Analysis Techniques and Measurements of Non-Relativistic Hadron Beams

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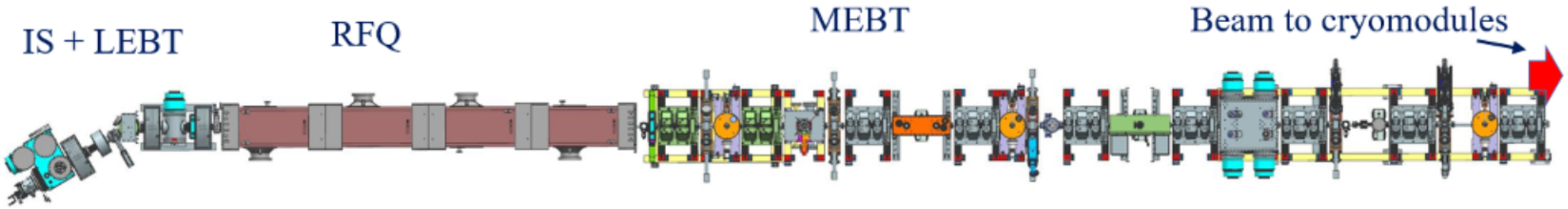
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Hadron accelerator front ends

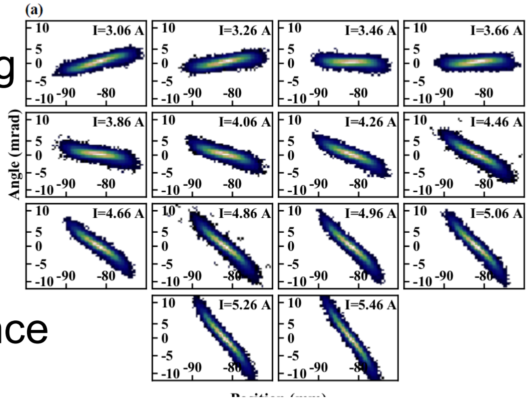
- Front ends consist of ion source, LEBT, RFQ, and MEBT
  - Designed to provide initial acceleration, bunching, and matching into the main accelerating structure
- The beam typically has low energy and is non-relativistic
  - ~10s of keV in LEBT, ~1 MeV in MEBT
  - Low rigidity causes the beam to evolve relatively rapidly
  - Can result in significant space charge effects
  - The beam can be easily manipulated and scraped
- Require a diagnostic suite in MEBT to ensure proper matching
  - SRF accelerators detailed knowledge of the beam tails is desired so they can be removed to avoid losses
- Presented measurements were taken at PIP2IT MEBT at Fermilab

PIP2IT MEBT beam parameters	
Species	H-
Energy	2.1 Mev
Current	5 mA
Bunch rep rate	162.5 MHz
Transverse emittance	<0.23 mm mrad



Transverse phase space measurements

- Typically quantified measured phase space with the emittance and Twiss parameters
  - But the measured contains more information that solely rms parameters
  - Can only directly compare the emittance between separate measurements
  - The beam rotates in x-x’ phase space during transport, making direct comparisons challenging



- Solution: convert the measured phase portraits into action-phase (J-φ) coordinates
  - $J = \frac{1}{2}\left(\beta u'^2 + 2\alpha u u' + \gamma u^2\right) \quad \phi = -\arctan\left(\frac{\alpha u + \beta u'}{u}\right)$
  - Action is a constant of motion under linear optics, phase varies with the betatron phase advance
- Measure x-x’ distribution then convert to J-φ coordinates
  - Intensity – J distribution should be stable
  - J-φ distribution shows tails as two branches in phase
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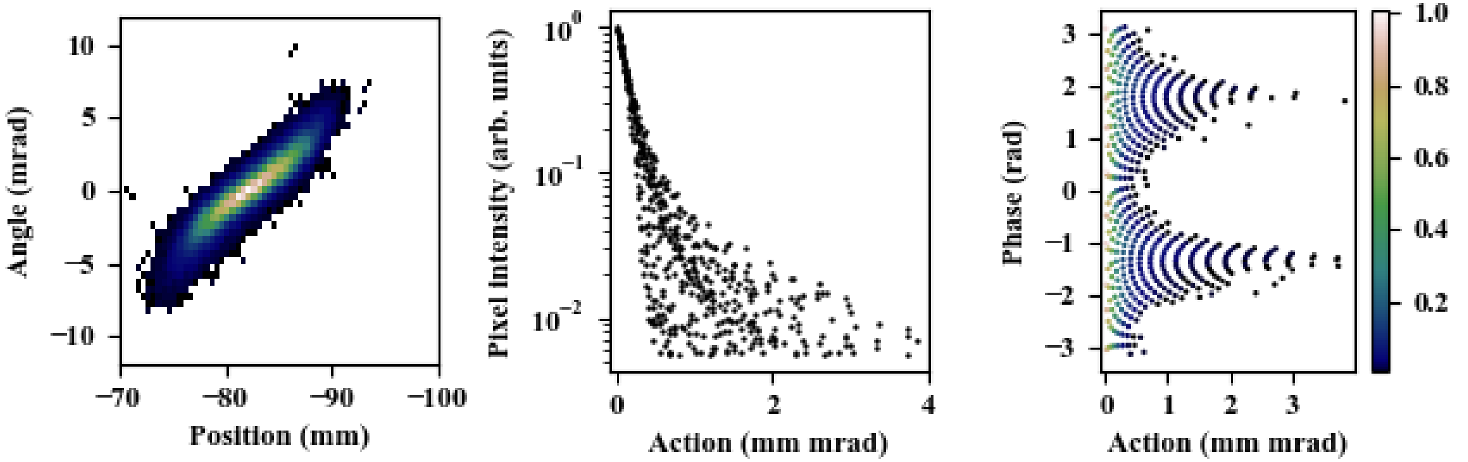
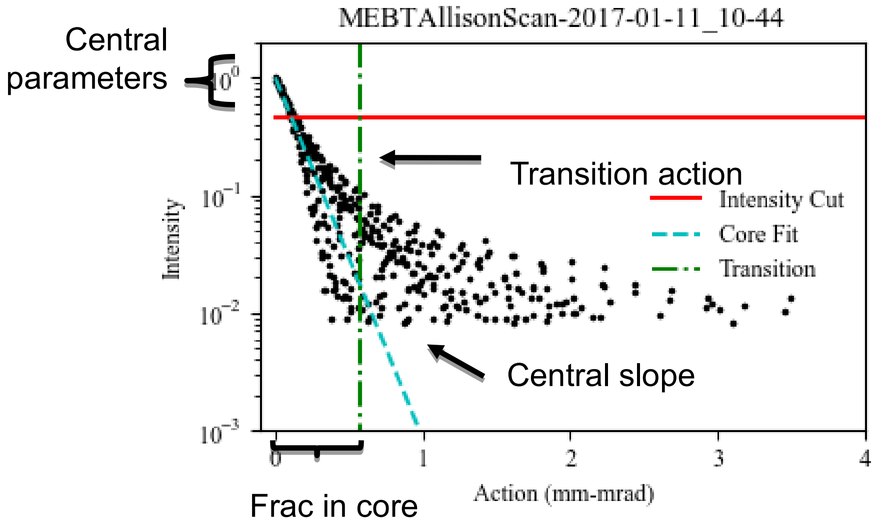


