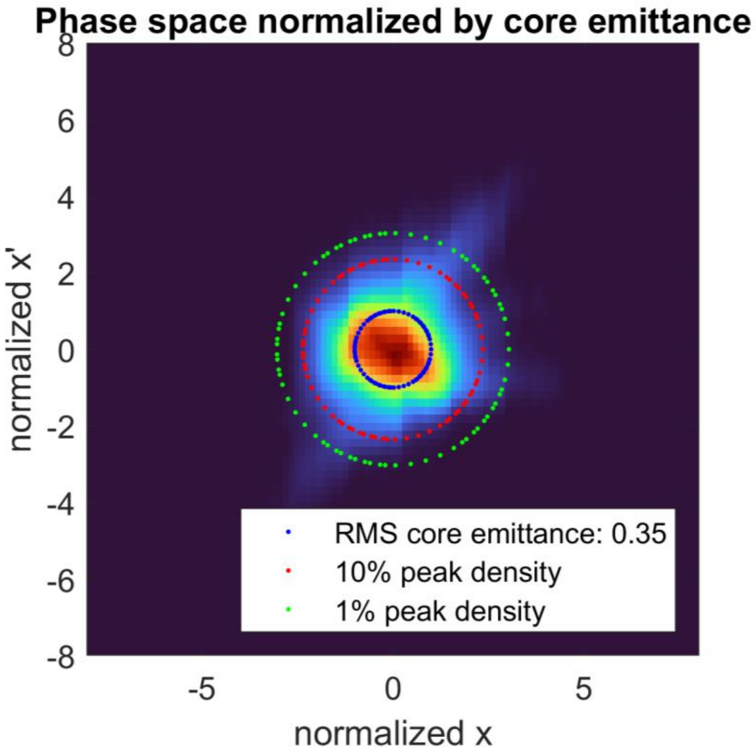
Phase space and emittance analysis of XFEL 250 pC beam



H. Qian
22.04.2021

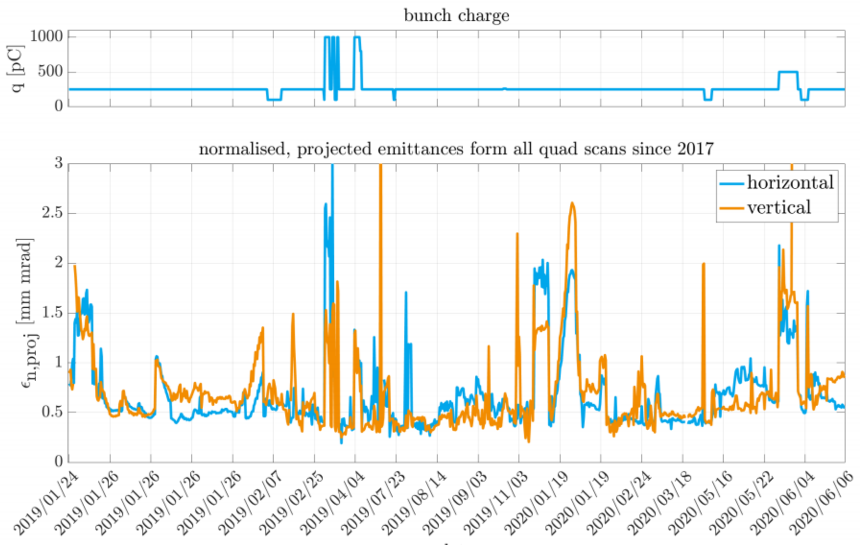
Outline

- Motivation
- Phase space description
- Analysis of simulations
- Analysis of experiments
- Why bad emittance
- SNR of fastscan at PITZ
- 500 pC vs 250 pC brightness
- Summary

Motivation

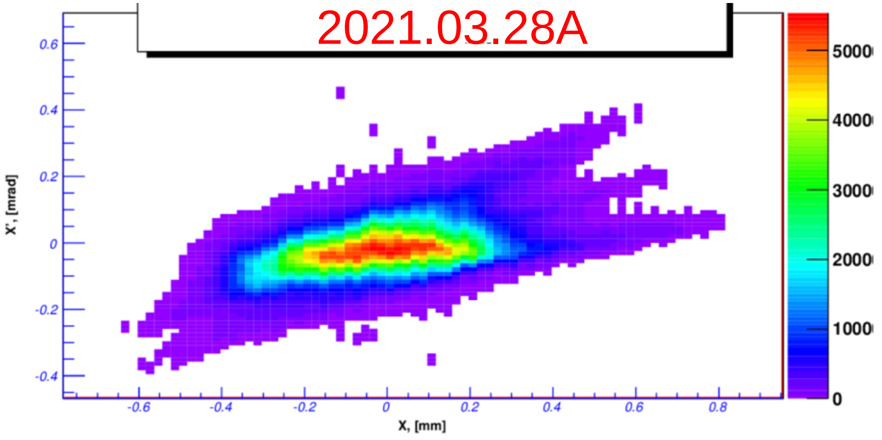
How to understand our emittance values?

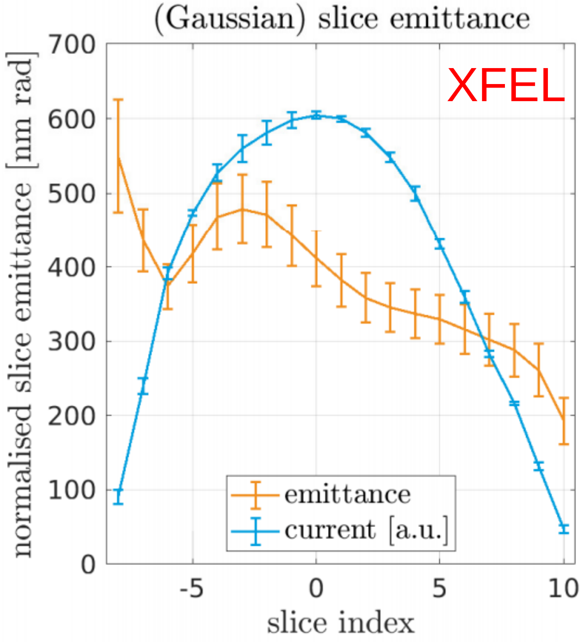
- 250 pC emittance statistics
  - PITZ: ~0.47-0.8 mm.mrad (BSA1mm, 6-8 ps Gaussian laser, 6.3 MeV/c)
  - XFEL: ~0.35 – 0.8 mm.mrad (BSA1mm, ~7 ps Gaussian laser, 6.3 MeV/c)
  - How to compare them?



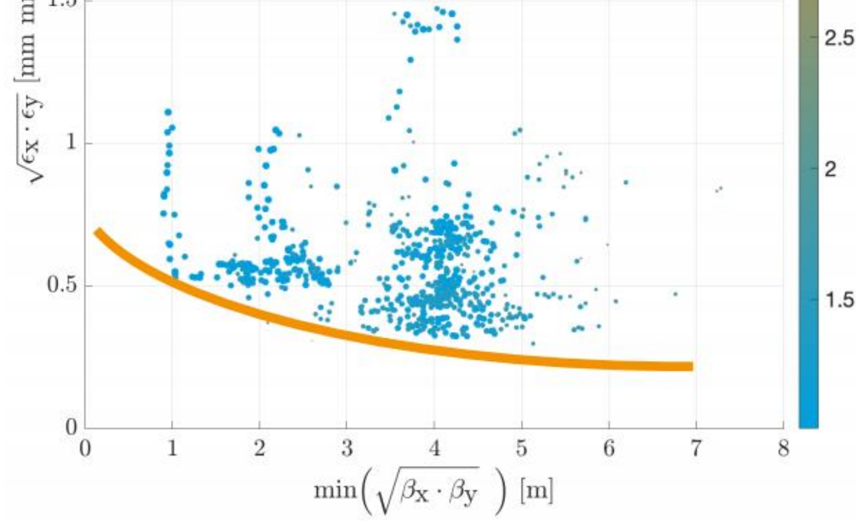
PITZ $\varepsilon_{proj} = 0.53 \pm 0.05\ \mu m$

2021.03.28A





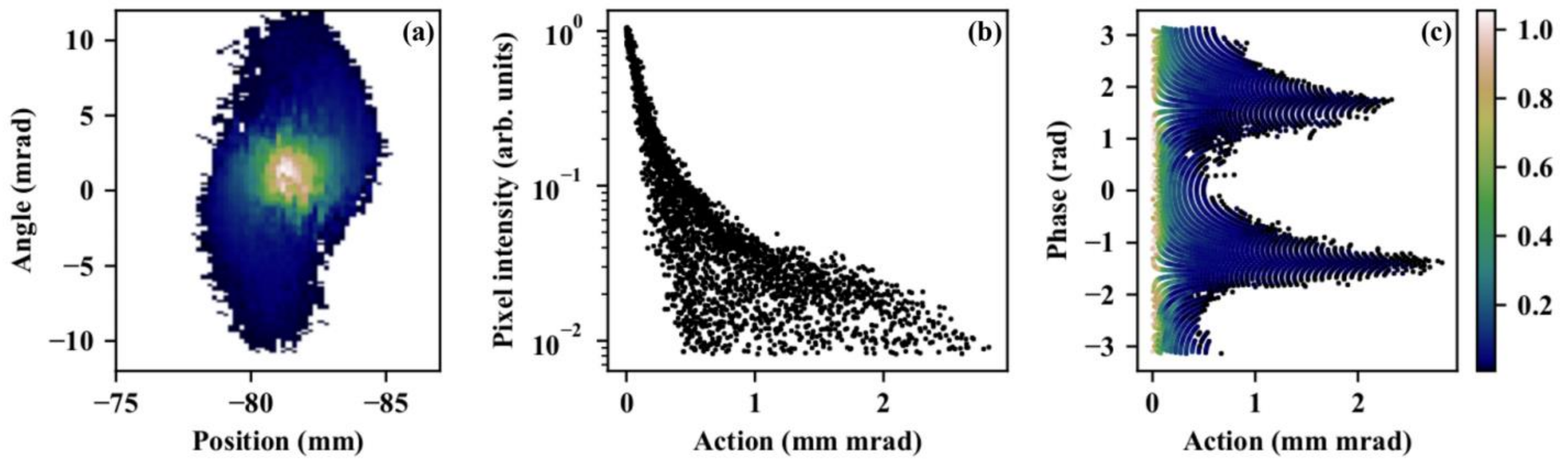
XFEL injector emittance statistics
2019.01 – 2020.06

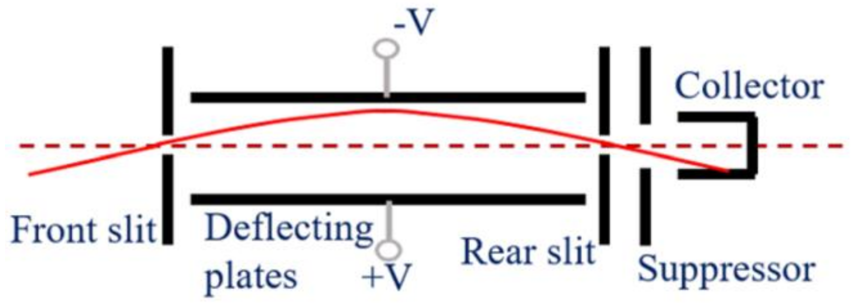


Motivation

A new method to analyze phase space data

- Inspired by a new method to analyze transverse phase space data
  - Get to know this idea during an interview
  - Method is published
    - C. Richard, J.P. Carneiro, L.R. Prost, A.V. Shemyakin, Analysis of Allison Scanner Phase Portraits Using Action-Phase Coordinates", in Proc. NAPAC'19, Lansing, MI, USA, Sep. 2019, paper TUPLS08.
    - C. Richard, M. Alvarez, J.P. Carneiro, B. Hanna, L.R. Prost, A. Saini, V. Scarpine, A.V. Shemyakin, Measurements of a 2.1 MeV H^- Beams with an Allison Scanner", Review of Scientic Instruments, 2020



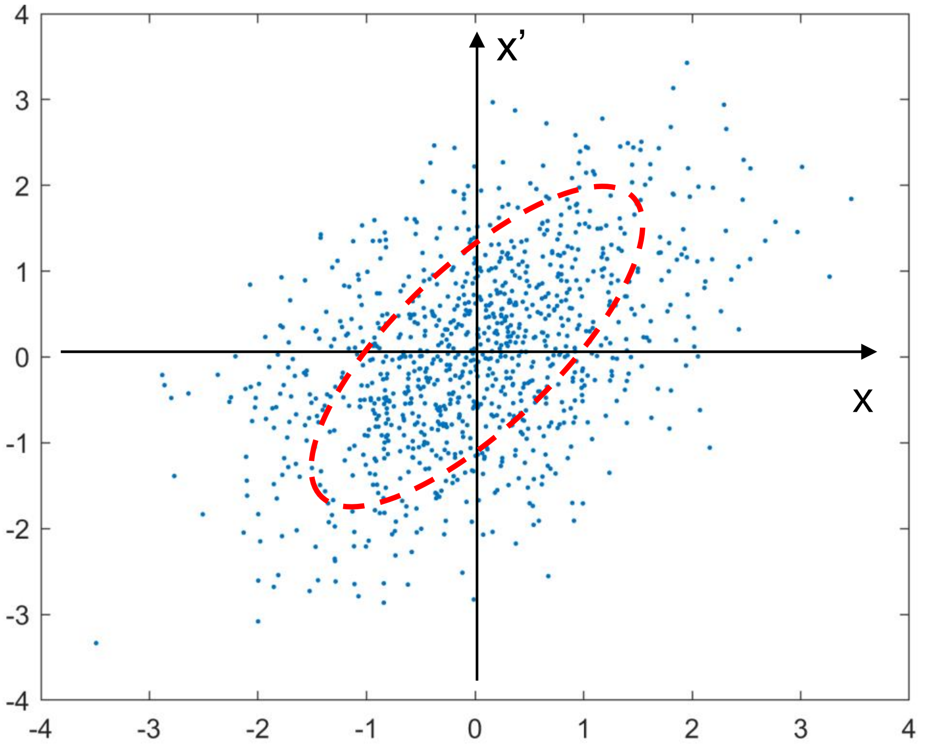


2.1 MeV H^-, v=0.048c

Phase space description

Position and angle coordinates

- Transverse phase space by trajectory perspective
  - position and angle, x and x'
  - RMS emittance, $\varepsilon_{rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x * x'\rangle^2}$
  - Twiss parameters, $\beta = \frac{\langle x^2\rangle}{\varepsilon}, \gamma = \frac{\langle x'^2\rangle}{\varepsilon}, \alpha = -\frac{\langle x*x'\rangle}{\varepsilon}$
  - RMS emittance ellipse, $\varepsilon_{rms} = \gamma x^2 + 2\alpha x x' + \beta x'^2$
  - ε_{rms} is the rms ellipse area divided by pi
  - Pro: easy to describe beam in real space
    - Projection to x, you have the x profile distribution
    - Projection to x', you have the x' profile distribution
    - With the 2nd order moments <xx>, <xx'>, <x'x'> and the transfer matrix, you can predict the beam change in real space

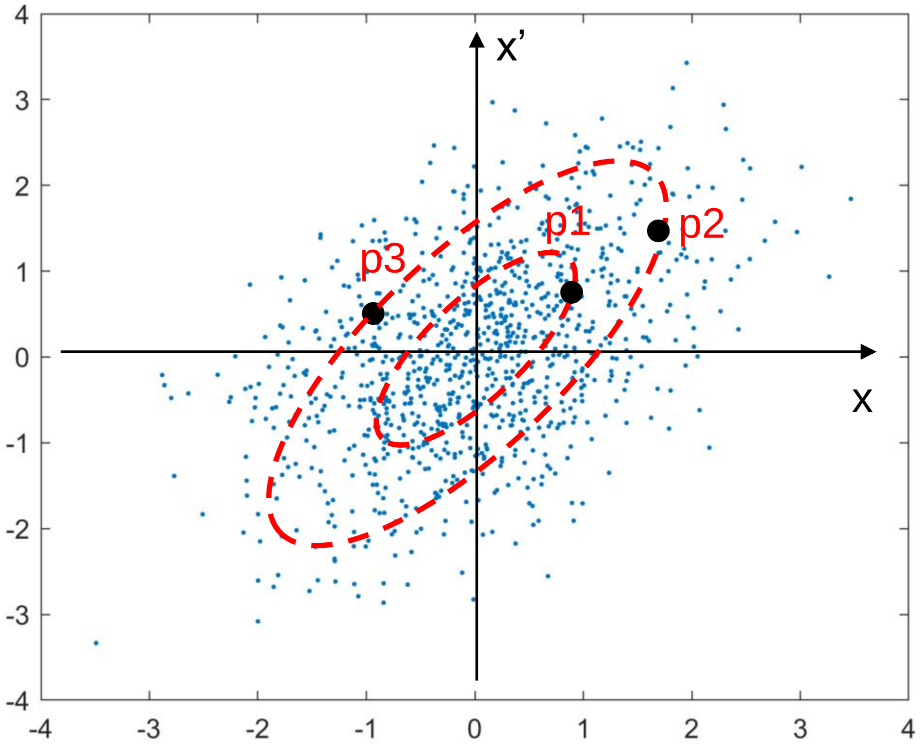


- Con: not a good way to describe beam quality in phase space, i.e. phase space density
  - A single parameter ε_{rms} describes the 2D beam phase space area, and Q/emit tells the phase space density.
  - If the 99% phase space distribution is the same, but outside 1% particles become very bad, then ε_{rms} becomes very bad, just like the sensitivity of rms calculation on 1D distribution tails.
  - Q/emit then predicts very poor beam brightness, misleading!

