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Optical Design of the PXIE MEBT scraping system

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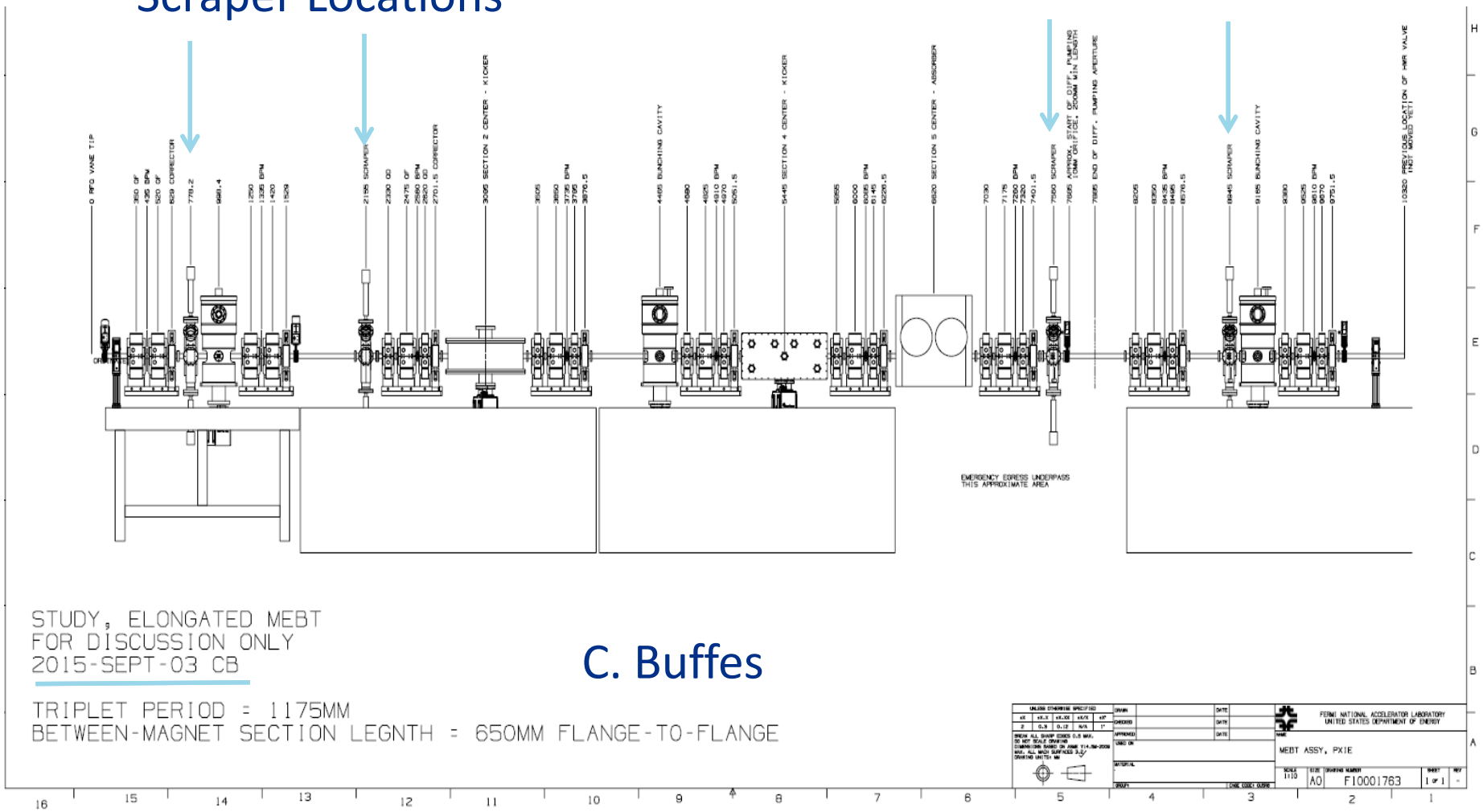
Overview

- MEBT
- Scraper System
- Scopes and Limitations of PXIE MEBT Scraping Systems
- Results
- Summary

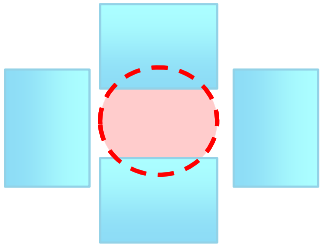
Medium Energy Beam Transport Section (MEBT)

Scraper Locations

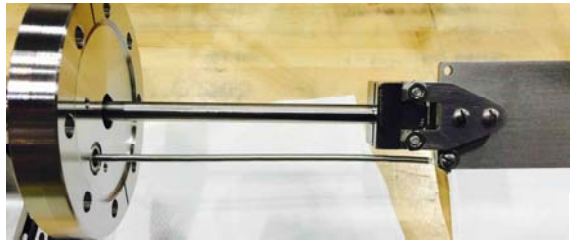


C. Buffes

Beam Scraping System



Pictorial presentation of a scraper set. 4 moveable, radiation – cooled blades.



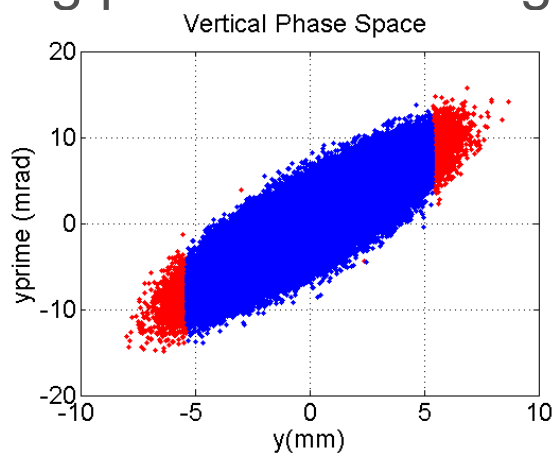
Single blade.
C. Baffes, K. Kendziora

View of scraper assembly from 45° port with all blades moved in.

- MEBT scraper system consists of 4 scraper sets, 4 blades in each set.
- The scrapers can be utilized as:
  - Diagnostic
    - Beam size and profile measurements; beam halo
  - Part of active protection system
    - Increased scraper current generates alarm signal for MPS
  - Scraping (the main function)
    - Scrape the beam halo or intercept the beam in case of incidents

Halo removal

- For effective halo removal, need two sets of scrapers
  - Scraper removes particles with largest offsets in the scraper location, leaving particles with large angles.

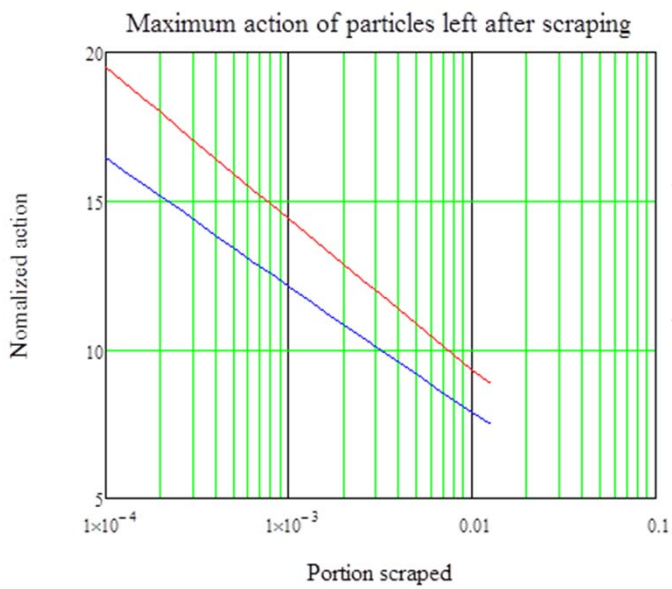


  - The second scraper set should be placed where these angles are transformed into large offsets, i.e. at a betatron phase advance ~π/2 after the first scraper
- The figure of merit may be the maximum action of particles left

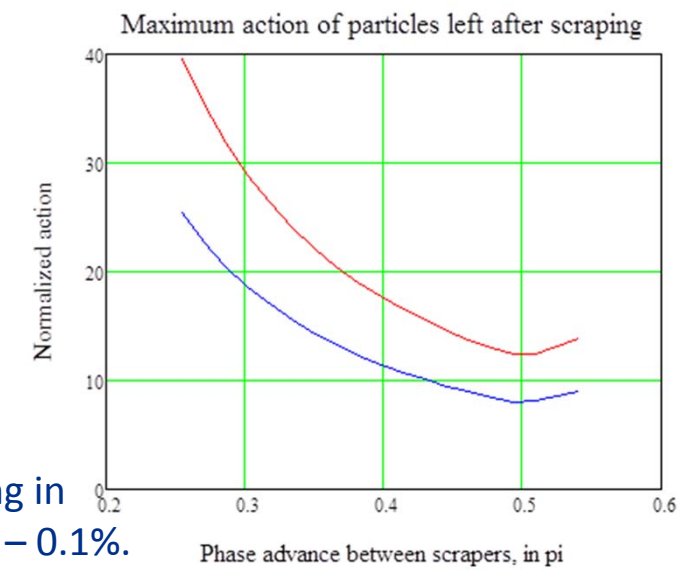
$$-2J_i = \gamma_{twiss} x_i^2 + 2\alpha_{twiss} x_i . x'_i + \beta_{twiss} x_i^2$$; normalized by rms emittance $J_n = J_i / \varepsilon_{rms}$

Simple estimations: two scraper sets in one plane

- Maximum action left after scraping with two scraper sets can be estimated in the simplest case – one plane
  - Two sets, Gaussian, no space charge, no non- linearity
  - Scrapers in each set are moved symmetrically in
  - Beam losses in two sets are equal
- For ~9ε, need to scrape ~1% with scrapers separated ~90º



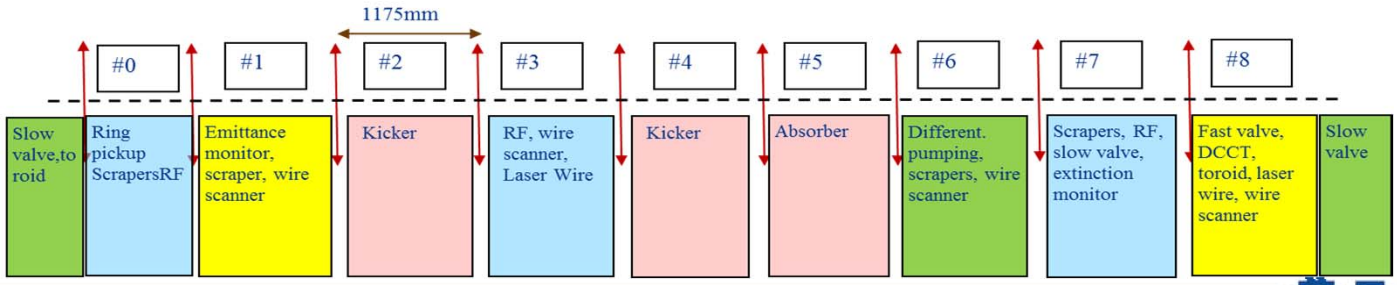
Blue - 90º, red - 81º of phase advance. Actions are normalized by the rms emittance of the initial beam.