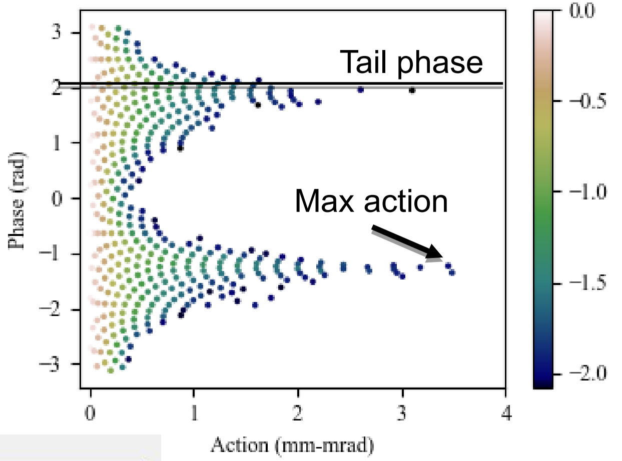
Action-phase parameterization

- Action is calculated with the “central” Twiss parameters
  - Fit Gaussian to upper portion of beam
    - $I_{\text{gauss}} = I_0 e^{-J/\epsilon_C} = I_0 e^{-\frac{1}{2\epsilon_C}\left(\gamma x^2+2\alpha x x'+\beta x'^2\right)}$
  - Used to avoid influence of tails in core definition
- Characterize beam with 7 parameters
  - Central Twiss, α, ß – shape of core
  - Central slope – emittance if it was Gaussian
  - Transition action – boundary between tails and core
  - Fraction in core – relative size of tails
  - Tail phase – avg phase of positive branch
  - Maximum action – max beam size