Phase space transformation

Action and phase coordinates

- Transverse phase space from density perspective
  - Use ellipse to gauge particles, not x and x'
    - P1 and P2 can be distinguished by different ellipse area
    - P2 and P3 sit on the same ellipse, they can be distinguished by their phase along the ellipse
  - New particle coordinates
    - Action (ellipse area/2pi)
      - $J_i = \frac{1}{2}\left(\gamma x_i^2 + 2\alpha x_i x_i' + \beta {x_i'}^2\right)$
      - Why not $\varepsilon_i = \gamma x_i^2 + 2\alpha x_i x_i' + \beta {x_i'}^2 = 2J_i$
        - $\varepsilon_{rms} = \frac{1}{N}\sum_i J_i \qquad \varepsilon_{rms} = \frac{1}{2N}\sum_i \varepsilon_i$
    - Phase
      - $J_i = \frac{1}{2}\left(\gamma x_i^2 + 2\alpha x_i x_i' + \beta {x_i'}^2\right) = \frac{1}{2\beta}\left(x_i^2 + (\alpha x_i + \beta x_i')^2\right)$
      - $\phi_i = \tan^{-1}\frac{\alpha x_i + \beta x_i'}{x_i}$



Pro: Like projection to x axis, if you project particles to the J axis, then you have the 1D phase space density profile, i.e. dQ/J, better to describe phase space quality

Con: cannot describe beam motion in real space

Phase space transformation

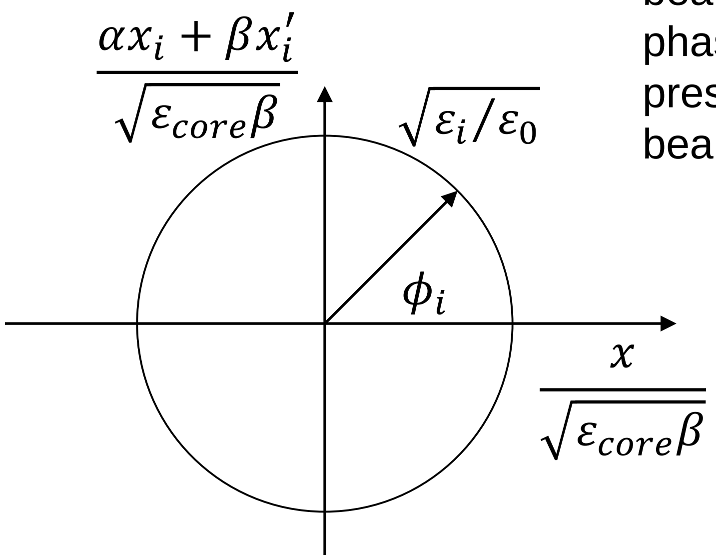
Action and phase coordinates

- Phase space transformation
  - $(x, x') \rightarrow (J, \phi)$, easier to compare phase space quality at different beamline locations, much better than single emittance parameter characterization
  - Phase space core emittance fitting
    - Gaussian distribution is a good approximation of beam core phase space (nonlinear effects is always stronger outside)
    - $dQ = \frac{Q}{2\pi\varepsilon_0}\exp\left(-\frac{\gamma x_i^2+2\alpha x_i x_i'+\beta {x_i'}^2}{2\varepsilon_0}\right)dxdx'$

      $= \frac{Q}{\varepsilon_0}\exp\left(-\frac{J}{\varepsilon_0}\right)dJ$
    - 2D fitting (intensity vs x & x') → 1D fitting (intensity vs J)
    - Halo particles does not matter anymore in comparing beam core quality, easily excluded by a threshold on J

- Phase space renormalization
  - $\varepsilon_i = \gamma x_i^2 + 2\alpha x_i x_i' + \beta {x_i'}^2$
  - $\frac{\varepsilon_i}{\varepsilon_0} = \left(\frac{x}{\sqrt{\varepsilon_0 \beta}}\right)^2 + \left(\frac{\alpha x_i+\beta x_i'}{\sqrt{\varepsilon_0\beta}}\right)^2$
  - With a radius of 1, it refers to core emittance ellipse, then easier to see intensity distribution w.r.t. beam core.

Without nonlinear effect, beam just rotates, i.e. phase space density is preserved along the beam line.



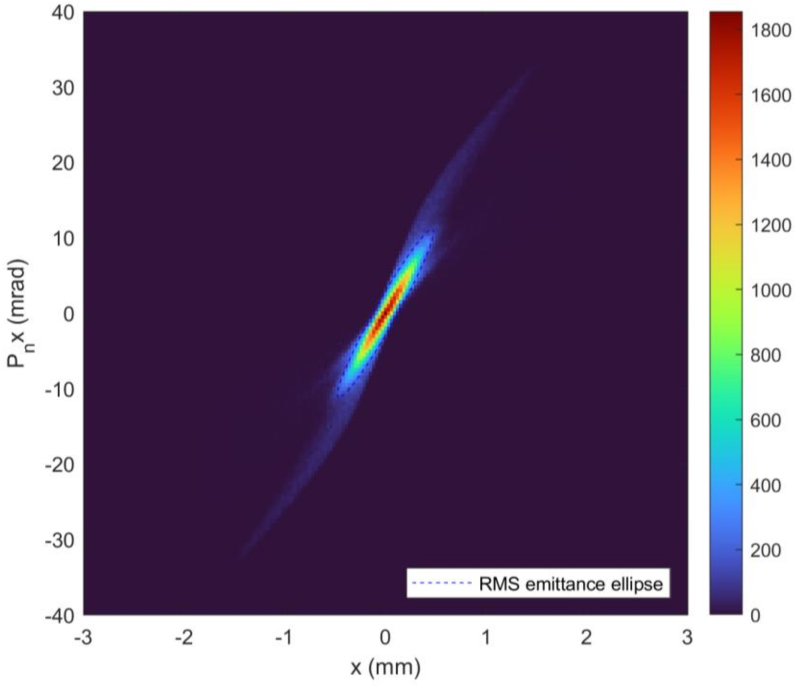
250 pC simulations with the PITZ beamline

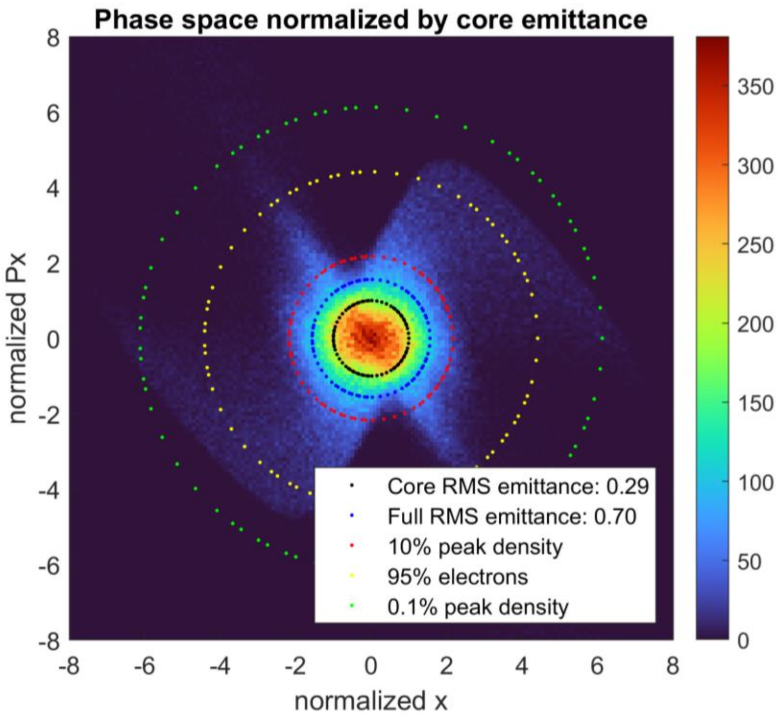
Q=250 pC

MBI ~7 ps FWHM, BSA1mm, gun 6.3 MeV/c, booster exit ~19.5 MeV/c

- Thermal emittance setting: 1 mm.mrad/mm
  - 100% rms emittance: 0.7 mm.mrad
  - 95% rms emittance: 0.42 mm.mrad

- Core emittance: 0.29 mm.mrad
- Peak brightness (dQ/Q)/dJ: 3/mm.mrad
- Peak brightness (dQ/Q)/dJ at cathode: 3.2/mm.mrad
  - Beam peak brightness is almost no degradation from cathode

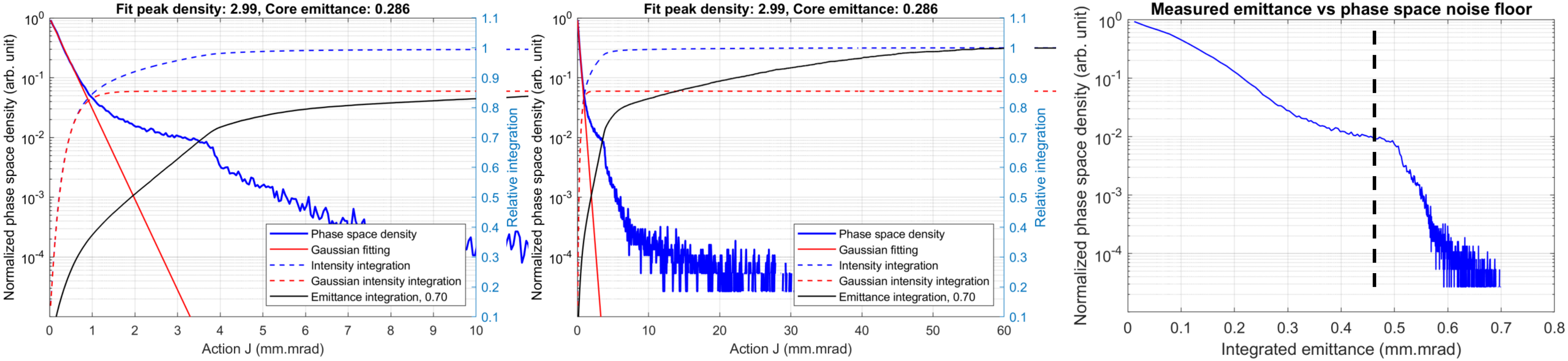




Q=250 pC

1D phase space density profile, projection to J axis

- Thermal emittance setting: 1 mm.mrad/mm
  - 100% rms emittance: 0.7 mm.mrad
  - 95% rms emittance: 0.42 mm.mrad
- Core emittance (86%): 0.29 mm.mrad
- Peak brightness dQdJ: 3/mm.mrad
- Peak brightness dQ/dJ at cathode: 3.2/mm.mrad

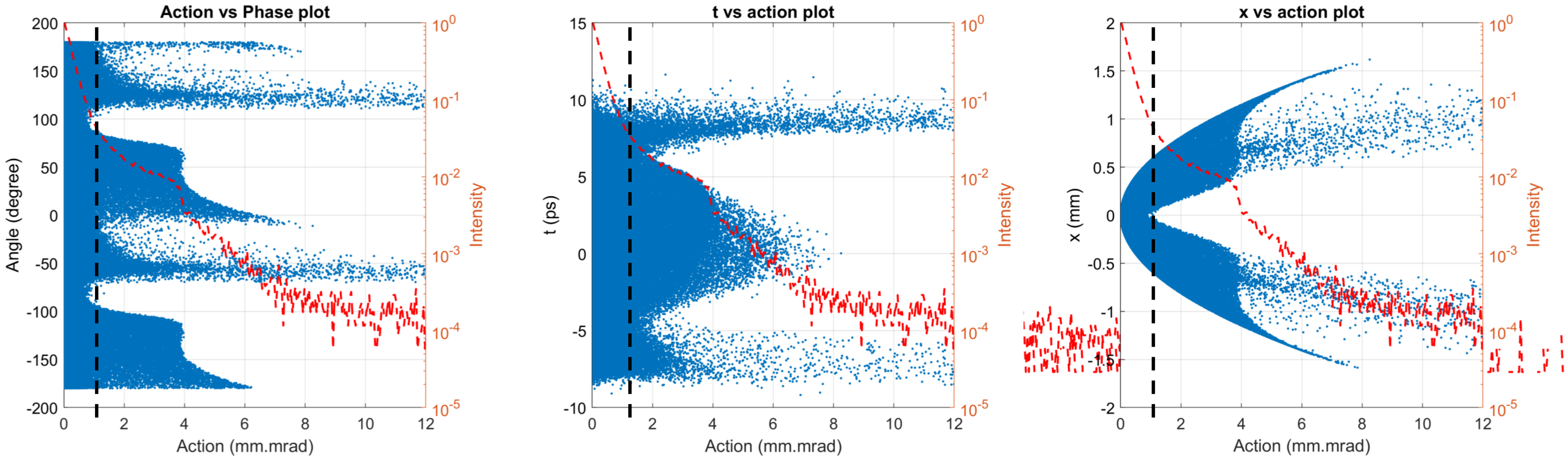


Core emittance reveals real peak brightness: 0.86Q/0.29=Q/0.34
100% emittance misleads beam brightness: Q/0.7 → a factor of 2 wrong!
95% emittance brightness: 0.95Q/0.42=Q/0.44 → somewhere in the middle, depends on the percentage of halo.

What do slit scan measure, between 0.4-0.5 mm.mrad (unscaled), close to simulated 95% emittance.

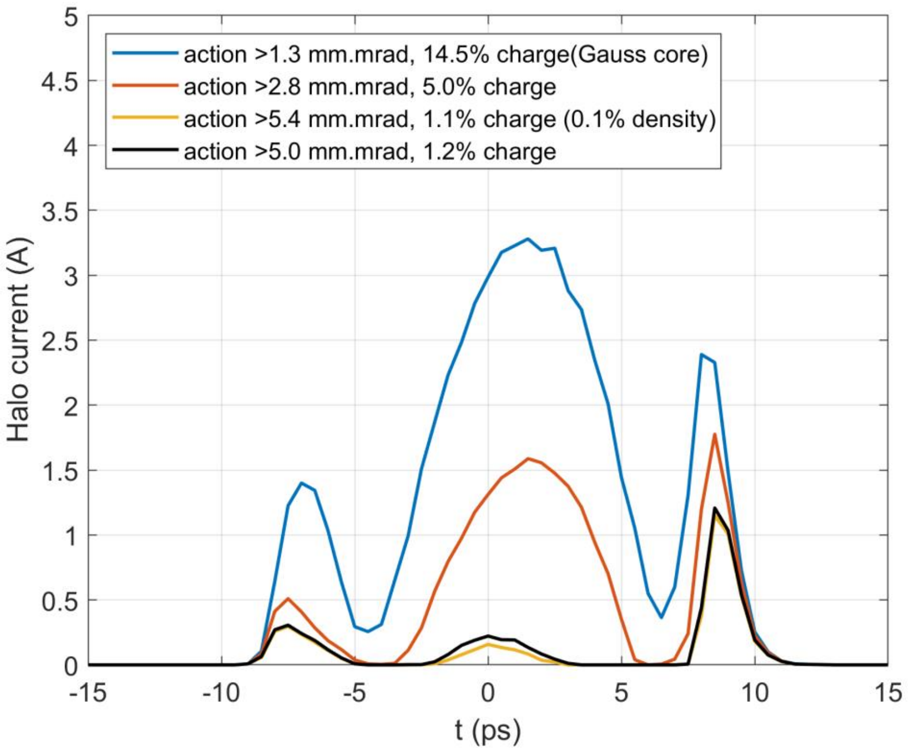
Q=250 pC

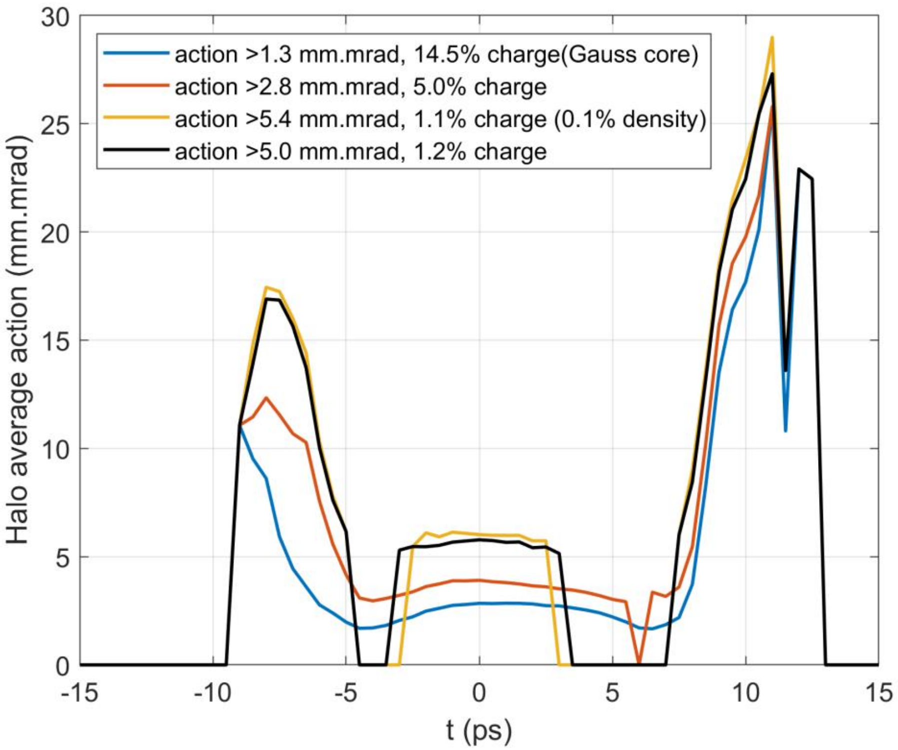
Where are the 'halo' beyond the 86% gaussian core?