Blue – 1% scraping in each scraper, red – 0.1%.

Limitations for the MEBT scraping system

- *Design specification for MEBT allows the total beam loss up to 5 %*
  - *Have enough beam from RFQ*
- Additional limitation from scraper design: power deposition per scraper
  - Nominal beam power in MEBT is 10.5 kW (2.1MeV x 5mA)
  - Max power is ~100W per set (~1% of total)
- In the last sections, the limitation is by the gas load
  - Need to keep loss at ~ 0.1% per set
- Scraper positions should be compatible with the mechanical design



Goals for the MEBT scraper system

- The main goal is to decrease irradiation of SRF
  - Accidental and by halo particles
  - Preferably, only particles well within SRF acceptance should go into HWR
- Remove transverse tails of the beam coming from RFQ and halo created by space charge
  - The relevant phase advance is affected by space charge
- Decrease effects from incidents
  - Malfunctioning of magnets etc.
  - Simulated example: misfiring kickers so that the voltage is half
  - In the case of dipole motion, the relevant phase advance is for zero space charge

Requirements for the scraper system in MEBT

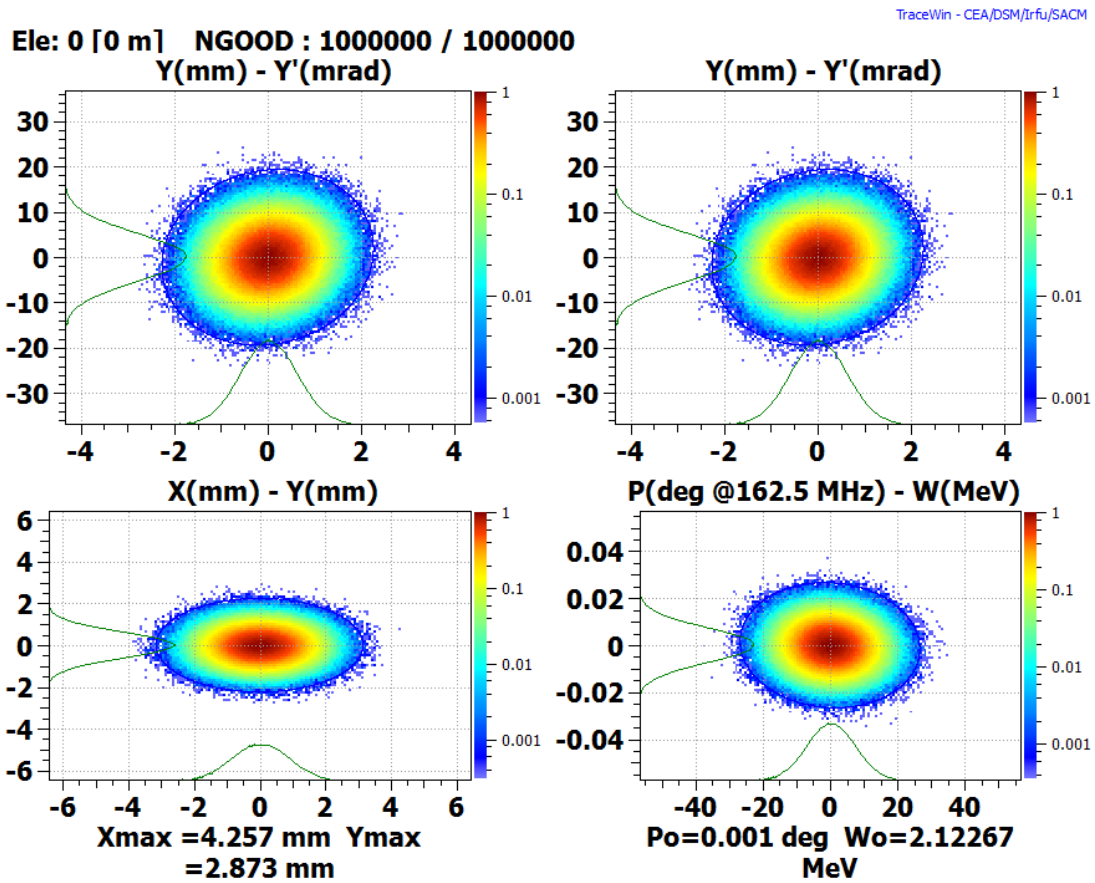
- 4 sets of scrapers with 4 blades in each
  - Two sets following RFQ and two upstream of HWR
- The first two sets intercept ~0.8% of beam each
- The downstream sets intercept ~0.1% each of the bunches passing through
- Position and insertion of the scrapers should be optimized to minimized the maximum action at the entrance of HWR
  - For transverse halo, assuming 5mA, $\varepsilon_t/\varepsilon_z$ = 0.21/0.28 μm (n)
  - For dipole motion
- The beam absorber is another scraping element, which should be taken in consideration

TraceWin simulations

- Several iteration of various placement of scrapers with the same initial parameters

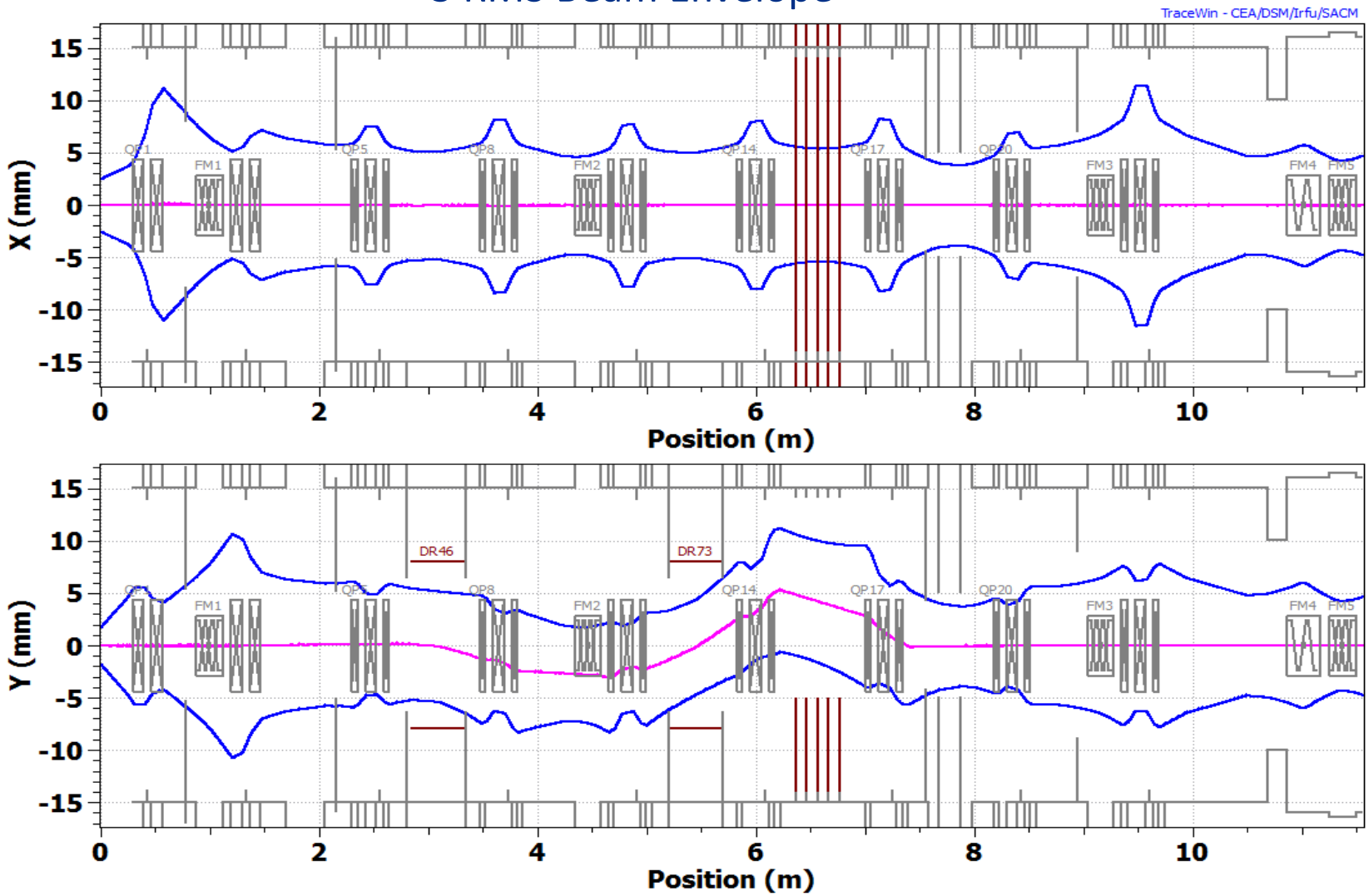
Initial Beam Distribution

- 5 mA beam current
- Initial normalized RMS emittance are
  - ε_t **= 0.21 pi mm mrad**
  - ε_z **= 0.28 pi mm mrad**
- 6-D Gaussian, uncoupled distribution
- Truncated at 6σ
- 1M macroparticles
- Twiss parameters from RFQ simulations