Central parameters

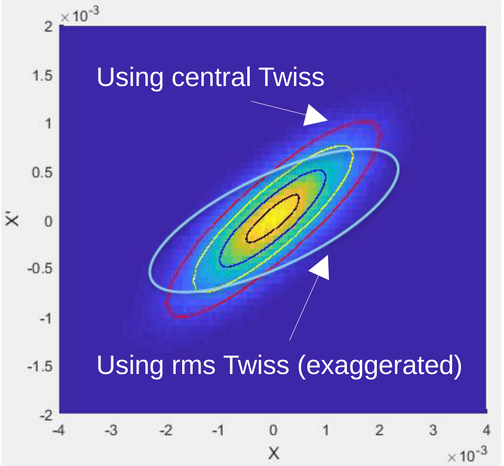
Transition action

Central slope

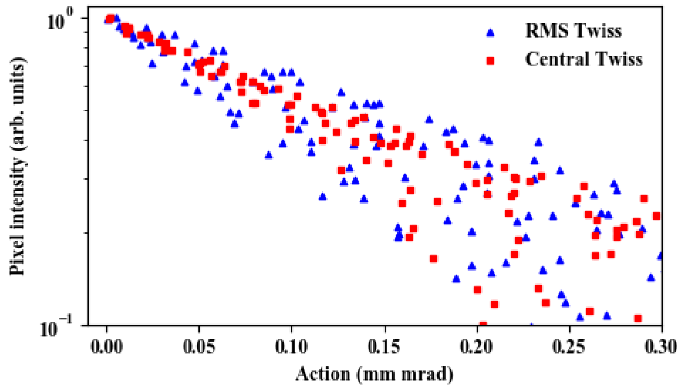

Frac in core

Tail phase

Max action

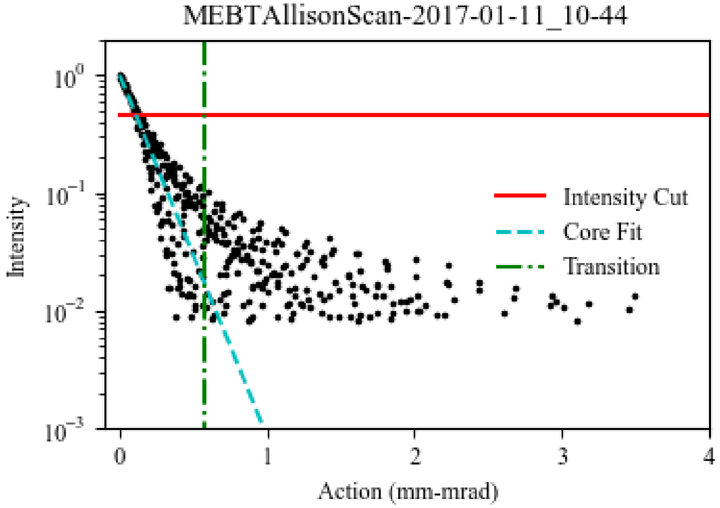

Using central Twiss

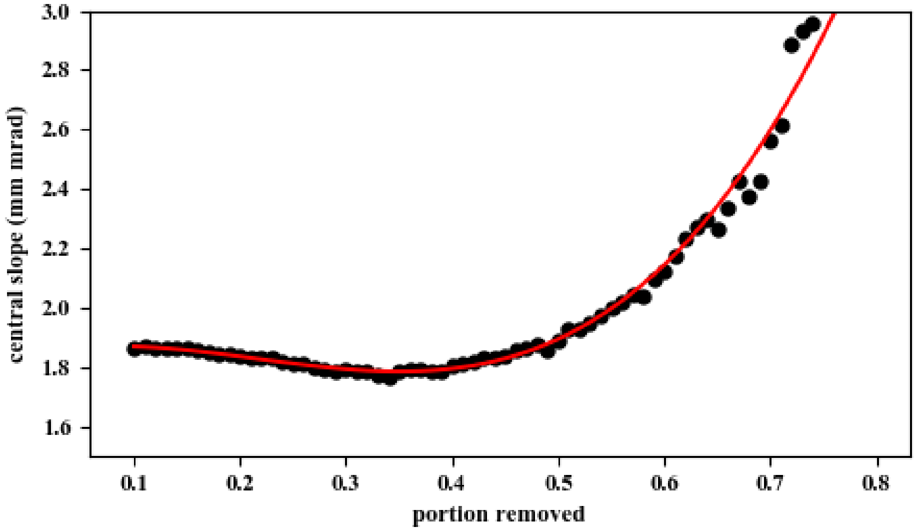
Using rms Twiss (exaggerated)

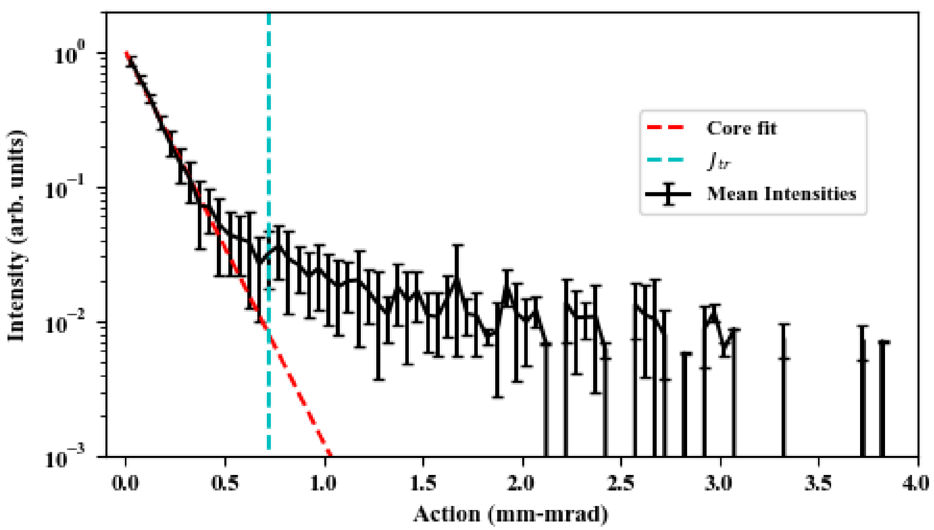


Determining central parameters

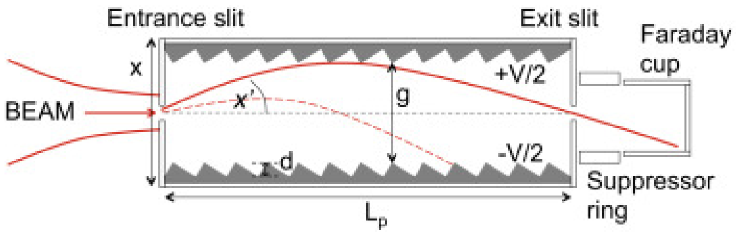
- Remove lowest intensity pixels then fit remaining pixels to a Gaussian
- Fit to a range of removed intensities, central parameters are set to the cut that gives the minimum central slope
  - Use to avoid affects of tails and poor statistics
- Transition action is where the average distribution deviates from the central fit