Q=250 pC

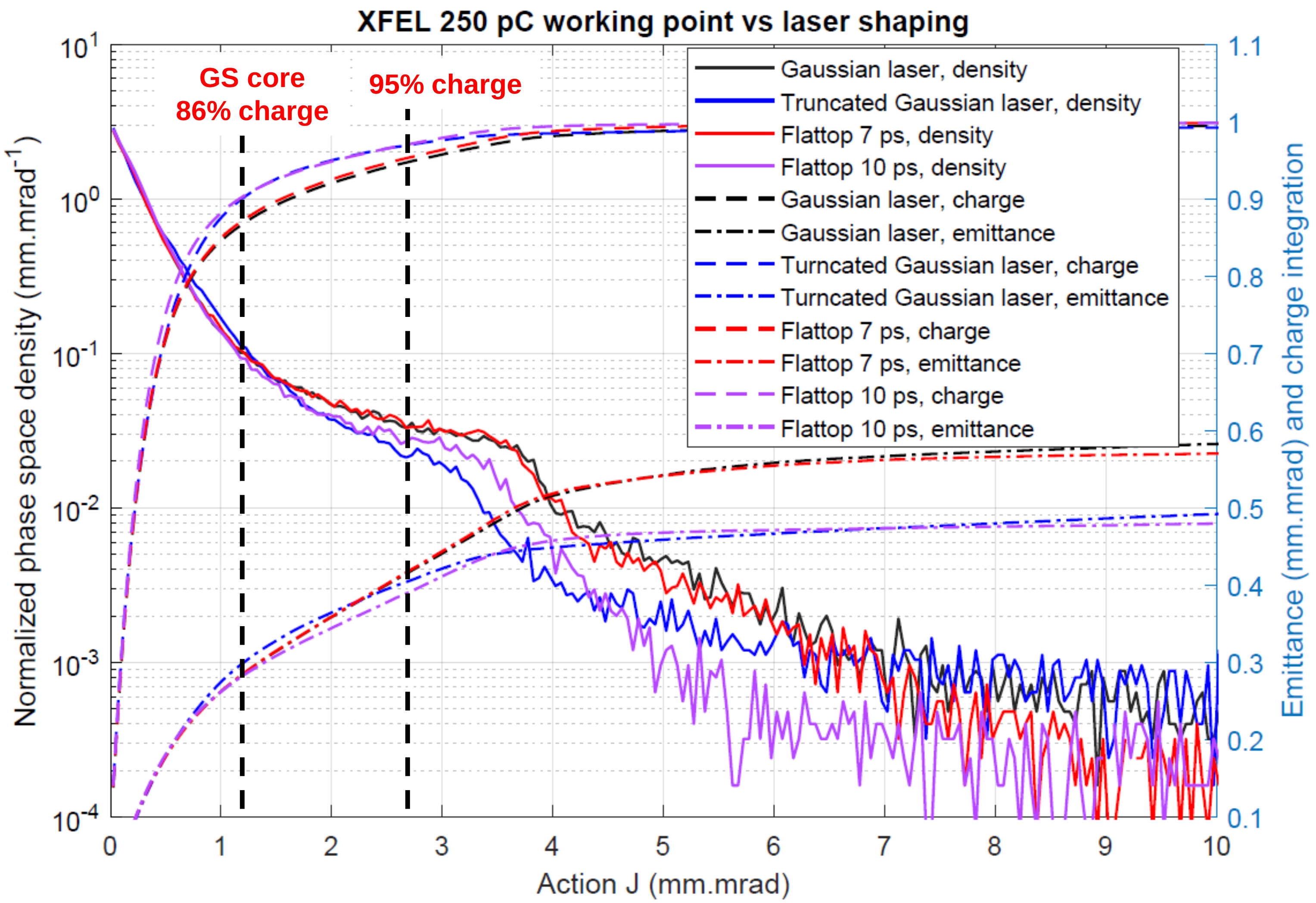
Where are the 'halo' beyond the 86% gaussian core?





250 pC vs laser spatial and temporal shaping

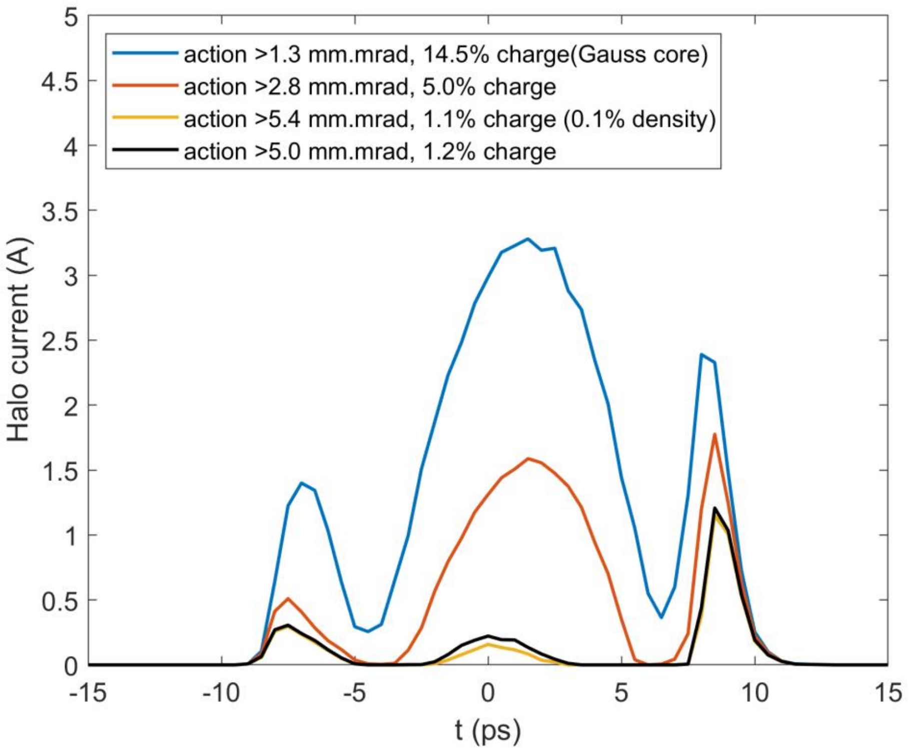
BSA1mm, 6.3 MeV/c, 1 mm.mrad/mm thermal emittance

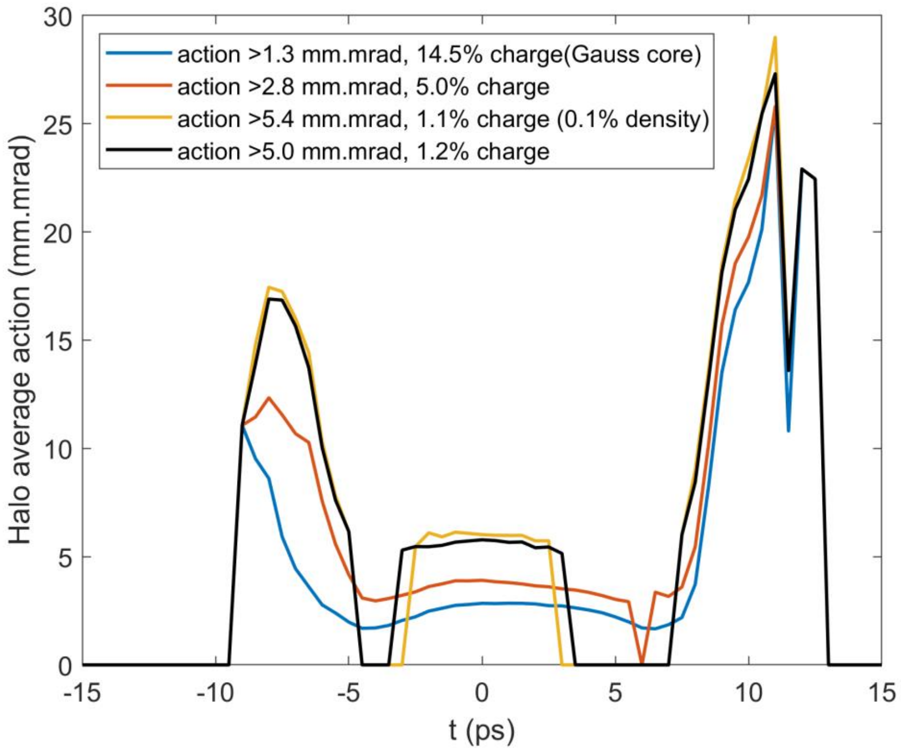


- Four laser shapes
  - Gaussian 6 ps FWHM, trans. Uniform
  - Gaussian 6 ps FWHM, trans. 1sigma truncation
  - Flattop 7 ps FWHM, 2 ps rising edge, trans. Uniform
  - Flattop 10 ps FWHM, 2 ps rising edge, trans. Uniform
- ~95% particles have the same emittance ~0.4 mm.mrad
- Core emittance is similar ~0.3 mm.mrad, peak density difference is negligible, ~3Q/mm.mrad
- 100% emi: 0.70/0.66/0.61/0.51
  - Not a good figure of merit for beam quality

Q=250 pC

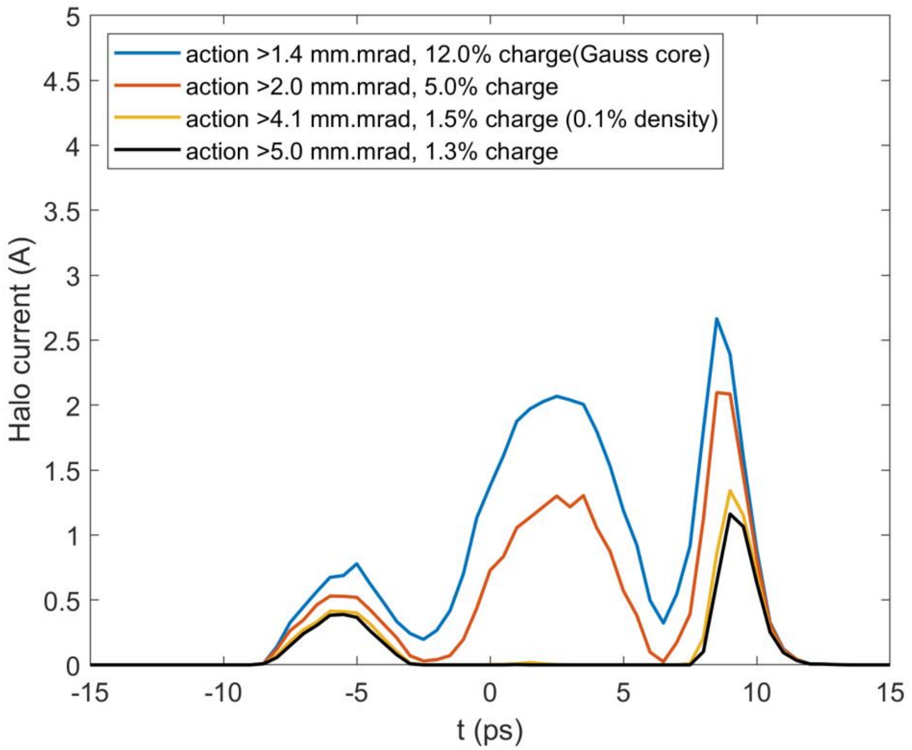
Gaussian 6 ps FWHM, trans. Uniform

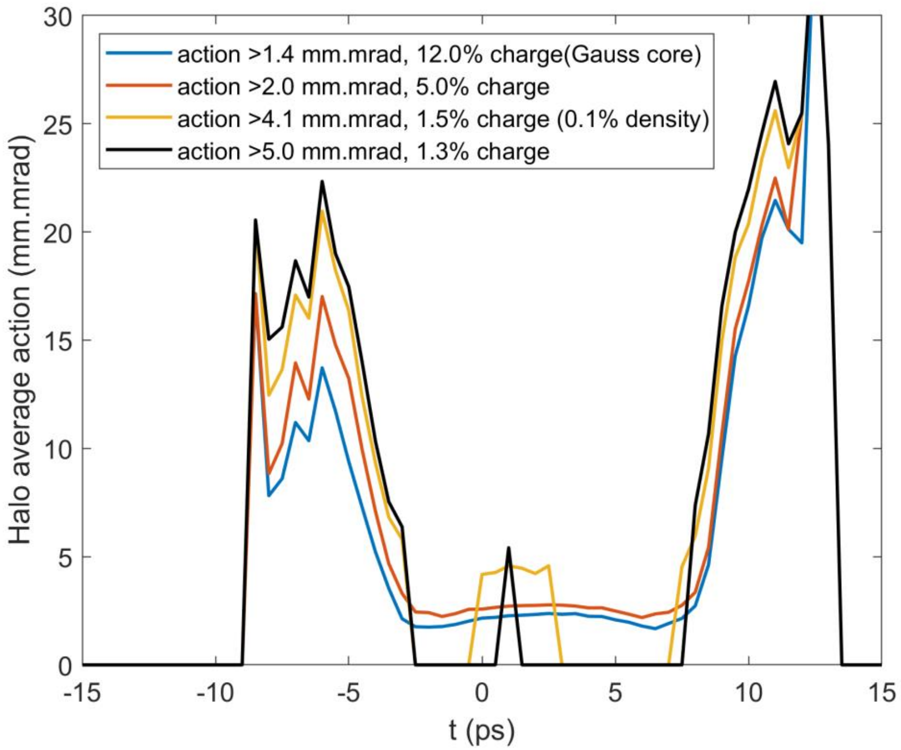




Q=250 pC

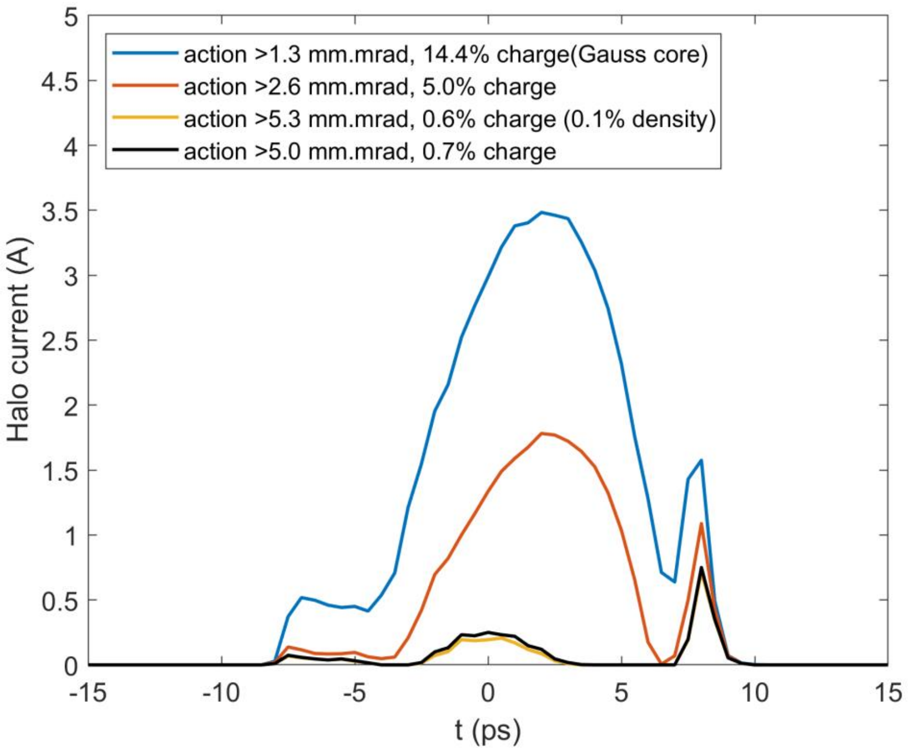
Gaussian 6 ps FWHM, trans. 1sigma truncation

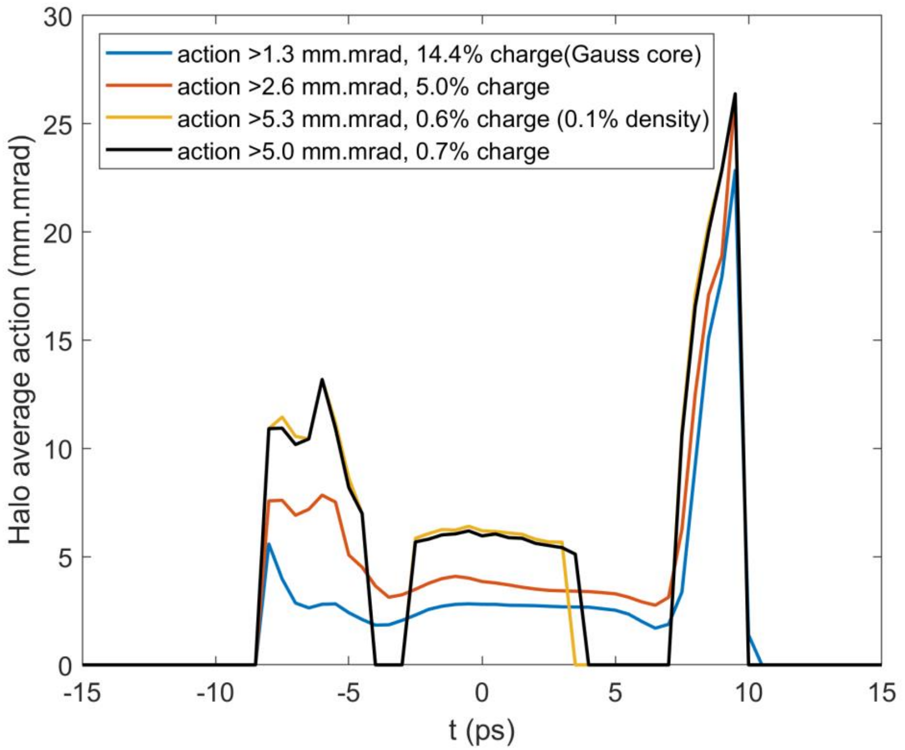




Q=250 pC

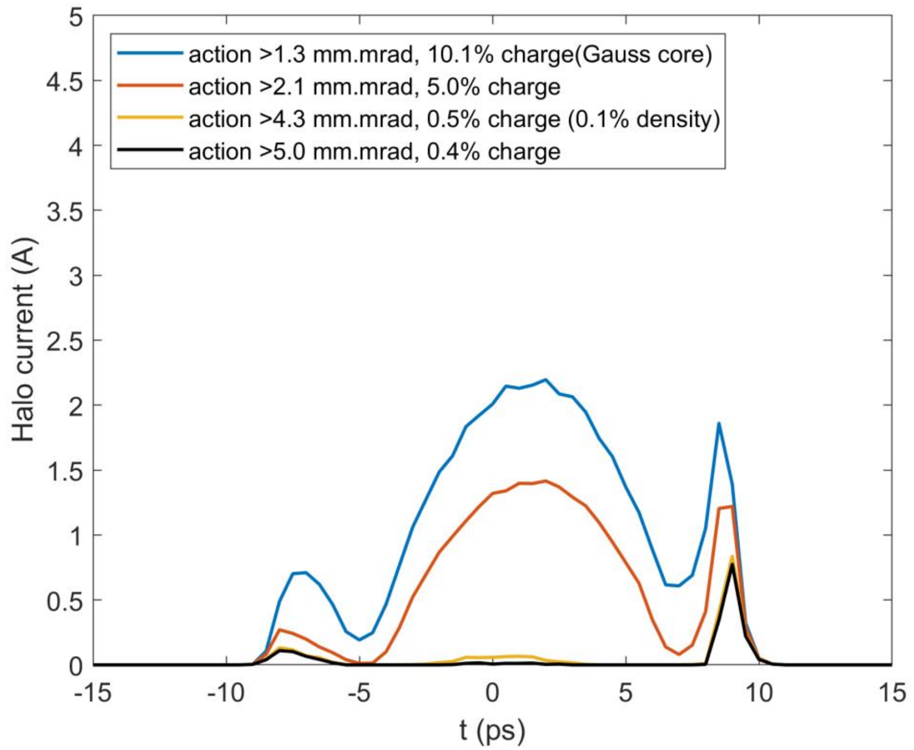
Flattop 7 ps FWHM, 2 ps rising edge, trans. Uniform