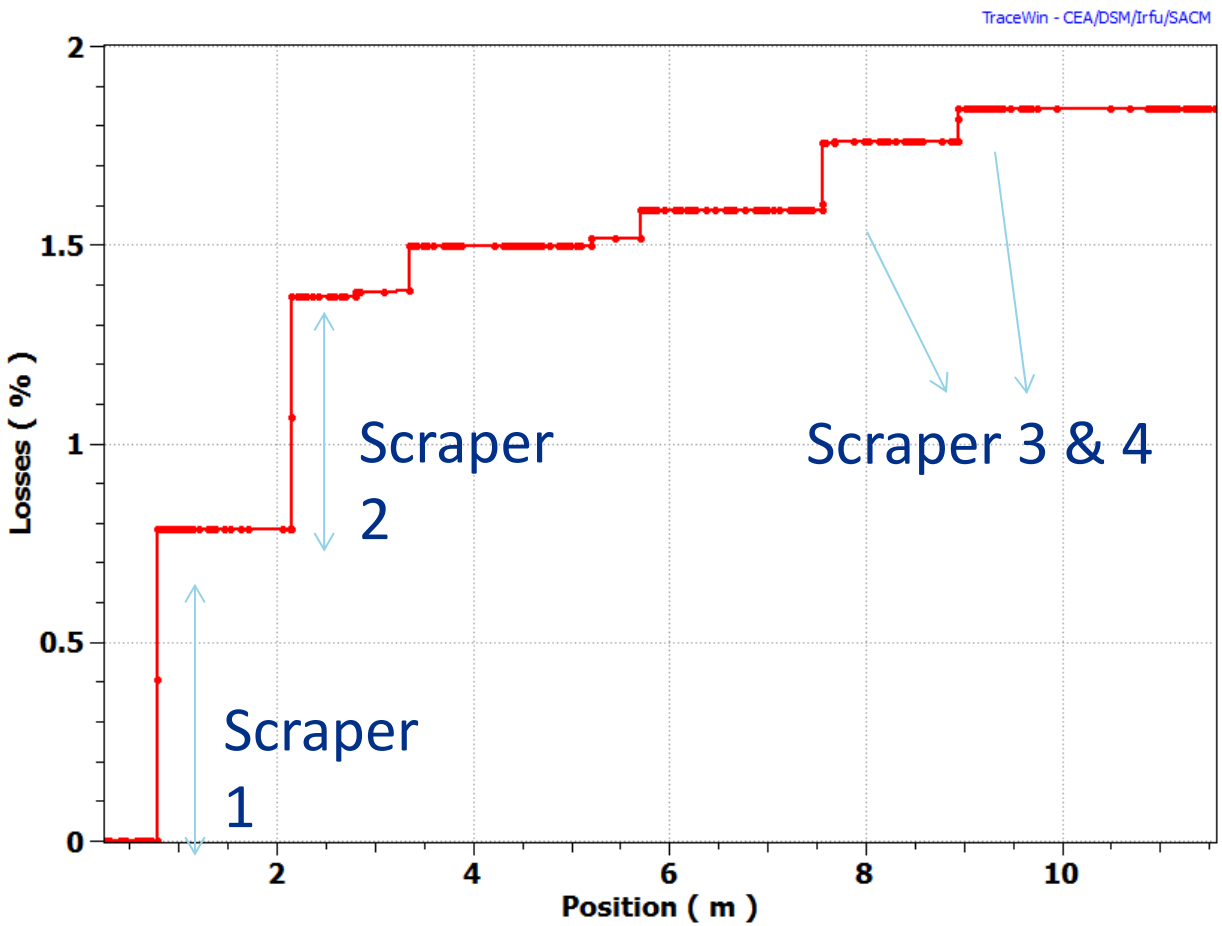


Transverse Beam Envelope in MEBT for Passing Beam

- 3 RMS Beam Envelope

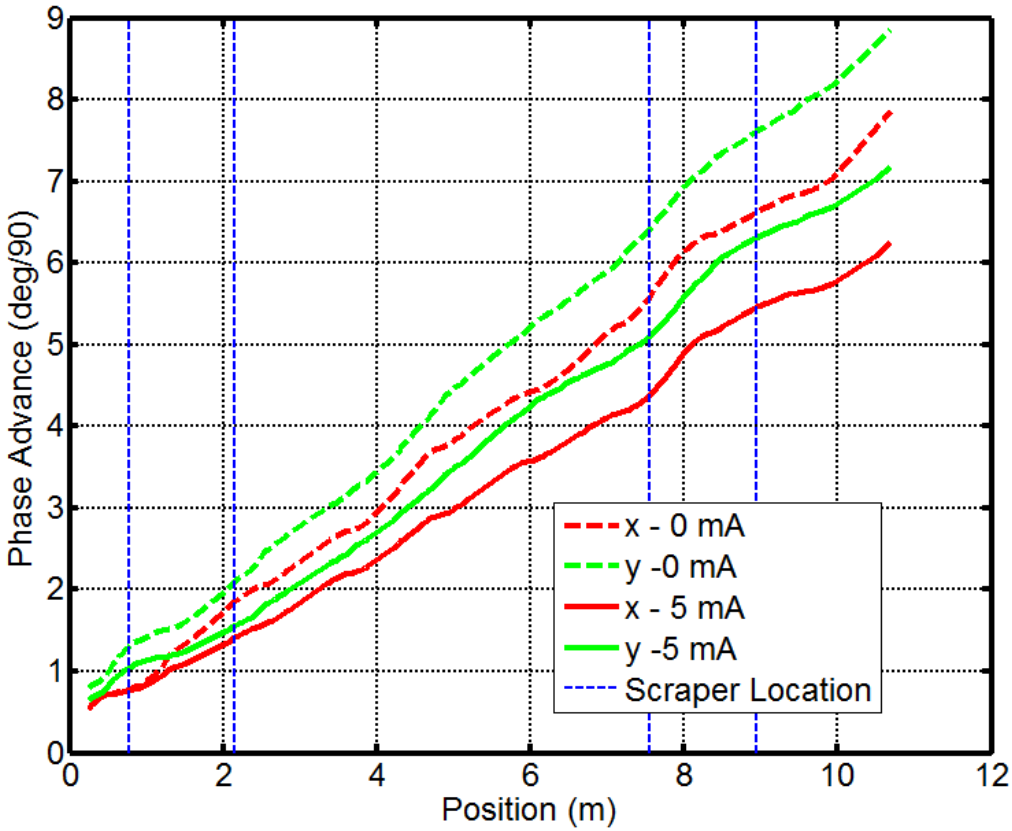


Beam Losses: Passing Beam



Scraper 1	Scraper 2	Scraper 3	Scarper 4
0.8 %	0.6%	0.16 %	0.08 %

Beam Phase Advance in MEBT



Phase Advance at Scraper Locations

		Scraper 1	Scraper 2	Scraper 3	Scraper 4
0 mA	x	70.3	166.5	504.4	595.6
	y	117.8	188.3	578.8	684.6
5 mA	x	68.4	127.2	395.3	491.2
	y	94.2	140.3	459.8	567.5

- Beam Phase advance is different in horizontal and vertical planes.
- Space charge effects reduces phase advances.

Notes on scraper placement

Phase Advance between scrapers, º
(optimum = 90 º)

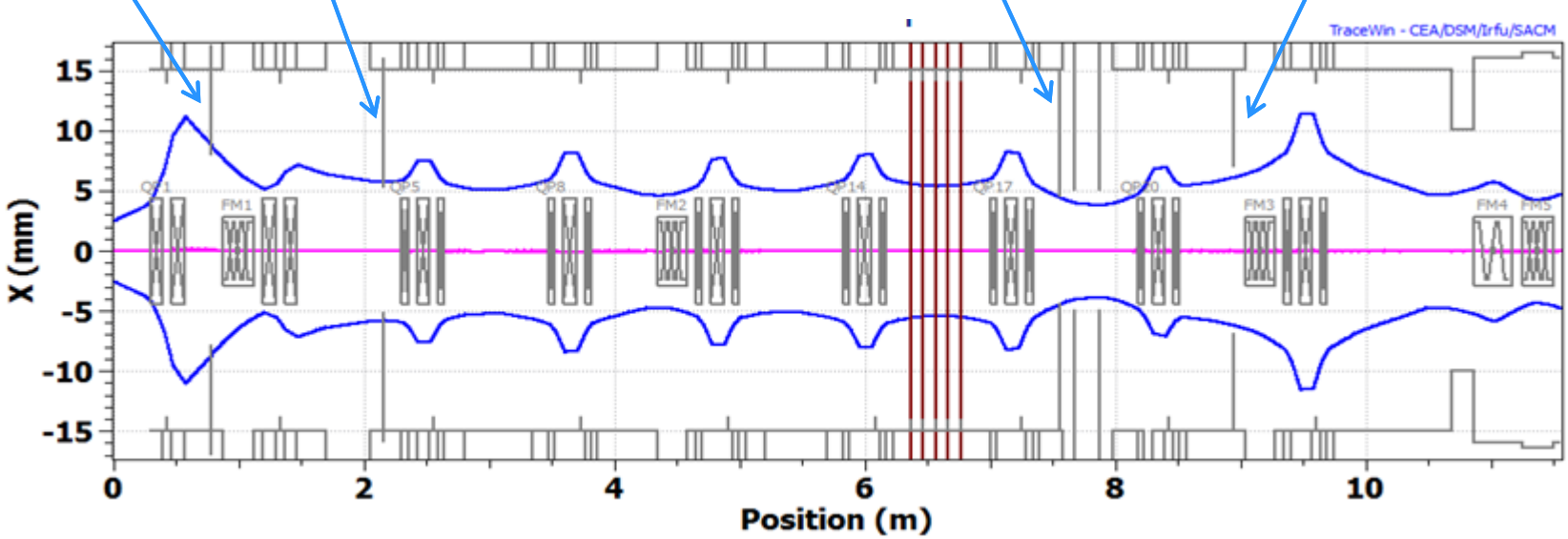
		Scraper 1-2	Scraper 2 -3	Scraper 3-4
0 mA	x	96.2	337.9	91.2
	y	70.5	390.5	105.8
5 mA	x	58.8	268	95.9
	y	46.1	319.5	107.7

