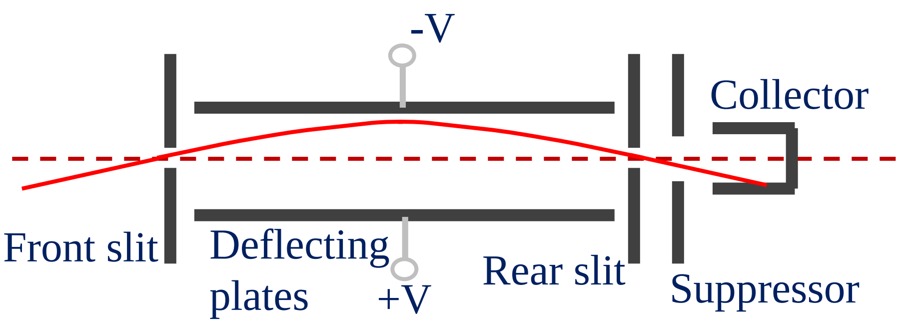
Purpose of the distribution measurements

- Tuning the MEBT
  - Help in checking and adjusting the MEBT optics
  - Beam parameters from the RFQ and through the MEBT
    - Including in-pulse variations, effect of scraping and chopping etc.
- Beam properties at the MEBT exit
  - Ultimate goal is to create a realistic initial distribution for SRF linac simulations

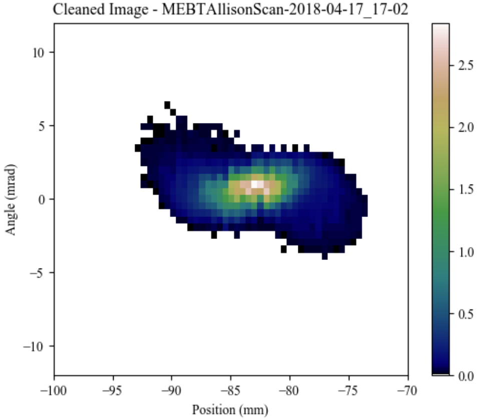
- MEBT Allison scanner

Allison Scanner for recording (y, y') phase portraits

- Two slits with electrostatic deflecting plates in between + beam collector with a suppressor electrode
  - The assembly is moved through the beam by a stepping motor

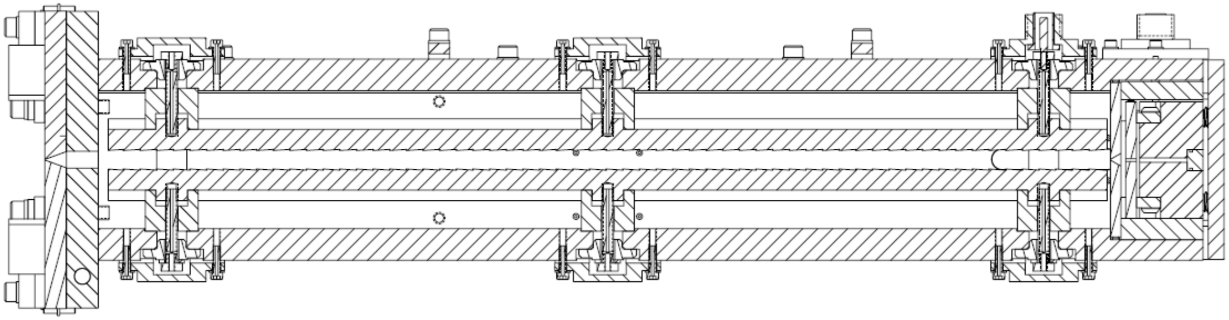


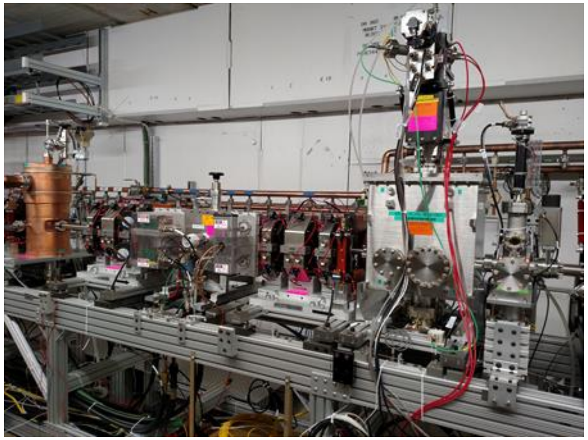
- Position of the front slit defines *y* coordinate; voltage between plates selects the angle (*y'*). Collector ("Faraday Cup") current I_{FC} is proportional to the phase density at (*y*, *y'*)
  - Phase portrait: set of "pixels" $I_{FC}(y, y')$
- Very positive experience with PIP2IT LEBT Allison Scanner
  - Modified LBNL/SNS design
- Typical scan: ~3000 points



MEBT Allison scanner

- Modified LEBT design (from 30 keV H^- to 2.1 MeV)
  - Higher instantaneous power => operated mainly with 10 µs pulses
  - Higher beam rigidity => smaller gap; lower angular range
  - Software and control hardware shared with the LEBT scanner





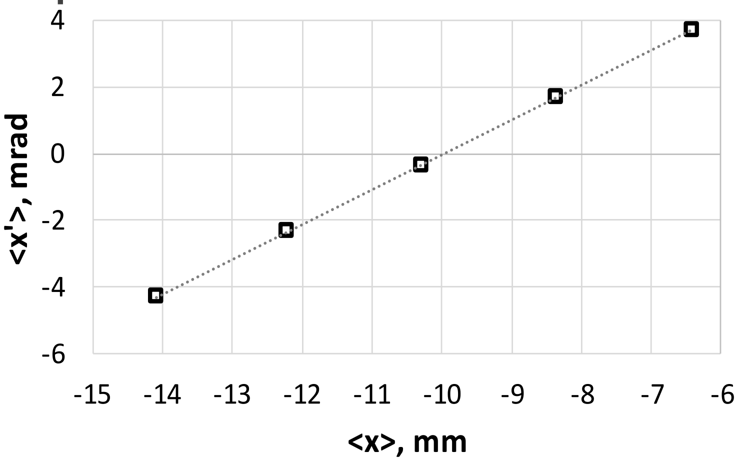
Parameters of MEBT scanner

Parameter	Value	Unit
Slit size	0.2	mm
Plate voltage	±1000	V
Plate length	300	mm
Plate separation	5.6	mm
Angle range	±12	mrad

MEBT Allison scanner installed at PIP2IT. The scanner can be installed vertically or horizontally.

Accuracy

- Coordinate accuracy - ±18 µm (mechanical measurements)
- Angular accuracy - < 50 µrad
  – Tested by comparing the phase portraits *x* and *x’* centroids of the beam deflected by an upstream dipole corrector
- Background removal – next slide
- The portrait integral stays constant (within 0.5%) with changing of upstream focusing and steering
  – Possible contribution of secondary particles is likely to be low



Angular calibration of the MEBT Allison scanner (in horizontal position). Angular center of the phase portraits is plotted vs their coordinate center while the beam is deflected by an upstream dipole corrector.

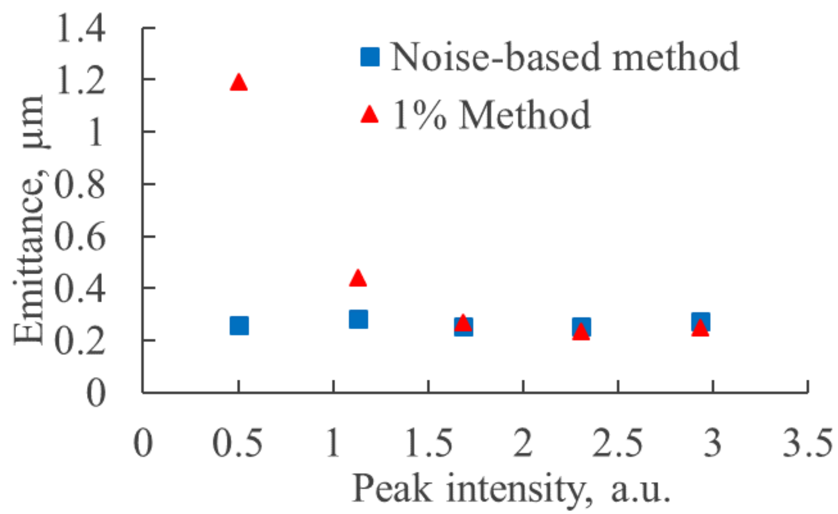
Background removal

- The background is determined by electronics noise
- Traditional way of cleaning is based on the signal
  - set to zero all pixels with intensity <1% of the peak
  - The threshold varies depending on the signal strength
- An alternative algorithm (in an offline analysis program)
  - Based on the background, not the signal
    - Choose an area far from the beam; calculate the noise
    - Define the rejection level so that the probability of finding a pair of remaining noise pixels neighboring each other is low. Remove pixels without non-zero neighbors.
      - Criterium: 1 of 100 portraits may contain a pair of noise pixels if the noise is random and the same over the portrait
  - In cases with full intensity, rejection level is ~0.5% of signal maximum

Background removal example

- Vertical rms emittance vs horizontal scraping
  - Looking for indications of coupling between planes
- With scraping, the maximum pixel intensity drops, decreasing the level of 1% rejection. The emittance calculation takes in more noise, and the reported emittance grows.
- With noise-based rejection level, the emittance stays constant.