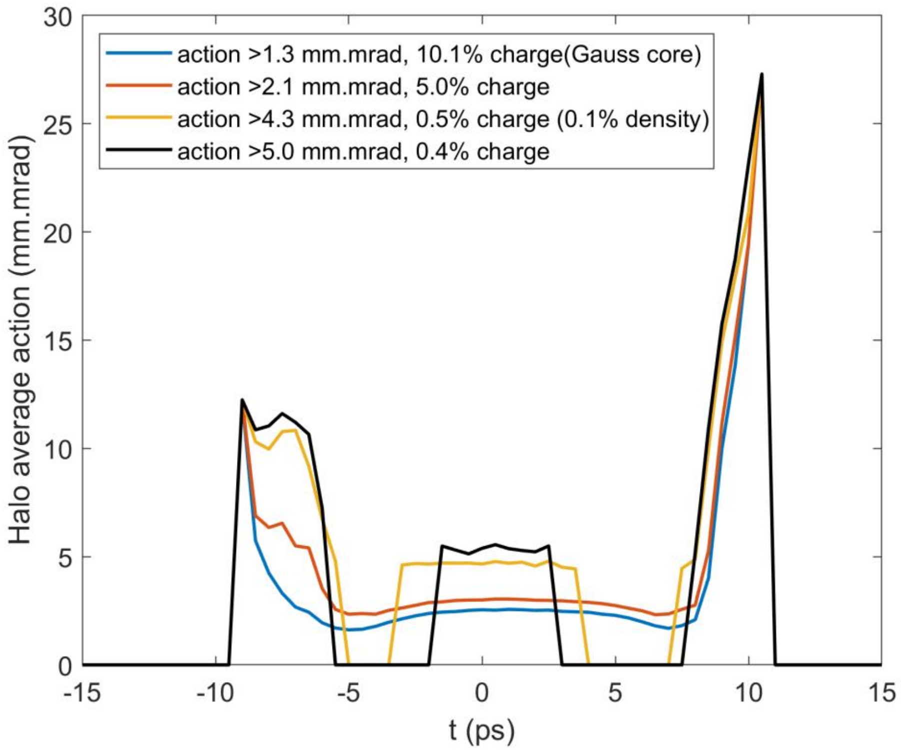




Q=250 pC

Flattop 10 ps FWHM, 2 ps rising edge, trans. Uniform



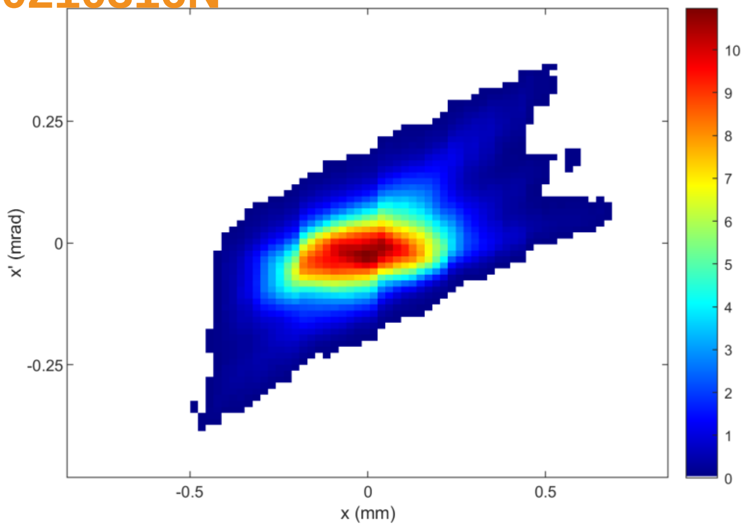


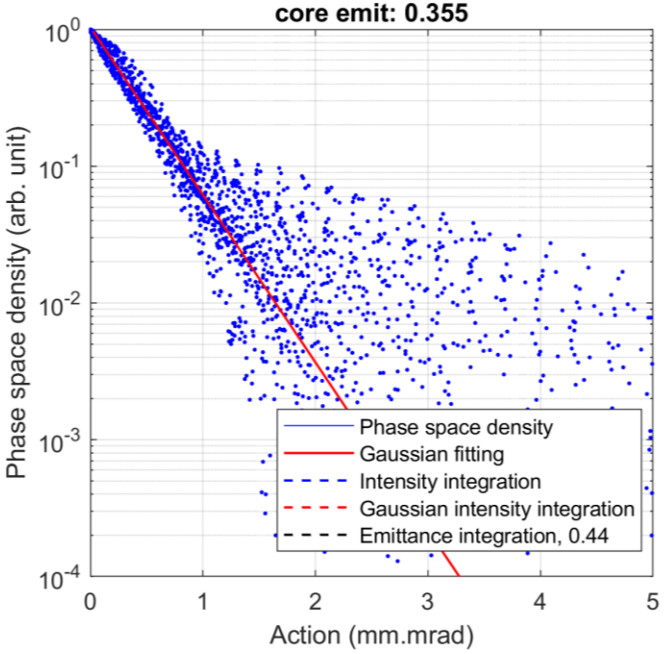
250 pC experiment data

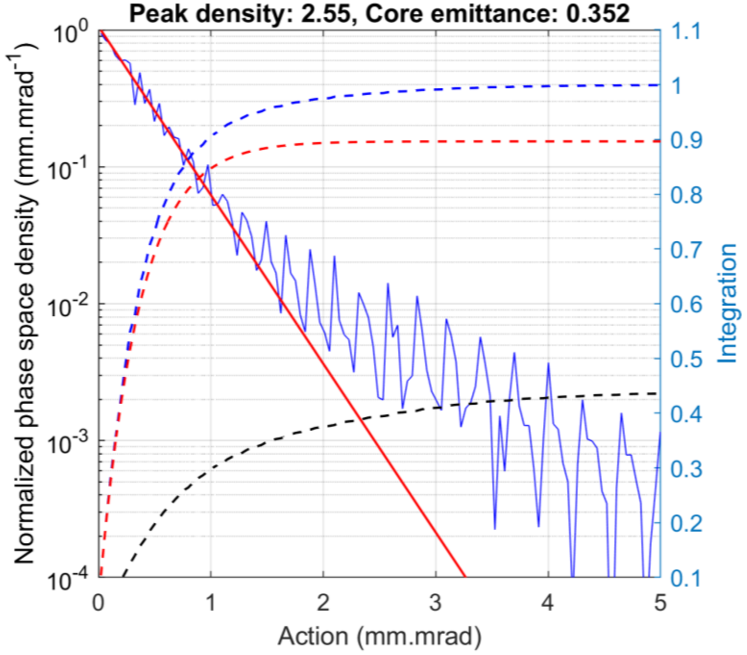
250 pC (Gaussian)

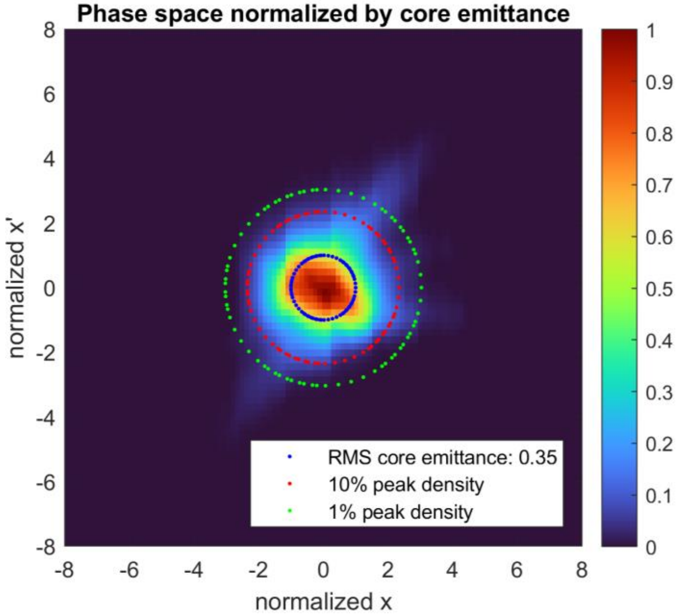
MBI ~7 ps FWHM, BSA1mm, 6.3 MeV/c

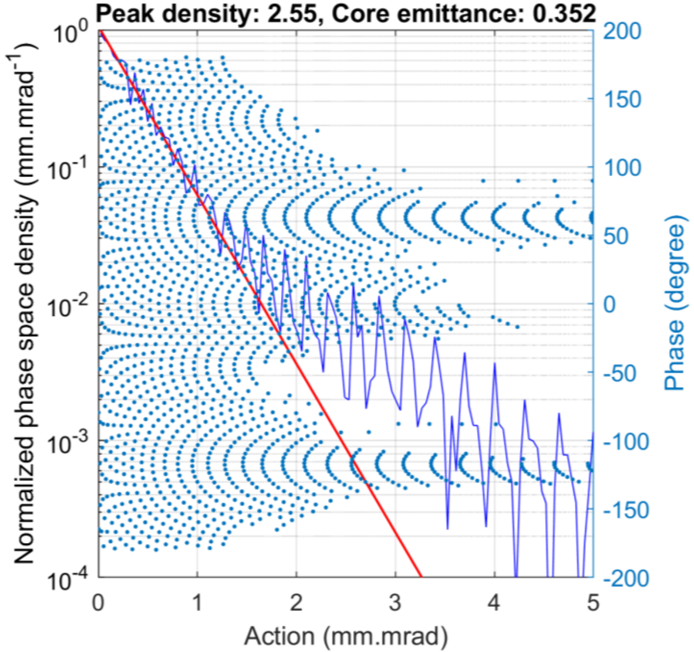
20210316N

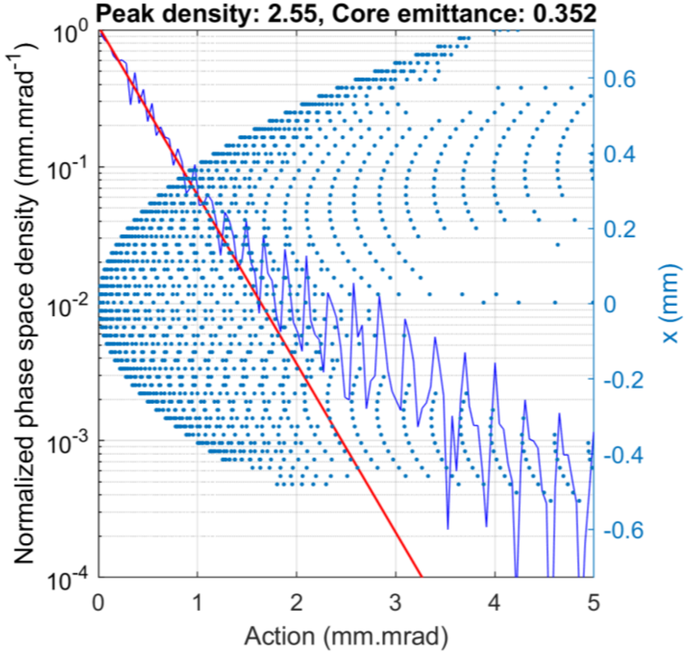












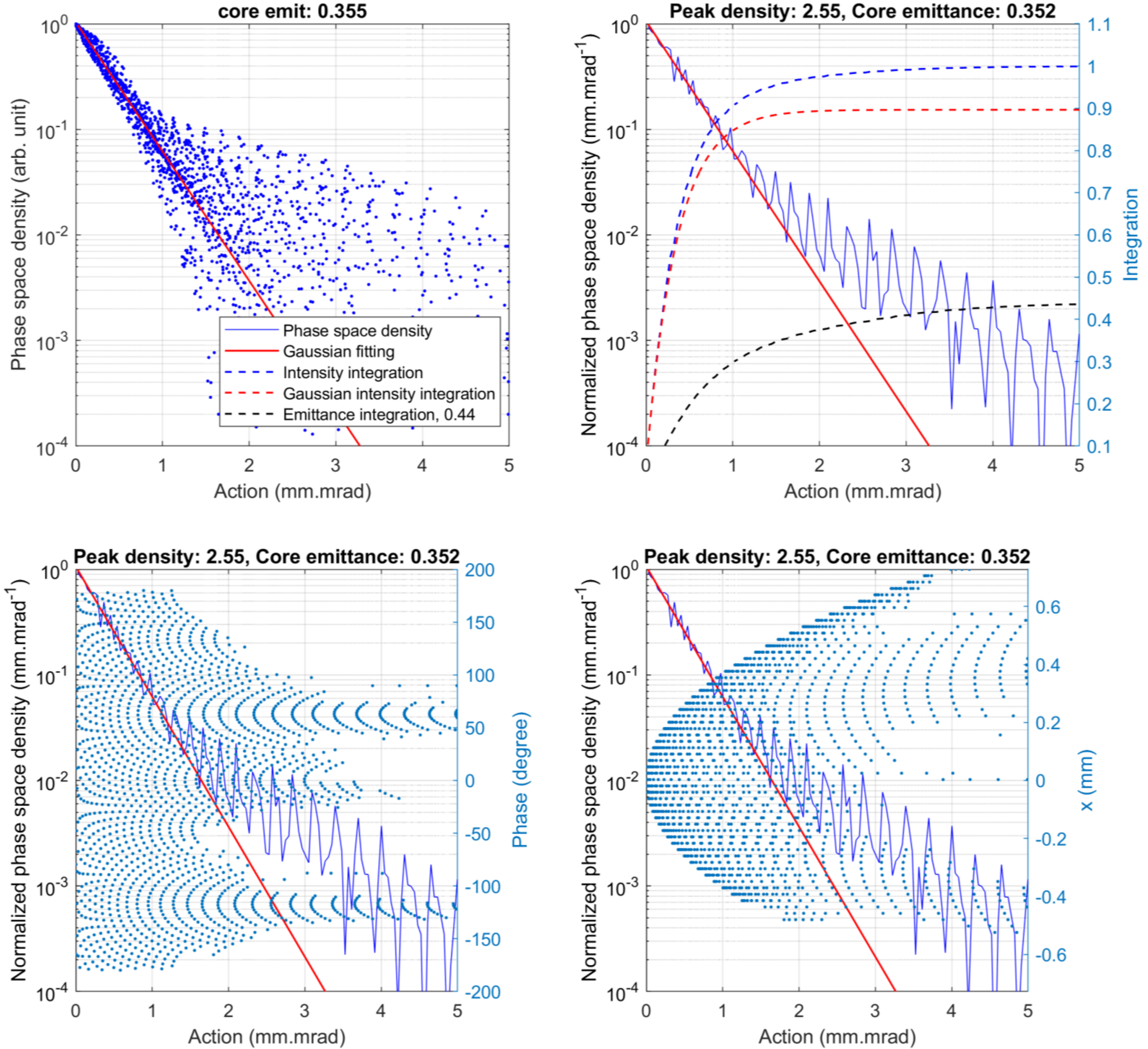
250 pC (Gaussian)

MBI ~7 ps FWHM, BSA1mm, 6.3 MeV/c
20210316N

	simu	exp	errbar
unscaled		0.46	0.01
scaled		0.55	0.01
Core	0.29	0.36	0.005
Peak density	3.00	2.53	0.11
Core ratio	86%	91%	

Assume measured phase space is 95% charge, i.e. 5% charge in halo below SNR is not measurable, then core raito:
91%*0.95→ 86%, fits simulations!