Slit size effects



- Measurements shown were taken at PIP2IT with an Allison scanner
  - Two fixed slits with voltage applied in gap
  - Scan position by moving device
  - Scan angle by scanning voltage

Parameter	Value	Unit
Slit size	0.2	mm
Slit separation	320	mm
Plate voltage	±1000	V
Plate length	300	mm
Plate separation	5.6	mm
Maximum measurable angle at 2.1 MeV	±12	mrad

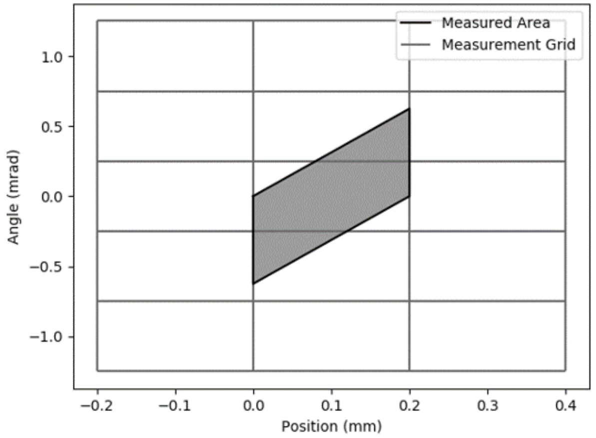
- The non-zero size of the slits distort the measured distribution
  - Passed phase space is a rhombus and can overlap with neighboring pixels
- Measured distribution can be found by integrating beam distribution over the front and back slits
- E.g. for a Gaussian beam and Allison scanner of length , and slit size the measured distribution is:

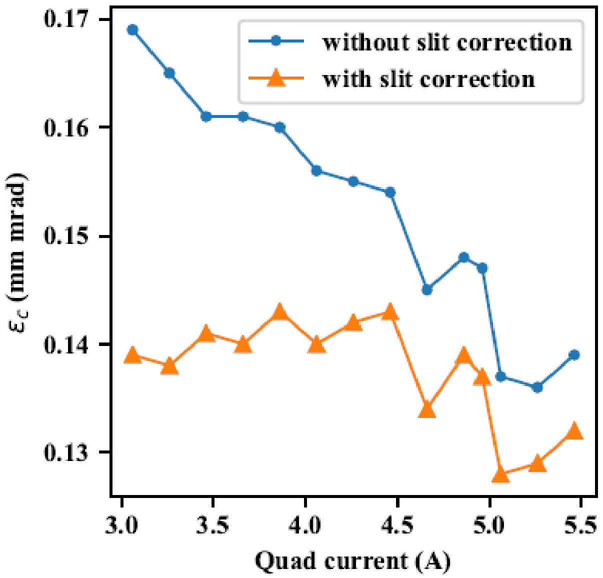
$$I_{\text{gauss}} = I_0 e^{-J/\epsilon_c} = I_0 e^{-\frac{1}{2\epsilon_c}\left(\gamma x^2 + 2\alpha x x' + \beta x'^2\right)}$$

$$I_{\text{meas}}(x, x') = \exp\left(-\frac{1}{2\epsilon_c}\left[\gamma x^2 + 2\alpha x x' + \beta x'^2\right]\right)$$
$$\left(1 + \frac{d^2}{6\epsilon_c^2}\left[\epsilon_c\left(\frac{2\alpha}{\ell} - \frac{2\beta}{\ell^2} - \gamma\right) + 2\left(\frac{\alpha x + \beta x'}{\ell}\right)^2 + \right.\right.$$
$$\left.\left.(\alpha x' + \gamma x)^2 - 2\left(\frac{\alpha x + \beta x'}{\ell}\right)(\alpha x' + \gamma x)\right]\right)$$

d = slit size
l = slit separation

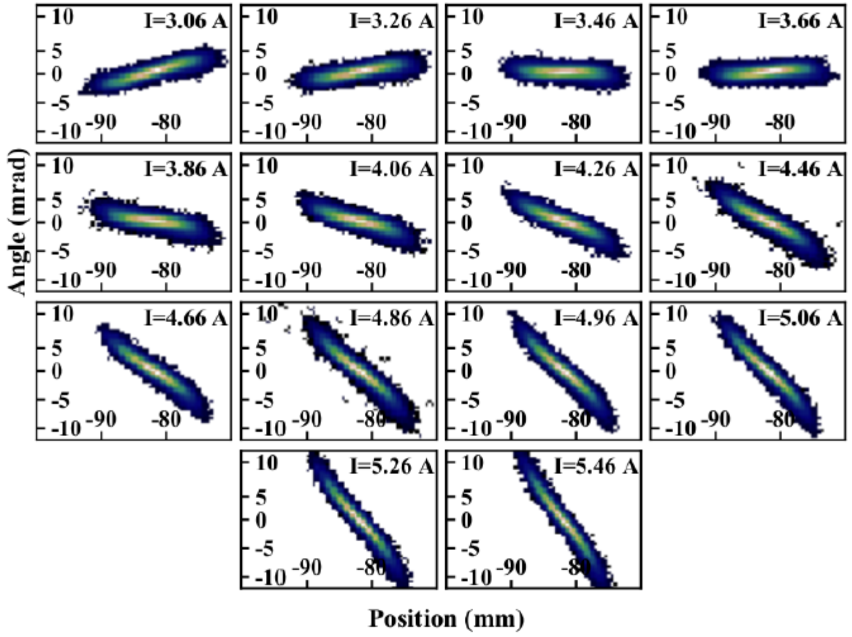
Single Setting Phase Space Area
d=0.2 mm, L=320 mm, step=0.5 mrad