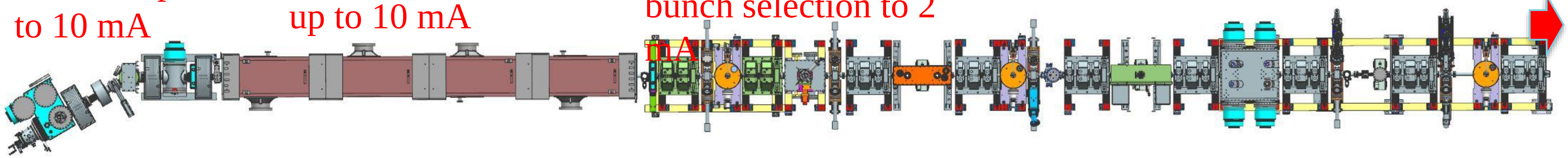
Dependence of the calculated beam emittance (rms, n) on the horizontal scraping. The scraping is represented by the decrease in the maximum pixel intensity. The beam current remaining after scraping is (for points from left to right) 1, 2, 3, 4, and 5 (not scraped) mA.



Definition: the rms emittance is reported as $\varepsilon = \sqrt{\sigma_x{}^2 \, \sigma_{x'}{}^2 - \sigma_x \sigma_{x'}}$ and expressed in µm=mm·mrad. “Normalized”: $\varepsilon_n \equiv \varepsilon \cdot \gamma\beta$

- PIP2IT warm front end

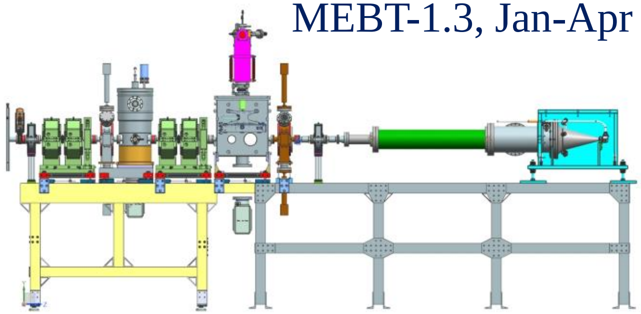
PIP2IT warm front end

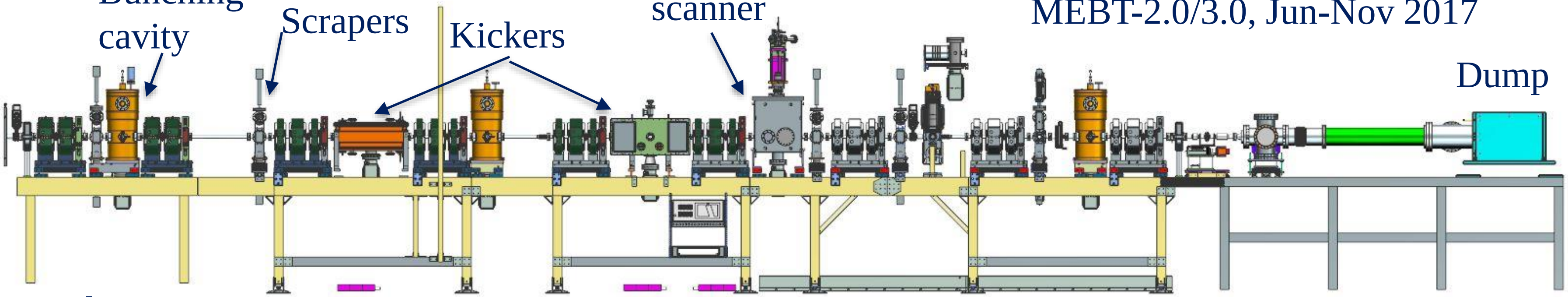


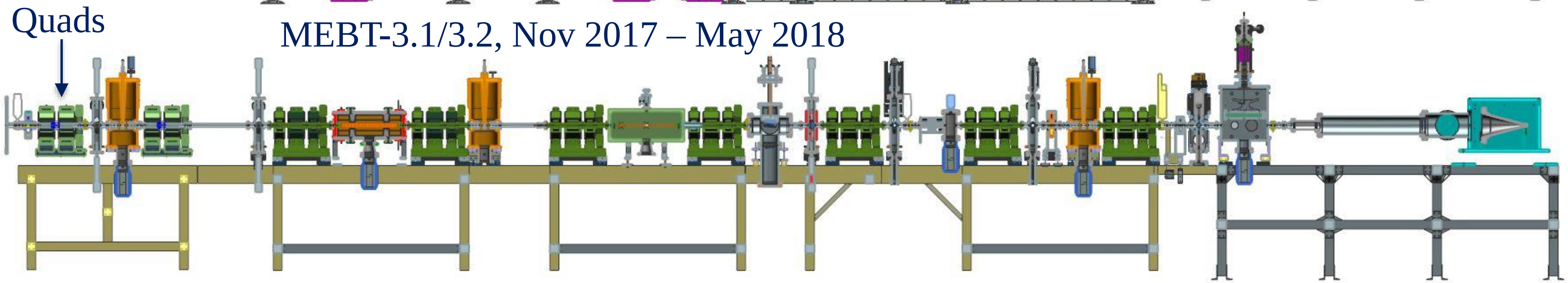
- MEBT: 10-m long with fast chopper
  - 2 quadrupole doublets and 7 triplets (produced by BARC, India)
  - 3 bunching cavities
  - Collimation system (4 sets x 4 scraper plates)
  - Differential pumping system
- Was assembled in several stages, with multiple measurements at each stage

Location of the Allison scanner at PIP2IT

- Three different locations of the Allison scanner
  - Horizontal orientation in the first, vertical in the other two

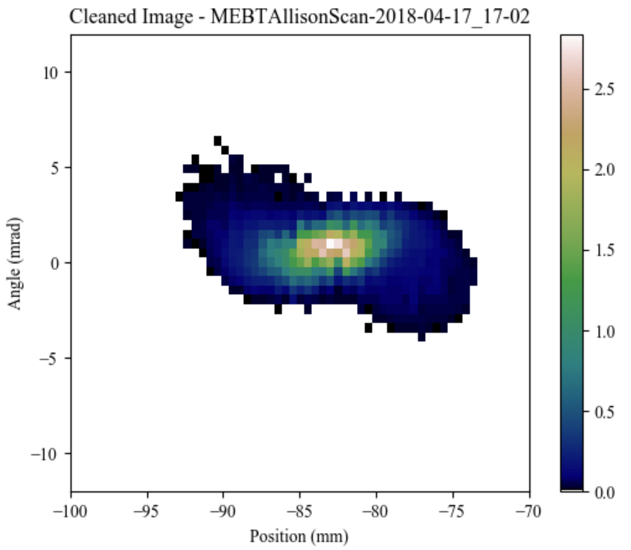






- Beam distribution

“Rms” and “core” parameters



- The central and low-intensity part of the beam oriented in the phase space differently
  - Calculated Twiss parameters depend on the choice of the pixel ensemble
- In this report, two choices are used
  - “Rms emittance and Twiss parameters”:
    - calculated with all pixels remaining after cleaning
  - “Core Twiss parameters”: calculated for the “core”, pixels with highest intensity composing 50% of the total image integral
    - Ensemble is fitted to a Gaussian distribution => α, β, ε_G

$$I_G(J,\varphi) = \frac{I_0}{2\pi \cdot \varepsilon_G} \cdot e^{-\frac{\gamma x^2 + 2\alpha x x' + \beta x'^2}{2\varepsilon_G}}$$