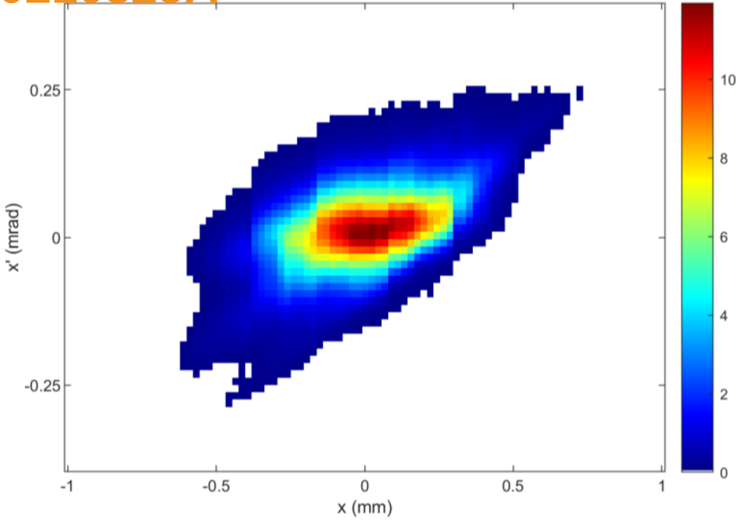
	simu	exp	errbar
unscaled		0.46	0.01
scaled		0.55	0.01
Core	0.29	0.36	0.005
Peak density	3.00	2.4	0.1
Core ratio	86%	86%	

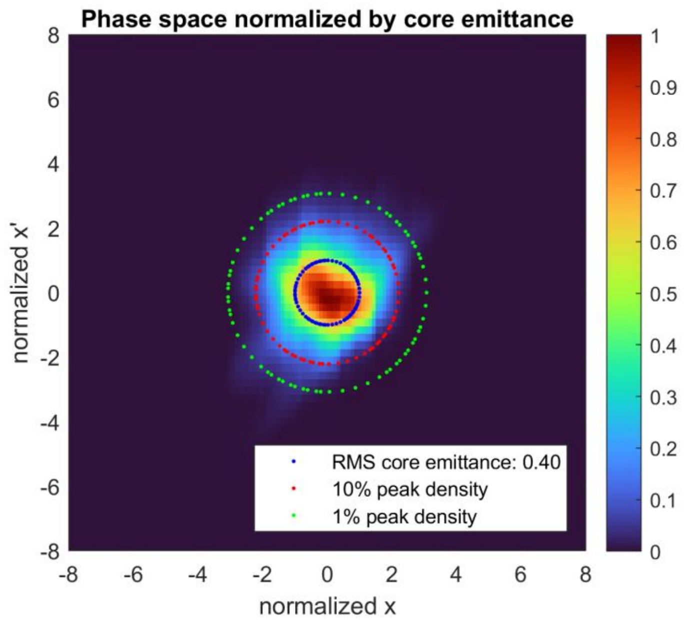


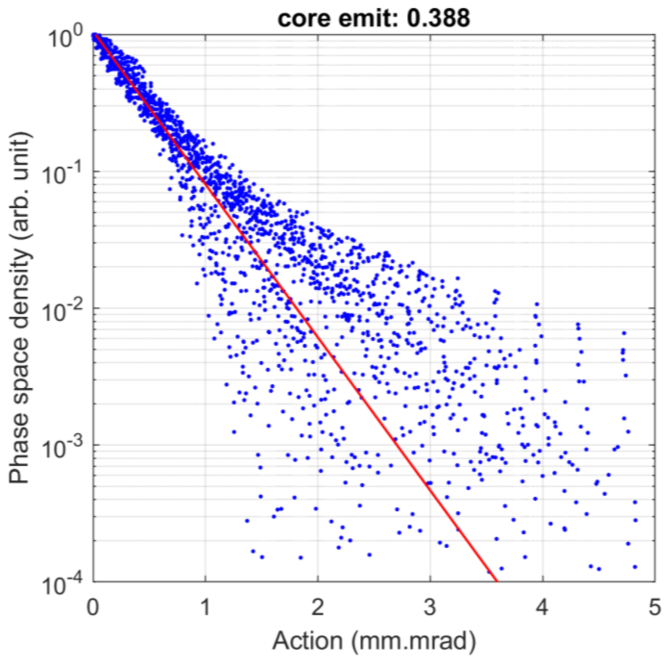
250 pC (Flattop)

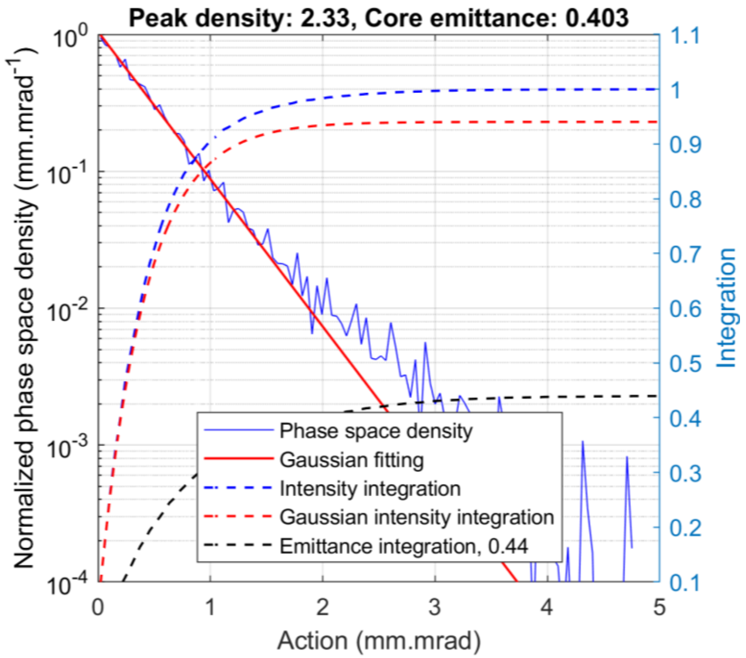
PHAROS~10 ps, BSA1mm, 6.3 MeV/c

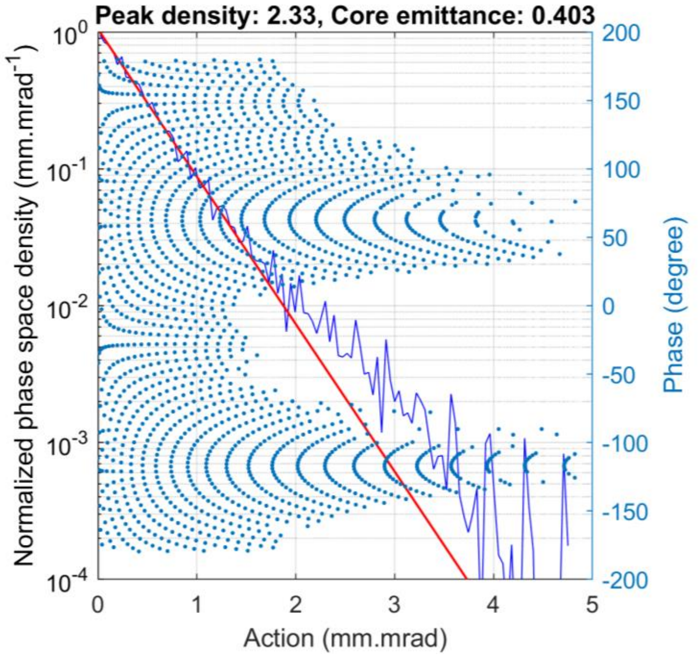
20210325A

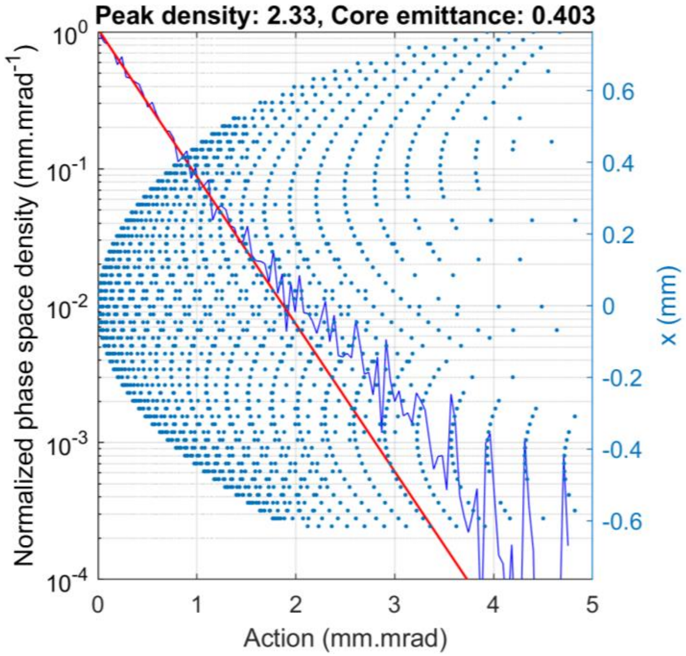












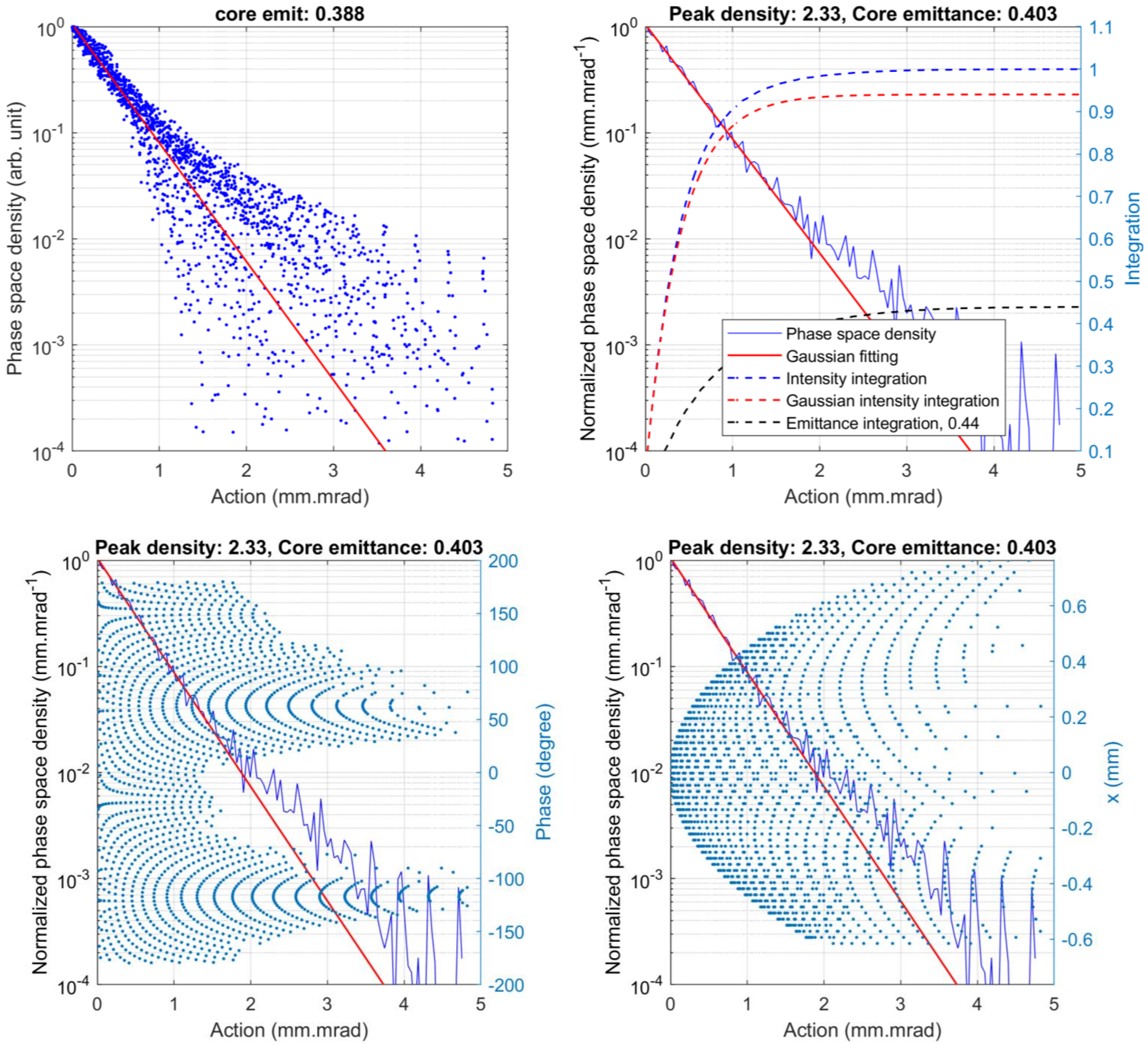
250 pC (Flattop)

PHAROS~10 ps, BSA1mm, 6.3 MeV/c
20210325A

	simu	exp	errbar
unscaled		0.45	0.01
scaled		0.52	0.01
Core	0.29	0.41	0.01
Peak density	3.06	2.31	0.03
Core ratio	90%	94%	

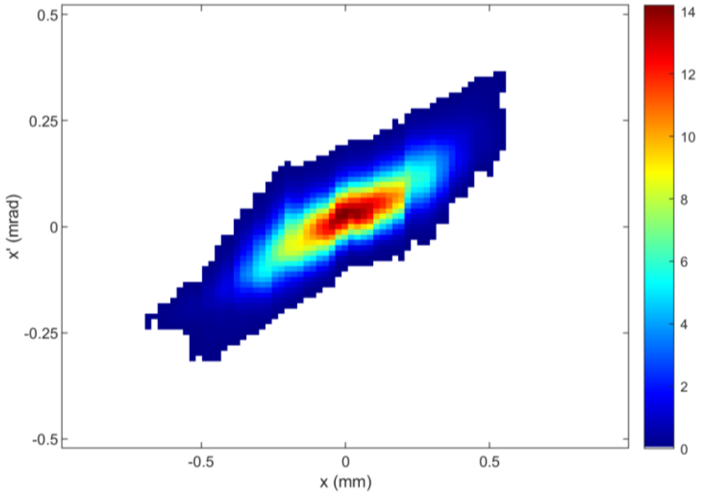
Assume measured phase space is 95% charge, i.e. 5% charge in halo below SNR, not measurable, then core raito:
94%*0.95→ 89.3%

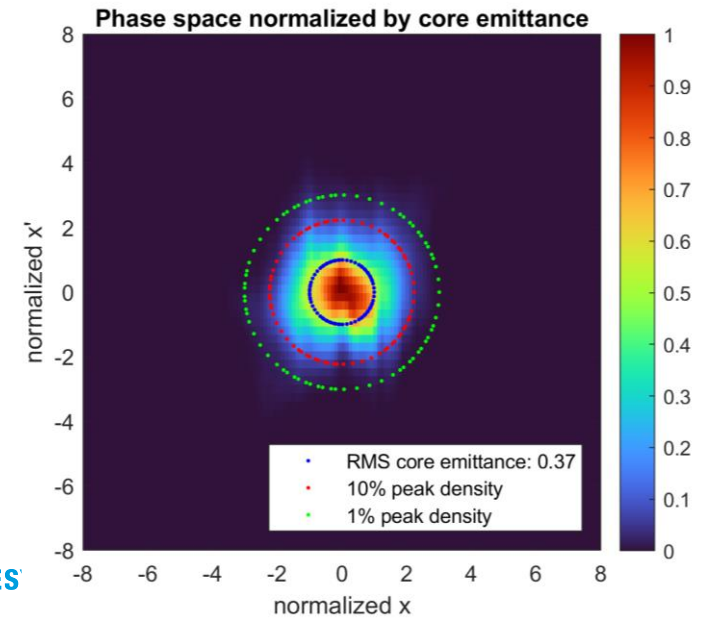
	simu	exp	errbar
unscaled		0.45	0.01
scaled		0.52	0.01
Core	0.29	0.41	0.01
Peak density	3.06	2.19	0.03
Core ratio	90%	89.3%	

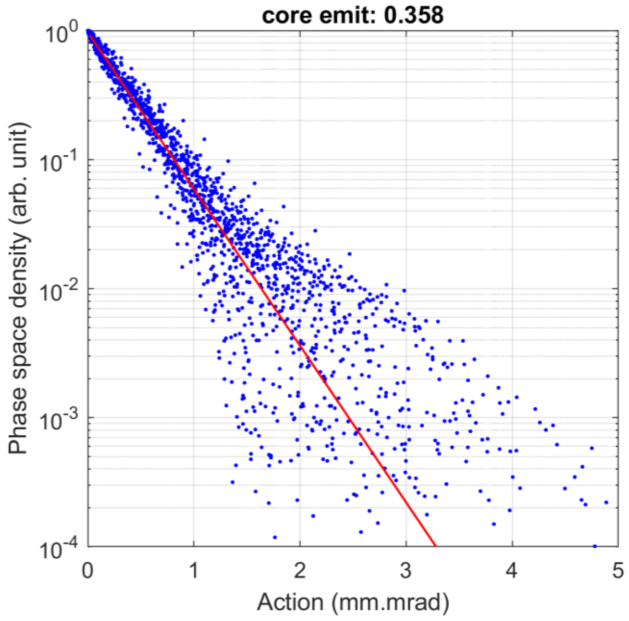


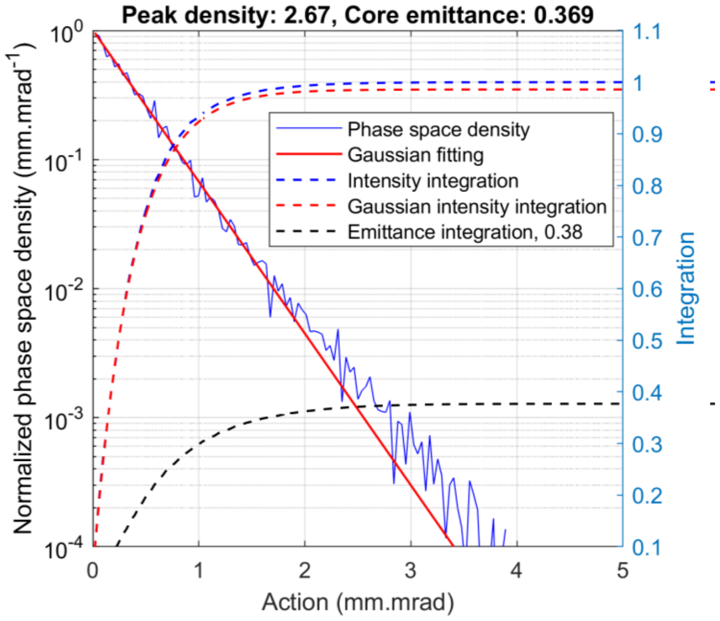
250 pC (1σ truncation)