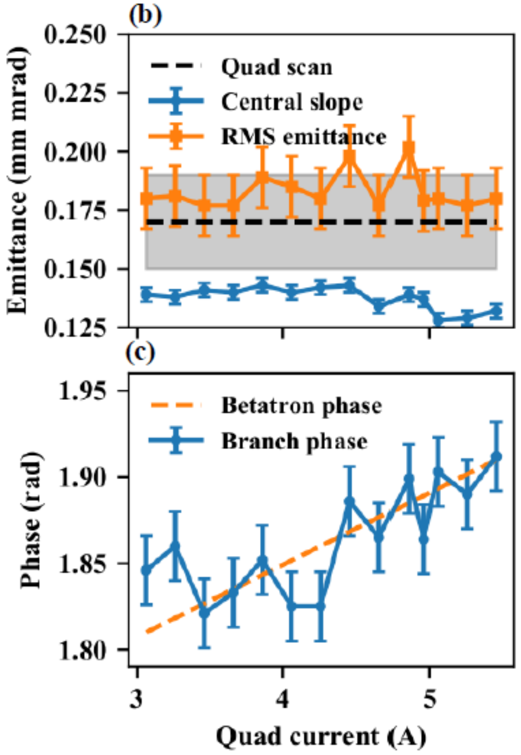


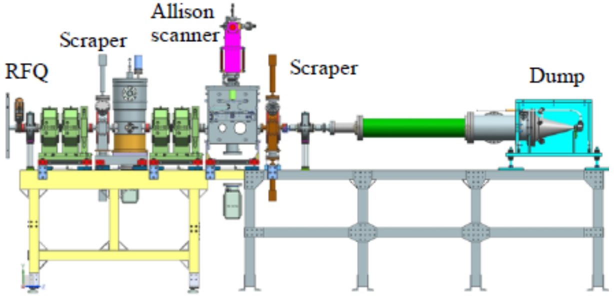


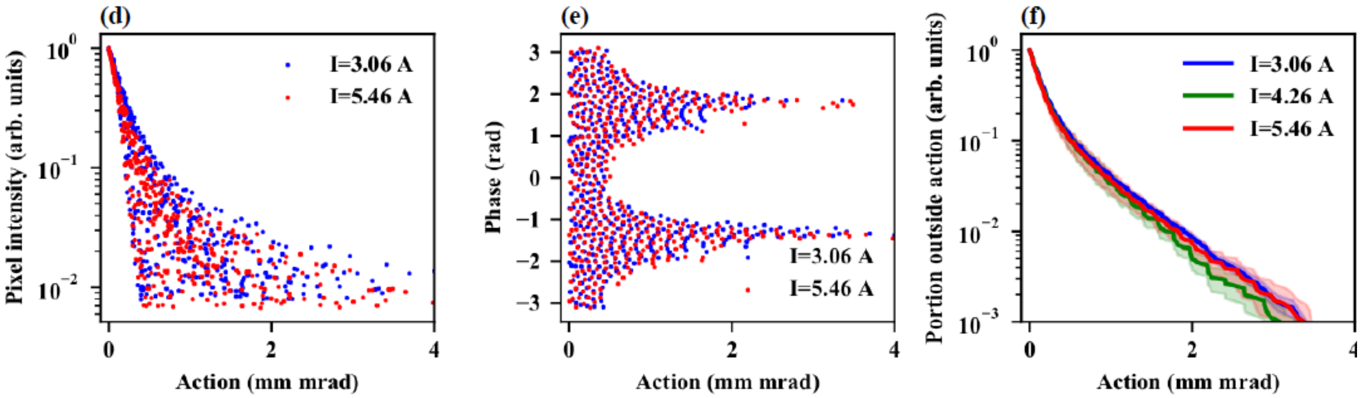
Quadrupole scan

- Action distribution is constant under linear optics
  - Vary strength of closest quadrupole to AS, distribution should not change
- Distribution of intensities in action is constant
  - Central slope and the fraction in core are constant
- Change of branch phase agrees with simulated change in betatron phase advance