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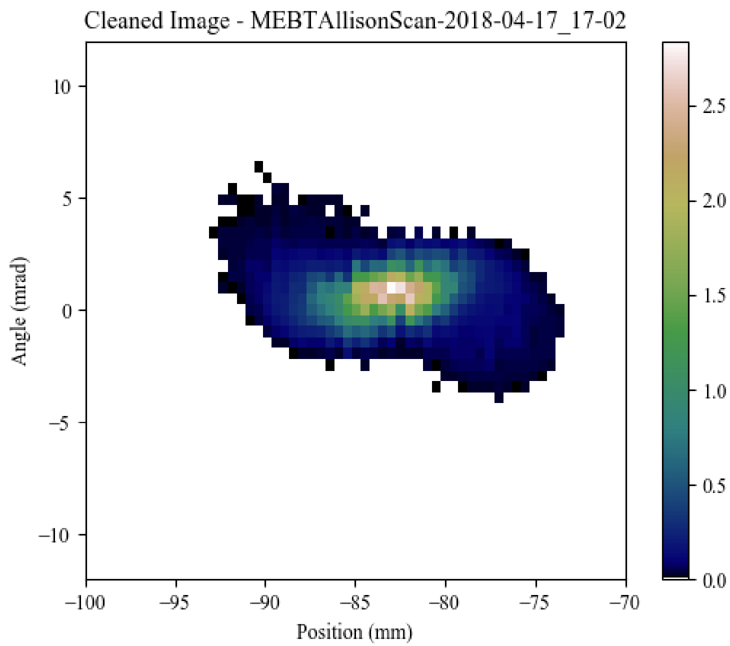
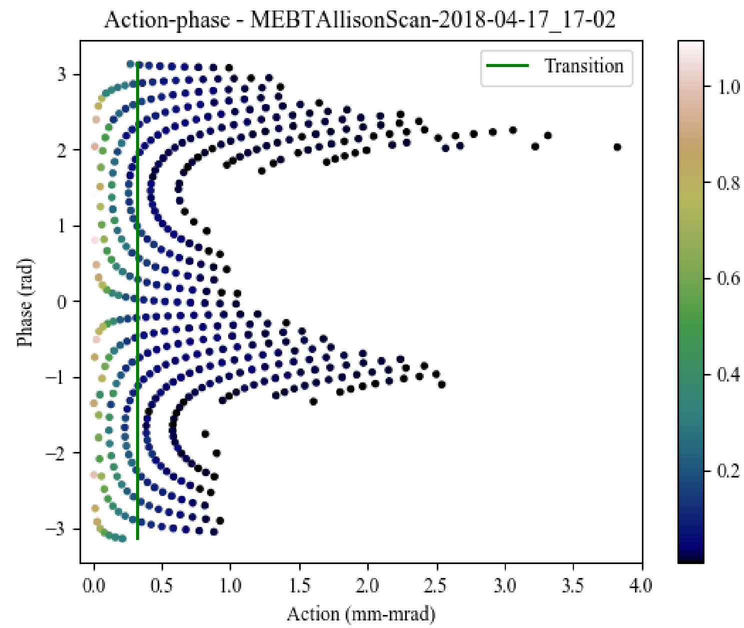
Distribution in action-phase coordinates

- Using Twiss parameters (α, β), one can transform coordinates from (Position x, Angle x') to (Action J, Phase φ)

$$J = \frac{1}{2}\left(\gamma x^2 + 2\alpha x x' + \beta x'^2\right) \qquad \varphi = \arctan\left(\frac{\alpha x + \beta x'}{x}\right)$$

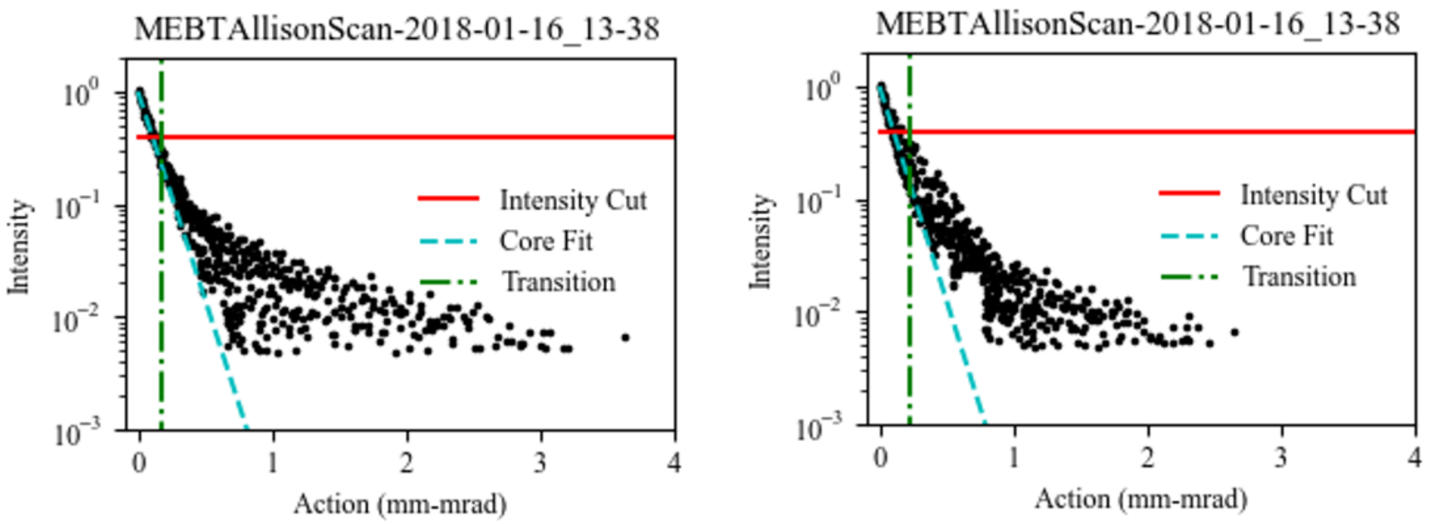
  – In a linear system, action of a particle stay constant, and the phase changes as the betatron phase advance





Distribution over action

- At the beam center, distribution over action looks differently for the rms and core definitions of the Twiss parameters
  - “Core”: intensities of pixels with the same action are similar
    - The scatter is comparable with contribution from pixilation
    - In the core, a good fit to an exponent (ε_G => “central slope”)
  - “Rms”: significant scatter of pixel intensities even in the core



$$I_G(J,\varphi) = \frac{I_0}{2\pi \cdot \varepsilon_G} \cdot e^{-\frac{J}{\varepsilon_G}}$$

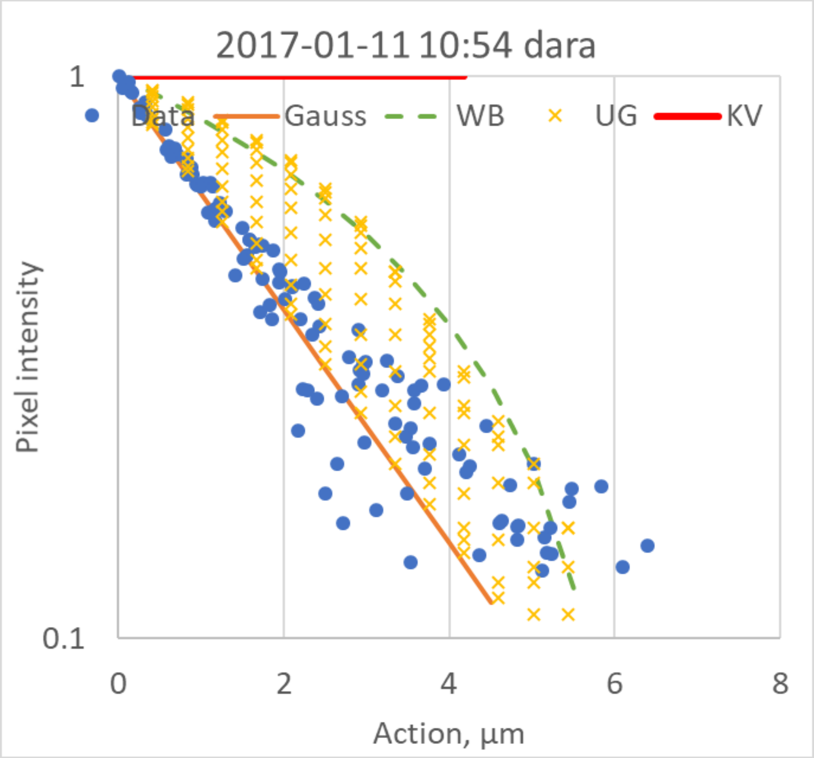
Distribution over action for the same phase portrait using “core” (left) and “rms” Twiss parameters.

How arbitrary is the choice of fitting function in the core?

- Distributions frequently used in simulations: K-V, Waterbag
  - Projections to one plane for the phase density
  - KV=$\frac{I_0}{2\pi\cdot\varepsilon_m}\begin{cases}1, J \le \varepsilon_m \\ 0, J > \varepsilon_m\end{cases}$, WB =$\frac{2\cdot I_0}{2\pi\cdot\varepsilon_m}\begin{cases}1 - {}^{J}/_{\varepsilon_m}, J \le \varepsilon_m \\ 0, J > \varepsilon_m\end{cases}$
- Distribution measured in the LEBT and projected into the ion source is close to **U**niform in space (limited by the output aperture of the ion emitting surface) and **G**aussian in angle
  - UG: $I_{UG}(J,\varphi) = \frac{I_0}{\pi\sqrt{2\pi}\cdot\varepsilon_{UG}}\cdot e^{-\frac{J\sin\varphi^2}{\varepsilon_{UG}}}\cdot\begin{cases}0, & \frac{J\cos\varphi^2}{2\varepsilon_{UG}} \ge 1 \\ \sqrt{1-\frac{J\cos\varphi^2}{2\varepsilon_{UG}}}, & \frac{J\cos\varphi^2}{2\varepsilon_{UG}} < 1\end{cases}$

Comparison

- Prediction from theory: relaxation toward Maxwell-Boltzman distribution*
  - For PIP2IT MEBT parameters, corresponds to a Gaussian beam: $I_G(J,\varphi) = \frac{I_0}{2\pi \cdot \varepsilon_G} \cdot e^{-\frac{J}{\varepsilon_G}}$
  - Should occur within meters
- The measured distribution in the core is close to Gaussian
  - Phase independent
  - Exponentially drops with action