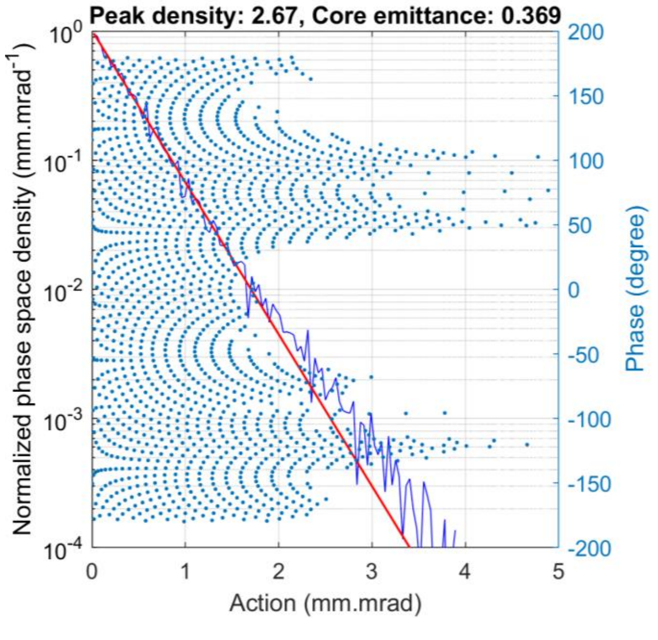
MBI ~7 ps FWHM, BSA1mm, 6.3 MeV/c
20191218A

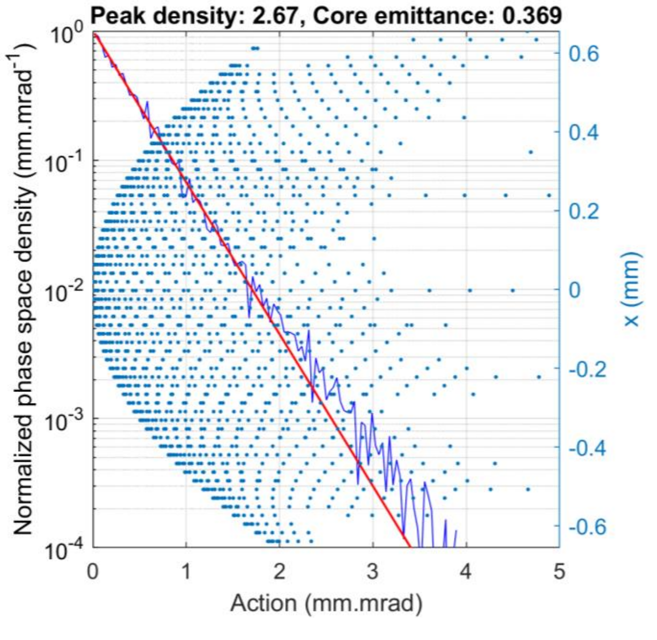












250 pC (1σ truncation)

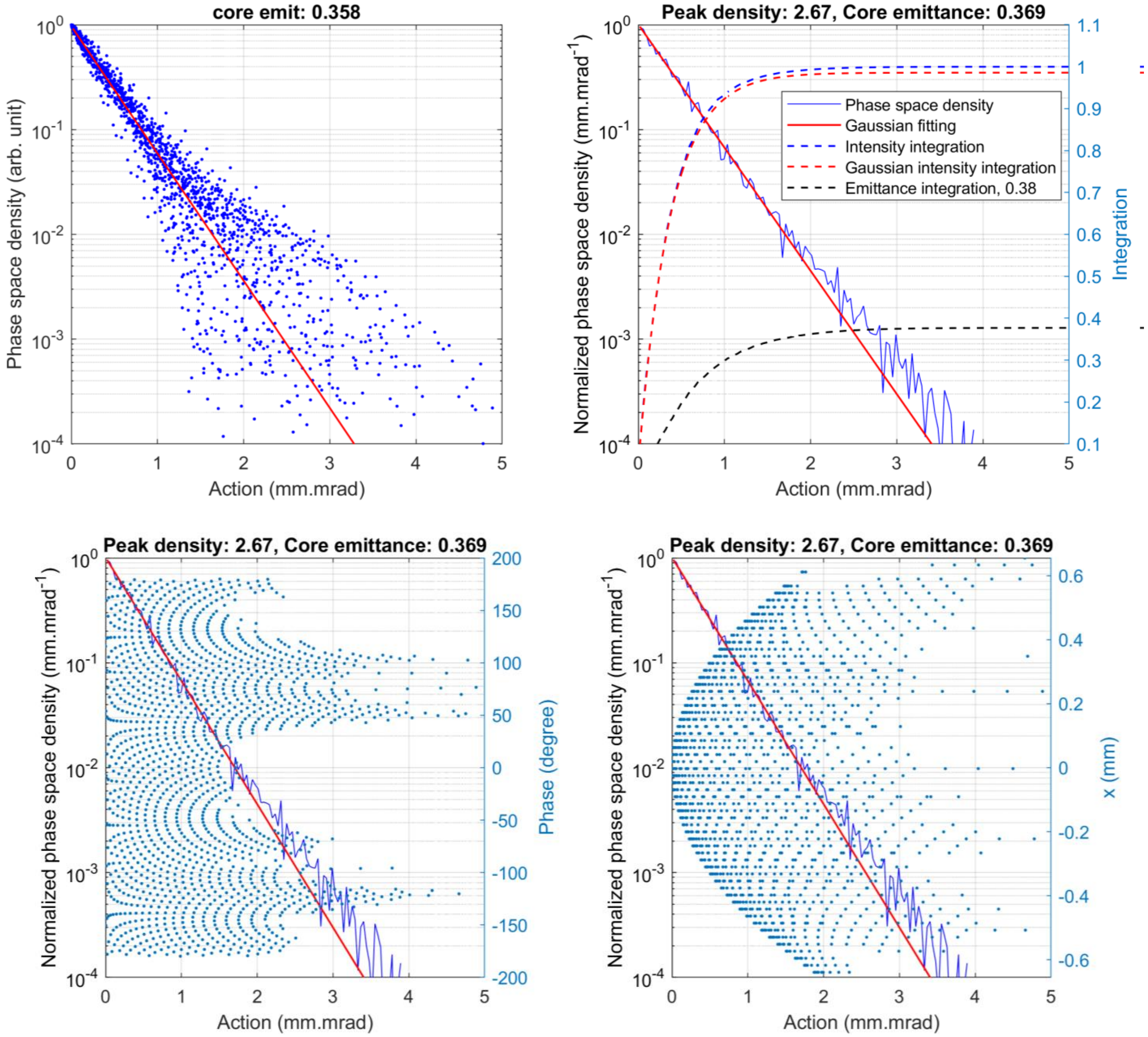
MBI ~7 ps FWHM, BSA1mm, 6.3 MeV/c
20191218A

	simu	exp	errbar
unscaled		0.38	0.004
scaled		0.44	0.007
Core	0.31	0.37	0.01
Peak density	3.0	2.64	0.10
Core ratio	88.6%	98%	

Assume measured phase space is 95% charge, i.e. 5% charge in halo below SNR, not measurable, then core raito:
98%*0.95→ 93%

	simu	exp	errbar
unscaled		0.38	0.004
scaled		0.44	0.007
Core	0.31	0.37	0.01
Peak density	3.0	2.51	0.10
Core ratio	88.6%	93%	

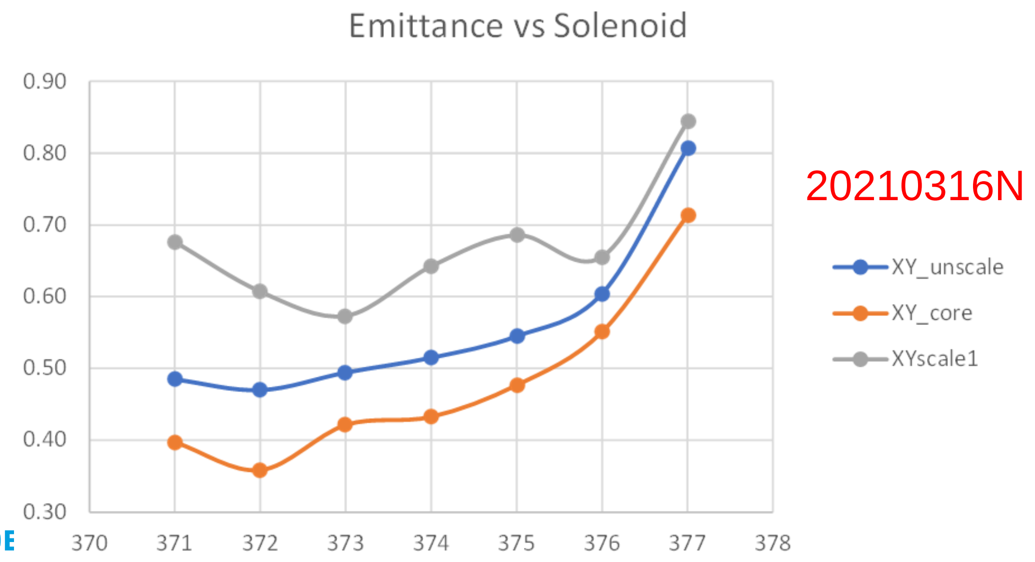
Core ratio is 4% higher

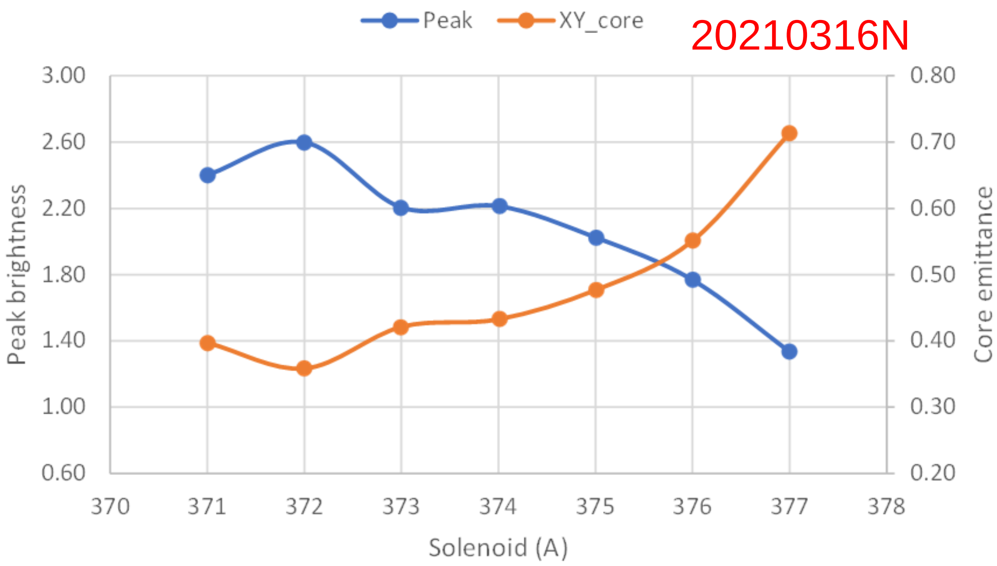


250 pC solenoid scan with MBI Gaussian laser

Good emittance measurements

- Since 07.2019
  - 0 dB camera gain, 2000 pixel intensity
  - 50 um slit for solenoid scan
- Consistently reach 0.35-0.4 mm.mrad core emittance at optimum solenoid point.
- Core emittance and unscaled emittance reach min at same solenoid point, saled emittance is a bit off in solenoid point.



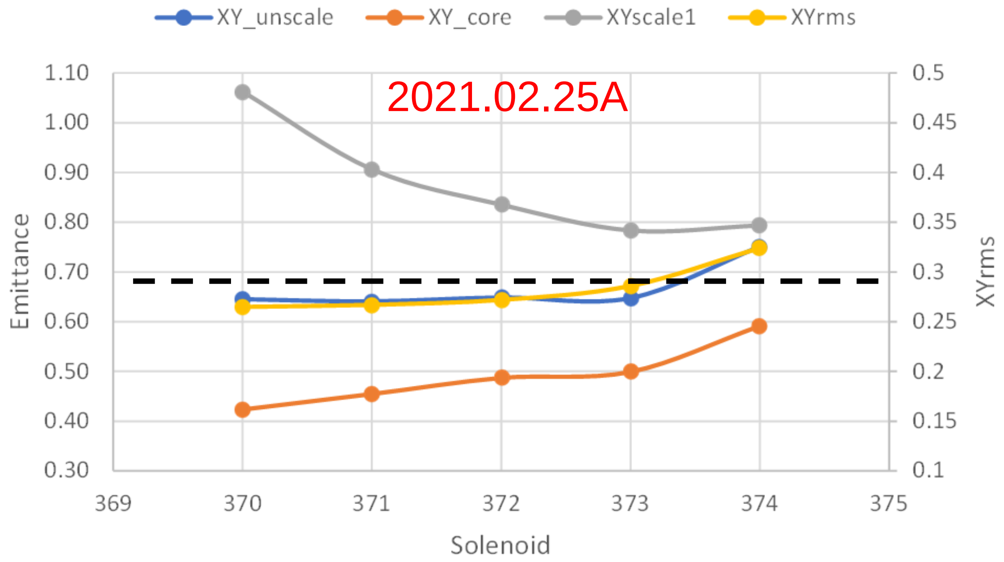


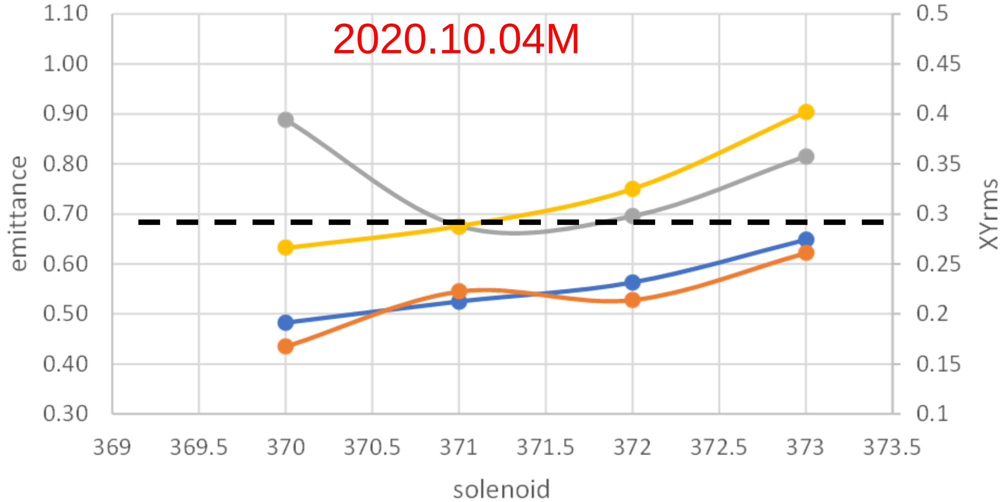
DE

250 pC solenoid scan with MBI Gaussian laser

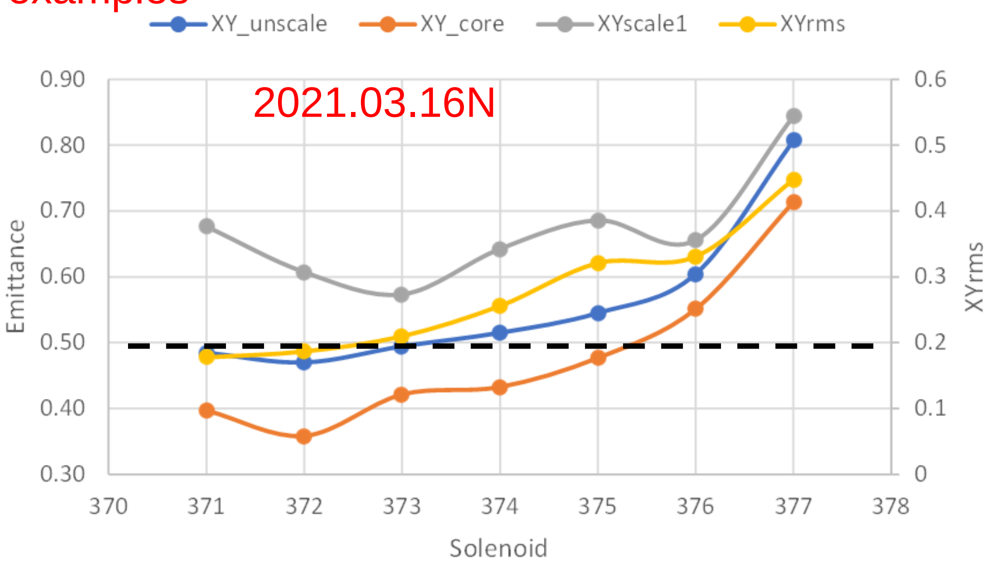
Bad emittance days vs good emittance days