1st set is moved upstream as far as possible

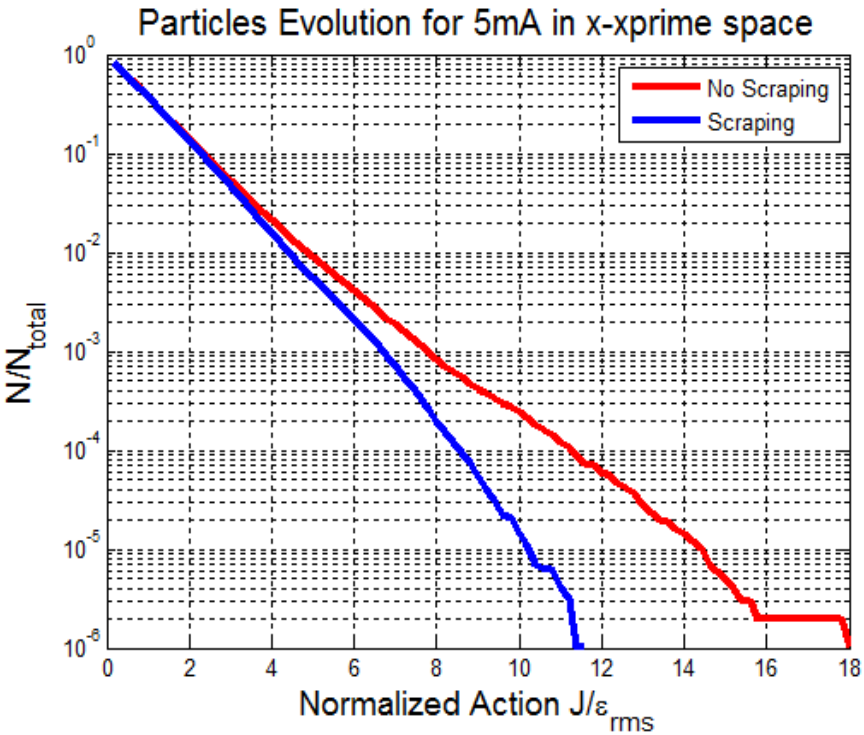
2nd set is moved downstream as far as possible

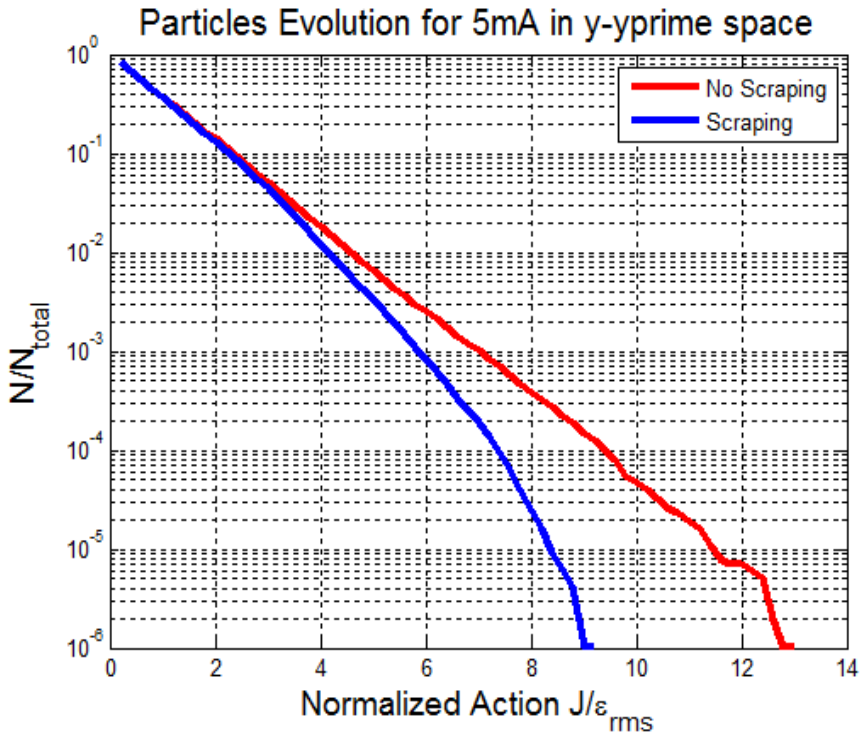
3rd set is upstream of differential pumping

4th set position is being optimized



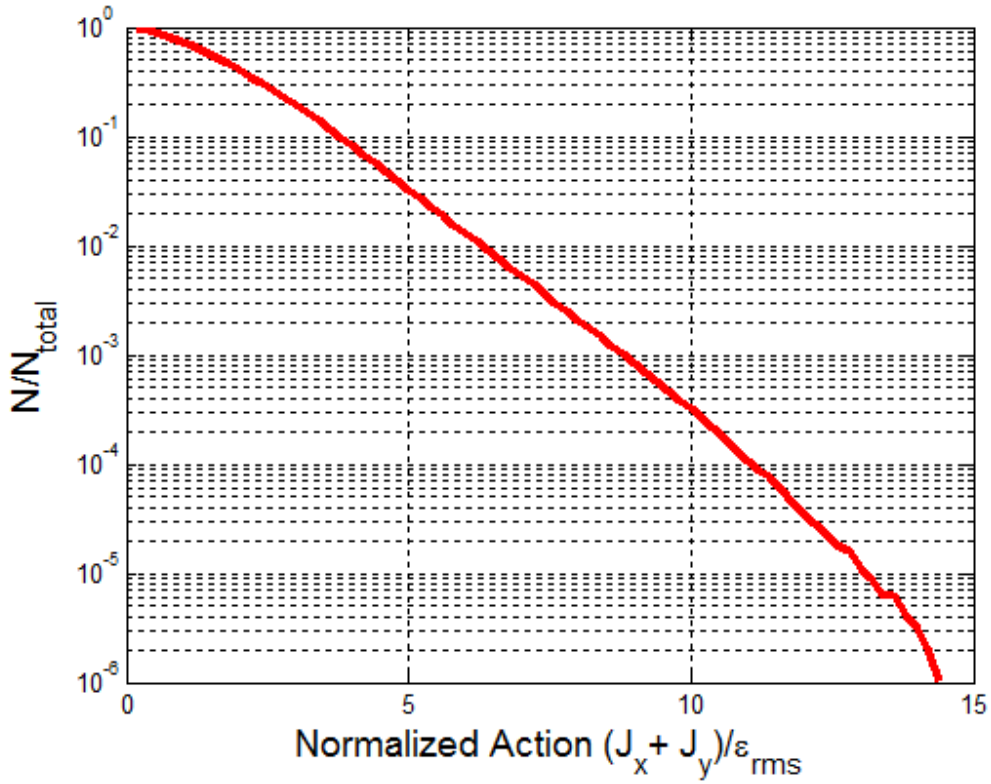
Particle Distribution at End of MEBT





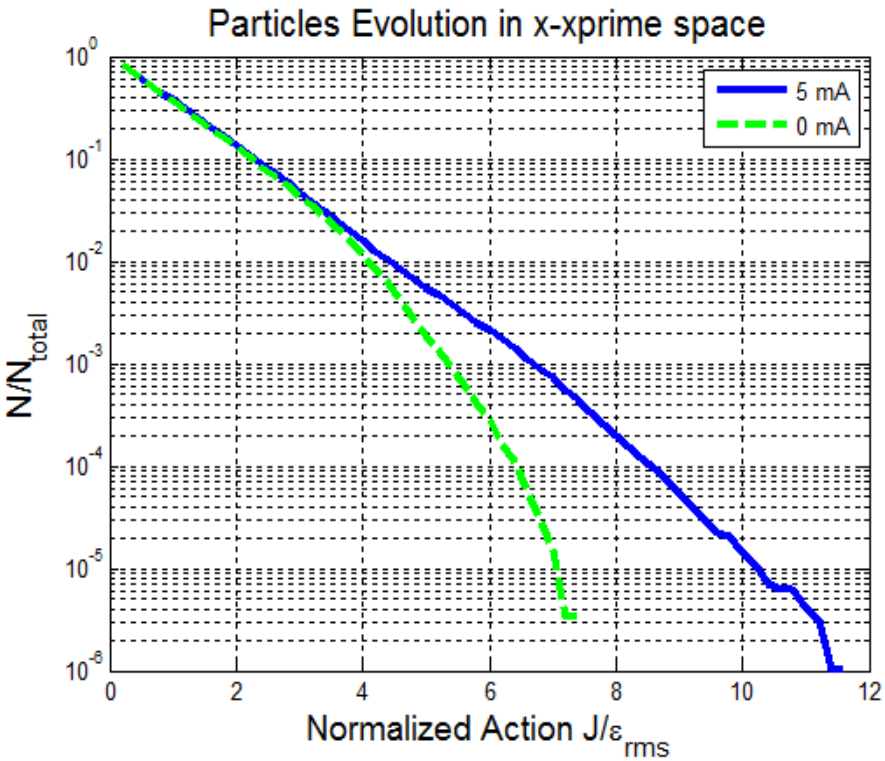
- Evolution of particle distribution at the end of MEBT for 5 mA beam current is compared for the cases without scraper and with scrapers (nominal scraping as shown in slide 12).
- Maximum action is limited to 12 and 9 in horizontal and vertical phase space.