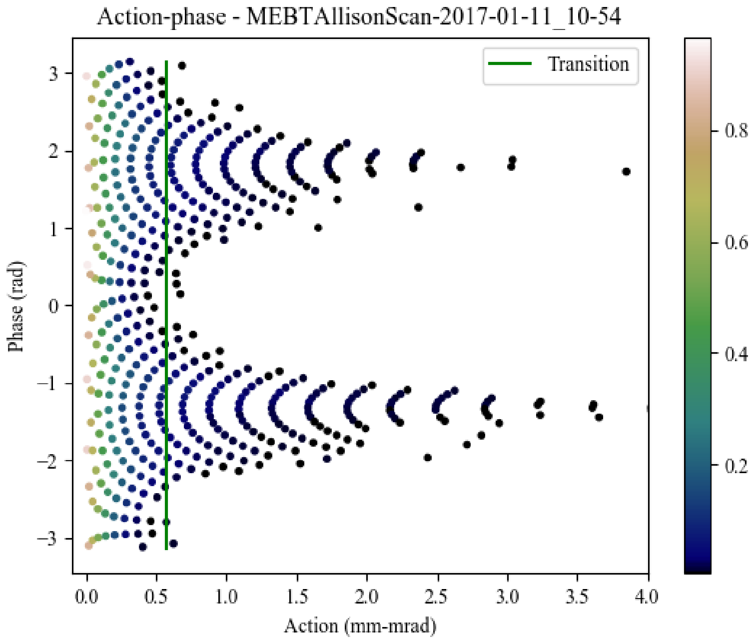


Comparison of the measured distribution over action (blue circles) in the beam core with several idealized distributions: Gaussian, KV, UG, and WB. Coefficient for Gaussian ("central slope") is 2.1 µm, rms emittance of the entire beam is 2.4 µm (unnormalized). Horizontal plane; 1st location.

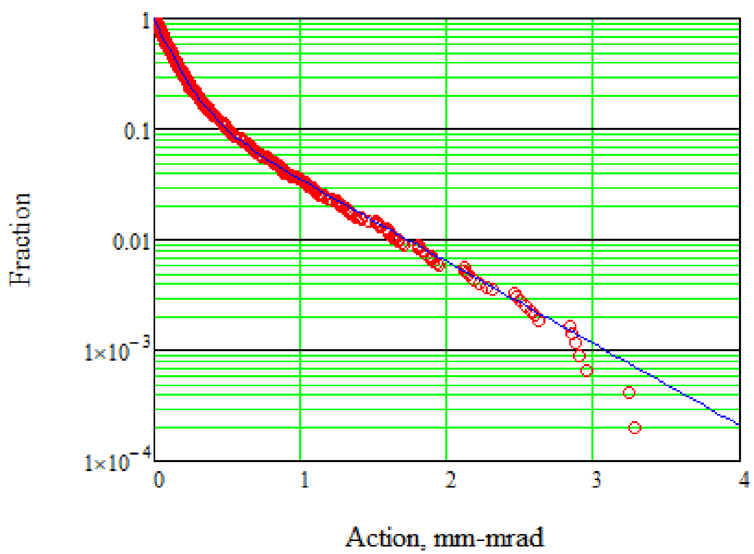
*Reiser, "Theory and design of charge particle beams"

Distribution of the entire beam

- Outside of the core, the phase density is strongly phase – dependent, and the average (over the phase) deviates from the core Gaussian fit



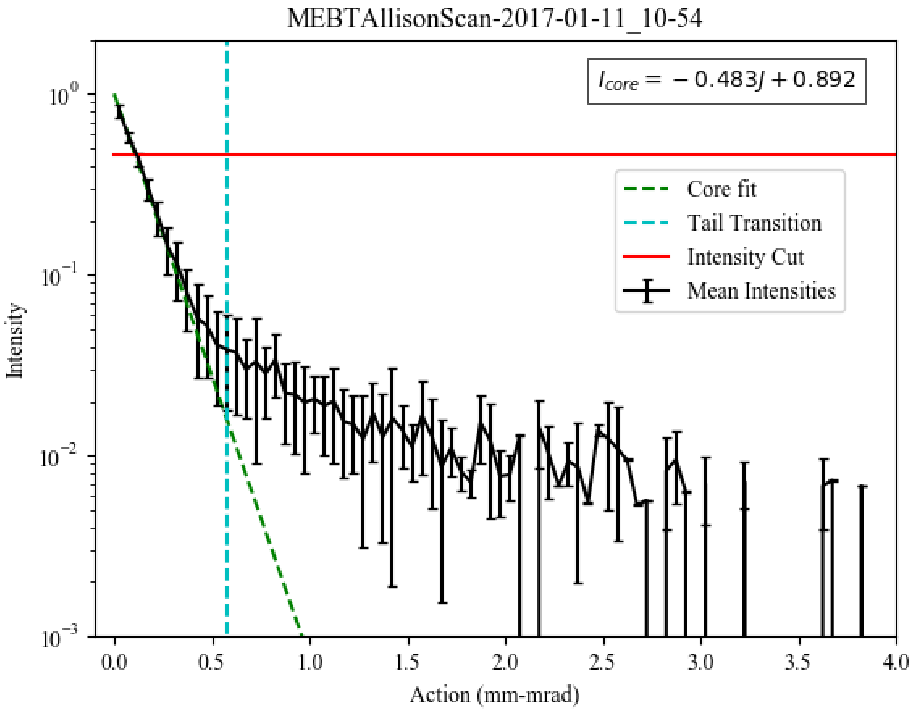
Phase portrait in action-phase coordinates. $\varepsilon_{rms\ n}$=0.16 μm.



Portion of particles outside of a given action. Action is normalized. The blue curve is fit with CC=0.81, ε1=0.13, ε2=0.59. $CC \cdot e^{\frac{-J}{\varepsilon 1}} + (1 - CC) \cdot e^{\frac{-J}{\varepsilon 2}}$

Core and tails

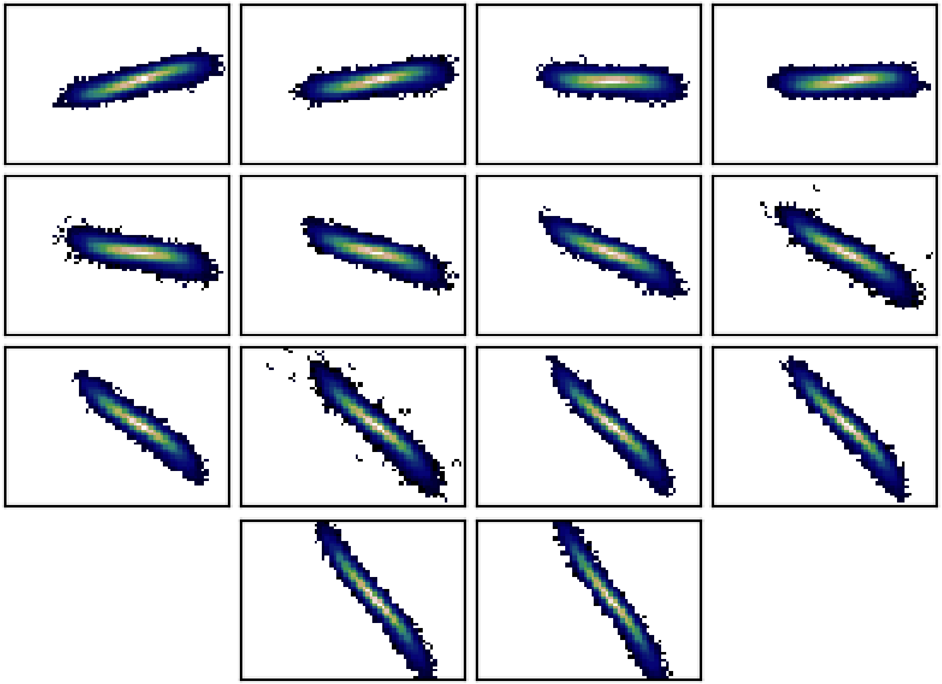
- The transition between core and tails may be defined as the action where the average pixel intensity in an action bin deviates from the core fit exceeds by >3x rms scatter
  - The core contains 70-90% of the total intensity

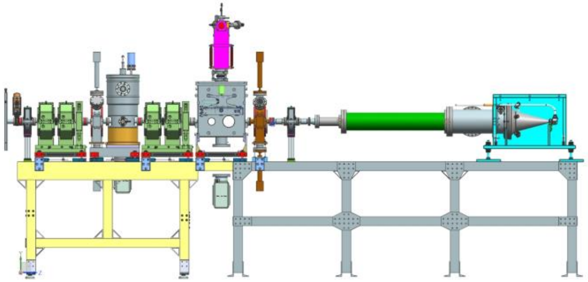


Average pixel intensity in action bin vs normalized action. $\varepsilon_{rms\ n}$=0.16 µm.