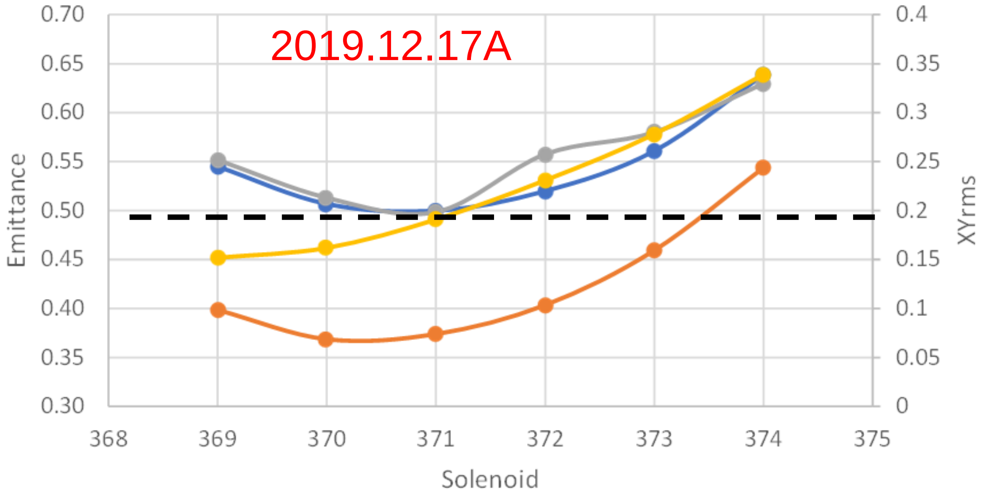
Bad examples





Good examples





250 pC solenoid scan with MBI Gaussian laser

Bad emittance days vs good emittance days

- Good emittance observations
  - High1.scr1 XYrms~0.2 mm
  - Scaled emittance, unscaled emittance and core emittance best point overlaps, max 1 A difference
  - Min emittance (same solenoid)
    - Scaled emittance 0.5-0.6 mm.mrad
    - Unscaled emittance ~0.5 mm.mrad
    - Core emittance 0.35-0.4 mm.mrad

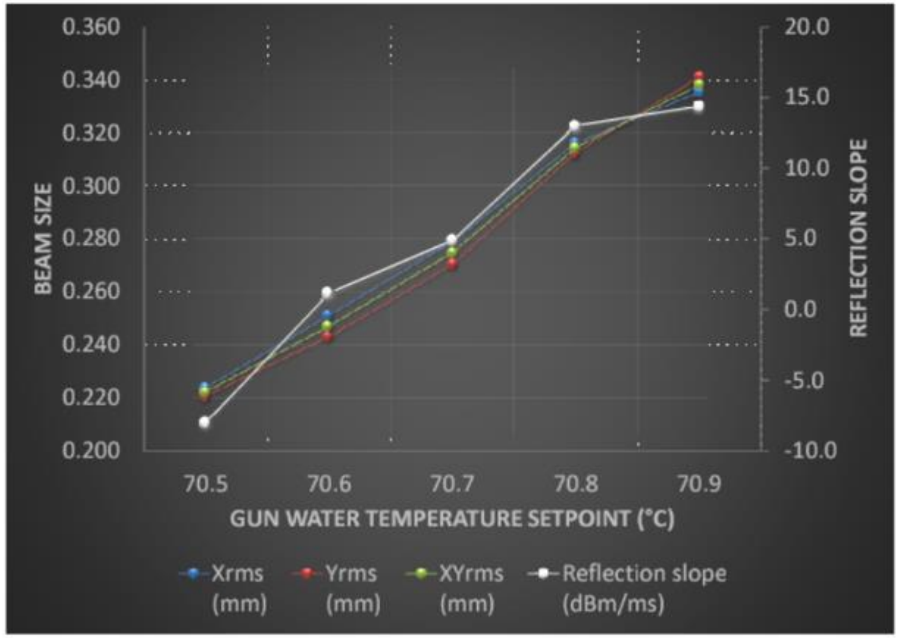
- Bad emittance observations
  - High1.scr1 XYrms~0.3 mm
  - Scaled emittance, unscaled emittance and core emittance best point do not overlap, 2~3 A difference
  - Scaling factor not reliable anymore, misleading emittance optimization?
  - Min emittance (not same solenoid)
    - Scaled emittance 0.7-0.8 mm.mrad
    - Unscaled emittance 0.5~0.65 mm.mrad
    - Core emittance 0.35-0.4 mm.mrad

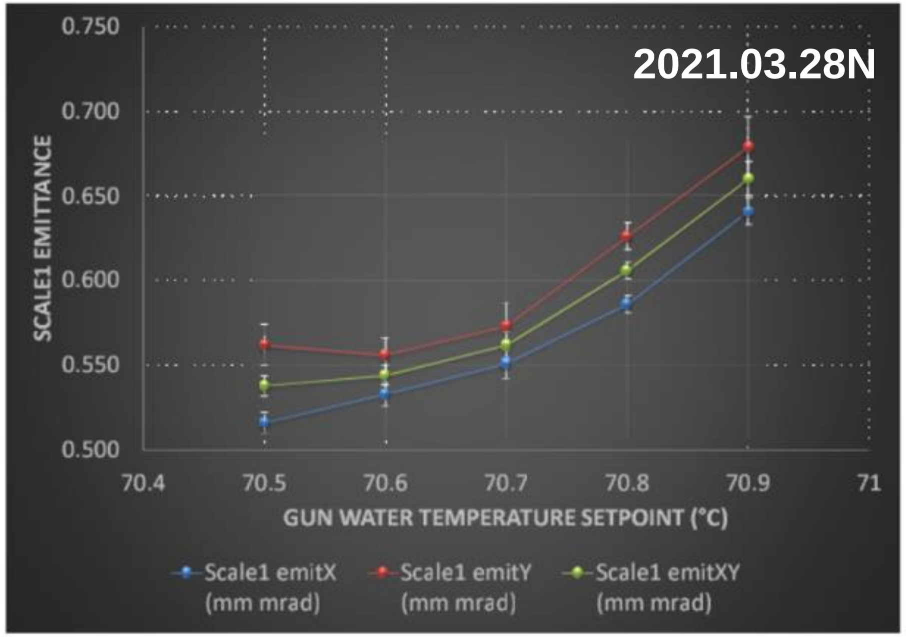
Emittance vs gun temperature, vs reflection

Higher RF reflection cause higher emittance?

High reflection cause bad emittance? Due to higher asymmetric field inside the coupler region? Or just RF focusing change due to higher reflection field inside coupler region? Take care of reflection slope during gun operation.

Gun temp SP (°C)	Xrms (mm)	Yrms (mm)	XYrms (mm)	Scale1 emitX (mm mrad)	Scale1 emitX error (mm mrad)	Scale1 emitY (mm mrad)	Scale1 emitY error (mm mrad)	Scale1 emitXY (mm mrad)	Scale1 emitXY error (mm mrad)	Reflection slope (dBm/ms)	Gun momentum (MeV/c)	Booster momentum (MeV/c)
70.5	0.224	0.221	0.222	0.516	0.006	0.562	0.012	0.538	0.006	-8.004	6.372	19.534
70.6	0.251	0.243	0.247	0.533	0.007	0.556	0.010	0.544	0.006	1.181	6.361	19.540
70.7	0.279	0.270	0.275	0.551	0.009	0.573	0.014	0.562	0.008	4.918	6.357	19.523
70.8	0.316	0.312	0.314	0.586	0.005	0.626	0.008	0.606	0.005	13.013	6.350	19.524
70.9	0.335	0.341	0.338	0.641	0.008	0.679	0.018	0.660	0.010	14.398	6.344	19.499





Is it just a focusing effect? Then why no better emittance after scanning solenoid?
RF dependent focusing from stronger reflection field? RF focusing asymmetry from reflection field due to the asymmetric coupler design? Higher coupler kick effect?

SNR of our slit scan

Why unscaled emittance corresponds to 95% simulated emittance?

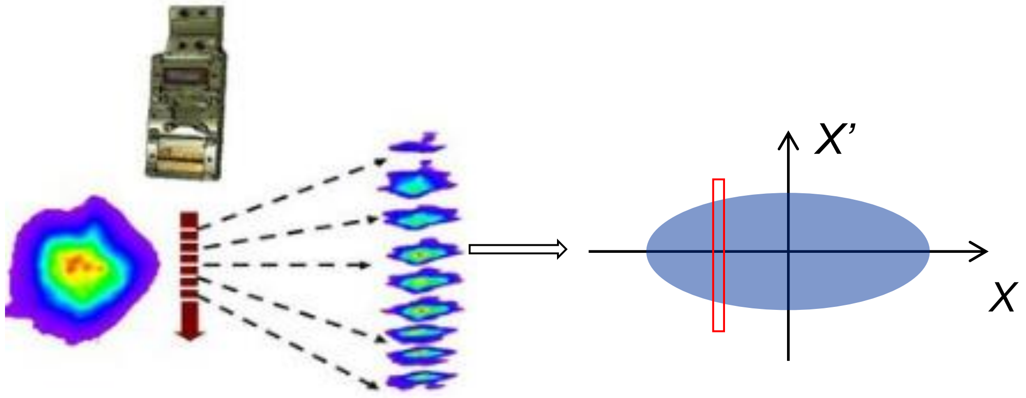
- Assume a gaussian model for simplification
  - Initial distribution at slit location

$$\rho(x,x') = \frac{Q}{2\pi\varepsilon} e^{-\frac{x^2}{2\sigma_x^2}-\frac{x'^2}{2\sigma_{x'}^2}}$$

  - Beamlet after slit

$$dQ(x_1,x') = \Delta_{slit}\frac{Q}{2\pi\varepsilon} e^{-\frac{x_1^2}{2\sigma_x^2}-\frac{x'^2}{2\sigma_{x'}^2}}$$

X1 is the slit location



- Beam after reaching measurement screen

$$dQ(x_1,x',y_2) = \Delta_{slit}\frac{Q}{2\pi\varepsilon} e^{-\frac{x_1^2}{2\sigma_x^2}-\frac{x'^2}{2\sigma_{x'}^2}} \frac{1}{\sqrt{2\pi}\sigma_y} e^{-\frac{y_2^2}{2\sigma_y^2}}$$

- Peak beamlet pixel signal when x1=0, x'=0, y2=0

$$Peak = \Delta_{slit}\frac{Q}{2\pi\varepsilon}\frac{1}{\sqrt{2\pi}\sigma_y}$$

- SNR defines the weakest beamlet pixel observable on measurement screen during slit scan

$$dQ(x_1,x',y_2) > \frac{Peak}{SNR} \qquad e^{-\frac{x_1^2}{2\sigma_x^2}} e^{-\frac{x'^2}{2\sigma_{x'}^2}} e^{-\frac{y_2^2}{2\sigma_y^2}} > \frac{1}{SNR}$$

$$\rho_{measured}(x_1,x') = \frac{Q}{2\pi\varepsilon} e^{-\frac{x_1^2}{2\sigma_x^2}-\frac{x'^2}{2\sigma_{x'}^2}} \operatorname{erf}(n)$$

$$n = \sqrt{\ln(SNR) - \frac{x_1^2}{2\sigma_x^2} - \frac{x'^2}{2\sigma_{x'}^2}}$$

SNR of our slit scan

Why unscaled emittance corresponds to 95% simulated emittance?

- Assume a gaussian model for simplification

$$\rho(x, x') = \frac{Q}{2\pi\varepsilon} e^{-\frac{x^2}{2\sigma_x^2} - \frac{x'^2}{2\sigma_{x'}^2}}$$

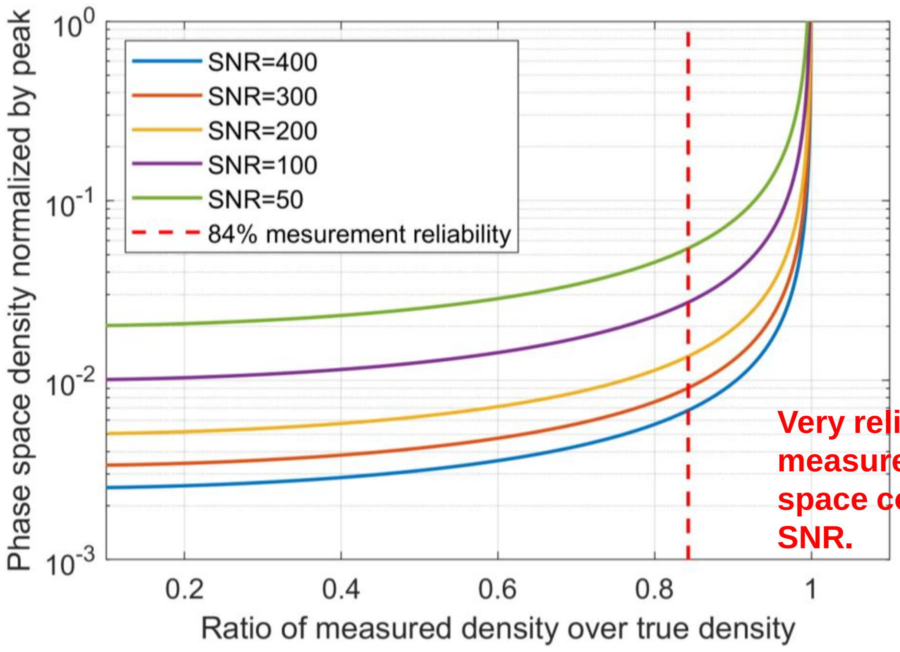
$$\rho_{measured}(x_1, x') = \frac{Q}{2\pi\varepsilon} e^{-\frac{x_1^2}{2\sigma_x^2} - \frac{x'^2}{2\sigma_{x'}^2}} \mathrm{erf}(n)$$

$$n = \sqrt{\ln(SNR) - \frac{x_1^2}{2\sigma_x^2} - \frac{x'^2}{2\sigma_{x'}^2}}$$

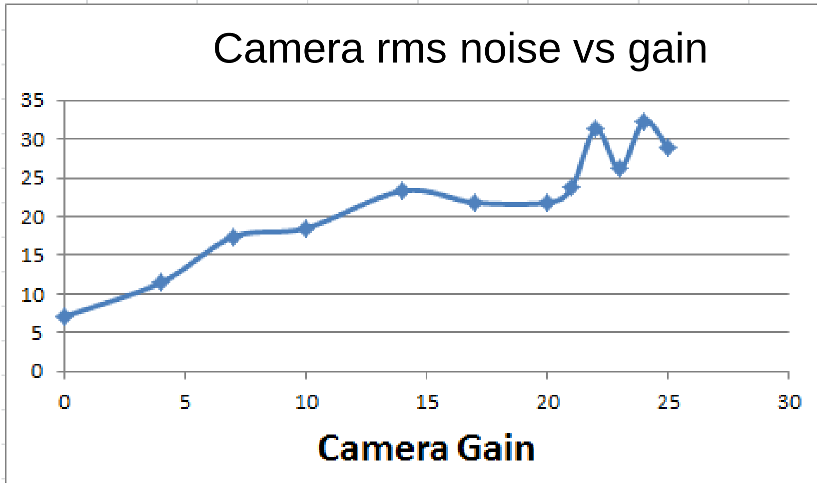
- Measured phase space density vs true density

$$\frac{\rho_{measured}}{\rho} = \mathrm{erf}(n)$$

- n>1, erf(1)>84% as a minimum criteria of reliable phase space density measurement
  - Then the lowest density measurable is $\frac{e}{SNR} = e\,\frac{\sigma_{noise}}{2000}$
  - Plug SNR=2000/8=250, then 10^{-2} density level can be measured.



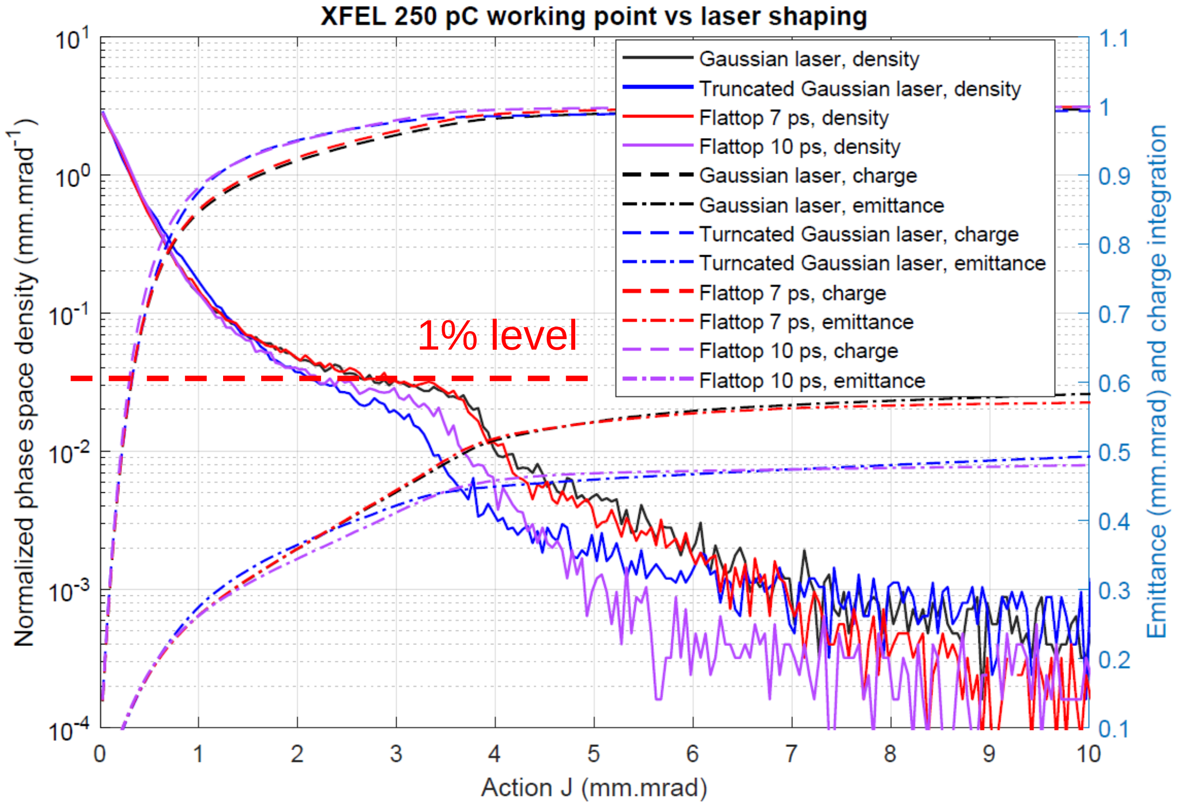
Very reliable measurement of phase space core area with our SNR.