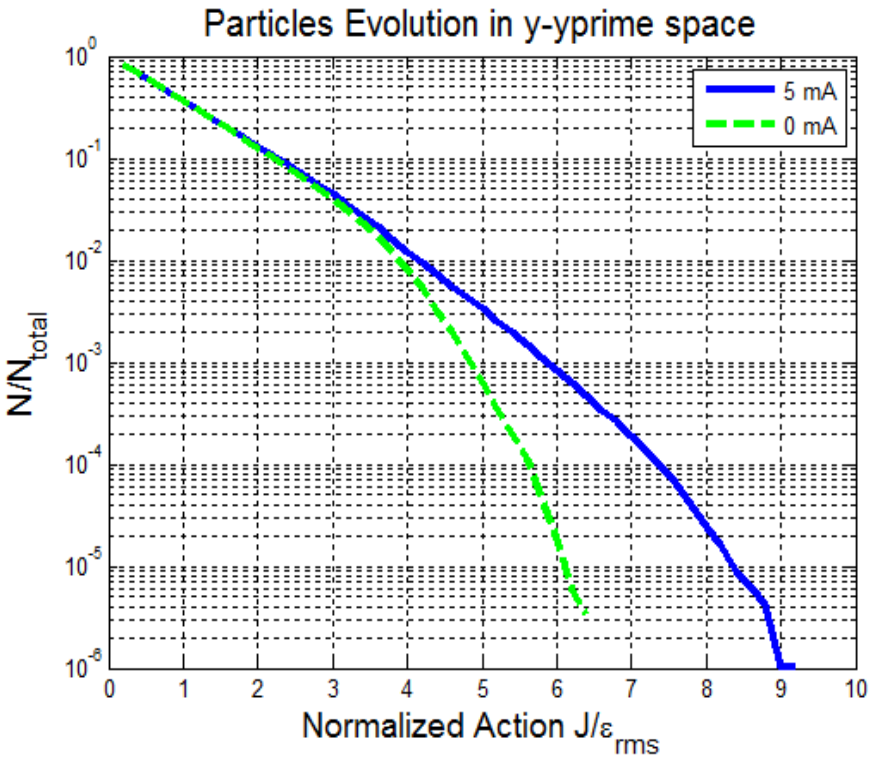
Particle Distribution at the End of MEBT in both planes (x,y)



- Evolution of particle distribution in both plane is analyzed at the end of MEBT for 5mA beam current for nominal insertions of scrapers.

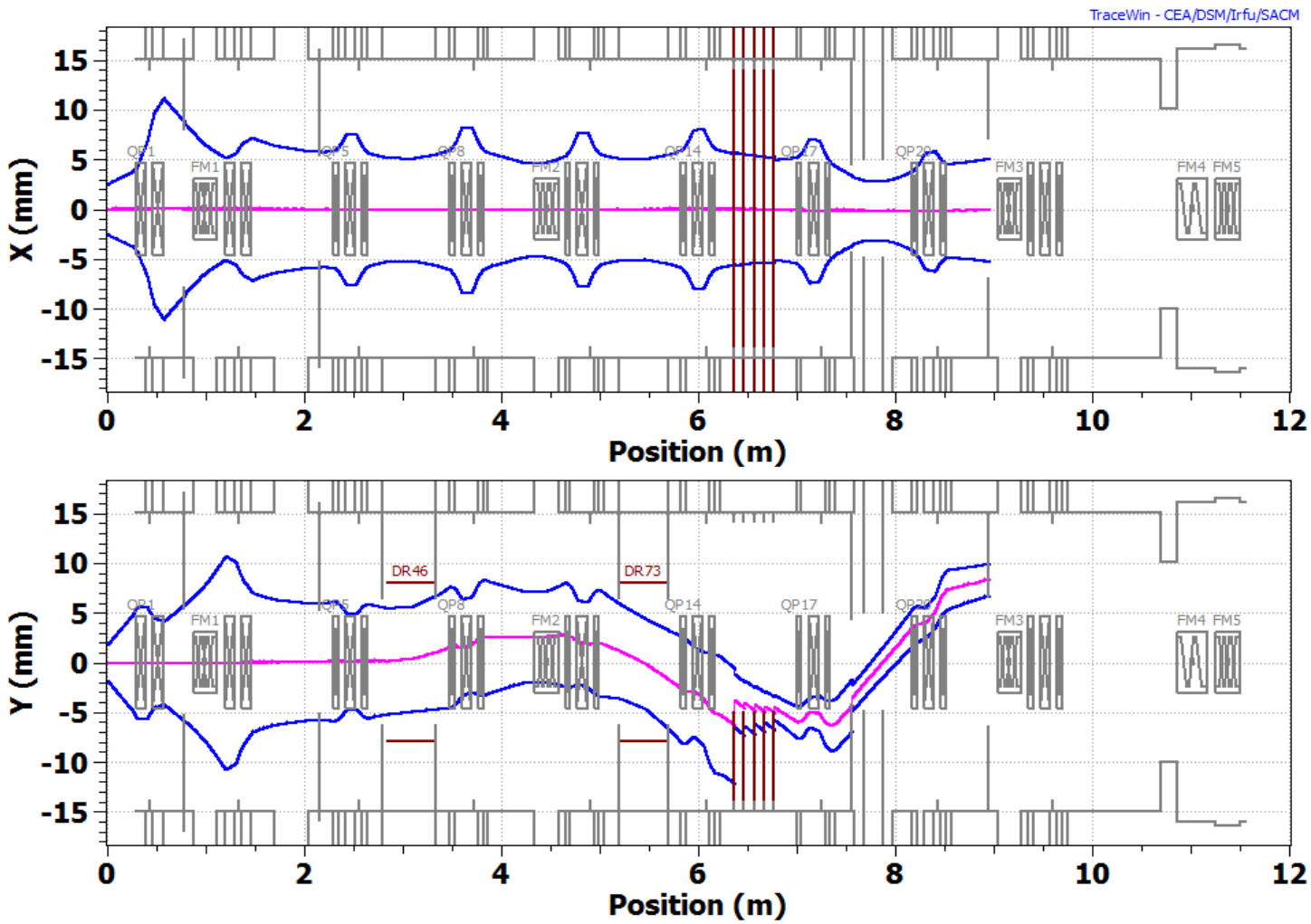
Space Charge Effects on Action





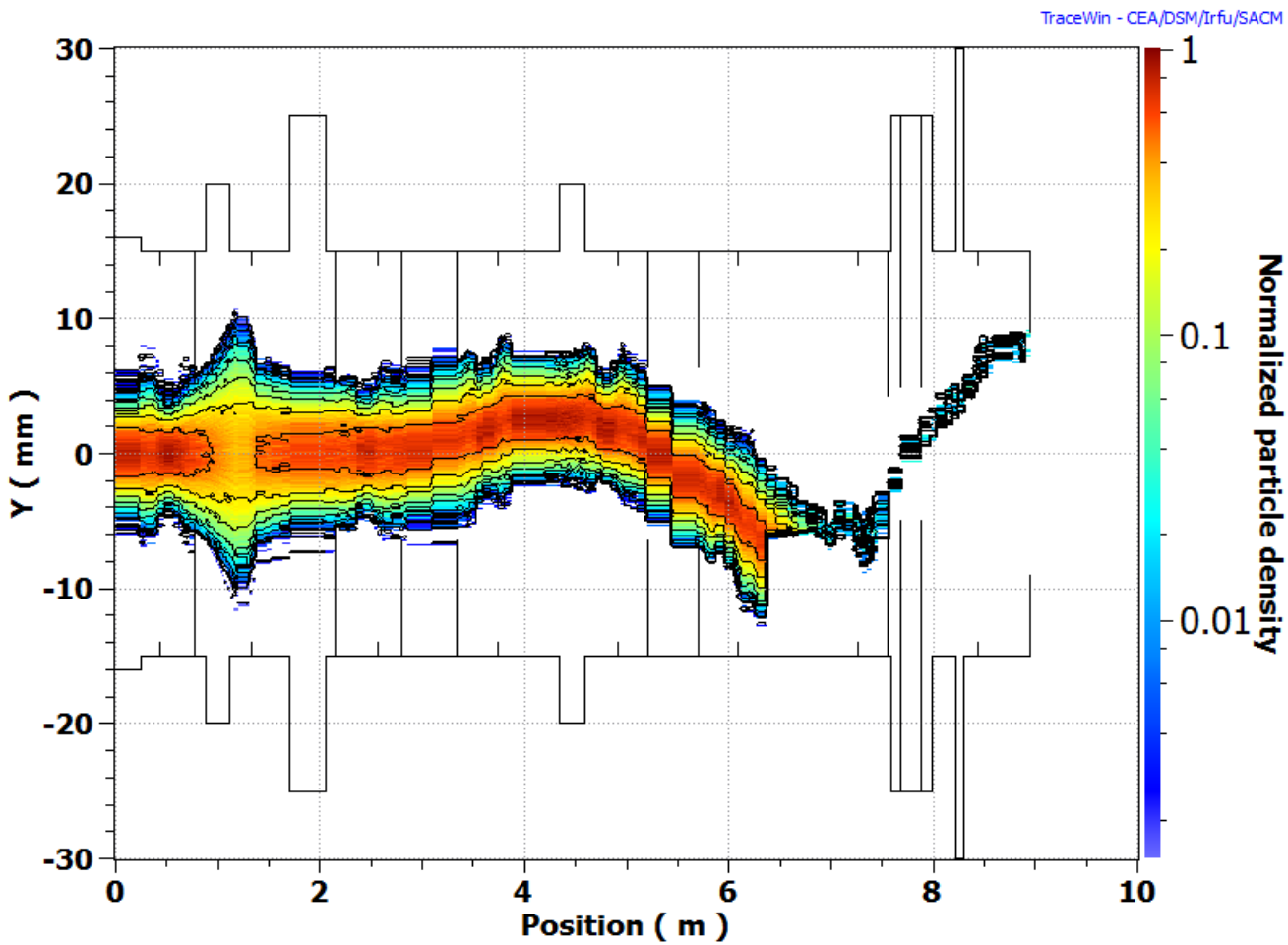
- Evolution of particle distribution for same fraction of scraping is estimated for 5 mA and 0 mA at the end of MEBT.
- Nonlinearity due to space charge results in more particles in outer-part of the core and therefore action is larger for same percentage of scraping in 5mA beam current case.