- Selected measurements

Quadrupole scan in (x, x')

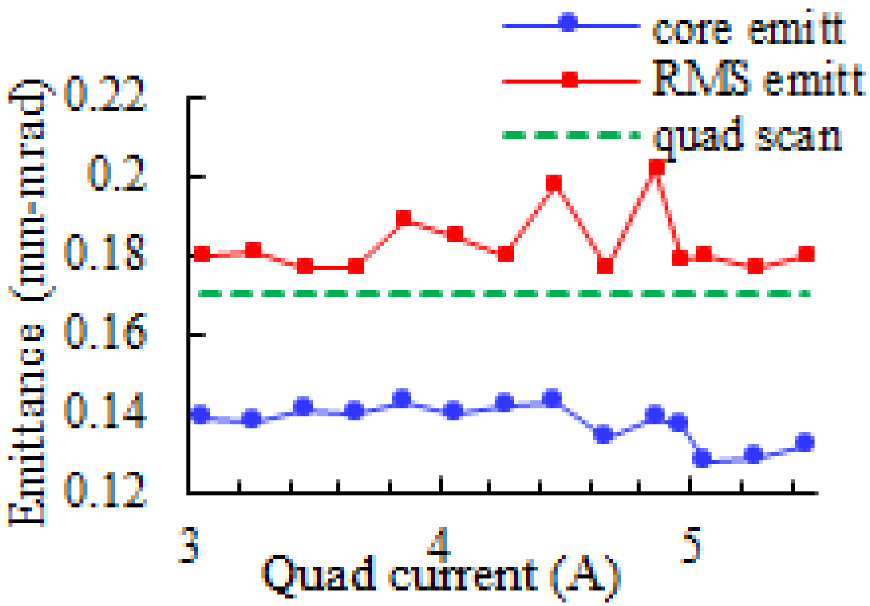




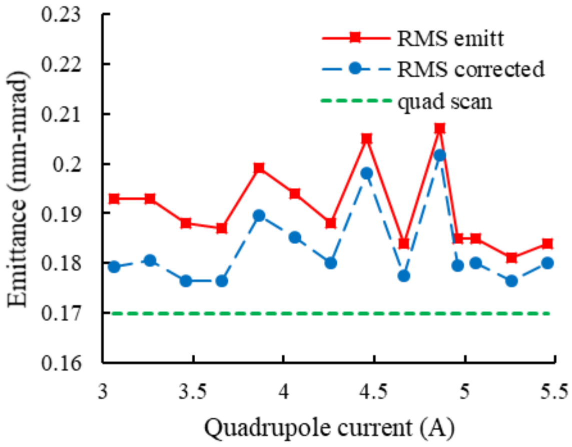
Phase portraits (x, x') recorded at different currents of quadrupole (the last one upstream of the scanner, focusing in X). The quadrupole current increases from left to right and from top to bottom from 3.06 A to 5.46 A. 11-Jan-2017.

- Can compare the rms emittance between images and with the emittance measured with a quadrupole scan (using the scraper)

Emittance measurement comparison



The rms emittance, central slope ("core emittance") vs the quad current compared with quadrupole scan result.



The blue curve represents correction for the finite slit size effect.

- Reasonable agreement with scraper measurements
  - Which are sensitive mostly to the core
- Max-min is 14% (4% rms)

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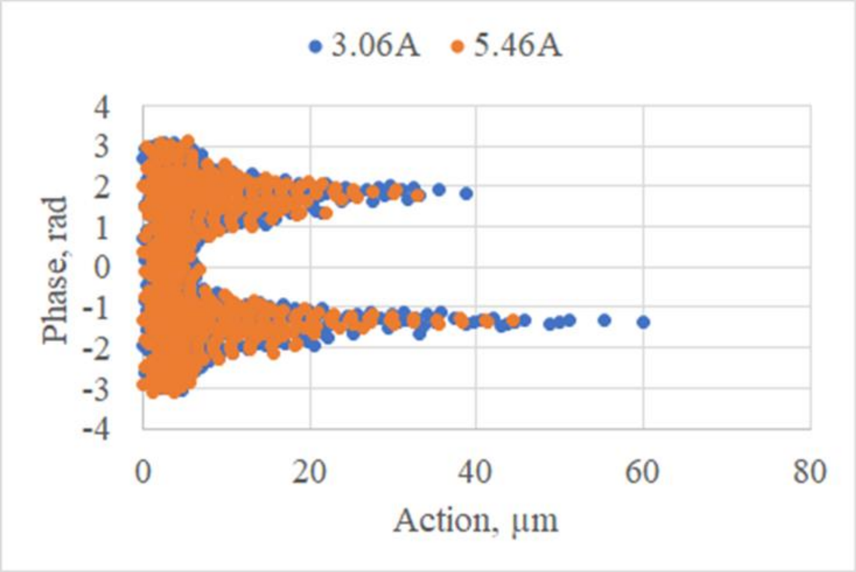
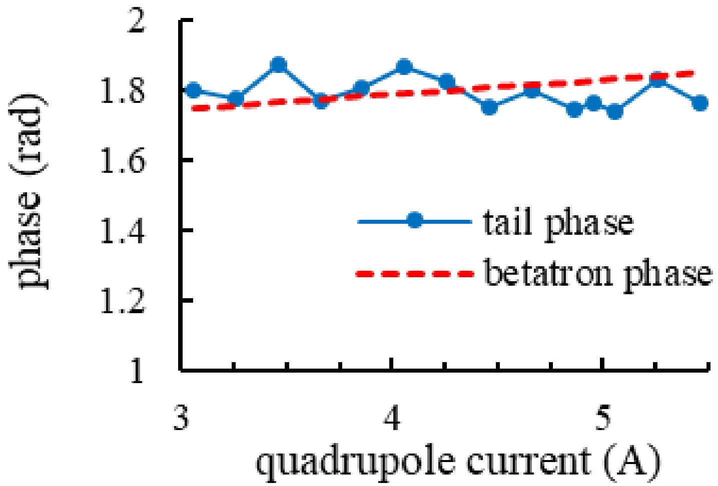
Quadrupole scan in (J,φ)

- In action-phase coordinates, the picture is essentially the same for all quad currents
  - Changes in the betatron phase advance over the scan might be too small
- All pixels behave as they should if belong to the beam



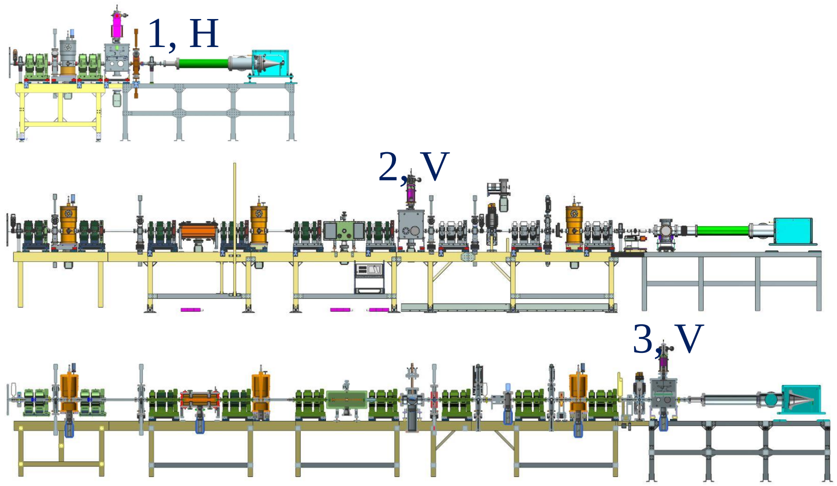
Phase portraits in (J,φ) coordinates for the largest and lowest quadrupole currents, overlapped.



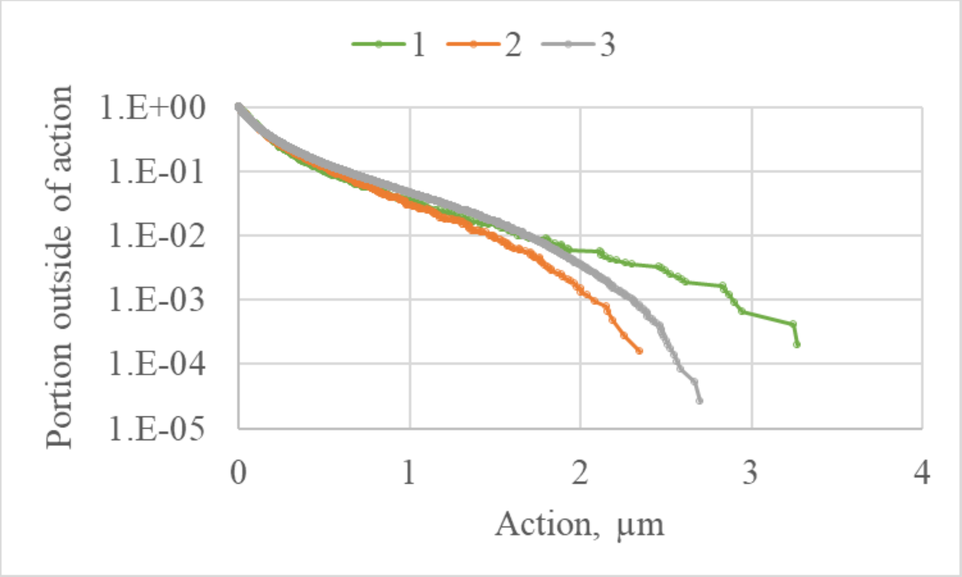
Phase of the positive brunch of the tail vs quadrupole current, compared with simulated slope of the betatron phase advance.