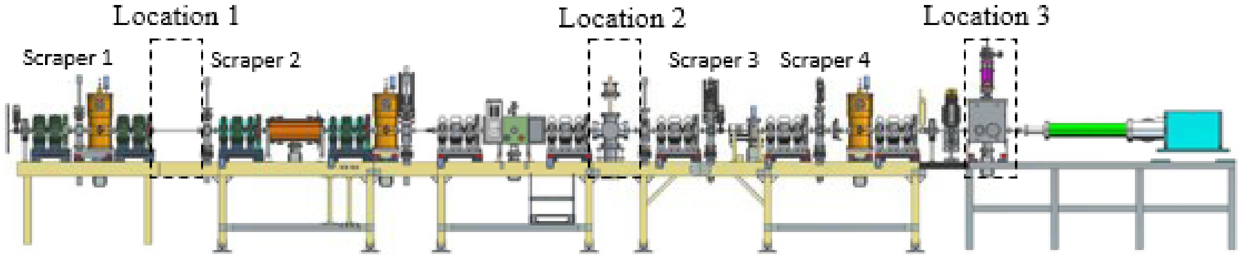


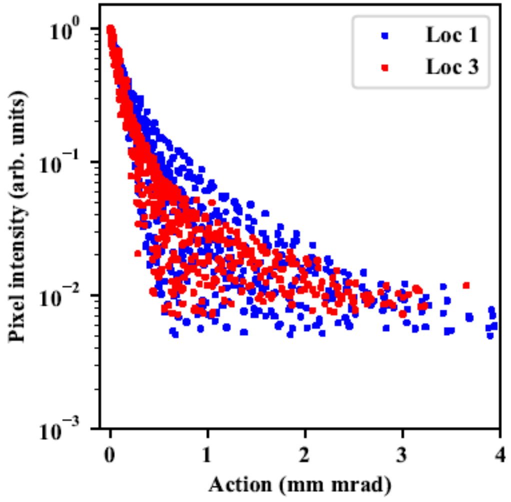
PIP2IT MEBT config 1

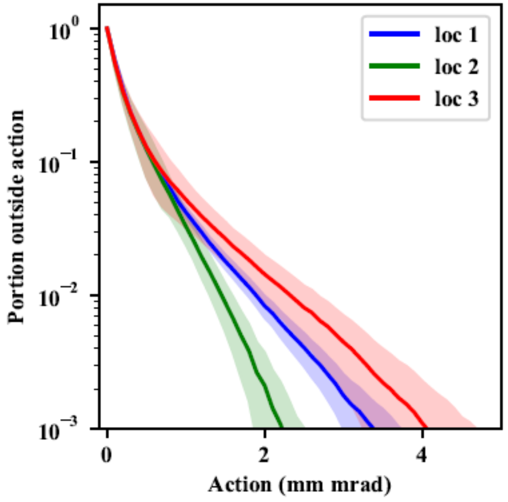
Distributions at different locations

- Phase portraits were taken at three locations along the PIP2IT MEBT
  - Location 1 measured the horizontal plane, Locations 2 and 3 measured the vertical plane
  - Values averaged over 10 scans at each location
- Both planes have similar rms emittances
  - But the central slope and percent of the beam in core is larger in the horizontal plane
- Signs of tail growth between locs 2 and 3

Location	rms ϵ	ϵ_c	% in core
1 - horz	0.20 ± 0.013	0.146 ± 0.003	88 ± 2.5
2 - vert	0.19 ± 0.015	0.117 ± 0.013	71 ± 11
3 - vert	0.22 ± 0.024	0.123 ± 0.011	72 ± 10

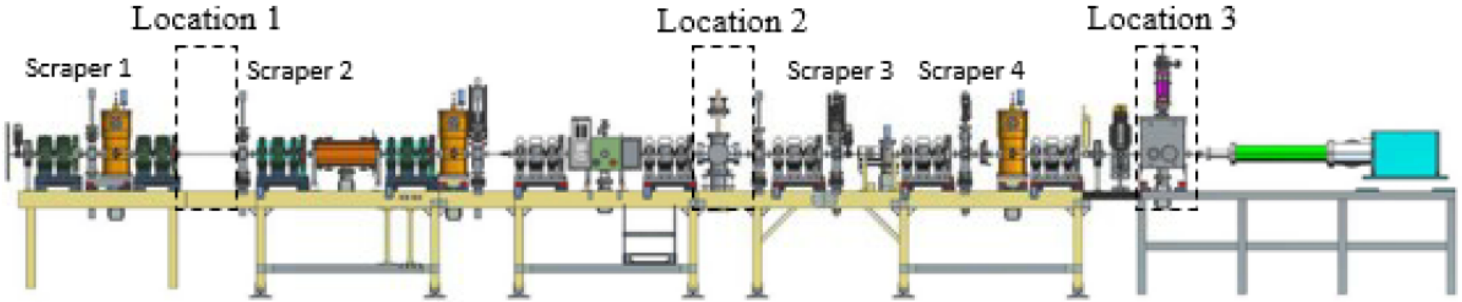






Beam tail removal

- Scrapers are inserted to remove particles with large action
  - Standard procedure: each scraper removes the same portion of the beam current
- It is possible for a scraper to not to remove the large action particles
  - Due to the phase dependence of the branches
- Phase dependence can be used to increase scraping efficiency
  - Scrapers that do not intercept the branches should remove less of the intensity



Blue pixels – non-scraped beam
Red pixels – scraped beam
Dashed line – estimate of where the beam was scraped