Deflected Beam: Kickers Polarity are reversed



- A small fraction of beam (0.05 %) left out from absorber section is intercepted at scraper 3 and 4

Beam Density along MEBT



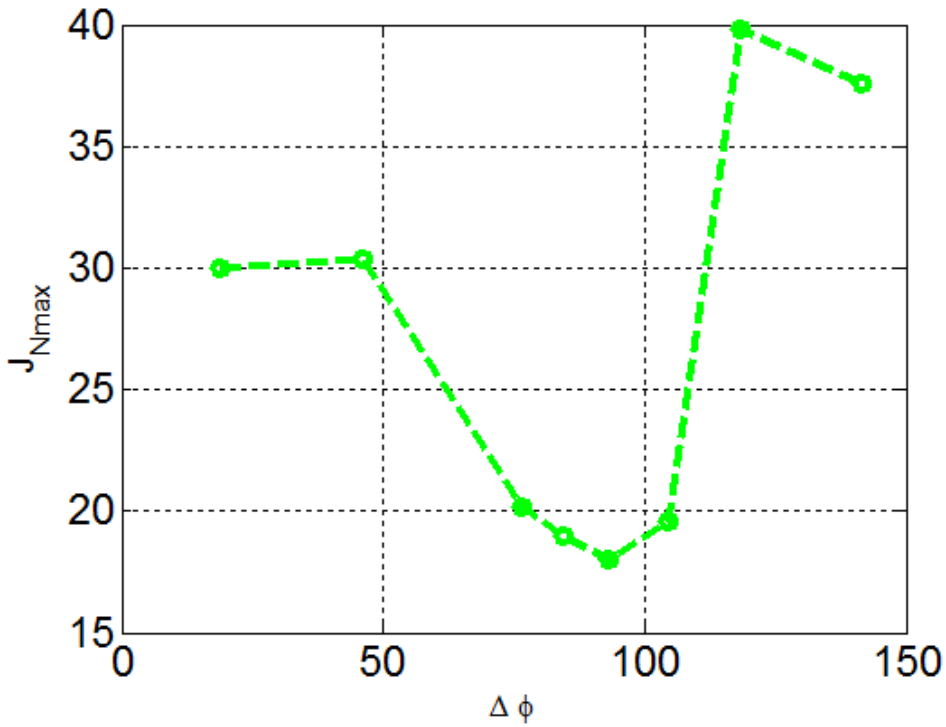
- *All particles are intercepted and no particles left after scraper 4 in MEBT.*

Summary

- Locations of scrapers in the MEBT are optimized to achieve
  - For passing bunches, interception of particles with large action
  - Avoiding beam losses in SRF section in case of dipole (trajectory) perturbations
- According to simulations, the scraping system should allow injection into HWR of a beam with negligible density of particles outside of ~3σ radius

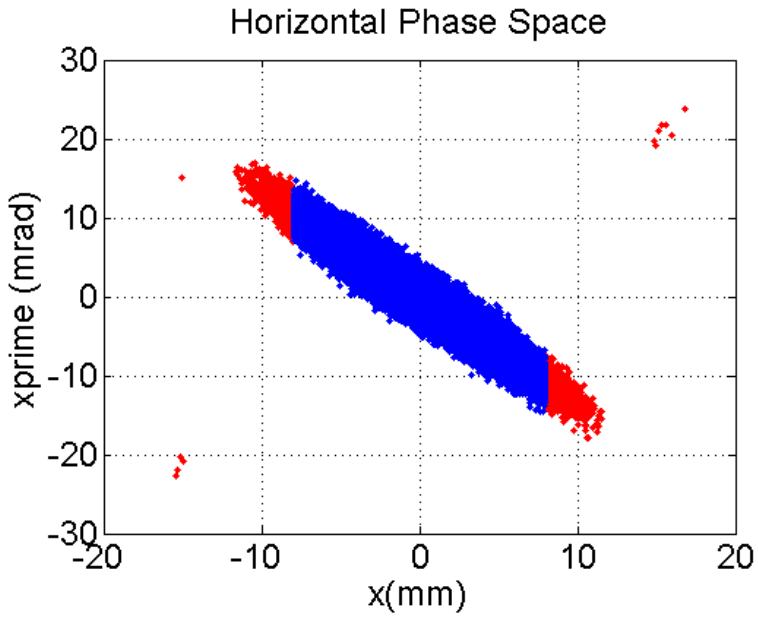
- Additional optimization of positions of the last two scraper sets might be needed after the next iteration of the mechanical design (MEBT-3)

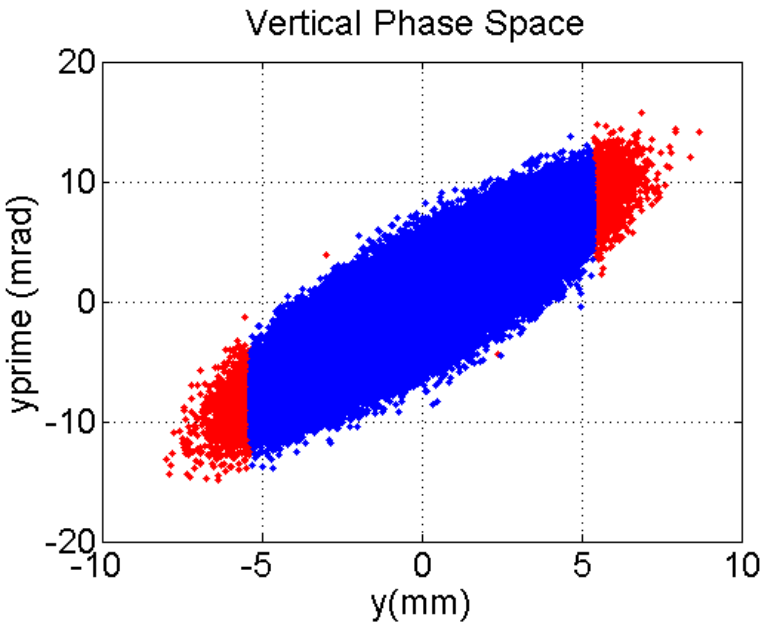
Variation in Action with Phase advance between two scrapers

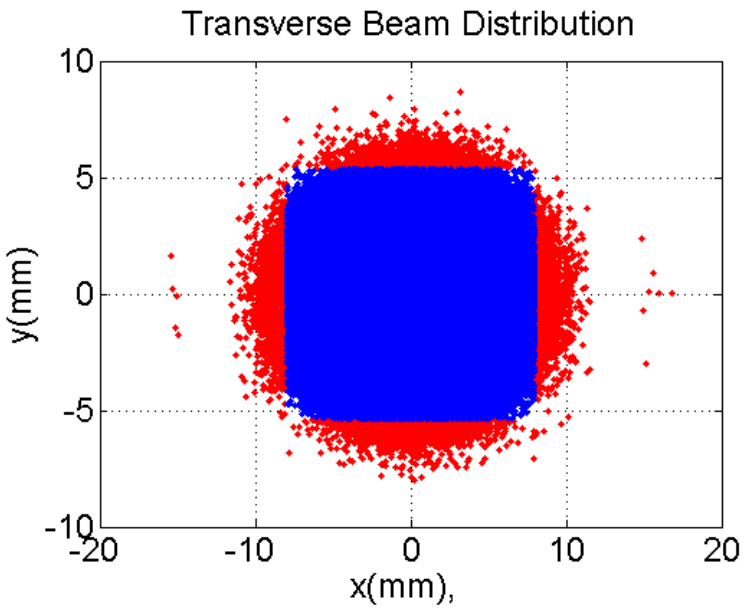


- Simulation is performed using first two scraping system in MEBT
- Second scraper is moved and placed at different location in MEBT
- Same percentage of particle scraped at each locations
- Maximum action is estimated at each locations and dependence of maximum action with phase advance is plotted