Measurements in 3 locations

- Within the scatter, the beam vertical distribution does not change significantly along the beam line
- Rms H and V emittances are the same



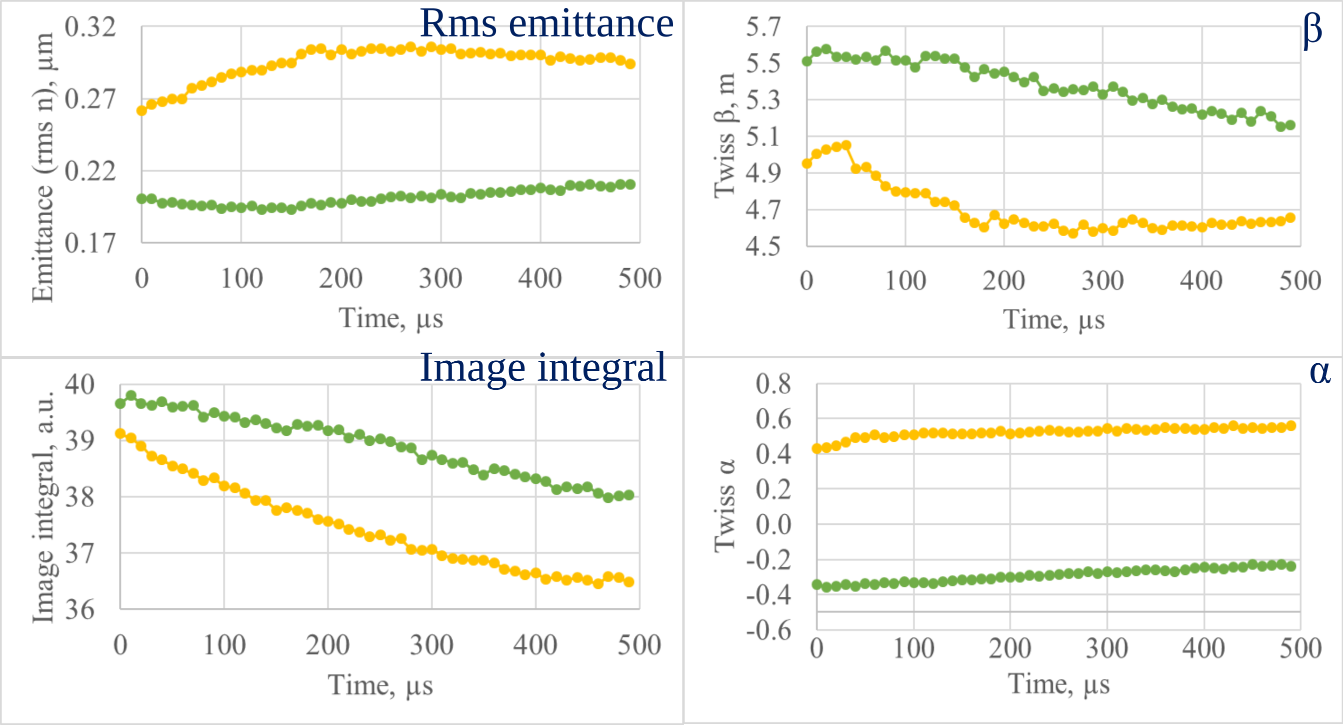
Location	rms ε, n μm	ε_c, n μm	% in core
1 – horz	0.205±0.013	0.146±0.003	88±2.5
2 – vert	0.197±0.015	0.117±0.013	71±11
3 – vert	0.223±0.024	0.123±0.011	79±4.8



Portion of particles outside of a given action. Action is normalized. Curves are numbered according to locations.

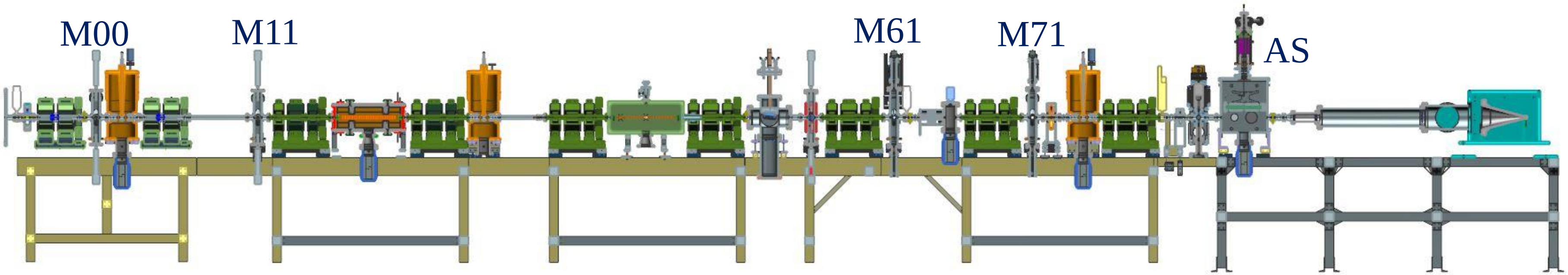
Measurements through 0.5 ms pulse

- Variations through pulse in the MEBT vs LEBT tuning
  - The beam size at the Allison scanner was increased to decrease the instant power density on the front slit
- Measurements with 10 µs pulse predict average parameters through 0.5 ms pulse within 10%

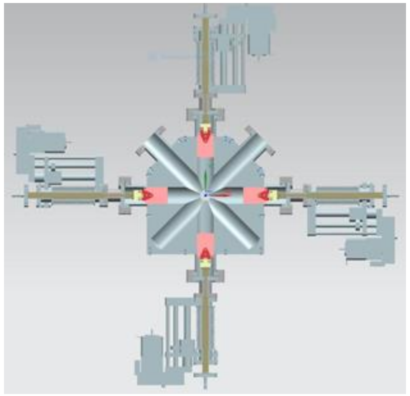


Green- LEBT nominal settings
Yellow- ion clearing in the LEBT is turned off

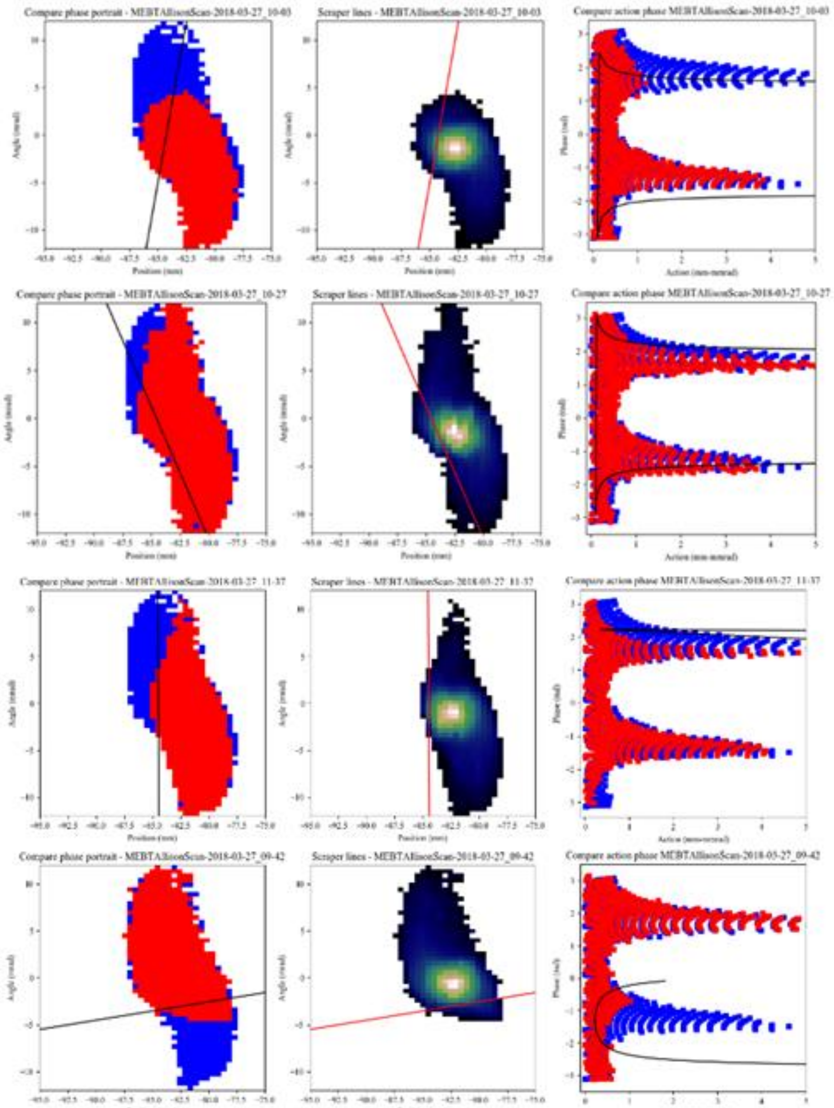
Scraping system



- 4 scraper assemblies (2 groups of 2)
  - 4 independently moveable, electrically isolated plates in each
- Several purposes
  - Protection from a beam loss caused by beam envelope and trajectory mismatches
  - Beam size measurements
  - Formation of low-emittance beam
  - Beam tails scraping
- How effective is tails scraping?