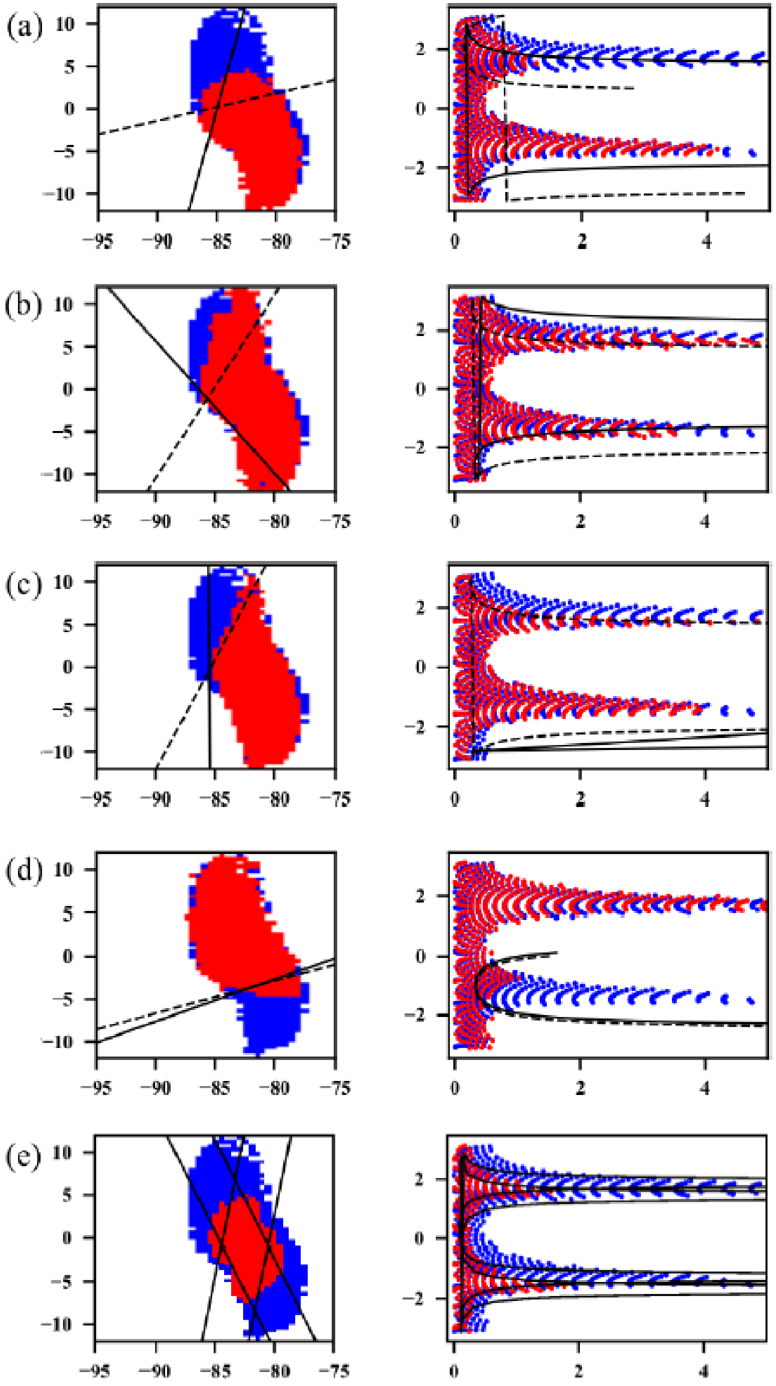
Scraper 1

Scraper 2

Scraper 3

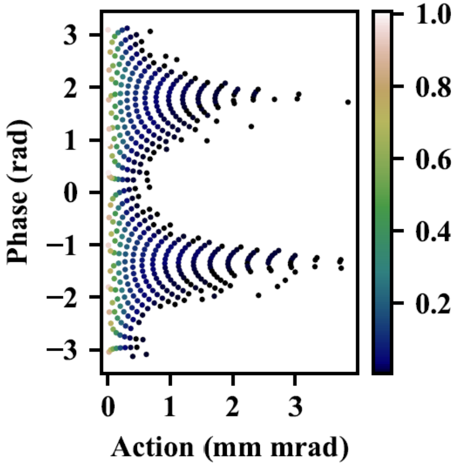
Scraper 4

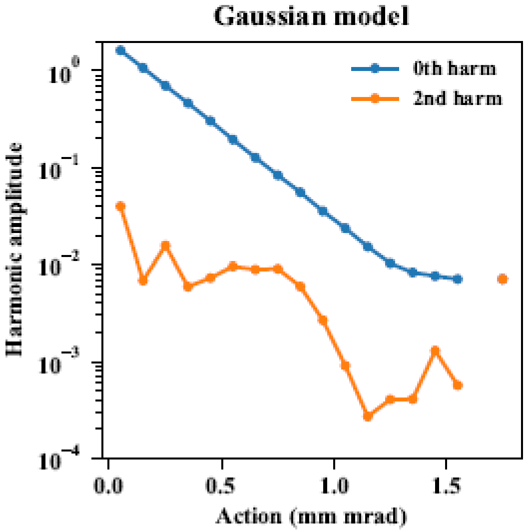
All scrapers

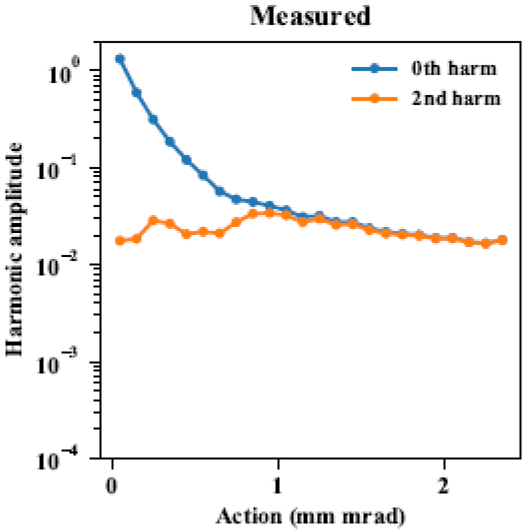


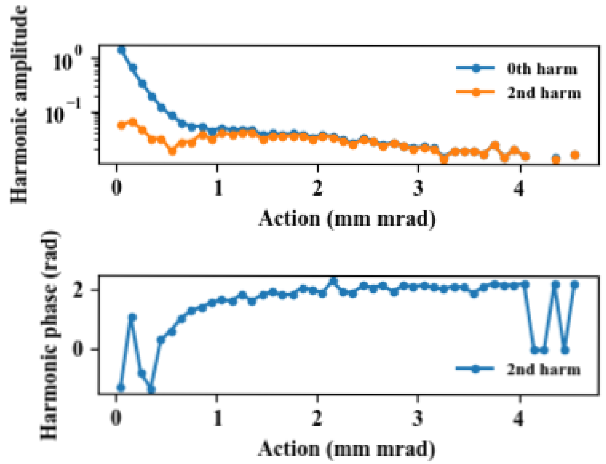
Relative size of beam tails

- The tails for two distinct branches in phase. Therefore, the tails contribute to the 2nd harmonic in phase
- Relative amplitude of tails can be measured by taking Fourier transform in each action bin
  - Compare the amplitudes of the 0th and 2nd harmonics as function of action
- At low action, e.g. the core, 0th harmonic dominates. In the tails it is comparable to the 2nd harmonic
  - For a synthetic Gaussian beam with noise, the 2nd harmonic is ~2 orders of magnitude lower than the 0th
- Phase of the 2nd harmonic shows the location of the tails





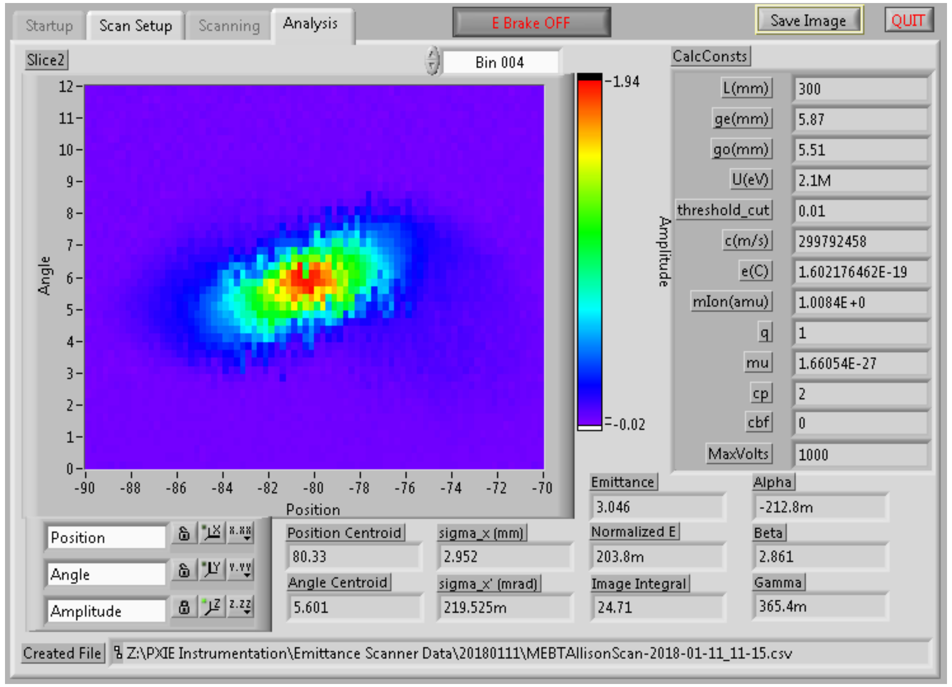




Summary

- Shown it is possible to measure distributions in action and they are stable under changes to optics
- Action distributions are useful for directly comparing different phase space measurements
  - E.g. comparing horizontal and vertical planes
- Future work
  - Presented studies were limited by noise
    - Dynamic range of only ~2 orders of magnitude making tail measurements challenging
    - Estimate we only measure ~95% of the total intensity
  - Beam measurements were distorted by beam jitter
    - Made directly correctly amplitudes for slit effects impossible (too noisy to deconvolve)
  - Continue to develop harmonic analysis

Example of noise due to beam jitter



CalcConsts

L(mm)	300
ge(mm)	5.87
go(mm)	5.51
U(eV)	2.1M
threshold_cut	0.01
c(m/s)	299792458
e(C)	1.602176462E-19
mIon(amu)	1.0084E+0
q	1
mu	1.66054E-27
cp	2
cbf	0
MaxVolts	1000

Position Centroid	80.33
Angle Centroid	5.601
sigma_x (mm)	2.952
sigma_x' (mrad)	219.525m
Emittance	3.046
Normalized E	203.8m
Image Integral	24.71
Alpha	-212.8m
Beta	2.861
Gamma	365.4m

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