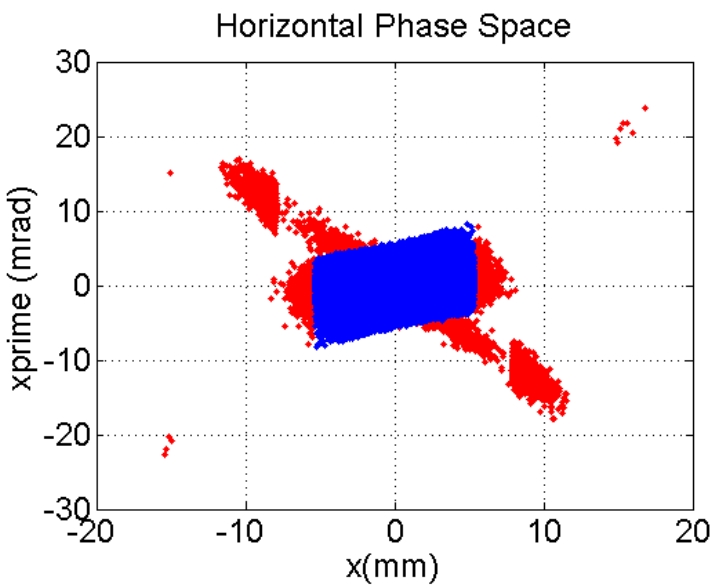
Phase space after Beam Scraper 1

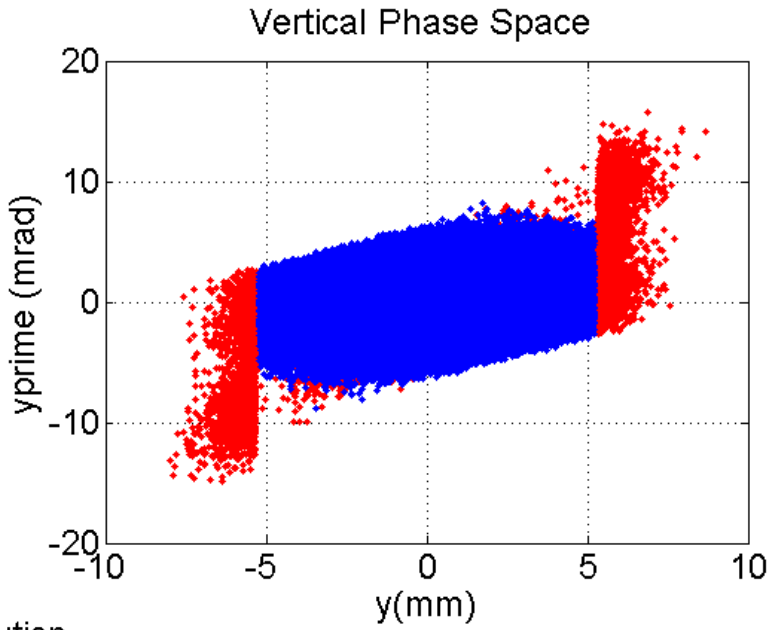


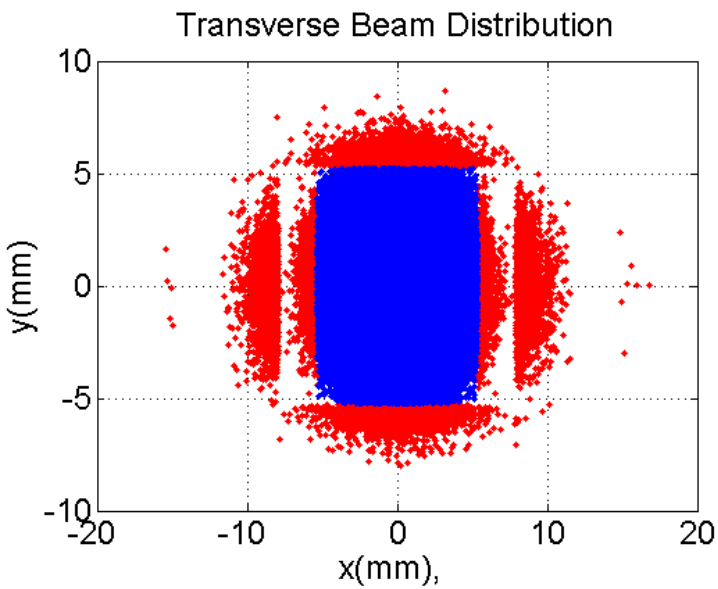




Phase space after Beam Scraper 2

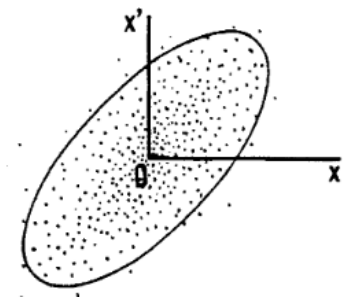






Estimation of Action

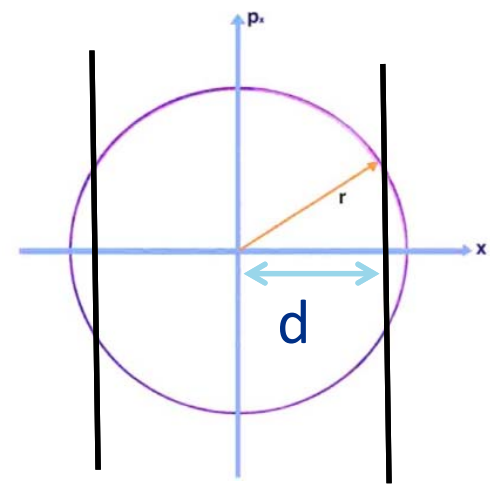
$$\gamma_{twiss} x_i^{\ 2} + 2\alpha_{twiss} x_i . x'_i + \beta_{twiss} x_i^{\ 2} = 2J_i$$



$$\beta_{twiss}\gamma_{twiss} x_i^{\ 2} + 2\alpha_{twiss}\beta_{twiss} x_i . x'_i + \beta^2{}_{twiss} x_i^{\ 2} = 2\beta_{twiss} J_i$$

$$\gamma_{twiss}\beta_{twiss} = 1 + \alpha^2$$

$$x_i^{\ 2} + (\alpha x + \beta x')^2 = (\sqrt{2\beta_{twiss} J_i})^2$$



Relative penetration depth into the beam $a_i = \dfrac{d_i}{\sqrt{2\beta_{twiss} J_{\max}}}$

Maximum action after two scrapers

$$J_{\max} = \frac{a_1^2 + 2 * a_1 a_2 \cos(\Delta\varphi) + a_2^2}{\sin \Delta\varphi^2}$$

Normalized Phase space

Fraction of particles scraped

A Gaussian Distribution function is represented as:

$$G(x,x') = \frac{1}{2\pi\sigma_x\sigma_{x'}} \exp\left(\frac{-(x-\bar{x})^2}{2\sigma_x{}^2}\right) \exp\left(\frac{-(x'-\bar{x}')^2}{2\sigma_{x'}{}^2}\right)$$

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} dxdx' G(x,x') = \frac{1}{2\pi\sigma_x\sigma_{x'}} \exp\left(\frac{-(x-\bar{x})^2}{2\sigma_x{}^2}\right) \exp\left(\frac{-(x'-\bar{x}')^2}{2\sigma_{x'}{}^2}\right) = 1$$

Fraction of particles scraped at first scraper:

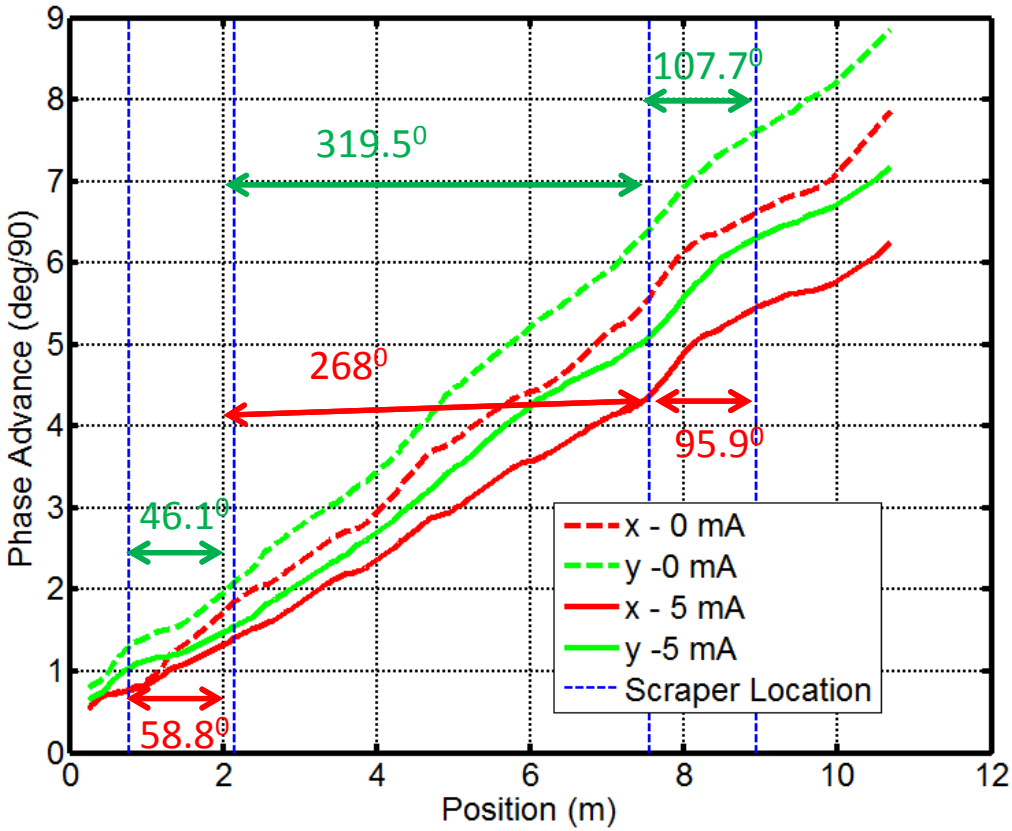
$$N(a) = 1 - \int_{-\infty}^{\infty} dx' \int_{-a}^{a} dx G(x,x')$$

$$N(a) = 1 - erf(a)$$

Fraction of particles scraped at first scraper:

$$N_2(a_1, a_2, \Delta\phi) = \frac{1}{\sqrt{\pi}} \int_{-a_1}^{a_1} e^{-u^2} \left(1 - erf\,\frac{(a_2 - u \bullet \cos(\Delta\phi))}{\sin(\Delta\phi)}\right) du$$