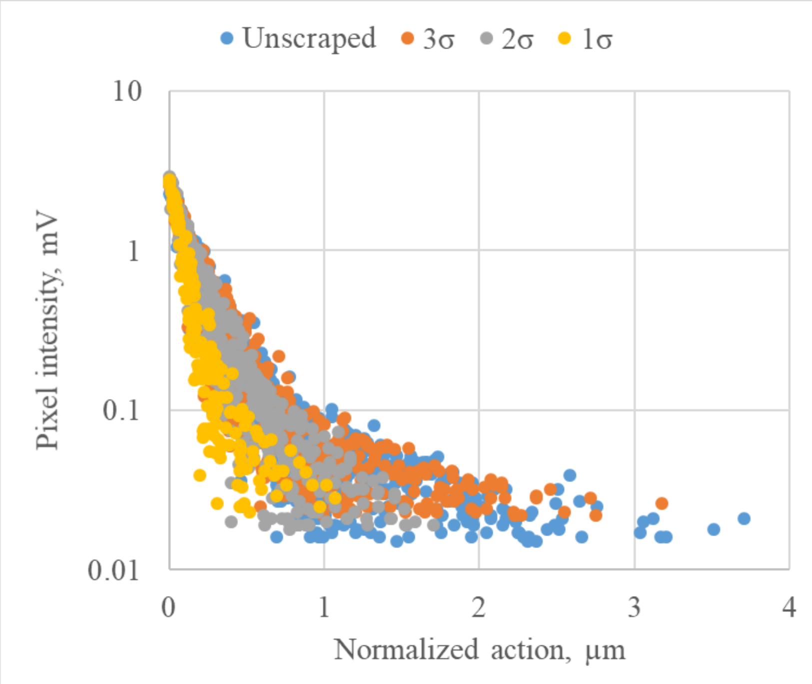
Portraits with scraping

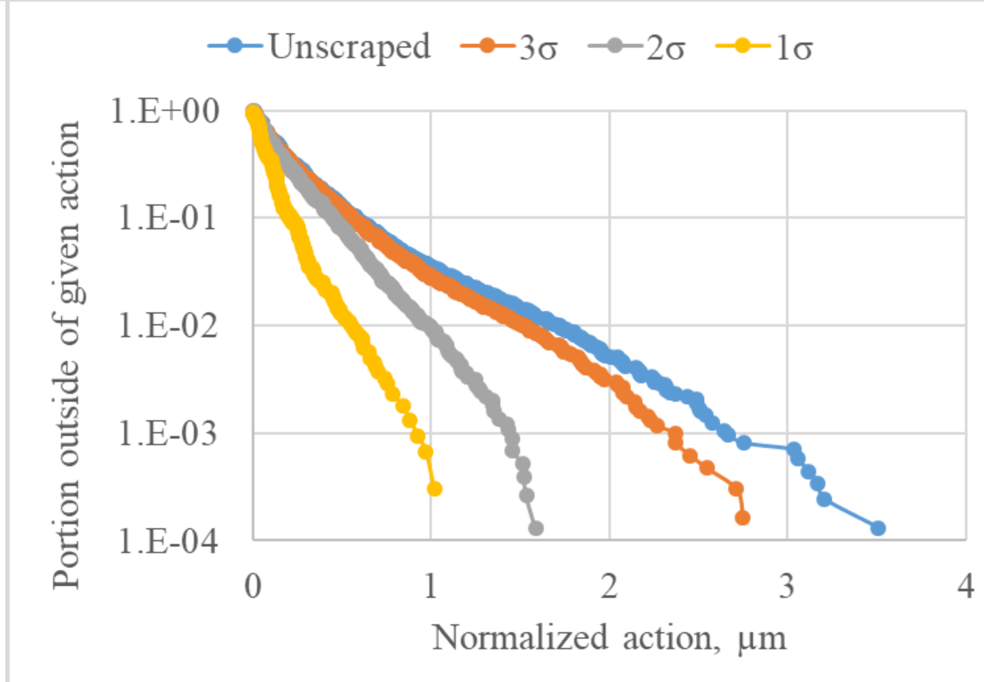


- While the cut boundary smears over the length, the scrape is not affected significantly
- Efficiency of a scraper depends on the betatron phase
  - Efficiency: decrease in max action at a given current cut

Phase portraits after moving, one at the time, a vertical scraper in assemblies (from top to bottom) M00, M11, M61, M71. In each case, 10% of the 5 mA beam is cut.
Middle column: original portraits in (x, x').
Left column: same portraits overlapped with the one of the unscraped beam.
Right column: the same overlapped portraits in (J, φ) coordinates.
Solid lines are the cut lines projected with the phase advance simulated for the beam core. 27-Mar-2018.

Result of scraping in vertical plane





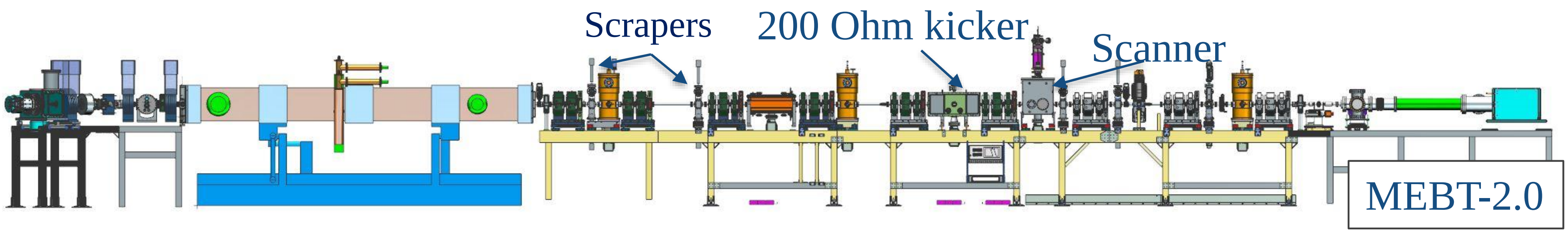
Distribution over action while inserting 4 vertical scrapers (M00 and M11) to N rms beam sizes. 17-Apr-2018.

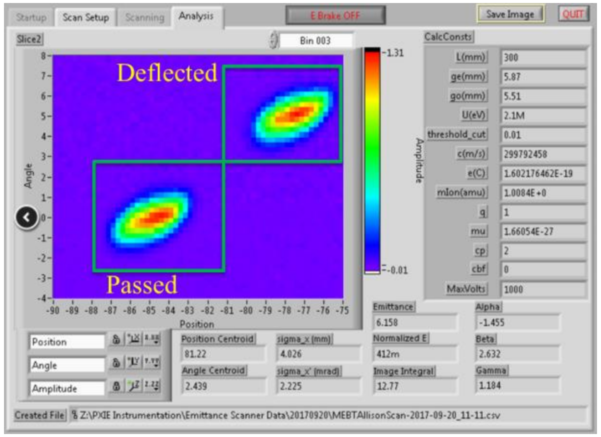
- “100%” beam emittance can be significantly decreased by scraping

Case	Scraped portion	Rms emittance	Central slope
Unscraped	0	0.236	0.148
3σ	<1 %	0.225	0.144
2σ	8%	0.181	0.145
1σ	43%	0.088	0.088

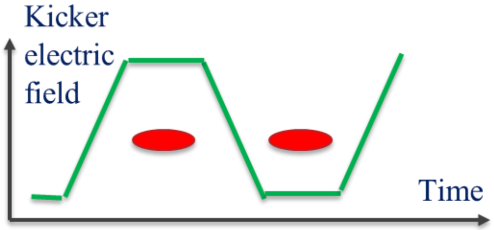
Chopper effect on the beam emittance

- Bunch-by-bunch chopper should not increase the emittance of passed bunches
  - Was measured in the MEBT configuration where both deflected and passed bunches could be transmitted to the Allison scanner
    - Possible only with the beam heavily scraped vertically (“flat” beam)