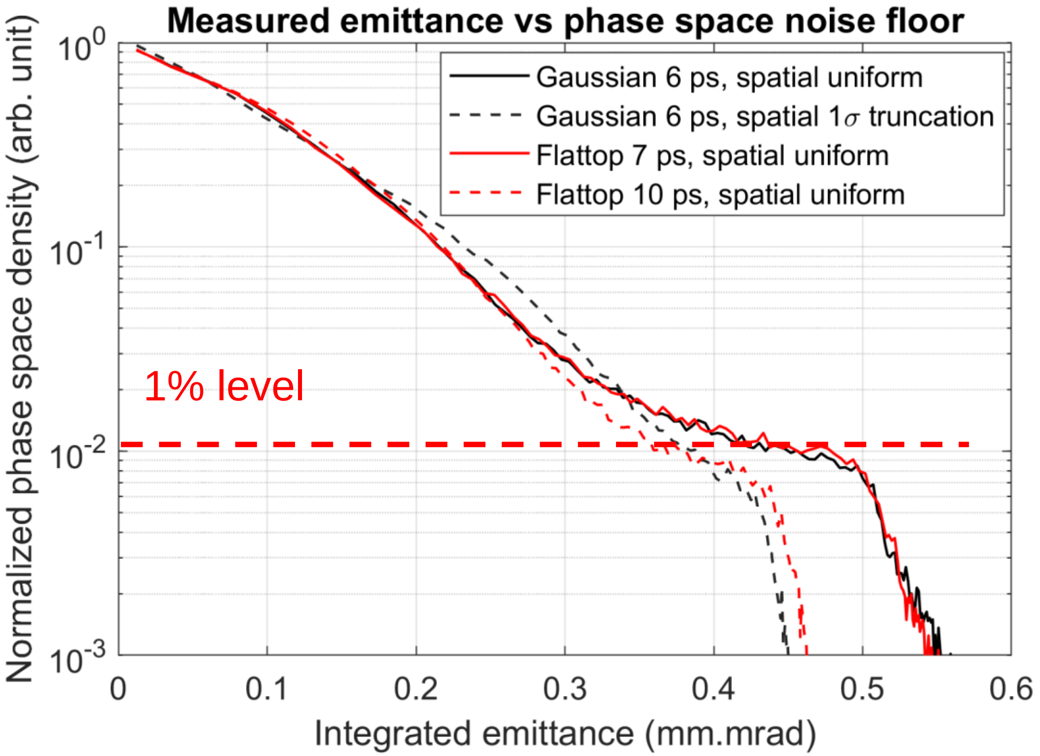


Emittance vs phase space density level

95% emittance for 1% density level

Simultions



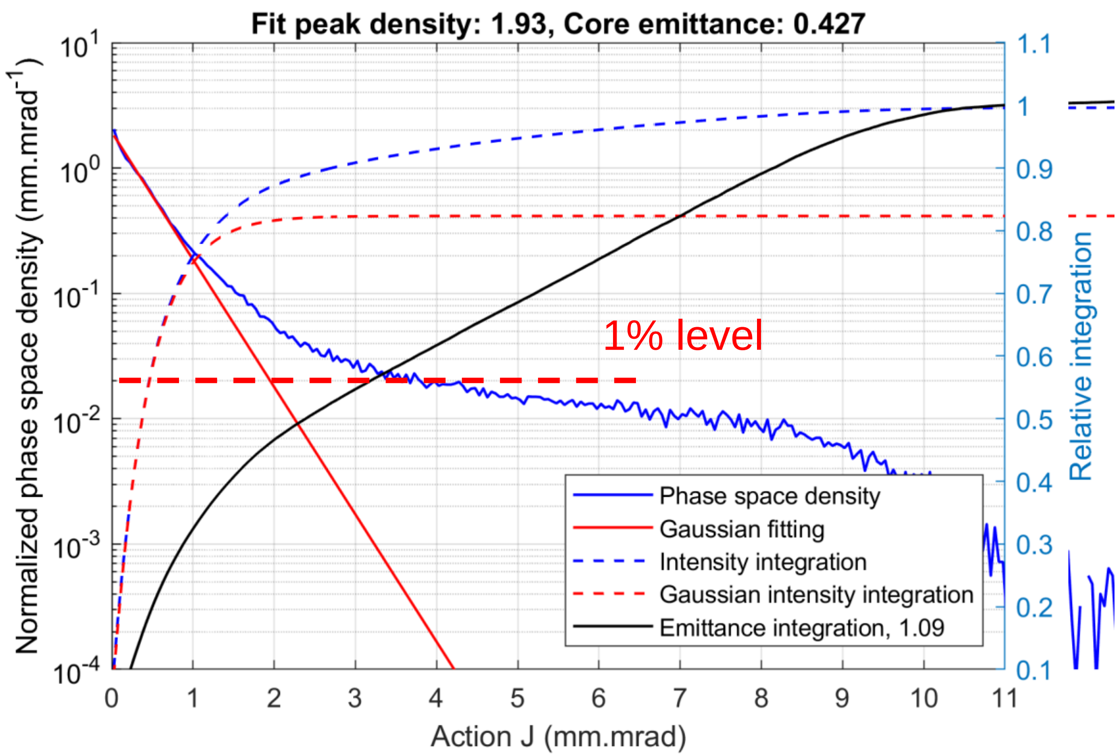


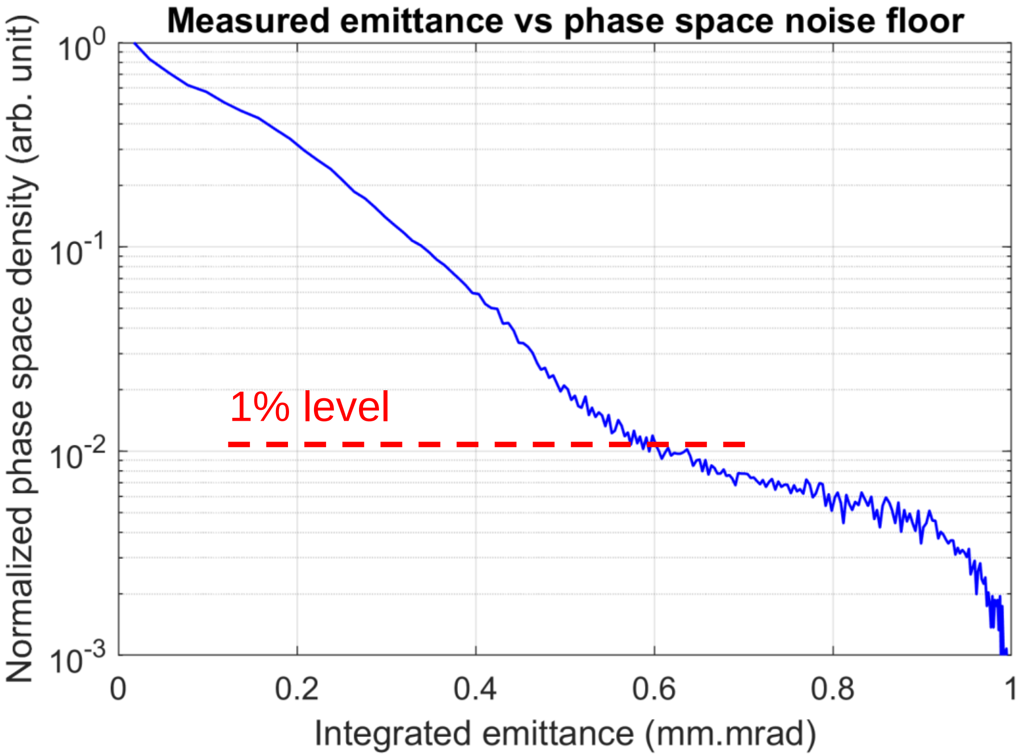
At 1% level, measured emittance is sensitive to SNR, i.e. rms noise.

What about 500 pC @XFEL working point

BSA1.3mm, 6~7 ps FWHM Gaussian, 6.3 MeV/c

Simultions





1% density level → 93% particles

1% density level → ~0.6 mm.mrad

What about 500 pC @XFEL working point

BSA1.3mm, 6~7 ps FWHM Gaussian, 6.3 MeV/c

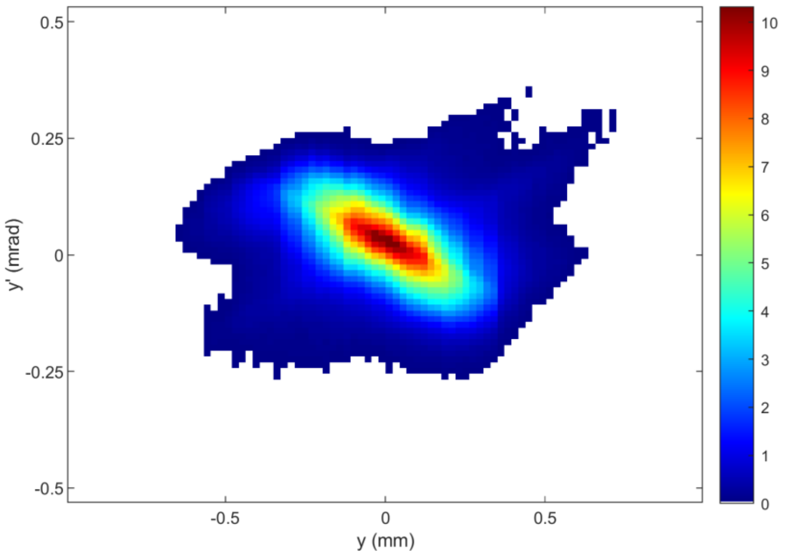
- 500 pC experiment

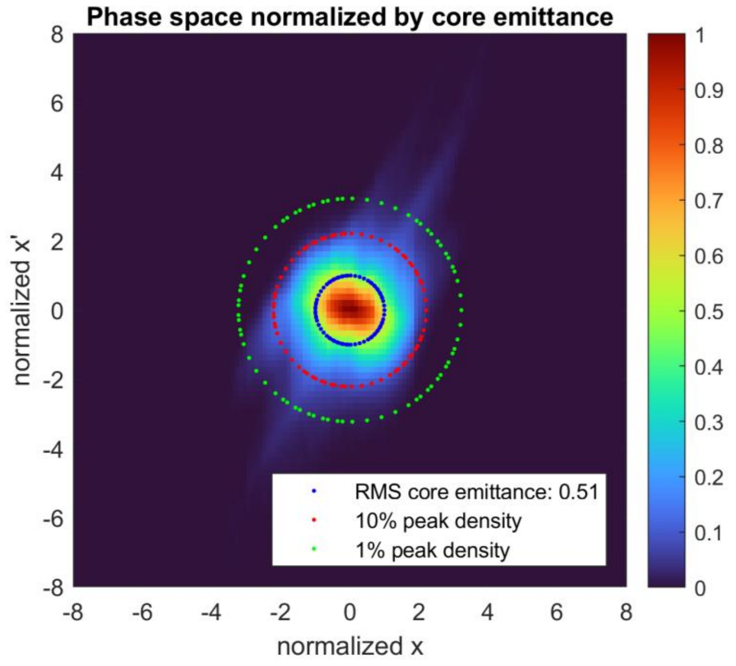
	simu	exp	errbar
unscaled		0.64	0.02
scaled		0.74	0.04
Core	0.427	0.51	0.001
Peak density	1.93	1.83	0.035
Core ratio	82%	93%	

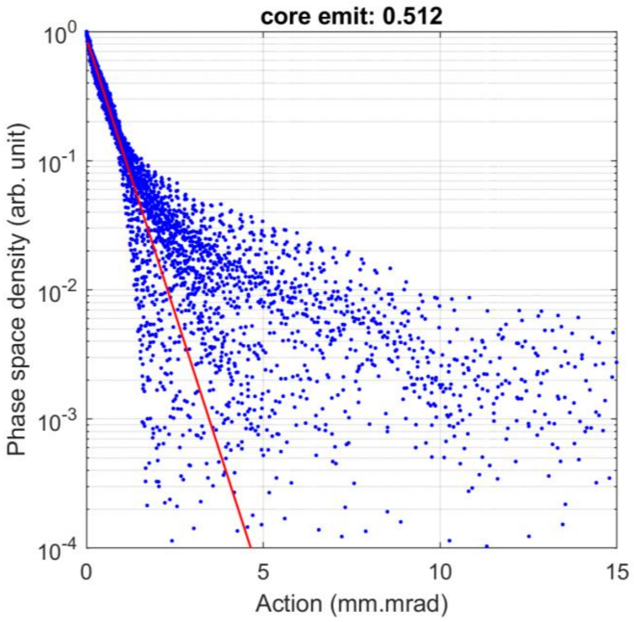
Assume measured phase space is 93% charge, i.e. 7% charge in halo below SNR, not measurable, then core raito:
93%*0.93→ 86%

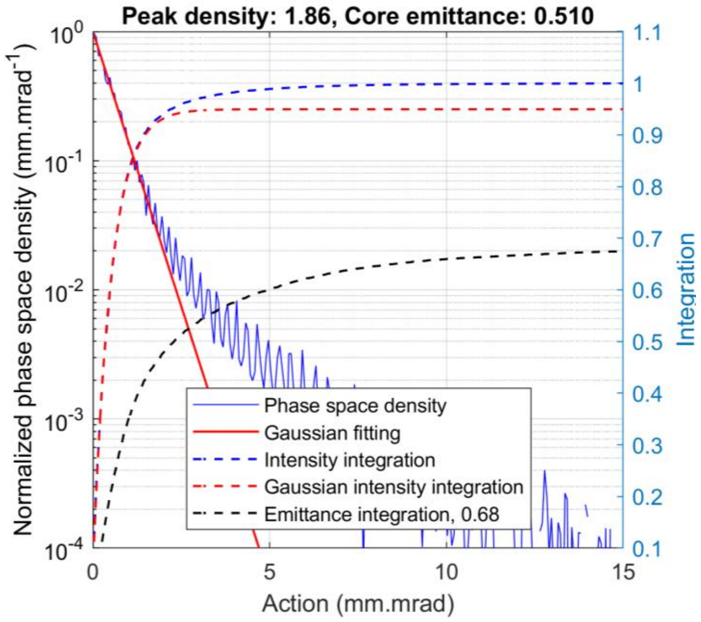
	simu	exp	errbar
unscaled		0.64	0.02
scaled		0.74	0.04
Core	0.427	0.51	0.001
Peak density	1.93	1.70	0.035
Core ratio	82%	86%	

Core ratio is 4% higher









Comparison between 250 pC to 500 pC

experiment data, Gaussian 6-7 ps laser, 6.3 MeV/c

- With Gaussian 6-7 ps laser

	250 pC Uniform	250 pC Flattop	250 pC Truncation	500 pC Uniform
unscaled	0.46	0.45	0.38	0.64
scaled	0.55	0.52	0.44	0.74
Core	0.36	0.41	0.37	0.51
Peak density	2.4	2.19	2.51	1.7
Core ratio	86%	89.3%	93%	86%

- 4D phase space peak brightness in normalized phase space
  - 250 pC*2.4/0.36 = 1667 pC/(mm.mrad)^2
  - 250 pC*2.19/0.41 = 1335 pC/(mm.mrad)^2 (FT 10 ps)
  - 250 pC*2.51/0.37 = 1695 pC/(mm.mrad)^2 (truncation)
  - 500 pC*1.7/0.51= 1667 pC/(mm.mrad)^2
  - Same electron peak density at 4D phase space!!

- 4D phase space density profile

$$\frac{dQ}{dJ_x dJ_y} = \frac{Q}{\varepsilon_{x_0}\varepsilon_{y_0}} \exp\left(-\frac{J_x}{\varepsilon_{x_0}} - \frac{J_y}{\varepsilon_{y_0}}\right)$$

  - Due to the same peak brightness, but higher core emittance of 500 pC than 250 pC, so density drops slower than 250 pC, within the same phase space area, average brightness is higher for 500 pC.

- Compared to simulations
  - 250 pC*3/0.29 = 2586 pC/(mm.mrad)^2
  - 500 pC*1.93/0.427 = 2260 pC/(mm.mrad)^2
  - 250 pC simulation peak brightness is 14% higher than 500 pC simulation
  - 250 pC simulation peak brightness is 55% higher than measurement
  - 500 pC simulation peak brightness is 36% higher than measurement

Summary

Ps: Brightness in this talk is transverse brightness.

- A new method is used to analyze transverse phase space density and emittance for both simulations and experiments.
- Based on the SNR of 250 for slit scan, up to 1% level peak phase space density can be reliably measured. This leads to a ~95% emittance measured without scaling from EMSY1 beam size.
- Core emittance in the center can be very reliably measured with our current SNR, very similar between different laser shaping.
- Measured unscaled emittance fits 95% emittance very well, but also sensitive to SNR variations.
- When have bad emittance, emittance scaling by EMSY1 beam size misleads emittance optimizations. Bad emittance after many optimizations can be due to high RF reflection when gun temperature is not set properly
- For 250 pC, PITZ unscaled emittance is ~95% emittance. Scaled emittance is in between 95% and 100% emittance. XFEL injector uses gaussian model to fit beam size instead of RMS size, so their emittance probably is more close to 95% emittance or lower.
- 500 pC has same measured peak brightness as 250 pC, both are worse than simulations by 30-50%.