Beam Phase Advance in MEBT



Phase Advance between scrapers

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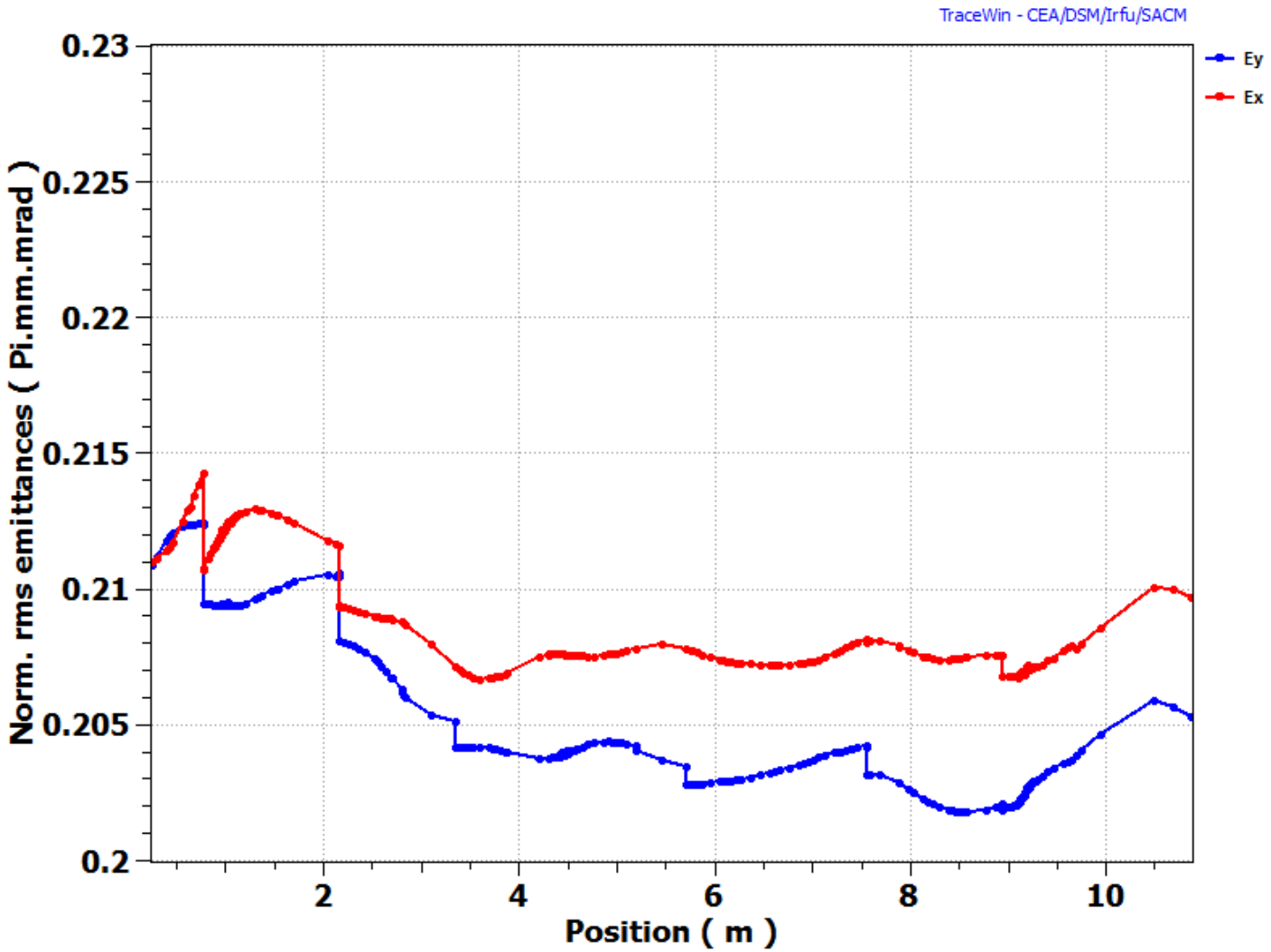
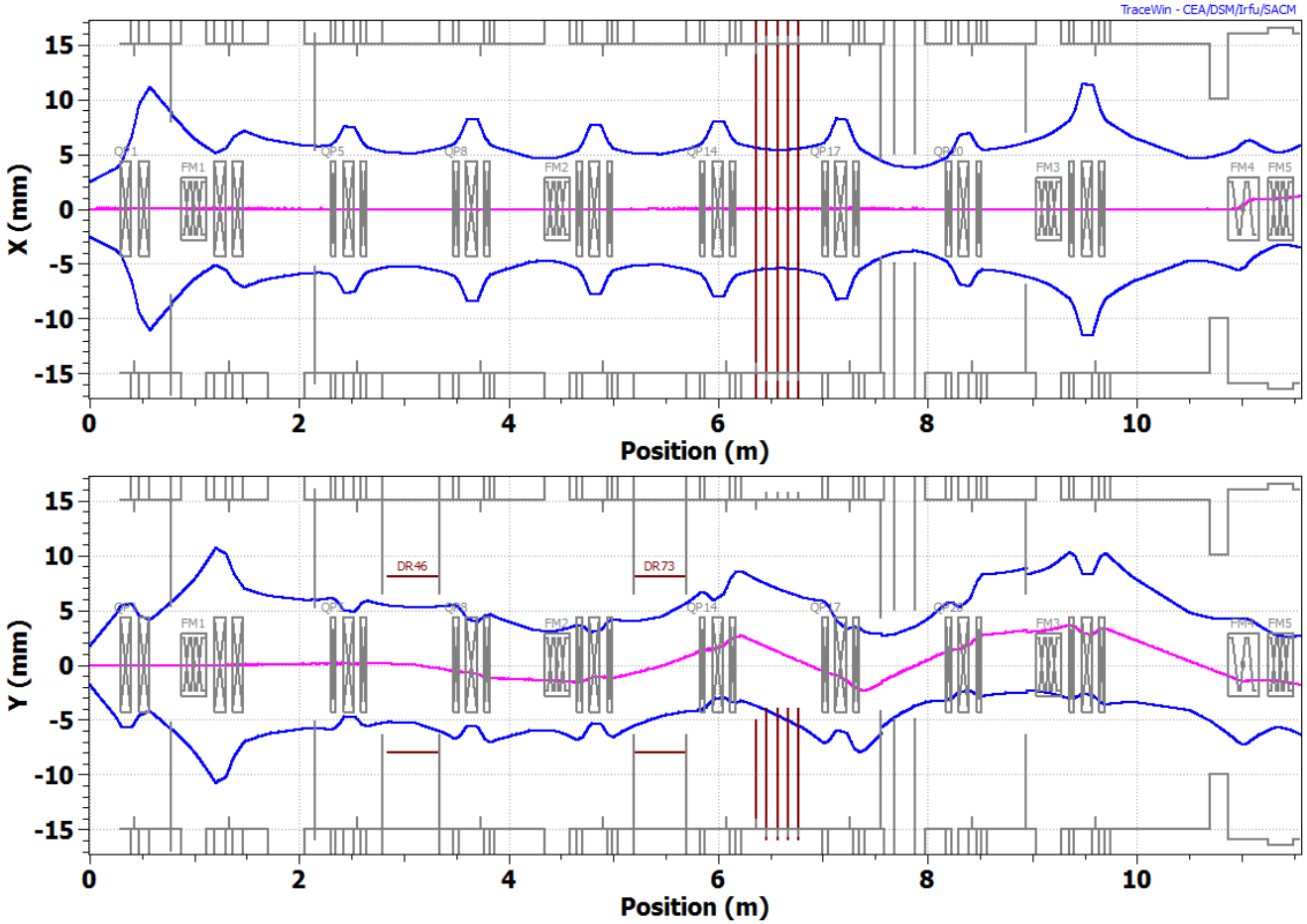
- Beam Phase advance is different in horizontal and vertical planes.
- Space charge effects reduces phase advances.

Transverse Beam Emittance



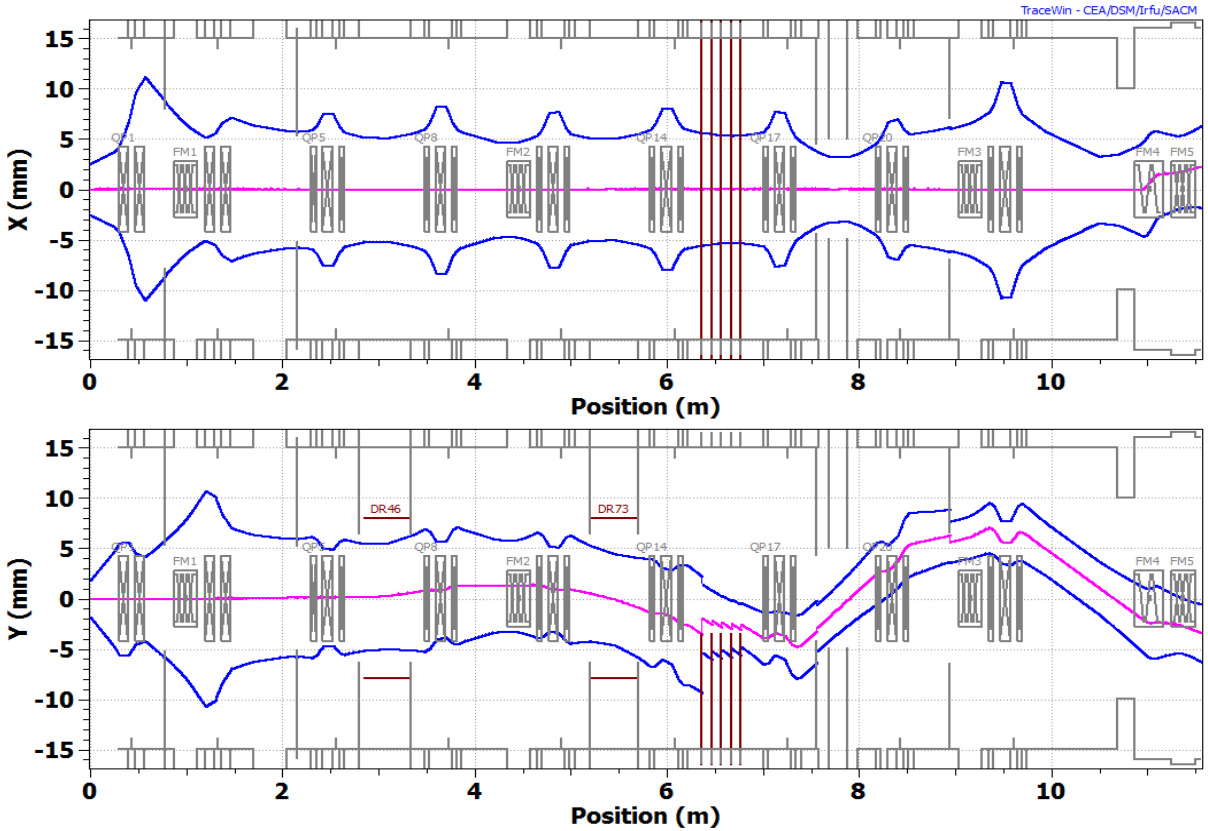
Beam Envelope passing Beam: Kicker Voltages varied

- Kicker voltage is half of its nominal value (125 V bw plate and axis)



Beam Envelope Deflected Beam: Kicker Voltages varied

- Kicker voltage is half of its nominal value (125 V bw plate and axis)



- ~ 4 % beam is left out