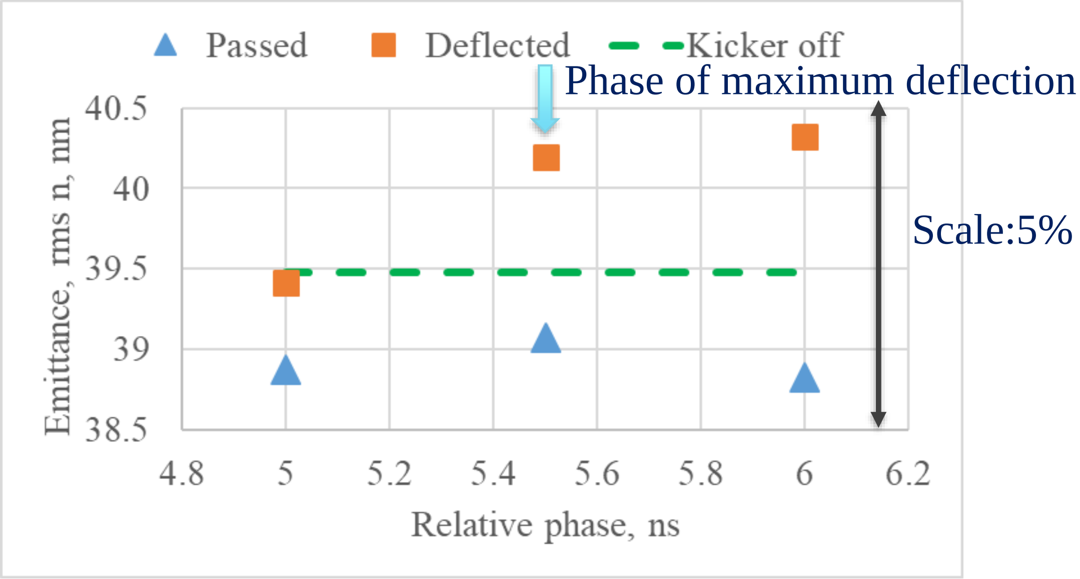


Phase portrait with the kicker pulsing at 81.25 MHz (i.e. deflecting every other bunch). Scraping a 5.1 mA beam to a “flat” beam with 1.5 mA. 20-Sep-2017.



No measurable effect from the kicker

- Emittance of passed bunches is equal to one with the kicker off within measurement uncertainties (~3%)



Comparison of emittances of passed and deflected bunches with the case of the kicker off for 3 different kicker phases with respect to the beam.
The kicker pulsing at 81.25 MHz. “Flat” beam. 10-Oct-2017.

Summary

- The MEBT Allison scanner is characterized.
  - No major artifacts are observed
- The beam transverse distribution is a combination of the phase-independent, Gaussian core and the long, strongly phase-dependent tails
  - >0.1% of the beam with actions >10x rms emittance
- The MEBT do not change significantly the transverse beam distribution
  - Acceptable changes through the pulse and with chopping
- Scraping in the beginning of the MEBT can significantly decrease the tails of the beam injected into the linac
  - Efficiency depends on the scraper location

Discussion (personal opinion)

- What distribution to chose at the end of the MEBT to proceed with linac simulations?
- Implicit intention (mine) before starting PIP2IT
  - "Measure the output beam properties and generate the linac input distribution based on these measurements"
  - Problems
    - How to translate several hundred measured points into 1M macroparticles of the distribution?
    - Measure only projections of the 6D distribution, while motion in different planes is coupled even for core particles*
    - Measure tails at 0.1% level and want to predict losses at 10^{-5}

*APT seminars: J.-P. Carneiro et al., Longitudinal Beam Dynamics Studies at the PIP-II Injector Test Facility, 11-Oct-2018;
B. Cathey, Six-Dimensional Measurements from the SNS Beam Test Facility, 9-Oct-2019

6D Gaussian

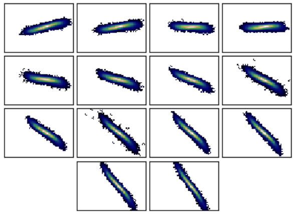
- The most frequent way to implement initial distribution:
  - Measure the rms parameters in 3 planes in MEBT
  - Generate 1M input distribution based on them
    - Includes far tails, e.g. cut at $\frac{J_x}{\varepsilon_x} + \frac{J_y}{\varepsilon_y} + \frac{J_z}{\varepsilon_z} \leq 9$
  - Easy to look at small losses
- If the main area of interest is far from the input (e.g. high energy only), may work reasonably well
  - After many betatron/plasma oscillations and scraping, the distribution in the interesting area might be weakly affected by details of the initial distribution
  - Not likely immediately after the start

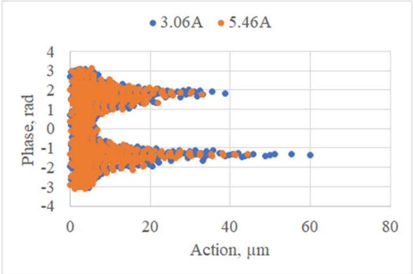
Start-to-end simulation

- Start with the 1M distribution measured at the ion source and pass it through the entire linac (standard for design reports)
- PIP2IT experience:
  - some discrepancy between measured and simulated Twiss parameters at the RFQ exit. Not clear why.
    - Many betatron periods in RFQ?
  - Discrepancy in MEBT optics
    - Field overlap between quads?
- Using a 6D Gaussian distribution with measured rms parameters for the simulation input sounds more prudent

Description in action-phase coordinates

- Phase density distribution is not sensitive to changes in linear focusing
  - J-φ picture only shifts vertically

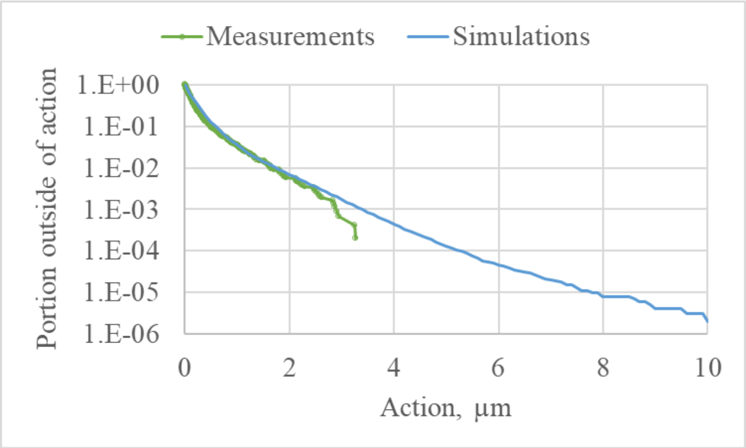




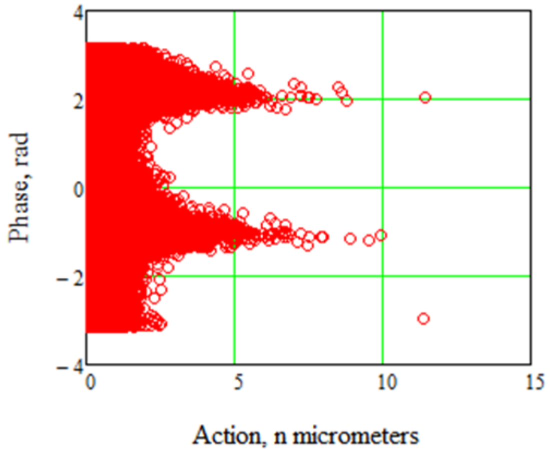
- The distribution is sensitive to non-linear effects that are not likely to be strongly affected by details of the linear focusing
  - Characteristic bunch sizes, β-function variations, magnet aberrations etc.
- Simulation predictions for the distribution should be good even there is a discrepancy in Twiss parameters

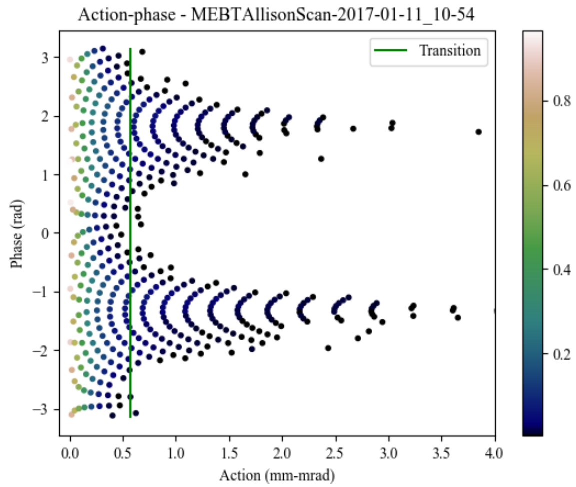
Comparison with simulations

- The simulated distribution in action-phase coordinates is similar to the measured one



Portion of particles outside of a given action in X plane. Green- measurements with AS on 11-Jan-2017, blue –distribution at the RFQ exit simulated with 1M macoparticles (J.-P. Carneiro).





The same simulated (left) and measured (right) data in J-φ coordinates. 10^6 macroparticles; 363 pixels.

Summary-II: Possible scenario

- To deal with tails, can proceed with start-to-end simulations and tweak linear focusing coefficients to match the rms parameters
  - Start with the ions source, where the distribution is simple (UG)
    - + large scraping in LEBT, + many oscillations upstream of MEBT
  - Compare with as many projection as possible; try to understand and resolve possible inconsistencies
  - For remaining discrepancies: adjust "fudge factors" in MEBT magnets to deliver in simulations the correct Twiss parameters
    - And may be the phase of the tails
- Use the resulting distribution as an input for linac simulations

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